“Tidal disruption of globular clusters in dwarf galaxies with triaxial dark matter haloes.”

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Punchline

- Globular clusters (GCs) around dwarf spheroidal (dSph) galaxies may survive tidal encounters
- Stellar substructure (morphology and kinematics) in dSph galaxies may be explained by past disruptions of GCs
- Simulation techniques grossly over-simplify the problem, but useful first step

Outline

- Motivation: subtructure in dSphs and existence of GCs near them.
- Properties of systems modeled
- Simulation techniques/caveats
- Results

Motivation: Substructure in dSph galaxies

- Milky Way (MW) dSph galaxies are DM dominated-- $M/L_V \sim 10^{1-3}\,[M/L_V]_\odot$:
  - Ideal testbed for CDM scenario
  - Standing dispute about presence of cores (triaxiality? projection effect? see work by J. Simon)

- dSph galaxies have substructure, contrary to expectation that it should be erased in a few crossing times (~100 Myr):
  - Morphology: Kinematically cold core in Sextans, kinematically distinct shell in Fornax, asymmetries across major/minor axes in Fornax (claims of butterfly shapes are sketchy)
  - Ages: 2 Gyr-old stellar populations in Fornax shell
  - Can prolong life of stellar substructure with cored density profile, challenge to CDM?
  - Can save CDM with formation of substructure that is not *in situ*

- Blue stragglers in Sextans are mass segregated, not enough time for this in Sextans, do it elsewhere (like a merging G.C.) and disrupt?

Motivation: Globular clusters in dSph

- Fornax (5) and Sagitarrius (4) contain GCs near $r_{1/2}$:

Name	Angular sep. (kpc)	[Fe/H]	R_c (pc)	R_t (pc)	$\log_{10}(L)$ (L ?)	$\log_{10}[\rho_?(0)]$ (M ? /pc^3)
For dSph	0.00	− 1.3	400 ± 4	2078 ± 20	7.13 ± 0.2	− 1.14 ± 0.20
F1	1.60	− 2.25	10.0 ± 0.3	60 ± 20	4.07 ± 0.13	0.48 ± 0.07
F2	1.05	− 1.65	5.8 ± 0.2	76 ± 18	4.76 ± 0.12	1.78 ± 0.07
F3	0.43	− 2.25	1.6 ± 0.6	63 ± 15	5.06 ± 0.12	3.47 ± 0.07
F4	0.24	− 1.65	1.8 ± 0.2	44 ± 10	4.69 ± 0.24	3.18 ± 0.07
F5	1.43	− 2.25	1.4 ± 0.1	50 ± 12	4.76 ± 0.20	3.27 ± 0.07
Sgr dSph	0.00	[− 0.5, − 1.3]	1560 ± 20	12600 ± 20	7.24 ± 0.2	− 2.96 ± 0.20
M54	0.00	− 1.65	0.91 ± 0.04	59 ± 21	5.36 ± 0.08	4.45 ± 0.05
Terzan 7	2.68	− 0.64	1.63 ± 0.12	23 ± 8	3.50 ± 0.10	1.97 ± 0.07
Terzan 8	4.40	− 2.25	9.50 ± 0.72	66 ± 26	3.67 ± 0.14	0.72 ± 0.23
Arp 2	3.07	− 1.65	13.67 ± 1.85	139 ± 49	3.59 ± 0.14	0.35 ± 0.25

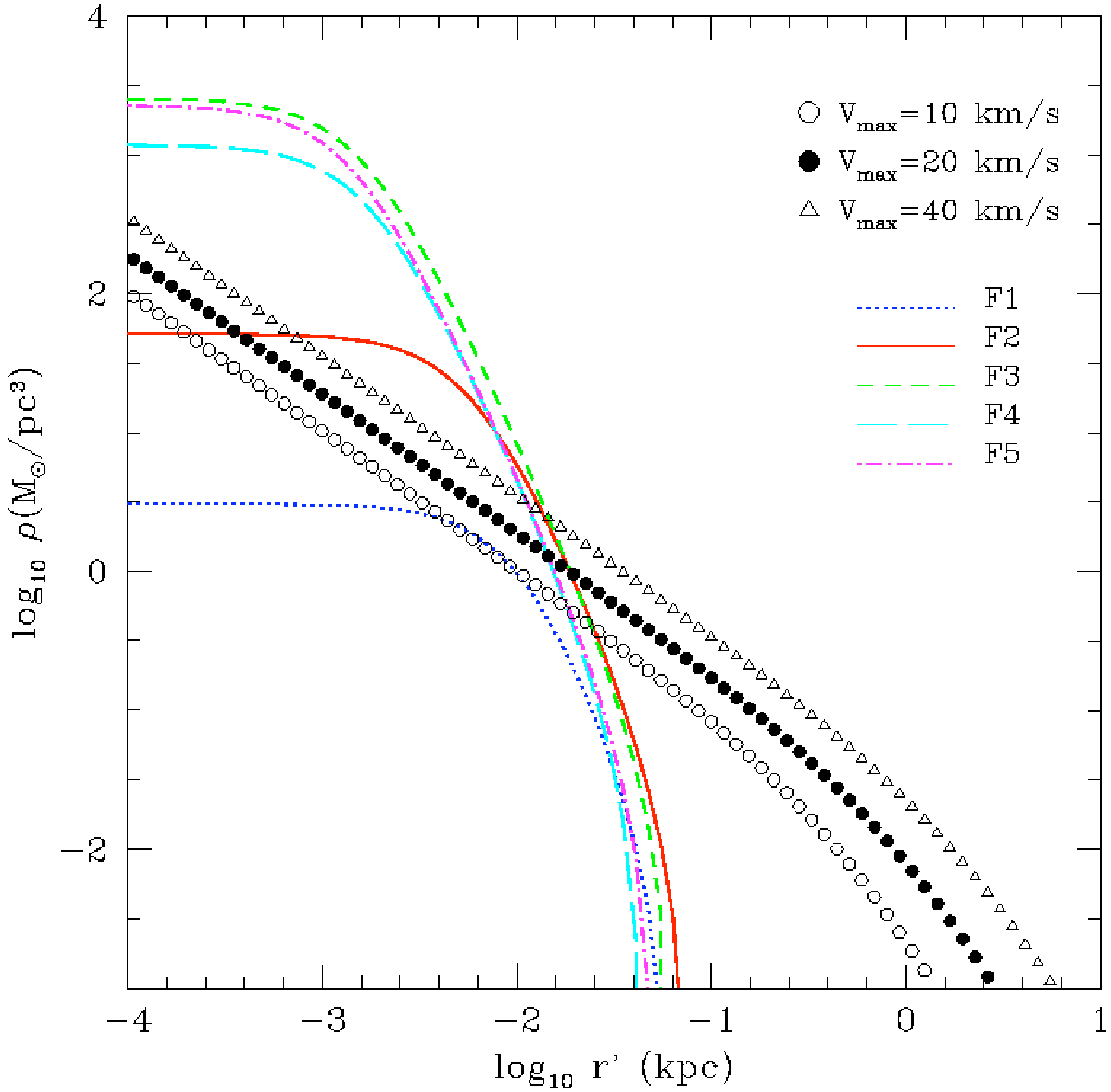
- Sinking time due to dynamical friction (DF) of order several giga-years: GC are not naturally expected where they're found

