Eighth UCLA Symposium:
Sources and Detection of
Dark Matter and Dark
Energy in the Universe

Cosmology: small scale issues

(dark matter satellites, cusps, etc.) and implications for cold vs. warm dark matter

Joel Primack
UC Santa Cruz

Marina del Rey - Wednesday, February 20, 2008

small scale issues

Satellites

Cusps

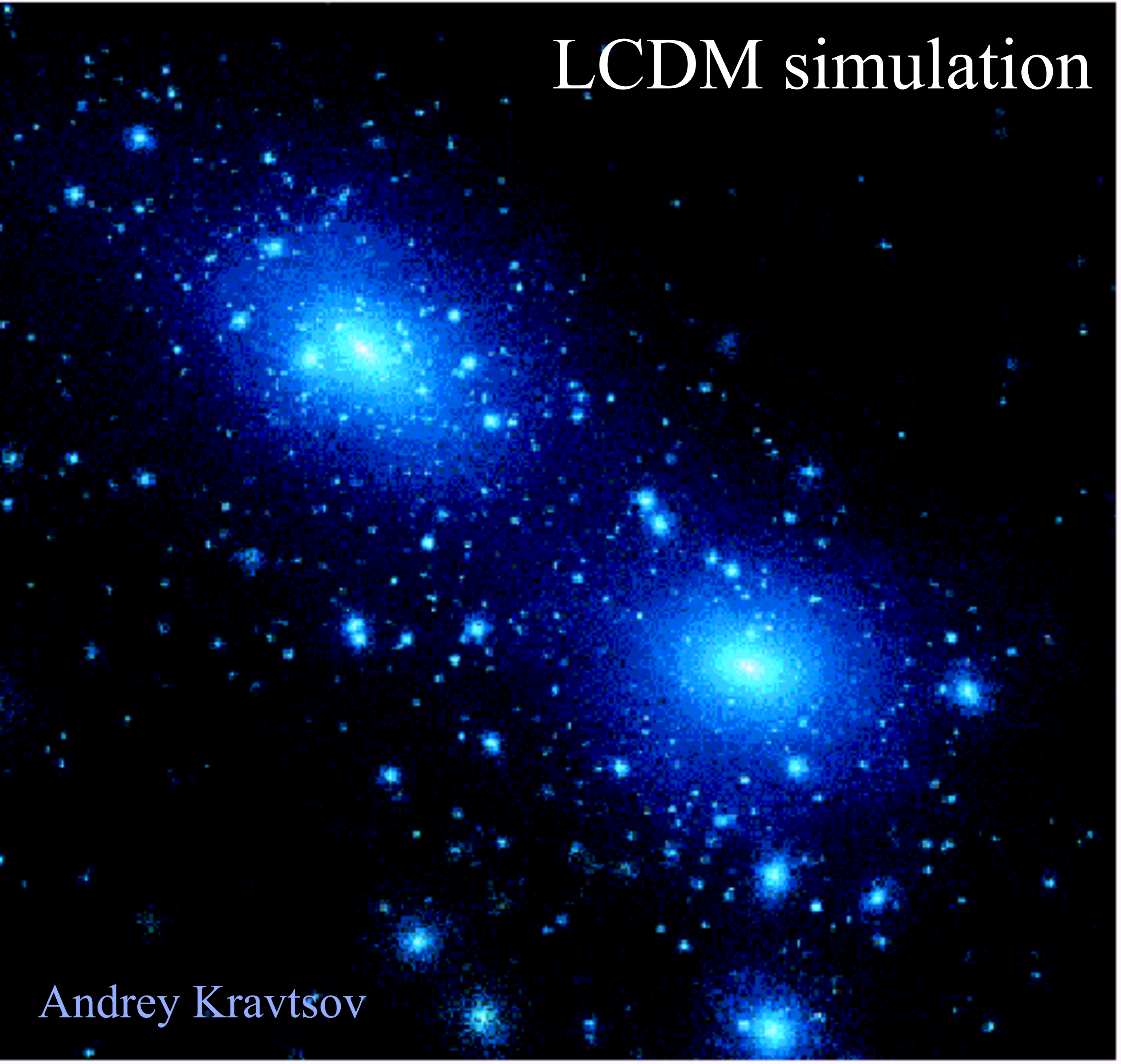
Angular momentum

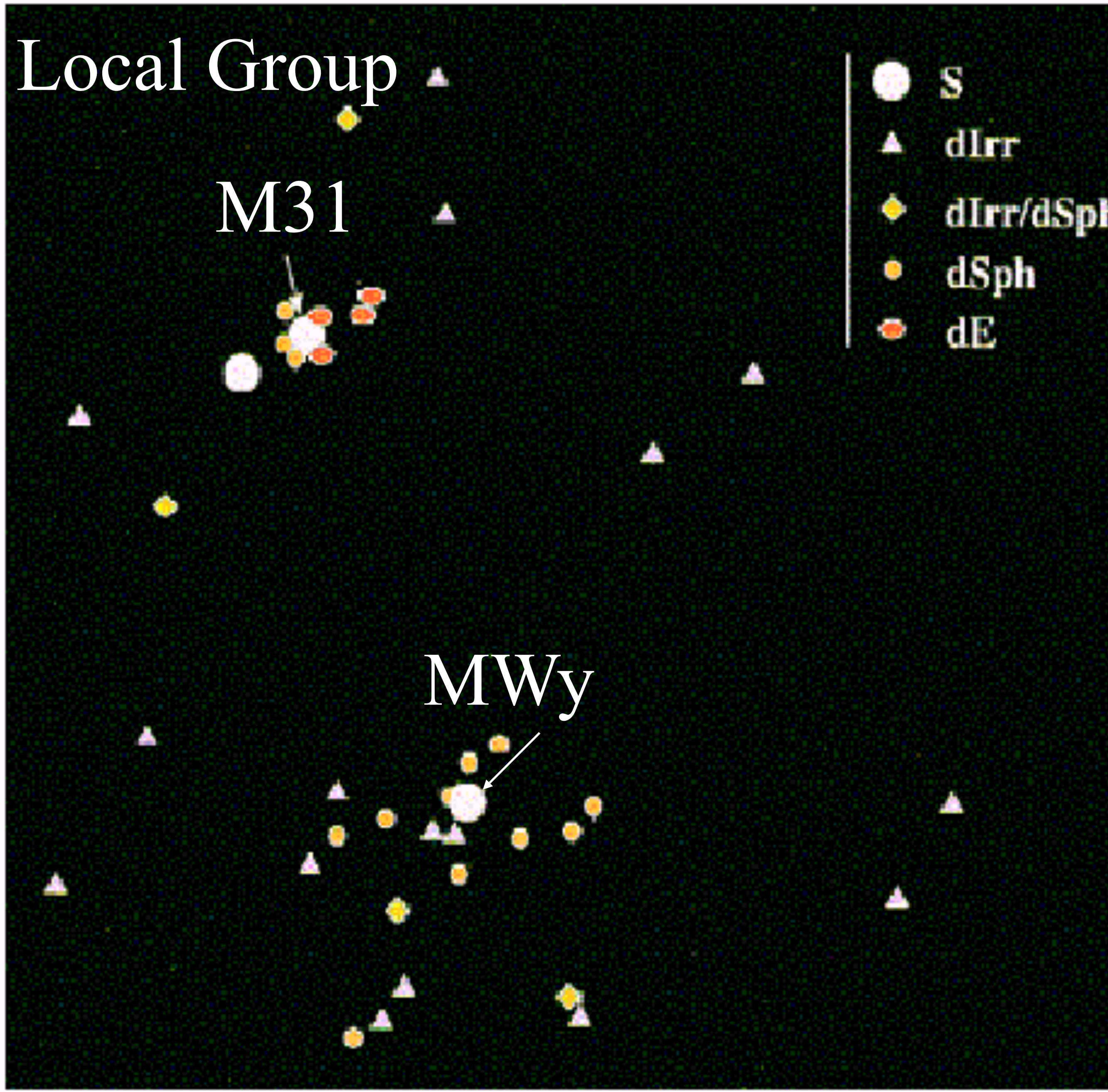
Satellites: radial distribution

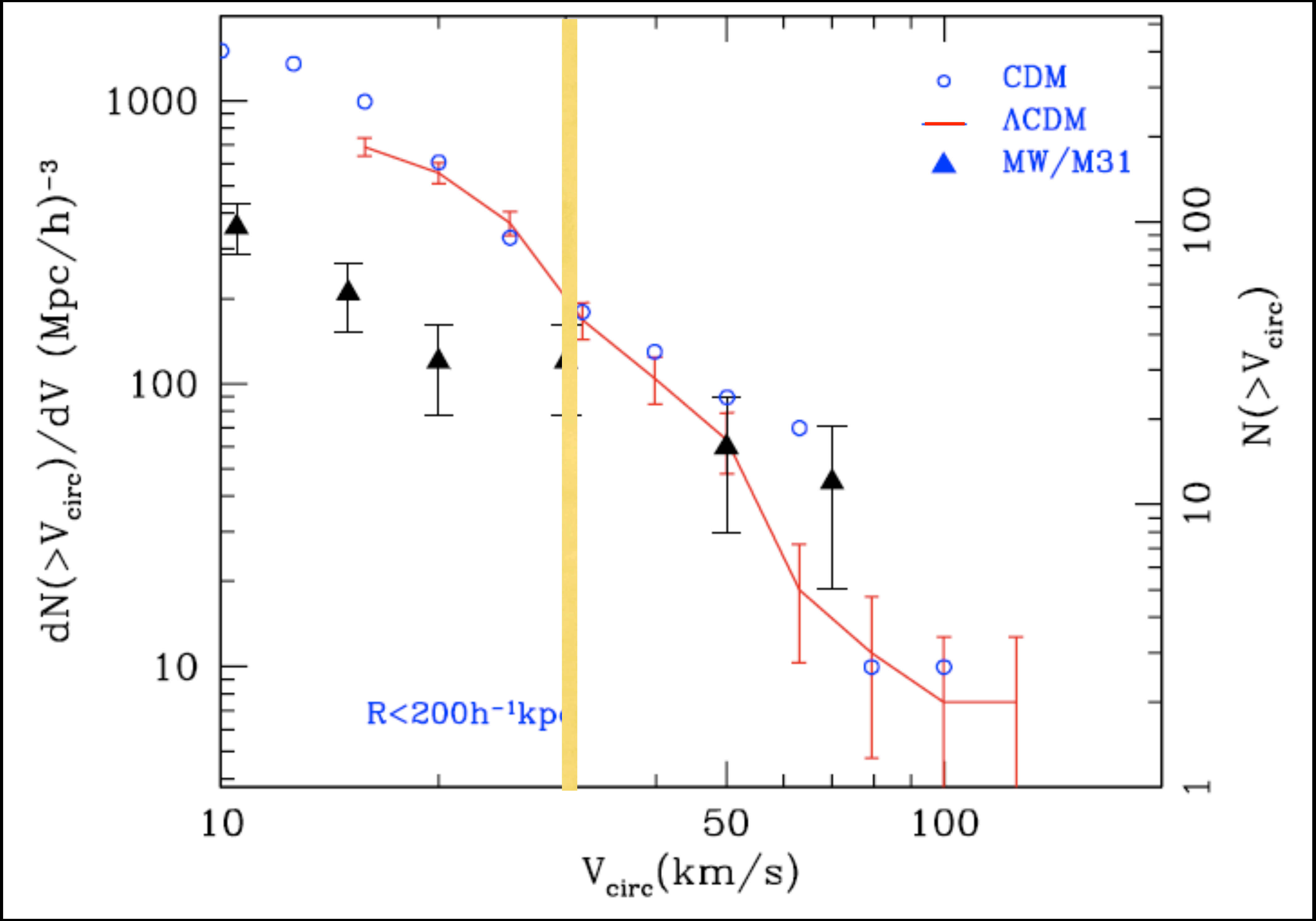
Simon White proposed that the observed bright satellite galaxies are hosted by the most massive subhalos, but this incorrectly predicts too large a radial distribution for the satellite galaxies in ΛCDM.

Andrey Kravtsov proposed instead that bright satellite galaxies are hosted by the subhalos that were the most massive when they were accreted. This correctly predicts the observed radial distribution, and also explains why nearby satellites are dSph while more distant ones are a mix of dSph and dIrr galaxies.

Can the **large** number of small-V_{circ} subhalos be reconciled with the **small** number of faint galaxies?







Does CDM Predict Too Many Satellite Galaxies?

