

The Physics of Disk Formation



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The Standard Model

The standard picture of disk formation (Fall & Efstathiou 1980) is based on two main **assumptions**

(1) Baryons & Dark Matter start out with identical angular momentum distributions (AMD)

(2) Baryons conserve their specific angular momentum when cooling to form the disk

Under these **assumptions**

- Total specific angular momenta of disk and dark matter are the same.
- Surface density distribution of disk reflects initial AMD of gas.
- Disk scalelength is $R_d \propto \lambda R_{\text{vir}}$.

Numerous models, of ever increasing complexity, have been constructed based on this general framework:

Dalcanton et al. 1997; Mo, Mao White 1998

Avila-Reese & Firmani 2000; van den Bosch 1998, 2000, 2001, 2002

It also is used in most semi-analytical models for galaxy formation

Kauffmann 1996; Somerville & Primack 1999; Cole et al. 2000

But are these assumptions justified?

Success & Failure

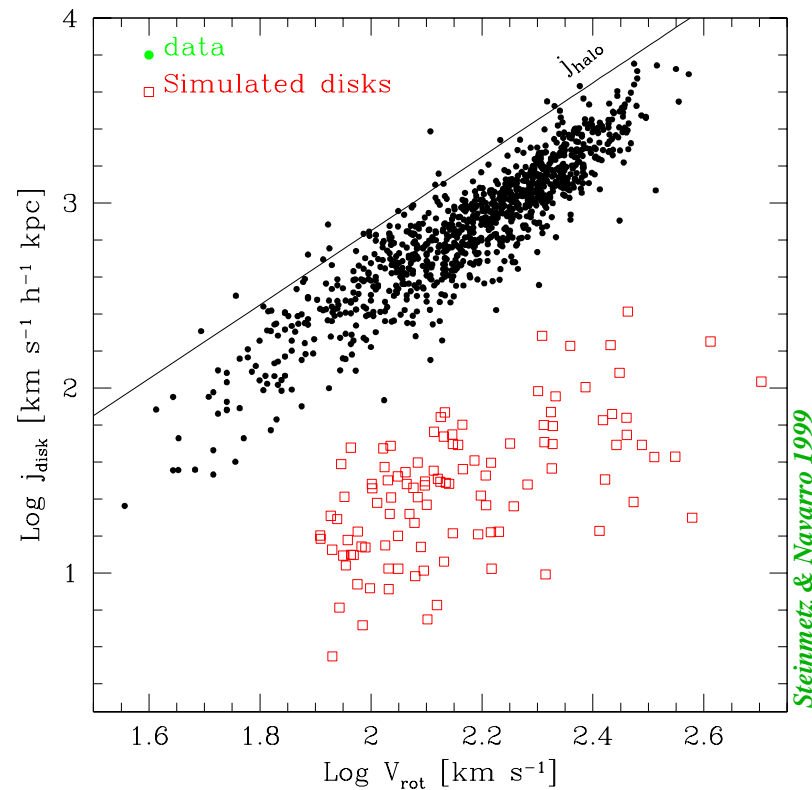
Successes

- **Distribution of disk scale lengths** (Mo, Mao & White 1998; de Jong & Lacey 2000)
- **Existence of LSB galaxies** (Dalcanton et al. 1997; Jimenez et al. 1998)
- **Formation of bulges out of low- j material** (vdB 1998)
- **Flat rotation curves** (Firmani & Avila-Reese 2000; vdB 2002)
- **When bulge present, exponential disks** (Avila-Reese & Firmani 2000; vdB 2001)
- **Tully-Fisher relation** (Mo, Mao & White 1998; Buchalter et al. 2001; Shen, Mo & Shu 2002)
- **Radial color gradients** (Avila-Reese & Firmani 2000)
- **“G-dwarf problem”** (Boissier & Prantzos 1999; Samland & Gerhard 2003)

