Observations of (mostly) Young Extragalactic Star Clusters

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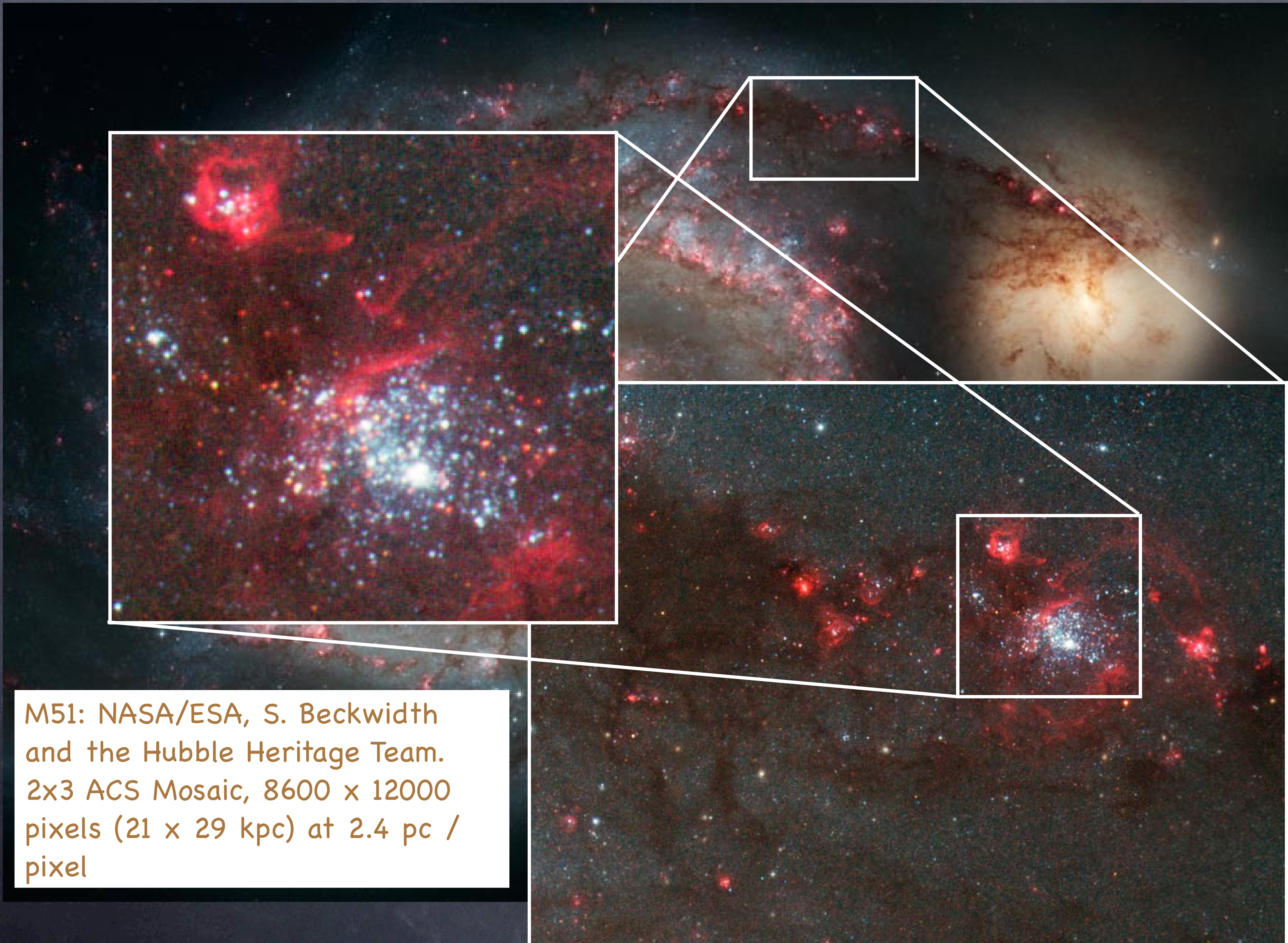
N-body models: A Customer's Perspective

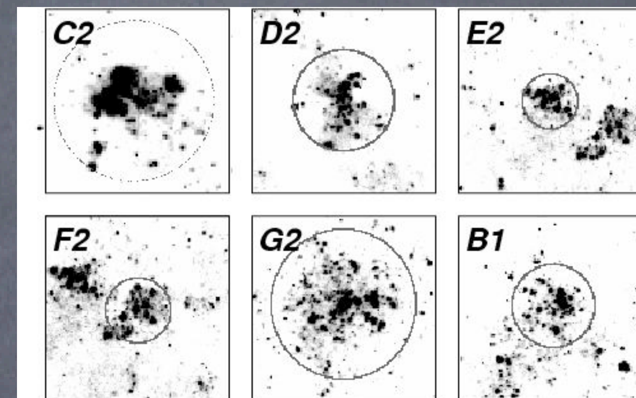
- Constancy (?) of cluster sizes (Red vs Blue GCs size difference, Faint Fuzzies)
- Dynamical Evolution of Star Clusters and Cluster Populations
- Power-law LF/MF in young cluster systems vs bell-shaped MF in old GC systems - Dynamical Evolution?
- The "Infant Mortality Problem" - Rapid cluster disruption in the initial ~10 Myrs. What causes this?
- Interpretation of dynamical mass measurements (mass segregation etc)

