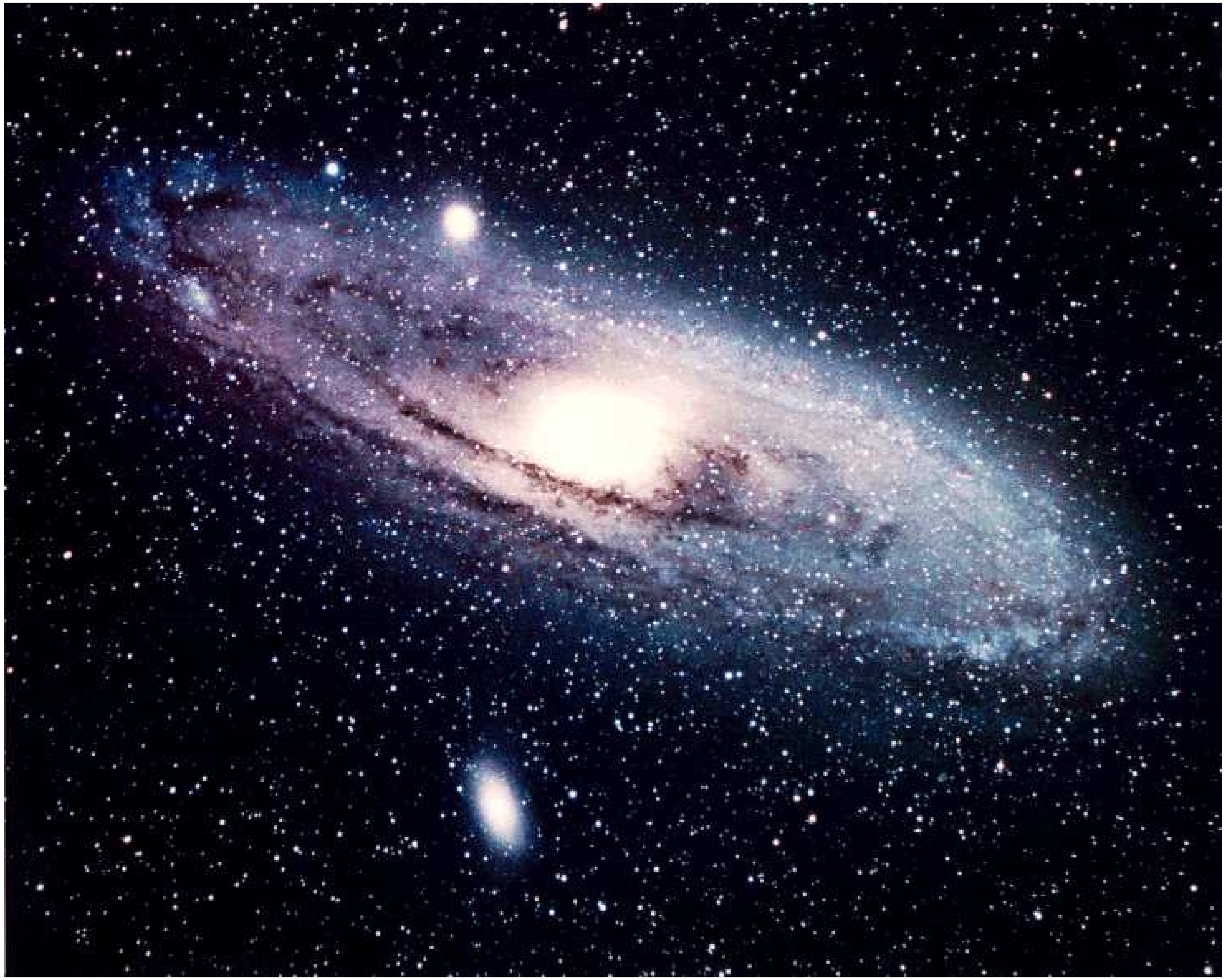
The Formation of Disk Galaxies



