The Evolution of Early-Type Galaxies across the Fundamental Plane

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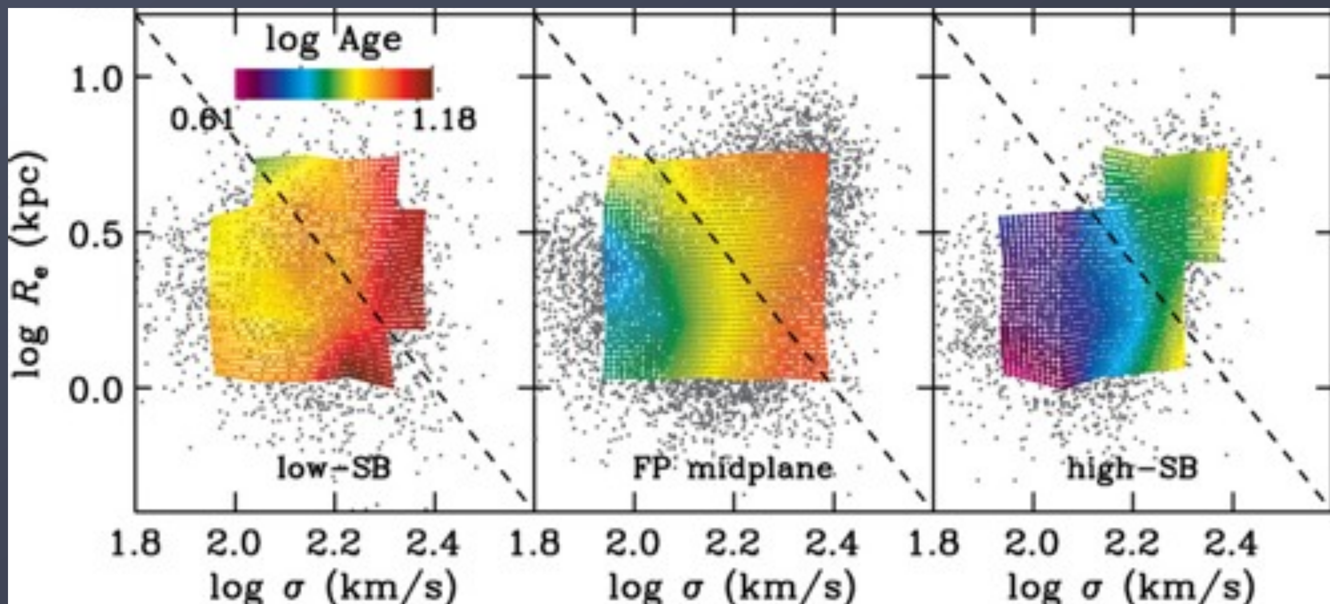
How do Elliptical Galaxies Evolve?

- In the major merger scenario, massive ellipticals form from wet mergers of spiral galaxies. Subsequent dry and minor mergers induce little star formation but significantly increase the radius, transforming compact ellipticals into the diffuse objects seen at low redshift (Naab et al. 2009, van Dokkum et al. 2010, Trujillo et al. 2011).

- Fundamental Plane: $R_e \propto \sigma^\alpha I_e^\beta$
  - Tilt from virial theorem arises from variations in mass-to-light ratio.
  - Age correlation: younger galaxies have higher surface brightnesses/ lower mass-to-light ratios (Forbes et al. 1998, Treu et al 2005).
    - Evidence of settling in major merger scenario?

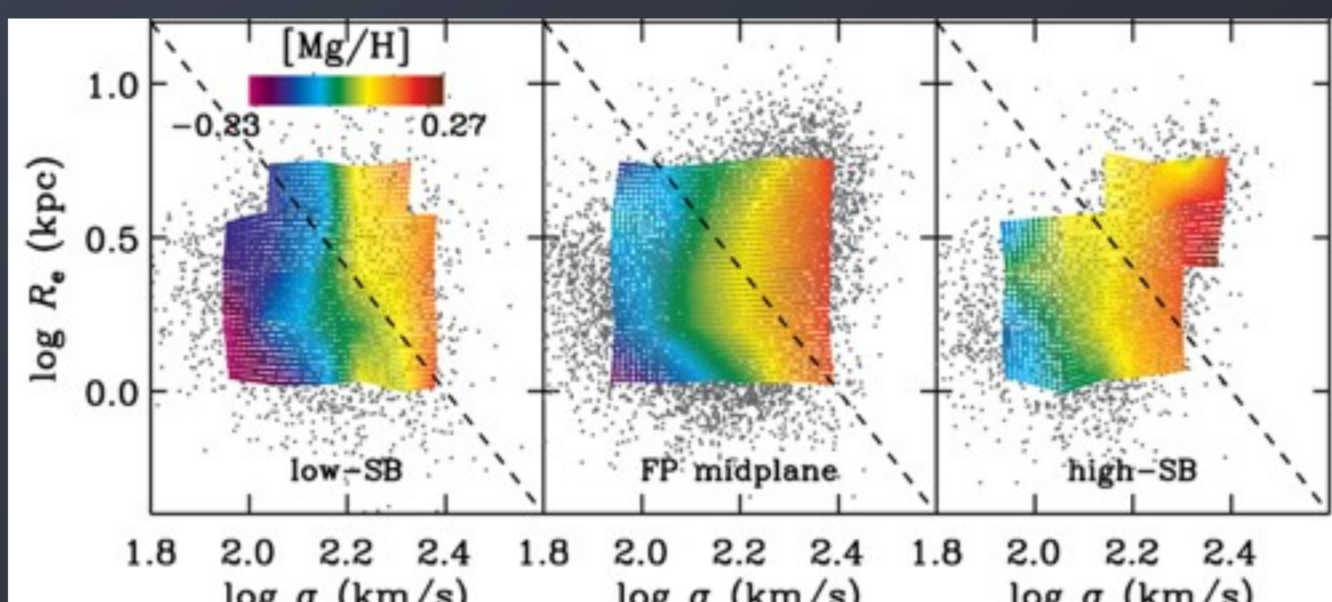
How do Elliptical Galaxies Evolve?



Graves et al. (2009)

SDSS

- Graves et al. (2009): Age and metallicity increase with velocity dispersion and are nearly independent of radius
- Galaxies that lie above the FP tend to be younger and more metal-rich



Graves et al. (2009)

6DFGS

- Magoulas et al. (2011 in prep.): find similar trends when galaxies are binned according to R_e, σ, and I_e

Questions to Consider

- How do the properties of progenitor disks affect the elliptical remnants of major mergers?

This Study

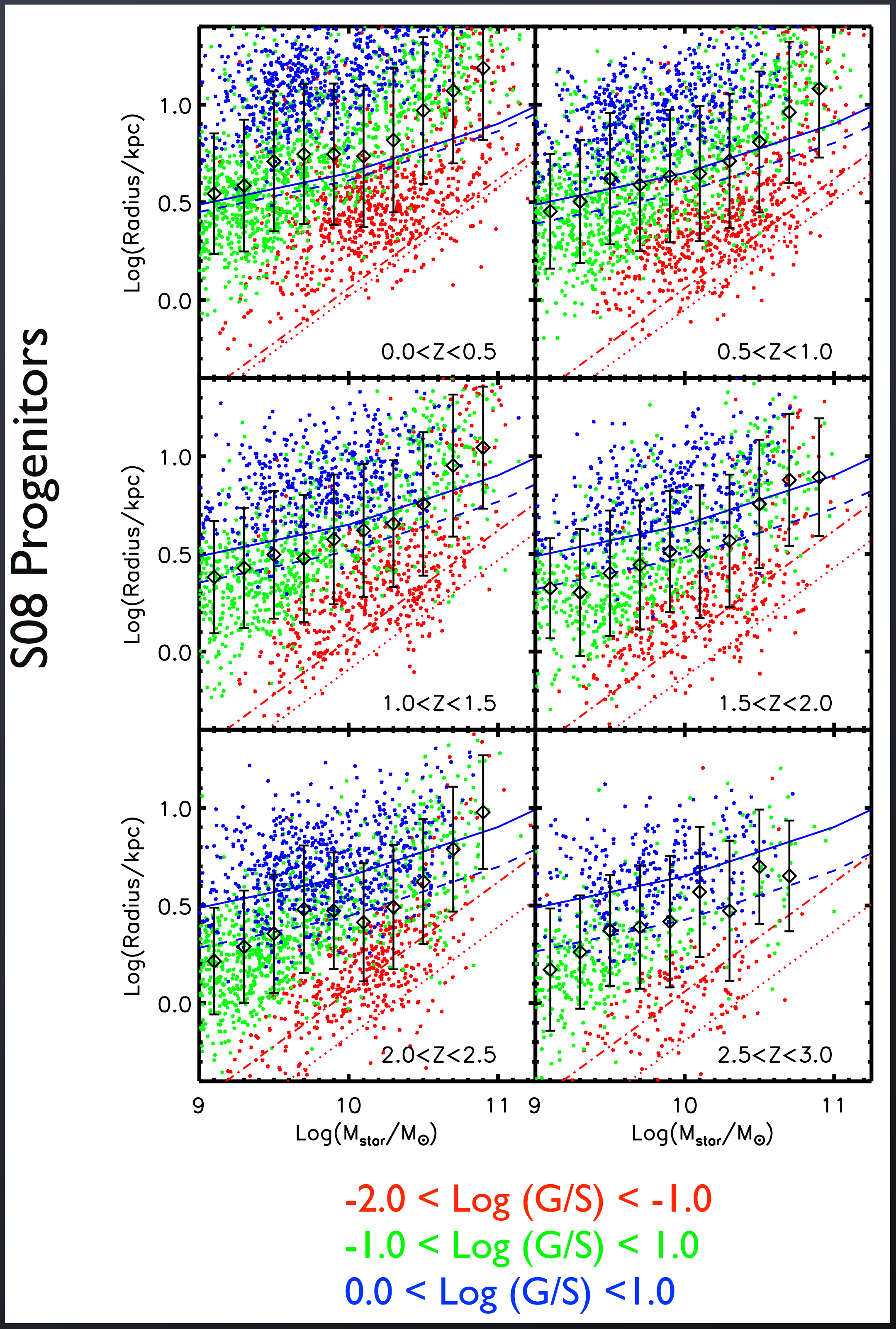
- Using simple physical principles, predict the Fundamental Plane properties for a statistical sample of elliptical galaxies in semi-analytic models (Croton et al. 2005, Somerville et al. 2008).
- Compare simulated Fundamental Plane with observations.
- How do stellar population parameters (age and metallicity) scale with Fundamental Plane residuals? What does this tell us about the star formation history of ellipticals?

