Disks in Triaxial Dark Matter Halos

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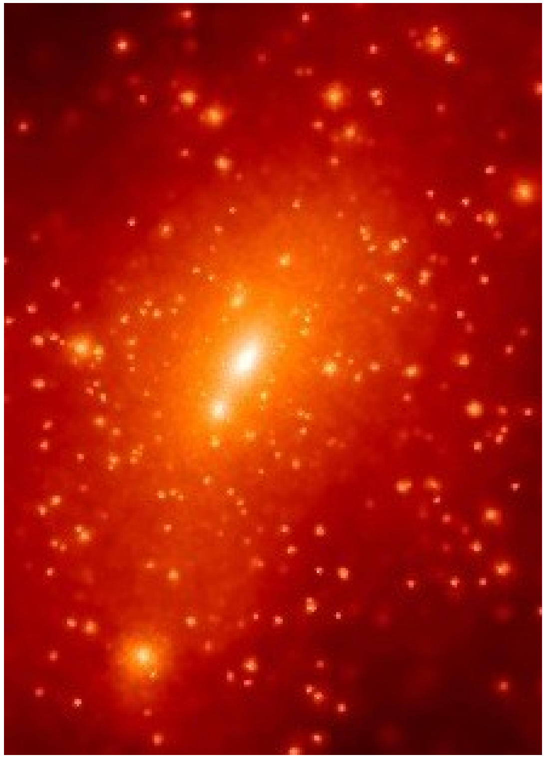
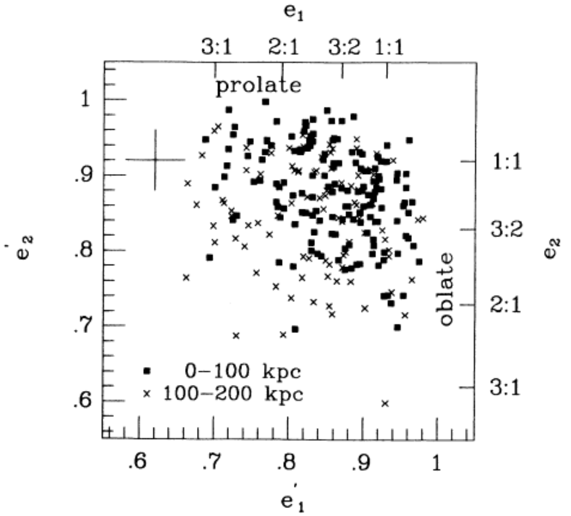
Cosmological Halo Shapes

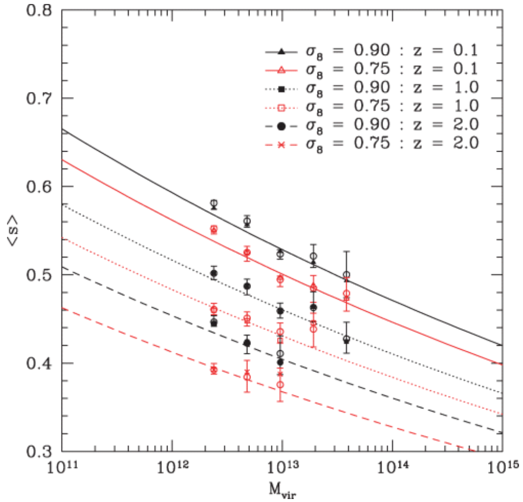
Dark matter halos and galaxy merger remnants are strongly triaxial: c/a ~ 0.4; b/a ~ 0.6 (Dubinski & Carlberg 1991, Jing & Suto 2002)

Observations (polar rings, Sgr tidal streams, X-ray halos, lensing, flaring HI disks, TF residuals) generally imply oblate halos b/a ~ 1; c/a > 0.8.





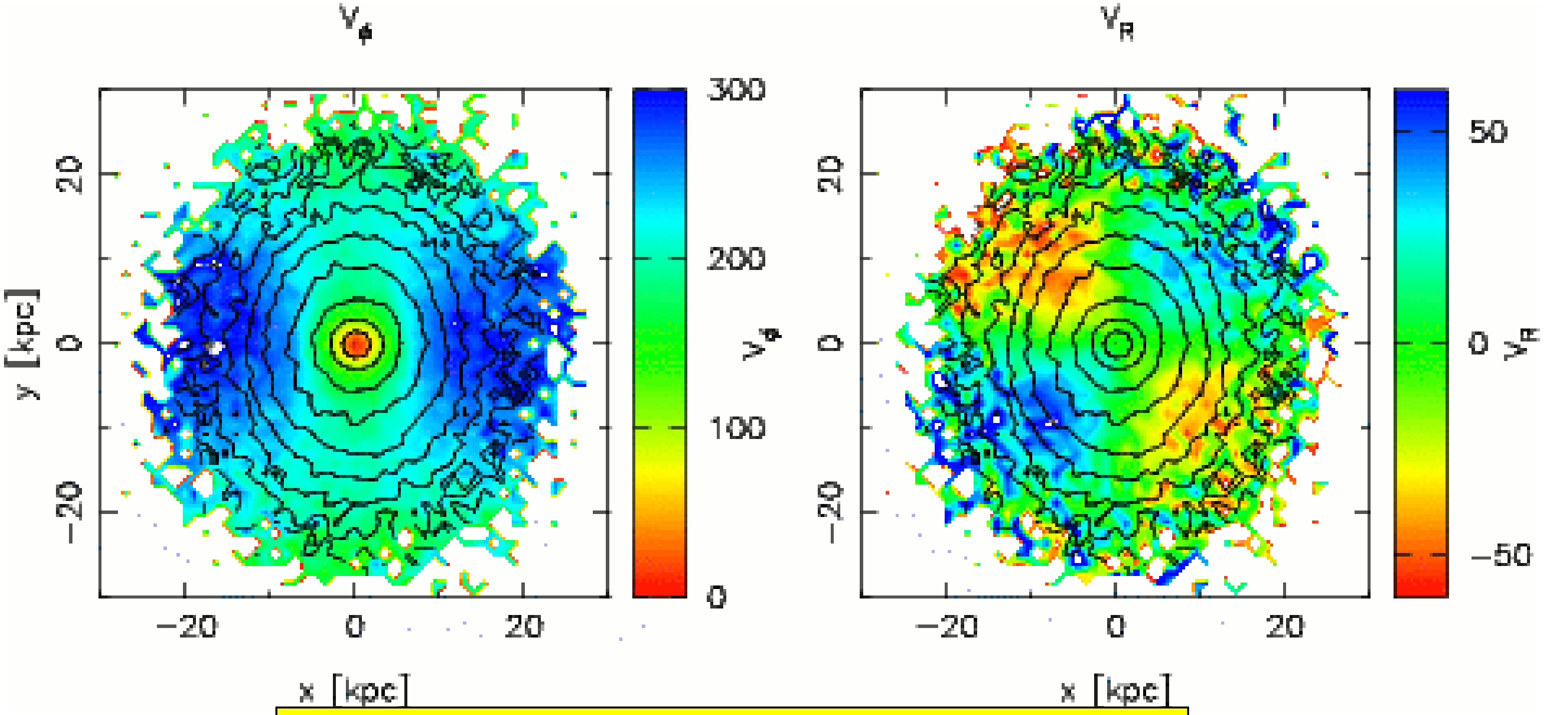
Frenk et al. 1988



Allgood et al. 2006

Shape depends weakly on mass <c/a> ~ M-0.05

Disk Velocity Field in Triaxial Halo



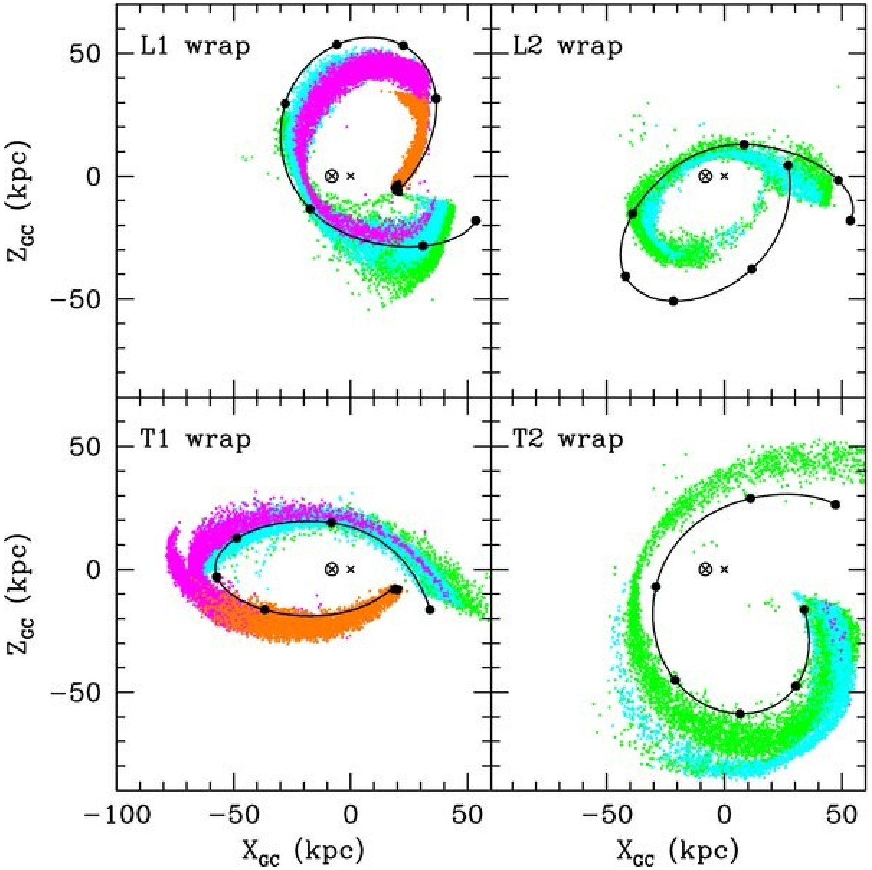
Major Axis

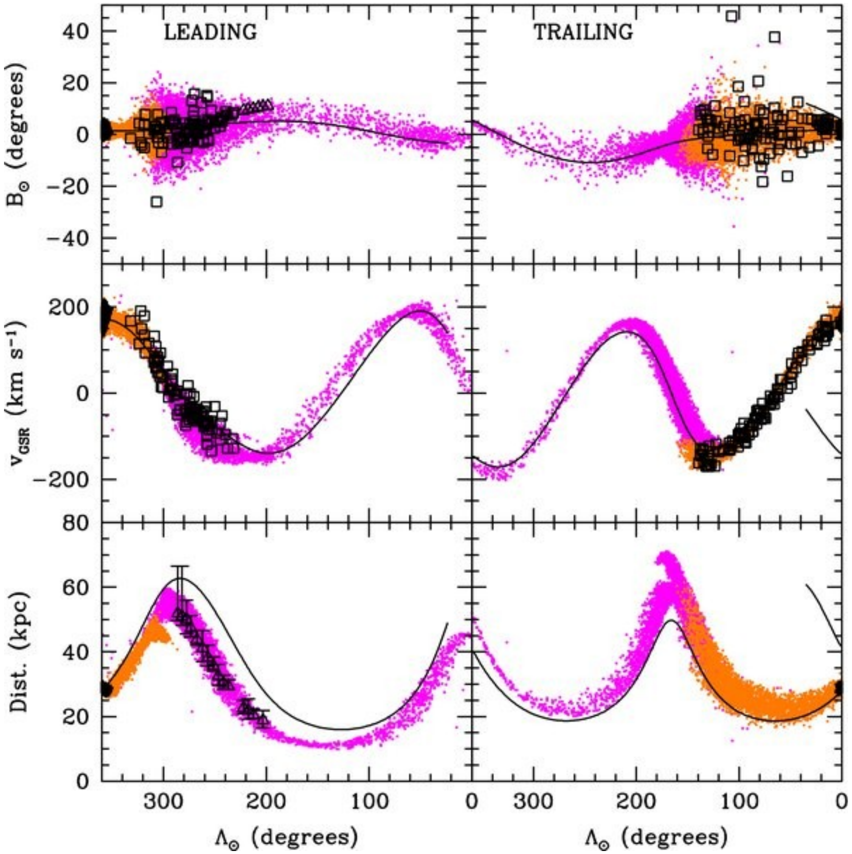
Large deviations from circular motions adds scatter to TF relation. εΦ = 0.1 adds 0.46 mag. of scatter

Franx & de Zeeuw 1992

Milky Way

Law & Majewski 2010

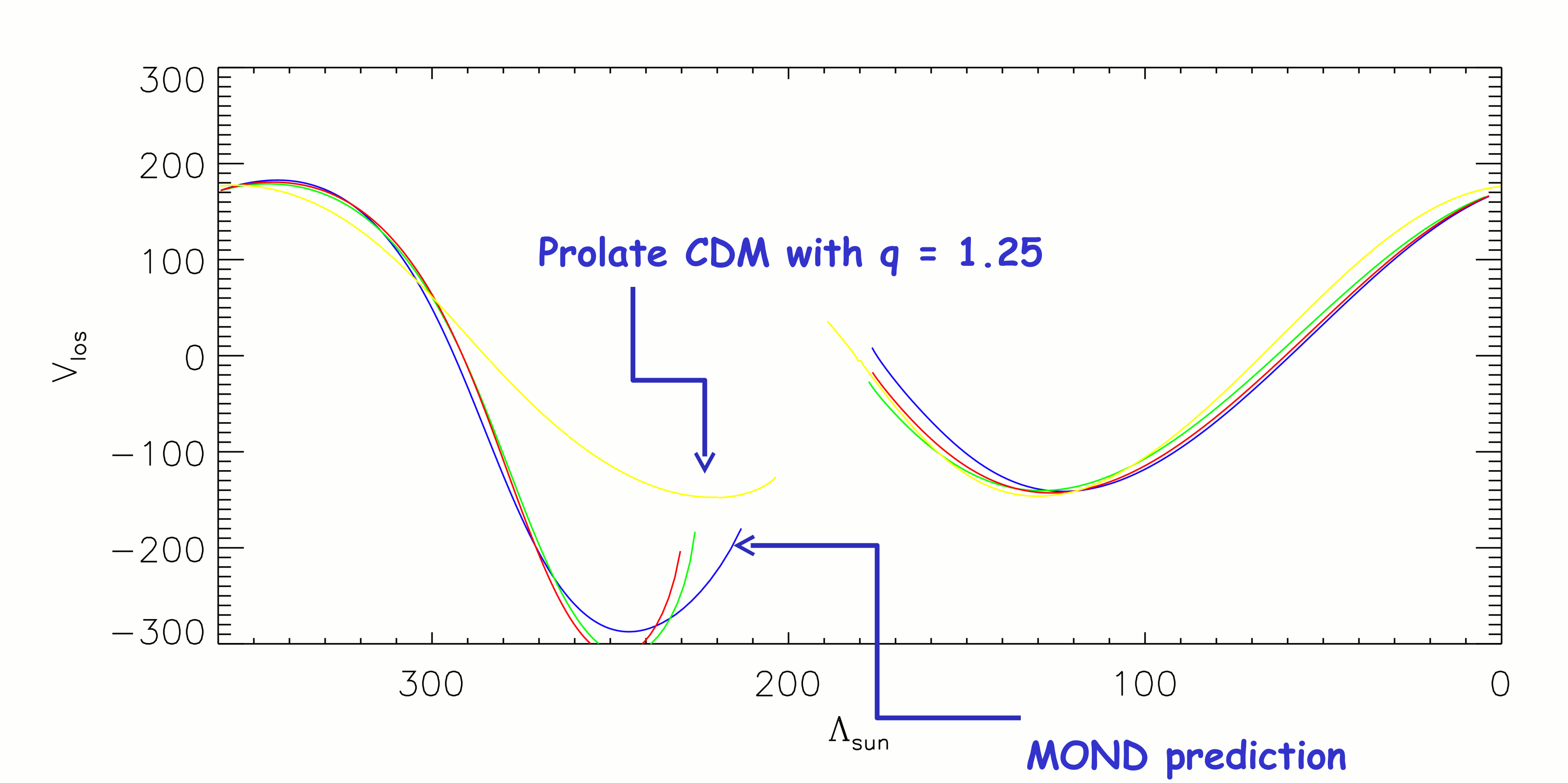




Based on the location and velocities of stars in the Sagittarius stream, MW halo is triaxial with c/a = 0.72 and b/a = 0.99 (pot). Nearly oblate with minor axis in plane of disk

Also Martinez-Delgado et al. 2004; Johnston et al. 2005; Helmi 2004

MOND?



