High Resolution Analysis of M87 Globular Clusters

Christopher Waters

Michigan State University

Introduction

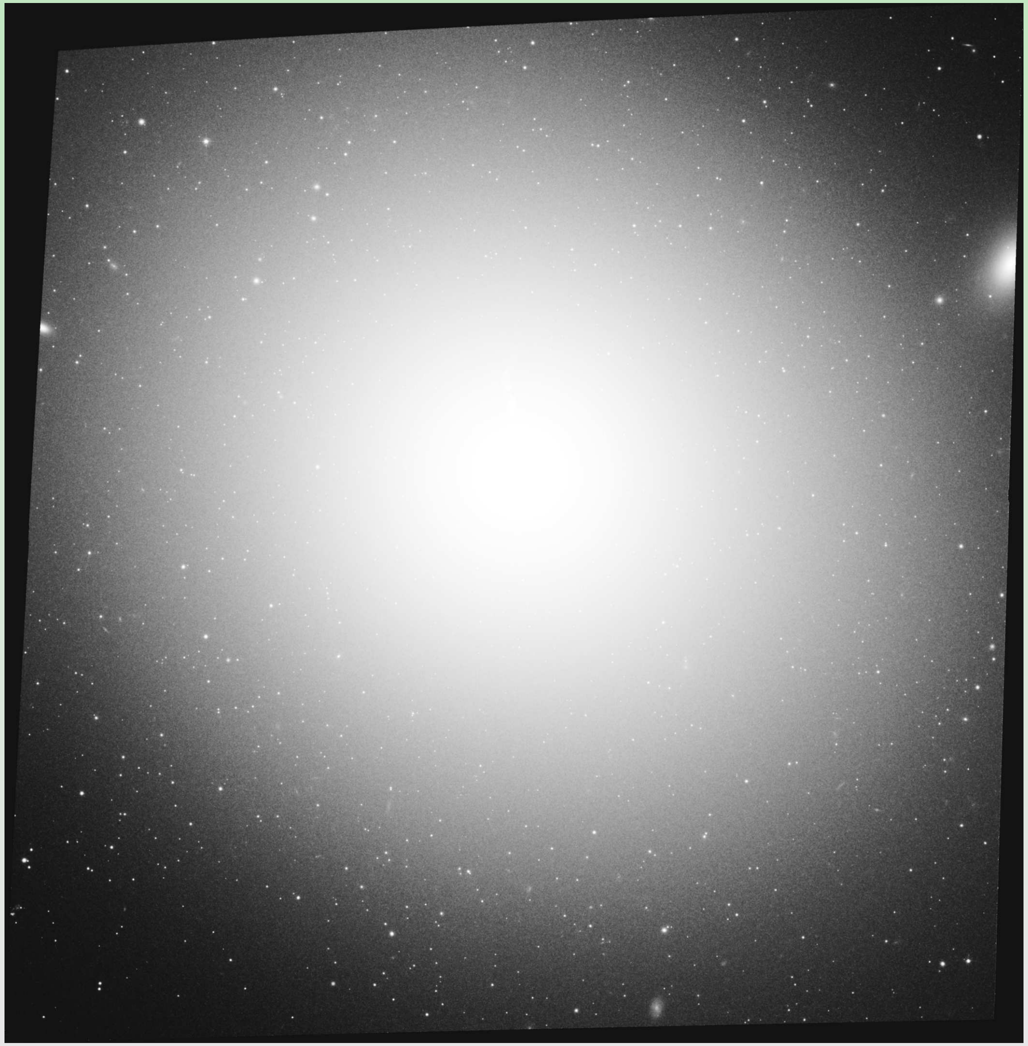
- Milky Way sample is small (N = 150)
- Generally comprised of heterogeneous data
- Extant extra-galactic samples biased towards brightest objects

Use deep HST observations of M87 to

- Constrain shape of the mass function
- Look at trends in color bimodality
- Fit King (1966) models of the cluster structure

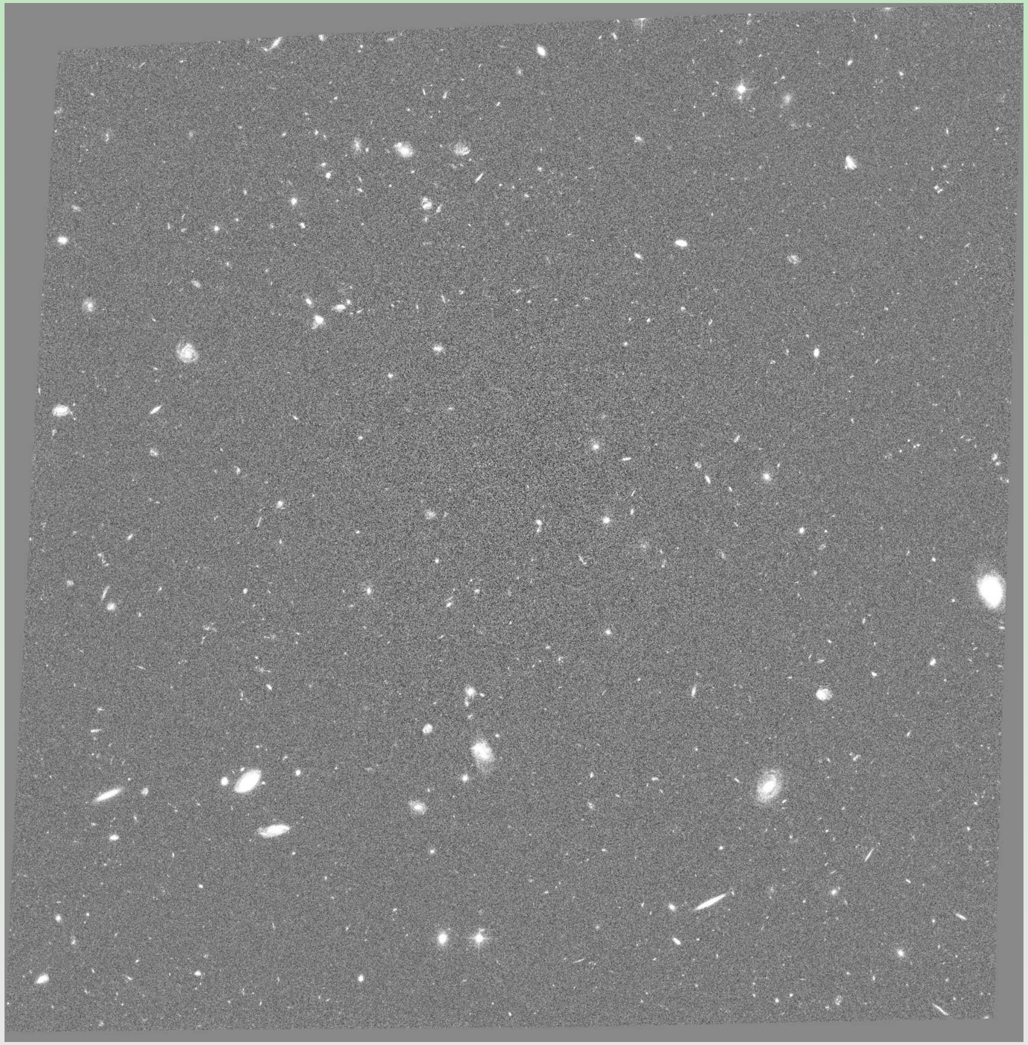
Data

- 50 Orbit HST/ACS observations
  - $t_{F606W} = 24500$s
  - $t_{F814W} = 73800$s
- Combined using Multidrizzle
- Detect and measure clusters with Source Extractor
- 2089 clusters in final sample
- Color corrected to V & I (Sirianni et al. 2005)



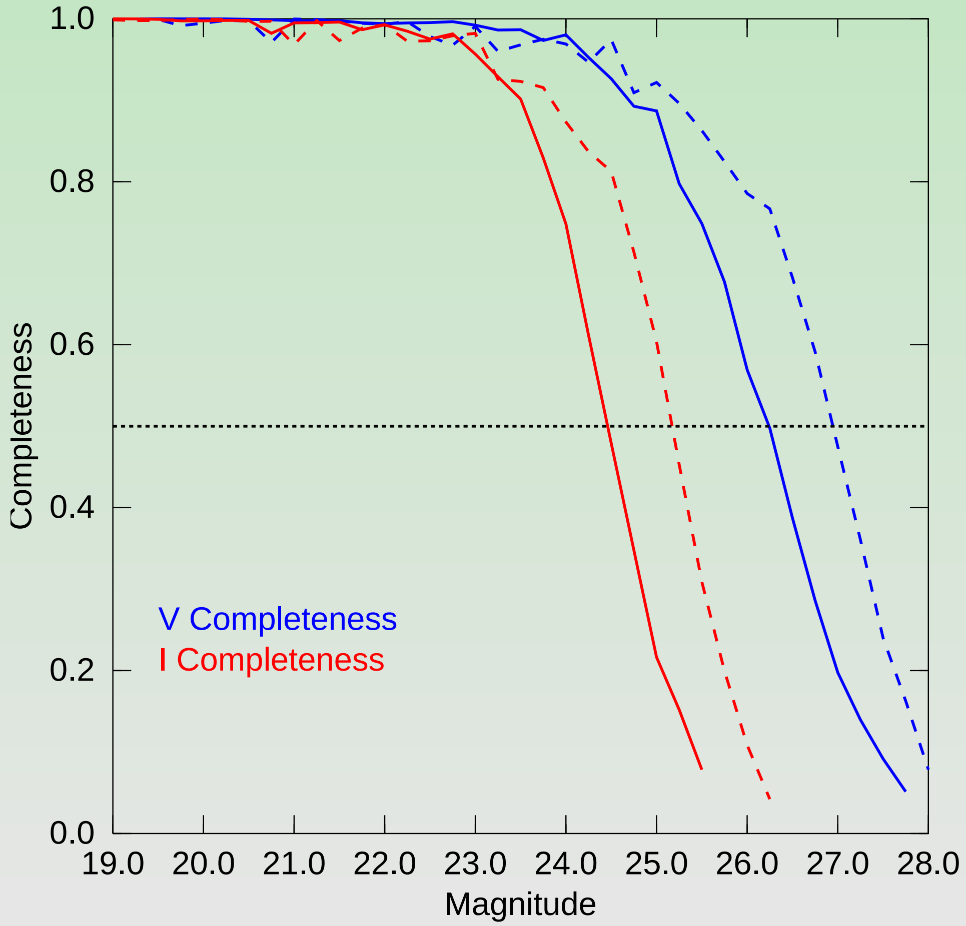
Contamination

- Main contaminant is background galaxies
- Degrade UDF to match our data using noise from model of M87 light
- Detect and measure UDF objects the same way
- Create sample to statistically remove contaminants.