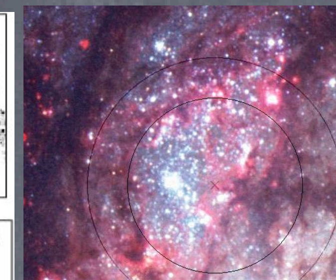


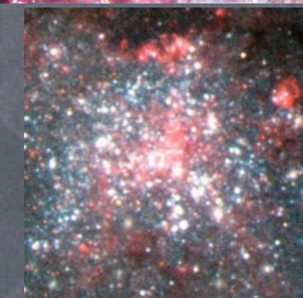
M51: NASA/ESA, S. Beckwidth and the Hubble Heritage Team. 2x3 ACS Mosaic, 8600 x 12000 pixels (21 x 29 kpc) at 2.4 pc / pixel

Clusters rarely form in isolation

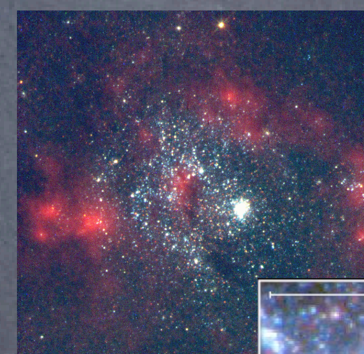
- Star clusters often form in complexes together with other clusters and stars (Antennae, M51, M83, NGC 6946, LMC, ...)
- Scales ~100 - 500 pc, masses few x 10^4 $M_\odot$ - 10^7 $M_\odot$ (Larsen et al. 2002; Bastian et al. 2005)
- $M \propto R^{2.33\pm0.19}$ (Bastian et al. 2005; ~constant surface density)
- Several clusters might merge and produce a single, more diffuse object (Elmegreen et al. 2000; Fellhauer & Kroupa 2002; 2005). Outcome: objects such as W3 in the merger remnant NGC 7252, or "faint fuzzies" in NGC 1023?
- Whitmore et al. 2005: cluster-cluster velocity dispersion ~10 km in Antennae; merging may be viable.



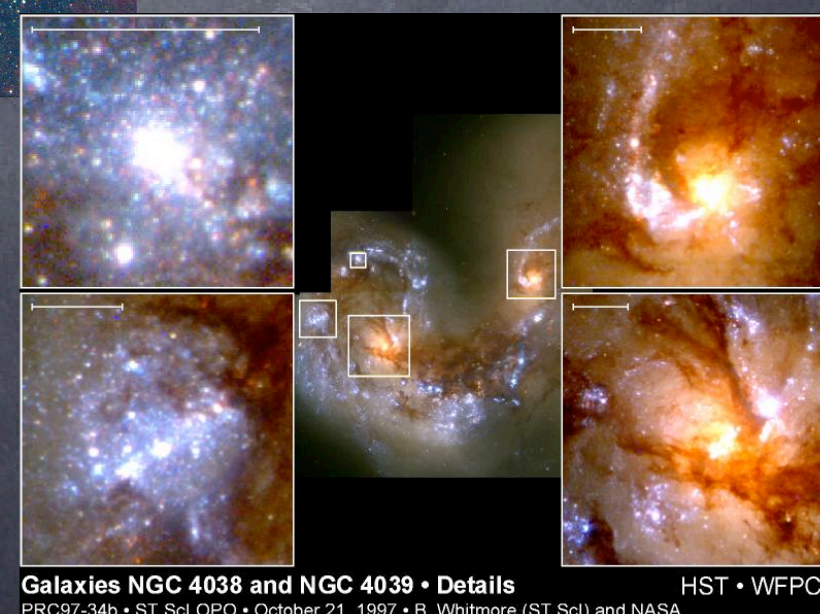




M51: Bastian et al. 2005



NGC 6946: Larsen & Richtler 1999



Cluster Sizes

Unlike complexes, only weak size-mass relation for YMCs: $r_{hlr} \propto Mass^{0.07}$.

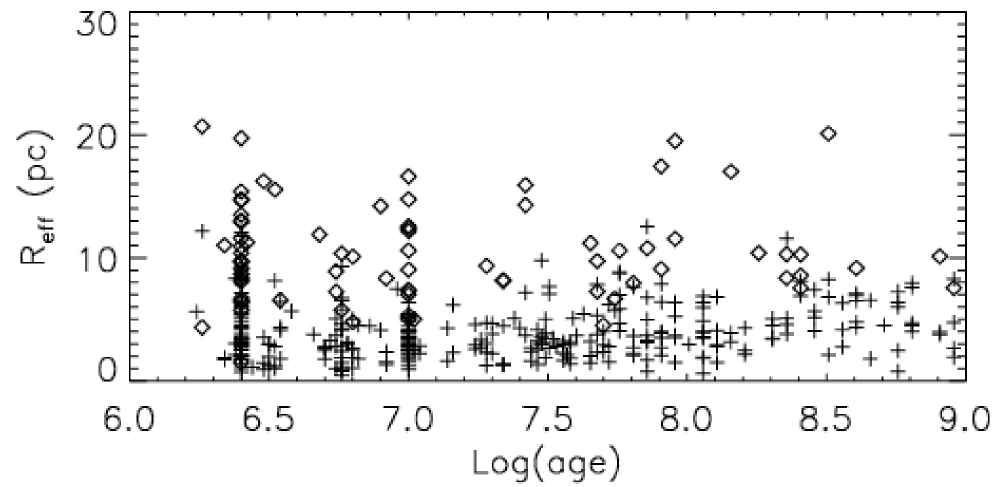
Mean half-light radii ~3 pc, almost independently of mass

