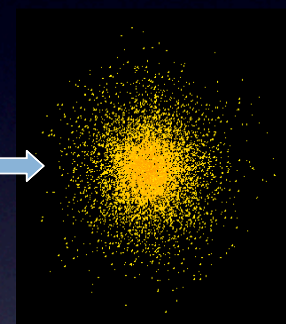
On the Origin of the Mass-Metallicity Relation for Metal-Poor Globular Clusters



Simulations from an observer's point of view

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Outline

1. Semi-Analytic Models (SAMs)

2. Blue Mass-Metallicity Relation (*blue-MMR*) in early-type galaxies

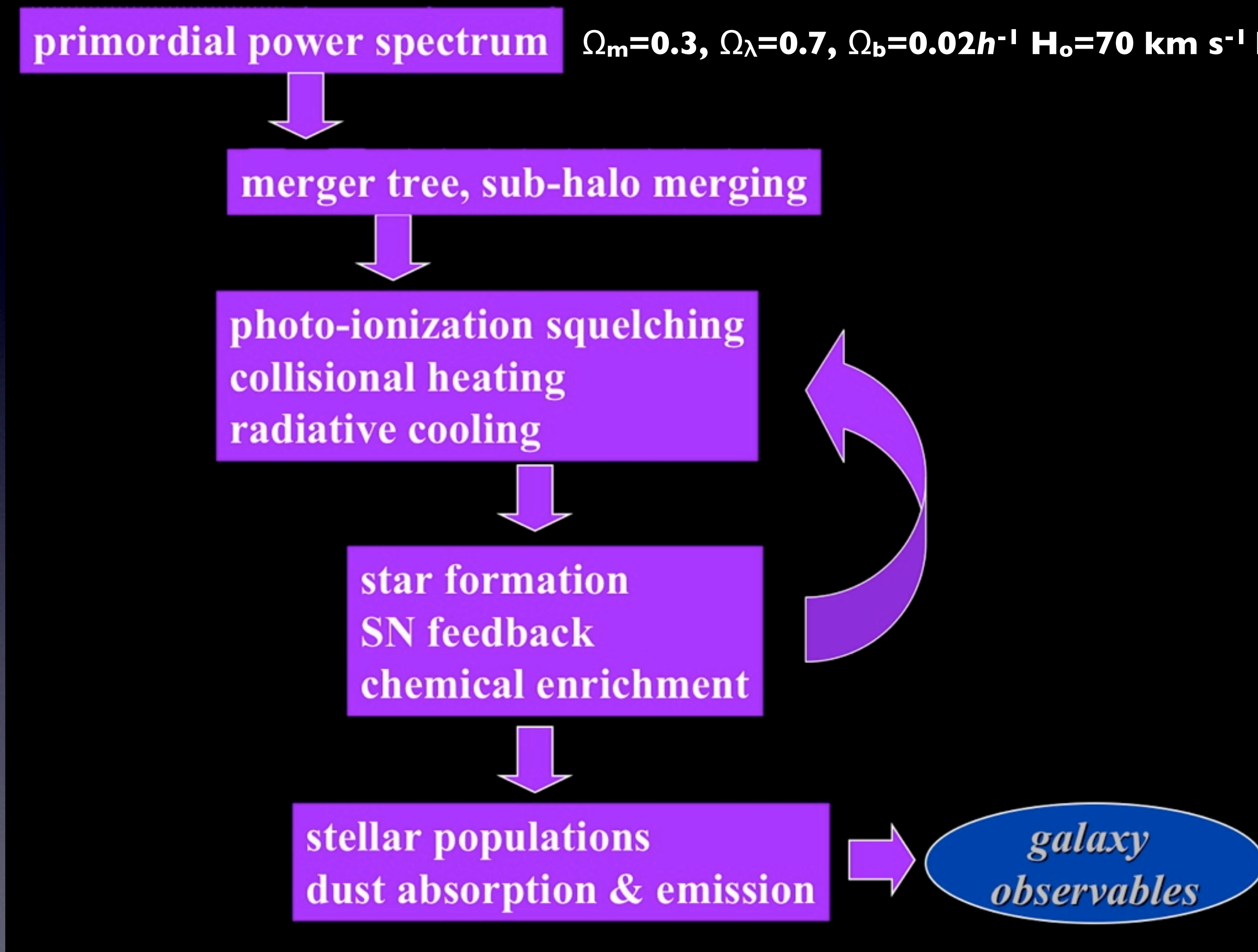
   2.1. Is the MMR “natural” to ΛCDM?