Problems

- **Without bulge, disks too centrally concentrated** (Bullock et al. 2001; vdB 2001)
- **Inverted color-magnitude relation** (Bell et al 2003; vdB 2002)

The Angular Momentum Catastrophe



- Disks that form in simulations are an order of magnitude too small
- Gas loses large fraction of specific angular momentum to dark matter
- Hierarchical formation & “over-cooling” are to blame

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:

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

Theoretical Predictions:

- $M_{\text{disk}} = f_m \left(\frac{\Omega_b}{\Omega_m} \right) M_{\text{vir}}$
 - $j_{\text{disk}} = \sqrt{2} f_j \lambda' R_{\text{vir}} V_{\text{vir}}$
 - $M_{\text{vir}} \propto V_{\text{vir}}^3 \quad R_{\text{vir}} \propto V_{\text{vir}}$
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Example: $\Omega_m = 0.3 \quad h = 0.7 \quad \lambda = 0.04 \quad V_{\text{rot}}/V_{\text{vir}} = 1.4$

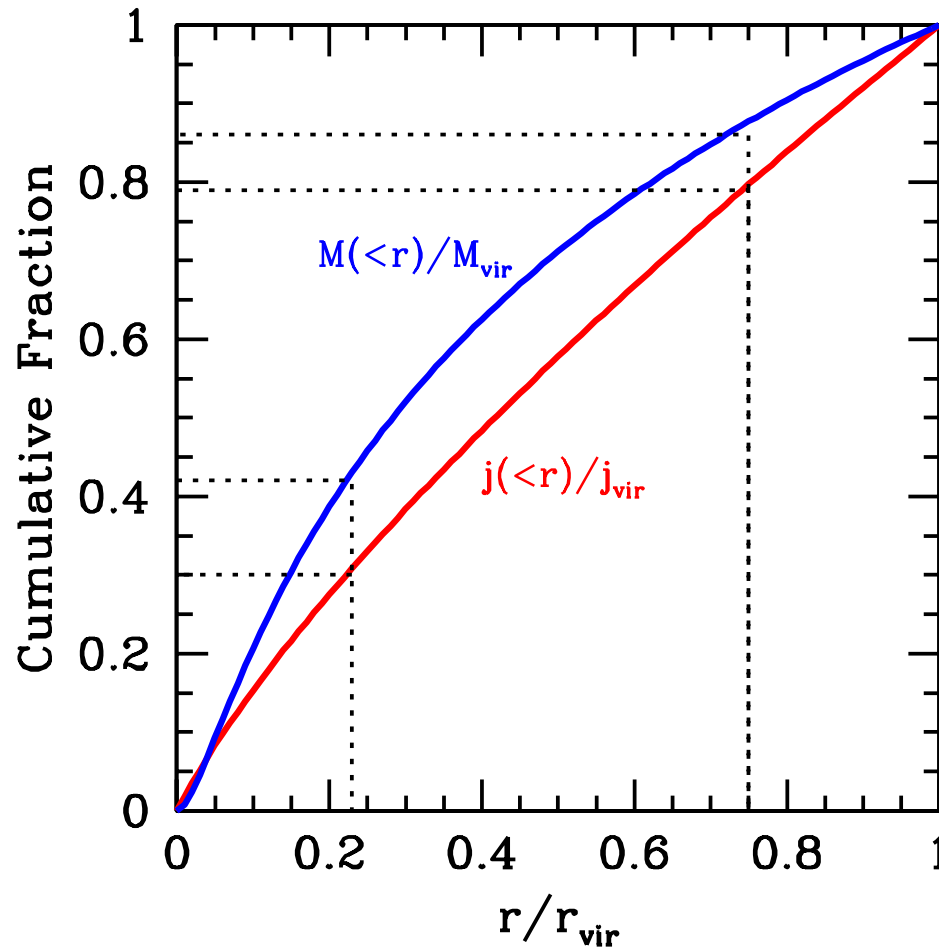
$$f_m = 0.42 \left(\frac{V_{\text{vir}}}{200 \text{ km s}^{-1}} \right)^{1/2} \quad f_j = 0.79$$

