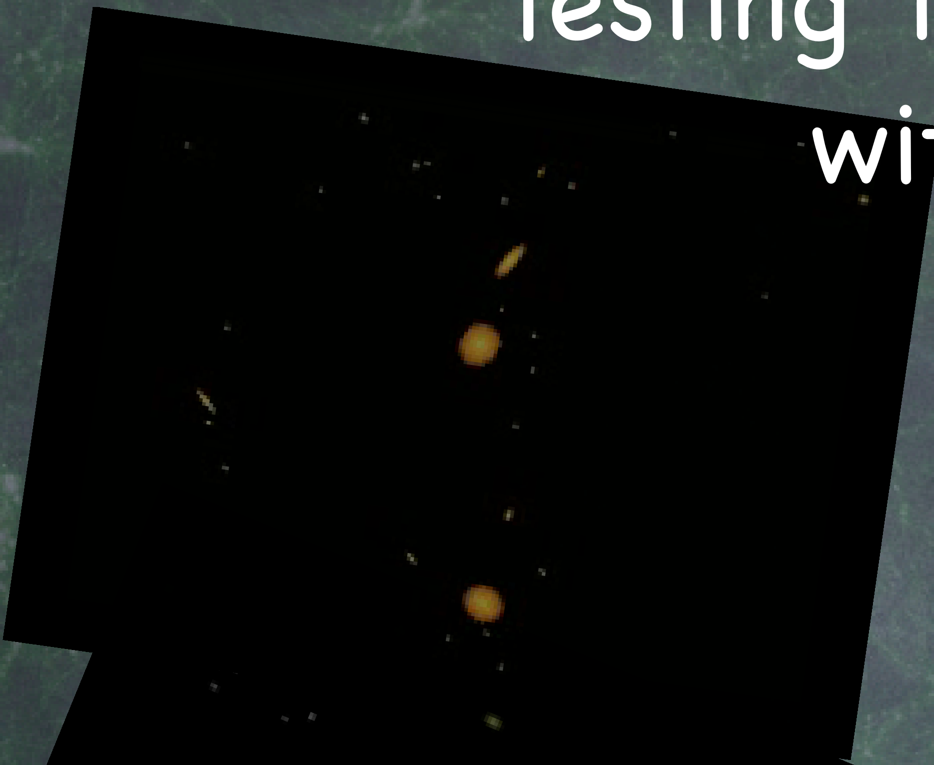
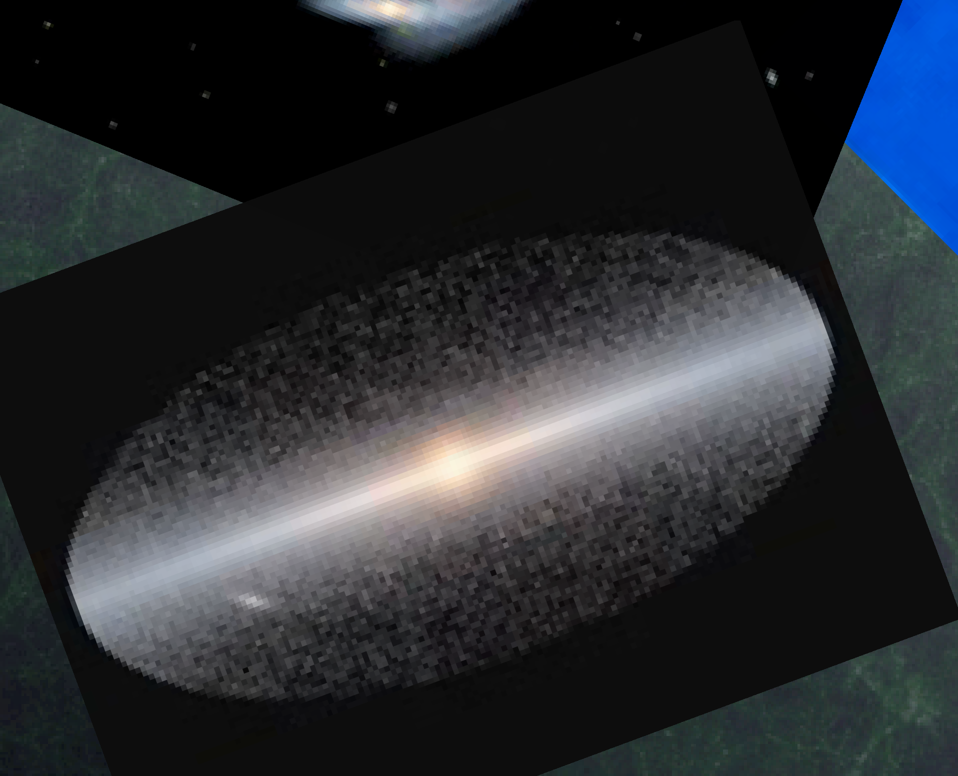
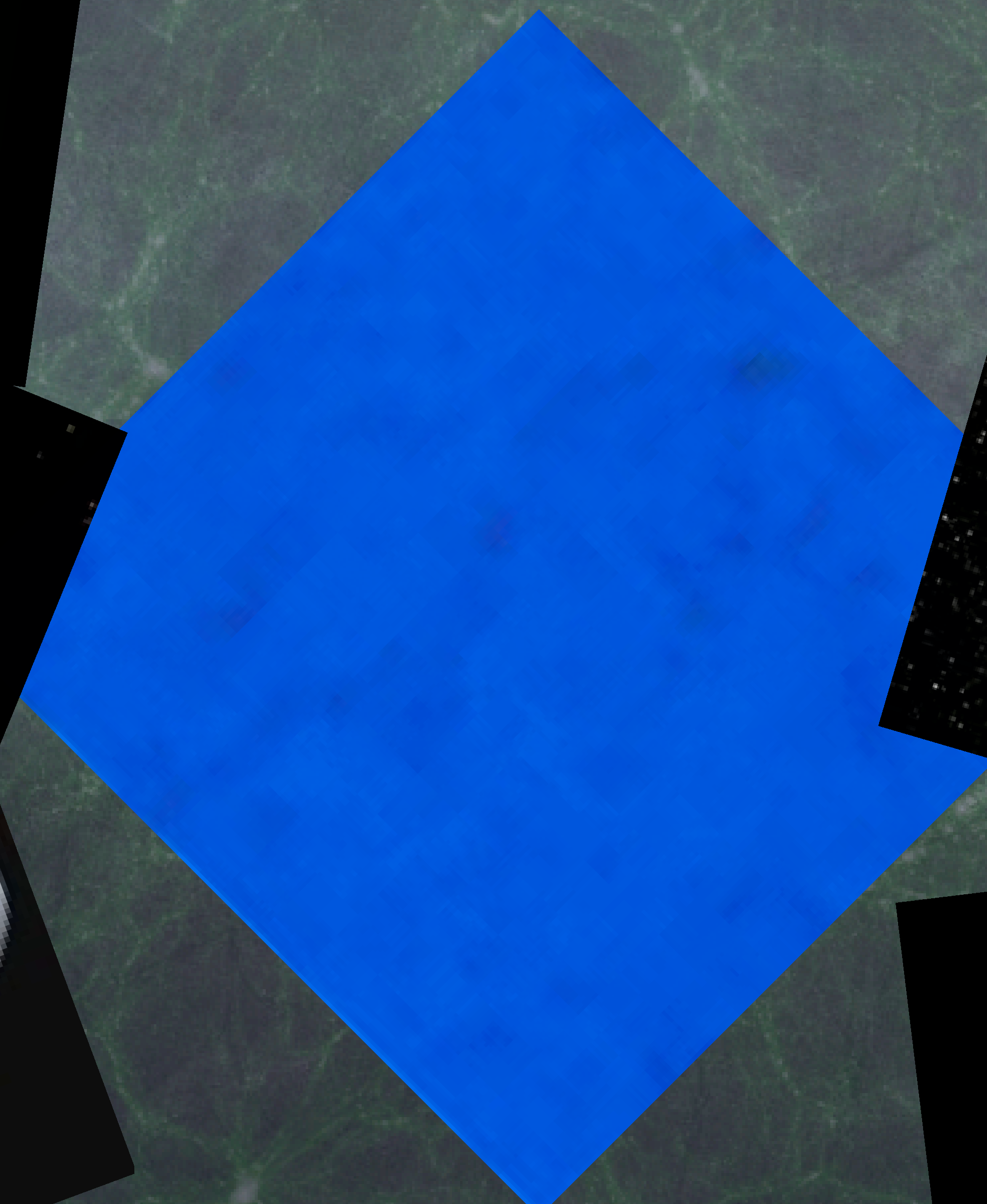
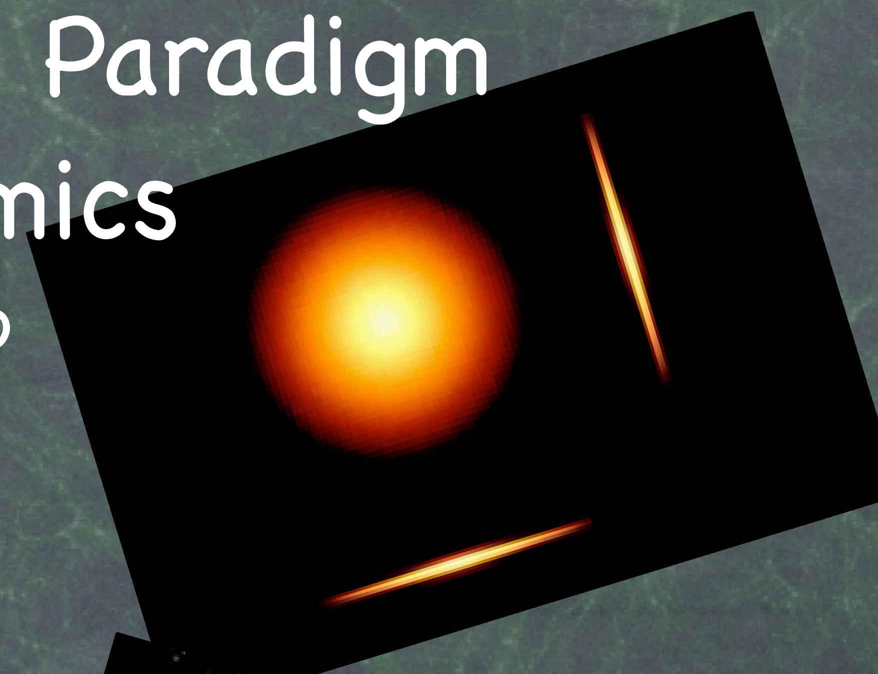
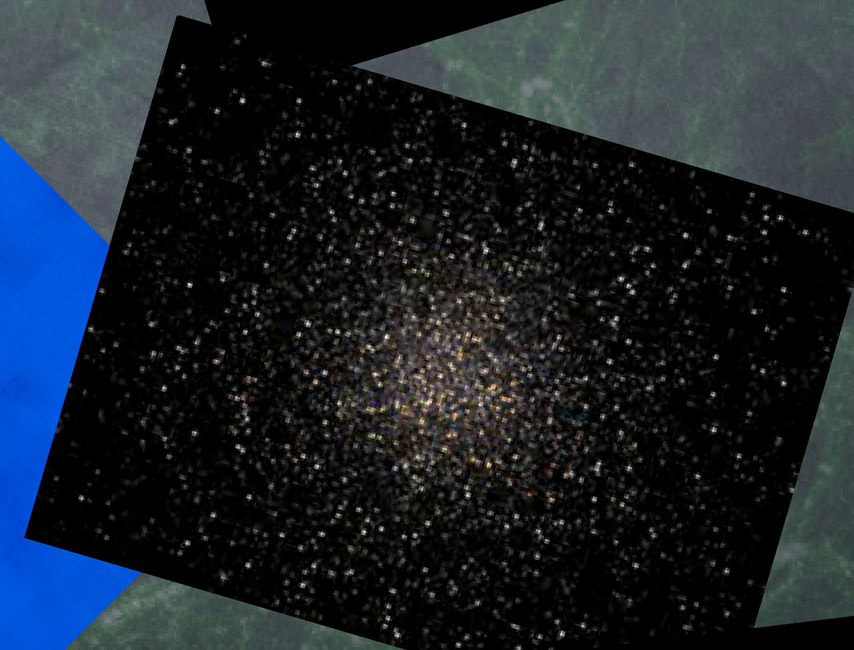
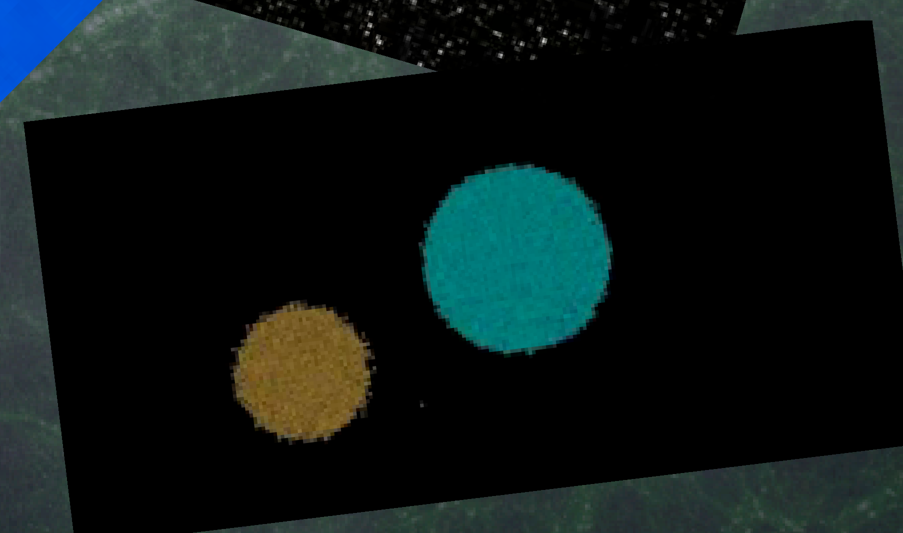
A Universe in Motion: Testing the Cosmological Paradigm with Galaxy Dynamics