   2.2. Are luminous GCs kin to dwarf ellipticals and ultra-compact dwarfs?

3. Future Work

Semi-Analytic Models (SAMs)

$\Omega_m=0.3$, $\Omega_\lambda=0.7$, $\Omega_b=0.02h^{-1}$ $H_o=70$ km s^{-1} Mpc^{-1}



SAMs

- Models based on code by R. Somerville (Somerville & Primack 1999, Somerville et al. 2001, Somerville 2007 *in preparation*)
- Assume "Standard" SAM parameters (i.e. SN feedback, feedback efficiency ∝ mass, 1:1-4:1 major mergers)
- Major mergers "build" bulge, minor mergers shift stars from small → large galaxy
- Luminosity, colors, metallicity based on BC03, Kennicutt SF law, Chabrier IMF
- Modified code to form GCs (currently metallicity only)

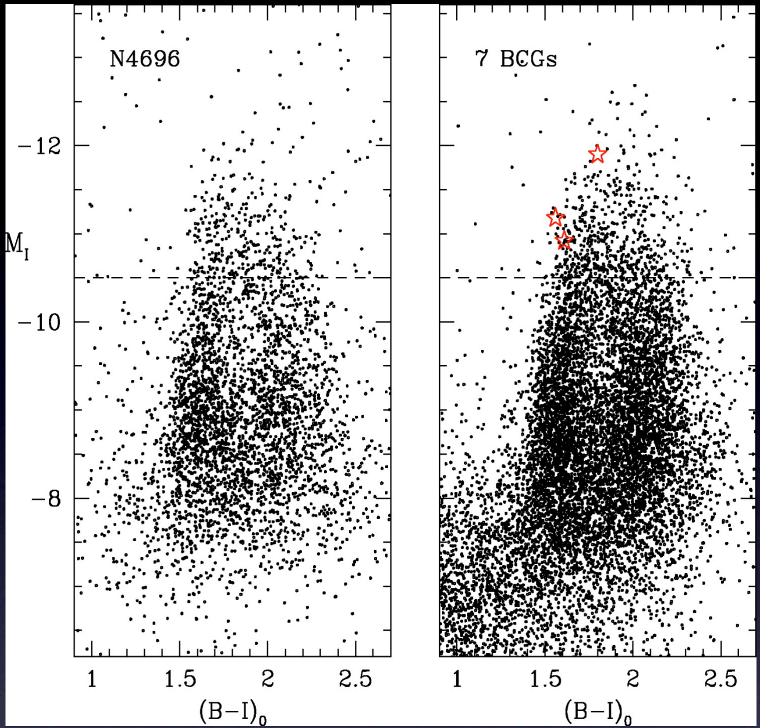
GOAL:

Testing contribution of *dwarf ellipticals* (dE) to *blue-MMR*

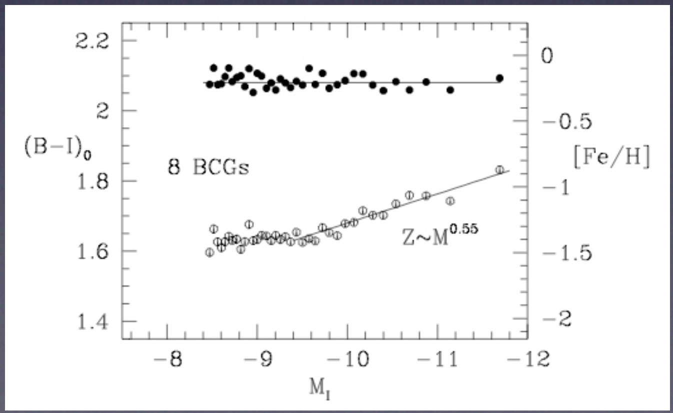
- Not testing simulated MPC contribution to blue-MMR
- Accretion/stripping of dwarfs *only*, not accretion of their GCs

Blue Mass-Metallicity Relation (***blue-MMR***)

- Harris et al. (2006) first noted that GC bimodality becomes unimodal at $M_I < -10.5$
- Also found in ACS Virgo Cluster Survey of early-type galaxies, Sombrero Galaxy, NGC 3311
- Hints of this trend in earlier studies (i.e. M87)
- Notably *absent* in NGC 4472 (gE in Virgo)

