The Graveyard of Galaxy Evolution: Age-Dating the Red Sequence in Clusters

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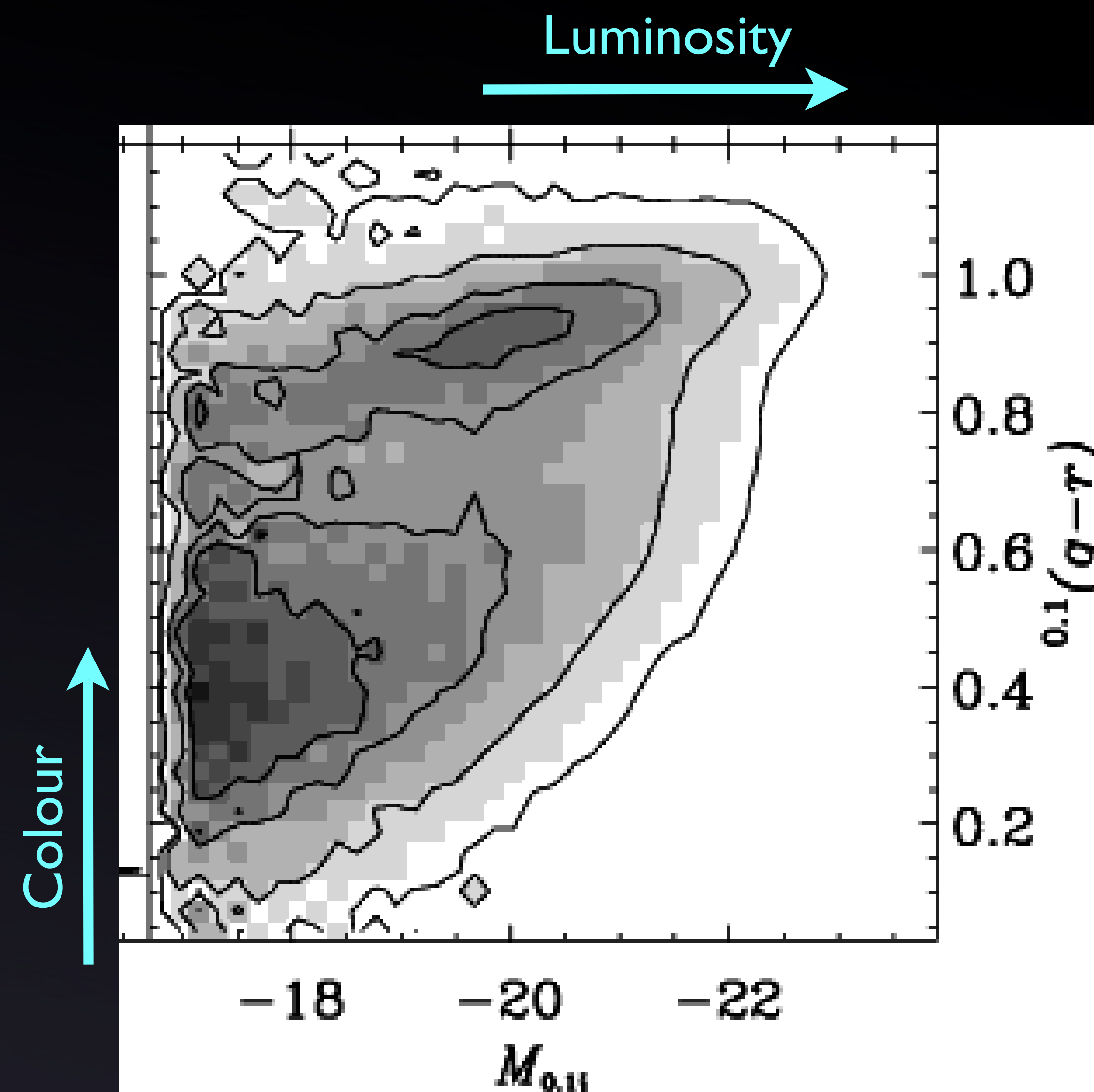
The Red Sequence and the Blue Cloud

- A bimodal galaxy population:
  - "Blue Cloud" forming stars
  - "Red Sequence" with no ongoing star-formation - the end-point of galaxy evolution
- Red sequence harbours ~50% of stellar mass at z=0 ; dominates rich clusters.
- A relic of early star-formation and chemical enrichment history.

AIM: To date the arrival of galaxies onto the red sequence, as a function of mass, environment, morphology, etc



Hogg et al. (2002)

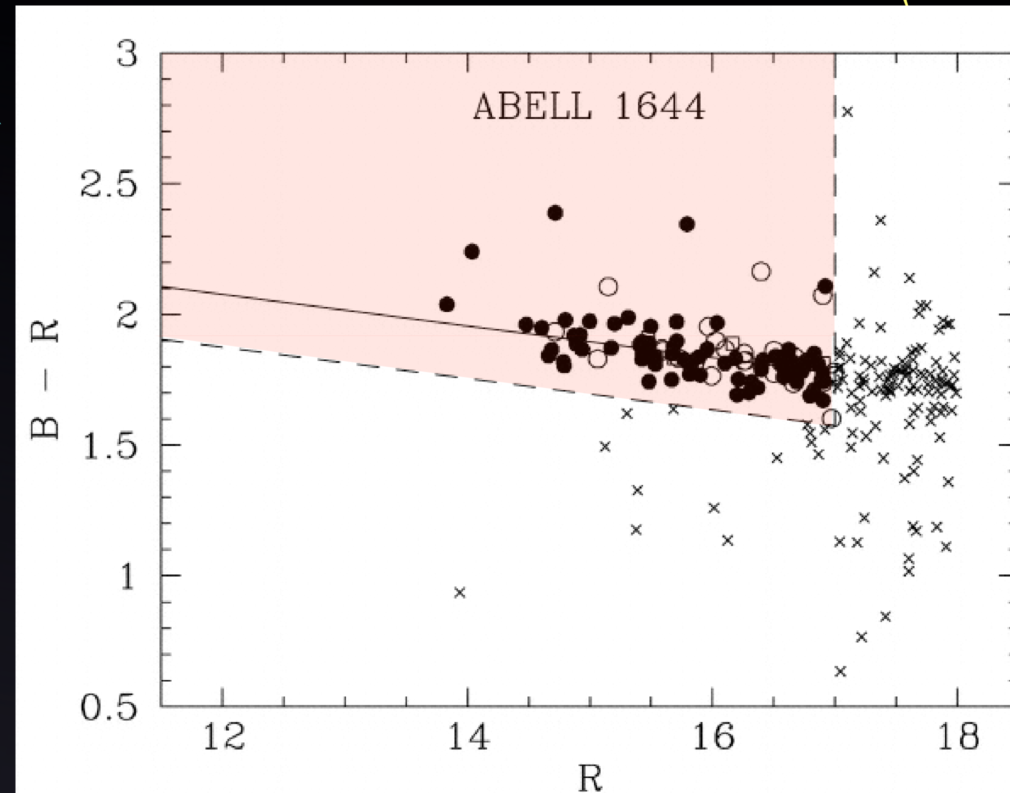
NOAO Fundamental Plane Survey (NFPS)

- All-sky survey of the most X-ray luminous clusters in z<0.067 and with |b| > 20 deg.
- B+R imaging from mosaic cameras at KPNO 0.9m+4m, CTIO 4m, CFHT.
- Multi-fibre spectroscopy from Hydra at WIYN, CTIO 4m, for red-sequence to R=17.
- Spectroscopic sample: 5479 galaxies in 93 clusters.
- Redshifts, velocity dispersions (Smith et al. 2004).
- "Lick" absorption-line indices (Nelan et al. 2005).
- Age indicators (HdF, HgF, Hbeta); Z/H indicators (Fe5270, Fe5335 etc) ; α/Fe indicators (Mgb, CN1)

