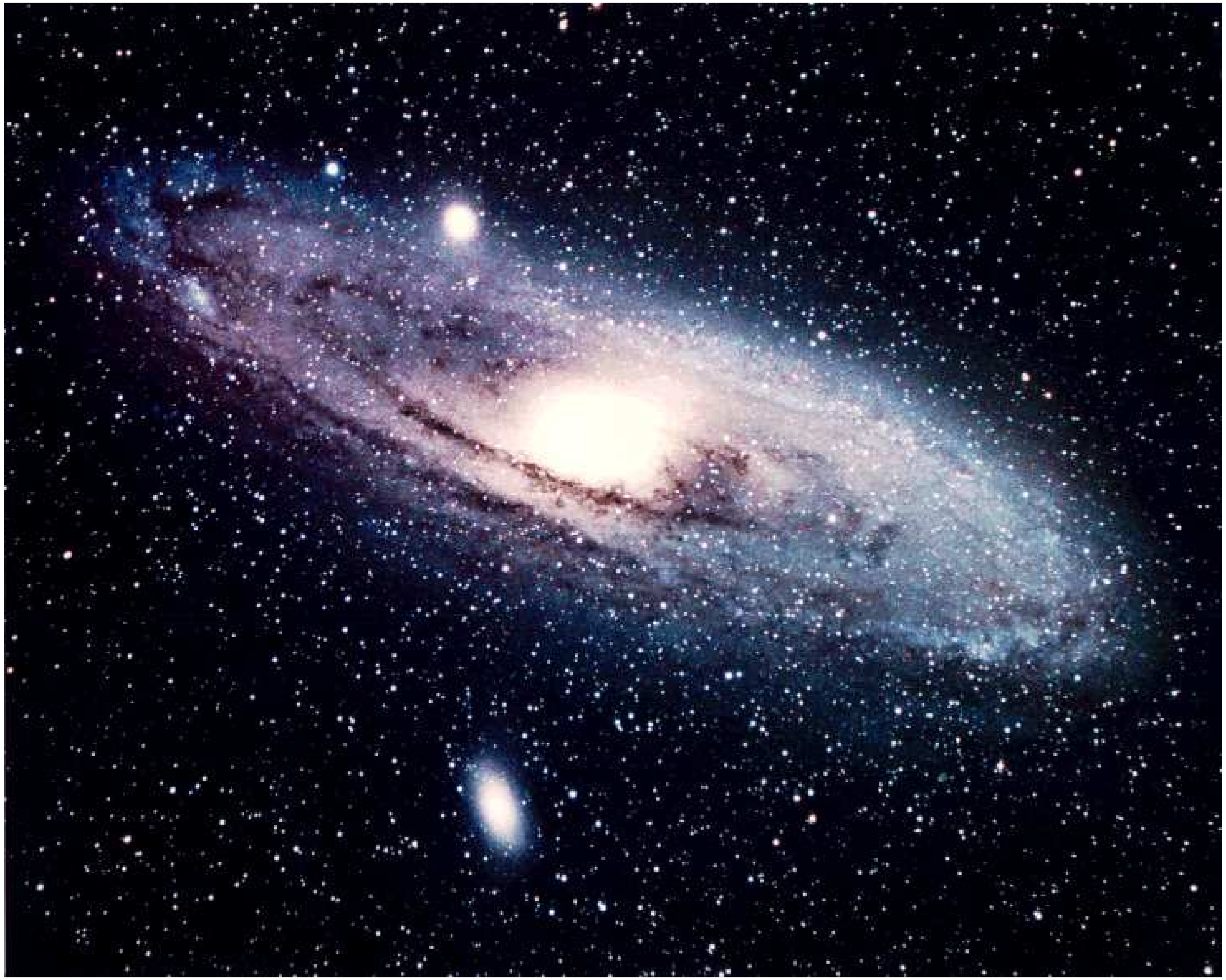
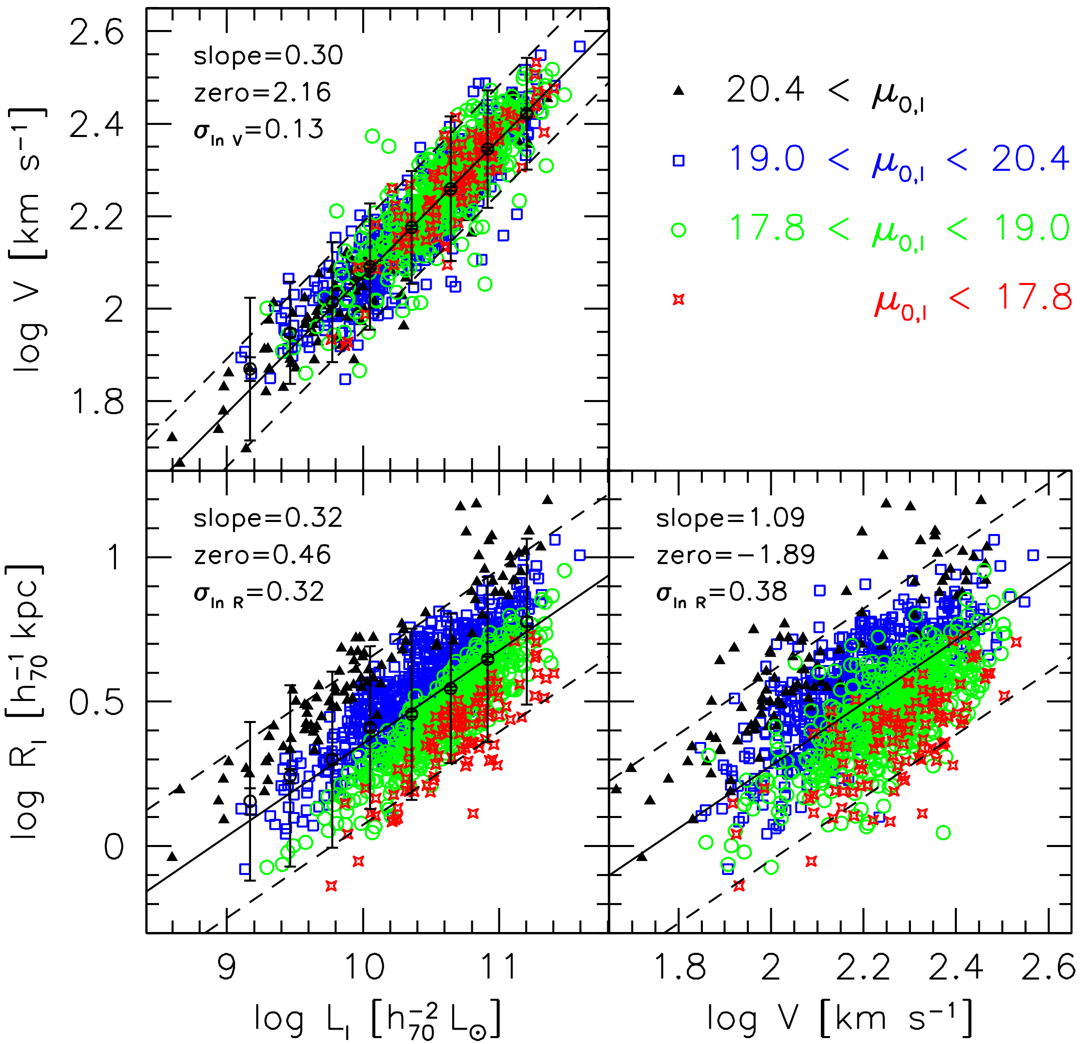
The Formation of Disk Galaxies



Frank van den Bosch, Aaron Dutton, Avishai Dekel & Stephane Courteau

astro-ph/0604553

Disk Scaling Relations



Sample of ~ 1300 galaxies with Hα RCs (Courteau et al. 2006)

Rotation velocities measured at $2.2R_I$

Uniform inclincation and extinction corrections

The Standard Picture

Disks galaxies are systems in centrifugal equilibrium

Structure of disks is governed by angular momentum content

The Three Pillars of Disk Formation

- **Angular momentum originates from cosmological torques**
- **Baryons and Dark Matter acquire identical angular momentum distributions.**
- **During cooling, gas conserves its specific angular momentum**

Gas settles in disk in centrifugal equilibrium

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

It is assumed that DM halo contracts in response to formation of disk

Model Description

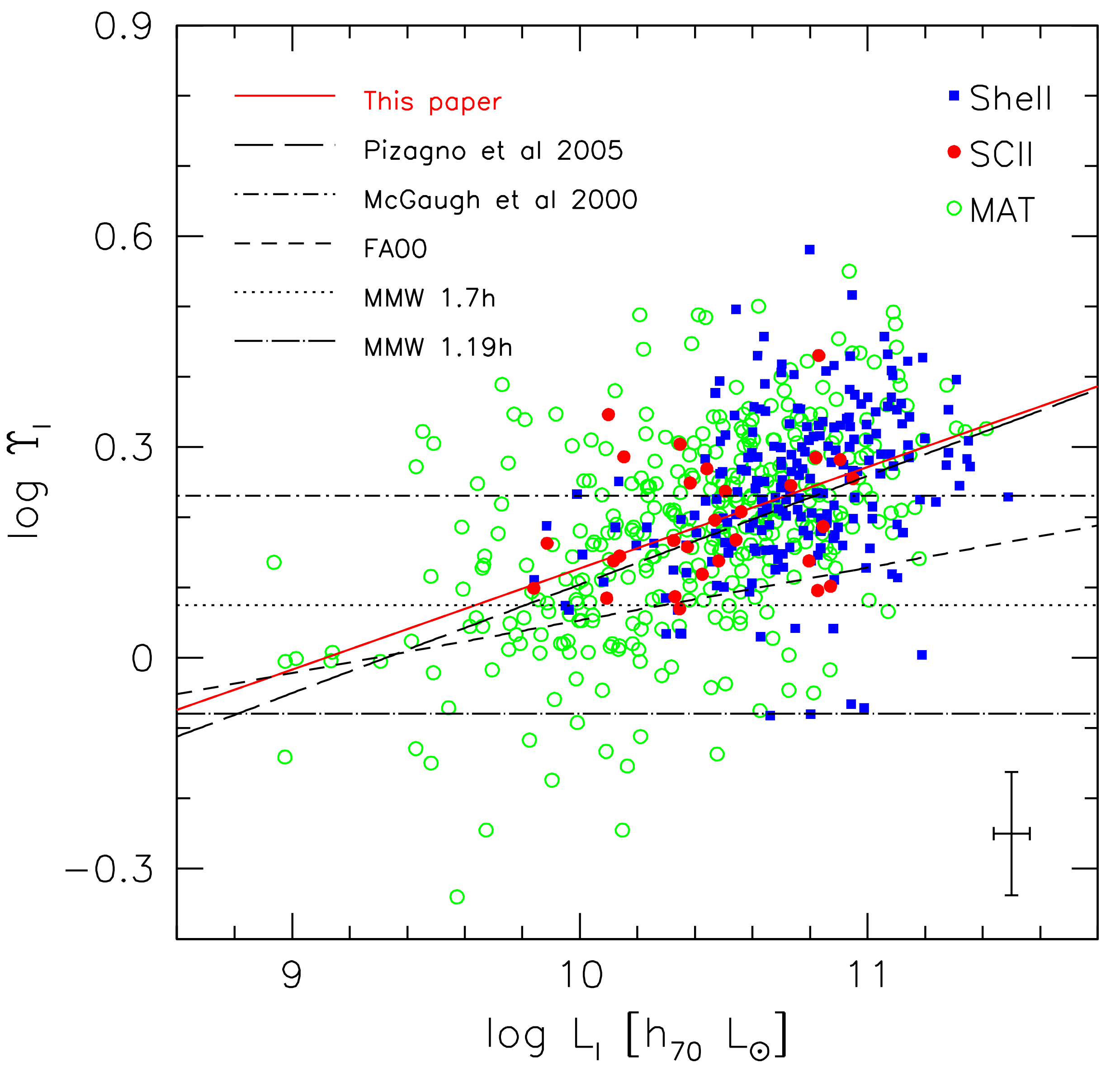
- Exponential disk in NFW dark matter halo (Mo, Mao & White 1998)
  Halo concentrations modelled as $c(M) = \eta \, c_{\rm bul}(M)$
- Modified Adiabatic contraction: $r_f = \Gamma^\nu r_i$
  Standard AC: $\nu = 1$, No AC: $\nu = 0$, Expansion: $\nu < 0$
- Disk mass fraction: $m_{\rm gal} \equiv \frac{M_{\rm gal}}{M_{\rm vir}} = m_{\rm gal,0} \left(\frac{M_{\rm vir}}{10^{11.5} h^{-1} \, {\rm M}_\odot} \right)^\alpha$
- Disk is split in stars and cold gas using star formation threshold density
  Material with $\Sigma(R) > \Sigma_{\rm crit}(R)$ is assumed to be in stars
- Bulge formation based on disk stability (van den Bosch 1998)
- Stellar mass-to-light ratios obtained from colors (Bell et al. 2003)

$$\log \frac{\Upsilon}{[\,({\rm M/L})_\odot]} = 0.172 + 0.144 \log \frac{L_I}{[10^{10.3} h_{70}^2 \, {\rm L}_\odot]} + \Delta_{\rm IMF}$$

e.g., Diet-Salpeter: $\Delta_{\rm IMF} = 0$ Kroupa: $\Delta_{\rm IMF} = -0.20$

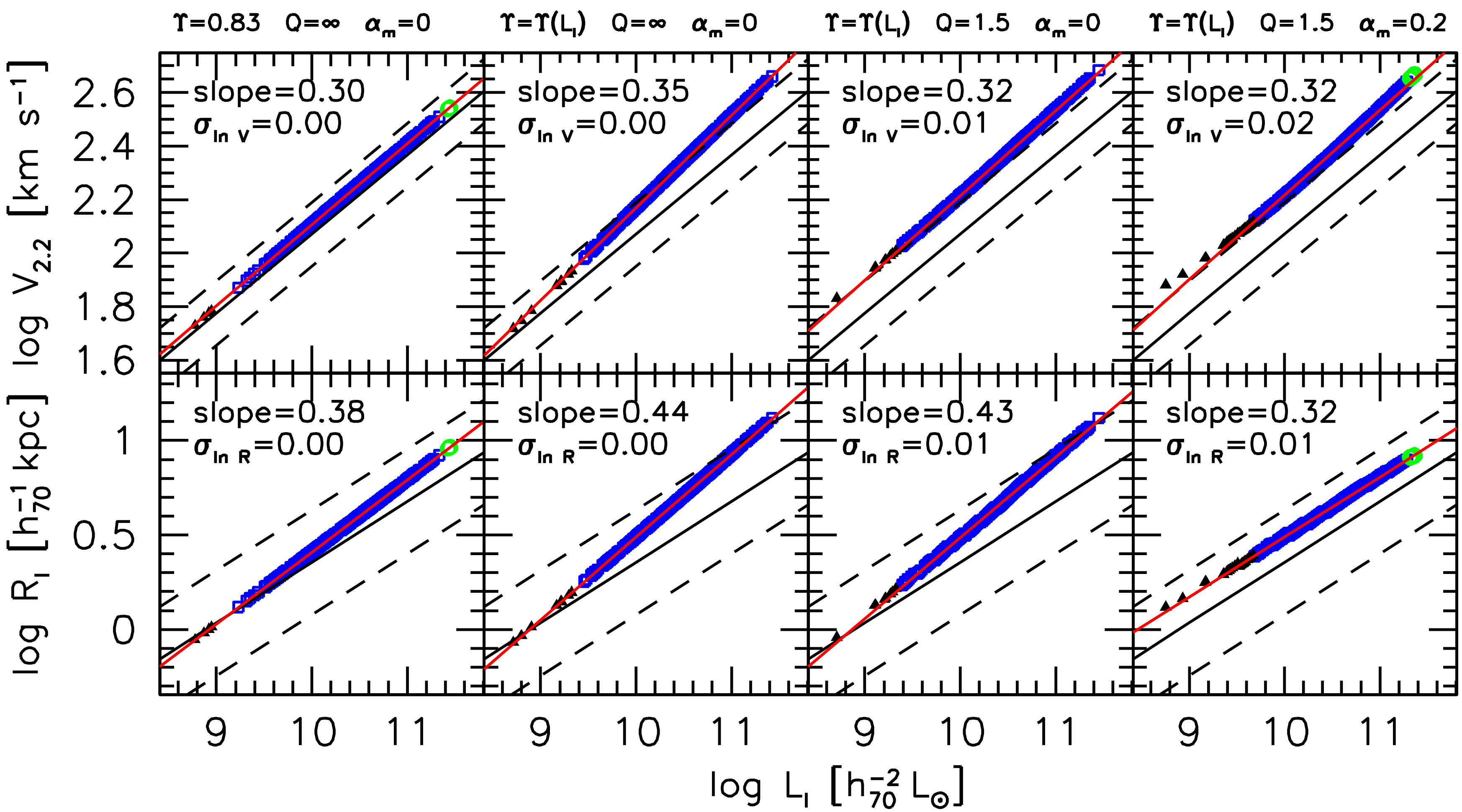
Free parameters: $\overline{\lambda}_{\rm gal}$, η , ν , $\overline{m}_{\rm gal,0}$, α , $\Delta_{\rm IMF}$

Stellar Mass-to-Light Ratios



The Υ_I of MMW where very low, and did not consider L-dependence.

