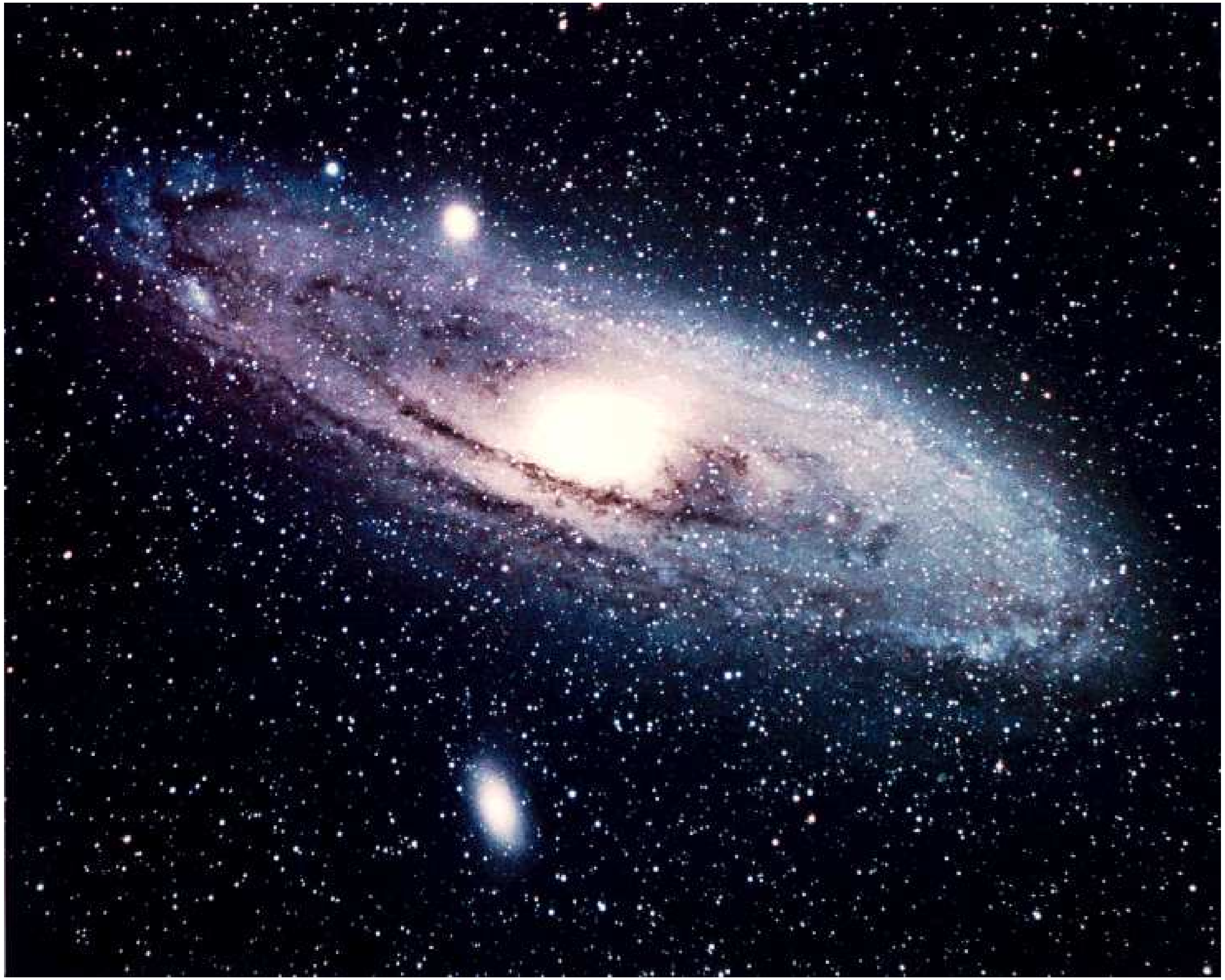
Angular Momentum Problems in Disk Formation