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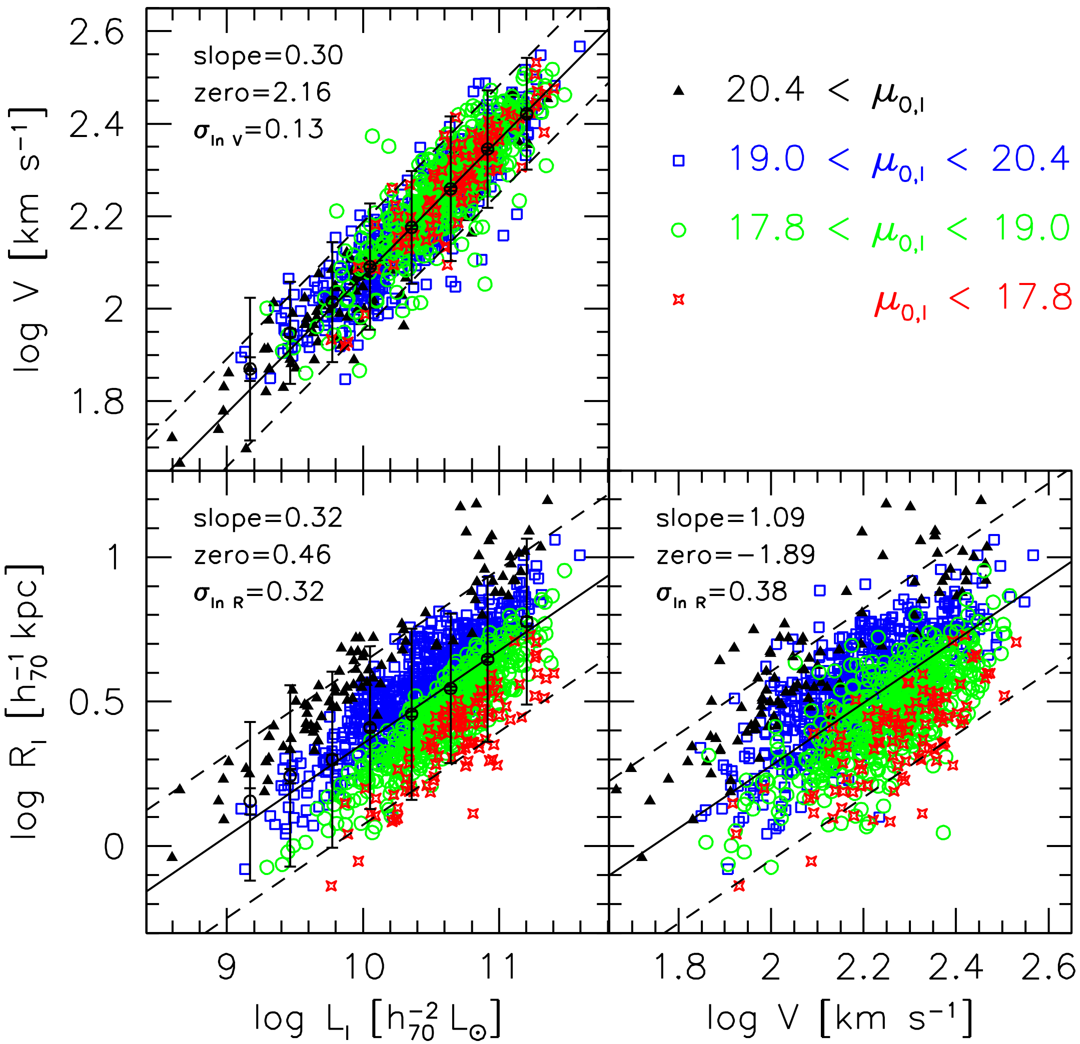
Disk Scaling Relations