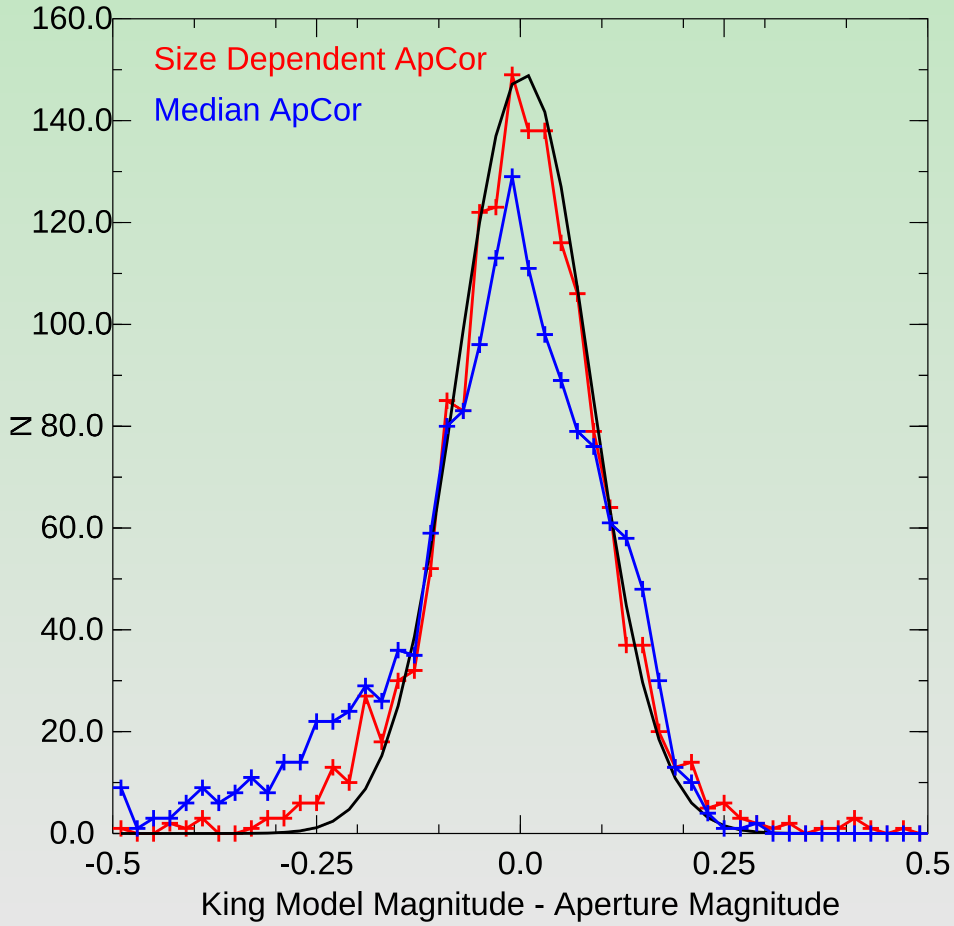
Completeness

- Add simulated clusters to image to estimate completeness
- Change in galaxy noise creates radial dependence
- Split sample at median cluster radius
- $M_{V,50\%\,inner} = -5.65 + 0.77(V-I)$
- $M_{V,50\%\,outer} = -5.18 + 0.73(V-I)$



Aperture Corrections

- Distribution of cluster sizes
- Measure flux in two apertures
- Difference correlates with cluster size
- Matches well with previous data and full King model fit photometry.



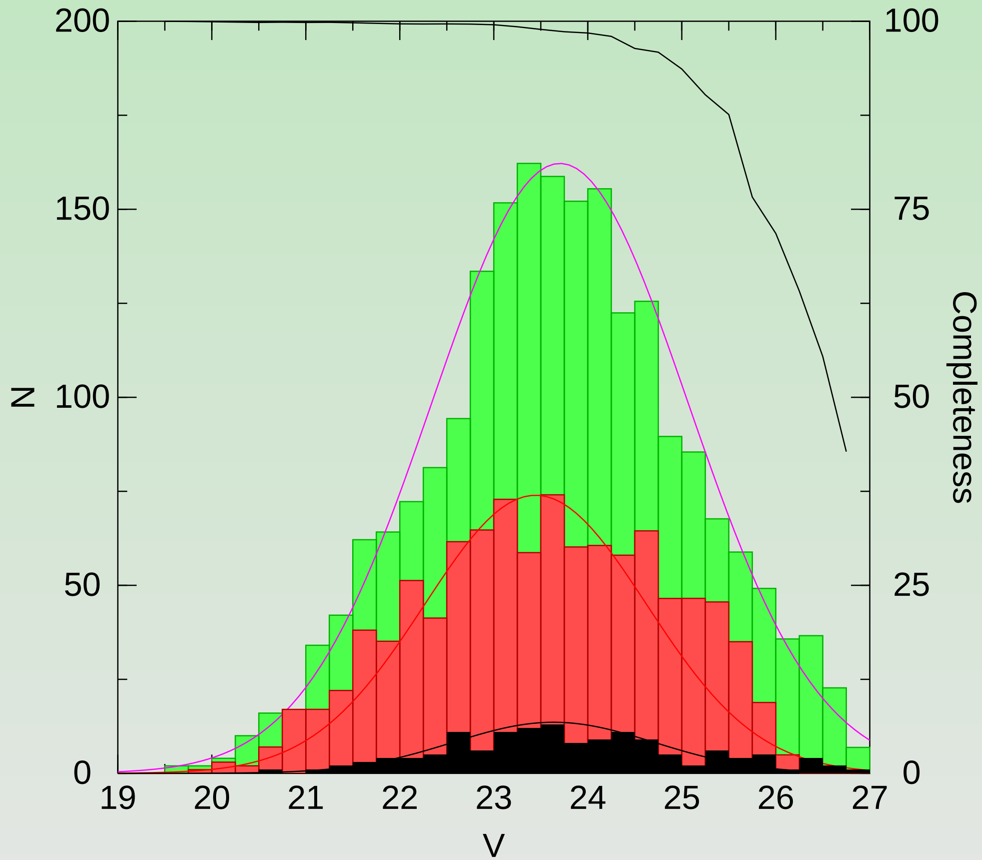
Final Cluster Sample

	$N_{clusters}$	N_{UDF}
Detected in both filters	5392	242
50% complete	3996	231
$0.5 < V - I < 1.7$	2832	110
Ellipticity $< \frac{1}{3}$	2168	31
$\mu_0 < \langle\mu\rangle$	2090	31
Final Sample	2089	31
Structure Fits	1579	

- More than ten times the sample size of the Milky Way!

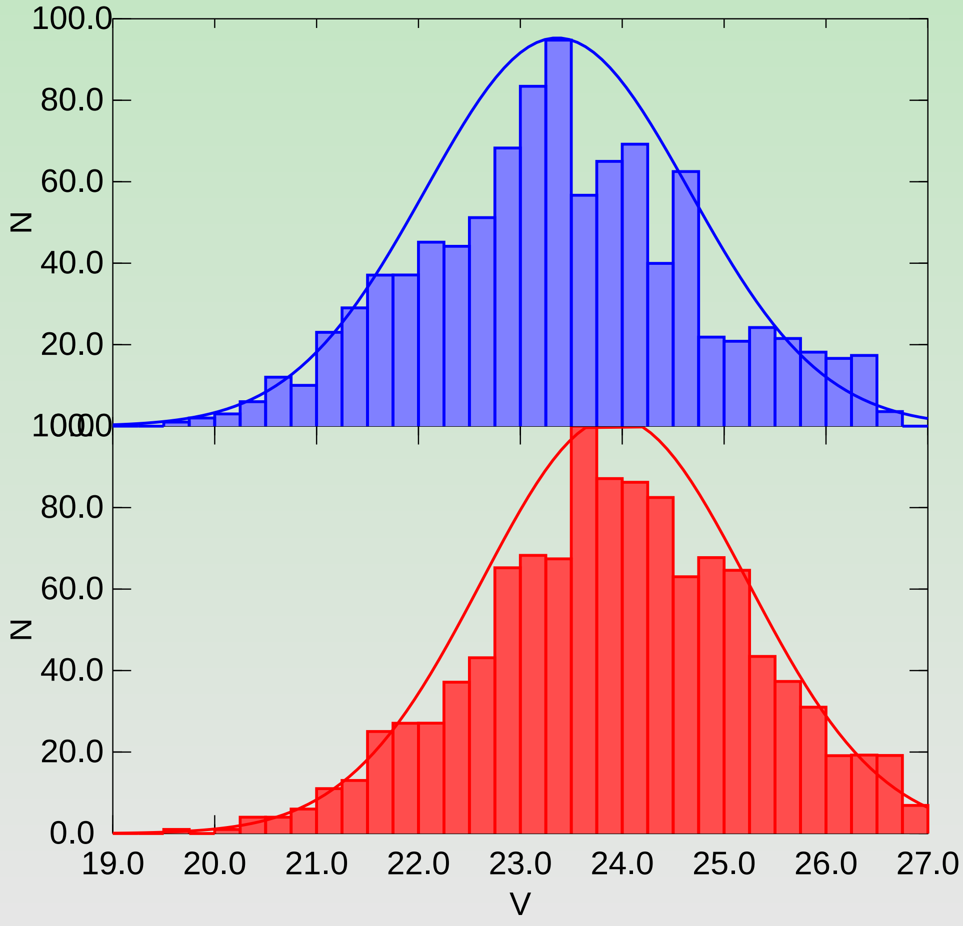
Luminosity Function

- Bin clusters in magnitude
- Weight clusters by inverse completeness
- Statistically remove UDF objects by assigning negative weights
- $\mu_V = 23.68 \; \sigma_V = 1.33$



Color Dependence

- Separate by color ($\langle V - I \rangle = 1.16$)
- Blue: $\mu_V = 23.35$ $\sigma_V = 1.22$
- Red: $\mu_V = 23.96$ $\sigma_V = 1.27$
- Blue clusters are brighter and have a smaller dispersion