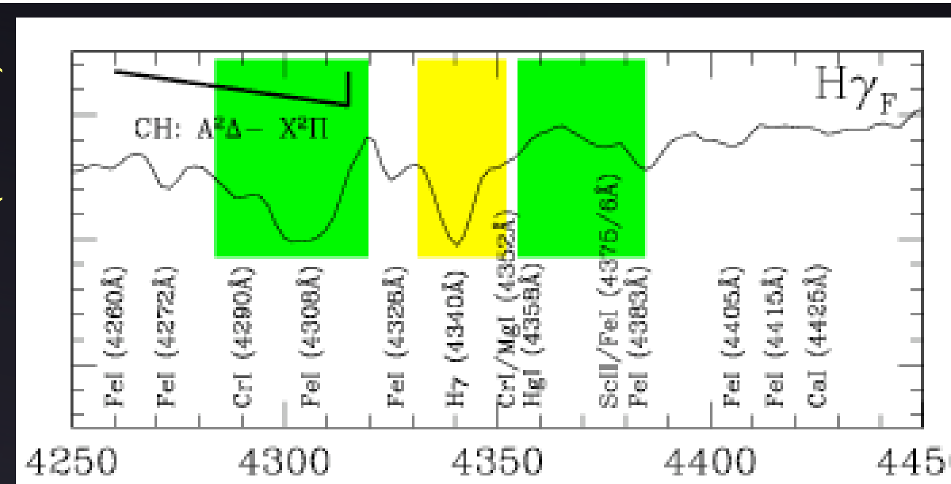
R Magnitude

Smith et al. (2004)

B-R colour

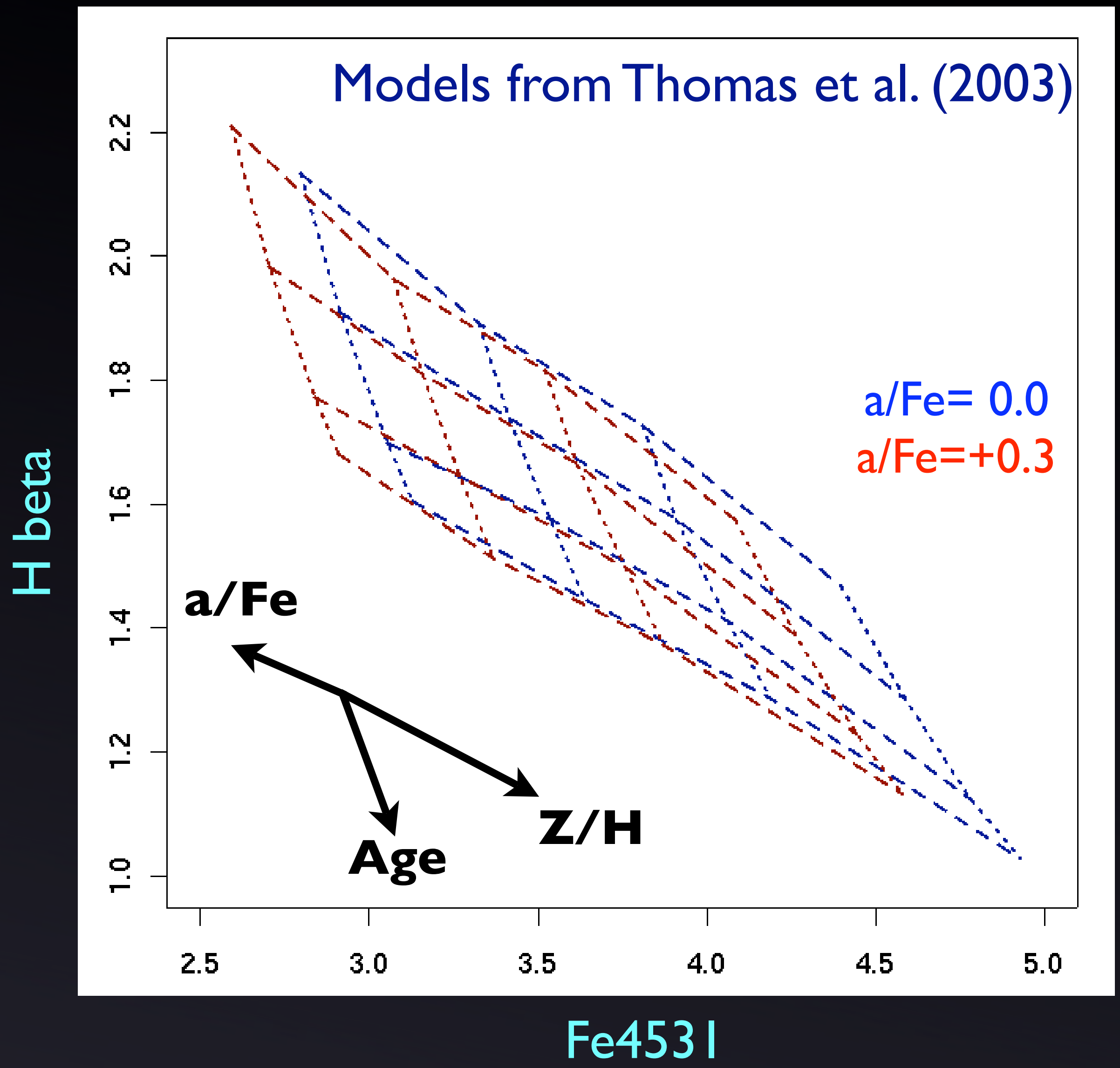


Puzia et al. (2005)



From Stellar Population models to Response Vectors

- Classical method uses "Diagnostic Plots" of Balmer vs metal lines.
- Need to "invert" to recover population parameters
- Absolute calibration of models (and data!) is uncertain
- How to interpolate off-grid points?
- How to deal with correlated errors in interpolated parameters?
- How to make use of multiple indices?