John Dubinski, Toronto



Outline

- Cosmology and galaxy dynamics
- Tools of the trade and computational challenges
- Case Studies:
  - Triaxial halos and disk dynamics
  - Interactions and mergers within clusters
- Movies

Convergence of the Cosmological Model

- Cold dark matter plus dark energy model established with accurate cosmological parameters
- Power spectrum of density fluctuations specifies the initial conditions
- Following Kuhn's theory of scientific revolutions, we now have an established paradigm that is being examined for flaws
- Galaxy dynamics is one test

Cosmology and Galaxy Dynamics: N-body perspective

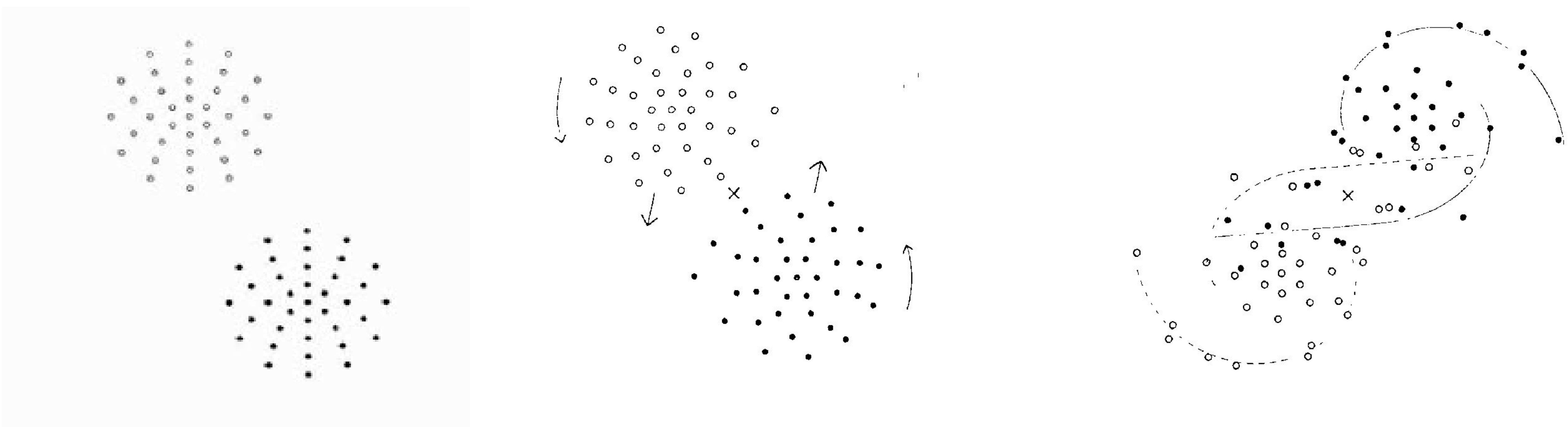
- Galaxies form in the collapse of gas and dark matter within the cosmological framework
- Stars form within disks embedded within dark halos and settle into orbits along with the dark matter in equilibrium configurations
- Are the observed structure and kinematics of galaxies consistent with the CDM paradigm?

Some Dynamical Issues

- Consistency of density profiles and rotation curves - cusp problem
- Bar-halo interactions - dynamical friction and pattern speeds
- Triaxial halos - non-circular orbits, misalignments and warps, tumbling halos, elliptical galaxy shapes
- Galaxy interactions and mergers within clusters

N-body Codes
From N=1 to 10 billion in 400 years!

Holmberg's table top simulation of a galaxy collision



Light bulbs, photometers, and lab books
37-particle galaxies – Gaussian surface density distribution
First attempt to model galaxy interactions!

Advances in N-body Simulation

- Moore's law - the N-body simulator's friend
- Direct N-body solver hardware - GRAPE
- O(N log N) poisson solvers - speed at the expense of accuracy
    - particle-mesh, treecodes, multipole expansion methods (field codes) and hybrids
- Parallel supercomputing - where it's at!

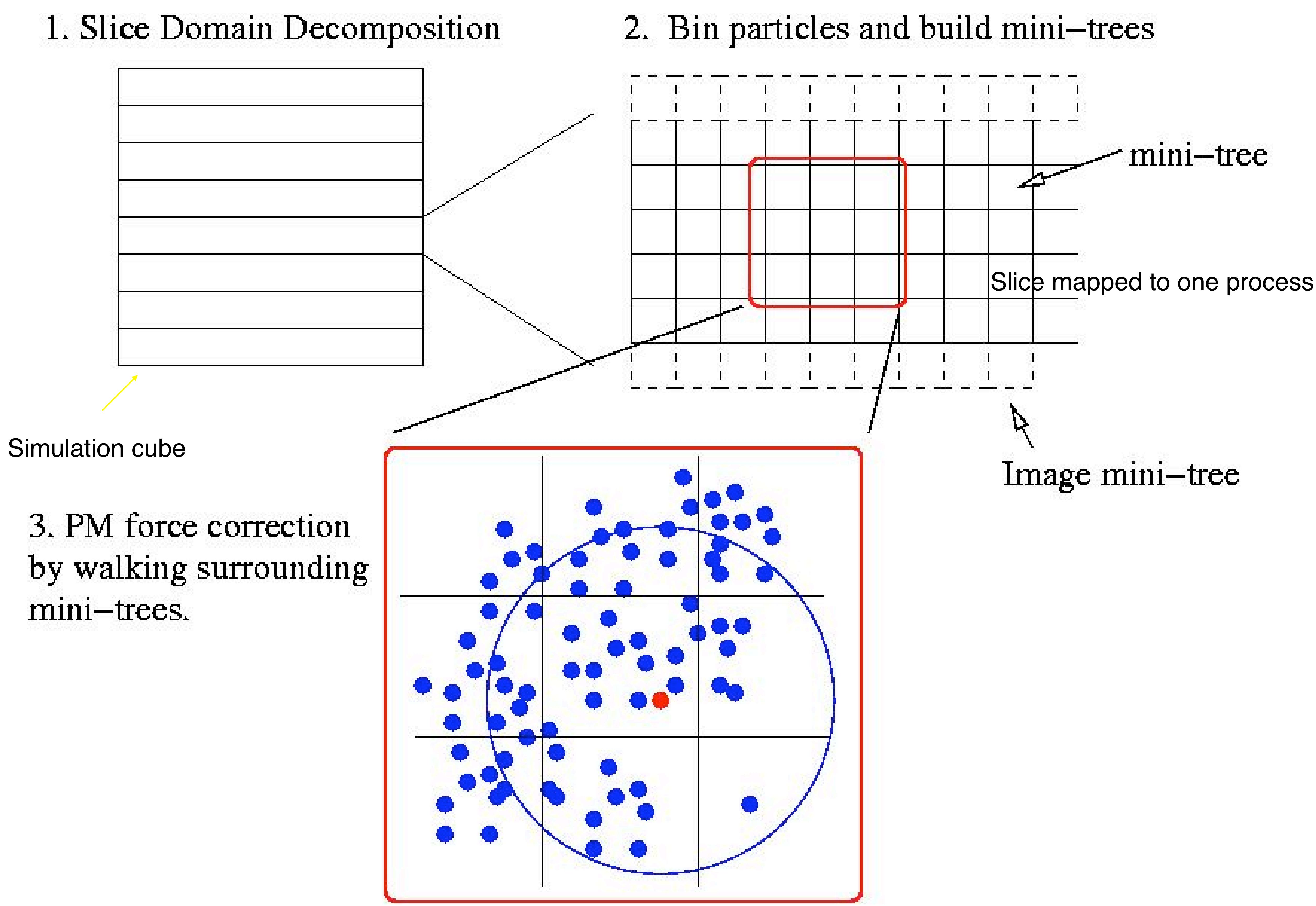
Cosmological Simulations

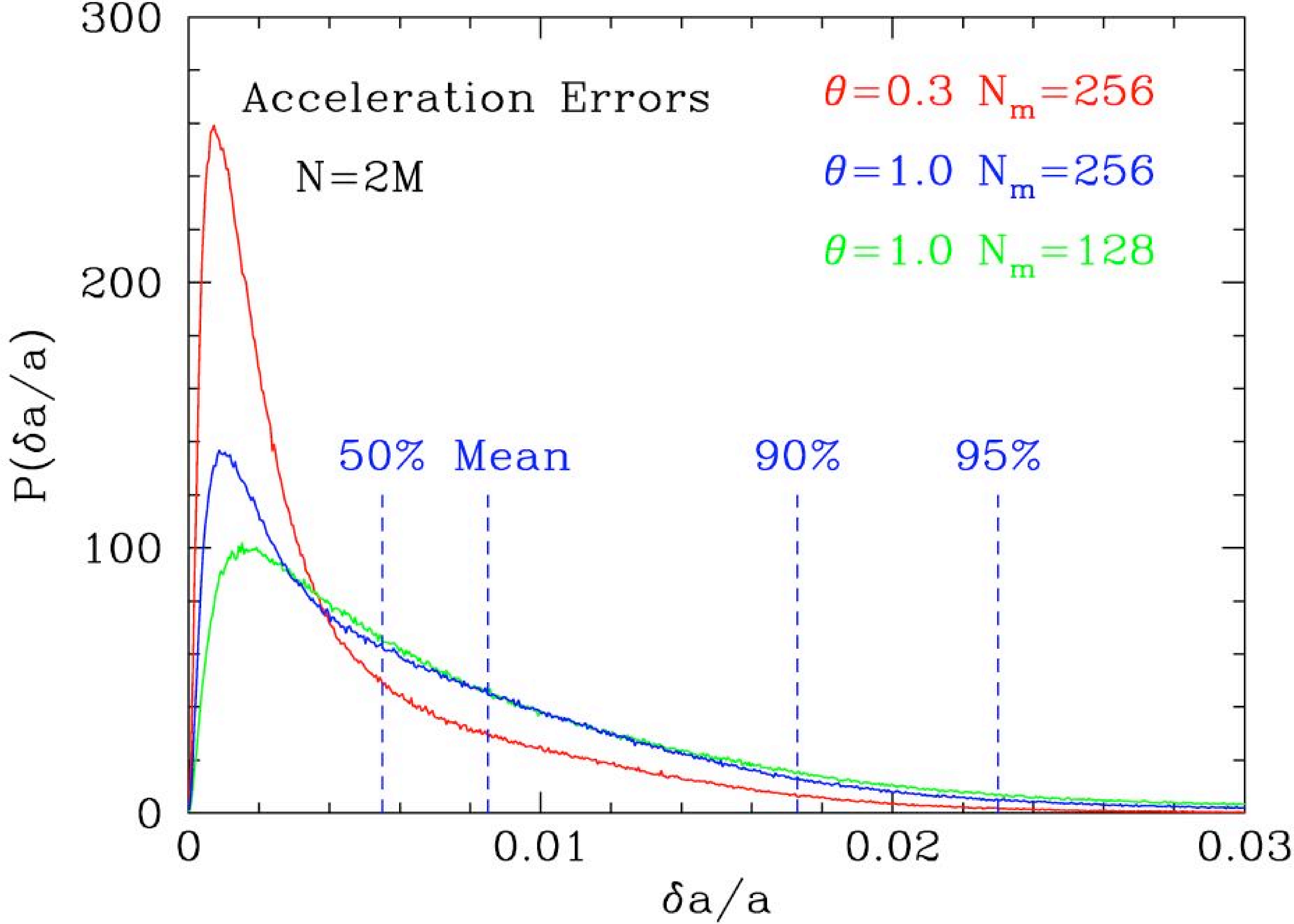
A new parallel particle-mesh/treecode hybrid for cosmological simulations: GOTPM
(Dubinski, Kim, Park, Humble 2004)

Features

- Parallel PM method using slice domain decomposition
- Local force correction using neighbouring "mini-trees" instead of PP or sub-meshes
- Like the P3M method all forces are corrected for near by particles in neighbourhood spheres - trees used instead
- slice widths determined by computational work to achieve good load-balance

Slice decomposition works but is not ideal for scaling to 1000's of processors.
3-D cuboid decomposition should be implemented!