Overview of the Model

- Covington et al. (2008, 2011) have formed an analytic model for predicting the sizes and velocity dispersions of elliptical galaxies following a major merger of two progenitor disk galaxies.
- Improves on the Cole et al. (2000) model by including dissipative losses due to star formation.
- Scaling parameters calibrated to results of N-body simulations (e.g. Cox et al. 2008).
- Using Bruzual and Charlot (2003) and semi-analytic models, we determine the (light-weighted) age, metallicity, and luminosity of ellipticals at redshift zero. Combined with the model of Covington et al., this allows us to track correlations across and through the Fundamental Plane.

The Role of Gas in Major Mergers

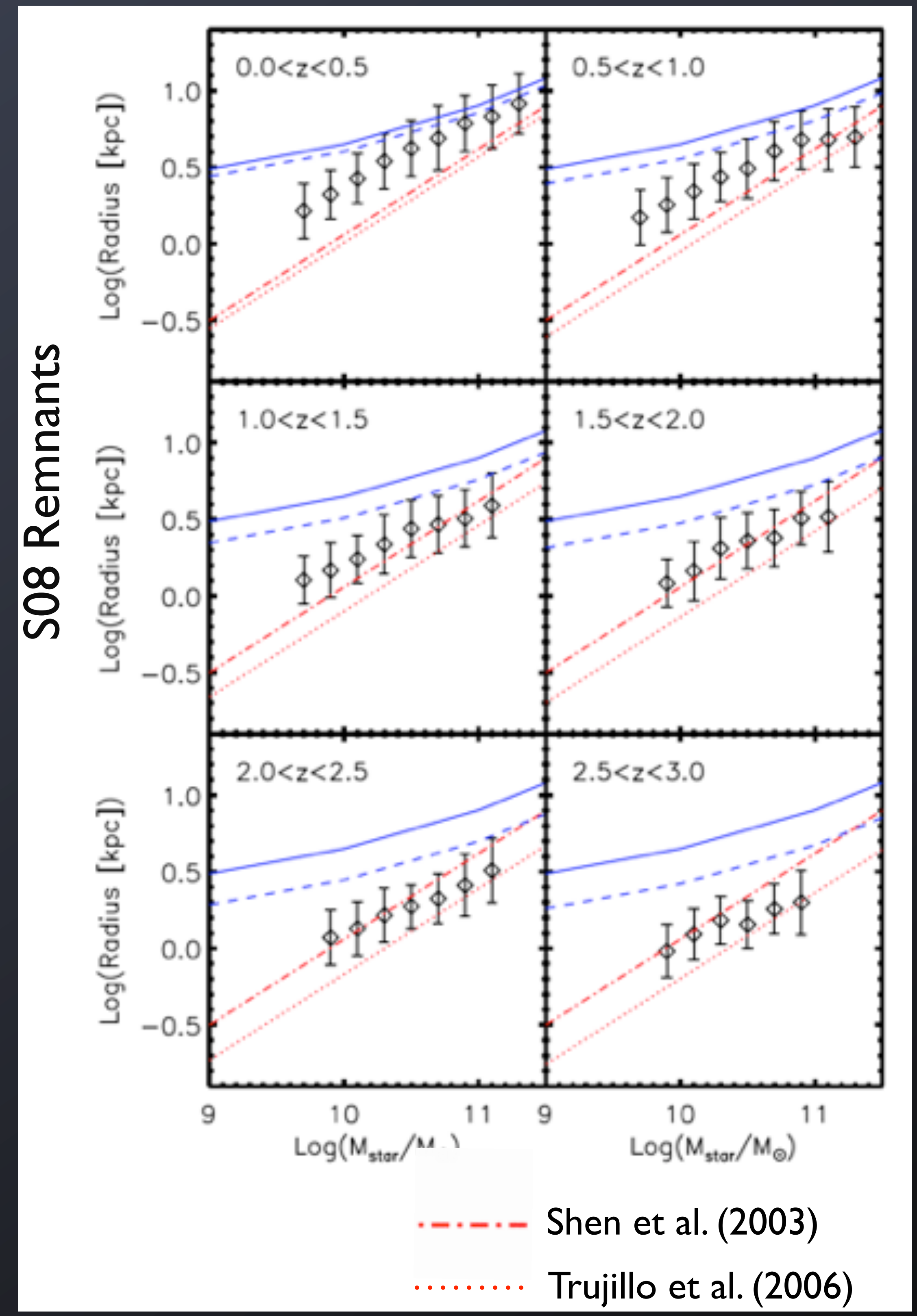
- Dissipationless merger: radius of the remnant increases roughly in quadrature with progenitor radii (Cole et al. 2000)
- Spiral progenitors with higher gas fractions undergo more dissipation, and are more compact than their gas-poor counterparts (and possibly their progenitors)
- Disk galaxies at lower mass are more gas-rich (Kannappan 2004, Saintonge et al. 2011)
- *At a given mass*, larger disk galaxies have lower surface densities, and correspondingly higher gas fractions



Covington et al. (2011)

The Remnants

- Compared to the spiral progenitors, elliptical remnants are:
  - More compact
  - Steeper size-mass relation
  - Decreased dispersion

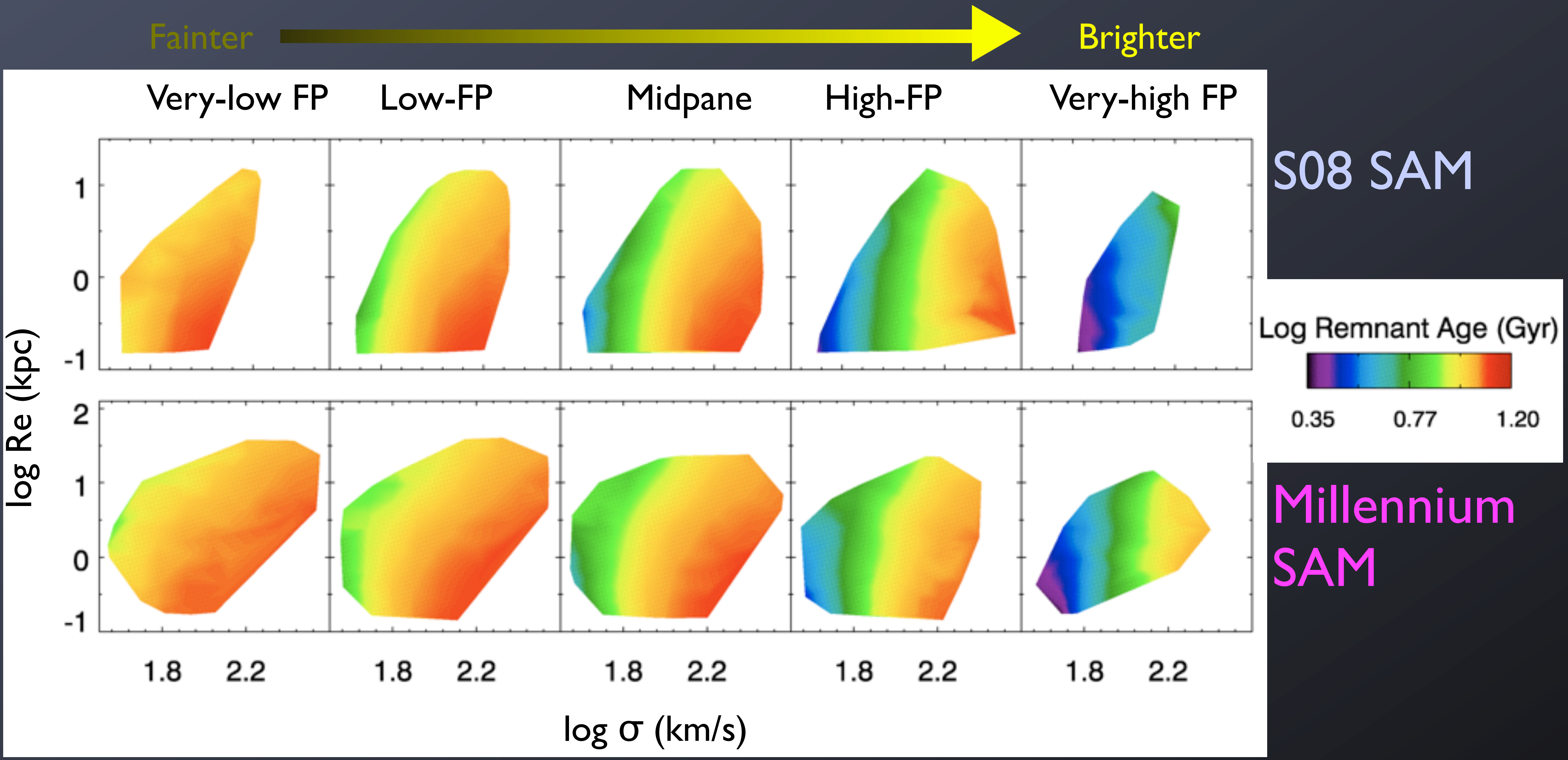


Covington et al. (2011)