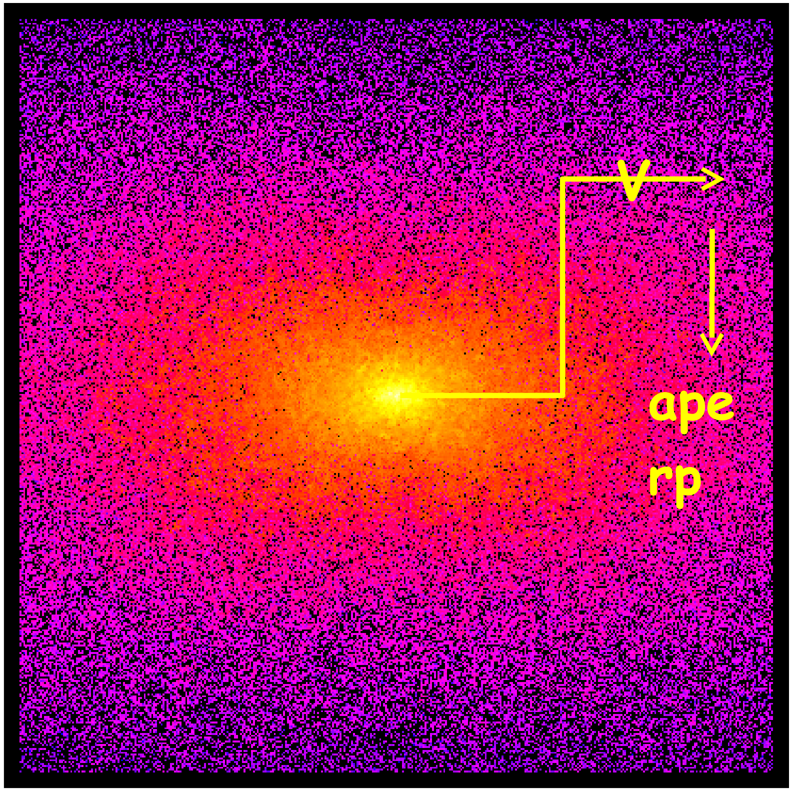
Prolate CDM with q = 1.25

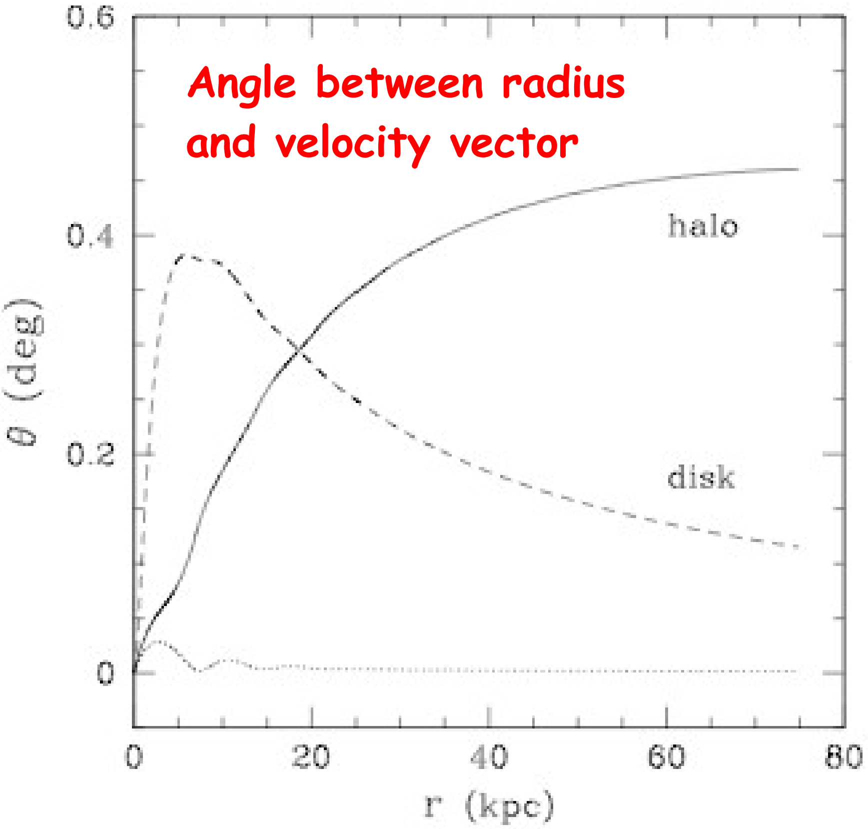
MOND prediction

MOND produces rounder potentials than standard Newton and is equally able to explain the velocities of stars in the Sagittarius stream.

Read & Moore 2005

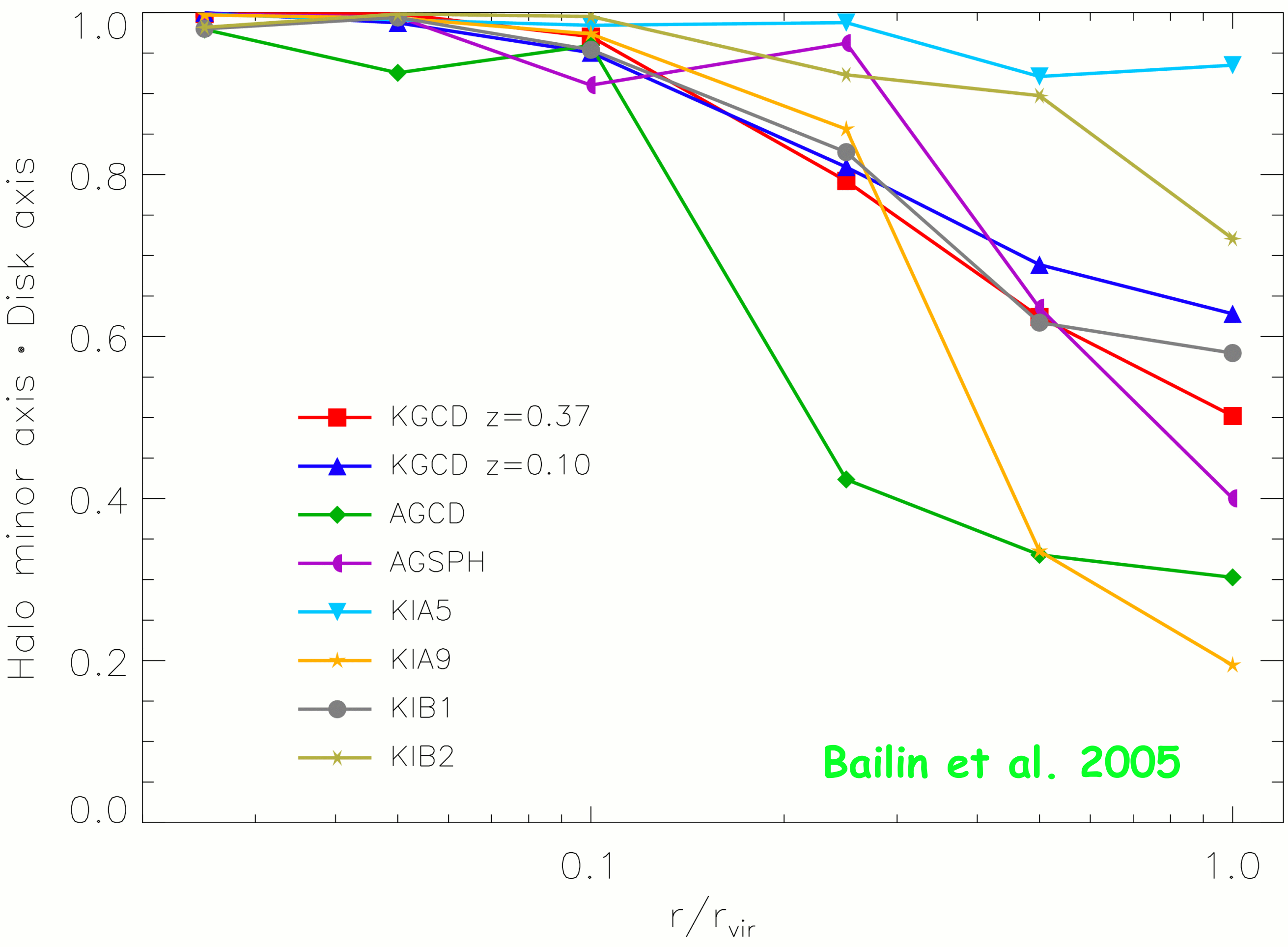
The Promise of Hyper Velocity Stars




Angle between radius and velocity vector

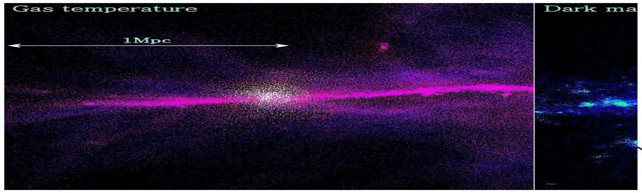
Stars kicked out by 3 body interactions with the central SMBG with v ~ 1000 km/s; about 10 are currently known

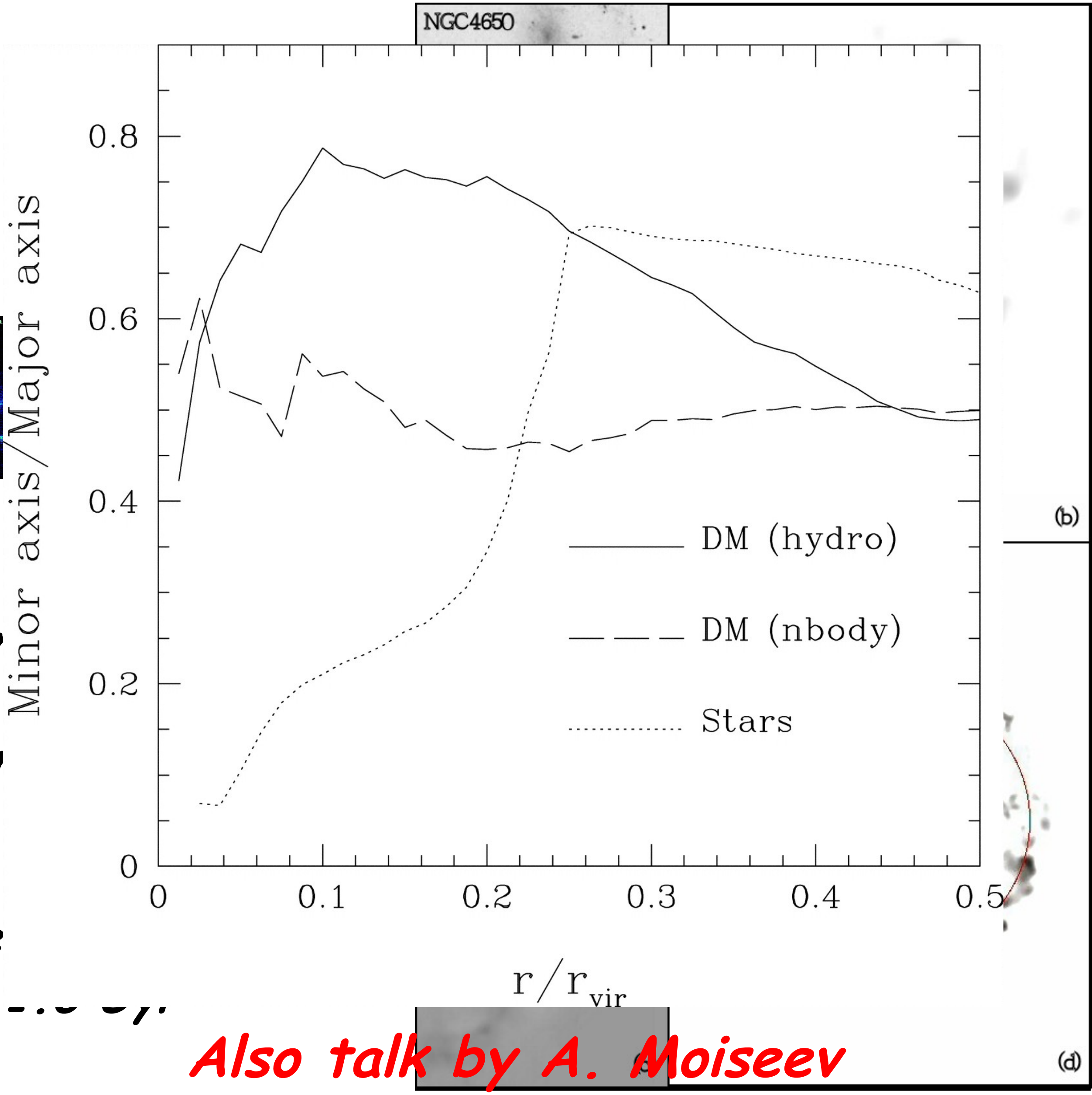
Gnedin et al. 2005



The inner halo is aligned with the disk, but further out there is no correlation. Halo vertically flattened by disk formation