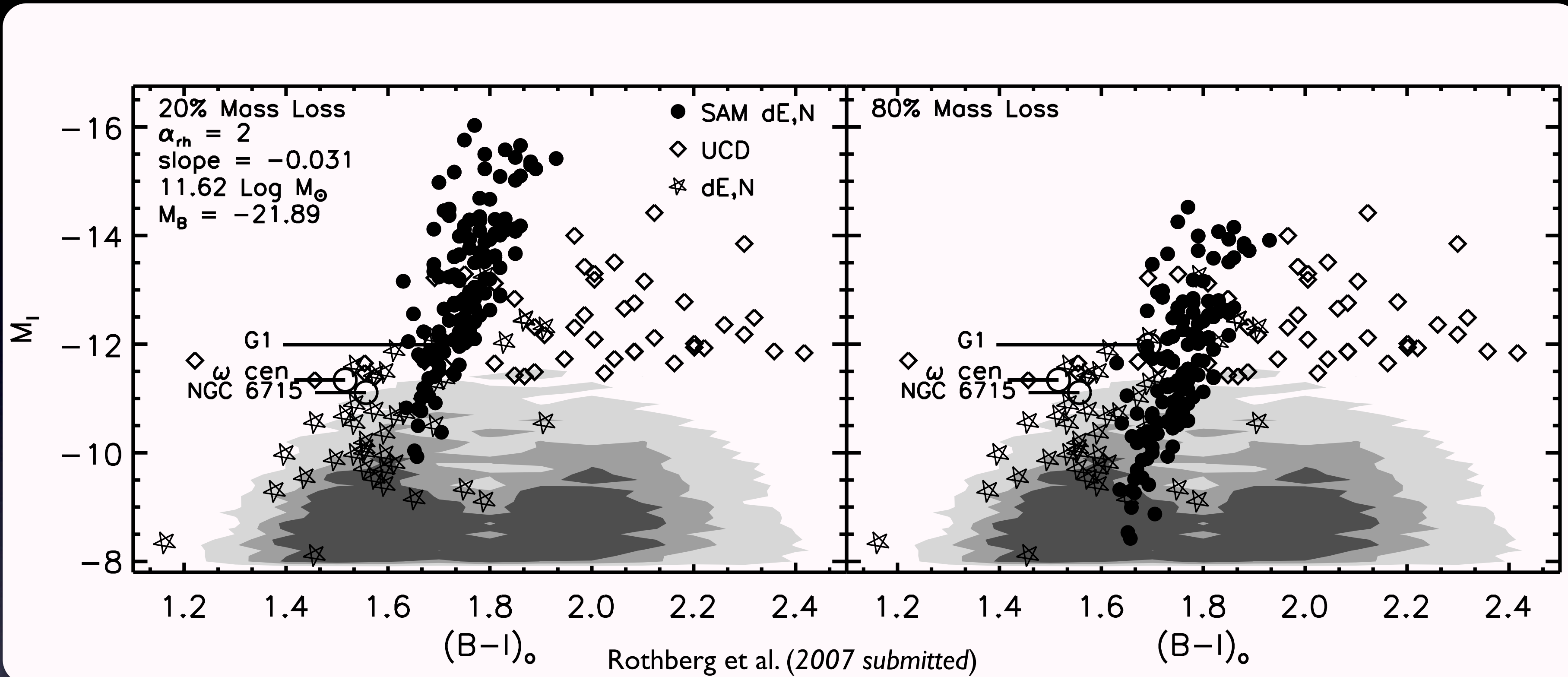


Harris et al. (2006) - BCG Survey w/ACS (HST).
Open red stars are NGC 6175, ω Cen, G1.



- Bekki et al. (2007) tested (*N*-body sims) whether GCs and dEs w/formation truncated at z~10 could form *blue-MMR*
  - found dE,N did not contribute significantly to *blue-MMR*

blue-MMR



- SAMs can reproduce observed ***blue-MMR*** (and a few UCDs) using "standard" prescription
- Assume simple tidal stripping (20-80% mass loss), recompute luminosity and colors

blue-MMR

- Simulated Slopes match observed slopes
- Slope does *not* change as a function of central galaxy luminosity/mass