Models without Scatter



- **Realistic models predict VL zero-point that is 2σ too high.**
- **When $\overline{\lambda}_{\rm gal} = \overline{\lambda}_{\rm DM} = 0.042$ disks are also too large.**
- **Taking account of $\Sigma_{\rm crit}$ yields VL slope in agreement with data.**
- **Slope of RL relation requires $\alpha_m \simeq 0.2$**

Zero-Point Solutions

There are a number of different ways to fix the VL zero-point problem:

- **Lower stellar mass-to-light ratios**

  Required $\Delta_{\rm IMF} \simeq -0.5$

  Most 'top-heavy', realistic IMF has $\Delta_{\rm IMF} \simeq -0.2$ (Kroupa IMF)

- **Lower halo concentrations**

  Required $\eta \simeq 0.4$

  WMAP3 cosmology yields $\eta \simeq 0.75$

- **Modify Adiabatic Contraction**

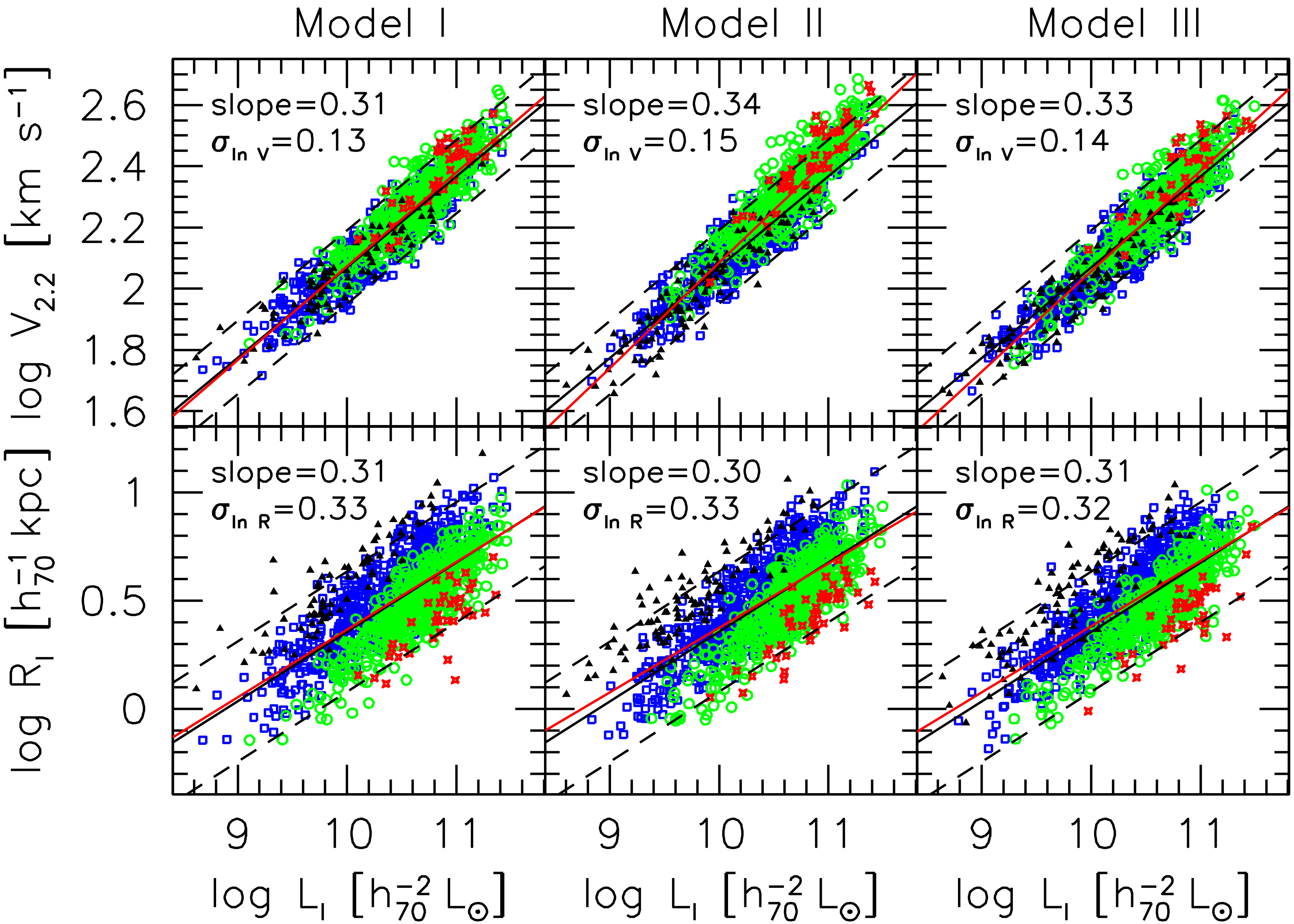
  Required $\nu \ll 0$ (significant expansion)

  When $\eta = 0.75$ and $\Delta_{\rm IMF} = -0.15$ we 'only' require $\nu = 0$

We now consider these three options including scatter

Model I:	$\eta = 0.8$ & $\nu = 0.8$	$\Rightarrow$	$\Delta_{\rm IMF} = -0.4$
Model II:	$\Delta_{\rm IMF} = -0.2$	$\Rightarrow$	$\eta = 0.5$
Model III:	$\nu = 0.0$ & $\eta = 0.8$	$\Rightarrow$	$\Delta_{\rm IMF} = -0.2$

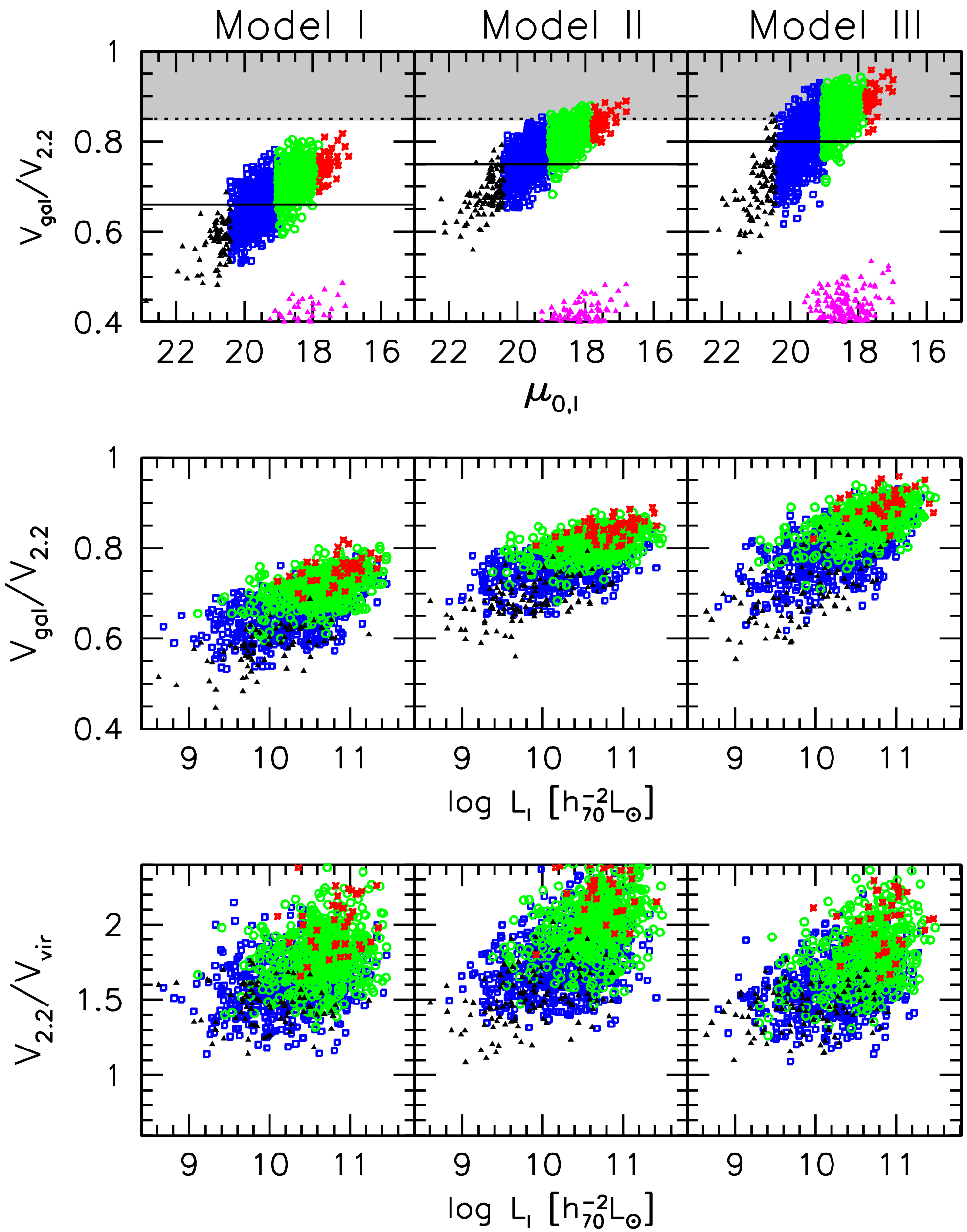
Three Models that seem to work



Observed scatter in RL relation requires $\sigma_{\ln\lambda} \lesssim 0.25$

NOTE: predicted scatter in halo spin parameters: $\sigma_{\ln\lambda} \simeq 0.5$

Velocity Ratios



$V_{2.2}$: **Circular velocity at** $2.2R_I$.

V_{gal}: **Contribution of disk to** $V_{2.2}$.

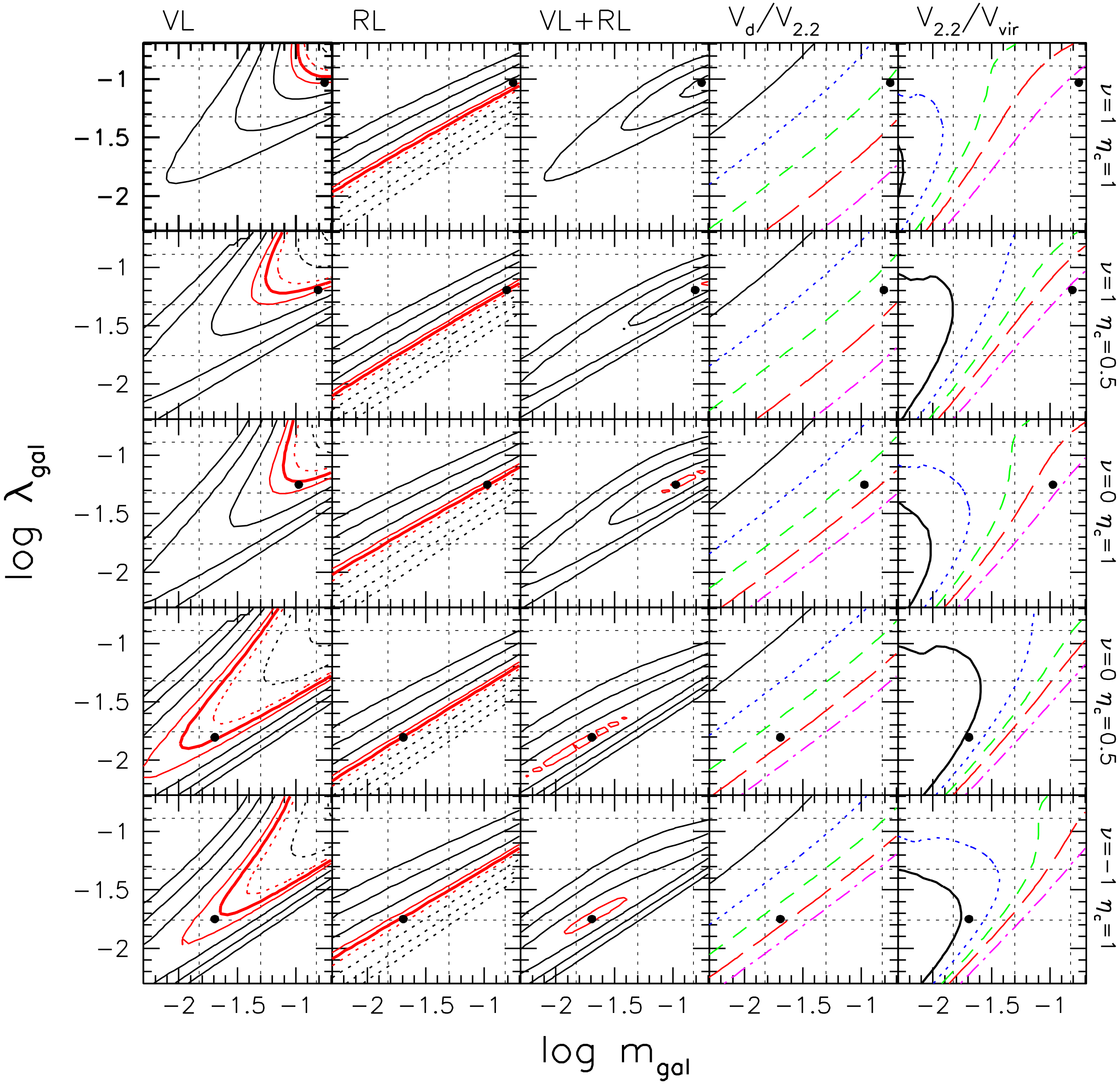
V_{vir}: **Virial velocity of the halo.**

Depending on model, on L_I, **and on** $\mu_{0,I}$ **disks are maximal or not.**

Note that $\langle V_{2.2}/V_{vir}\rangle \simeq 1.7$.