Formation of polar ring galaxies: Evidence for cold accretio



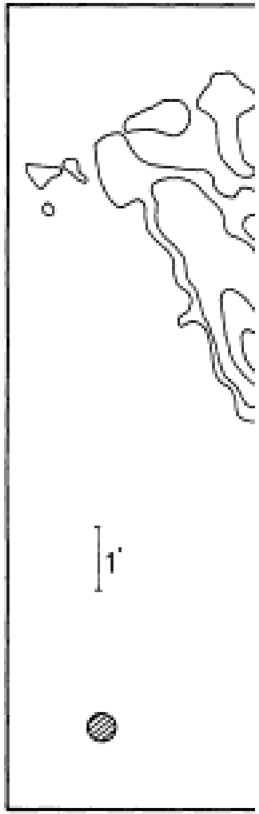


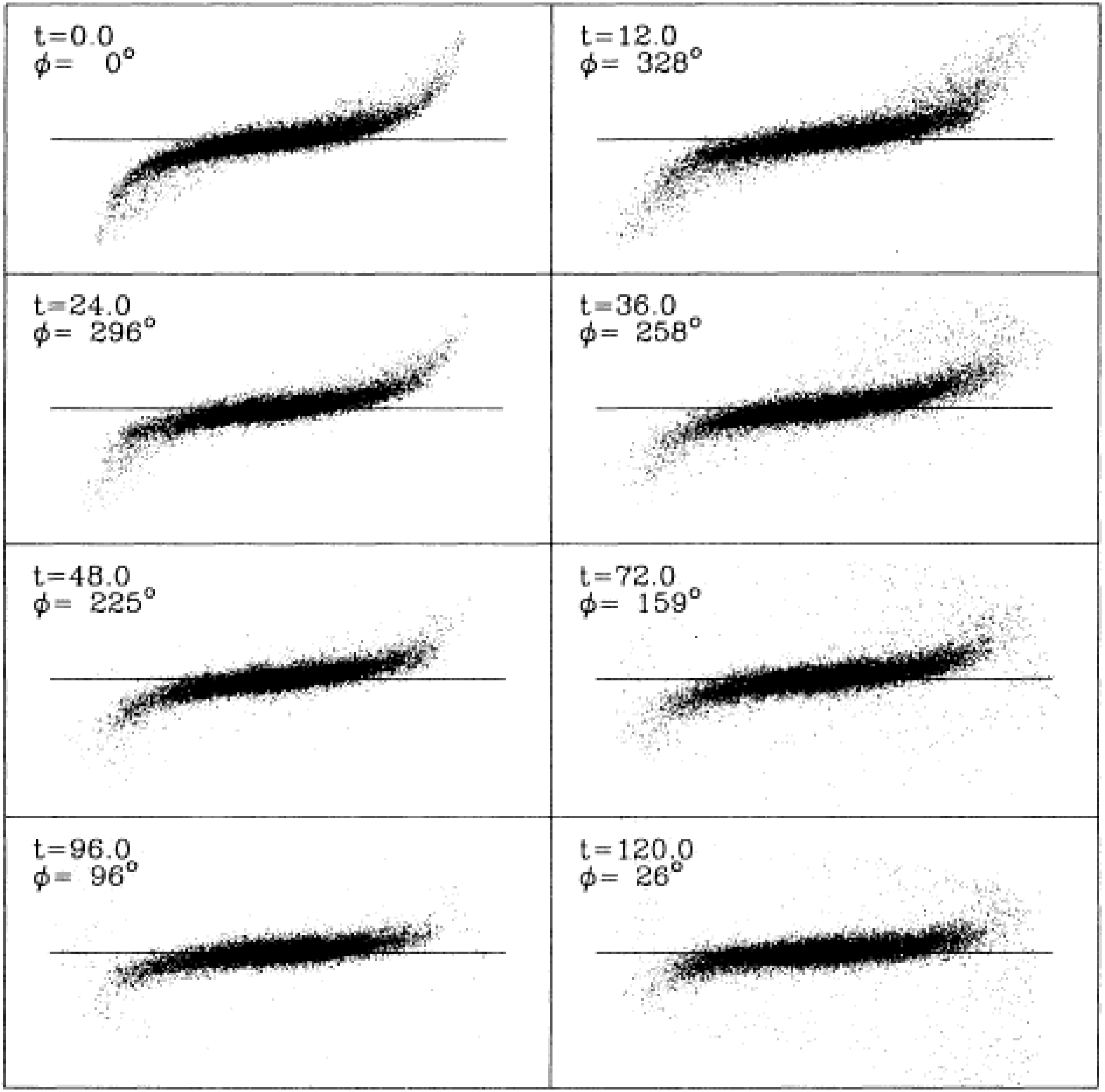
- Cold gas accretion alo
- Small offset between filament and galaxy ce
- Gas precesses around
- Creation of a gaseous
- No major/minor merge
- Isolated survives only
- qΦ ~ 0.9

Macciò et al. 2006

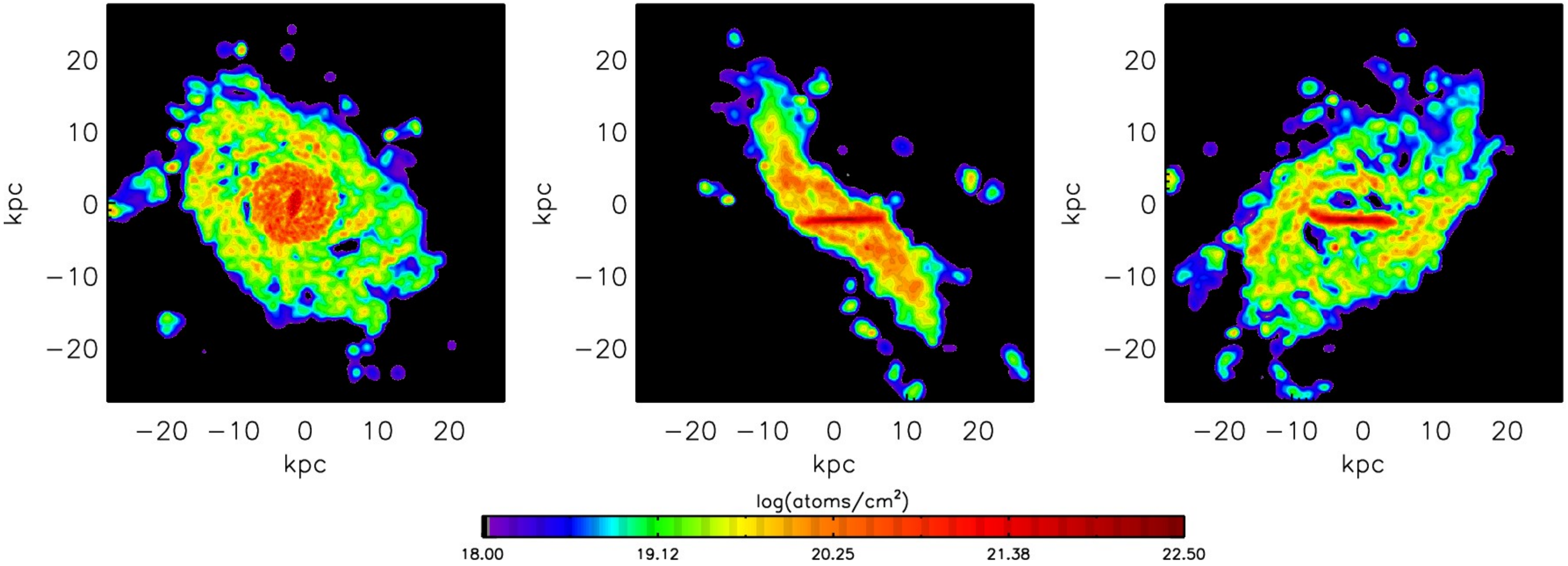
Also talk by A. Moiseev

Toomre (1983) an
are caused by disk.



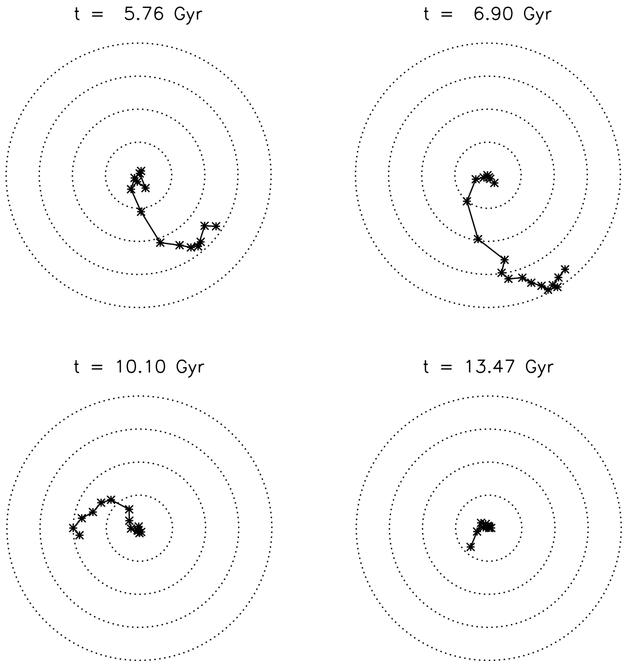


Dubinski & Kuijken 1995



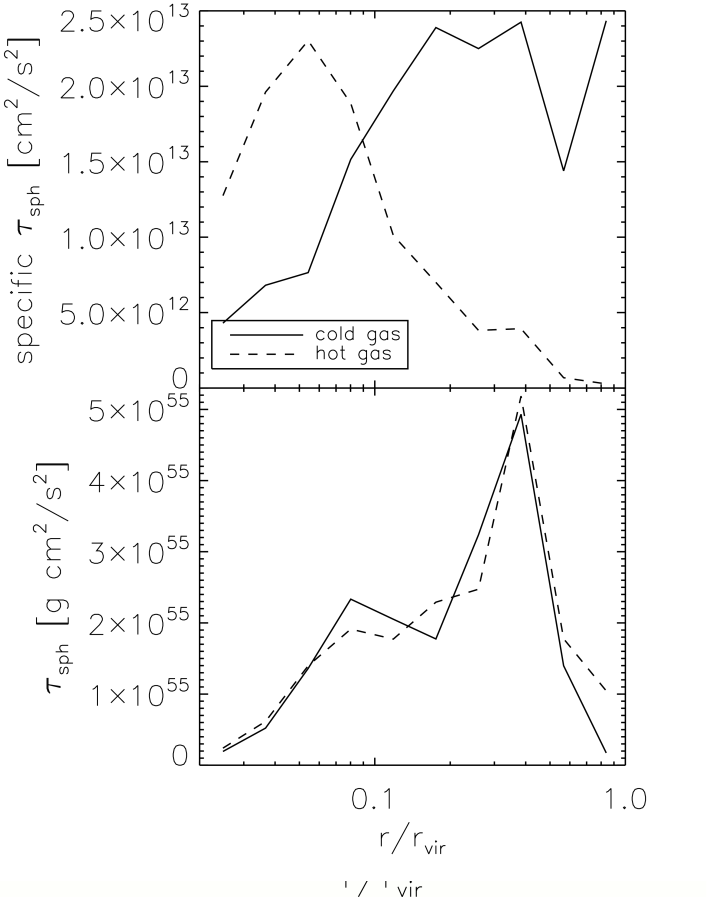
Persists for ~ 7 Gyr

- cold flow/stream/filament?
- merger?
- dark matter halo torque?



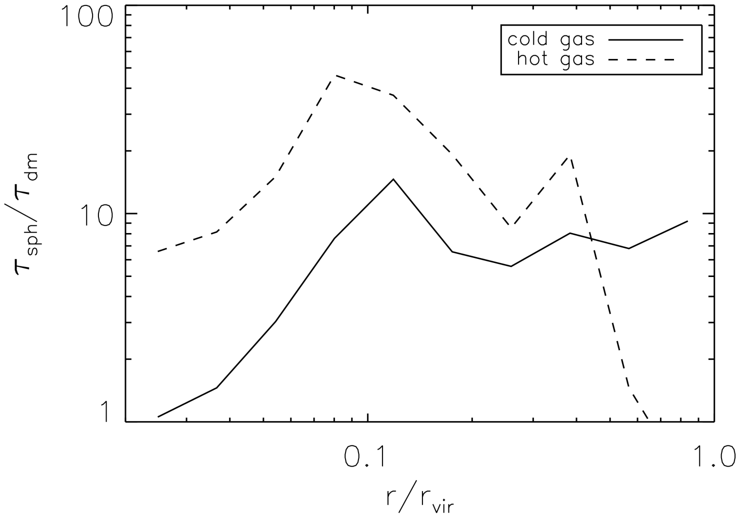
Also talk by G. Jozsa

- *The angular momentum of massive hot halo reflects some average accreted angular momentum*
- *The central disk can easily be reoriented by torques from e.g. infalling satellites - in general it is not aligned with the angular momentum of the halo*
- *Incoming gas encounters the spinning hot halo and is gradually torqued on its way to the center - it materializes as a warp if there is enough accretion and it is aligned with the halo (recall Bailin et al.*

