Redshift Evolution in Galaxy Scaling Laws

“Fundamental Planes” part 2.1
Recall, TF follows (to lowest order) from halo scalings:

at fixed $M$:

$v \sim v_{\text{halo}} \sim (1+z)^{1/2}$
DEEP2: See significant evolution in TF

Zeropoint offset of ~1.5 magnitude at z = 1

Weiner et al. 2004
But *baryonic* TF:

Kassin et al. 2007
Bouche et al. 2007: appears to hold out to $z \sim 2-3$
Redshift Evolution
SIZE-MASS RELATIONS

TF doesn’t evolve: doesn’t mean projections (e.g. size-mass) don’t

Disk galaxies: naively assume (Mo, Mao, & White)

\[ R_d \sim \frac{M}{v^2} \]
\[ v \sim v_{\text{halo}} \]
\[ R_d \sim \frac{1}{H(z)} \]

Weiner et al. 2005
FP and TF don’t evolve: doesn’t mean projections (e.g. size-mass) don’t

COMBO–17:
Disk galaxies
Mass–radius relation
No shift in zeropoint vs. time

Toy model prediction
GEMs sees the same: weak evolution in disk size–mass relation

Somerville et al. 2007
Redshift Evolution
SIZE-MASS RELATIONS

Weak disk size-mass evolution: why?

- $R_d \sim R_c$ (break radius of halo profile), not $R_{200}$ (most mass in $R_c$, so $V^2 \sim M / R_c$)

- $R_c = R_{200} / c$ (concentration)

- $c \sim 1 / (1 + z)$ --- cancels most predicted evolution!

Observed

Predicted (including $c$

Predicted ($R_d \sim R_{200}$)
Disks are weakly evolving: do we expect to see the same in ellipticals?
Caution: The red sequence at z~1 contains a wide range of morphologies

Color maps (blue is dark)

- Merger
- Post-merger
- Blue center
- Normal E/So
- Normal spiral
- Blue ring

Harker et al. 2004
Many ellipticals being/recently formed: even normal E/S0s are often disturbed

Red-sequence E/S0 galaxies in HDF–N. 40% of all spheroidal galaxies to 23 R mag are disturbed. Roughly 1/3 of these show blue centers and are also candidate AGNs.

Van Dokkum & Ellis 2003
See an offset in magnitude in the FP

Gebhardt et al. 2003

(Field)
See an offset in magnitude in the FP

Treu et al.
(Clusters)
But again, evolution consistent with stellar population fading

And scatter remains small
Given weak disk evolution, and that this is (to lowest order) the virial relation, perhaps we should not be surprised.
What about spheroid sizes?

Redshift Evolution
SIZE-MASS RELATIONS

Trujillo et al. 2007
Spheroids are getting smaller >2x as quickly as disks!
By $z \sim 3$, massive ellipticals are little bigger than a starburst (~kpc)

Zirm et al.
Why are ellipticals so much smaller than disks at high-z?

Same answer as at low-z: gas. just more of it
Why are ellipticals so much smaller than disks at high-z?

Same answer as at low-z: gas. just more of it

Increased dissipation >> smaller, more compact remnants (Cox et al.; Robertson et al.)
Faber-Jackson & size-mass vs. disk gas content

- \( f_{\text{gas}} = 0.1 \)
- \( f_{\text{gas}} = 0.4 \)
- \( f_{\text{gas}} = 0.8 \)
High-z galaxies are more gas-rich:

- Expect more compact remnants (see also Khochfar & Silk)
Where are they now?

Dry (spheroid-spheroid) merger:

Typical orbits weakly bound -- $E_{\text{final}} = E_{\text{initial}} = 2 \left( M_i \ast \sigma_i^2 \right)$

$M_f = 2 M_i$ -- so $\sigma_f = \sigma_i$

virial theorem -- $R_f = 2 \ast R_i$

Relative to the slope of the size mass relation ($R \sim M^{1/2}$), you’re rapidly moving up (increasing $R$)

High-z early mergers are *exactly* the systems expected to have more dry mergers
Direction dry mergers move you these $z \sim 3$ galaxies are the most massive galaxies today.
unclear how much room there is for dry mergers in the most massive galaxies

Van Dokkum et al. (2005)

We see them happening...