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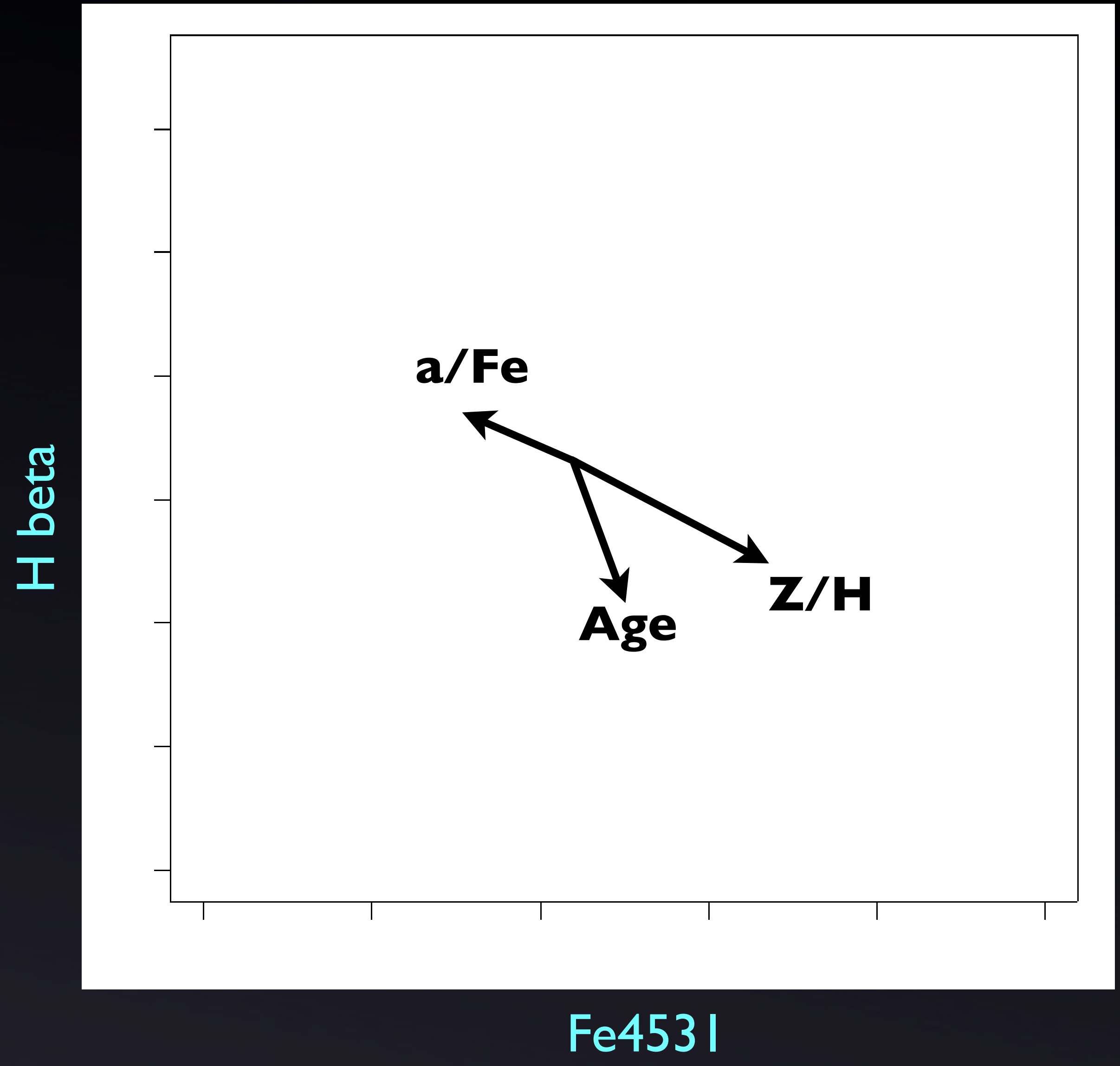
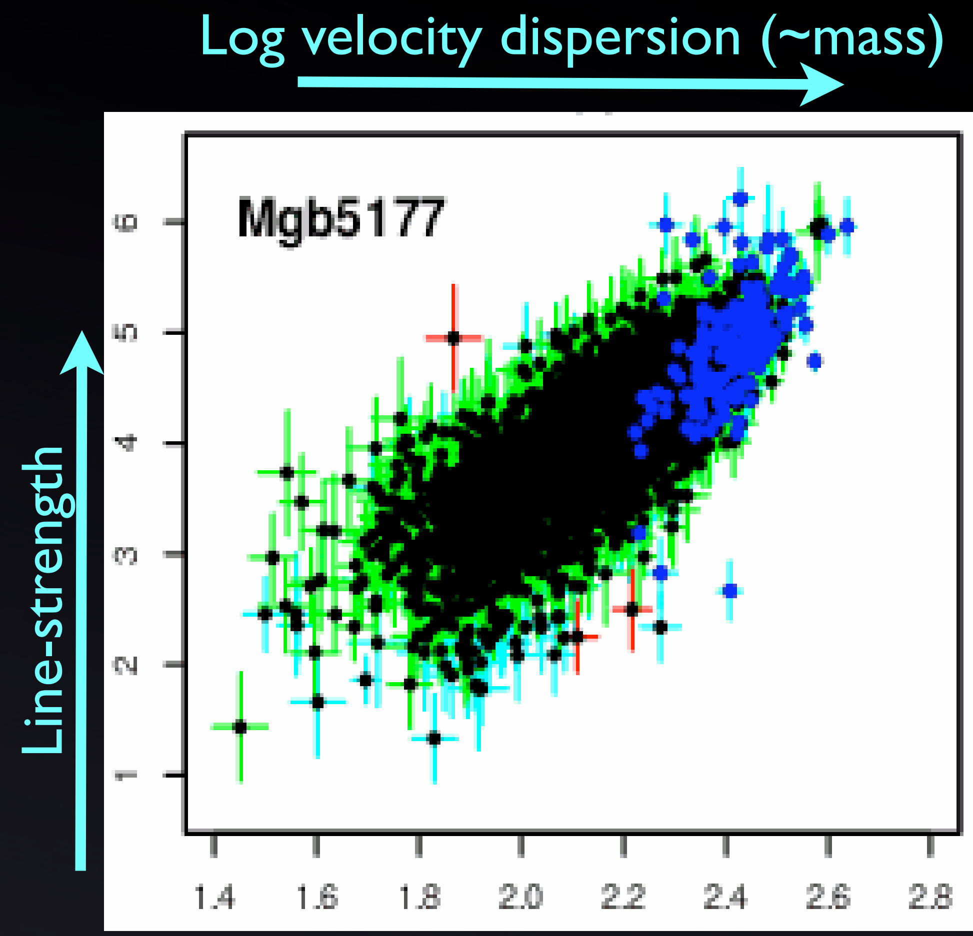
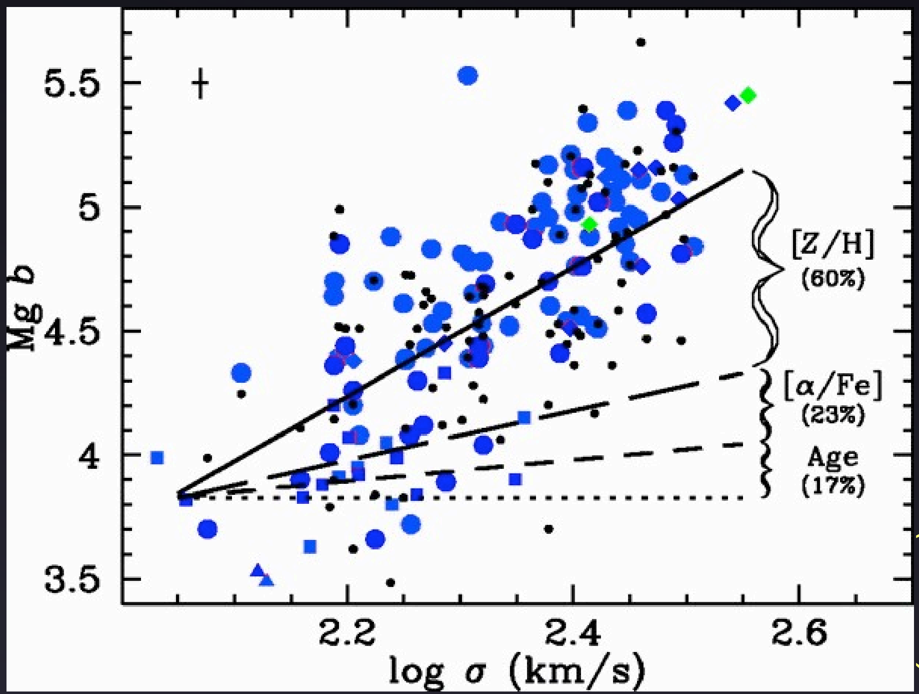


The Mass Scaling Relations

- Use velocity dispersion σ as proxy for galaxy mass.
- Index-sigma relations, trace scaling of stellar population with mass,
- e.g. classic Mgb - σ relation
- Mgb depends on Age, Z/H and α/Fe (Thomas et al. 2003)
- So which of these parameters vary with mass to drive the relationship?



Smith et al. (2006)



Thomas et al. (2005)

NB: Compared to Thomas et al. (2005), NFPS covers ~2x the range in σ, or ~10x baseline in mass

Model-fitting ingredients

LINEAR RESPONSES (simplified pop. model)

$$\mathrm{Mgb} = f_0 + f_1 \log\mathrm{Age} + f_2\,[\mathrm{Z/H}] + f_3\,[\alpha/\mathrm{Fe}]$$

$$\mathrm{HgF} = g_0 + g_1 \log\mathrm{Age} + g_2\,[\mathrm{Z/H}] + g_3\,[\alpha/\mathrm{Fe}]$$

$$\mathrm{Fe5270} = h_0 + h_1 \log\mathrm{Age} + h_2\,[\mathrm{Z/H}] + h_3\,[\alpha/\mathrm{Fe}]$$

PARAMETER SCALINGS

$$\mathrm{Age} \propto \sigma^{X}$$

$$\mathrm{Z/H} \propto \sigma^{Y}$$

$$\alpha/\mathrm{Fe} \propto \sigma^{Z}$$

MEASURED INDEX SLOPES

$$\mathrm{Mgb} = a_1 \log \sigma + b_1$$

$$\mathrm{HgF} = a_2 \log \sigma + b_2$$

$$\mathrm{Fe5270} = a_3 \log \sigma + b_3$$

etc...