1. Slice Domain Decomposition
2. Bin particles and build mini–trees
mini–tree
Slice mapped to one process
Simulation cube
Image mini–tree
3. PM force correction
by walking surrounding
mini–trees.


Acceleration Errors
N=2M
θ=0.3 N_m=256
θ=1.0 N_m=256
θ=1.0 N_m=128
50%
Mean
90%
95%
P(δa/a)
δa/a
300
200
100
0
0
0.01
0.02
0.03

Simulations with GOTPM

- N=512^3, L=65 Mpc/h, $\Omega = 0.3, \Lambda = 0.7$
- >2000 "quality" halos
  - N>10K (largest halos have N~1M)
  - softening=3 kpc/h
- NFW seal of approval, halos with large chi-squared rejected

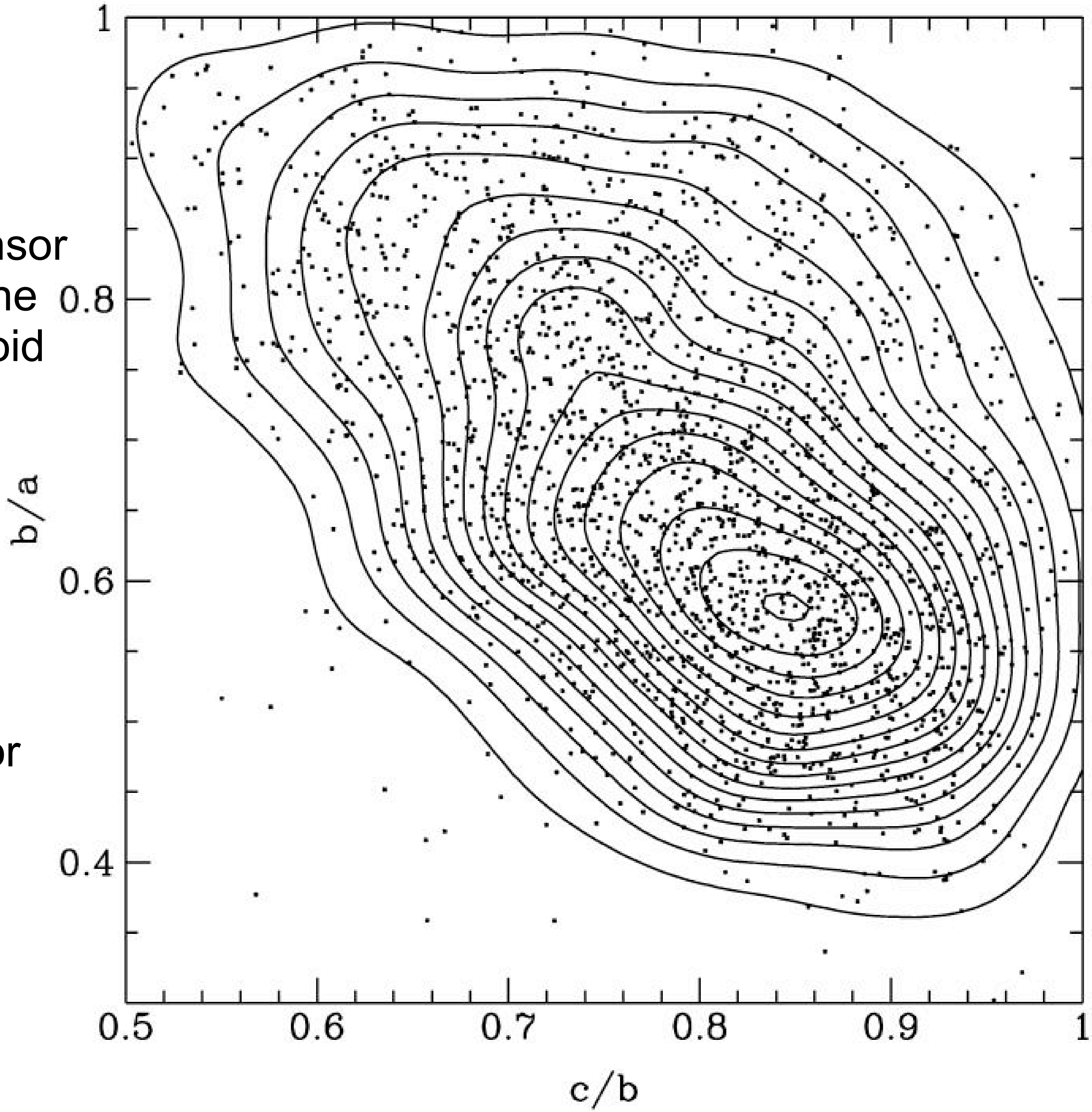
Halo Shape Distribution

Shapes determined
Using normalize
Moment of inertia tensor
Iteratively to determine
Best fit perfect ellipsoid
within r_s

Peak of distribution

b/a=0.6
c/b=0.85 or c/a=0.51

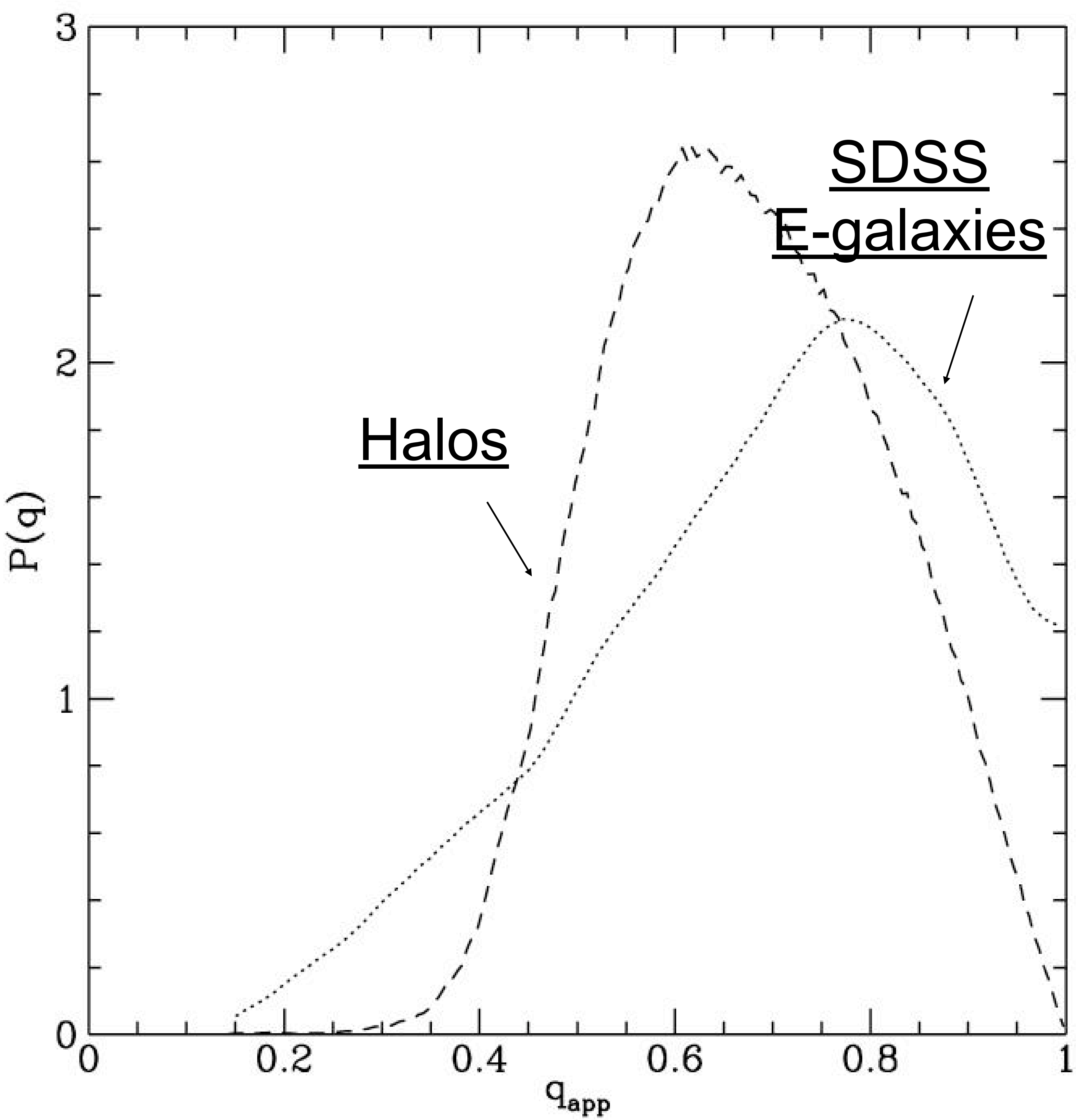
Not many spherical or
axisymmetric halos



Halos vs. Ellipticals

- Halos look a lot like ellipticals
- Centrally concentrated and triaxial
- How far can you go with this comparison?
- Surface brightness profiles, fundamental plane and shape distribution