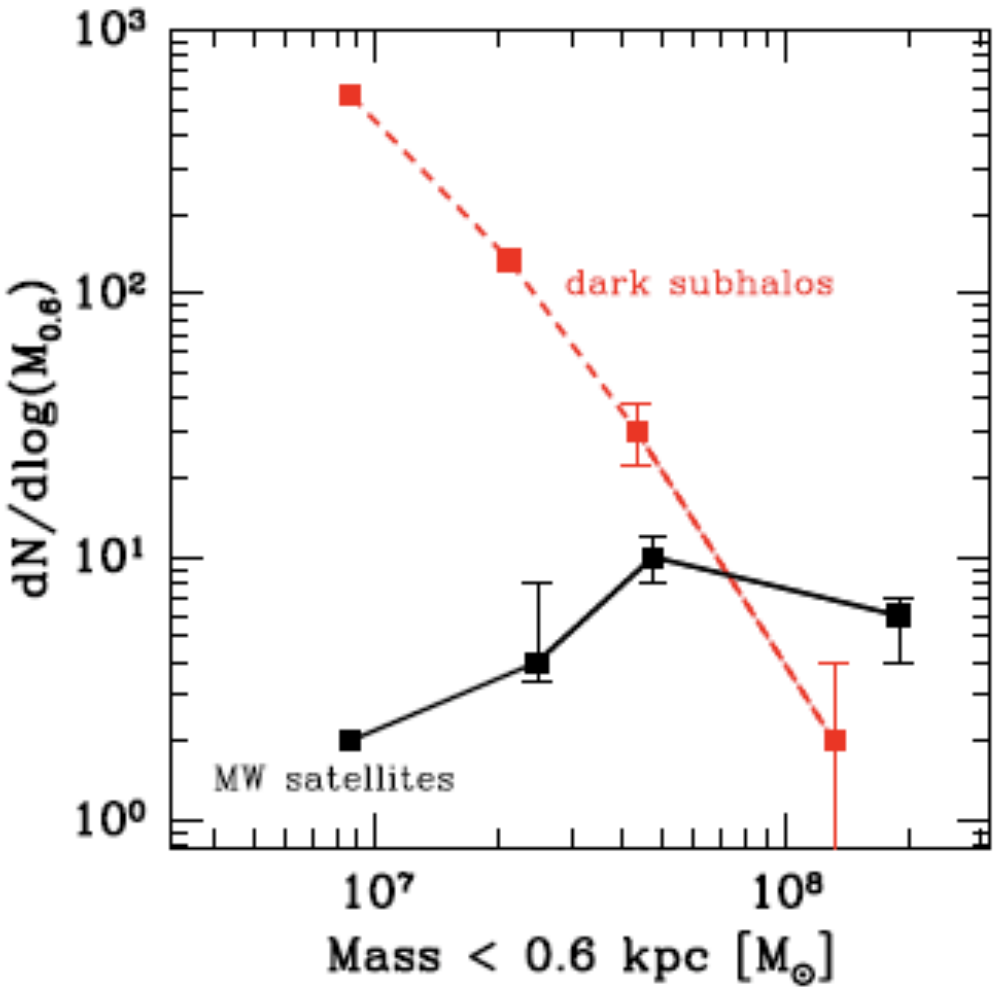
Klypin+1999
ΛCDM

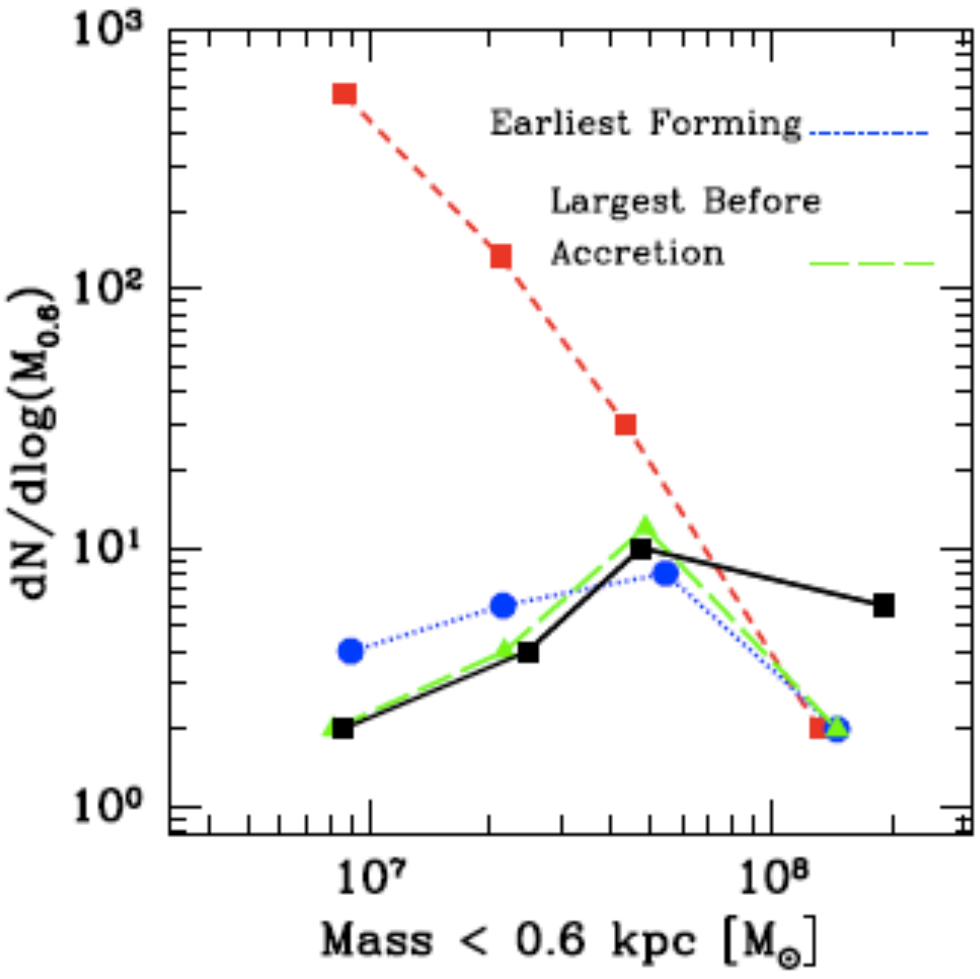
There are more subhalos with Vcirc < 30 km/s than observed satellites around MWy and M31

Redefining the Missing Satellites Problem

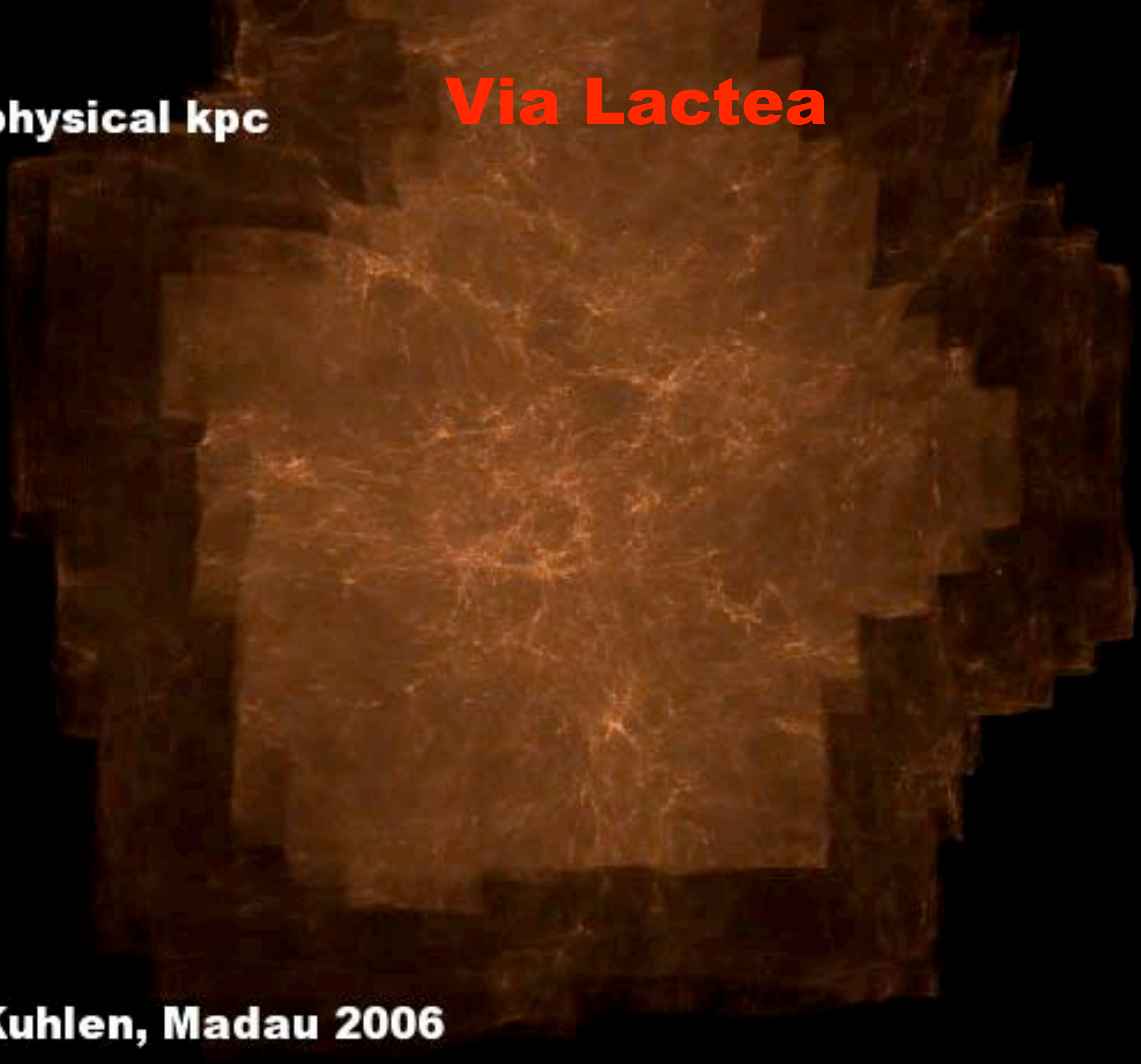
Louis Strigari, James Bullock, Manoj Kaplinghat, Juerg Diemand, Michael Kuhlen, & Piero Madau, ApJ, 669, 676 (2007)

We present comprehensive mass models for the well-known Milky Way dwarf satellites, and derive likelihood functions to show that their masses within 0.6 kpc ($M_{0.6}$) are strongly constrained by the present data. We show that the $M_{0.6}$ mass function of luminous satellite halos is flat between ~ 10^7 and 10^8 $M_\odot$. We use the **Via Lactea** N-body simulation to show that the $M_{0.6}$ mass function of CDM subhalos is steeply rising over this range. We rule out the hypothesis that the 11 well-known satellites of the Milky Way are hosted by the 11 most massive subhalos. We show that **models where the brightest satellites** correspond to the **earliest forming subhalos** or the **most massive accreted objects** both reproduce the observed mass function.





Via Lactea



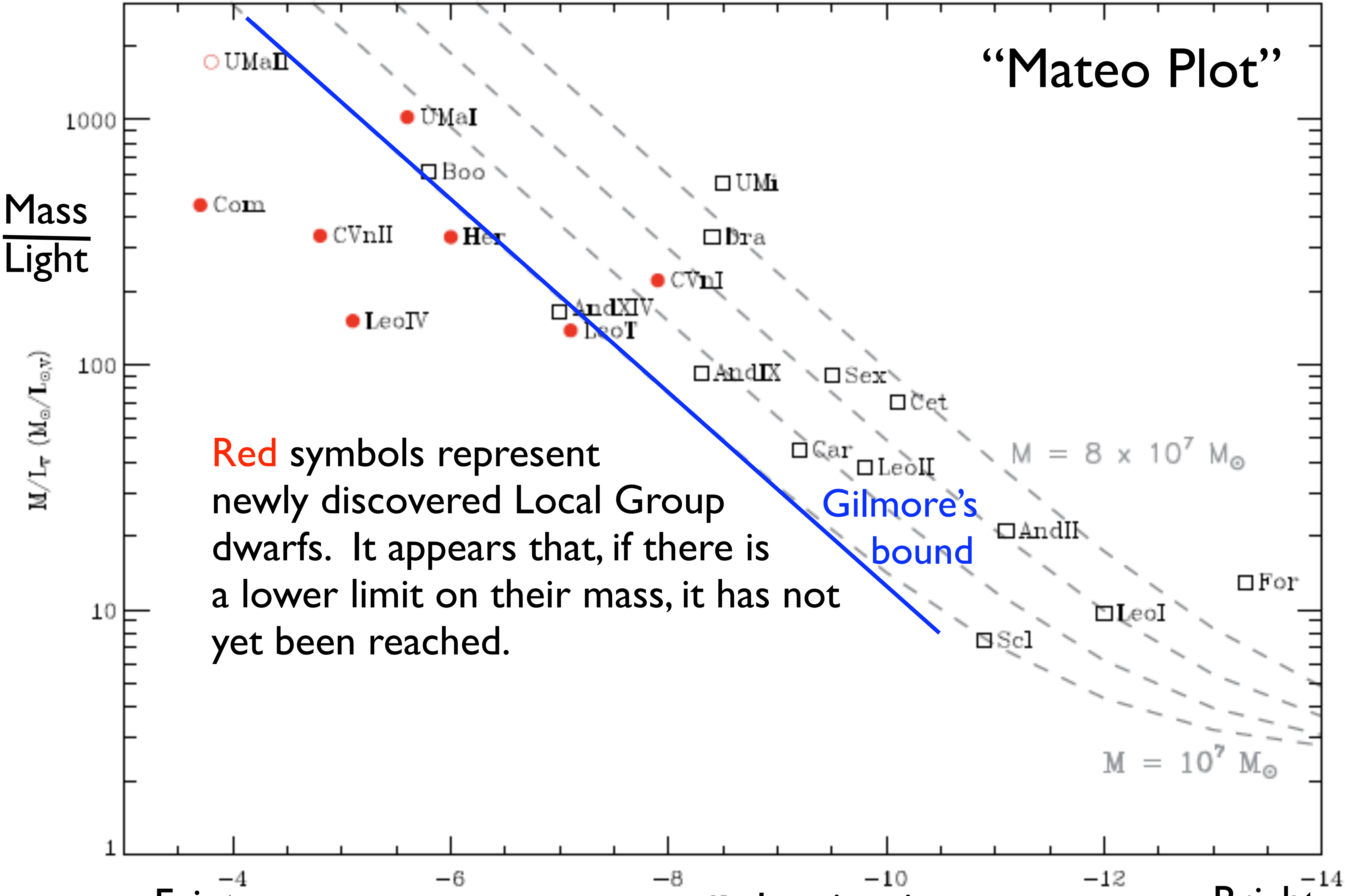
Diemand, Kuhlen, Madau 2006

The Kinematics of the Ultra-Faint Milky Way Satellites: Solving the Missing Satellite Problem