MPIA Theory Group Seminar, 07/03/2006

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

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

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

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

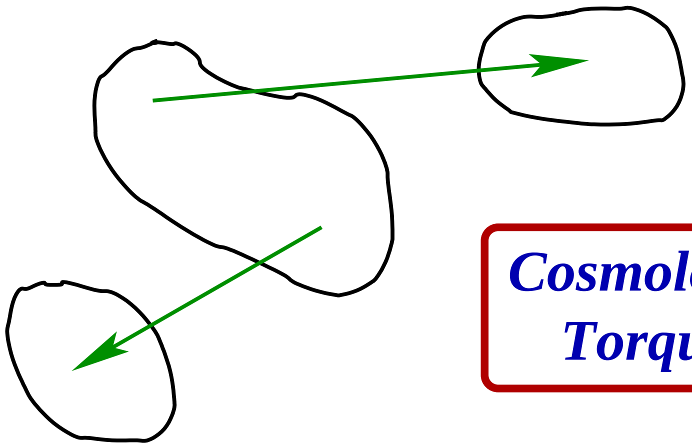
Numerical simulations have shown that $\langle\lambda\rangle \simeq 0.04$

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

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

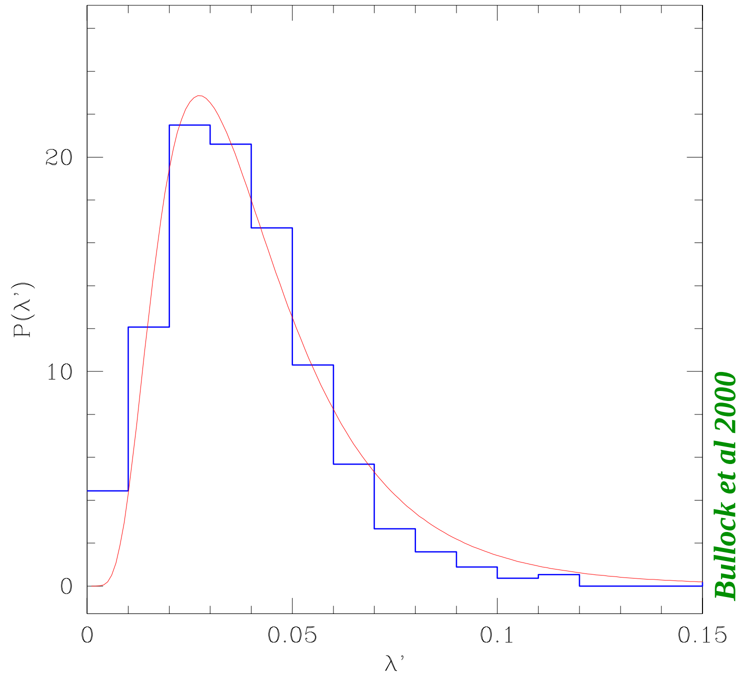
Thus λ^{-1} reflects roughly the collapse factor of the baryons