Distribution of Projected Axis Ratios

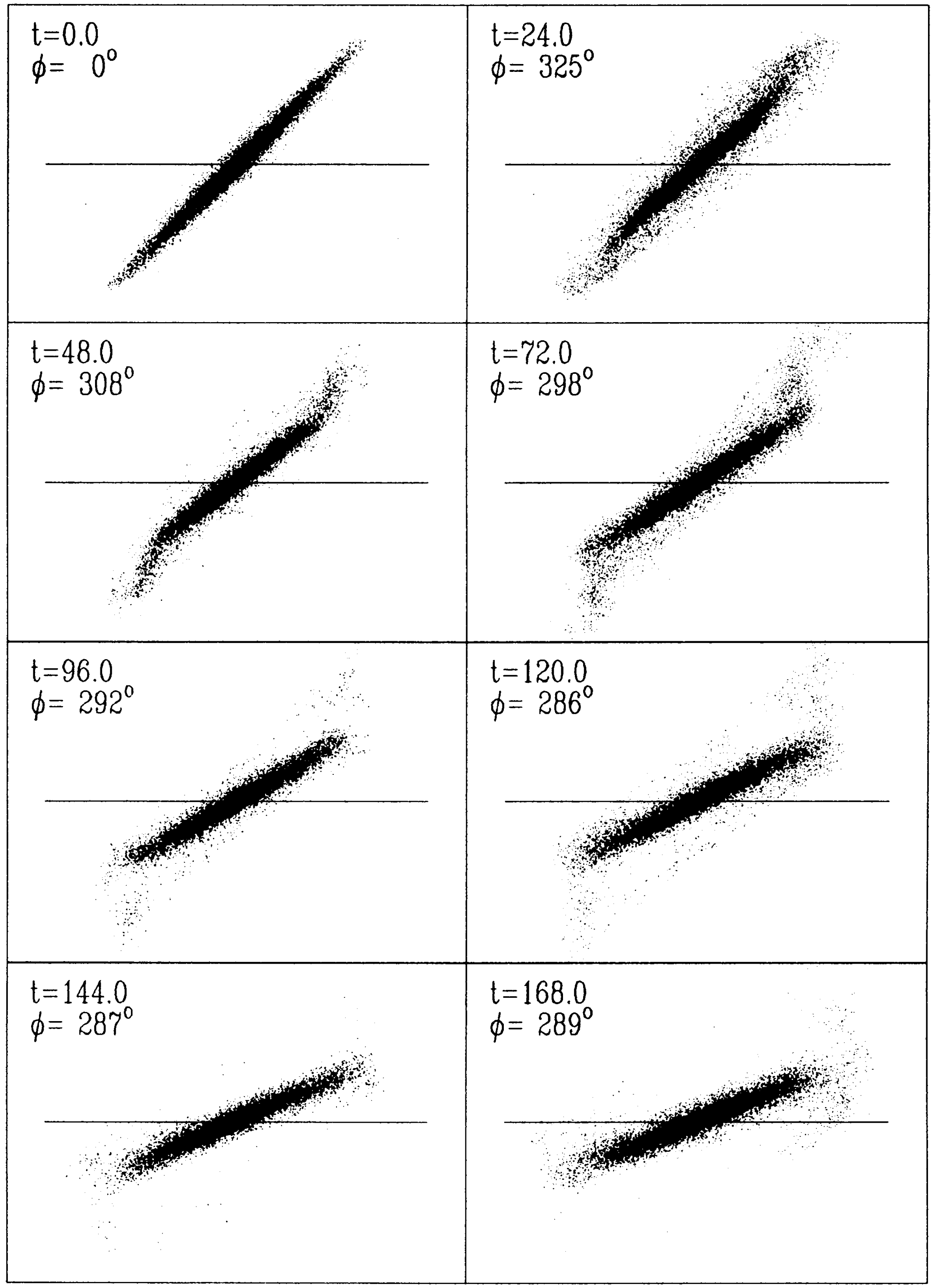


Disks in triaxial halos

- Misalignment between the halo leads to a torque -> disk precession within halo
- Warped modes? No. Dynamical friction brings the halo and disk into a common plane.
- Disks should settle into the principal plane of their triaxial halo - probably aligned with the angular momentum vector of the halo
- Flattening of the halo in the disk plane should manifest itself through non-circular orbits

align with each other within a few orbital periods.

bulge and halo, the spherically averaged density profiles do not change dramatically.



Disk and halos settle into a common plane if initially misaligned because of halo-disk interactions
(Dubinski & Kuijken 1995)

We may therefore expect disks to lie within the principal plane of a triaxial dark halo

Bailin and Steinmetz (2004)
Halos are slowly tumbling.
Disks will be carried along by the halo and may warp as they are slowly flipped over.

FIG. 13.—Evolution of a highly inclined disk (model C) in a dynamic bulge and halo potential. The precession stops by $t \sim 120$. The disk holds together despite the large inclination and differential precession. Note also how at late times, after the precession has slowed, the disk takes on a slow warp shape, bending down towards the halo equatorial plane.

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Closed Orbits in Flattened Potentials

- Assume the disk forms in a principle plane (reasonable assumption since J vectors point along minor axis)
- Calculate closed loop orbits in the perfect ellipsoid potential for an ideal NFW model or use the data directly with an SCF expansion of the potential generated by the particles
- For low mass disks the orbital shape and kinematics could be reflected directly by the potential

Potential for flattened dark halos

Perfect Ellipsoid Approximation for Dark halos

$$\rho \equiv \rho(m) \sim \frac{1}{m(1+m)^2}$$

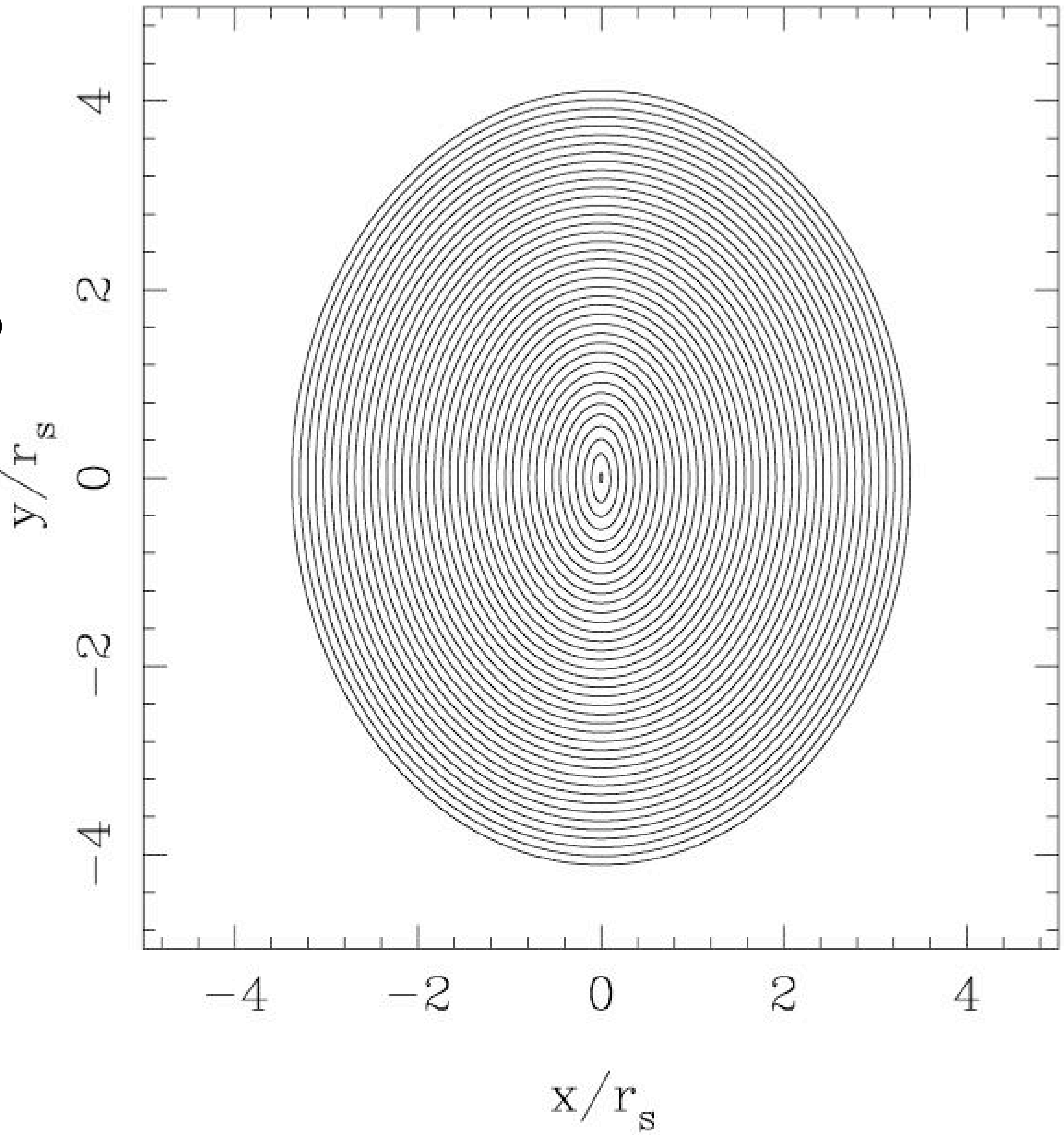
$$m^2 = x^2 + \frac{y^2}{q_1^{\ 2}} + \frac{z^2}{q_2^{\ 2}}$$

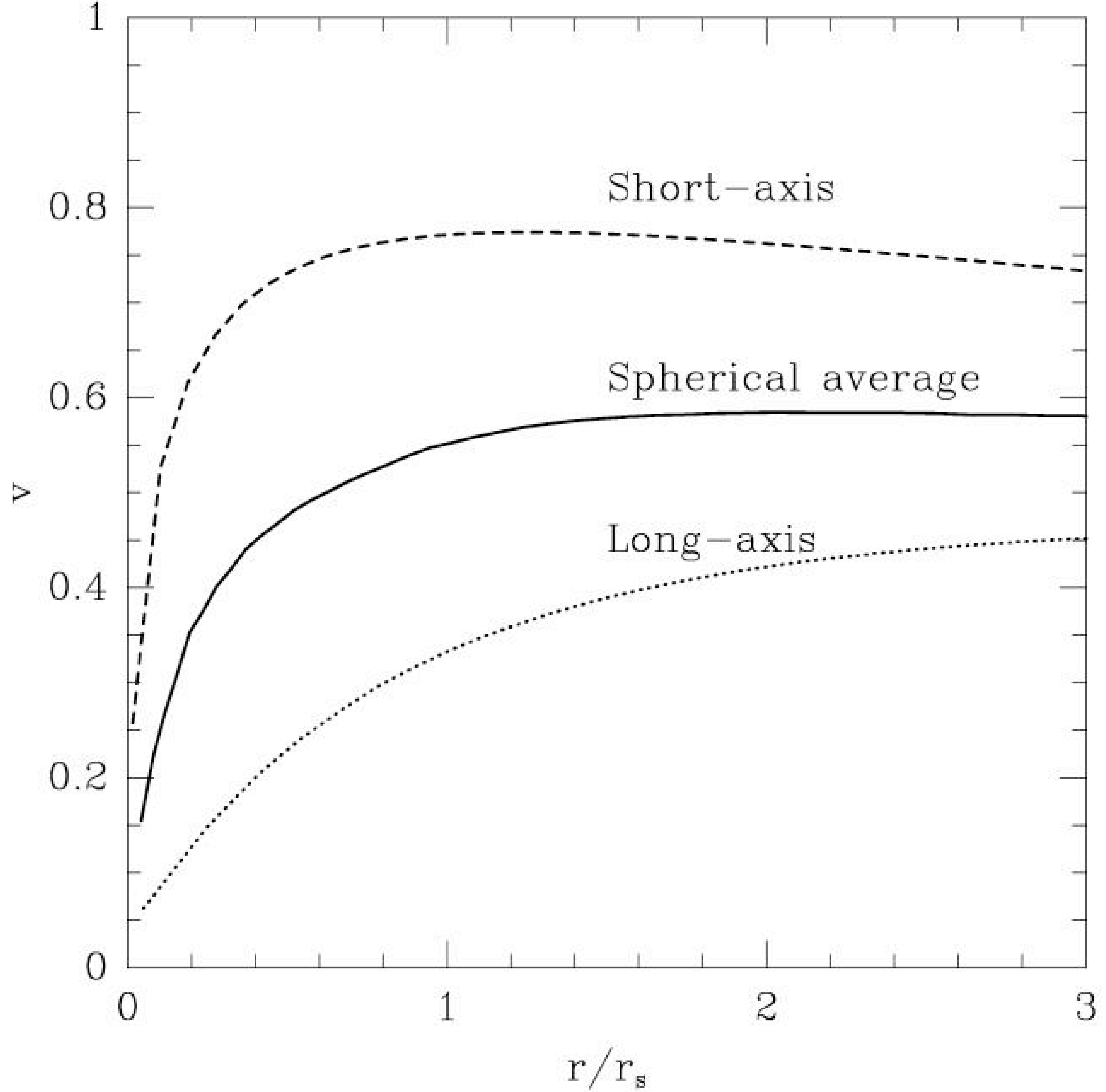
Typically, q1=0.6, q2=0.5, you can compute the potential
Using standard methods e.g. Chandrasekhar (1969)

Or you can go straight to the data and use a “self-consistent field” expansion e.g. Hernquist and Ostriker (1991)