Joshua Simon & Marla Geha, ApJ 670, 313 (2007)

Our understanding of the missing satellite problem and the evolution of dwarf galaxies is being rapidly revised by the **discovery of a large population of new, very faint Local Group dwarfs** in the Sloan Digital Sky Survey and other wide-field imaging surveys. In the past 3 years, at least 20 of these galaxies have been identified, nearly doubling the previously known population. The new dwarfs include 8 additional Milky Way dwarf spheroidals. Since these were discovered in a survey that covered only about 1/5 of the sky, the presence of about 40 more dwarf spheroidals is suggested. These recently discovered MWy satellites have velocity dispersions $\sigma = 3.3$ to 7.6 km/s. With Mass/Light ratios approaching 1000 $M_\odot/L_\odot$, they are the **darkest known stellar systems** in the universe.

“Mateo Plot”



Mass / Light

Faint

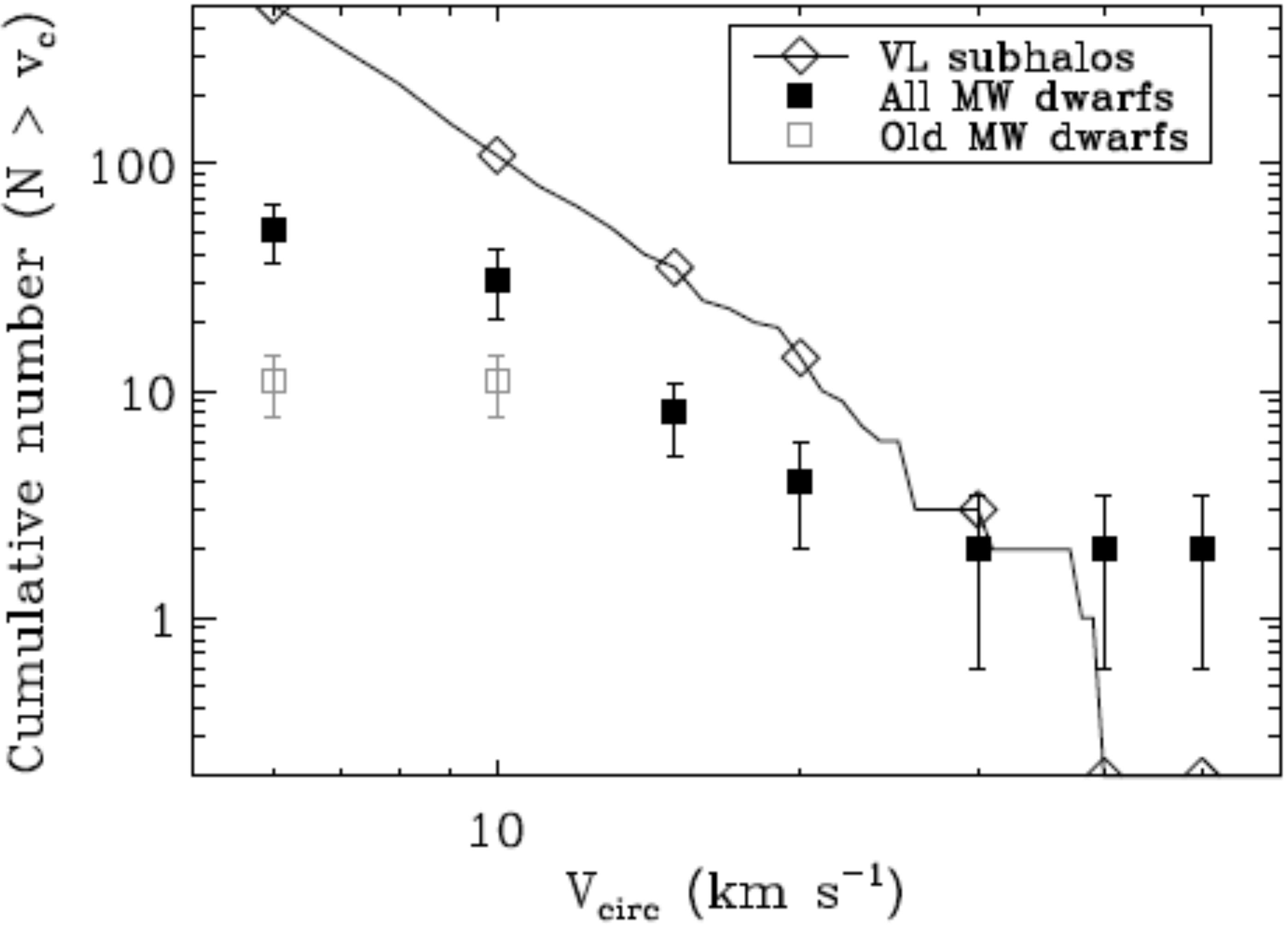
Luminosity

Bright

Gilmore’s bound

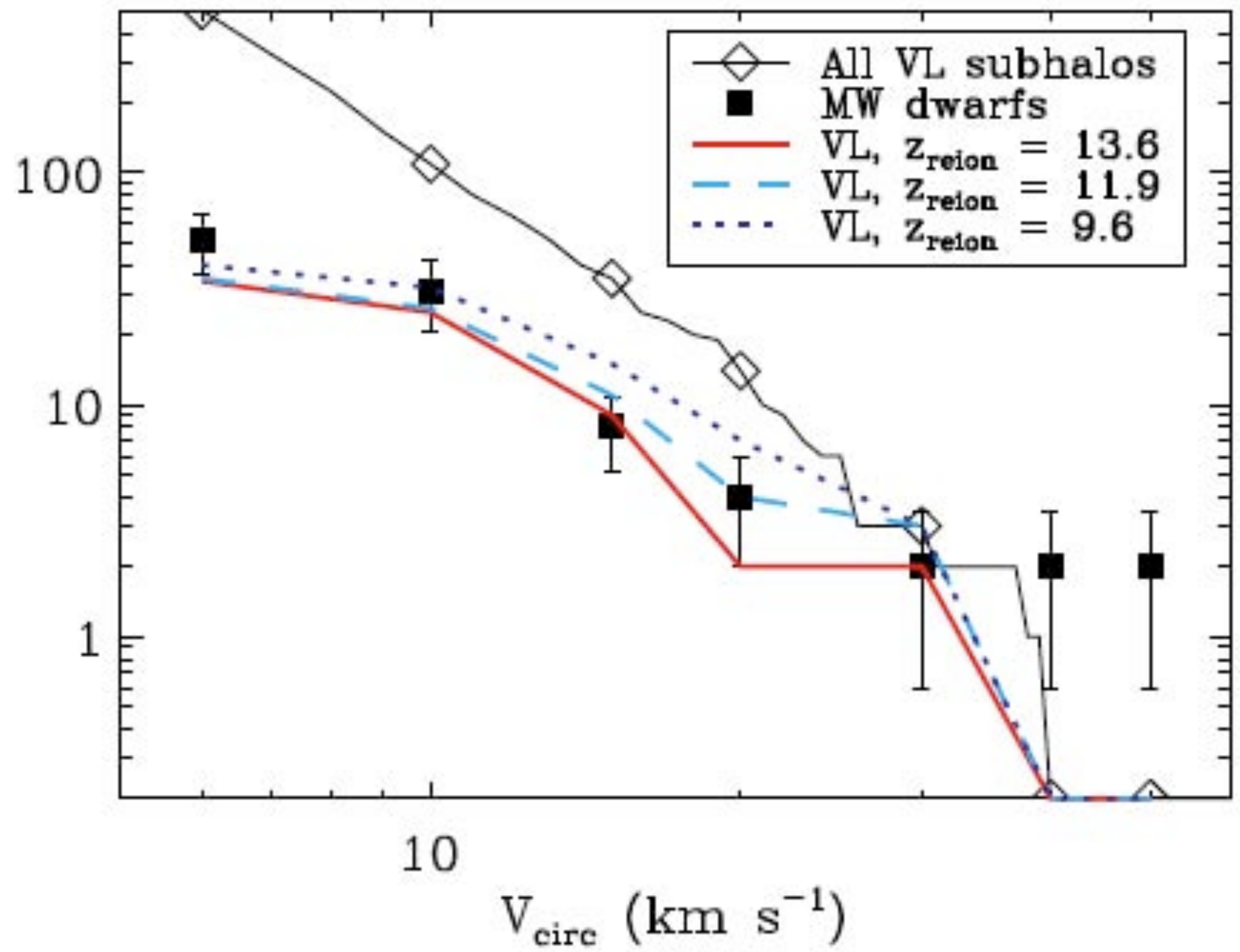
Red symbols represent newly discovered Local Group dwarfs. It appears that, if there is a lower limit on their mass, it has not yet been reached.

Simon & Geha, ApJ 670, 313 (2007)



Cumulative number of Milky Way satellite galaxies as a function of halo circular velocity, assuming Poisson errors on the number count of satellites in each bin (computed independently for the new and old dwarfs). The filled black squares include the new circular velocity estimates from Simon & Geha 2007, who follow Klypin+1999 and use $V_{circ} = \sqrt{3}\,\sigma$. Diamonds represent all subhalos within the virial radius in the Via Lactea simulation (Diemand+2007).

Simon & Geha, ApJ 670, 313 (2007)



Effect of reionization on the missing satellite problem. The solid red curve shows the circular velocity distribution for the 51 most massive Via Lactea subhalos at $z = 13.6$, the dashed cyan curve at $z = 11.9$, and the dotted blue curve at $z = 9.6$. Thus, supression of star formation in small dwarfs after reionization can account for the observed satellites in ΛCDM, as suggested by Bullock+2000, Somerville 2002, Benson+2003, and Moore+2006.

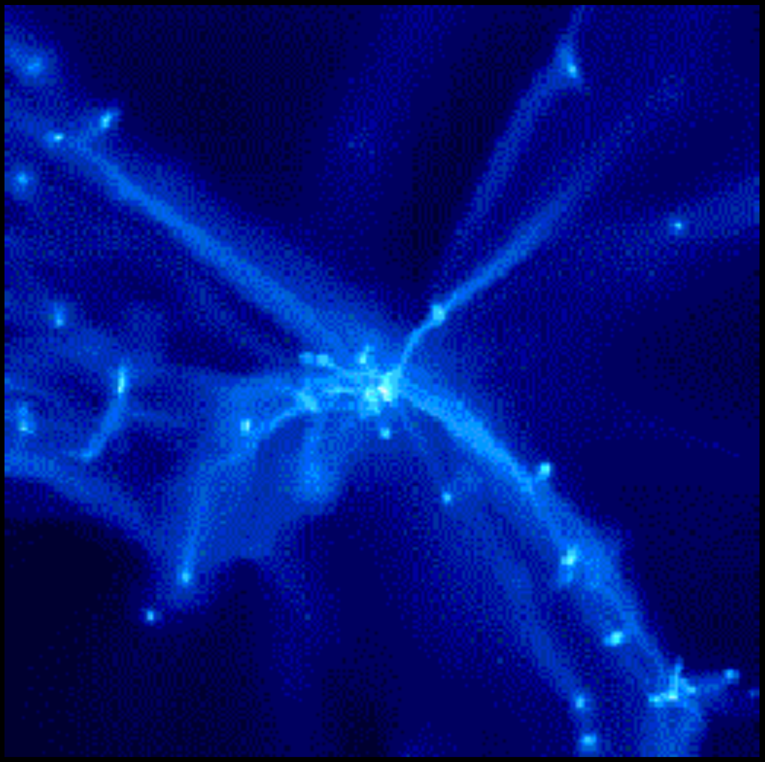
Does this mean that the "Too Many Subhalos" problem has been solved? Not quite...