Angular Momentum & Dark Matter

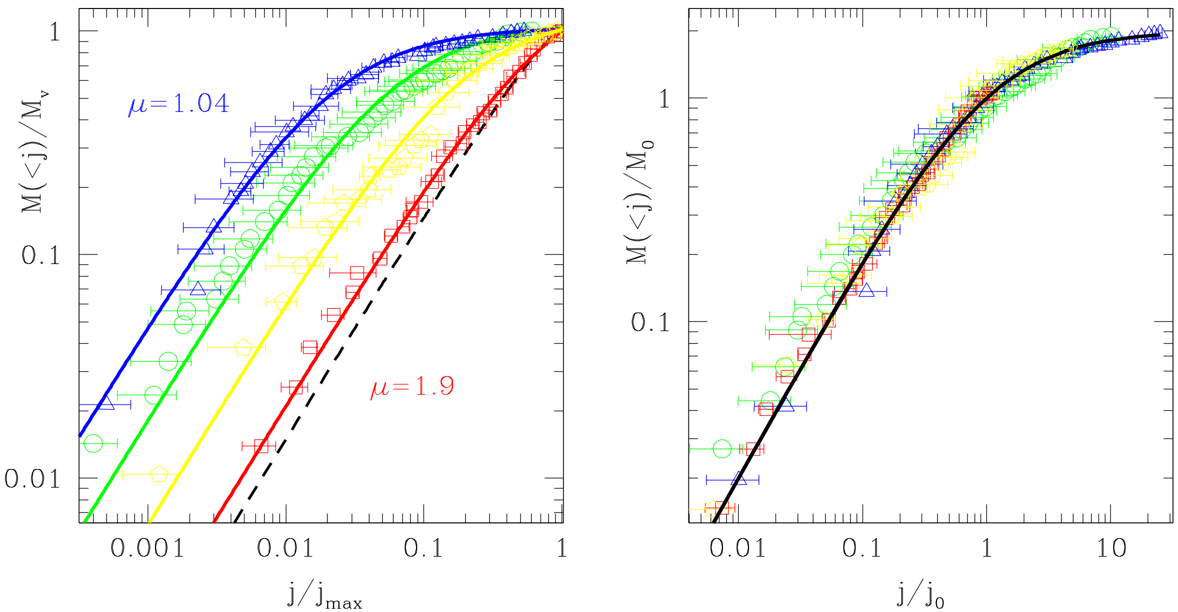


Cosmological Torques

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



Bullock et al 2000



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

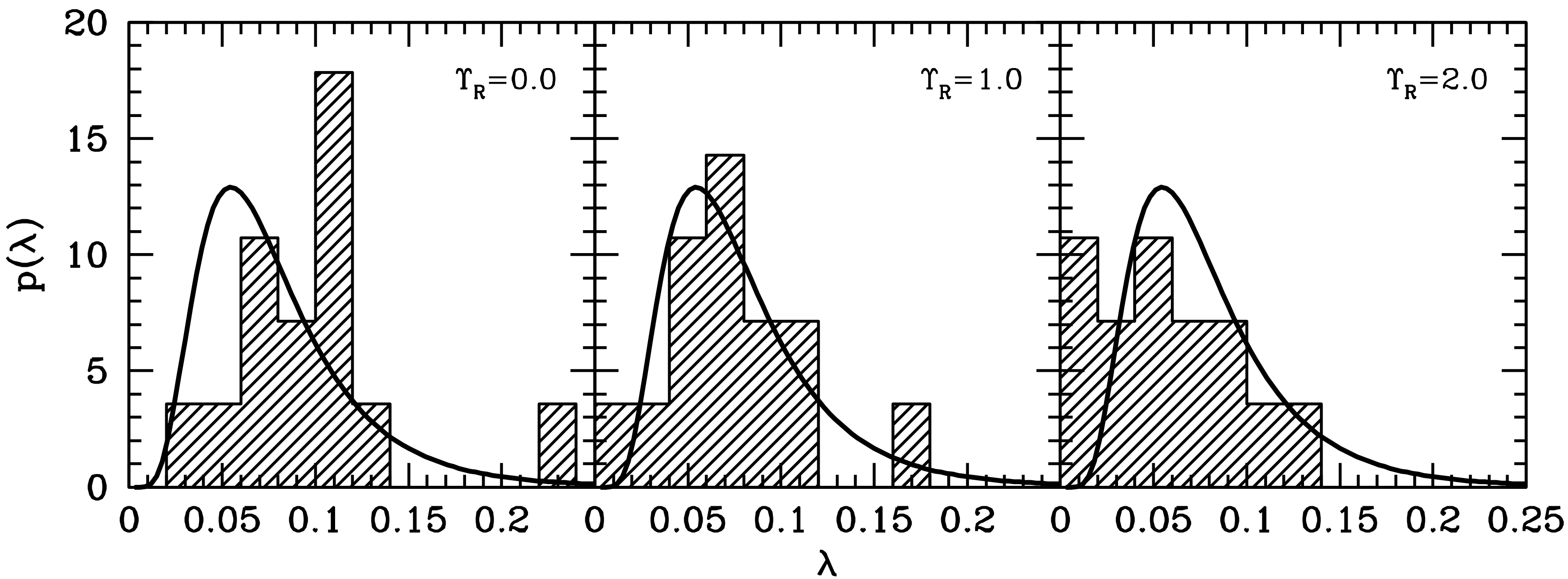
Cold Dark Matter haloes have a Universal Angular Momentum distribution... *Bullock et al 2000*