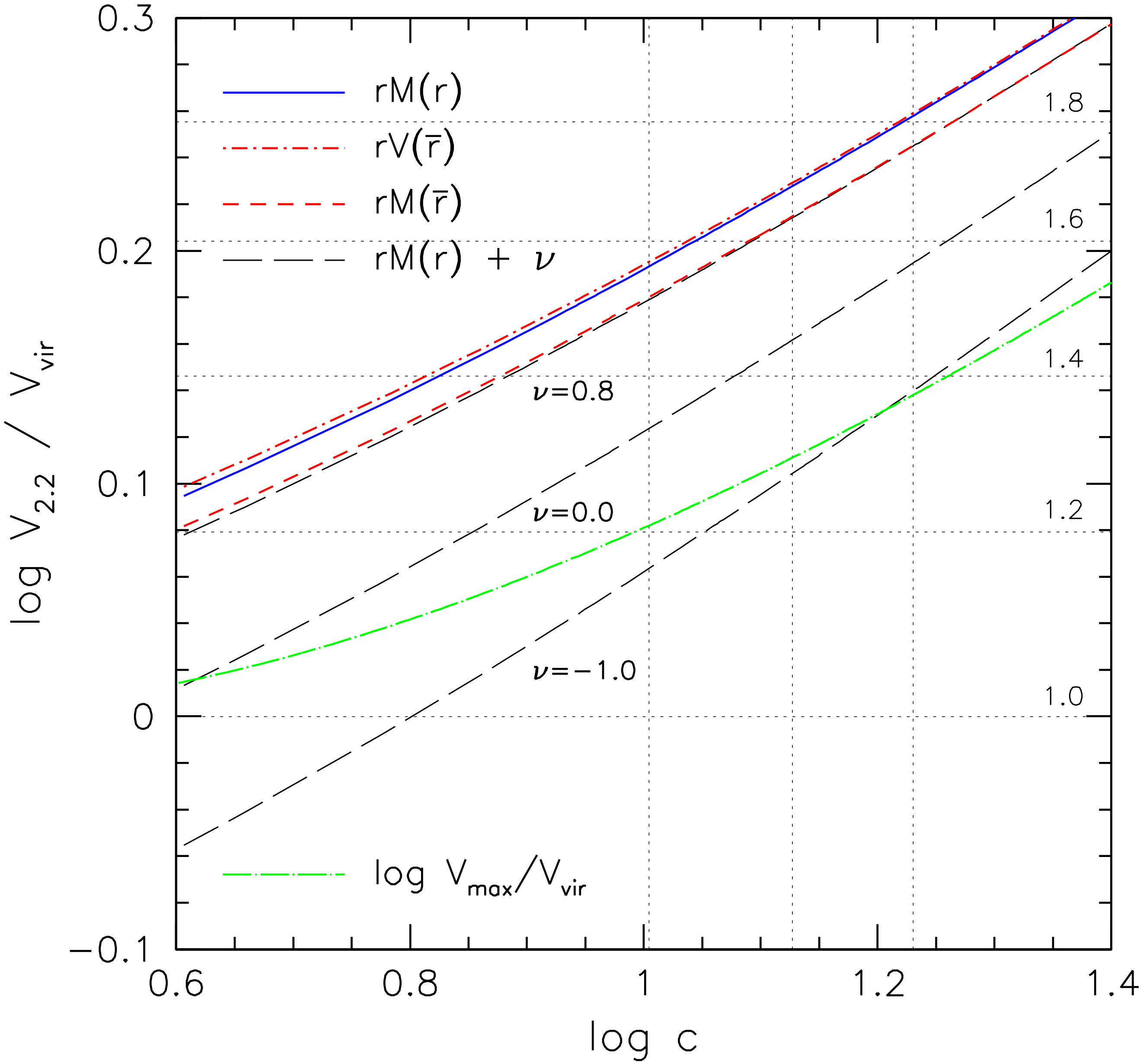
This implies that these models can not simultaneously match the luminosity function of disks.

Zero-Point Constraints



Simultaneously matching LF and the VL and RL zero-points requires $\nu \lesssim 0$

AC or no AC, that's the question...



Assuming that $V_{\rm rot} = V_{\rm max}$ is equivalent to assuming $\nu < 0$!!

CONCLUSIONS

Simultaneously fitting LF and the VL and RL zero-points requires:

- Halo expands rather than contracts

  $\Rightarrow$ Disks form out of merging clumps, not out of smooth cooling flows.

  NOTE: Assuming $V_{\rm rot} = V_{\rm max}$ is equivalent to assuming halo expansion

- Disk mass fractions with $m_{\rm gal,0} \ll f_{\rm bar}$ and $\alpha \simeq 0.2$

  $\Rightarrow$ In MW sized halo, only $\sim 20\%$ of baryons end up in disk.

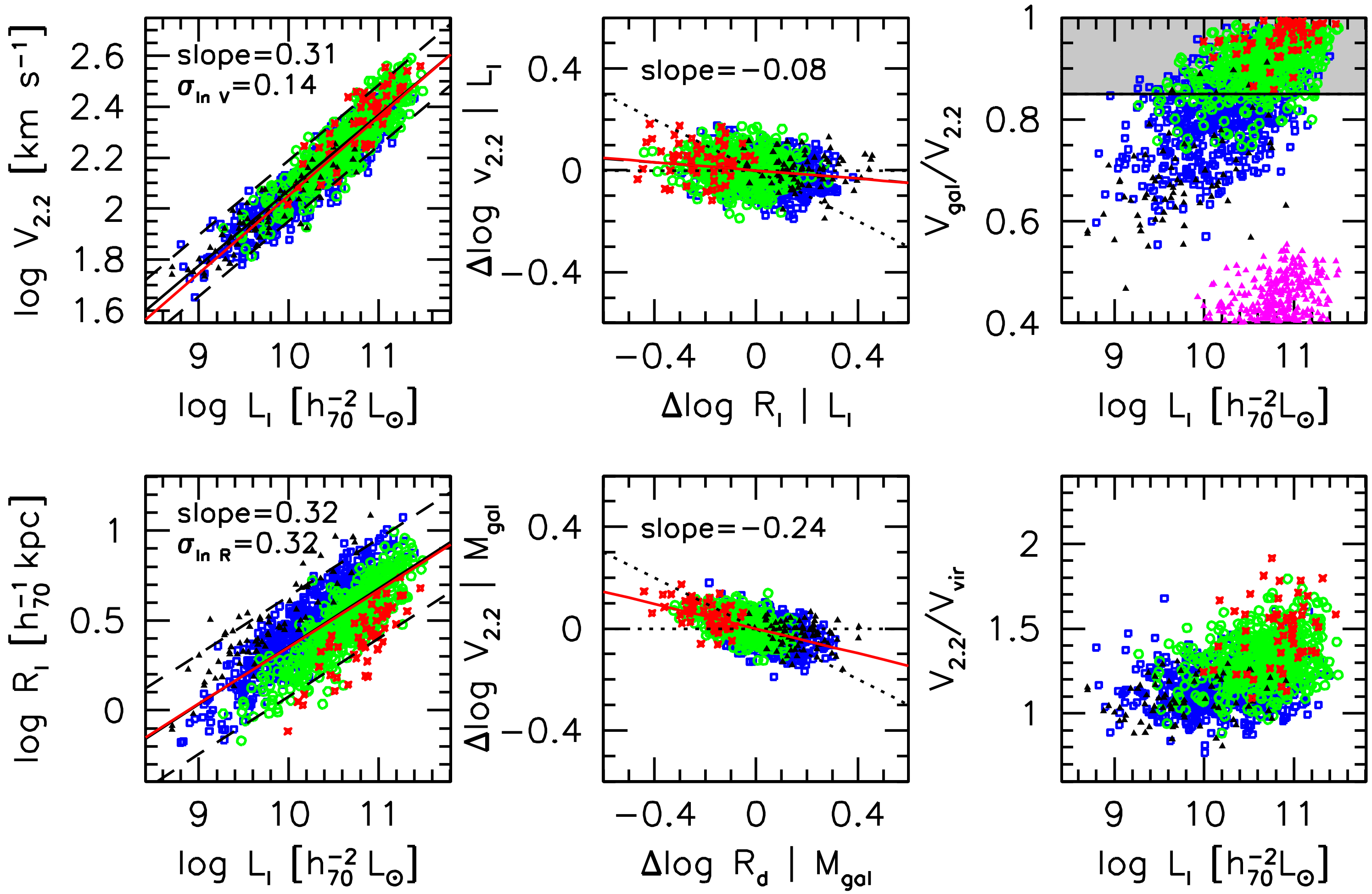
- Galaxy spin parameters: $\overline{\lambda}_{\rm gal} < \overline{\lambda}_{\rm DM}$ and with about half the scatter.

  $\Rightarrow$ Disks form only in sub-set of haloes with quiescent merger history.

Galaxy Formation Discussion Points

- **TF Zeropoint & Galaxy LF**
- **Overcooling & AGN feedback**
- **Angular Momentum Problems & Disk Rotation Curves**
- **Downsizing & SF histories**
- **The Baryon Budget; What is the role of the WHIM?**

The Model That Works



Model fits slopes, zero points and scatter of VL and RL relations

Model fits surface brightness independence of VL relation

Model is consistent with LF of disks: $\langle V_{2.2}/V_{\rm vir}\rangle \simeq 1.2$

The Spin Parameter

Tidal Torque Theory (second-order perturbation theory):

$$\mathbf{J}(t) = \int_\gamma \rho(\mathbf{r},t)\,[\mathbf{r}(t) - \mathbf{r}_{\rm cm}(t)] \times [\mathbf{v}(t) - \mathbf{v}_{\rm cm}(t)]\,{\rm d}^3\mathbf{r}$$

conversion to comoving variables yields:

$$\mathbf{J}(t) \propto a^2(t)\bar{\rho}_0 \int_\gamma [1 + \delta(\mathbf{x},t)]\,(\mathbf{x} - \bar{\mathbf{x}}_{\rm cm}) \times \dot{\mathbf{x}}{\rm d}^3\mathbf{x}$$

It is convenient to express the specific angular momentum, $j_{\rm vir} = J_{\rm vir}/M_{\rm vir}$, in terms of the dimensionless spin parameter

$$\boxed{\lambda \propto \frac{j_{\rm vir}}{R_{\rm vir}\,V_{\rm vir}}}$$

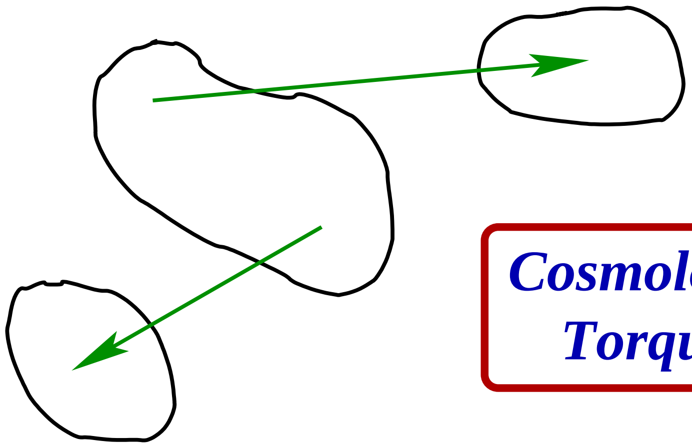
Numerical simulations have shown that $\langle\lambda\rangle \simeq 0.04$

Using that $j_{\rm d} \propto R_{\rm d} V_{\rm rot}$, and assuming that $V_{\rm rot} \propto V_{\rm vir}$, we see that

$$\boxed{R_{\rm d} \propto \lambda R_{\rm vir}}$$

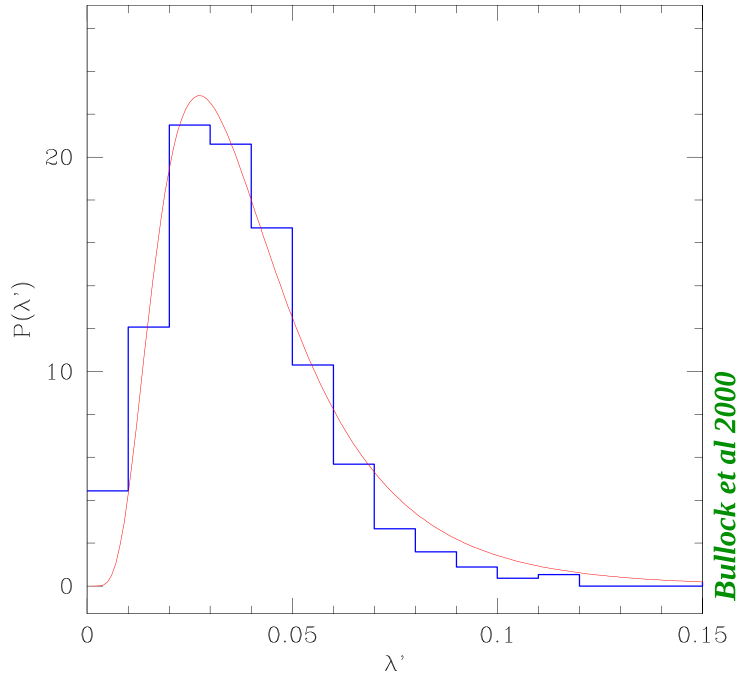
Thus λ^{-1} reflects roughly the collapse factor of the baryons

Angular Momentum & Dark Matter

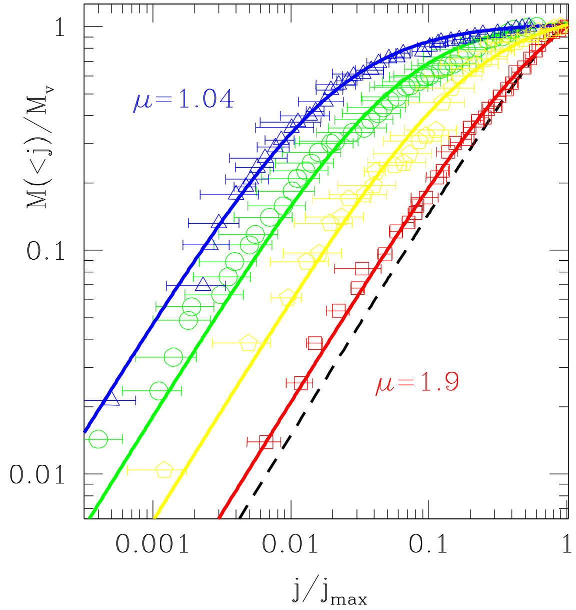


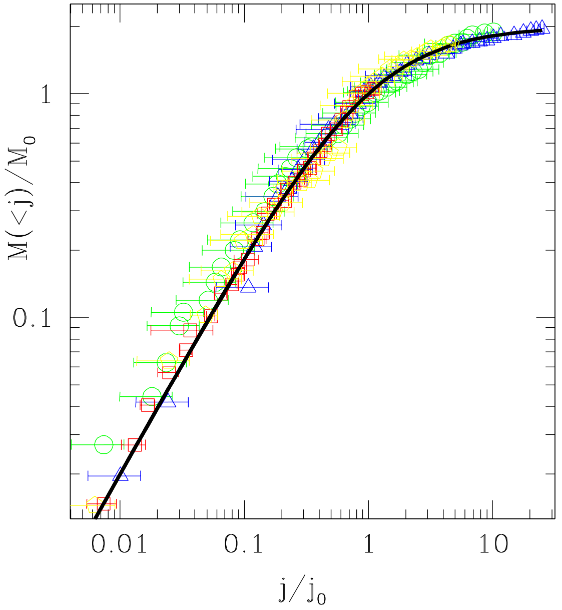
Cosmological Torques

$$\lambda = \frac{J\,|E|^{1/2}}{GM^{5/2}} \propto \frac{j_{tot}}{R_{vir}V_{vir}}$$



Bullock et al 2000





Cold Dark Matter haloes have a log−normal distribution of halo spin parameters...

Cold Dark Matter haloes have a Universal Angular Momentum distribution...