- Undesirable explanations: CDM is wrong (cored halos) (Goerdt et al. 2006), tidal heating by MW pushes GCs out

- Worth asking: Will CDM dwarves generically destroy pre-existing GCs, or is their absence artefact of formation process?

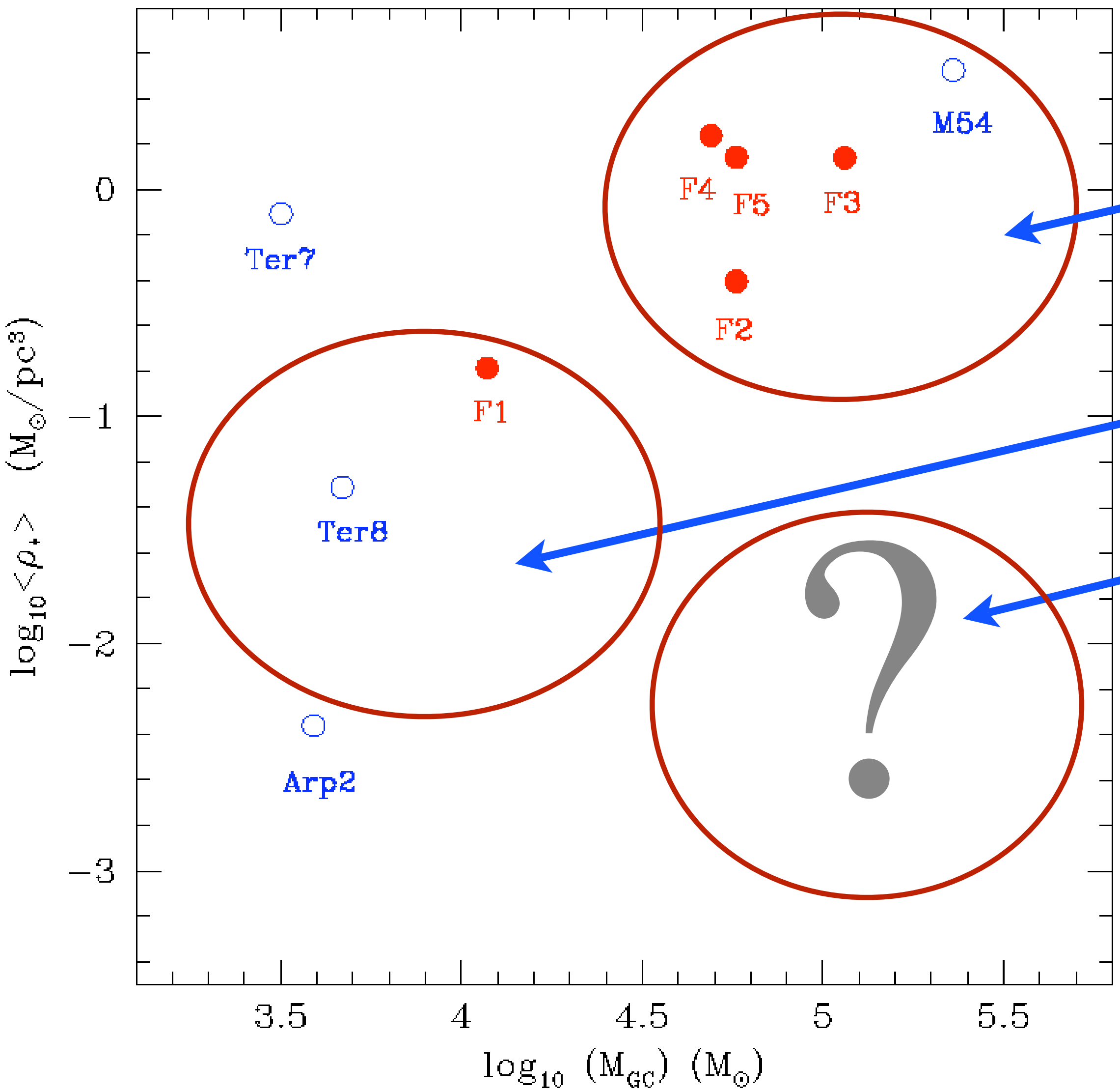
- Could tidal disruption of GCs explain kinematic/morphological irregularities/excess surface brightness in MW dSphs?