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).**

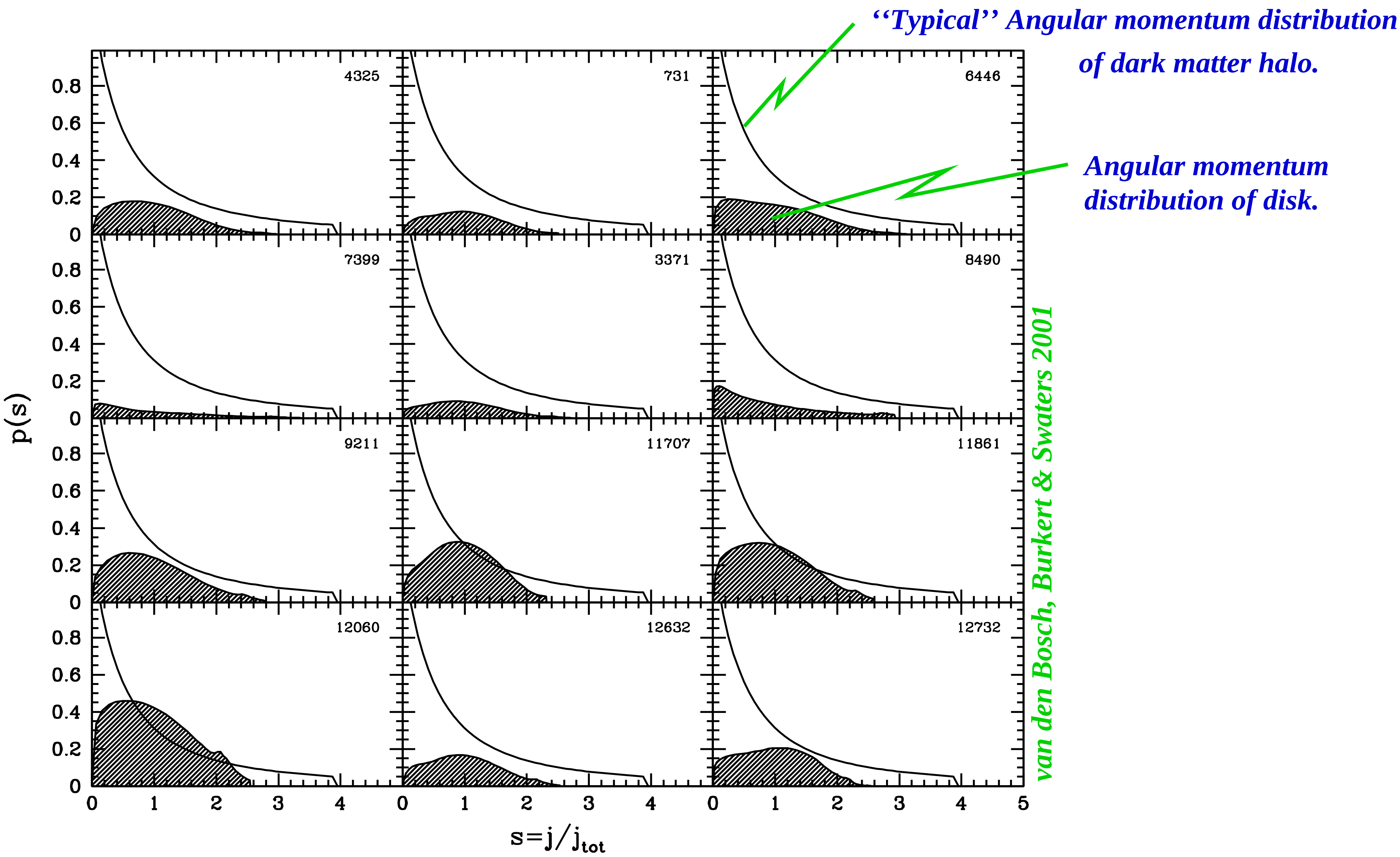
$$M(<j) = 2\pi \int_0^{R_j} \Sigma_{\rm disk}(R)\, R\, {\rm d}R \quad \text{with} \quad j = R_j V_{\rm circ}(R_j)$$