(see also Navarro & Steinmetz 2000)

Disk Scaling Relations II

$$f_m = 0.42 \left(\frac{V_{\text{vir}}}{200 \text{ km s}^{-1}} \right)^{1/2}$$

$$f_j = 0.79 \left(\frac{\lambda'}{0.04} \right)^{-1}$$



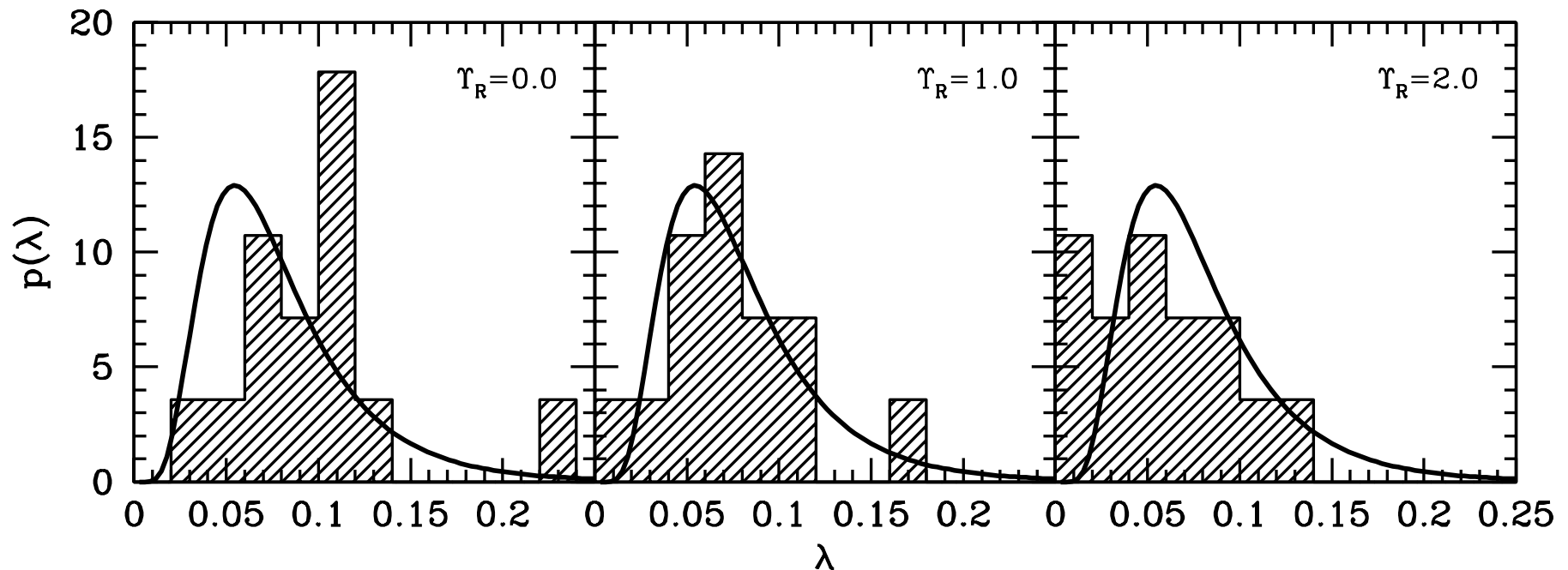
- $M(r)$ from NFW profile with $c = 20$ (Navarro, Frenk & White 1997)
- $j(r) \propto r$ from N -body simulations (Bullock et al. 2001)

