Galaxy formation in the Illustris simulation

Shy Genel

ITC/Harvard

Hernquist, Sijacki, Springel, Torrey, Vogelsberger

Vogelsberger+, Nature, accepted ; Genel+, MNRAS, in prep.

Introduction

challenges in ab initio
modeling of galaxy populations

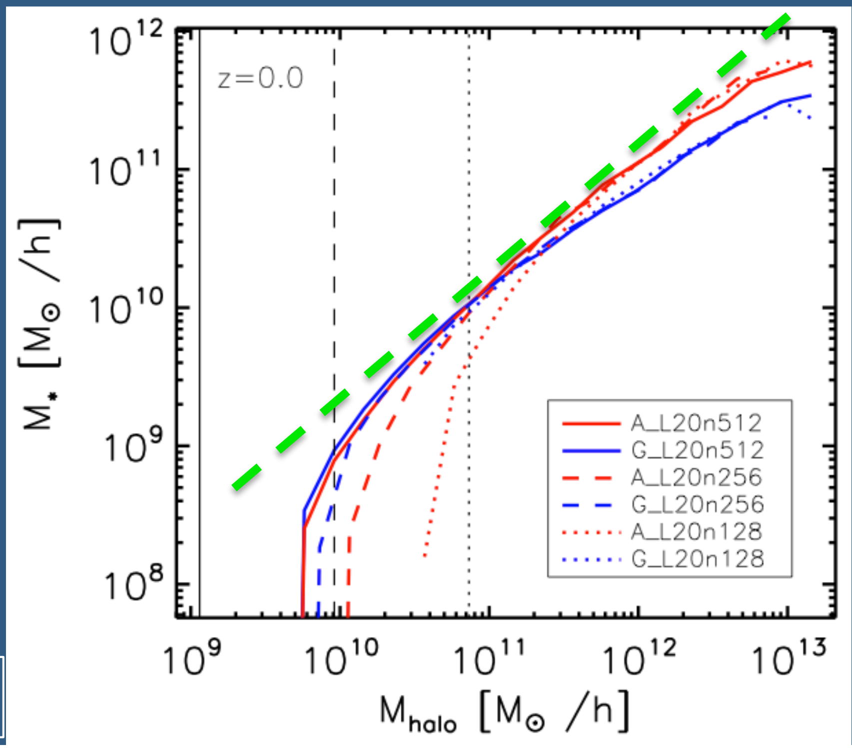
The overcooling problem

"Baryon conversion efficiency" without effective feedback:

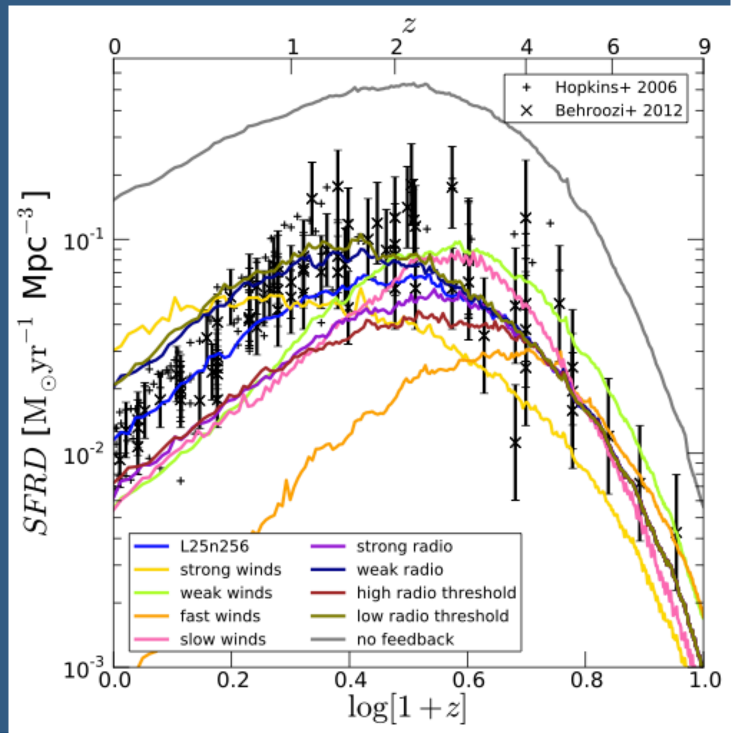
Close to 100% of the cosmic baryon fraction at $M_{halo} > \approx 10^{12} M_{sun}$ is in stars

(Related: "The missing satellites problem")

Vogelsberger, Genel et al. 2013

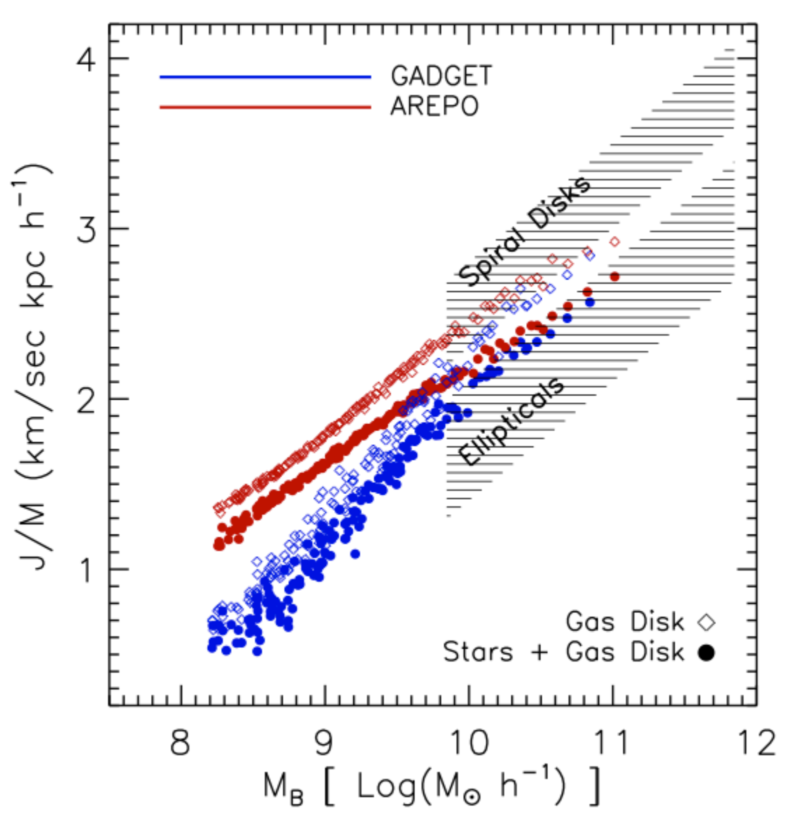


Keres et al. 2013



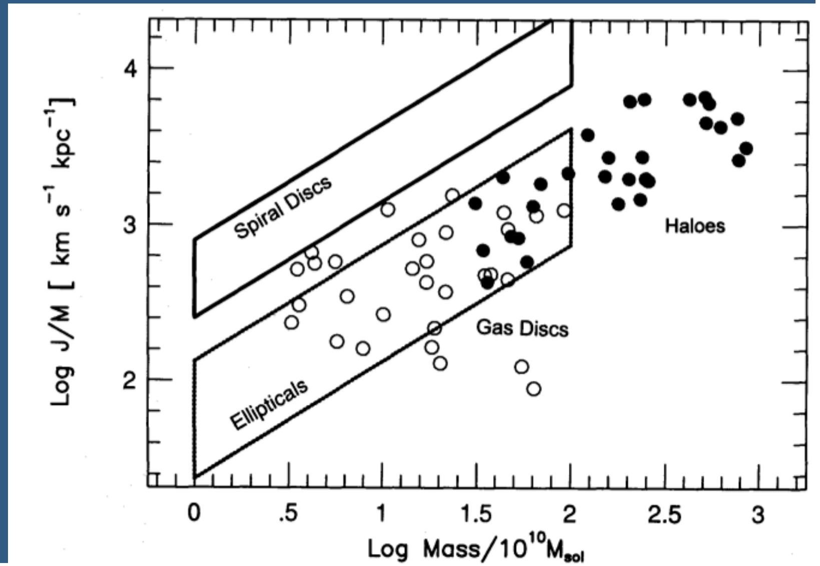
The angular momentum problem

Hydrodynamical cosmological simulations are struggling to produce disk galaxies

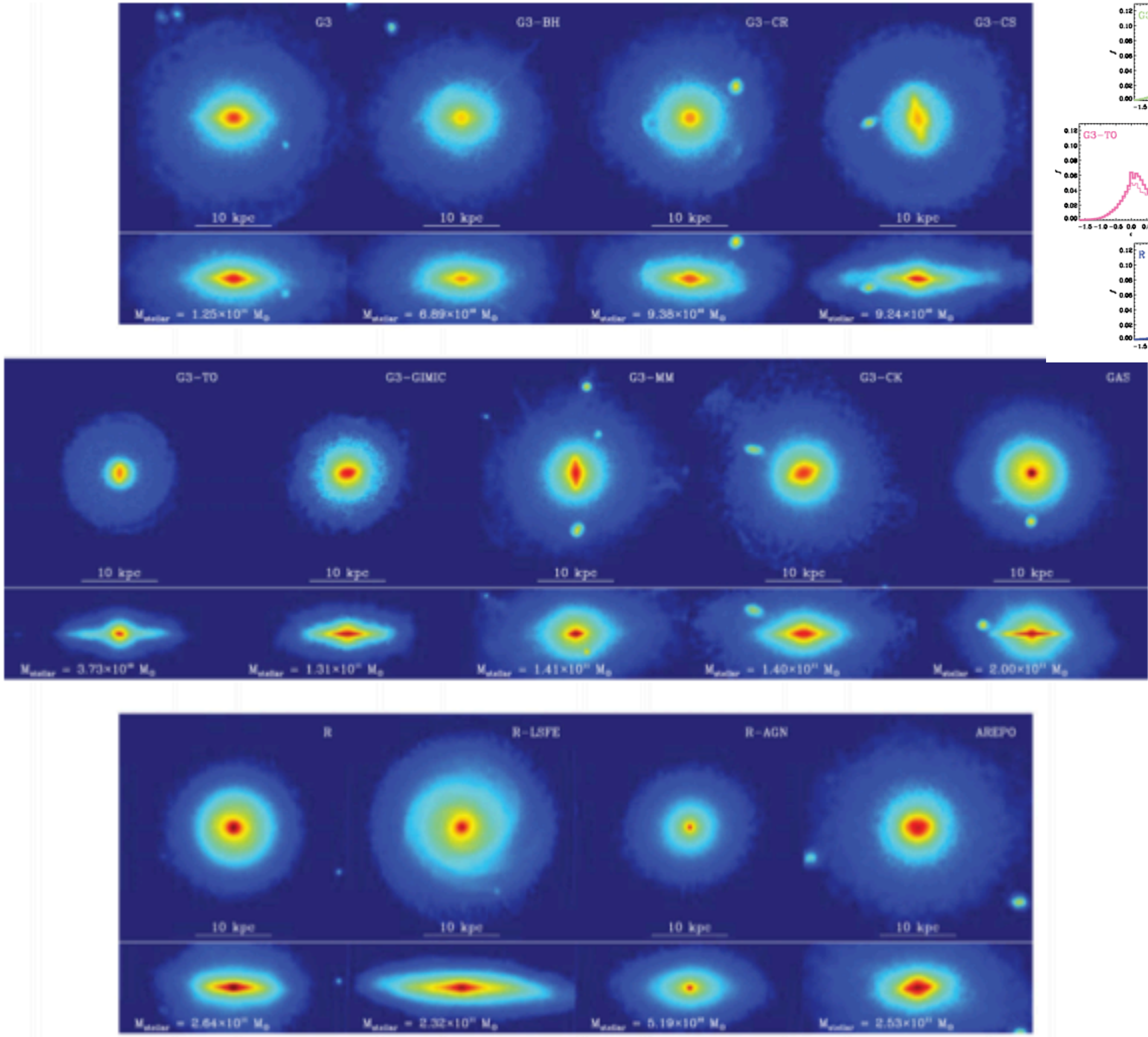


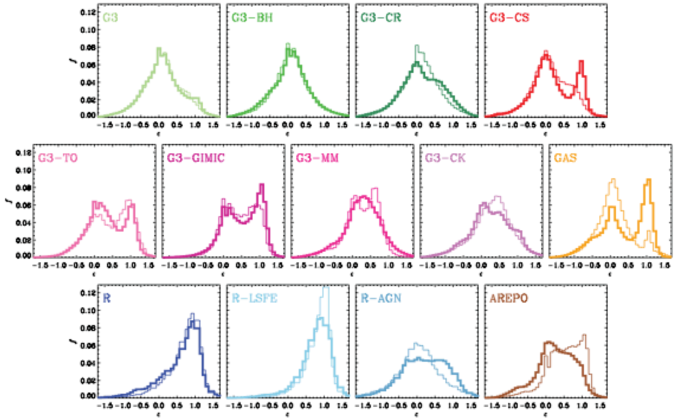
Torrey et al. 2012

Navarro et al. 1995



The angular momentum problem





Scannapieco et al. 2012

"Aquila" comparison project:

too low angular momentum, even with feedback

Why is it hard to solve those problems?

The computational challenge

- To “resolve” galaxies/ISM -> at least ~1kpc
- To probe various environments and get statistical samples -> at least ~$(100\mathrm{Mpc})^3$
- $(100\mathrm{Mpc}/1\mathrm{kpc})^3 = 10^{15}$ --> unfeasible --> strong spatial adaptivity required
- However, usually it is only feasible to use up to ~$2\times512^3 \approx 10^8$ resolution elements (to z=0) -->

Mass resolution in a $(100\mathrm{Mpc})^3$ box:

10^{10} halos with only ~20 resolution elements

Physics of galaxy formation

- Gravity
- Hydrodynamics
- Radiative cooling
- Star formation

The Routine

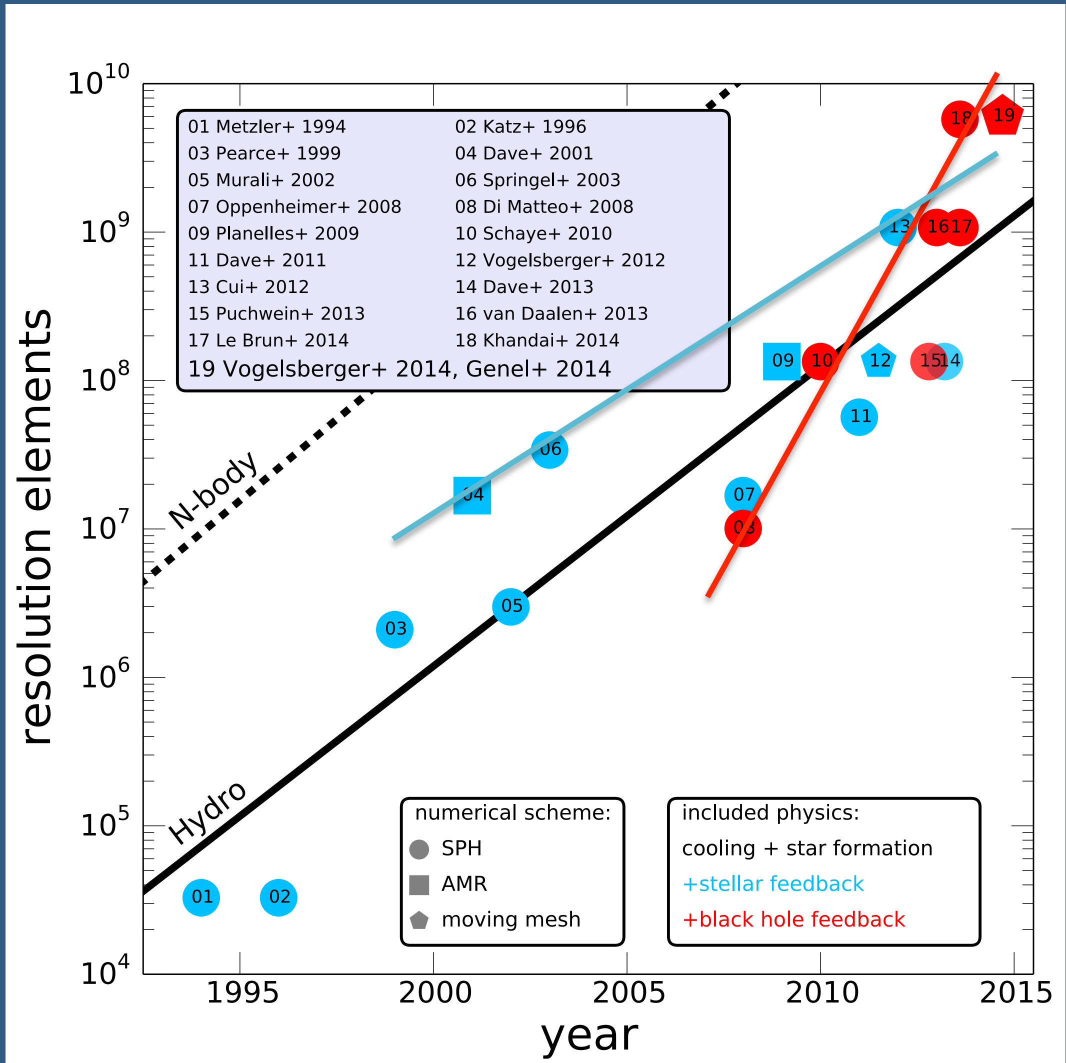
- Galactic winds
- BH activity

The Frontier

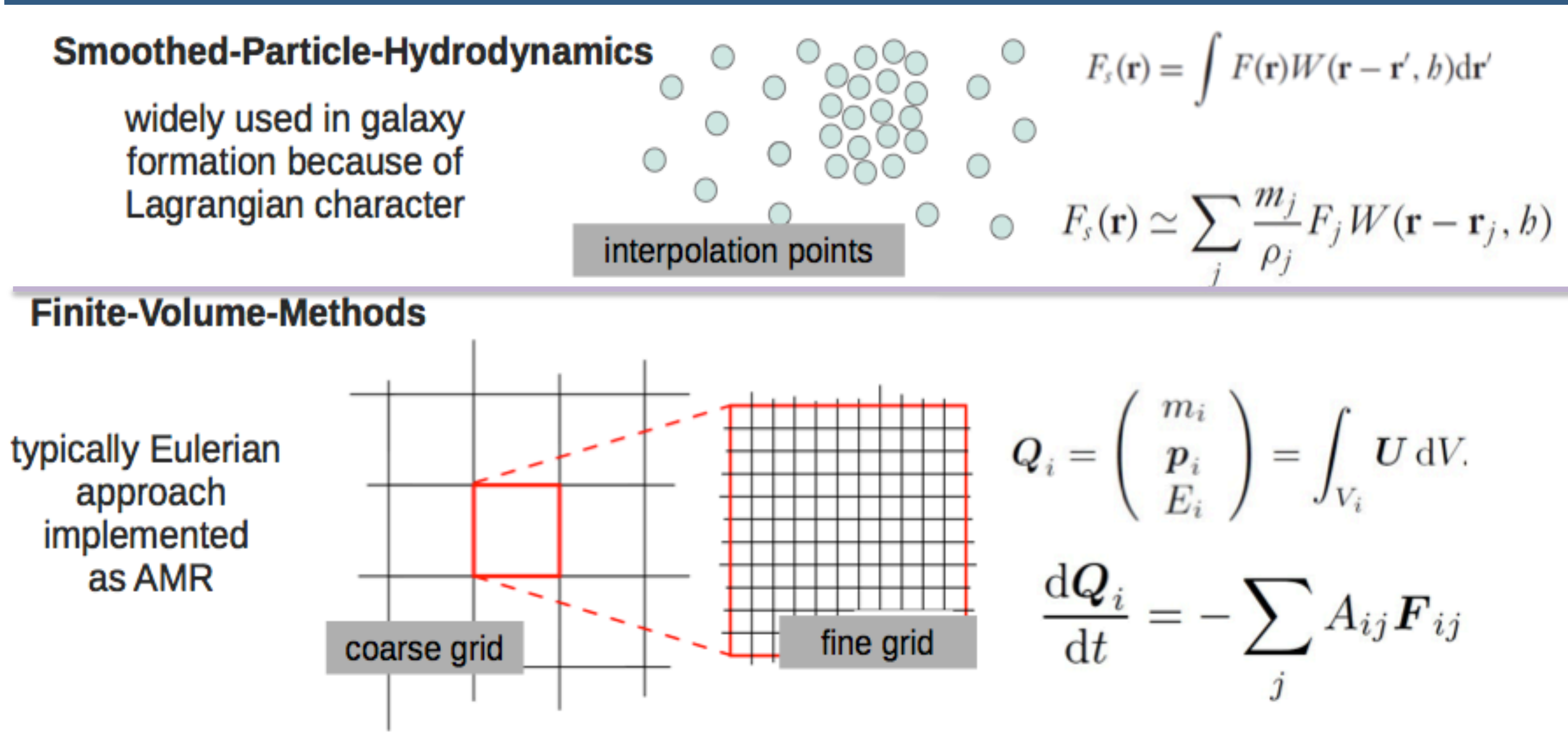
- Dust and radiative transfer
- Magnetic fields, cosmic rays

The Future

Simulation sizes over time



Hydrodynamics in galaxy formation



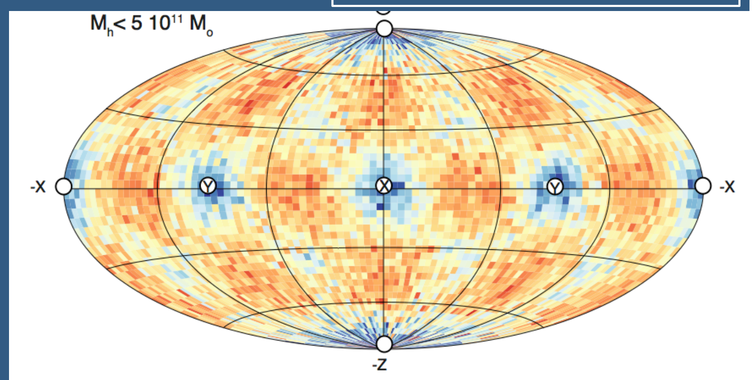
SPH

AMR

Courtesy of Mark Vogelsberger

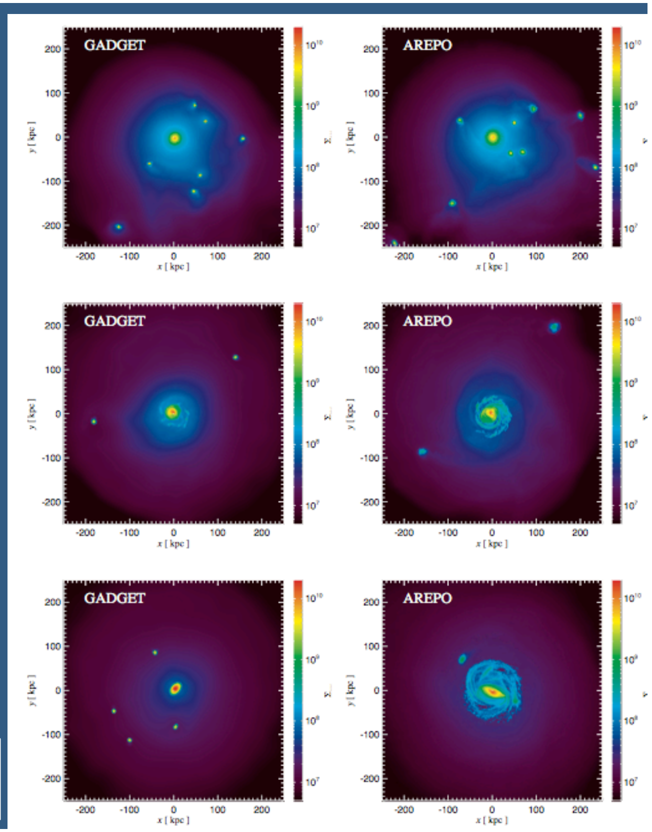
Downsides of hydro solvers

Dubois et al. 2014



- AMR:
  - Grid alignment
  - Galilean invariance

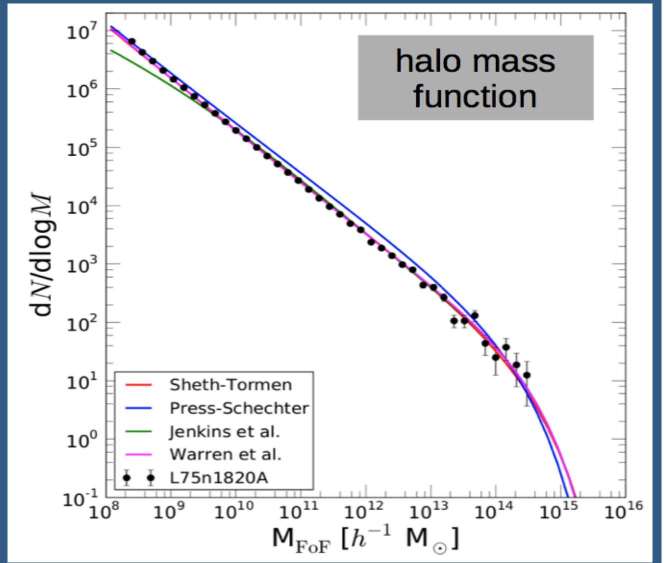
- SPH:
  - Shock capturing and broadening
  - Shot noise
  - SPH artificial surface tension -> fluid instability



