Surveying the Dynamical Structure of Globular Cluster Systems

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SAGES Legacy Unifying Globulars and Galaxies Survey

- NSF funded (2008-2010)
- 25 representative early-type galaxies:
  - spread of luminosities, environments, photometric and kinematical properties
- Global properties, with focus on halo tracers:
  - field stars, planetary nebulae, globular clusters
  - photometry, kinematics, metallicities
  - Subaru/Suprime-Cam, Keck/DEIMOS *(high-quality, deep wide-field imaging + spectroscopy)*

SLUGGS

SLUGGS survey

- Dark matter content of galaxies
- Angular momenta of galaxies
- Total numbers and spatial distributions of GCs
- Orbits of stars and GCs
- Chemical properties of stars and GCs

⇒ *Use GCs to trace galaxy properties and assembly*

⇒ *Constrain formation and destruction of GCs*

GCS orbital anisotropy: diagnostic #1

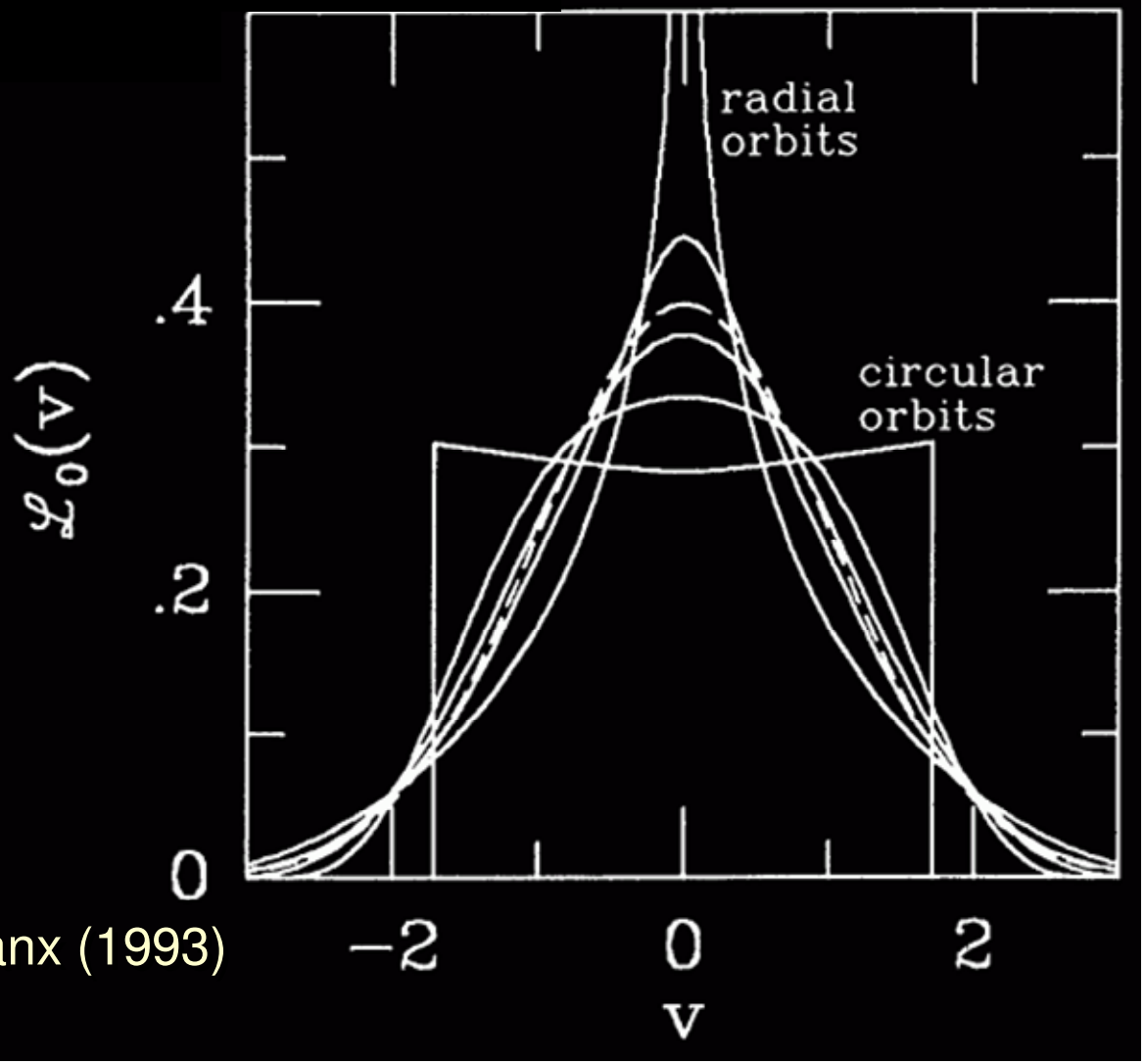
$$v_c^2 = \frac{GM(r)}{r} = -\sigma_r^2 \left(\frac{d\ln\nu}{d\ln r} + \frac{d\ln\sigma_r^2}{d\ln r} + 2\beta \right)$$

h_4 , κ_p measure *shape* of line-of-sight velocity distribution (LOSVD)

h_4 , $\kappa_p = 0$: Gaussian;
isotropic orbits

h_4 , $\kappa_p > 0$: "peaked";
radial orbits

h_4 , $\kappa_p < 0$: "flat-topped";
tangential orbits



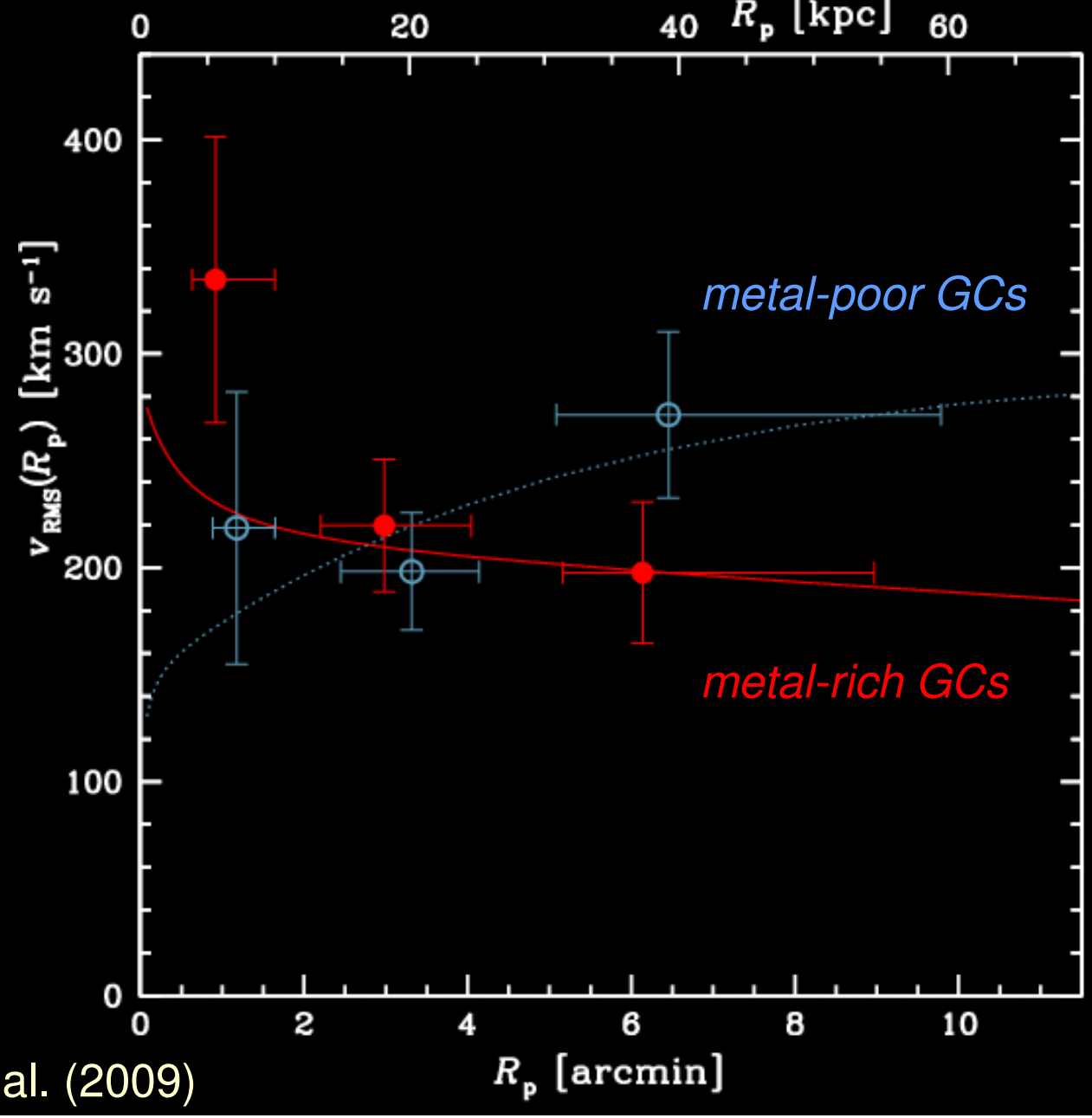
van der Marel & Franx (1993)

