Galaxy formation in the Illustris Simulations

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ITC/Harvard

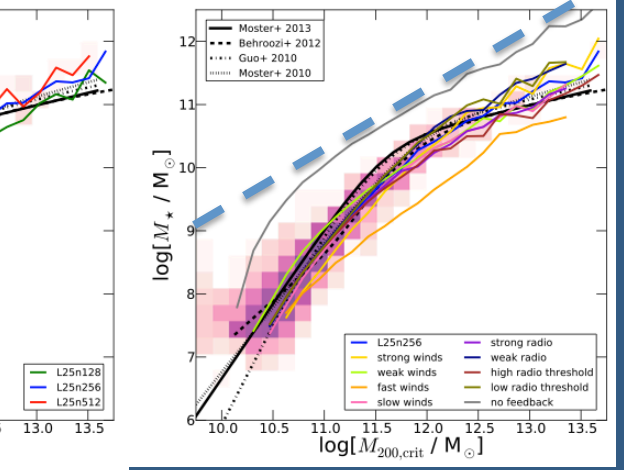
Hernquist, Sijacki, Snyder, Springel, Torrey, Vogelsberger

The overcooling problem (z=0)

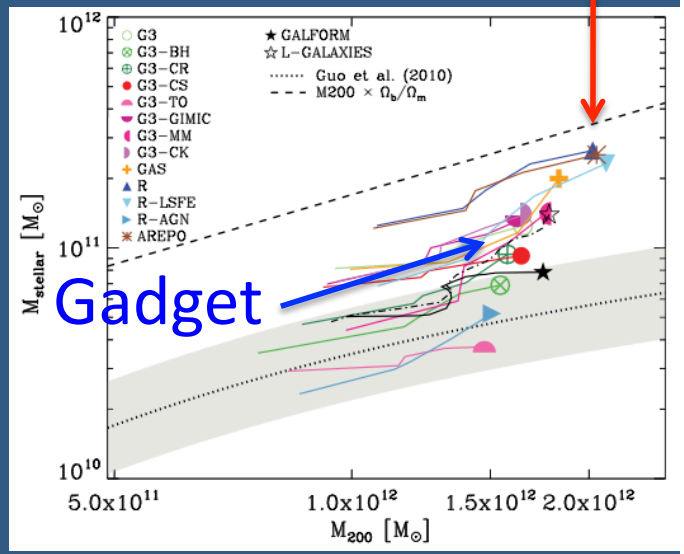
"Baryon conversion efficiency" without effective feedback:

- Close to 100% of the cosmic baryon fraction is in stars at $M_{halo} \gtrsim 10^{12} M_{sun}$
- 'Numerical quenching' with (standard) SPH

Arepo & RAMSES



Vogelsberger+ 2013



Scannapieco+ 2012

The computational challenge

- To "resolve" galaxies/ISM -> at least ~1kpc
- To probe dense environments and get statistical samples -> at least ~$(100\mathrm{Mpc})^3$

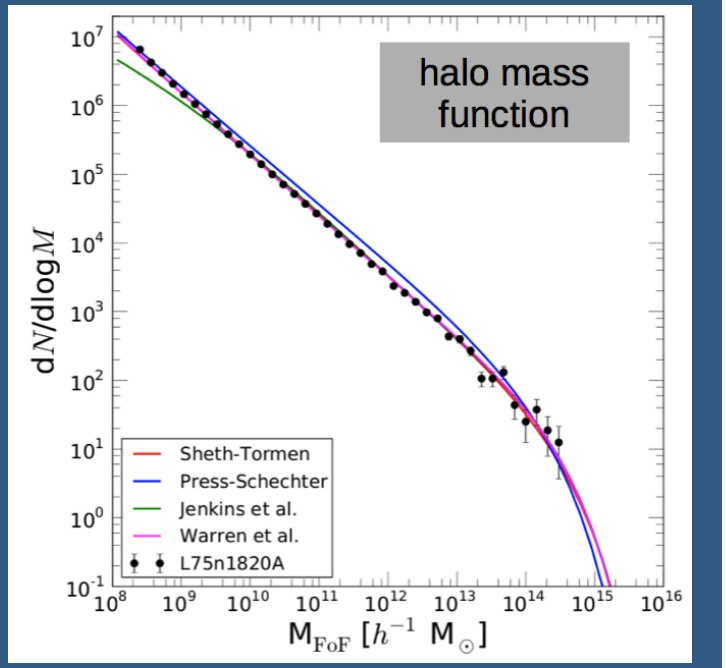
However, usually it is only feasible to use up to ~2×512^3 resolution elements (to z=0) ==>

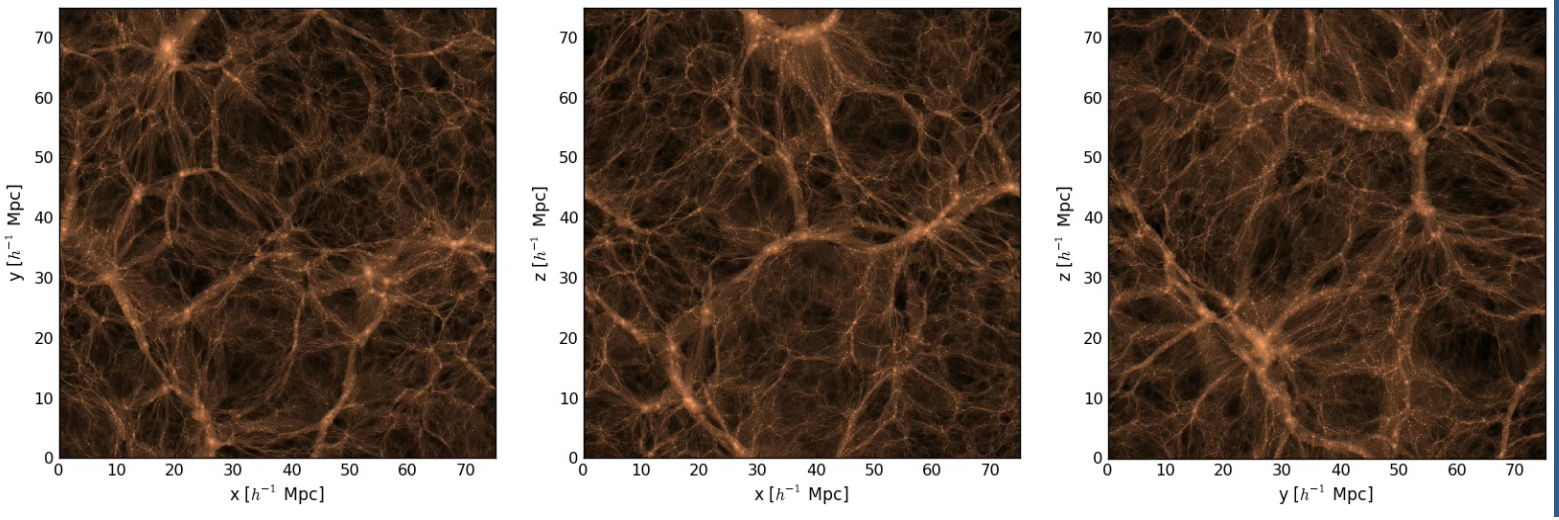
In a $(100\mathrm{Mpc})^3$ box:

- 10^{10} halos with only ~20 resolution elements
- Worse than ~1kpc spatial resolution

The Illustris Simulations

- (75Mpc/h)^3
- N-body+hydro with Arepo (Springel 2010)
- WMAP-7 cosmology
- ~10 M>$10^{14}M_{sun}$ halos @ z=0
- >10^3 M~$10^{12}M_{sun}$ halos @ z=0





Genel+ in prep.
Sijacki+ in prep.
Vogelsberger+ in prep.

Illustris simulations: resolution, flavors & status

	"Resolved halos" mass [M_{sun}/h]	Baryonic resolution element mass [M_{sun}/h]	Gravitational softening [ckpc/h]	DM-only	Non-radiative	Full Physics
1820^3	1.7×10^8	9×10^5	1.0->0.5	DONE	Pending	z~0.3 ETA: September
910^3	1.4×10^9	7×10^6	2.0->1.0	DONE	DONE	DONE
455^3	1.1×10^{10}	6×10^7	4.0->2.0	DONE	DONE	DONE

Overall: ~40Mcpu-hours, ~400TB

Illustris galaxy formation physics

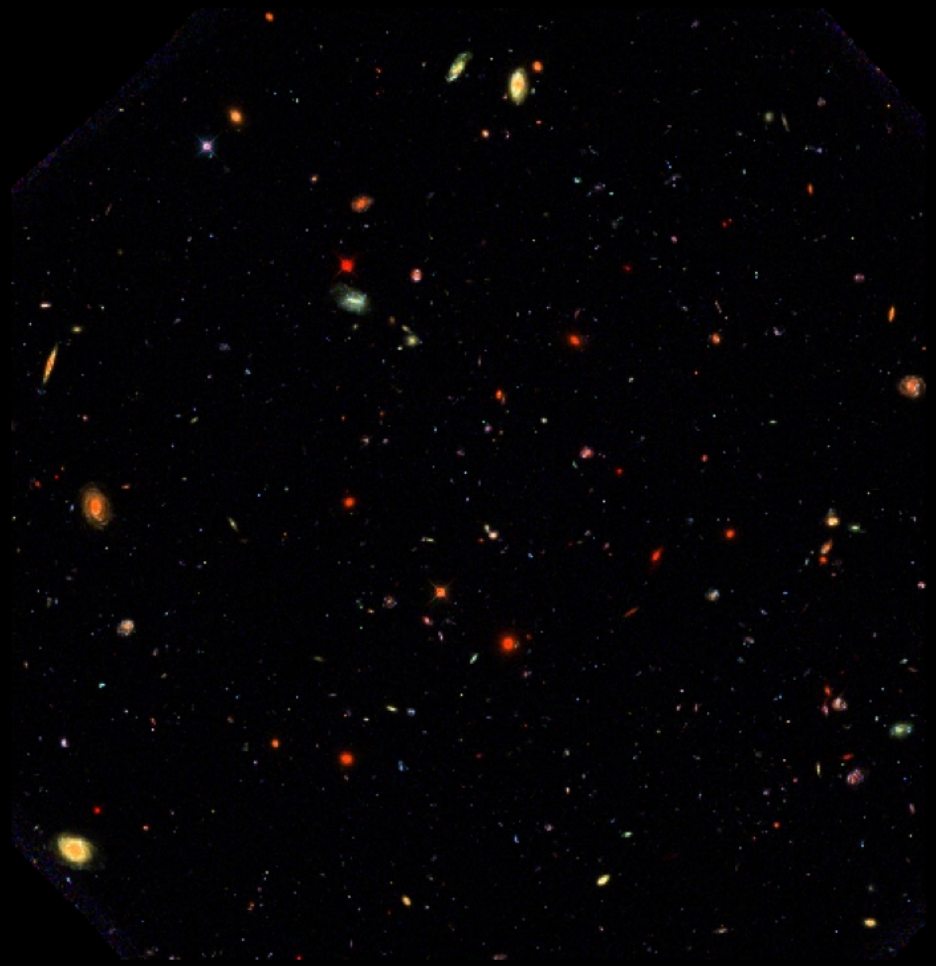
- Star formation and evolution: mass loss, SN rates
- Chemical enrichment following 9 elements
- Primordial + metal line cooling
- UV/X-ray cosmic background +

  self-shielding + AGN proximity effects
- Galactic winds (hydro-decoupled, energy-driven)
- BH growth +

  quasar & radio-mode feedback

Vogelsberger, Genel+ 2013

Mock HST Deep Fields



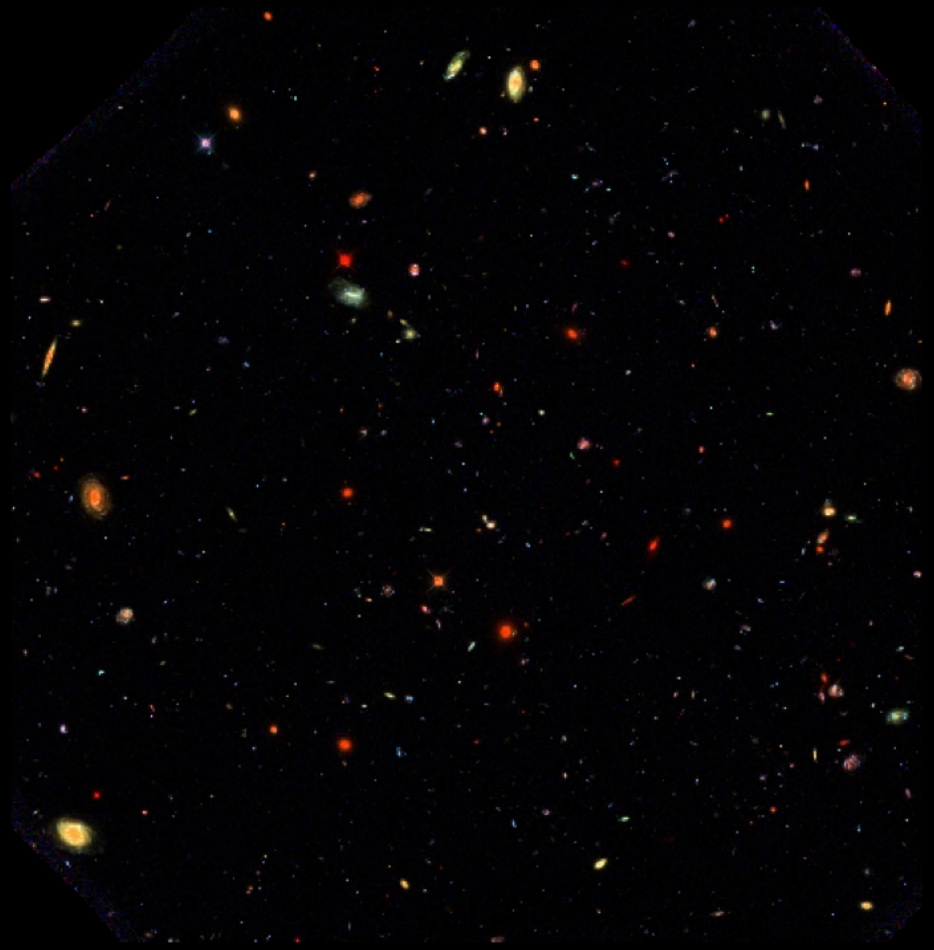
old simulations

HST observation

→ *too many stars*

Snyder, MV+ (in prep)