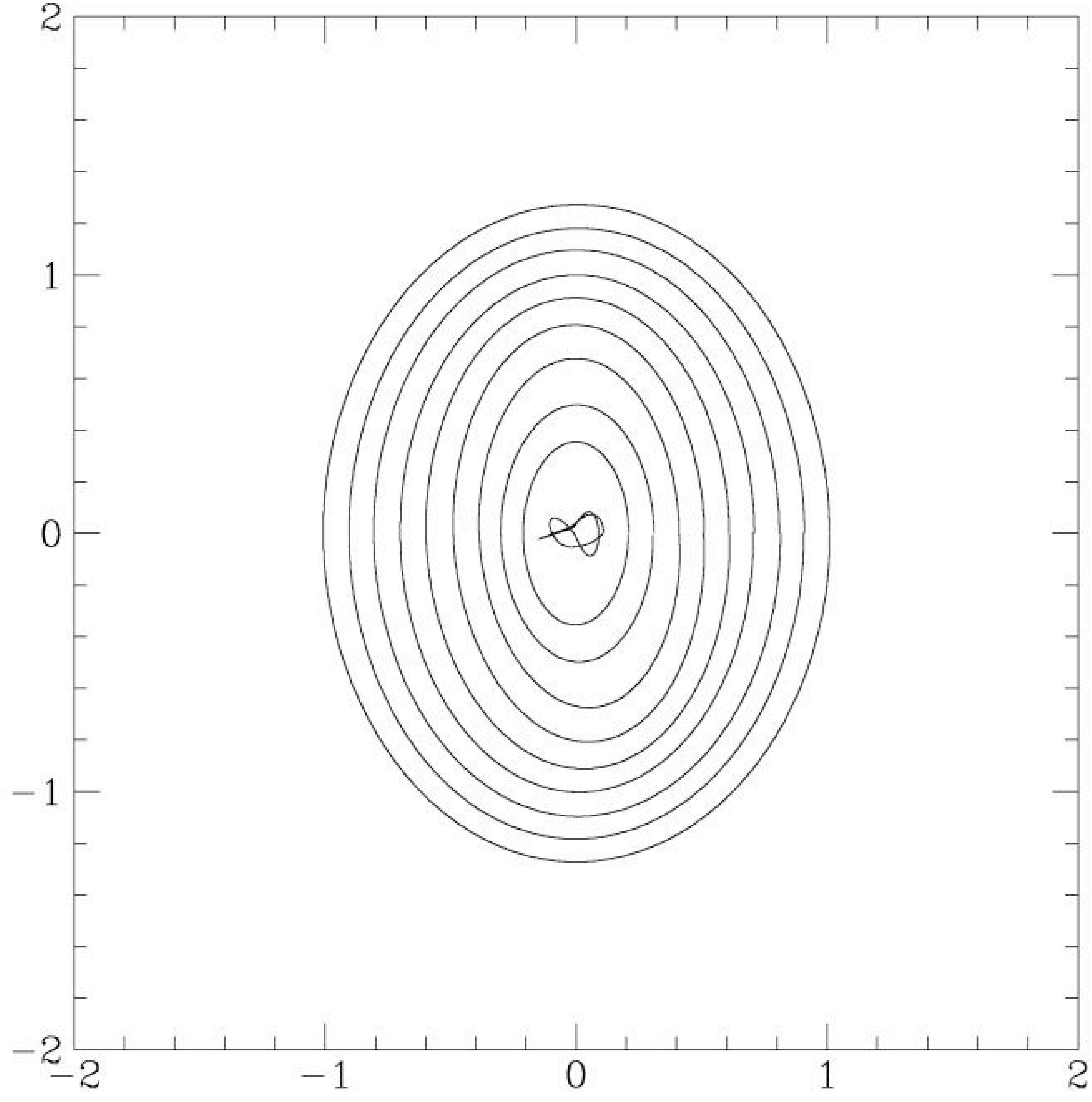
Loop orbits
in a-b plane

Typical halo
q1 = 0.5
q2 = 0.4




Short-axis
Spherical average
Long-axis
v
r/r_s
0
0.2
0.4
0.6
0.8
1
0
1
2
3

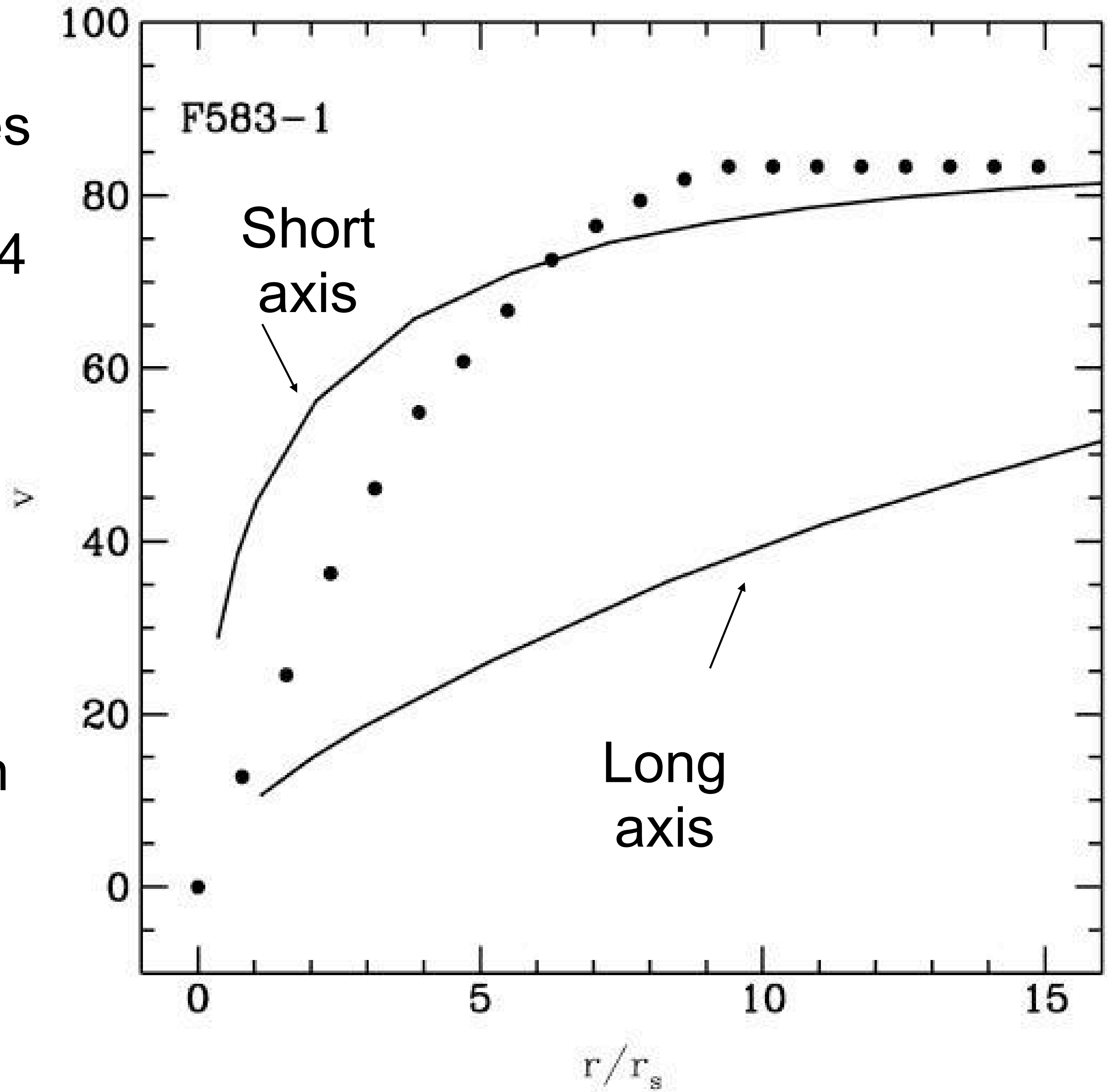
Closed orbits in the principle plane of an N-body dark halo using the SCF potential



- Expected rotation curves from two independent views with q1=0.5 q2=0.4 and c=10

- Short axis too cuspy
- Long axis too shallow
- Somewhere in between

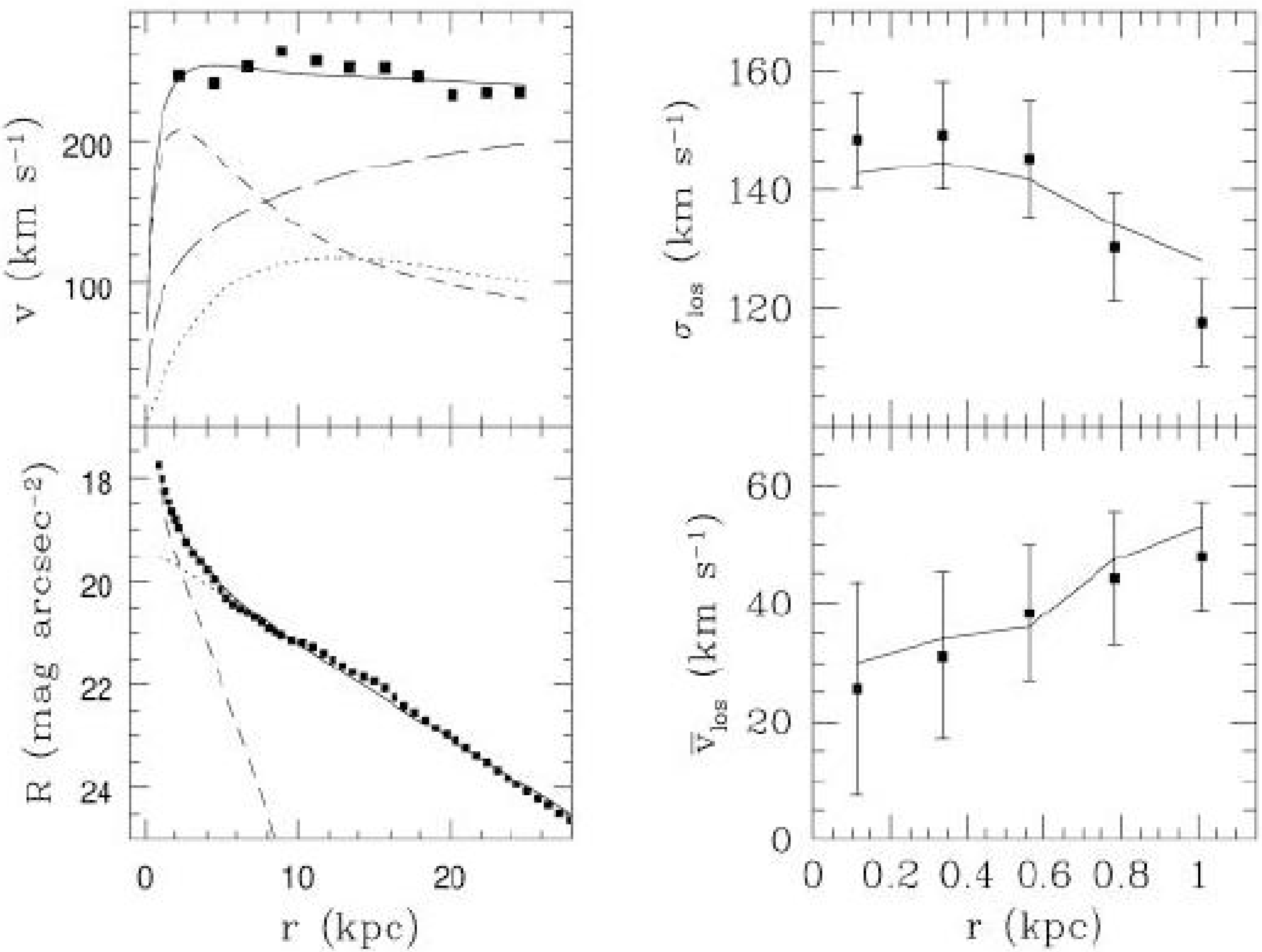
- Interpretation of rotation curves is more subtle than direct spherical profile predictions