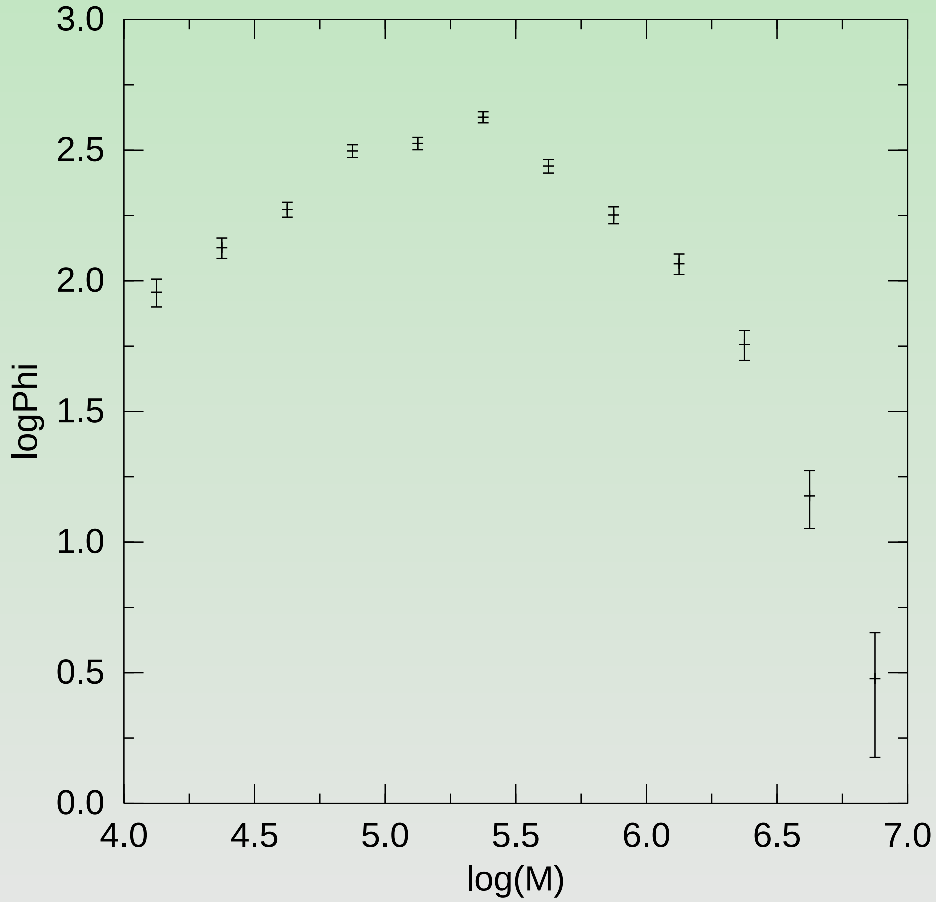


Comparisons

Reference	μ	σ	t-test	F-test
These data (V)	23.68	1.33	...	...
Waters et al. 2006 (V)	23.60	1.42	0.33	0.65
Kundu et al. 1999 (V)	23.55	1.39	0.19	0.75
These data (I)	22.53	1.28	...	...
Jordan et al. 2007 (z)	22.69	1.24	6.9e-23	1.8e-4
Waters et al. 2006 (I)	22.50	1.30	0.07	0.14
Kundu et al. 1999 (I)	22.55	1.28	0.31	0.04
Harris et al. 1996 (V)	23.70	1.18	0.26	6.8e-3

Constructing Mass Function

- Bin in mass, weight by completeness
- $\Upsilon_{blue} = 2.0$, $\Upsilon_{red} = 2.6$ based on Bruzual & Charlot SSP models
- Consistent with the difference in GCLF means



Mass Loss Models

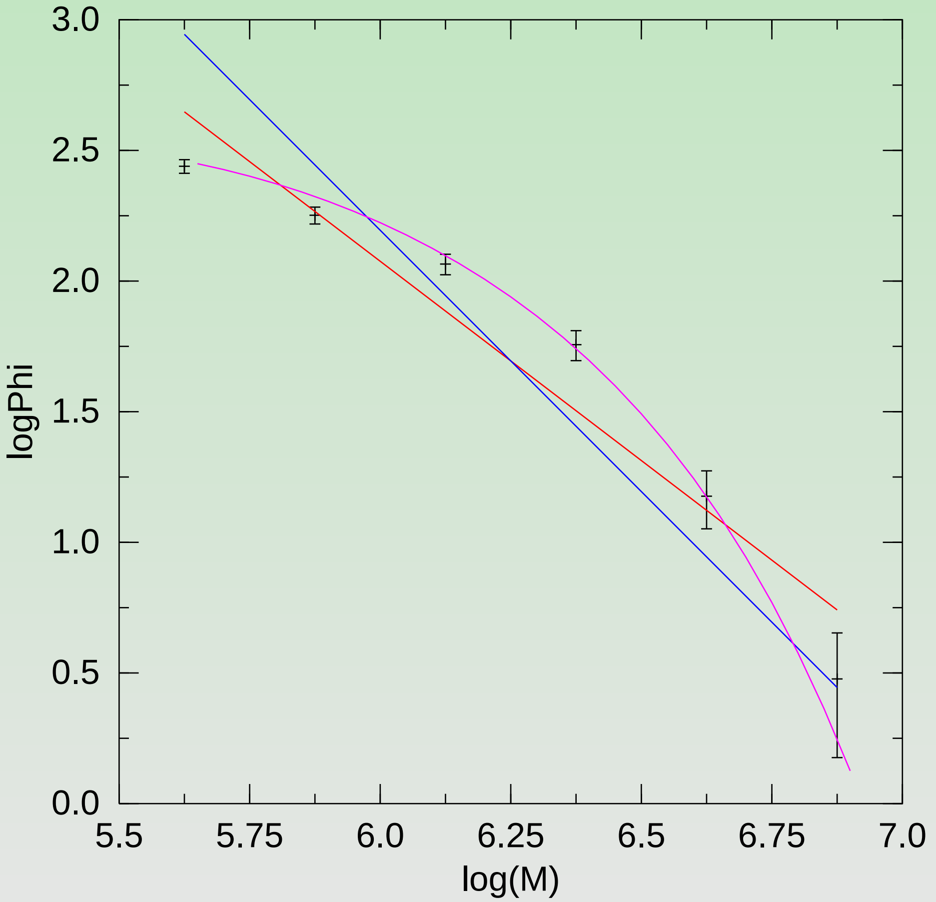
Take two-body relaxation mass loss of the form $\frac{dM}{dt} = -kM^{\gamma}$ to compare variety of published models:

- Fall & Zhang (2001) $\gamma = 0.0$
- Baumgardt & Makino (2003) $\gamma = 0.25, 0.18$
- Lamers et al. (2005) $\gamma = 0.38$

Parameterize fit by $\Delta_{\gamma} = M_0 \left(\frac{t}{t_{diss}}\right)^{1/1-\gamma} \sim k \times T$, the total mass lost over the cluster's lifetime.

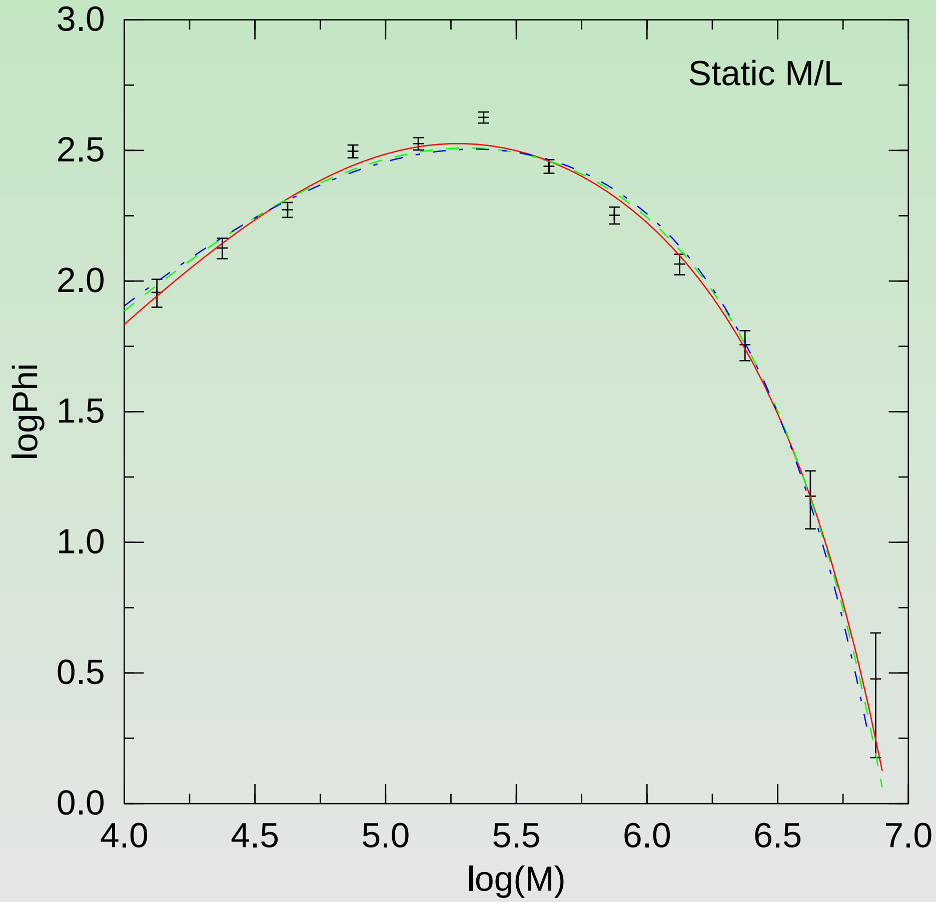
ICMF Choice

- Needs to accurately represent high mass end
- Use Schechter like function of Burkert & Smith (2000): $\Phi = M^{-1.5} e^{-M/M_c}$
- Better match than powerlaw or log normal



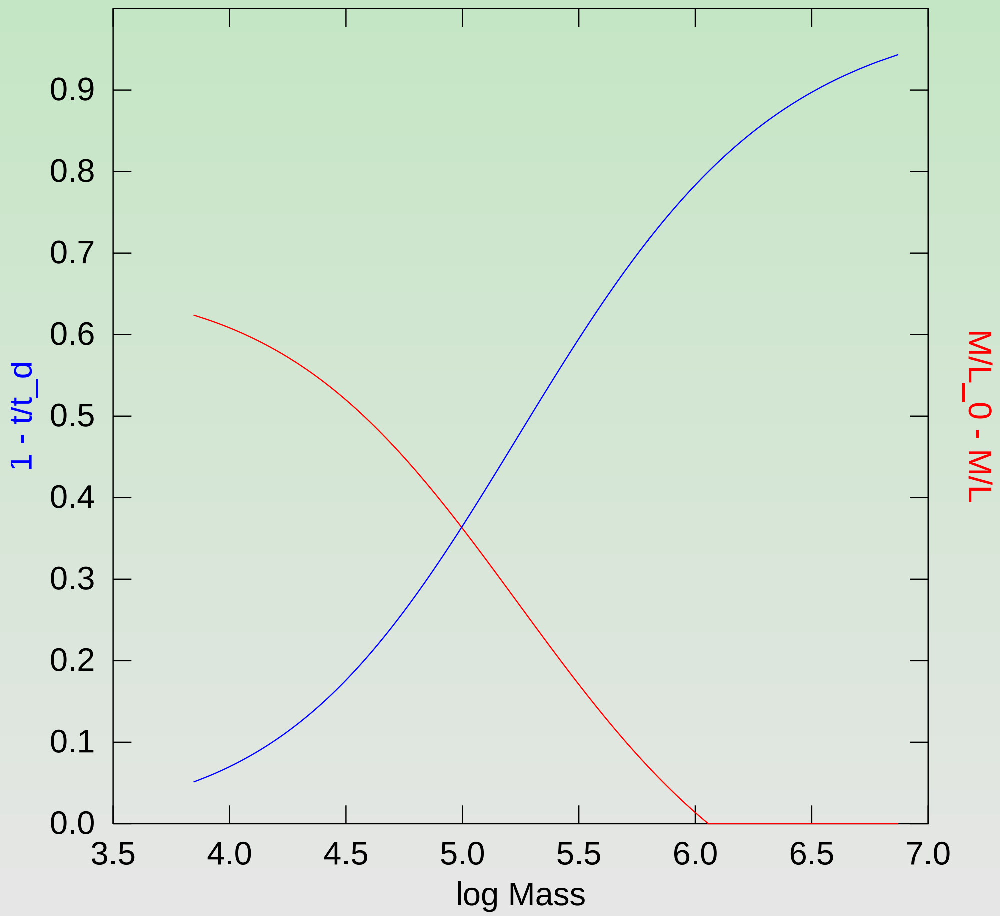
Fits

- Fit observed GCMF with evolved ICMF
- Find best Δ,M_C,A for a given γ value
- Generally consistent but misses peak, overpredicts low mass end
- $\Delta_{0.0} = 128759 M_\odot$
- $\Delta_{0.25} = 142424 M_\odot$
- $\Delta_{0.38} = 174895 M_\odot$