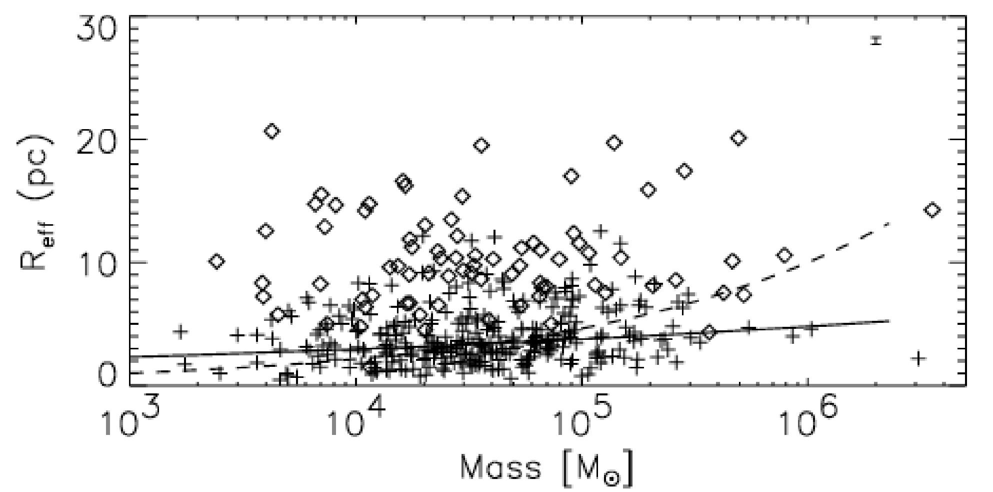
(Zepf et al. 1999; Larsen 2004; Bastian et al. 2005)

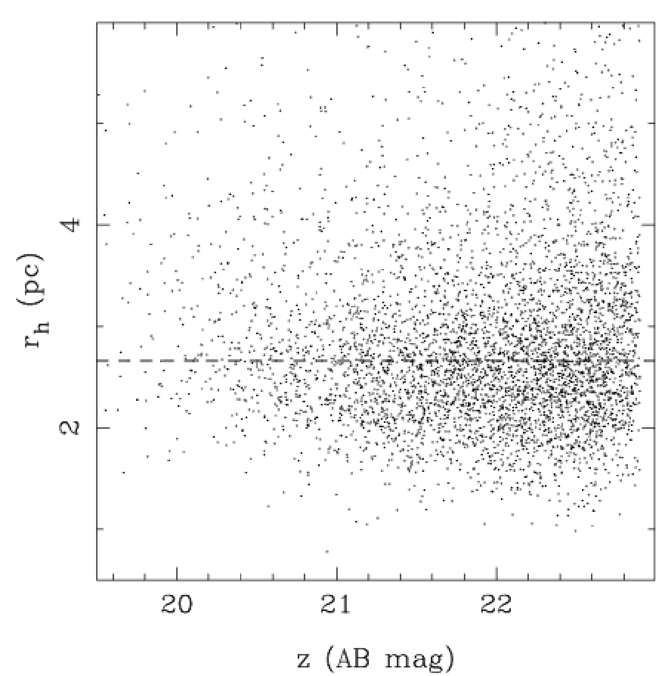
Density increases strongly with mass:

$\rho(r_{hlr}=3 \text{ pc}, M=10^6 M_\odot) = 2000 M_\odot pc^{-3}$

$\rho(r_{hlr}=2 \text{ pc}, M=10^3 M_\odot) = 7 M_\odot pc^{-3}$



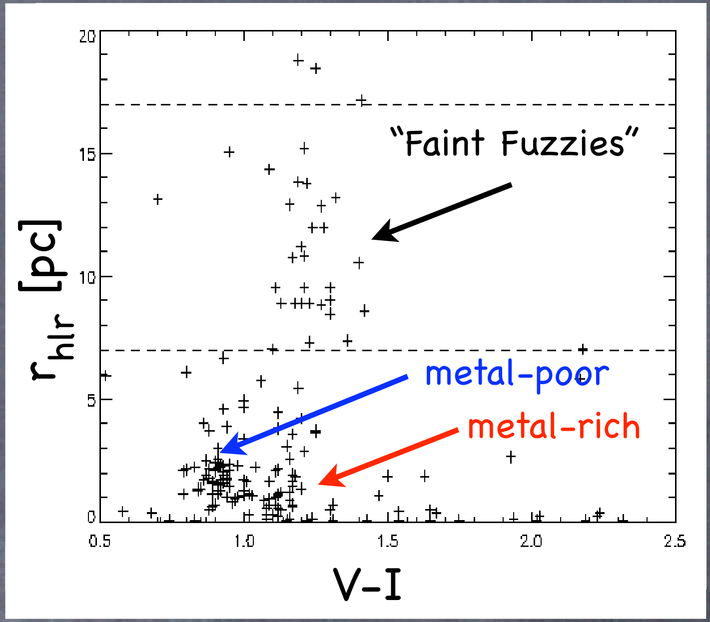




Same for old GCs: Jordán et al. 2005 (ACS Virgo Cluster Survey - see talk tomorrow!)

Not all clusters have the same size!