Sijacki et al. 2012

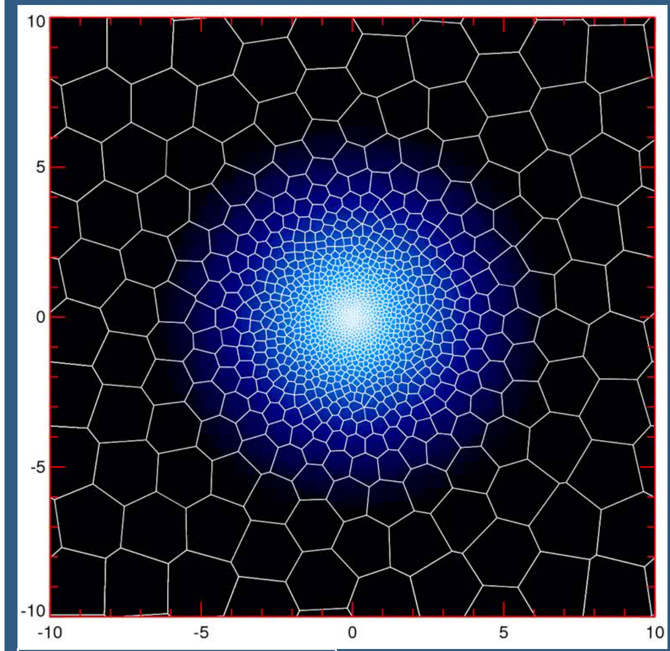
Illustris: methods

The Illustris Simulation

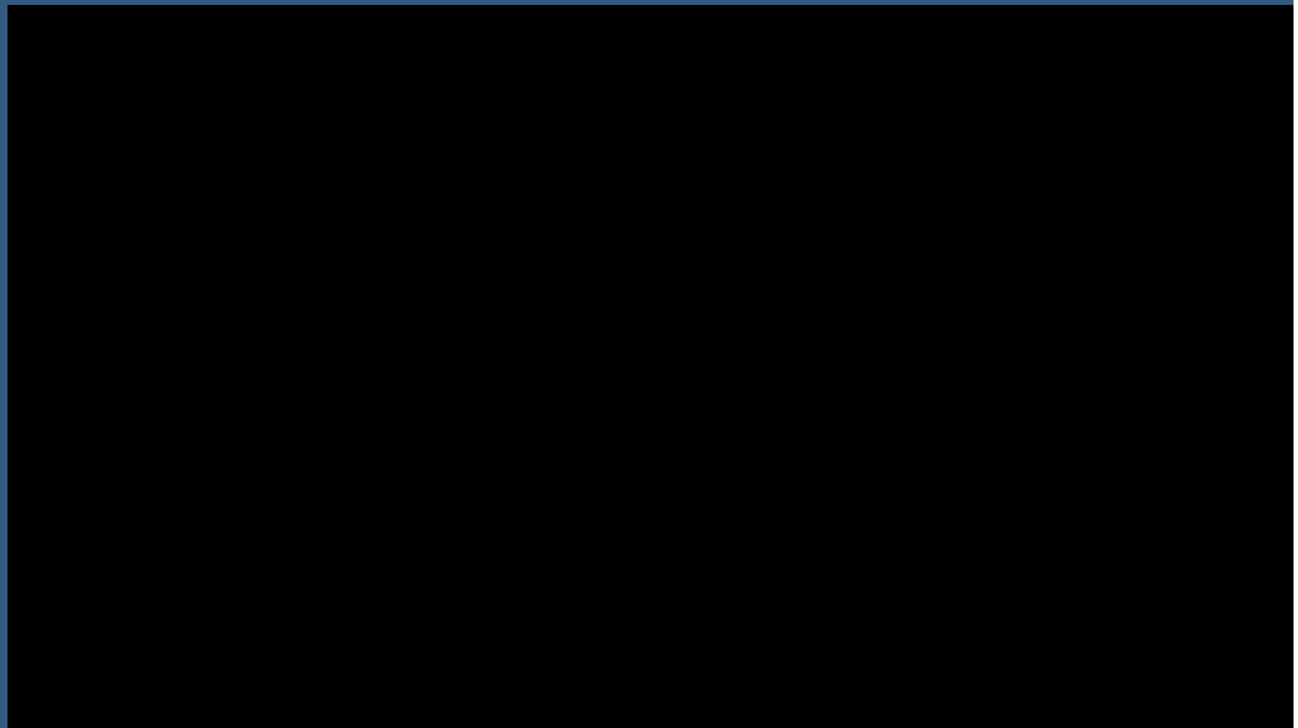


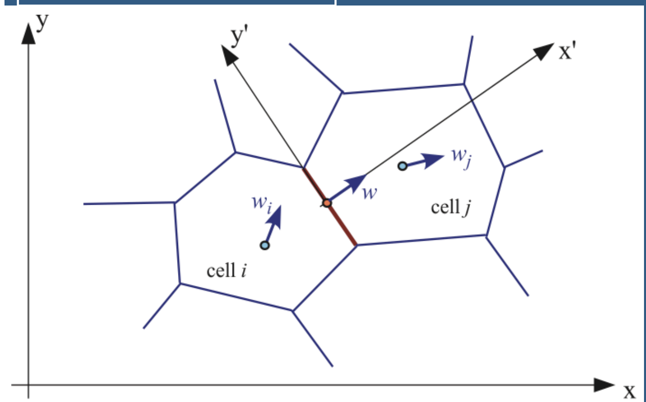
- A (106.5 Mpc)^3 box run to z=0
- Baryonic resolution: 1.3×10^6 M_{sun}
- Resolution elements: 2×1820^3
- N-body+hydro with Arepo
- Galaxy formation physics (SF, winds, AGN…)
- Gravitational spatial resolution: 0.7-1.4 ckpc
- WMAP-7 cosmology
- 10 $M>10^{14}M_{sun}$ halos @ z=0
- $>10^3$ $M\approx10^{12}M_{sun}$ halos @ z=0

Arepo: Godunov scheme on a moving Voronoi mesh



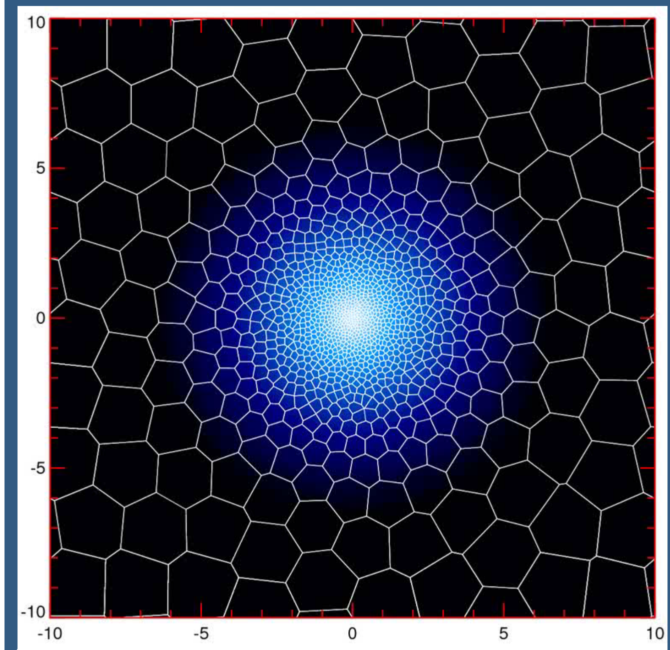
Springel 2010



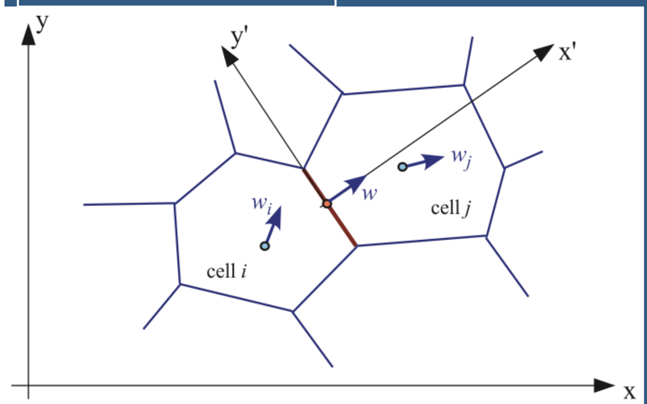


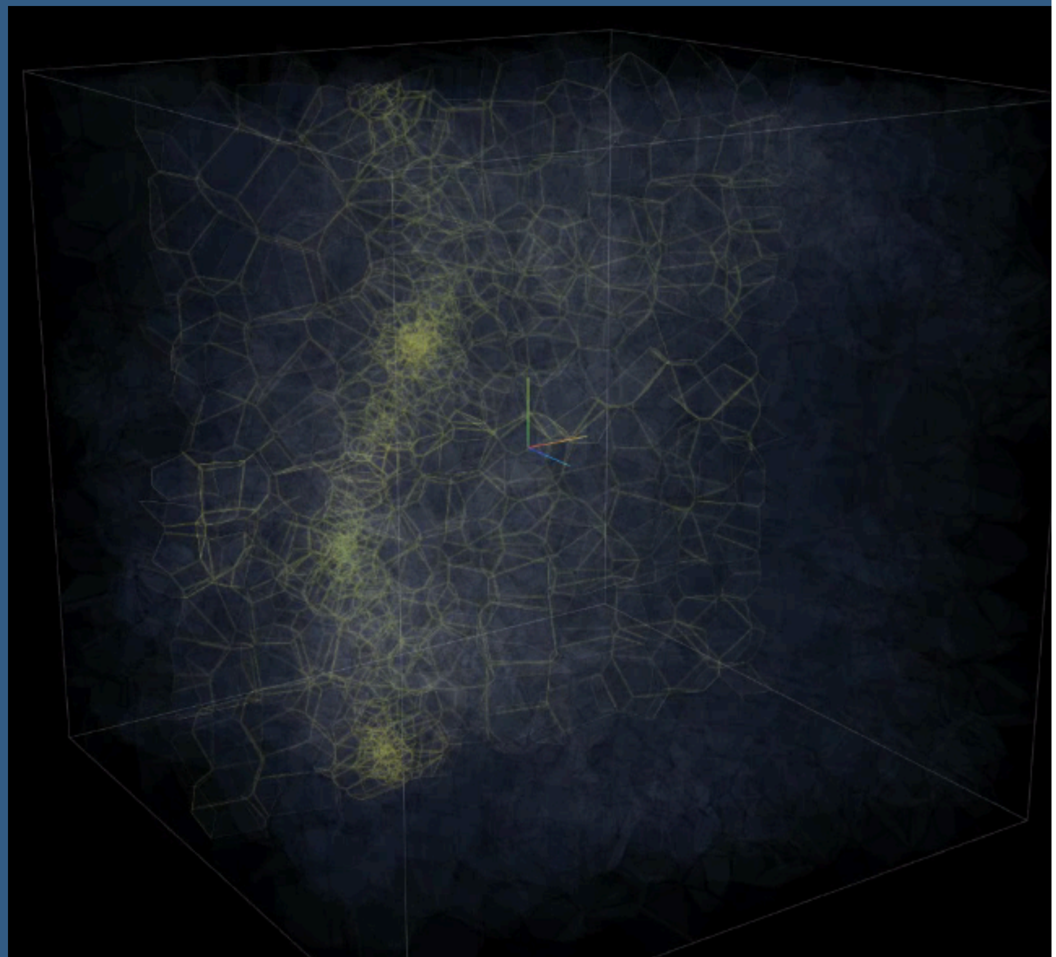
Courtesy of Dylan Nelson

Arepo: Godunov scheme on a moving Voronoi mesh



Springel 2010





Courtesy of Dylan Nelson

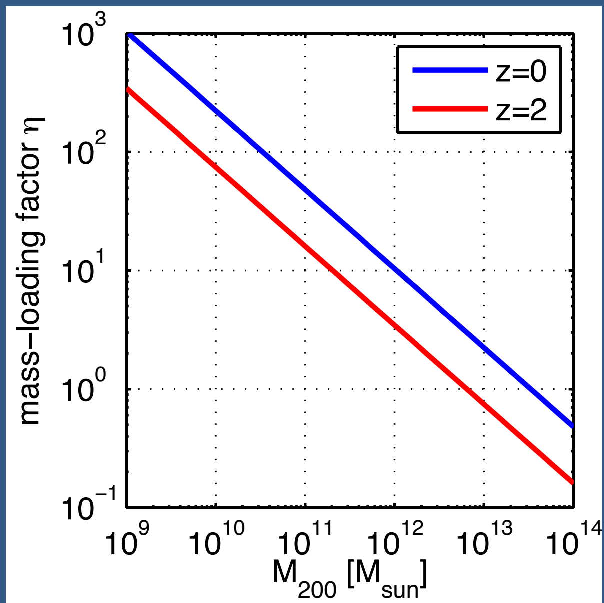
Vogelsberger, Genel et al. 2013

Galaxy formation physics

- Galactic winds

(à-la Springel & Hernquist 2003)

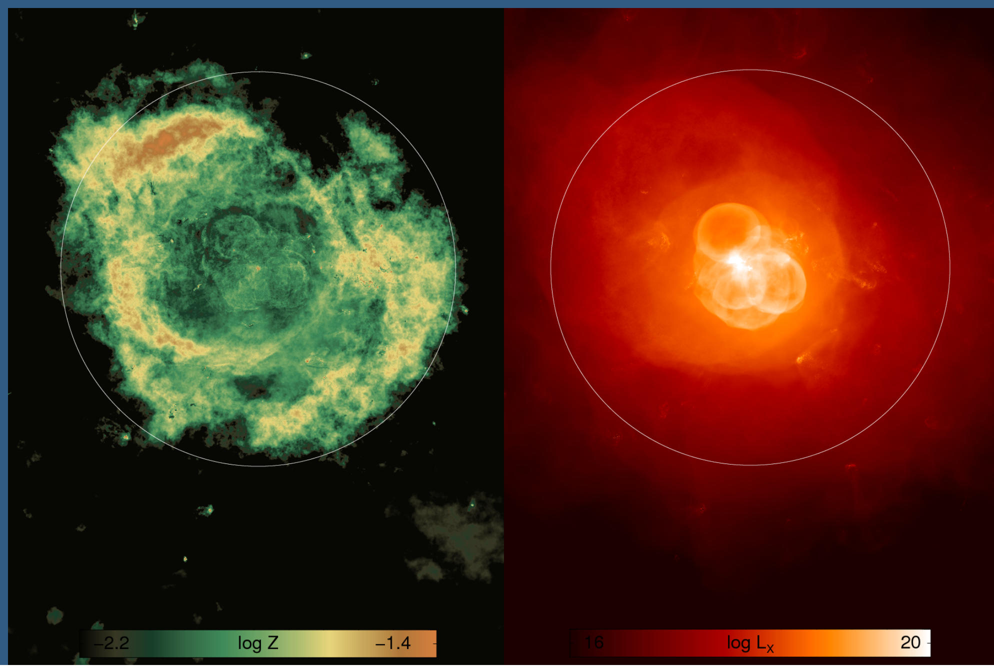
  - Kinetic
  - Energy scaling
  - Decoupled



- Black Holes

(à-la Springel 2005, Sijacki 2007)

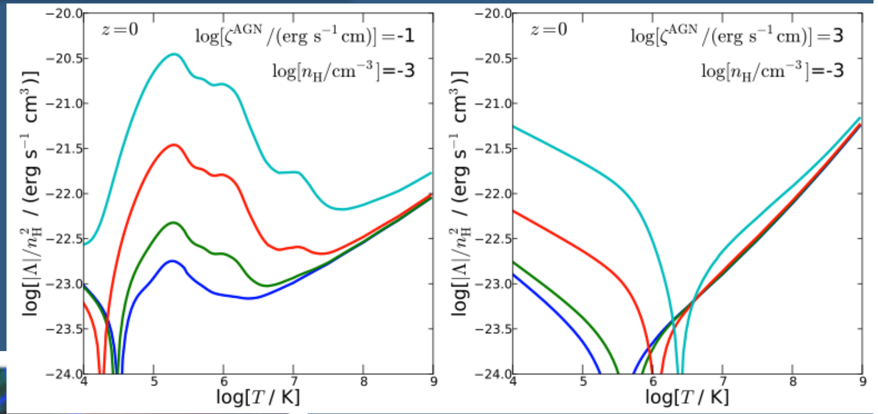
  - Bondi accretion & mergers
  - Thermal ('quasar-mode'), bubble ('radio-mode'), and radiative feedback

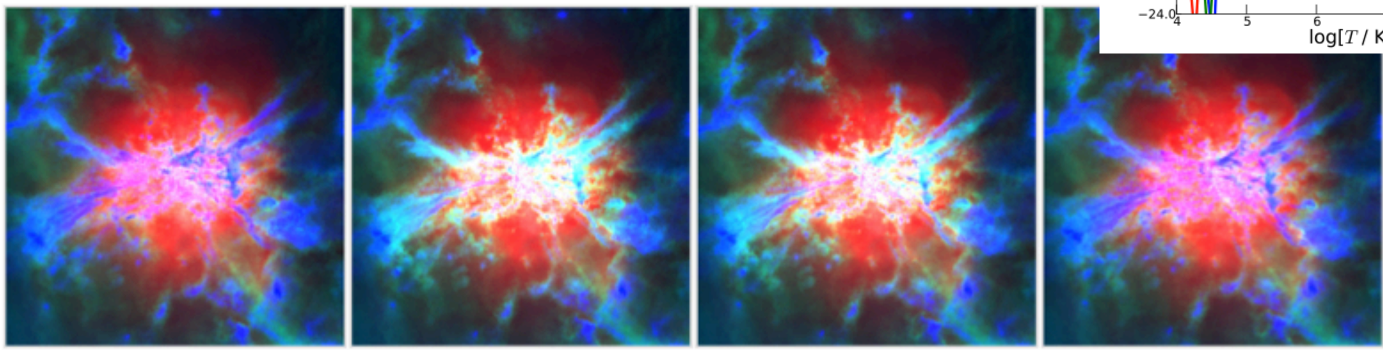


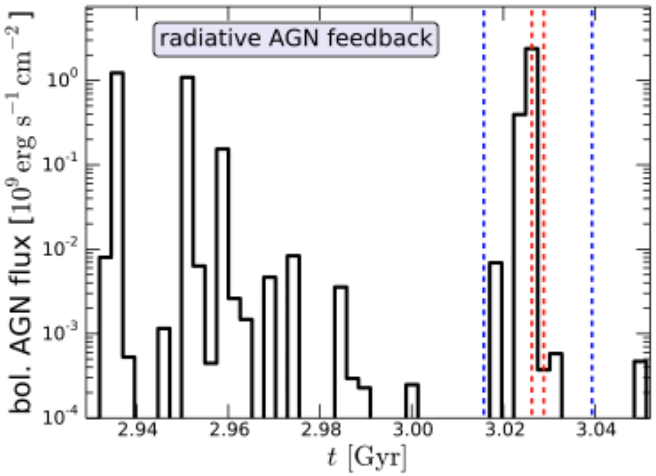
Radiative AGN feedback

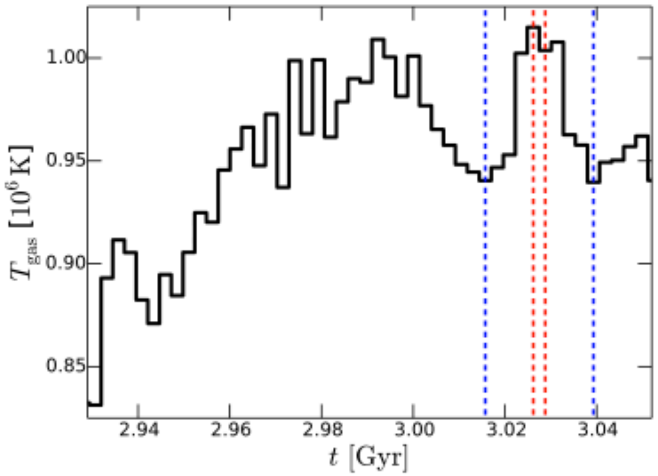
Modified heating and cooling

in halos around accreting BHs





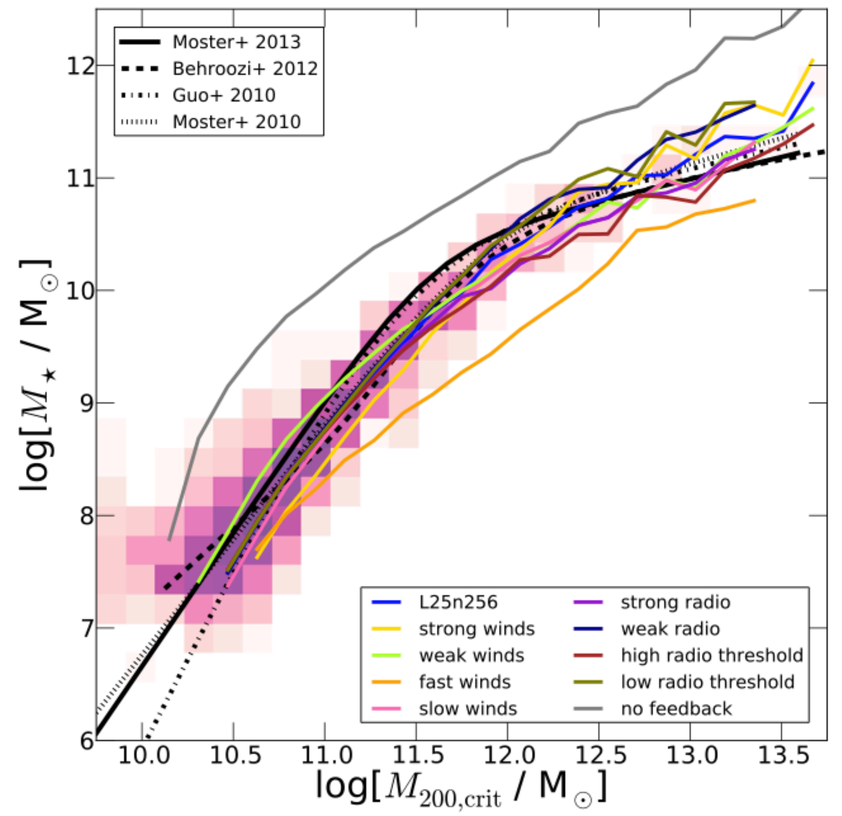




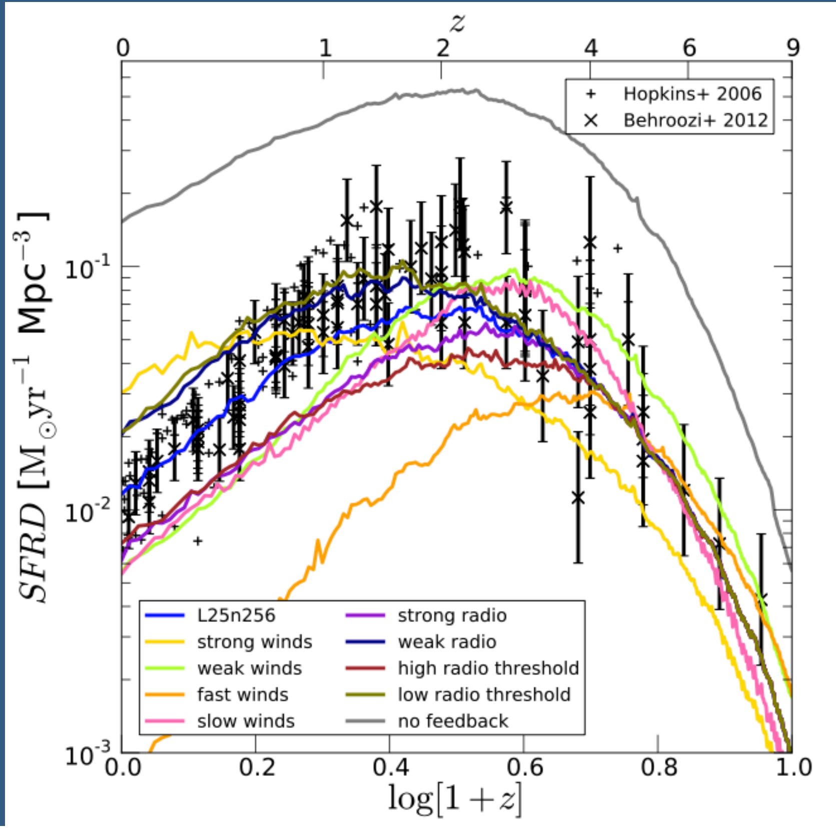
Tuning feedback parameters

Constraints used for tuning feedback parameters:

Baryon conversion efficiency



Cosmic SFR density

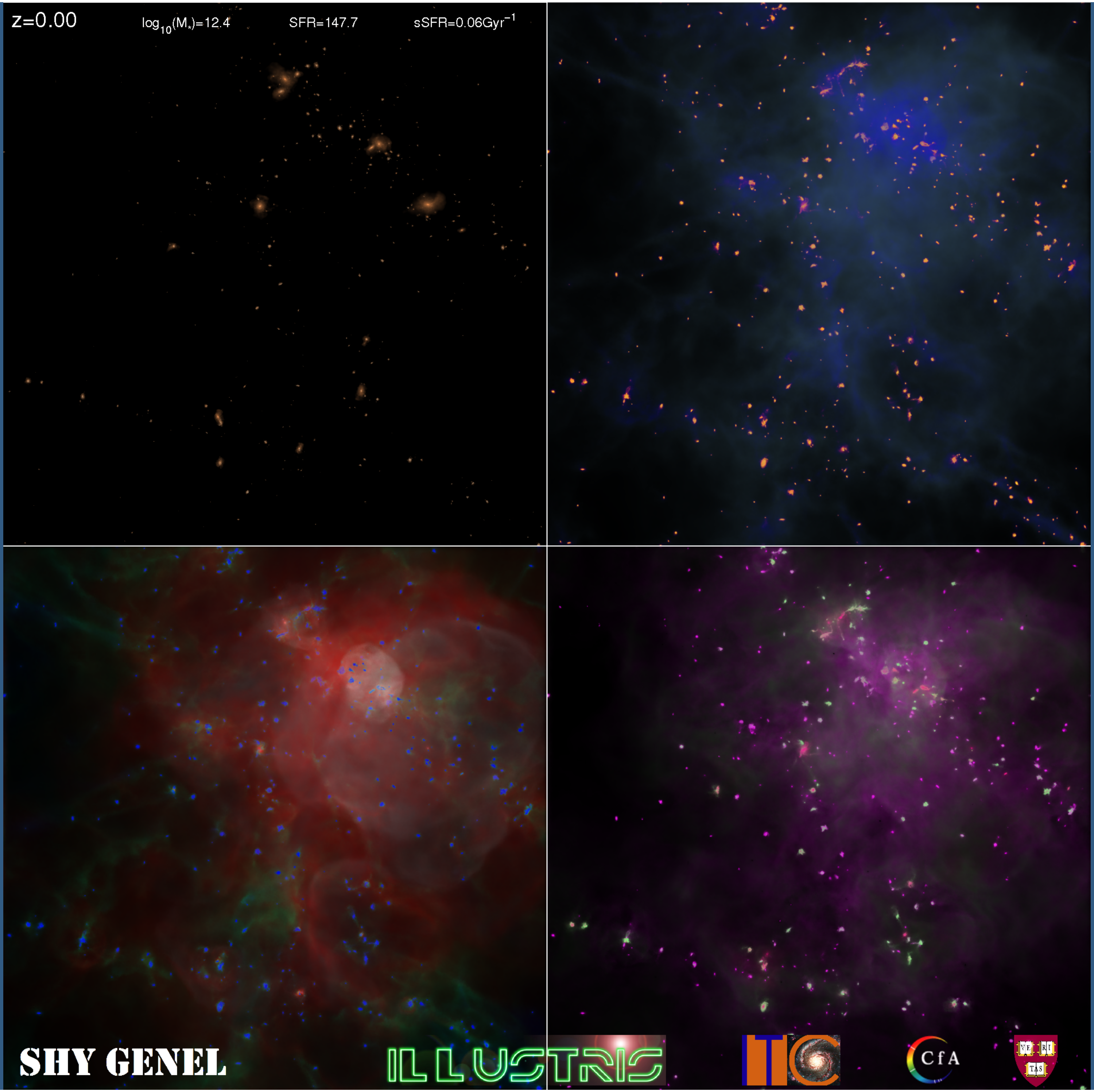


Vogelsberger, Genel et al. 2013


stars
z=10.00
log10(M*)=8.2
SFR=4.6
sSFR=28.14Gyr-1
ρgas
Tgas
Zgas
SHY GENEL
ILLUSTRIS
CfA

stars

ρ_{gas}



T_{gas}

Z_{gas}

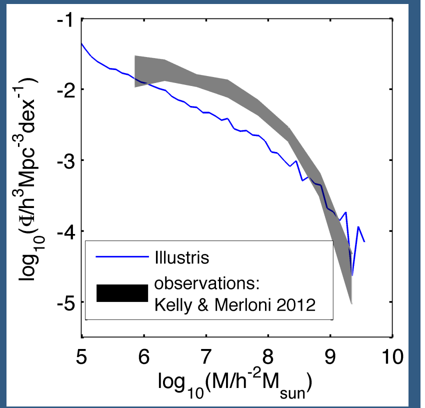
Illustris: results

I. Galaxy bimodality

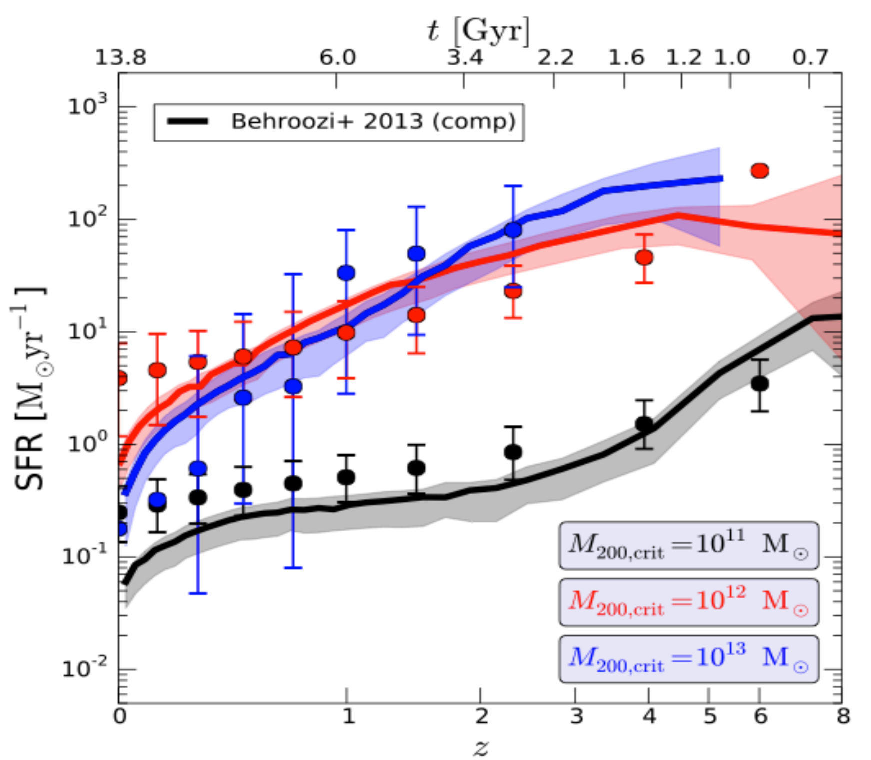
Cosmic star-formation rate history

Contributions from different halo masses reproduced well,

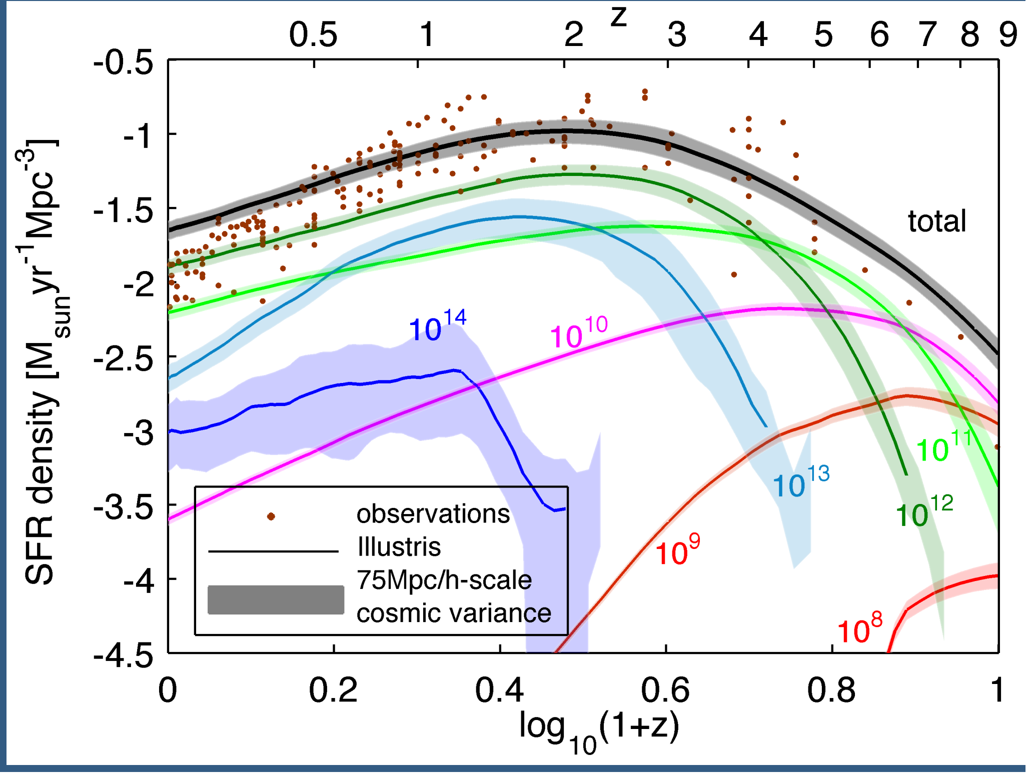
except too much SF in 10^{11}-$10^{12}M_{sun}$ halos @ z<~1



SFR in different halo masses



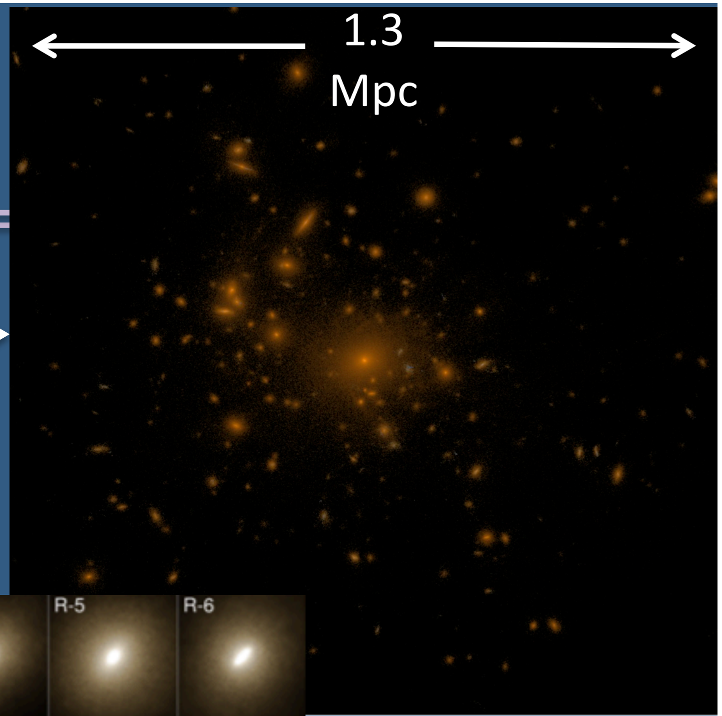
Cosmic SFR density



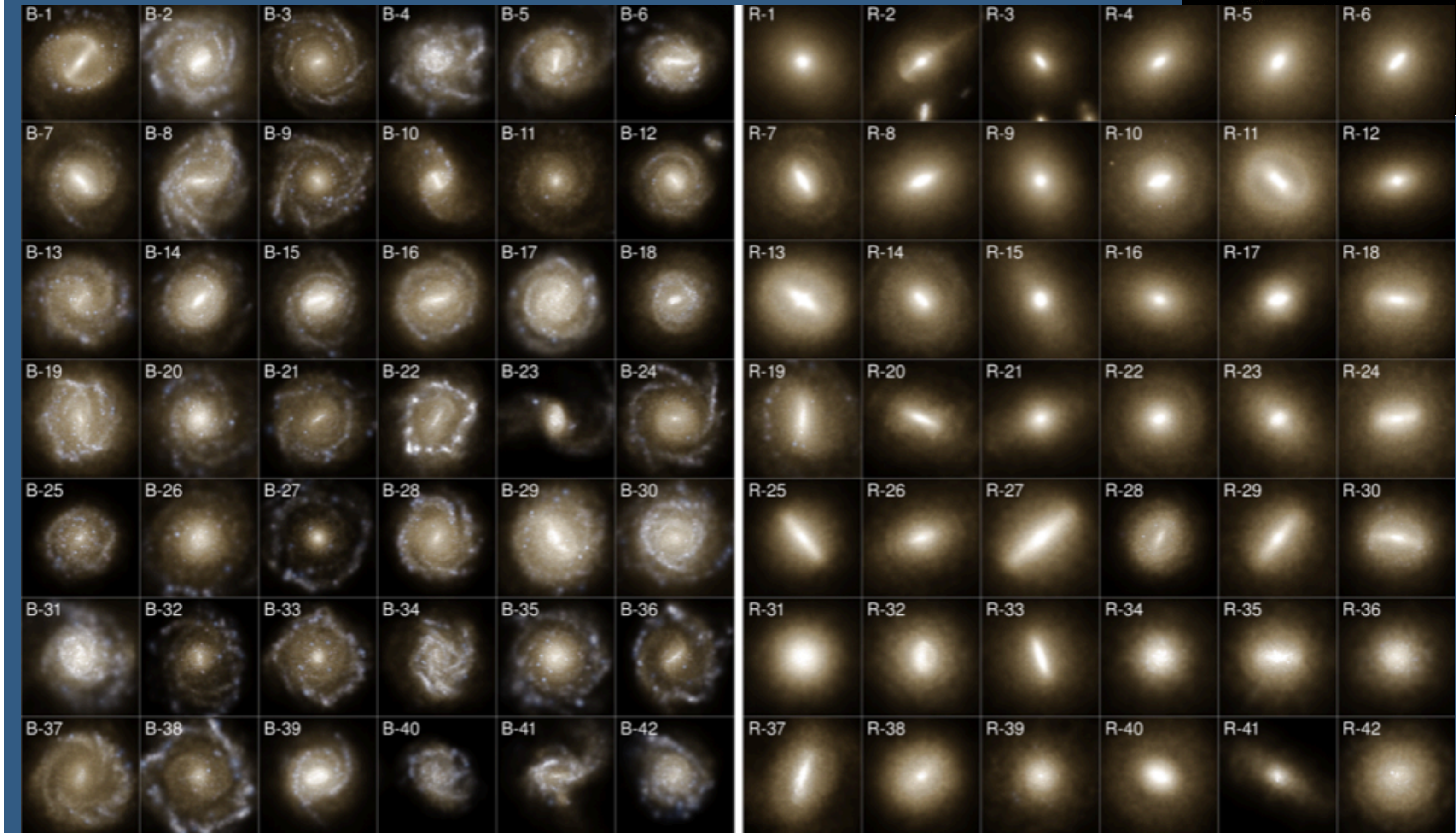
Galaxy morphological bimodality

Galaxy bimodality

$2{\times}10^{14}M_{sun}$
halo

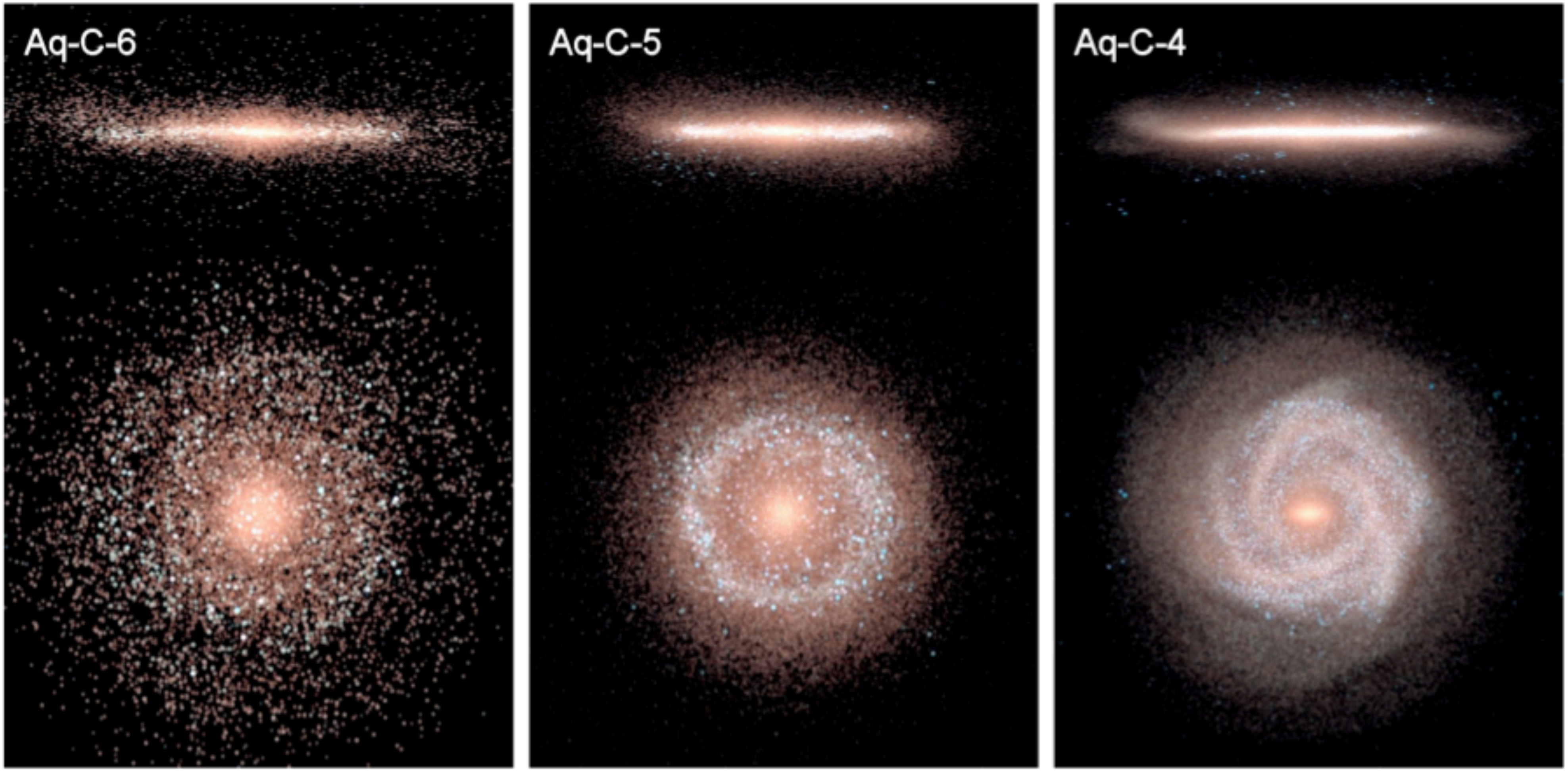


$10^{12\text{-}13}M_{sun}$ halos



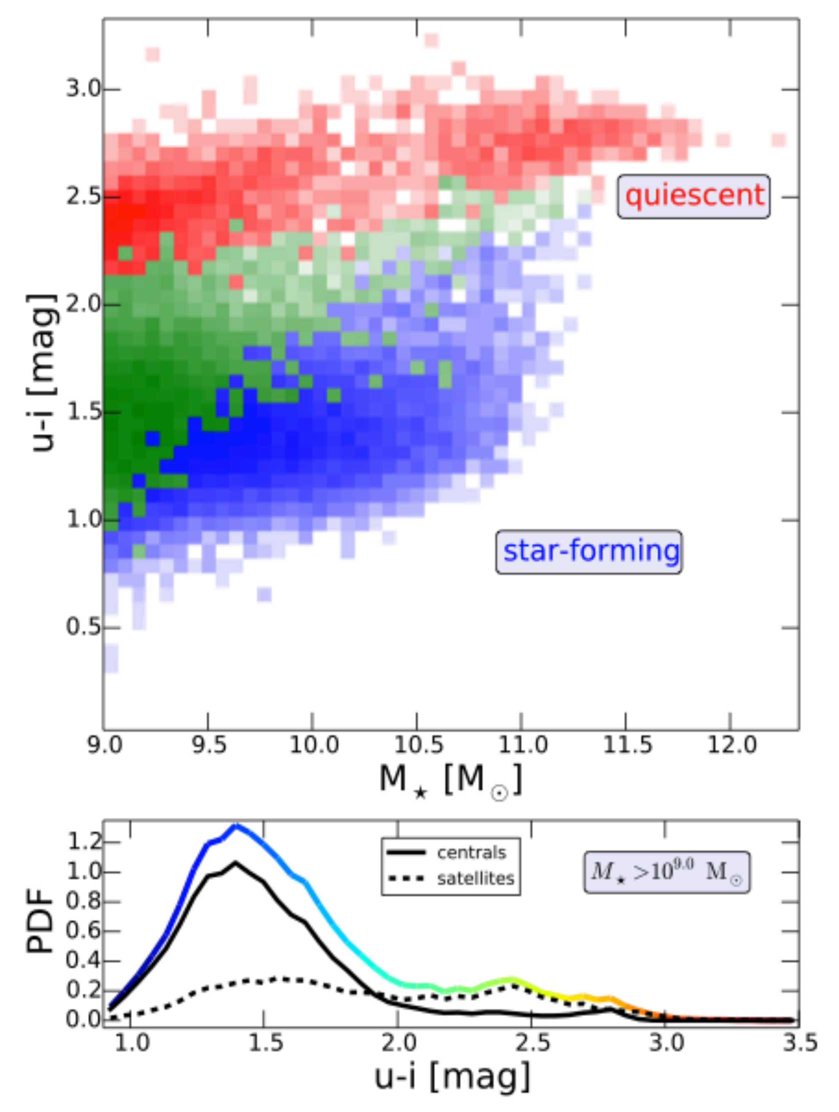
Disk galaxies and resolution effects

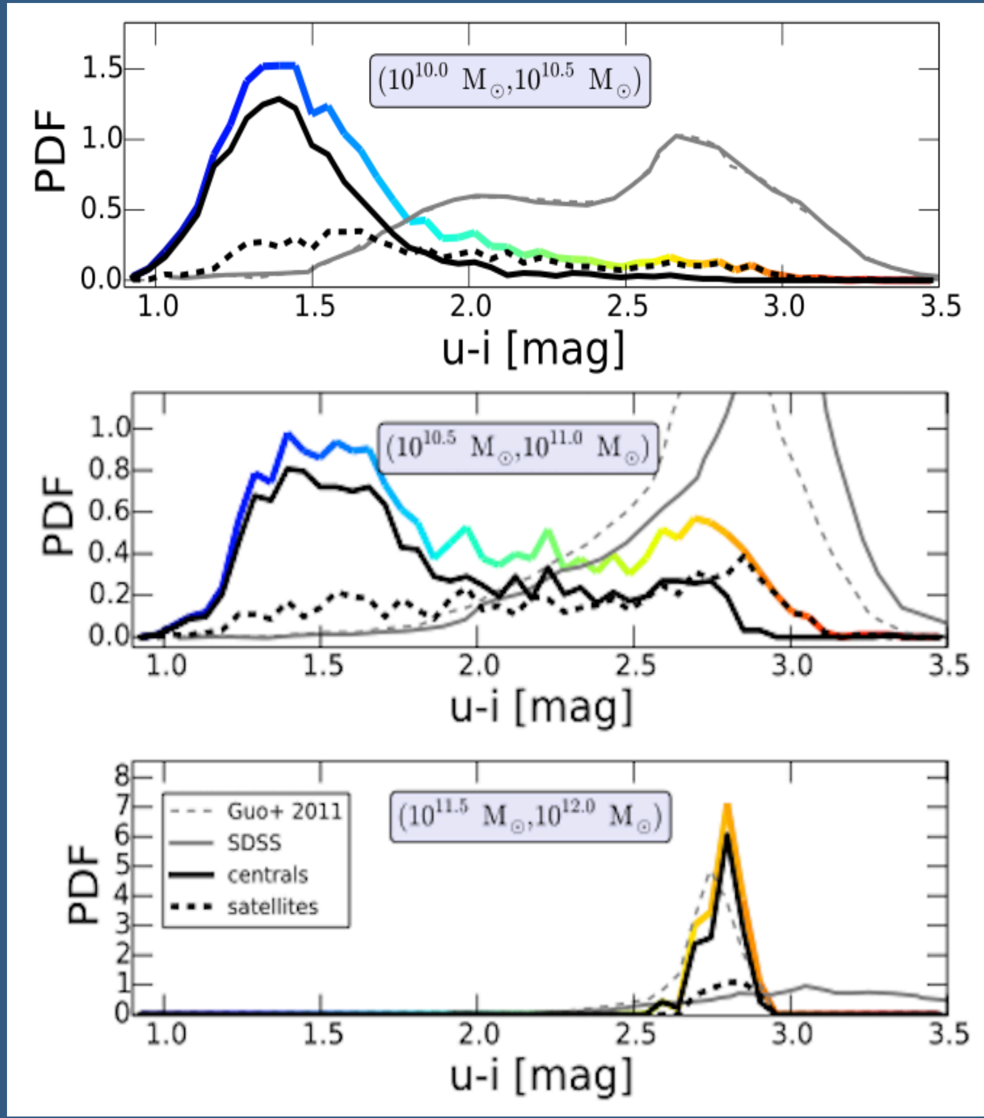
Increasing resolution →



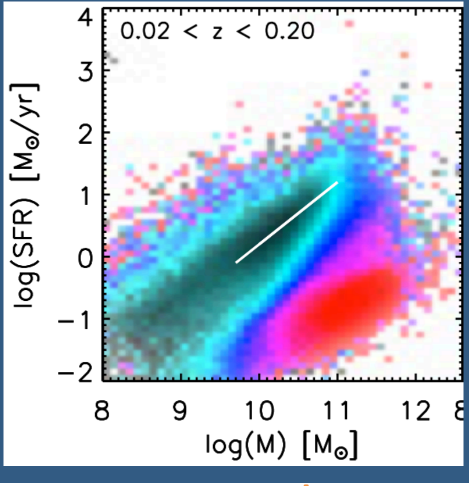
Illustris resolution "Aquila" project resolution Marinacci et al. 2013