Binning Galaxies in the FP

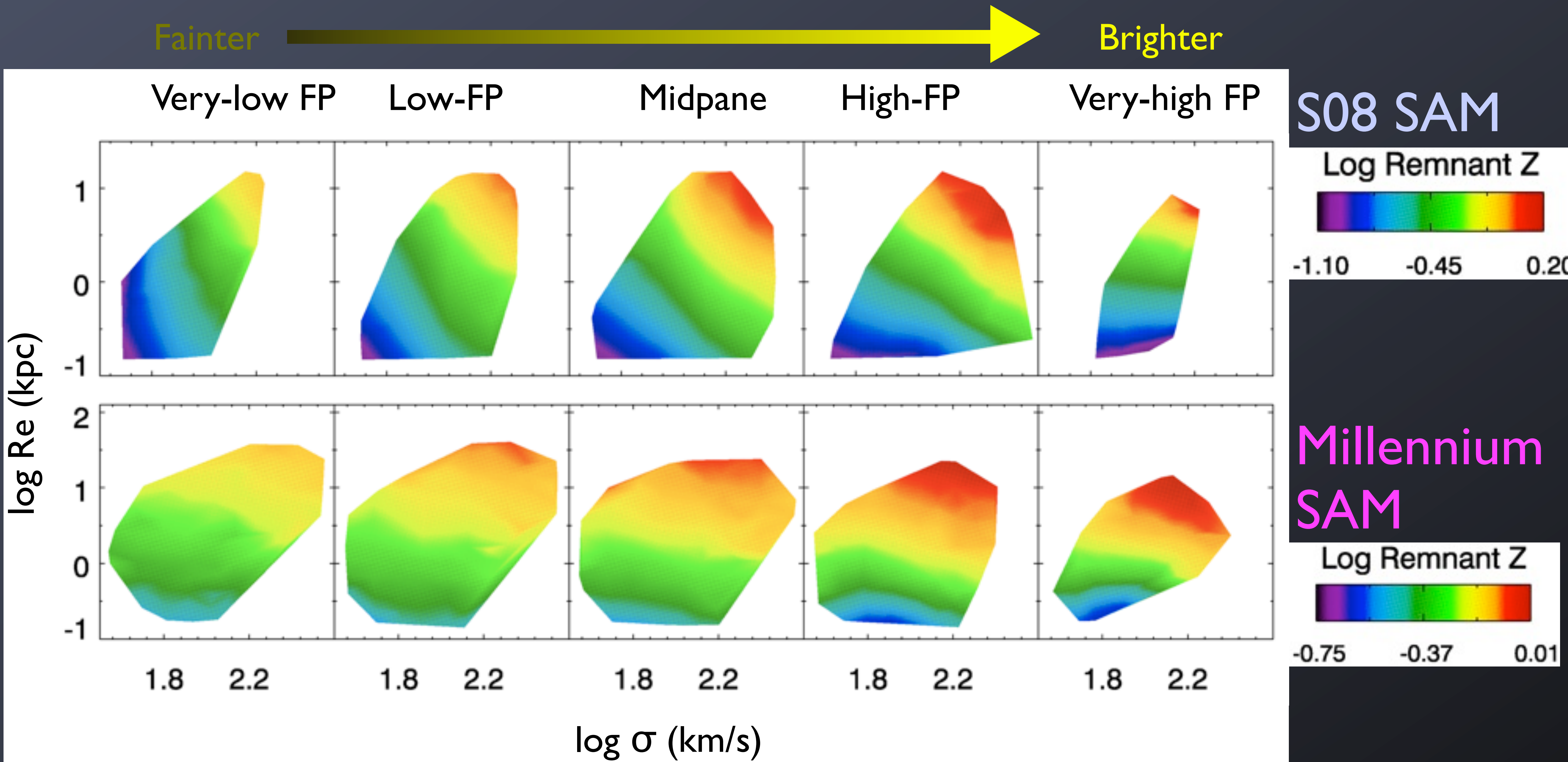
- Calculate effective radius (R_e), velocity dispersion (σ), and surface brightness (I_e) for all elliptical galaxies following a major merger.
- Form a FP by finding a linear fit relating surface brightness to velocity dispersion and radius.
- Separate galaxies into 5 slices based on their locations above or below the FP, where surface brightness is the independent variable. Galaxies above (below) the FP have surface brightnesses that are higher (lower) than their radii and velocity dispersions would predict.
- Select all the galaxies within one FP slice.
- Bin the galaxies according to their radii and velocity dispersions. Calculate the median of a property (age, metallicity, gas fraction...) within each bin.

Trends Through the Fundamental Plane: Age



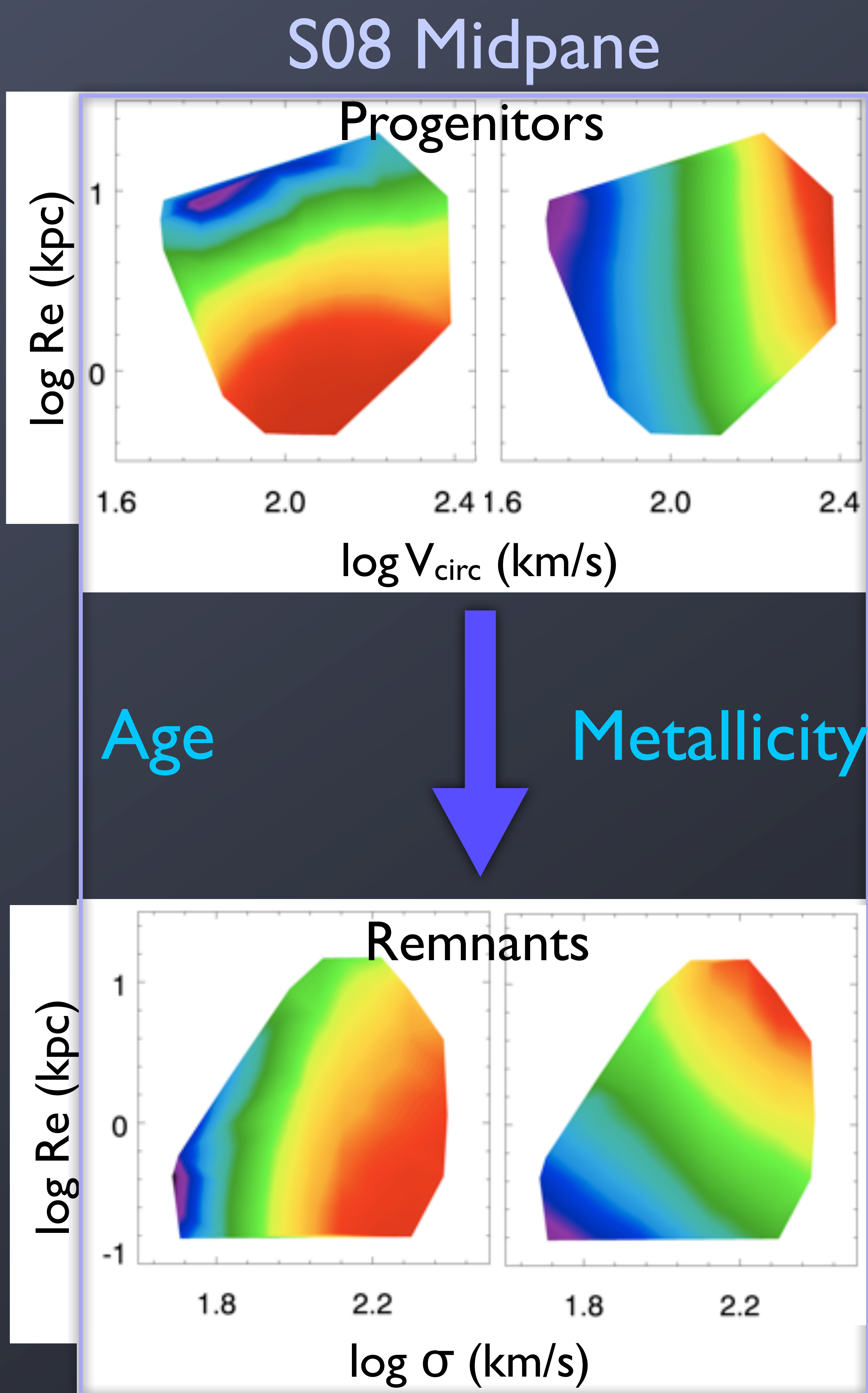
- For both SAMs, age decreases strongly with velocity dispersion and is nearly independent of radius
- Galaxies that lie above the FP tend to be younger