Bell et al. (2006)
But....

unclear how much room there is for dry mergers in the most massive galaxies

But others argue even ~1 is too many for a massive galaxy

Major caveat: our knowledge of stellar populations

Maraston: M/L is much lower
*when galaxies are younger*

Scarlata et al. (2007)
Red galaxies: How do we determine how galaxies shut down?
The color-magnitude diagram from SDSS

The color-magnitude sequence of early-type galaxies.

Hogg et al.,
Indeed, there are very significant stellar population trends as a function of elliptical mass:
Motivation

QUASARS AND SPHEROID FORMATION

Croton+ 06

Yang+ 03

Bell+ 04
**c) Interaction/“Merger”**
- now within one halo, galaxies interact & lose angular momentum
- SFR starts to increase
- stellar winds dominate feedback
- rarely excite QSOs (only special orbits)

**d) Coalescence/(U)LIRG**
- galaxies coalesce: violent relaxation in core
- gas inflows to center:
  - starburst & buried (X-ray) AGN
- starburst dominates luminosity/feedback,
  - but, total stellar mass formed is small

**e) “Blowout”**
- BH grows rapidly; briefly dominates luminosity/feedback
- remaining dust/gas expelled
- get reddened (but not Type II) QSO:
  - recent/ongoing SF in host
  - high Eddington ratios
  - merger signatures still visible

**f) Quasar**
- dust removed: now a “traditional” QSO
- host morphology difficult to observe:
  - tidal features fade rapidly
- characteristically blue/young spheroid

**g) Decay/K+A**
- QSO luminosity fades rapidly
- tidal features visible only with very deep observations
- remnant redens rapidly (E+A/K+A)
- “hot halo” from feedback
- sets up quasi-static cooling

**a) Isolated Disk**
- halo & disk grow, most stars formed
- secular growth builds bars & pseudobulges
- “Seyfert” fueling (AGN with $M_\text{BH}>10^8$)
- cannot redden to the red sequence

**b) “Small Group”**
- halo accretes similar-mass companion(s)
- can occur over a wide mass range
- $M_{\text{halo}}$ still similar to before:
  - dynamical friction merges the subhalos efficiently

**h) “Dead” Elliptical**
- star formation terminated
- large BH/spheroid - efficient feedback
- halo grows to “large group” scales:
  - mergers become inefficient
- growth by “dry” mergers
Motivation

MERGERS AND THE BLUE-RED TRANSITION

Woo et al.: Disks aren’t “turned off” (red = bulge)?
Motivation

CIRCUMSTANTIAL EVIDENCE

Tremaine+ 02; Onken+ 04; Nelson+ 04; Peterson+ 04, 05; Barth+ 04, 05; Greene & Ho 05

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Quasars were active/BHs formed when SF shut down...

BH Formation Times:

Spheroid Formation Times:

Nelan+05; Thomas+05; Gallazzi+06

Hopkins, Lidz, Hernquist, Coil, et al. 2007
Motivation

CIRCUMSTANTIAL EVIDENCE

Borch+06;
Bundy+06;
Fontana+04,06;
Pannella+06;
Franceschini+06

Hopkins, Bundy, Hernquist+ 06

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Motivation

CIRCUMSTANTIAL EVIDENCE

- Observed RS Buildup to $z \sim 1$ = Expectation if *all* new mass to the RS “transitions” in a quasar-producing merger

Hopkins, Bundy, Hernquist+ 06
Motivation
CIRCUMSTANTIAL EVIDENCE

Sanchez+ ‘05
GEMS
0.5 < z < 1.1
Optical QSOs

Nandra+ ‘06
DEEP2
0.7 < z < 1.4
X-ray QSOs

(also, Kauffmann+ 03;
local SDSS hosts)
Motivation

CIRCUMSTANTIAL EVIDENCE
The Model

PREDICTIONS

- **z=0 mass functions**

- **M/L vs. M_halo**

- **red fractions:**

Merger Timescale Recalculated With:
- Dynamical Friction
- Group Capture (Collisional)
- Angular Momentum ( Orbital) Capture

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The Model

PREDICTIONS

- Mass function redshift evolution:
- Mass density:
- Age vs. mass:
Great!

