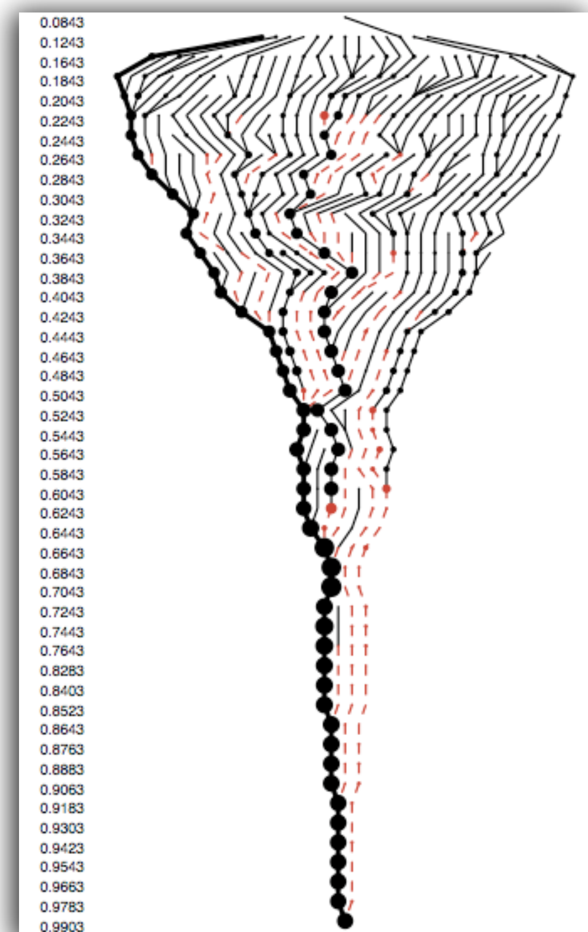
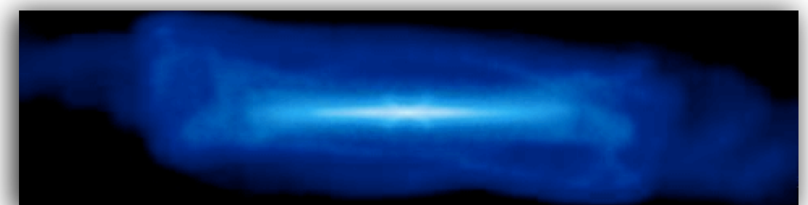
Dark Halo Mergers and Disk Survival





James Bullock

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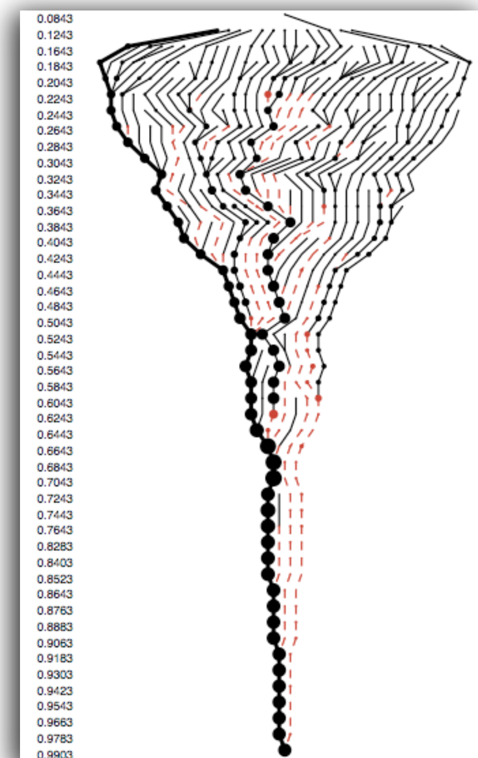
UNIVERSITY OF CALIFORNIA, IRVINE

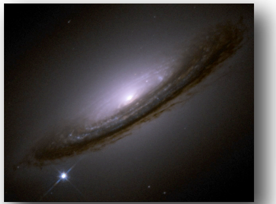
arXiv:0711.5027

MERGER HISTORIES OF GALAXY HALOS AND IMPLICATIONS FOR DISK SURVIVAL

Kyle R. Stewart[1], James S. Bullock[1], Risa H. Wechsler[2], Ariyeh H. Maller[3], and Andrew R. Zentner[4]



Kyle Stewart



Disks in a hierarchical cosmology?

- Most big galaxies in the universe come in the form of disks.
- Disk galaxies have been notoriously difficult to form in LCDM simulations. (e.g. Navarro & White 94)
  - Doing better recently, but not there yet.

Different models suggest qualitatively different pictures for disk galaxy assembly:
-Quiescent formation
-Gas-rich *mergers*
-Accreted thick disks...

Abadi et al. 03
Brook et al. 04;
Robertson et al. 04, 06
Kaufmann et al. 07
Governato et al. 04, 07

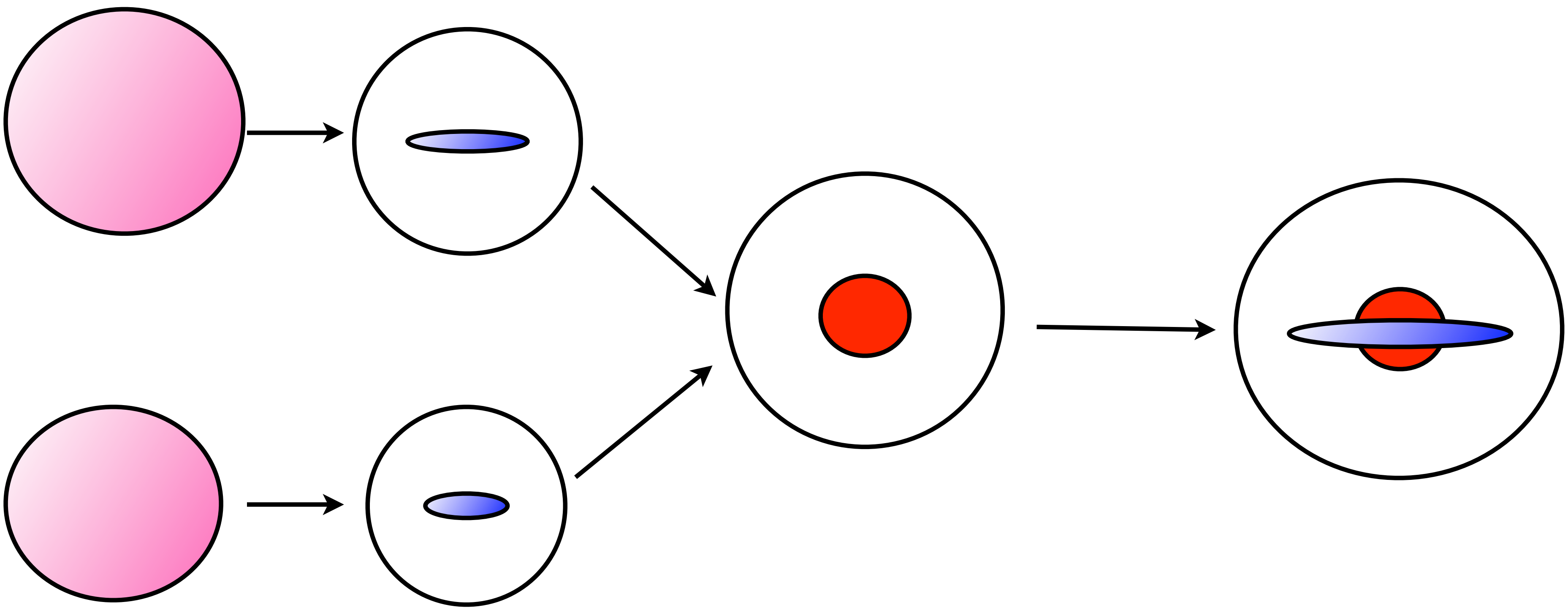
Disks in a hierarchical cosmology?

Given the uncertain astrophysical inputs, we may ask a more conservative question:

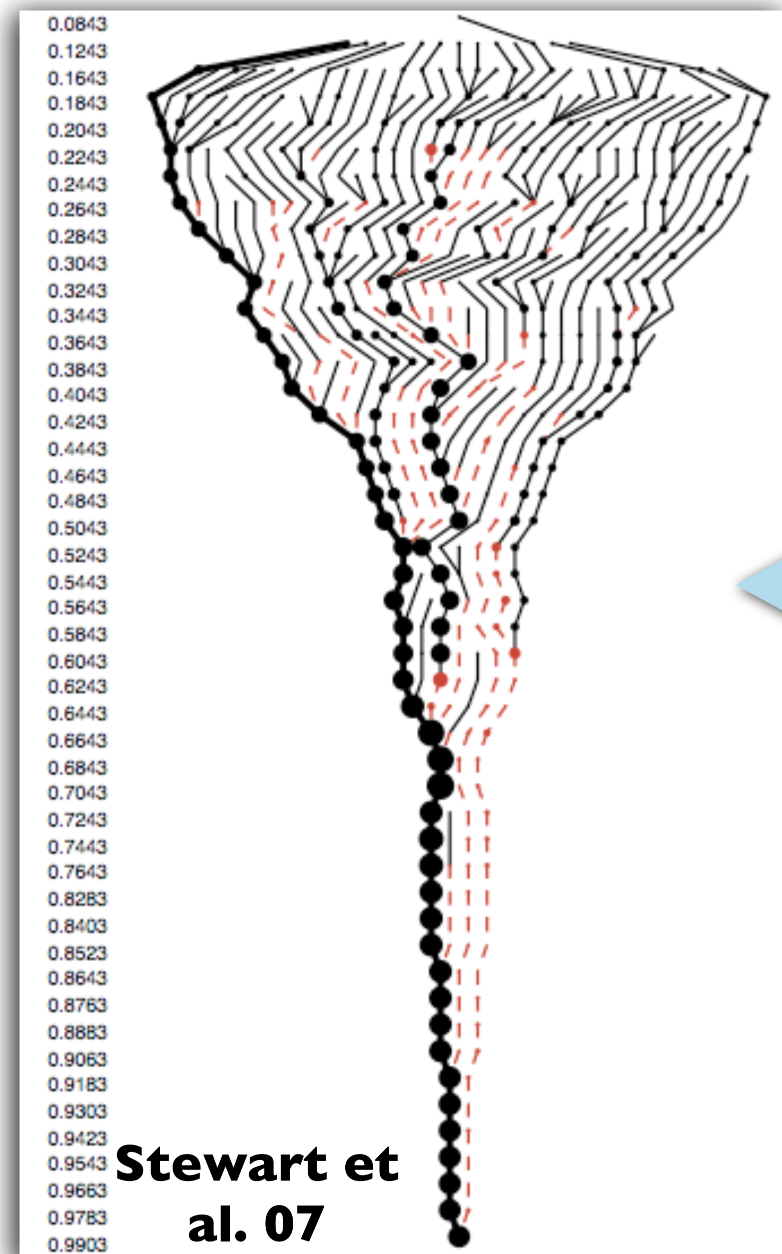
Even if a thin disk could form... could it ever survive the expected bombardment?

Toth & Ostriker 92
Walker, Mihos, Hernquist 96
Velazquez & White 99
Font et al. 01
Gauthier et al. 06

A Standard Cartoon...



e.g. Somerville & Primack 99 ... Springel et al. 05... etc.



How minor are these mergers?

Can disks survive?

Late Type Fraction vs. Halo Mass

Weinmann et al. 06

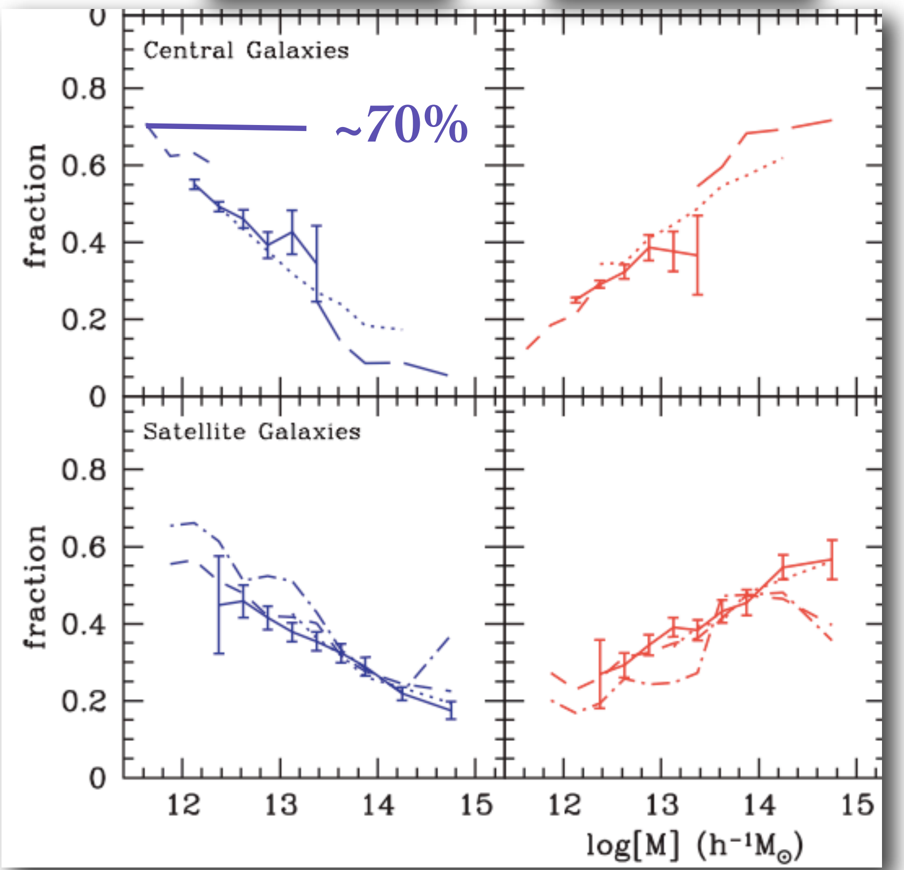
SDSS halo/gp catalog

Late type classification:
- -Color
- -SSFR
- -concentration

$M=10^{12}\ M_{sun}$

~70%
Late-type fraction

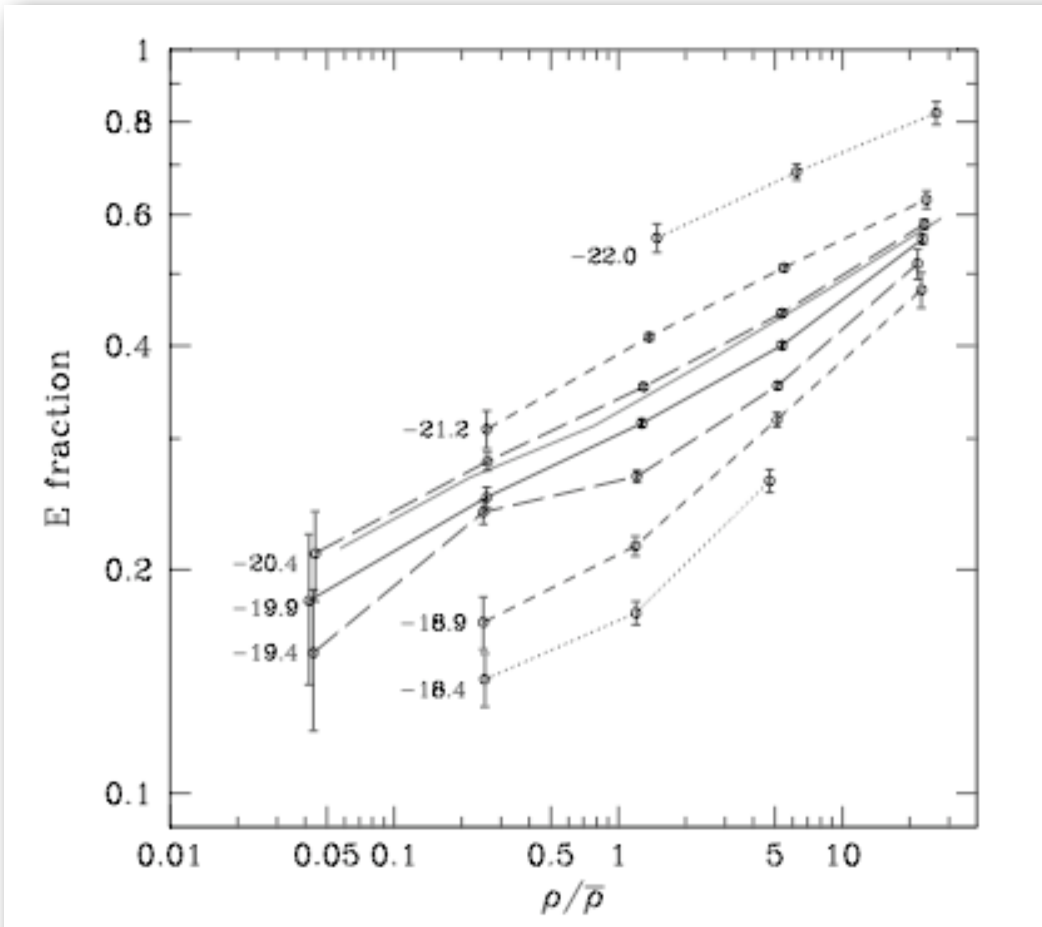
Late type | Early type



Host Halo Mass

Park et al. 07
SDSS

~30%
Early-type fraction
for M_r~= -20



Kautsch, Gregel, Bazazza, & Gallagher 2006

A&A 445, 765–778 (2006)

Non-trivial fraction of disk galaxies are super-thin, no bulge at all!

Catalog of edge-on disk galaxies from SDSS

w/ bulge	intermediate	flat. no bulge
~34%	~50%	~16%

Late-type bulges => Internal secular processes?

The Astrophysical Journal, 658:960–979, 2007 April 1

OLD AND YOUNG BULGES IN LATE-TYPE DISK GALAXIES[1]

C. M. Carollo,[2] C. Scarlata,[2] M. Stiavelli,[3] R. F. G. Wyse,[4] and L. Mayer[2]
Received 2006 April 7; accepted 2006 October 18

ABSTRACT

We use *HST* ACS and NICMOS imaging to study the inner $B - I$ and $I - H$ colors of nine late-type spiral galaxies, which we interpret on the basis of different star formation histories. The colors and scale lengths of the bulges of these late-type systems are correlated with those of the disks in which they are embedded. We find that in about half of the systems, the bulk of the bulge mass formed more recently than the disk. In the remainder, early bulge formation was supplemented by continuing "rejuvenating" star formation. More massive bulges are generally older. These results extend previous findings down to the smallest bulge mass scales, bordering on the masses of nuclear star clusters. The variety and extended star formation histories of late-type bulges could be naturally explained by the contribution of several processes at different epochs and operating on different timescales. On the other hand, the scaling relations between bulge stellar age and bulge/galaxy mass and between bulge and disk scale lengths hint at similar processes for all components and suggest that late-type bulges of all (masses and) stellar ages result from the internal evolution of the parent disks. We show that dynamical friction of massive clumps in gas-rich disks is also a plausible mode for the formation of late-type bulges, especially for those that are older than their surrounding disks. If disk evolutionary processes are indeed responsible for the formation of the entire family of late-type bulges, CDM simulations need to produce a similar number of initially bulgeless disks in addition to the disk galaxies that are observed to be bulgeless at $z = 0$.