Mock HST Deep Fields



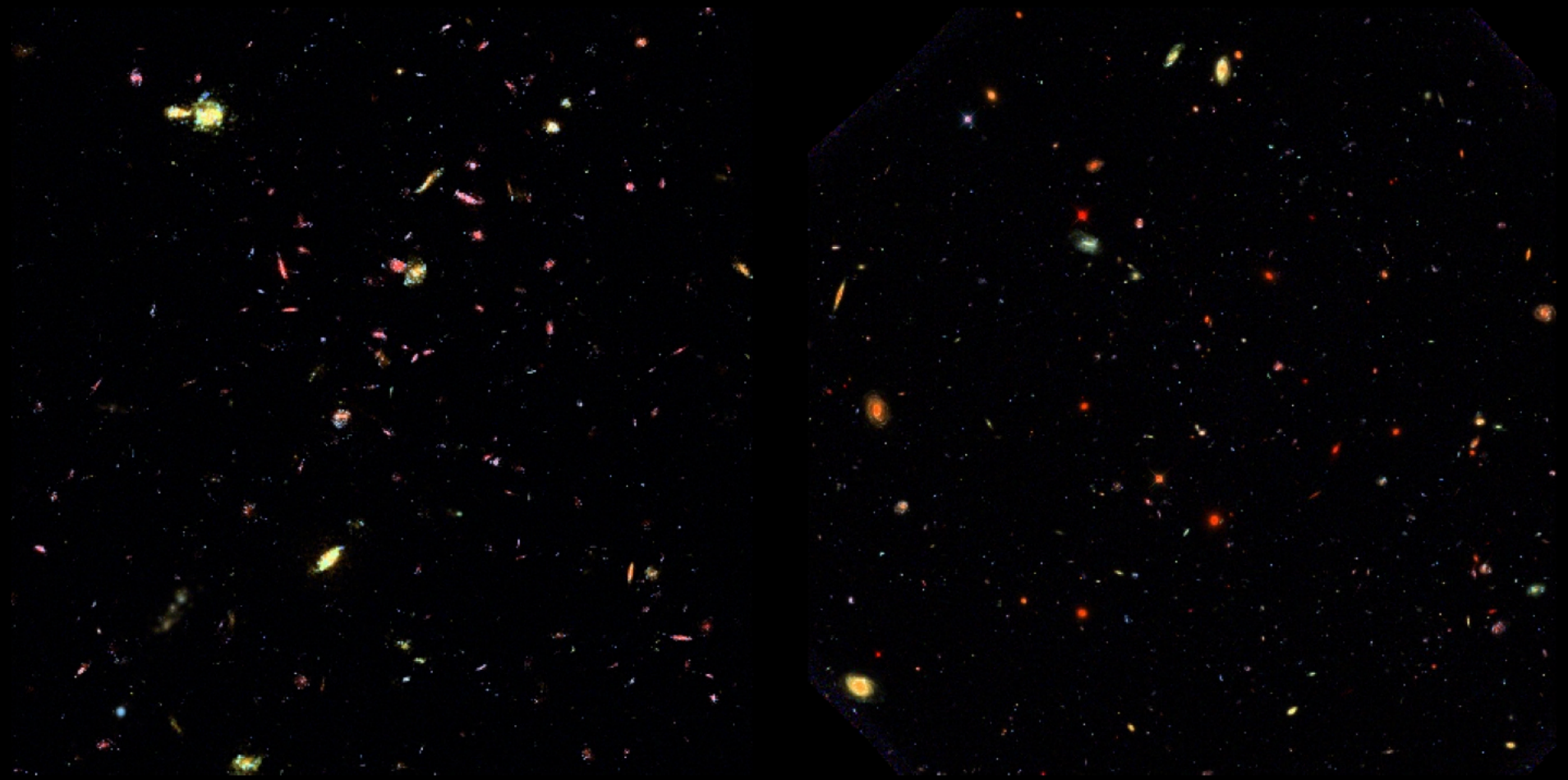
+ metal line cooling
+ stellar mass loss

→ *even more (young) stars*

HST observation

Snyder, MV+ (in prep)

Mock HST Deep Fields



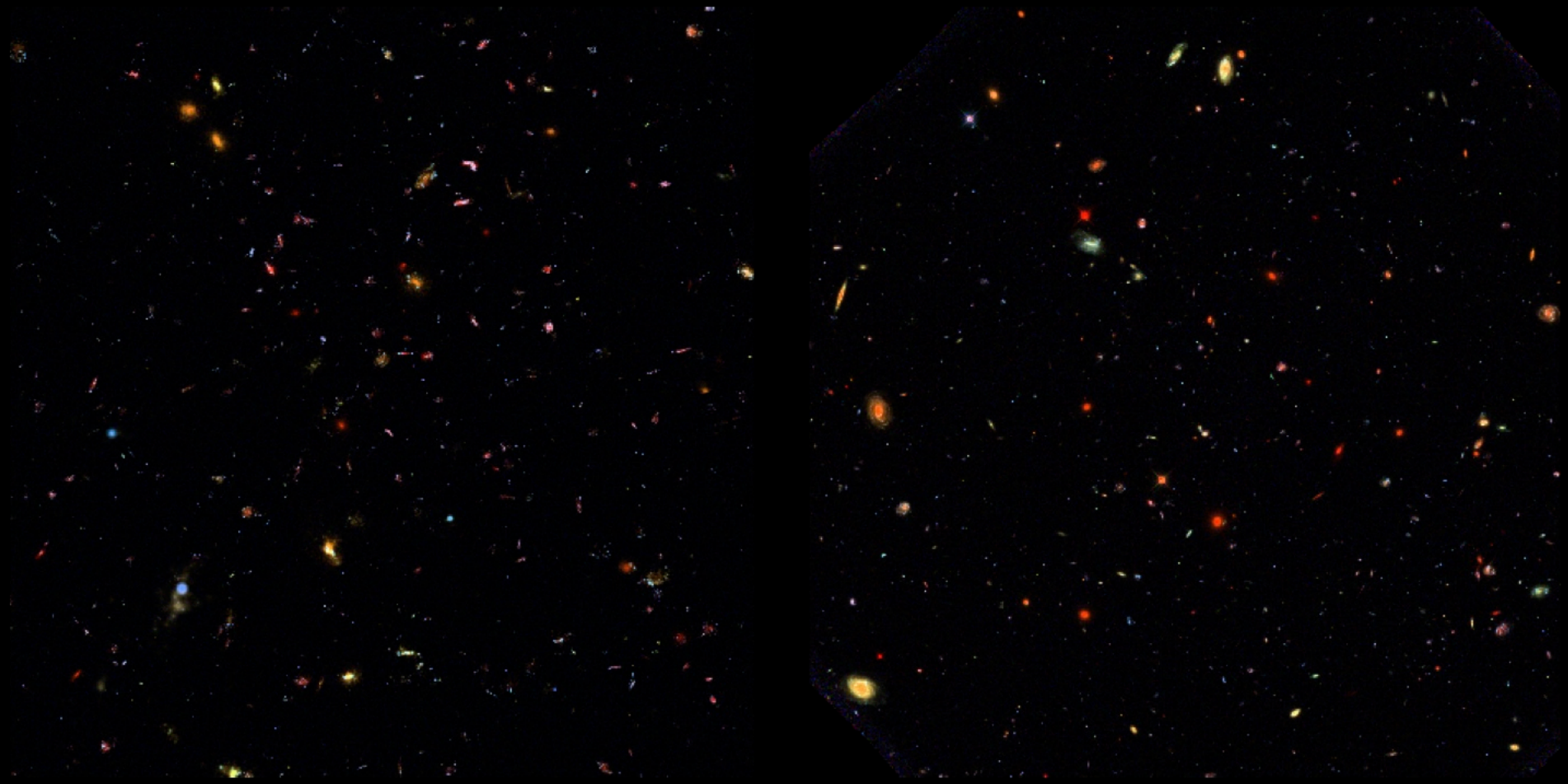
+ SNII feedback

HST observation

→ *too many blue galaxies*

Snyder, MV+ (in prep)

Mock HST Deep Fields



+ AGN feedback

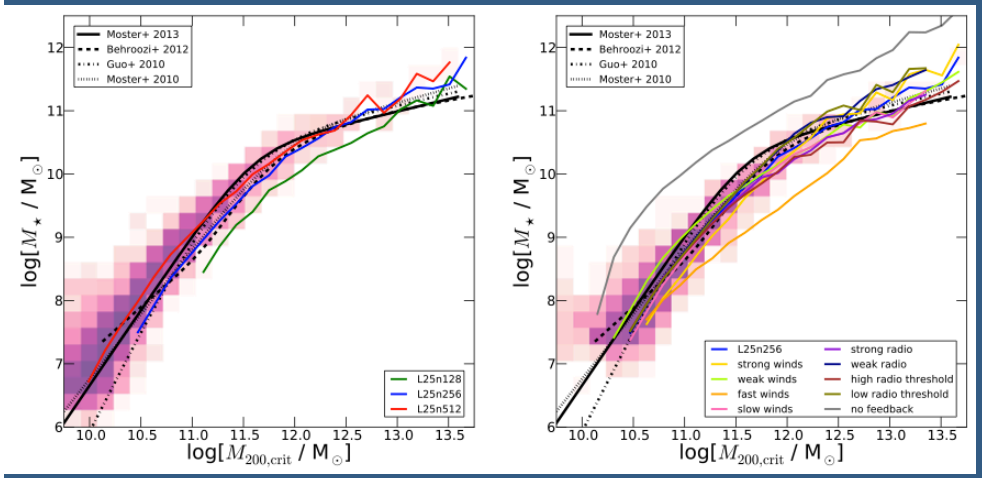
HST observation

→ *reasonable population*

Snyder, MV+ (in prep)

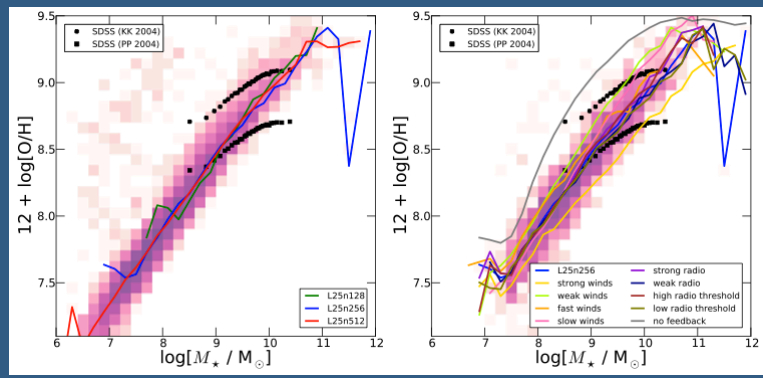
Towards realistic galaxy populations

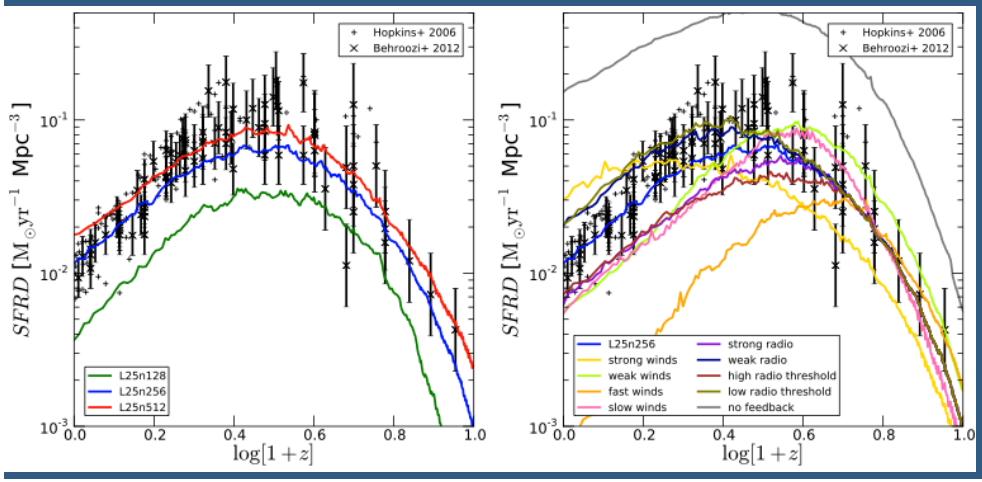
Constraints used for tuning feedback parameters:



Baryon Conversion efficiency

M-Z relation

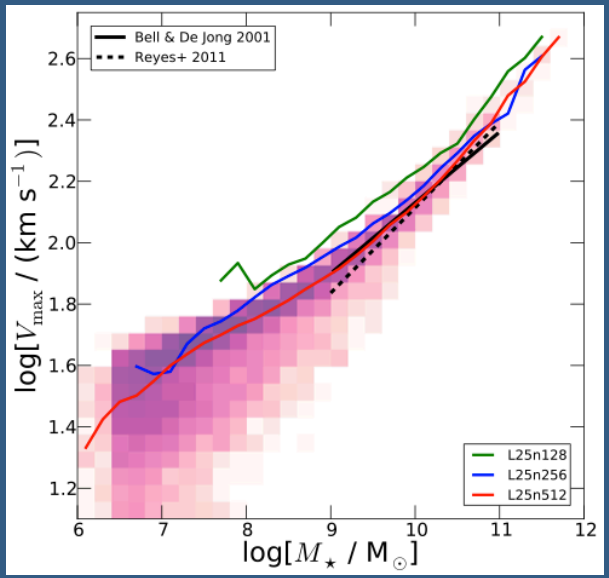




Cosmic SFH

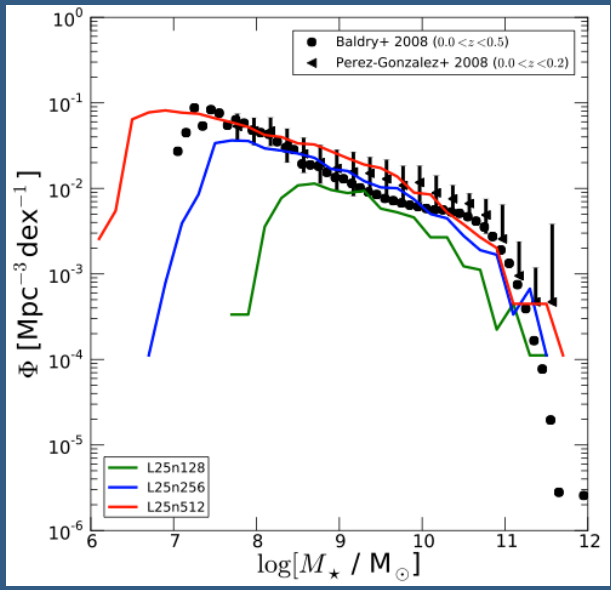
Vogelsberger, Genel+ 2013

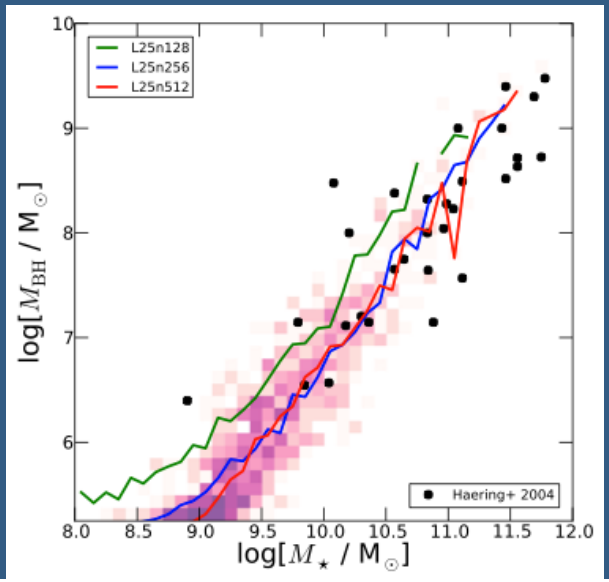
Towards realistic galaxy populations



Tully-Fisher relation

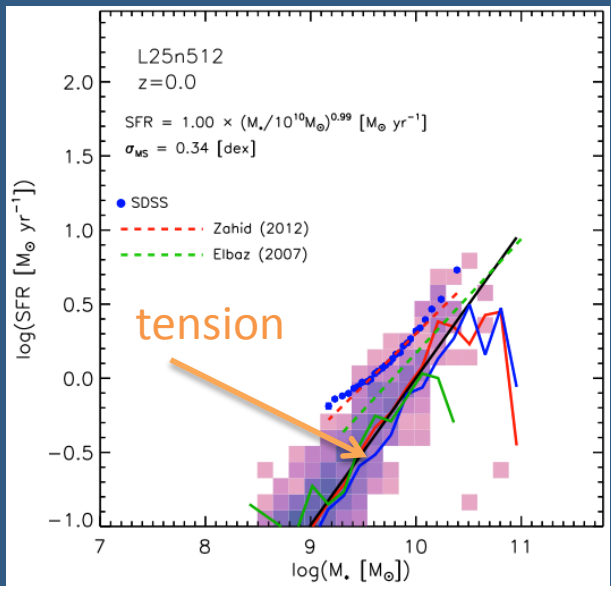
Stellar mass function





Black hole mass - stellar mass relation

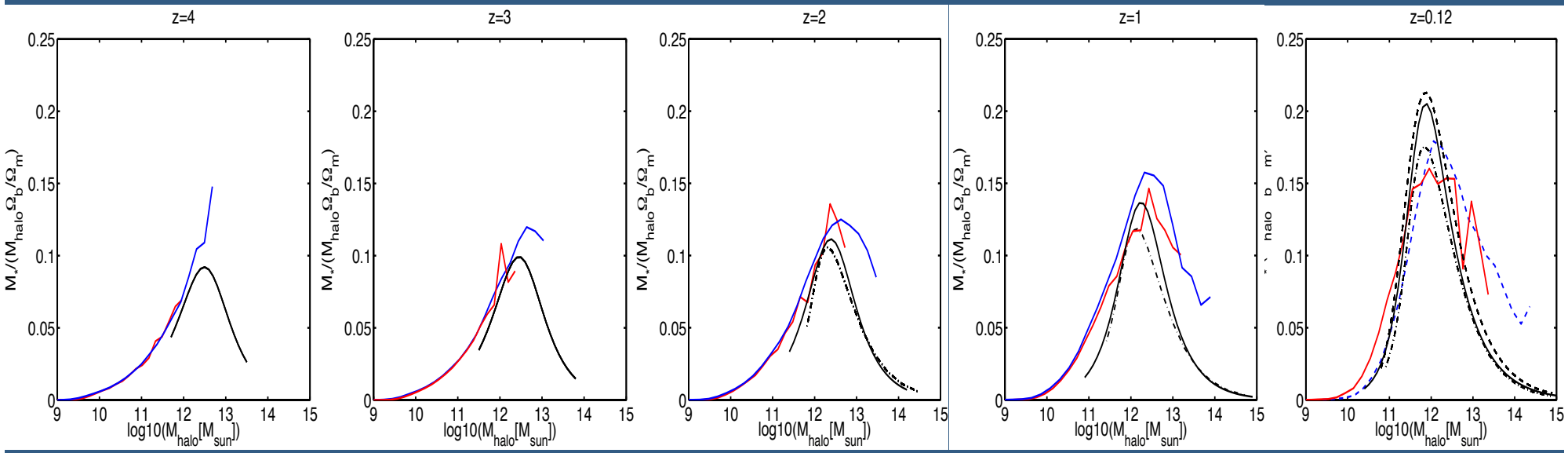
SFR - stellar mass relation



Torrey, Vogelsberger, Genel+ 2013

Towards realistic galaxy populations

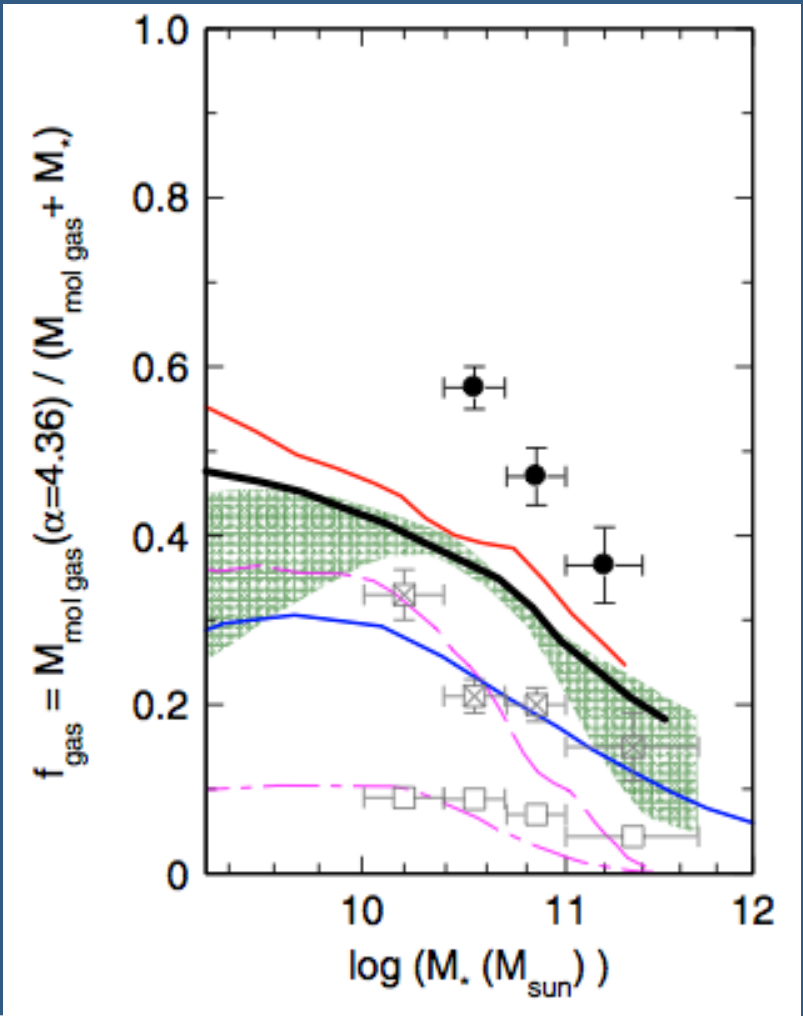
Stellar mass – halo mass relation @ z > 0



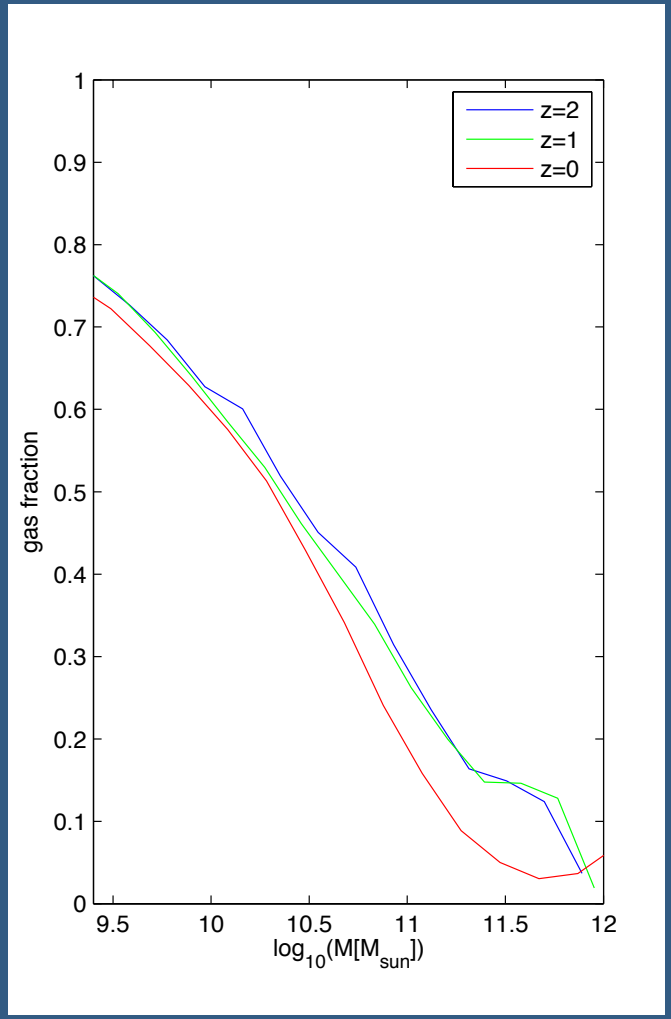
Genel+ in prep.