...BUT...
Great!

...BUT....

Croton et al.

Monaco et al.

Bower et al.

Kang et al.

Cattaneo et al.
Lowest-Order Predictions are Fundamentally Non-Unique:
HOW DO WE BREAK THE DEGENERACIES?

- Identify broad classes of quenching models:

- Are there unique, robust predictions of the different classes of quenching mechanisms?
Lowest-Order Predictions are Fundamentally Non-Unique:
HOW DO WE BREAK THE DEGENERACIES?

Identify broad classes of quenching models:

- Khochfar & Silk (w. Naab et al.)
- Cattaneo et al. (alt)
- Somerville et al. (new)
- Hopkins et al. (too many)
- Croton et al.
- De Lucia et al.
- Bower et al.
- Cattaneo et al. (standard)
- Kang et al.
- Monaco et al. (no QSO)
- Bower et al. (sometimes)
- Noeske et al.
Comparing Quenching Models
HOW DO WE BREAK THE DEGENERACIES?
### Motivation

**WHAT DO WE KNOW?**

<table>
<thead>
<tr>
<th>Morphology:</th>
<th>Mergers</th>
<th>Hot Halos</th>
<th>Secular</th>
</tr>
</thead>
<tbody>
<tr>
<td>BH/AGN:</td>
<td>classical bulges/spheroids</td>
<td>little effect</td>
<td>“pseudobulges”</td>
</tr>
<tr>
<td>Feedback:</td>
<td>*quasar &amp; remnant massive BH</td>
<td>*little BH growth</td>
<td>*Seyferts?</td>
</tr>
<tr>
<td></td>
<td>*kinematic</td>
<td>*fuel for low Mdot modes?</td>
<td>*small (&lt;10^7 M_sun) BHs</td>
</tr>
<tr>
<td></td>
<td>*quasar</td>
<td>*accretion shocks</td>
<td>*Seyfert?</td>
</tr>
<tr>
<td></td>
<td>*starburst</td>
<td>*gravitational</td>
<td>*stellar winds</td>
</tr>
<tr>
<td>Timescales:</td>
<td>short (&lt;Gyr)</td>
<td>~Hubble time</td>
<td>~Gyr?</td>
</tr>
</tbody>
</table>

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Comparing Quenching Models
HOW DO WE BREAK THE DEGENERACIES?

- $f_{\text{red}}$ vs. $M_{\text{halo}}$ and $M_{\text{gal}}$
  - smooth dependence on $M_{\text{halo}}$
  - no characteristic scale
  - high even in low $M_{\text{halo}}$ (for massive galaxies)
Comparing Quenching Models
HOW DO WE BREAK THE DEGENERACIES?

“Halo Quenching” Model:
- step function in $M_{\text{halo}}$: strong characteristic scale
- no residual $M_{\text{gal}}$ dependence
- no $f_{\text{red}}$ in low $M_{\text{halo}}
Comparing Quenching Models

HOW DO WE BREAK THE DEGENERACIES?

Secular Model:
- little dependence on M_halo (weak *inverse* dependence)
- low f_red even in massive halos when M_gal << M*

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Comparing Quenching Models

HOW DO WE BREAK THE DEGENERACIES?

- Merger Model:
  - appropriate mixed dependence on $M_{\text{halo}}$ and $M_{\text{gal}}$
  - no sharp scale in $M_{\text{halo}}$
Comparing Quenching Models

HOW DO WE BREAK THE DEGENERACIES?

- Passive (low SSFR) galaxies:
  - same trends
  - avoid dusty/metal-rich disk contamination
Comparing Quenching Models

HOW DO WE BREAK THE DEGENERACIES?
Comparing Quenching Models
HIGH-REDSHIFT PASSIVE GALAXIES

- High-z passive (low SSFR) galaxies:
  - $z \sim 2 - 4$
  - Very compact, $n \sim 4$: Spheroids/Merger remnants
  - High (low-lum) AGN fraction

Kriek et al., Labbe et al., Zirm et al.
Comparing Quenching Models
HIGH-REDSHIFT PASSIVE GALAXIES

Kriek et al., Daddi et al.,
Grazian et al., Van Dokkum et al.
Comparing Quenching Models

DICHOTOMY IN ELLIPTICAL KINEMATICS

Lauer et al., Bender et al., Pasquali et al.