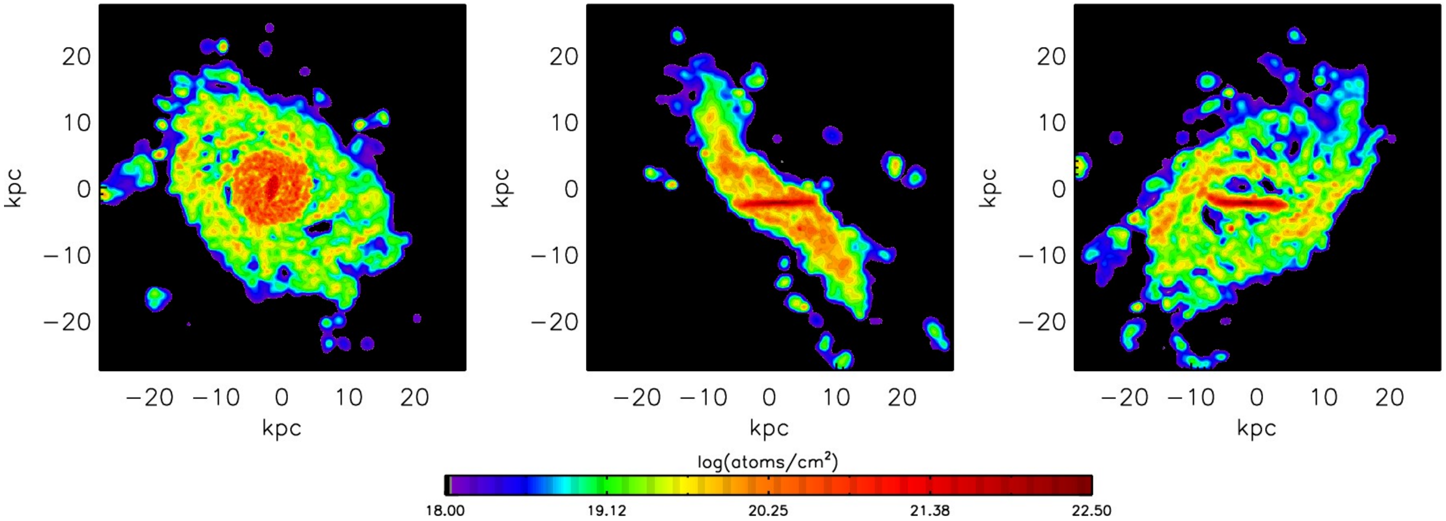


The angular momenta of hot and cold gas are remarkably well aligned

The cold gas feels strong hydrodynamic torques from hot gas

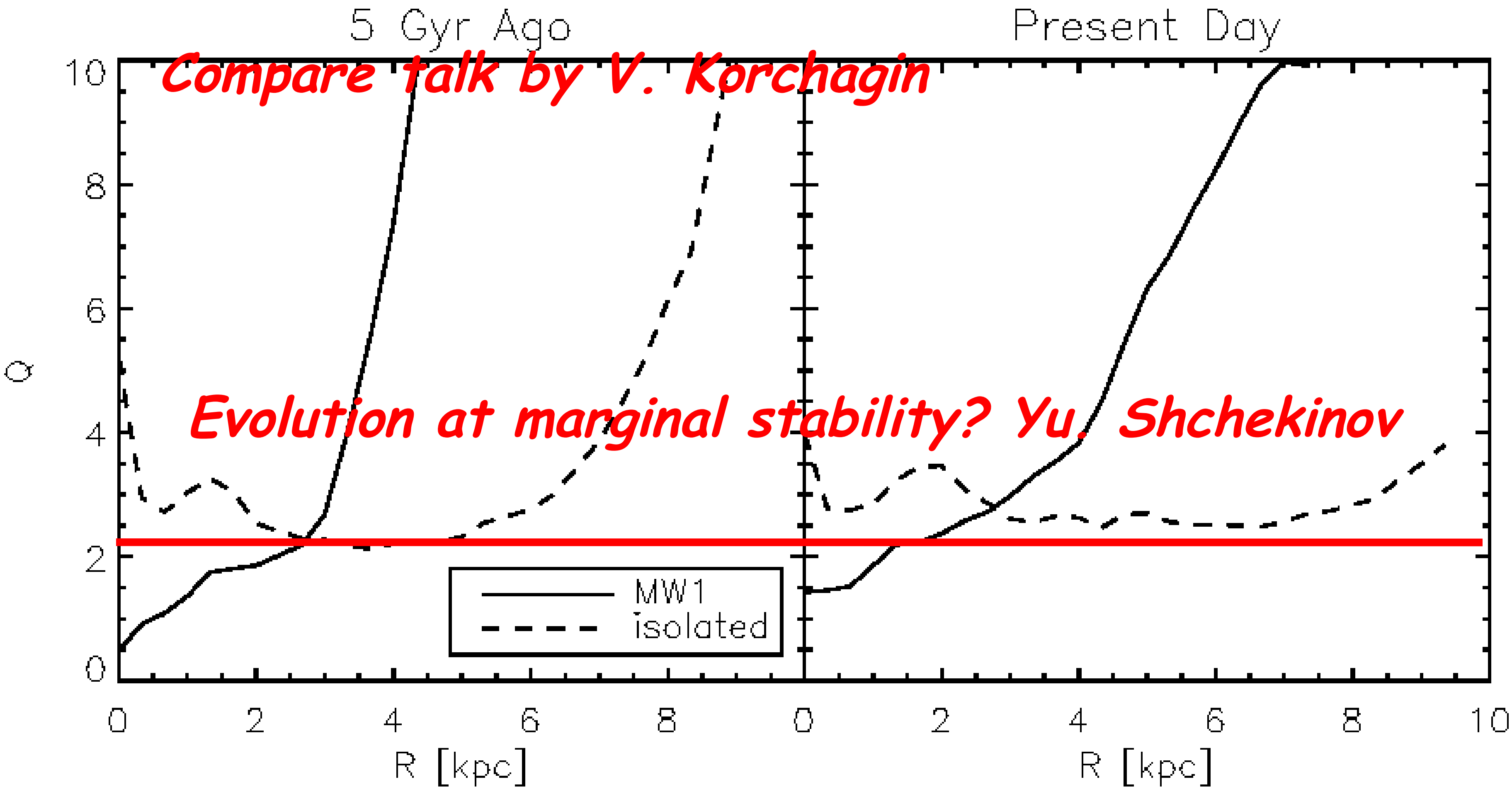


Since z ~ 2 DM halo has b/a ~ 0.8-0.9 and c/a ~ 0.5-0.7 But there is no coupling between gas angular momentum vector and halo minor axis



The warped disk corresponds to spin of (invisible) hot halo

(Roškar et al. 2010)

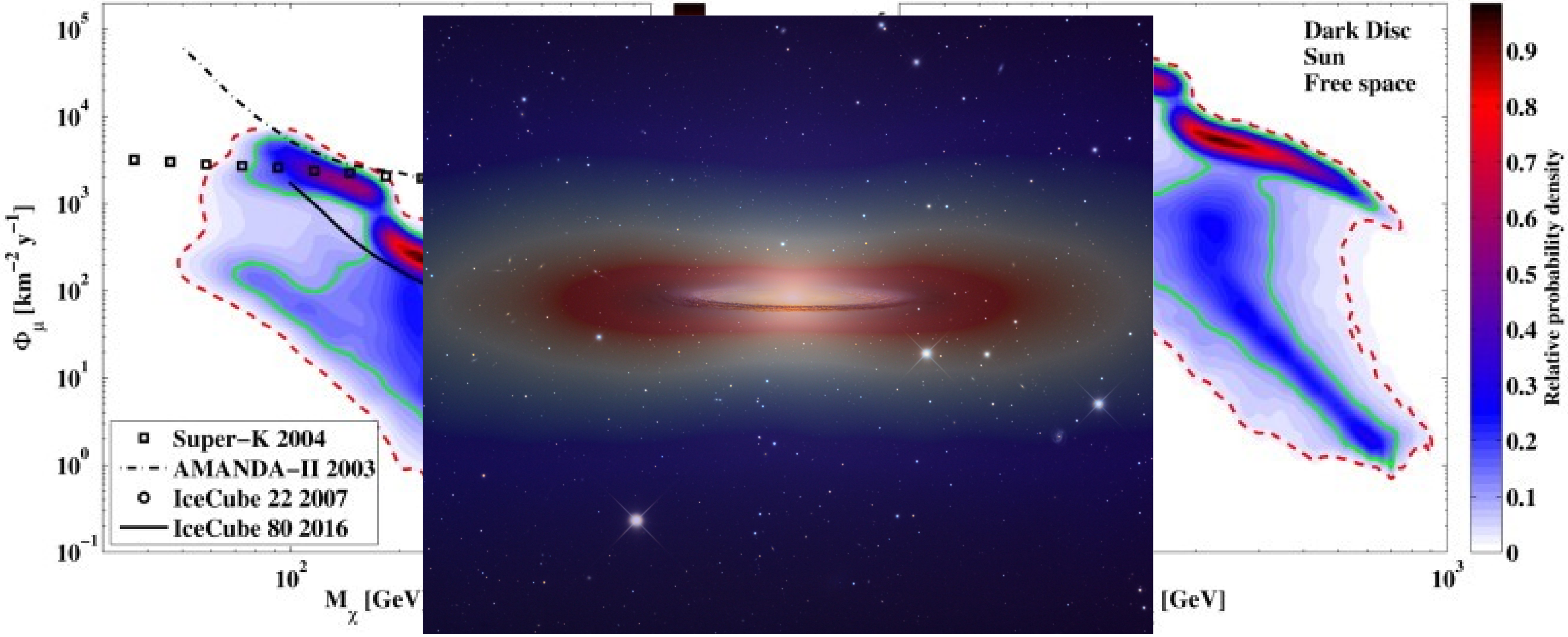


Compare talk by V. Korchagin

Evolution at marginal stability? Yu. Shchekinov

(Roškar et al. 2010)

Dark Disks



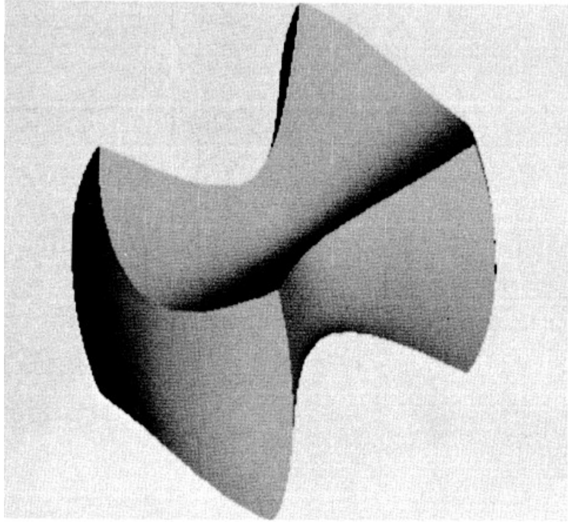
Satellite galaxies dragged into plane of the disk (Quinn & Goodman 1986; Quinn et al. 1993). These deposit their dark matter in a disk

Rotation leads to a low relative velocity wrt Sun enhancing capture of DM within Sun/Earth □ Enhanced annihilation signature

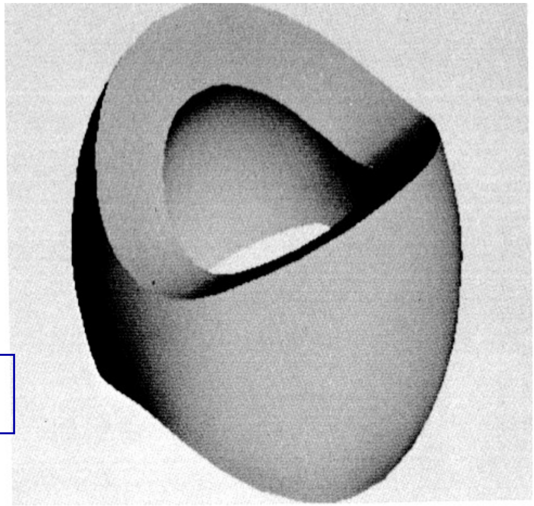
Read et al. 2008

Bruch et al. 2009

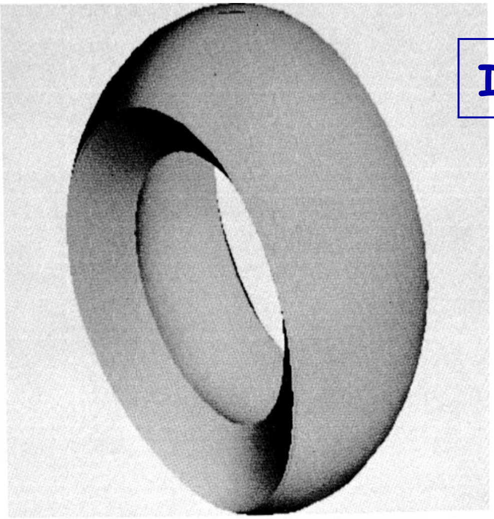
Orbits in Triaxial Halos



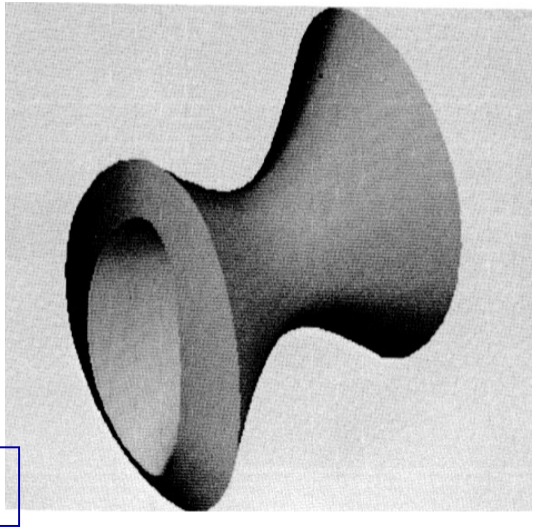
Box orbit



Short-axis loop



Inner long-axis loop



Outer long-axis loop

Statler 1987

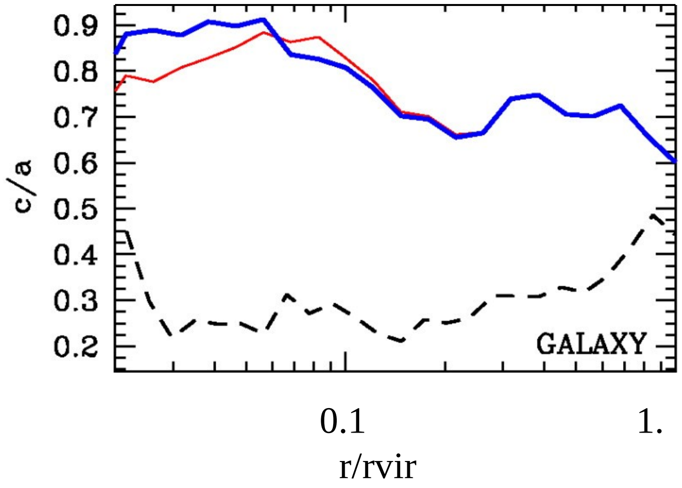
Cooling Baryons Effect on Halo Shape

N-body+gas simulations with cooling+star formation more spherical shapes in dark matter and stars (e.g Kazantzidis et al.2004)

Gas cools & sinks to the center of the potential

Similar results for mergers of disk galaxies

Kazantzidis et al. 2004



— DM profile

— DM+stars

------------ DM profile in Simulations without Cooling+SF

Also Dubinski 1994

Orbital Cause of Shape Changes

What causes the change from Triaxial □ Axisymmetric ?

Chaotic mixing due to scattering of box orbits by the central mass concentration (Norman et al. 1996, Merritt & Quinlan 1998, Valluri & Merritt 1998, Maccio et al. 2007)

Central potential changed from triaxial to spherical. To maintain self consistency □ regular orbits change their shapes and orbital types (Hernquist & Barnes 1987, Holley-Bockelmann et al. 2002).