Trends Through the Fundamental Plane: Metallicity



- S08: metallicity increases with radius and velocity dispersion
- Millennium: weaker trend with velocity dispersion
- Galaxies that lie above the FP have slightly higher metallicities

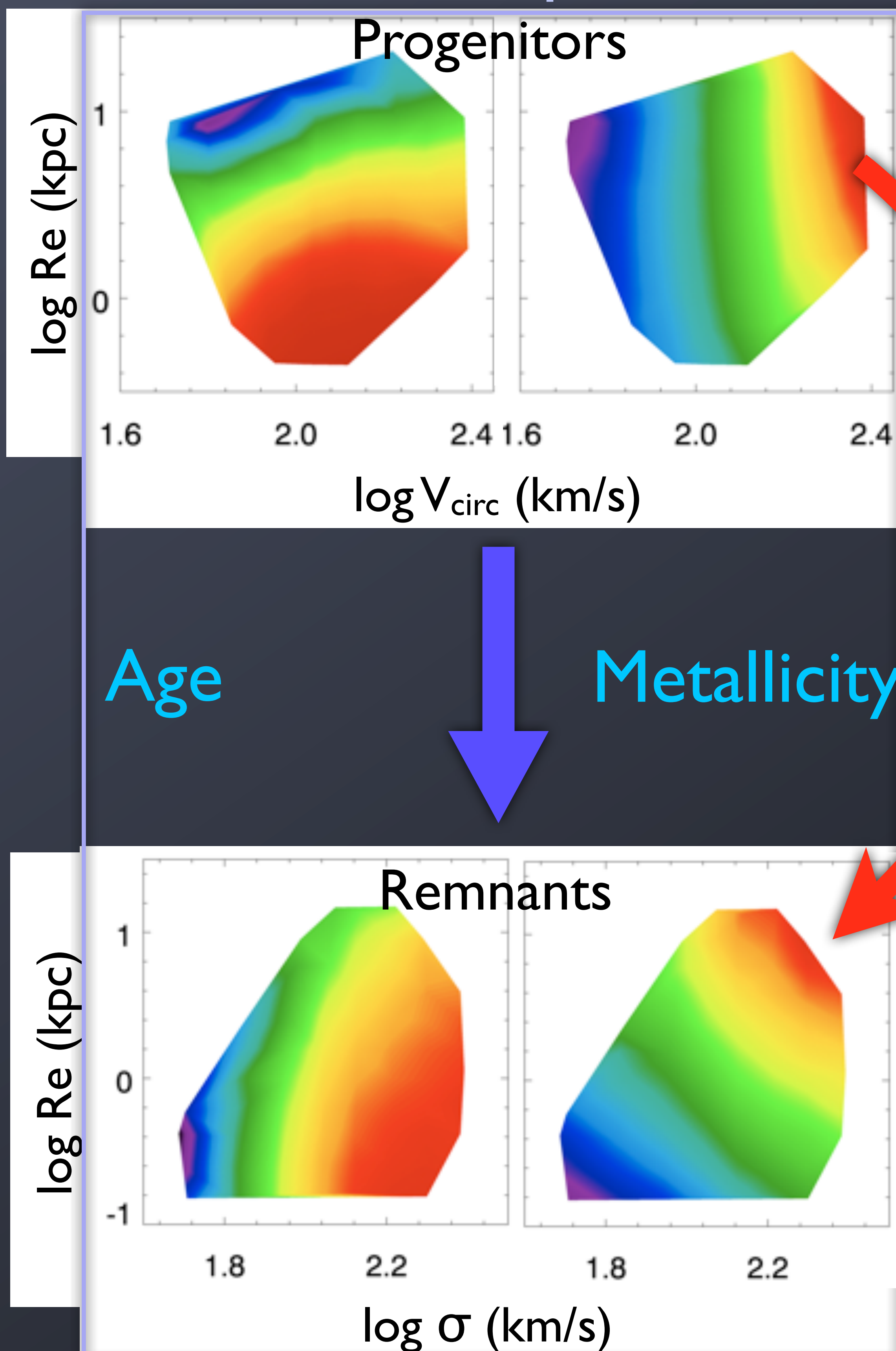
Comparison to Spiral Progenitors



- Close correspondence between ages and metallicities of progenitors and remnants
- Remnants are rotated ~90° from their corresponding progenitors
- Rotation is present across all FP panes

Comparison to Spiral Progenitors

S08 Midpane



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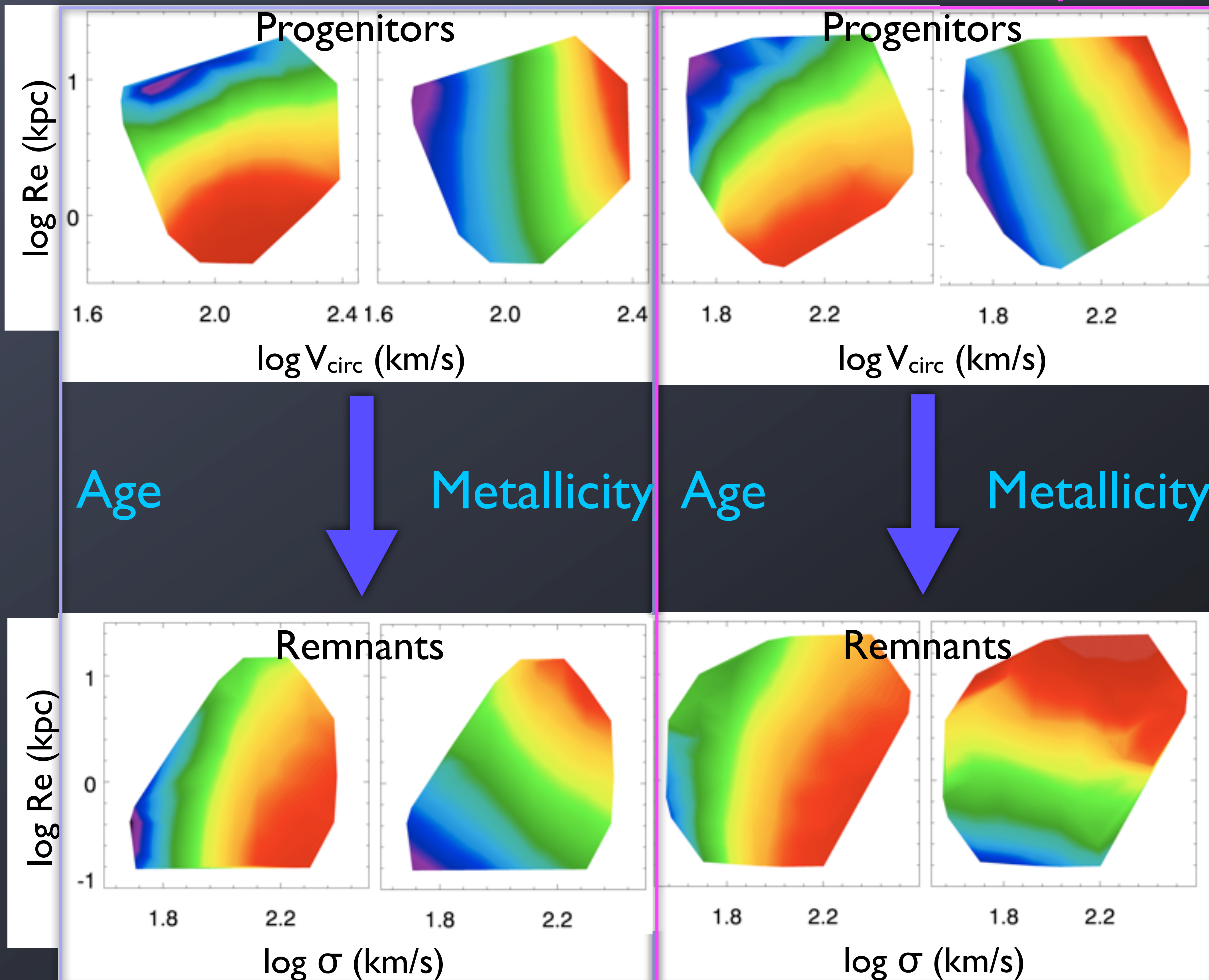
Rotation