Towards realistic galaxy populations

Gas fractions



Tacconi+ 2013

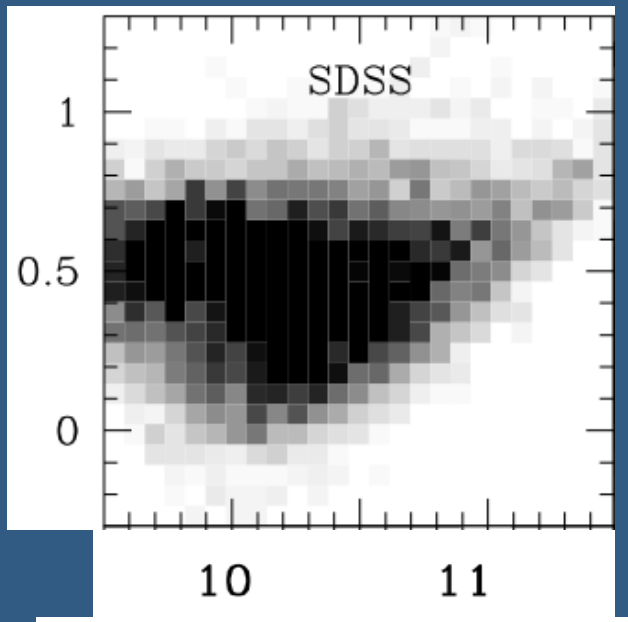


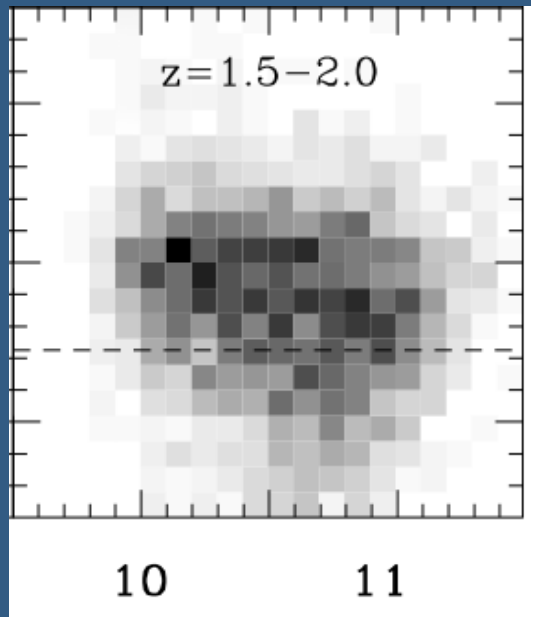
Genel+ in prep.

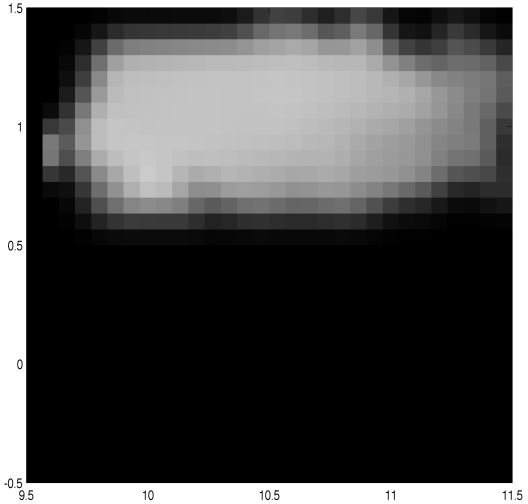
Towards realistic galaxy populations

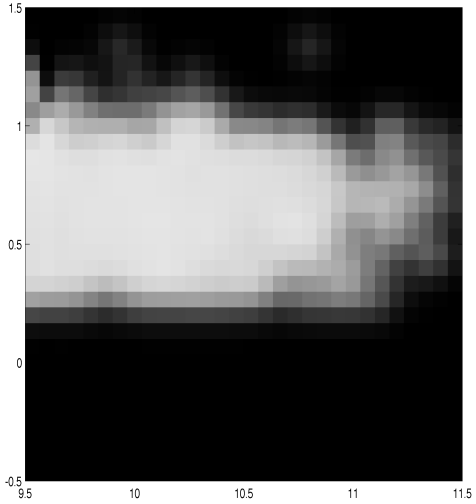
Galaxy size evolution

Williams+ 2010









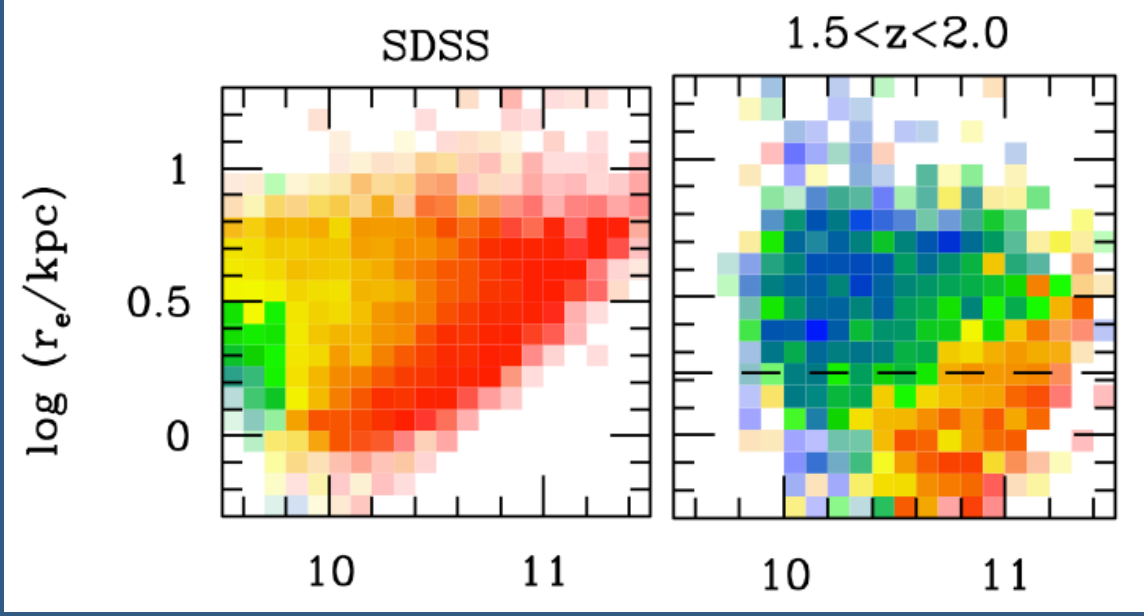
Genel+ in prep.

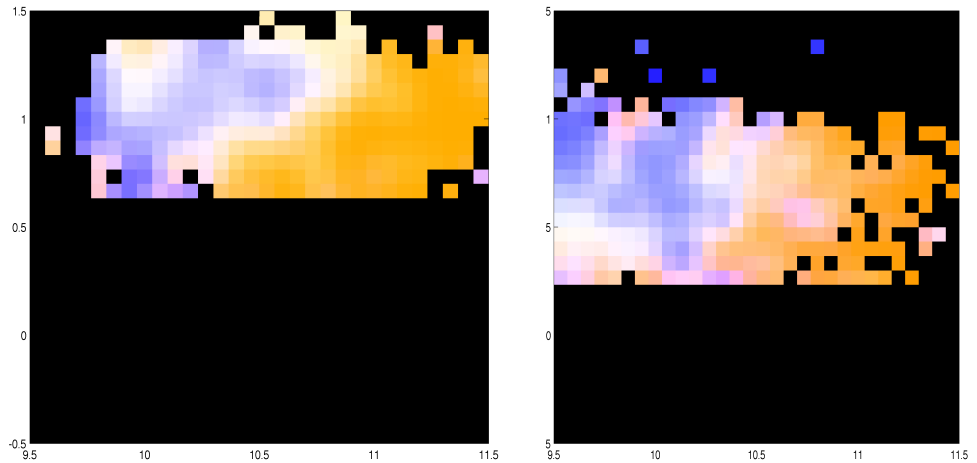
Towards realistic galaxy populations

Williams+ 2010

Galaxy size evolution

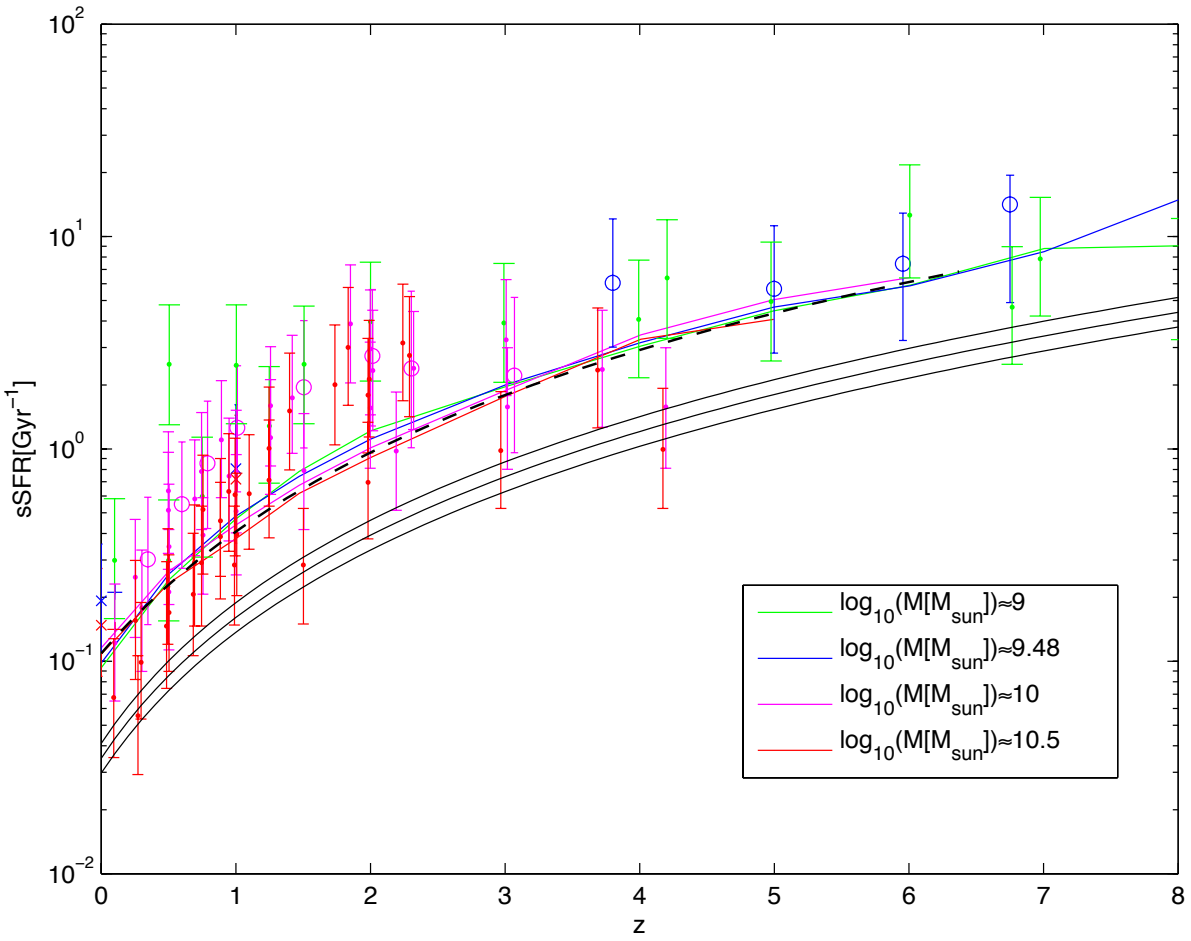
- At fixed mass, larger galaxies are more SF-ing
- At fixed size, more massive galaxies are more quenched





Towards realistic galaxy populations

Evolution of the sSFR

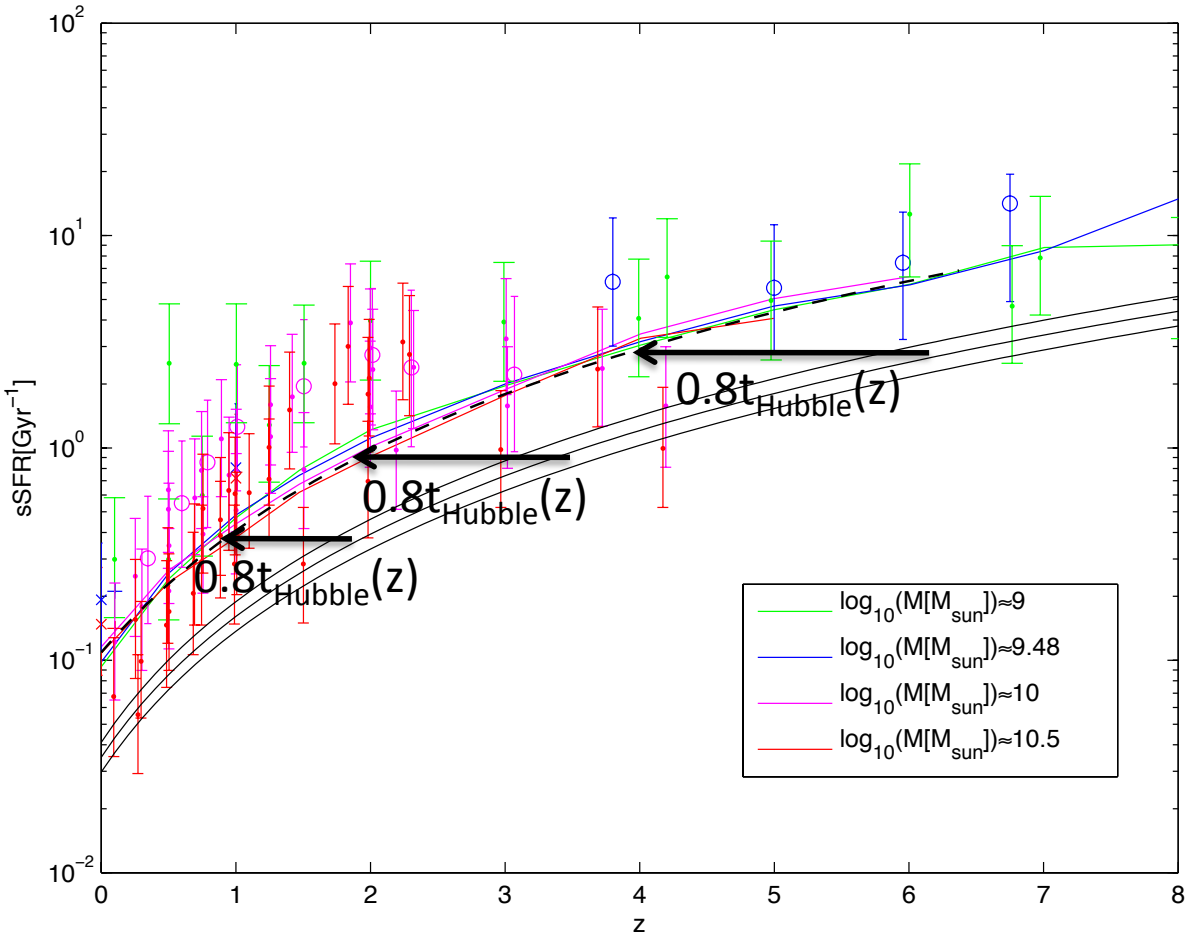


Observed data compiled by Behroozi+ 2013

Genel+ in prep.