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

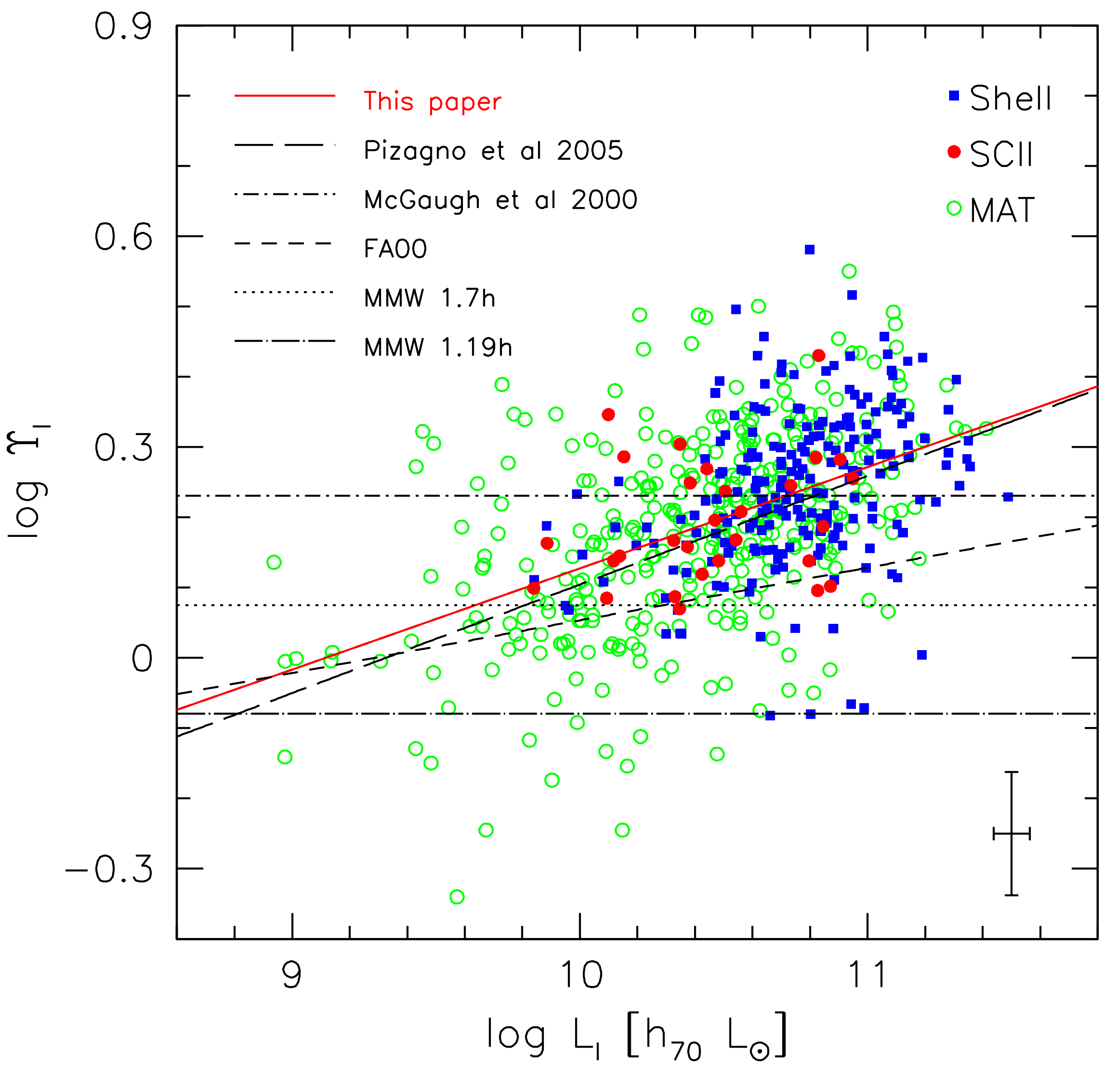
- Exponential disk in NFW dark matter halo (Mo, Mao & White 1998)
  Halo concentrations modelled as $c(M) = \eta \, c_{\rm bul}(M)$
- Modified Adiabatic contraction: $r_f = \Gamma^{\nu} r_i$
  Standard AC: $\nu = 1$, No AC: $\nu = 0$, Expansion: $\nu < 0$
- Disk mass fraction: $m_{\rm gal} \equiv \frac{M_{\rm gal}}{M_{\rm vir}} = m_{\rm gal,0} \left(\frac{M_{\rm vir}}{10^{11.5} h^{-1} \, {\rm M}_{\odot}} \right)^{\alpha}$
- 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: $\Delta_{\rm IMF} = -0.20$