Galaxy color bimodality

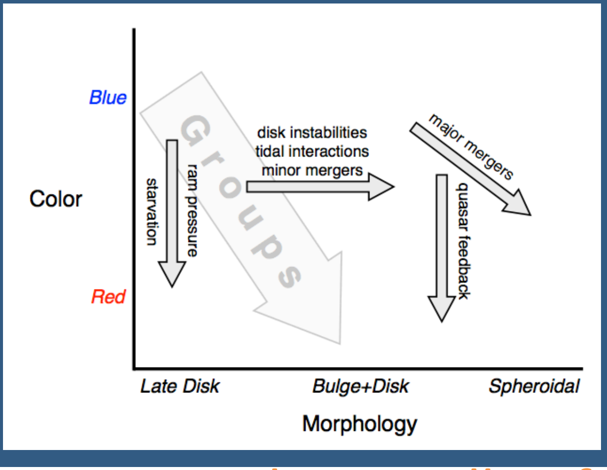




SF activity and galaxy structure at z=0

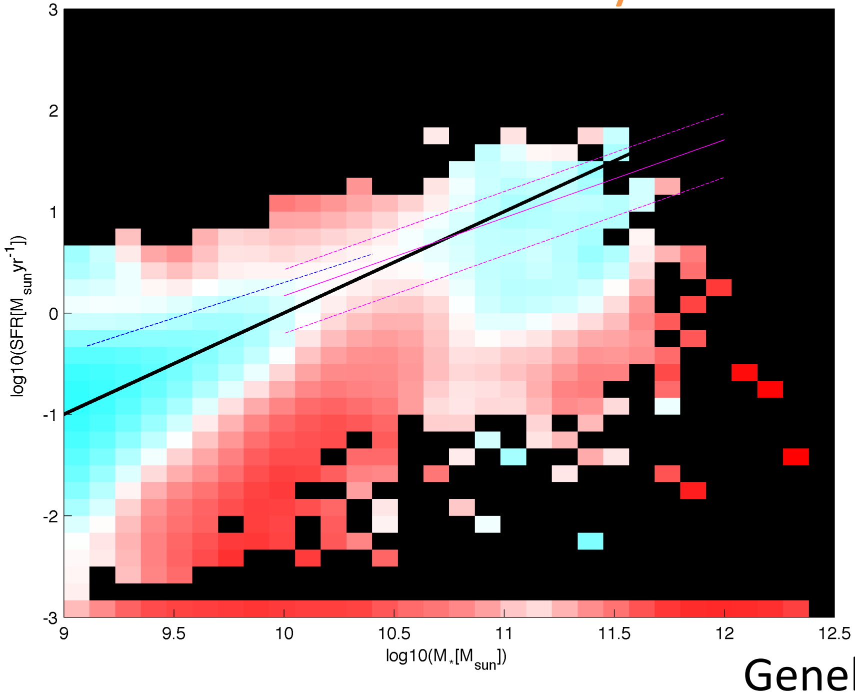


Wuyts+ 2011

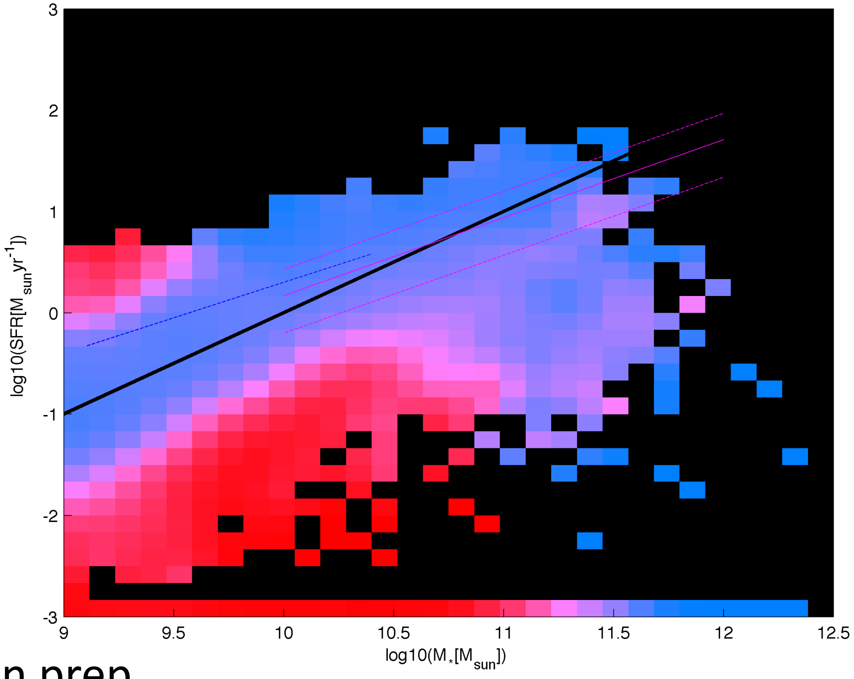


George+ 2013

Color: circularity



Color: satellite fraction



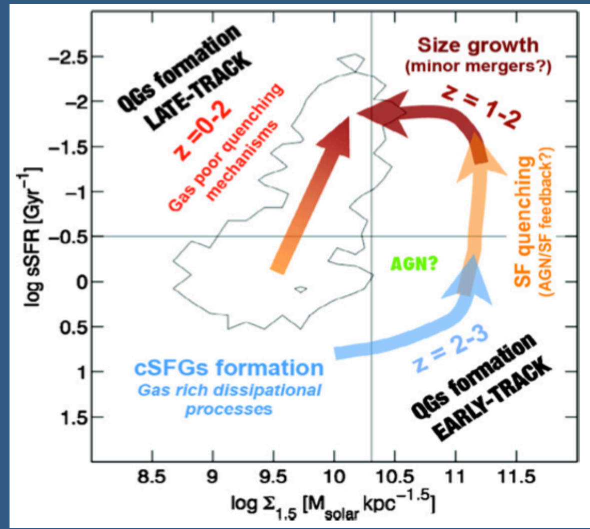
Genel et al. in prep.

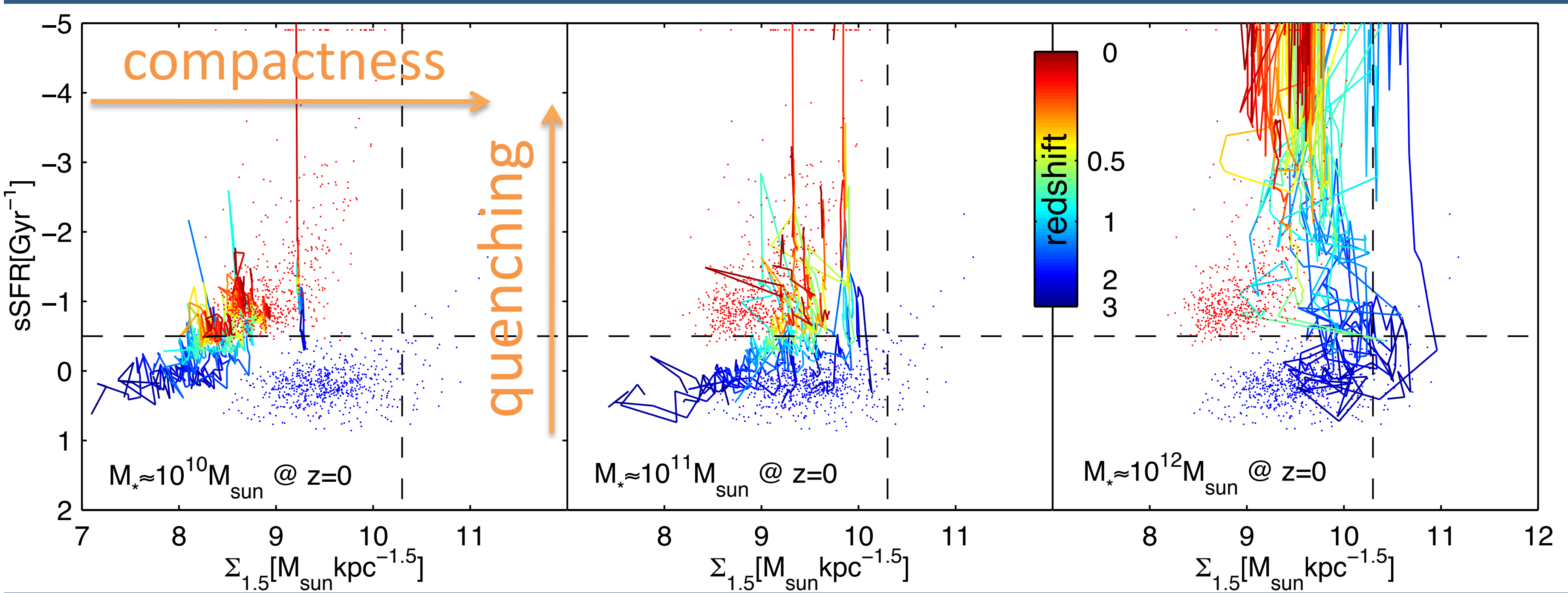
Co-evolution of size and SFR

Barro+ 2013

- Massive galaxies quench early on, and then `inflate’

- Low-mass galaxies quench later, and gradually `compact’



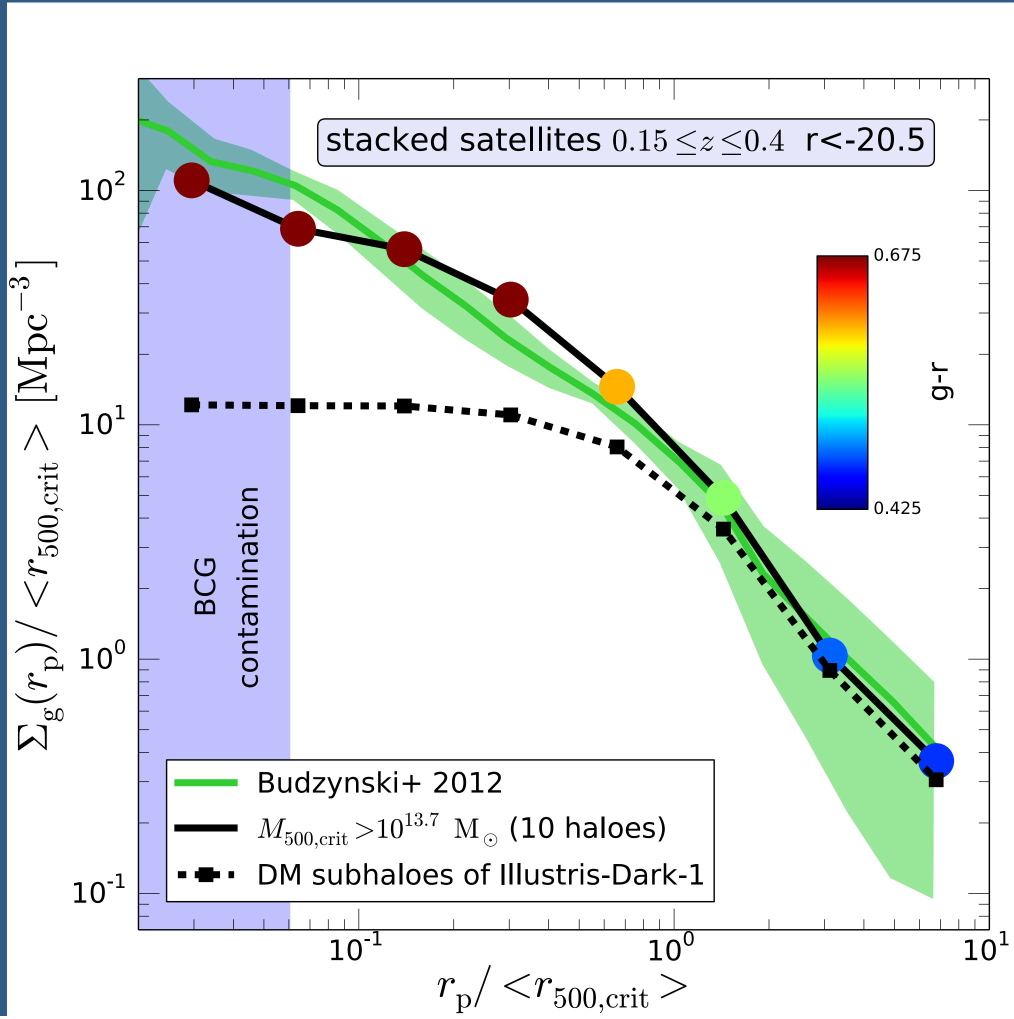


Illustris: results

II. Radial distribution of satellite galaxies

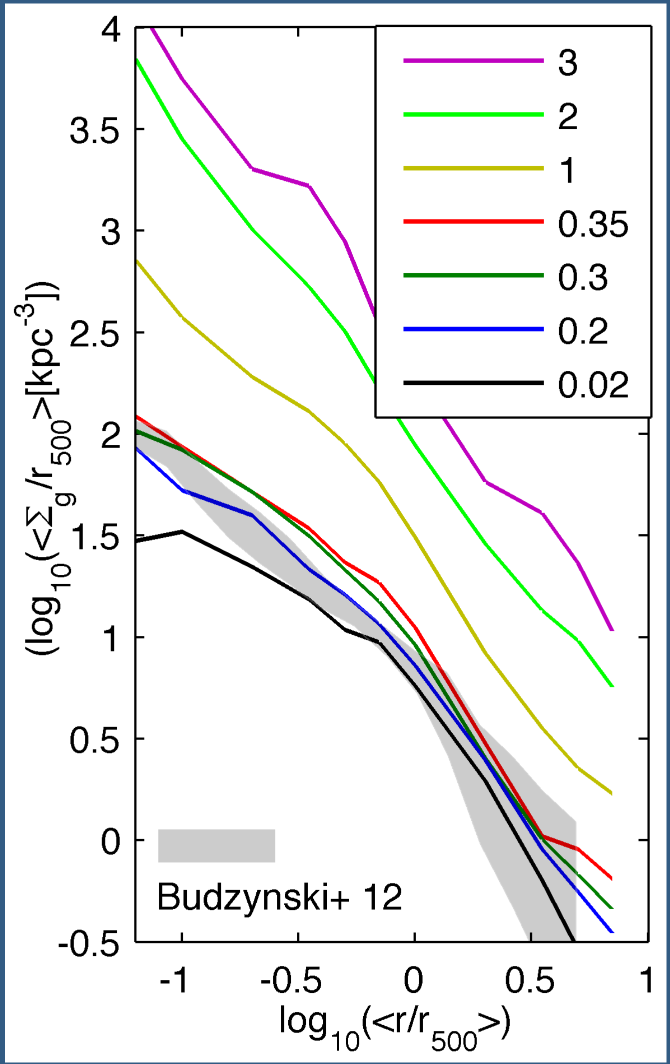
Satellite galaxy profiles

- Radial profiles of bright galaxies (M_r<-20.5) around the ≈100 most massive BCGs (M_{halo}>≈$10^{13}M_{sun}$)
  - Good match to observations
  - Significantly more concentrated than subhalos from DM-only simulations
  - Color gradient



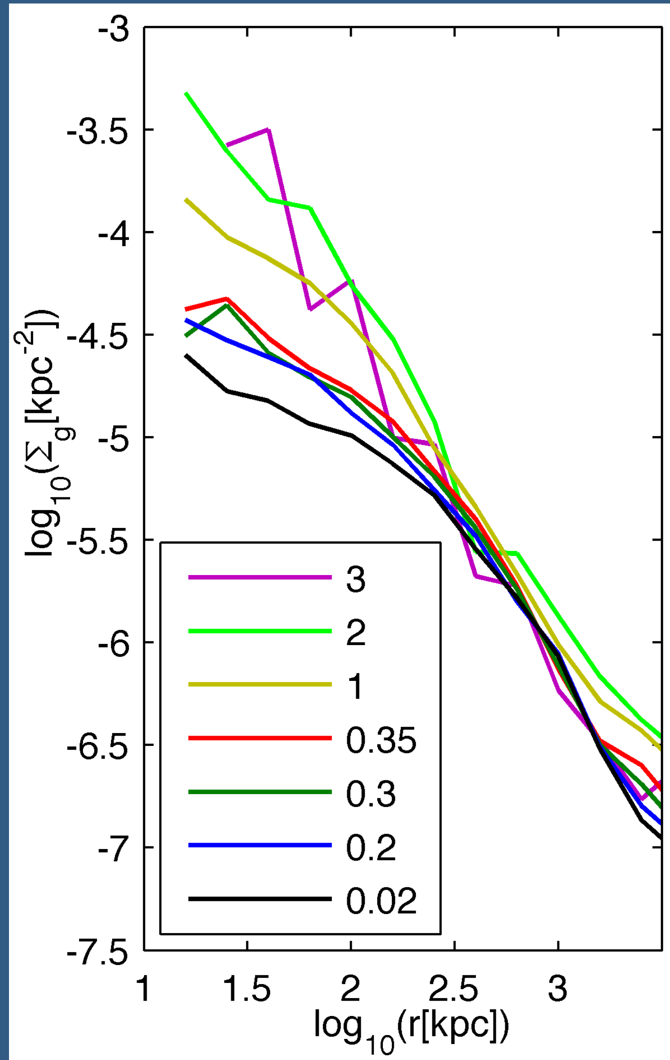
Satellite galaxy profiles

- (Almost) no evolution @ z≈0.15-0.4, in agreement with observations
- Strong evolution towards higher redshift



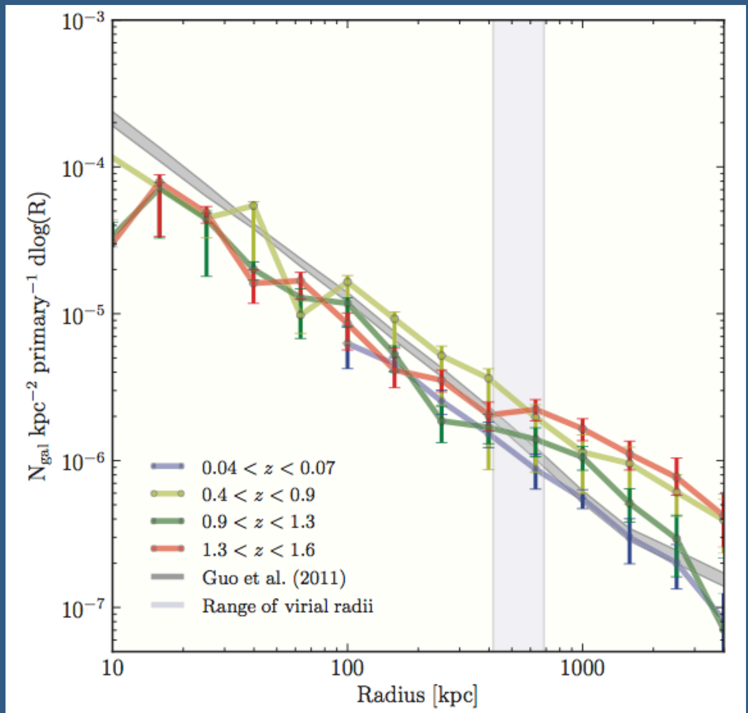
Satellite galaxy profiles

- (Almost) no evolution @ z≈0.15-0.4, in agreement with observations
- Strong evolution towards higher redshift
- But in physical (non-normalized) units:
    - At r<300kpc, evolution is significantly reduced
    - At r>300kpc, no evolution is found out to z≈1.6

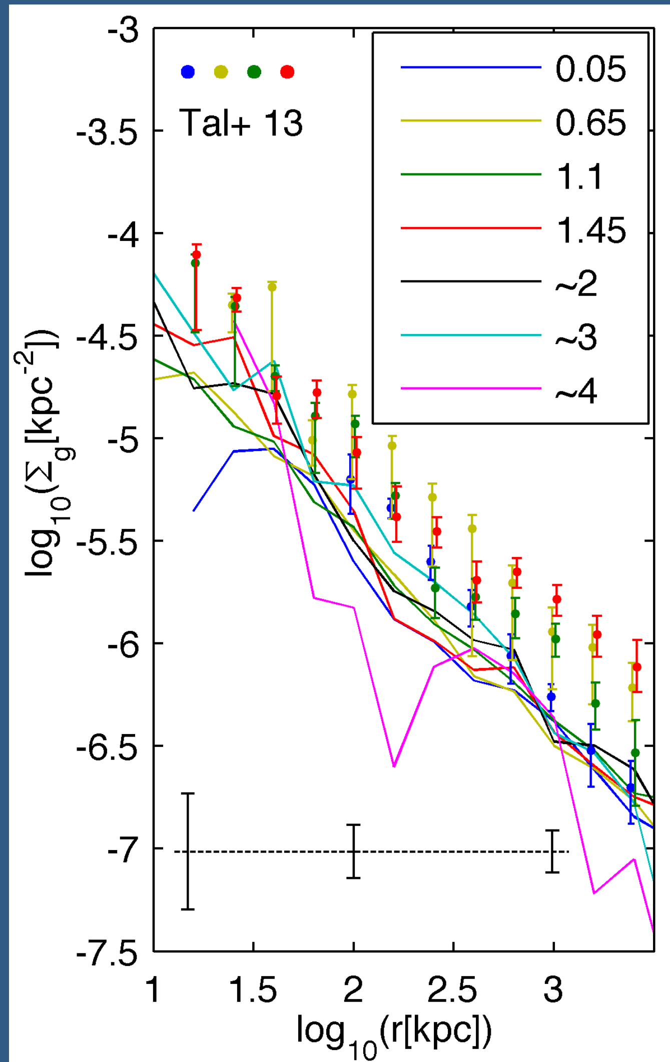


Satellite galaxy profiles

- When satellite selection is by mass ratio (rather than fixed luminosity), no evolution is observed out to z≈4, at all radii



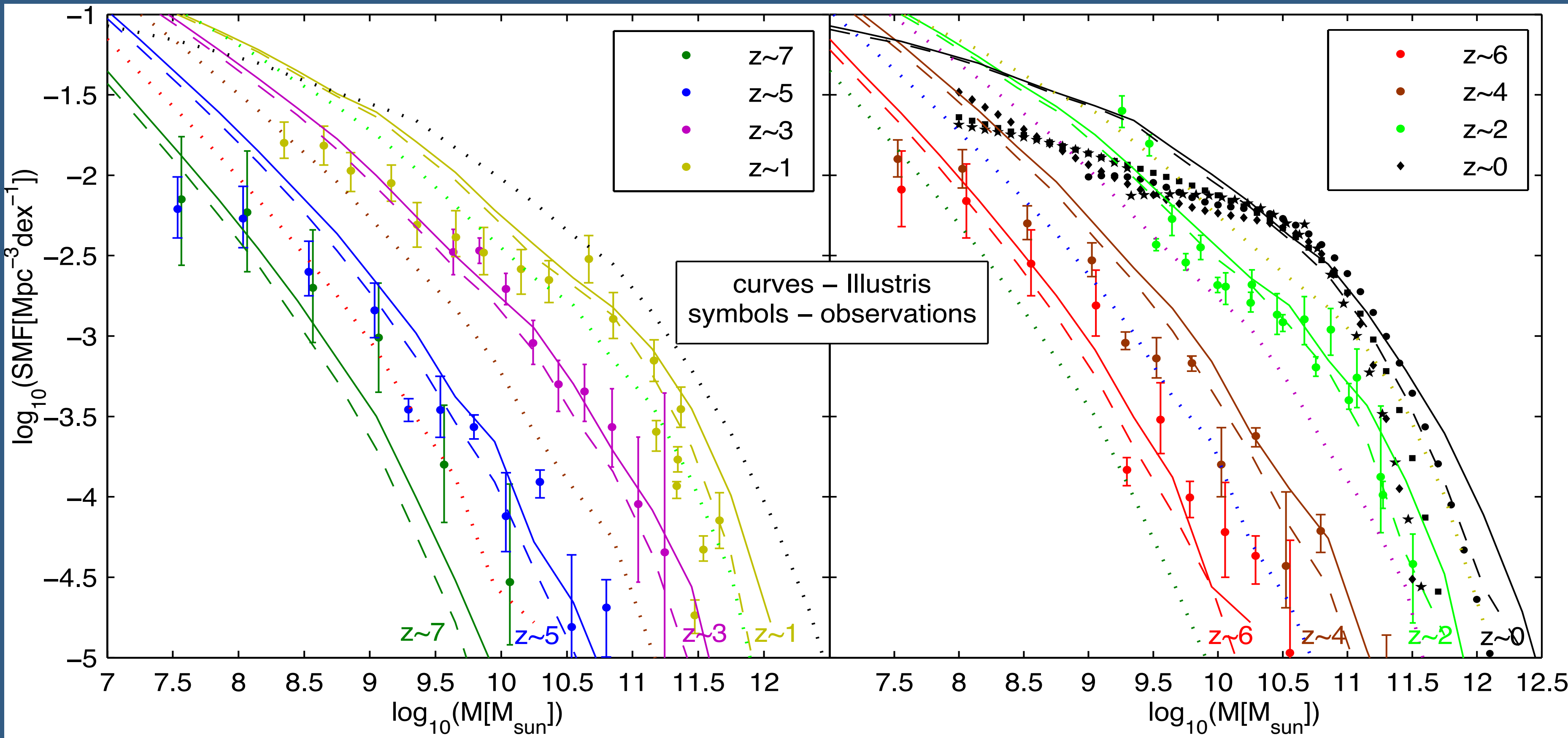
Tal et al. 2013



Illustris: results

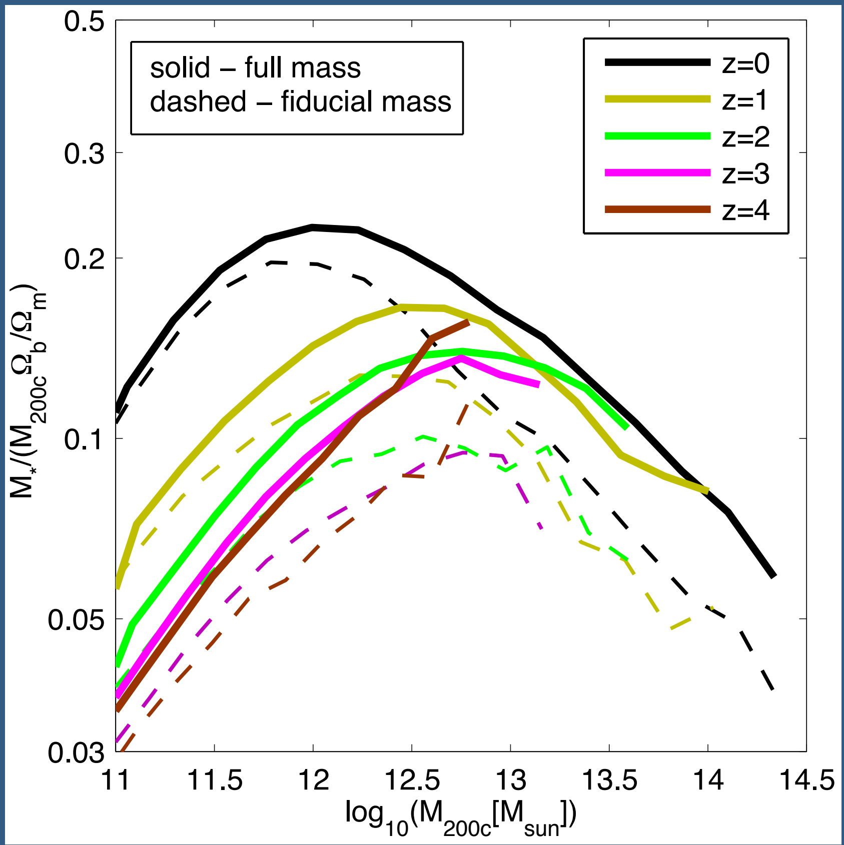
III. High-z galaxies

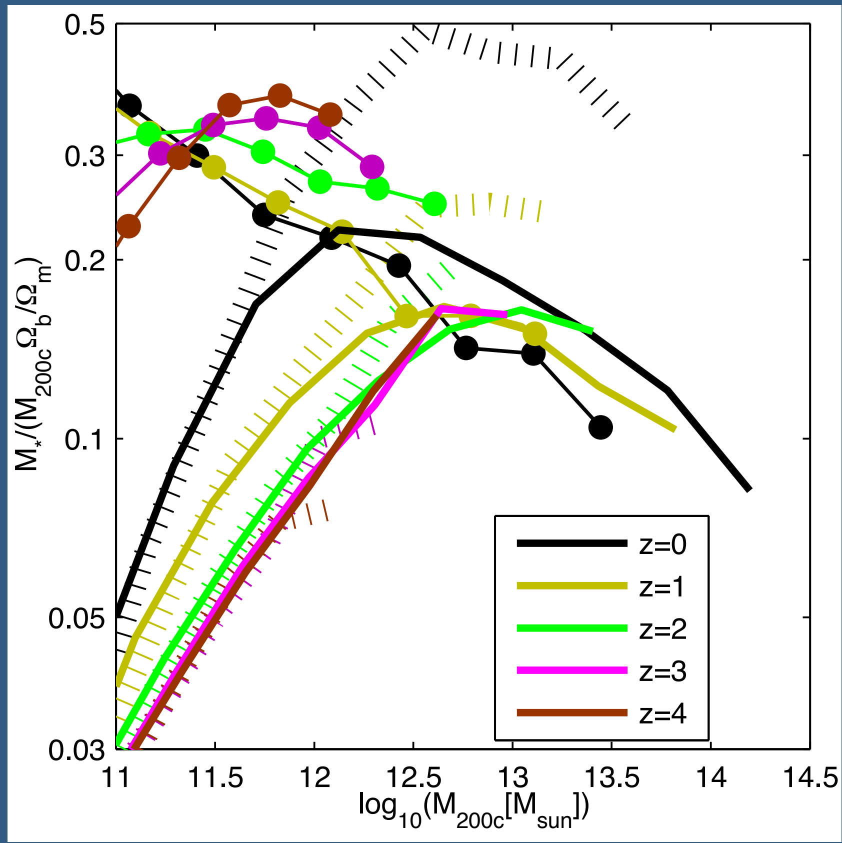
Stellar mass functions @ 0 ≤ z ≤ 7



- Potential caveats:
  - Faint-end slope too steep
  - Suppression at massive-end too weak @ z<1