Table 1. Slope of Blue GCs in Observed & Simulated Galaxies

Observed Galaxies		
Galaxy	M_B	Slope
NGC 4696[a]	-22.44	$-0.029_{\pm 0.003}$
NGC 4472 (M49)[b]	-21.87	$-0.008_{\pm 0.024}$
NGC 4486 (M87)[b]	-21.69	$-0.042_{\pm 0.015}$
NGC 4649 (M60)[b]	-21.49	$-0.028_{\pm 0.009}$
NGC 4594 (M104)[c]	-21.38	$-0.035_{\pm 0.005}$
NGC 3348[a]	-21.34	$-0.051_{\pm 0.008}$
NGC 5557[a]	-21.33	$-0.055_{\pm 0.005}$
NGC 1407[a]	-21.25	$-0.045_{\pm 0.009}$
NGC 3258[a]	-21.18	$-0.051_{\pm 0.002}$
NGC 3258[a]	-21.01	$-0.051_{\pm 0.002}$
NGC 3268[a]	-21.01	$-0.058_{\pm 0.002}$
NGC 7049[a]	-20.79	$-0.038_{\pm 0.011}$
ACSVCS ($-21.7 < M_B < -21$)[b,d]	...	$-0.037_{\pm 0.004}$
ACSVCS ($-21 < M_B < -20$)[b]	...	$-0.033_{\pm 0.011}$
ACSVCS ($-20 < M_B < -18.4$)[b]	...	$-0.032_{\pm 0.012}$
ACSVCS ($-18.4 < M_B < -15.2$)[b]	...	$-0.009_{\pm 0.013}$

Simulations		
Galaxy	Avg. No Dwarfs	Slope
All Models	76	$-0.033_{\pm 0.0003}$
Models ($M_B < -21.7$)	178	$-0.033_{\pm 0.0003}$
Models ($-21.7 < M_B < -21$)	21	$-0.027_{\pm 0.002}$
Models ($-21 < M_B < -20$)	8	$-0.033_{\pm 0.003}$
Models ($-20 < M_B < -17.1$)	4	$-0.016_{\pm 0.012}$

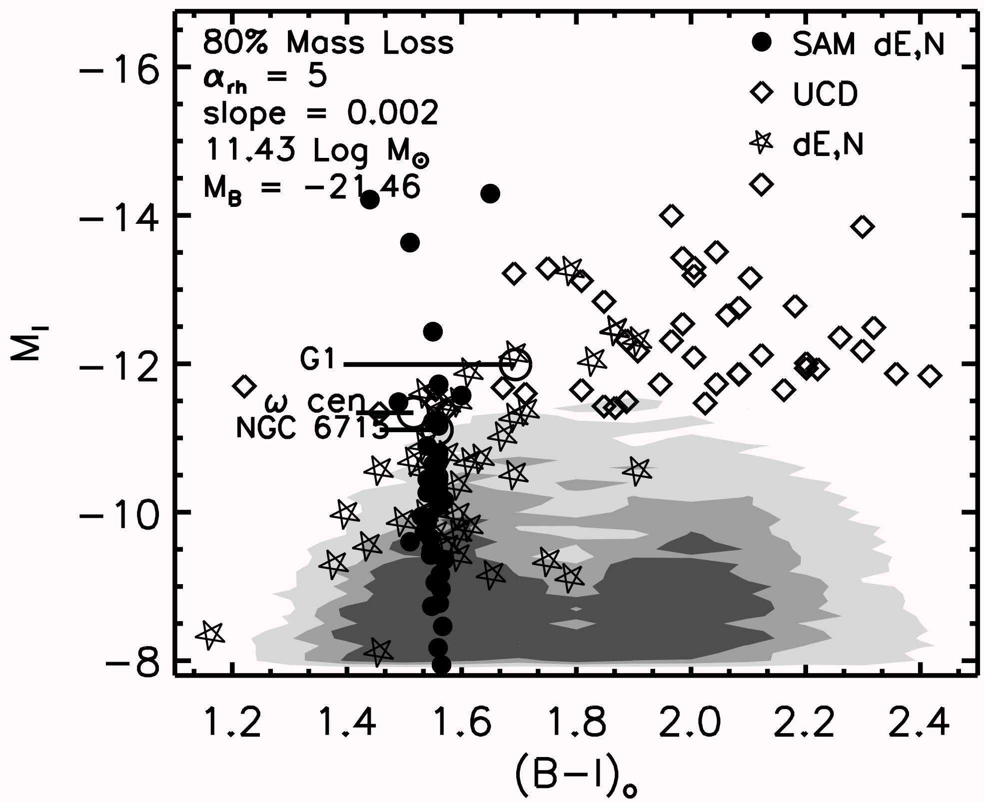
Rothberg et al. (*2007 submitted*)