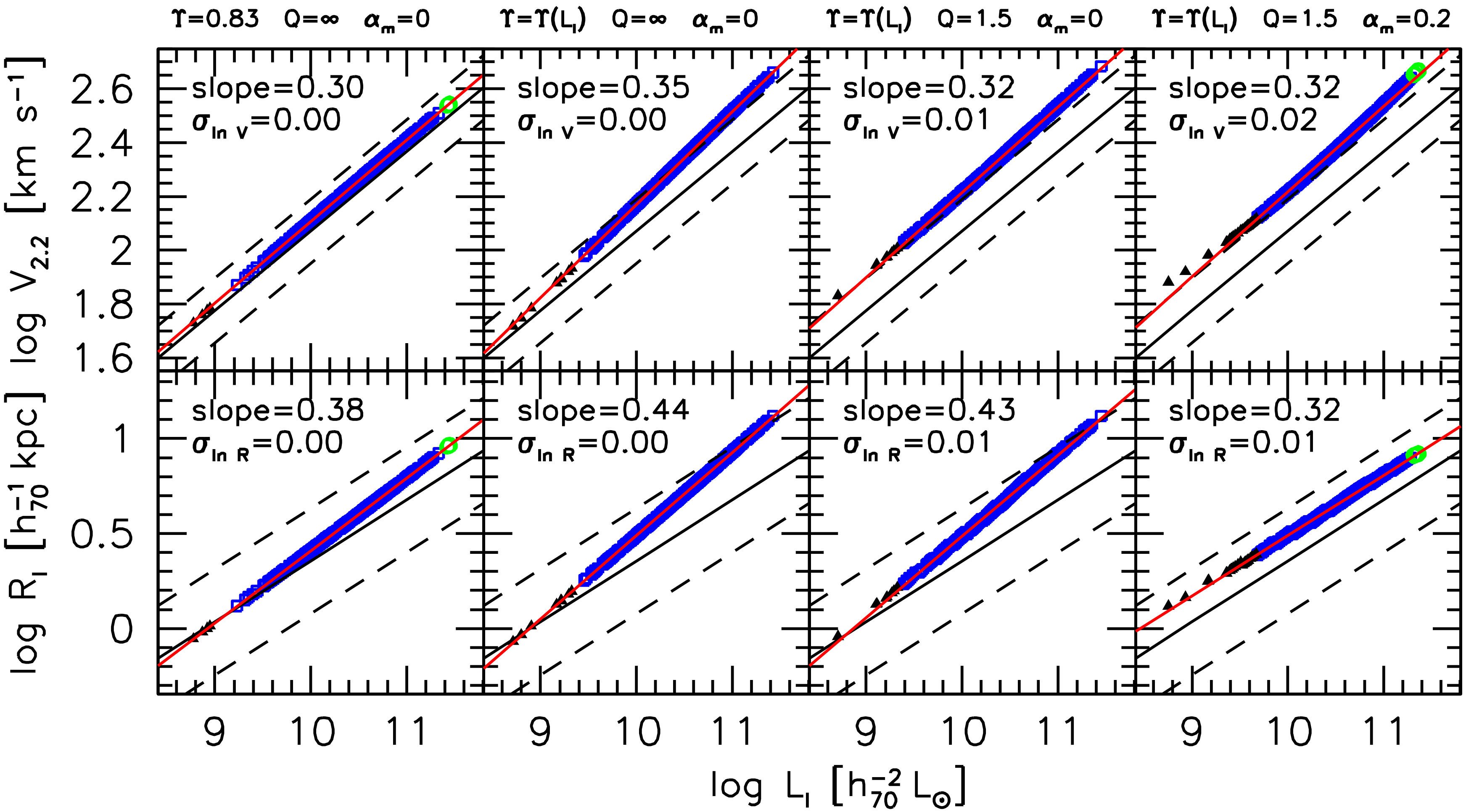
Free parameters: $\overline{\lambda}_{\rm gal}$, η , ν , $\overline{m}_{\rm gal,0}$, α , $\Delta_{\rm IMF}$