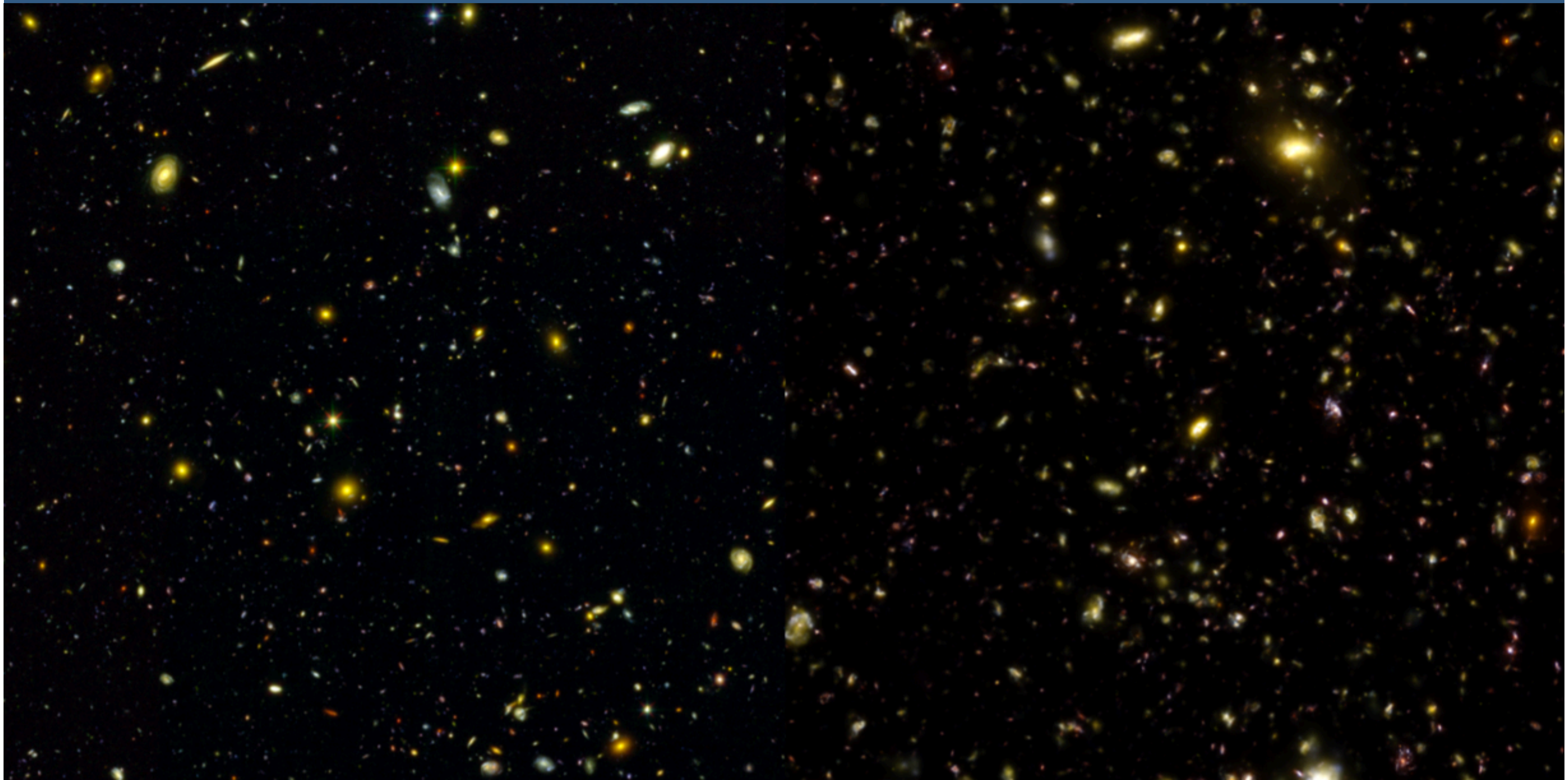
M_*-M_{halo} relation @ $0 \le z \le 4$



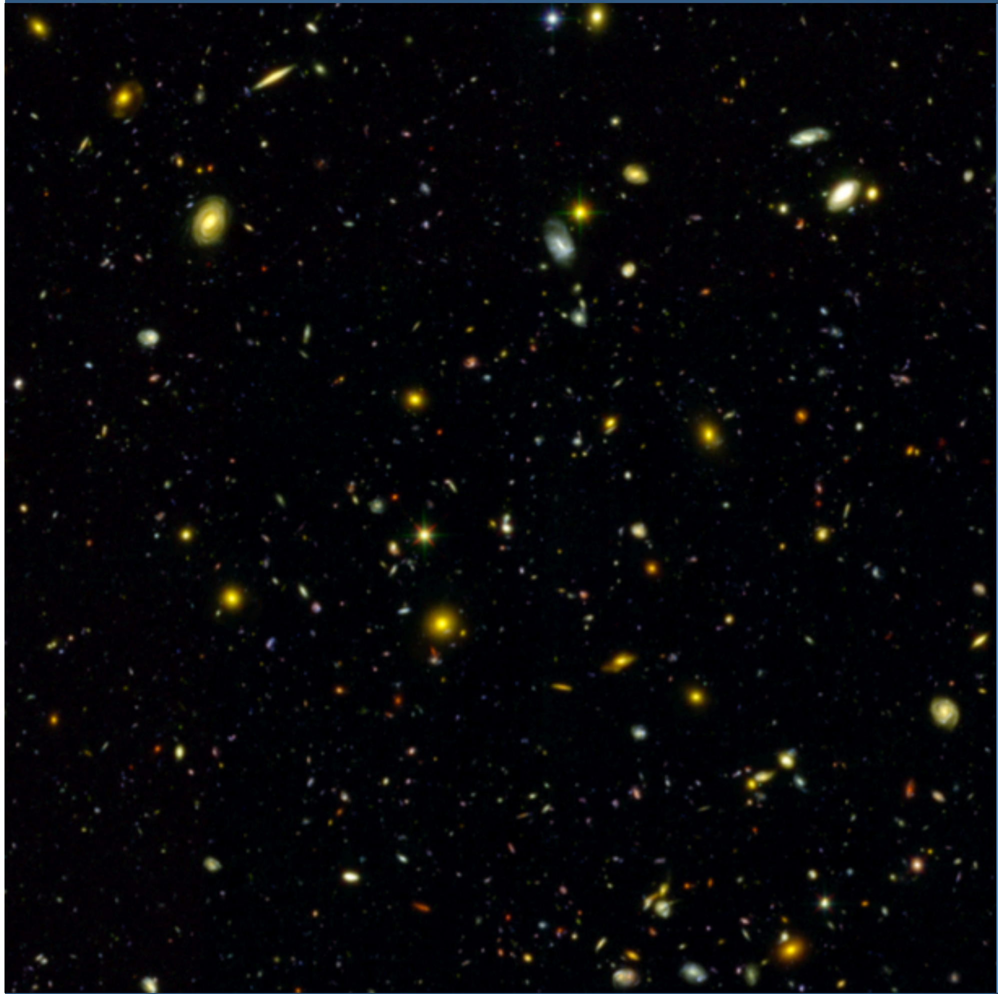


- Low-mass end: normalization increases with cosmic time
- High-mass end: no redshift evolution – conspiracy of galactic winds and AGN?