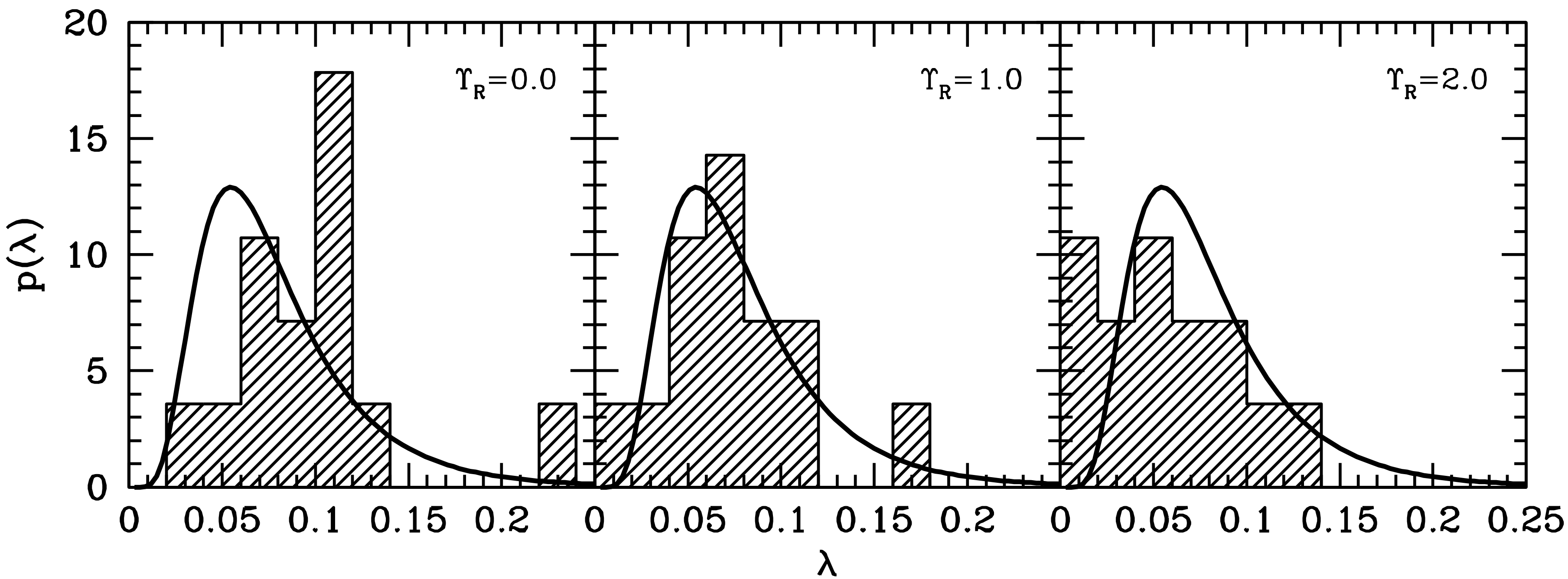
Bullock et al 2000

Testing the Paradigm

TEST: **Compare angular momentum distributions of disks and CDM haloes. If standard paradigm is correct, these should be identical.**

DATA: **14 dwarf galaxies whose rotation curves are in good agreement with CDM haloes** **(van den Bosch & Swaters 2001).**

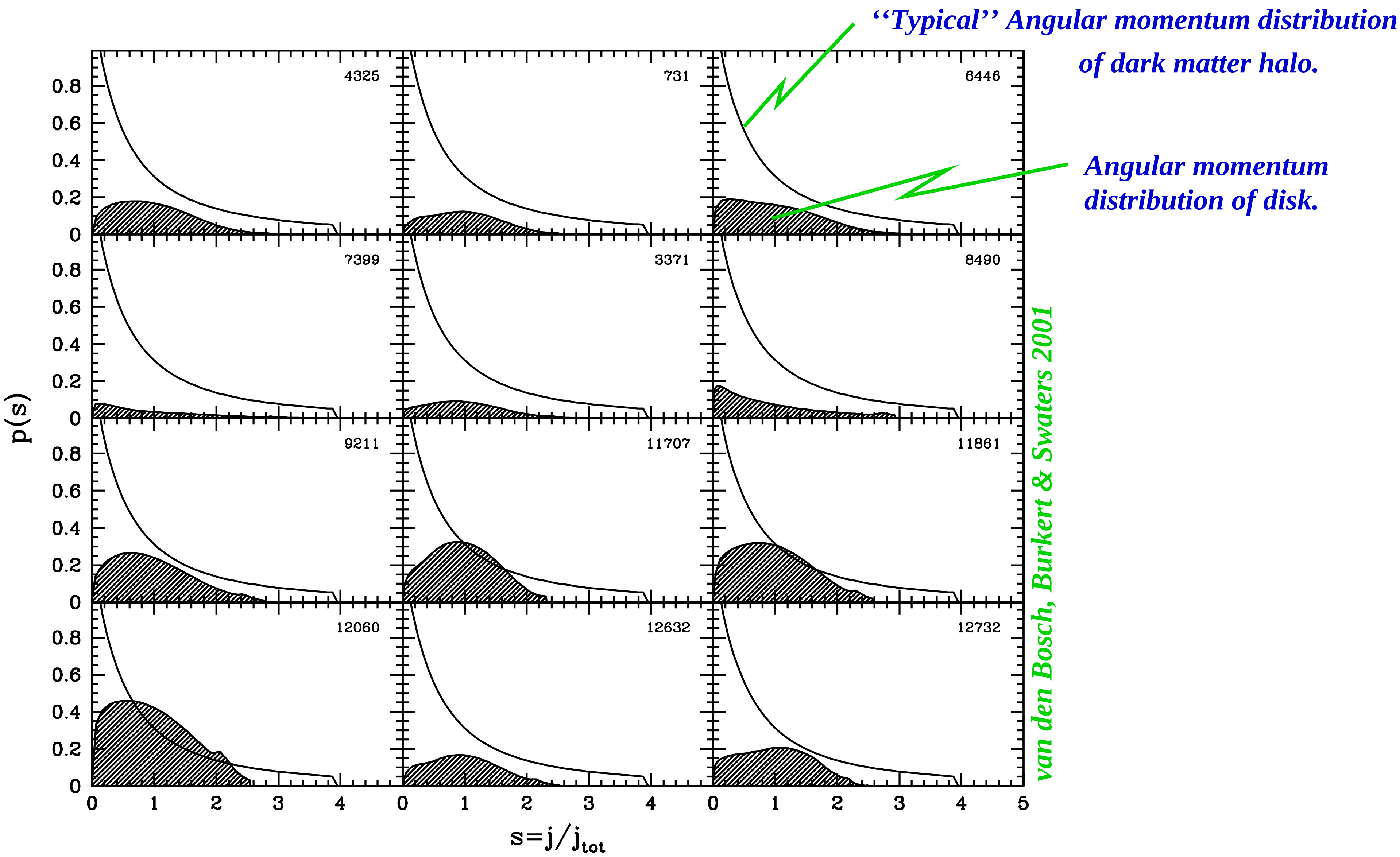
$$M(< j) = 2\pi \int_0^{R_j} \Sigma_{\rm disk}(R)\, R\, {\rm d}R \quad \text{with} \quad j = R_j V_{\rm circ}(R_j)$$



Disks and CDM haloes have same $p(\lambda)$.

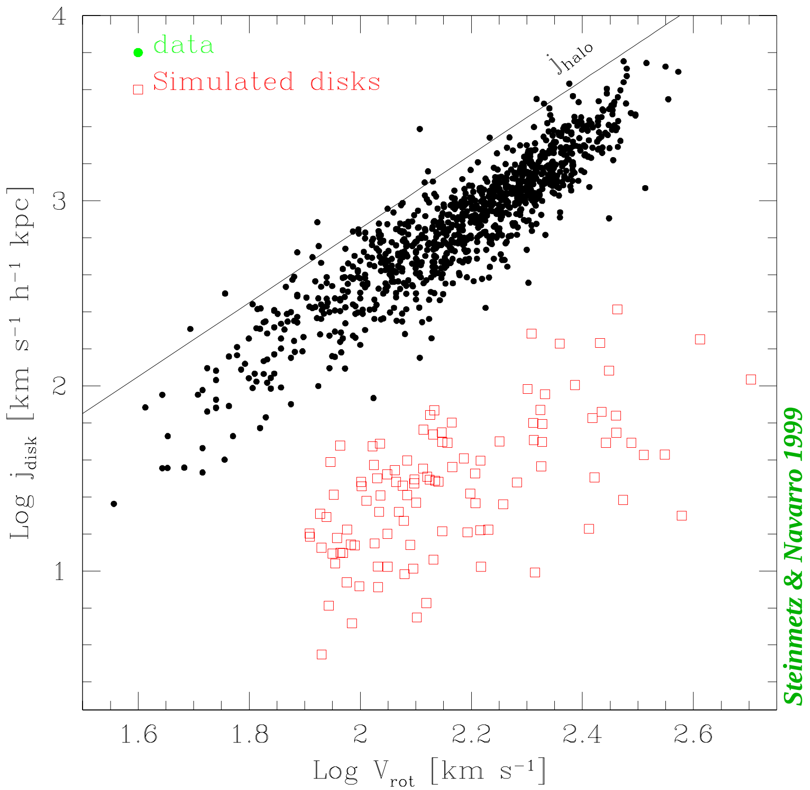
van den Bosch, Burkert & Swaters 2001

Angular Momentum Distributions



Disks (of dwarf galaxies) have angular momentum distributions that are clearly different than those of cold dark matter haloes!!!

The Angular Momentum Catastrophe



- **Disks that form in simulations are an order of magnitude too small**
- **Gas looses large fraction of specific angular momentum to dark matter**
- **Hierarchical formation & "over-cooling" are to blaim**

White & Navarro 1993; Navarro & Steinmetz 1999

SOLUTIONS

(1) Prevent Cooling: feedback, preheating **(Weil et al. 1998; Sommer-Larsen et al. 1999)**

(2) Modify Power Spectrum: WDM, BSI, RSI... **(Sommer-Larsen & Dolgov 2001)**

Disk Scaling Relations I

Observations:

- $M_{\rm disk} = 3.1 \times 10^9 \, h^{-2} \, {\rm M}_\odot \, \left(\frac{V_{\rm rot}}{100 \, {\rm km \, s^{-1}}}\right)^{3.5}$ (Bell & de Jong 2001)
- $j_{\rm disk} = 3.3 \times 10^2 \, {\rm km \, s^{-1}} h^{-1} \, {\rm kpc} \, \left(\frac{V_{\rm rot}}{100 \, {\rm km \, s^{-1}}}\right)^2$

Theoretical Predictions:

- $M_{\rm disk} = f_m \left(\frac{\Omega_b}{\Omega_m}\right) M_{\rm vir}$
- $j_{\rm disk} = \sqrt{2} \, f_j \, \lambda' \, R_{\rm vir} V_{\rm vir}$
- $M_{\rm vir} \propto V_{\rm vir}^3$ $\quad R_{\rm vir} \propto V_{\rm vir}$

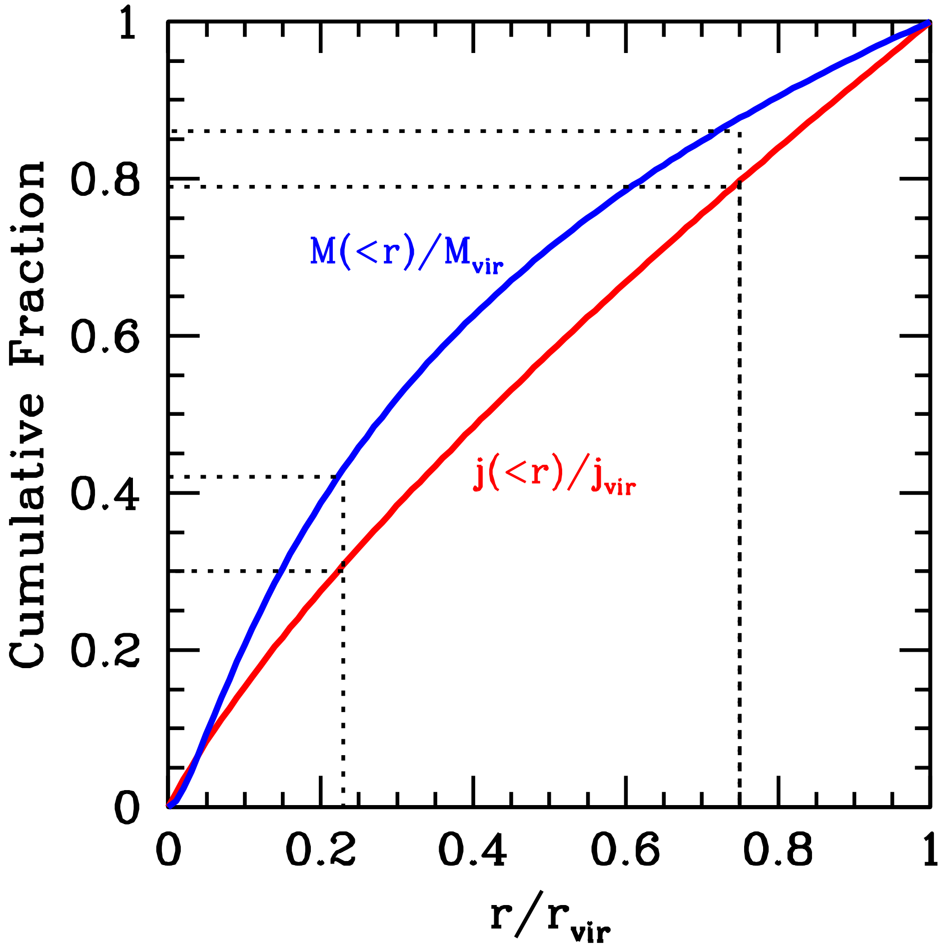
Example: $\Omega_m = 0.3 \quad h = 0.7 \quad \lambda = 0.04 \quad V_{\rm rot}/V_{\rm vir} = 1.4$

$$f_m = 0.42 \left(\frac{V_{\rm vir}}{200 \, {\rm km \, s^{-1}}}\right)^{1/2} \qquad f_j = 0.79$$

(see also Navarro & Steinmetz 2000)

Disk Scaling Relations II

$$f_m = 0.42 \left(\frac{V_{\rm vir}}{200\ {\rm km\,s^{-1}}}\right)^{1/2} \qquad f_j = 0.79 \left(\frac{\lambda'}{0.04}\right)^{-1}$$



- $M(r)$ from NFW profile with $c = 20$ **(Navarro, Frenk & White 1997)**
- $j(r) \propto r$ from N-body simulations **(Bullock et al. 2001)**

Gas in Proto-Galaxies

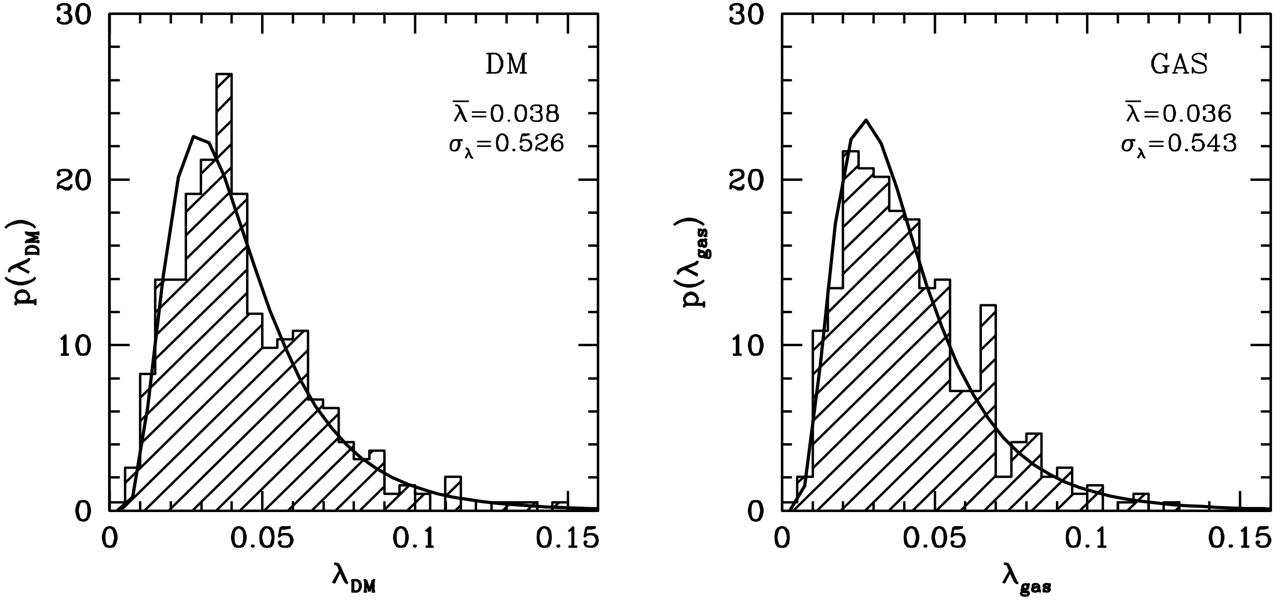
TEST: **Do the gas and dark matter have the same angular momentum distributions before cooling? gas can shock...**