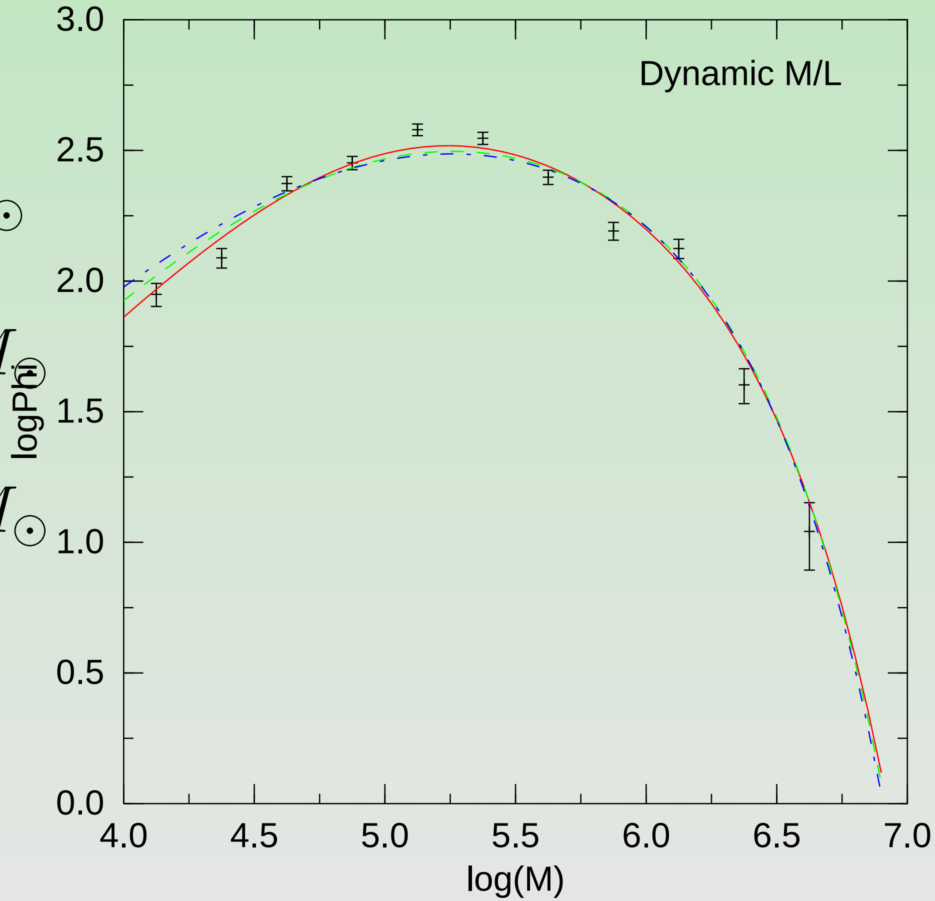
Mass to Light Evolution

- Baumgardt & Makino N-body simulations show preferential loss of low mass stars
- Larger drop in mass relative to luminosity
- $\Delta\Upsilon = \begin{cases} 0 & \frac{t}{t_{diss}} < 0.2 \\ \frac{1}{8} - \frac{5}{8}\frac{t}{t_{diss}} & \frac{t}{t_{diss}} > 0.2 \end{cases}$
- Consistent with calculations of Kruijssen & Lamers (2008)



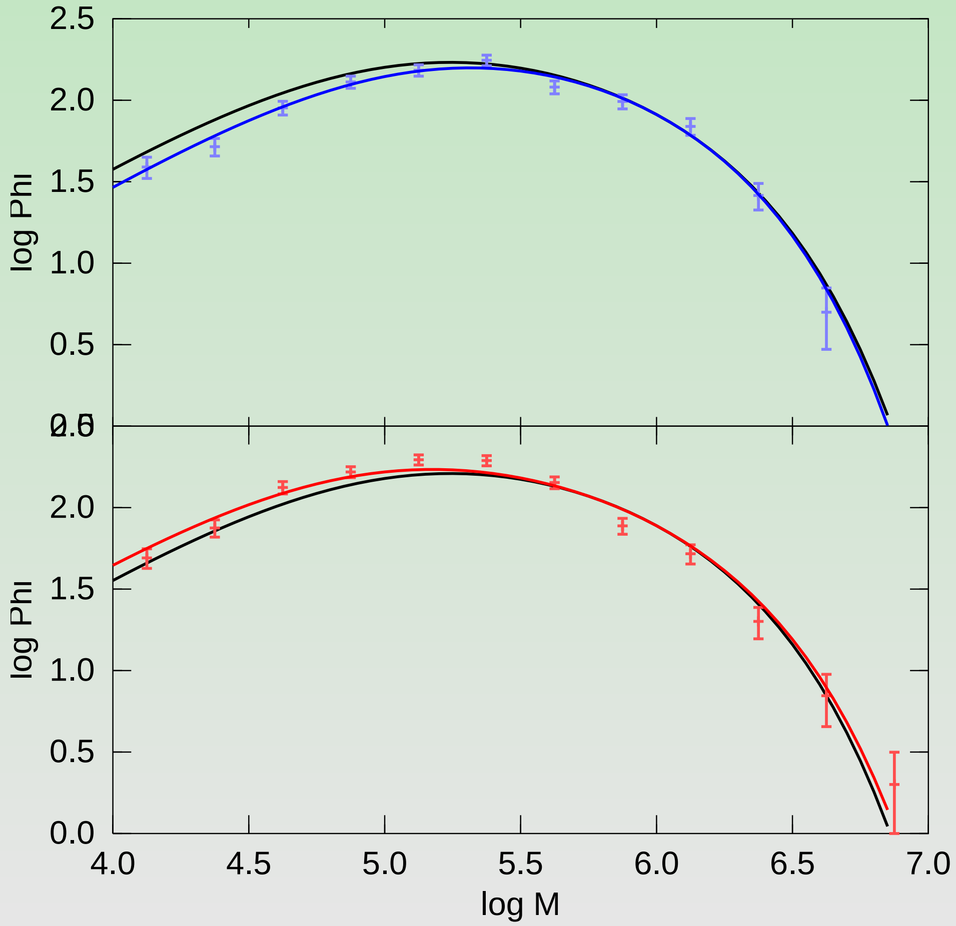
New Fits

- Refit, incorporating dynamic M/L
- Better match to low mass data
- $$\Delta_{0.0} = 115684 \pm 10240\ M_\odot$$
- $$\Delta_{0.25} = 117080 \pm 14929\ M_\odot$$
- $$\Delta_{0.38} = 116554 \pm 18987\ M_\odot$$
- F+Z model yields formal best fit, but all models consistent
- $$\Delta_{FZ}(\langle\rho_{hm}\rangle) = 110181\ M_\odot$$



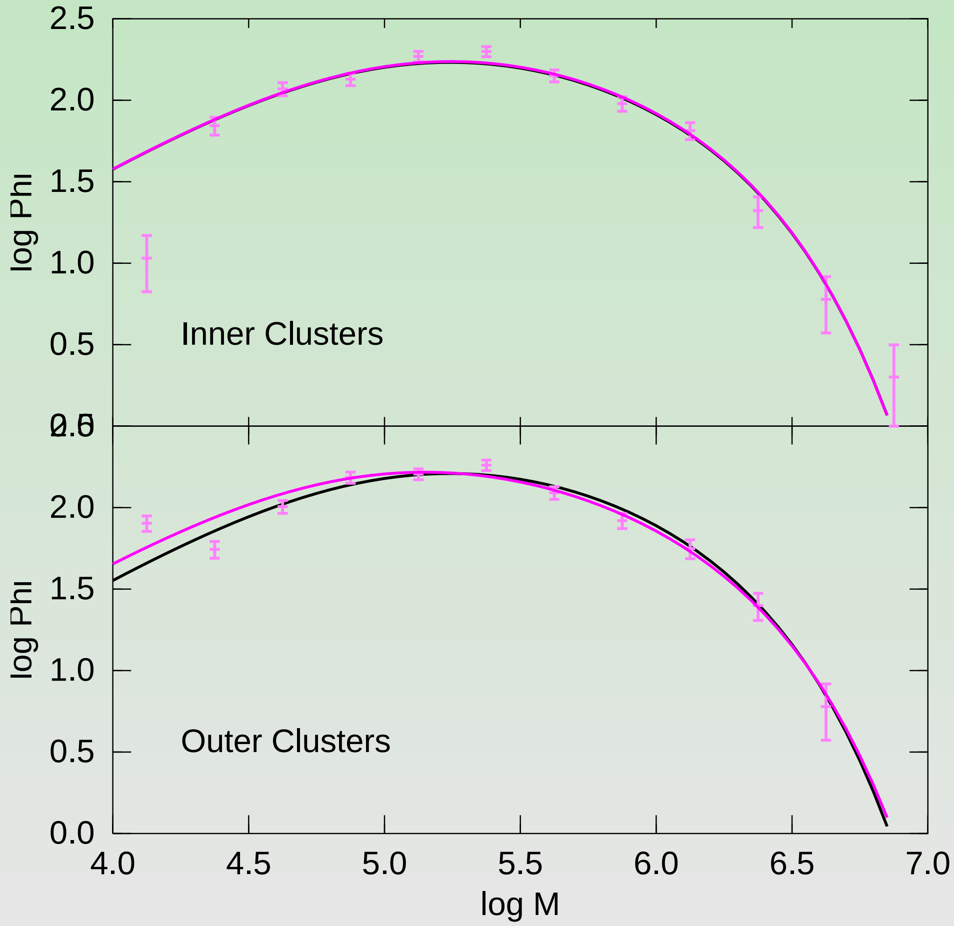
Color Dependence

- Separate by cluster color and fit
- Blue clusters have a much larger Δ value
- Explains narrower dispersion of blue clusters
- $\Delta_{0.0,blue} = 146083 M_{\odot}$
- $\Delta_{0.0,red} = 93835 M_{\odot}$