Subject headings: galaxies: bulges — galaxies: evolution — galaxies: formation — galaxies: spiral — galaxies: stellar content

Online material: color figures, machine-readable table

Suggests an even higher fraction of galaxies without significant mergers.
Also e.g. Kormendy 05

The Milky Way

DM Halo: $M_0 \sim 1.4 \times 10^{12}\ M_{sun}$

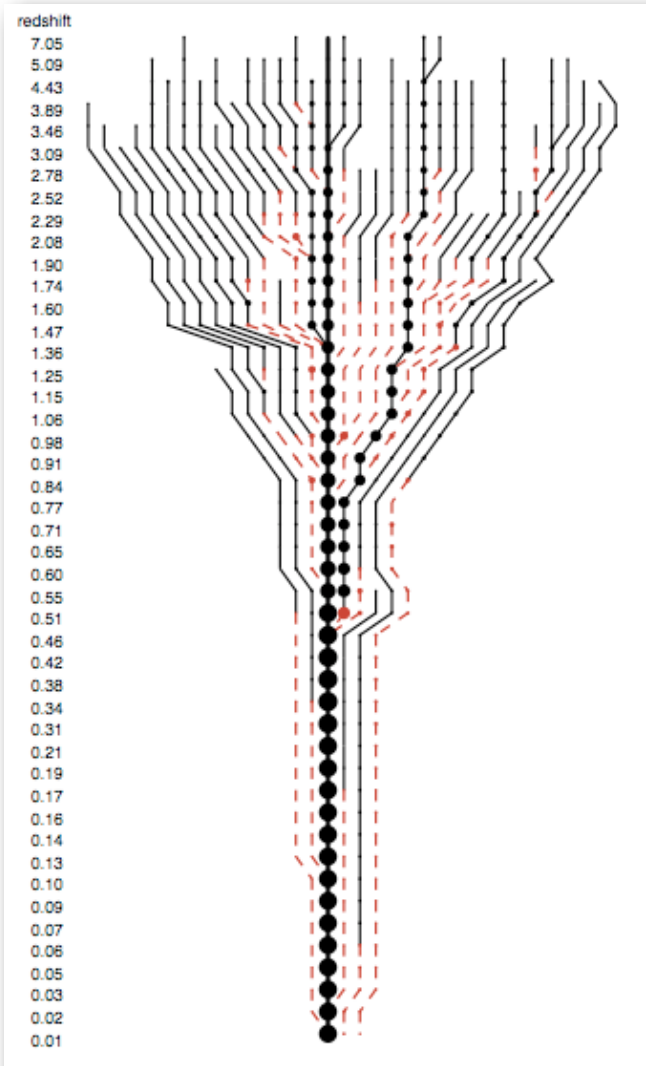
- **Disk:** $M_d \sim 4 \times 10^{10}\ M_{sun}$
  Oldest stars, ~10 Gyr
- **Thick Disk:** $M_{td} \sim 10^9\ M_{sun}$
  Uniformly old ~ 10Gyr
- **Bulge:** Mostly old ~ 10Gyr

→ Fairly quiescent merger history

Klypin et al. 02; Wyse 04

Stewart et al. 07

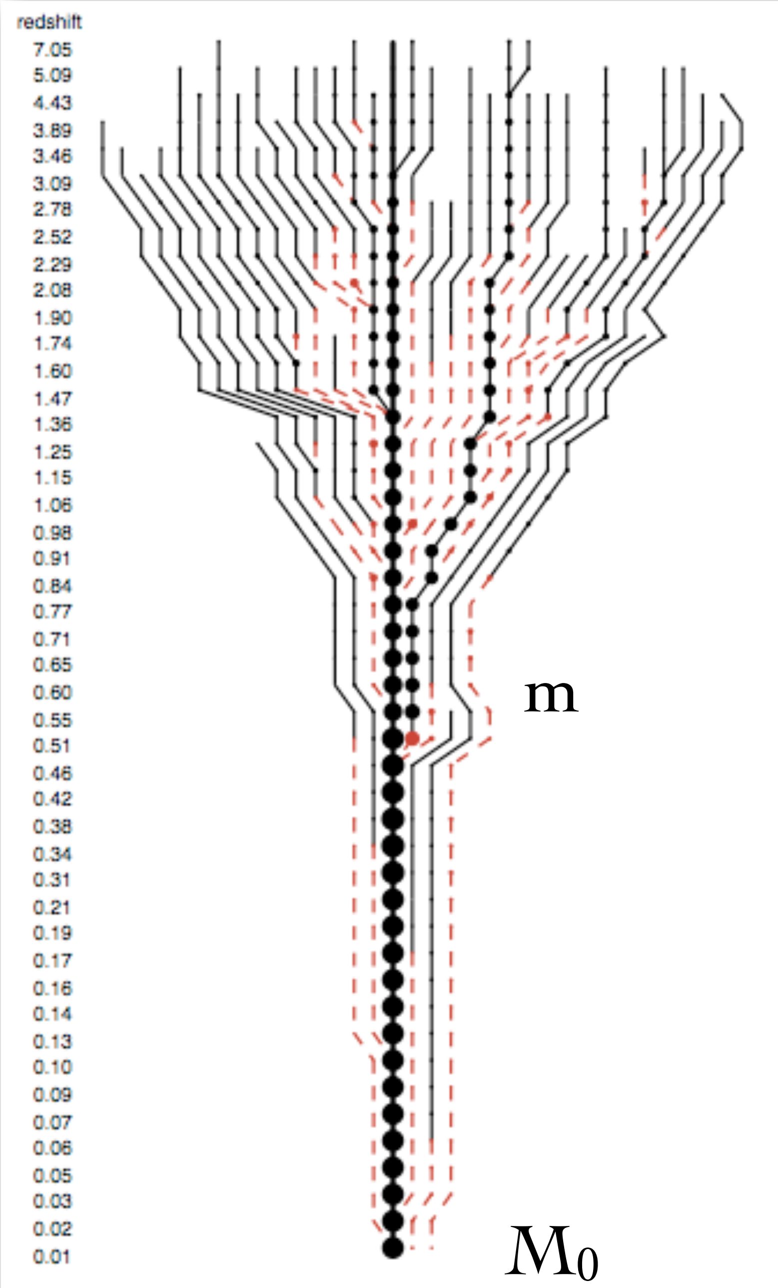
- LCDM, $\sigma_8 = 0.9$



- ART N-body
  $L = 80\ h^{-1}$Mpc box
  $N_p = 512^3$

- 17,000 halos at z=0
  $M_0 = 10^{11}$-$10^{13}\ h^{-1}\ M_{sun}$
  $m_{min} = 10^{10}\ h^{-1}\ M_{sun}$

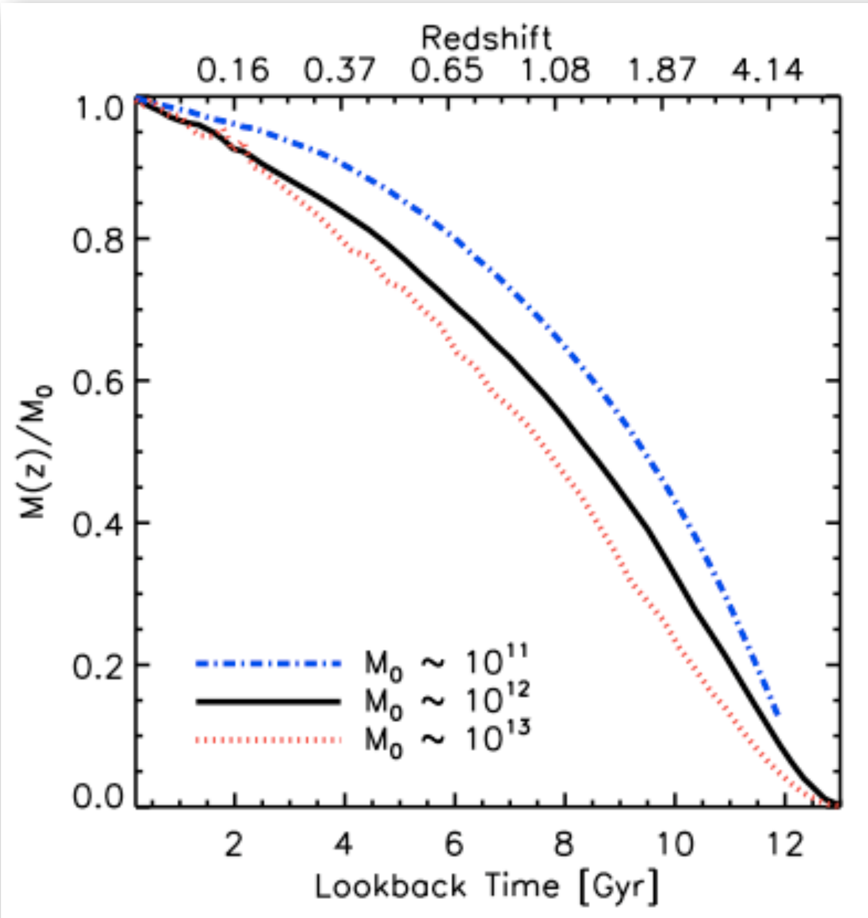
- BDM -- spherical overdensity halo finder.



Stewart et al. 07

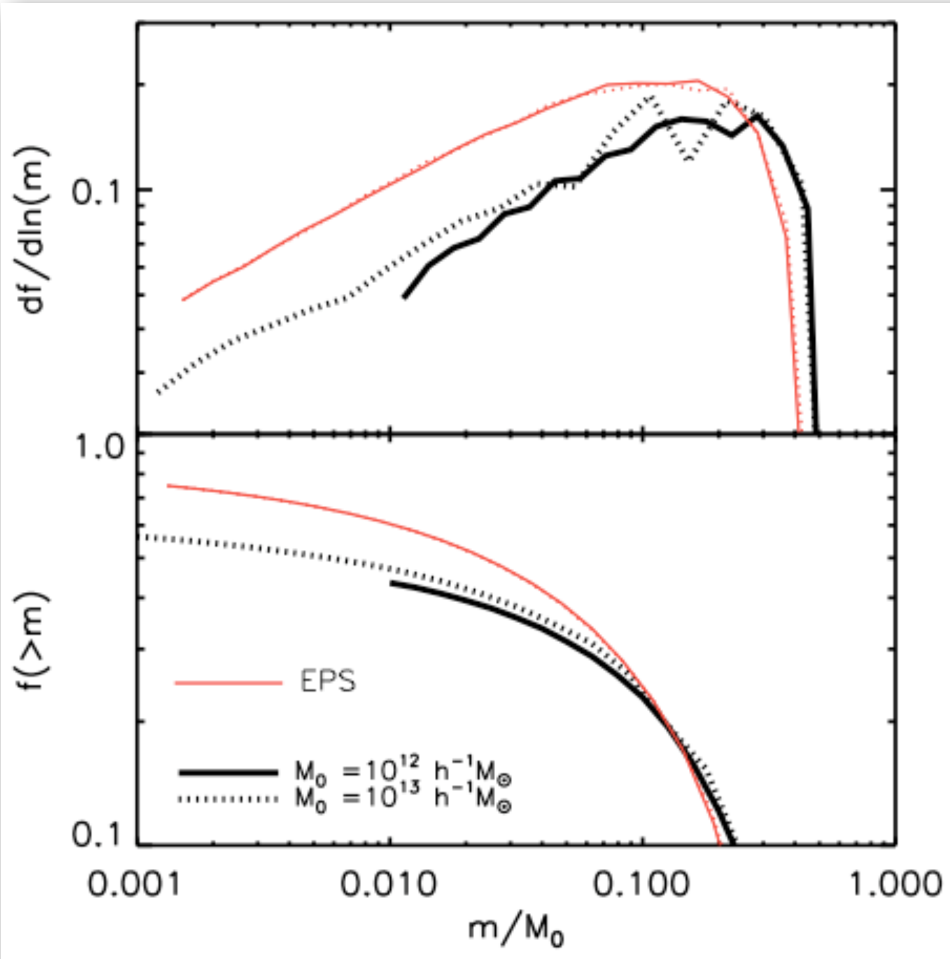
- Count mergers of infalling objects **m** into halos of z=0 masses $\mathbf{M_0}$
- Count as fall within halo virial radius
- Use absolute cuts on m NOT ratios m/M_z

Average Mass Accretion Histories



- Rapid early accretion rate
- Small halos form earlier
- Well known (e.g. Wechsler et al. 02)

How is mass accreted?

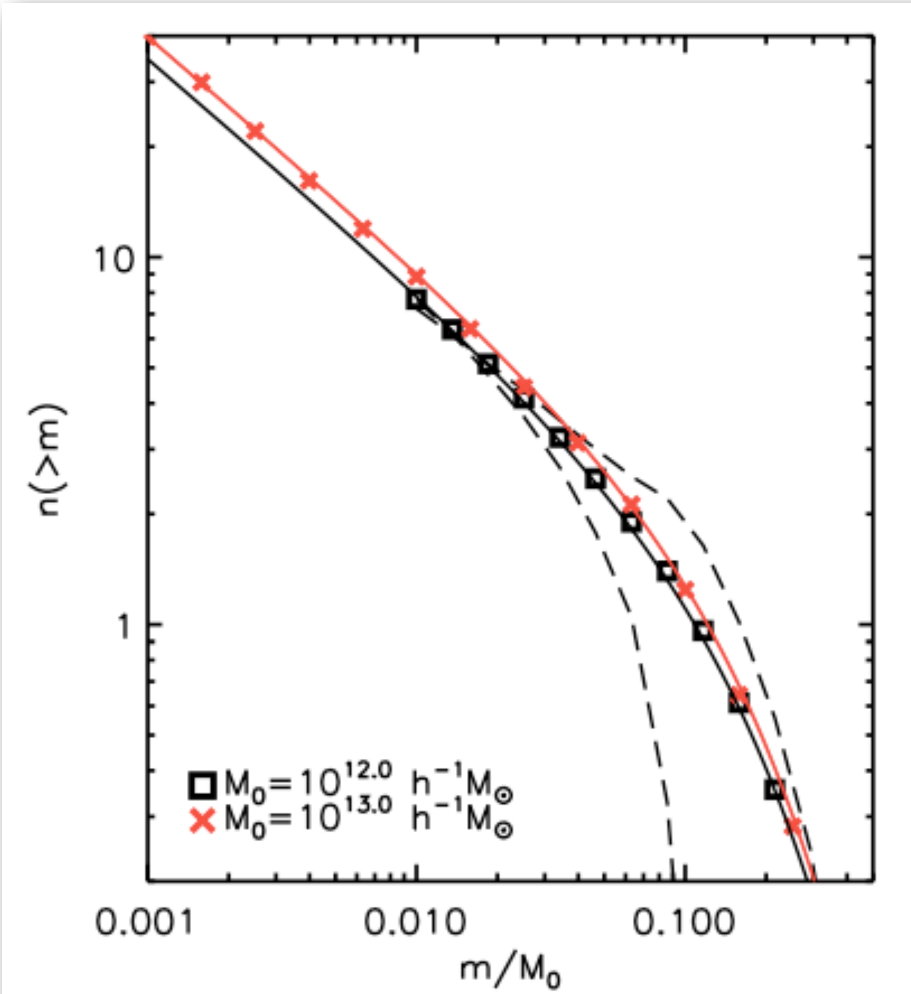


~1/10 events dominate mass growth.

For typical $10^{12}\ M_{sun}$ halo:

- $M \sim 10^{11}$ mergers dominate mass buildup.

Cumulative # of accretions larger than m

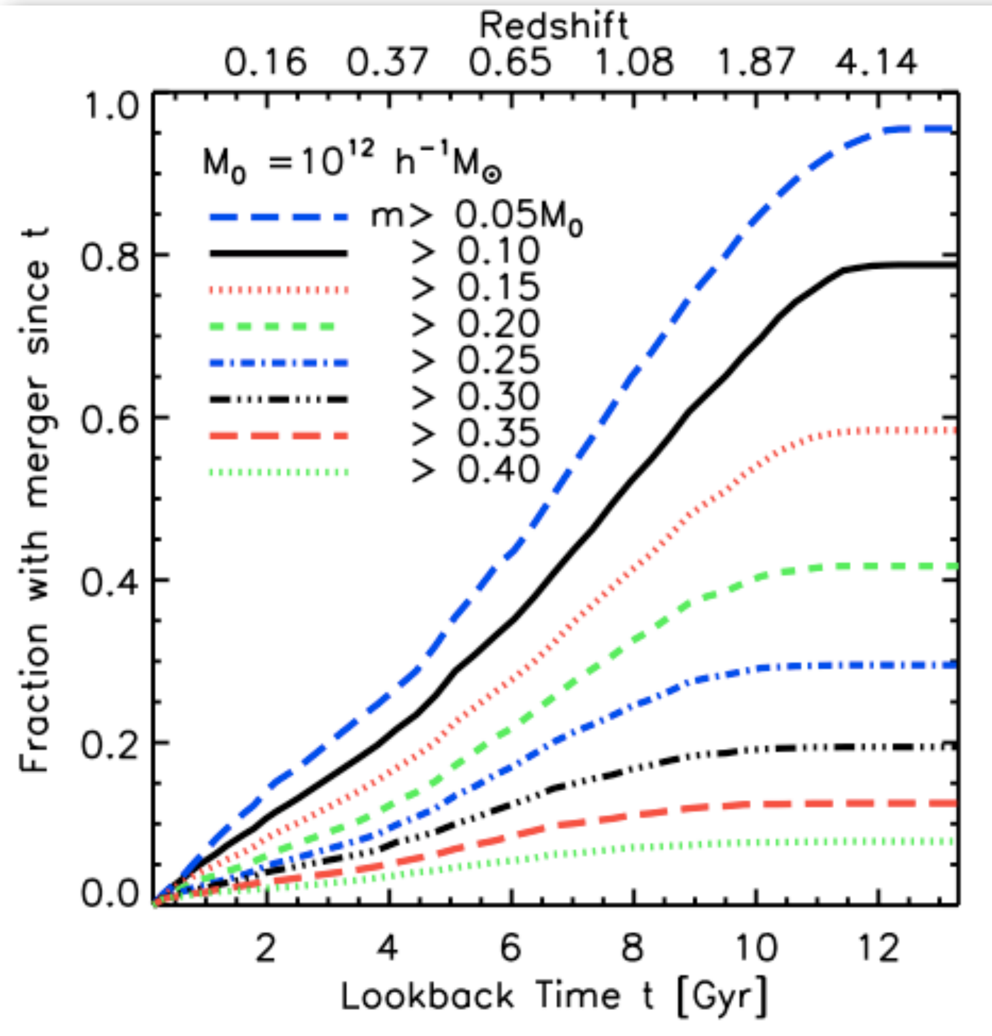


Approximately self-similar in m/M_0

For typical 10^{12} M_{sun} halo:

- ~1 10^{11} merger
- ~7 10^{10} mergers
- increasing #'s of smaller mergers

Fraction of halos with merger larger than m since time t

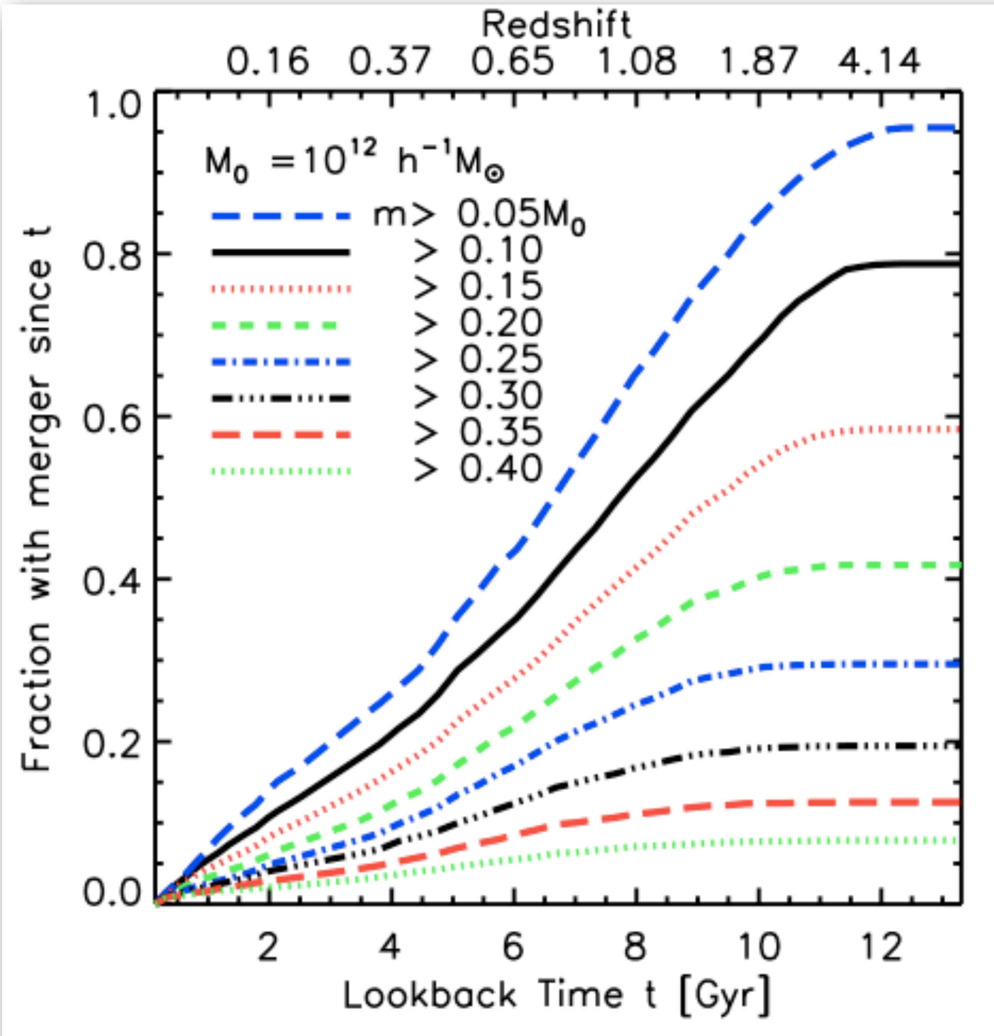


10^{12} M_{sun} halos in last 10 Gyr:

- ~70% have m=10^{11} merger
- ~95% have m=5.10^{10} merger

See Cohn & White 07
for similar result at z=10

Fraction of halos with merger larger than m since time t



10^{12} M_{sun} halos in last 10 Gyr:

- ~70% have m=10^{11} merger
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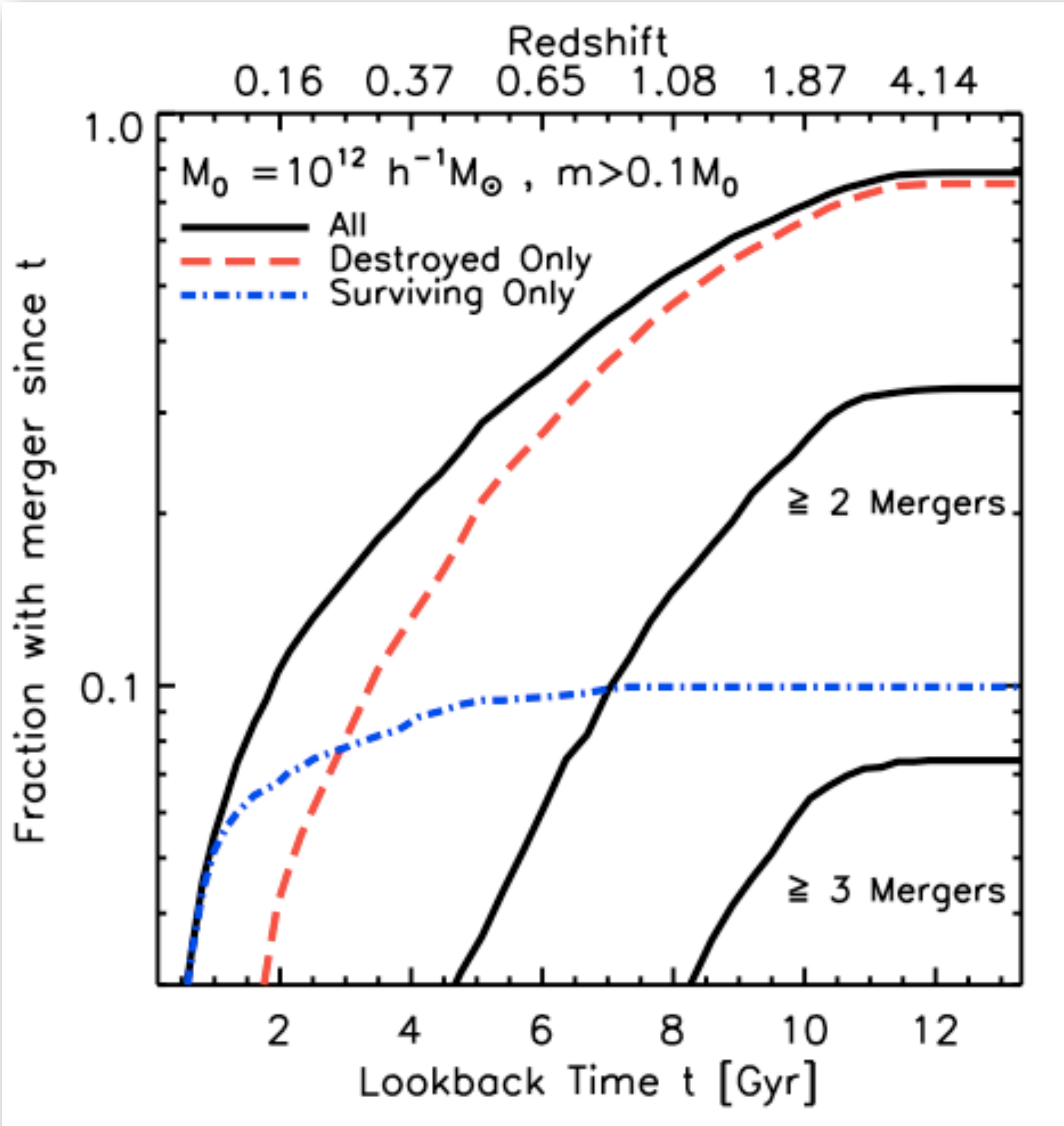
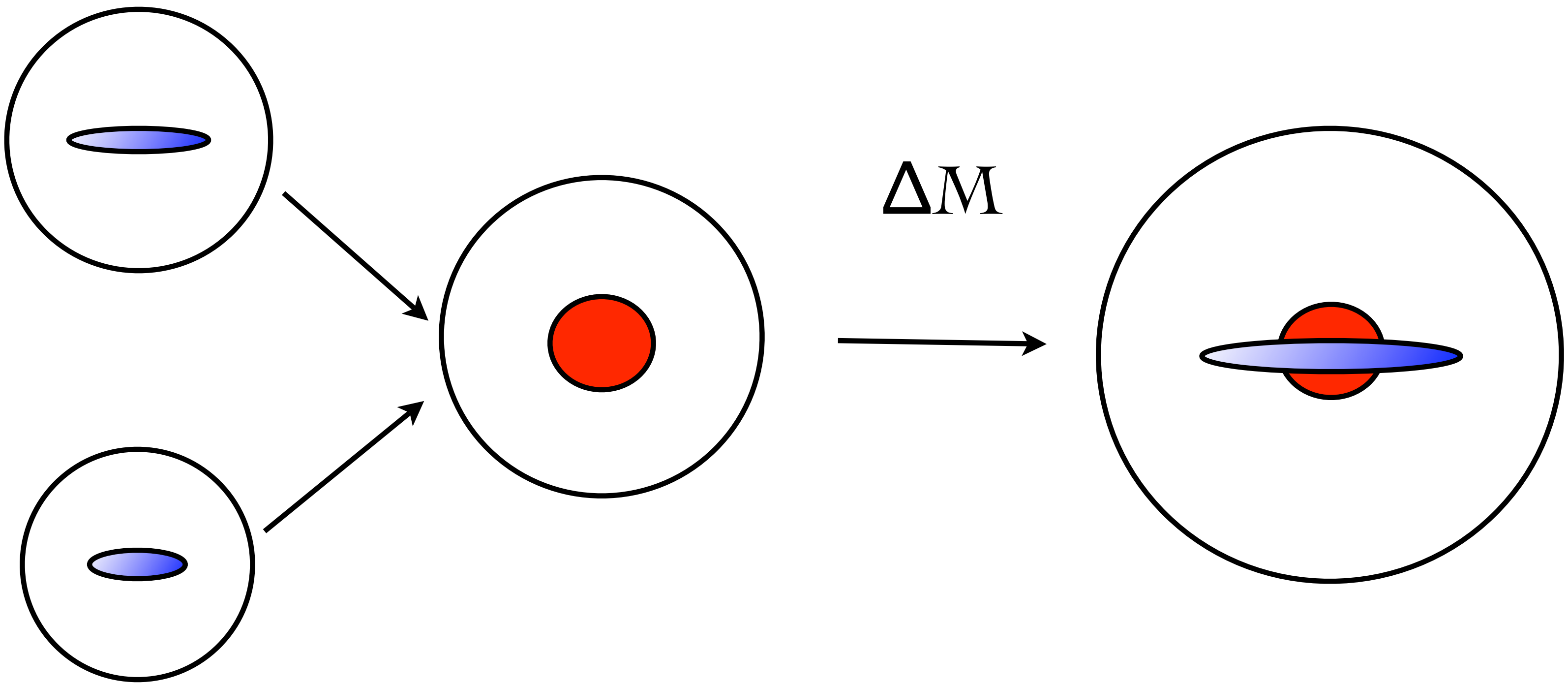
larger than **current** mass of MW disk

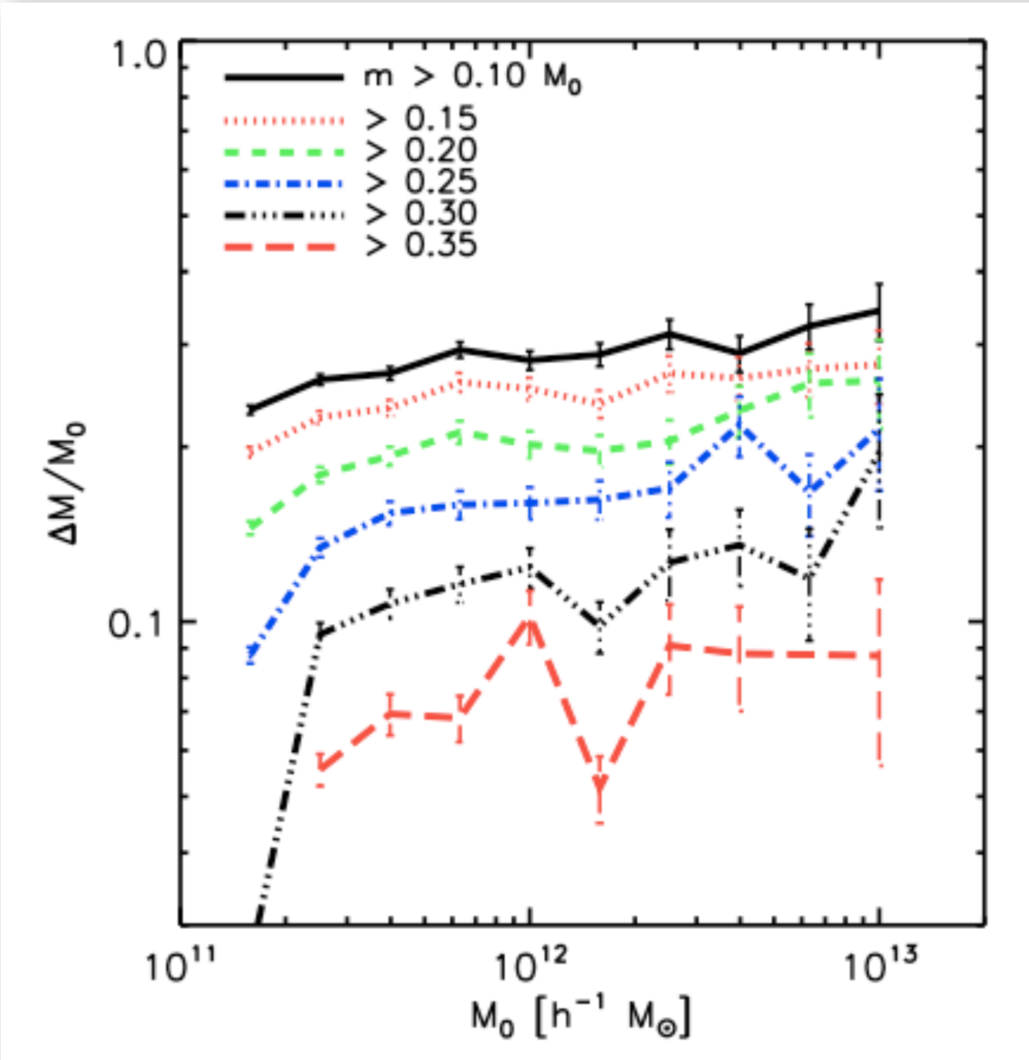

Redshift
0.16 0.37 0.65 1.08 1.87 4.14
1.0
0.1
$M_0 = 10^{12} h^{-1} M_\odot$, $m > 0.1 M_0$
All
Destroyed Only
Surviving Only
≧ 2 Mergers
≧ 3 Mergers
Fraction with merger since t
2 4 6 8 10 12
Lookback Time t [Gyr]

Mass accreted since last large merger?



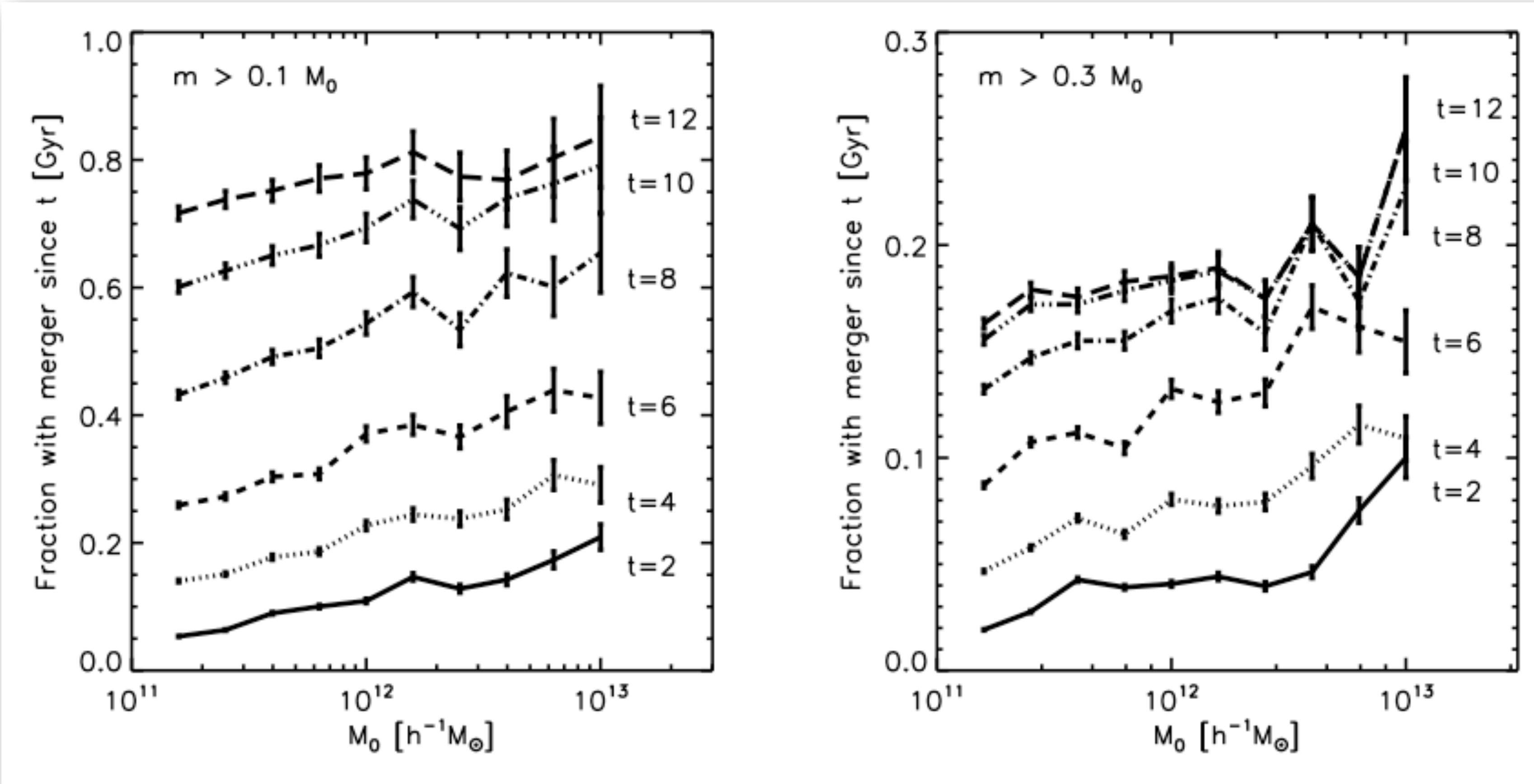
Final disk fraction: $\Delta M/M_0$?

Mass accreted since last large merger:



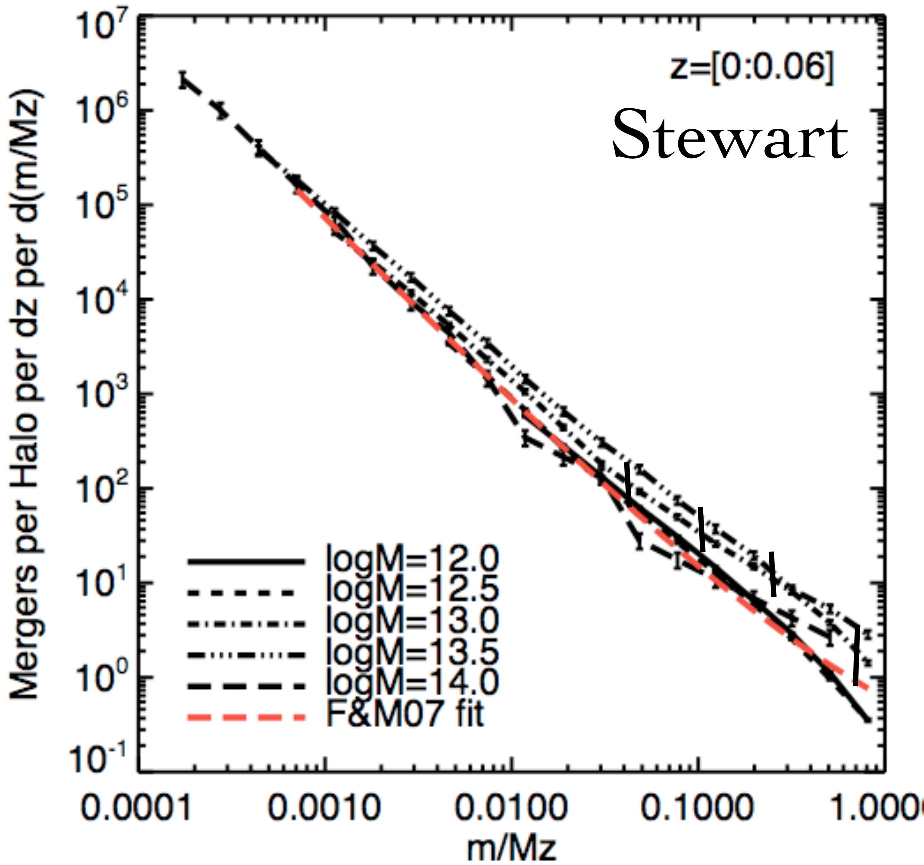
Typically, small fraction of final mass is accreted since last large merger.