GCS orbital anisotropy: diagnostic #2

Constrain mass independently (X-rays, PNe, multiple GC pops)

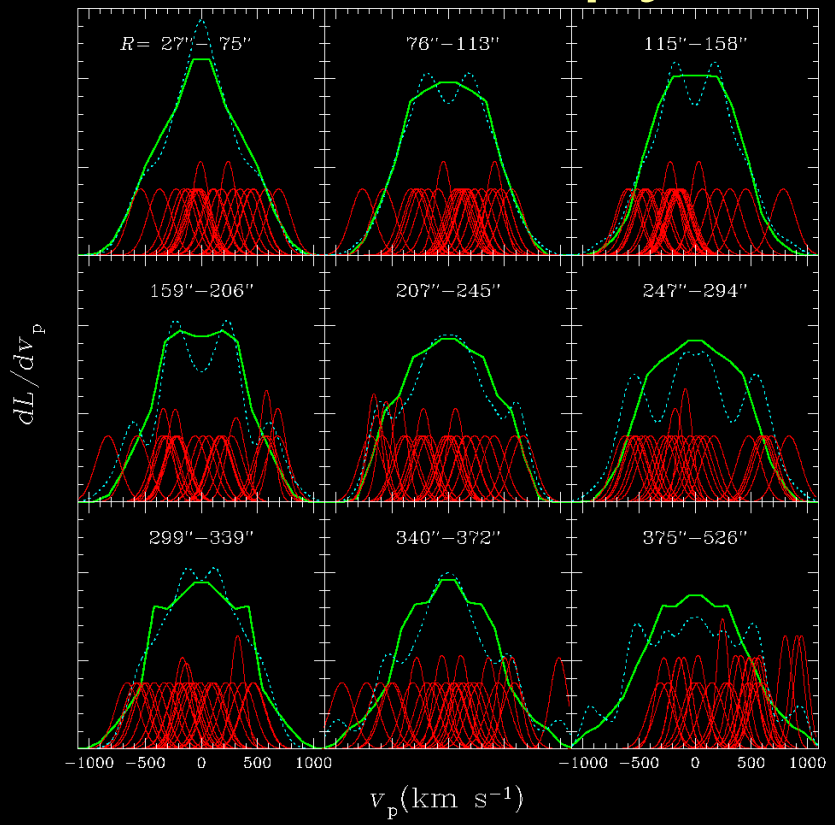
NGC 1407:

~200 GC velocities fr. Keck/DEIMOS



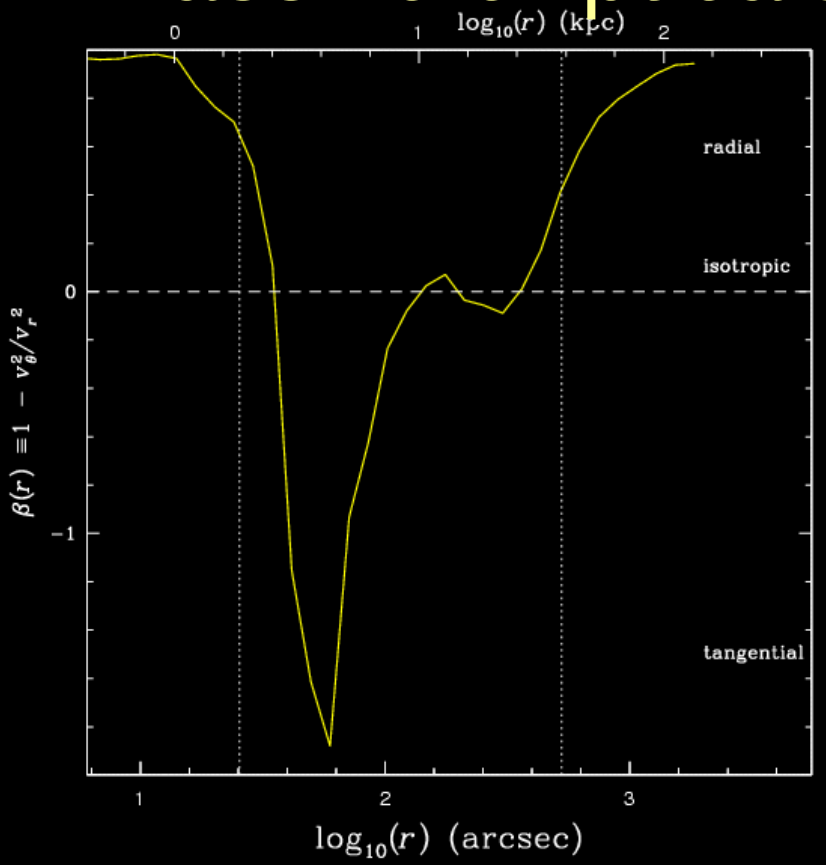
Romanowsky et al. (2009)

Orbit anisotropy results in massive ellipticals



Schwarzschild orbit model fit of stellar + GC kinematics in M87
(fr. Cohen & Ryzhov 1997, etc.)

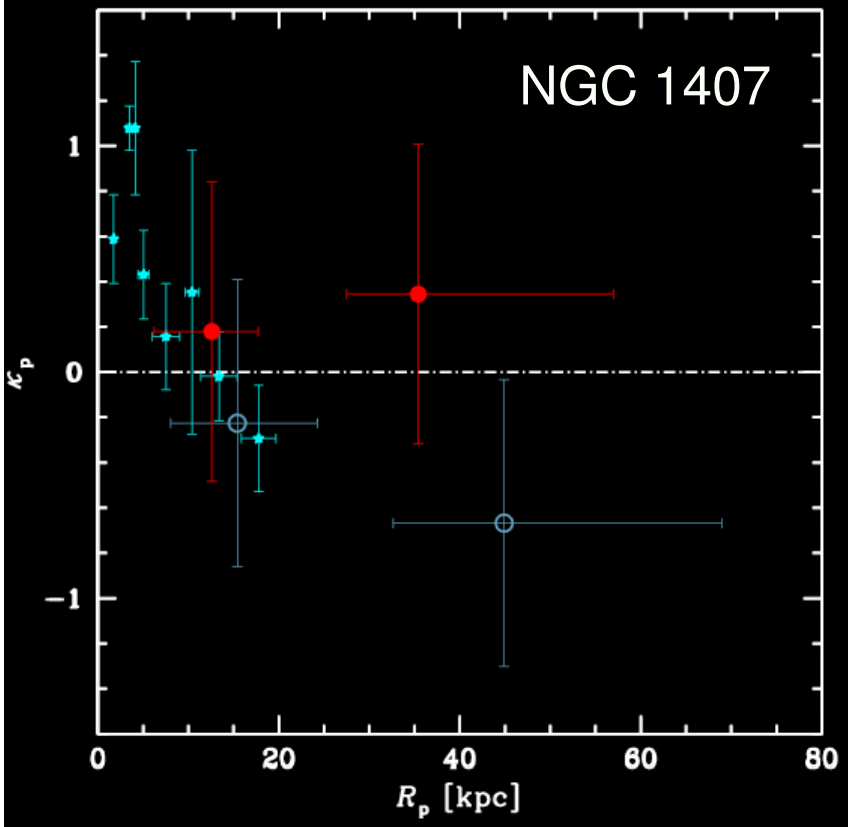
Unbinned LOSVD fitting, shown in radial bins:
- **model**
- **data**
- **simulated from data**



GCS roughly isotropic overall, possibly tangential toward center

Romanowsky & Kochanek (2001);
cf. Côté et al. (2001);
Wu & Tremaine (2006);
Chanamé et al. (2008)

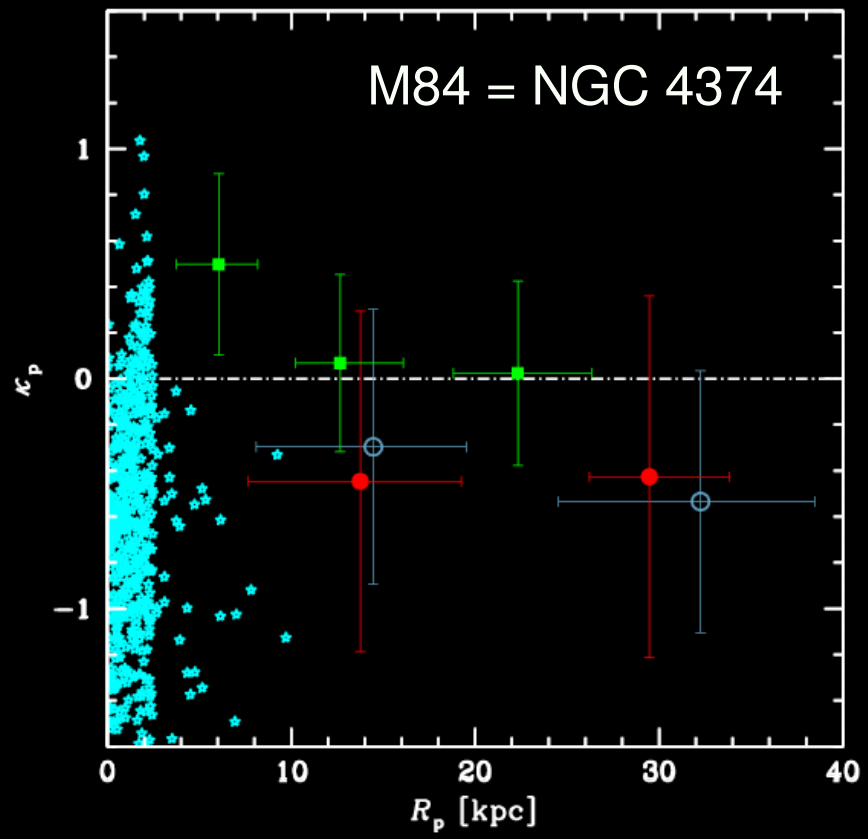
Orbit anisotropy results in massive ellipticals



metal-rich GCs: β ~ 0 (isotropic)

metal-poor GCs: β ~ –4 (tangential)