MODEL CONSTRAINTS

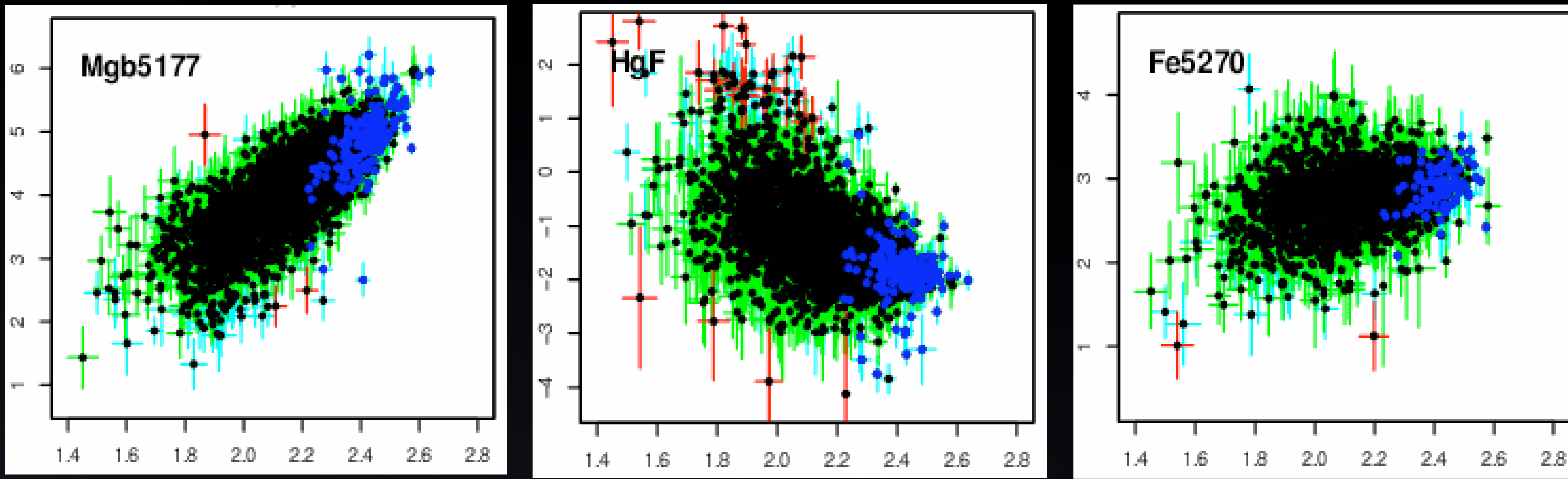
$$a_1 = f_1 X + f_2 Y + f_3 Z$$

$$a_2 = g_1 X + g_2 Y + g_3 Z$$

$$a_3 = h_1 X + h_2 Y + h_3 Z$$

etc...

- Never attempt to measure Age (etc) for individual galaxies.
- Need at least three indices to recover age, Z/H and a/Fe scalings.
- Differential method: insensitive to absolute calibration of models and data.
- Not over-sensitive to "off-grid" points (unlike multi-index χ^2 methods).
- Responses calculated over restricted parameter space as spanned by E/S0s.



Smith et al. (2006)

Data

Model

Unknowns

$$\frac{dI}{d\log\sigma} = \frac{\partial I}{\partial \log t}\frac{d\log t}{d\log\sigma} + \frac{\partial I}{\partial [Z/H]}\frac{d[Z/H]}{d\log\sigma} + \frac{\partial I}{\partial [\alpha/\mathrm{Fe}]}\frac{d[\alpha/\mathrm{Fe}]}{d\log\sigma}$$

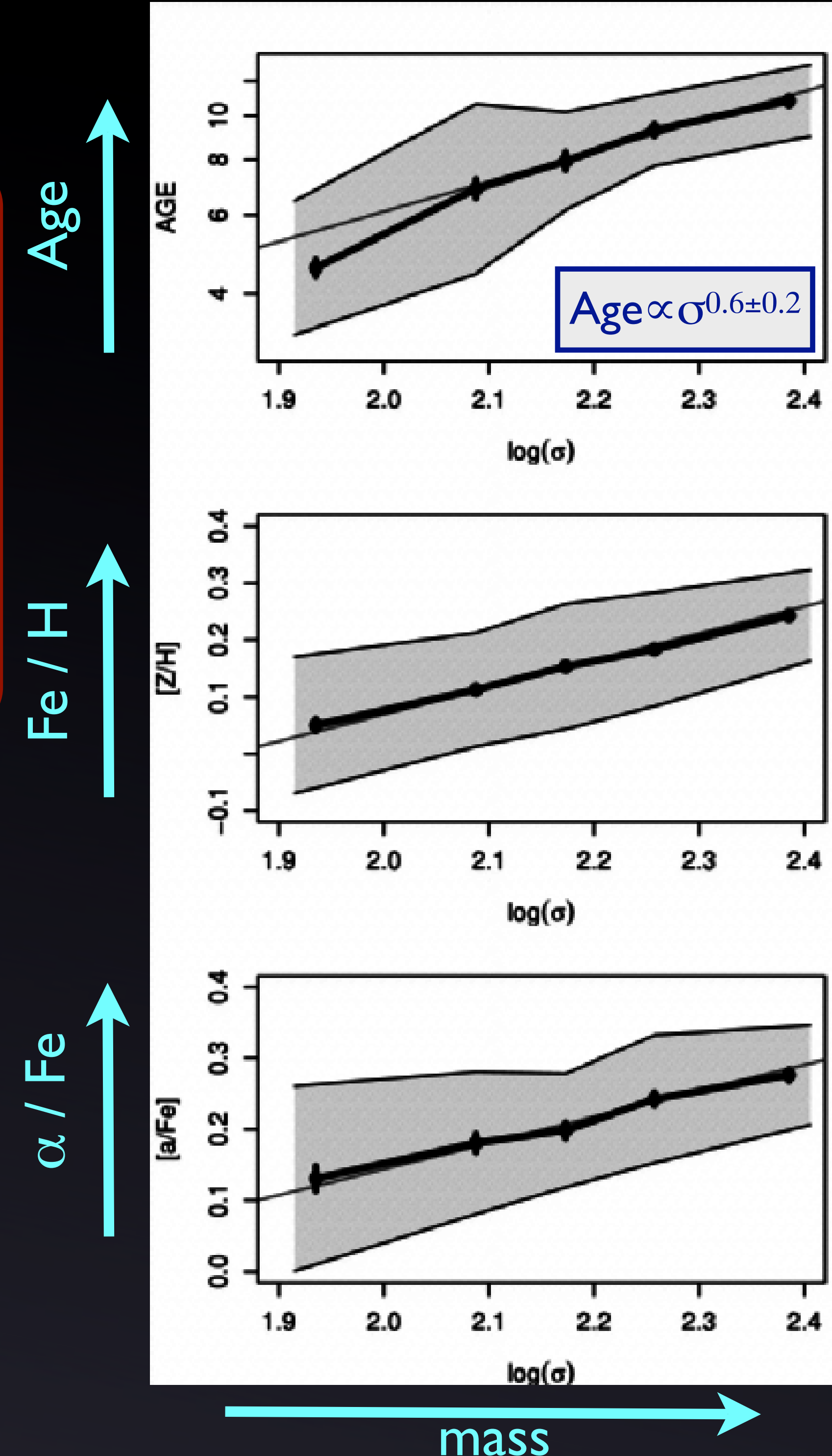
- With just three non-degenerate indices we can solve for the scaling relation slopes.
- More robustly, use many partially-redundant indices to over-constrain the model.
- In practice, use the "NFPS 12": HdF, HgF, Hbeta, CN1, Fe4668, Mgb5177, Fe4531, Fe5270, Fe5335, Fe5406, Fe5709, Fe5782 (Nelan et al. 05, Smith et al. 06)

Mass Scaling Relations: Results

- Compared to σ=300 km/s, galaxies of σ=100km/s have:
  - Younger "ages" (by factor 1.9 ± 0.2) (!!)
  - Lower total metallicity (by 0.25 ± 0.04 dex)
  - Less alpha-enriched (by 0.15 ± 0.03 dex) (star-formation timescale ~8x longer)

- Errors derived from running fits with different choices of indices.
- Similar results from averaged-index grid-inversion
- Strong age-vs-mass relation Age $\propto \sigma^X$ with

  X=0.6±0.1 (Nelan et al, revised to X=0.7 in Smith et al.)
- Low-mass (100km/s) red-sequence galaxies have ages only ~ 7 Gyr, corresponding to z~1.