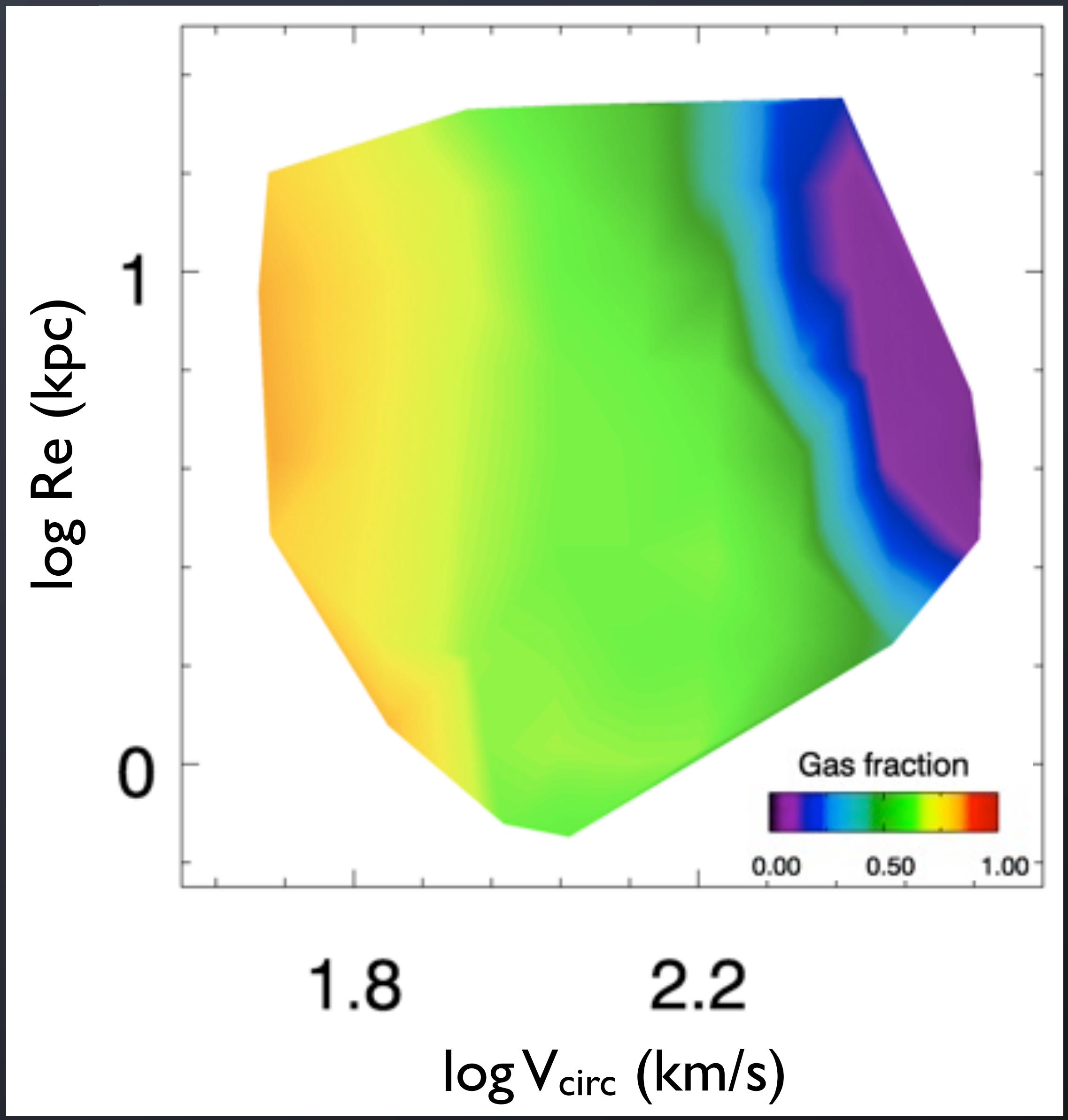
Comparison to Spiral Progenitors

S08 Midpane | Millennium Midpane



The Role of Gas in Major Mergers

Millennium Progenitors



The Role of Gas in Major Mergers

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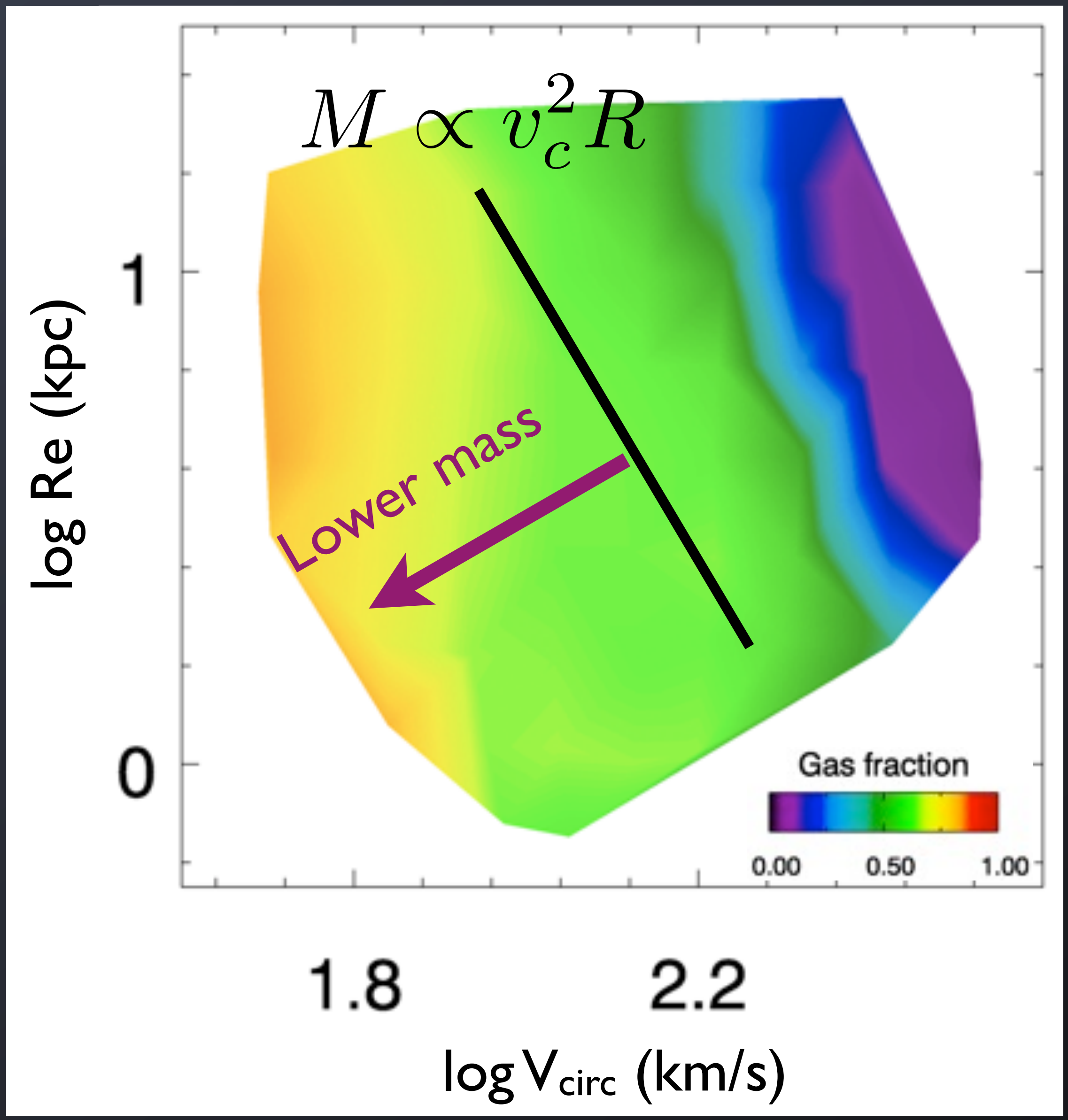