Towards realistic galaxy populations

Evolution of the sSFR



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Towards realistic galaxy populations

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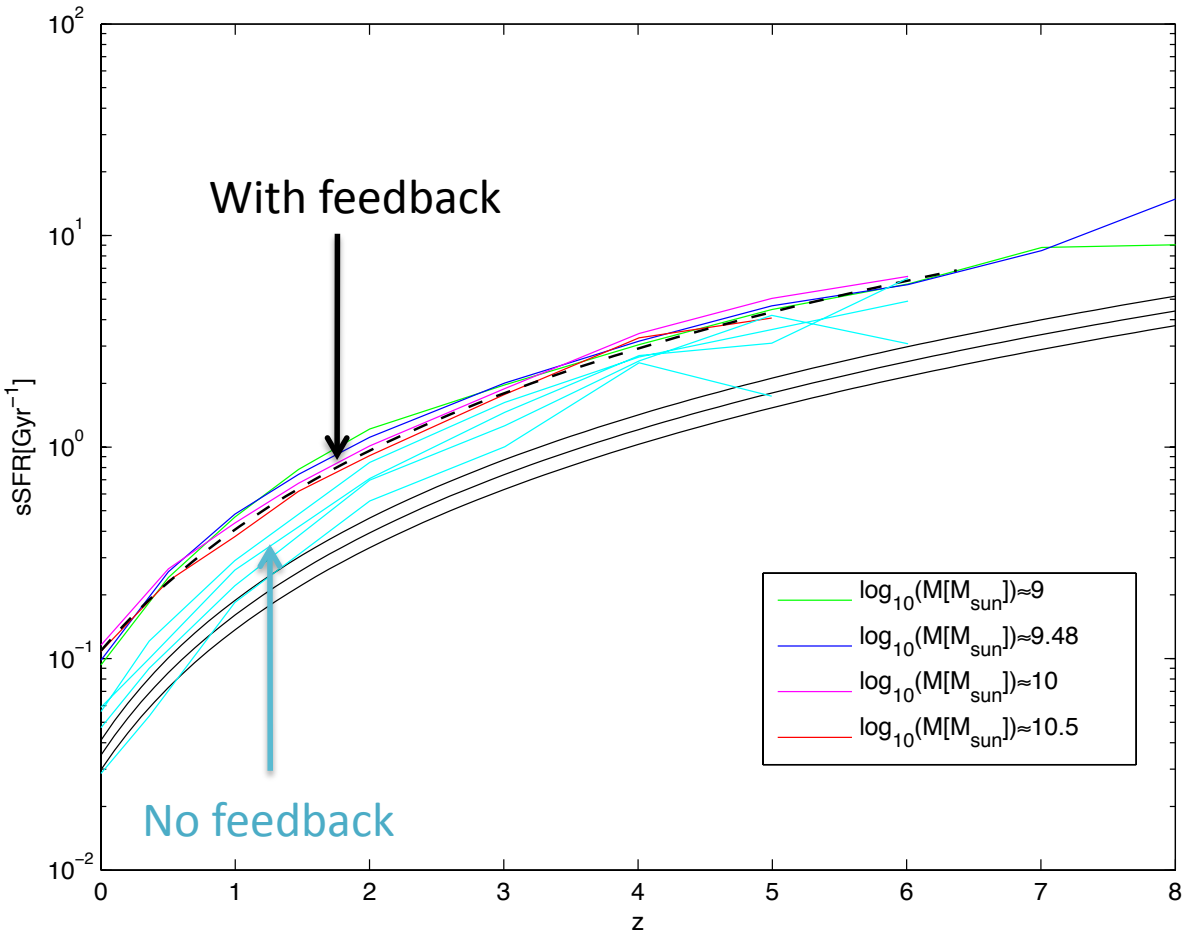
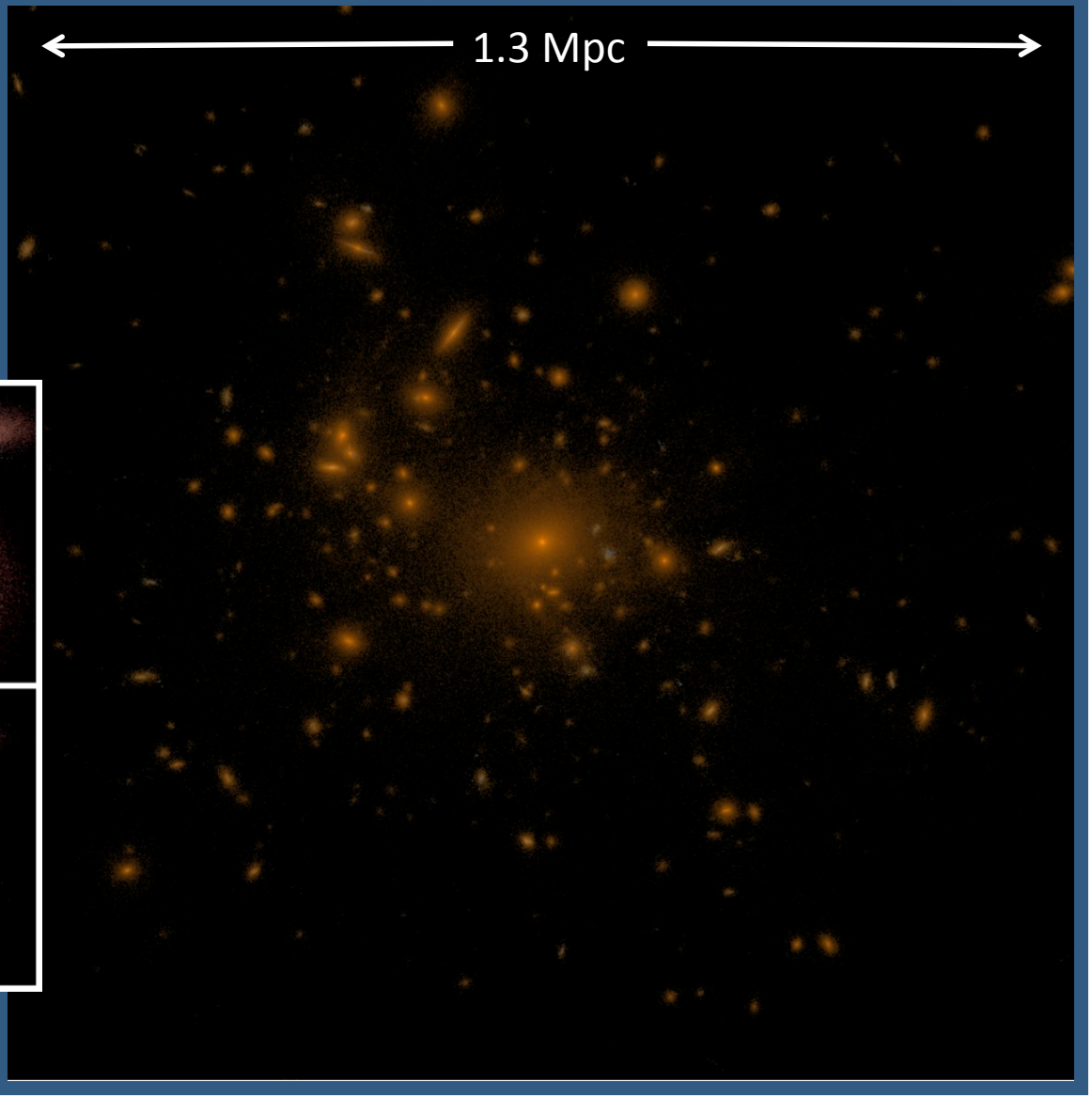


Genel+ in prep.

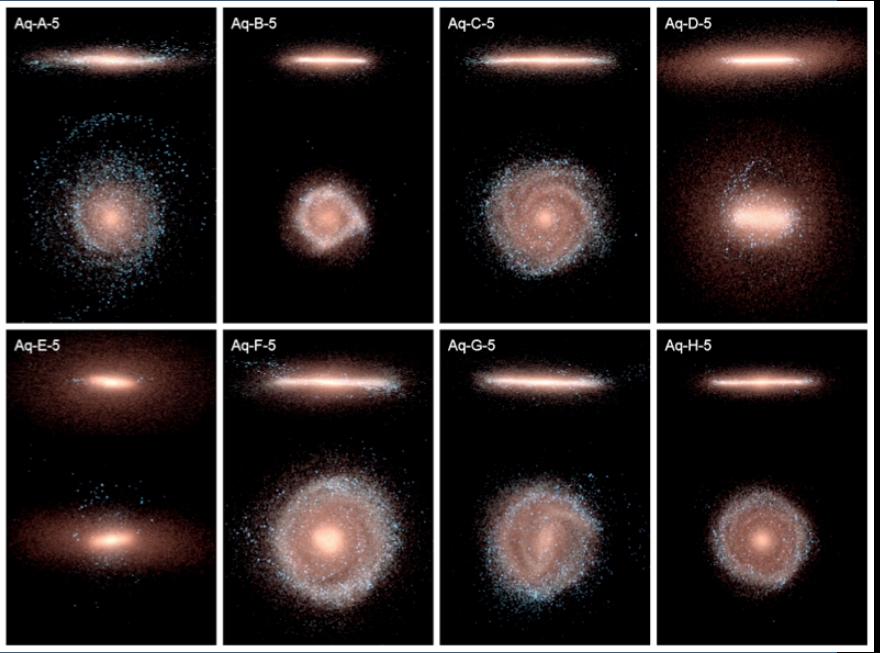
Galaxy bimodality

Genel+ in prep.