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

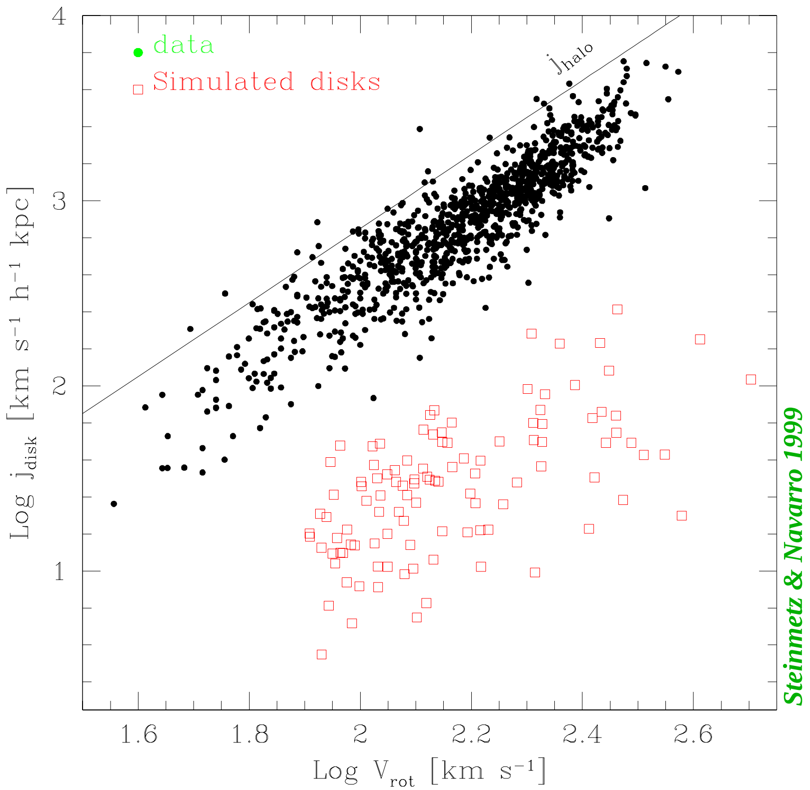
van den Bosch, Burkert & Swaters 2001

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:

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

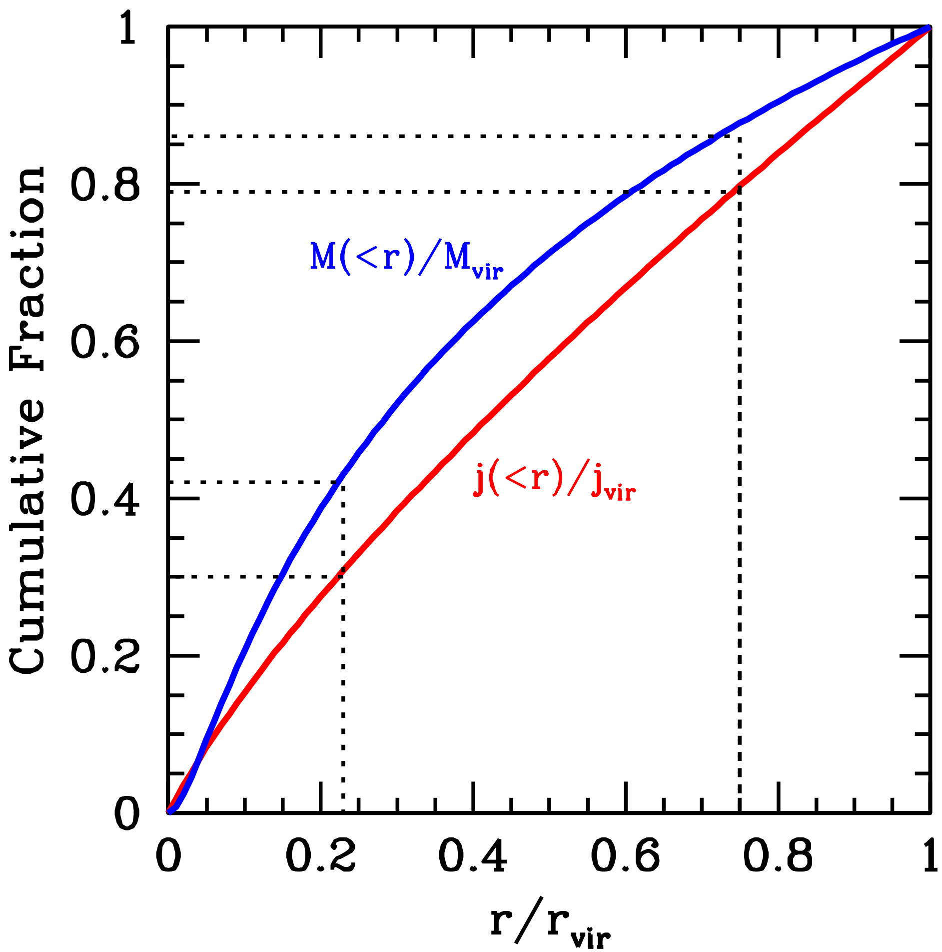
Example: $\Omega_m = 0.3 \qquad h = 0.7 \qquad \lambda = 0.04 \qquad V_{\rm rot}/V_{\rm vir} = 1.4$

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

(see also Navarro & Steinmetz 2000)