Monotonous dwarves and exciting clusters



- dSph relatively boring in density dist.
- Wide variety in GC densities
  - $\rho_{\rm F1} < \rho_{\rm dSph}$
  - $\rho_{\rm F2} \sim \rho_{\rm dSph}$
  - $\rho_{\rm F3-F5} \gg \rho_{\rm dSph}$
- Criterion for tidal disruption is $\rho_{\rm GC} \lesssim 3\rho_{\rm dSph}$

The density and masses of GC in dSph



- May fall to center of dSph due to DF
- May be tidally shredded if orbital apogee is close enough to dSph
- Absence could be explained by:
  - GC formation process
  - DF+tidal shredding:
    - Massive, high density GC should live closer to dSph centers
    - Light, low density GC should live near dSph outskirts
    - Seems true for Fornax dwarves!

This is a toy model!

- Stellar pops in Fornax GCs are metal-poor, coeval with stellar pops of GCs in MW
- Stellar pops in Fornax substructure are ~2 Gyr old
- Best thought of as a toy-model/*gedanken-experiment*:
  - Can dense star clusters make their way to the center of dSph. to become nuclear star clusters? (double nuclei)
  - Will GC like those found around Fornax generically survive, sink?
  - Do disrupted GCs around dSphs leave detectable stellar debris?

Toy halo/GC properties

- dSph dark matter assumed to be triaxial NFW halo with mean c(M):

$$\rho = \frac{\rho_0}{\left(\frac{r}{r_s}\right)\left(1 + r/r_s\right)^2}$$

$$r^2 = x^2/a^2 + y^2/b^2 + z^2/c^2$$

- x/y/z: major/intermediate/minor axis. Axis ratios chosen to fit mean seen in simulation

- GC assumed to be best-fit King profile with parameters given in table

- dSph substructure can safely be ignored because it is further out than the GC (NOT because there is less substructure in dwarves than in host halo, e.g. Acquarius vs Via Lactea II conversation.)

Computational method

- SUPERBOX Particle-mesh used to calculate GC star self-gravity, particles. 3 (near/intermediate/tidally stripped) overlaid grids of 64^3 cells each.
  - 10^5 particles
- Smooth halo is unresolved, dynamical friction must be be put in by hand:

$$\vec{f}_{\rm df} = -2\sqrt{2\pi} G \rho_{\rm NFW} \frac{\vec{v}}{\sigma^3(m)} B(v/\sigma[m]) M_{\rm GC} \ln \Lambda$$

- Total force is due to smooth halo, particle-mesh (GC stars), and dynamical friction (bound stars only). Star positions are evolved.

Caveats

- $\delta t = \frac{t_{\rm cr}}{25} \sim$ Myr $\rightarrow 10^4 \rightarrow 10^5$ time steps needed

- Use of mesh method neglects close 2-body encounters, underestimates $\vec{f}_{\rm df}$

- Core collapse occurs after roughly $t_{\rm 2body,relax}$: all but F1 would experience repeated episode of core collapse, energy injection by hard binaries, re-expansion, etc...

- Real dSph potentials are likely to evolve due to tidal forces in MW halo (more on this later)