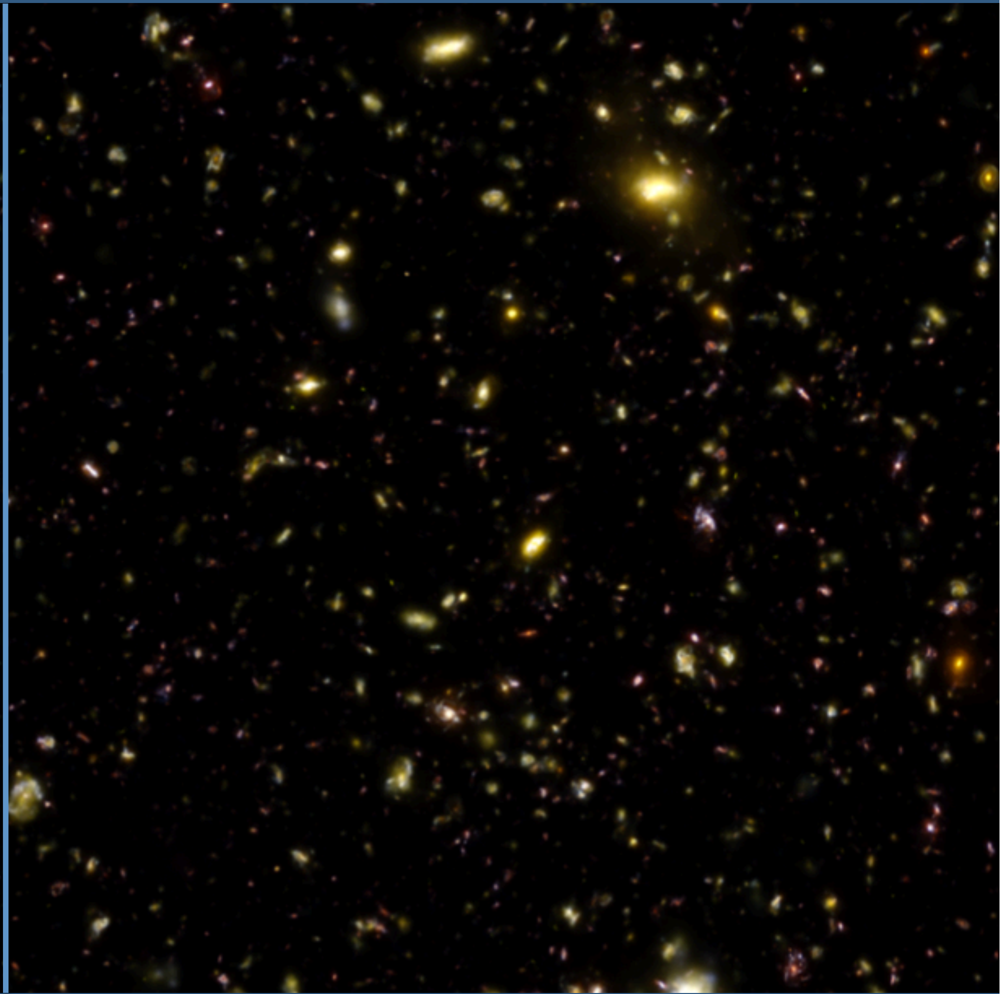
Mock HUDF



Mock HUDF



HST

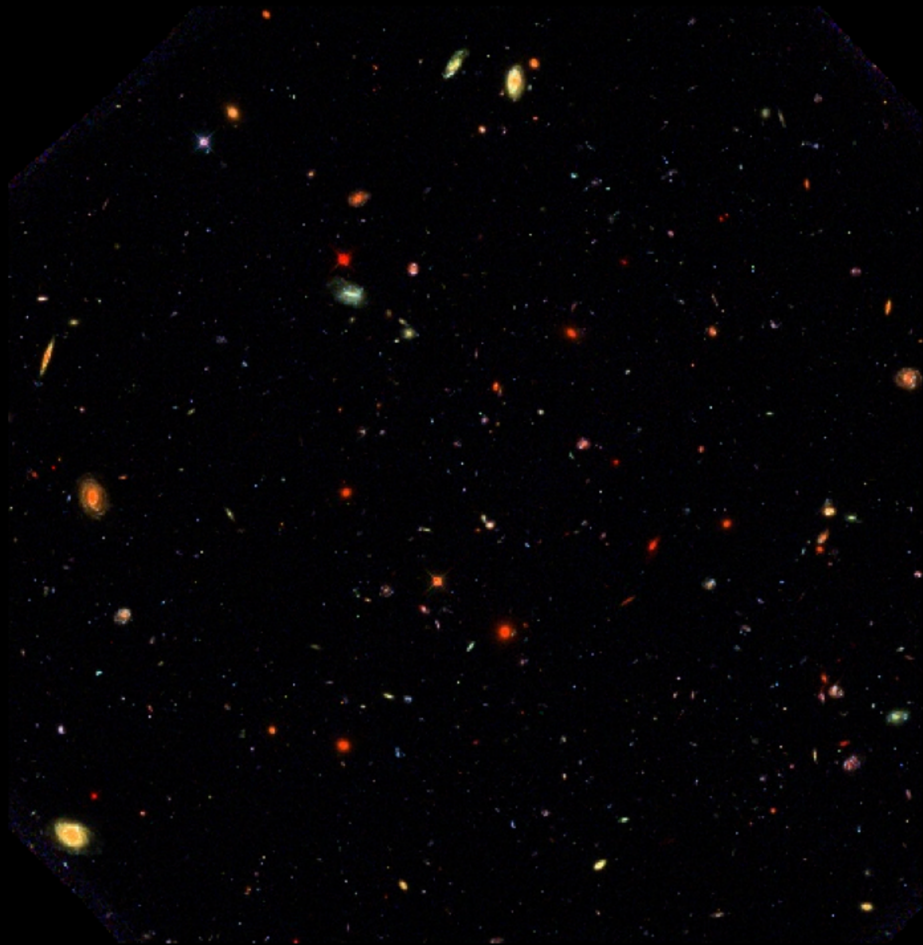


Illustris

Mock HST Deep Fields

old simulations

→ *too many stars*

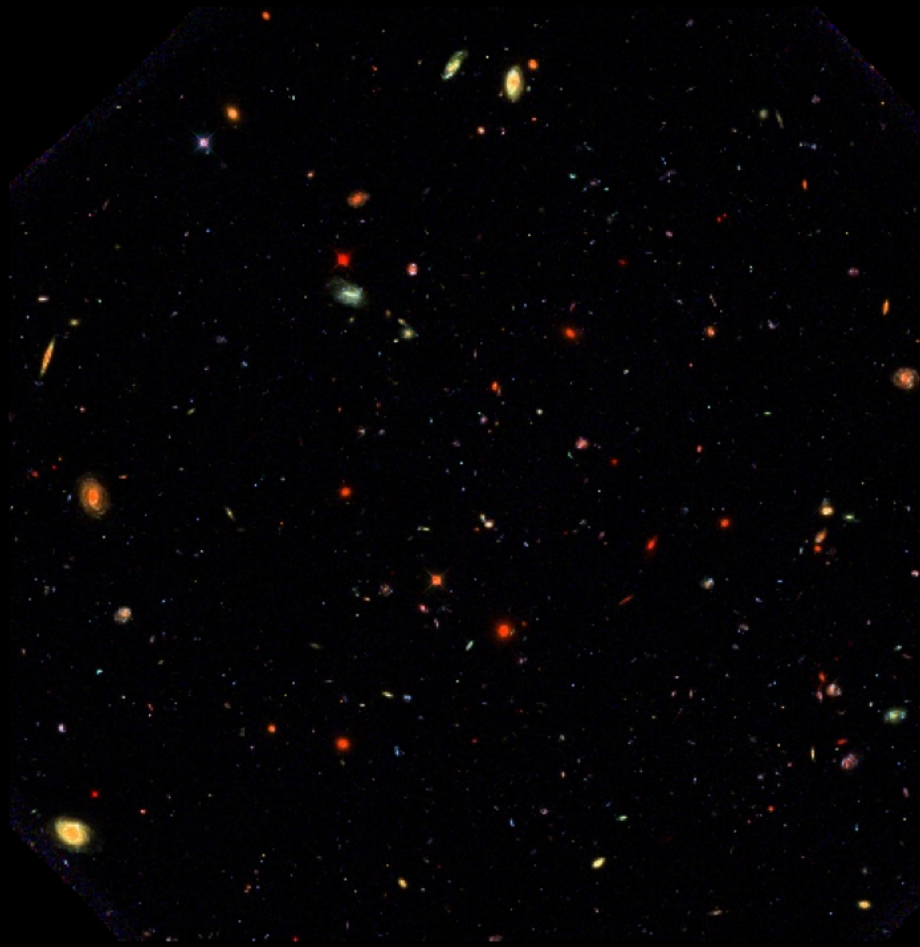


HST observation

Mock HST Deep Fields

+ metal line cooling
+ stellar mass loss

→ *even more (young) stars*

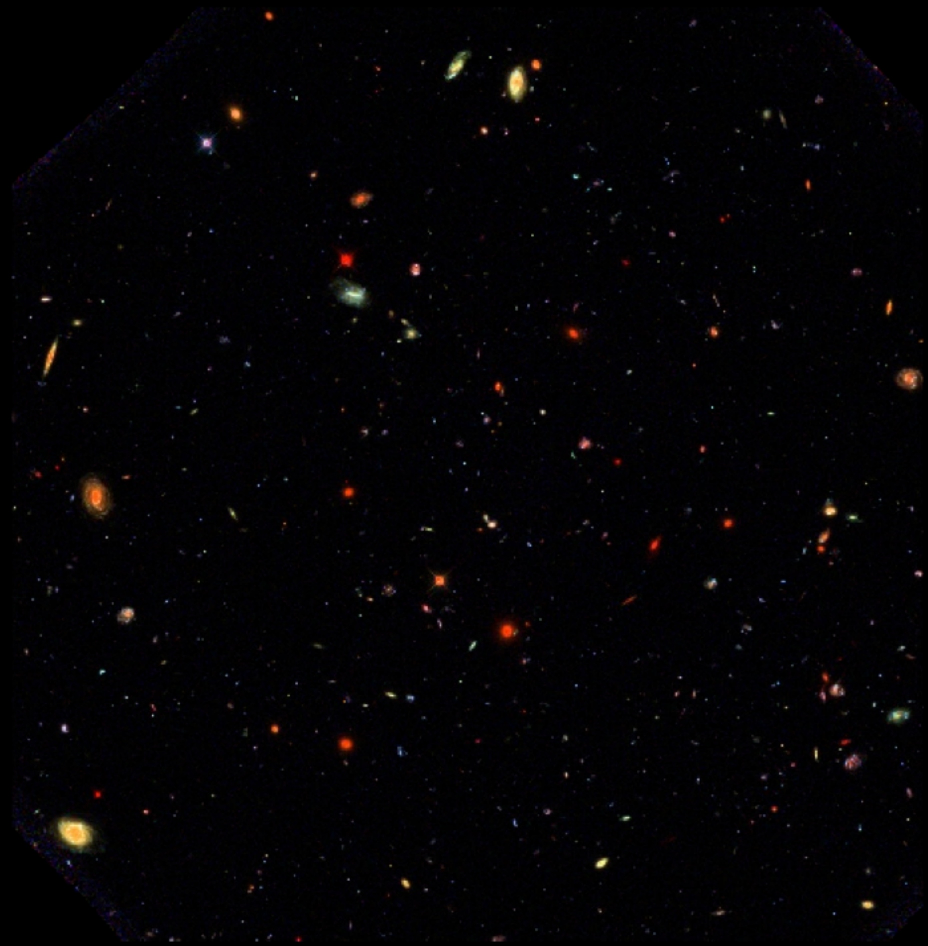


HST observation

Mock HST Deep Fields

+ SNII feedback

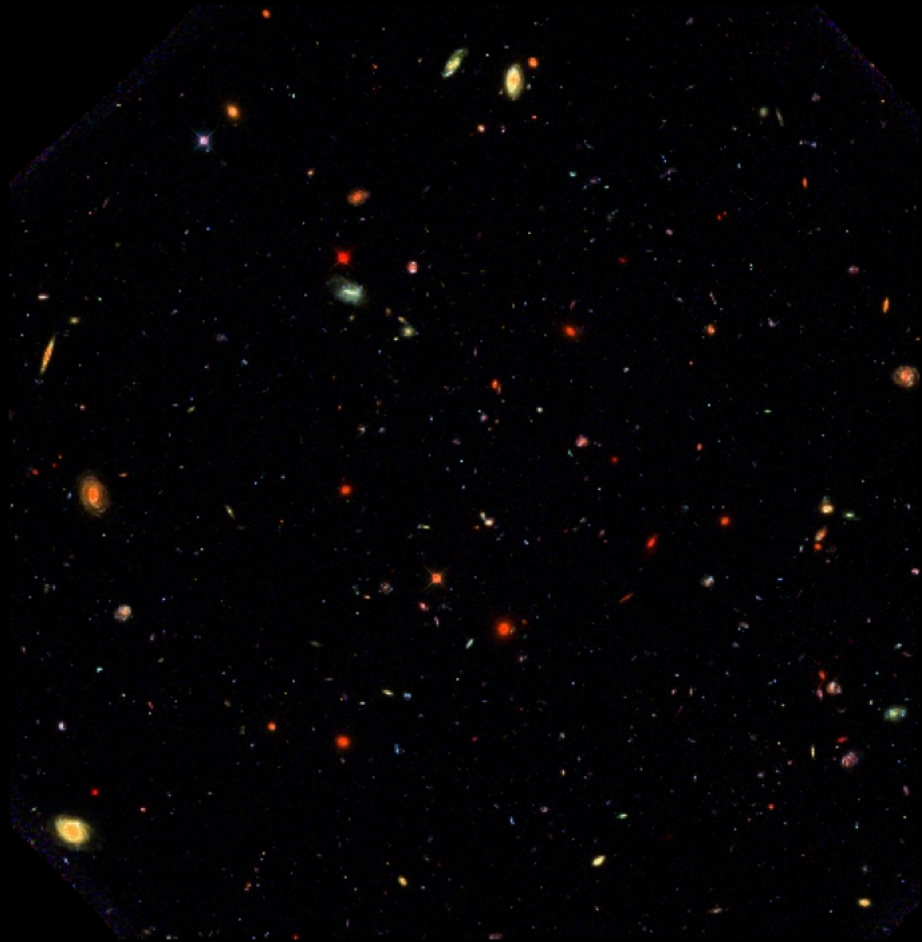
→ *too many blue galaxies*



HST observation

Mock HST Deep Fields

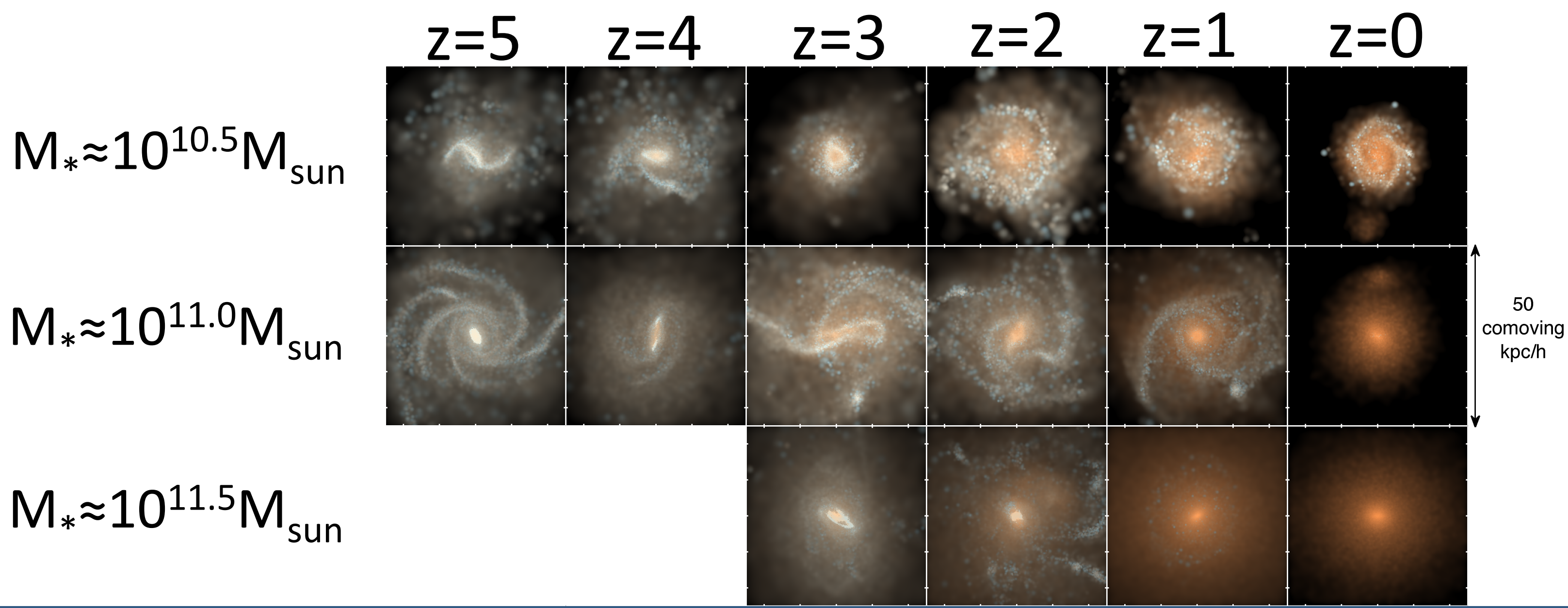
+ AGN feedback



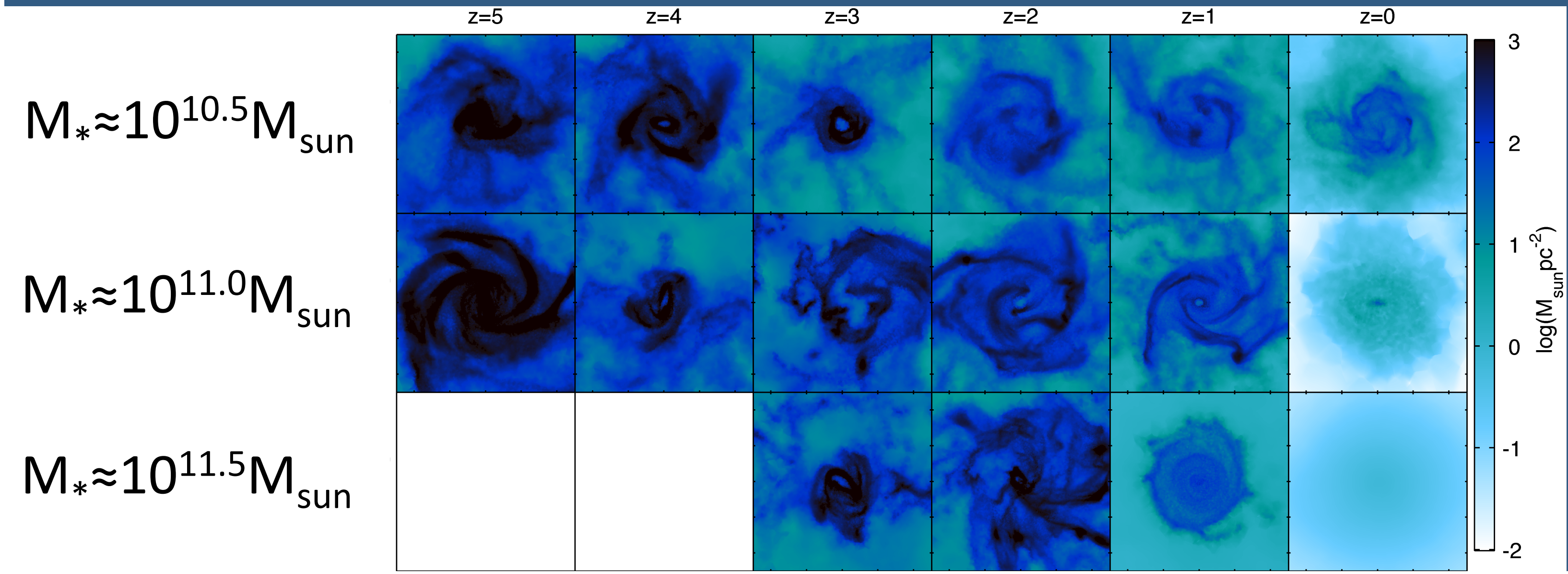
HST observation

→ *reasonable population*

Massive galaxies @ $0 \leq z \leq 5$



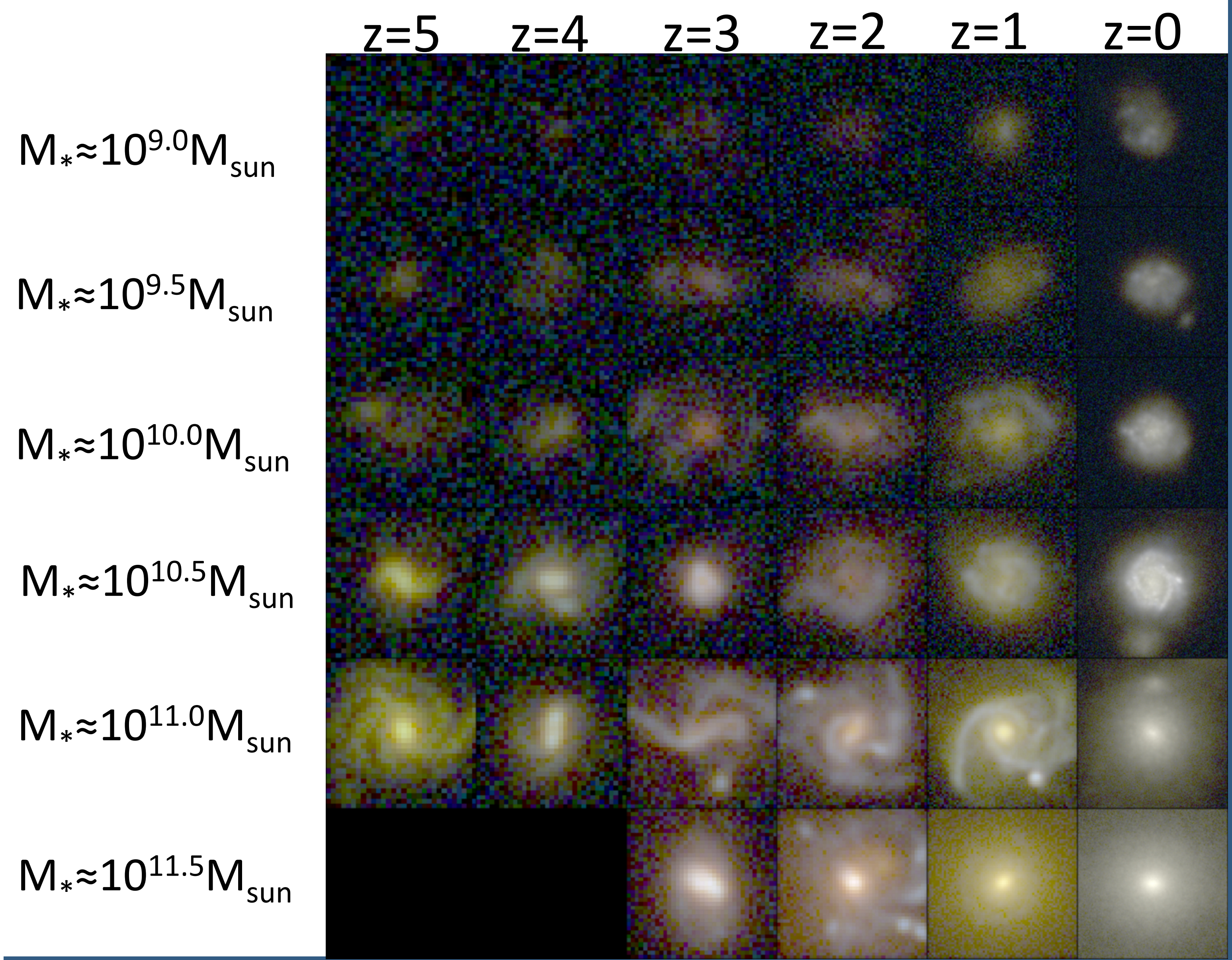
Stars



Gas

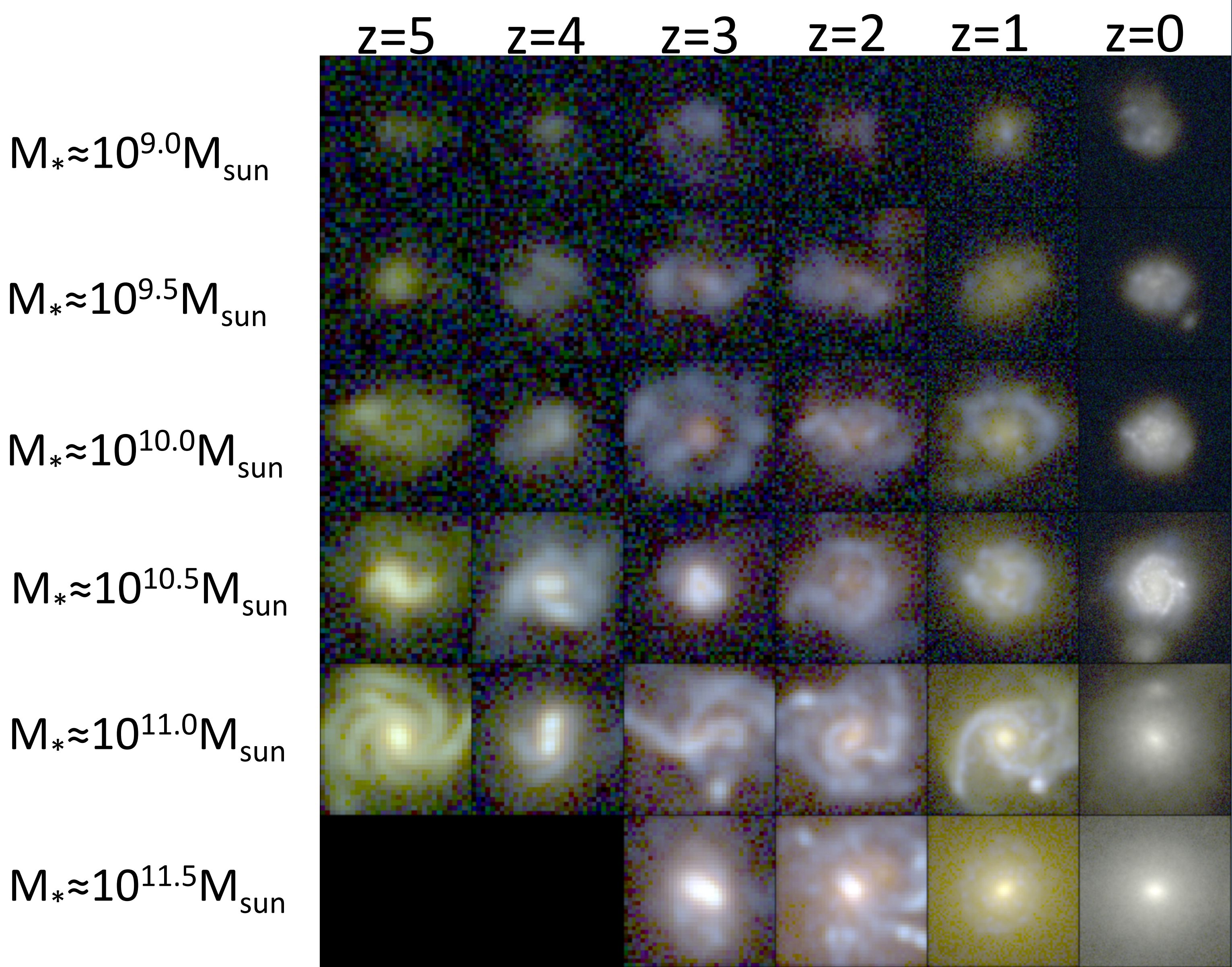
HUDF mock observations

With and without dust attenuation



HUDF mock observations

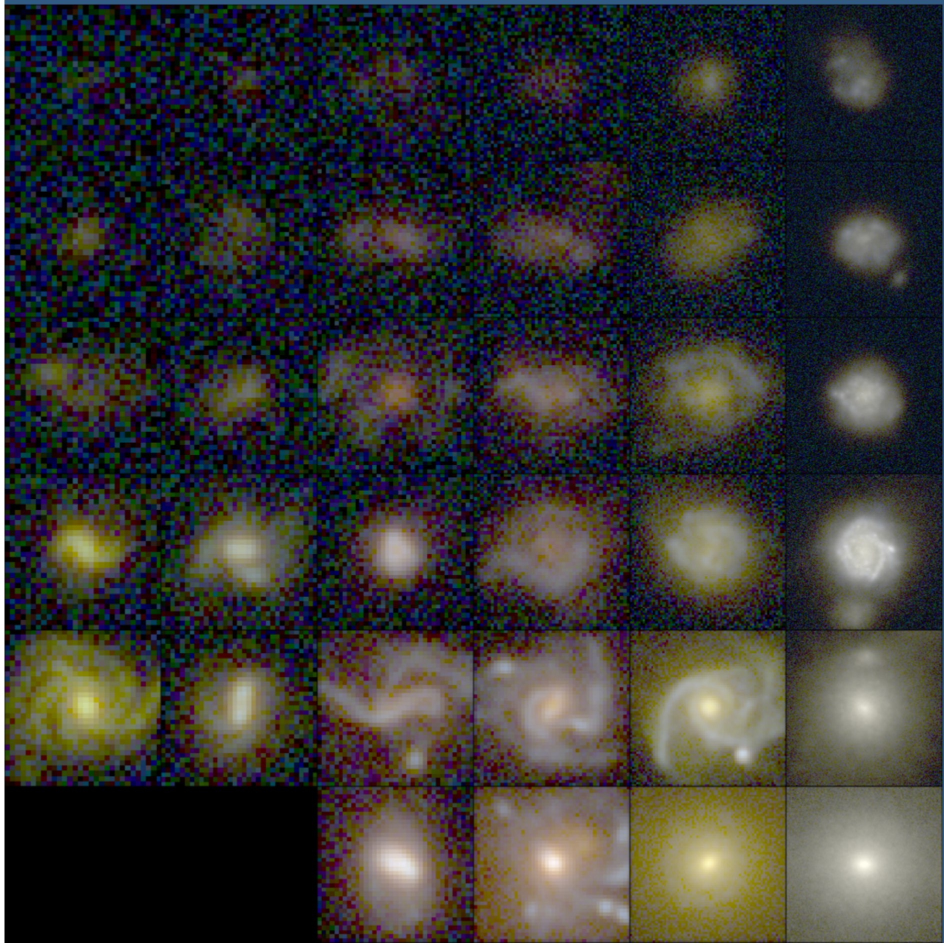
With and without dust attenuation



HUDF mock observations

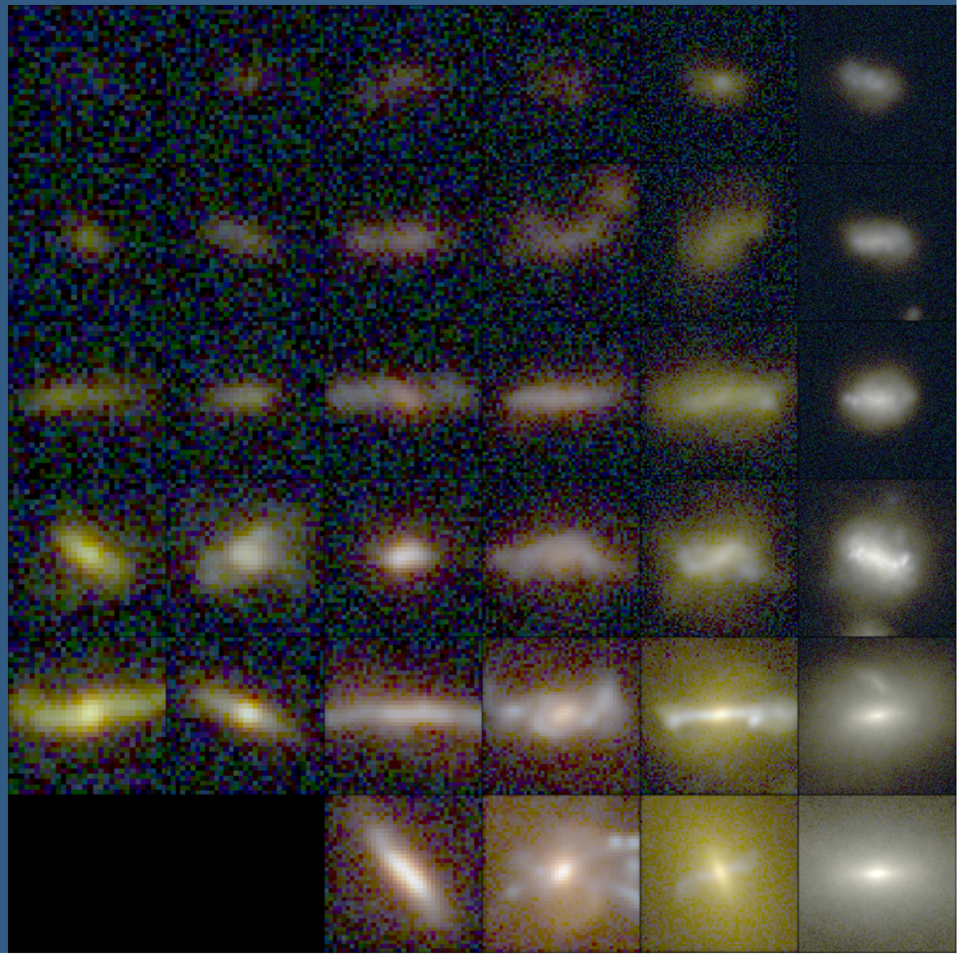
Face-on

z=5 z=4 z=3 z=2 z=1 z=0



Edge-on

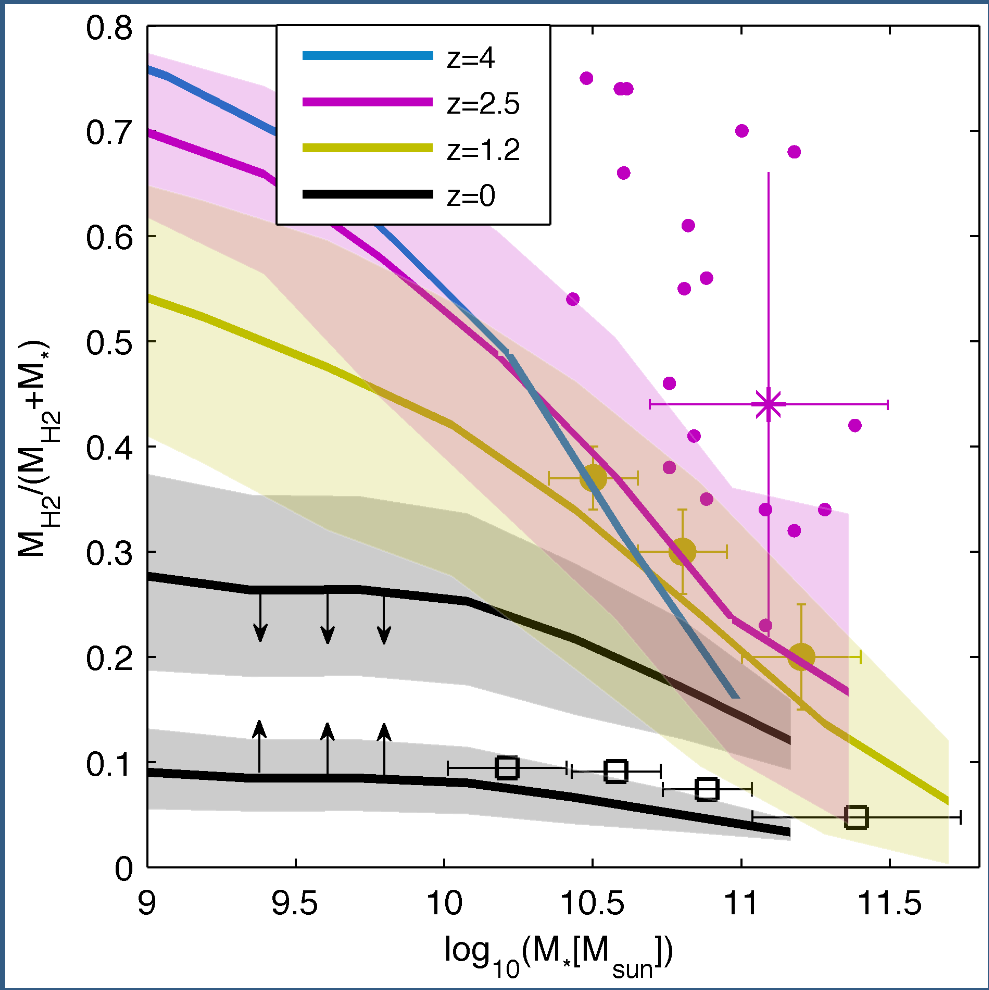
z=5 z=4 z=3 z=2 z=1 z=0



Galactic molecular gas fractions

- Illustris predicting increasing gas fractions only up to z~2, thereafter remaining approx. constant

- Illustris possibly under-estimating z~2 gas fractions compared to observations

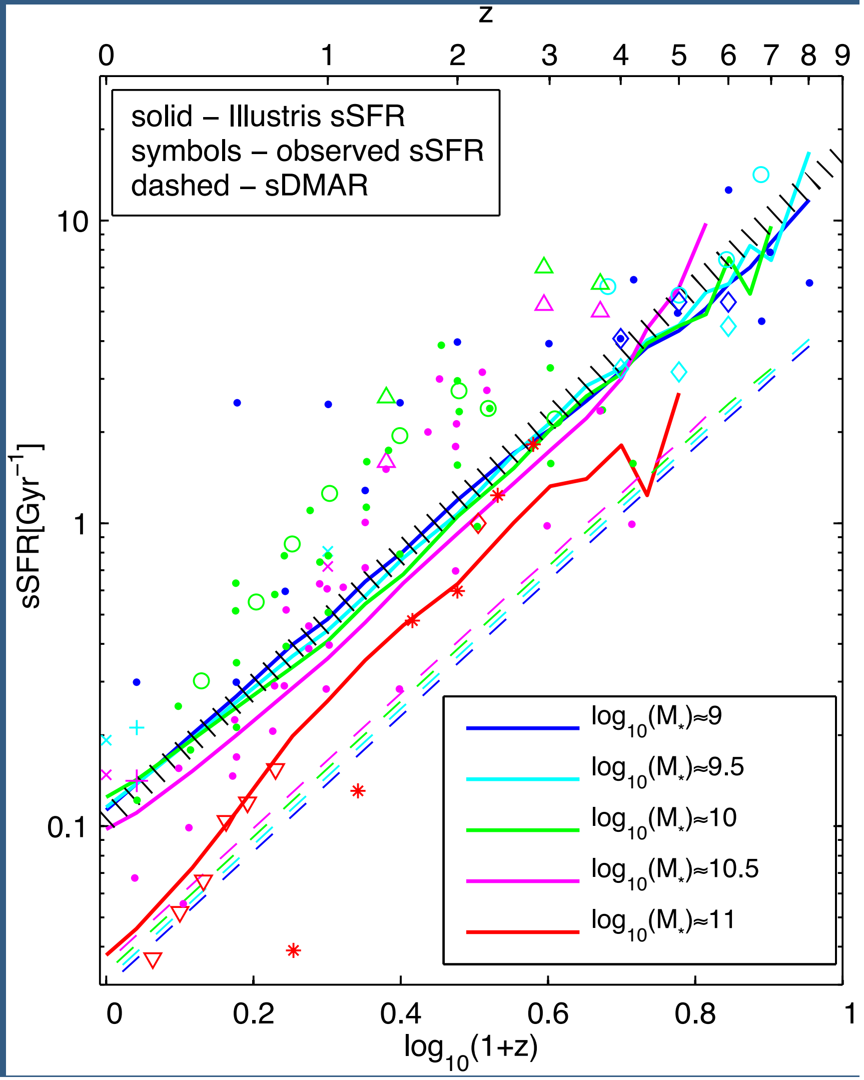


Specific star-formation rates

- Observed 'bump' at z~1-3 not reproduced by any hydrodynamical simulation, including Illustris