NO *blue-MMR*

- Model should be able to account for lack of ***blue-MMR*** (NGC 4472)

- Supernovae (SN) Feedback Efficiency may provide answer

$$\dot{m}_{\rm rh} = \epsilon_0^{SN} \left(\frac{V_0}{V_c}\right)^{\alpha_{\rm rh}} \dot{m}_*$$

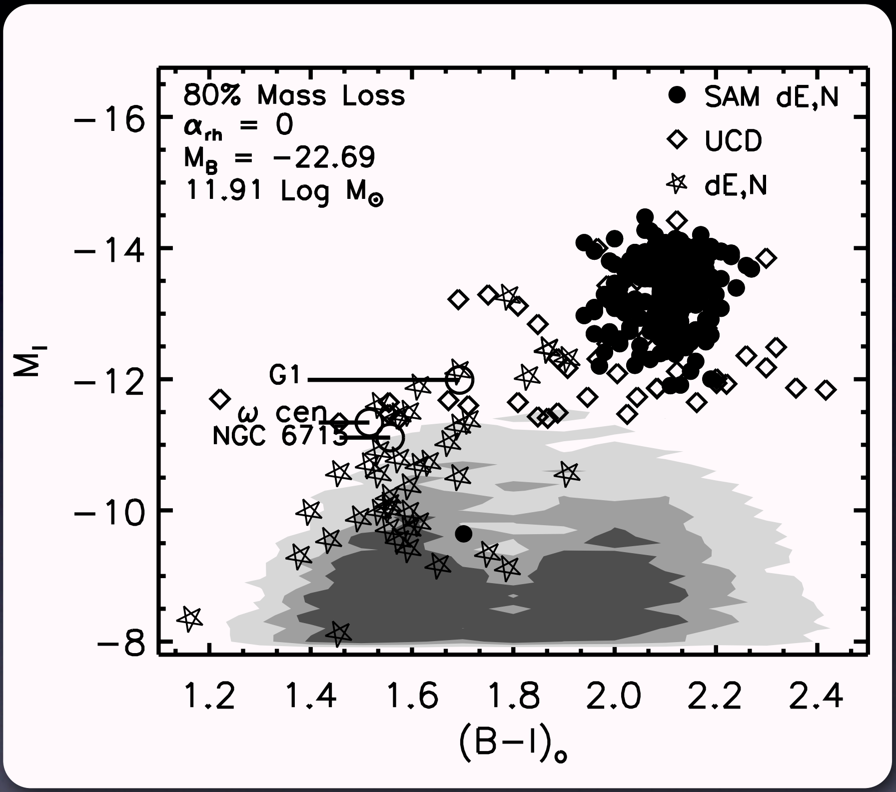


Rothberg et al. (*2007 submitted*)

Increase the dependency on galaxy mass of gas reheated via SN (α_{rh})
i.e increase reheating efficiency

Accounting for Ultra-Compact Dwarfs (UCDs)

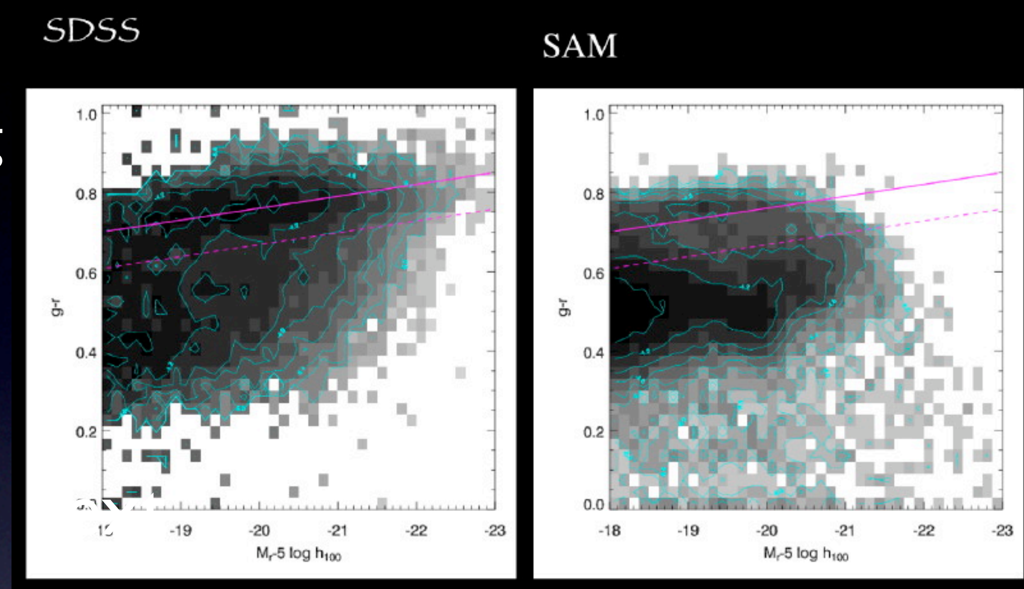
- UCDs do not show same MMR relation - large scatter in properties
- Large variations in UCD observed properties (Virgo, Fornax, Abell 1689, & Hydra)
- Changing α_{rh} to no or little dependency on mass (α_{rh} = 0) *can* produce objects coincident with UCDs
  - Observations show support for (Martin 1999, Martin et al. 2002, Martin 2005) in starburst dwarfs