Nelan et al. (2005)

Comparison with other work

Strong age-vs-mass relation Age $\propto \sigma^X$ with X=0.6±0.2 (Nelan et al, revised to X=0.7 in Smith et al.)

Confirms previous hints from much smaller samples:

- Caldwell et al. (2003) : X=0.8-1.2
- Thomas et al. (2005) : X ~ 0.8

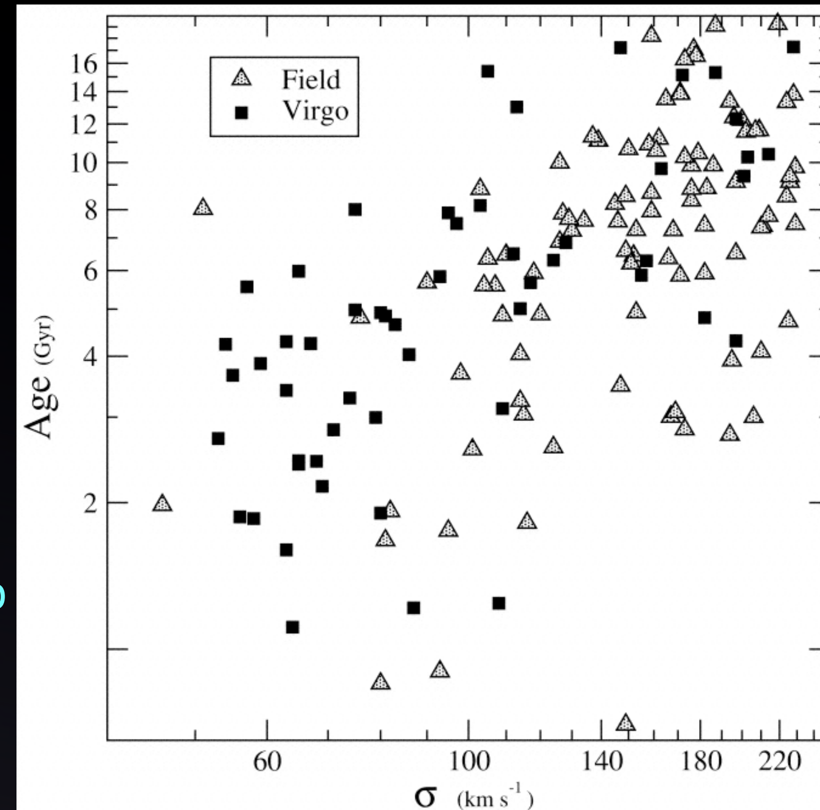
  (NOT ~0.2 as often quoted!)

...And supported by studies from SDSS (more galaxies, but narrower mass baseline) :

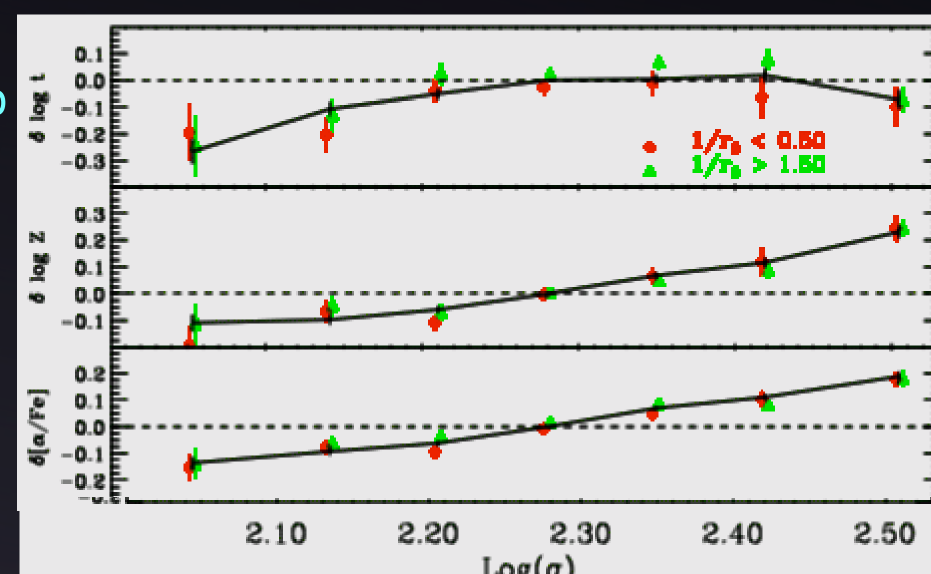
Need a careful treatment of selection bias for flux-limited samples; most severe for samples dominated by L<L*.

- Bernardi et al. (2006) : X=0.8-1.2
- Clemens et al. (2006) : X ~ 0.75

Need a careful treatment of selection bias for flux-limited samples -- most severe for samples dominated by L<L*....