Testing the Paradigm

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

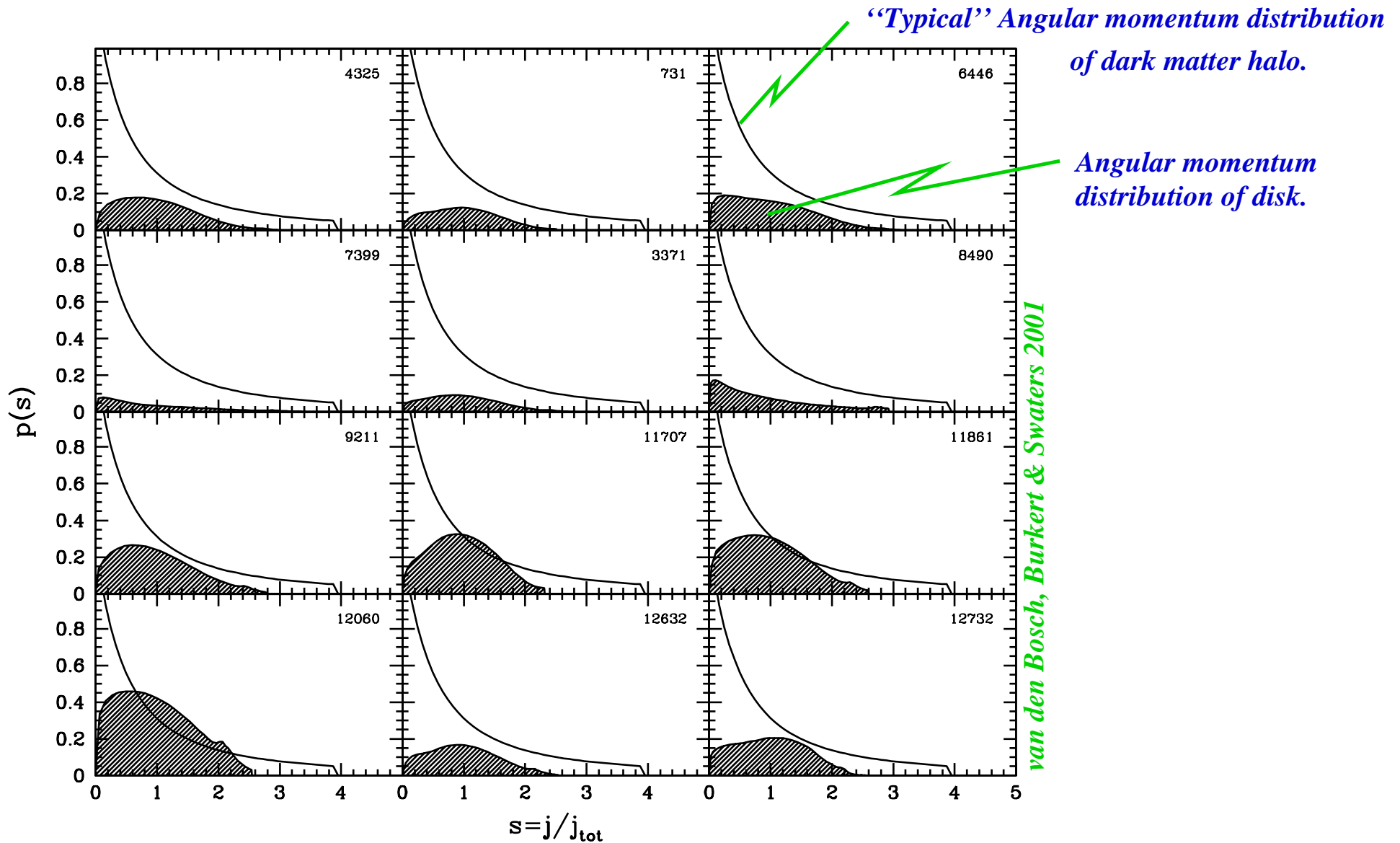
DATA: 14 dwarf galaxies whose rotation curves are in good agreement with CDM haloes (van den Bosch & Swaters 2001).