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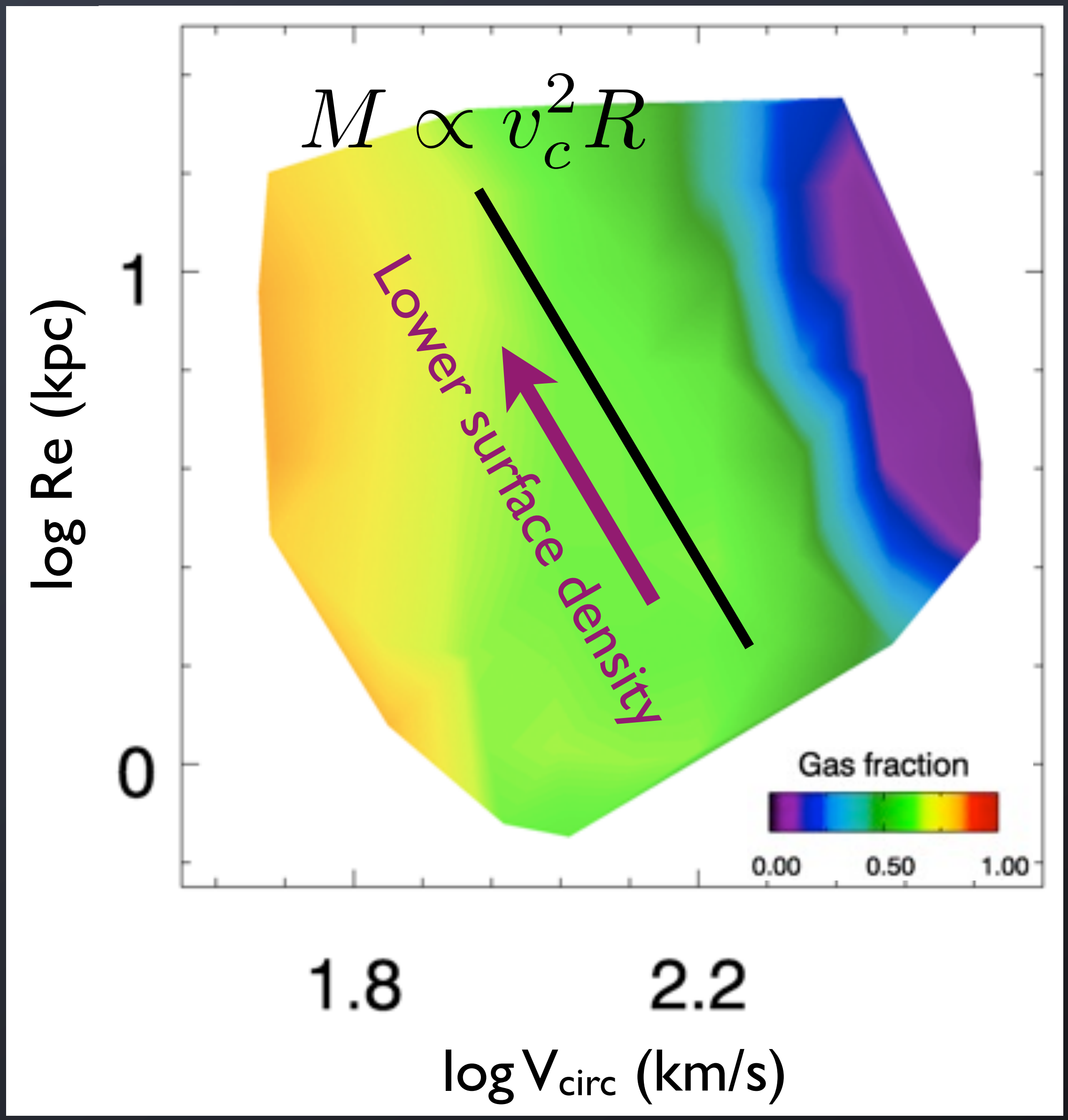
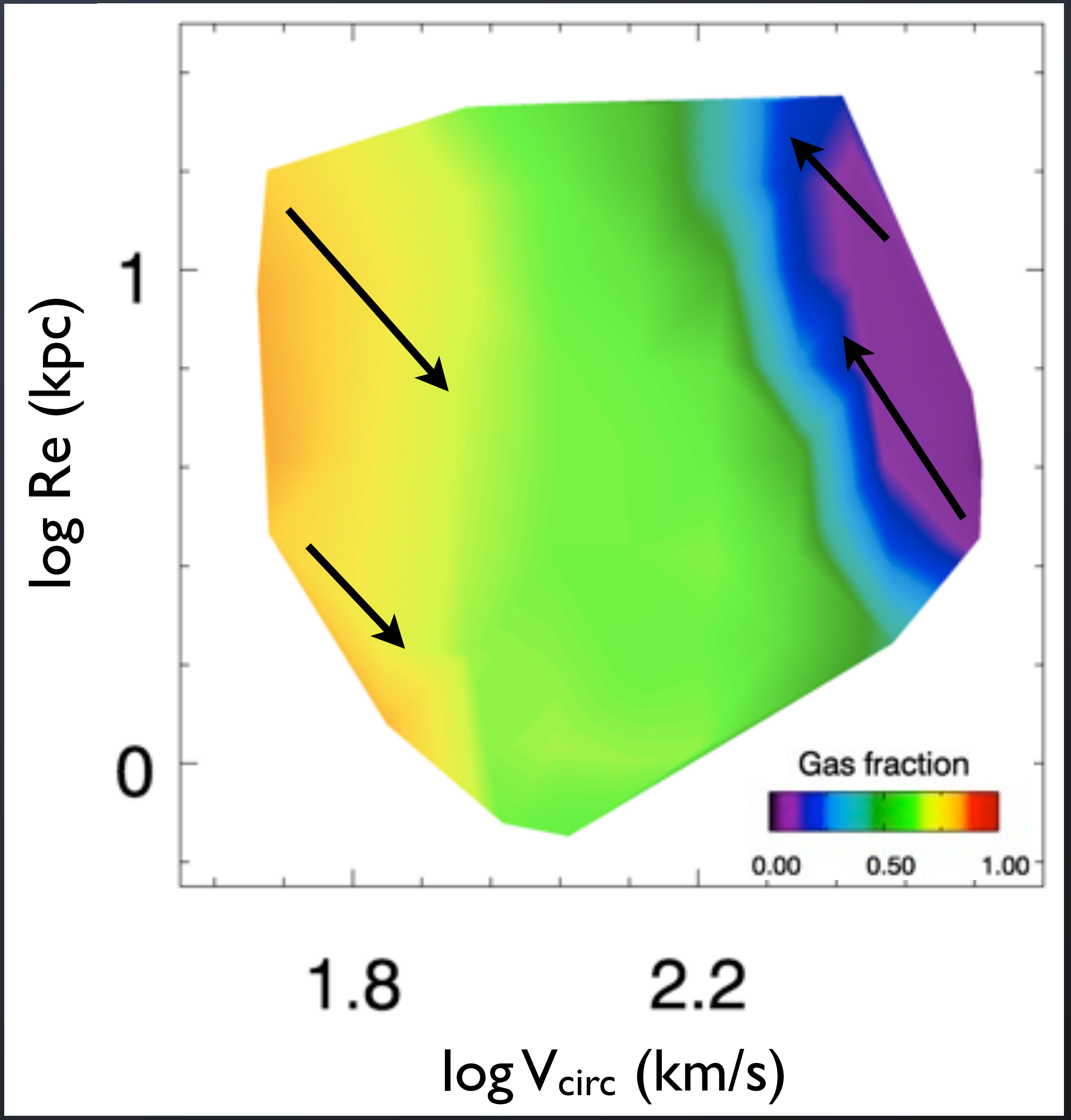


The Role of Gas in Major Mergers

- Disk galaxies at lower mass are more gas-rich (Kannappan 2004, Saintonge et al. 2011)
- *At a given mass*, larger disk galaxies have lower surface densities, and correspondingly higher gas fractions
- Progenitors with higher gas fractions undergo more dissipation, and are more compact than their gas-poor counterparts
- From the model: $\sigma^2 = \dfrac{G C_{sig} M_f}{R_f(1 - f_{dm,f})}$

Millennium Progenitors



- Progenitors with higher (lower) gas fractions produce remnants with smaller (larger) radii and larger (smaller) σ. This creates the rotation between the progenitors and remnants.

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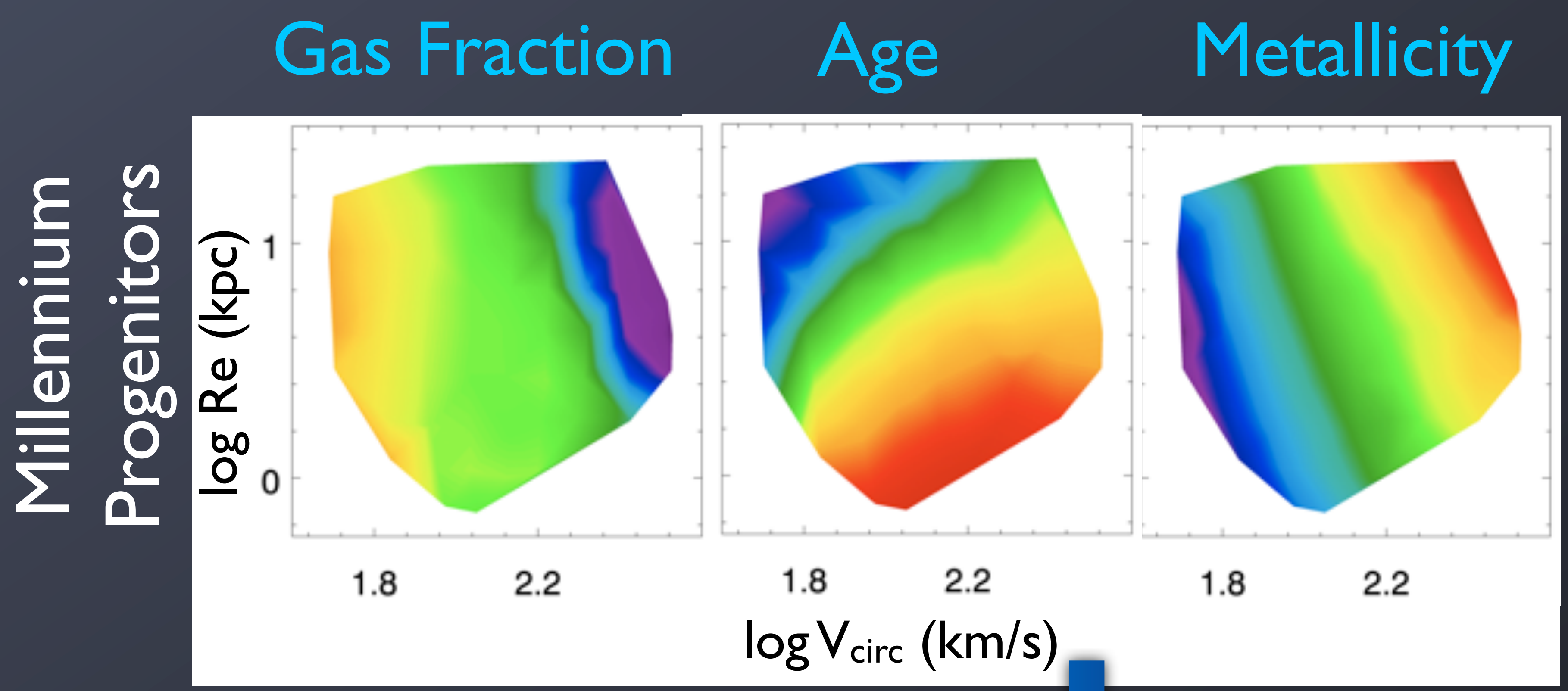