- Simulated evolution follows closely the DM halo accretion rates

- Mass dependence reversed between halos and galaxies, as observed



Illustris: results

IV. Baryonic effects on matter distribution

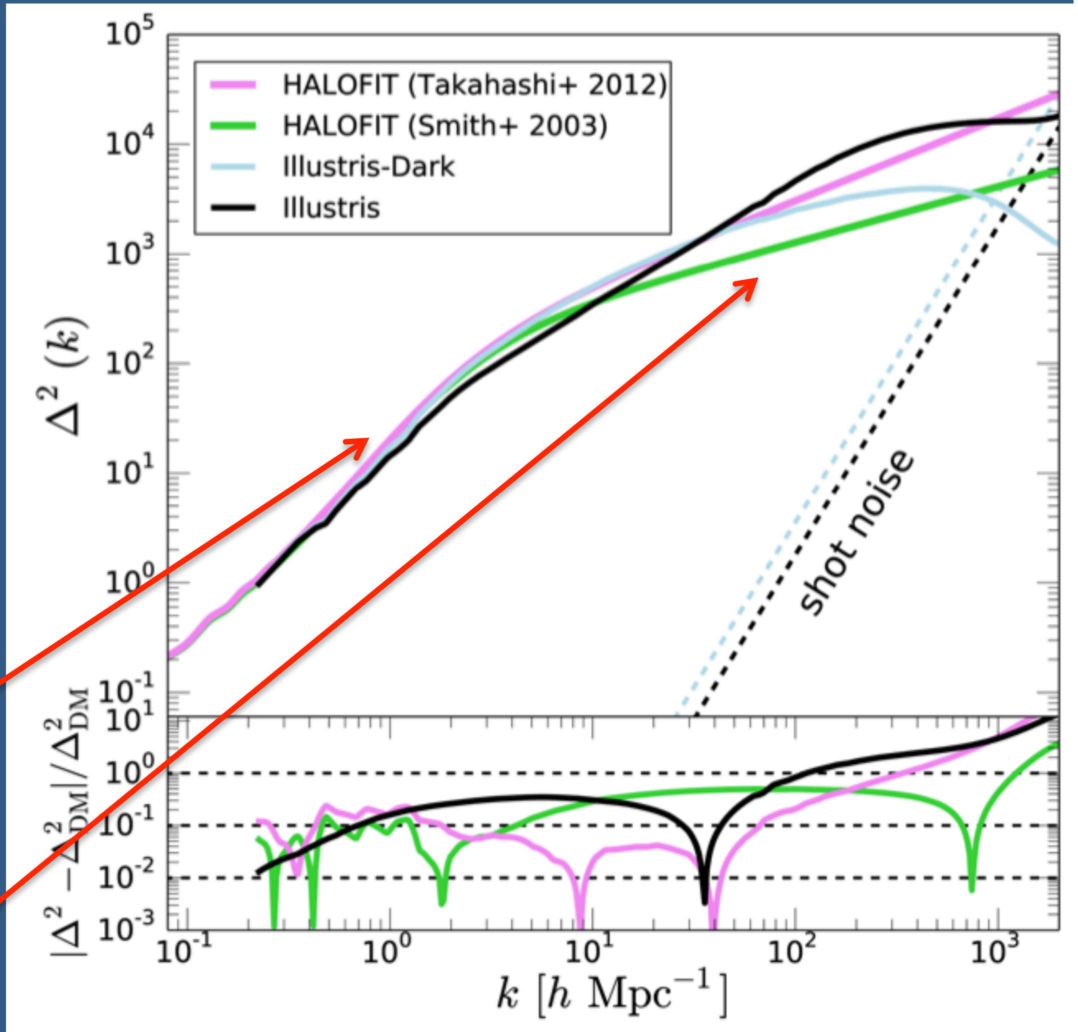
The matter power spectrum

The non-linear matter power spectrum:

• N-body simulations, and corresponding fitting formulae, deviate strongly from the hydrodynamic result

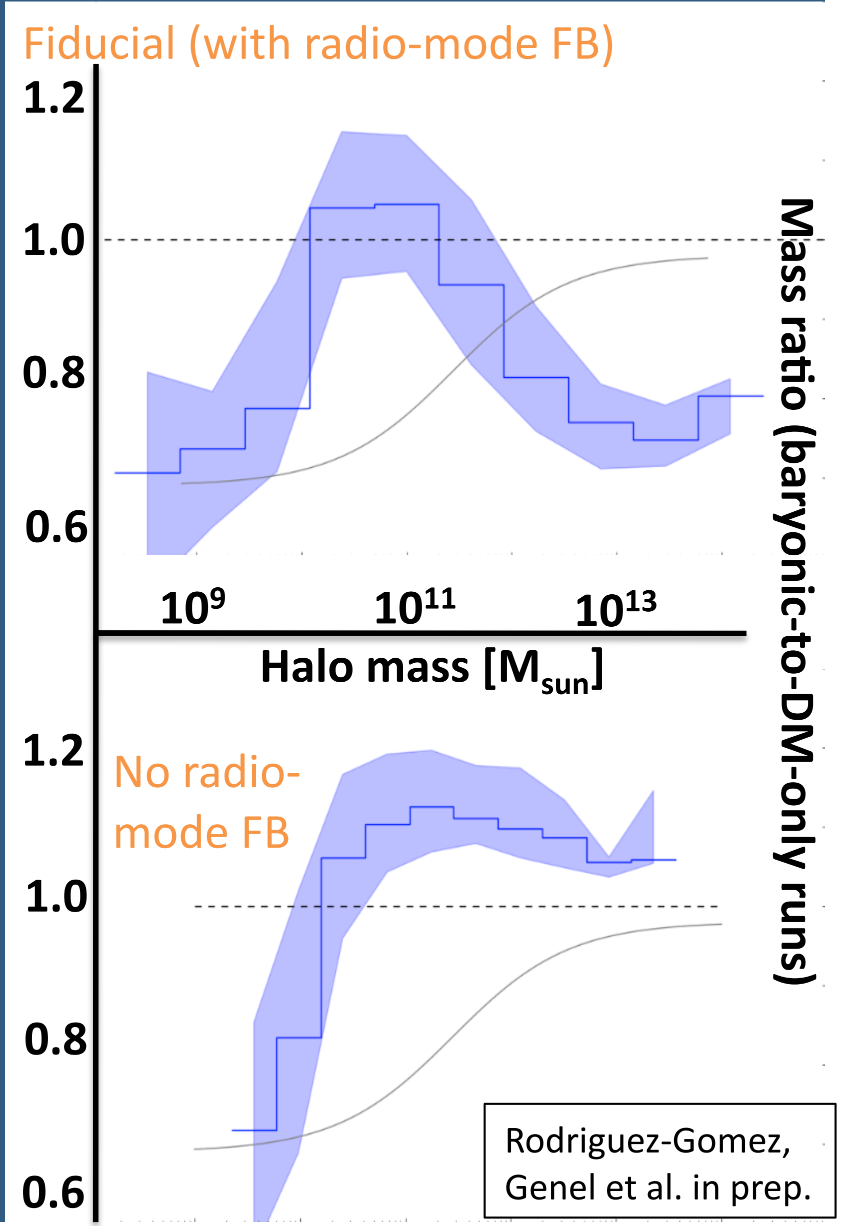
• Suppression on scales 30kpc-5Mpc by up to 40%

• Enhancement of power spectrum on scales <30kpc



Baryonic effects on halo masses

- Hydrodynamics, cooling, galactic winds, AGN – all affect halo masses, at difference mass scales
- Strong sensitivity to the included physics and to their implementation
- Both enhancement and suppression of halo masses are possible



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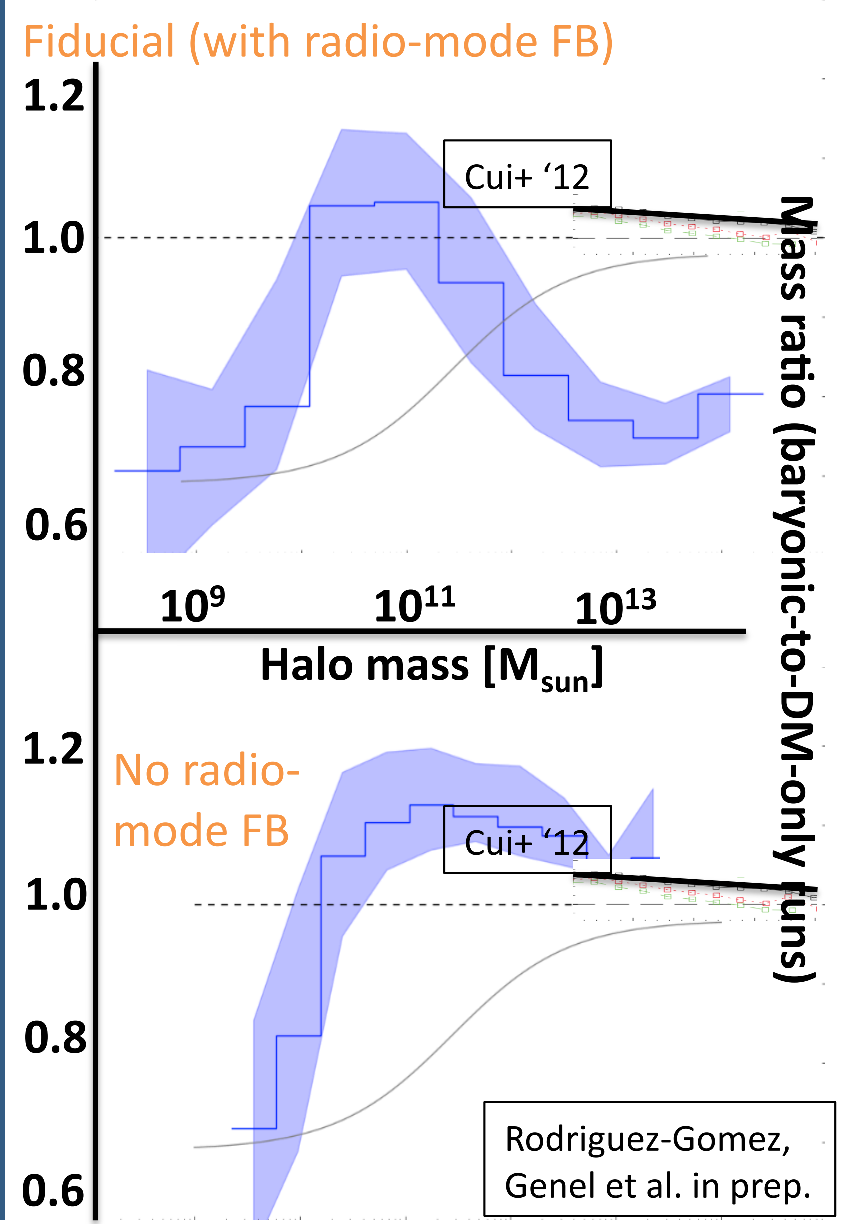

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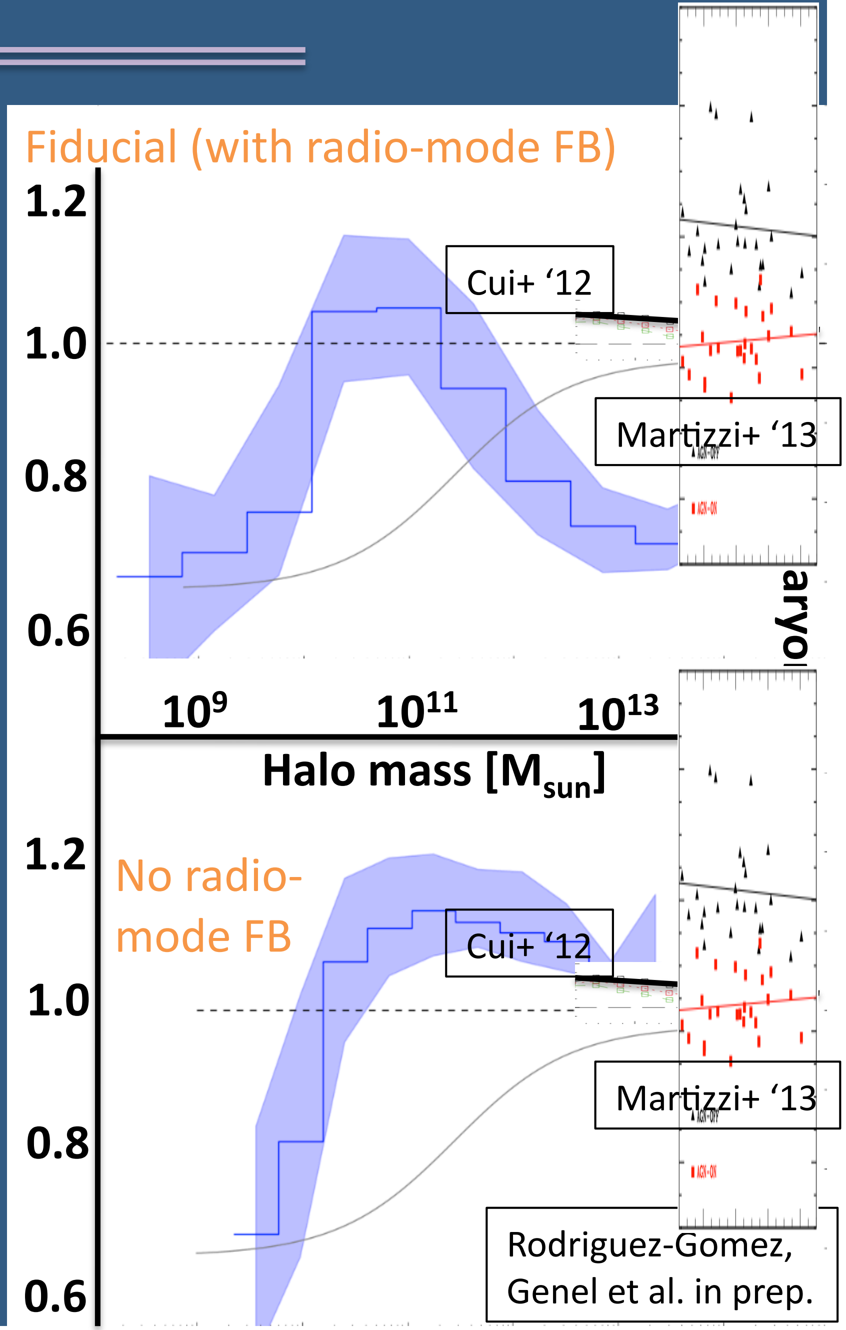
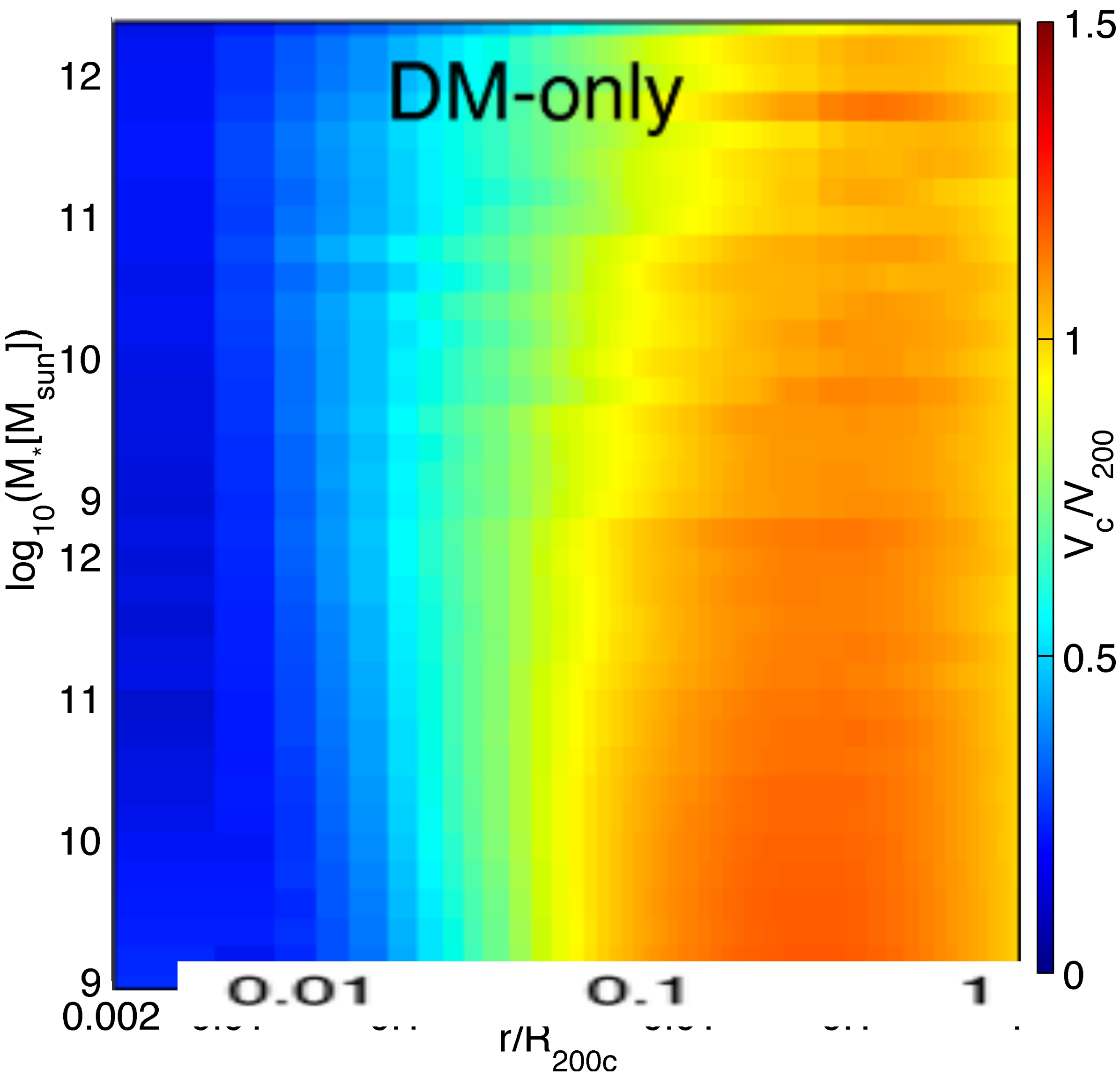


Halo structure – radial profiles

- Circular velocity profiles out to R_{200} for a range of stellar masses

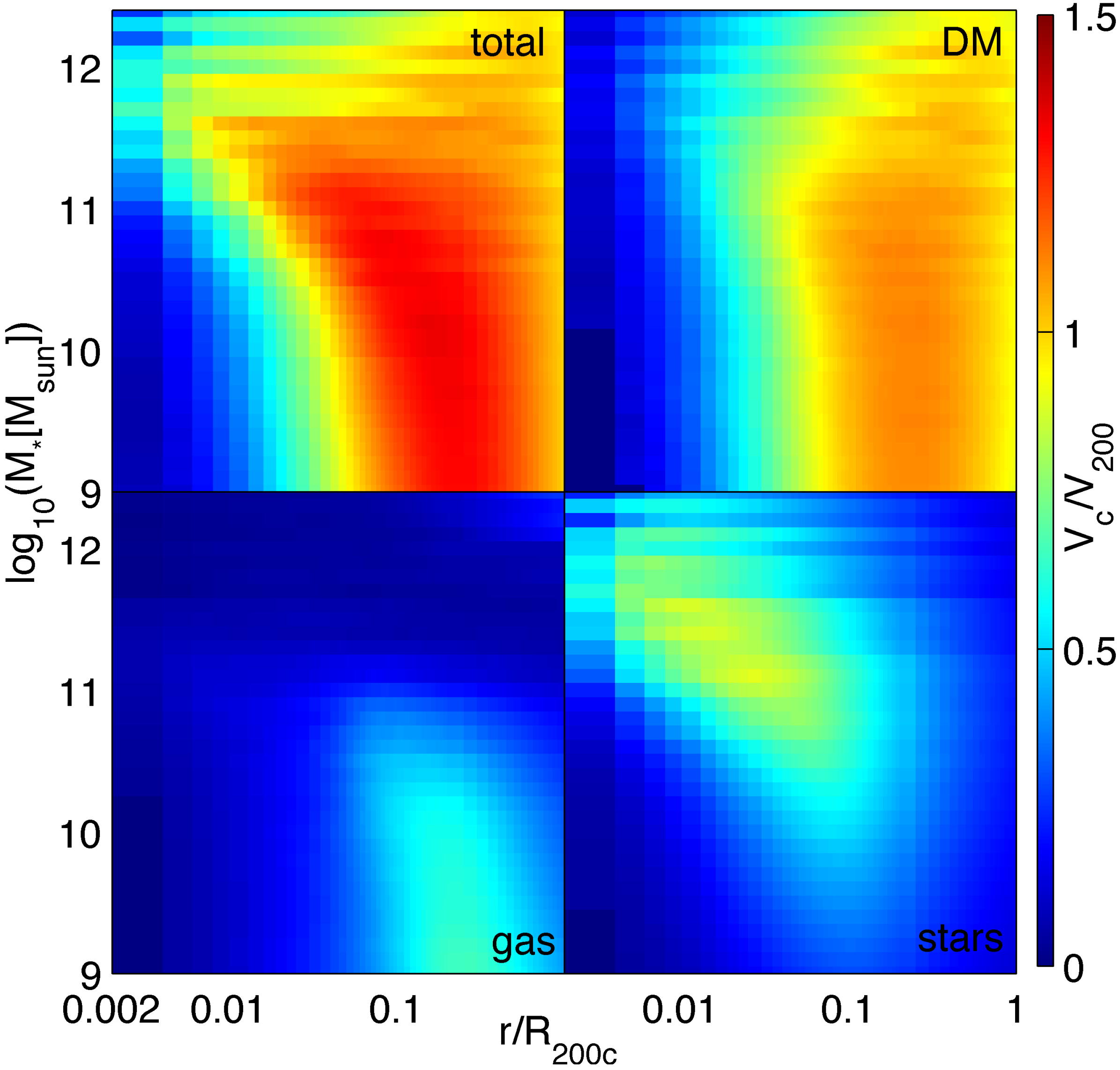
- DM-only simulation ("Illustris-Dark") is matched to hydro simulation to give DM-only profiles as a function of "stellar mass"

- NFW: peak V_c reached @ $r>0.1R_{200}$



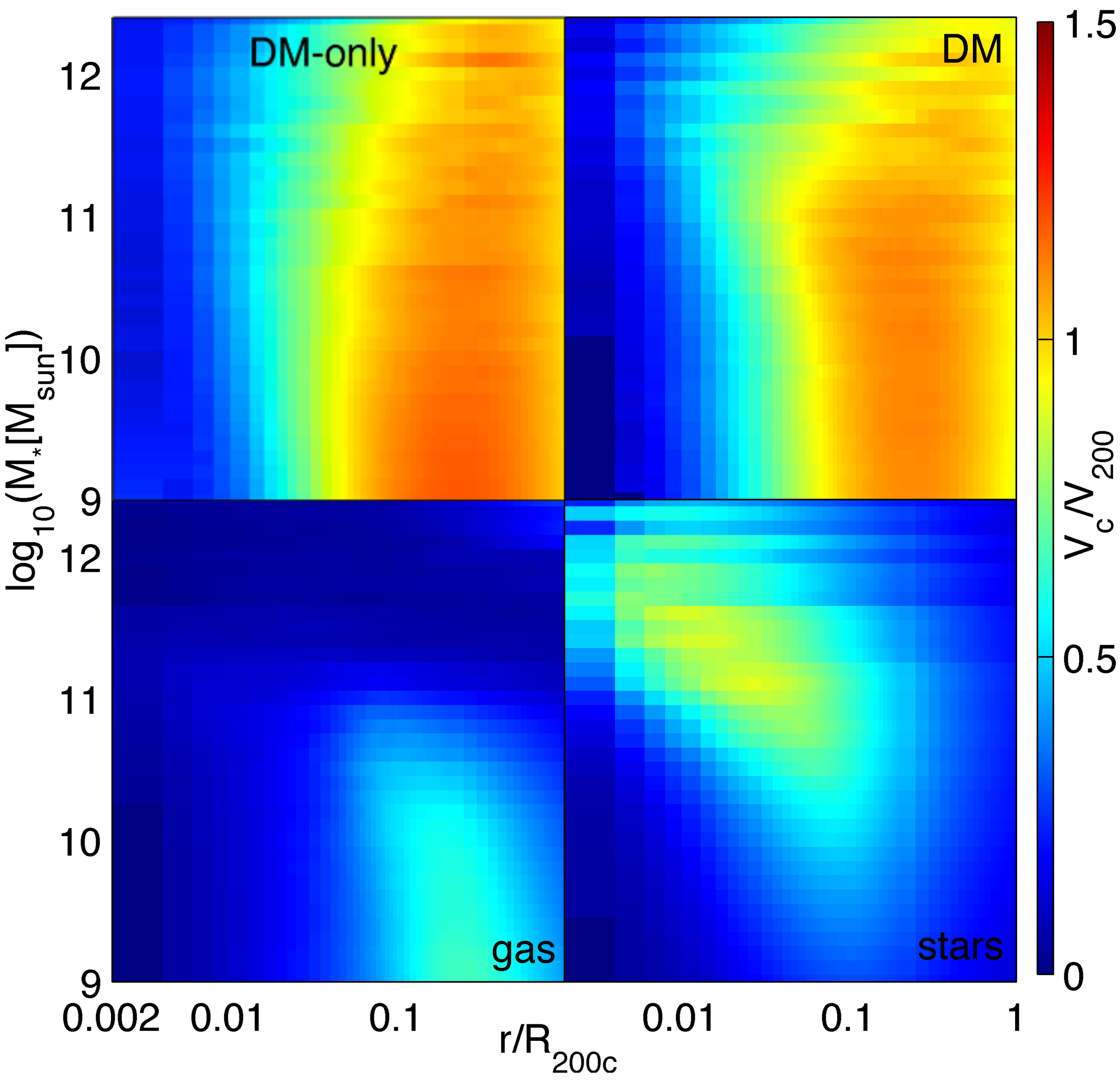
Halo structure – radial profiles

- Circular velocity profiles out to R_{200} for a range of stellar masses
- All profiles within $r<0.1R_{200}$ are rising or flat
- Gas contribution always small
- Baryons (stars) control V_{max} only within $10^{10.5}<M_*<10^{11.5}$