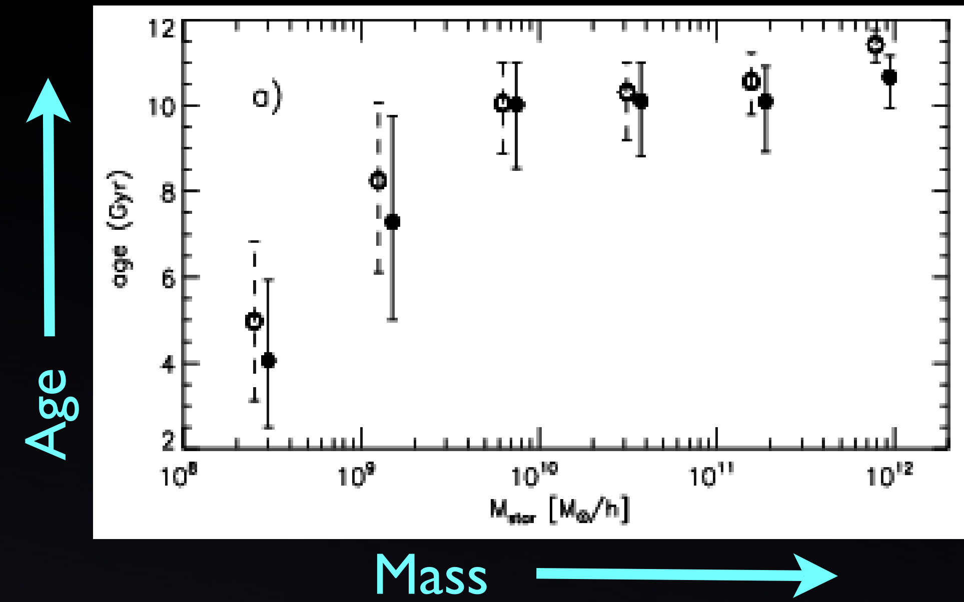


Mass →

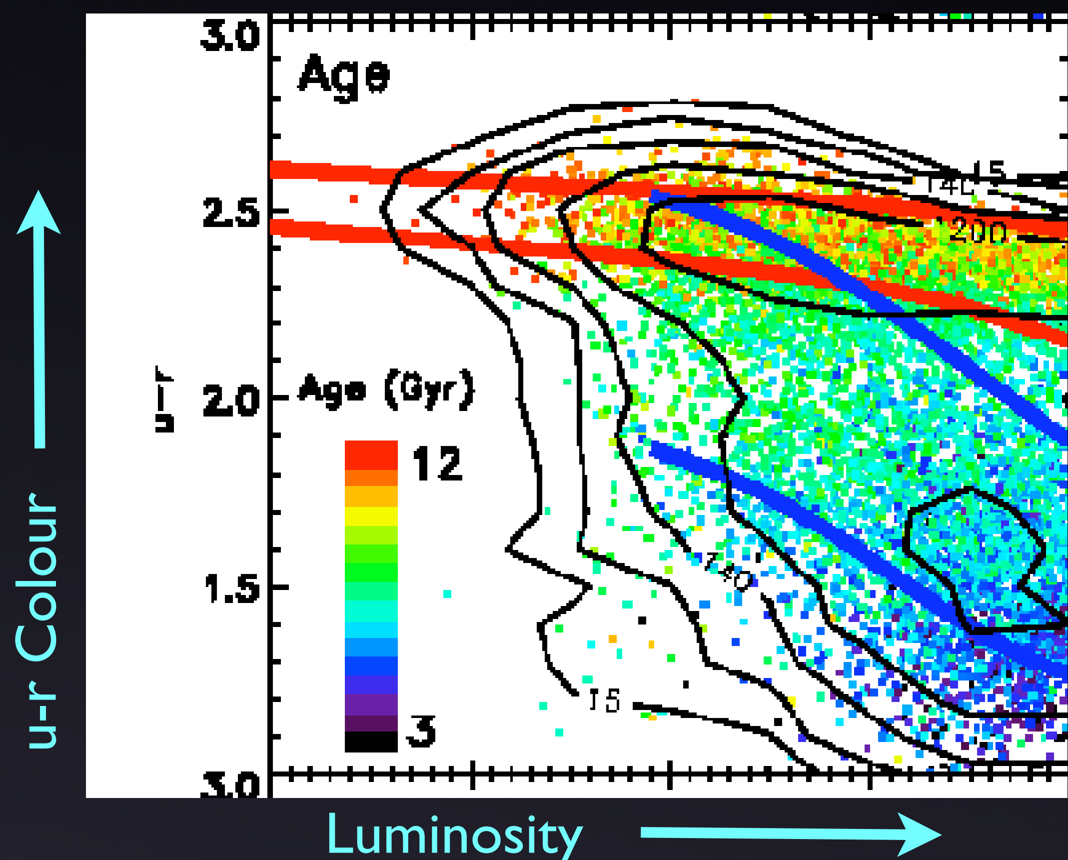


Comparison with galaxy formation models

- Emerging observational consensus for "red-sequence down-sizing" -- can hierarchical models reproduce this?
- Recent semi-analytic models with AGN feedback (Croton et al., de Lucia et al., Bower et al., Cattaneo et al.) are more successful than older attempts.
- Detailed behaviour differs among published models (fundamental, or due to different selection?)
- Coming soon: detailed comparisons with Bower et al. versions, attempting to match NFPS selection cuts.



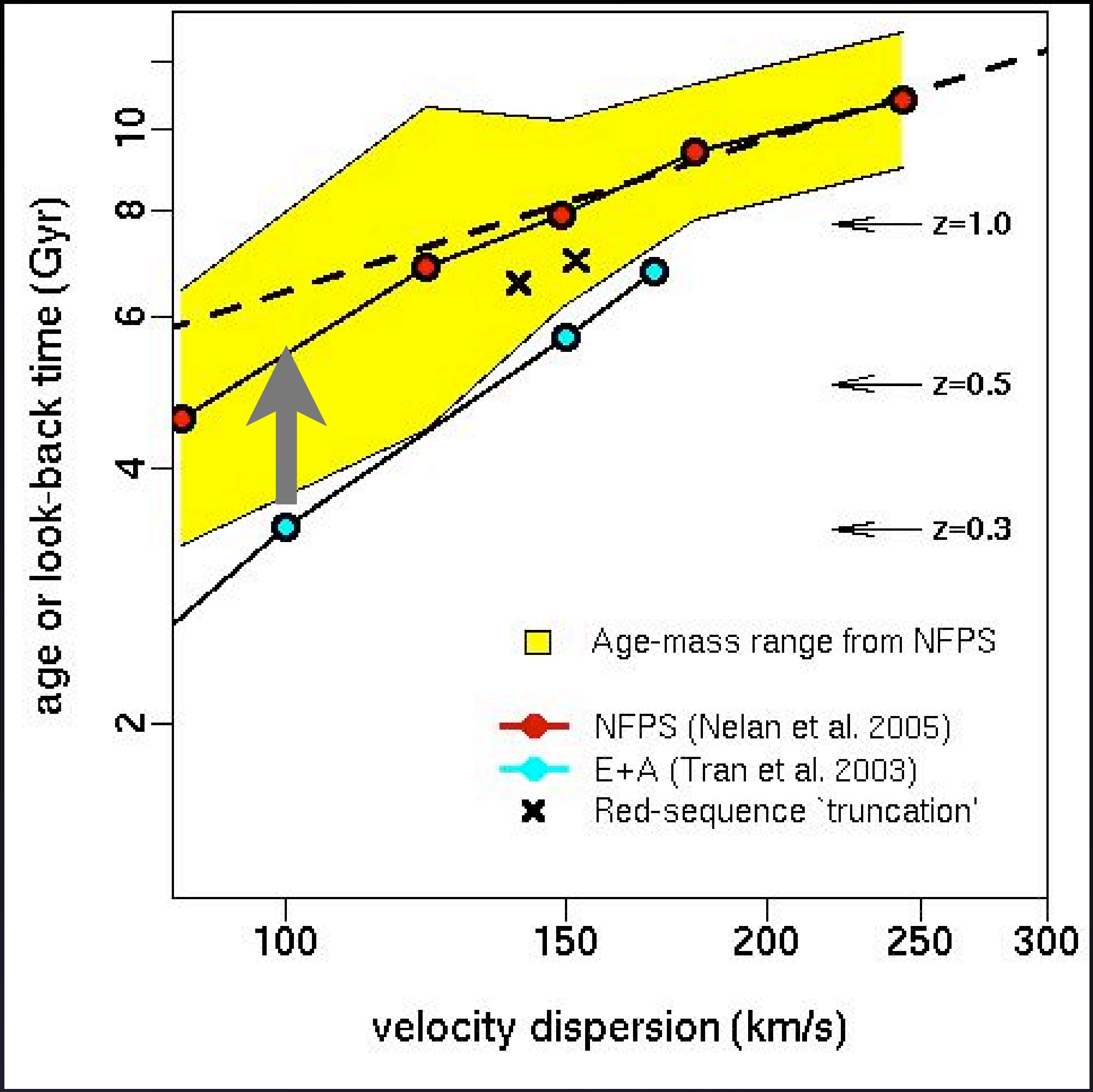
de Lucia et al. (2005)



Cattaneo et al. (2006)

Red Sequence Down-sizing in Context - I

- Interesting to compare to intermediate redshift observations...
- Luminosity of red sequence “truncation” at z=0.8 (de Lucia et al. 2004) corresponds to sigma ~ 150 km/s at lookback time ~6 Gyr.
- Mass scale of E+A galaxies follows the age-mass relation too, with an offset of ~2 Gyr
- DEEP2 “Quenching mass” follows similar track.
- Hopkins et al. link QSO luminosity function to low-z spheroids, indicating similar trend
- Jorgensen et al. FP mass-dependent evolution in clusters; Treu et al. in field.



Adapted from Smith (2005)

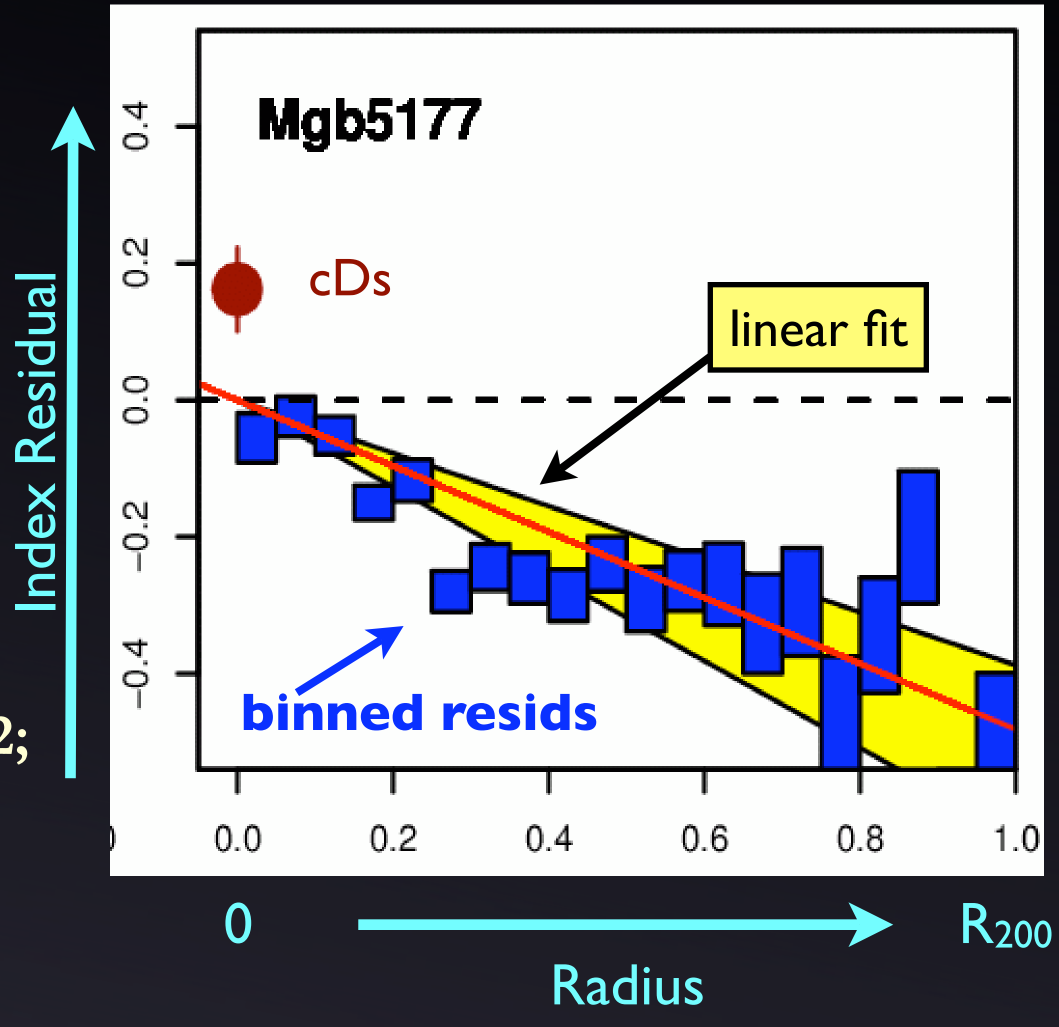
Environmental Dependence of Red-Sequence Ages