Key idea: Chaos □ Irreversibility

Numerical noise in N-body systems ensure that they are dynamically irreversible but with care this can be minimized

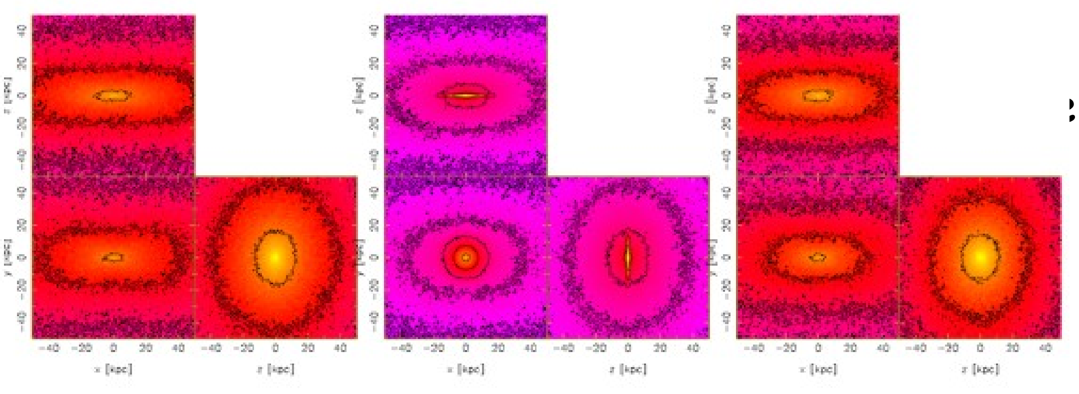
Loss of box orbits may affect the annihilation cross section at the center of the MW and may decrease the speed of SMBH mergers

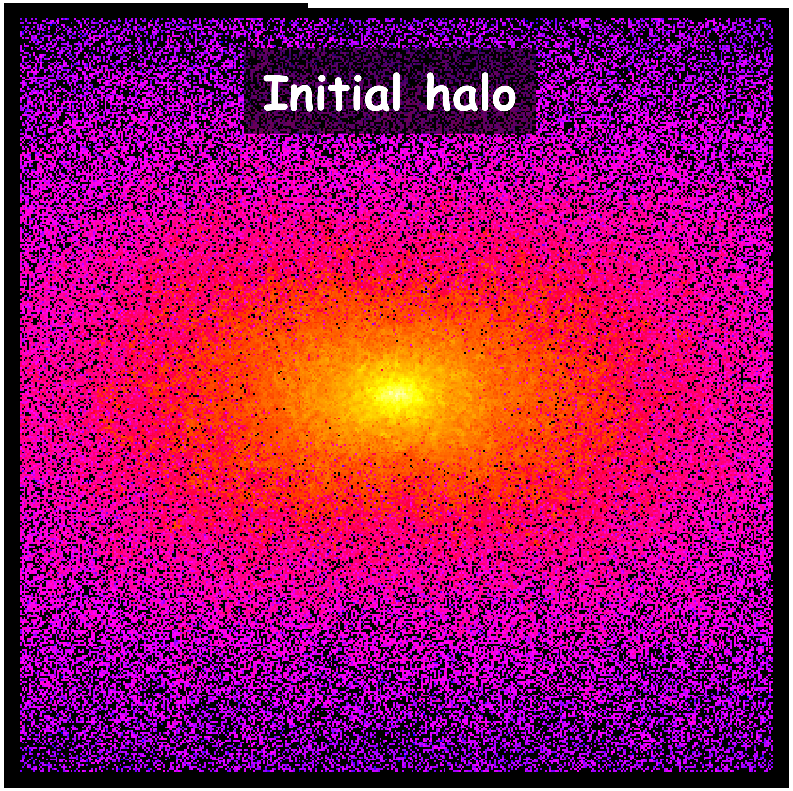
Reversibility Experiments

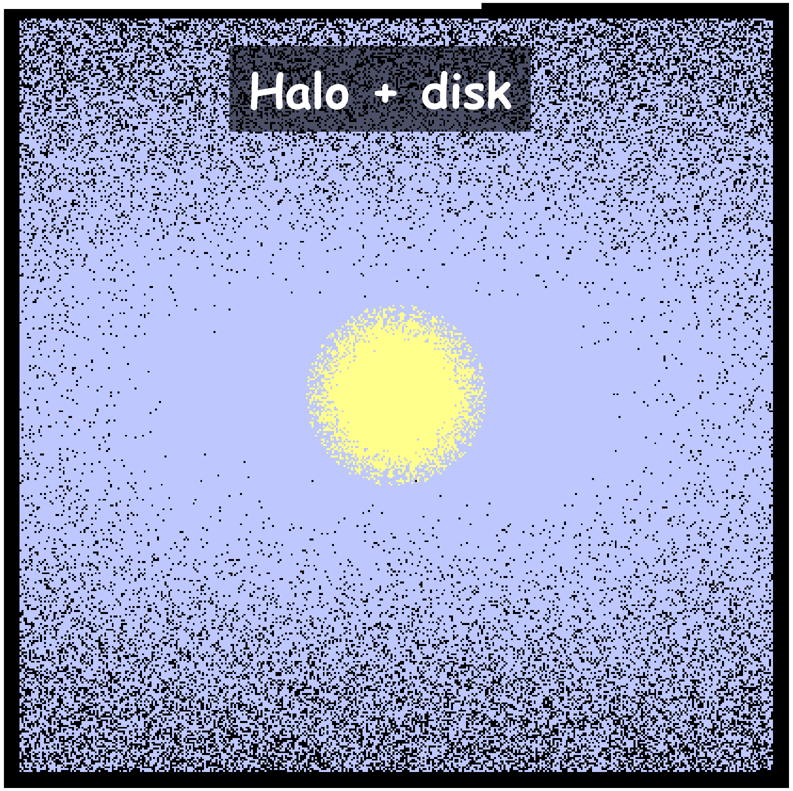
Experiments

Adiabatically

Then “evapor







Simulations: 3 Models

PKDGRAV experiments with NFW halos.

Phase a : initial triaxial/prolate halos

- Halos generated by mergers with Mvir = 6.5□1011 - 4.5□1012 M□ using 4 x 106 particles

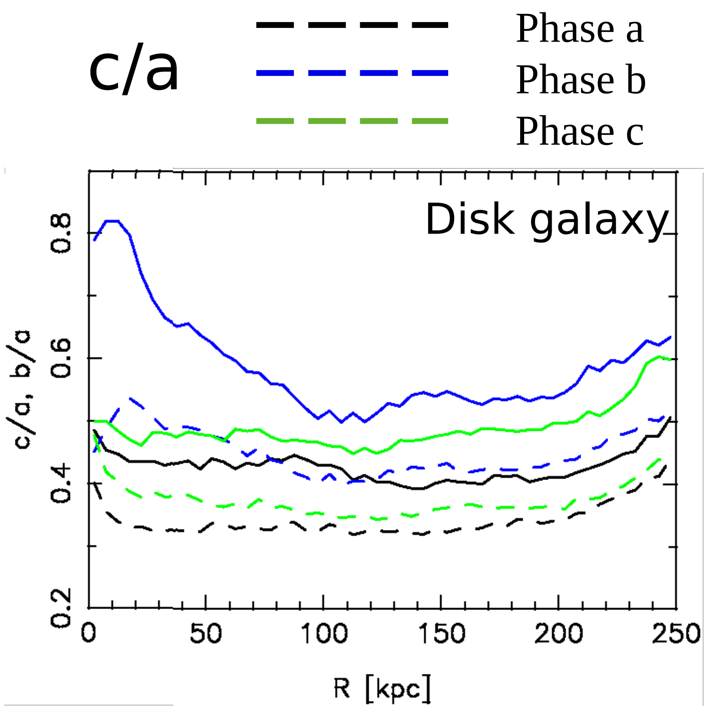
Phase b: baryonic component grown adiabatically (5-10Gyr)

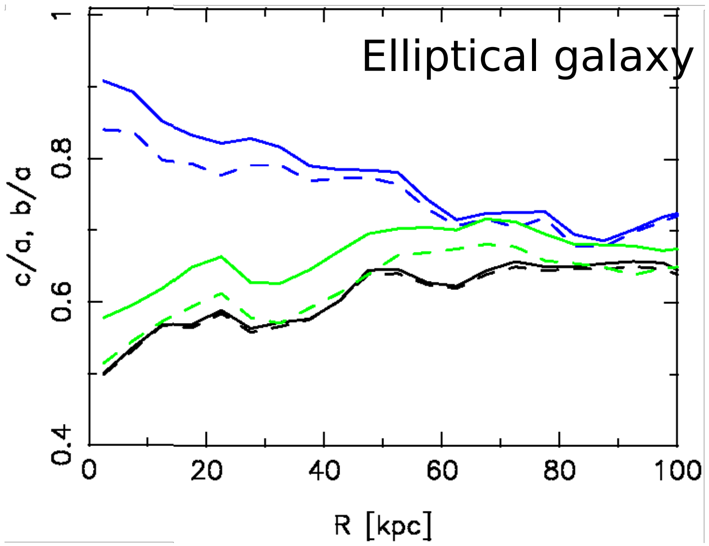
- Model SA1: Disk component symmetric about short axis
  - Mb= 1.75 □1011 M□ (3.8%), Rb=3kpc
- Model PfB2: softened, point mass (elliptical)
  - Mb= 7 □1010 M□ (10%), Rb=3kpc
- Model PlB3: hard, point mass
  - Mb= 3.5 □1010 M□ (5.3%), Rb=0.1kpc

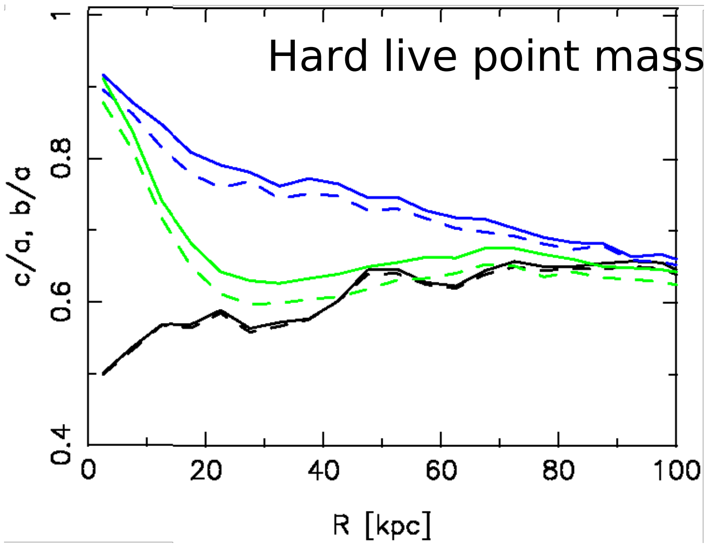
Phase c: system after the baryonic component is evaporated

Debattista et al. 2008

- With baryonic component c/a increase at all radii
- After evaporation halo is only slightly less triaxial than initial halo
- Halo shape is almost reversible very little non-linear (chaotic) evolution