Need to include shapes, viewing directions and correct disk models

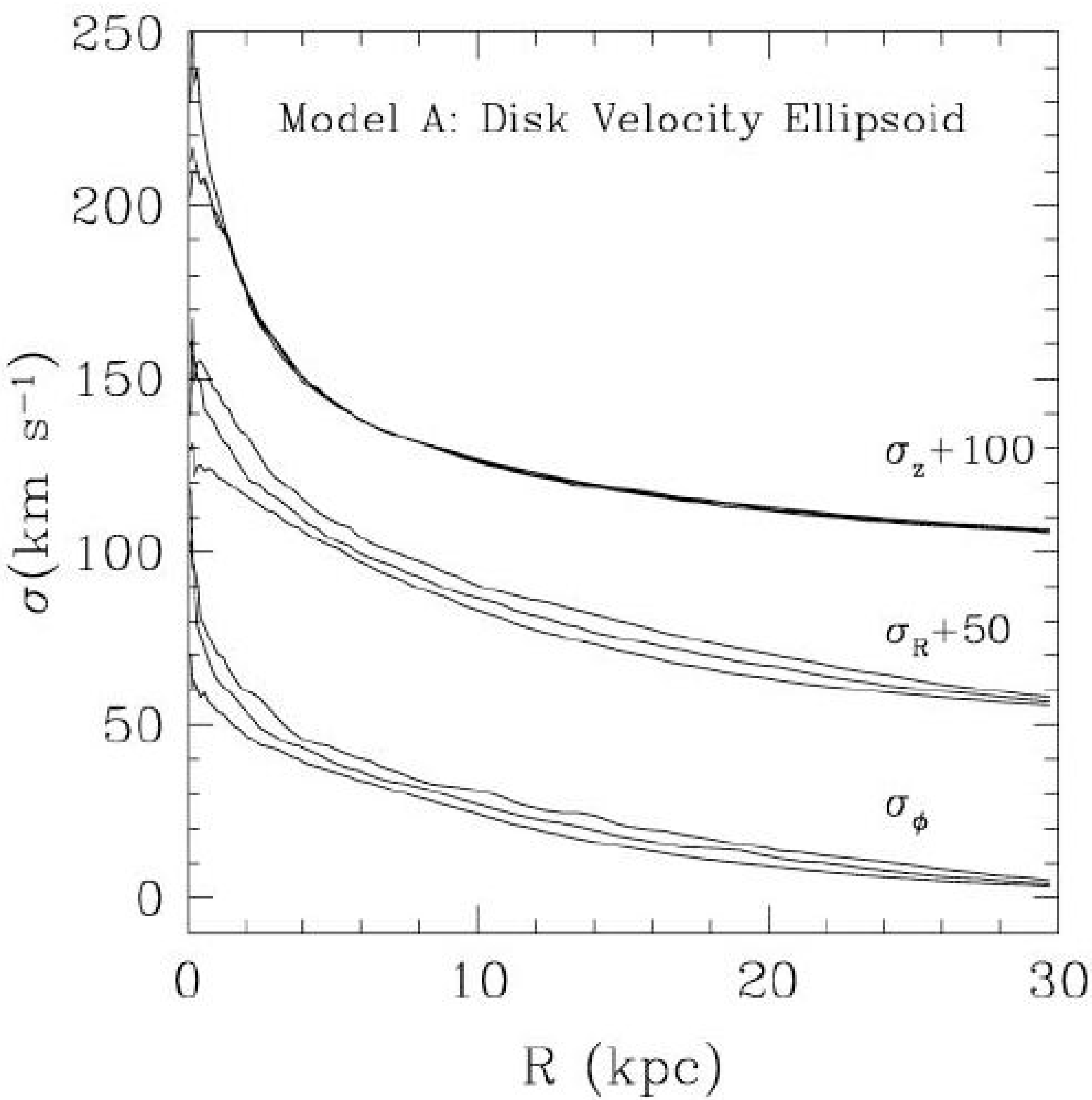
Modelling Disk Galaxies

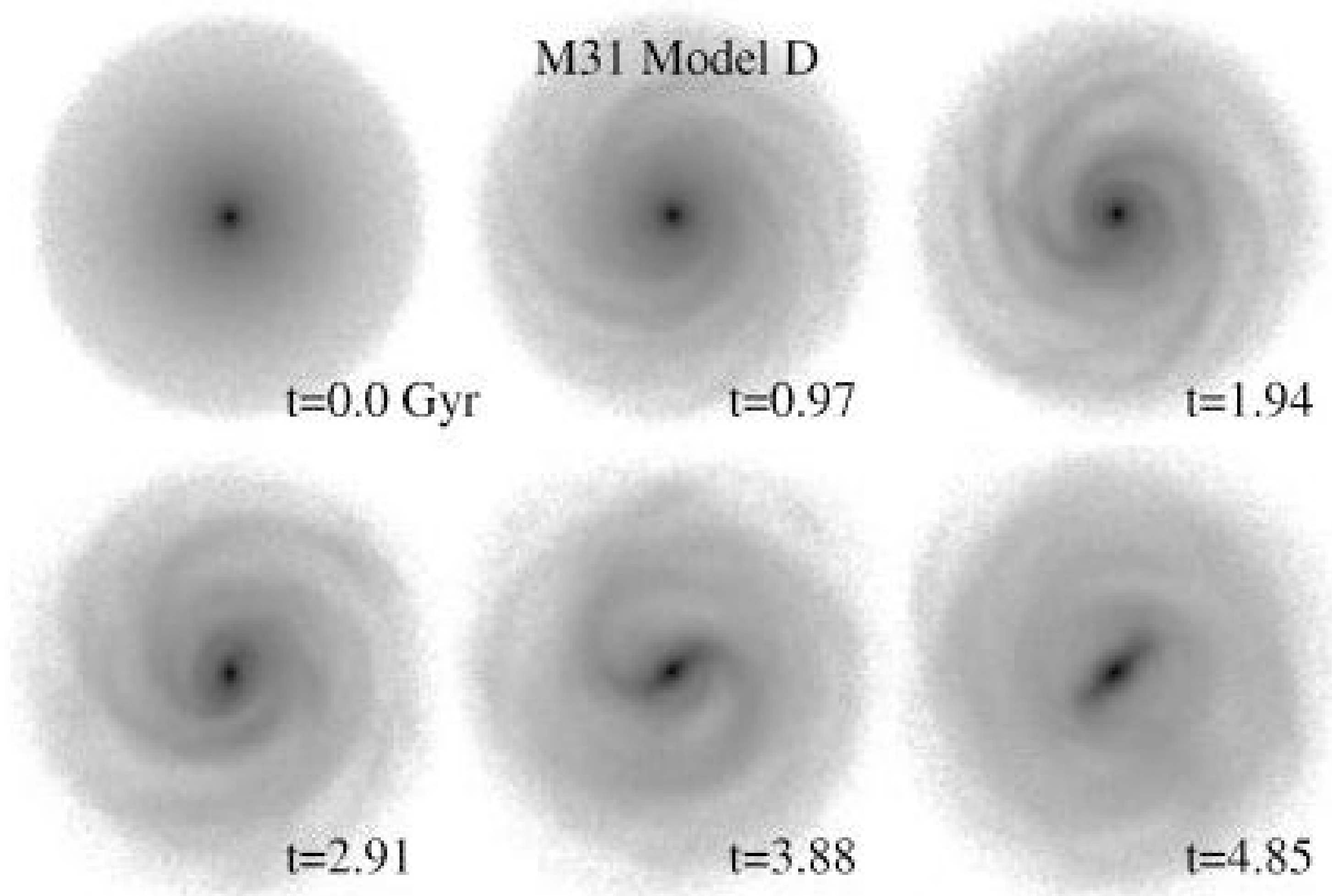
- Kuijken and Dubinski 1995 - disk, bulge, halo models from a composite distribution function - oblate dark halos
- Widrow and Dubinski 2005 - spherical NFW halo model, Hernquist bulge model, blackholes - methods for determining best fit parameters to real galaxies e.g. Milky Way, M31



v (km s^{-1})
100
200
R (mag arcsec^{-2})
18
20
22
24
0
10
20
r (kpc)
σ_{los} (km s^{-1})
120
140
160
$\bar{v}_{los}$ (km s^{-1})
0
20
40
60
0
0.2
0.4
0.6
0.8
1
r (kpc)