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



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

Angular Momentum Distributions



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

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 Λ CDM cosmology with **non-radiative** gas; Analyze individual haloes.

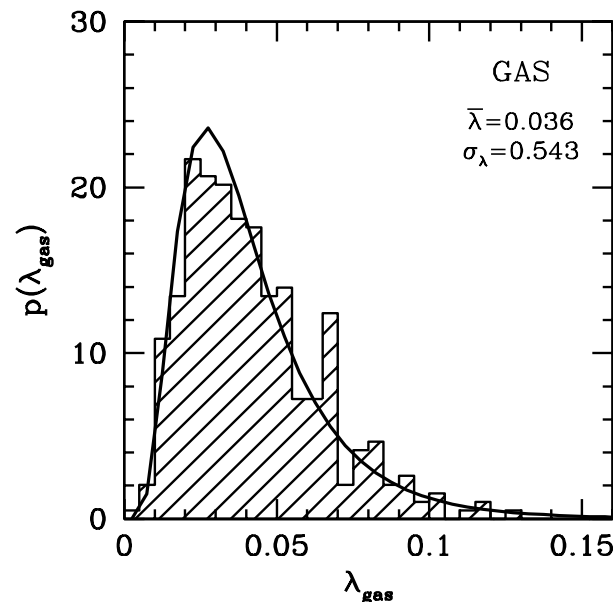
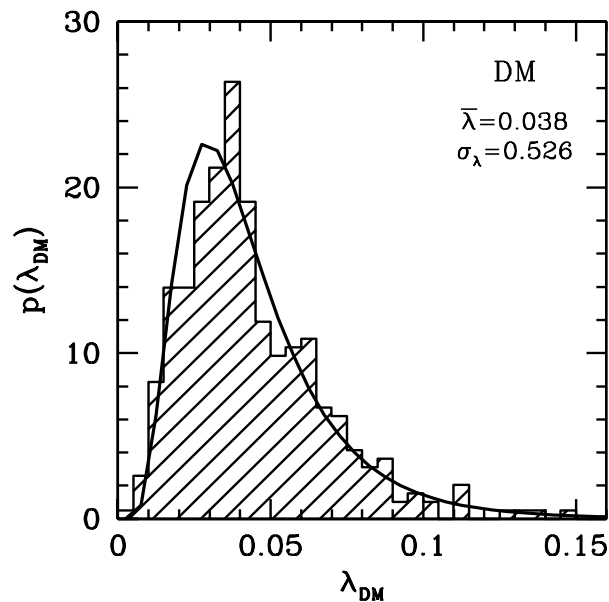
Gas and dark matter are fluids for which $\vec{v} = \vec{u} + \vec{w}$

\vec{v} = microscopic velocity (DM particles in simulation)