- the more reliable $M_{0.6}$ method of Strigari+2007 should be applied to the newly discovered Local Group satellite galaxies

- the details of "squelching" of star formation in dwarfs need to be worked out and compared to the new data

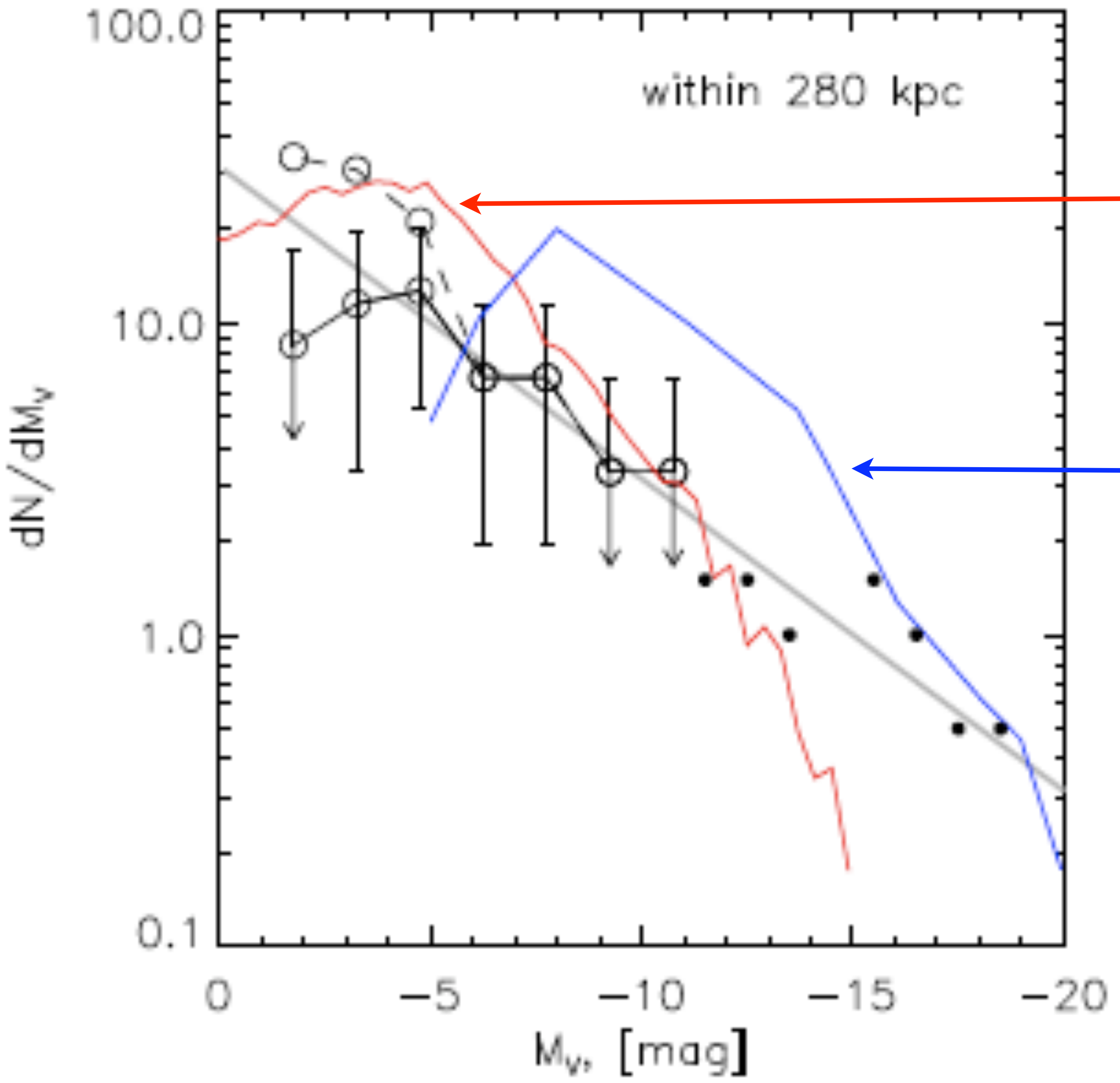
- simulations must have converged in resolving all relevant subhalos

Modeling of dwarfs



1. N-body (DM only) Simulations
   - solve equations of gravity for particles of dark matter (& sometimes stars)
2. Hydrodynamic Simulations
   - solve equations of gravity and hydrodynamics/thermodynamics for particles of dark matter and gas
3. Semi-Analytic Models
   - treat gravity and “gastrophysics” via analytic approximations based on 1 & 2

Luminosity Function of the Local Group: SDSS Data Compared with Semi-Analytic Models



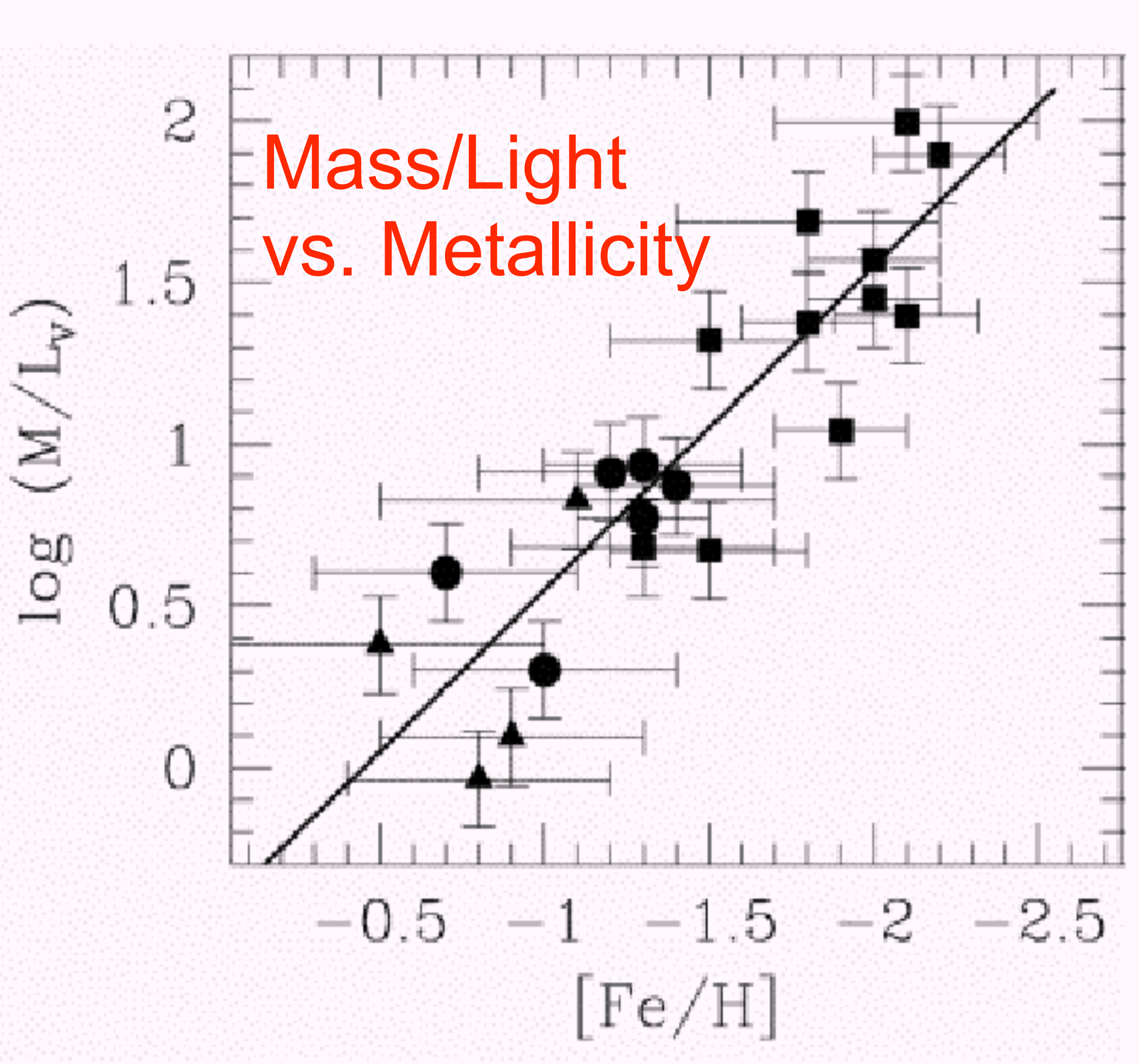
Benson+2002

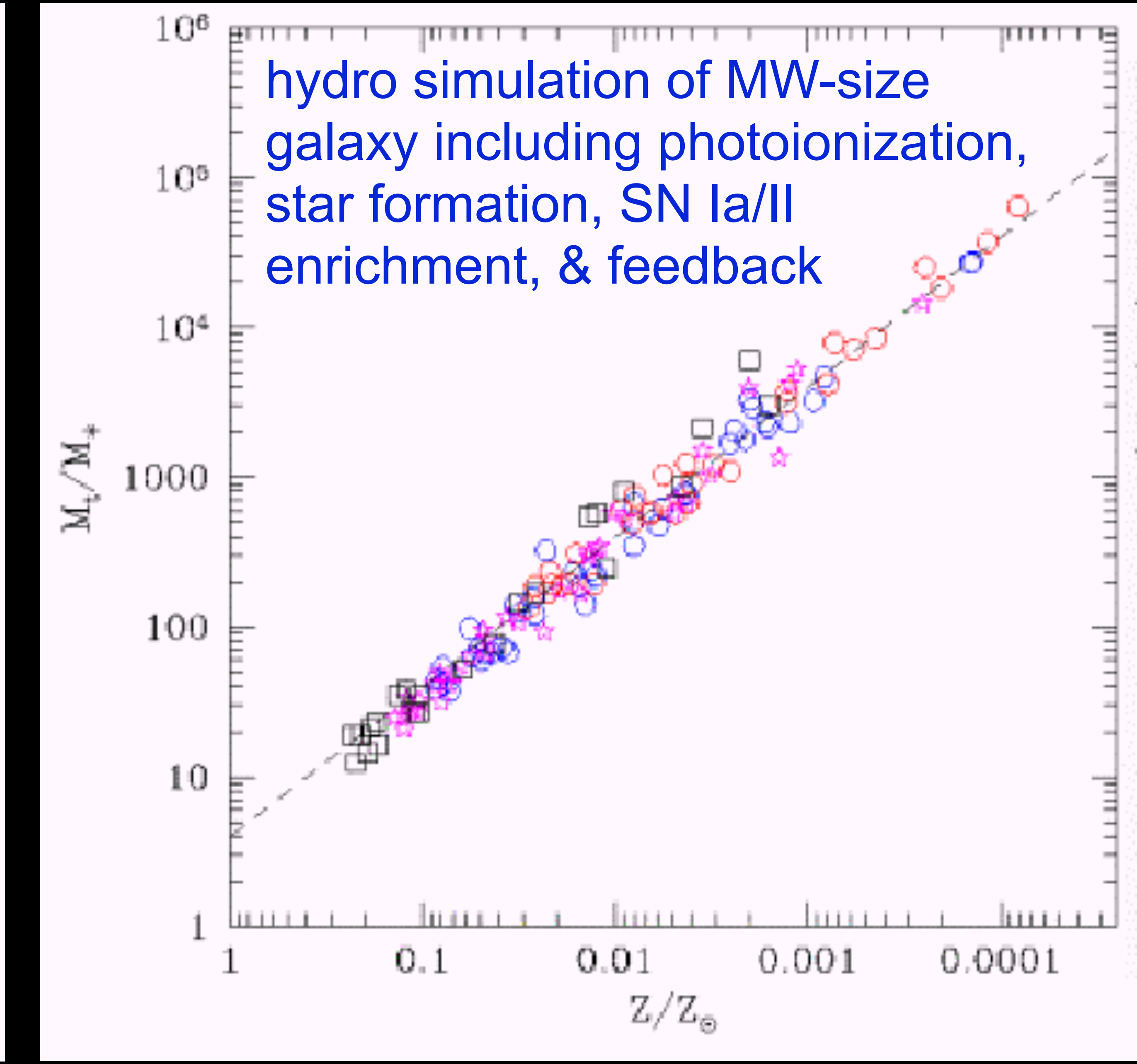
Somerville 2002

The models include reionization, feedback, and (for Benson+) tidal stripping. Neither model agrees perfectly with the data.

This figure is from Koposov, Belokurov,+ arXiv0706.2687.

Challenge to explain other properties of LG dwarfs


Mass/Light vs. Metallicity


hydro simulation of MW-size galaxy including photoionization, star formation, SN Ia/II enrichment, & feedback

Prada & Burkert 2002; cf. Dekel & Woo 2003

Andrey Kravtsov 2003

Note: feedback may not be essential (Simon+06)

Does this mean that the "Too Many Subhalos" problem has been solved? Not quite...