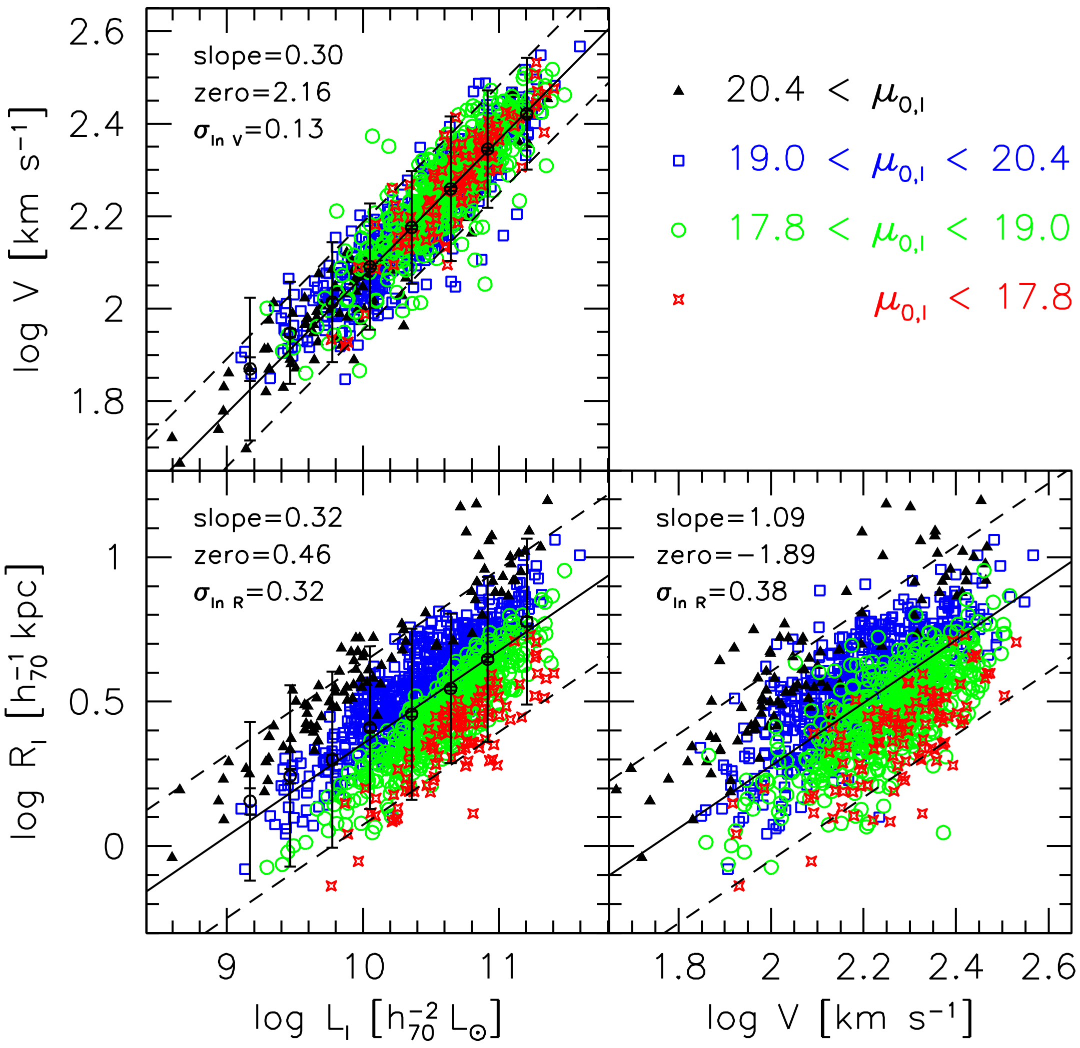
Disk Scaling Relations II

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



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

Disk Scaling Relations III



Sample of $\sim$ 1300 galaxies with Hα RCs (Courteau et al. 2006)

Note surface brightness independence of TF relation!

Model Description

- Exponential disk in NFW dark matter halo
- Adiabatic contraction
- Disk is split in stars and cold gas using star formation threshold density
- Bulge formation based on disk stability
- Empirical stellar mass-to-light ratios: $\Upsilon = \Upsilon(L)$

We construct samples with scatter in c, Υ, $\lambda_{\rm gal}$, and $m_{\rm gal}$