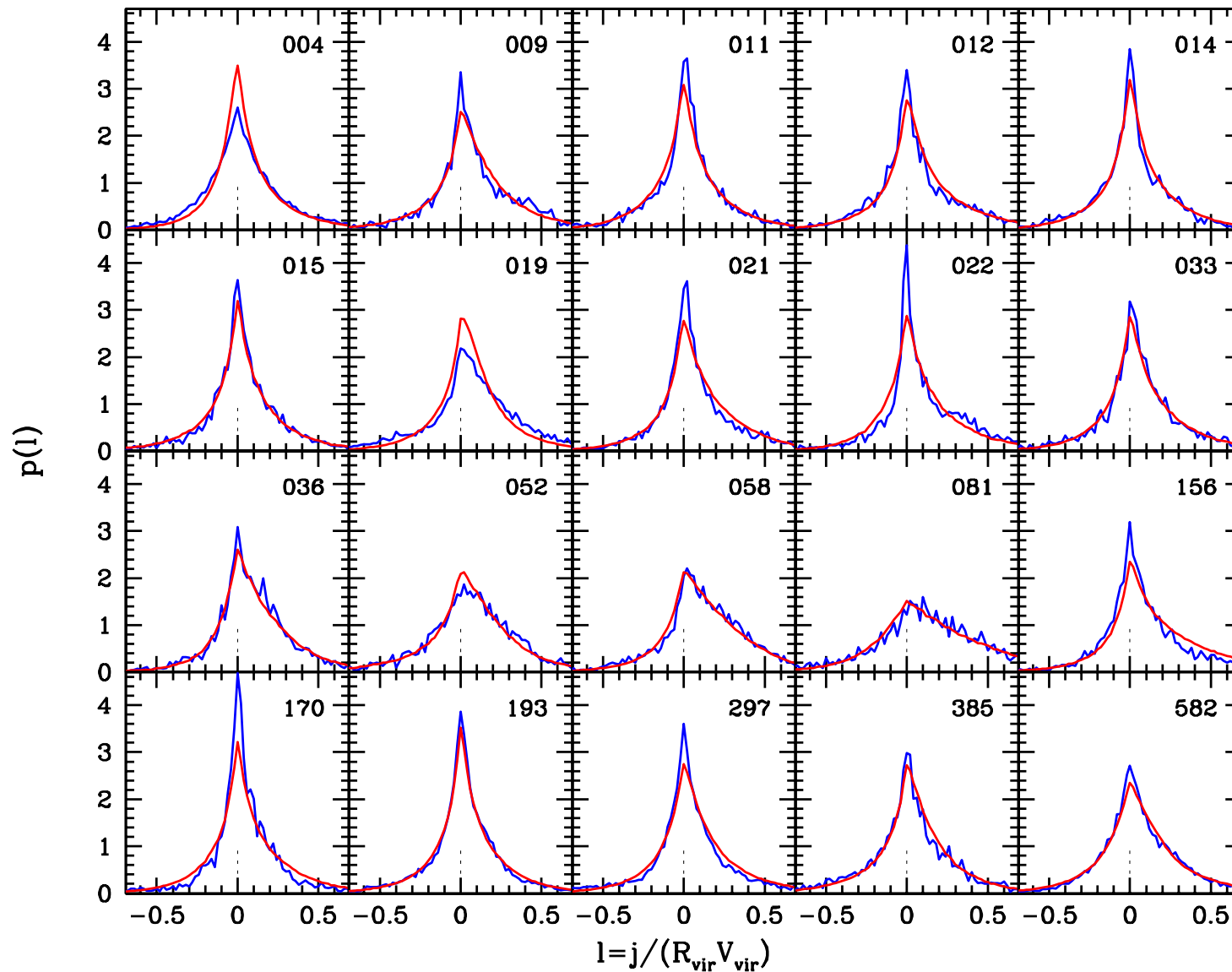
\vec{u} = streaming motions (SPH particles in simulation)

\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...