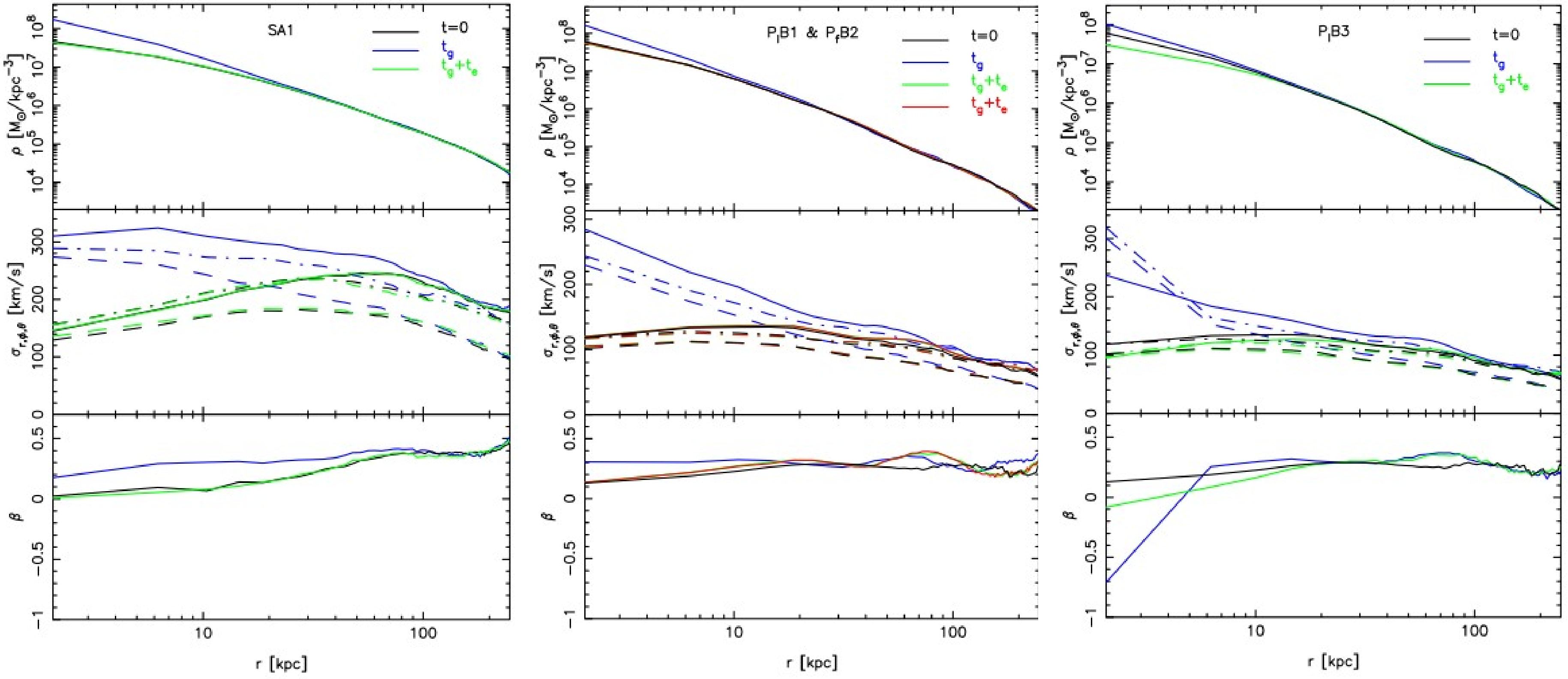






also Kalapotharakos 2008

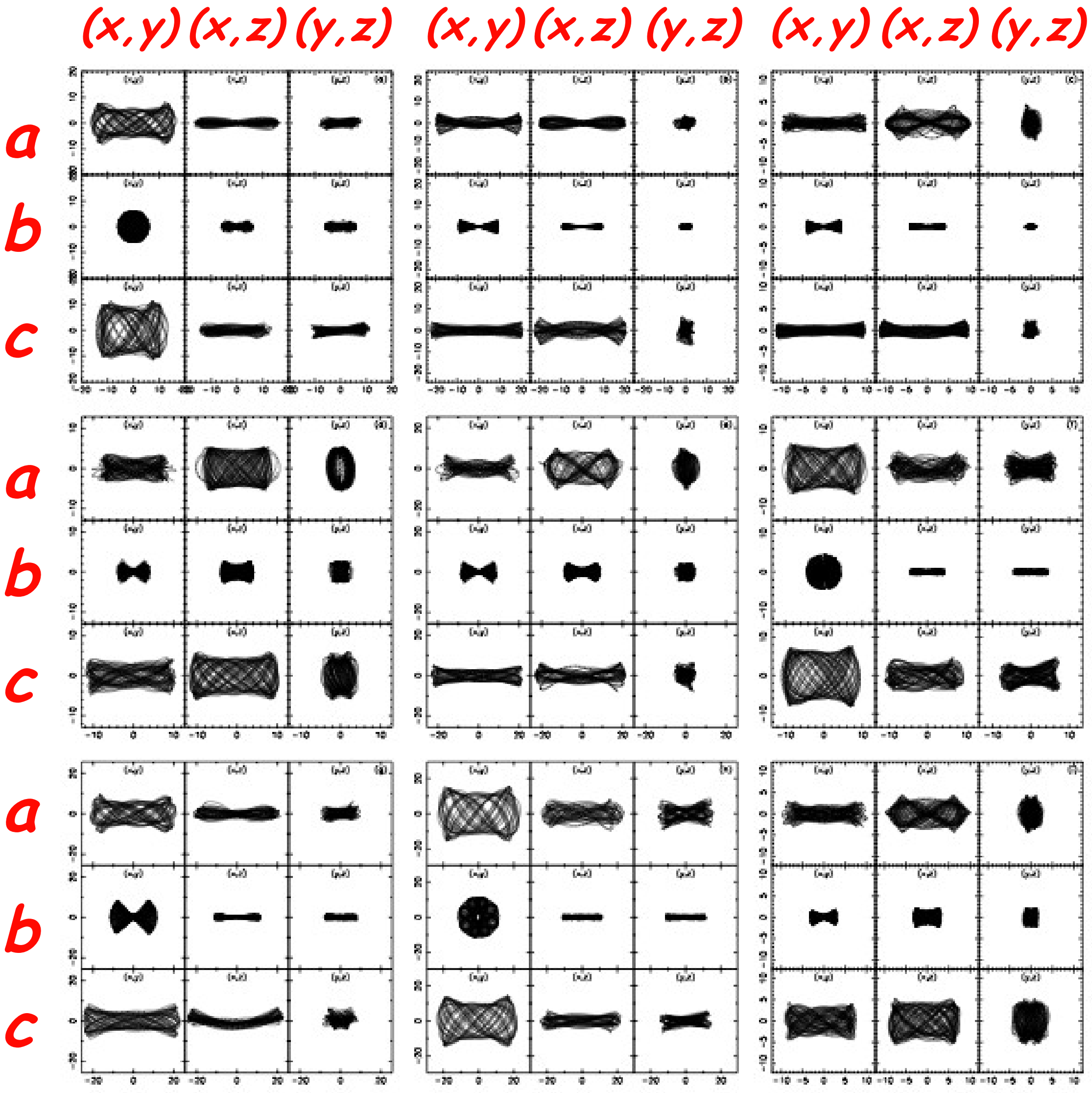
Halo Profile & Kinematics



Baryon growth induces radial anisotropy, except when change is irreversible: then tangential anisotropy

□r
□□
□□

Orbital Transformation: Disk Case

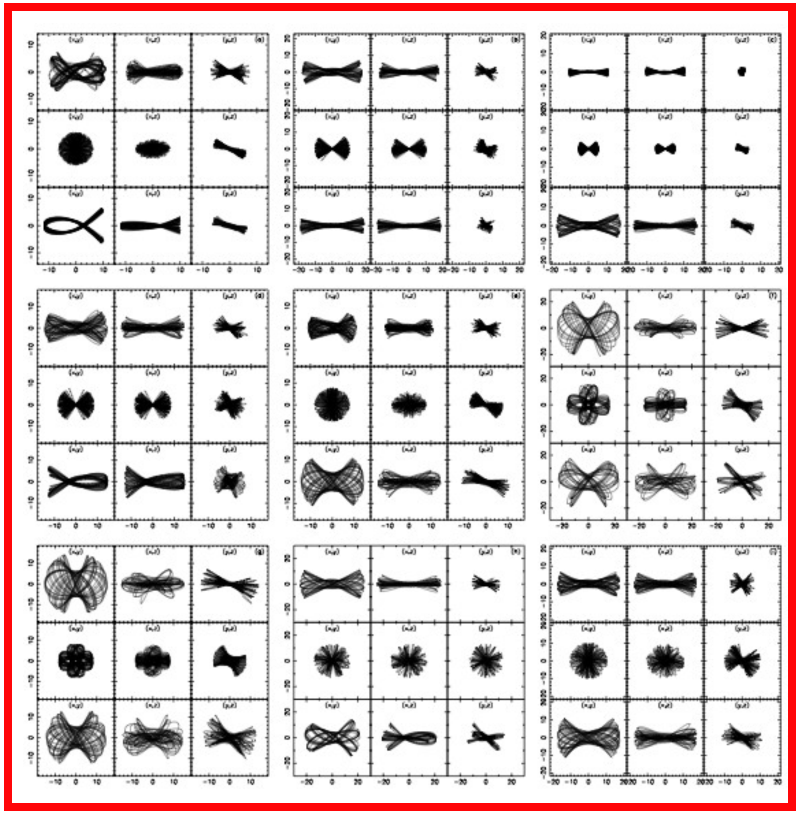


X > Y > Z

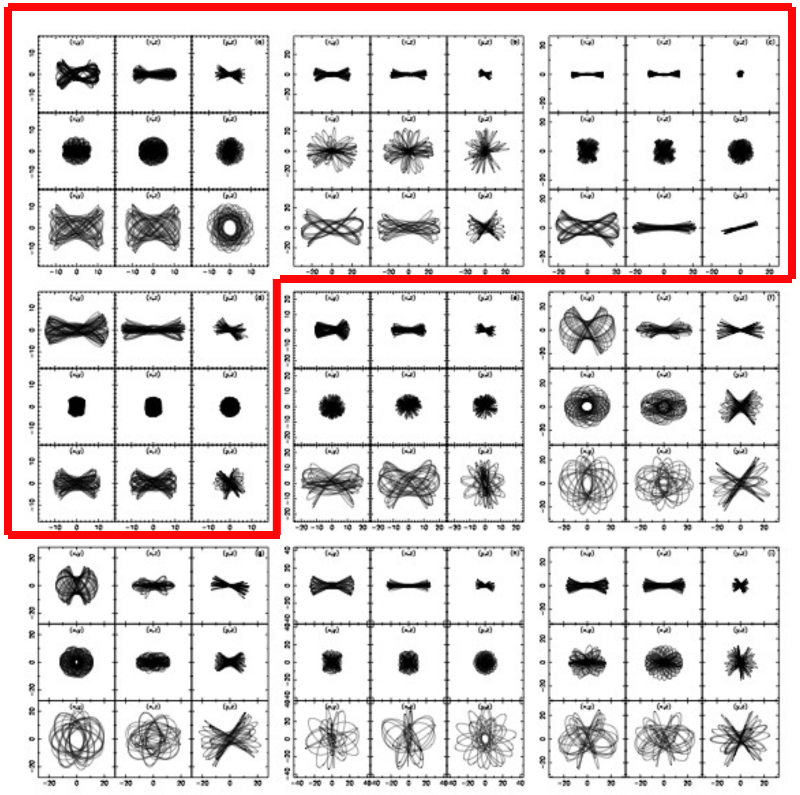
“Boxy” or “box-like” orbits in SA1 become rounder and sometimes transform to loops but do not appear to become chaotic

Orbital Transformation: PfB2, PlB3

Elliptical



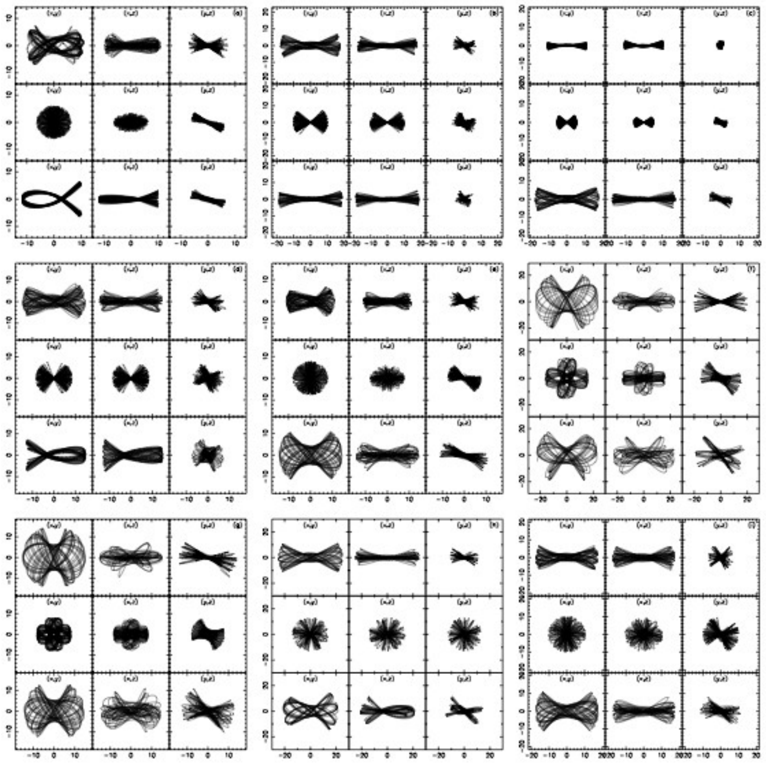
Hard Center



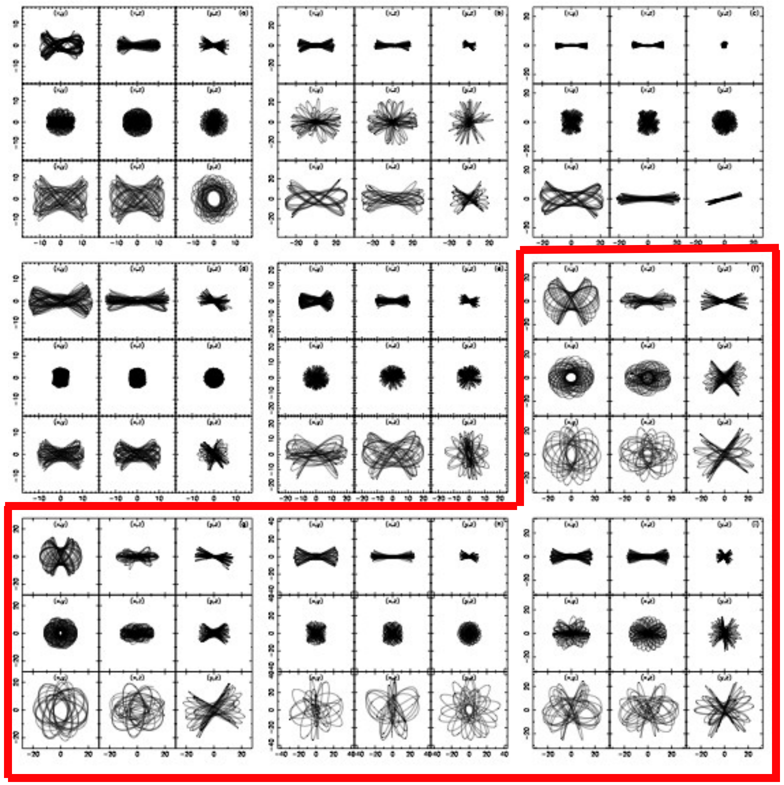
Untransformed orbits

Orbital Transformation: PfB2, PlB3

PfB2



PlB3



Transformed orbits

Orbital Frequency Analysis

Regular orbits are quasi-periodic

Fourier Transform yields □k and Ak

All frequencies are integer linear combinations of 3 fundamental frequencies of motion □i

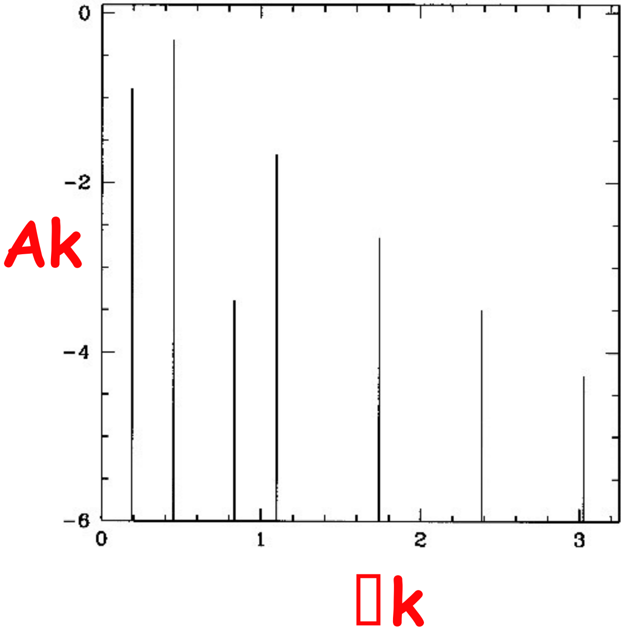
Frequencies can be used:

To identify chaotic orbits

To classify regular orbits into major orbit families:

- Box orbits
- Short axis (z) tubes
- Long axis (x) tubes
- Resonant and Periodic orbits

To map the phase space



Laskar 1990, 1996

Orbital Frequency Analysis

Grainy N-body potential causes noise

All orbits in a spherical potential are regular.
Frequency drift in spherical potential: measure of non-linearity due to graininess

Frequencies computed over two time series t1, t2
log(□ f) = log|[□ (t1)- □ (t2)]/□ (t1)|.