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- the details of "squelching" of star formation in dwarfs need to be worked out and compared to the new data

- simulations must have converged in resolving all relevant subhalos Via Lactea II resolves to ~10 kpc

Via Lactea II

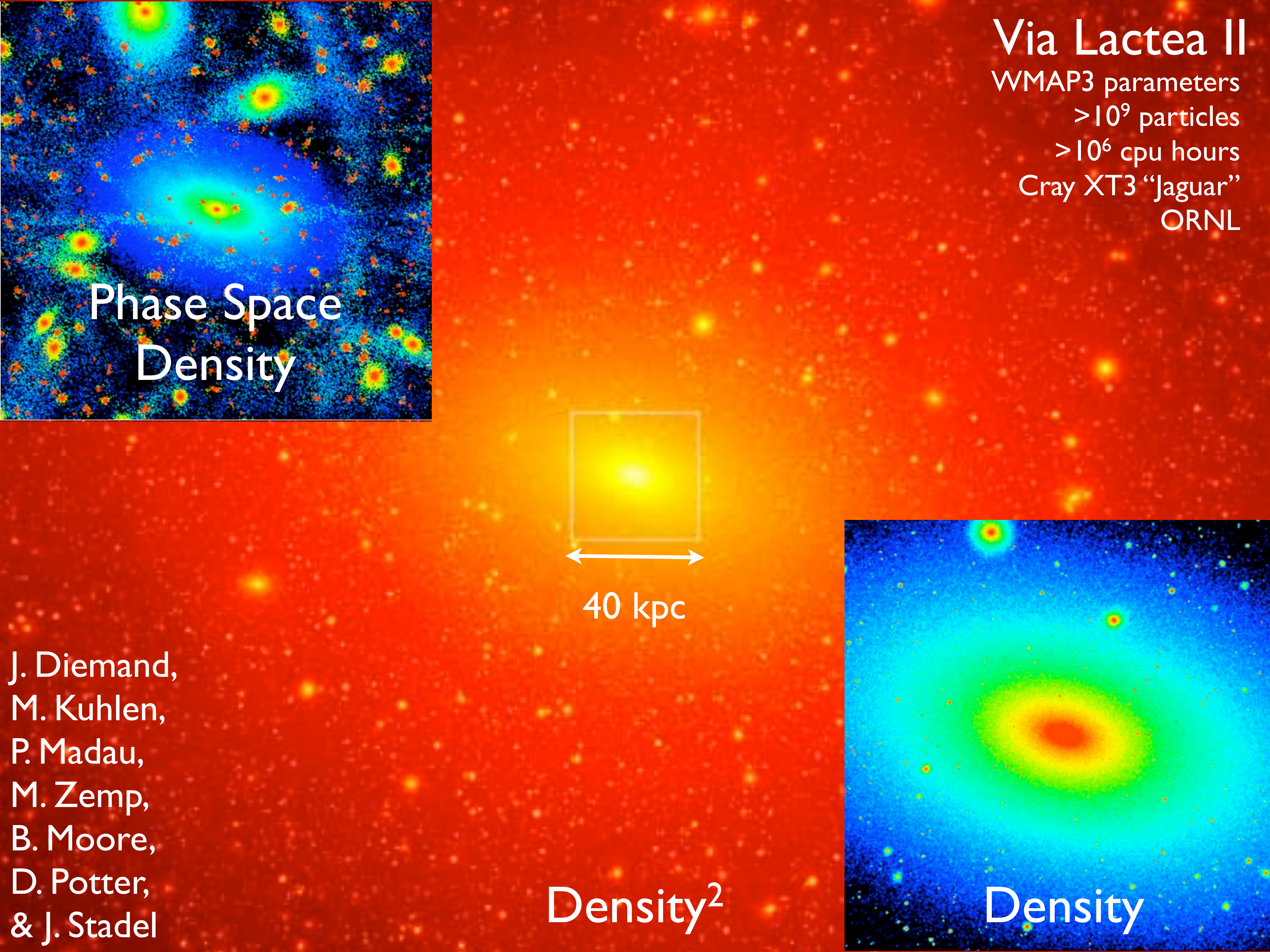
WMAP3 parameters

>10^9 particles

>10^6 cpu hours

Cray XT3 “Jaguar”

ORNL



J. Diemand,
M. Kuhlen,
P. Madau,
M. Zemp,
B. Moore,
D. Potter,
& J. Stadel

ΛCDM May Be Able To Explain the Observed Gravitational Lensing Flux Anomalies

The fraction of mass in Via Lactea II subhalos of mass ~10^6 - 10^8 $M_\odot$ is ~0.5%. This is about the amount needed to explain the flux anomalies observed in radio images of quasars that are quadruply gravitationally lensed by foreground elliptical galaxies (Juerg Diemand and R. Benton Metcalf, private communications). Free streaming of WDM particles can considerably dampen the matter power spectrum in this mass range, so a WDM model with an insufficiently massive particle (sterile neutrino m_ν < 10 kev) fails to reproduce the observed flux anomalies (Marco Miranda & Andrea Maccio 2007, MNRAS, 382, 1225). We need more than the 6 radio quads now known!

The Kinematics of the Ultra-Faint Milky Way Satellites: Solving the Missing Satellite Problem

Joshua Simon & Marla Geha, ApJ 670, 313 (2007)

Hogan & Dalcanton (2000) introduced the parameter

$$Q \equiv \rho/\sigma^3$$

as an estimate of the coarse-grained phase-space density of the dark matter in galaxy halos. Liouville’s theorem implies that observed values of Q set a hard lower limit on the original phase-space density of the dark matter. All of the galaxies except UMa I, CVn I, and Hercules have

$$Q > 10^{-3}\ M_\odot\ \mathrm{pc}^{-3}\ (\mathrm{km\ s}^{-1})^{-3},$$

about an order of magnitude improvement compared to the previously-known dSphs. This places significant limits on non-CDM dark matter models. The subhalos in Via Lactea II (Diemand+2008) that could host MWy satellites have densities and phase space densities comparable to these.

Observational Constraints on Warm Dark Matter

Hogan & Dalcanton (2000) showed that for a thermal relic particle X

$$Q \equiv \rho/\sigma^3 = 5\mathrm{x}10^{-4}\ M_\odot\ \mathrm{pc}^{-3}\ (\mathrm{km\ s}^{-1})^{-3}\ (m_X/\mathrm{keV})^4$$

Simon & Geha (2007) found Q > 10^{-3}, which implies m_x > 1.2 keV

The latest constraint from HIRES + SDSS Lyman-α forest data is m_X > 4 keV (sterile neutrino m_ν > 28 keV) at 2σ (Viel+2008).

Yoshida, Sokasian, Hernquist, & Springel (2003) argued that, while the first stars can reionize the universe starting at z~20 in ΛCDM, the absence of low mass halos in ΛWDM delays reionization unless m_X > 10 keV. O'Shea & Norman (2006) showed that reionization is significantly delayed in ΛWDM even with m_X = 15 keV. The actual constraint on m_X has not yet been determined in detail.

If the WDM is produced by decay, the velocity distribution and phase space constraints can be different (Kaplinghat 05, mCDM Strigari+07).

Observational Constraints on Sterile Neutrinos

Sterile neutrinos that mix with active neutrinos are produced in the early universe and could be the dark matter. However, they decay into X-rays + light neutrinos, and nonobservation of these X-rays from various sources give upper limits on m_s:

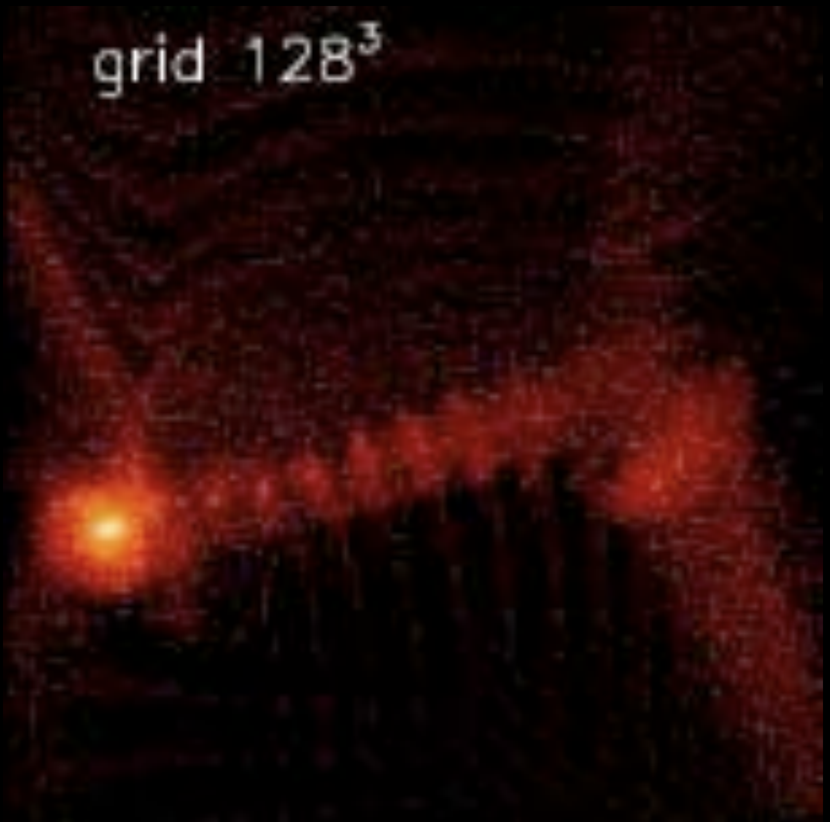
Virgo cluster	< 8 keV
Coma cluster	< 6 keV
X-ray background	< 5 keV
Milky Way	< 3.5 keV

Seljak+06 and Viel+06 pointed out that these upper limits are inconsistent with the lower limits from Lyman-α forest data, thus ruling out such sterile neutrinos as the dark matter.

The latest constraint from HIRES + SDSS Lyman-α forest data is sterile neutrino $m_s > 28$ keV at 2σ (Viel+2008).

Warm Dark Matter Substructure in Simulations

Various authors (e.g., Bode, Ostriker, & Turok 2001, Knebe, Devriendt, Gibson, & Silk 2003; Götz & Sommer-Larsen 2003) have claimed that ΛWDM substructure develops in simulations on scales below the free-streaming cutoff. If true, this could alleviate the conflict between the many small subhalos needed to give the observed number of Local Group satellite galaxies and needed to explain gravitational lensing flux anomalies. However, Wang & White (2007, MNRAS, 380, 93) recently showed that such substructure arises from discreteness in the initial particle distribution, and is therefore spurious.



Lyman-α forest,
satellite abundance,
gravitational lensing,
reionization ⇒

Warm Dark Matter
has to be rather
Tepid

Hot

Warm

Tepid

Cool

Hot

Warm

Tepid

Cool

Cold Dark Matter

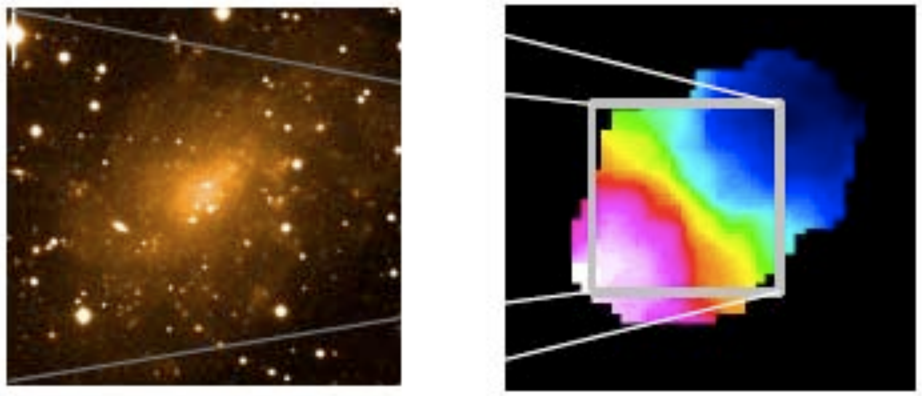
meta**CDM** from late decays
can satisfy Lyα forest limits but
nevertheless lead to cored dSph

Other Challenges to ΛCDM

- **CUSPS IN GALAXY CENTERS** Problem first recognized by Flores and me 94, and Moore 94, but HI beamsmearing and other observational errors were underestimated (Swaters+03, Spekkens+05); the data imply inner slope $r^{-\alpha}$ $0 \leq \alpha < 1.5$. LSB galaxies are mainly dark matter so complications of baryonic physics are minimized, but could still be important (Rhee+04, Valenzuela+07). The only case where the Blitz group sees no radial motions is consistent with $r^{-\alpha}$ with $\alpha \approx 1$ (NFW) as ΛCDM predicts (Simon+05). The non-circular motions could be caused by nonspherical halos (Hayashi & Navarro 06). Dark matter halos are increasingly aspherical at smaller radii, at higher redshift, and at larger masses (Allgood+06, Flores+07, Bett+07), and this can account for the observed rotation curves (Hayashi+07, Bailin+07, Widrow 08).