Results: Orbits/mass loss

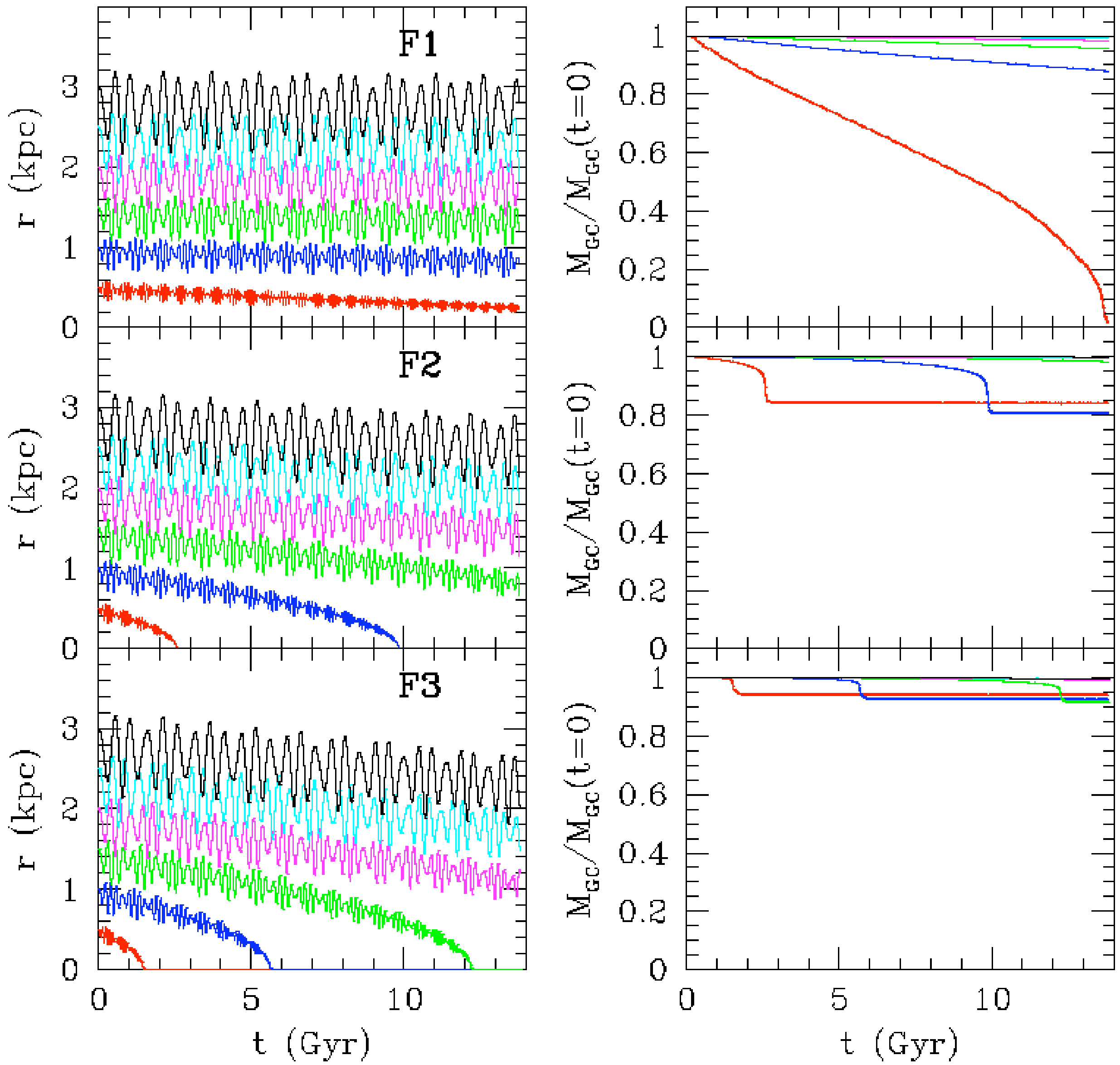
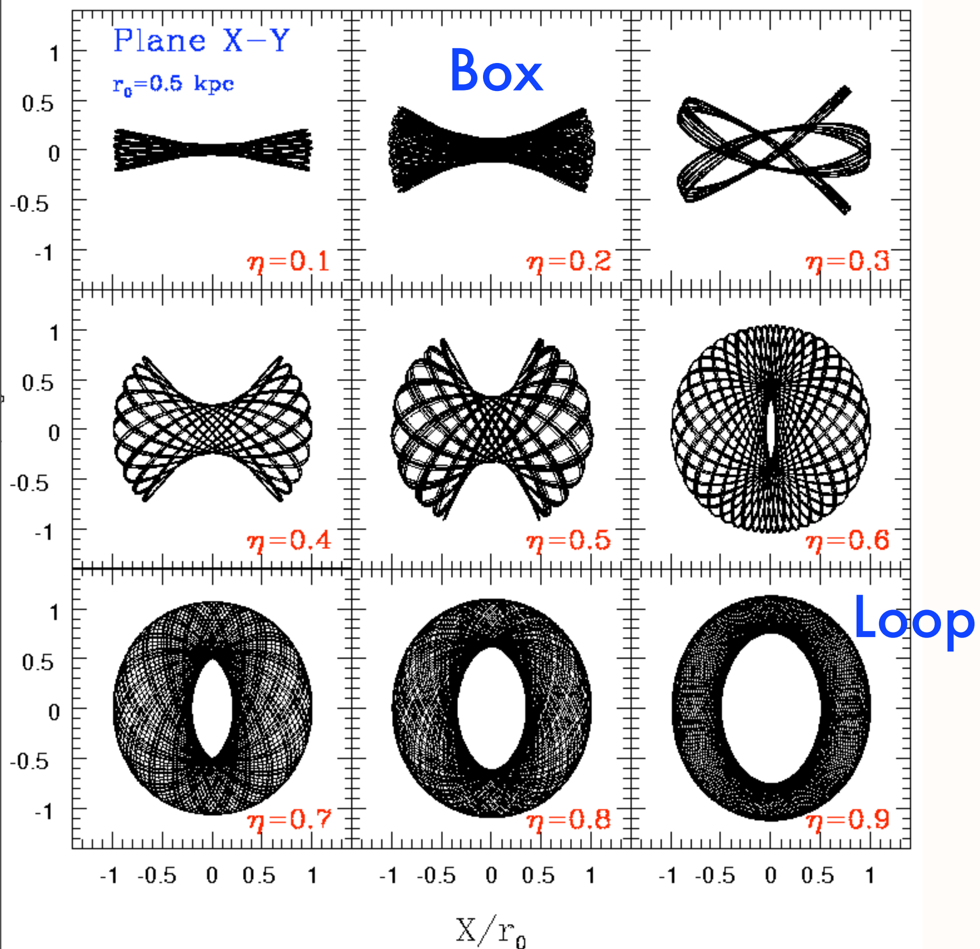


Figure 5. Galactocentric distance (*left column*) and mass (*right column*) evolution of the clusters F1, F2 and F3 in a dwarf galaxy halo with a peak velocity $V_{\rm max}$ = 20 km/s. Different colours denote different initial galactocentric distances (r_0). The orbits are confined to the $X - Y$ plane (i.e., the plane formed by the halos's long and intermediate axis) and have an orbital circularity $\eta = 1$ (i.e. the initial velocity v_0 is such that $v_0(r_0) = V_c(r_0)$).

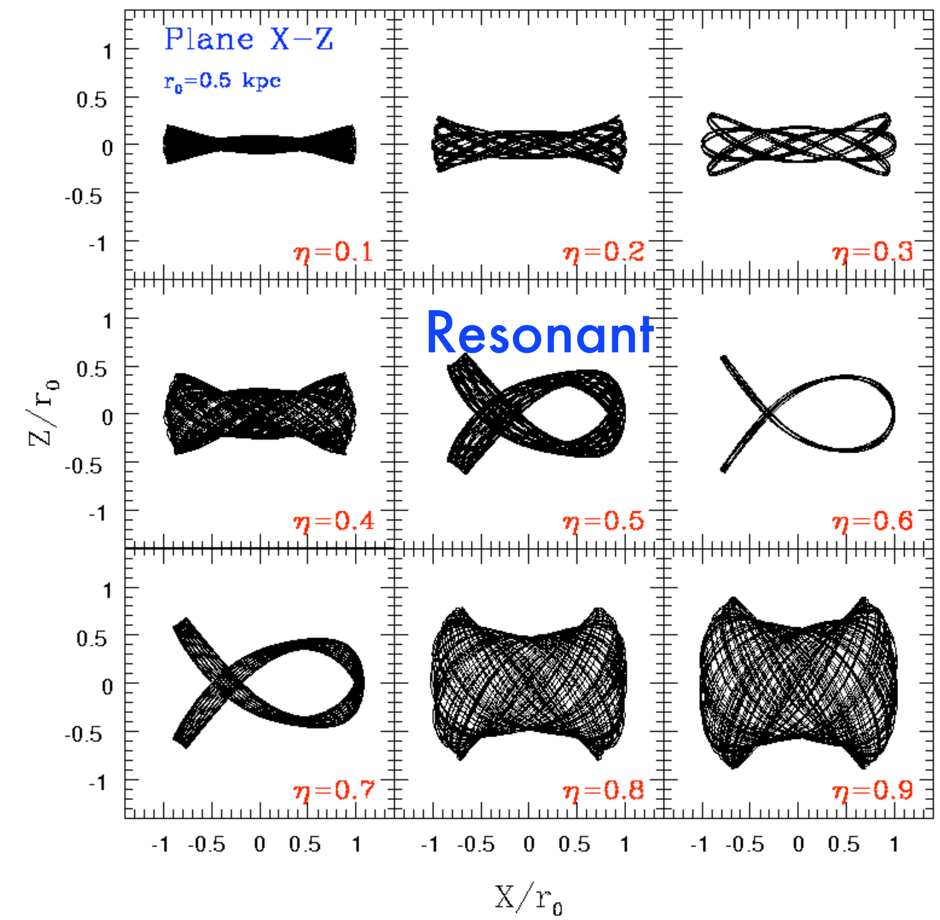
- F2/F3 sink to halo center with negligible mass loss for sufficiently close start (e.g. M54 at center of Sag. dSph)
- F1 almost unaffected by DF, significant tidal mass loss for close start