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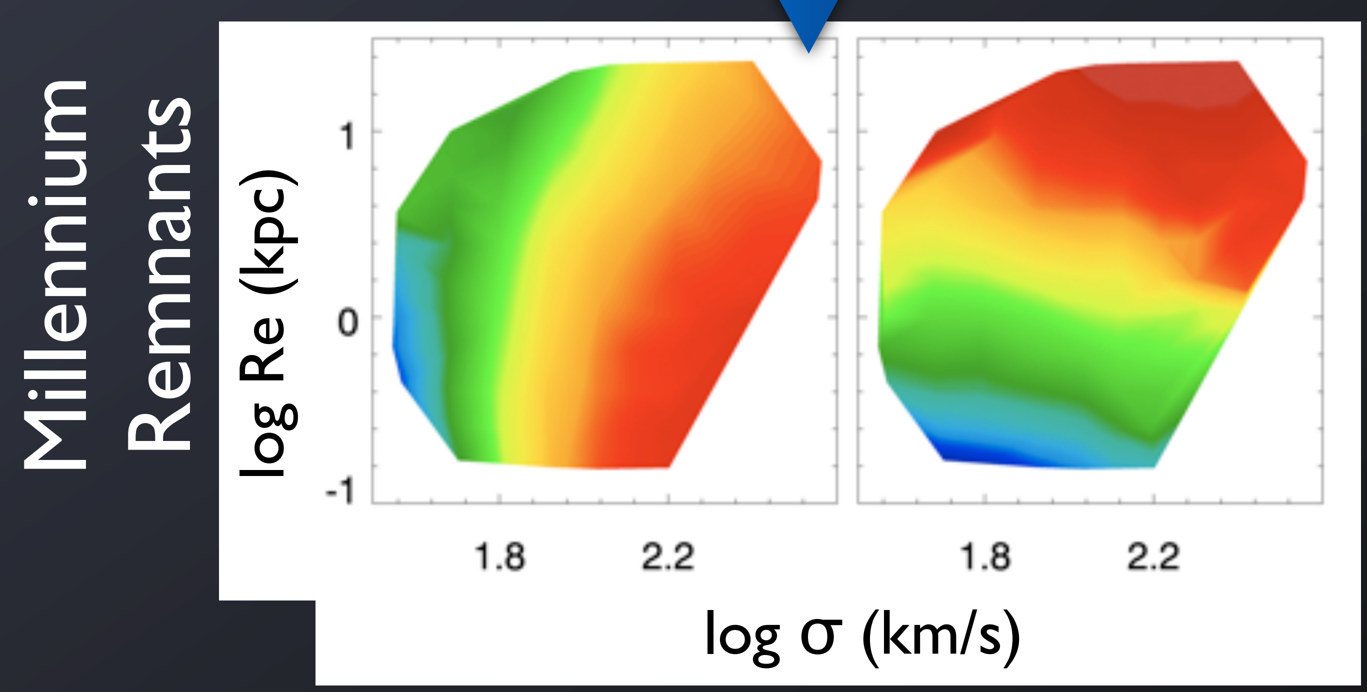
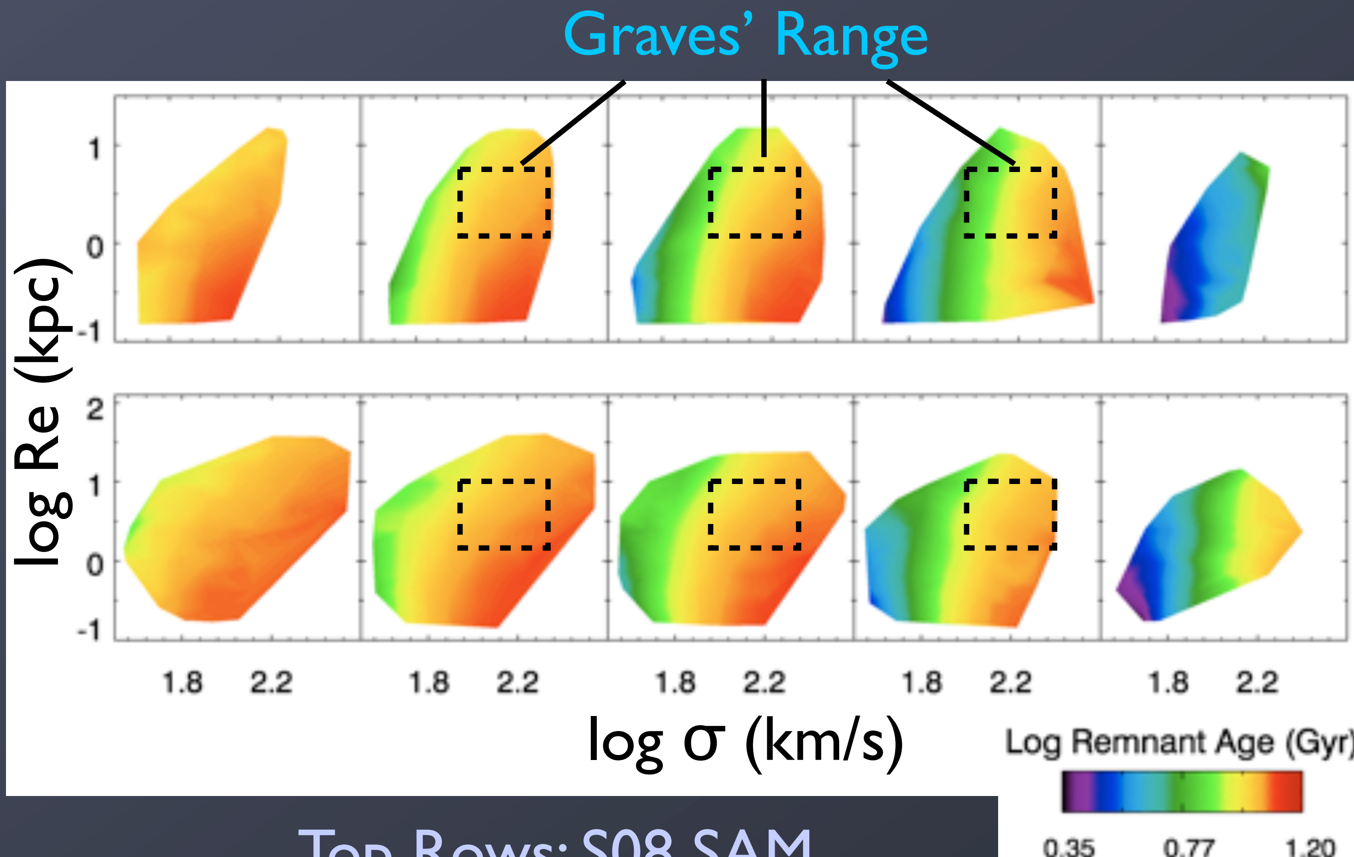
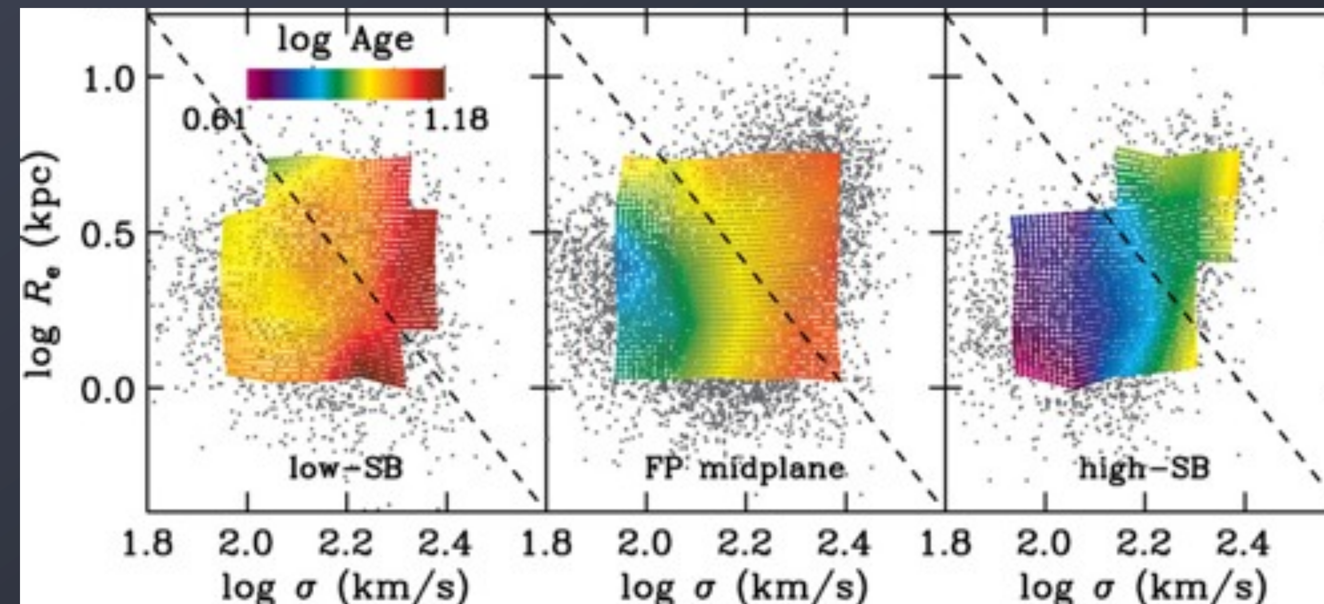