Romanowsky et al. (2009)



overall GCs: tangential

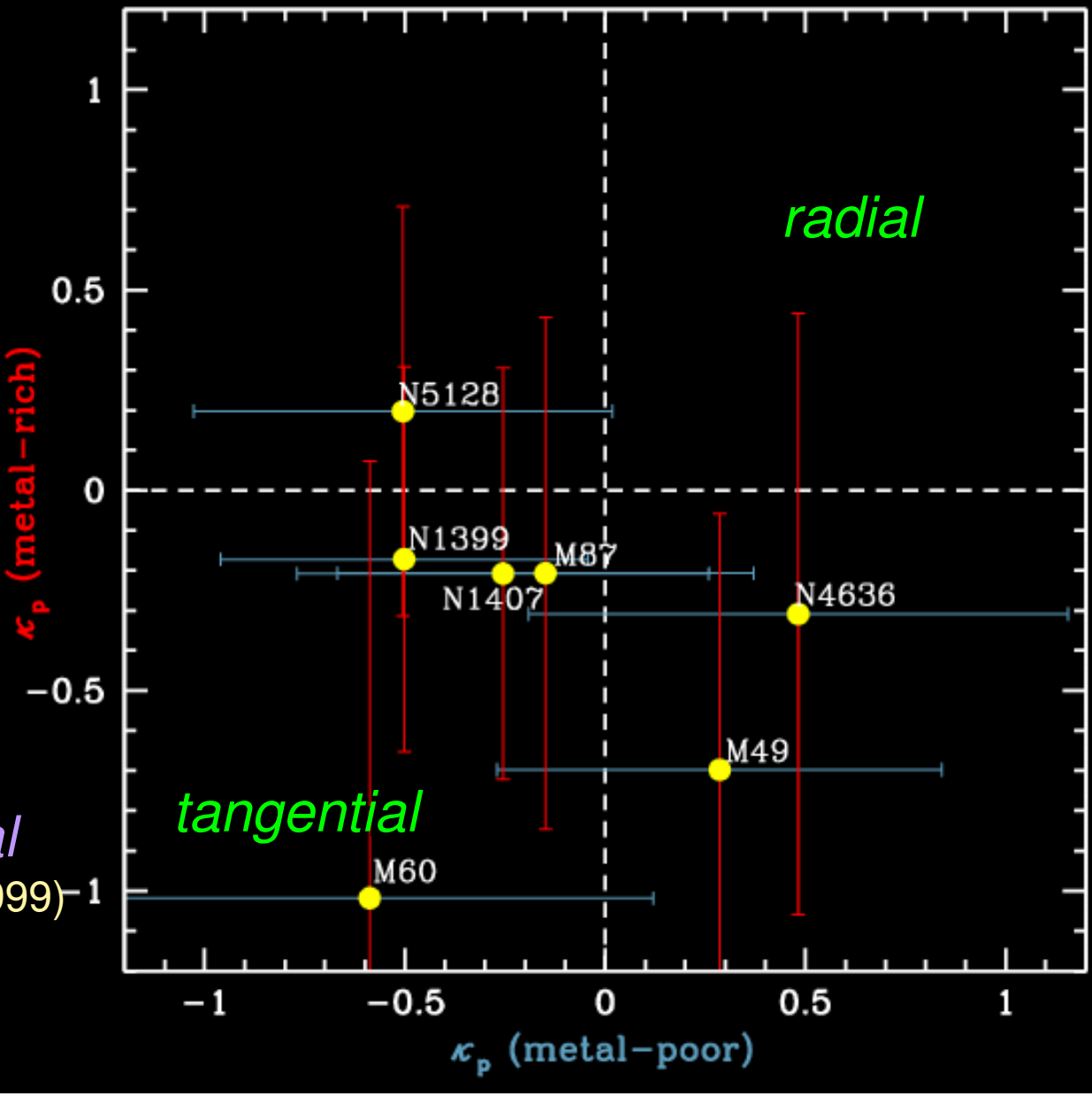
PNe: isotropic?

Coccato et al. (2009);
Kumar et al. (in prep)

GCS orbit anisotropy in massive ellipticals

All systems so far roughly isotropic / tangential overall
(literature compilation:
Côté et al. 2001, 2003;
Richtler et al. 2004;
Schuberth et al. 2006;
Woodley et al. 2007;
Hwang et al. 2008;
Romanowsky et al. 2009;
Kumar et al. in prep)

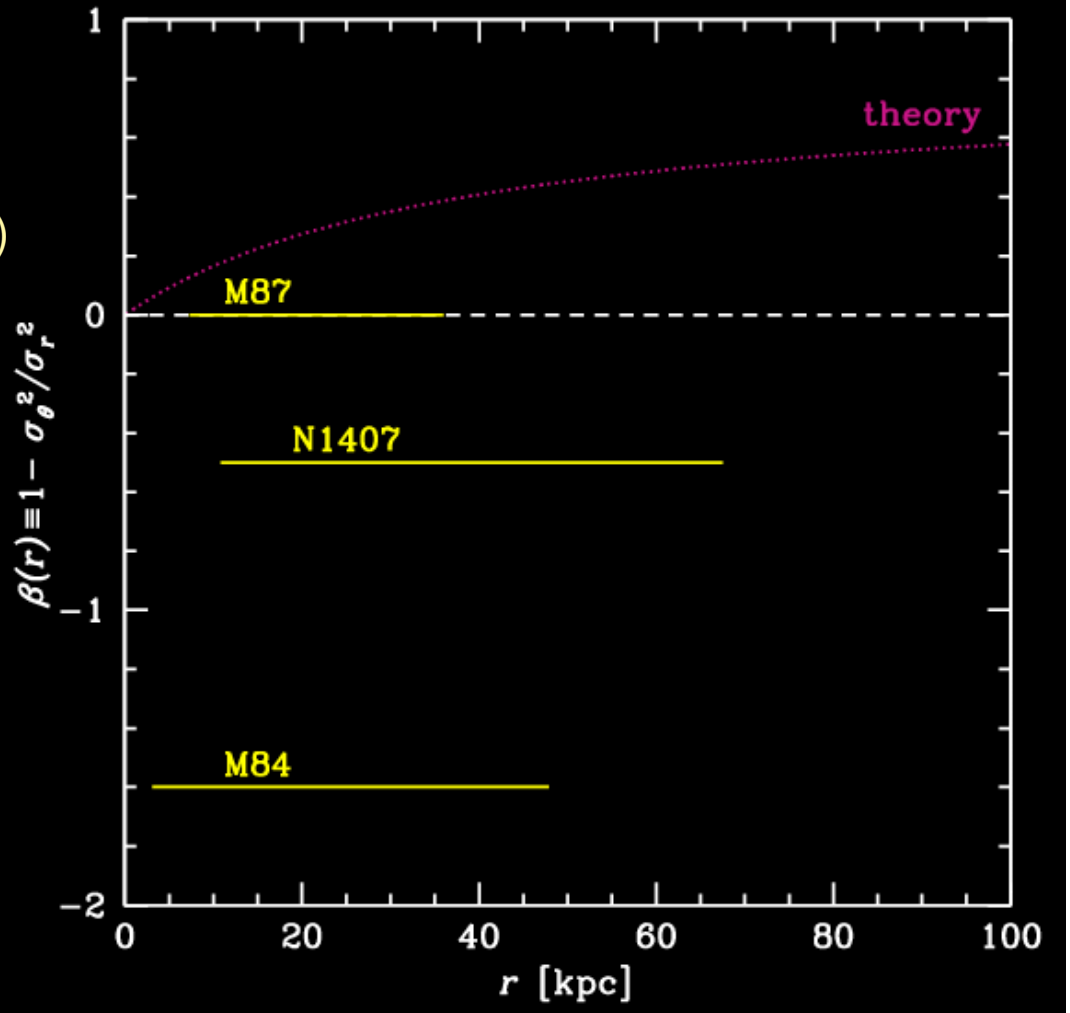
cf. Milky Way: halo GCs mildly radial
(e.g. van den Bosch et al. 1999)