Merger fractions vs z=0 Halo Mass:

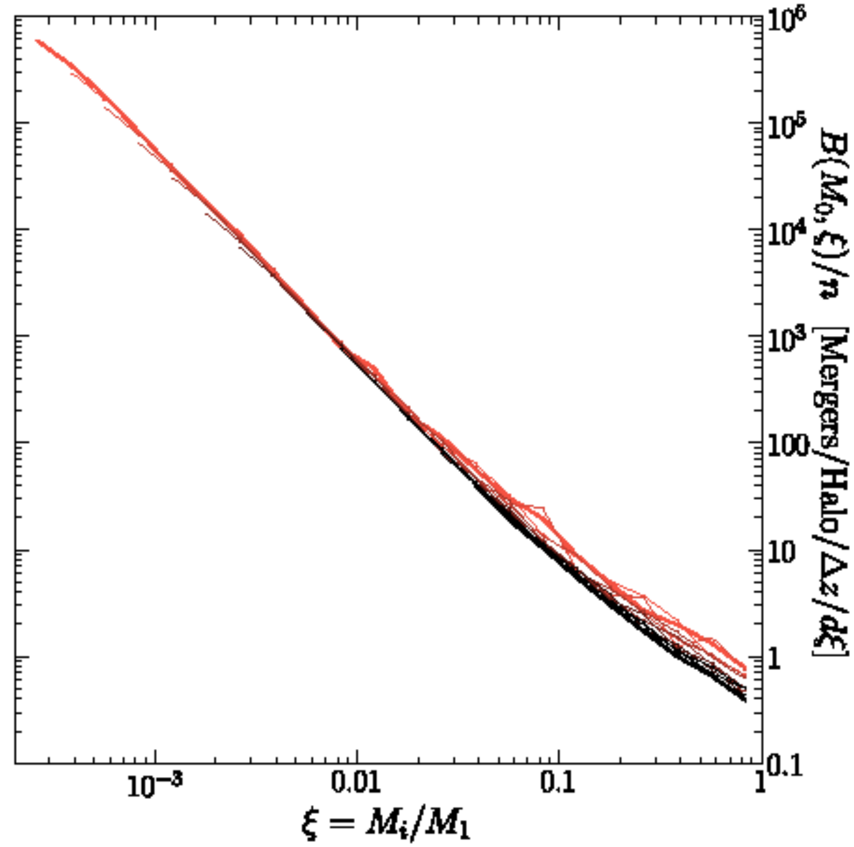


Very weak mass trend, more prominent for larger mergers

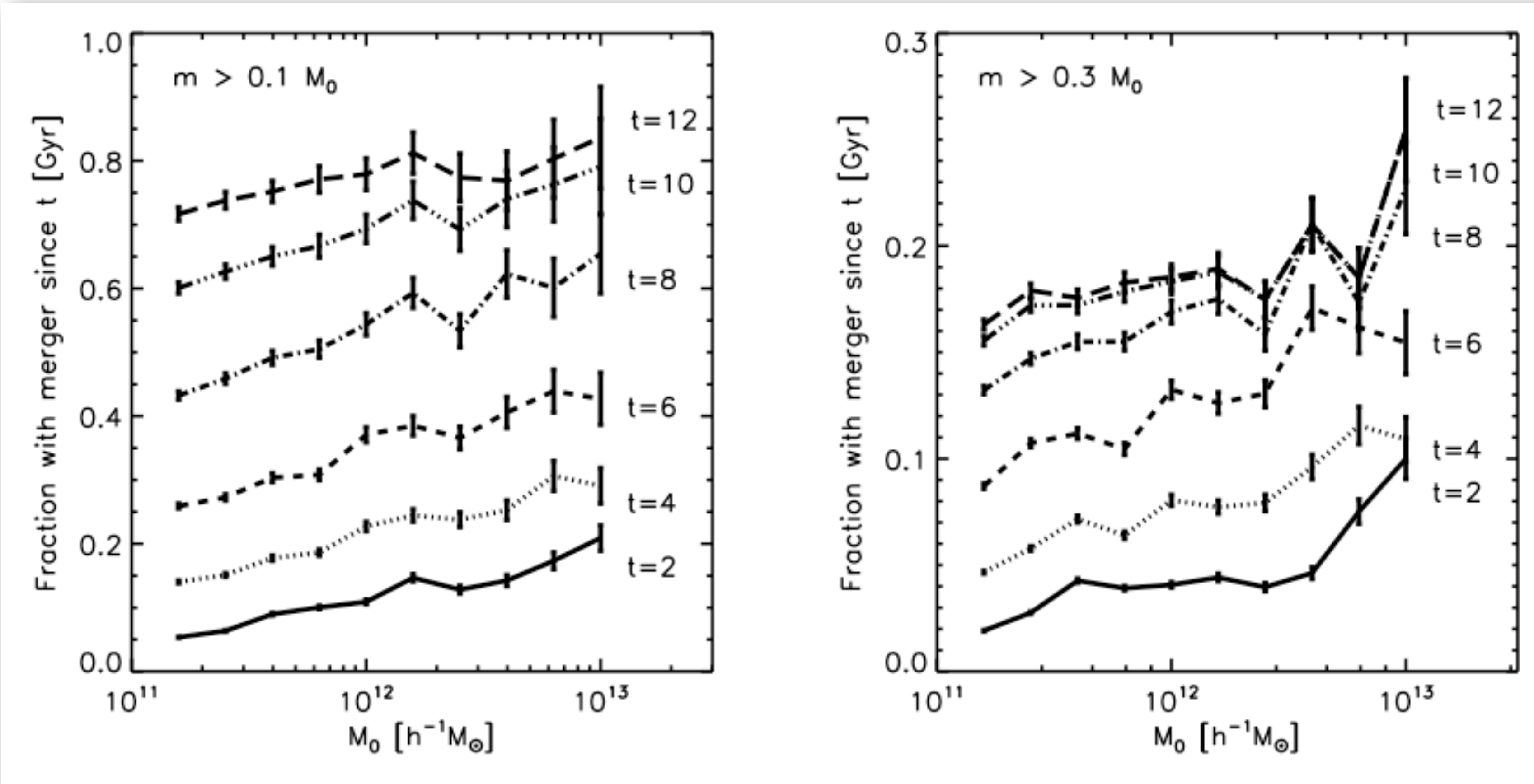
Universal instantaneous merger rates



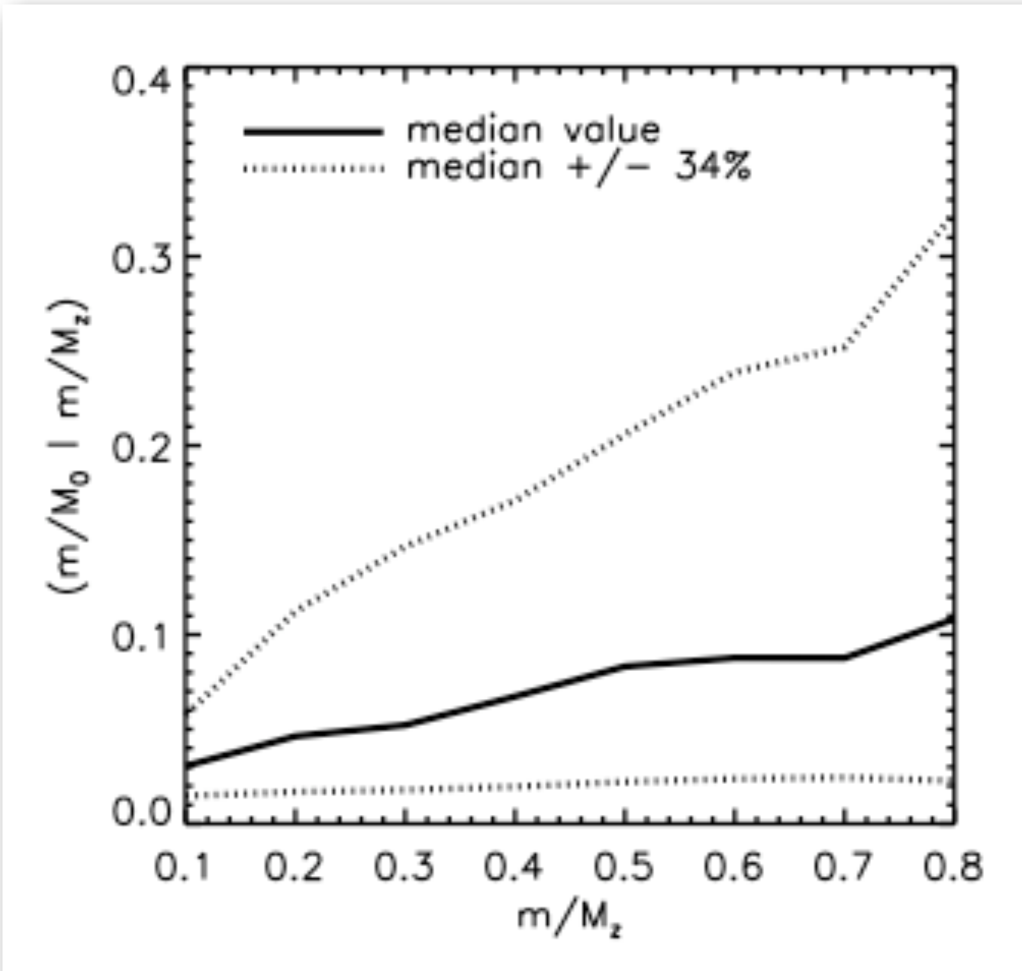
Fakhouri & Ma 07



Observed Trends: Galaxy Type vs. Halo Mass
Likely driven by astrophysics, not halo merger rates

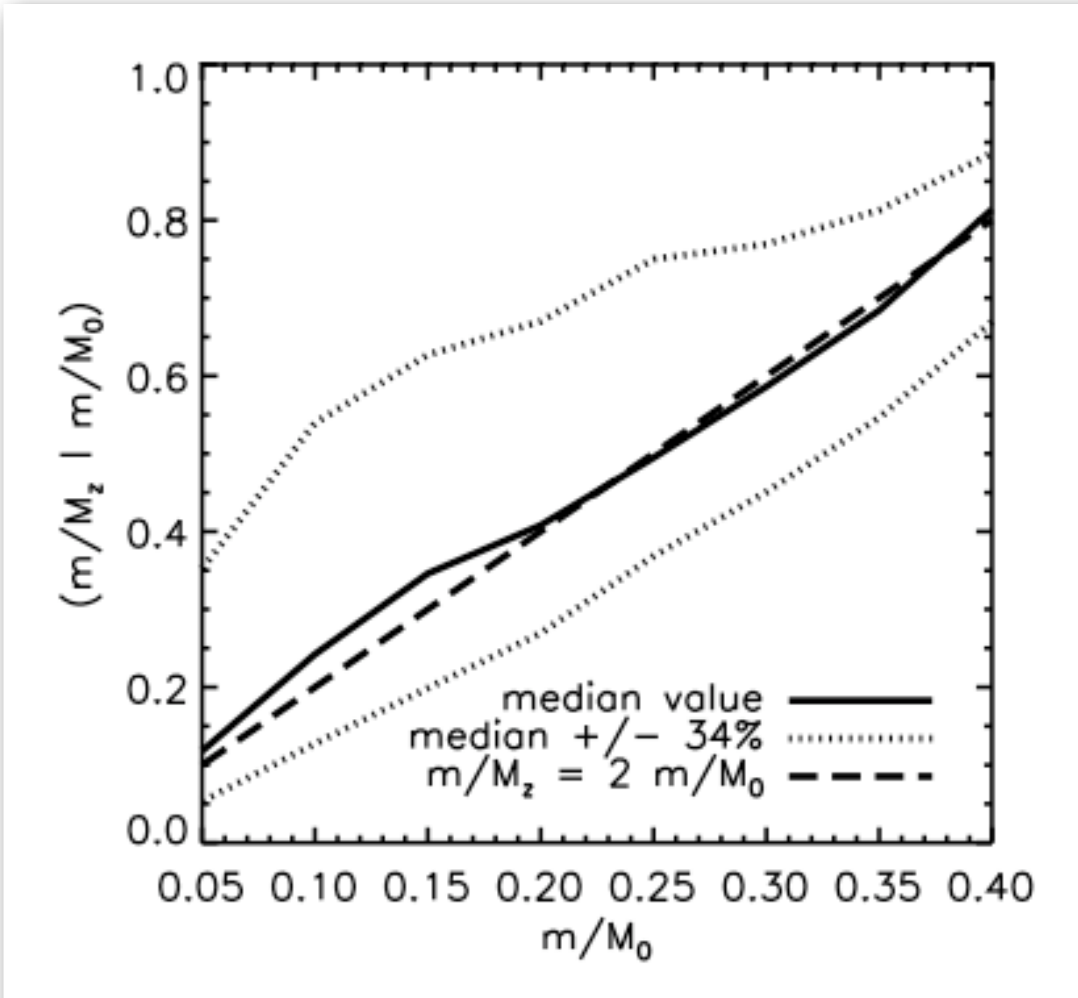


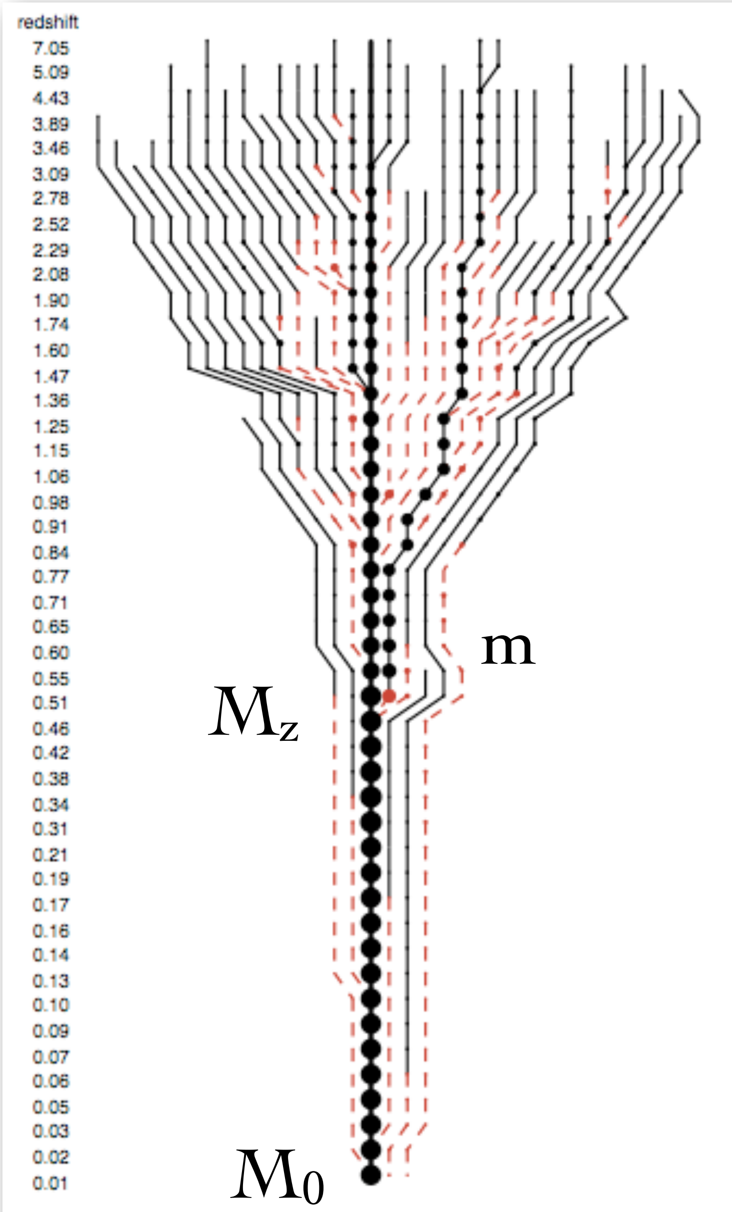
Why not use mass ratios? m/M_z

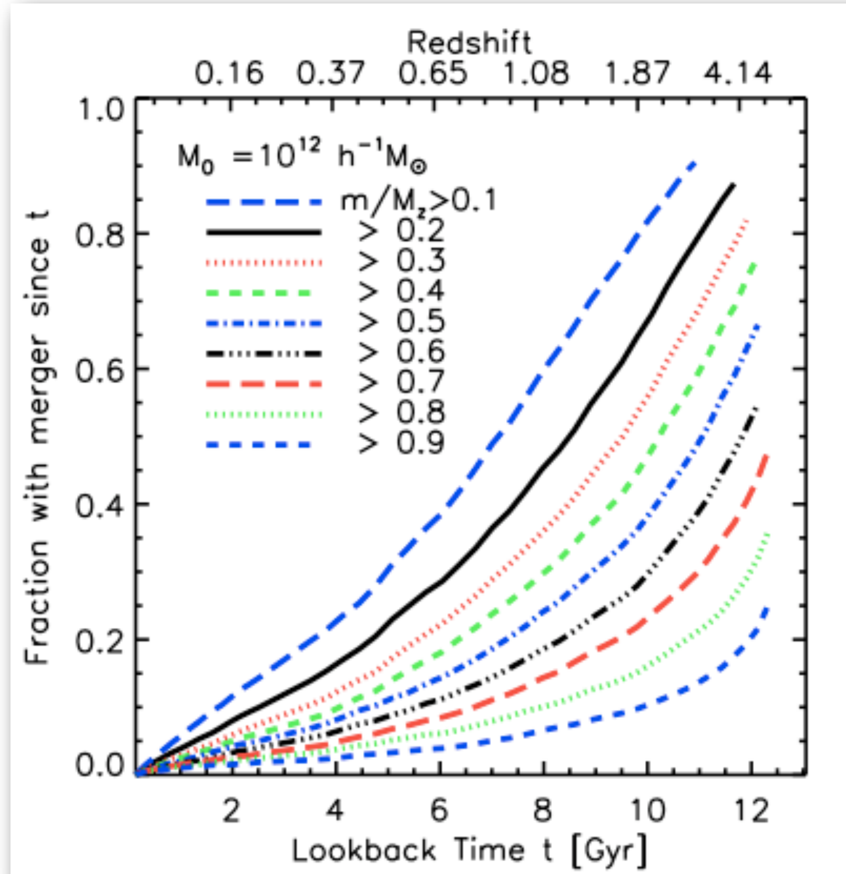


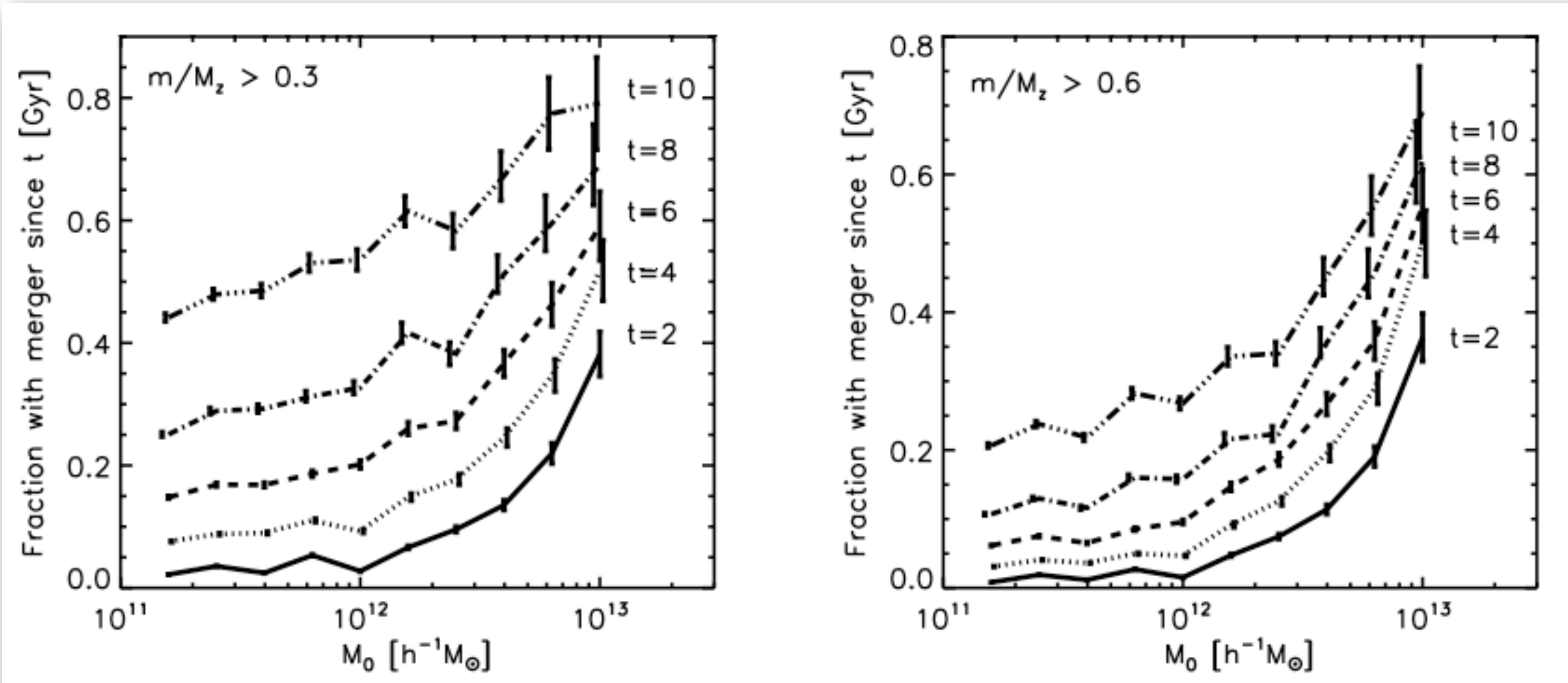
Most high m/M_z events are small in an absolute sense

Typically $m/M_0 \sim 0.5\ m/M_z$




redshift
7.05
5.09
4.43
3.89
3.46
3.09
2.78
2.52
2.29
2.08
1.90
1.74
1.60
1.47
1.36
1.25
1.15
1.06
0.98
0.91
0.84
0.77
0.71
0.65
0.60
0.55
0.51
0.46
0.42
0.38
0.34
0.31
0.21
0.19
0.17
0.16
0.14
0.13
0.10
0.09
0.07
0.06
0.05
0.03
0.02
0.01
m
M_z
M_0


Redshift
0.16 0.37 0.65 1.08 1.87 4.14
$M_0 = 10^{12}\ h^{-1} M_\odot$
$m/M_z > 0.1$
> 0.2
> 0.3
> 0.4
> 0.5
> 0.6
> 0.7
> 0.8
> 0.9
Fraction with merger since t
0.0
0.2
0.4
0.6
0.8
1.0
2 4 6 8 10 12
Lookback Time t [Gyr]


m/M$_z$ > 0.3
Fraction with merger since t [Gyr]
t=10
t=8
t=6
t=4
t=2
M$_0$ [h^{-1}M$_\odot$]
m/M$_z$ > 0.6

Summary: Lots of fairly large mergers

10^{12} M_{sun} halos
in last 10 Gyr:

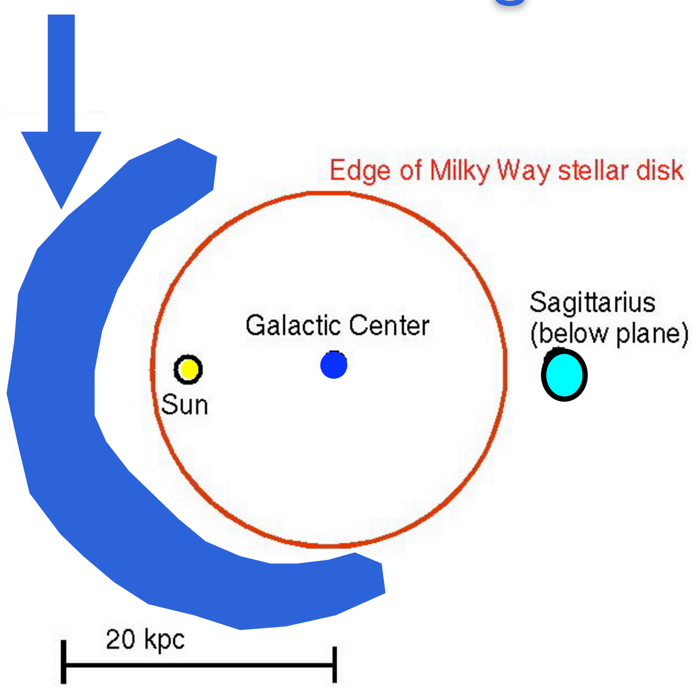
- ~70% have an $m=10^{11}$ merger
- ~95% have at least one $m=5.10^{10}$ merger

larger than **current** mass of MW disk

Evidence for merging in the MW?