- When and how is the red-sequence established? What is the role of the cluster environment?
- Model index-sigma relations with an extra term describing cluster-centric radius effects:
- Sample is ~3000 emission-free cluster members with $R<R_{200}$, cDs excluded.
- Partial residual, isolating radial effect: $\delta = I - (a \log s + c + d\, z/z_0)$
- Significant detection of radius coefficient, b, for many indices.
- e.g. Mgb decreases with large R, after controlling for mass. (Previously detected in Coma by Guzman et al. 1992; Carter et al. 2002).
- Which parameter varies with radius to drive the index trends?

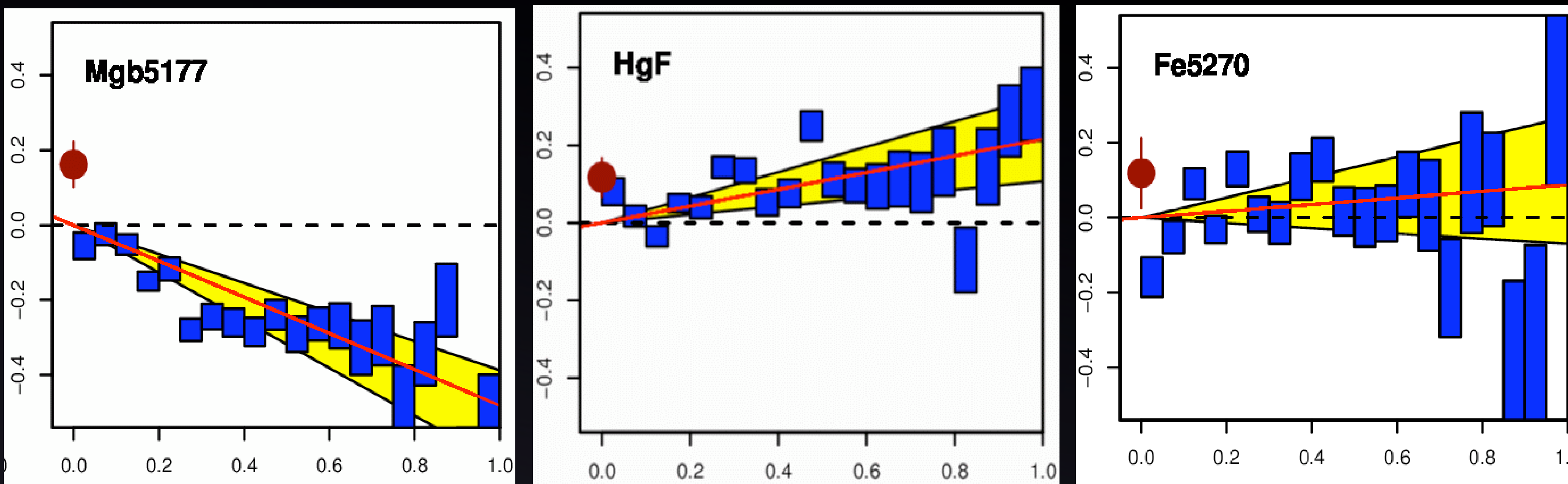
Model:

$$I = a \log \sigma + b\,(R/R_{200}) + c$$

Smith et al. (2006)



Origin of the Index Residual vs Radius Relations



Smith et al. (2006)

Data — Model — Unknowns

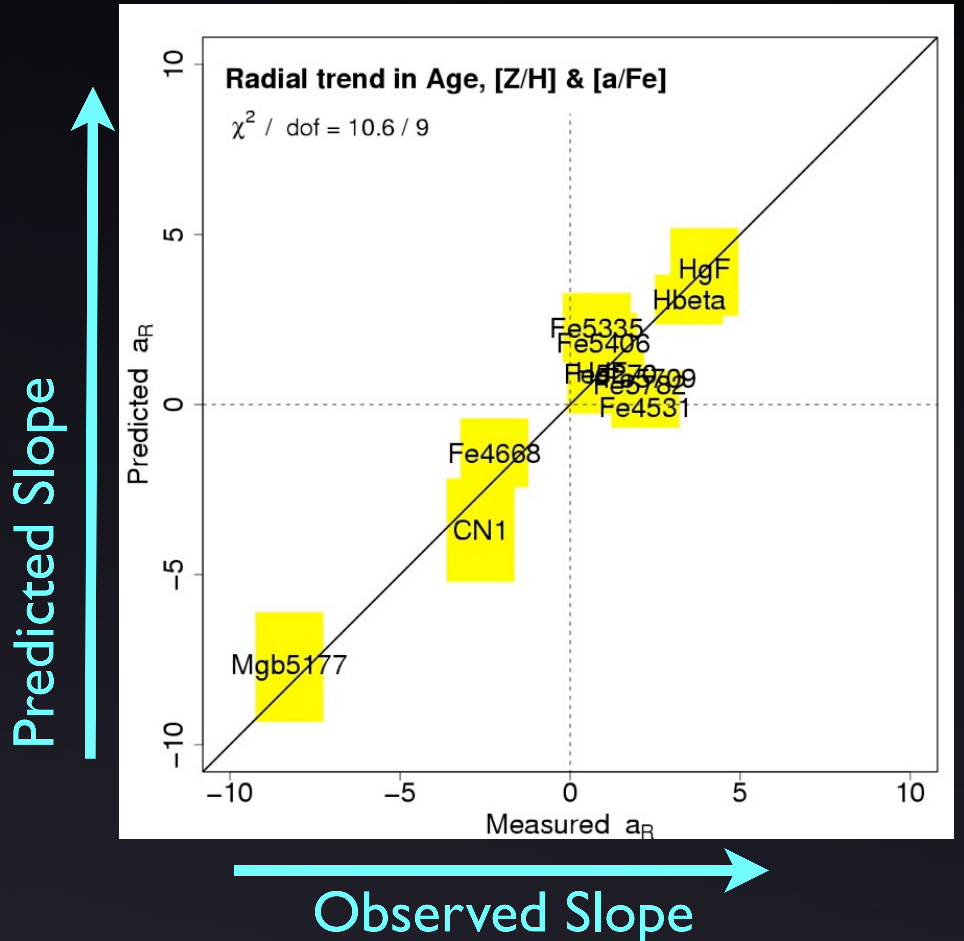
$$\frac{dI}{dR_{\rm cl}} = \frac{\partial I}{\partial \log t}\frac{d\log t}{dR_{\rm cl}} + \frac{\partial I}{\partial [Z/{\rm H}]}\frac{d[Z/{\rm H}]}{dR_{\rm cl}} + \frac{\partial I}{\partial [\alpha/{\rm Fe}]}\frac{d[\alpha/{\rm Fe}]}{dR_{\rm cl}}$$