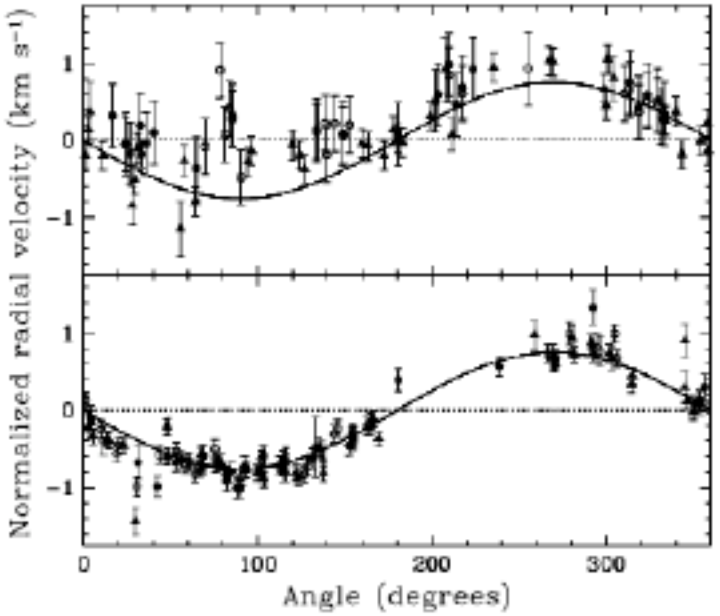
Noncircular motions

DDO 39



Swaters, Verheijen, Bershady, Andersen 2003

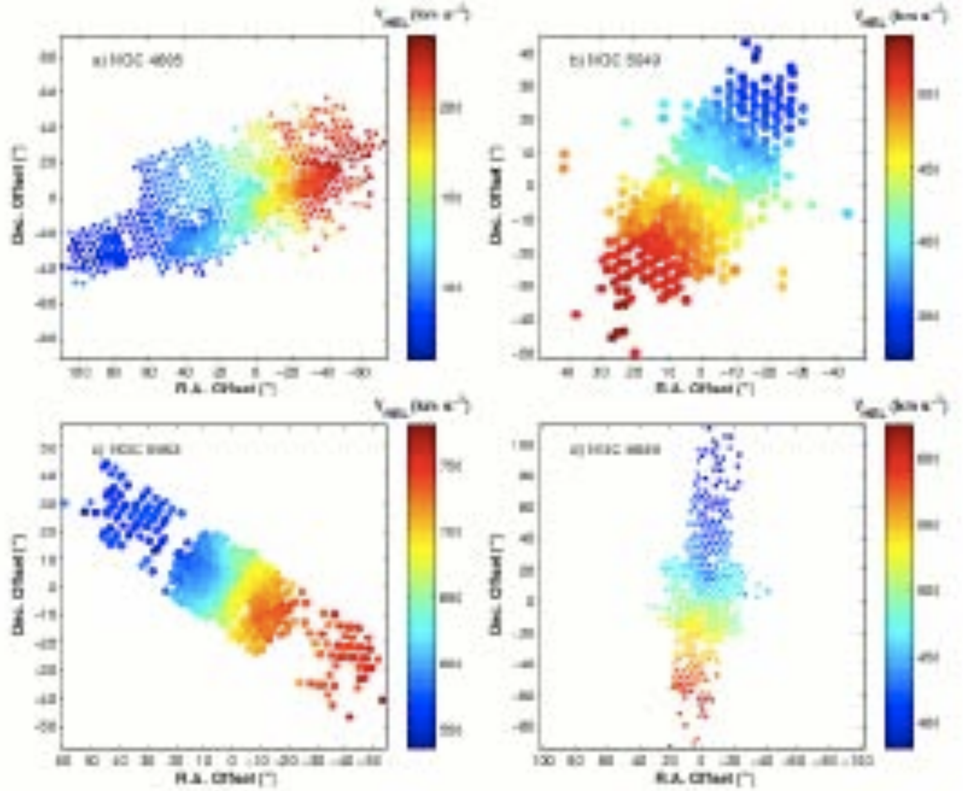
Strong noncircular motions exist even in galaxies that seem as regular as DDO 39:



Swaters et al. 2003

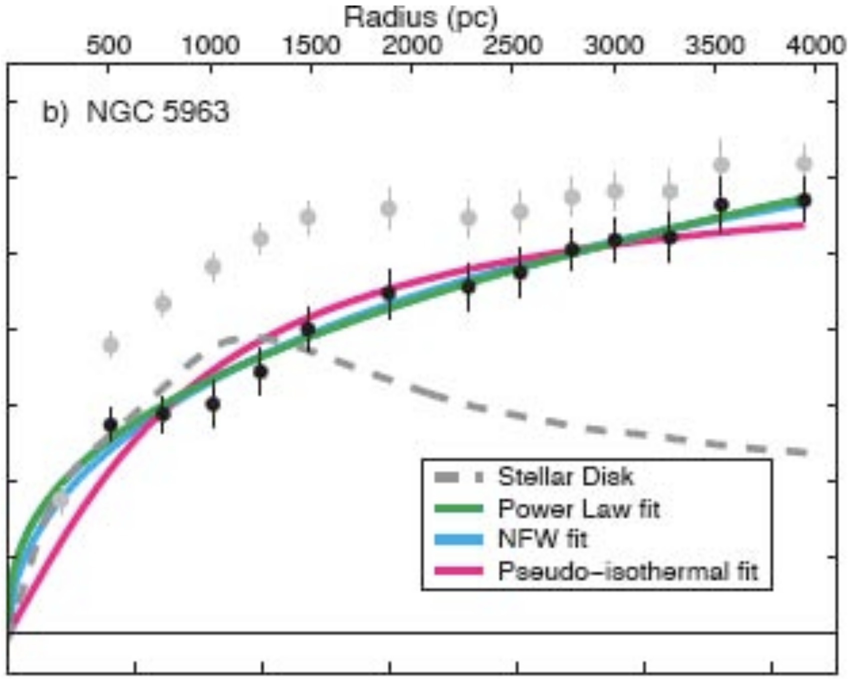
Noncircular motions are common:

- 4 out of 5 galaxies studied by Simon et al. (2003, 2005) have detectable radial motions
- 4 out of 6 in Swaters et al. (in prep) show noncircular motions
- Majority of galaxies in GHASP survey (Garrido et al. 2003)

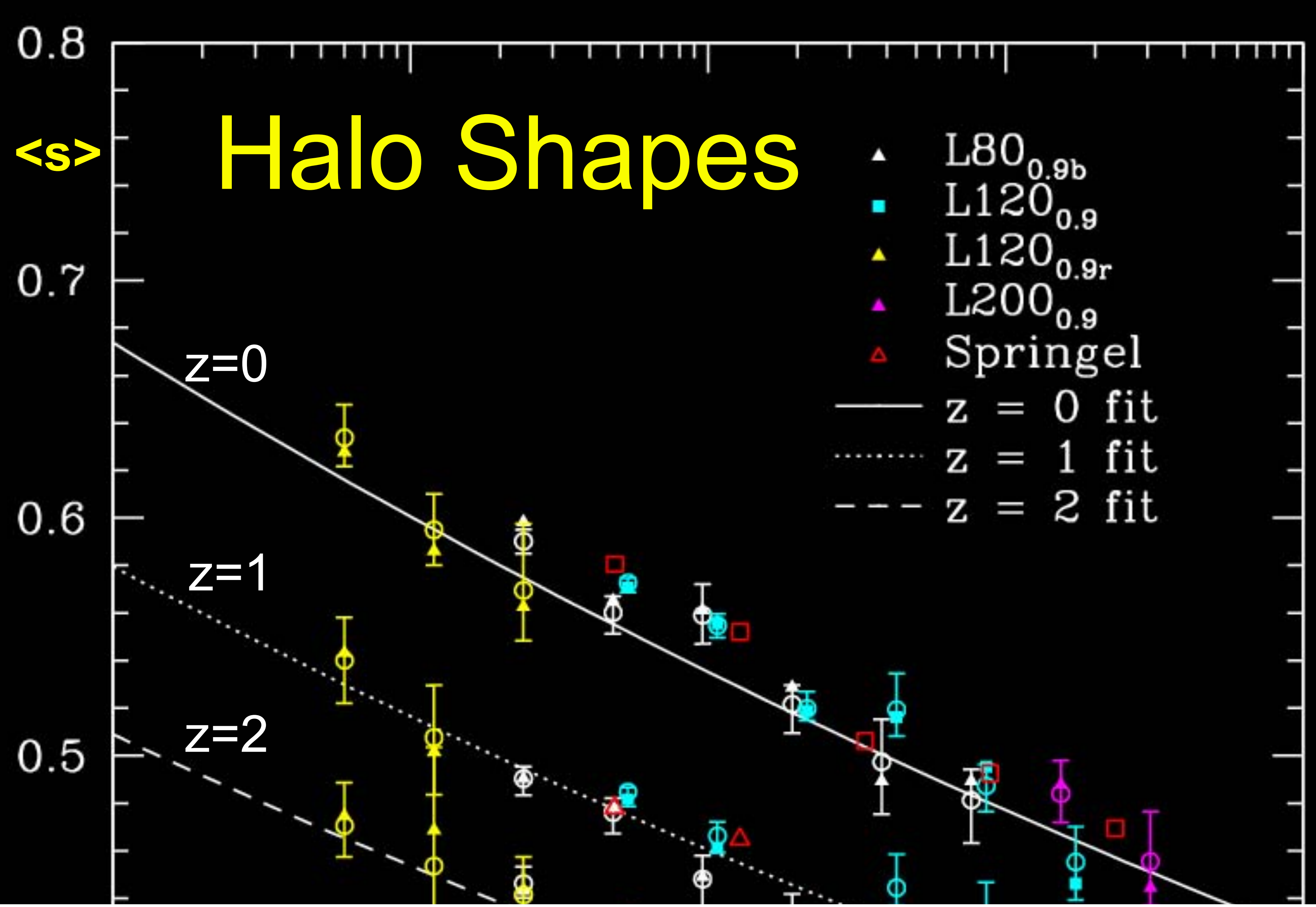


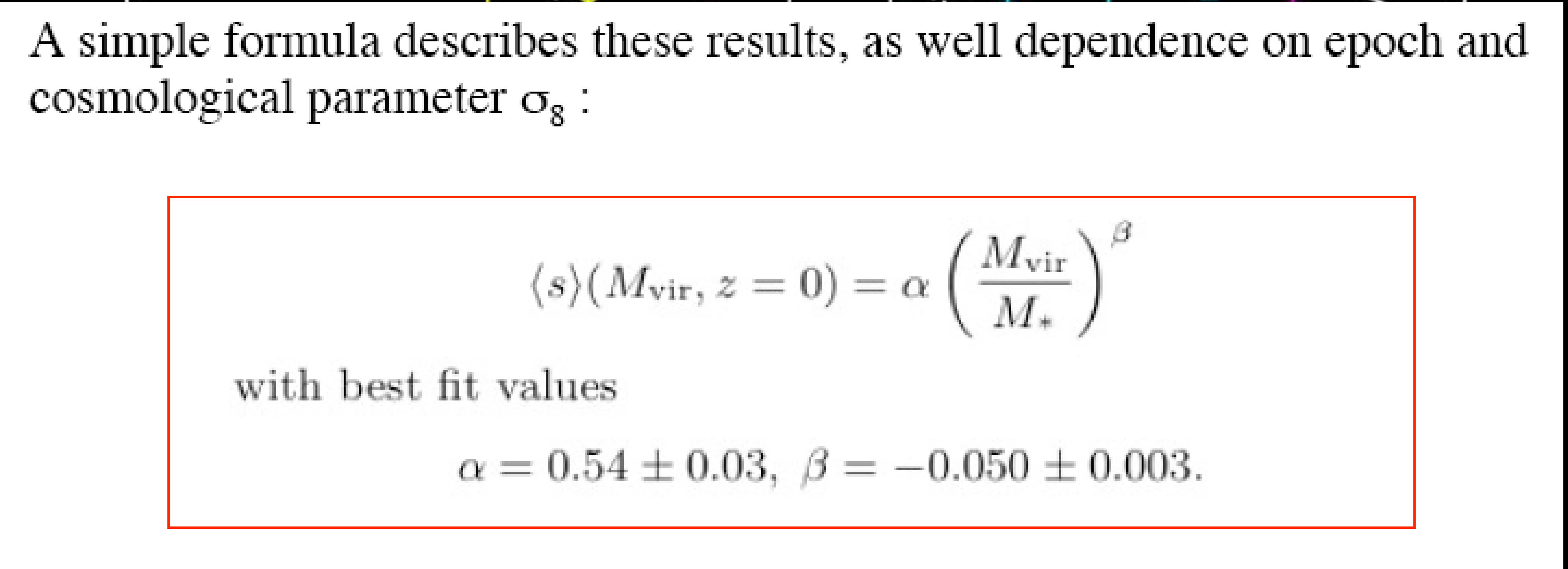
Simon+2003, 2005 obtained 2D velocity profiles of 5 low-mass spiral galaxies using CO, Hα, and HI. They subtracted the baryons to obtain dark matter profiles.