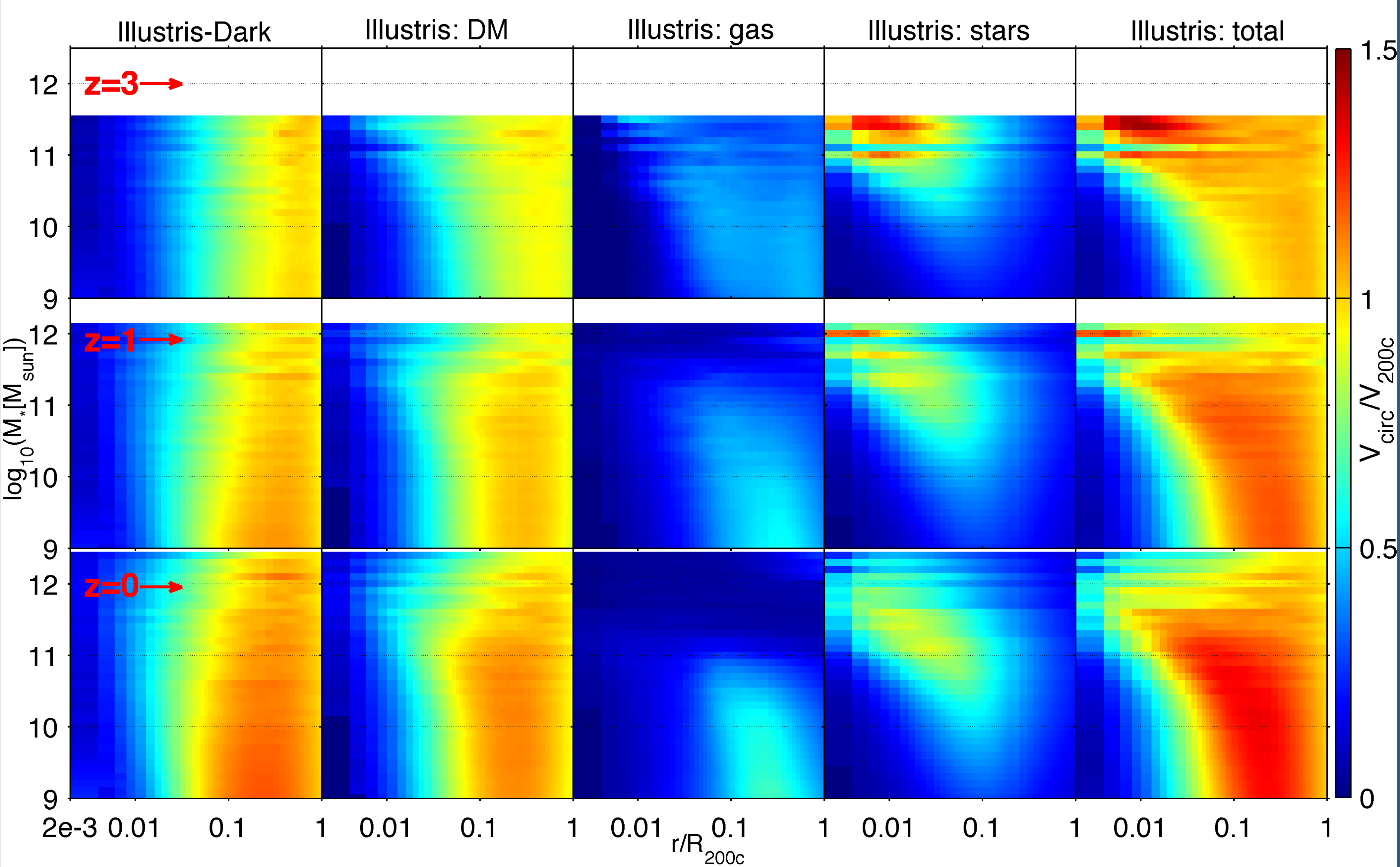


Halo structure – radial profiles

- Circular velocity profiles out to R_{200} for a range of stellar masses
- DM responds to baryons:
    - contraction @ $10^{10.5}<M_*<10^{11.5}$
    - @ $M_*>10^{11.5}$:
        - small-radius contraction
        - large-radius weak expansion



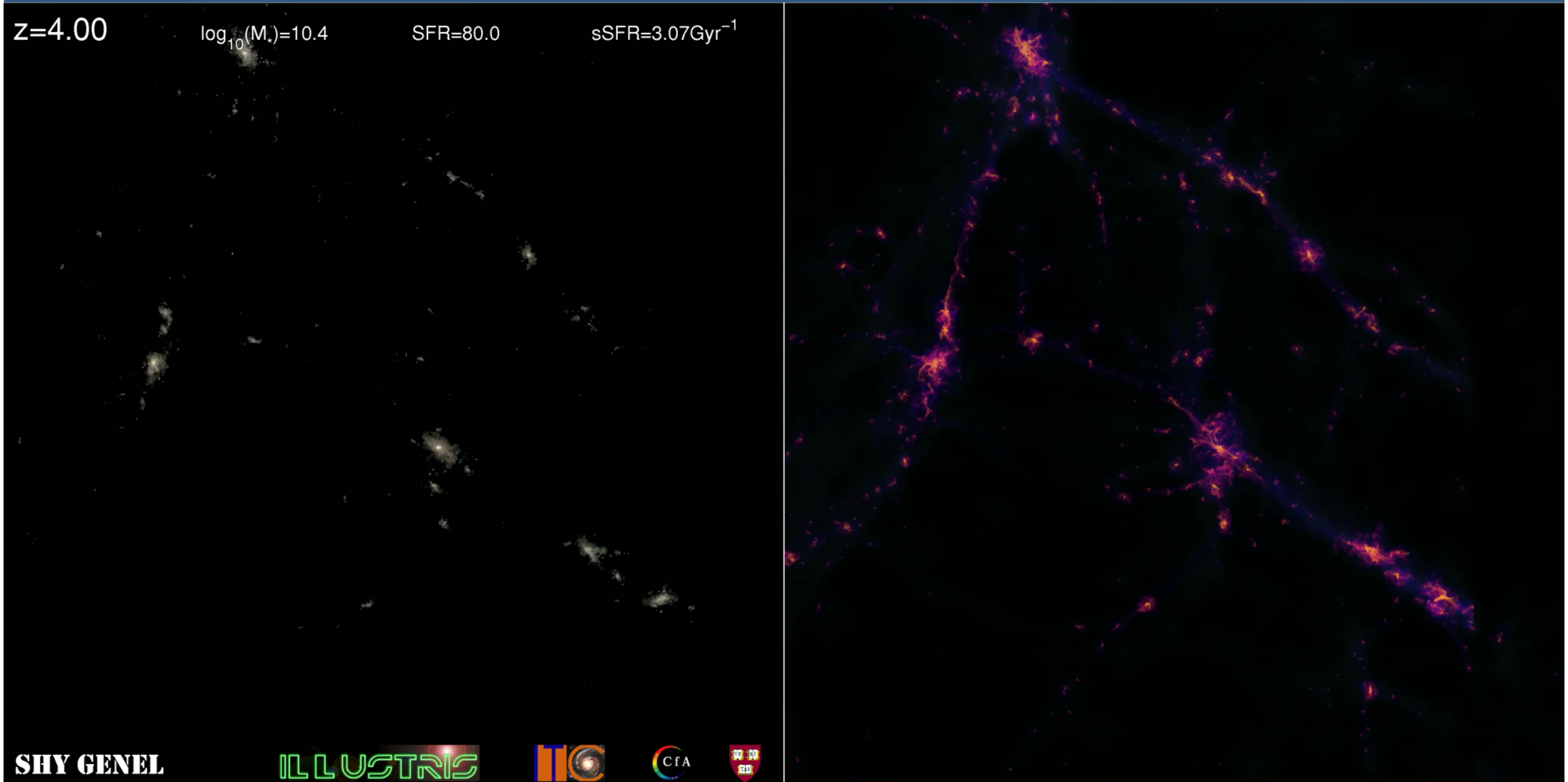
Halo structure – radial profiles



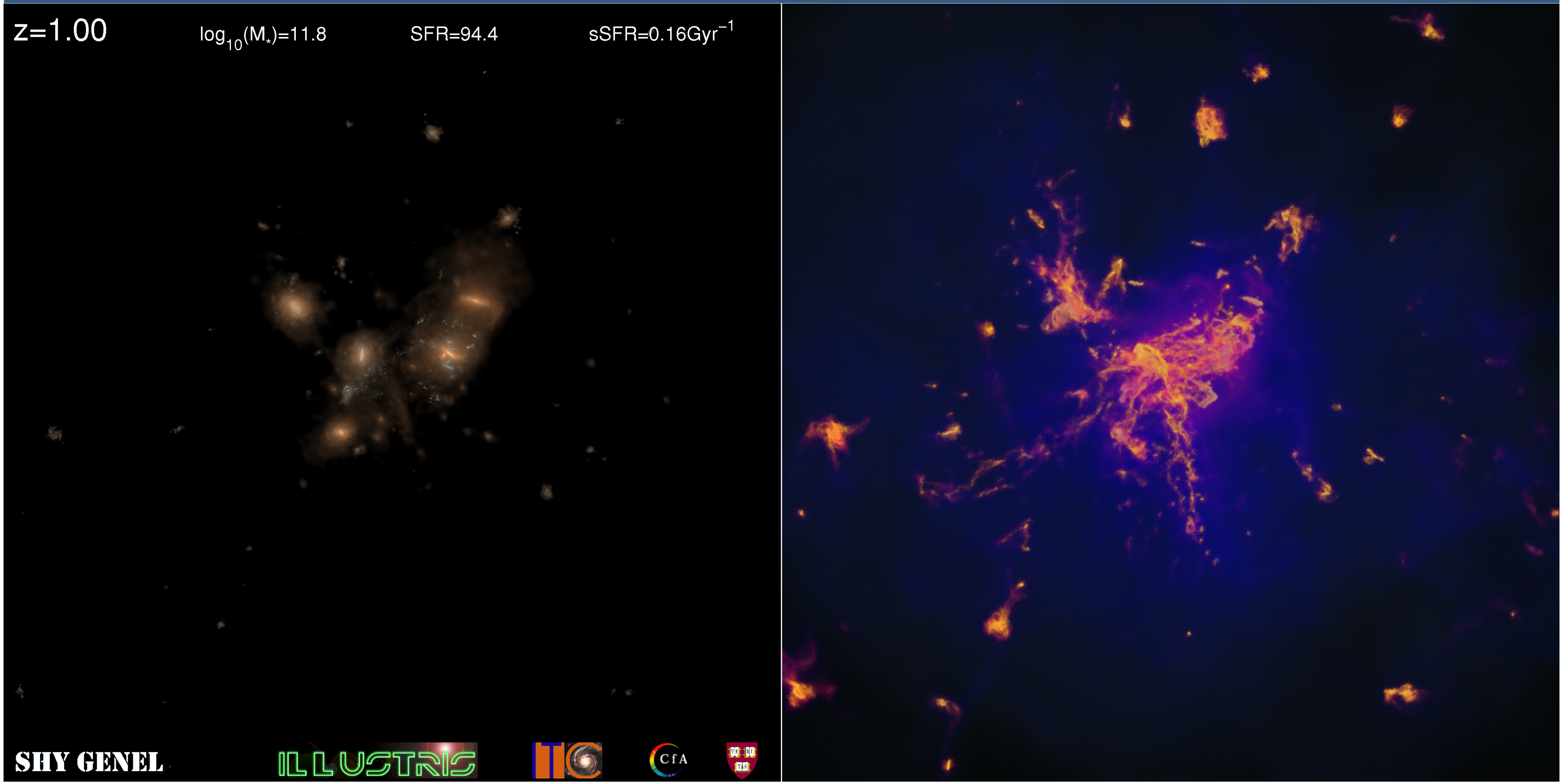
Illustris: results

V. Effects of strong radio-mode feedback

Formation of a massive elliptical



Formation of a massive elliptical

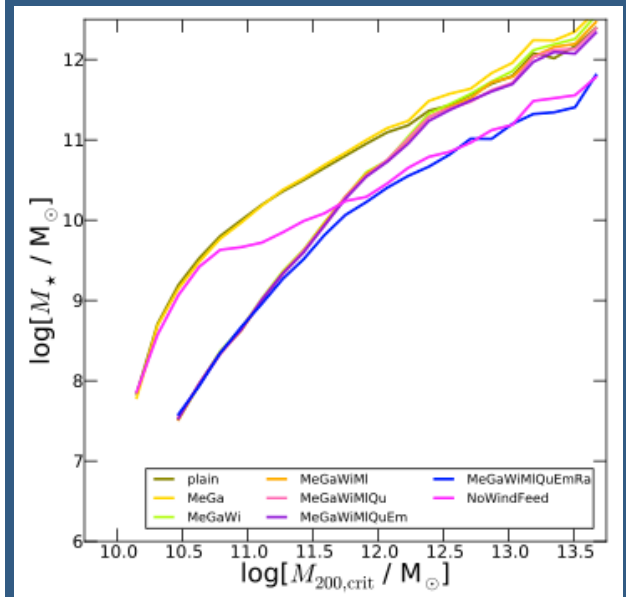


Mass content of massive halos

• Stellar mass possibly suppressed enough

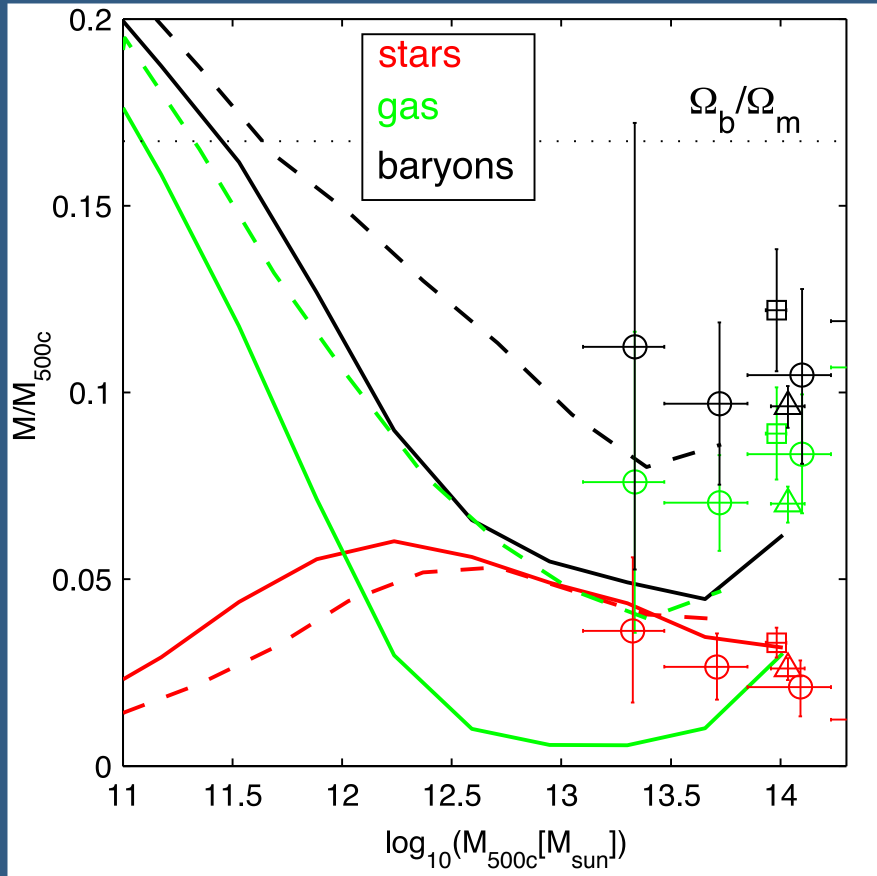
… at the expense of

• Very strong suppression of gas mass inside R_{500c}



No radio mode

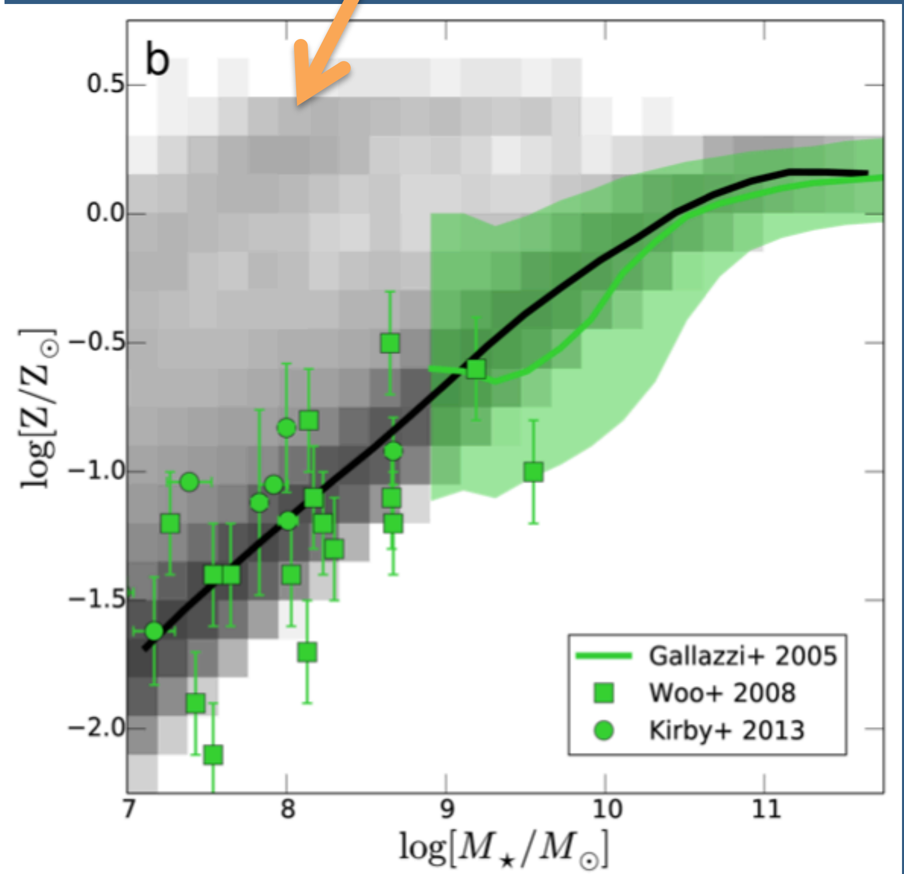
With radio mode

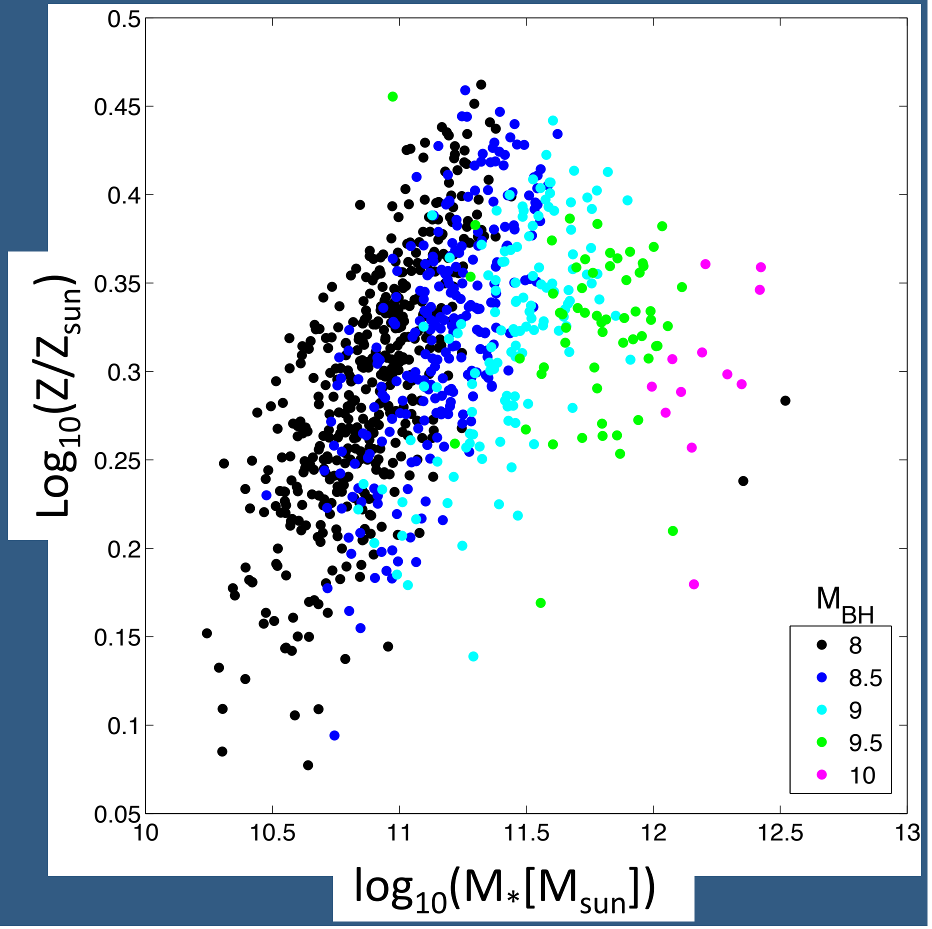


Stellar metallicities

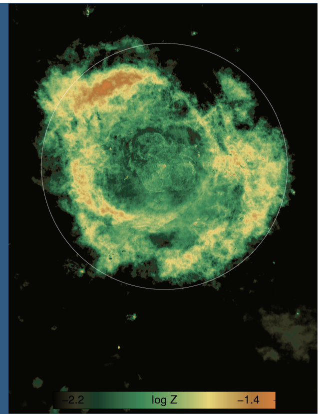
- The Z_{*}-M_{*} relation reproduced
- Metal-rich stripped satellites

- The relation peaks, and decreases again at $M^{*}>10^{11.5}$



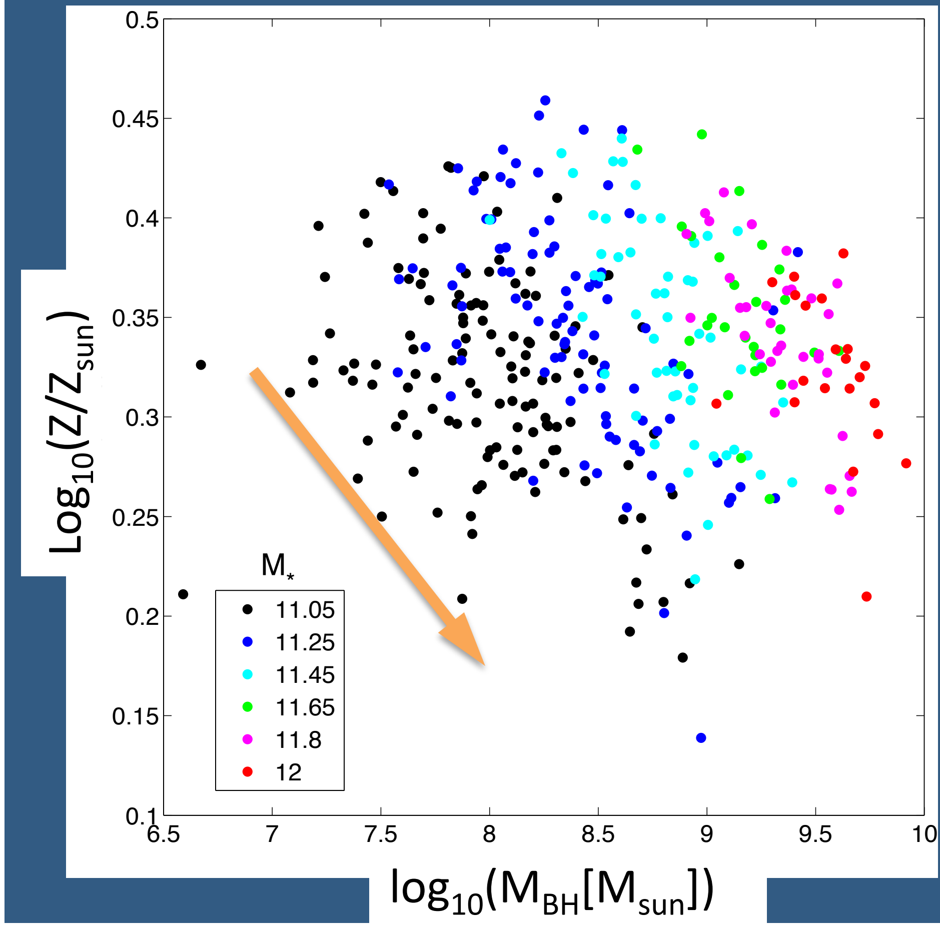


Stellar metallicities

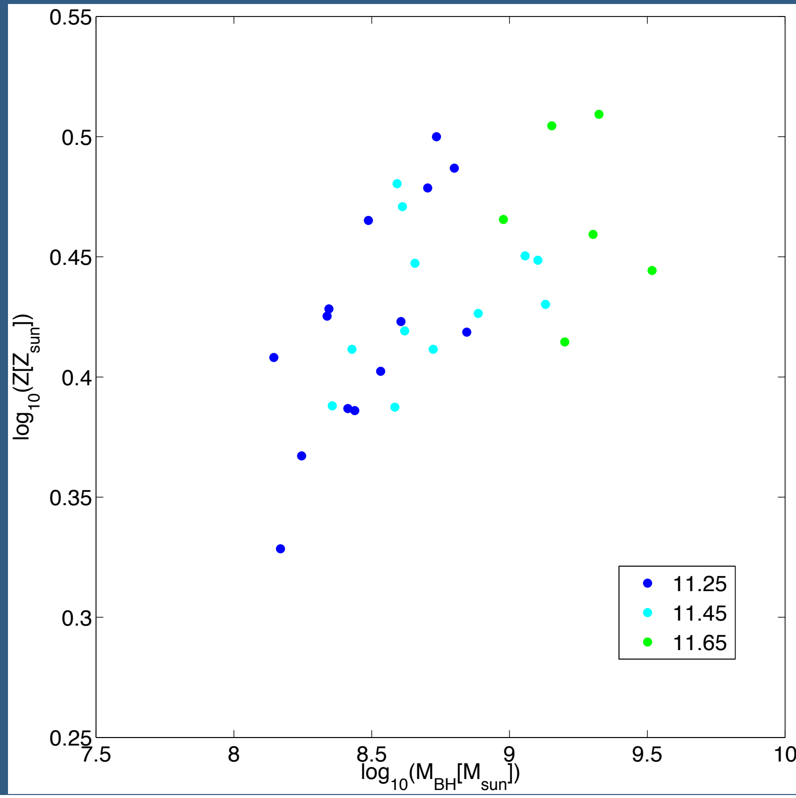


- For a given stellar mass:

$M_{BH} \uparrow \; Z \downarrow$



- Without radio-mode AGN: no such correlation



Summary

- Galaxy bimodality
- Satellite galaxy profiles – evolution in clusters
- Stellar mass build-up across cosmic time
- High-z complex morphologies
- Baryonic effects on matter distribution at all scales <10Mpc
- AGN feedback