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**

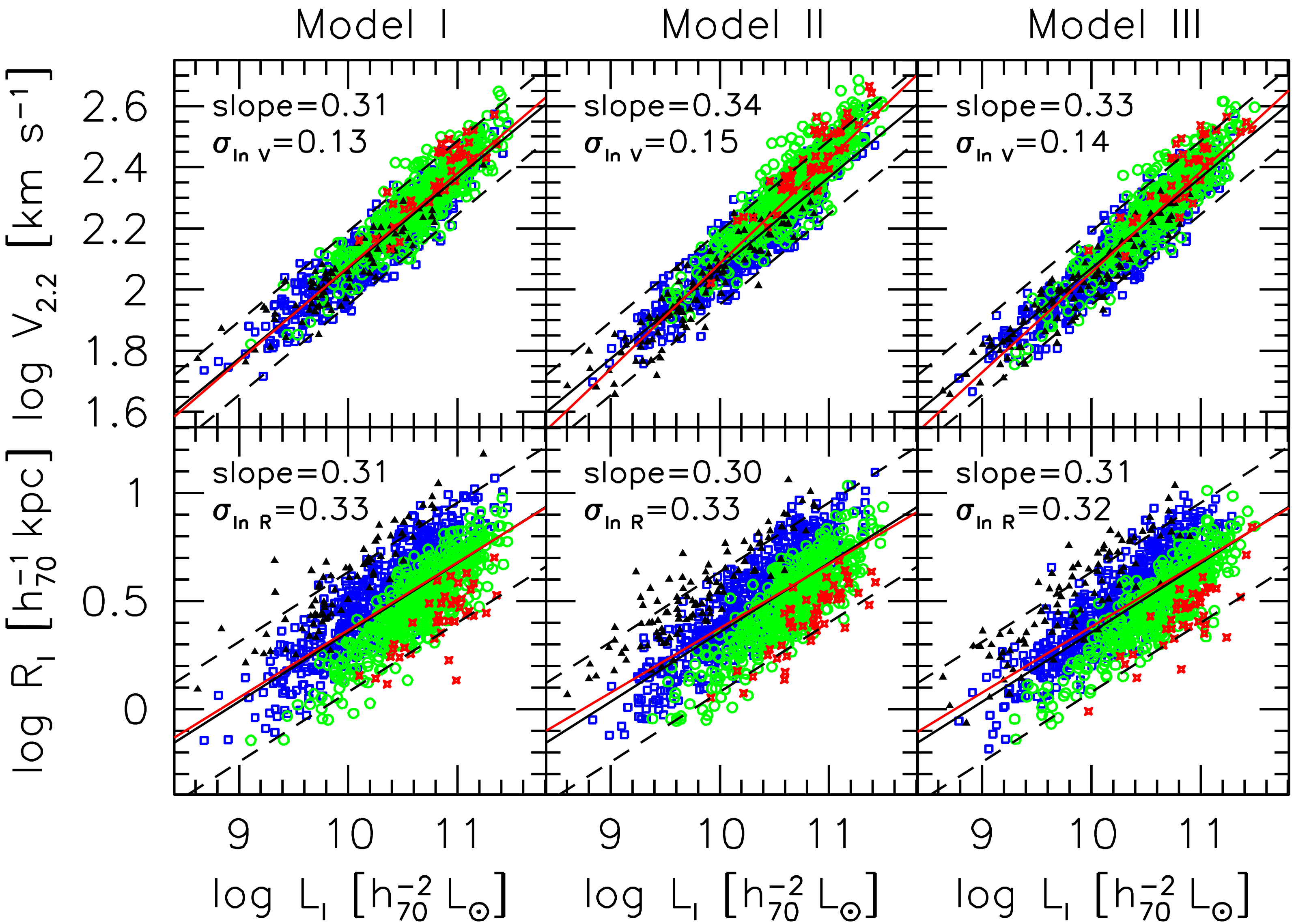
  Required $\nu \ll 0$ (significant expansion)