NGC 5963
w/o radial v
fits NFW



Halo Shapes





A simple formula describes these results, as well dependence on epoch and cosmological parameter σ_8 :

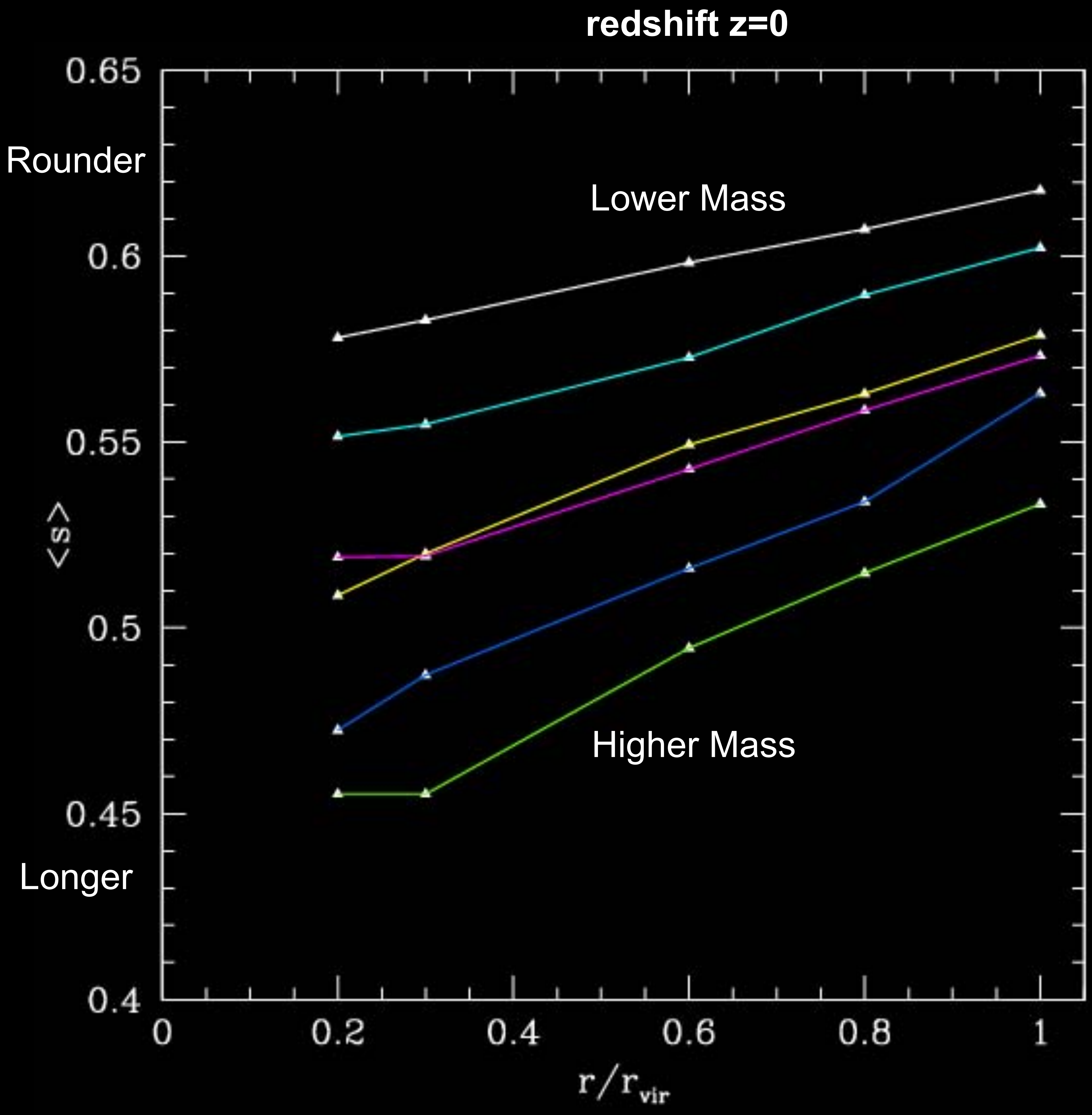
$$\langle s \rangle (M_{\rm vir}, z=0) = \alpha \left(\frac{M_{\rm vir}}{M_*} \right)^{\beta}$$

with best fit values

$$\alpha = 0.54 \pm 0.03, \ \beta = -0.050 \pm 0.003.$$

<s> = short / long axis of dark halos vs. mass and redshift. Dark halos are more elongated the more massive they are and the earlier they form. We found that the halo <s> scales as a power-law in Mhalo/M*. Halo shape is also related to the Wechsler halo formation scale factor ac.

Allgood+2006



Halos become more spherical at larger radius and smaller mass. As before,

$$s = \frac{\text{short axis}}{\text{long axis}}$$

These predictions can be tested against cluster X-ray data and galaxy weak lensing data.

Allgood+2006

Other Challenges to ΛCDM

- **GALAXY HALO CONCENTRATION**

It remains unclear how much adiabatic contraction (Blumenthal+86,93, Mo+98, Gnedin+04) occurs in galaxies (Dutton+08), since there are potentially offsetting effects.

Halos hosting low surface brightness (LSB) galaxies may have higher spin and lower concentration than average (Wechsler+02,06, Maccio+07), which would improve agreement between ΛCDM predictions and observations.

Despite all this, halos hosting galaxies may still be predicted by ΛCDM to be more concentrated than the data indicates (Alam+02), although lower P(k) normalization parameter $\sigma_8 \approx 0.75$ could help (Zentner & Bullock 03). However, X-ray clusters are consistent with higher $\sigma_8 \approx 0.9$ (Buote+07).

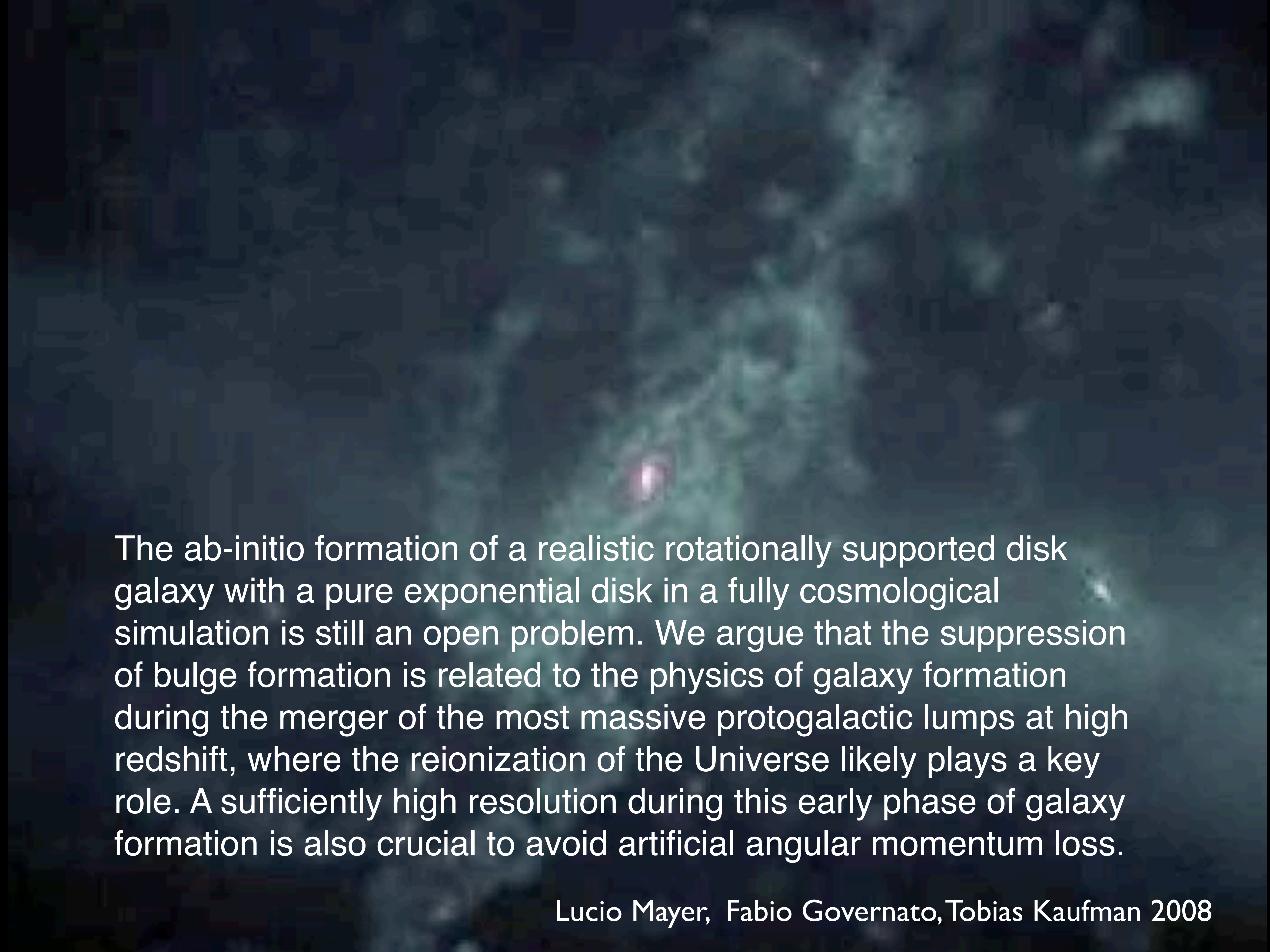
Other Challenges to ΛCDM

- **ANGULAR MOMENTUM ISSUES**

Catastrophic loss of angular momentum (Navarro & Benz 91, Navarro & Steinmetz 00) due to overcooling in hydrodynamic simulations (Maller & Dekel 02). Spiral galaxies would be hard to form if ordinary matter has the same specific angular momentum distribution as dark matter (Bullock+01). How do the disk baryons get the right angular momentum?

Mergers give halos angular momentum – too much for halos that host spheroids, too little for halos that host disks (D'Onghia & Burkert 04)? Role of AGN and other energy inputs? Role of cold inflows (Birnboim & Dekel 03, Keres+05, Dekel & Birnboim 06)?

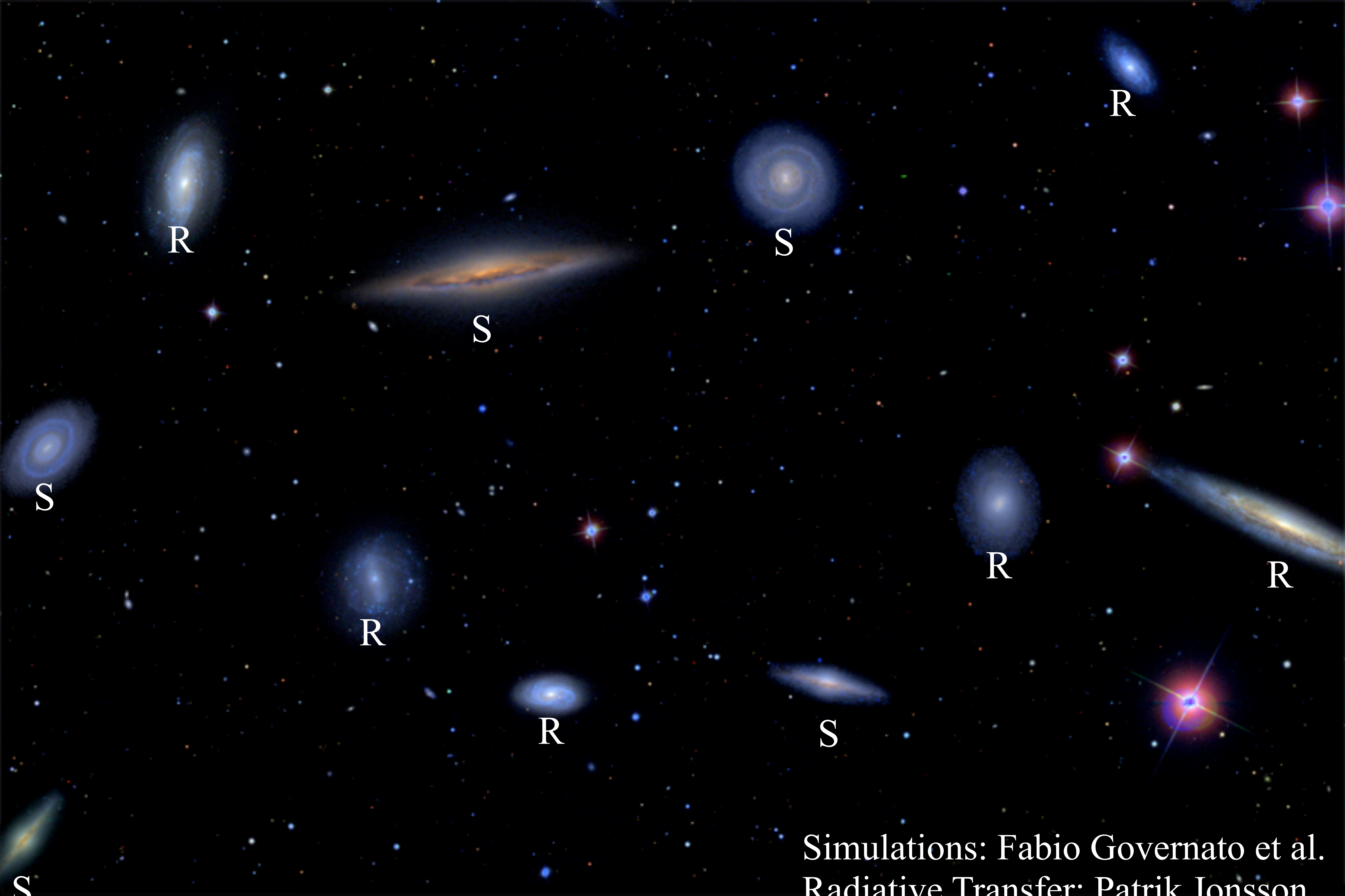
Can simulated disks agree with observed Tully-Fisher relation and Luminosity Function? Recent high-resolution simulations (Governato+07, Ceverino & Klypin 08) are encouraging.