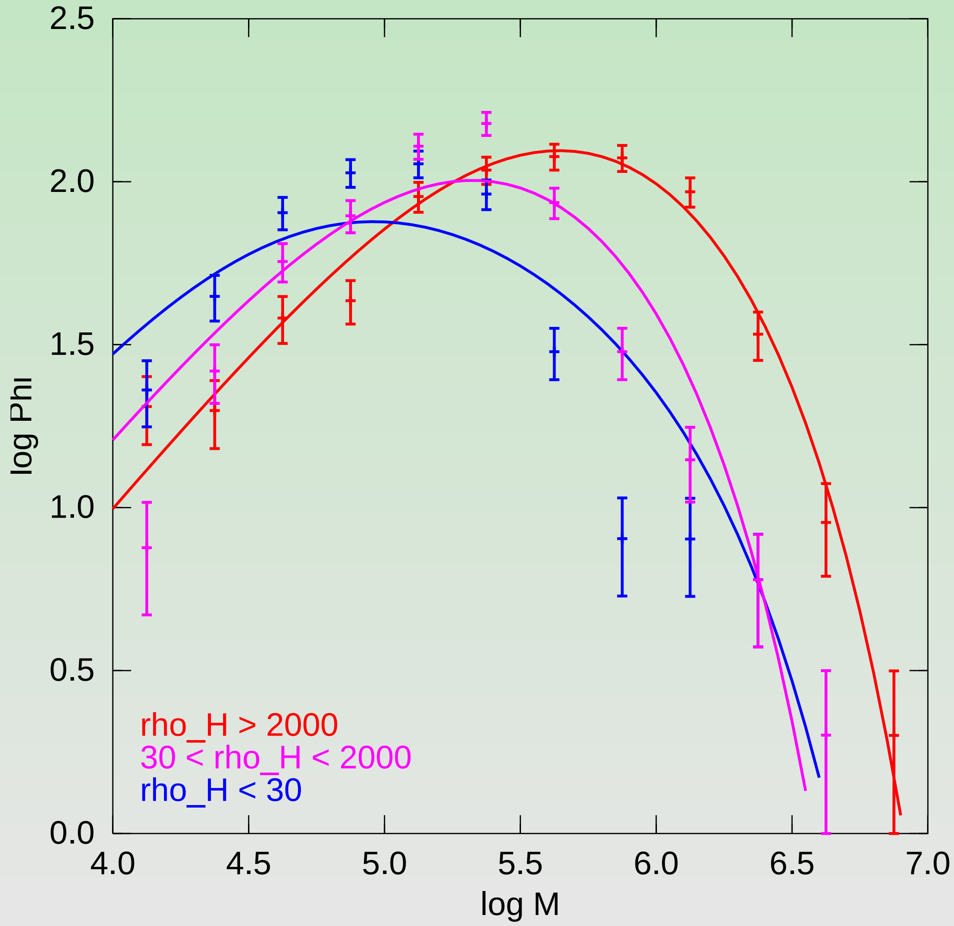
Radial Dependence

- Only have projected distance
- Statistically deproject using King model fit to radial distribution
- Lack of 3D positions makes comparison to B+M and Lamers model predictions for Δ_γ difficult
- $\Delta_{0.0,inner} = 117096 M_\odot$
- $\Delta_{0.0,outer} = 87134 M_\odot$



Density Dependence

- F+Z model includes explicit density dependence
- Selecting clusters based on density forces r_H distribution to filter available masses
- This can create biases in the GCMF of density selected samples
- $\Delta_{fit} \propto \langle \rho_{hm} \rangle^{1/2}$



Mass Function Summary

- Mass loss from a Schechter IMF matches the shape of the GCLF and GCMF well
- Dynamical effects on the cluster M/L are important to the final GCMF shape
- Various values of γ give similar GCMF curves
- Average mass loss rate matches theoretical predictions very well

To be published in Waters, Zepf, Lauer, & Baltz 2009 (in prep.)

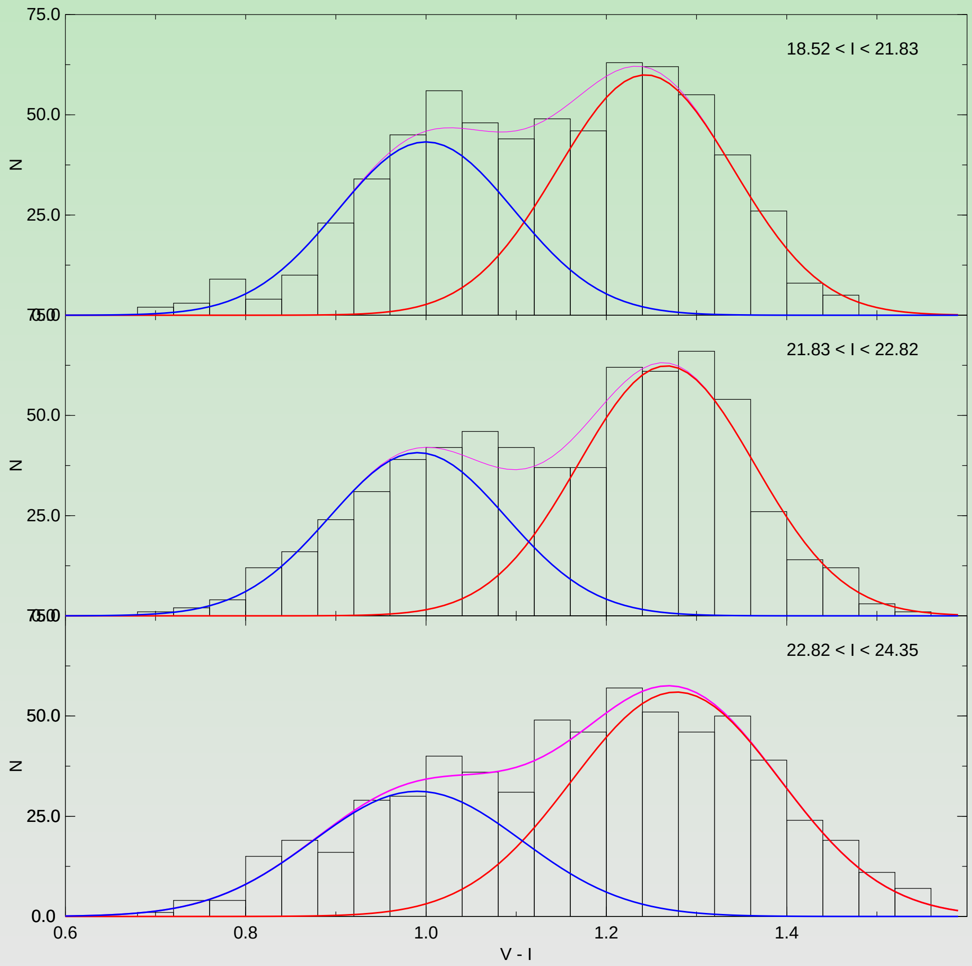
Previous 30 orbit WFPC2 analysis in Waters, Zepf, Lauer, Baltz, & Silk, 2006, ApJ, 650, 885

Cluster Color Bimodality

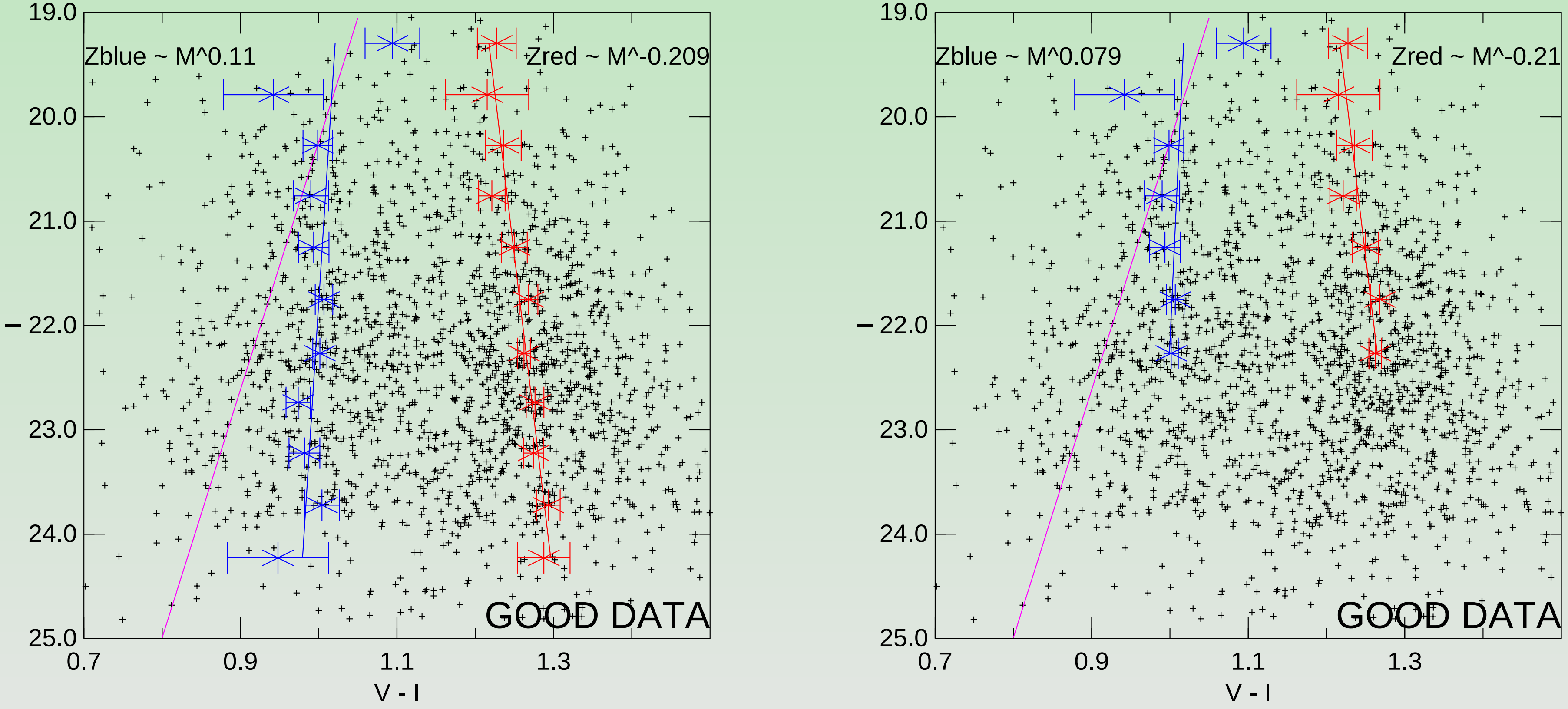
- Previous ACS observations of extragalactic globular clusters suggested a “blue tilt”
  - More massive blue (metal-poor) clusters may be redder than less massive blue clusters
  - This could be a sign of self-enrichment, where more massive clusters retain more metals
- Originally found in single orbit ACS data or data with similar signal to noise
- Milky Way globular clusters do not show such a tilt
- Check with very deep ACS observations of M87