3.5M particle test disk simulation

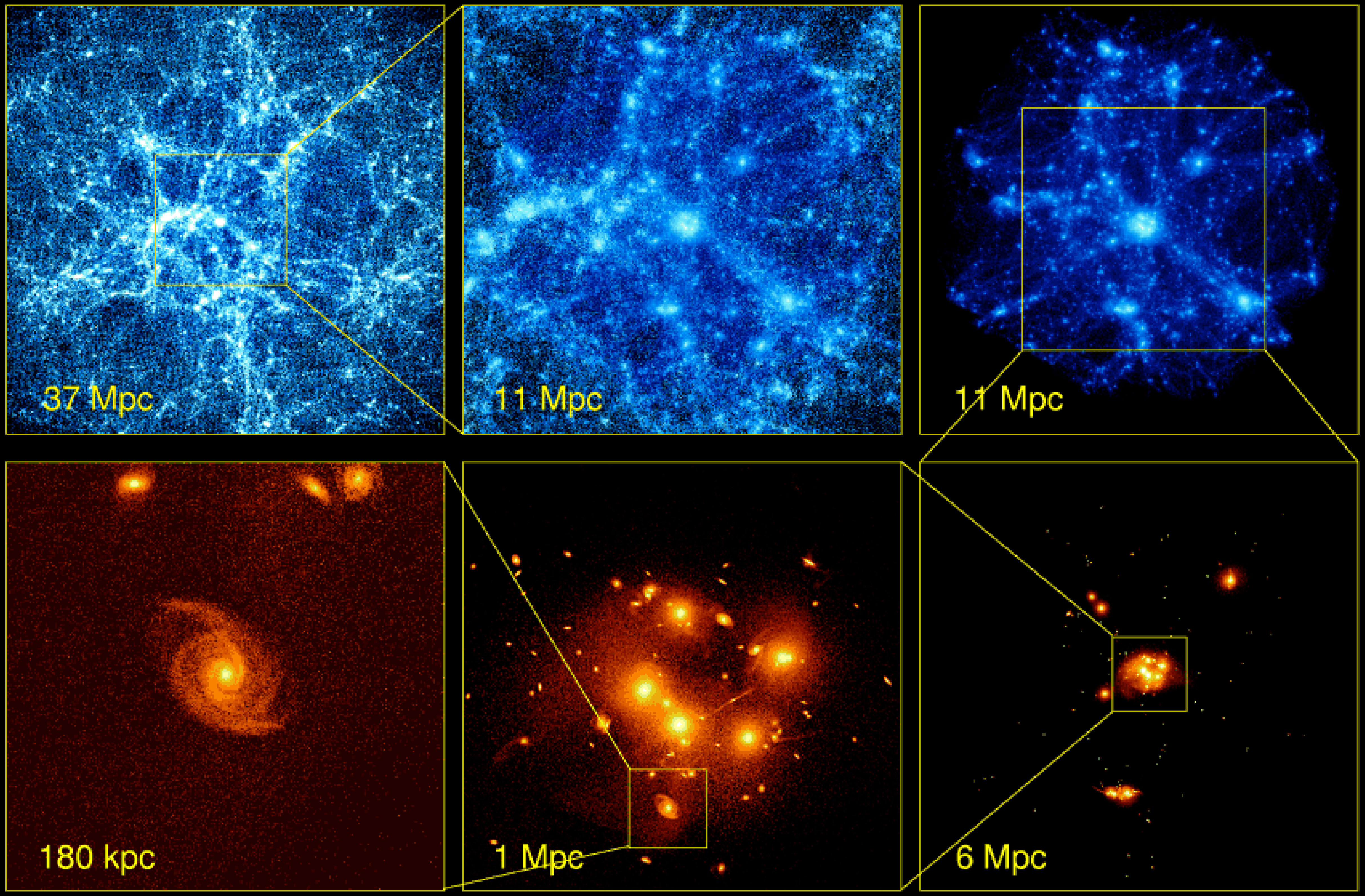



M31 Model D
t=0.0 Gyr
t=0.97
t=1.94
t=2.91
t=3.88
t=4.85

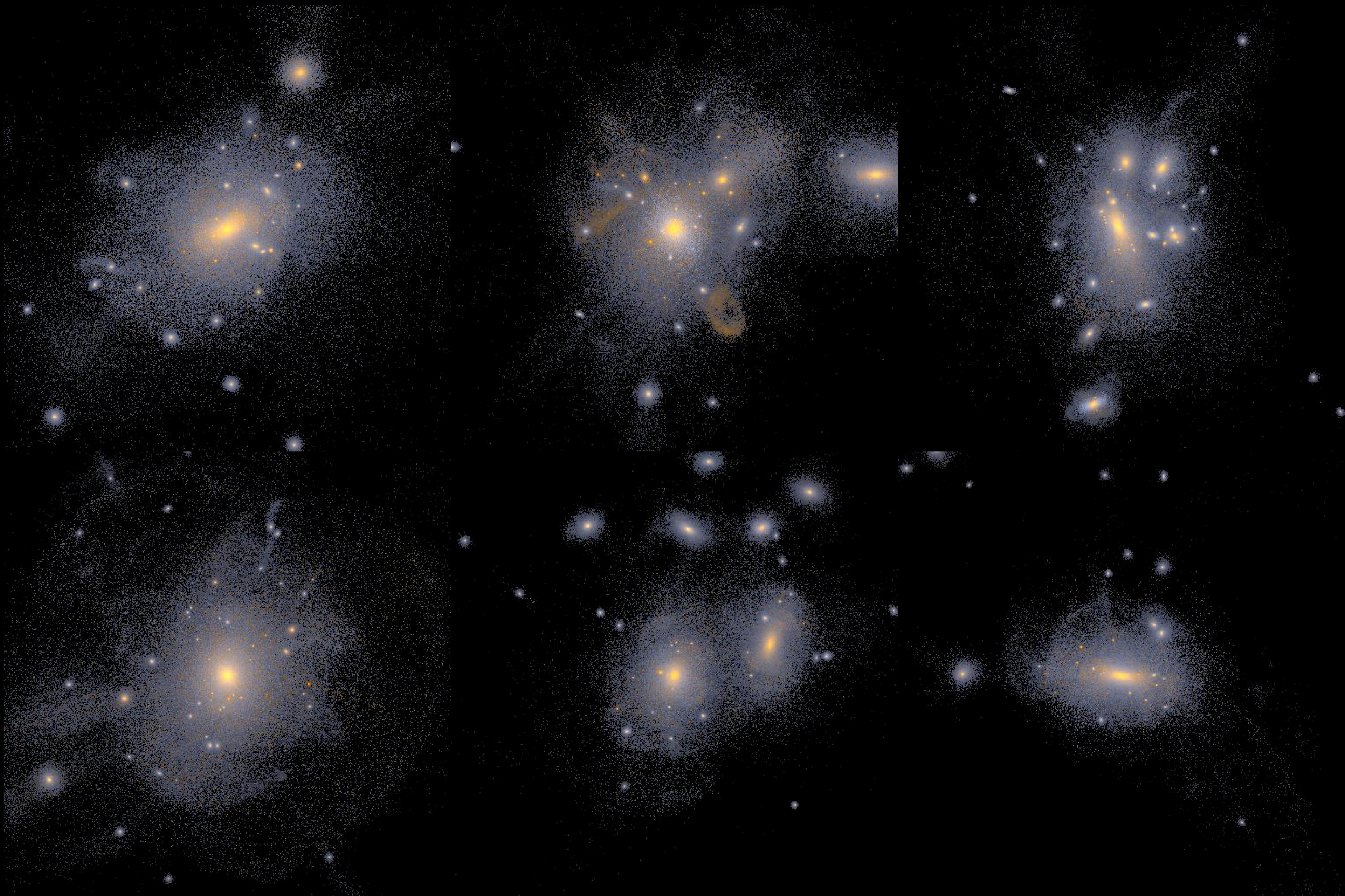
Embedding Disk Galaxies within Cosmological Simulations

- Moore et al. 96 galaxy harassment
- Galaxy interactions within a cluster
  - formation of the giant elliptical
  - merging of groups to form ellipticals
  - tidal stripping - intragalactic stars in clusters

Simulated Cluster at z=1.3



Omega=1 CDM



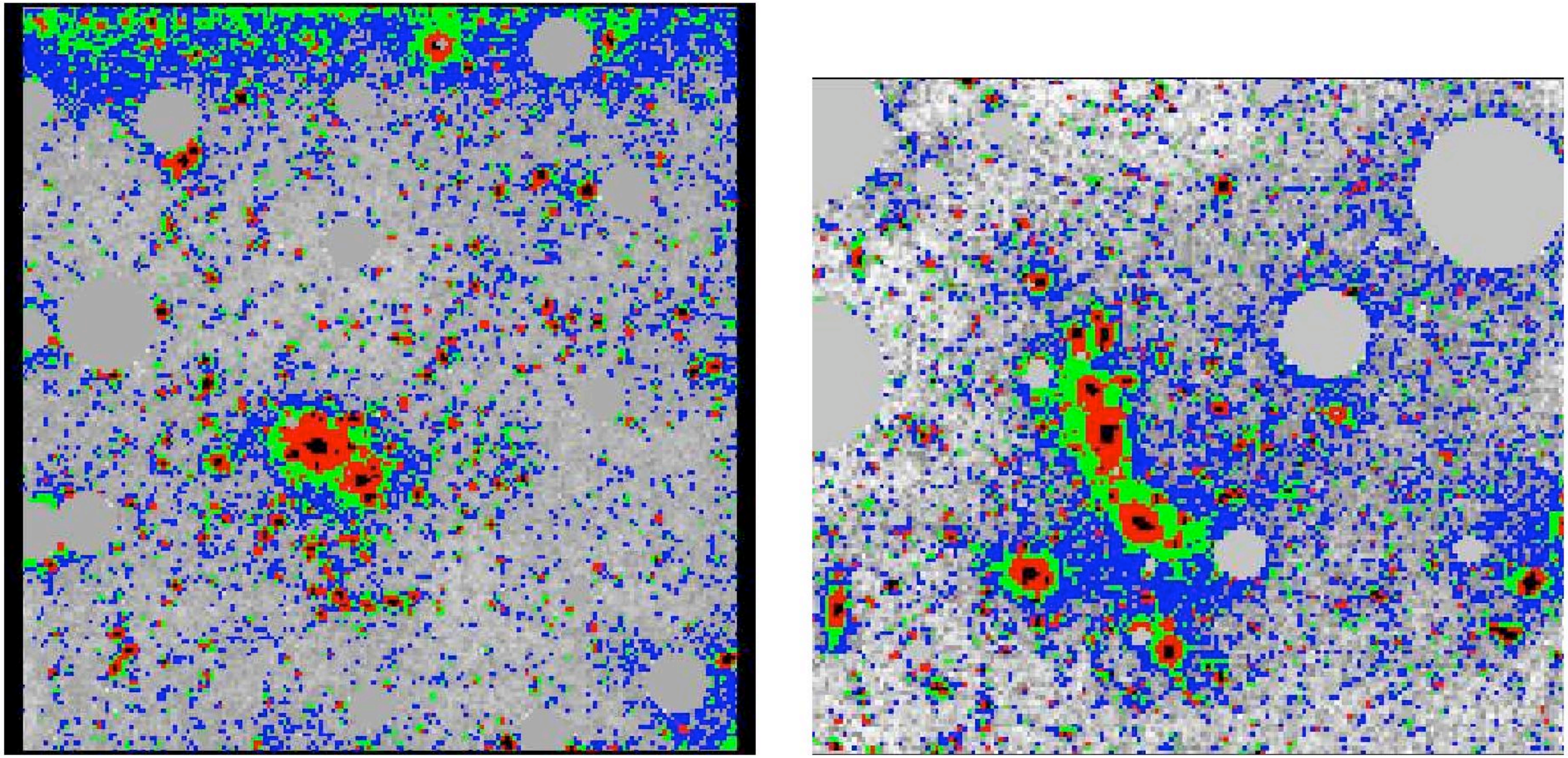
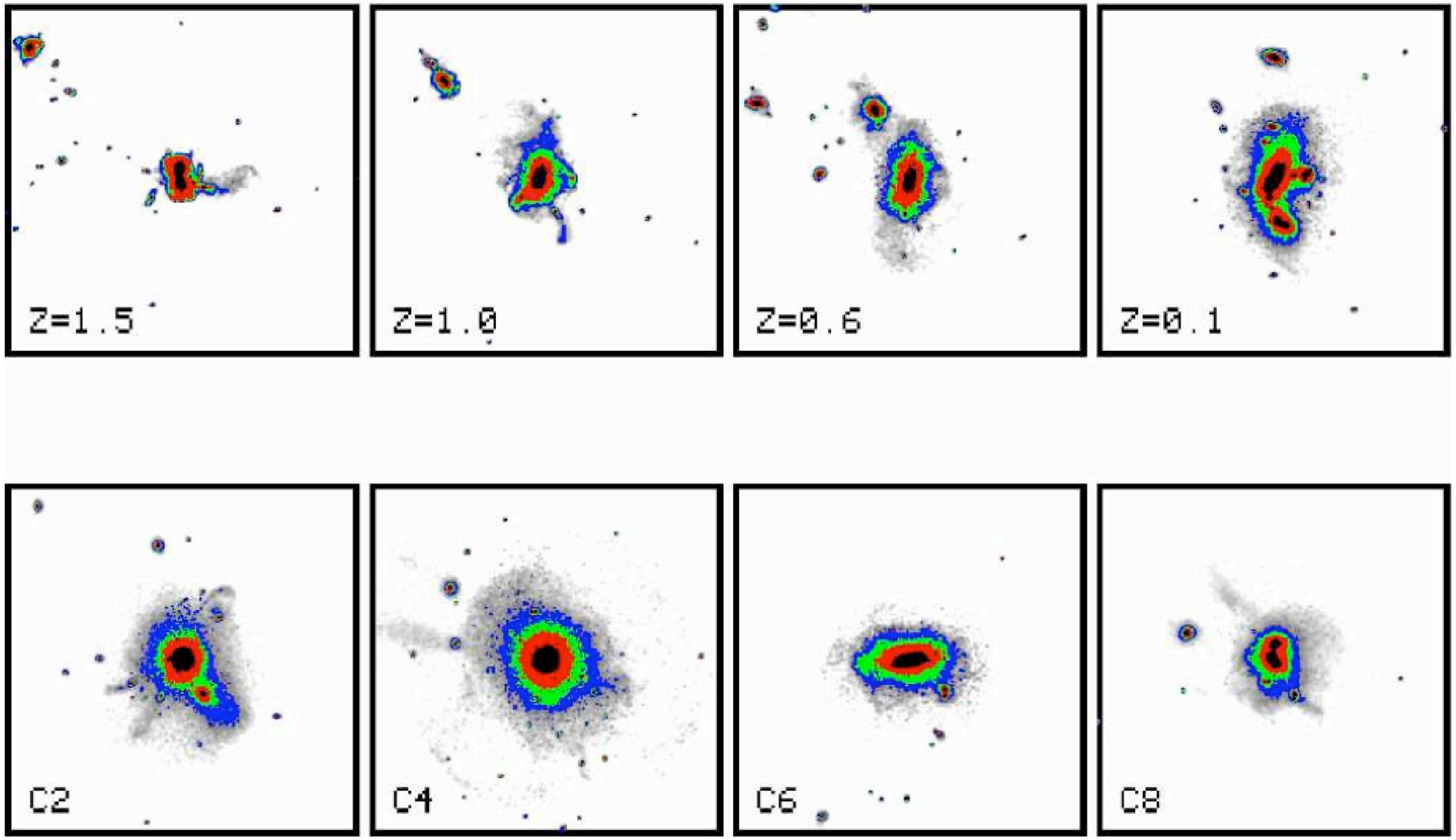


Fig. 7.— Images of Abell 801 (left), and Abell 1234 (right), binned up into 11 $\times$ 11 pixels bins. North is left, and east is at the bottom of these images. The color black represents all bins with an average surface brightness from $\mu_V = 20$ to 24 mag arcsec^{-2}, the color red represents all bins from $\mu_V = 24$ to 26 mag arcsec^{-2}, the color green represents all bins from $\mu_V = 26$ to 27 mag arcsec^{-2}and the color blue represents all bins from $\mu_V = 27$ to 28 mag arcsec^{-2}. All bins with surface brightnesses below $\mu_V = 28$ are uncolored. A flat-fielding fluctuation can be seen at the top of Abell 801.