TOOL: **Numerical N-body/SPH simulation of ΛCDM cosmology with non-radiative gas; Analyze individual haloes.**

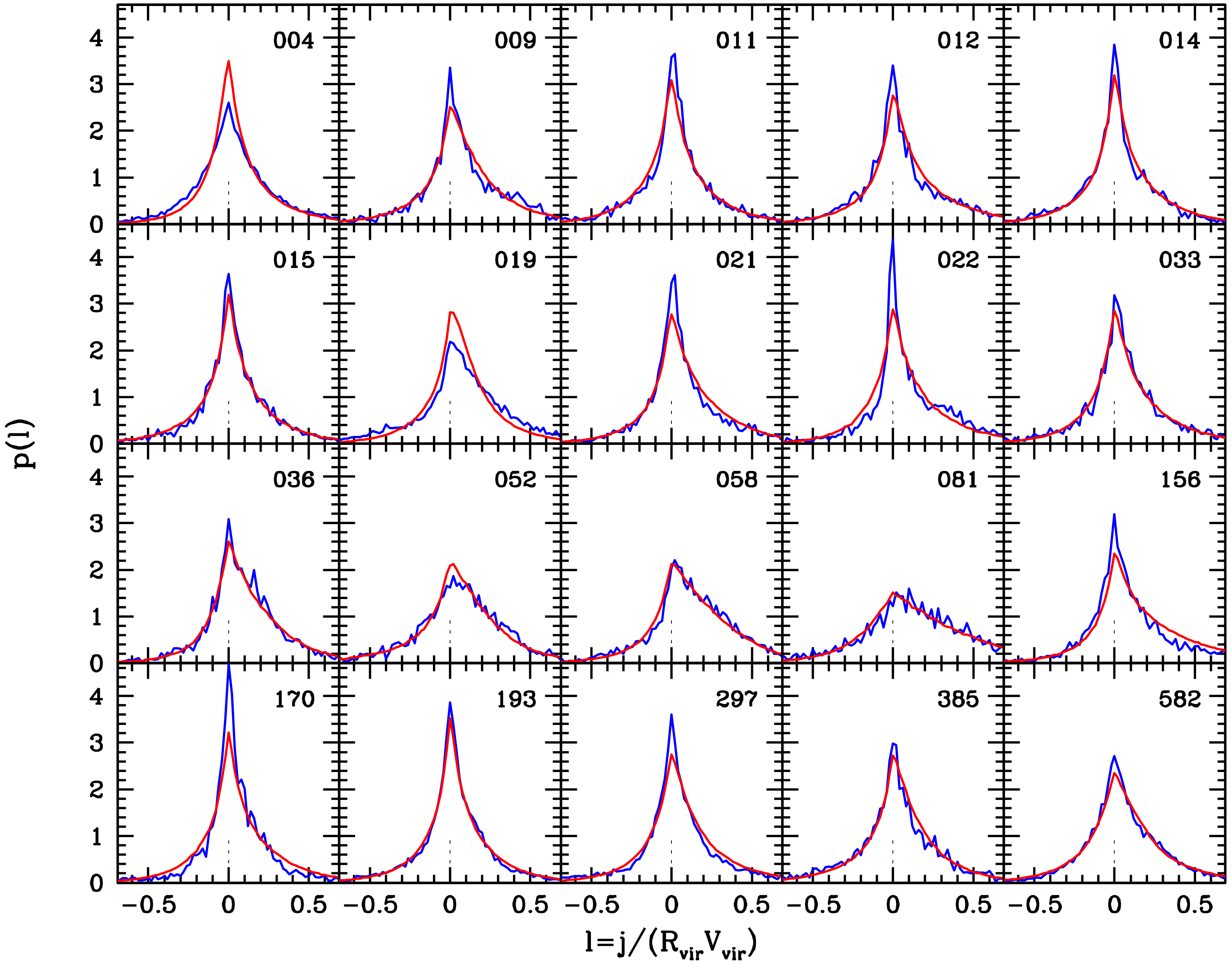
Gas and dark matter are fluids for which $\vec{v} = \vec{u} + \vec{w}$

- $\vec{v}$ =**microscopic velocity (DM particles in simulation)**
- $\vec{u}$ =**streaming motions (SPH particles in simulation)**
- $\vec{w}$ =**random motions (related to temperature of gas particles)**

THERMAL BROADENING: **Add random velocities to SPH particles with dispersion given by particle's temperature.**



A more detailed comparison...



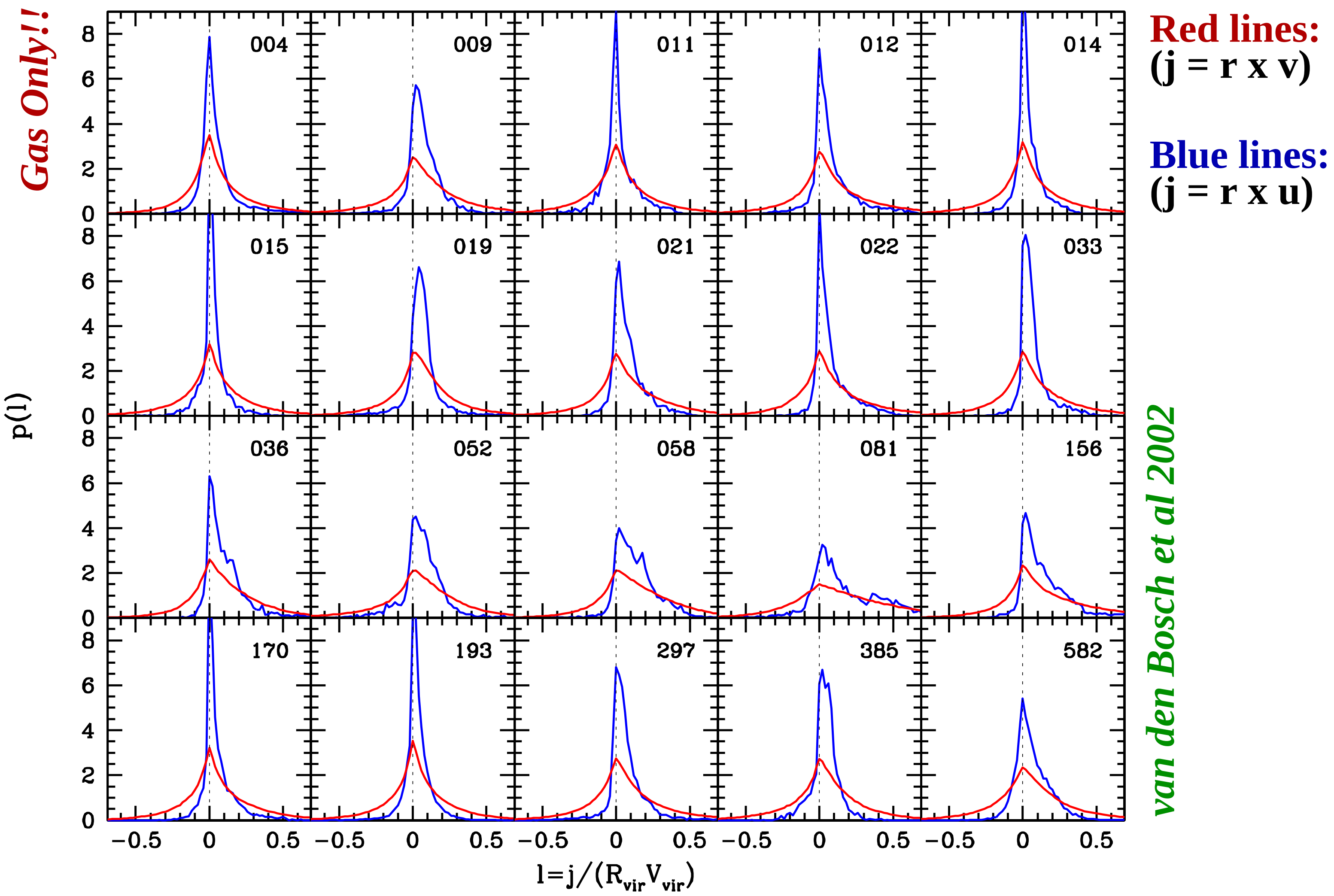
Blue lines:
Dark Matter

Red lines:
Gas

van den Bosch et al 2002

- **AMDs of gas and dark matter are virtually identical**
- **Virialization shocks do not affect AMD of gas**
- **Apparently, the standard assumption is correct**

and what it means for disk formation



Between 10 & 40 percent of gas has negative specific angular momentum!!!

A new problem?

Bulge Formation?

- **Disks do not contain counter-rotating material...**
- **About 40% of haloes forms Early-Type galaxies**
- **Virtually no bulge-less systems can form**

Cooking Up a Disk Galaxy

- **Mass Accretion History (MAH):** $M_{\rm vir}(r, \phi, \theta, t | M_0)$
- **Angular Momentum Distribution (AMD):** $J_{\rm vir}(r, \phi, \theta, t | \lambda_0)$
- **Cooling model:** $t_{\rm form} = \max[t_{\rm cool}(Z/Z_{\odot}), t_{\rm ff}]$

After a time $t_{\rm form}$ mass element $m(r, \phi, \theta, t)$ ends up in the disk at a radius R given by $j(r, \phi, \theta, t) = R \cdot V_{\rm circ}(R, t + t_{\rm form})$.

$$\text{MAH + AMD} \longrightarrow j(r, \phi, \theta, t) \longrightarrow M_{\rm disk}(R, t)$$

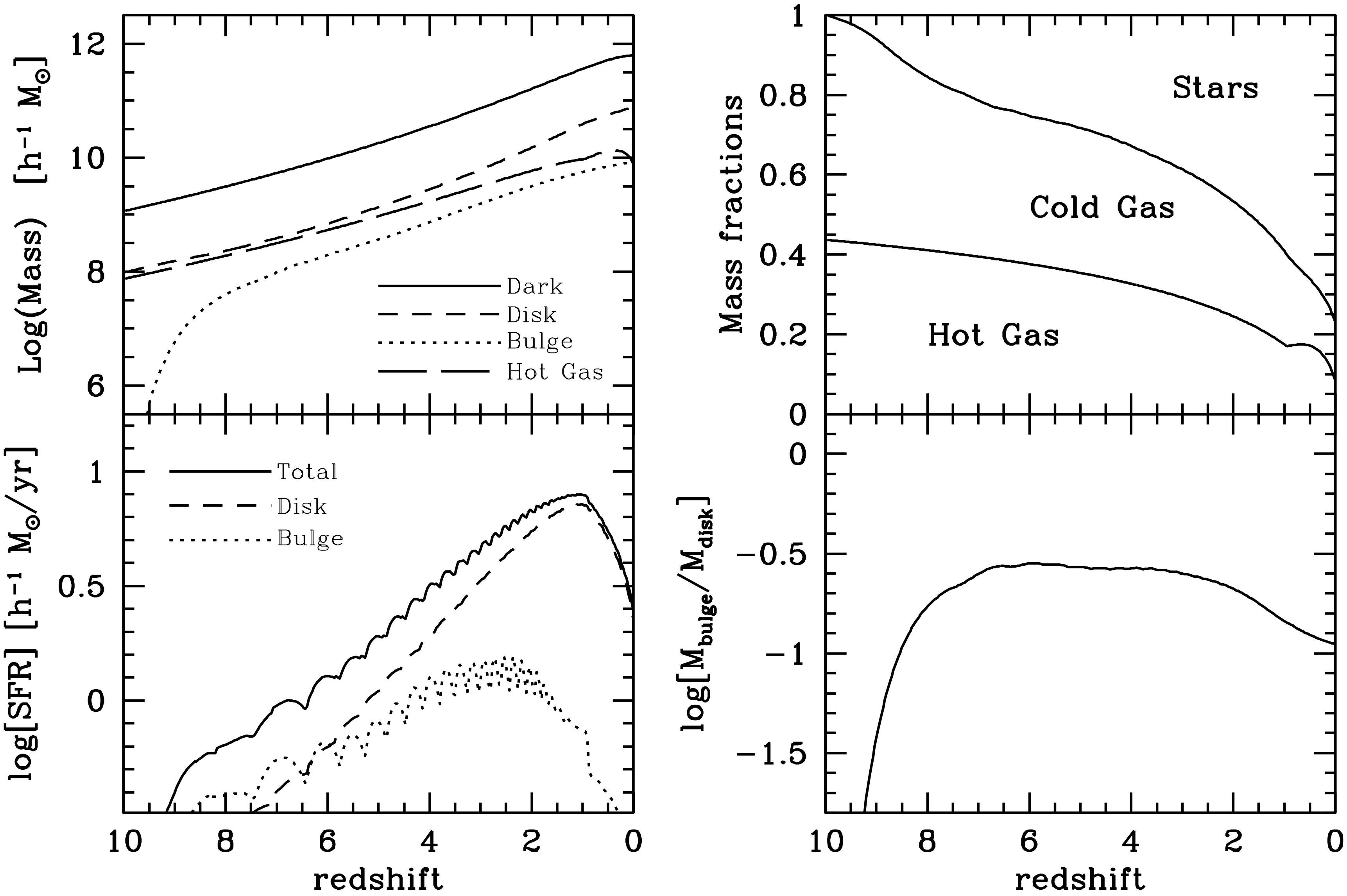
Additional model ingredients:

- **Bulge Formation:** **Disk stability...**
- **Star Formation:** **SFR, SF thresholds,...**
- **Feedback:** **galactic winds, heating,...**
- **Stellar Population Models:** **IMF, stellar remnants,...**
- **Chemical Evolution:** **stellar yields, mixing...**

van den Bosch 1998, 2000, 2001, 2002

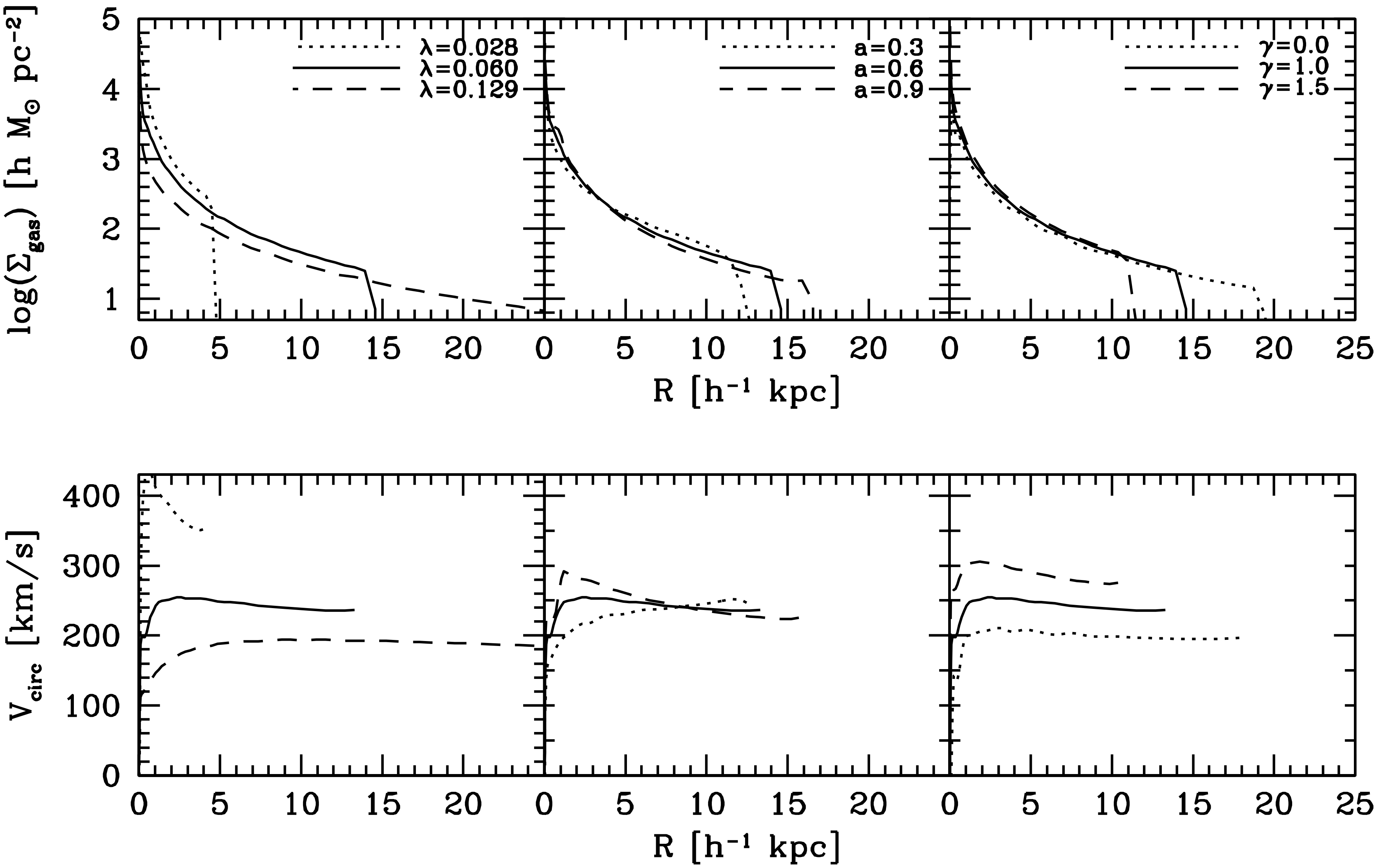
Avila-Reese & Firmani 2000; Firmani & Avila-Reese 2000

An Example

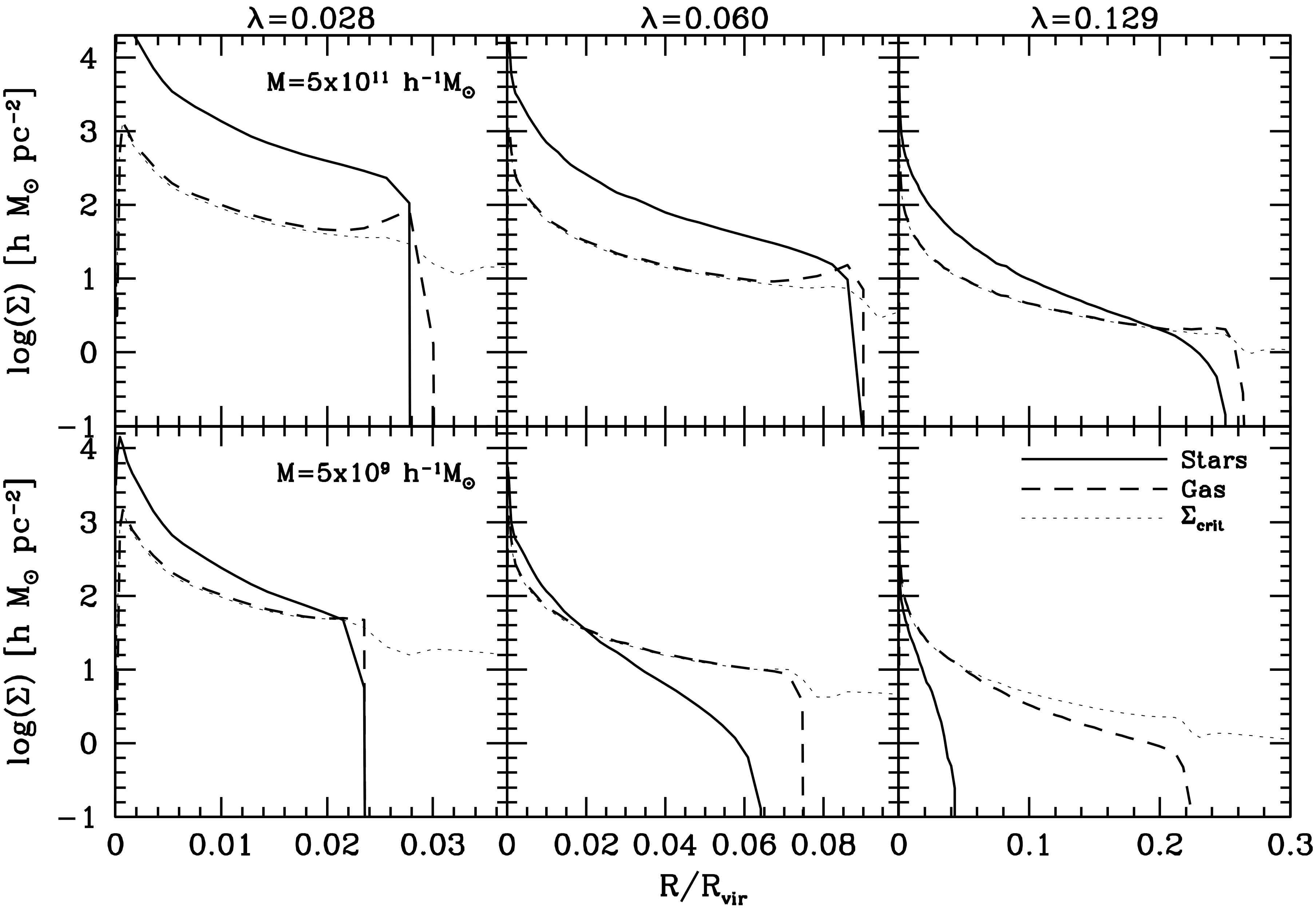


$M_{\rm vir} = 5 \times 10^{11} h^{-1}\,{\rm M}_\odot$, $\lambda = 0.06$, average MAH