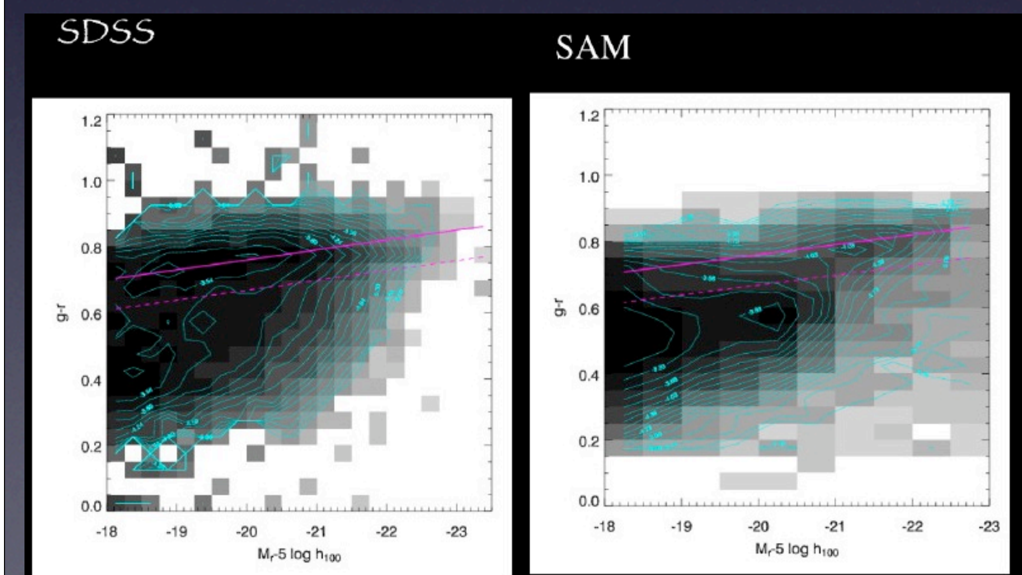


Rothberg et al. (*2007 submitted*)

Is α_{rh} just a knob?

- ΛCDM SAMs have over-cooling problem, produce too many bright *blue* galaxies
- α_{rh} also affects LF (curvature at faint end)





- SN feedback restores proper MMR for galaxies, *if*, $\alpha_{rh} \sim 2$
- Newer AGN feedback, momentum driven winds improve CMDs

Future Work

- Need to resolve theoretical and observational differences
  - Models need SN feedback, assume fixed amount
- Observations *suggest* SN feedback may vary, but why?
  - Environment?
  - Galaxy Mass? (dwarfs vs. larger systems)
- Newer models will incorporate *(IN PROGRESS)*:
  - mass & luminosity computed for all *GCs*
  - more sophisticated tidal stripping physics, new & improved feedback
- Observations of early-type galaxies, their GCs, and surrounding dEs and UCDs in *different environments* *(IN PROGRESS)*

Conclusions

(**final** *preliminary* results!)

- SAMs show simulated tidally stripped dE,N match the slope of the *blue-MMR*
- Slope invariant as function of mass/luminosity host galaxy
- Feedback Variations:
  - Can remove *blue-MMR* *if* dependence of SN feedback efficiency *increases* with mass
  - SAMs can produce UCDs *if no* dependence of SN feedback efficiency on galaxy mass

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