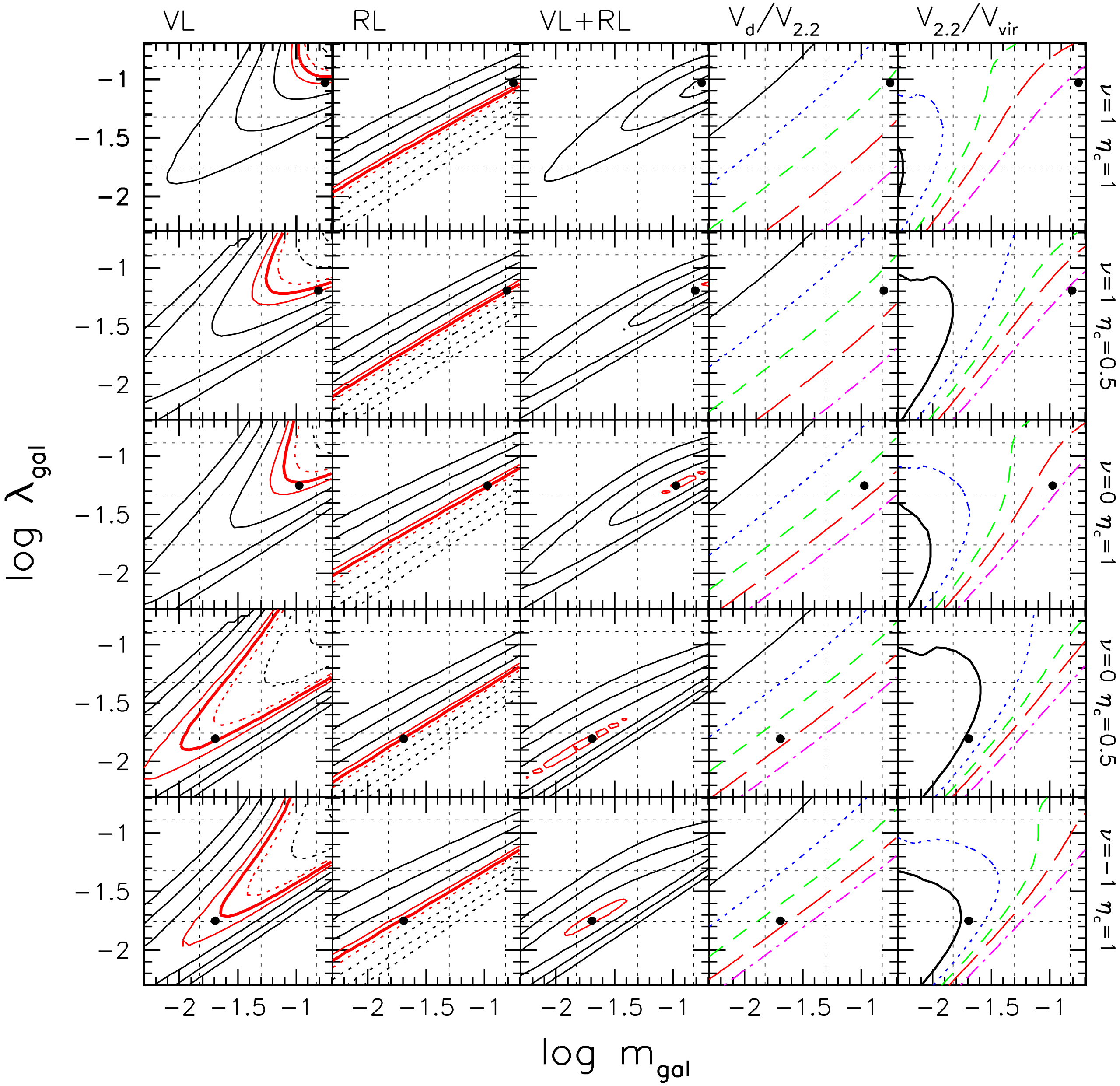
Sampling of $M_{\rm vir}$ is such that we reproduce observed distribution of L

Free parameters: $\overline{\lambda}_{\rm gal}$, $\overline{m}_{\rm gal}$, $\overline{c}$ (cosmology), and $\overline{\Upsilon}$ (IMF)

In addition we tune $\sigma_{\ln c}$, $\sigma_{\ln \lambda}$, $\sigma_{\ln \Upsilon}$