  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:	$\nu = 0.0$ & $\eta = 0.8$	$\Rightarrow$	$\Delta_{\rm IMF} = -0.2$

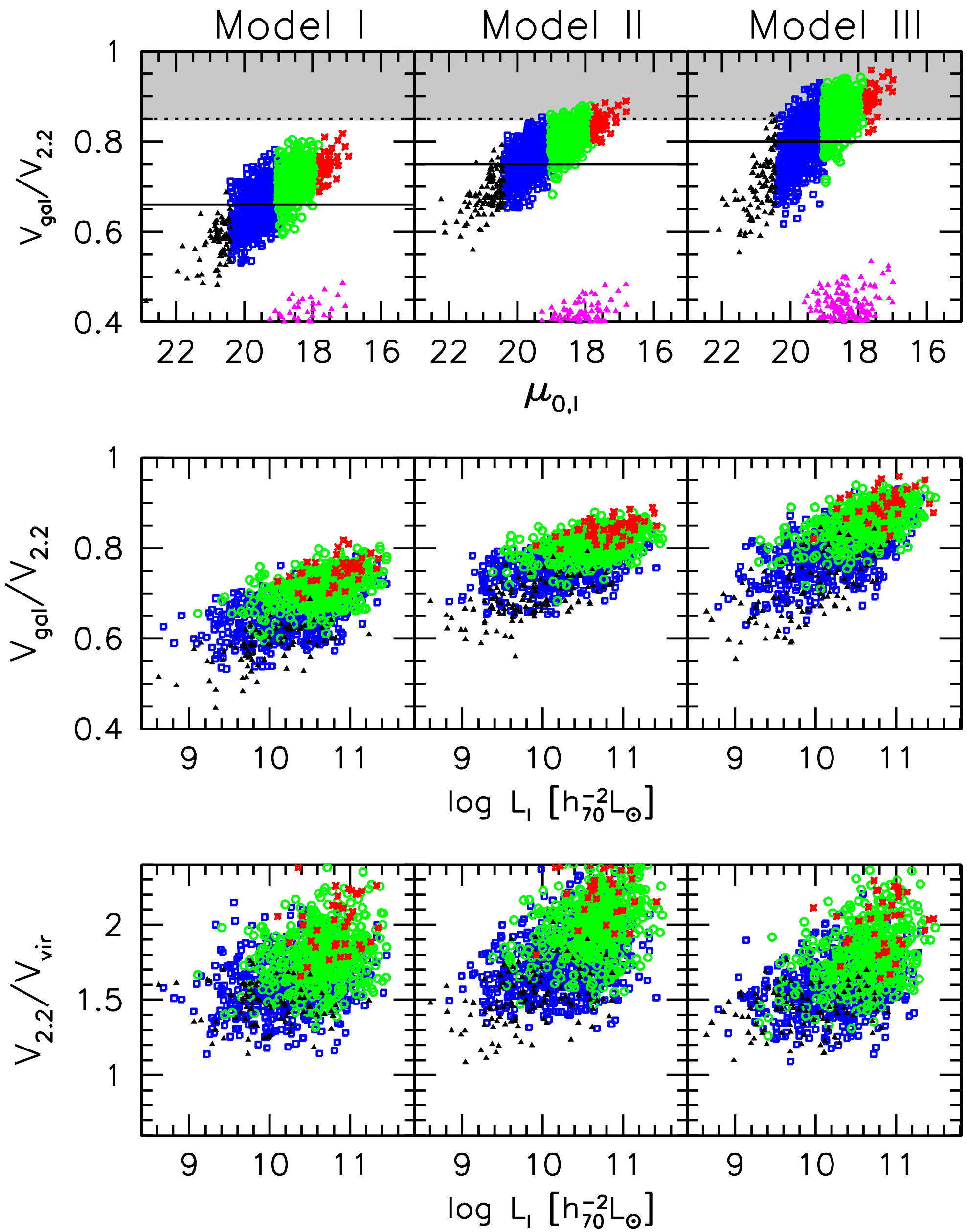
Three Models that seem to work



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 $2.2 R_I$.