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Comparing Quenching Models
DICHOTOMY IN ELLIPTICAL KINEMATICS

See also Naab et al., Kang et al., Kochfar & Silk
LF vs. Redshift
UV THROUGH IR

The graph illustrates the luminosity density as a function of redshift (z). Different scenarios are depicted, including:
- Mergers Dominate BH/Bulge Growth
- Empirical Secular (Disk Instabilities -> Pseudobulges)
- Maximal Secular (All Spheroids Initially Formed by Disk Instability)
- Extreme (Unphysical) Secular (All Spheroid Mass From Disk Instabilities: No Accretion/Minor Mergers/Gas-Rich Mergers)

The histograms on the bottom show the distribution of colors (u-r) for blue and red galaxies, with data from Strateva et al. 2001, and disk instabilities/bars from Barazza et al. 2006, as well as E+A/merger remnants from Goto 2005.
Comparing Quenching Models

SUMMARY

- **Strong arguments for association between mergers, quasars, & blue-red transition:**
  - clustering, number densities, merger fractions, morphologies, host colors/SFHs, LF evolution, kinematics, etc.

- But, how is quenching over a Hubble time accomplished by a single, potentially high redshift gas-rich major merger?
How Could Mergers Be Associated with “Maintenance”?

1. “Complete” quenching from a single event
   - energetics might be ok...
   - high redshifts: densities larger, cooling in filaments
   - can it really work for a Hubble time?

2. Buying time
   - expel cold gas at the end of the merger
   - heat remaining gas to much larger $t_{\text{cool}}$
   - only need ~couple Gyr to “naturally” develop a hot halo
   - still needs “radio mode” when that hot halo is formed
(3) Hot halos from merger feedback
- quasar/starburst heats gas to $t_{\text{cool}} \gg t_{\text{dyn}}$
- merger simulations end up with quasi-static, pressure supported gas equilibrium inside $R_{\text{vir}}$
- new gas will shock: don’t need to “pre-heat” everything
“Transition” vs. “Maintenance”

- Move mass from Blue to Red:
  - Exhaust *all* cold gas
- Rapid (<~ Gyr)
- Small scales (~pc - kpc)
- “Quasar” mode (high mdot):
  - Soltan: most BH mass
  - short-lived (~10^7-10^8 yr)
- Morphological Transformation:
  - Violent relaxation
  - Classical spheroid formation
- Gas-rich/Dissipational Mergers

- Keep it Red:
  - Prevent new cooling
- Long-lived (~Hubble time)
- Large (~R_vir) scales
- “Radio” mode (low mdot):
  - *small* mass gain
  - long-lived (~Hubble time)
- Subtle morphological change:
  - (regular vs. giant ellipticals)
  - “dry”/dissipationless mergers
- Halo Processes?

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Summary

- Models where merger history supplements quenching make robust, qualitatively distinct predictions
  - Detailed observations can break degeneracies
  - Compared to models where a simple halo mass threshold or secular mechanisms set quenching, only the merger model appears to match these observations:
    - Bivariate red fraction (vs. M_halo & M_gal)
    - High-z passive populations
    - Elliptical dichotomy
    - Evolution of color-morphology-density relations

- Mergers work *with* hot halos
  - Buy time for hot halos to develop
  - Directly shock low-mass systems to “hot halo” mode

- Caveats:
  - Satellites
  - Secular AGN fueling & pseudobulge formation are probably important: M_bulge < $10^{10}$ M_sun, M_bh <~ $10^{7}$ M_sun
COMBO-17: Color bi-modality to $z=1.1$

25,000 galaxies

17-color photo $z$'s

R-band selected to $R = 24$

Bell et al. 2004
COMBO-17: Disk galaxies
Mass–radius relation
No shift in zeropoint vs. time

Toy model prediction