The ab-initio formation of a realistic rotationally supported disk galaxy with a pure exponential disk in a fully cosmological simulation is still an open problem. We argue that the suppression of bulge formation is related to the physics of galaxy formation during the merger of the most massive protogalactic lumps at high redshift, where the reionization of the Universe likely plays a key role. A sufficiently high resolution during this early phase of galaxy formation is also crucial to avoid artificial angular momentum loss.

Lucio Mayer, Fabio Governato, Tobias Kaufman 2008

Real or **S**imulated ?



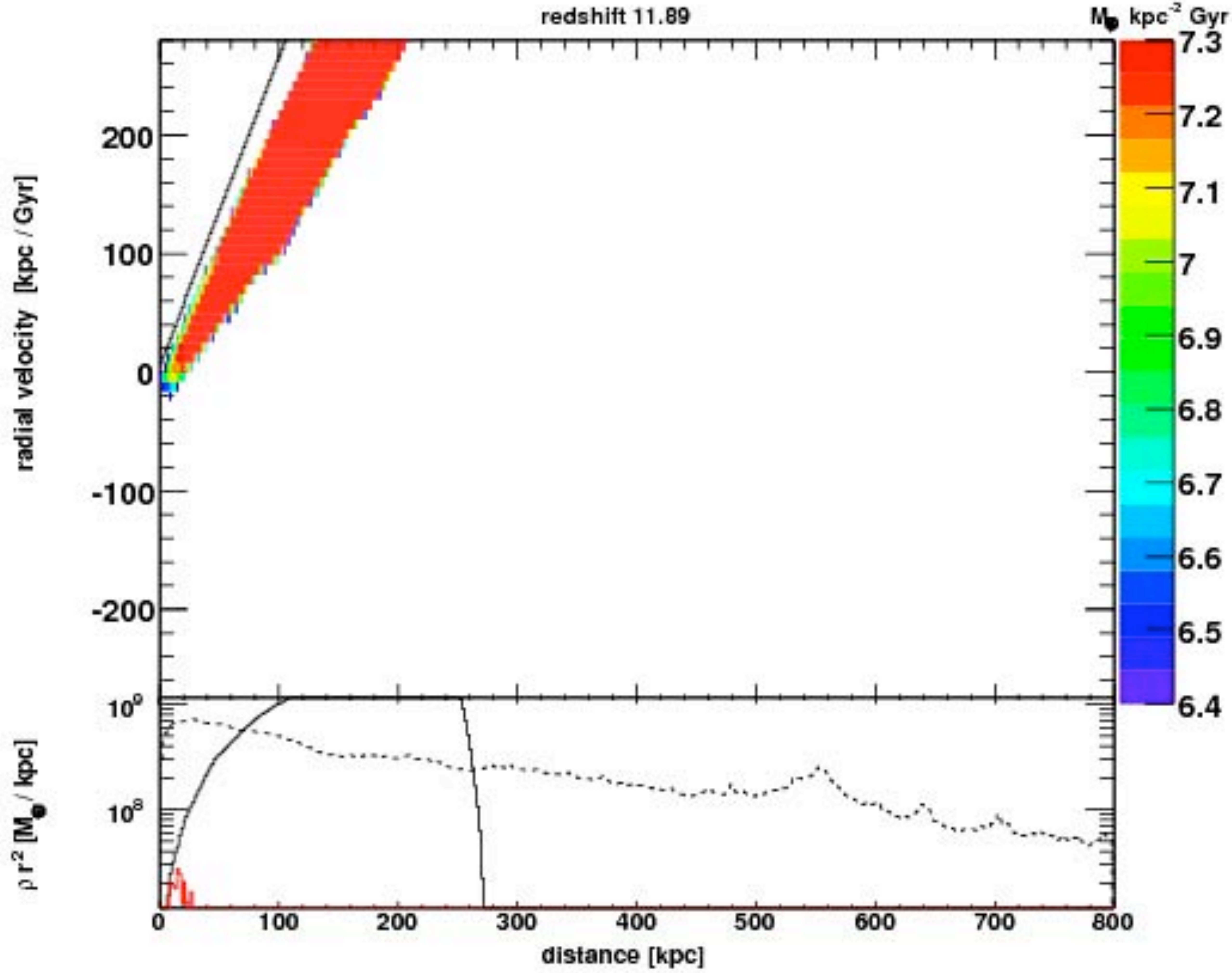
Simulations: Fabio Governato et al.
Radiative Transfer: Patrik Jonsson

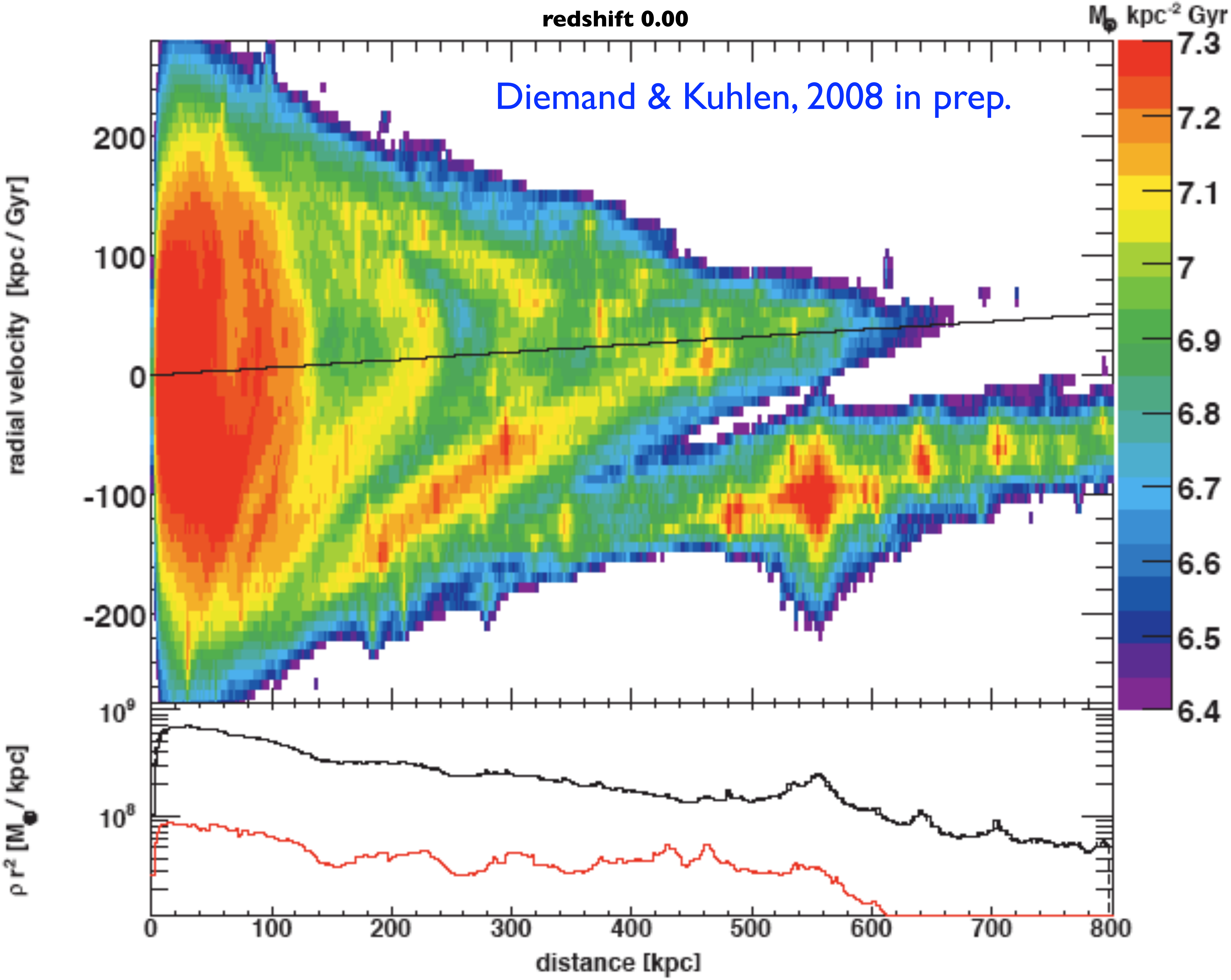
WHAT IS THE DARK MATTER?

Lensing limits on MACHOs are getting stronger - skewness of high-z vs. low-z Type Ia SN disfavors $10^{-2} < M_{MACHO}/M_{\odot} < 10^{8}$ (Metcalf & Silk 07).

Prospects for DIRECT and INDIRECT detection of WIMPs and AXIONs are improving… But what kind of WIMP? SUSY LSP, NLSP->LSP, KK, ...

Sikivie has claimed that caustics caused by phase wrapping as dark matter falls into the Milky Way will lead to potentially detectable effects in DM searches. This is not expected in realistic ΛCDM models. Caustics are seen in the Via Lactea simulation, but with very little density enhancement and only at great galactocentric distances.


redshift 11.89
M☉ kpc⁻² Gyr
7.3
7.2
7.1
7
6.9
6.8
6.7
6.6
6.5
6.4
radial velocity [kpc / Gyr]
200
100
0
-100
-200
ρ r² [M☉ / kpc]
10⁹
10⁸
0
100
200
300
400
500
600
700
800
distance [kpc]


redshift 0.00

Diemand & Kuhlen, 2008 in prep.

WHAT IS THE DARK ENERGY??

We can use existing instruments to measure $w = P/\rho$ and see whether it changed in the past. But to get order-of-magnitude better constraints than presently available, and a possible detection of non-cosmological-constant dark energy, better telescopes (e.g. LSST, SNAP) will probably be required both on the ground and in space, according to the Dark Energy Task Force (Albrecht+06).

The National Academy Beyond Einstein report (released September 2007), recommended JDEM as the first Beyond Einstein mission. NASA and DOE are negotiating their relationship and how to structure the JDEM competition.

small scale issues

Satellites

The discovery of many faint Local Group dwarf galaxies is consistent with ΛCDM predictions. Reionization, lensing, satellites, and Lyα forest data imply that WDM must be Tepid or Cooler.

Cusps

The triaxial nature of dark matter halos plus observational biases suggest that observed velocity structure of LSB and dSpiral galaxies are consistent with cuspy ΛCDM halos.

Angular momentum

ΛCDM simulations are increasingly able to form realistic spiral galaxies, as resolution improves and feedback becomes more realistic.

OUTLOOK

- We now know the cosmic recipe. Most of the universe is invisible stuff called “nonbaryonic dark matter” (~23%) and “dark energy” (~73%). Everything that we can see makes up only about 1/2% of the cosmic density, and invisible atoms about 4%. The earth and its inhabitants are made of the rarest stuff of all: heavy elements (0.01%).

- The ΛCDM Cold Dark Matter Double Dark theory based on this appears to be able to account for all the large scale features of the observable universe, including the details of the heat radiation of the Big Bang and the large scale distribution of galaxies.

- Constantly improving data are repeatedly testing ΛCDM. The main ingredients have been checked several different ways. There exist no convincing disagreements, as far as I can see. Possible problems on subgalactic scales may be due to the poorly understood astrophysics of gas, stars, and massive black holes.

- But we still don’t know what the dark matter and dark energy are, nor really understand how galaxies form and evolve. There’s lots more work for us to do, much of which will be discussed at this meeting.