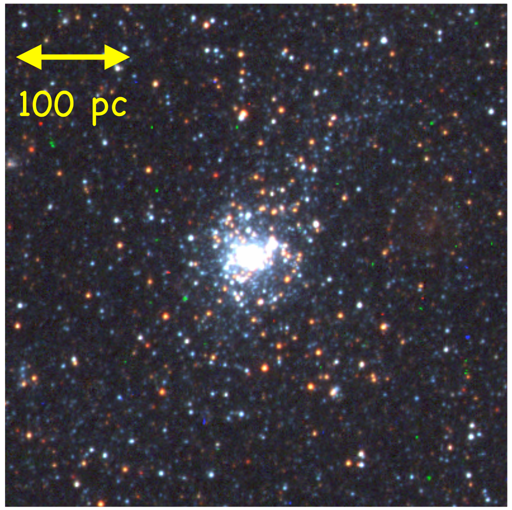
NGC 1023:
Larsen & Brodie 2000

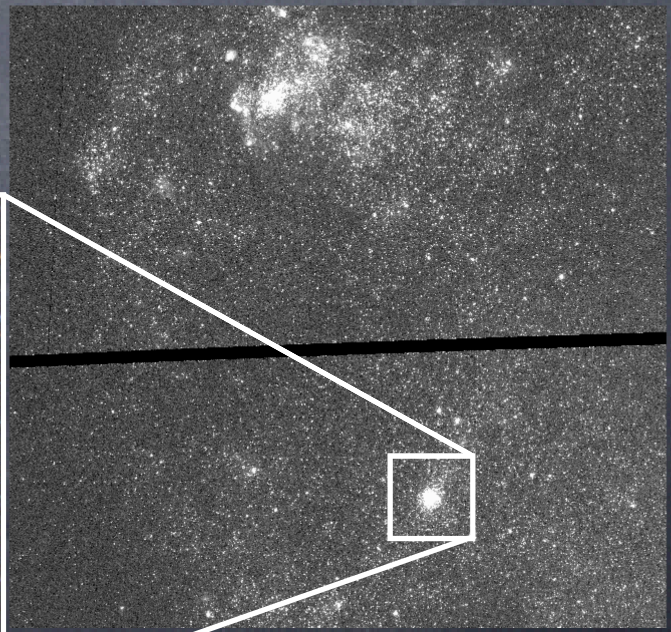


- ~20% size difference between metal-rich and metal-poor GCs: projection effect or mass segregation (see talk by Andrés Jordán) but probably not physical

- "Faint Fuzzy" clusters in lenticular galaxies: GC-like ages, but half-light radii 7-20 pc

- "Cousin" to FFs in NGC 1313? r_{hlr} ~ 20 pc, age ~ 30 Myr, mass ~10^5 $M_\odot$ (ACS data, Larsen et al., in prep.)

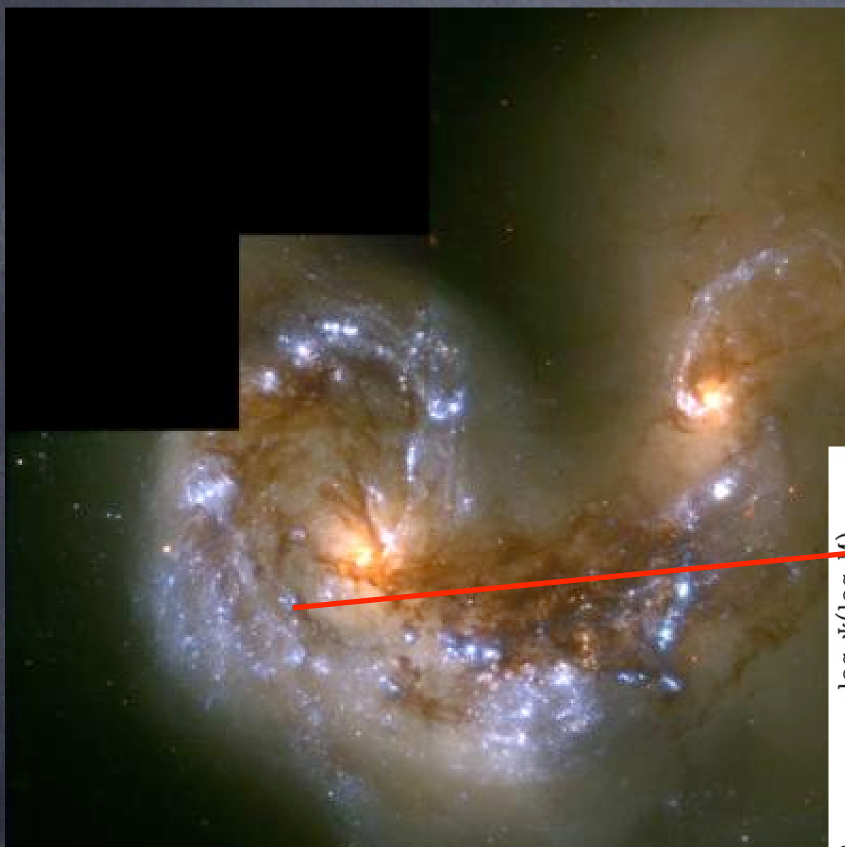




NGC 1313

Evolution of Cluster Populations

NGC 4038/4039 “The Antennae”