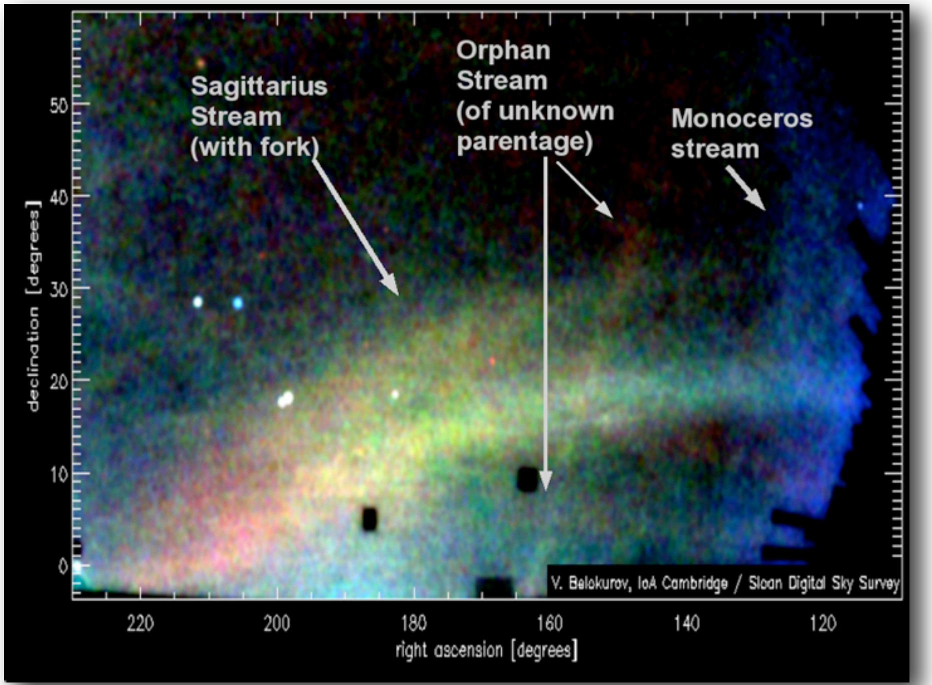
Structures in the Milky Way Halo & Disk?

monoceros ring

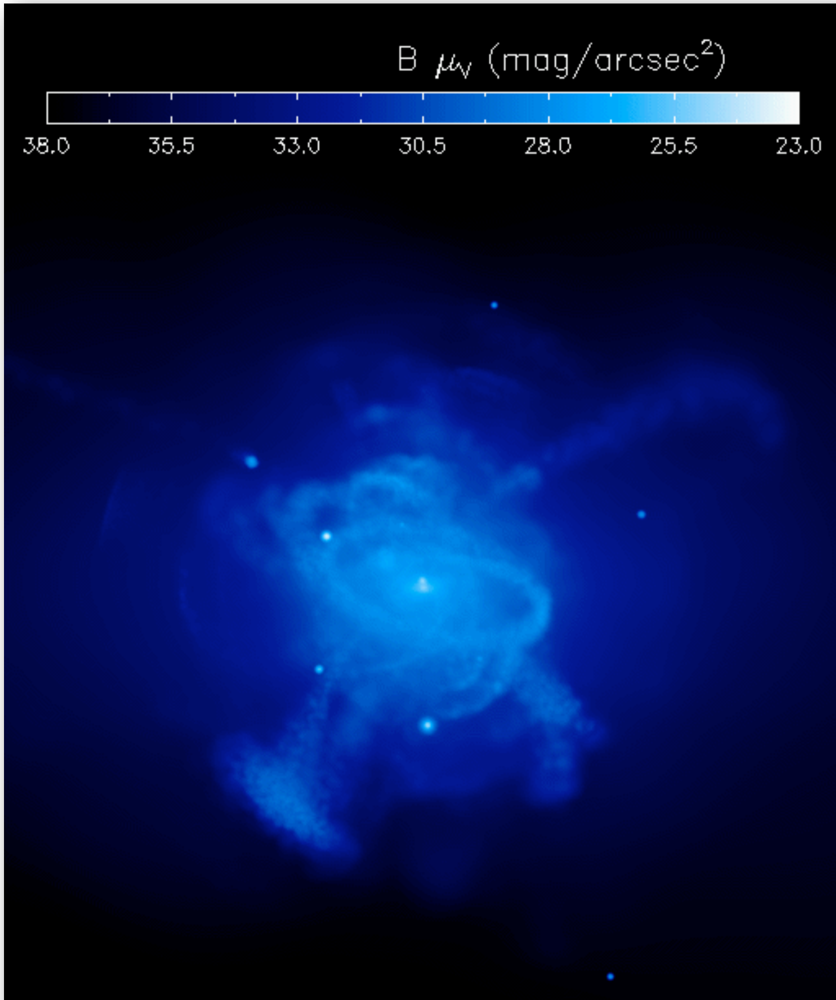


Newberg et al. 02
Yanny et al.

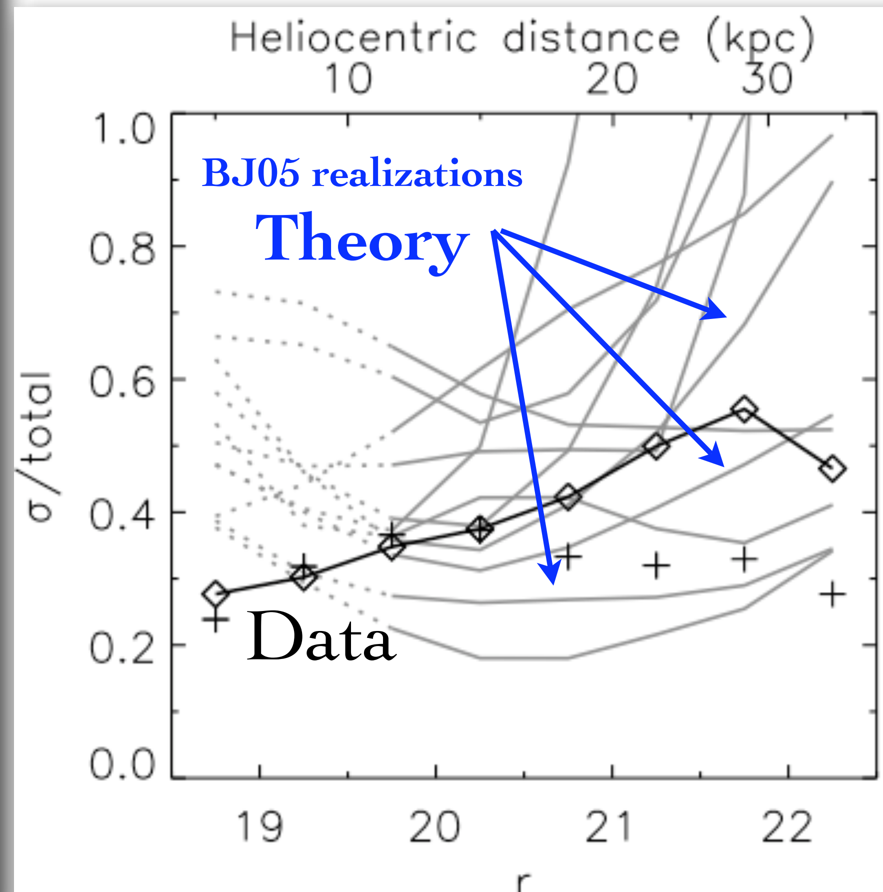
Belokurov et SDSS



Spatial structure in stellar halo <--> Evidence for past accretions?

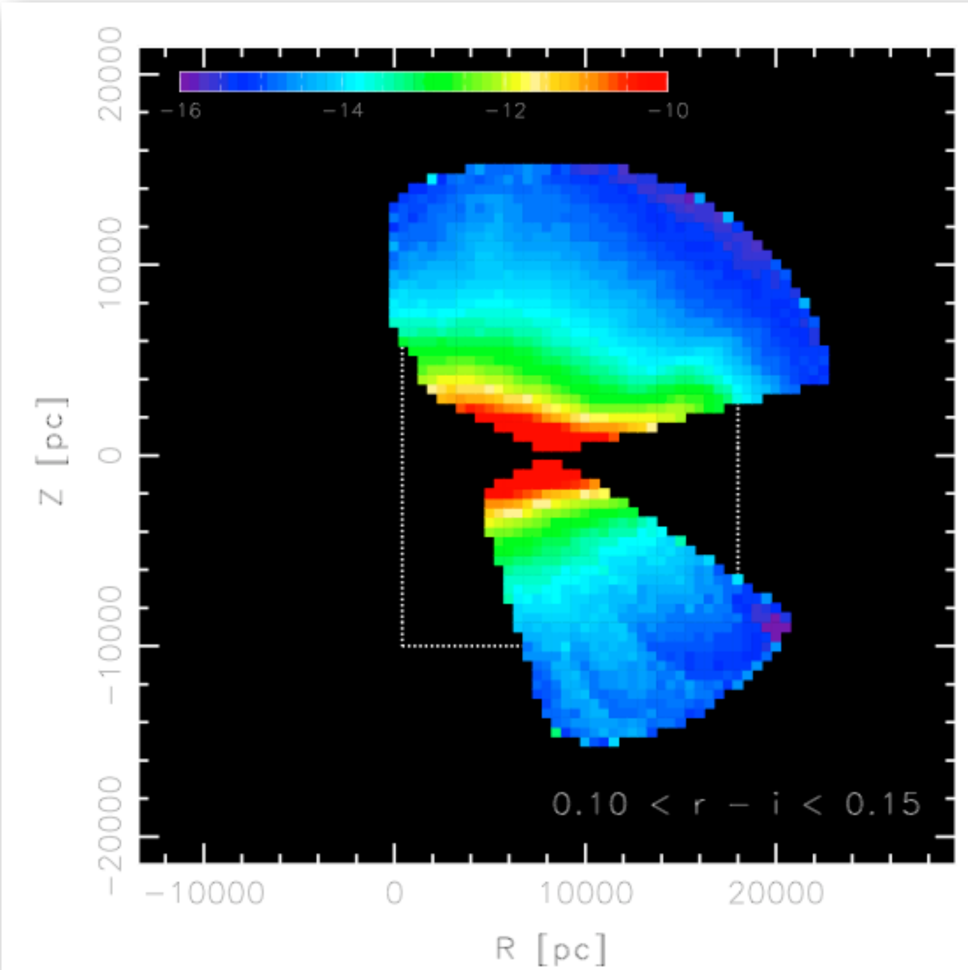


Bell et al. 2007



Bullock, Kravtsov, & Weinberg 2001
JSB & Johnston 05; Robertson et al. 05; Font et al. 05, 06; Johnston, JSB et al. 07

SDSS Tomography of the Milky Way Disk



Juric et al. 05, Newberg et al. 06

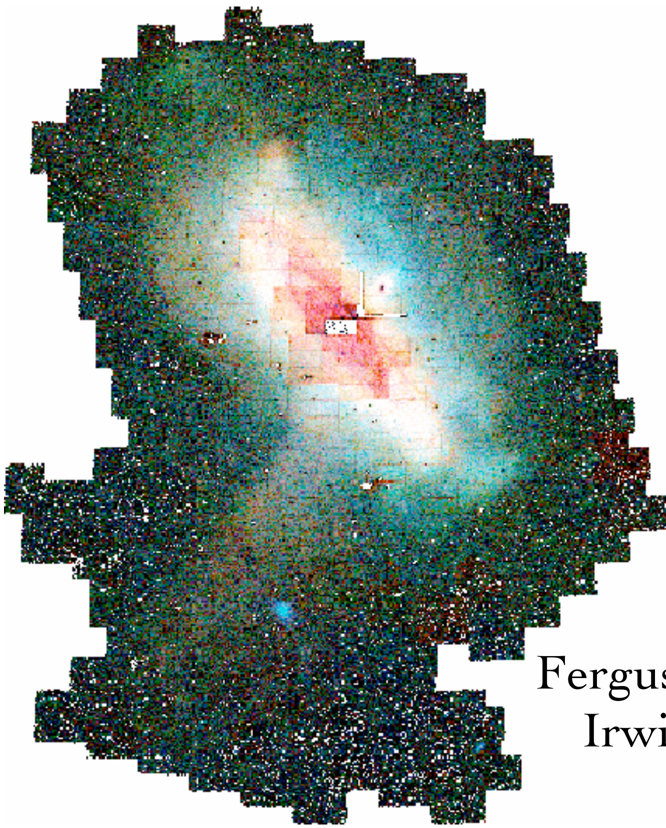
- Outer edges of thick disk disturbed...
- Smooth fitting functions break down...

Also structures in MW thick disk:

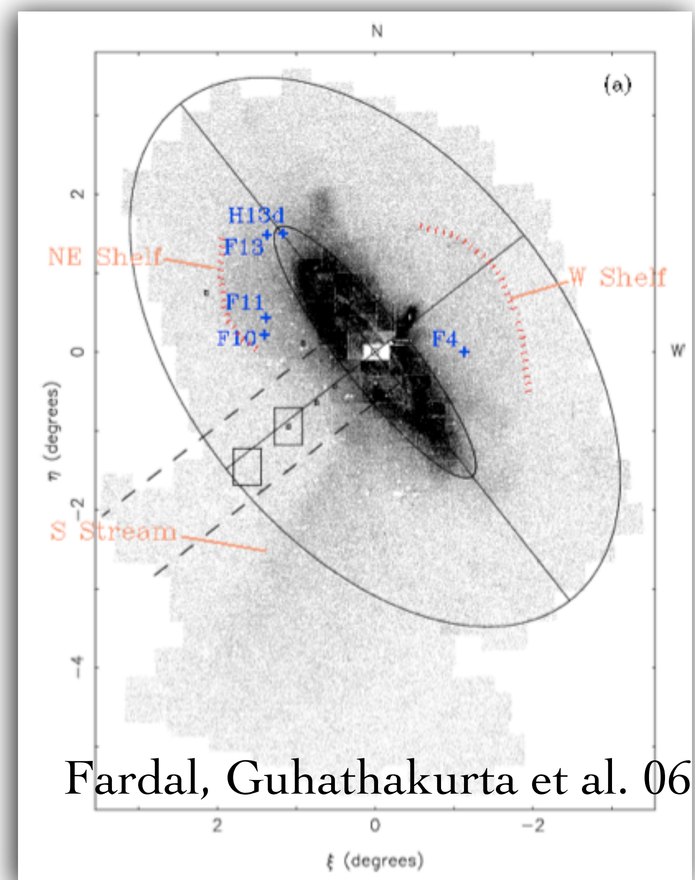
Eggen 96; Gilmore et al. 02; Wyse et al. 06; Helmi et al. 06

M31

Diffuse structure in M31 halo...



Ferguson et al.,
Irwin et al.