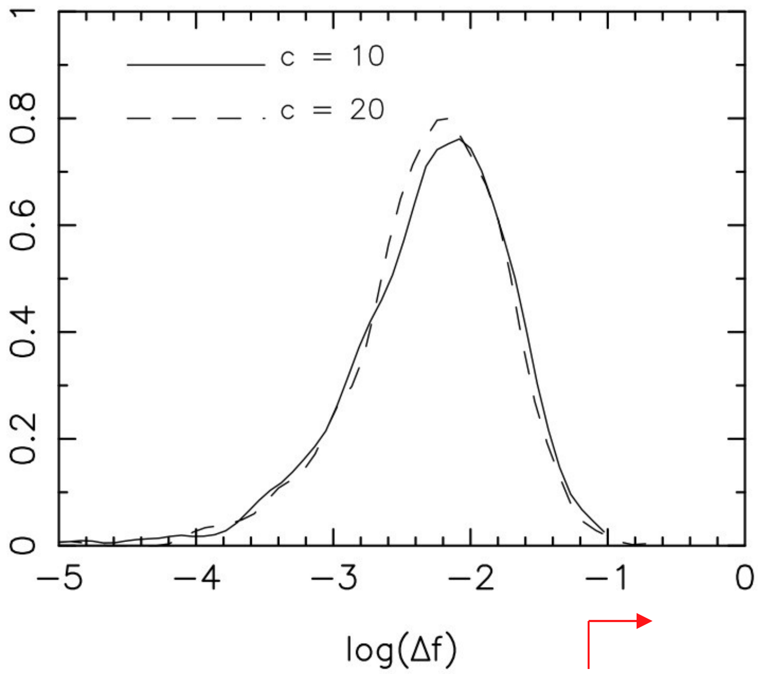
99% of orbits in spherical NFW halo

have Log(□f) < -1.2. Orbits defined as *CHAOTIC* if Log(□f) > -1.2

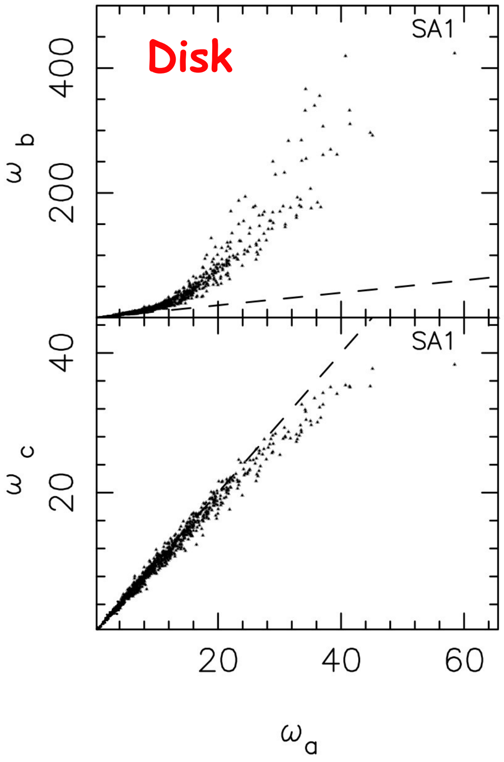
Analyze orbits in frozen potential

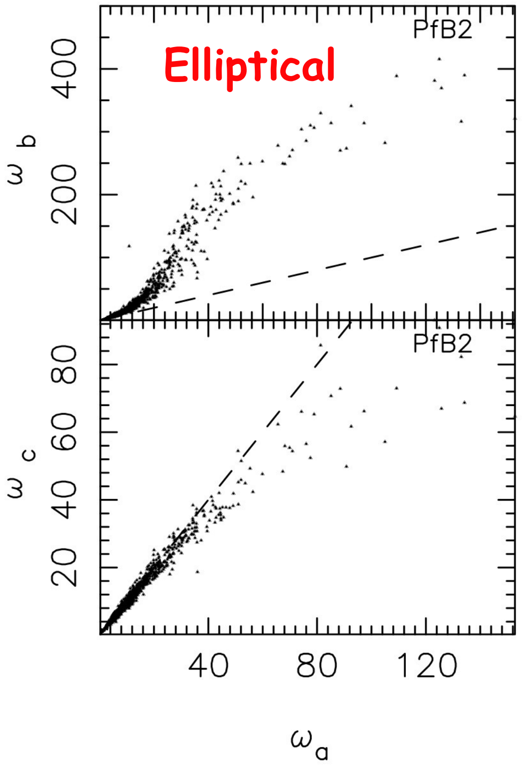
necessary for obtaining accurate frequencies

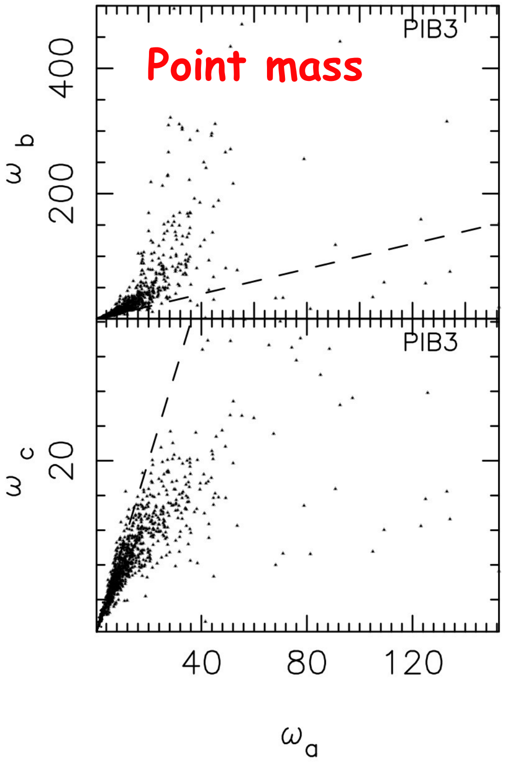
necessary for accurate orbit classification



Frequency at the 3 Stages



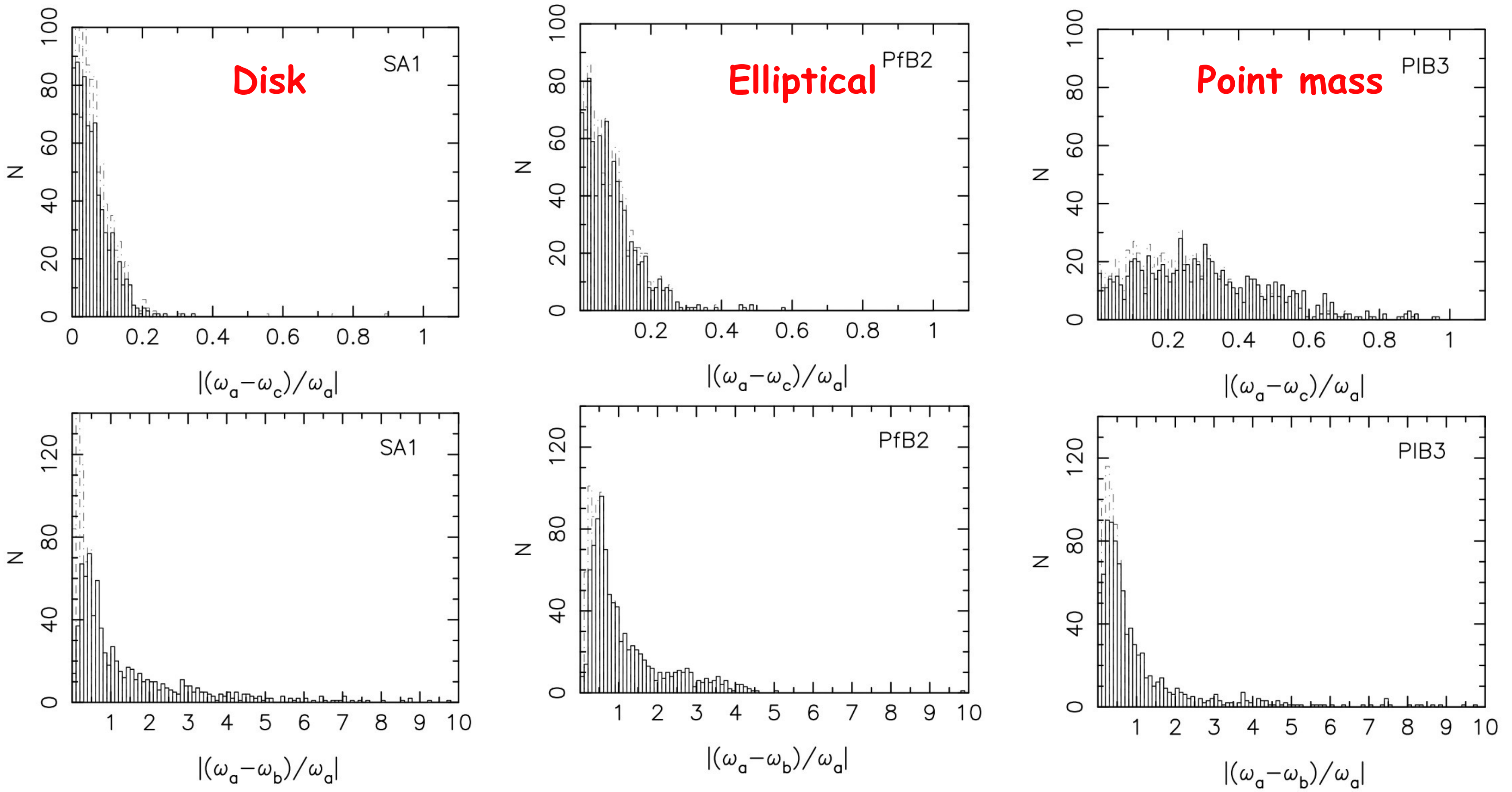




When a disk (SA1) or elliptical galaxy (PfB2) is grown - frequency changes are well behaved

Hard point mass produces a great deal of scattering in frequencies

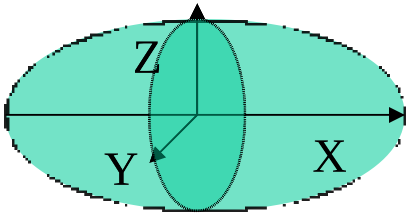
Fractional Frequency Change



Permanent change in frequencies (TOP) small (< 10% for >90% of orbits) except in case of hard point mass

Median change of orbital frequency (BOTTOM) independent of type of baryonic component - all three distributions have peak ~ 0.65

Orbital Classification



Orbit classification (Carpintero & Aguilar 1998)

Search for rational ratios of fundamental frequencies

Initial state (phase a)

Model SA1 (triaxial) - box orbit dominated (83%); X-tubes (11%)

Models PfB2/PlB3 (prolate)- X-tubes (77%); box orbits (15%)

With baryonic component (phase b)

SA1 - 57% of boxes become Z-tubes & chaotic orbits (34% of orbits formally chaotic)

PfB2/PlB3 - X-tube fraction only slightly changed

Post-evaporation (phase c):

SA1 orbit populations revert to original type distribution

PfB2/PlB3 X-tubes convert to Z-tubes and boxes

Permanent orbit type change is not adequate to explain change in halo shapes

Relatively large chaotic fraction in SA1b (34%) does not lead to permanent shape change! Why?

Orbit Type	**Run SA1**			**Run PfB2**			**Run PlB3**		
	Phase a	*Phase b*	*Phase c*	*Phase a*	*Phase b*	*Phase c*	*Phase a*	*Phase b*	*Phase c*
Box	0.83	0.35	0.82	0.15	0.08	0.28	0.15	0.02	0.21
X-Tube	0.11	0.08	0.12	0.77	0.71	0.53	0.77	0.76	0.59
Z-Tube	0.02	0.23	0.03	0.07	0.08	0.15	0.07	0.11	0.14
Chaotic	0.04	0.34	0.03	0.01	0.13	0.04	0.01	0.11	0.06

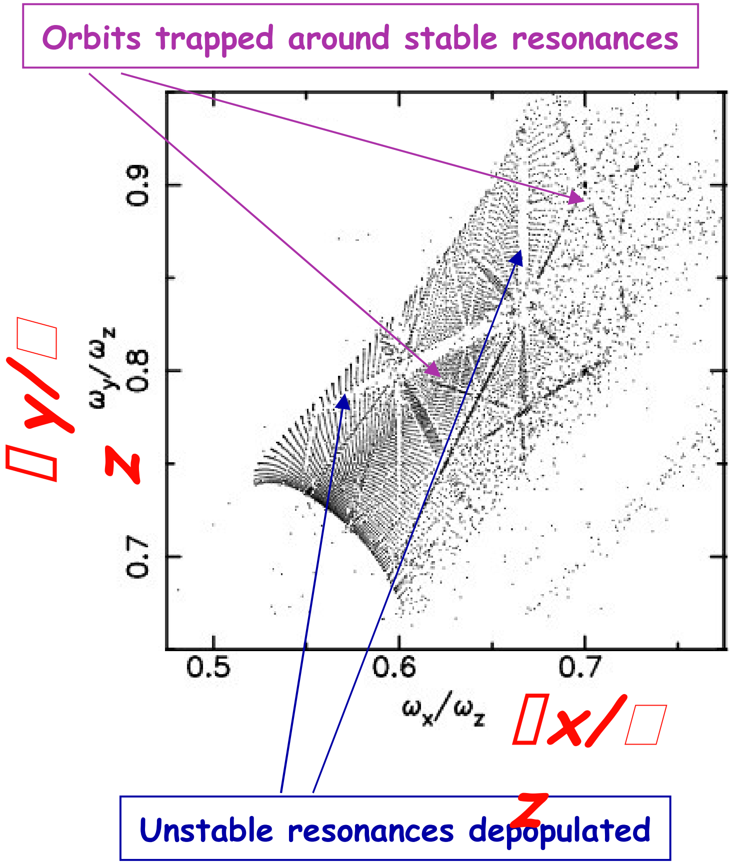
Frequency Maps

Plots of ratios of fundamental frequencies can show the full structure of phase space.

Orbits cluster around stable resonances due to resonant trapping

Unstable resonances appear as blank lines - unstable regions of frequency space are depopulated

In SA1 phase b 34% of orbits are chaotic - but the model returns to its original shape. Why no chaotic diffusion?