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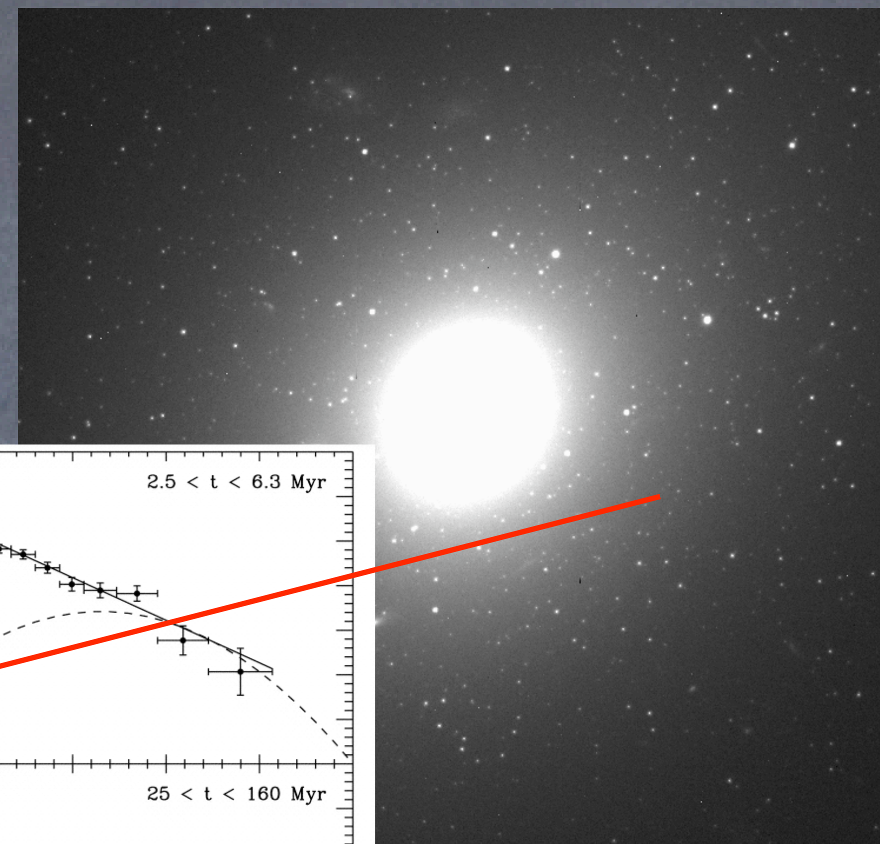
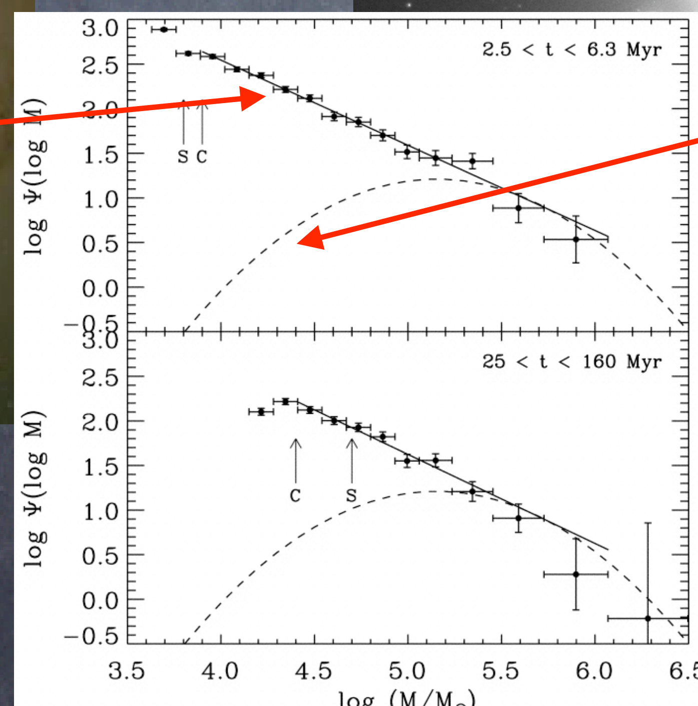




Does an initial power-law MF always evolve into a bell-shaped distribution over a Hubble time?

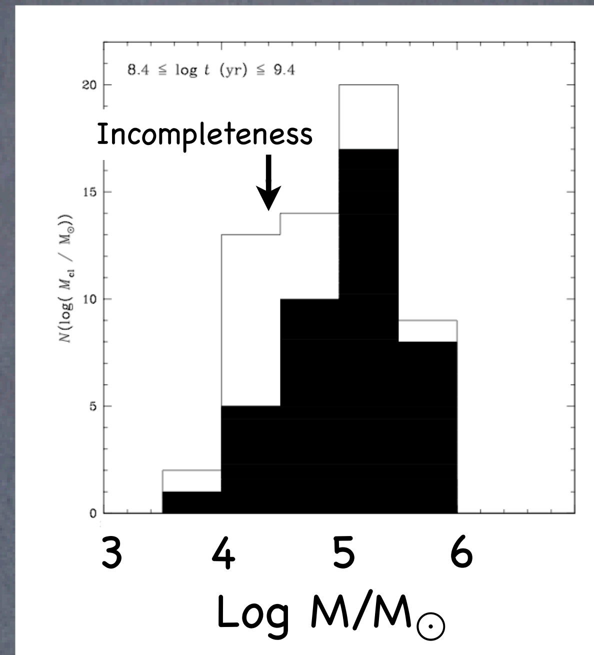
Fall & Zhang 1999

Evolution of the MF:

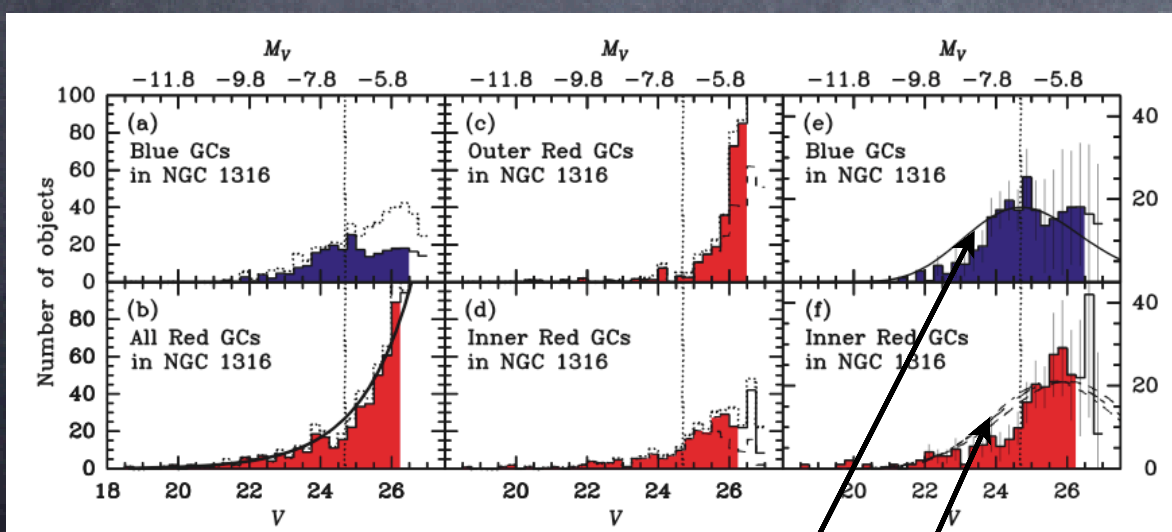
- Under what circumstances does a power-law MF evolve towards the observed GCMF? What are the constraints on orbits? Galactic potentials (bulges/disks/GMCs)? Cluster sizes/concentrations? Reproduce radial trends (e.g. turn-over)?
- Fall & Zhang 2001: largely analytical models (Spitzer 1987, etc: two-body relax., gravitational shocks, stellar ev. + static spherical potential). Turn-over develops at ~2×10^5 $M_\odot$ after 12 Gyr for a wide range of initial MFs. Best fit to data for significant radial anisotropy in velocity distribution.
- Vesperini et al. 2003: Power-law MF -> turn-over, but only for strongly anisotropic velocity distributions, inconsistent with M87 data. Vesperini & Zepf 2003: Disruption of low-mass, low-concentration clusters due to early mass loss may provide "missing link" between power-law and bell-shaped MFs.
- Lamers et al. 2005: Initial power-law MF does not evolve towards Galactic GCMF. Observed disruption times of galactic open clusters ~ factor of 5 shorter than predicted by N-body models (Baumgardt & Makino 2003).
- See also poster by Waters & Zepf

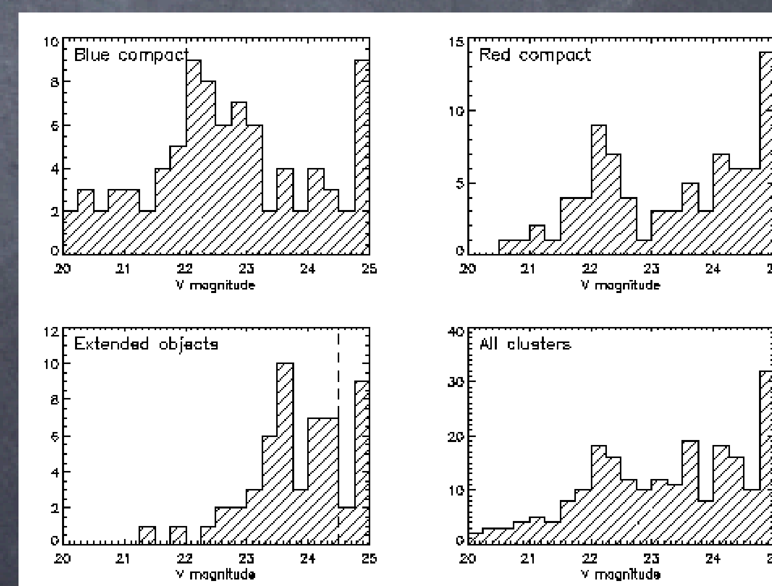
Constraints on Dynamical Evolution

- de Grijs et al 2003: turn-over at $2\times10^5\ M_\odot$ in M82 at ~1 Gyr,
- Goudfrooij et al. 2004: NGC 1316 (~3 Gyr), inner red GCs show TO at 1 mag fainter than blue GCs
- "Faint Fuzzy" clusters in NGC 1023: Ages similar to GCs, but no turn-over (Because of longer two-body relax. timescales?)