Fardal, Guhathakurta et al. 06

R~40 kpc disk-like configuration of stars:

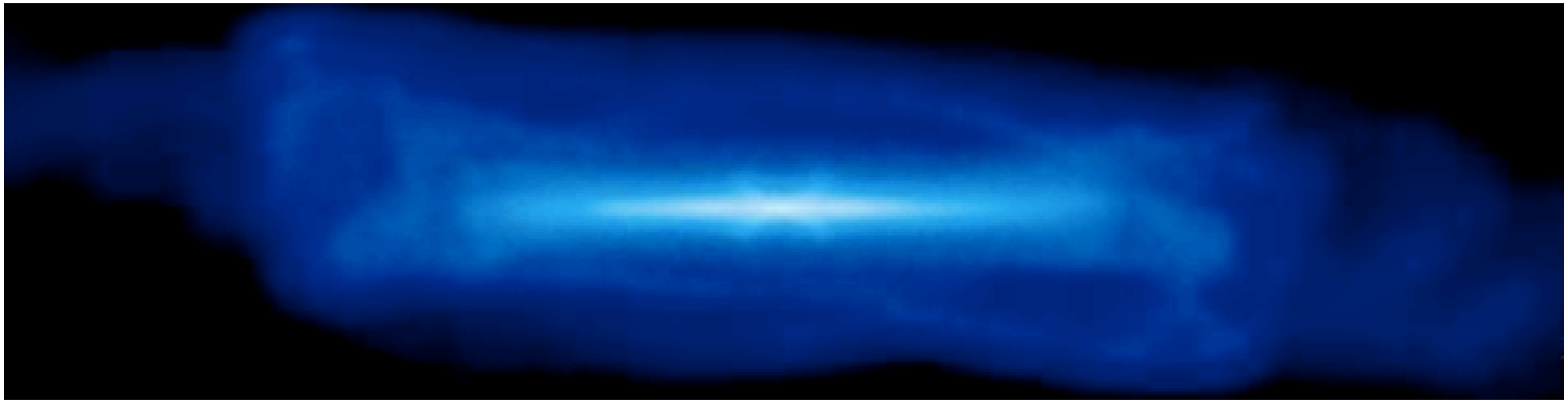
- ~30 km/s velocity dispersion
- Lags thin disk rotation by ~40 km/s
- Intermediate age stars (~ thick disk)

Ibata et al. 05
Brown et al. 06

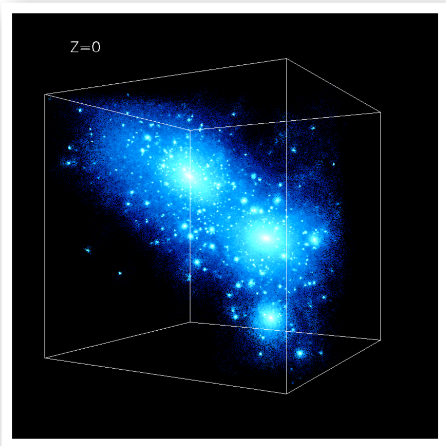
Disk Response to Infalling Dark Halos

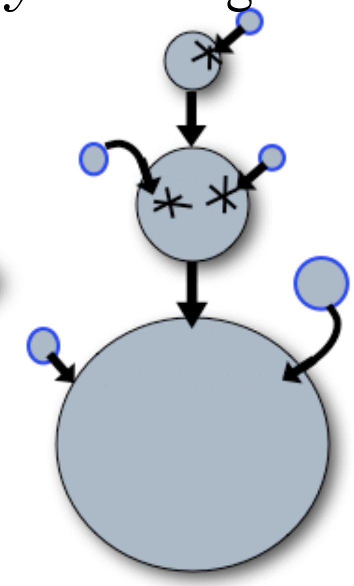
Kazantzidis, JSB, Zentner, Kravtsov, Moustakas

astro-ph/07



1. Extract Merger History from high-resolution N-body simulations

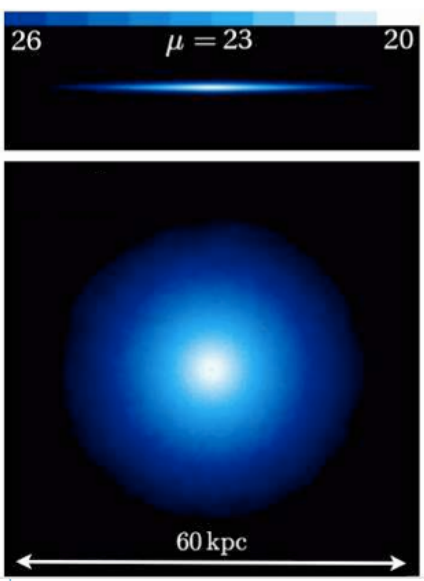




Klypin et al. 01
Kravtsov et al. 04
Zentner et al. 05

2. Initialize well-resolved MW-type disk

Widrow & Dubinski 05



$h = 250$ pc

$R_d = 2.8$ kpc

$f_{res} \sim 50$pc

$N_{dm} = 2.10^6$

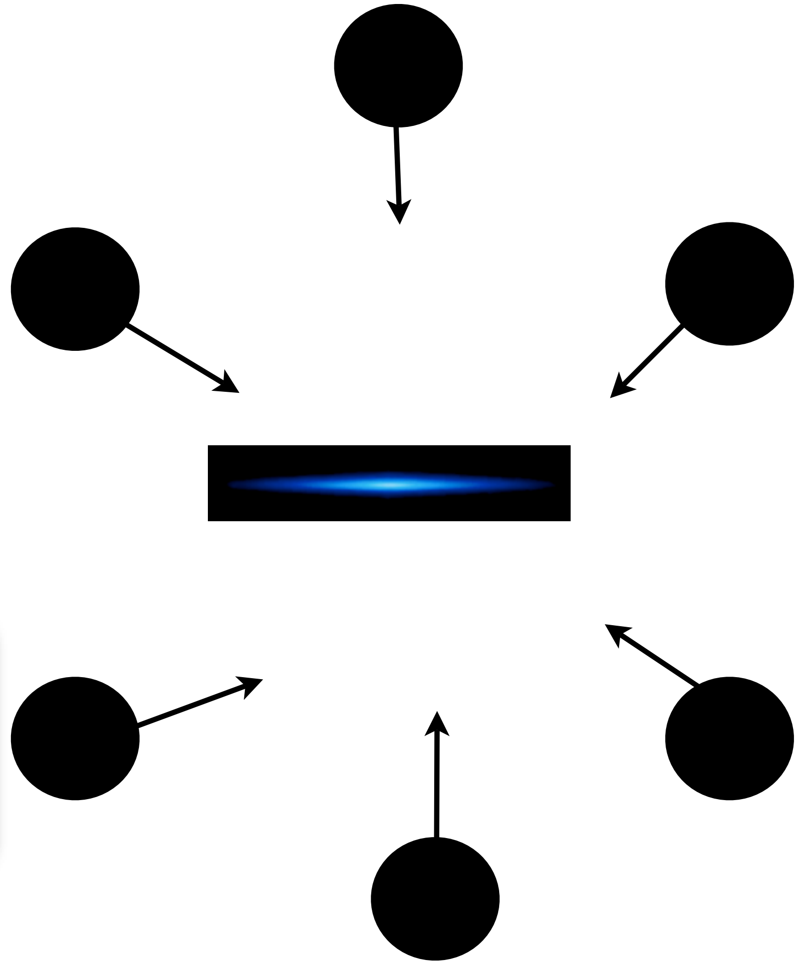
$N_{disk} = 10^6$

$N_{bulge} = 5.10^5$

$N_{sat} = 5.10^5$

3. Simulate impacts with M ~ (0.2-0.6) M_{disk}~(0.7-2) x 10^{10} M_{sun}.
Use Orbits, Masses, Density Profiles measured as they cross within 50 kpc.

Model	z	t (Gyr)	M_{sat} ($10^{10} M_\odot$)	V_{peak} (km s^{-1})	r_{peak} (kpc)	r_{tid} (kpc)
(1)	(2)	(3)	(4)	(5)	(6)	(8)
G1S1	0.96	7.6	1.14 (32.6%)	42.4	6.9	24.8
G1S2	0.89	7.3	1.98 (56.6%)	59.8	8.1	21.5
G1S3	0.54	5.3	1.48 (42.3%)	50.3	7.6	23.0
G1S4	0.32	3.6	1.57 (44.8%)	42.2	4.1	19.6
G1S5	0.20	2.4	0.75 (21.4%)	41.5	5.7	27.3
G1S6	0.11	1.4	0.73 (20.9%)	39.8	3.7	23.2



Note:
Ignore 2 largest (~5-10 x 10^{10} M_{sun}) substructures to be conservative.

3. Simulate Impacts of all Substructures with M>0.2Mdisk.
Use Orbits, Masses, Density Profiles etc. from Simulation.

Model	z	t (Gyr)	M_{sat} ($10^{10} M_\odot$)	V_{peak} ($\mathrm{km\,s^{-1}}$)	r_{peak} (kpc)	r_{tid} (kpc)
(1)	(2)	(3)	(4)	(5)	(6)	(8)
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G1S2	0.89	7.3	1.98 (56.6%)	59.8	8.1	21.5
G1S3	0.54	5.3	1.48 (42.3%)	50.3	7.6	23.0
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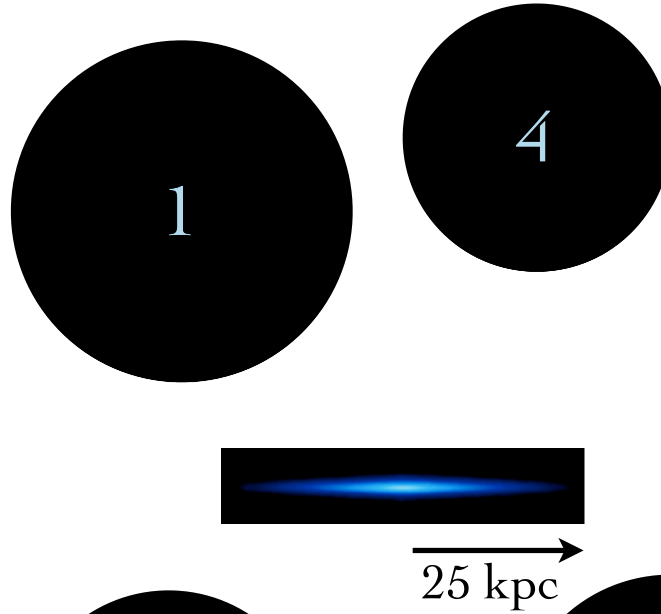
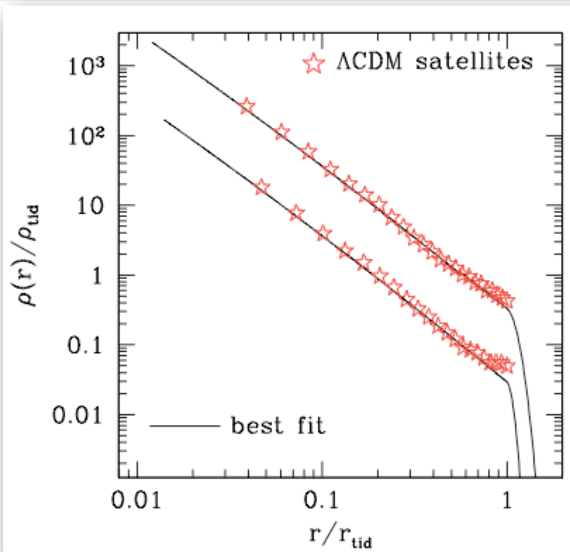
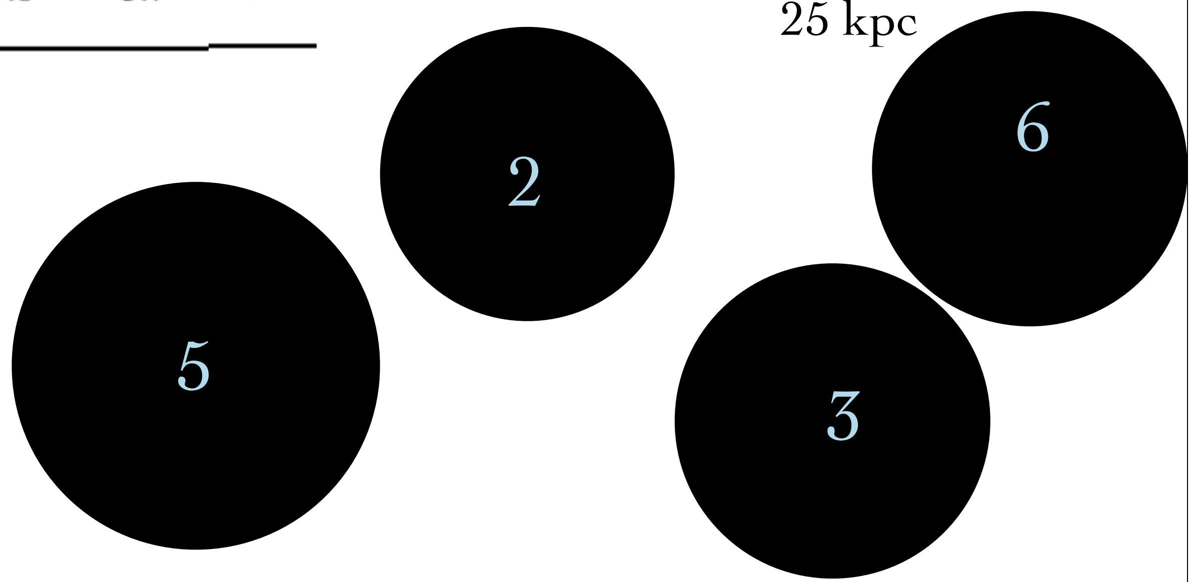




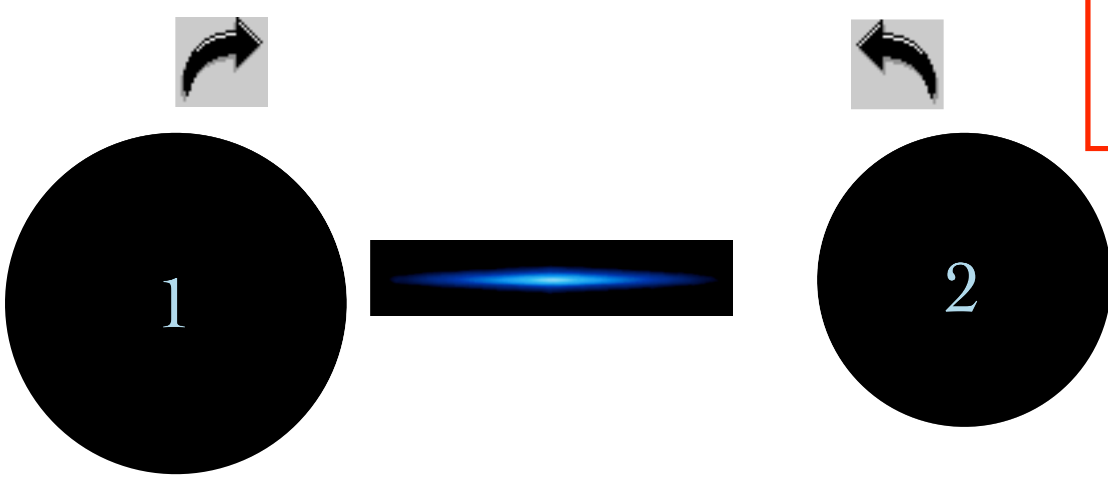


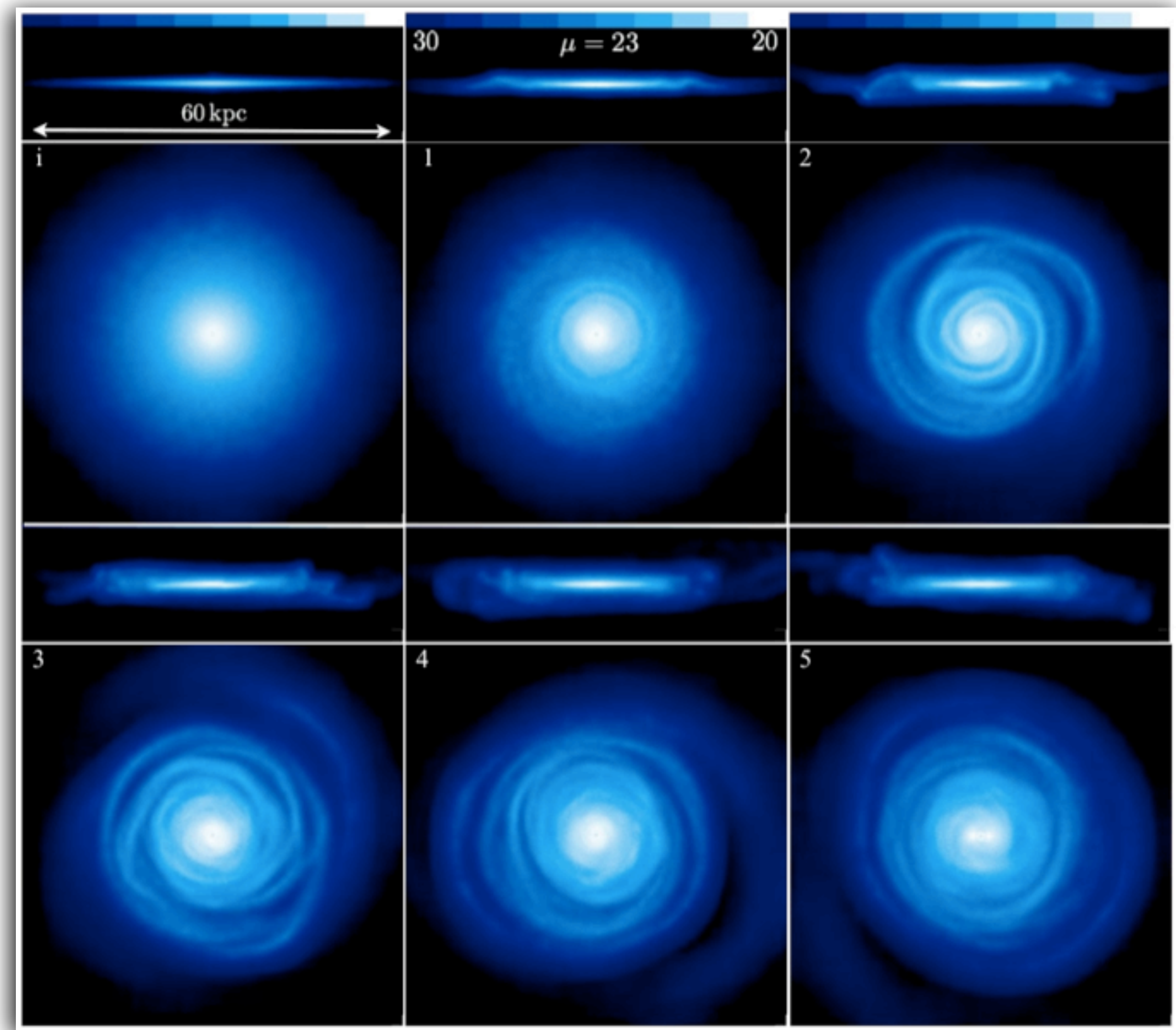
Prograde, retrograde, & polar orbits

Model	z	t (Gyr)	M_{sat} ($10^{10}M_\odot$)	V_{peak} ($\mathrm{km\,s^{-1}}$)	r_{peak} (kpc)	r_{tid} (kpc)	r_{peri} (R_d)	r_{apo} (R_d)	θ (°)
(1)	(2)	(3)	(4)	(5)	(6)	(8)	(9)	(10)	(12)
G1S1	0.96	7.6	1.14 (32.6%)	42.4	6.9	24.8	2.6	17.7	93.3
G1S2	0.89	7.3	1.98 (56.6%)	59.8	8.1	21.5	2.6	15.7	86.6
G1S3	0.54	5.3	1.48 (42.3%)	50.3	7.6	23.0	6.2	19.8	45.1
G1S4	0.32	3.6	1.57 (44.8%)	42.2	4.1	19.6	0.5	10.3	59.9
G1S5	0.20	2.4	0.75 (21.4%)	41.5	5.7	27.3	3.7	34.3	117.7
G1S6	0.11	1.4	0.73 (20.9%)	39.8	3.7	23.2	1.1	21.6	144.5

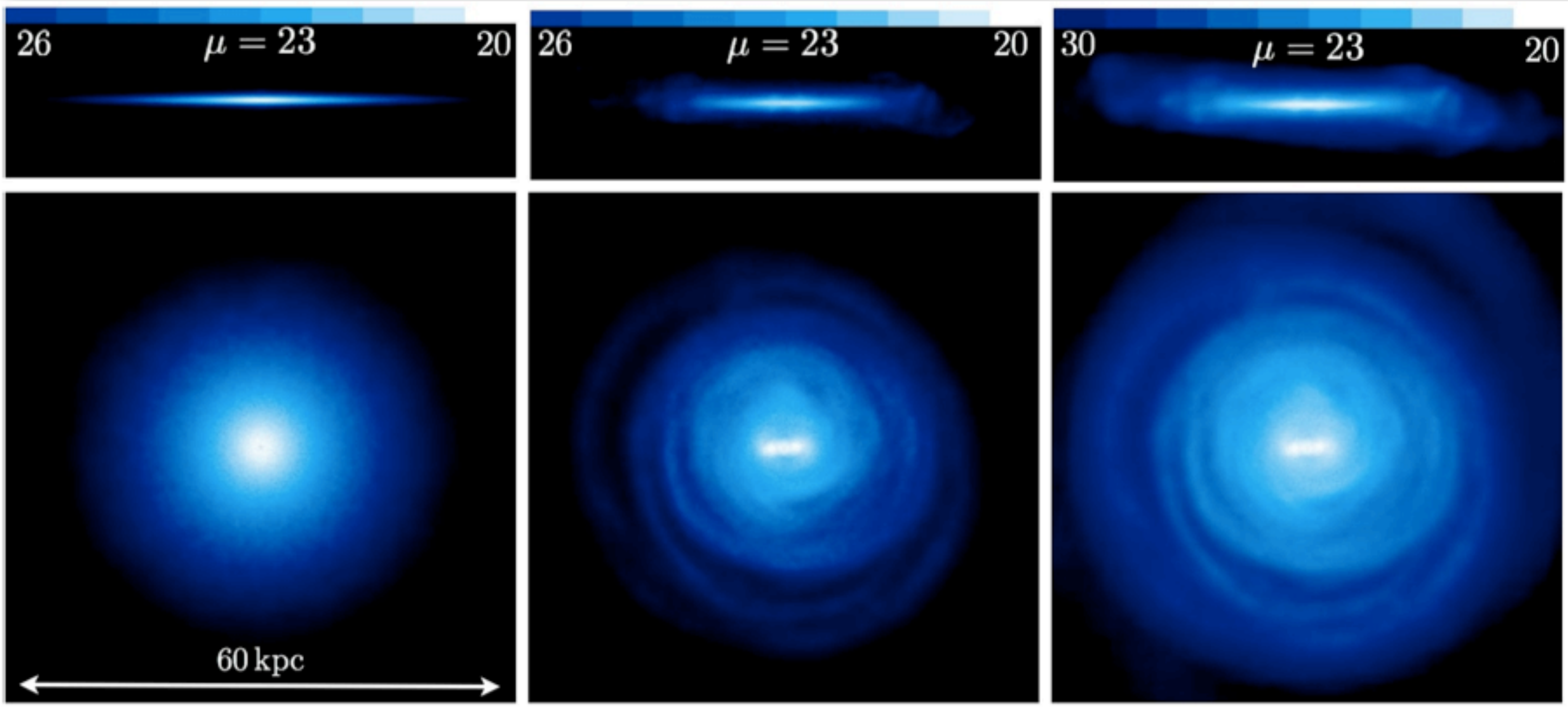
Prograde ($<90^0$) and retrograde ($>90^0$) orbits.