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

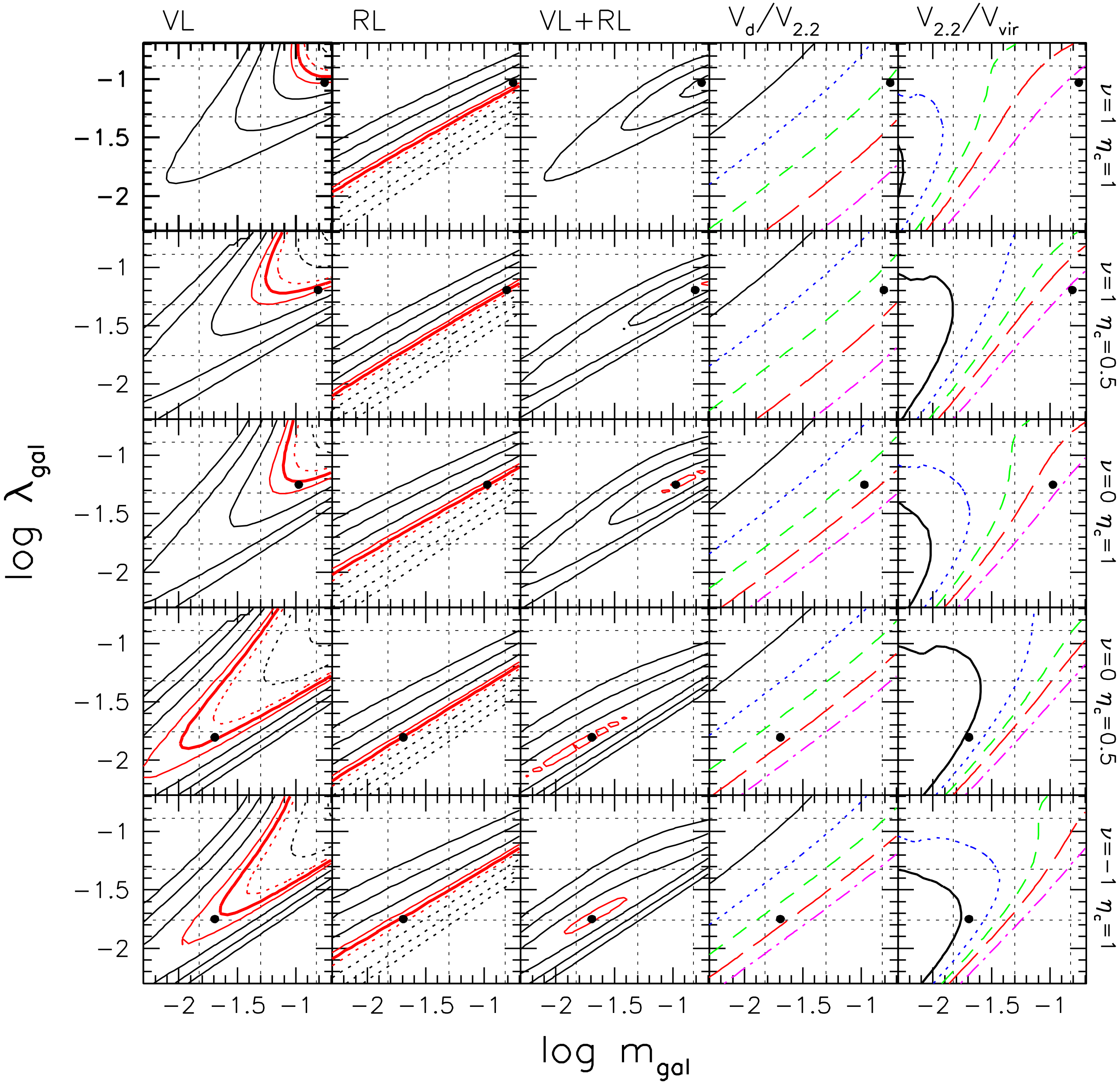
V_{vir}: Virial velocity of the halo.