Mixture Modeling

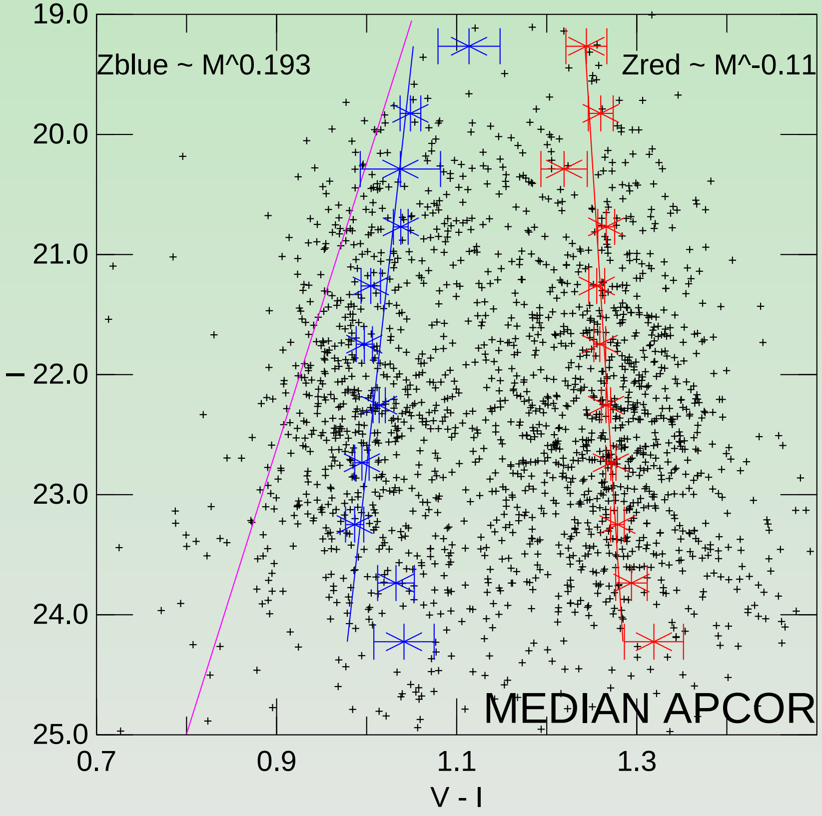
- KMM quantifies color bimodality
- Bin data in I magnitude
- Find best homoscedastic fit in each bin
- Bootstrap to remove outliers

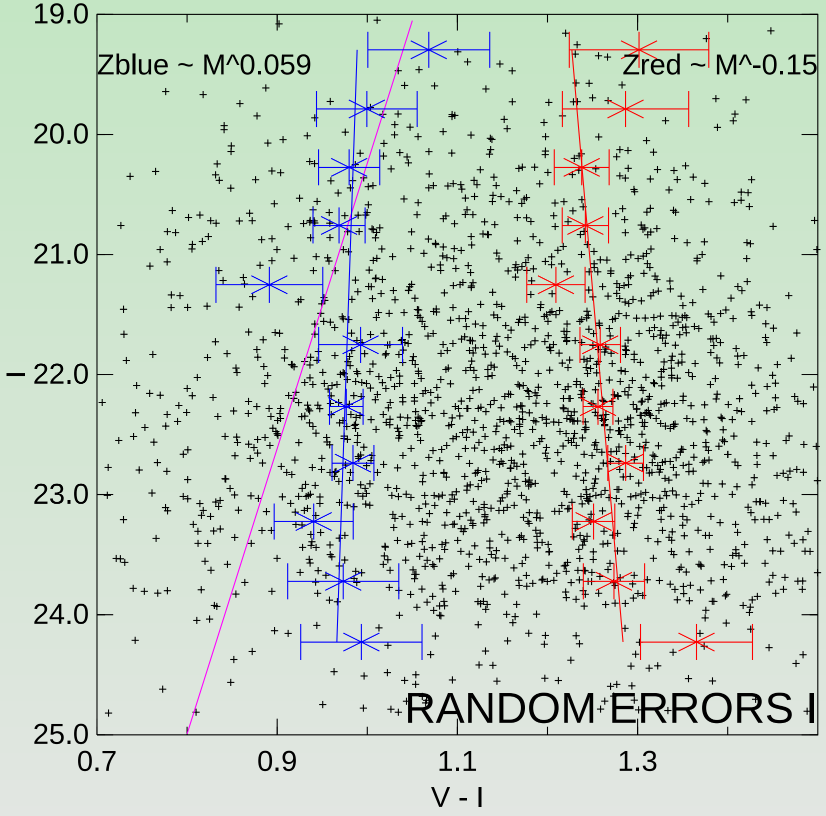


Results


Zblue ~ M^0.11
Zred ~ M^-0.209
GOOD DATA
19.0
20.0
21.0
– 22.0
23.0
24.0
25.0
0.7
0.9
1.1
1.3
V - I
Zblue ~ M^0.079
Zred ~ M^-0.21
GOOD DATA
19.0
20.0
21.0
– 22.0
23.0
24.0
25.0
0.7
0.9
1.1
1.3
V - I

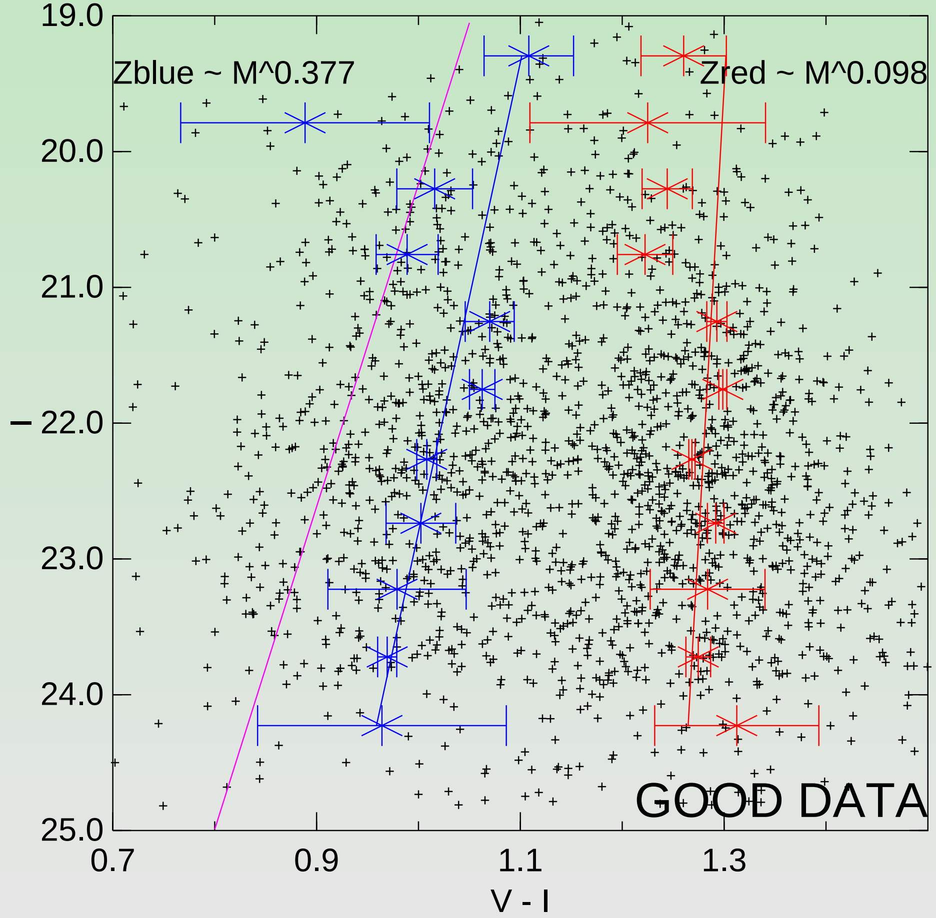
Why No Blue Tilt?





Heteroscedastic Fits

- Highly dependent on outliers
- Poor representation of data
- Bootstrapped log likelihood test yields $p_{heteroscedastic} = 0.03$



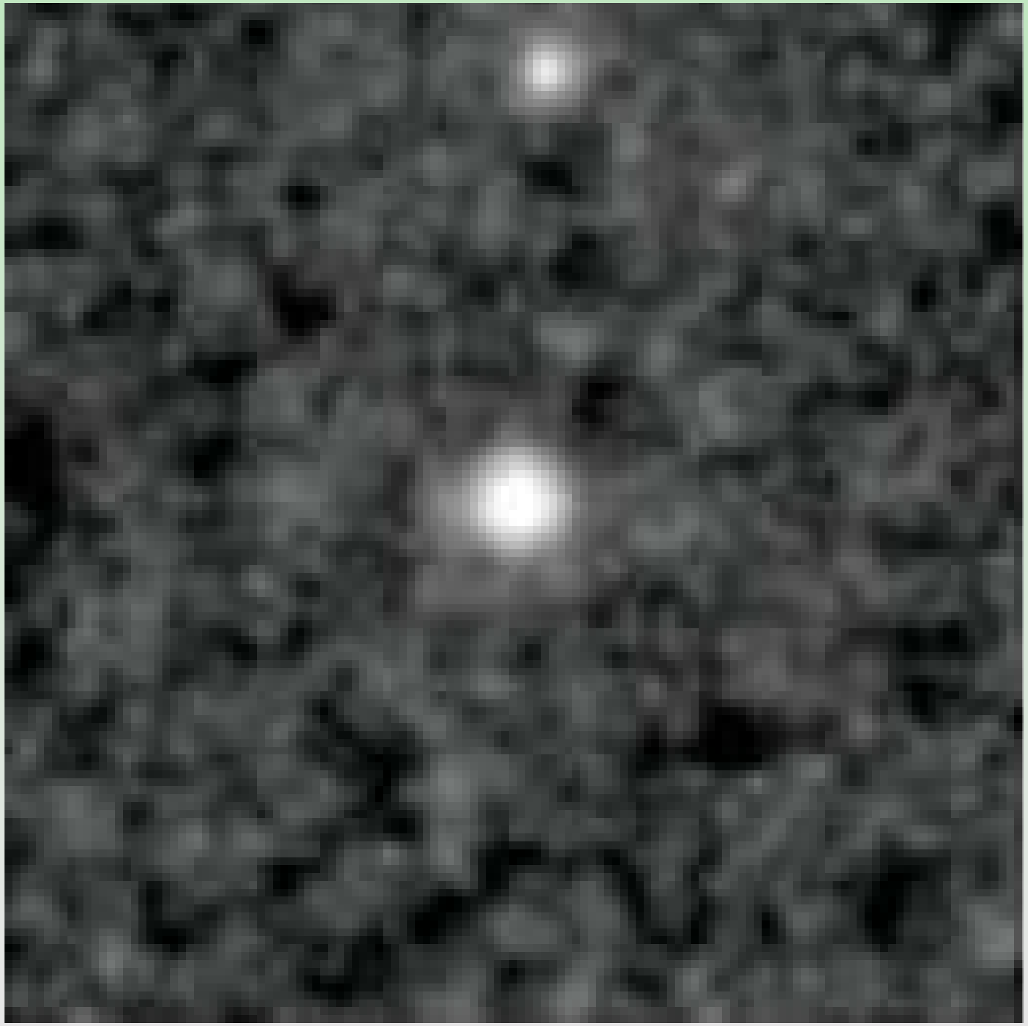
Implications

- No blue tilt observed in this very deep dataset
  - Best fit mass-metallicity trend of $Z \propto M^{0.08}$
  - Self enrichment of metals that affect broad-band colors must be minimal
- Interpretation of KMM test results requires caution
- Likely difficulties in previous measurements of the blue tilt:
  - Size dependent aperture corrections
  - Bias due to low signal to noise