Feldmeier et al. 2004

Feldemeir et al. 2004



Simulations: Dubinski, Geller and Koranyi 2002

Feldmeier et al. 2004

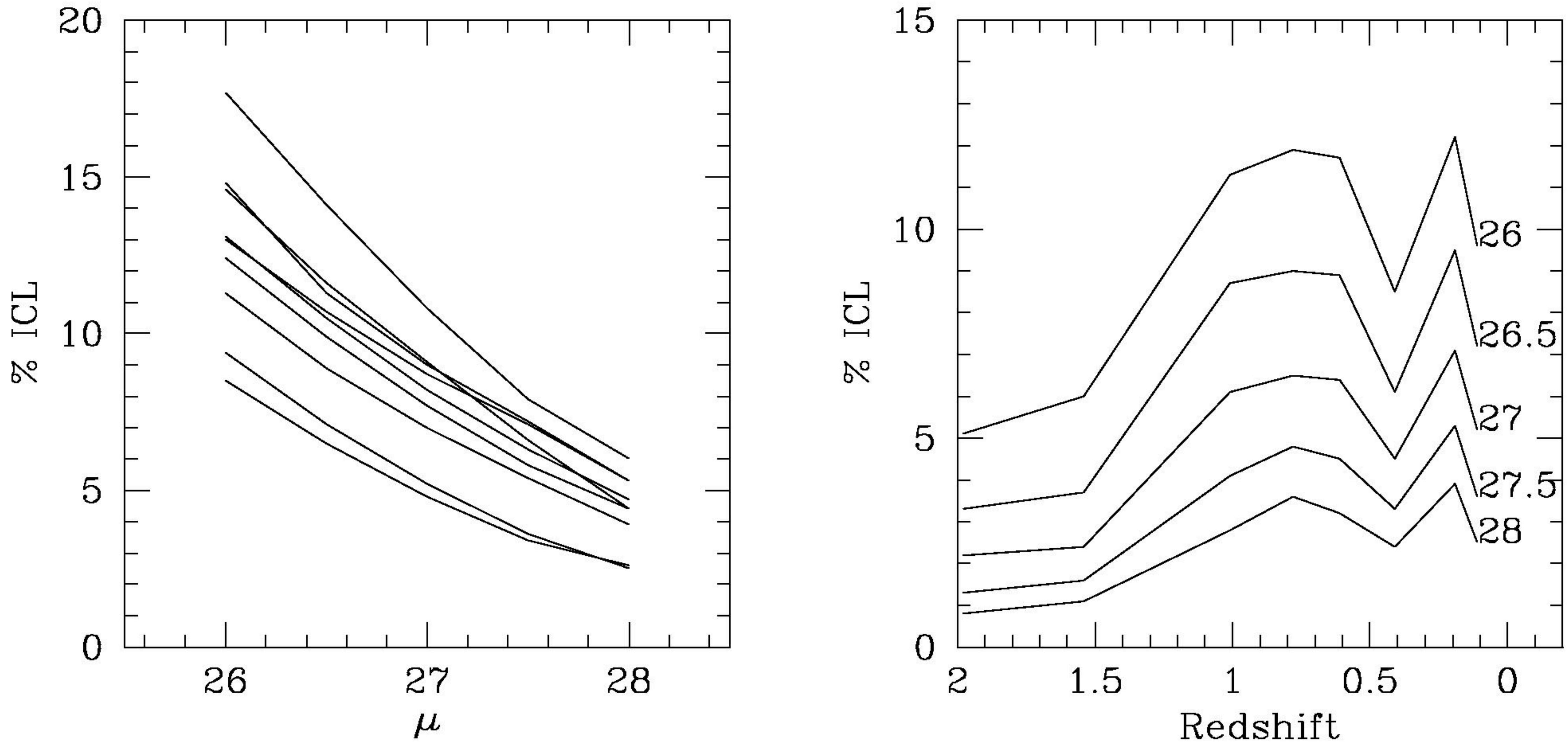


Fig. 15.— The fraction of ICL found in the simulations by Dubinski (1998), as a function of surface brightness, measured in an identical way as the observations. On the left is the results from nine clusters all found at a redshift of zero. On the right is the results from the evolving cluster as a function of redshift. See the text for further explanation.

Merging spirals and the fundamental plane

- Toomre: mergers of spirals lead to the ellipticals
- Hypothesis: Imagine a population of spiral galaxies with correct LF and Tully-Fisher scaling relations and then let them interact and merge within a cosmological environment. Does this lead to the fundamental plane scaling relations? Assume gas is unimportant (!)

Fundamental Plane Relation for Ellipticals

Correlation between 3 observed quantities:

1. scale radius
2. velocity dispersion
3. surface brightness

$$\log r_e = \alpha \log \sigma - \beta \log \langle I_e \rangle + \text{gamma}$$

Observed values:

$\alpha = 1.2$ to 1.5 $\quad \beta = -0.7$ to -0.9

Expectation for homologous virialized systems with "universal" profile:

$\alpha = 2.0 \quad \beta = -1.0$

Why the difference?

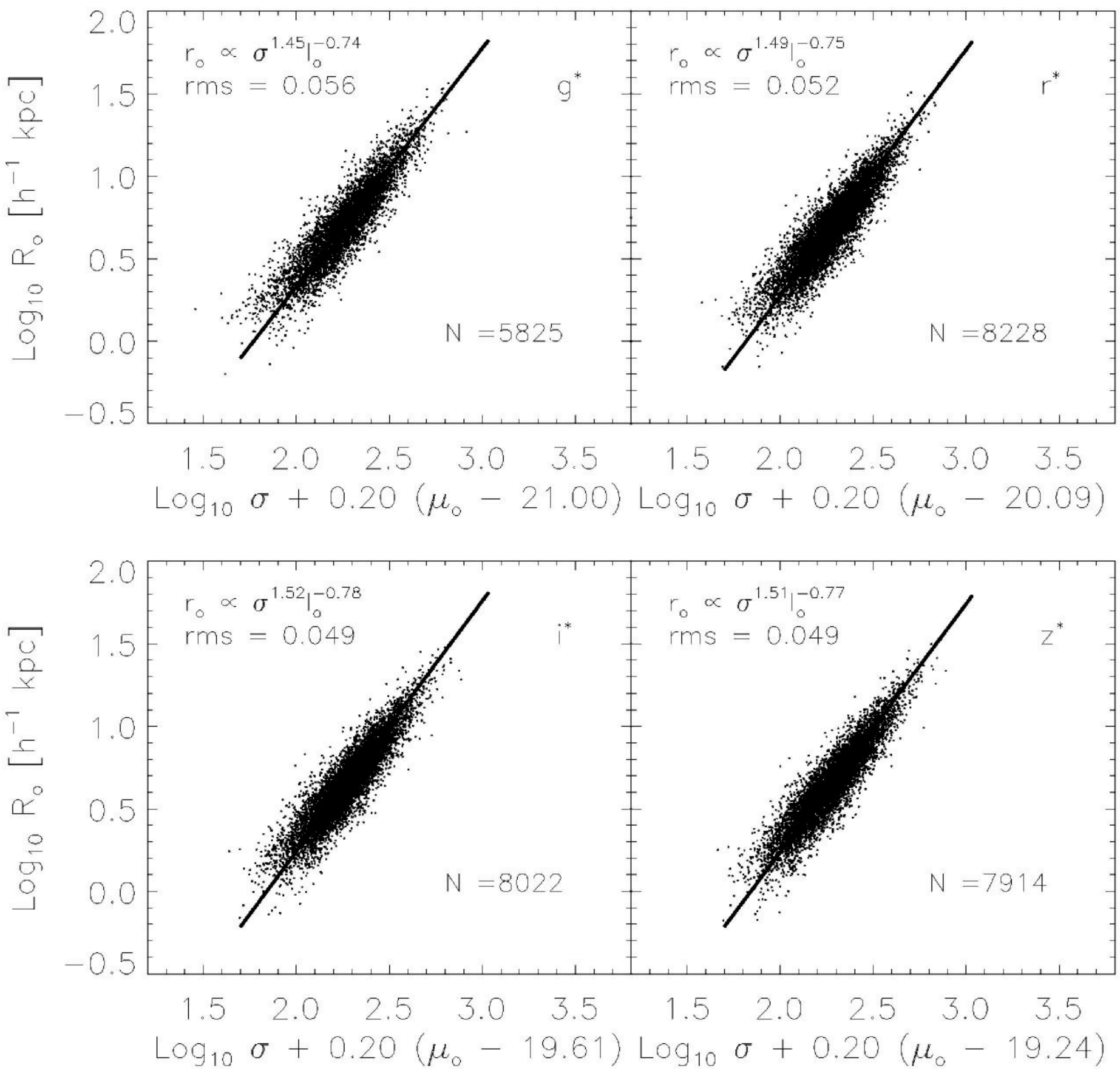
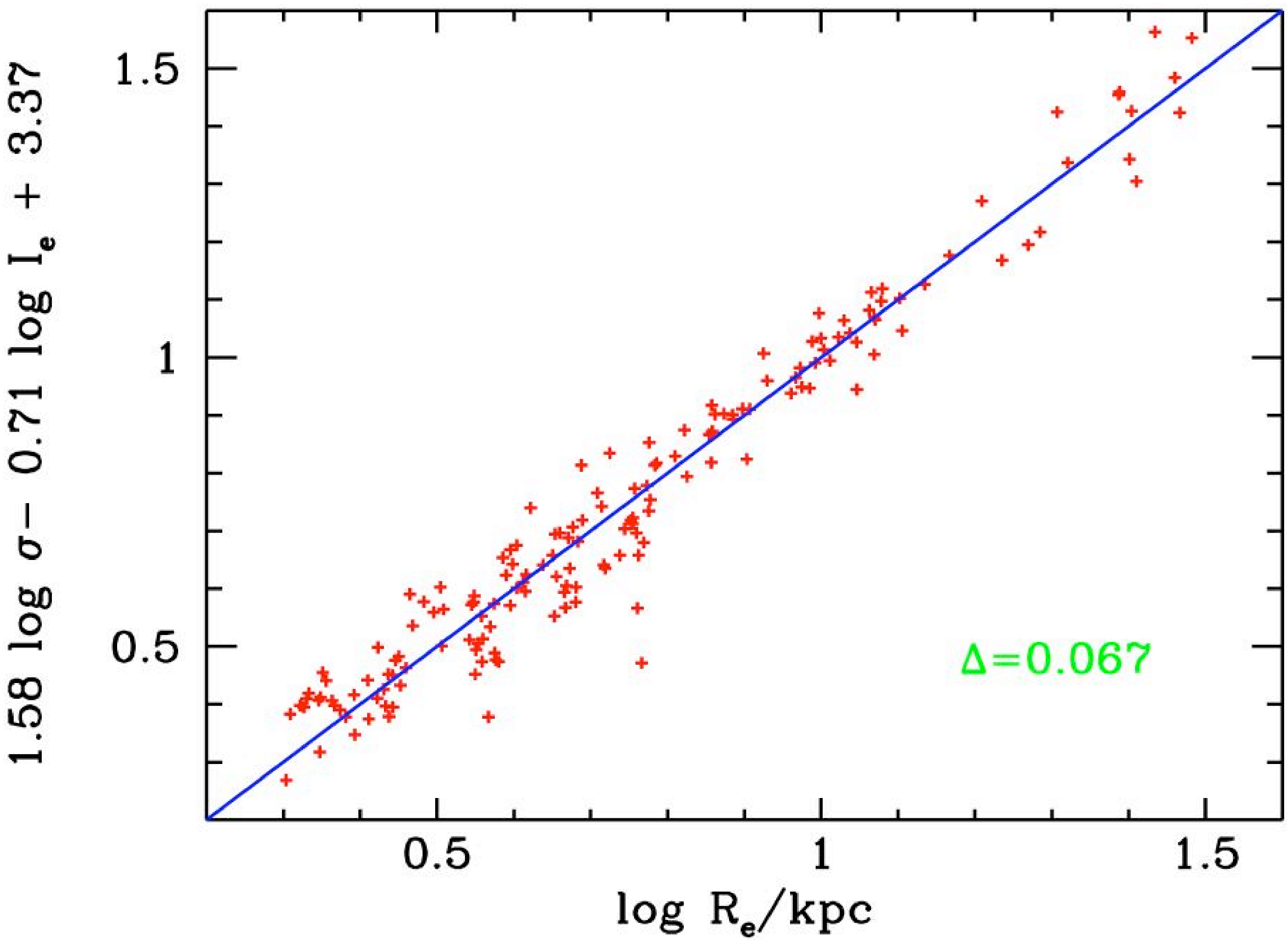


FIG. 1.—FP in the four SDSS bands. Coefficients shown are those that minimize the scatter orthogonal to the plane, as determined by the maximum likelihood method. Surface brightnesses have been corrected for evolution.

N-body experiments

- 10 clusters with 300 ordinary spiral galaxies embedded at z=3 in Omega=1 :(
- Results: ~200 ordinary merger remnants that look like ellipticals
- Measure the effective radius, mean surface brightness and central velocity dispersion to determine a fundamental plane for merger remnants

Simulated Fundamental Plane
162 Merger Remnants



Conclusions

- Many powerful methods and computers around so lots of scope to increase N and dynamic range - exciting times!
- Complex disk-halo interaction needs to be explored further using current halo results if we really wish to test the CDM paradigm with galaxy dynamics - triaxial effect is large!
- Galaxy interactions in clusters seem to produce right amount of intracluster light - mergers of ordinary spirals may create FP

Gravitas

- Collaborative animation project with Toronto composer John Farah (classical, ambient minimalism and techno)
- Create a compilation of high quality animations of galaxy dynamical phenomena set to music - art, science and education
- ESA is releasing a Hubble 15th anniversary DVD on April 24 throughout Europe - contains 5 of our tracks in the bonus section
- A self-published DVD will be released by us over the summer at www.galaxydynamics.org