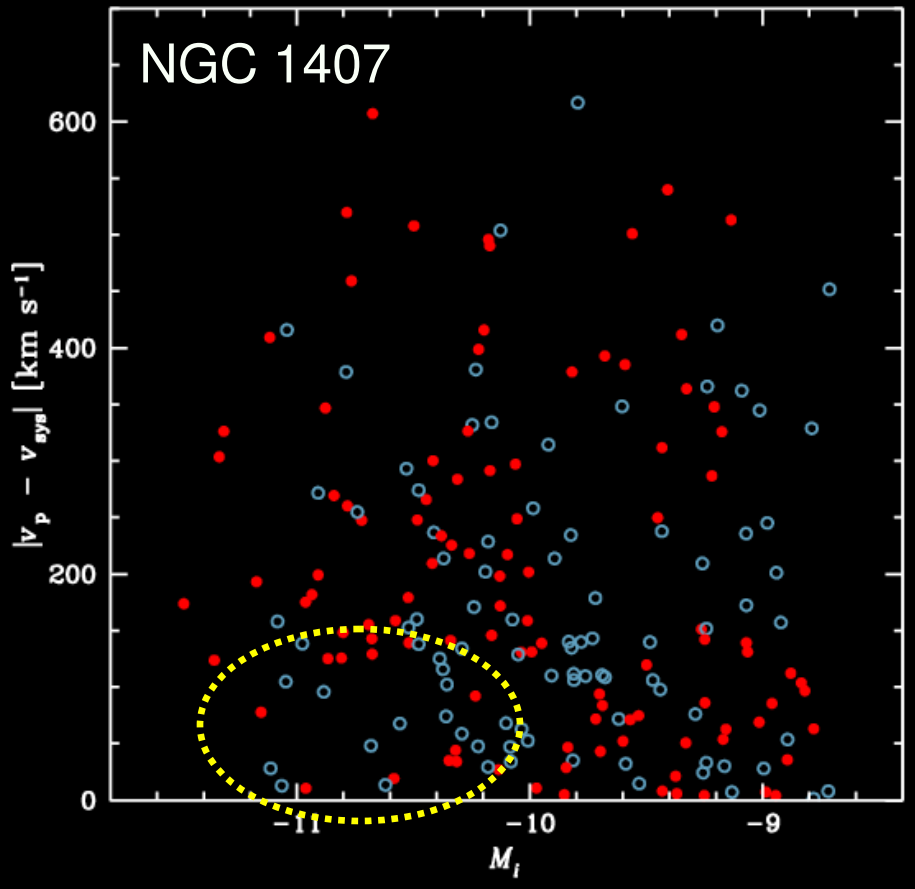
GCS orbit anisotropy in massive ellipticals

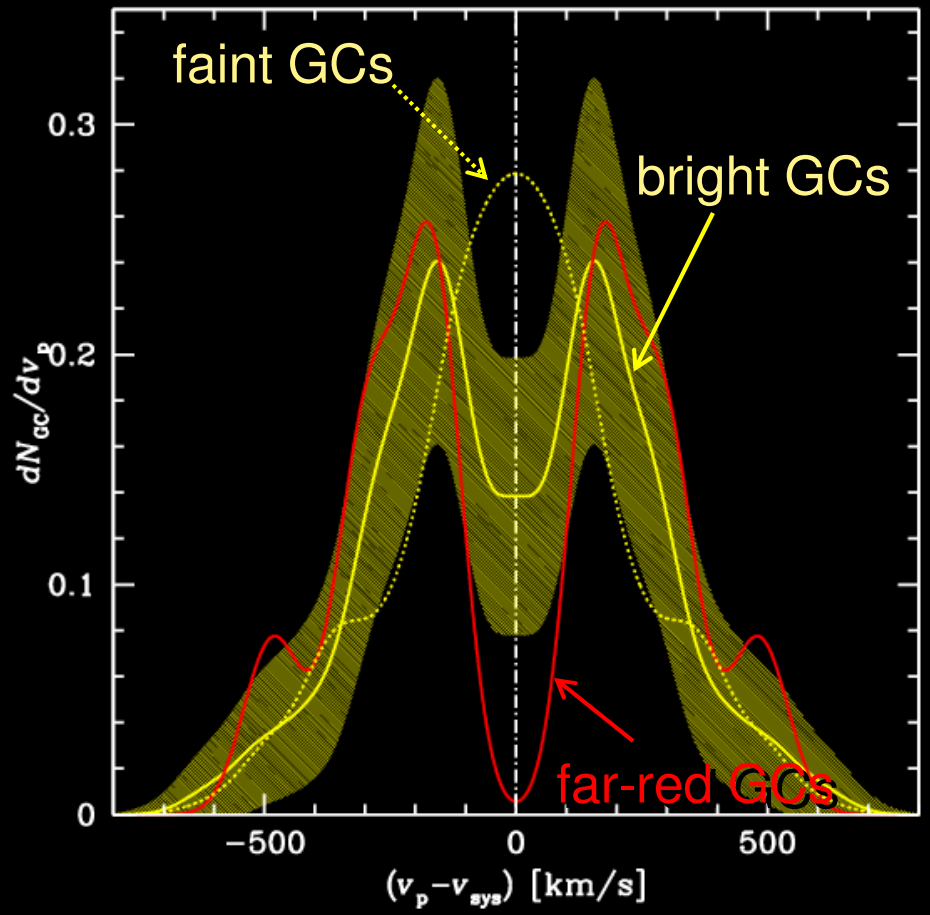
Beyond GCLF problems:
how did GCs get these orbits??

Generic expectation for halo particles on radial orbits (infall)
(e.g. van Albada 1982;
Diemand et al. 2005; Abadi et al. 2006)
→ *confirmed in stellar/PN halos*
→ *GCs either deposited on tangential orbits (subhalo accretion?), or:*
→ *GCs on radial orbits were eroded or circularized after last major merger (to ~50 kpc!)*



Orbit clues from luminosity dependence

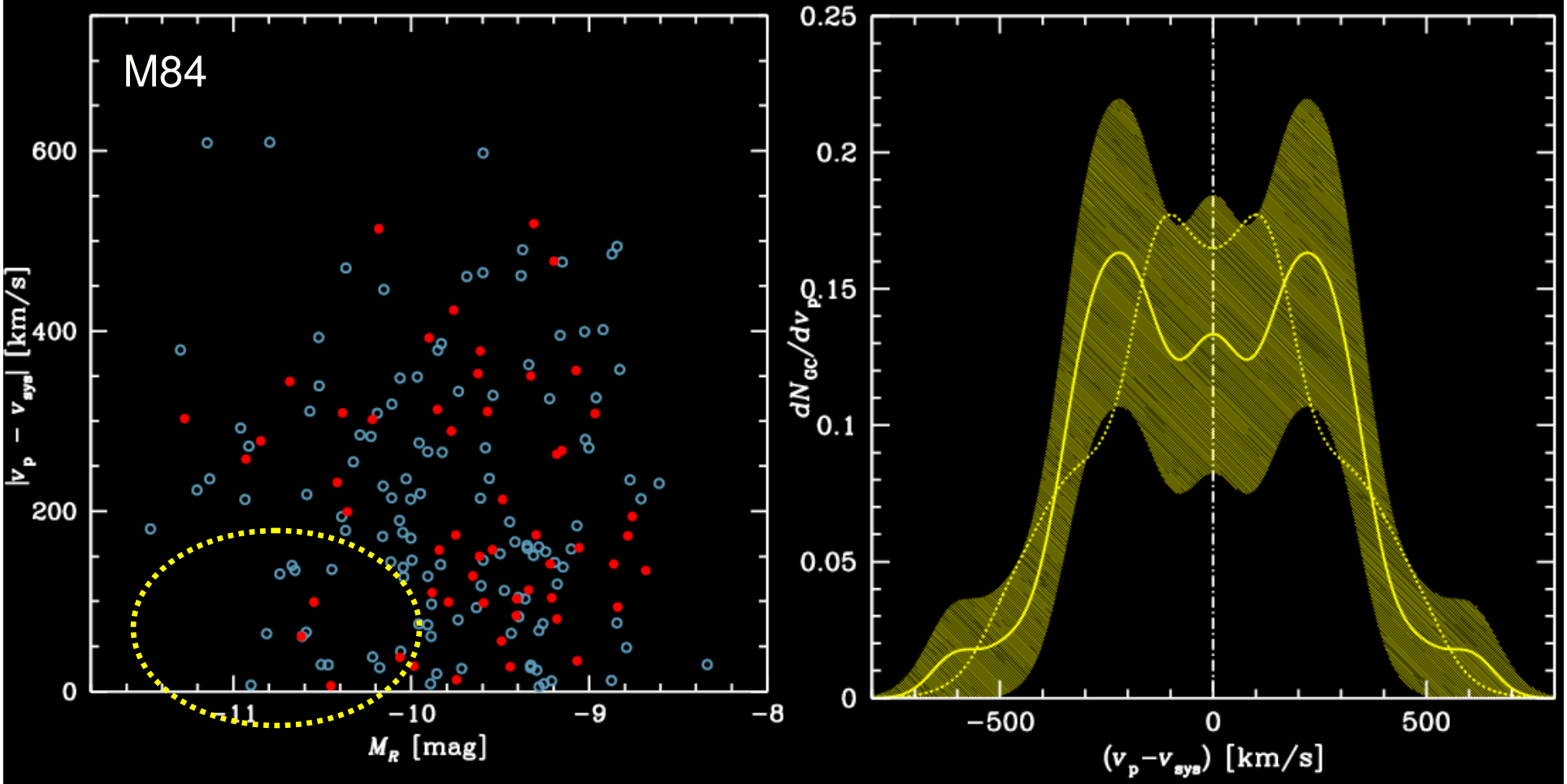




NGC 1407:

Bright GCs on more tangential orbits (increasing with color), and slightly steeper dispersion profile with radius

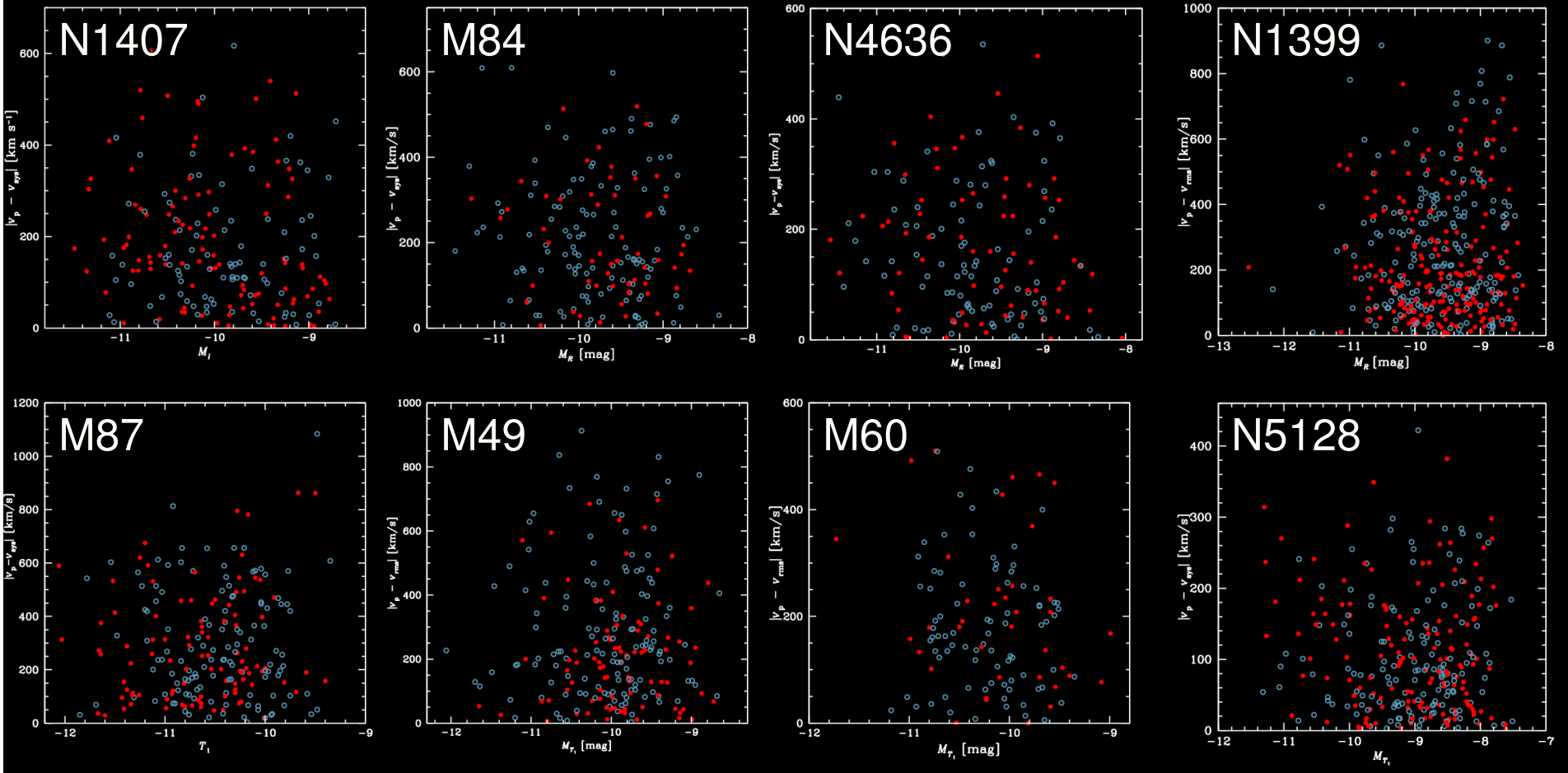
Orbit clues from luminosity dependence



M84:

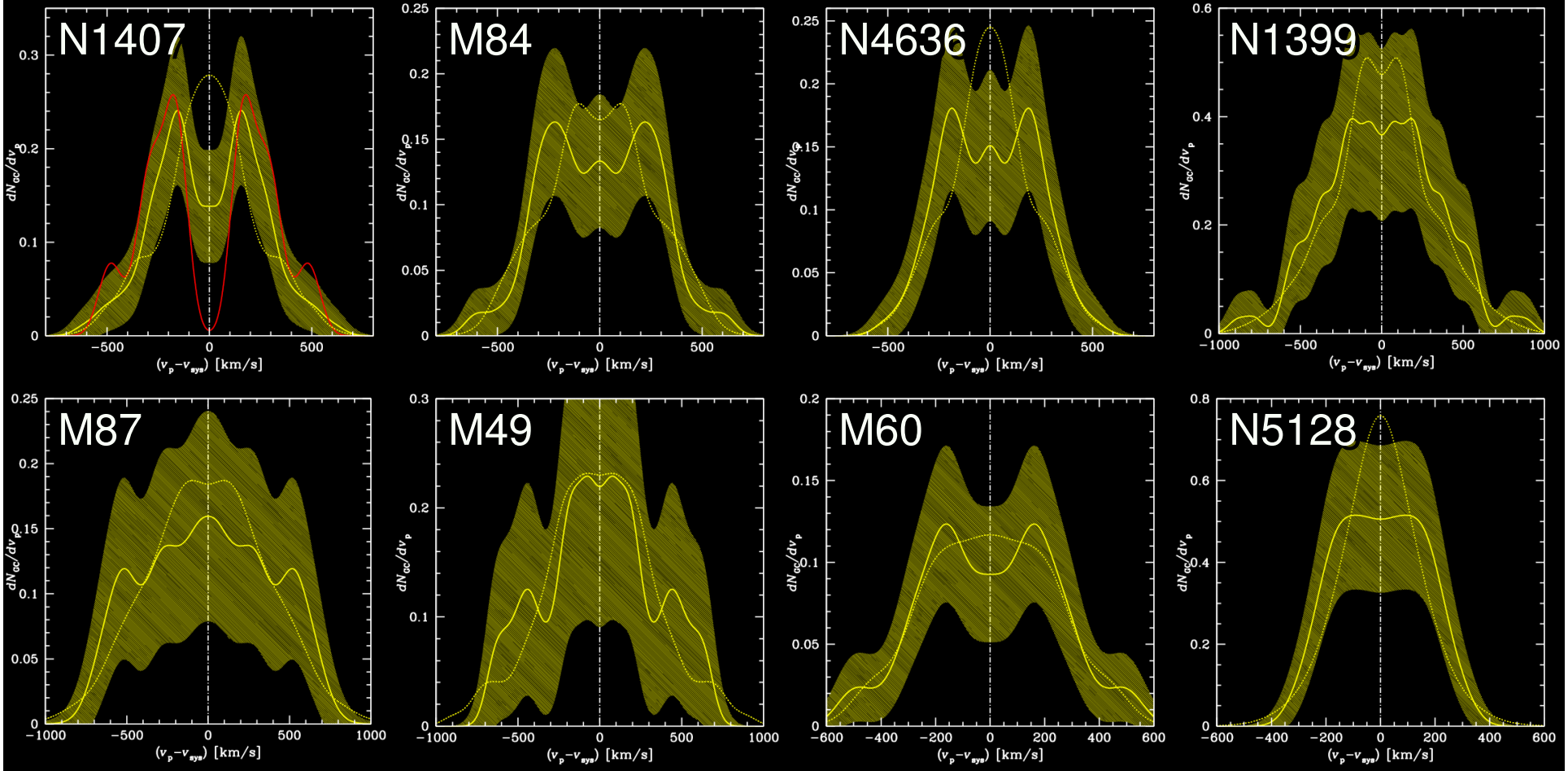
Bright GCs on more tangential orbits

Bright GC velocities in massive Es



~100-400 GC velocities per galaxy: Côté et al. (2001, 2003); Richtler et al. (2004); Schuberth et al. (2006); Woodley et al. (2007); Hwang et al. (2008); Romanowsky et al. (2009); Kumar et al. (2009)

Bright GC LOSVDs in massive Es



- *Bright GCs show flat-tops / double-peaks in almost all cases!* (significant in ~3 cases)
- No metallicity dependence in general
- Boundary: M_R ~ -10.5 ± 0.5 M_{GC} ~ 2×10^6 M_{sun}
  - where *M/L* and r_e change! (e.g. Rejkuba et al. 2007; Mieske et al. 2008)

Explaining GC orbits

Preferential erosion of GCs on radial orbits, or circularization, after last major merger, to ~50 kpc ?