Examples of G.C. Orbits



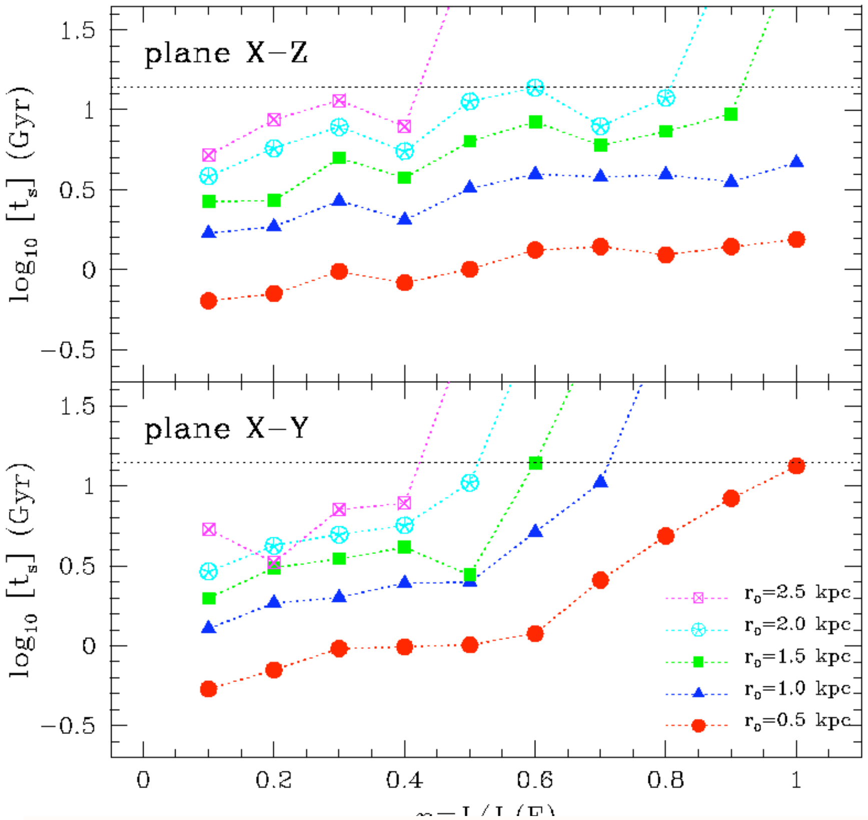
Angular momentum of equivalent circular orbit

$$\eta = J/J_c(E)$$



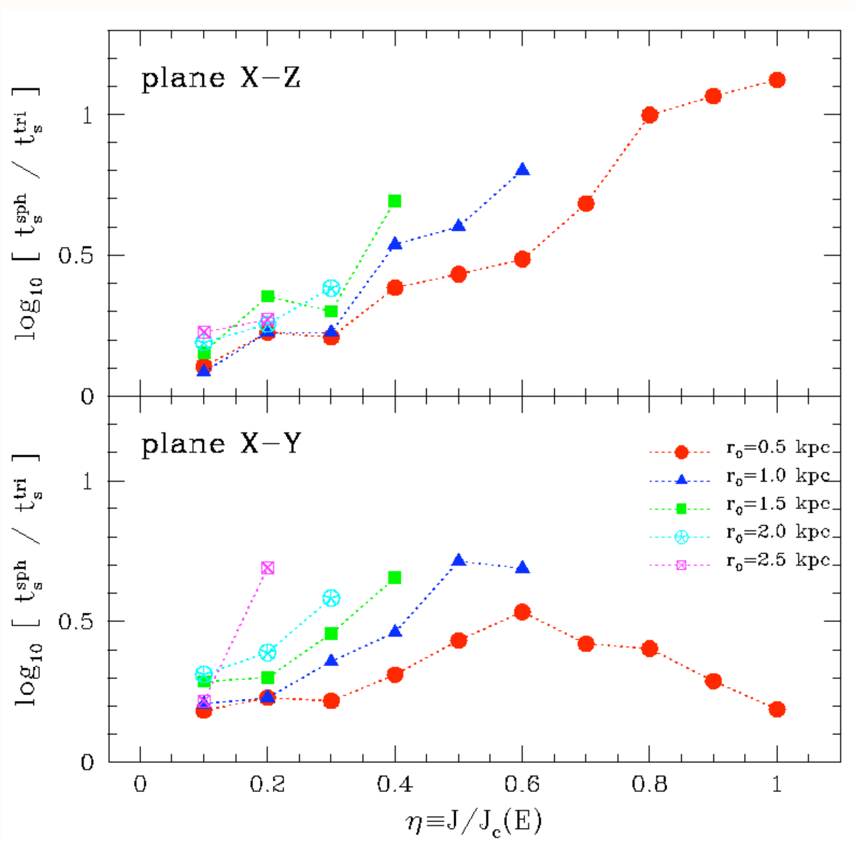
- Orbits initially lie in XY or XZ symmetry plane
- Expect centro-phobic orbits to be more stable to tidal disruption (less time spent in dense regions)