$2\times10^{14}M_{sun}$ halo

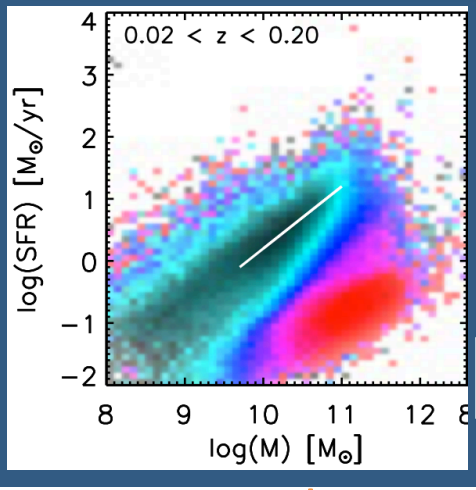


$10^{12}M_{sun}$ halos

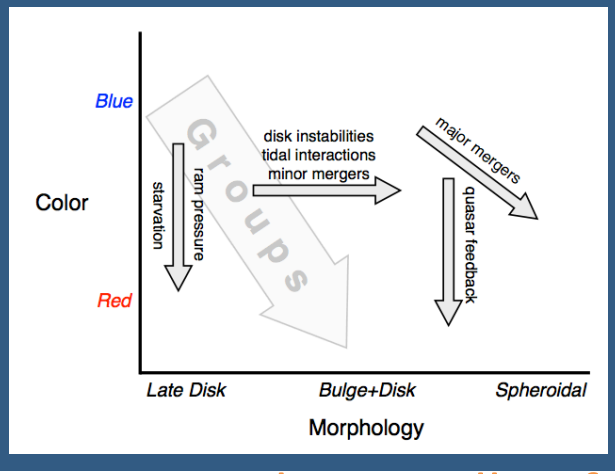


Marinacci+ 2013

SF activity and galaxy structure at z=0

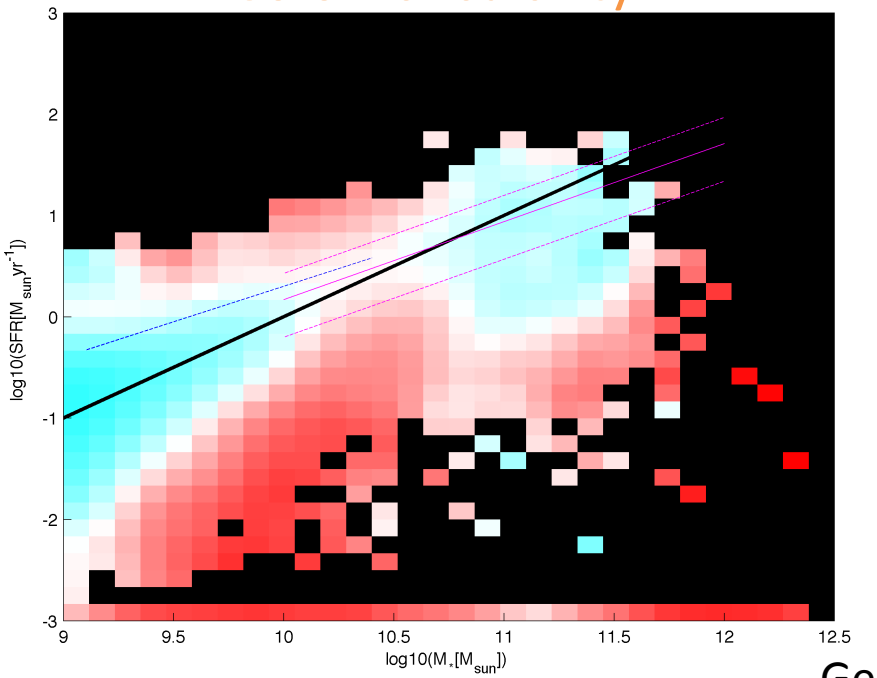


Wuyts+ 2011

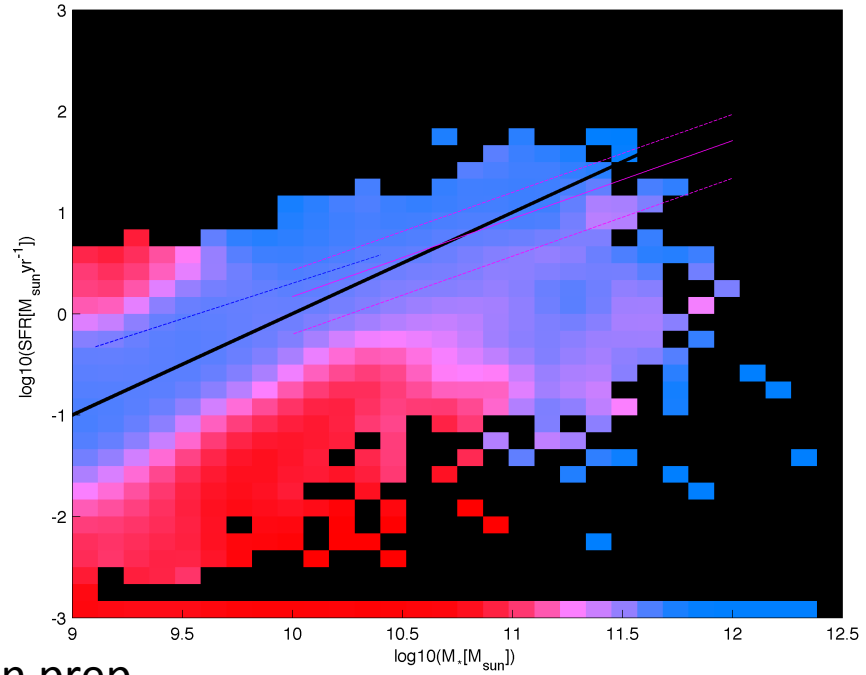


George+ 2013

Color: circularity



Color: satellite fraction

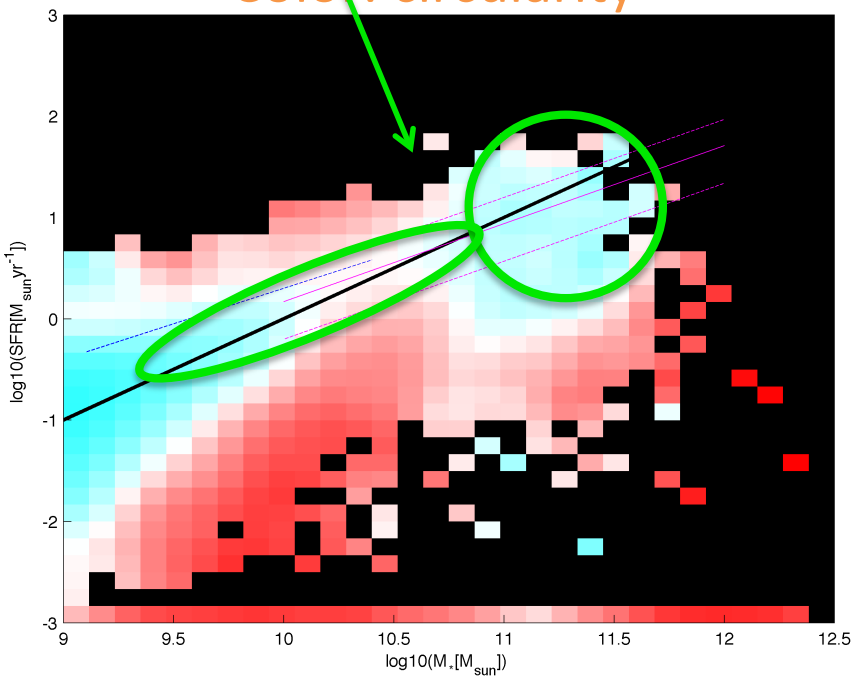


Genel+ in prep.

SF activity and galaxy structure at z=0

- Disky star-forming centrals

Color: circularity



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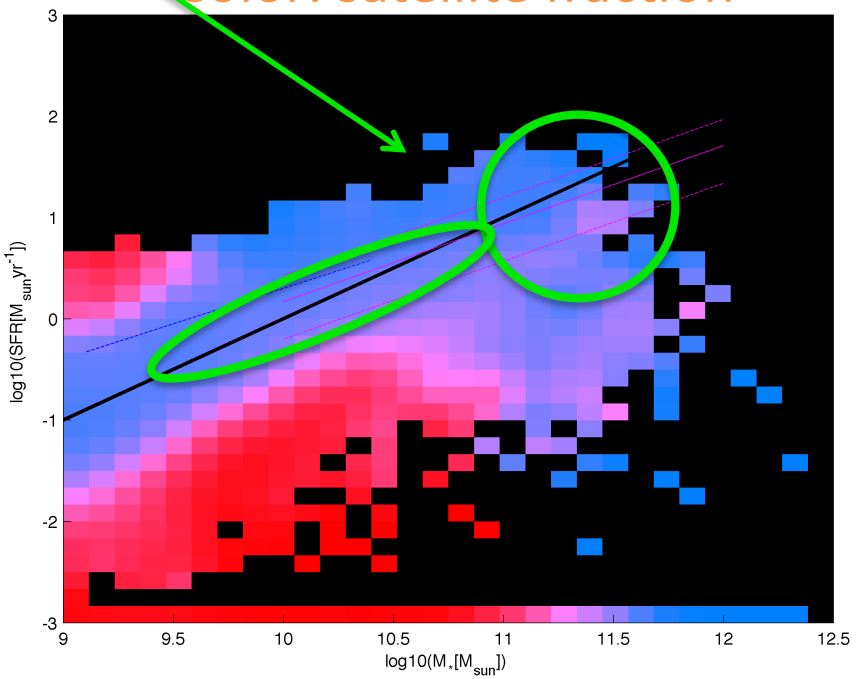
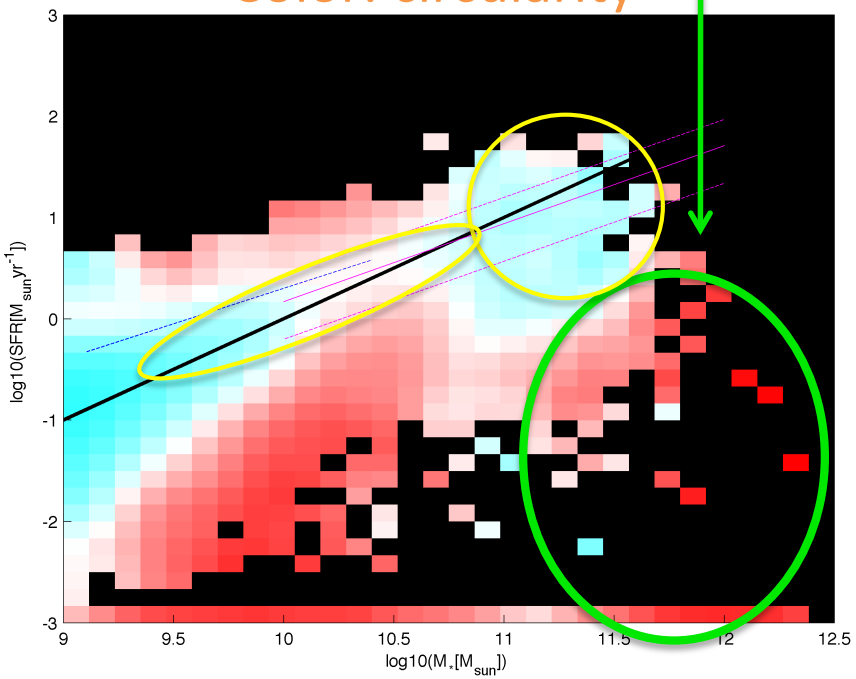


SF activity and galaxy structure at z=0

- Disky SF-ing centrals
- Quenched spheroidal massive centrals

Color: circularity



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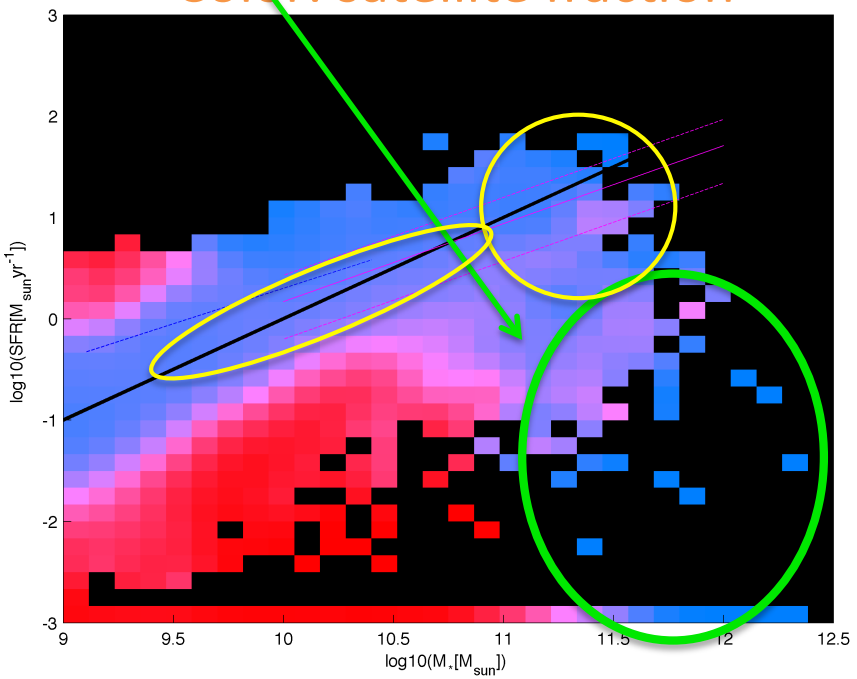
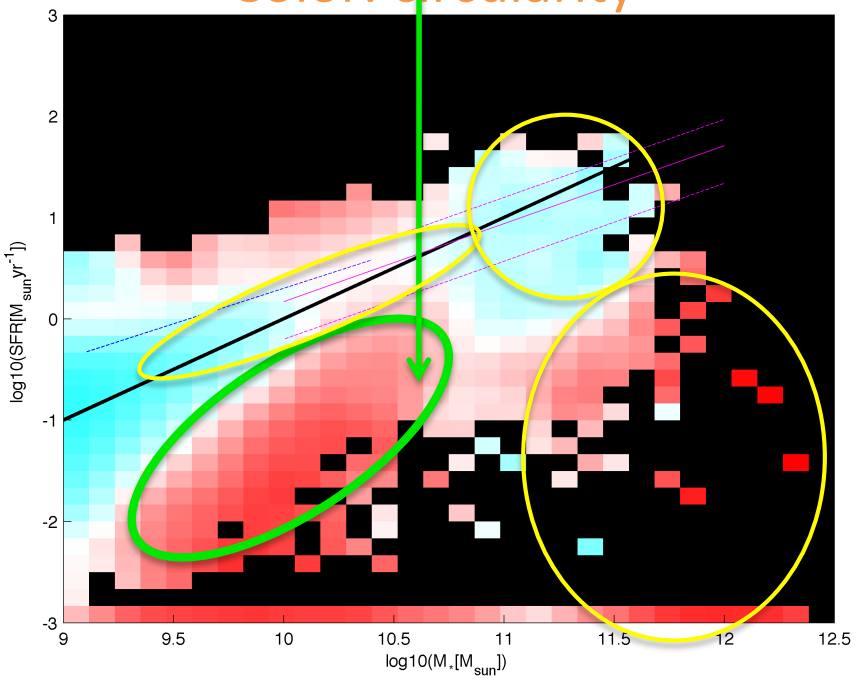


SF activity and galaxy structure at z=0

- Disky SF-ing centrals
- Quenched spheroidal massive centrals
- Quenched spheroidal satellites