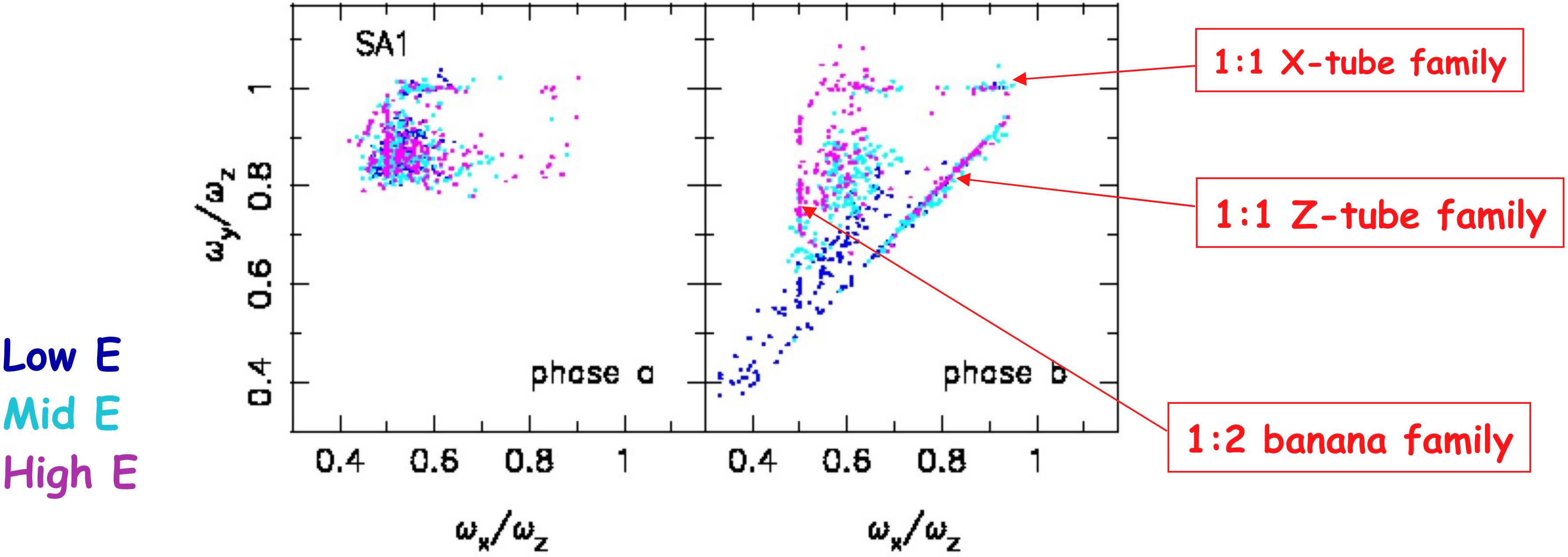
Orbits trapped around stable resonances

Unstable resonances depopulated

Valluri & Merritt 1998

Like a Poincare surface of section integrate ~10,000 orbits at a single energy for frequency map.

Frequency Map of SA1



Low E

Mid E

High E

1:1 X-tube family

1:1 Z-tube family

1:2 banana family

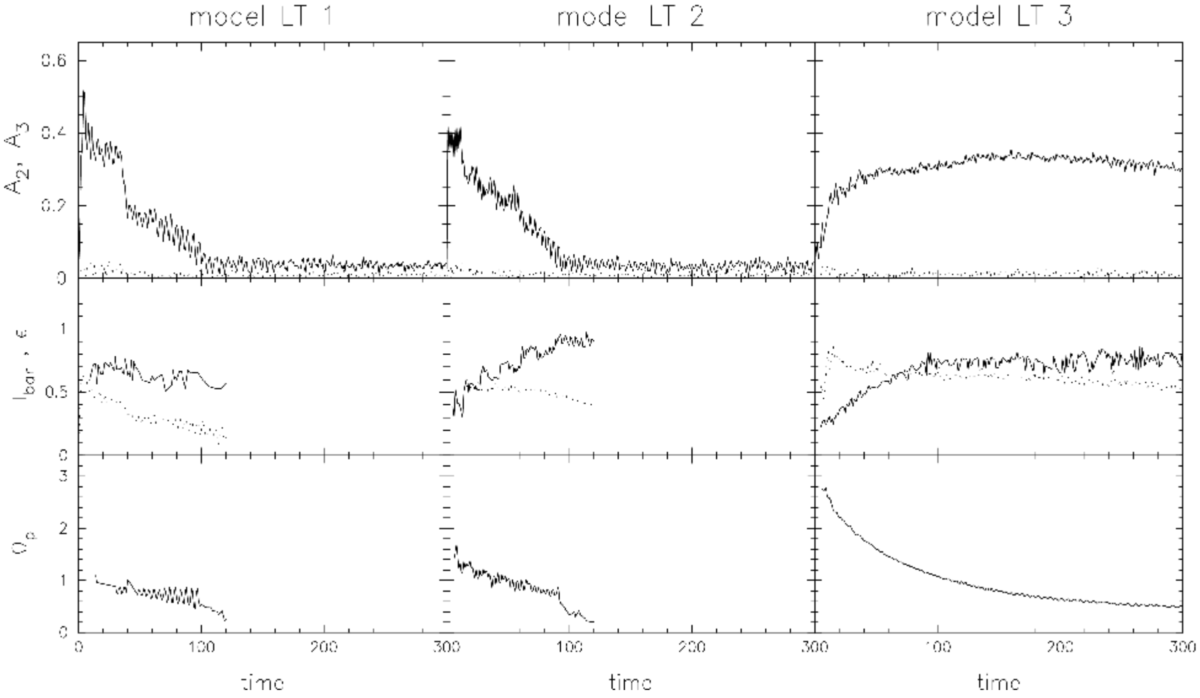
Orbits span full range of energies (binned in 3 equal energy intervals)

3 Global resonances appear in phase b (over wide range of energies)

Large fraction of orbits resonantly trapped around 3 main resonances

60% of chaotic orbits have frequency ratios within ±10% of these resonances and therefore do not diffuse chaotically

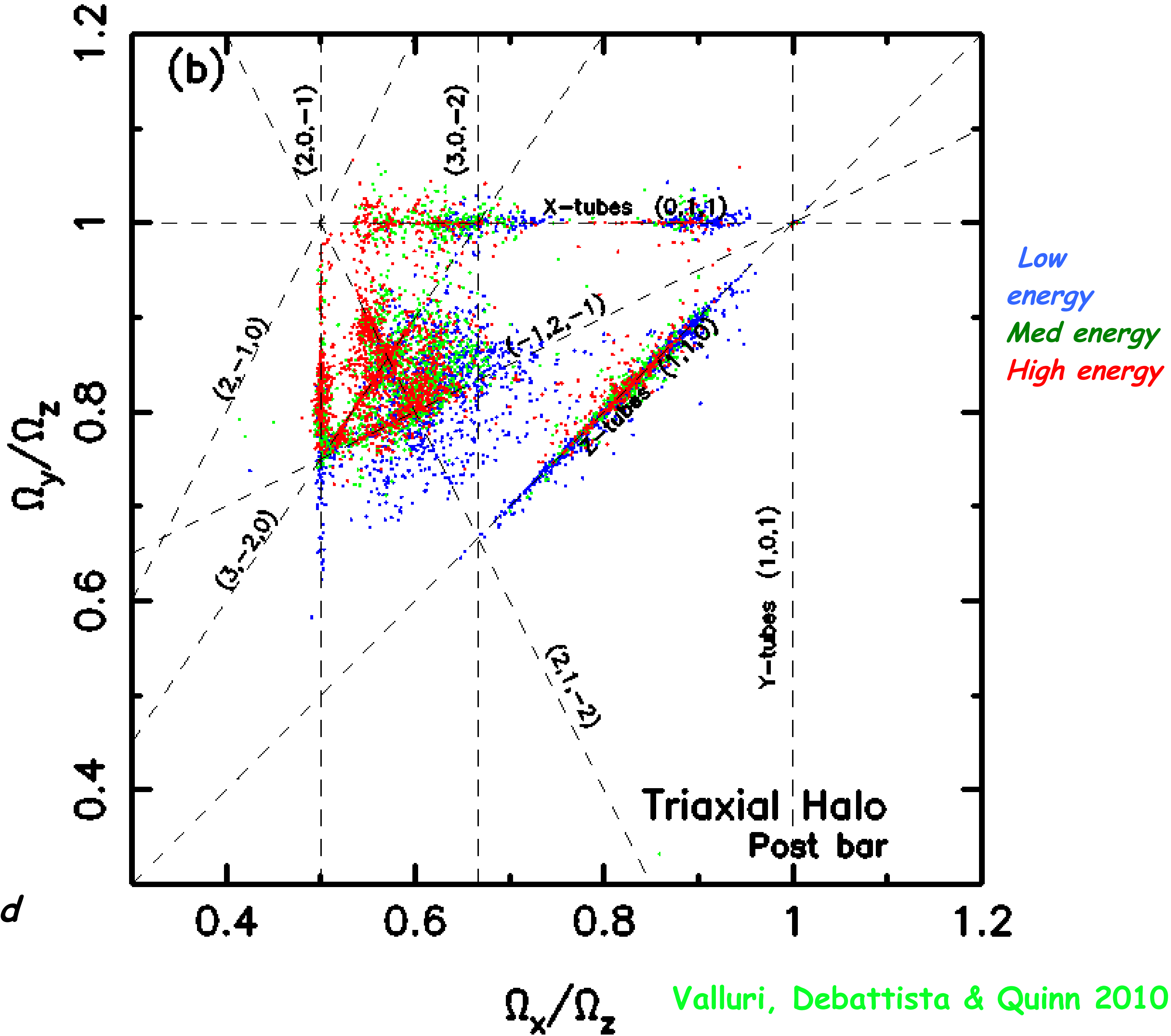
Bars and Triaxial Halos



Berentzen et al. 2006

Bars are weakened inside triaxial halos, unless the disk is massive enough to weaken the halo triaxiality (Berentzen et al. 2006) but Machado & Athanassoula (2010) stress the importance of disk initial conditions

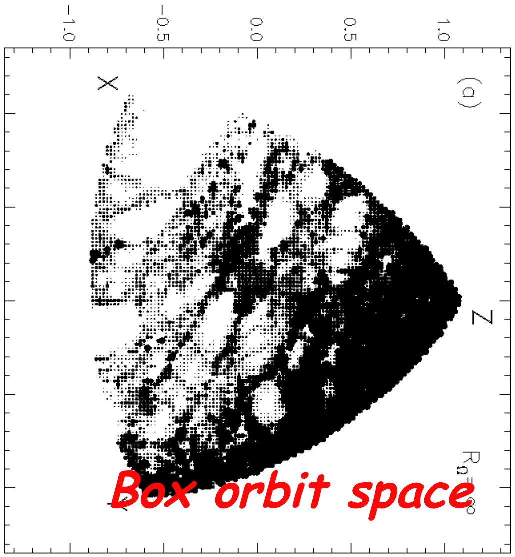
Bar scatters the low energy boxes, some z-tubes and banana orbits



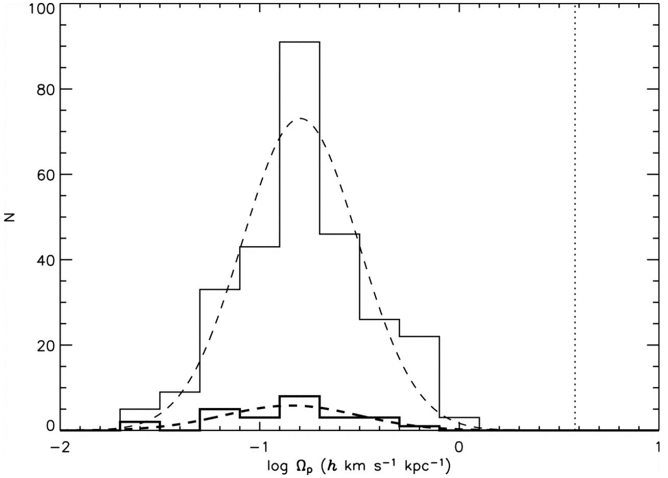
Valluri, Debattista & Quinn 2010

Figure Rotation

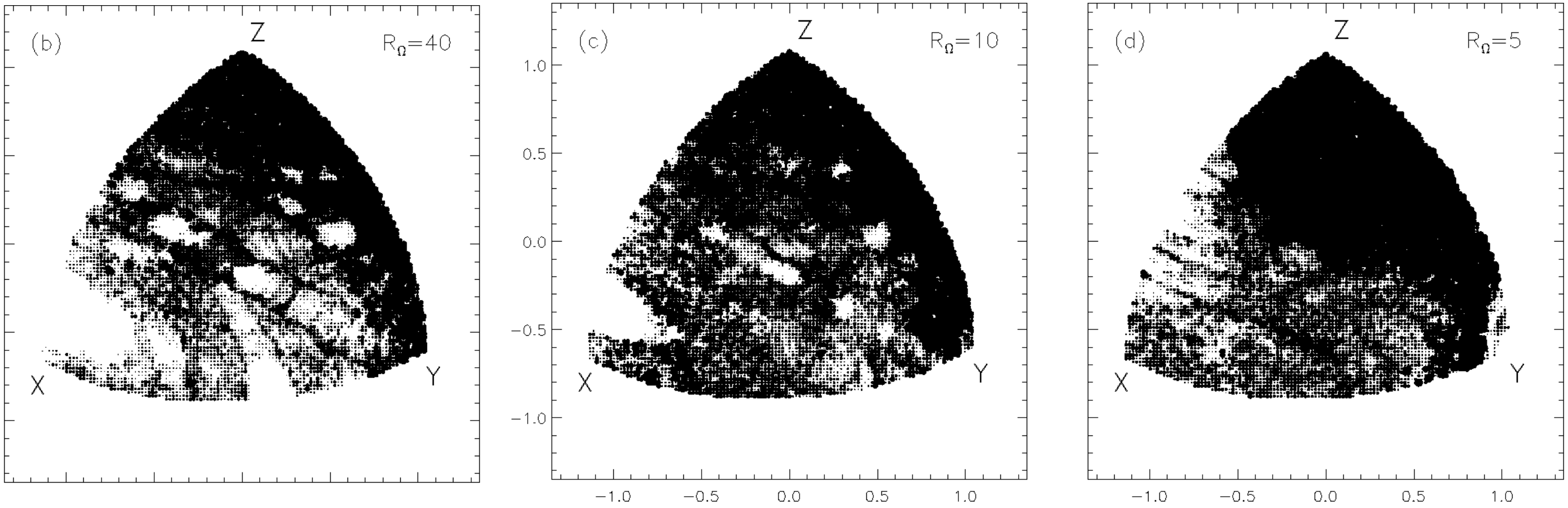
$$\log(\Delta f_x) = \log \left| \frac{\omega_x(t_1) - \omega_x(t_2)}{\omega_x(t_1)} \right|$$



Box orbit space



Bailin & Steinmetz 2004



Increasing figure rotation increases the fraction of chaotic space in triaxial Dehnen models ($\gamma = 1$)

Diebel & Valluri 2010

Conclusions

- Dark matter halos that form hierarchically are in general strongly prolate/triaxial. A variety of observational constraints, one of the strongest of which is the TF relation, suggest quite round halos. Better constraints expected in future (eg HVSs).

- Warps may be an important diagnostic of the angular momentum of the hot gas halo, which torques up any misaligned infalling gas. SF on the warp can lead directly to thick disk formation.

- The condensation of baryons to the centres of triaxial halos changes their shapes and kinematics, but the underlying orbits supporting triaxiality are not scattered (for most baryon distributions) but transformed. Most orbits that become chaotic remain confined near resonances and do not diffuse.