M82:
8.4 < log t < 9.4
de Grijs et al. 2003





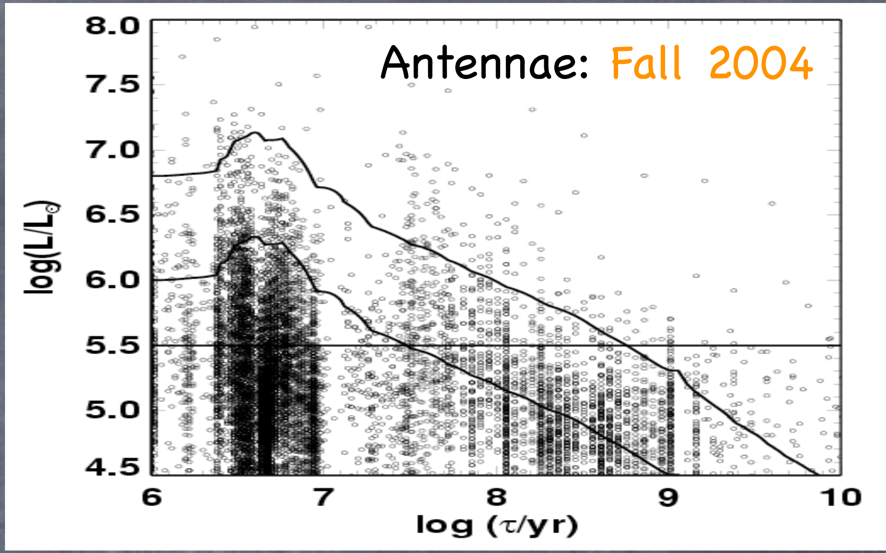
Goudfrooij et al. 2004

Fall & Zhang 2001

NGC 1023: Larsen & Brodie 2000

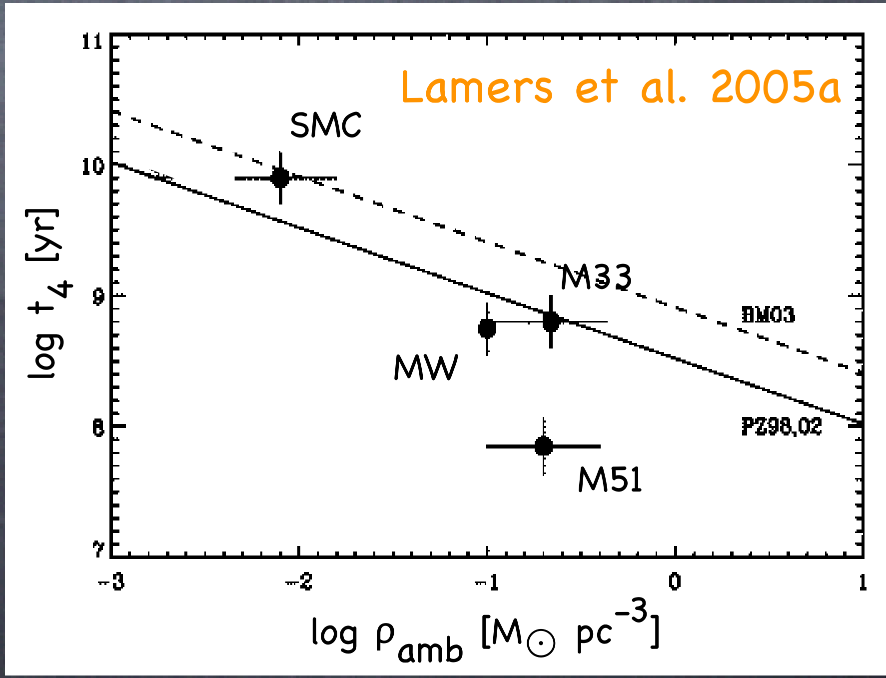
Disruption in Different Environments

- "Infant mortality" - majority (~90%) of clusters disrupt in first 10 Myrs (Tremonti et al. 2001 for NGC 5253; Lada & Lada 2003 for MW; Fall 2004 and Mengel et al. 2005 for Antennae; Bastian et al. 2005 for M51). Largely independent of mass. Probably due to early mass loss (Kroupa & Boily 2002)



- Boutloukos & Lamers 2003:

  $t_{dis} = t_4 \, (M/10^4 \, M_\odot)^\gamma$, $\gamma \sim 0.6$. Disruption time-scale t_4 of $10^4 \, M_\odot$ cluster depends strongly on environment: 70 Myr near centre of M51, about 1 Gyr in solar neighbourhood, and 8 Gyr in SMC (Lamers et al. 2005a; 2005b)



- MW: N-body models (Baumgardt & Makino) predict disruption times that are too long by about a factor of 5 (Lamers et al. 2005b)

Dynamical Masses and M/L ratios

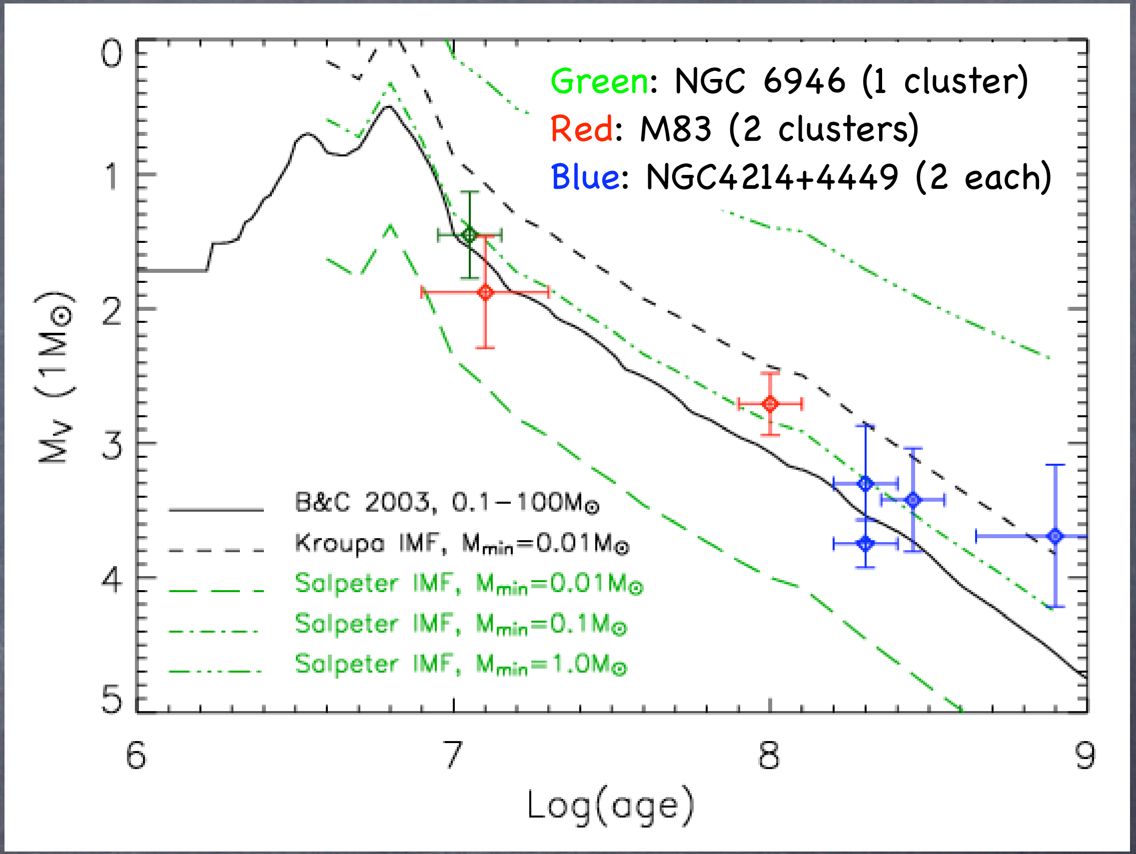
- Verify photometric mass estimates by application of virial theorem
- Cluster sizes + velocity dispersions → mass estimates
- Dynamical masses + photometric/ spectroscopic ages → constraints on stellar IMF via SSP models