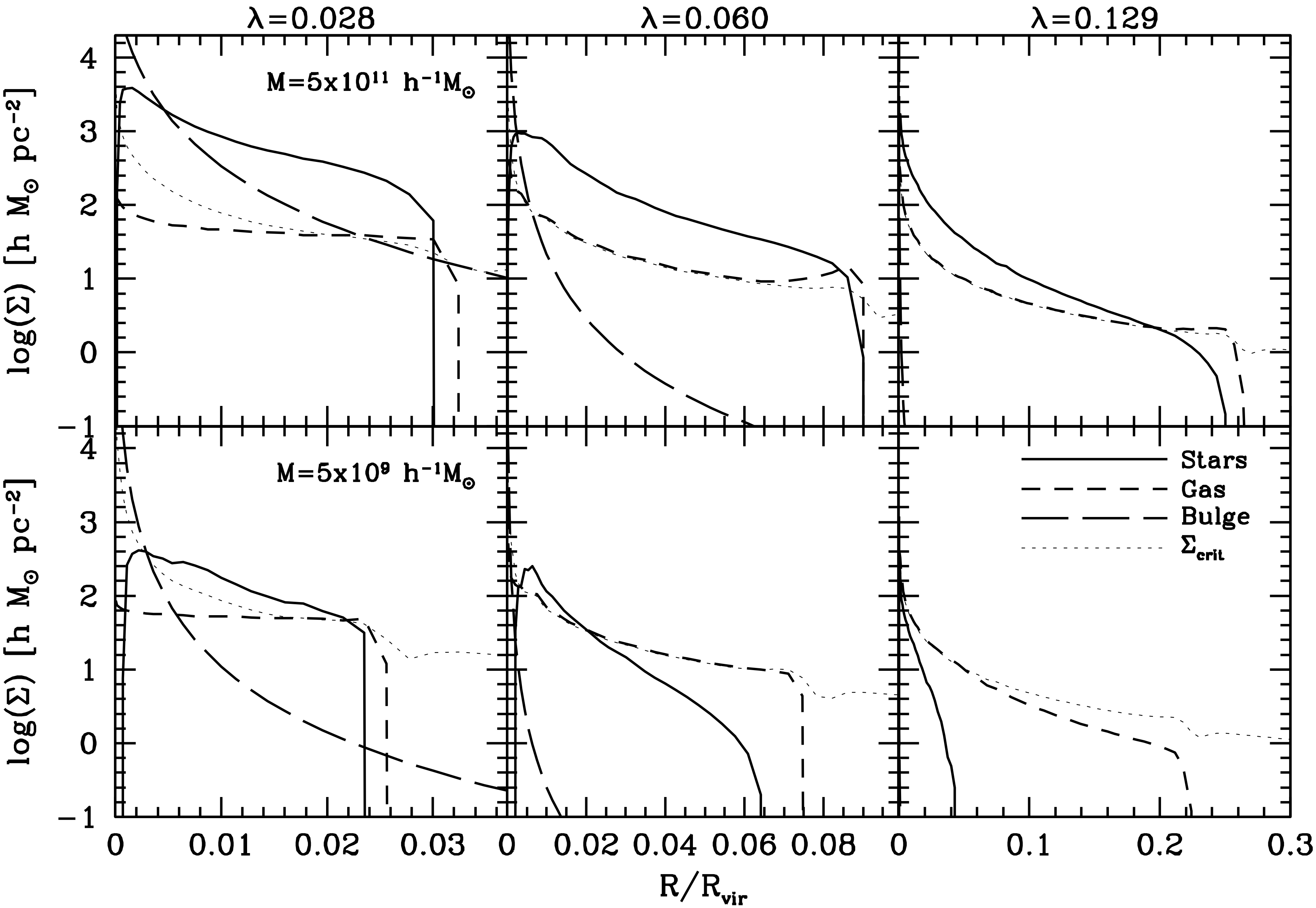
Cooling Only



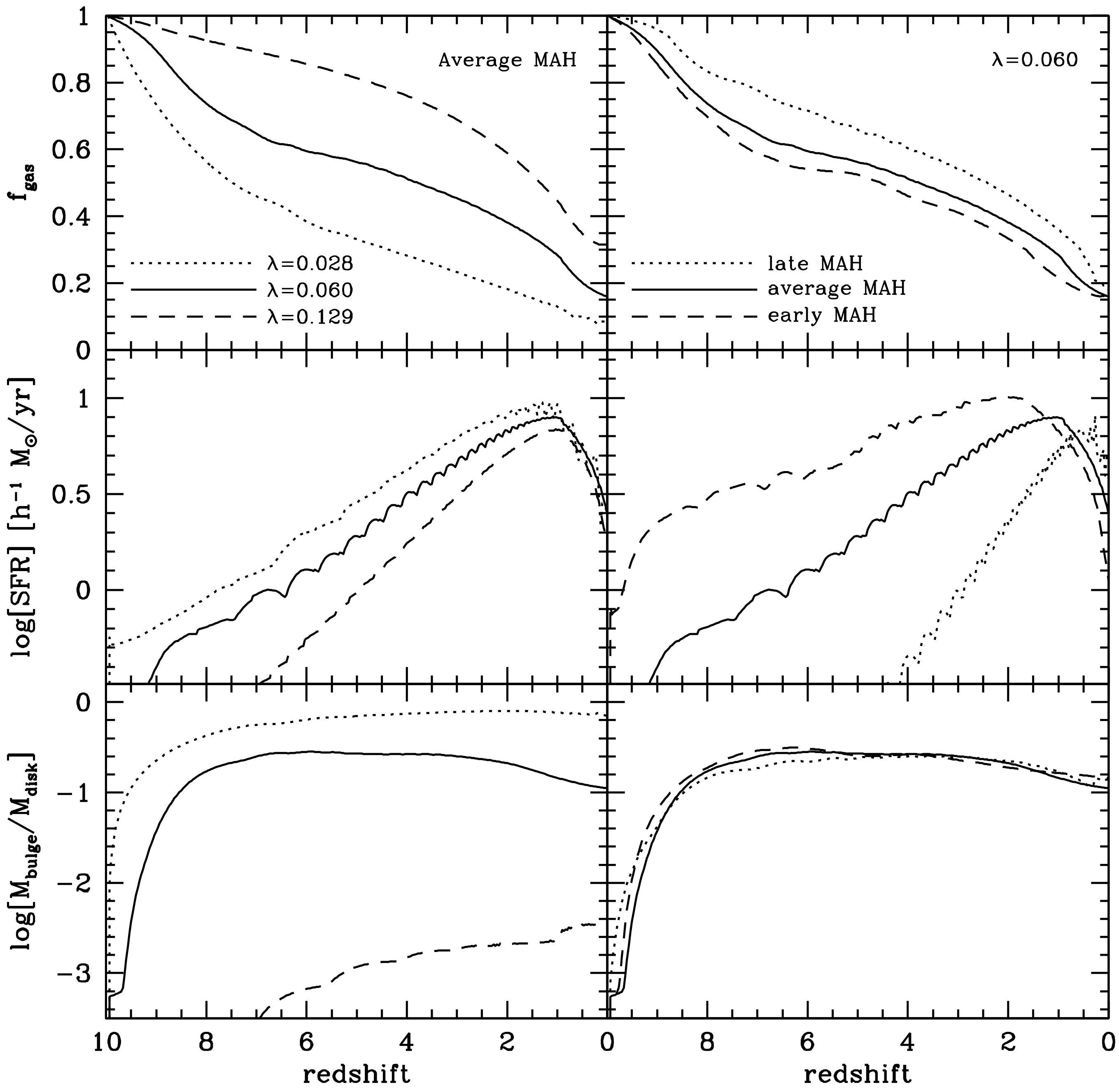
Cooling + Starformation



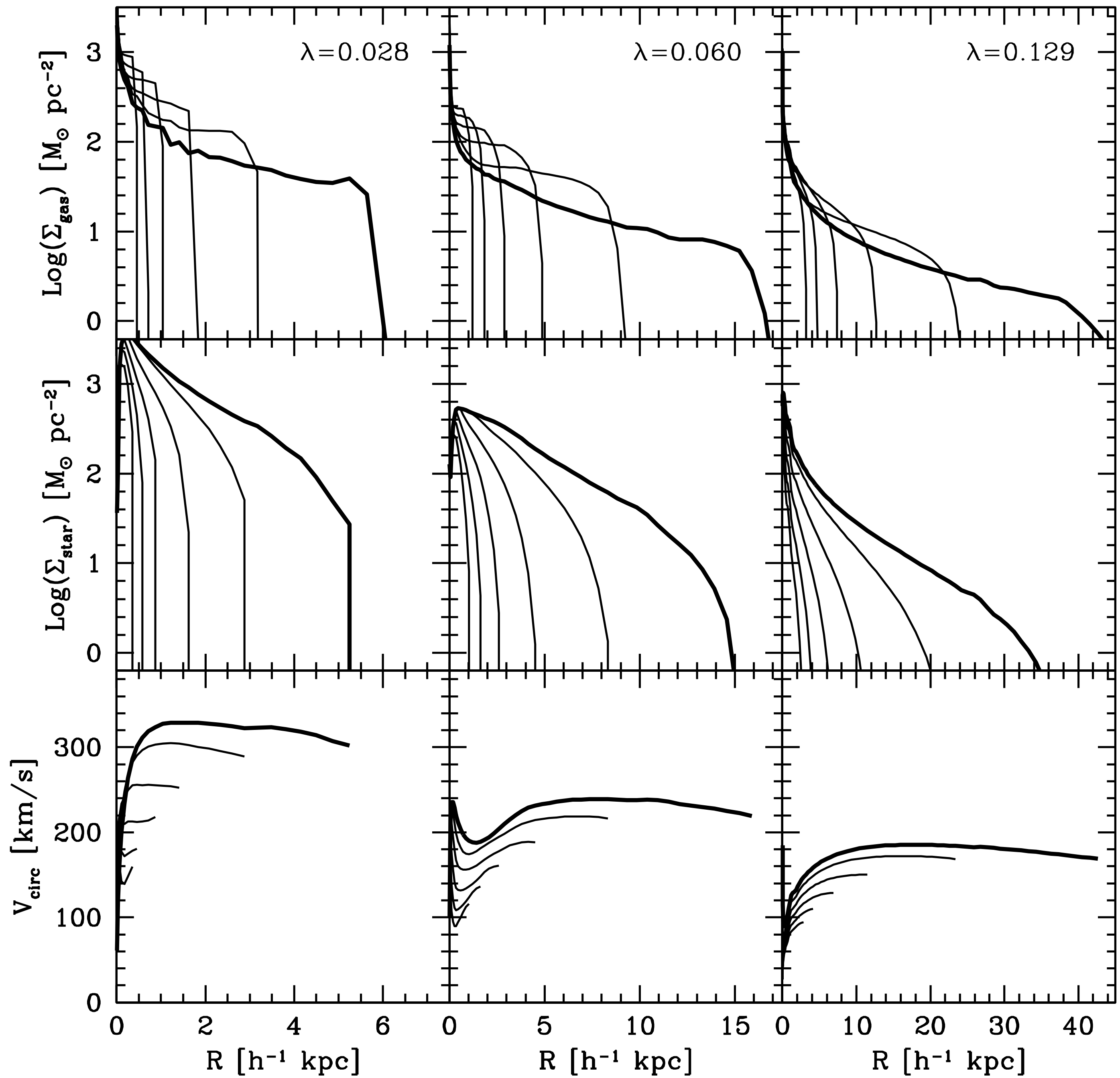
With Bulge Formation



Parameter Dependencies



The Inside-Out Formation of Disks



Halo Virial Properties

Define the virial radius, $r_{\rm vir}$, as the radius inside of which the average density is equal to $\Delta_{\rm vir}\rho_{\rm crit}$

$$\bar{\rho} = \frac{3\,M_{\rm vir}}{4\,\pi\,r_{\rm vir}^3} = \Delta_{\rm vir}\frac{3\,H^2(z)}{8\,\pi\,G}$$

For a ΛCDM concordance cosmology with ($\Omega_m = 0.3, \Omega_\Lambda = 0.7$) at redshift $z = 0$ one has that $\Delta_{\rm crit} = 101$ (Bryan & Norman 1998)

Substituting some characteristic values then yields

$$r_{\rm vir} = 282 h^{-1}\,{\rm kpc}\,\left(\frac{V_{\rm vir}}{200\,{\rm km\,s^{-1}}}\right)\left(\frac{\Delta_{\rm vir}}{101}\right)^{-1/2}\left(\frac{H(z)}{H_0}\right)^{-1}$$

and using the definition of virial velocity, $V_{\rm vir} = \sqrt{G\,M_{\rm vir}/r_{\rm vir}}$ one obtains that

$$M_{\rm vir} = 2.7\times 10^{12} h^{-1}\,{\rm M}_\odot\,\left(\frac{V_{\rm vir}}{200\,{\rm km\,s^{-1}}}\right)^3\left(\frac{\Delta_{\rm vir}}{101}\right)^{-1/2}\left(\frac{H(z)}{H_0}\right)^{-1}$$

Disk Scale Lengths

Consider a disk with mass M_d that formed inside a halo of mass $M_{\rm vir}$. If the disk has an exponential mass density then

$$\Sigma(R) = \Sigma_0 \, \mathrm{e}^{-R/R_d} \qquad \text{with} \qquad M_d = 2\,\pi\,\Sigma_0\,R_d^2$$

The angular momentum of the disk is given by

$$\begin{aligned} J_d &= 2\,\pi \int_0^\infty \Sigma(R)\,R\,V_c(R)\,R\mathrm{d}R \\ &= 2\,\pi\,\Sigma_0\,R_d^3\,V_{\rm vir} \int_0^\infty x^2\,\mathrm{e}^{-x}\,\frac{V_c(x\,R_d)}{V_{\rm vir}}\,\mathrm{d}x \\ &= M_d\,R_d\,V_{\rm vir}\,f_R \end{aligned}$$

Here f_R is the disk-mass-weighted ratio of the circular velocity $V_c(R)$ to the virial velocity $V_{\rm vir}$. For a singular isothermal sphere $f_R = 1$

Let specific angular momentum of disk be a fraction f_j of that of halo:

$$j_d = R_d\,V_{\rm vir}\,f_R = f_j\,\sqrt{2}\,\lambda'\,R_{\rm vir}\,V_{\rm vir}$$

and thus: $$R_d = \sqrt{2}\left(\frac{f_j}{f_R}\right)\lambda\,R_{\rm vir}$$

(Mo, Mao & White 1998)

Substituting typical values yields:

$$R_d = 8h^{-1}\,\mathrm{kpc}\left(\frac{f_j}{f_R}\right)\left(\frac{\lambda}{0.04}\right)\left(\frac{V_{\rm vir}}{200\,\mathrm{km\,s^{-1}}}\right)\left(\frac{\Delta_{\rm vir}}{101}\right)^{-1/2}\left(\frac{H(z)}{H_0}\right)^{-1}$$

Disk Scale Lengths II

Value of f_R depends on $M_{\rm disk}/M_{\rm vir}$, λ, and halo concentration c:

NFW halo:

$$\frac{V_c(r)}{V_{\rm vir}} = \frac{1}{x} \frac{\ln(1+cx) - cx/(1+cx)}{\ln(1+c) - c/(1+c)}$$

with $x = r/r_{\rm vir}$. The circular velocity $V_c(r)$ reaches a maximum $V_{\rm max}$ at $r_{\rm max} = 2.163 r_s = 2.163 r_{\rm vir}/c$.

$$\frac{V_{\rm max}}{V_{\rm vir}} \simeq 0.465 \sqrt{\frac{c}{\ln(1+c) - c/(1+c)}}$$

which is larger than unity for all realistic values of c

Disk contribution : disk adds mass, therefore increases $V_c(r)$ and thus f_R.

Adiabatic Contraction: when disk formation is slow compared to dynamical time the halo responds adiabatically to the formation of the disk; actions are adiabatic invariants

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Adiabatic contraction is typically taken into account by considering the approximate adiabatic invariant $r\,M(r)$; which is only exact for circular orbits in a spherical potential. Nevertheless, tests have shown this approximation to be sufficiently accurate (Barnes & White 1984; Blumenthal et al. 1986; Jesseit, Naab & Burkert 2000)

Global Properties of Disk Galaxies

Main global parameters of a disk galaxies are: $M_d,\ R_d,\ V_{\rm rot}$

These parameters reveal the following charachteristics:

- **Flat Rotation Curves:** $V_{\rm rot}(R) = V_{\rm rot}$ **(e.g., Rubin & Ford 1970)**
- **Exponential Disks:** $\Sigma(R) = \Sigma_0 {\rm e}^{-R/R_d}$ **(e.g., Freeman 1970)**
- **(Baryonic) Tully-Fisher relation:** $M_d \propto V_{\rm rot}^{3.5}$ **(Bell & de Jong 2001)**
- **Size–Velocity relation:** $R_d \propto V_{\rm rot}$ **(e.g., Courteau 1997)**

Disk Scaling Relations I

Observations:

- $M_{\rm disk} = 3.1 \times 10^9\, h^{-2}\, {\rm M}_\odot \left(\frac{V_{\rm rot}}{100\ {\rm km\,s^{-1}}}\right)^{3.5}$ (Bell & de Jong 2001)
- $j_{\rm disk} = 3.3 \times 10^2\ {\rm km\,s^{-1}} h^{-1}\ {\rm kpc} \left(\frac{V_{\rm rot}}{100\ {\rm km\,s^{-1}}}\right)^2$

Theoretical Predictions:

- $M_{\rm disk} = f_m \left(\frac{\Omega_b}{\Omega_m}\right) M_{\rm vir}$
- $j_{\rm disk} = \sqrt{2}\, f_j\, \lambda'\, R_{\rm vir} V_{\rm vir}$
- $M_{\rm vir} = 2.4 \times 10^{11} h^{-1}\ {\rm M}_\odot \left(\frac{V_{\rm vir}}{100\ {\rm km\,s^{-1}}}\right)^3 \left(\frac{\Delta_{\rm vir}}{200}\right)^{-0.5}$
- $R_{\rm vir} = 100 h^{-1}\ {\rm kpc} \left(\frac{V_{\rm vir}}{100\ {\rm km\,s^{-1}}}\right) \left(\frac{\Delta_{\rm vir}}{200}\right)^{-0.5}$

Implications:

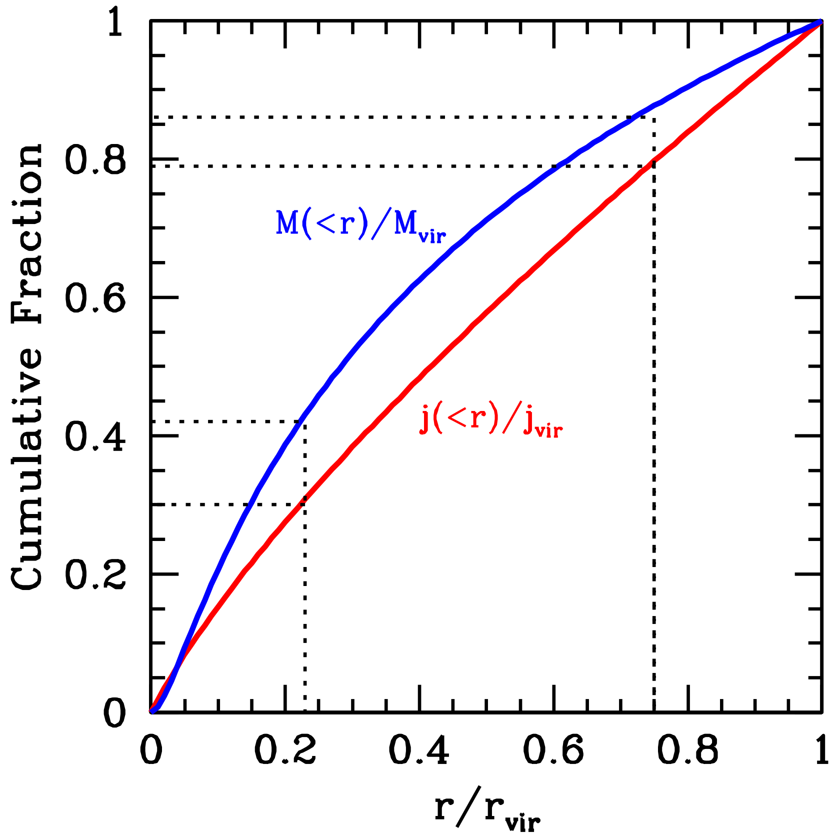
- $f_m = 0.65\, \Omega_m h \left(\frac{V_{\rm rot}}{V_{\rm vir}}\right)^{3.5} \left(\frac{V_{\rm vir}}{100\ {\rm km\,s^{-1}}}\right)^{0.5} \left(\frac{\Delta_{\rm vir}}{200}\right)^{0.5}$
- $f_j = 0.57 \left(\frac{\lambda'}{0.04}\right)^{-1} \left(\frac{V_{\rm rot}}{V_{\rm vir}}\right)^2 \left(\frac{\Delta_{\rm vir}}{200}\right)^{0.5}$

Disk Scaling Relations II

ΛCDM: $\Omega_m = 0.3$ $h = 0.7$ $\Delta_{\rm vir} = 101$ $V_{\rm rot}/V_{\rm vir} = 1.4$

$$f_m = 0.30 \left(\frac{V_{\rm vir}}{100\ {\rm km\,s^{-1}}}\right)^{1/2} \qquad f_j = 0.79 \left(\frac{\lambda'}{0.04}\right)^{-1}$$

(see also Navarro & Steinmetz 2000)

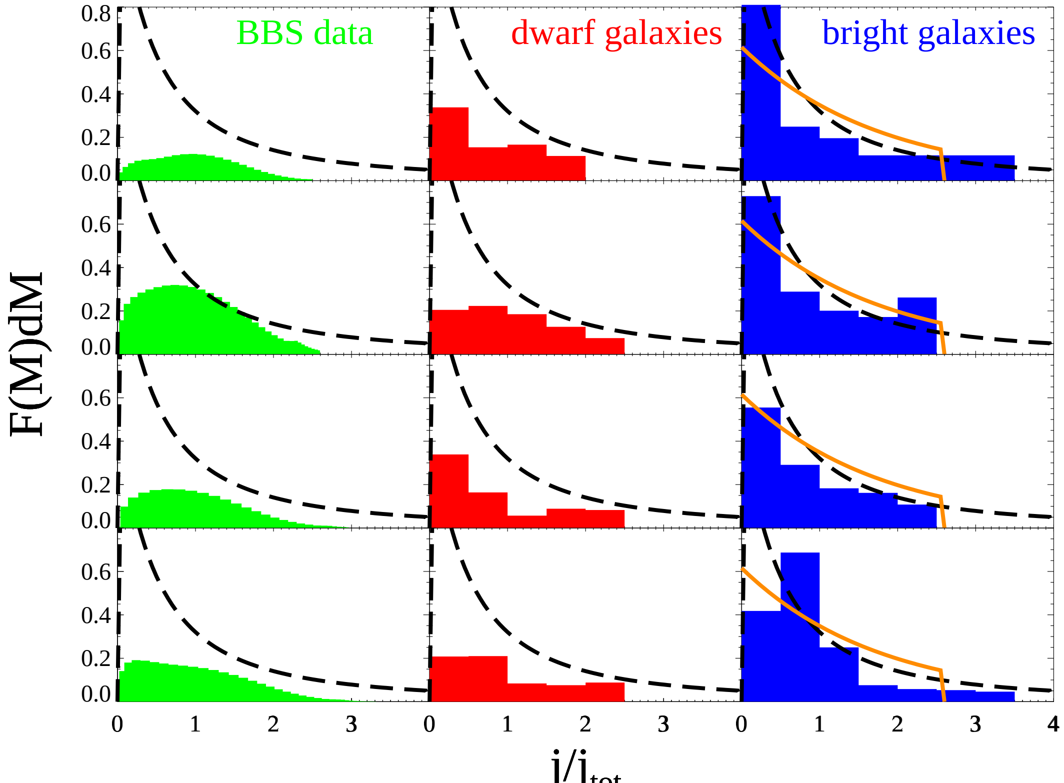


- $M(r)$ from NFW profile with $c = 20$ (Navarro, Frenk & White 1997)
- $j(r) \propto r$ from N-body simulations (Bullock et al. 2001)