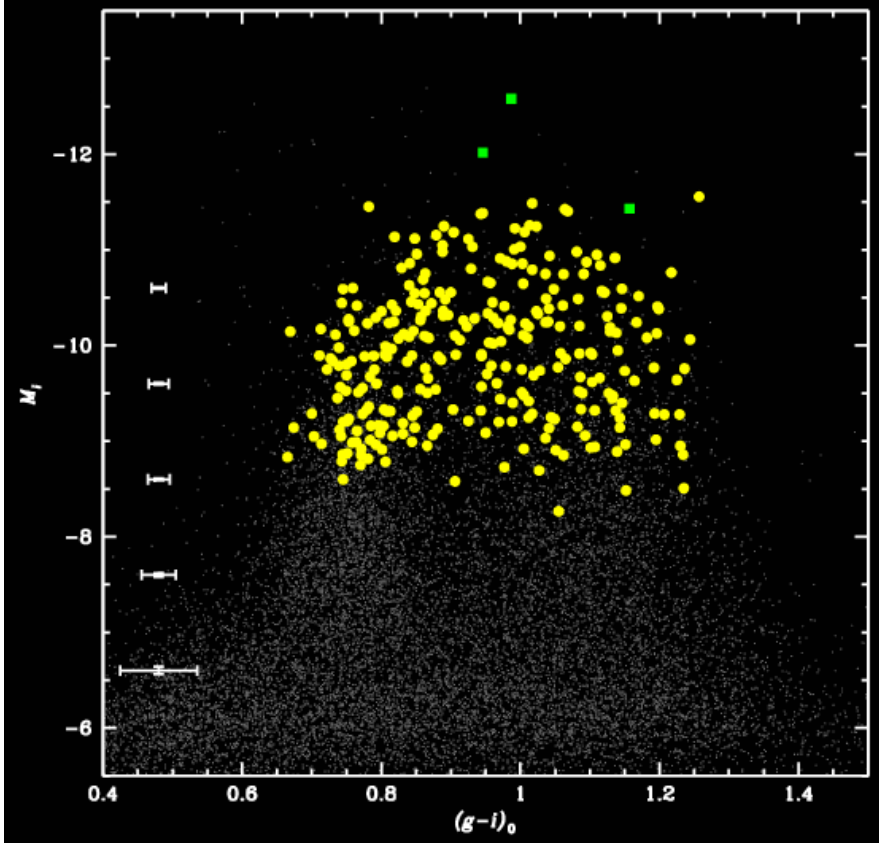
- *NB Bright GCs don't have to be preferentially destroyed, since mass-independent depletion would leave only "lucky" GCs at bright end*
- *GCs eroded during major merger?*

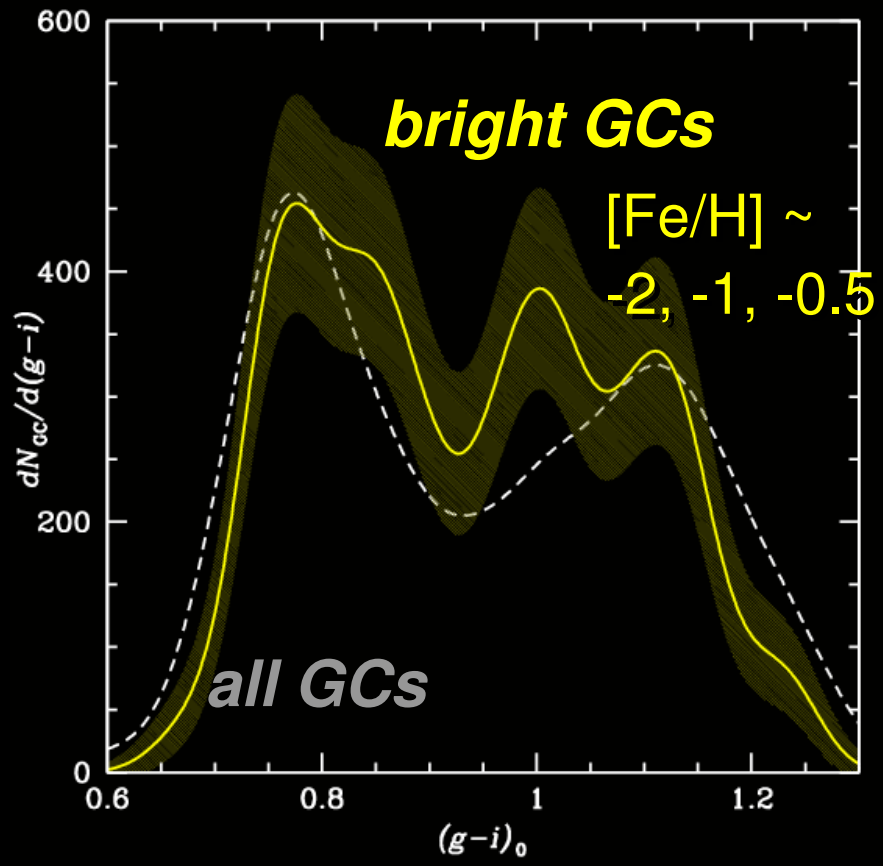
dynamical friction operates to ~ 1 kpc, evaporation to ~ 5 kpc?
(e.g. Vesperini et al. 2003)
⇒ *DM around bright GCs?*
⇒ *revised treatments of shocks or triaxiality?*
(Dehnen et al. 2004; Capuzzo-Dolcetta & Vicari 2005)

GCs deposited on tangential orbits ?

accretion from satellite galaxies? (e.g. Prieto & Gnedin 2008)
⇒ M_{GC} *dependence?*
⇒ *most GCs arrive after galaxy assembly,*
unless group-central ellipticals have distinct formation mode