To be published as Waters, Zepf, Lauer, & Baltz, 2009, ApJ, 692.
Available now on astro-ph: arXiv:0811.0391

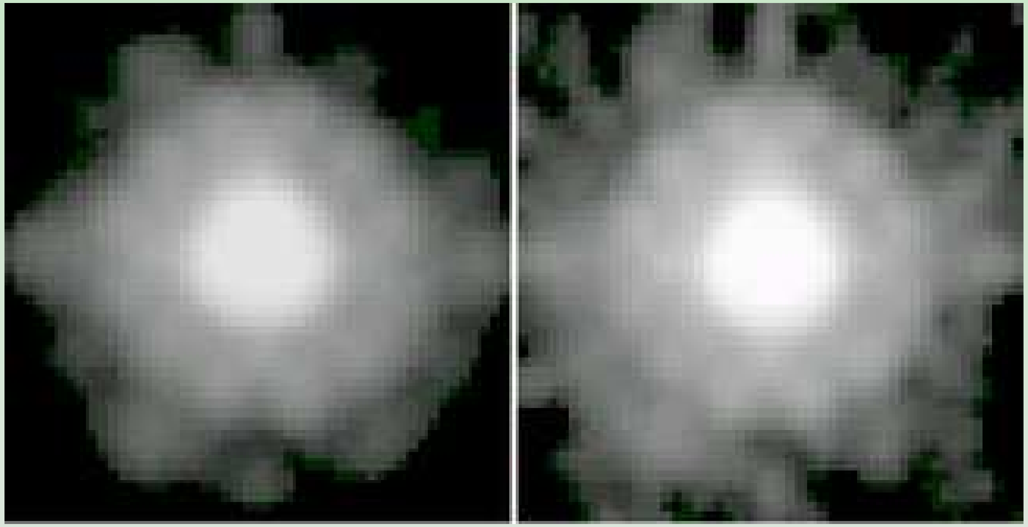
Benefits of High Resolution

- Clusters are resolved
- Fit PSF convolved 2d King models to cluster images
- Find best fitting
  - Position: x_0,y_0
  - Photometry: F,B
  - Structure: c,r_t



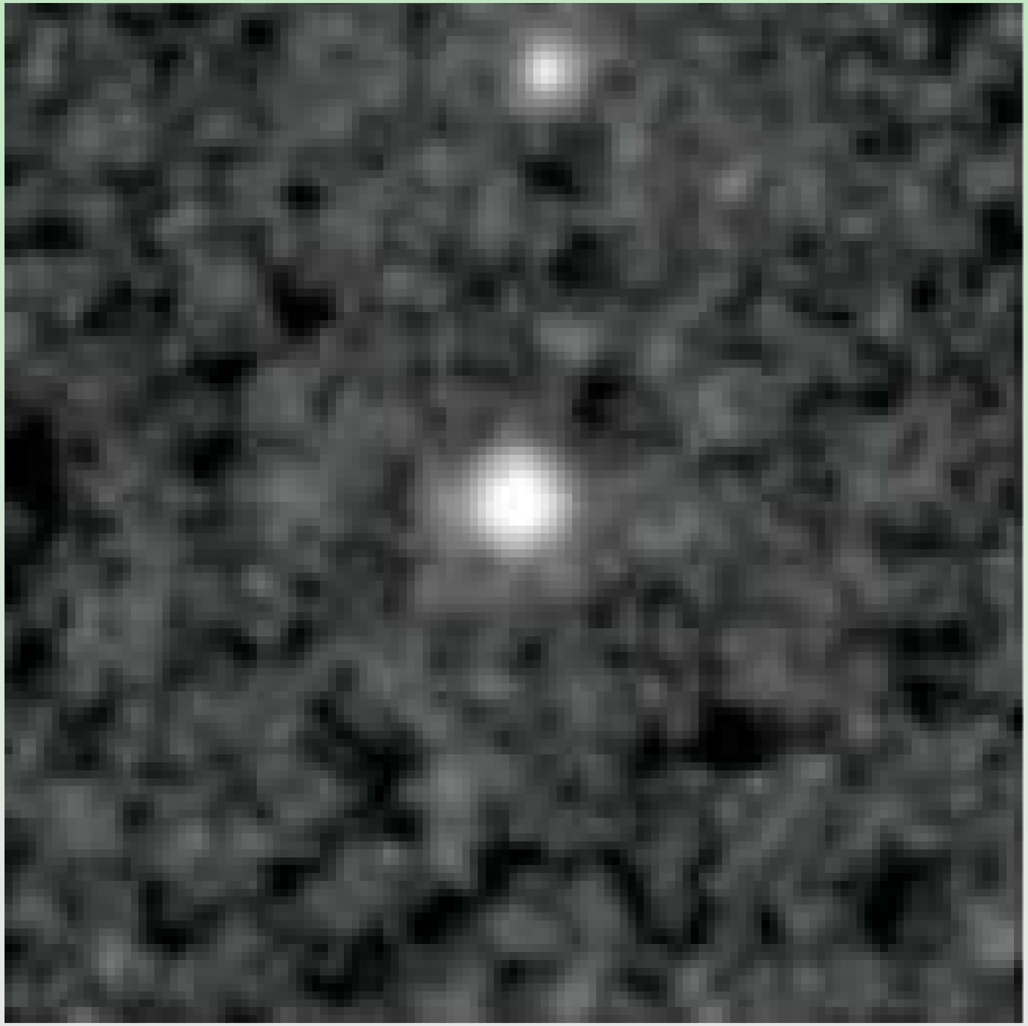
PSFs

- PSFs are position dependent
- Use empirical Anderson & King (2006) PSF models
- Create PSF images to match data images
- Combine in same way as data to ensure accuracy
- Match the one unsaturated star well.



Fitting Results

- 2089 total clusters
- 1579 with reliable fits
  - $I < 25$
  - $r_t > 5pxl(9pc)$
  - $r_t < 128pxl(226pc)$



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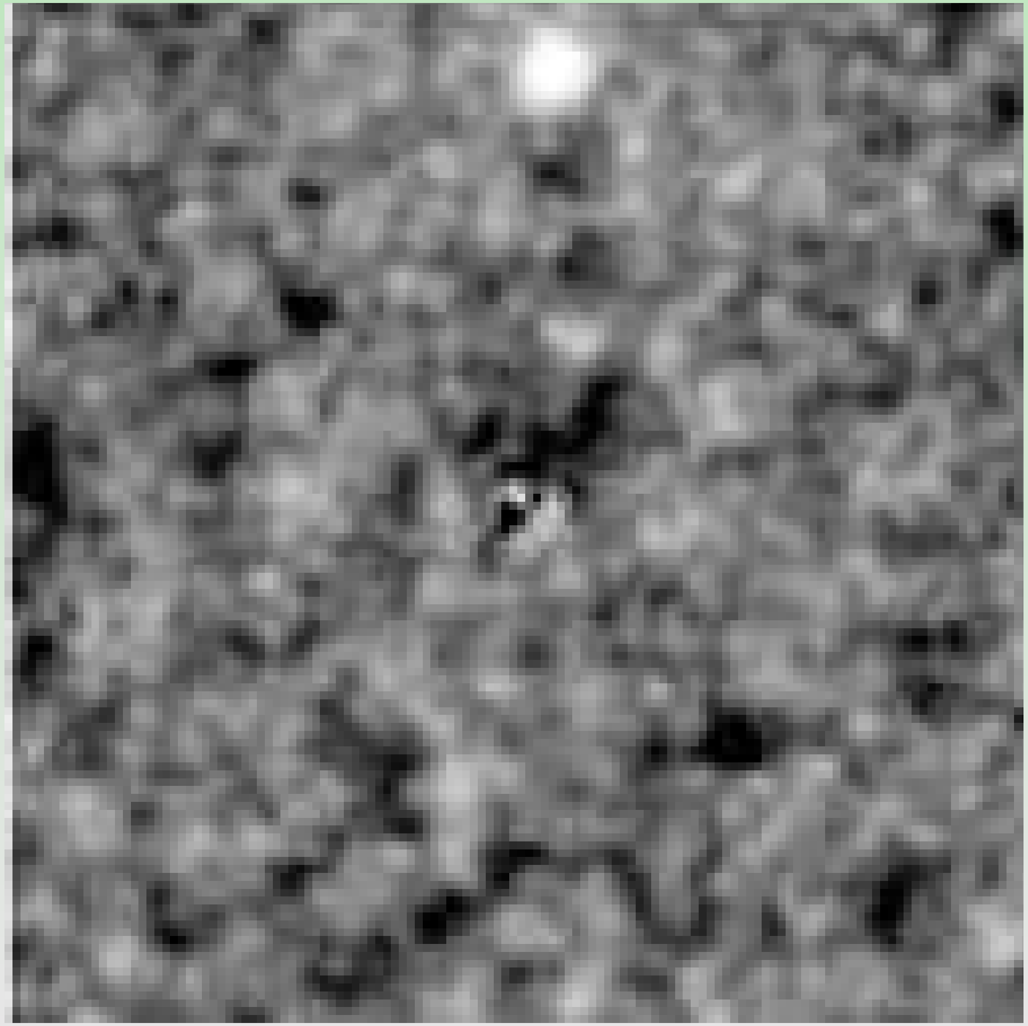