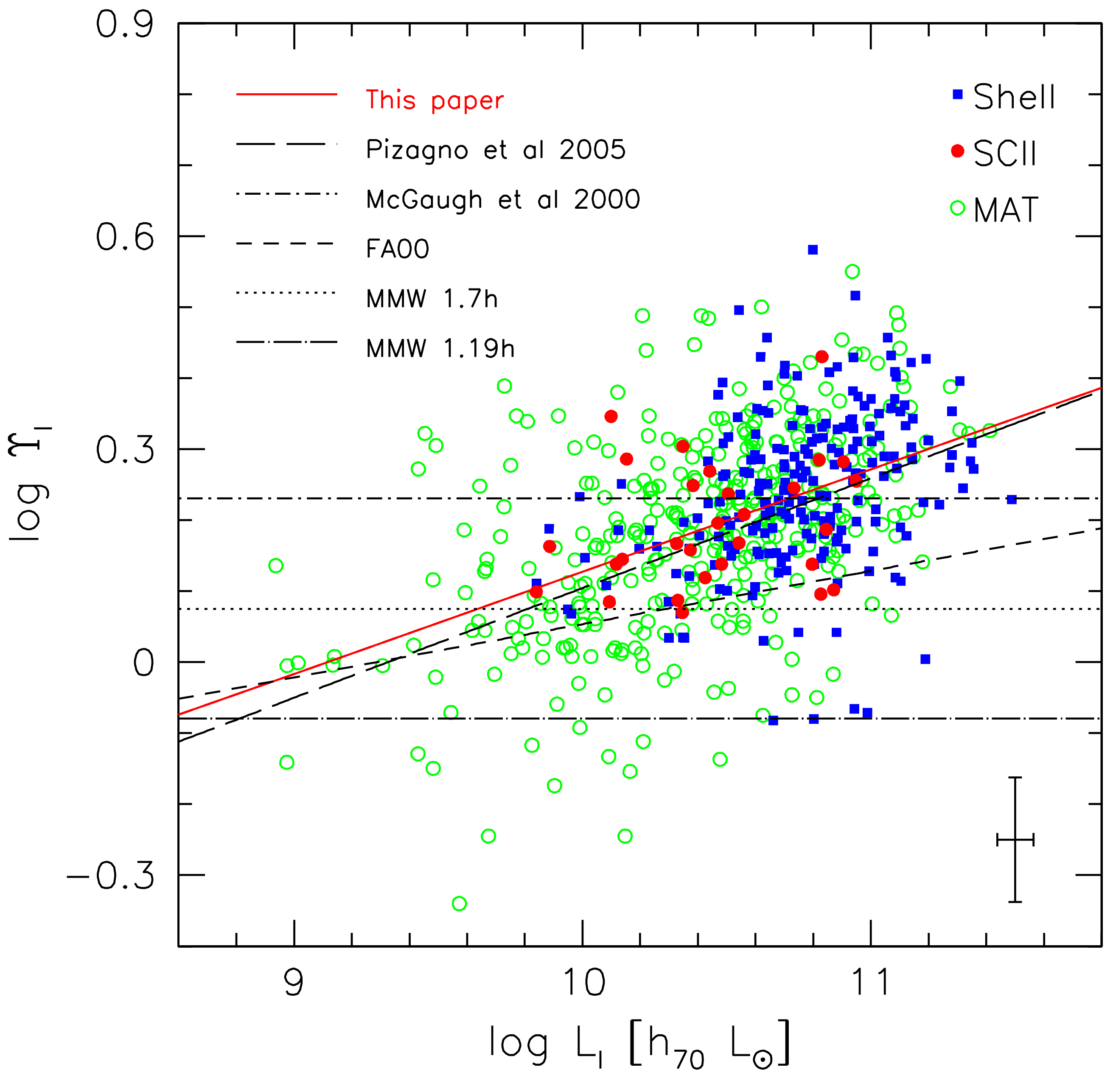
The Maller & Dekel Solution

- **Angular momentum originates from satellite accretion rather than from cosmological torques** **(Vitvitska et al 2002; Maller, Dekel & Somerville 2002)**
- **Most of the final angular momentum originates from the last major merger(Maller & Dekel 2002)**
- **Most of the low angular momentum material originates from the many, uncorrelated, minor accretion events (Maller & Dekel 2002)**

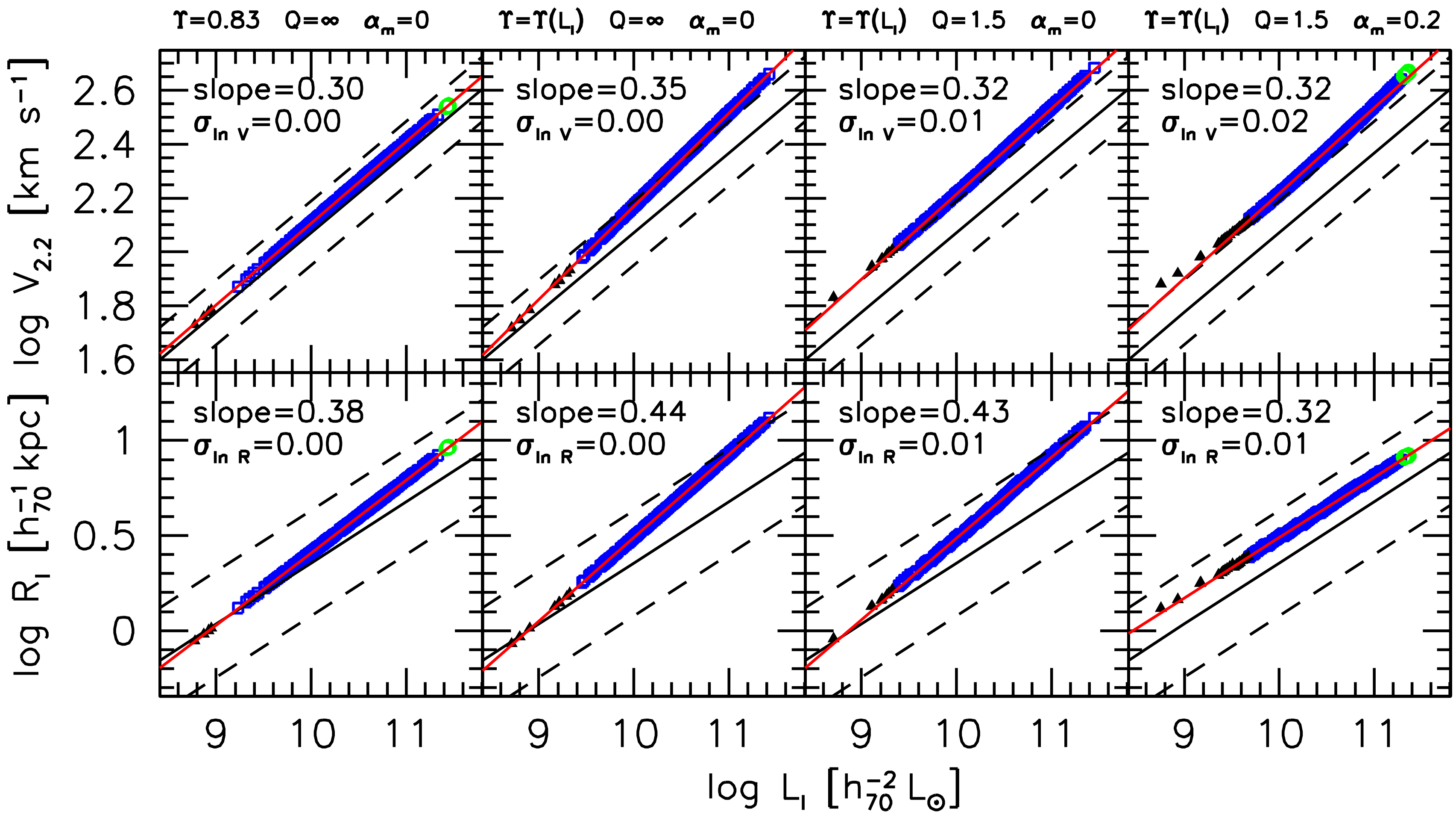
SOLUTION: remove gas from low mass progenitors



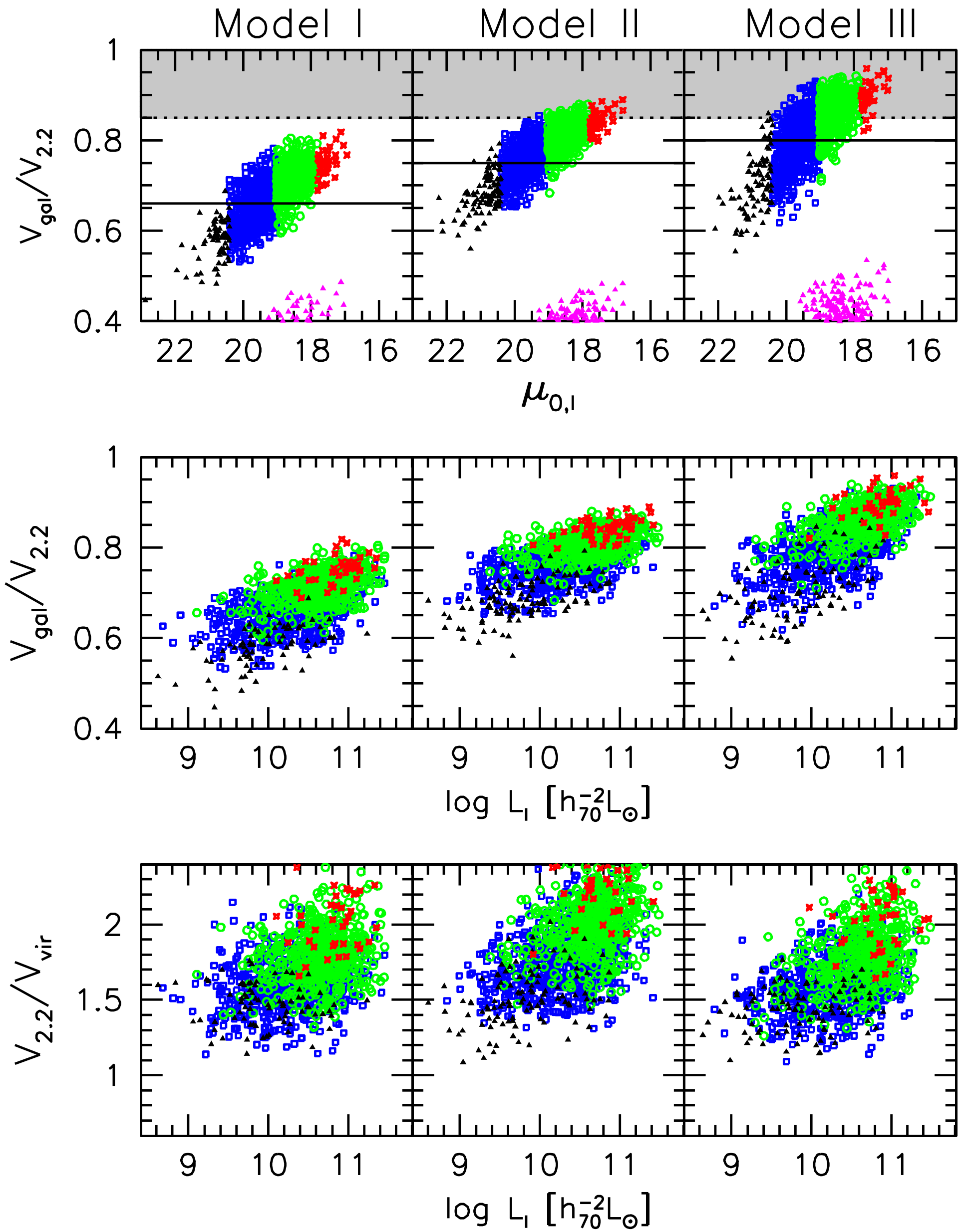
Stellar Mass-to-Light Ratios



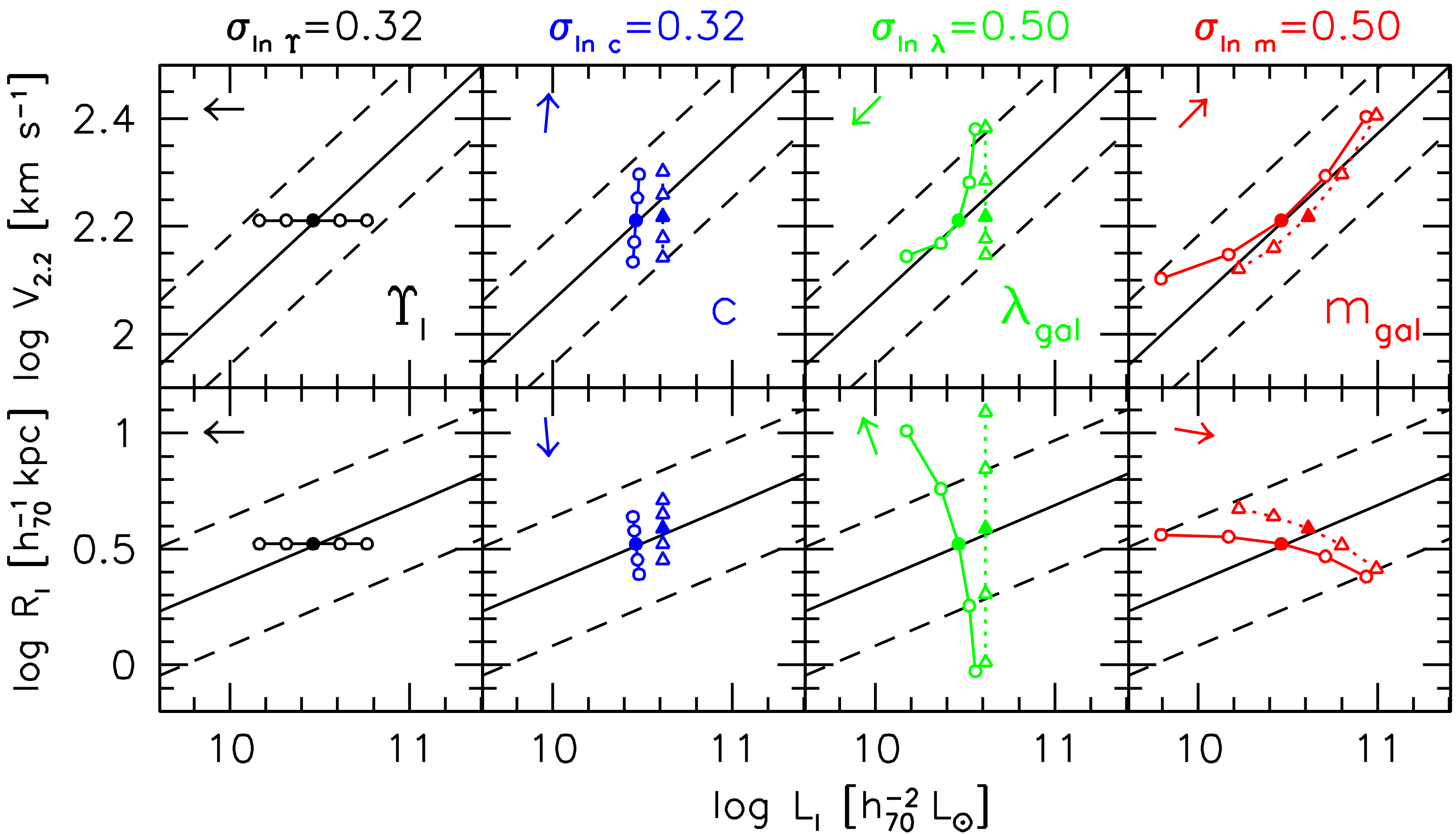
Slopes & Zero-points



Standard Models II



Scatter



σ_ln ϒ=0.32
σ_ln c=0.32
σ_ln λ=0.50
σ_ln m=0.50
log V_2.2 [km s^-1]
log R_I [h_70^-1 kpc]
ϒ_I
c
λ_gal
m_gal
2.4
2.2
2
1
0.5
0
10
11
log L_I [h_70^-2 L_⊙]