Results: GC Survival times



Triaxial case

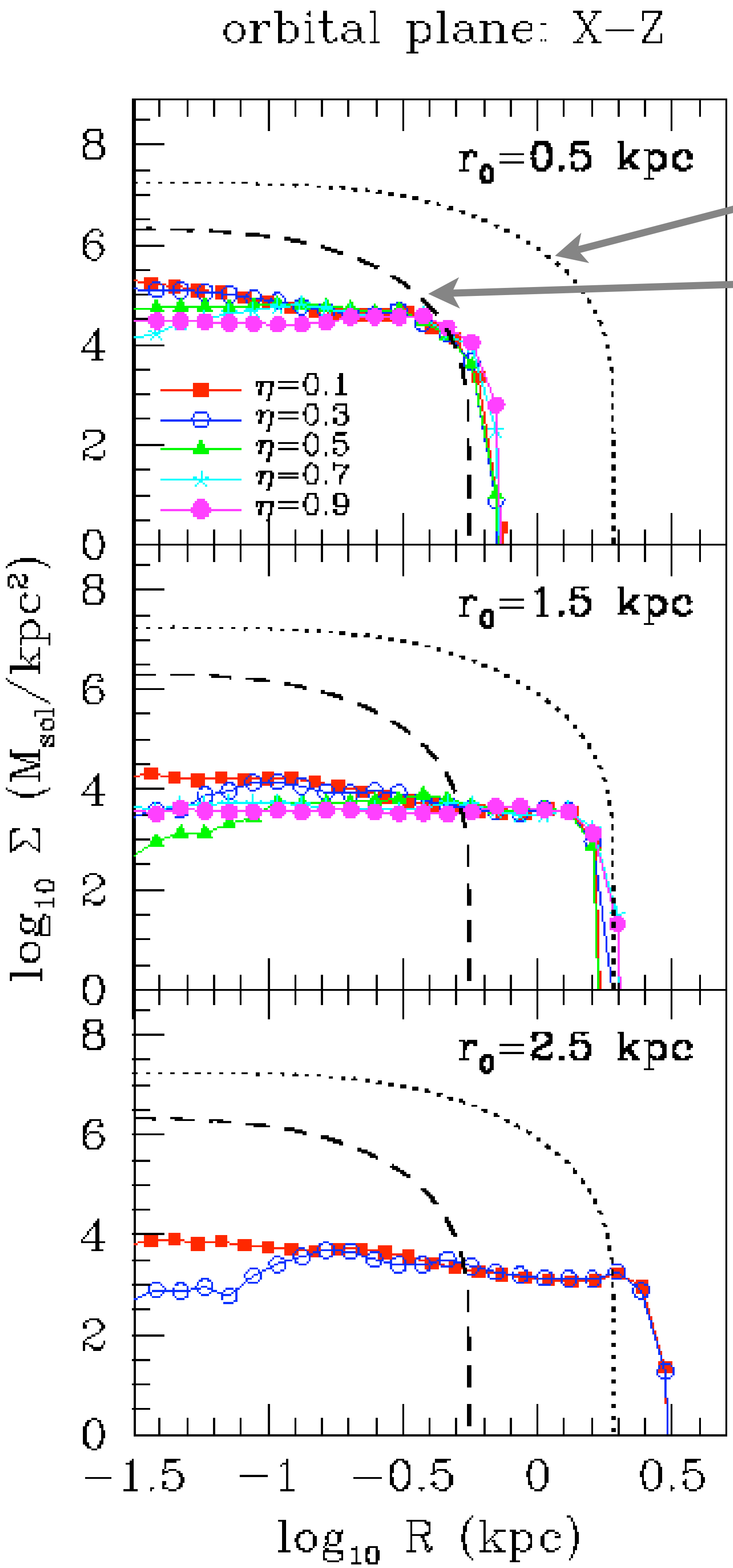
- 95% mass loss defined as disruption
- Sufficiently close in, F1 is disrupted independent of angular momentum
- Further out, centro-phobic orbits can help a GC survive tidal destruction