Impacts are generally quite radial, with max to min radii > 6:1



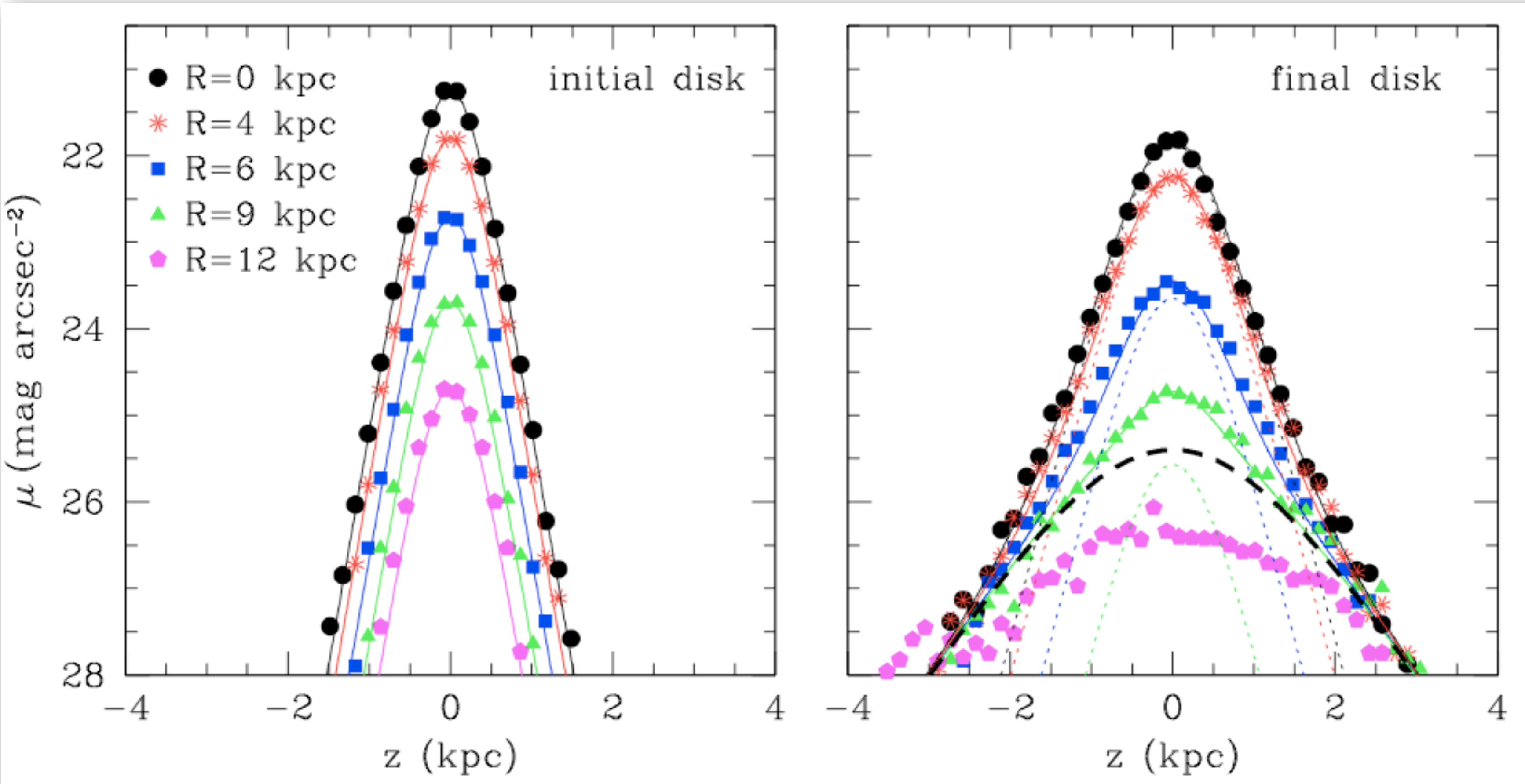

30
$\mu = 23$
20
60 kpc
i
1
2
3
4
5

Initial disk Final disk Final disk (deep)



Kazantzidis, JSB, Zentner, Kravtsov, Moustakas 07

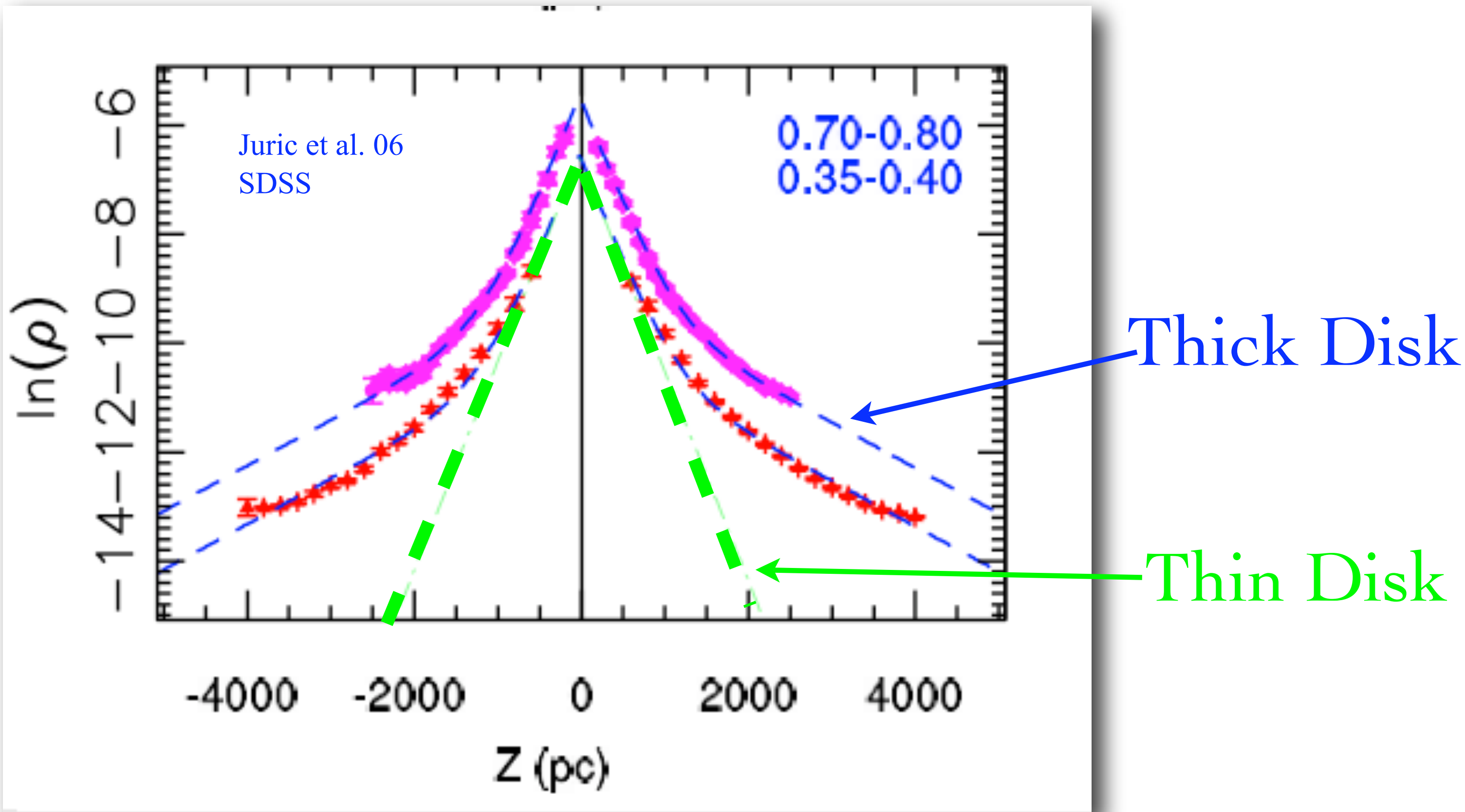
Thin+thick disk



MW Disk(s): Thin + Thick

- Thin vertical scale height, ~250pc, + thick disk component ~2.4kpc

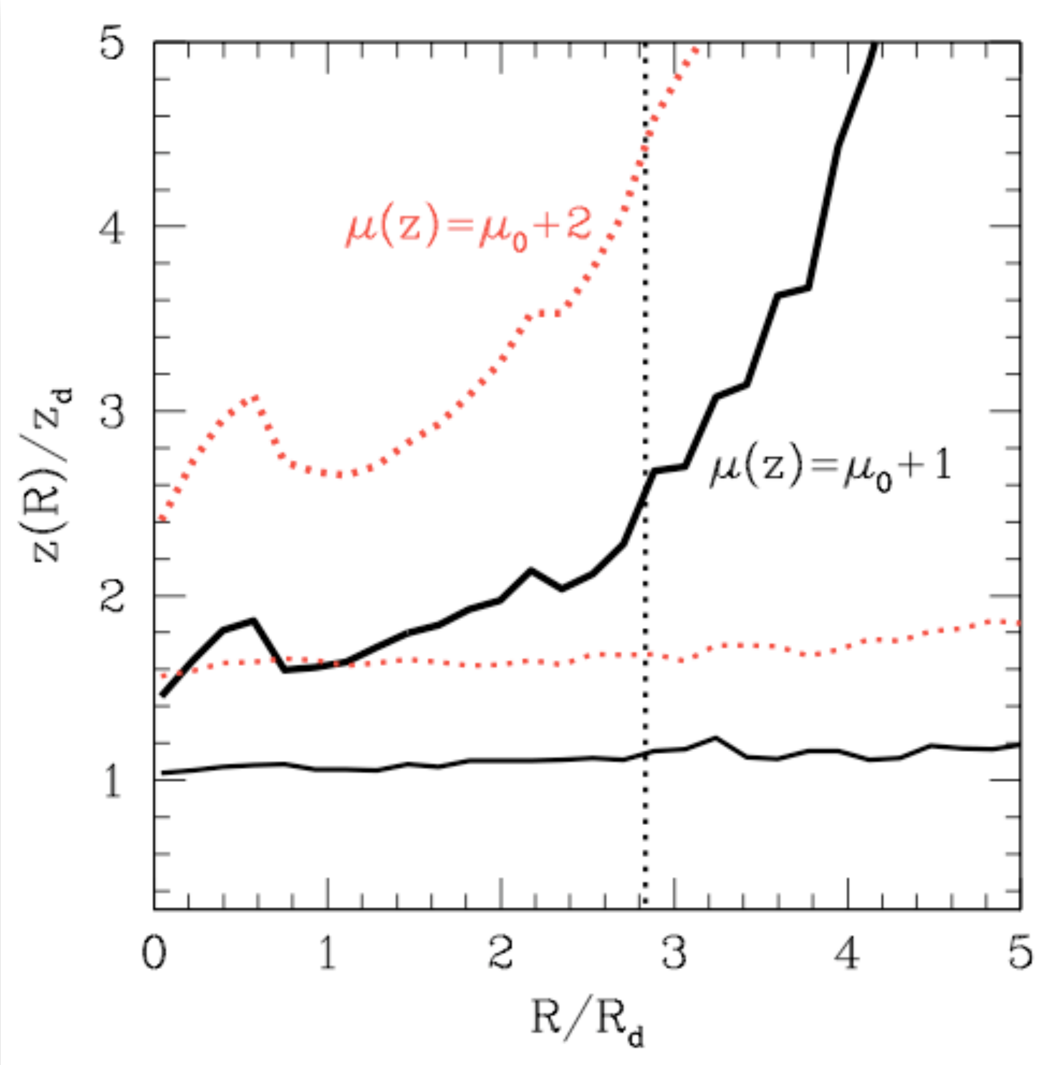
Kent et al. 1991; Freudenreich 1998; Dehnen & Binney 1998; Vallenari et al. 2000;



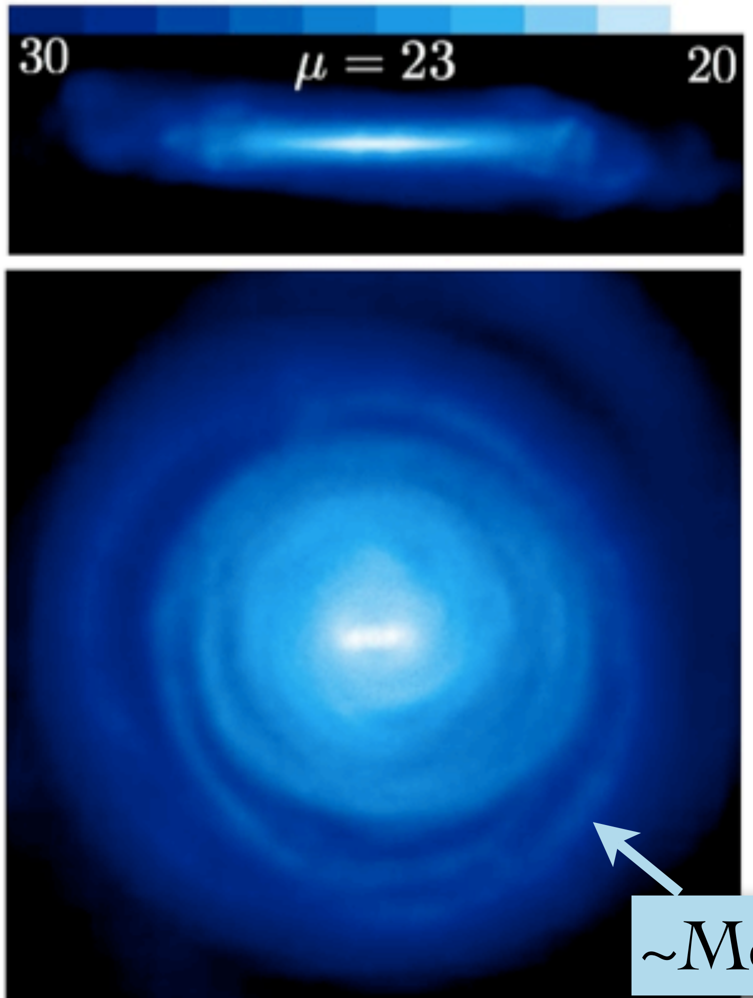
Flare

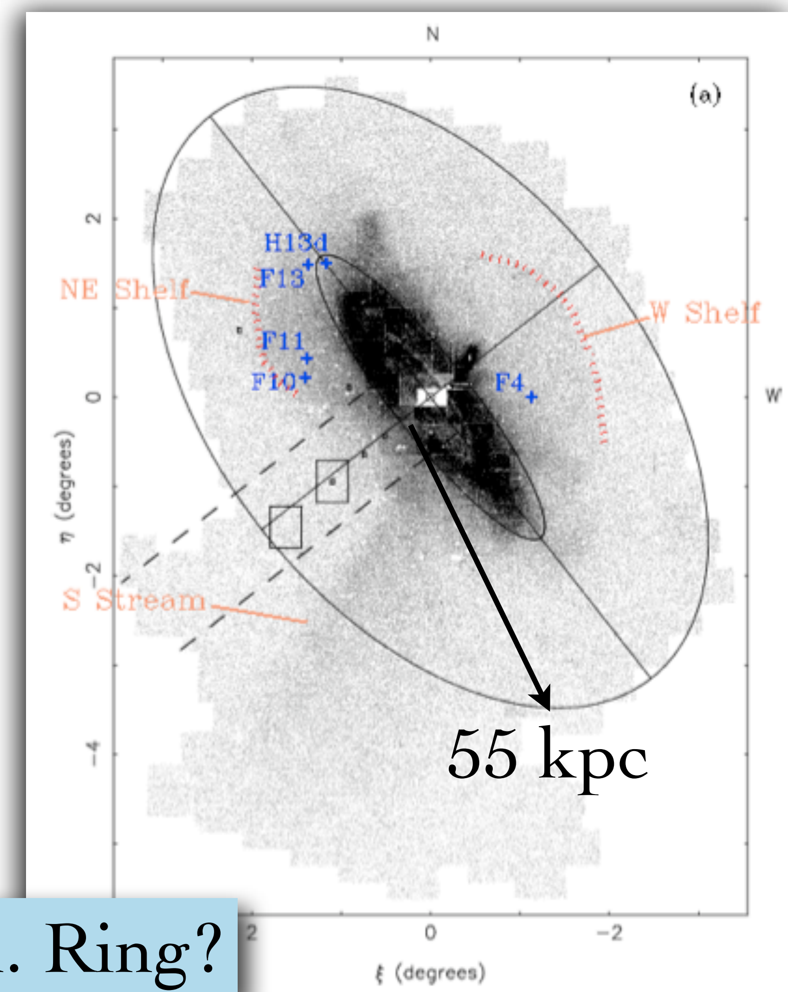
$$\Delta z(R) \propto \frac{\Delta e_z}{\Sigma_d(R)[\alpha\Sigma_d(R) + 2z(R)\beta\bar{\rho}_s(R)]}$$

$$\Delta z \sim \Sigma_{\rm disk}^{-2}$$



Interesting faint structures: ring, flare, loops



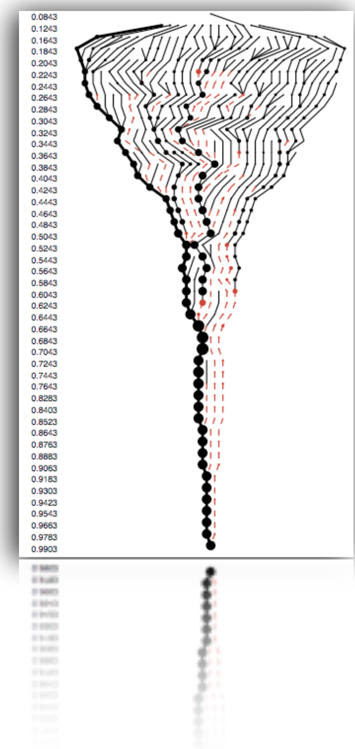


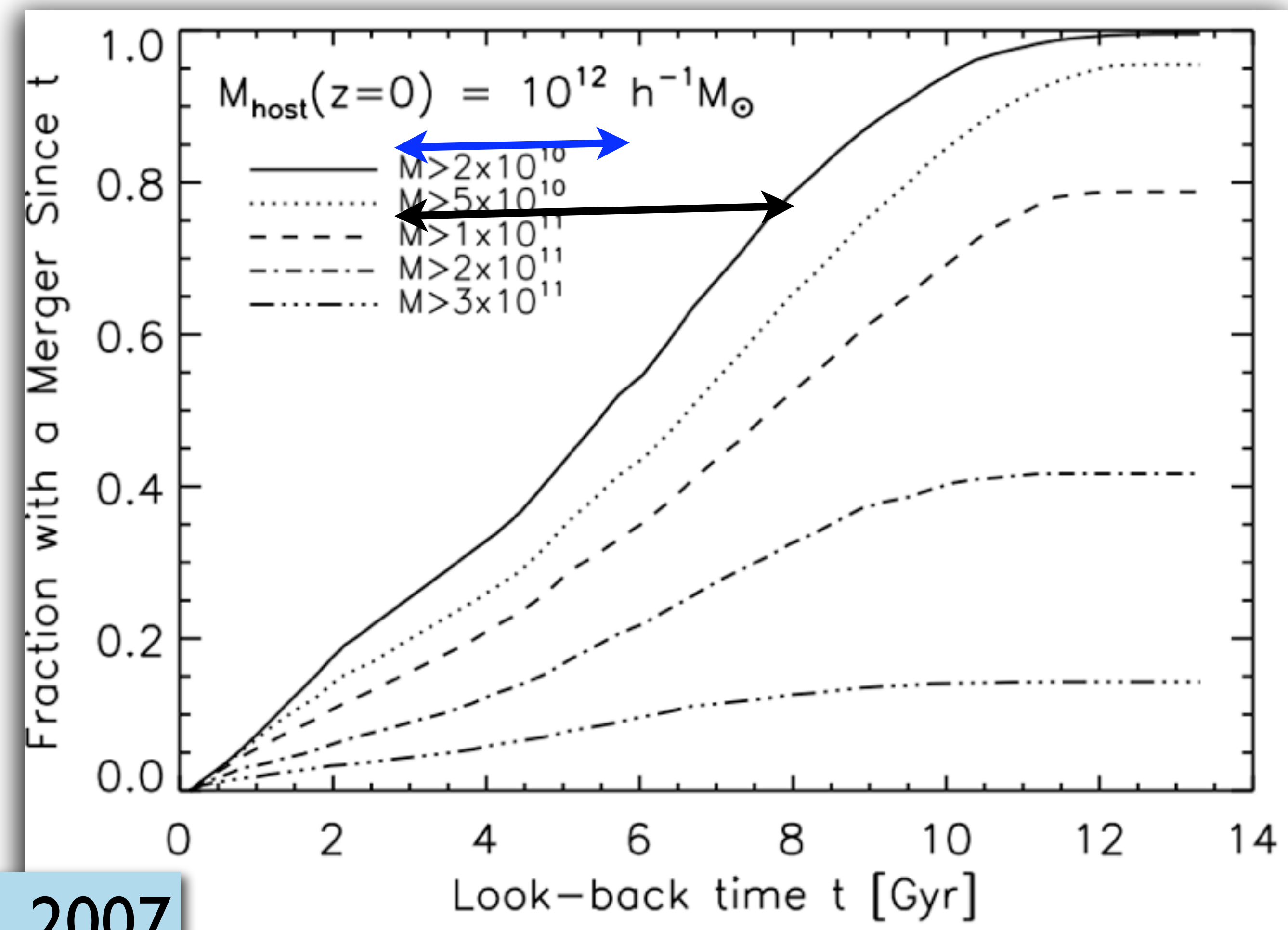
~Mon. Ring?