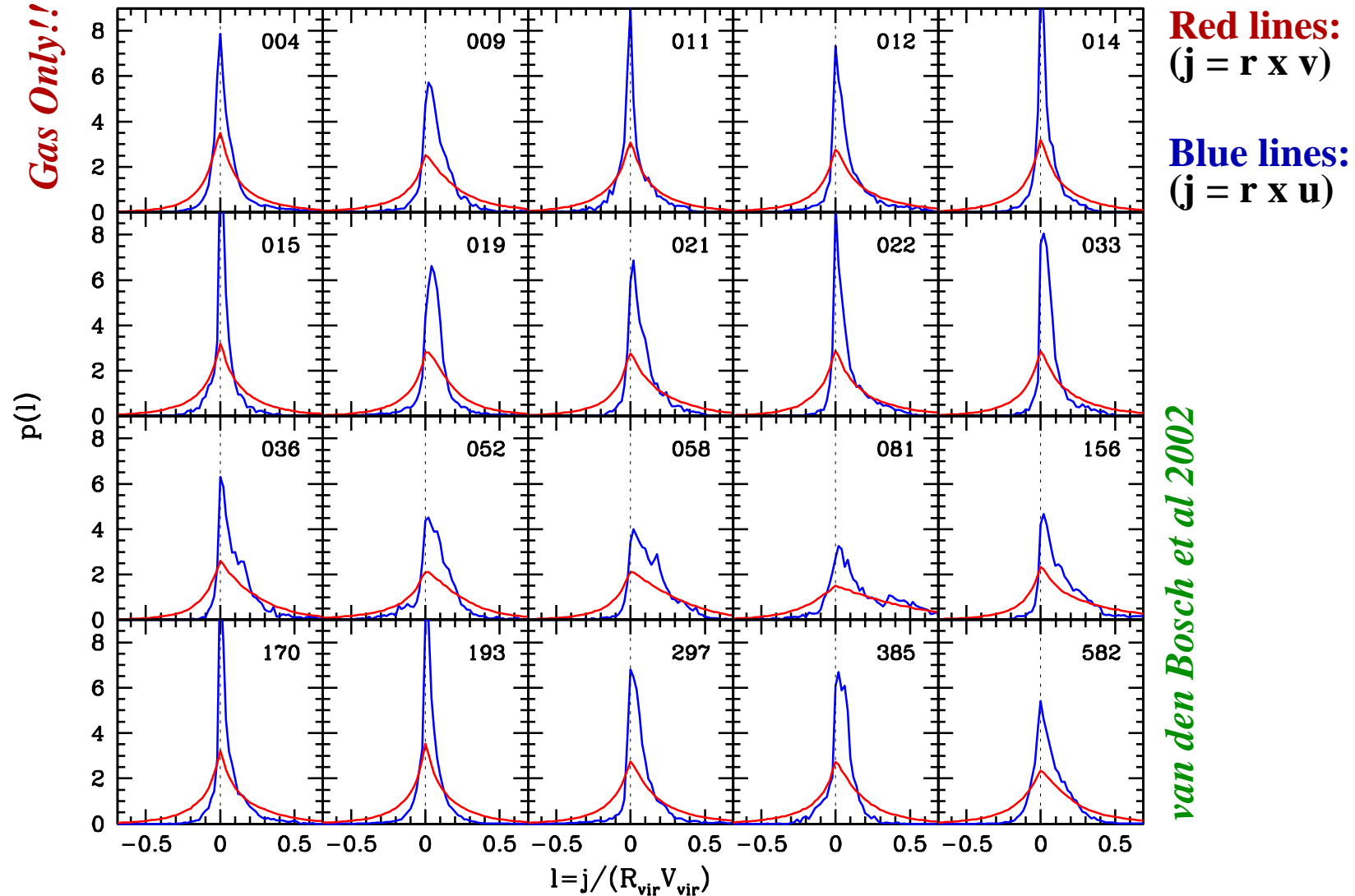
Blue lines:
Dark Matter

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?

- Disks do not contain counter-rotating material...

Bulge Formation?

- About 40% of haloes forms Early-Type galaxies

- Virtually no bulge-less systems can form

CONCLUSIONS

★ small mass haloes form before big mass haloes

★ cooling very efficient in low mass haloes at high z

⇒ **Angular Momentum Catastrophe & Inverted Color-Magnitude Relation**

★ haloes have too much **low** angular momentum material

⇒ **Morphology Problem! Too much bulge, too little disk**

★ haloes have too much **negative** angular momentum material

⇒ **No detailed conservation of specific angular momentum possible**

Standard Model for Disk Formation is Incomplete and/or Incorrect

Future Prospectives

(1) More detailed modelling of feedback & reionization

(2) Cold Accretion vs Hot Accretion

Katz et al. 2003; Birnboim & Dekel 2003

(3) Satellite accretion & streamers

e.g., Ferguson, & Sancisi, this meeting

(4) Running Spectral Index...