- **With three or more indices we can fit for the radial trend slopes...**

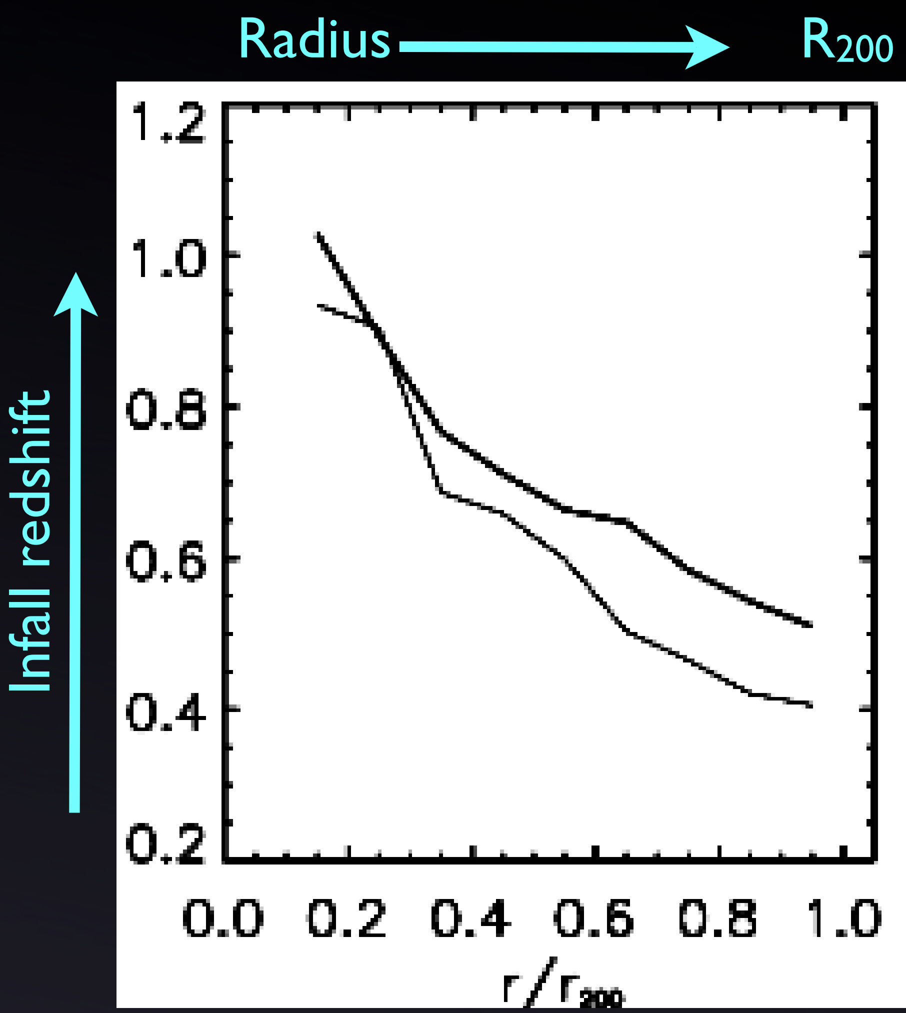
A model for cluster-centric trends

- Results: at R_{200}, galaxies are...
  - 16 ± 4 % younger and
  - 10 ± 2 % less alpha-enriched (~2x longer star-formation timescale)
  - similar in metallicity (2 ± 3%)
- ...compared to galaxies of the same mass in the cluster core.

Smith et al. (2006)

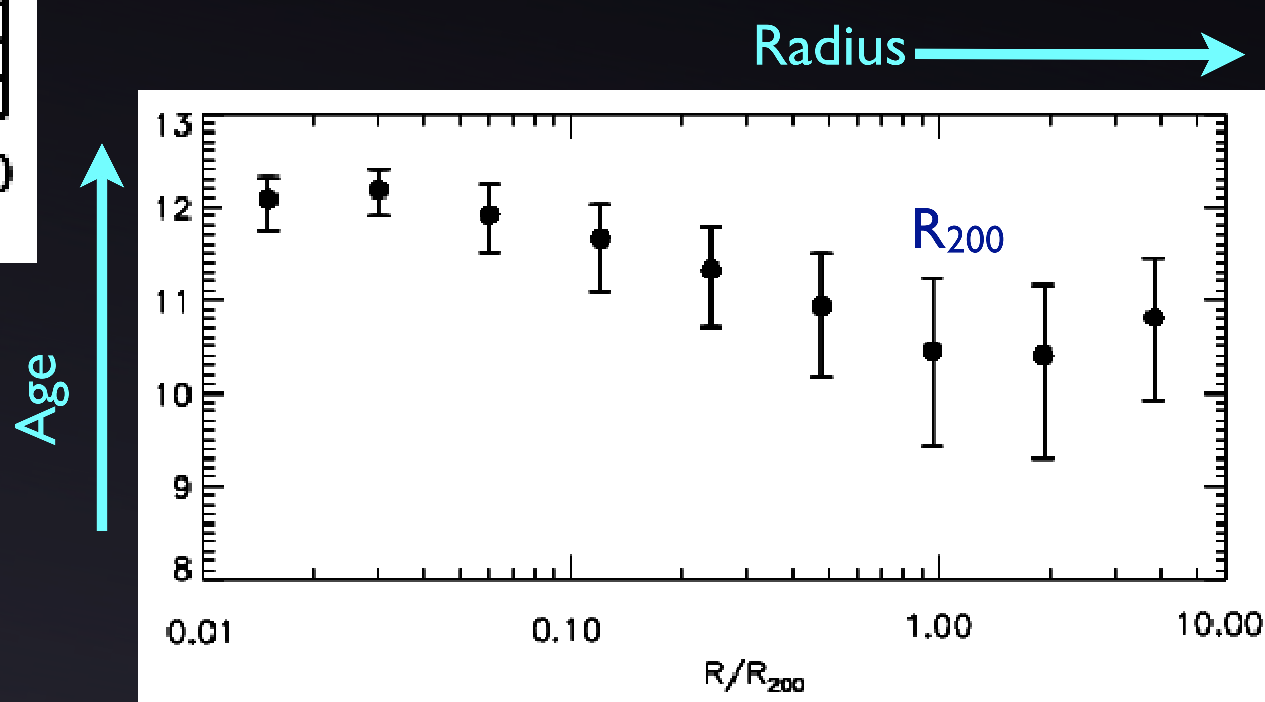


- Fit to trends of 12 indices (same set as used by Nelan et al. 2005)
- Model adequately describes the radial trends in all of the indices.
- Must have both Age and a/Fe variations (cf. Guzman et al. 1992; Carter et al. 2002).
- Hint that radial trends are stronger in the low-mass objects...



Gao et al. (2004)

- Cluster environment causes “suffocation” by stripping of gas halo (Larson & Tinsley 1980, etc.)
- Star formation truncated within 1-2 Gyr of infall into cluster.
- N-body: clusters not well-mixed even within R_{200} (Gao et al.): z_{infall} - R_{cl} correlation
- So expect some radial age gradient, at the 10-20% level out to R_{200}.



de Lucia et al. (2005)

Summary

- Existence of age-mass relation now well established (Nelan et al. 2005, Thomas et al. 2005, Bernardi et al. 2005, etc).
- Ties in with (some) observations at higher redshifts (E+A mass evolution, red sequence truncation, FP rotation...).
- Detailed comparisons to semi-analytic models underway.
- Clear evidence for cluster-centric trends in stellar populations, independent of particular synthesis models.
- Pattern of radial trends best reproduced if outer galaxies are younger and had longer star-formation time-scales, after controlling for mass (and morphology).
- New observations obtained with AAOmega vastly improve coverage at low-masses -- stay tuned....

For full details, see:

Smith, Hudson, Nelan et al. 2004, AJ, 128, 1558 (Survey paper)
Nelan, Smith, Hudson et al. 2005, ApJ, 632, 137 (Mass scalings)
Smith, Hudson, Lucey et al. 2006, MNRAS, 369, 1419 (Radial trends)