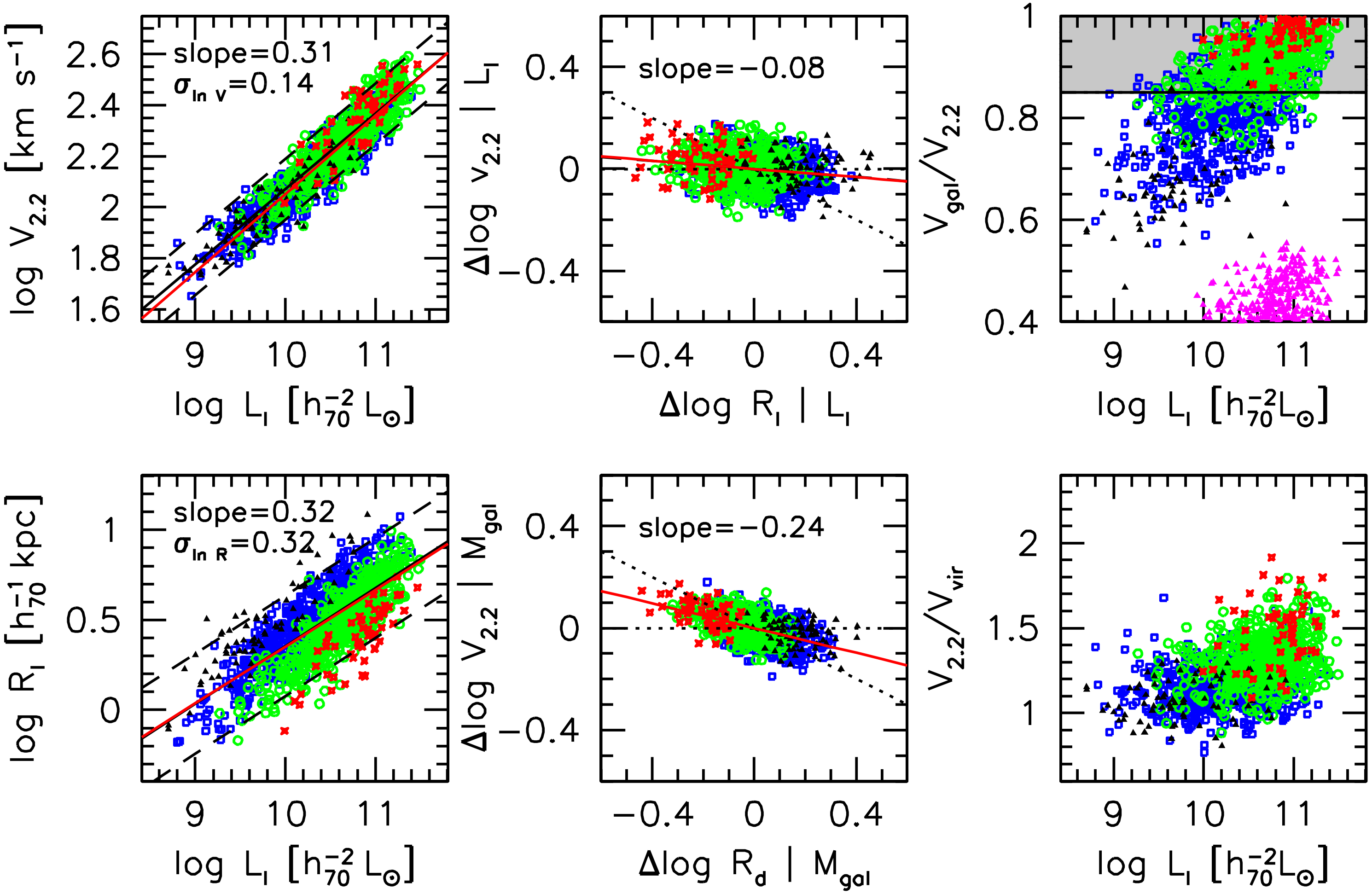
Finally, we can modify adiabatic contraction

Zero-Point Constraints



Dutton, vdB, Dekel & Courteau, 2006

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 galaxy luminosity function!!

CONCLUSIONS

Problems for the Standard Problem

★ cooling very efficient in low mass haloes at high z

⟹ Angular Momentum Catastrophe

★ haloes have too much low angular momentum material

⟹ Morphology Problem! Too much bulge, too little disk

★ Standard model can not fit TF zero point

⟹ Haloes are too centrally concentrated

A Revised Model for Disk Formation

(1) Disks form out of Merging Clumps

(2) Dynamical Friction and 3-Body Interactions cause Halo Expansion

(3) Disks form in subset of haloes with quiescent merger history

This results in low $\overline{\lambda}_{\rm gal}$ and low $\sigma_{\ln \lambda}$

(4) Formation efficiencies of disks are low

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