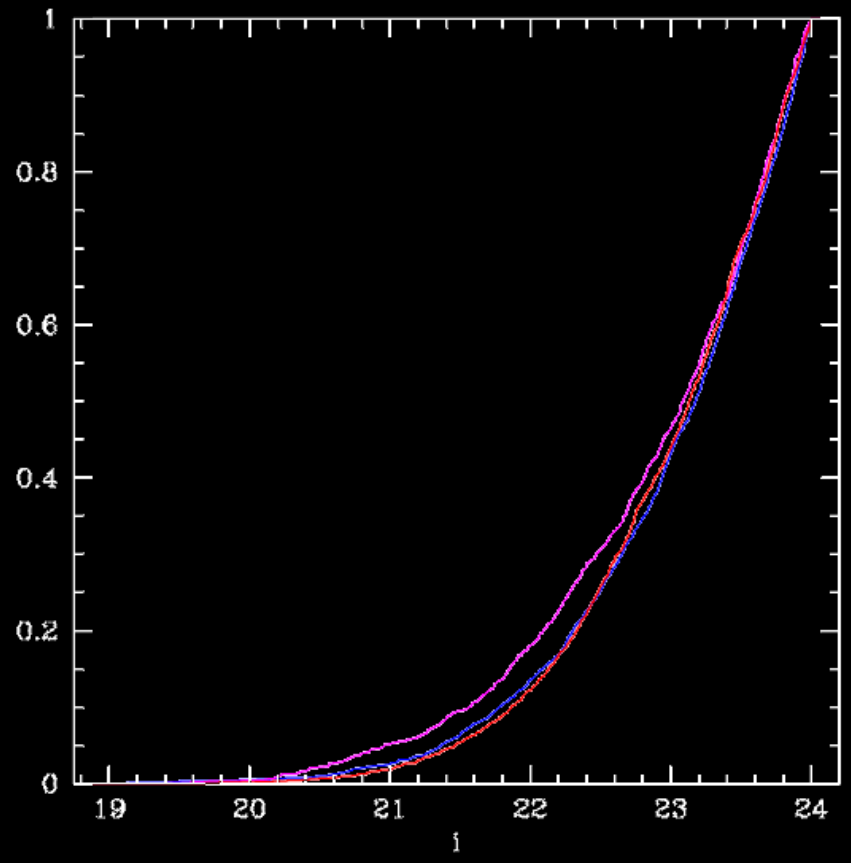
Third GC population in NGC 1407



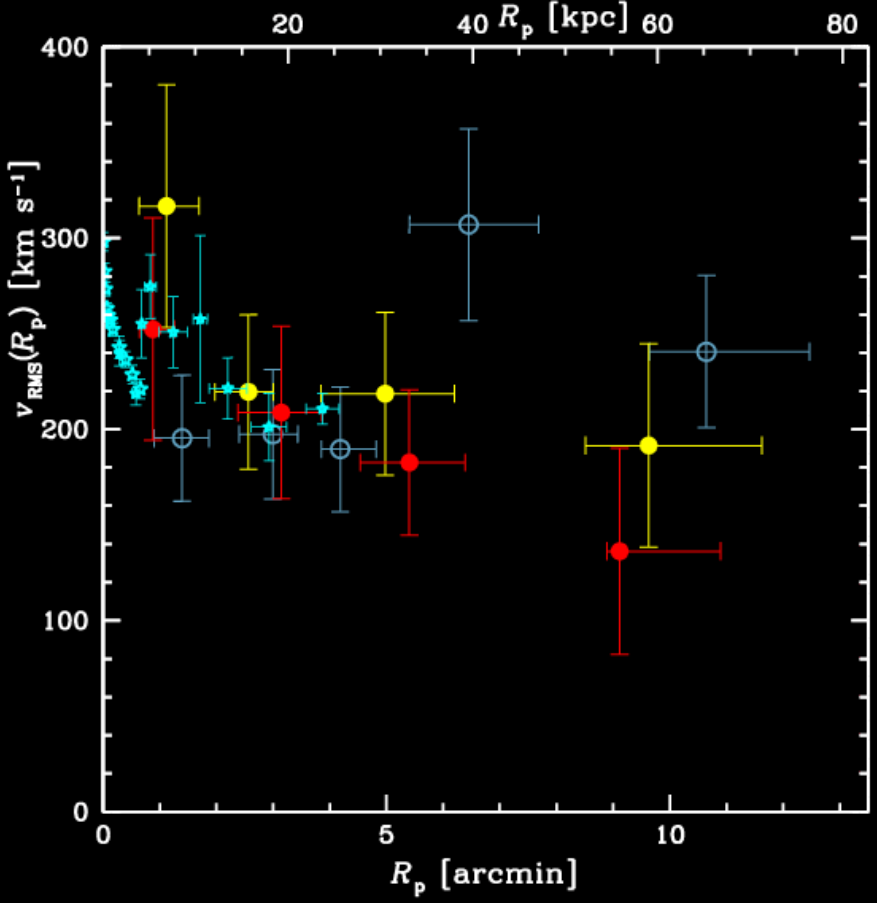


Spectroscopically-confirmed GCs in NGC 1407
(Romanowsky et al. 2009)

Third GC population in NGC 1407

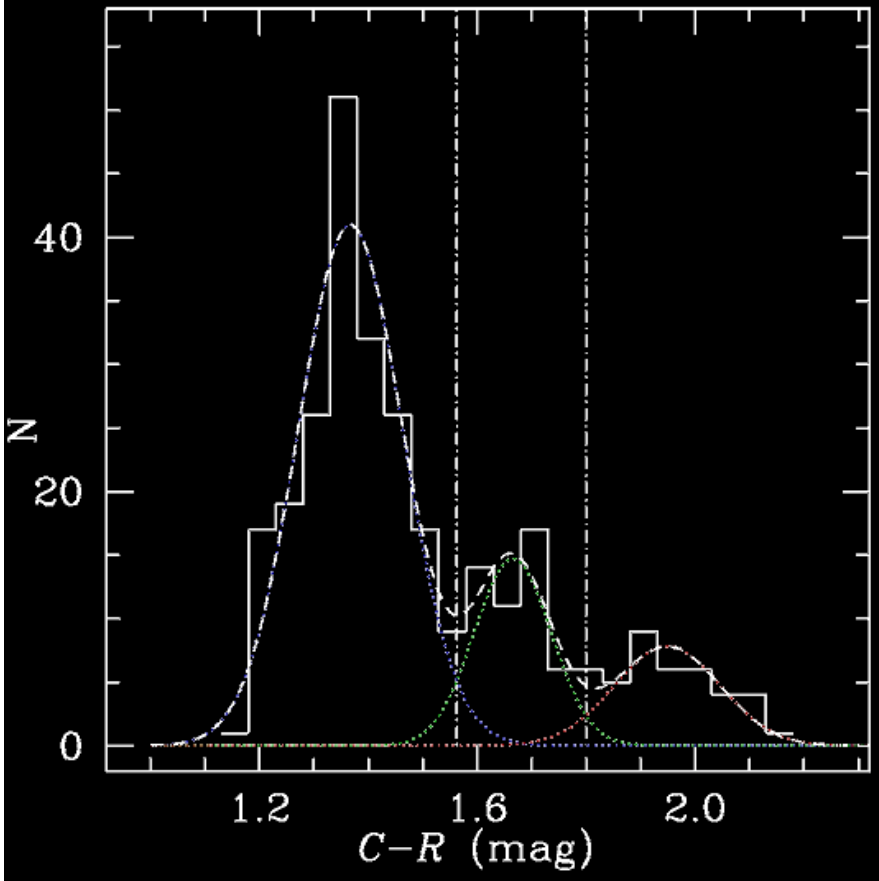


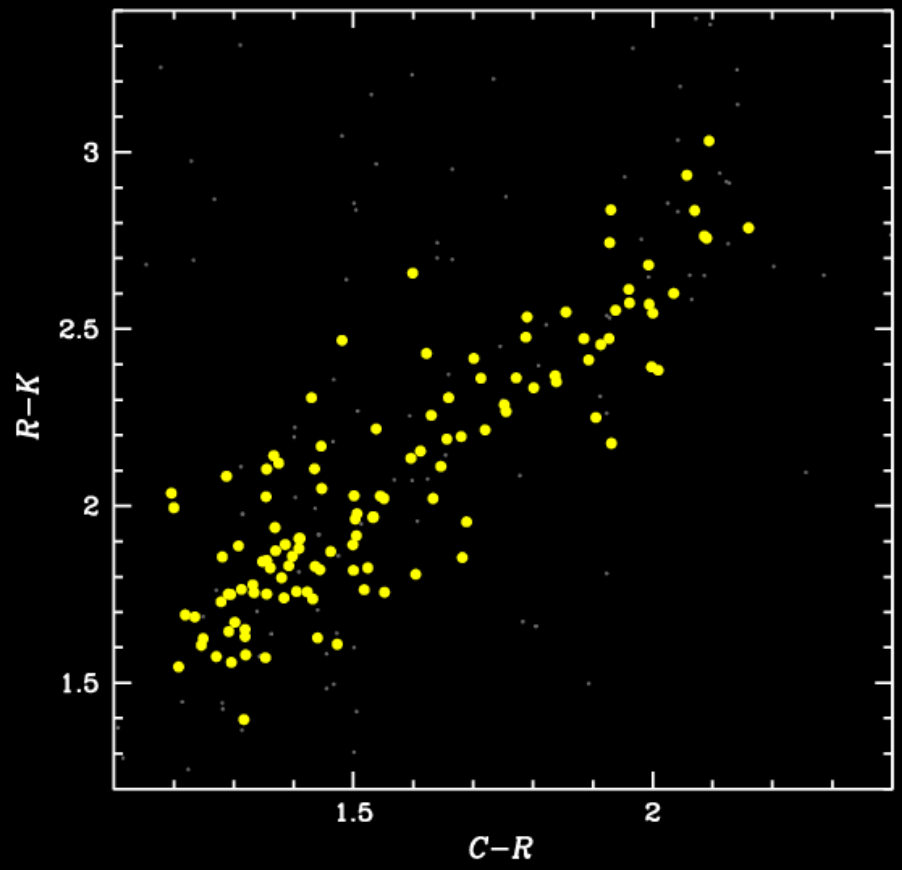
Intermediate pop shows up as distinct luminosity function



Number density and velocity dispersion profiles intermediate to metal-poor, metal-rich