Observations

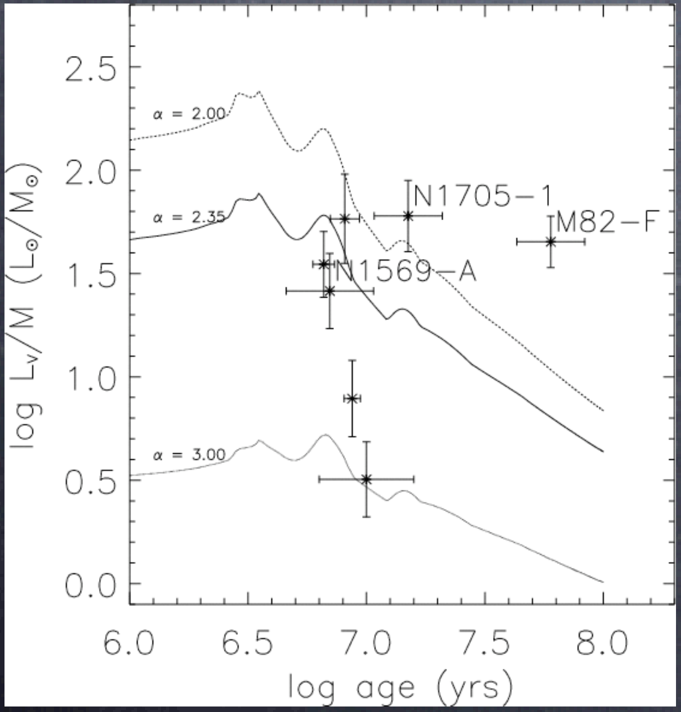
- Masses in the range 10^5 - 10^6 $M_\odot$ generally confirmed (Ho & Filippenko 1996; Smith & Gallagher 2001; Mengel et al. 2003; Larsen et al. 2001,2004a,2004b; Gilbert & Graham 2003; McCrady et al. 2004). Exist in many environments: spirals, dwarfs, mergers, nuclear starbursts / rings, ...
- Some "extreme" objects, e.g. NGC 7252 W3 (8×10^7 $M_\odot$; Maraston et al. 2004) - but "normal" IMF
- Generally, no consistent picture concerning IMFs: Some studies find non-standard (mostly top-heavy) IMFs (Smith & Gallagher 2001; McCrady et al. 2004) while others find "normal" IMFs (Larsen et al.; Gilbert & Graham).

M/L ratios and the (I)MF

	r_{hlr} [pc]	M [$10^5 M_\odot$]
N4214-10	4.33±0.14	2.6±1.0
N4214-13	3.01±0.26	14.8±2.4
N4449-27	3.72±0.32	2.1±0.9
N4449-47	5.24±0.76	4.6±1.6
M83-A	7.6±1.1	5.2±0.8
M83-B	2.8±0.4	4.2±0.7
N6946-A	10.2±1.6	17.6±5



Larsen & Richtler 2004 (M83: VLT/UVES)
Larsen, Brodie & Hunter 2004 (Keck/HIRES, NIRSPEC)



Mengel et al. 2002

Problems

$$M_{vir} = \eta \, r_{hlr} \, \sigma_x^2 / G$$

$\eta = 10$?

- Mass segregation - what value to use for η? (Boily, Lançon et al 2005: $\eta \sim 20$)
- Role of binaries
- Macroturbulence in red supergiant atmospheres ~10 km/s)
- Youngest clusters relaxed? What is a "safe" age?
- Small number statistics ($10^5\ M_\odot$ cluster has about 20 RSGs at 10 Myr)

Questions

- Can GCs have formed with an initial power-law mass distribution?
- Is there a real size difference betwen red and blue GCs?
- What causes "infant mortality"?
- Is merging of star clusters important?
- How accurately can we derive dynamical masses from integrated photometry/spectroscopy?