Color: circularity



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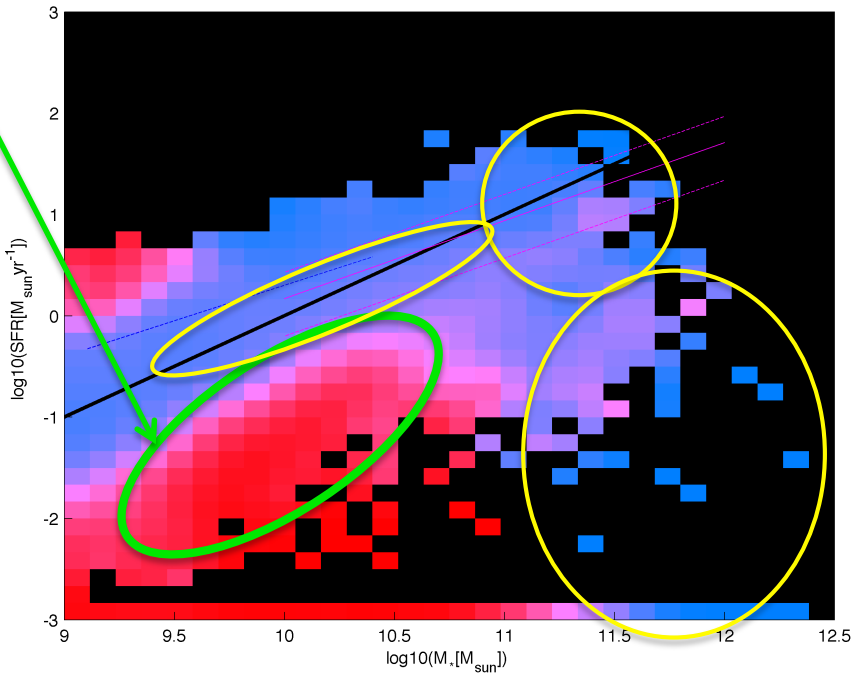
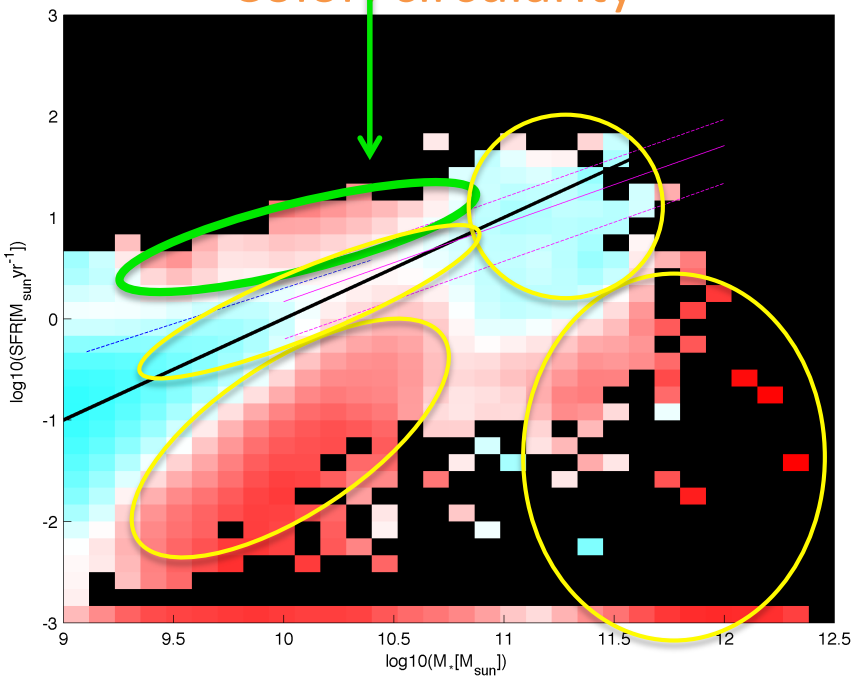


SF activity and galaxy structure at z=0

- Disky SF-ing centrals
- Quenched spheroidal massive centrals
- Quenched spheroidal satellites
- High-SF irregular (interacting) centrals

Color: circularity



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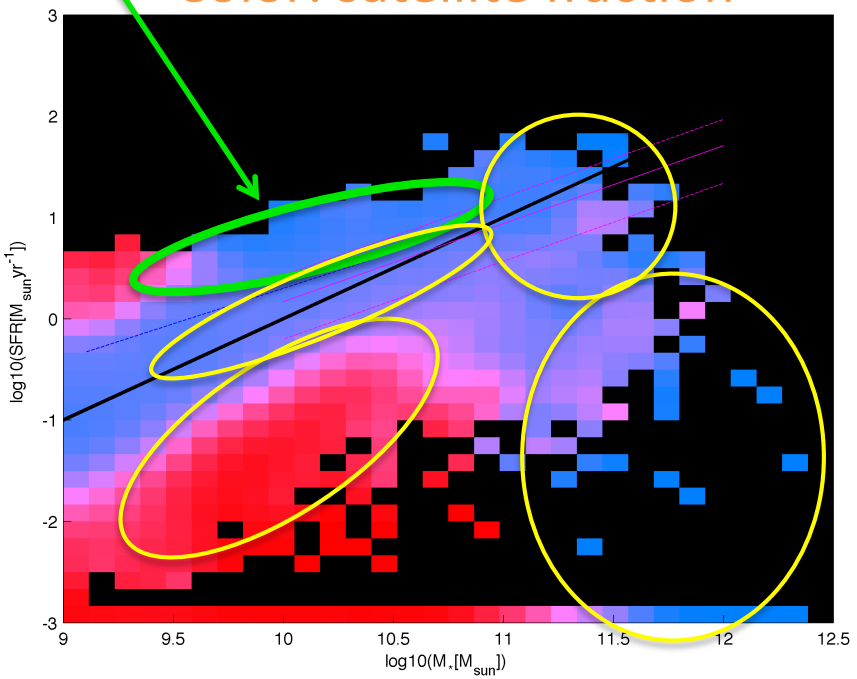

SF activity and galaxy structure at z=0

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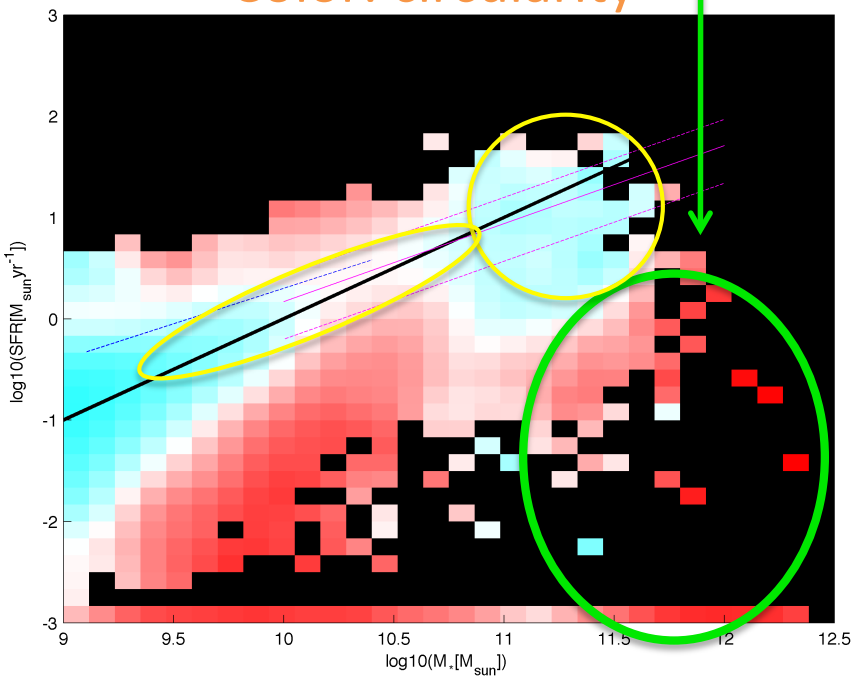
Color: circularity



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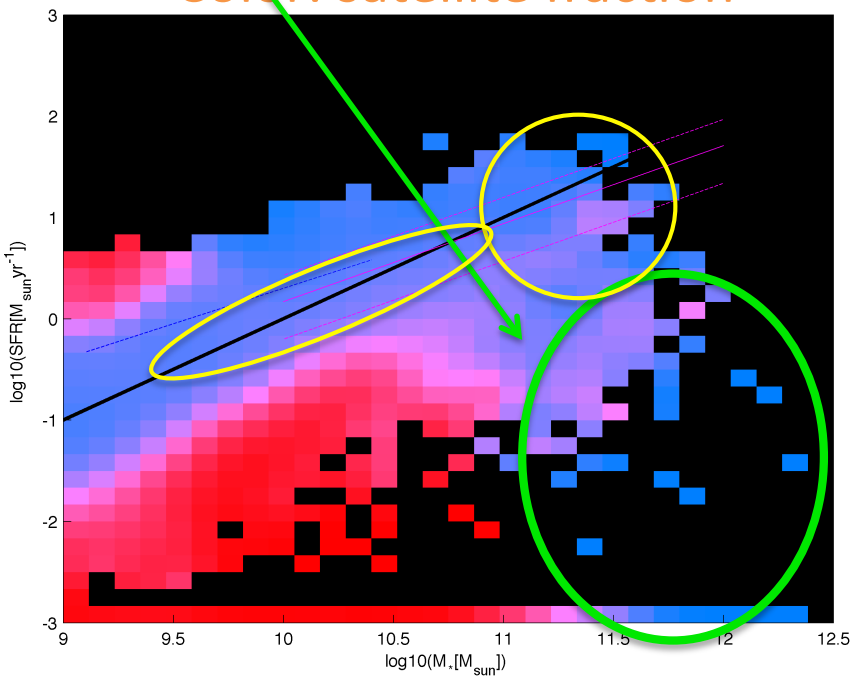

SF activity and galaxy structure at z=0

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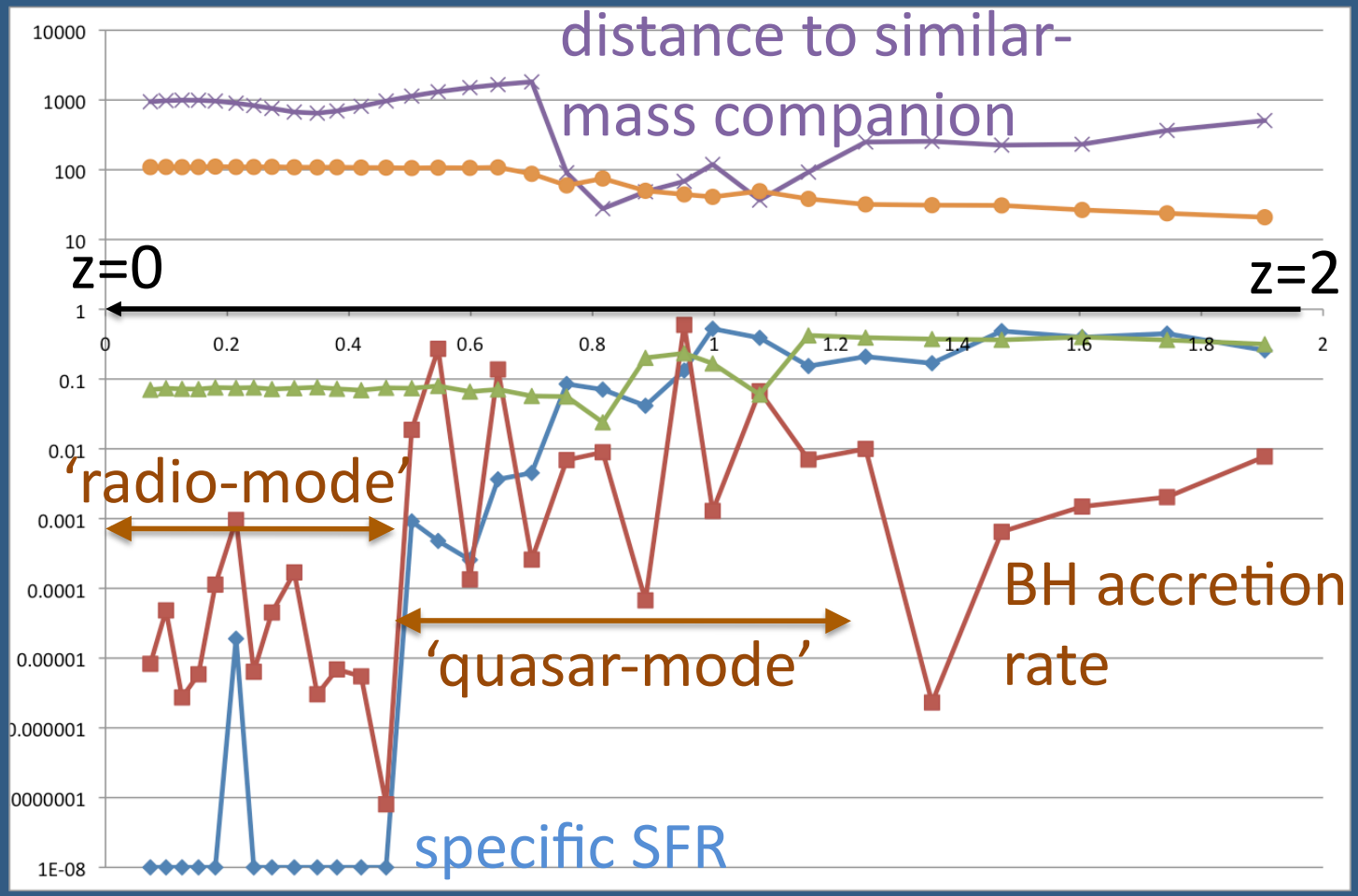