Third GC subpopulation in M84

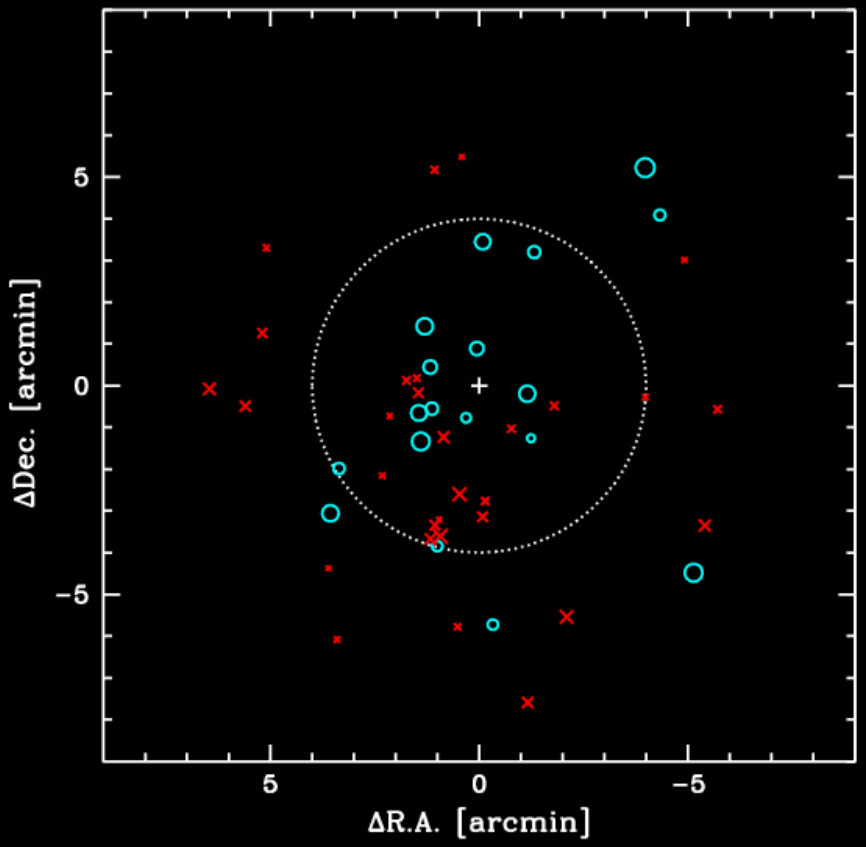




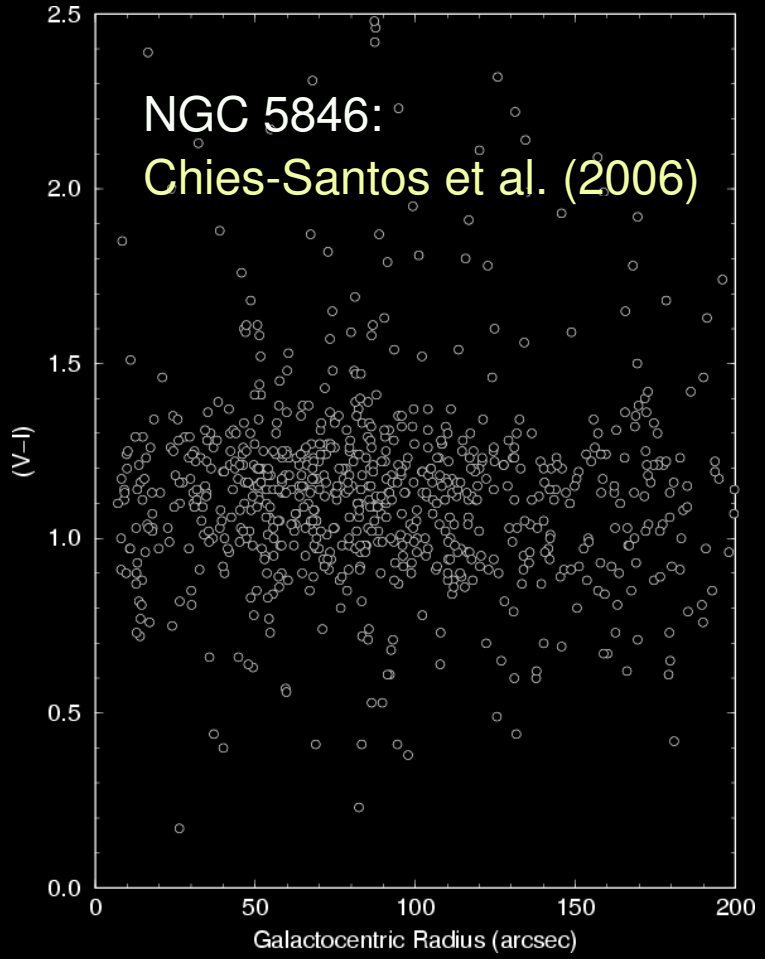
Old, intermediate-*Z*, bright, centrally concentrated (< 20 kpc)

(Kumar et al. in prep; Hempel et al. in prep)

Third GC subpopulation in M84

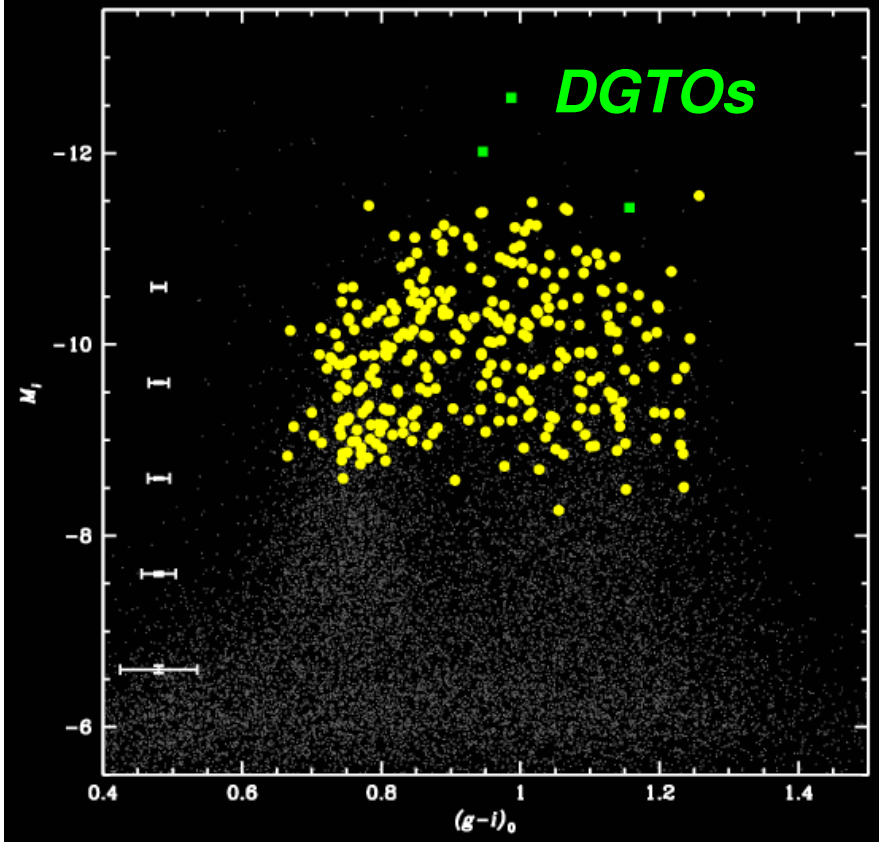


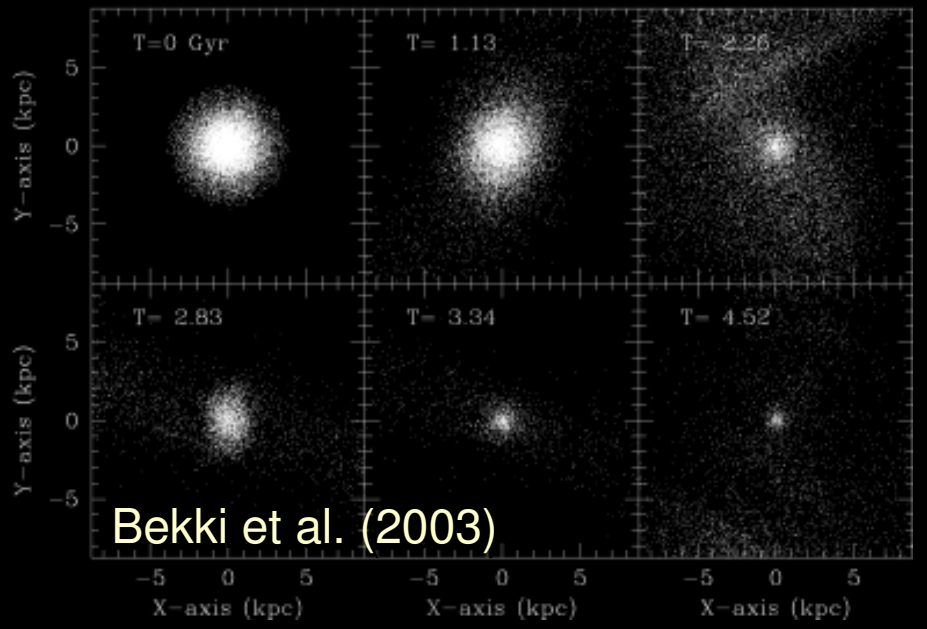
Flattened rotating structure!



Other third peaks known but peculiar GCLF is important: not simply another SF episode!

Origin of third GC populations



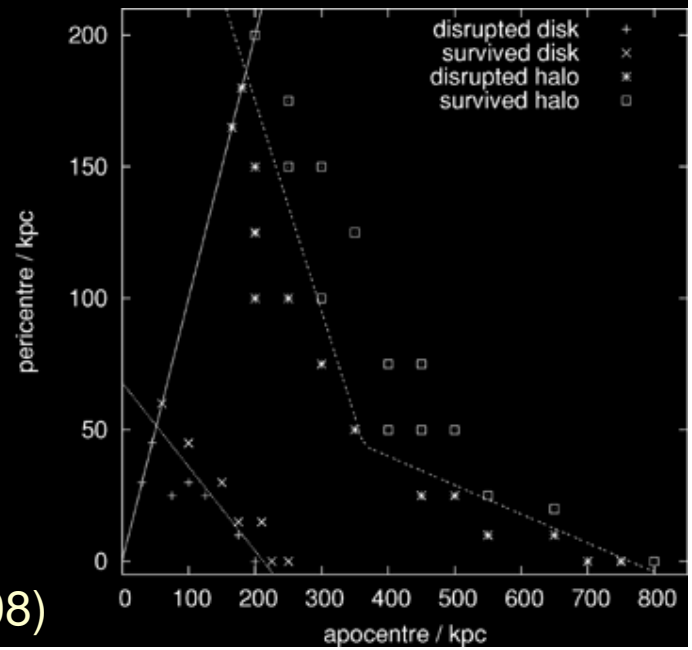


Bekki et al. (2003)

Faint extension of UCDs/DGTOs?

⇒ tidally harrassed dwarf galaxies?

should have radial orbits??



Goerdt et al. (2008)

- *SLUGGS survey of halo properties (incl. GCs) of nearby early-type galaxies*
- *Non-radial GC orbits difficult to explain*
- *Bright GCs ($M_V < -10$) show strongly tangential orbits*
- *Intermediate-Z subpops: extension of DGTOs?*