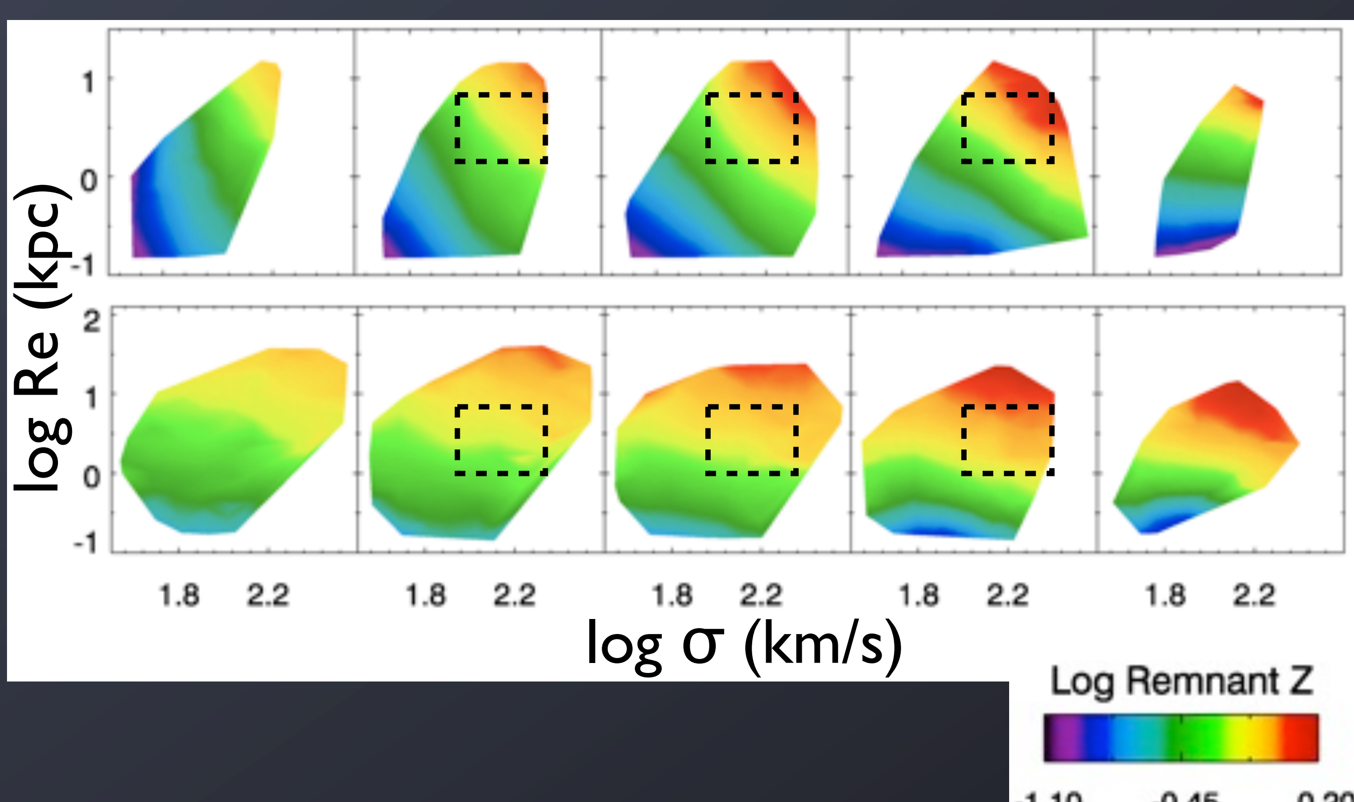
Comparison with Observations

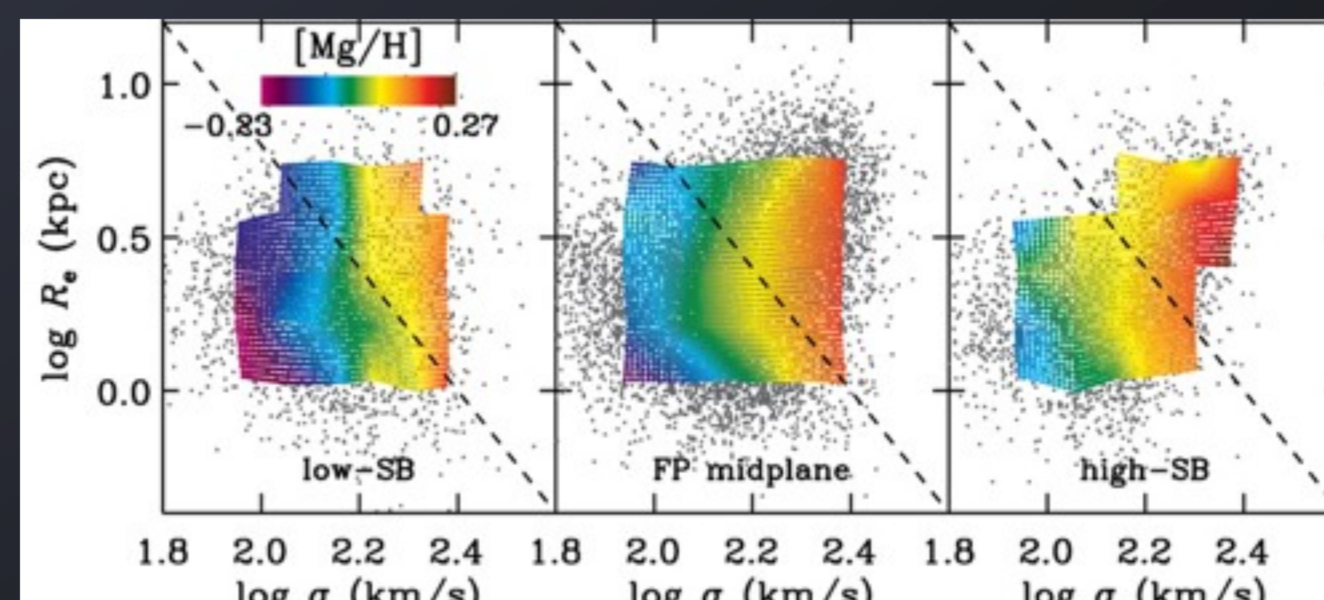




Graves et al. (2009)

Top Rows: S08 SAM
Bottom Rows: Millennium SAM





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Comparison with Observations/ Subsequent Evolution

- Both SAMs produce age-FP trends that are similar to observations.
- The trends through the FP are also similar to observations: galaxies with higher residual surface brightnesses are younger and more metal-rich.
- Both SAMs produce metallicity-FP correlations that have a higher dependence on radius than found in observations.

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- The trends through the FP are also similar to observations: galaxies with higher residual surface brightnesses are younger and more metal-rich.
- Both SAMs produce metallicity-FP correlations that have a higher dependence on radius than found in observations.
- Naab et al. (2009), Oser et al. (2011): minor mergers can significantly increase the radii of ellipticals while leaving the velocity dispersion relatively unchanged.
- Caveat: since our age-FP and metallicity-FP trends differ by ~90°, pure rotations cannot match both sets of observations. Both SAMs fail to reproduce observed trends in age-M_{star}, while they do match observations of Z-M_{star} (Somerville et al. 2008).

Conclusions

- Major mergers rotate the age-FP and metallicity-FP relations from those of the progenitors
    - For elliptical remnants, age is strongly correlated with σ, while metallicity is more strongly correlated with radius
    - Galaxies that lie above the FP tend to be younger and metal-enhanced
- For a full treatment of stellar population parameters, our model must be directly interfaced with SAMs
    - Consider minor mergers and alternative pathways to elliptical galaxy formation
    - Track metallicity of individual elements, including Type Ia supernova (Arrigoni et al. 2009)
    - Direct comparison with Graves et al. (2009b) using Lick indices