$M_\star$

kinematic circularity

SF activity and galaxy structure at z=0

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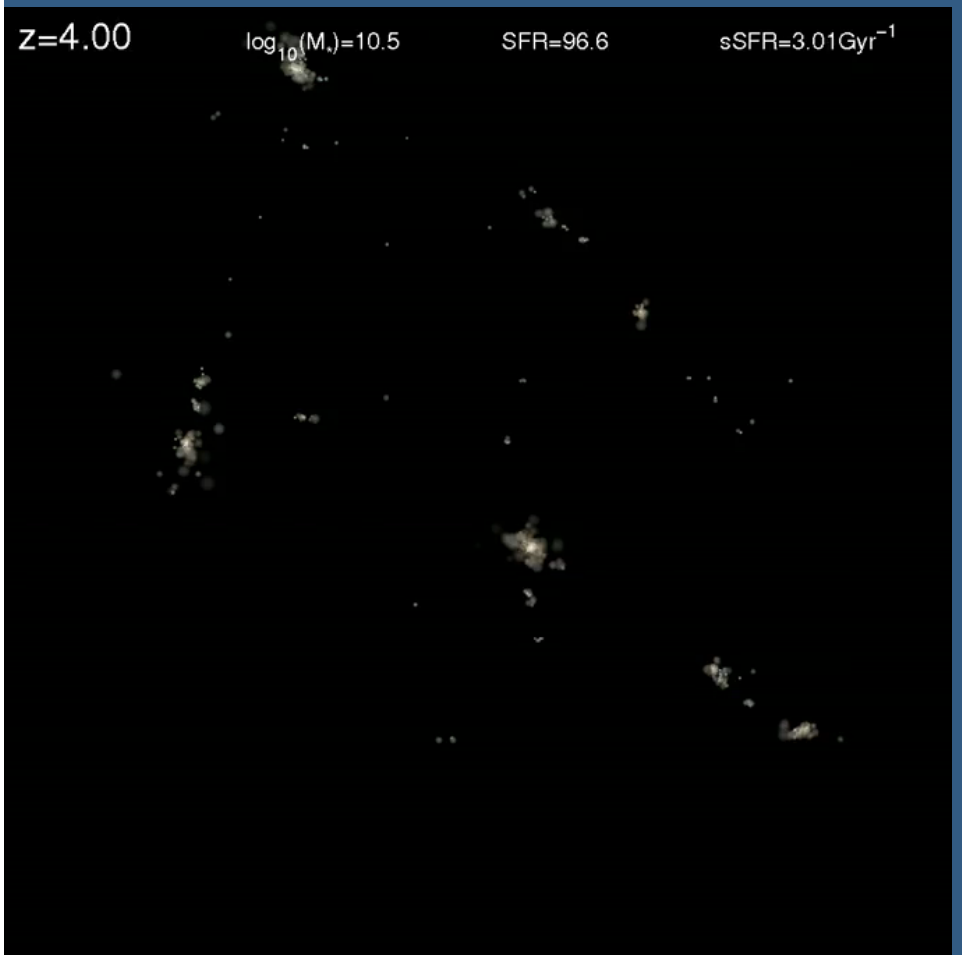
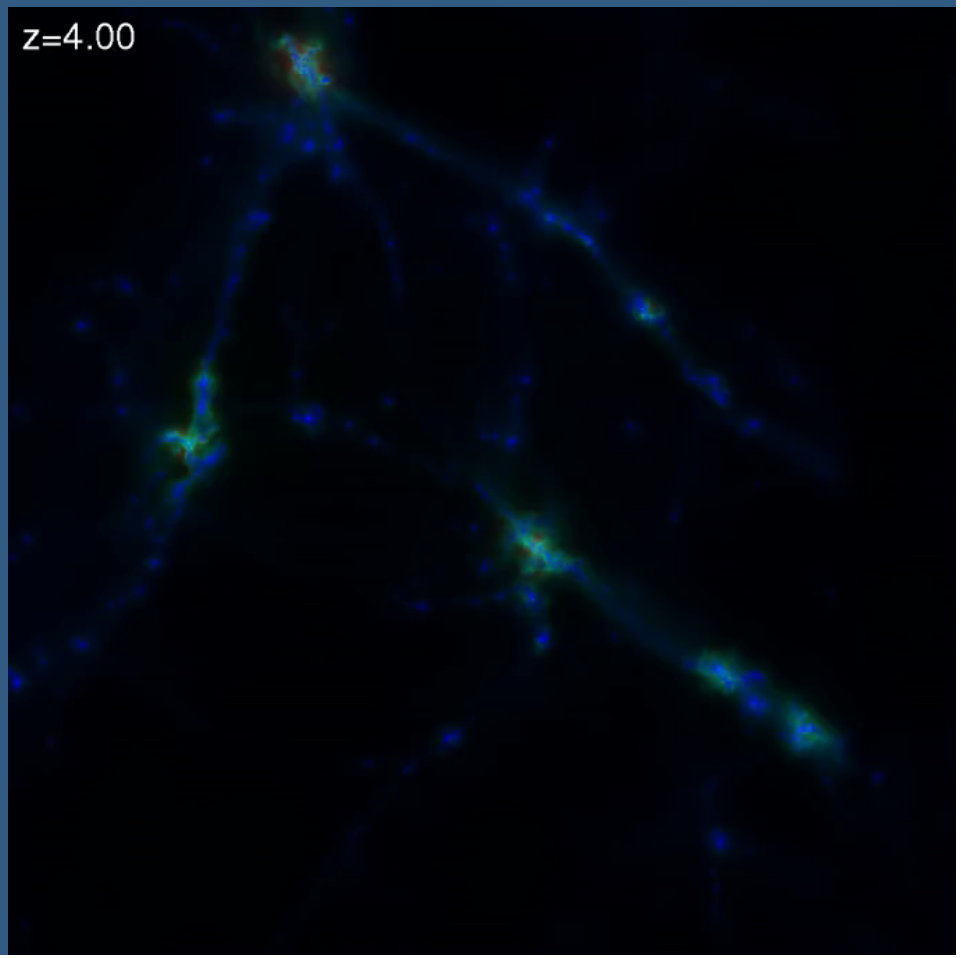
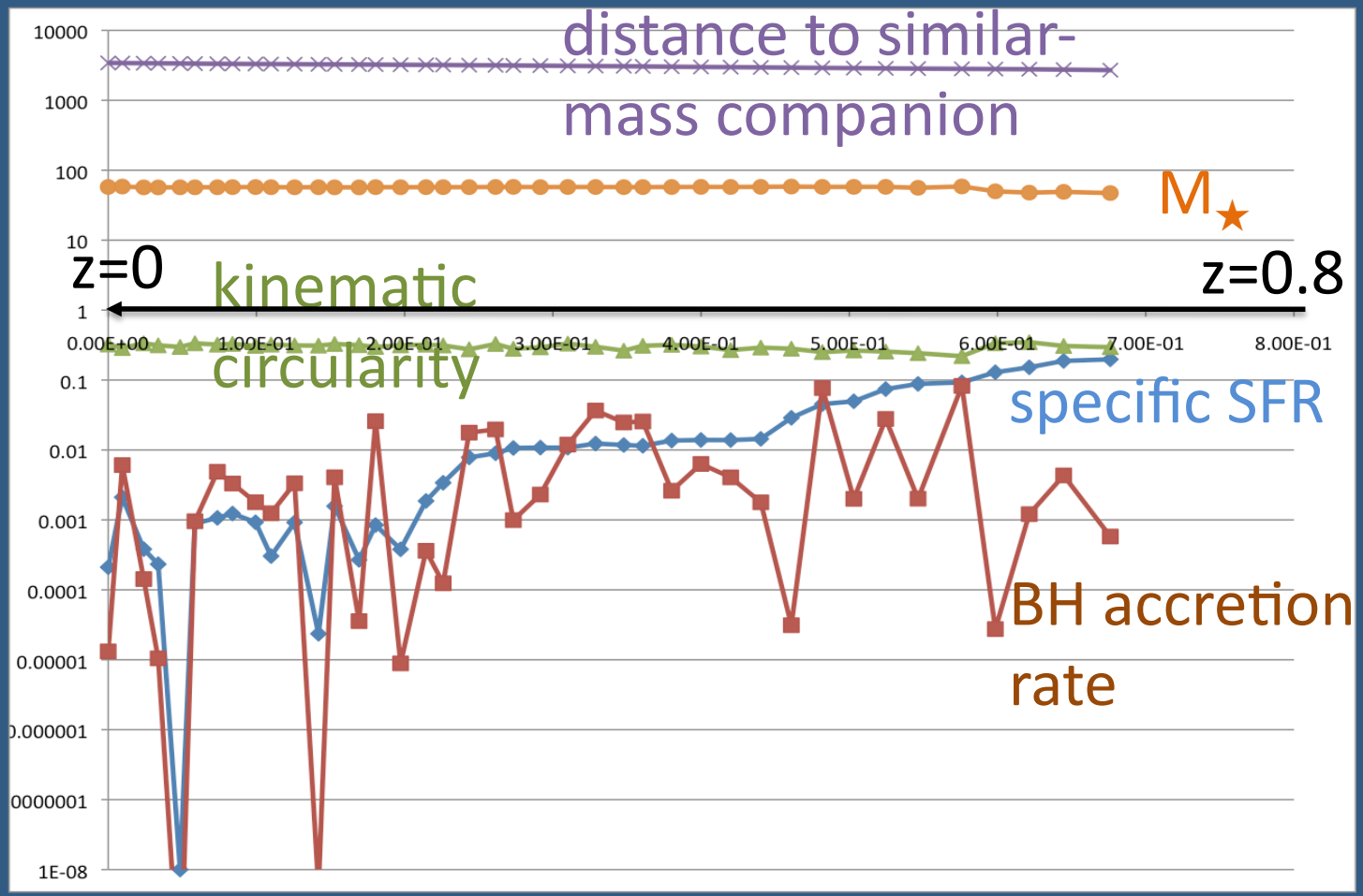
- Quenched spheroidal massive centrals





SF activity and galaxy structure at z=0

- Disky SF-ing centrals
- Quenched DISKY massive centrals



SF activity and galaxy structure at z=0

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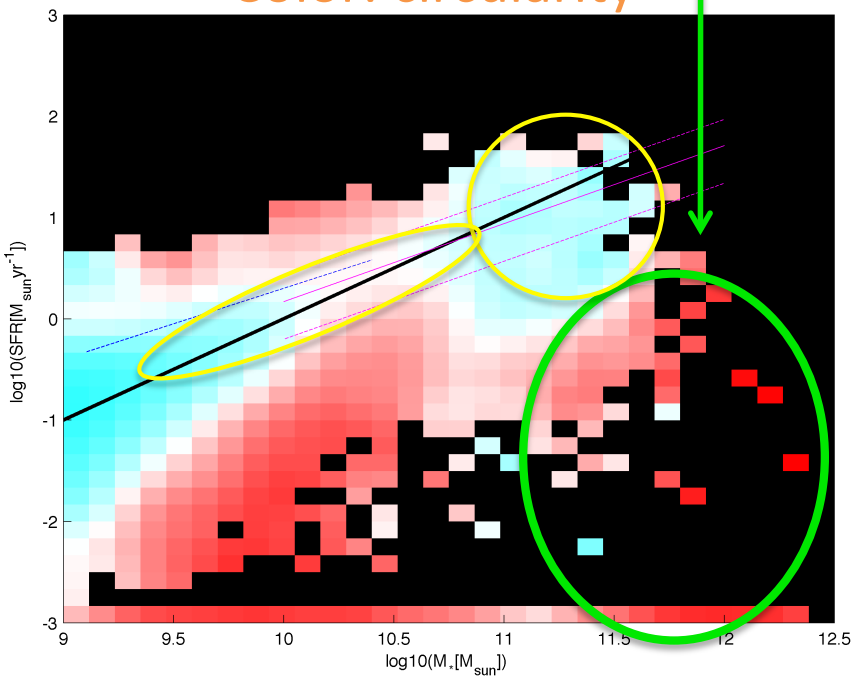
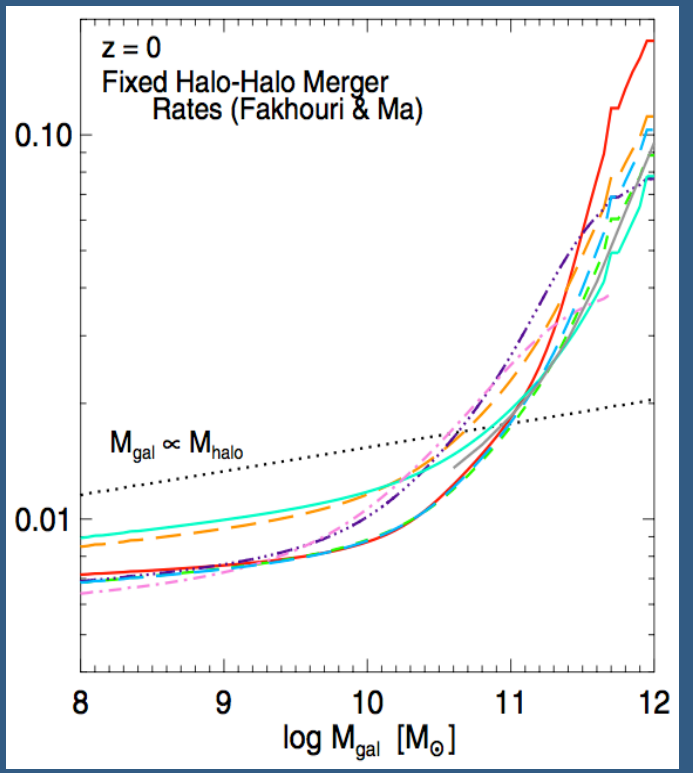
Color: circularity





Hopkins+ 2010

Summary

- Match to many statistical galaxy scaling relations and properties in the Illustris simulations
- Strong feedback on both ends is required
- Galaxy bimodality: there exists a close (and evolving) morphology-SF relation, albeit with scatter and outliers
- Mass, environment, interactions & AGN all play a role in determining the relation