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

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

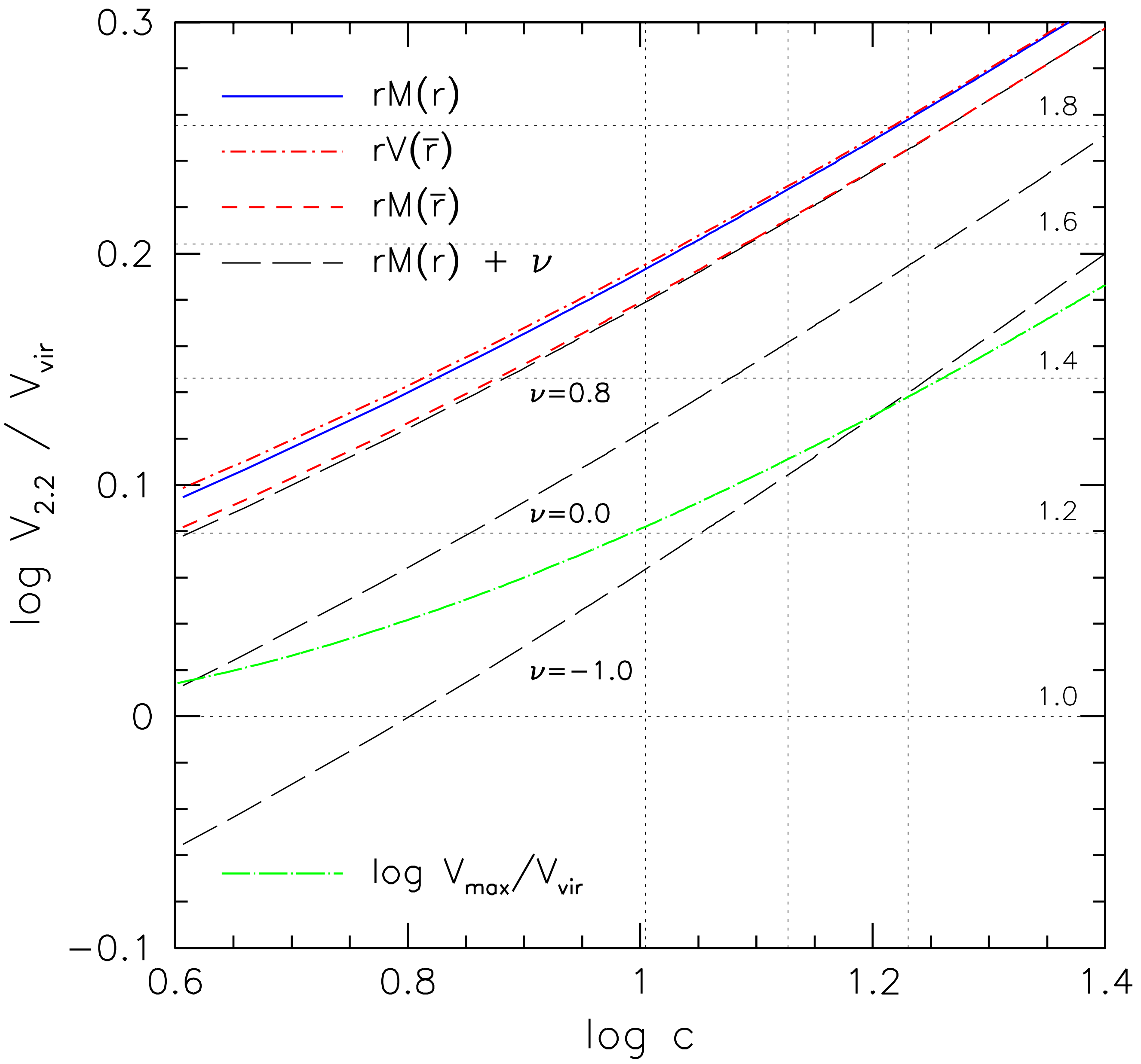
This implies that these models can not simultaneously match the luminosity function of disks.

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.