Spherical vs. triaxial

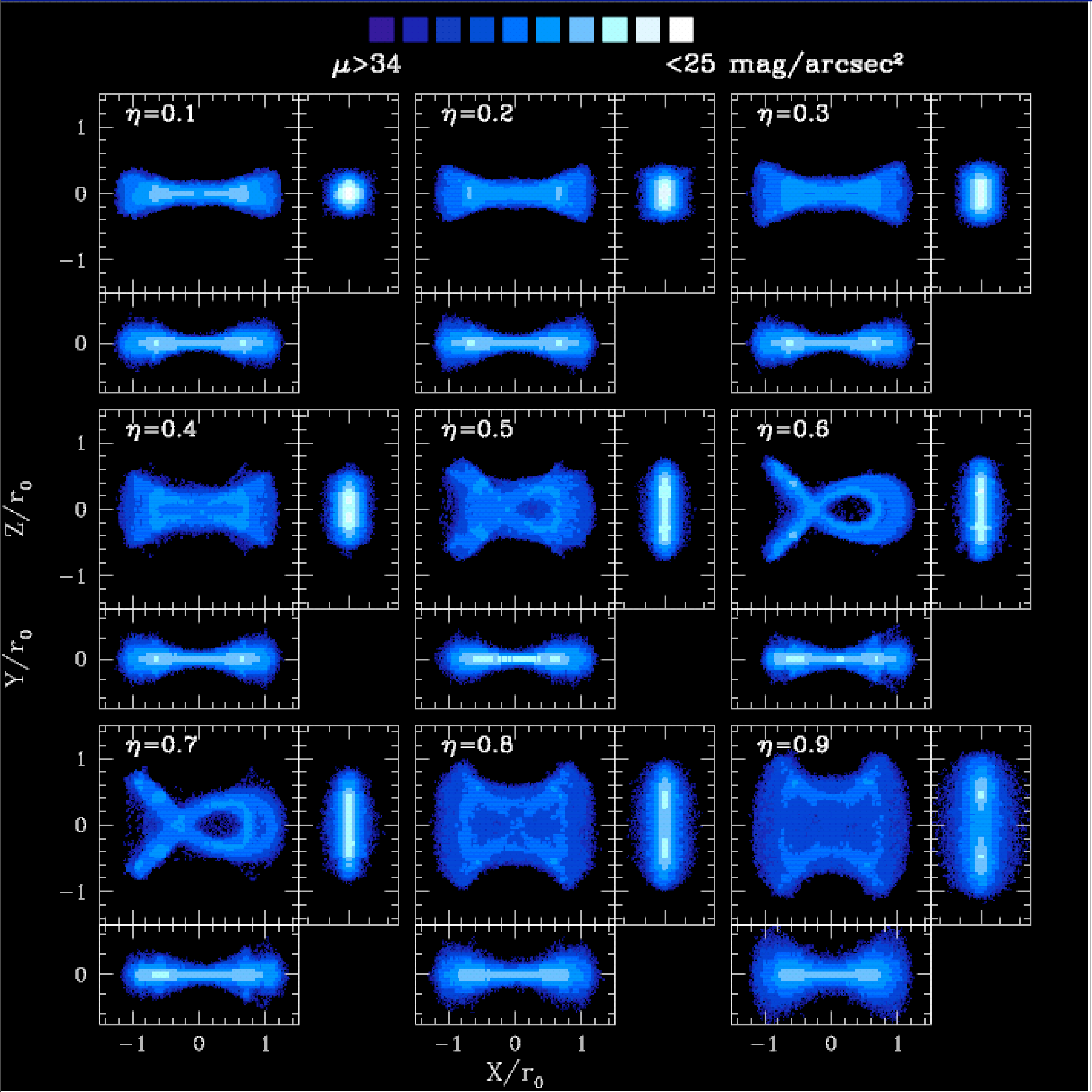
- GCs survive longer in spherical halos: More centro-phobic rosettes, no box or resonant orbits
- Higher angular momentum, fewer passes through higher density regions, more robust GCs

Results: Surface brightness of debris



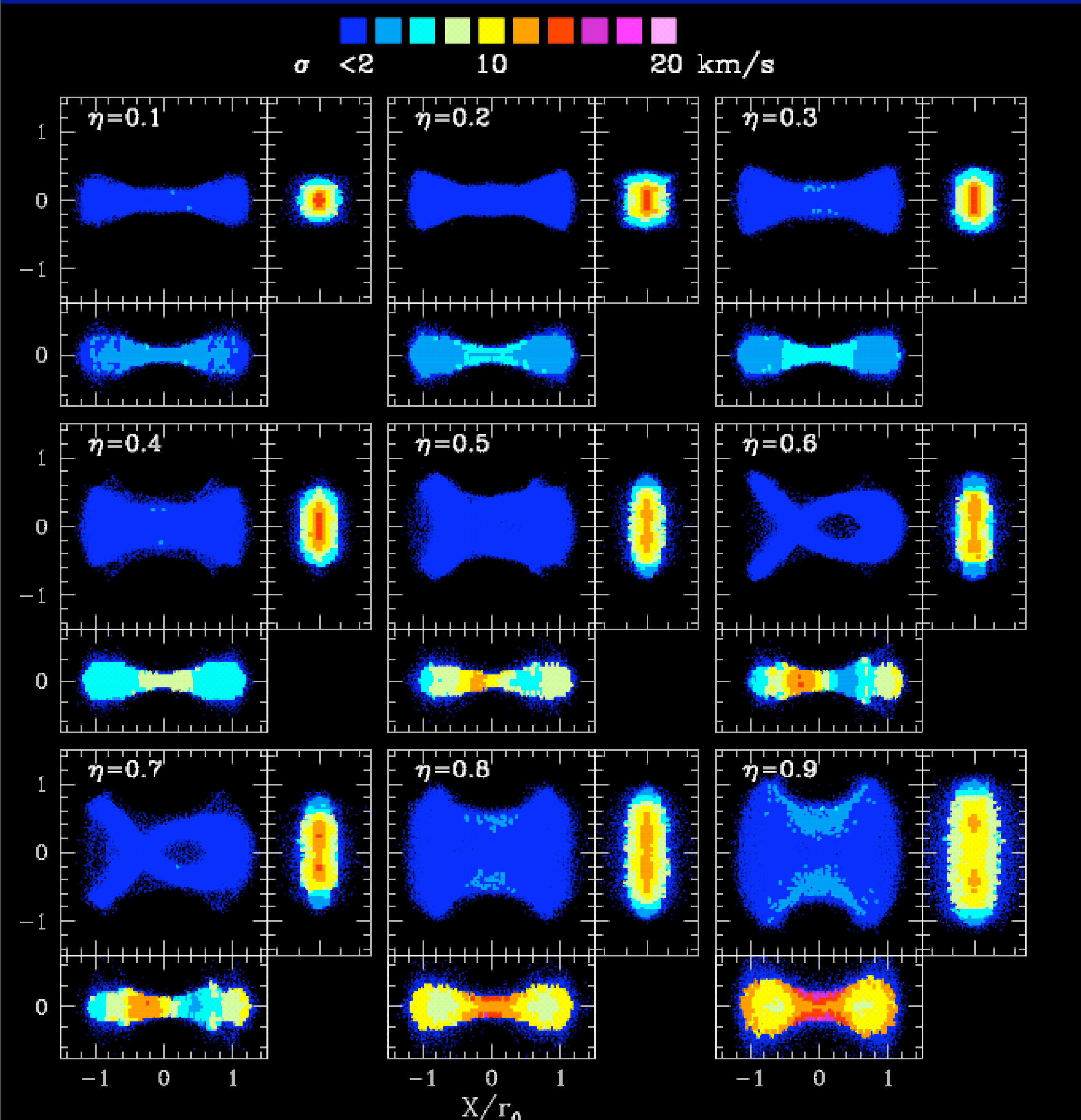
- GCs for wider variety of ang. mom. disrupted for close start
- Further start spreads debris over larger area in disruptive case
  - Lower central Σ
  - Conceivable detectable region at outer edge, tenuous!
  - Excess light beyond dSph King radius in Carina, Sculptor, Leo I, Ursa Minor?