60 kpc

CENTER FOR COSMOLOGY

Worry: Largest impact was ~2.10^{10} M_{sun}
~70% MW halos have a 10^{11} M_{sun} merger in last 10 Gyr



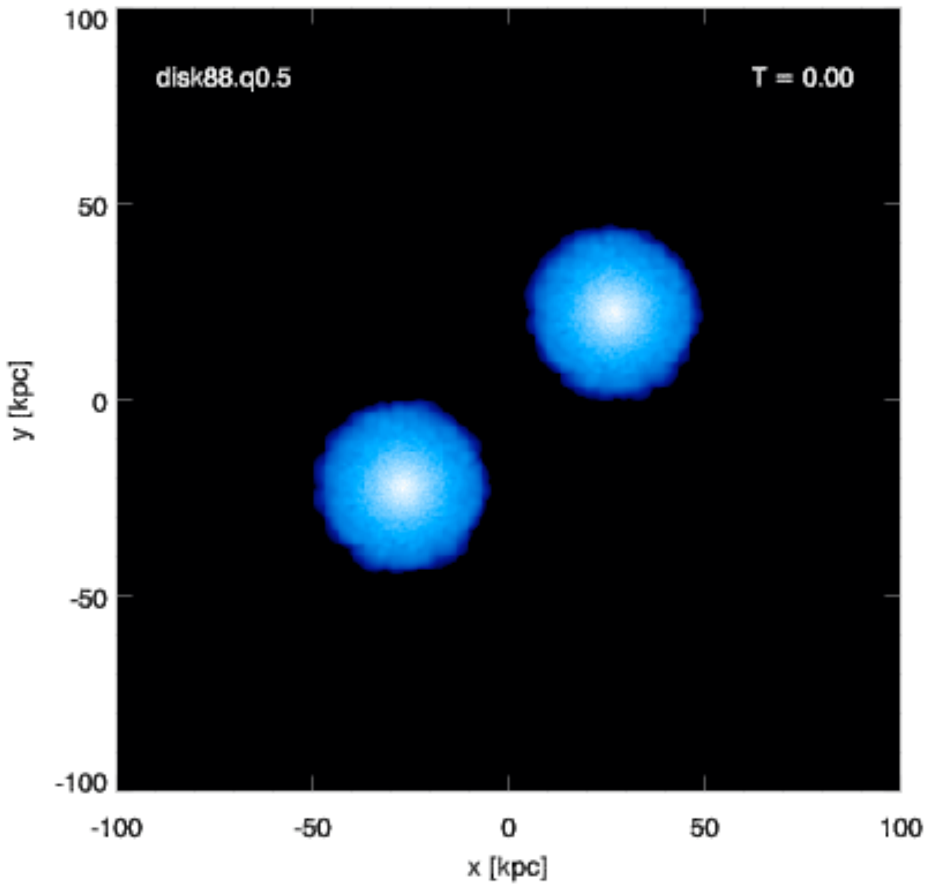


Stewart et al. 2007

A way out?

"A merger-driven scenario for cosmological disk galaxy formation"

Robertson, JSB **et al. 06**

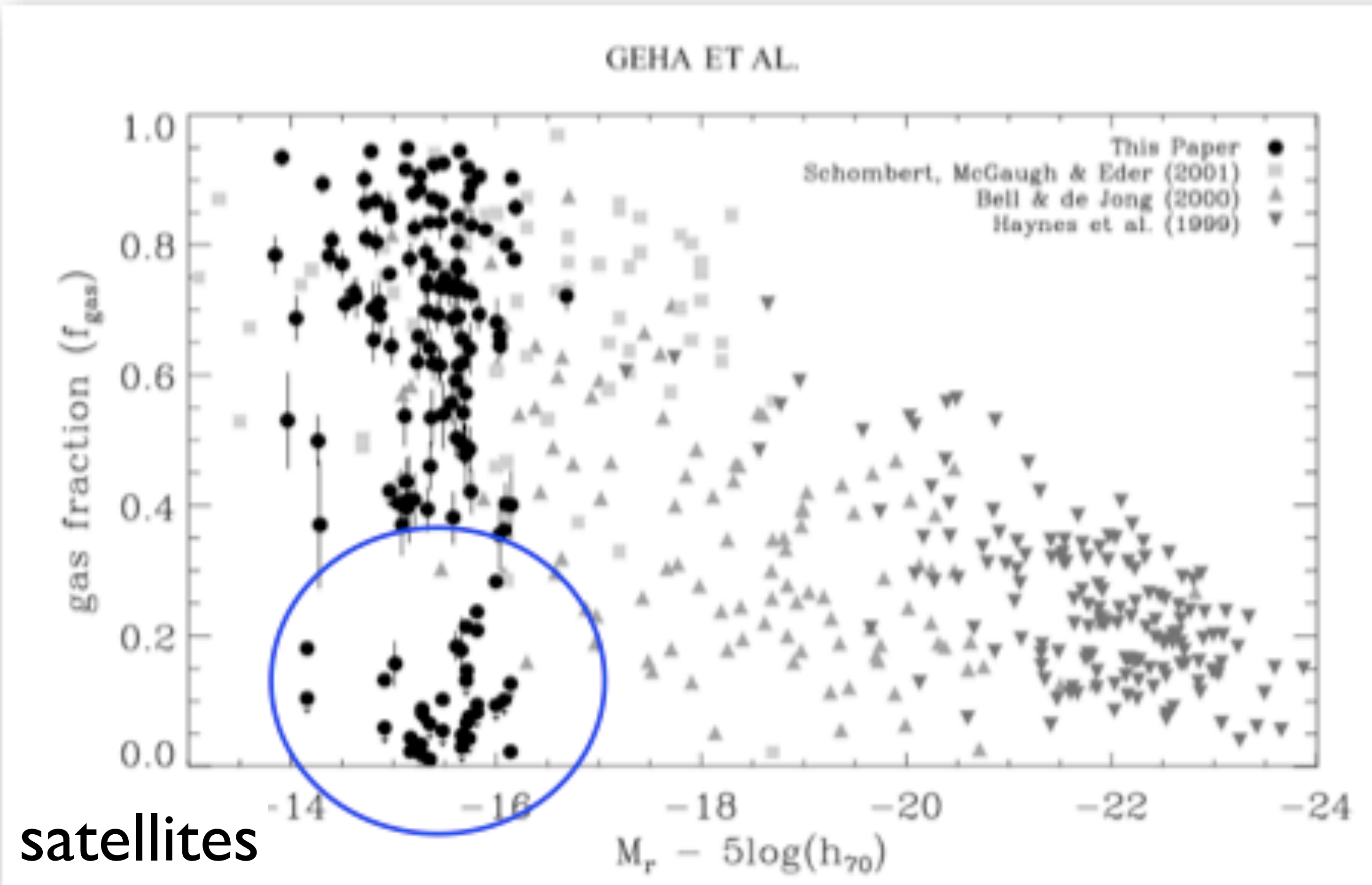


Proof of principle:

- Mergers common in CDM halos & important in j-acquisition
- Stellar mergers make spheroids,destroy disks (Quinn et al. 93, Walker et al. 96)
- What about gas-rich mergers?

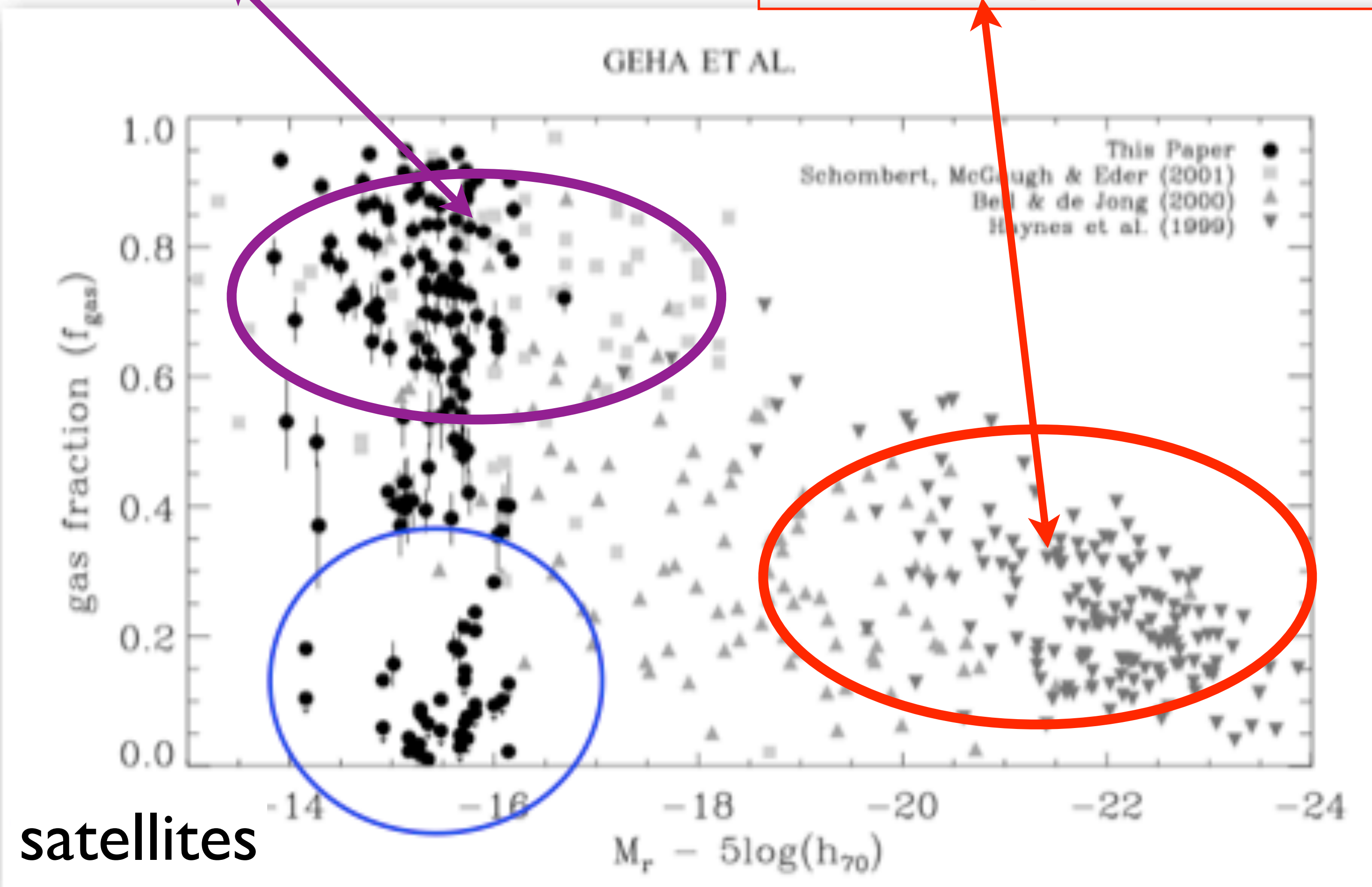
High gas fractions + efficient ISM feedback can allow disks to form from mergers

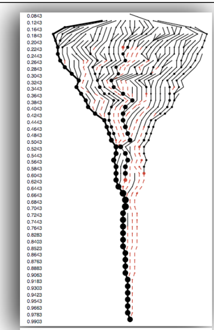
Small galaxies: more gas rich than big ones



Small, gas-rich galaxies merge to make disks?

larger, gas poor galaxies merge & produce spheroids?





Take Home Messages

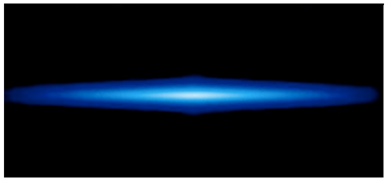
- ~70% MW-size halos have a $m=10^{11}\ h^{-1}M_{sun}$ merger in last 10Gyr
- ~95% MW-size halos have at least one $m = 5.10^{10}\ h^{-1}M_{sun}$ merger
- More simulations necessary to test whether this is as bad as it seems.

larger than **current** mass of MW disk

- Smaller, $\sim 2.10^{10}\ M_{sun}$ events, may not be as ruinous as previously suspected.
- Gas rich mergers may provide an explanation. Or CDM is in trouble....

Conclusions

- ~70% of MW-size halos accrete objects that are significantly larger than MW disk

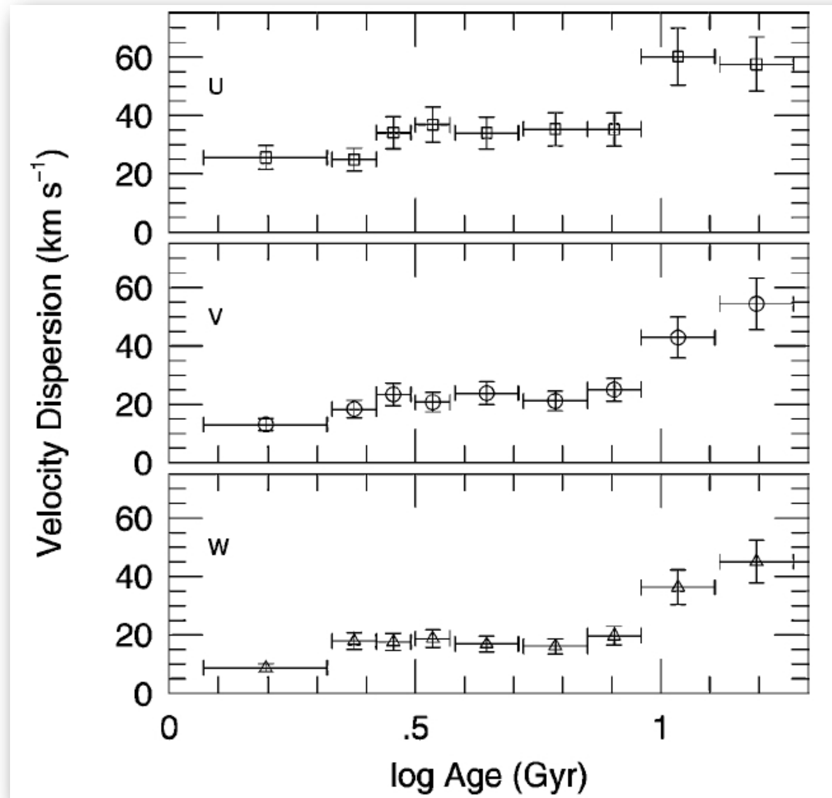


The Milky Way

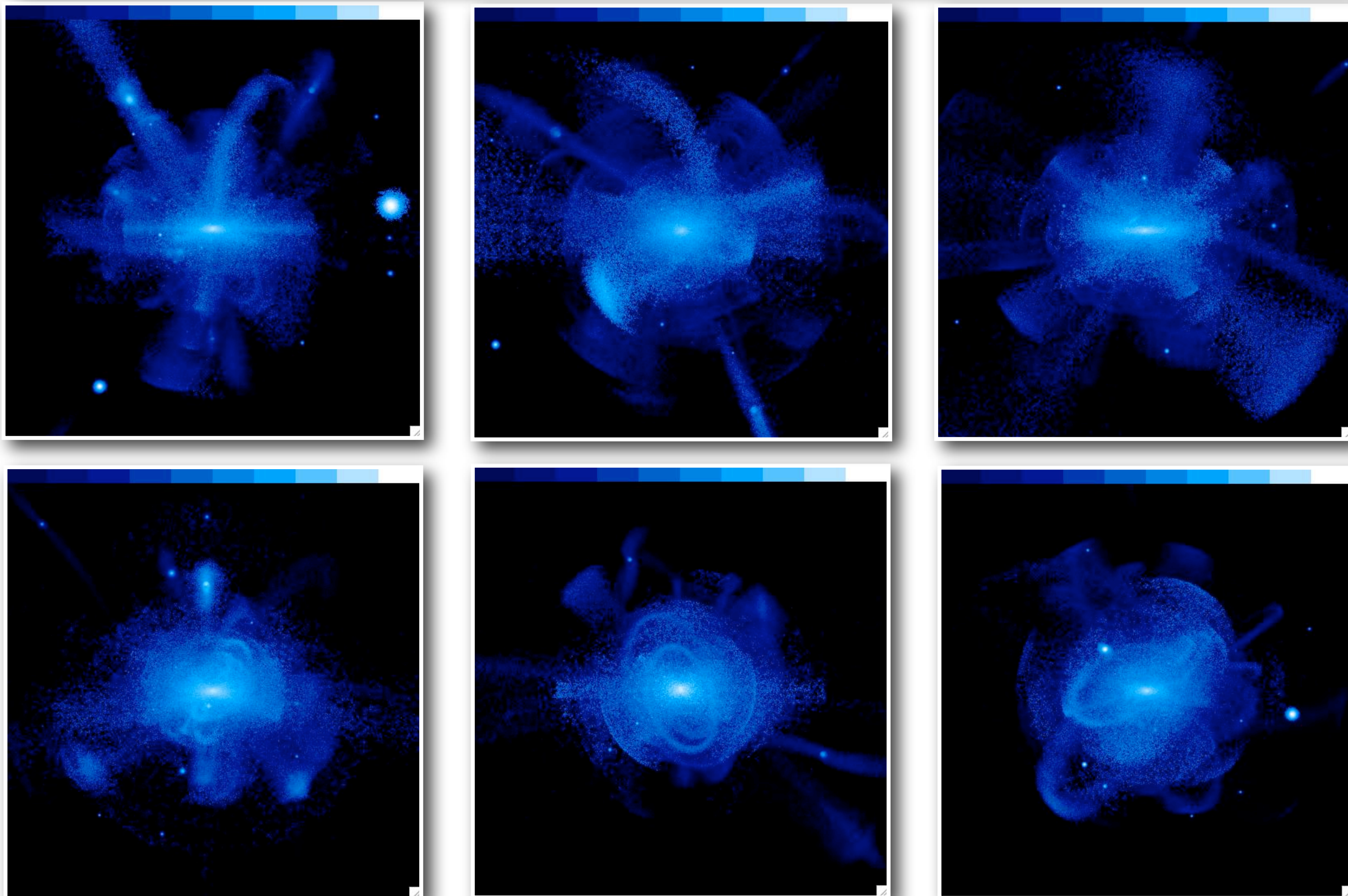
- Thin disk contains old stars ~10Gy.

  Quillen & Garnet 2000; Freeman & Bland-Hawthorn 2002)
  Nordstrom et al. (bigger sample) 2004

- Is such a configuration possible given a typical merger history?



JSB & Johnston 05; Font et al. 05, 06; Robertson et al. 05; Johnston, JSB et al. 07



Cohn & White 07