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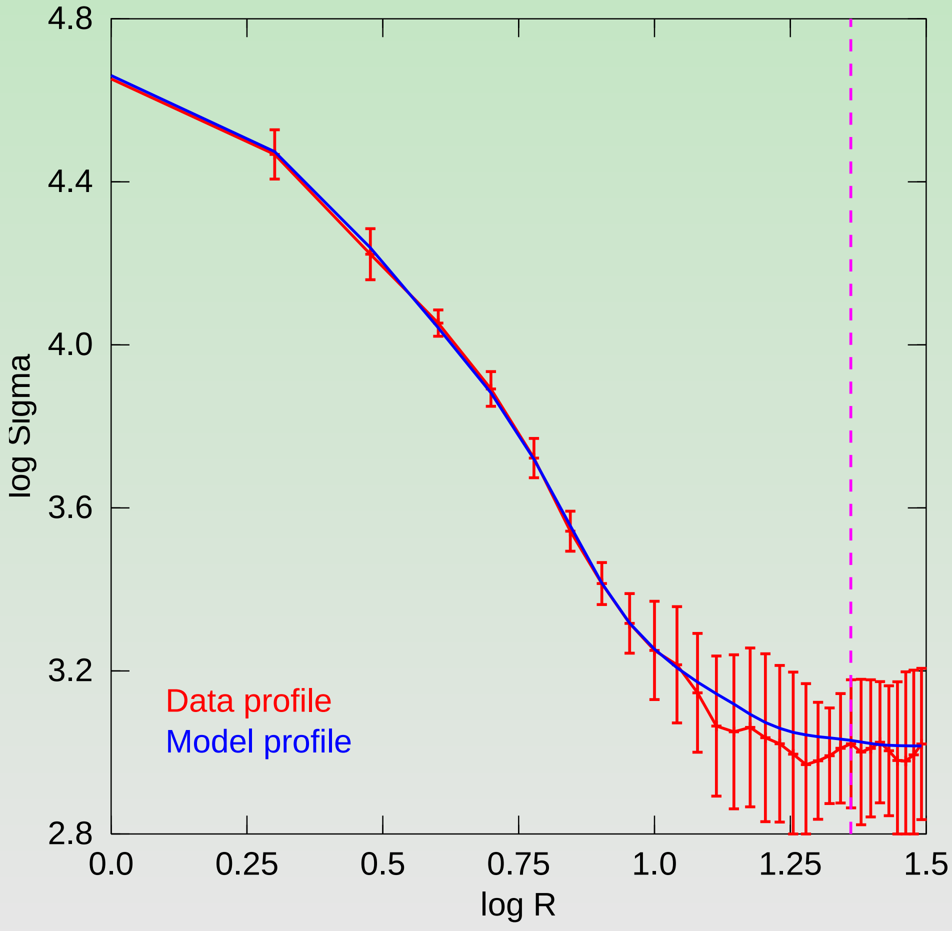
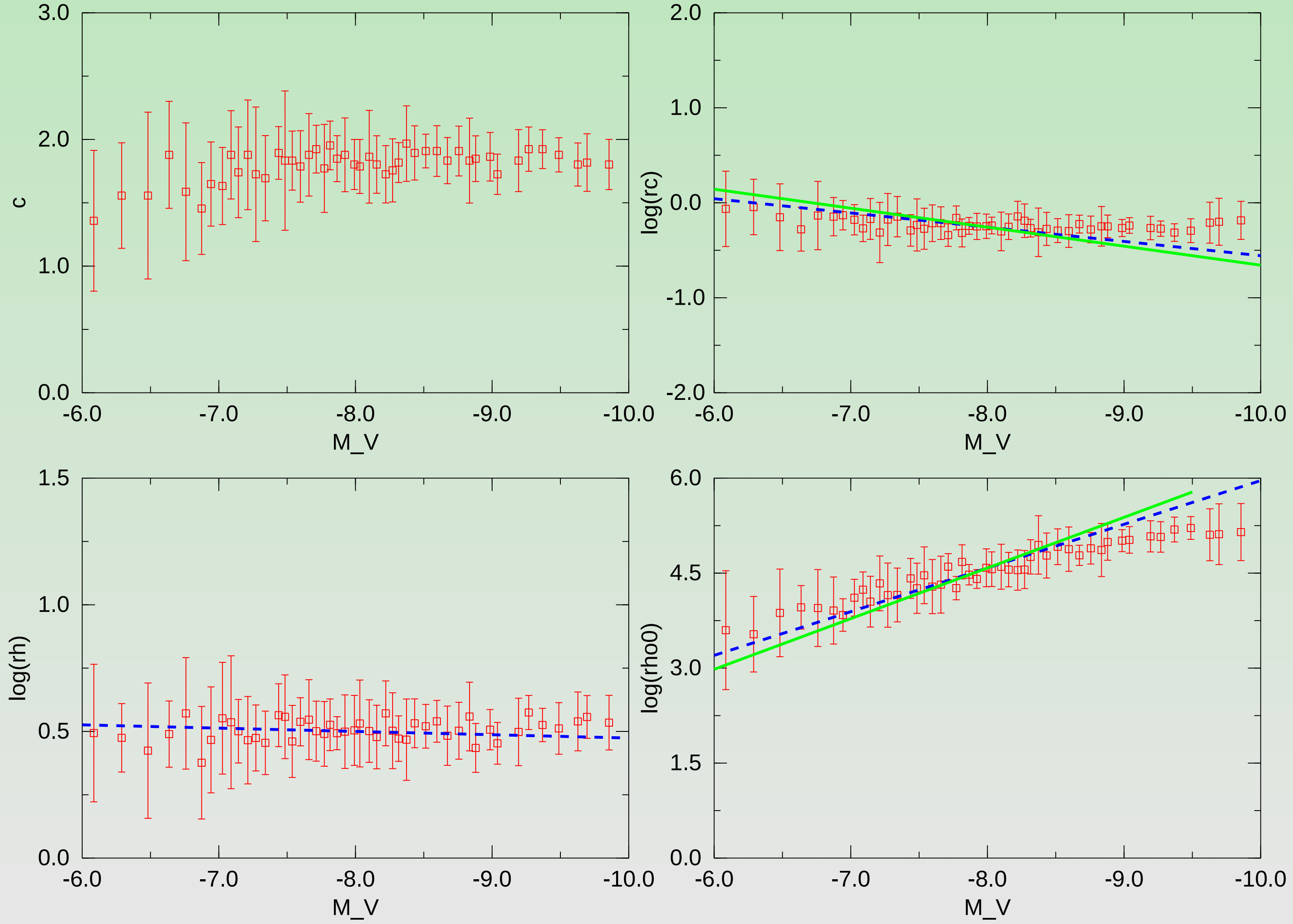
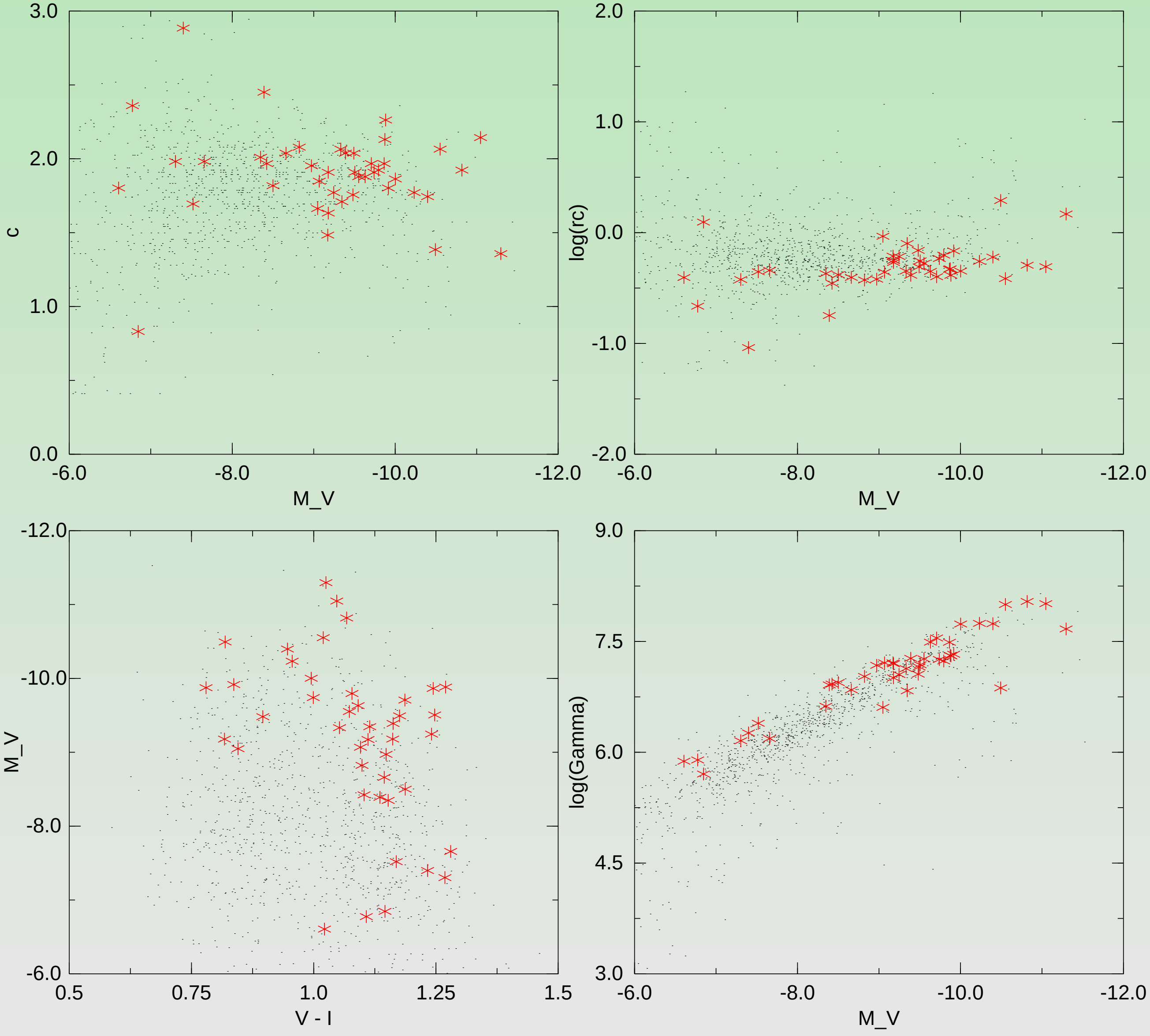


Binned Trends with Luminosity



LMXBs



3.0
2.0
1.0
0.0
c
-6.0
-8.0
-10.0
-12.0
M_V
2.0
1.0
0.0
-1.0
-2.0
log(rc)
-6.0
-8.0
-10.0
-12.0
M_V
-12.0
-10.0
-8.0
-6.0
M_V
0.5
0.75
1.0
1.25
1.5
V - I
9.0
7.5
6.0
4.5
3.0
log(Gamma)
-6.0
-8.0
-10.0
-12.0
M_V

Conclusions

- Reliable fits can be performed for the majority of the M87 clusters
- PSF quality is the main constraint
- M87 structure trends seem to match well with Milky Way results
- LMXB probability matches well with both M and Γ (still need to do statistics)

First paper published using cluster fitting code on M31 GCs: Peacock et al. 2008 (arXiv:0811.0275).
M87 results forthcoming as Waters et al. 2009 (in prep.)