Results: debris morphology



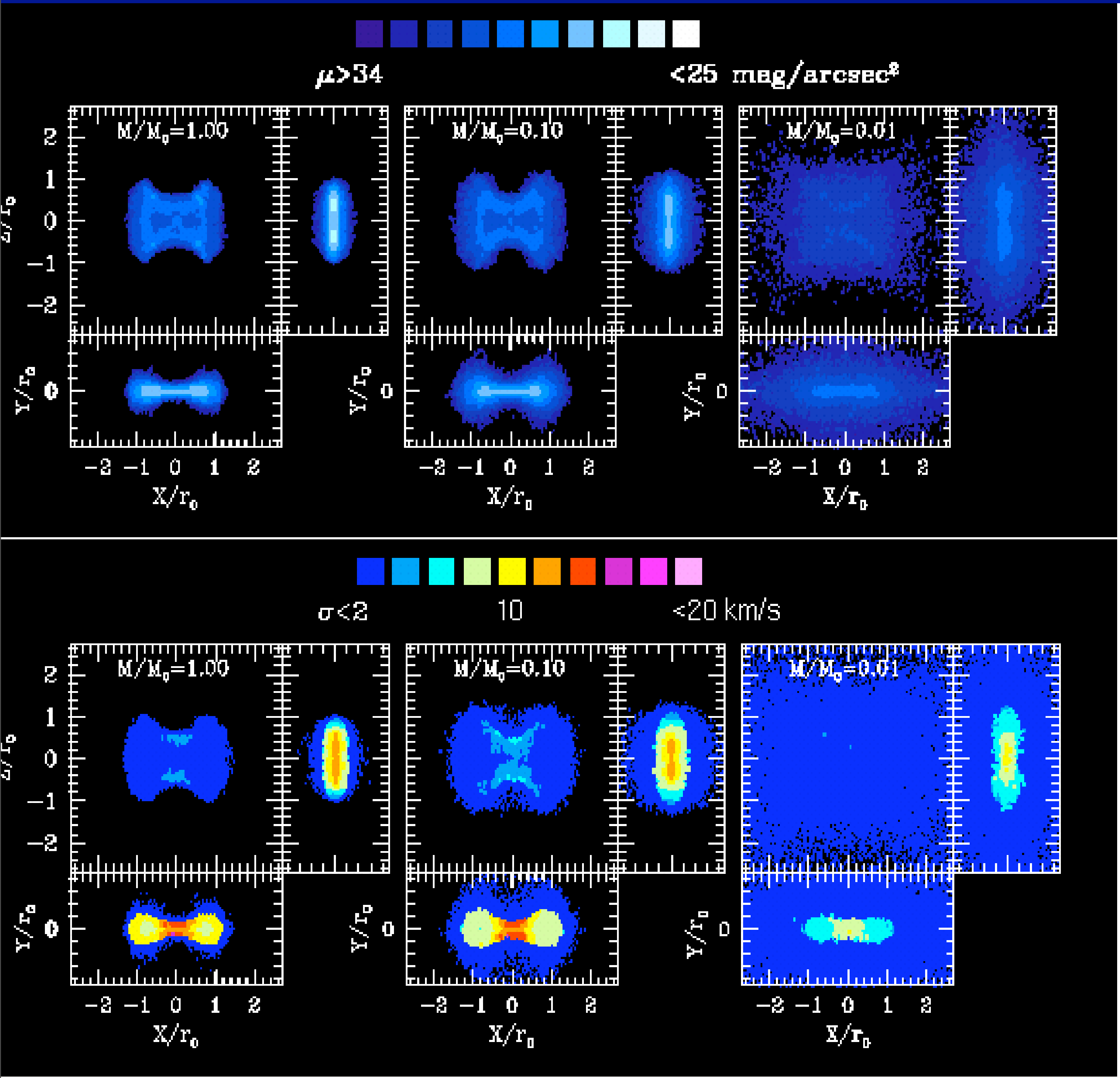
- Debris morphology clearly traces orbit of GC
- Debris most clearly seen face on in imaging

Results: debris kinematics



- Kinematic ‘fossil’ of original orbit best seen in orbital plane
- Hints of rotation seen in Carinae, Leo I, Sculptor, Fornax: rotating sub-population would be a tell-tale sign of disrupted stellar remnant
- UMi has kinematically cold clump: but asymmetric (more undetected, or unrelated to GC)
- CV has extremely kinematically cold, central, metal poor clump, and a metal rich one, not as cold
- Chemical tagging could conceivably add support to the GC hypothesis: Fornax GC are metal-poor

Results: ‘Shedding’ dSph NFW halo



- Real dwarves lose mass due to tidal interactions with host halo
- Simulation run for additional Hubble time with 90 or 99% of dwarf mass suddenly removed
- Crude approximation to tidal mass loss from dwarf
- Dwarf potential well made shallower: GC debris puffs out
- Debris becomes cold and more diffuse

Concluding thoughts

- A good first start
- Simulations should be re-done with realistic initial distances, radial/angular velocities, off-axis orbits (input from a new n-body simulation?)
- Full distribution of halo geometries should be used
- A live dSph DM halo orbiting in MW halo would yield more robust conclusions, more realistic dF results, account for mass loss