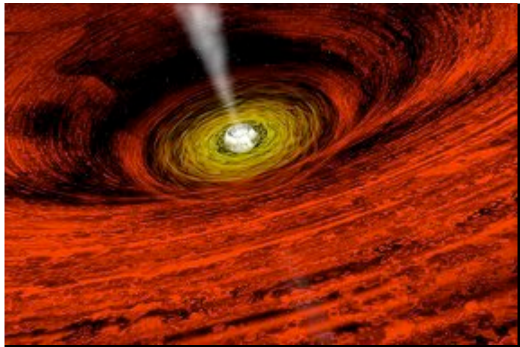
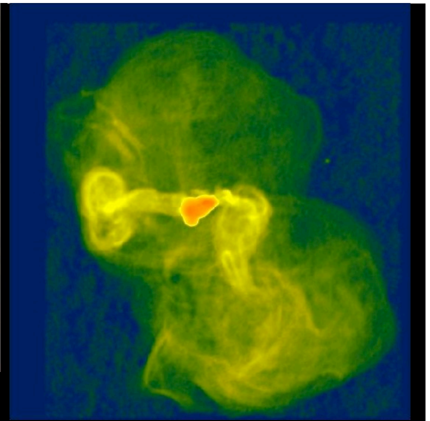


AGN Feedback: Where, When & How?

rachel somerville

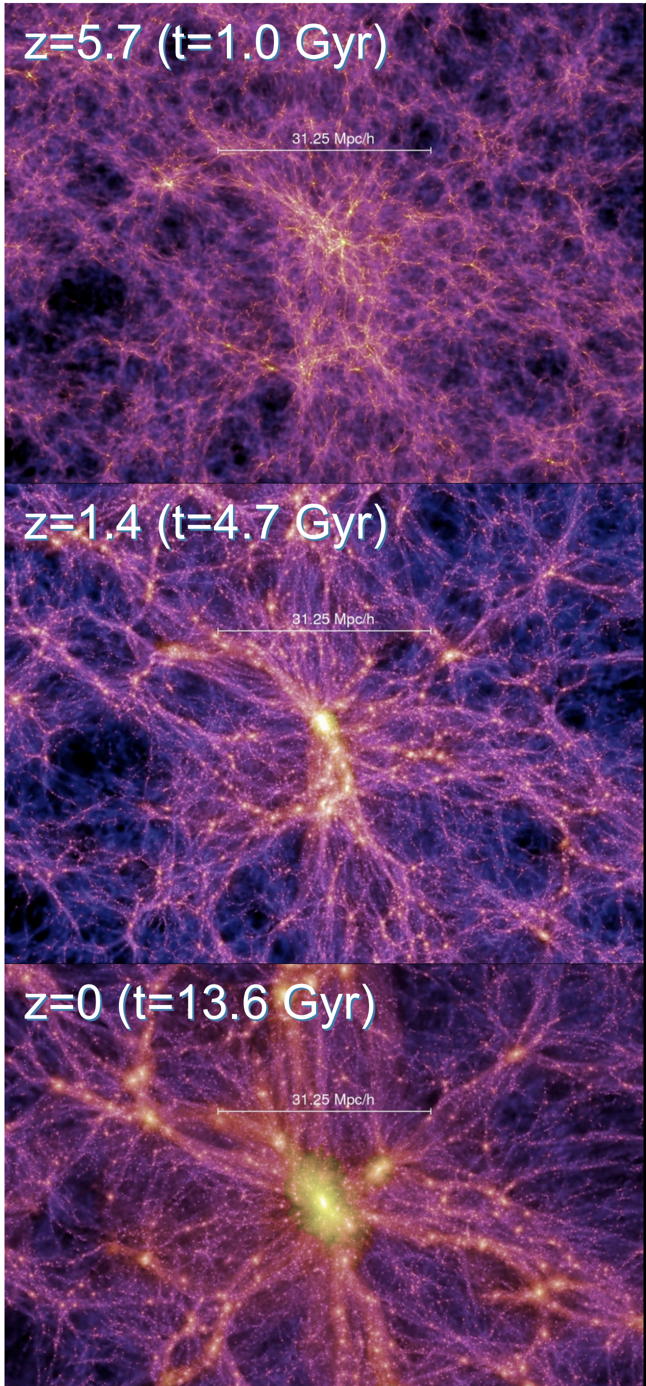
Max Planck Institute

for Astronomy, Heidelberg

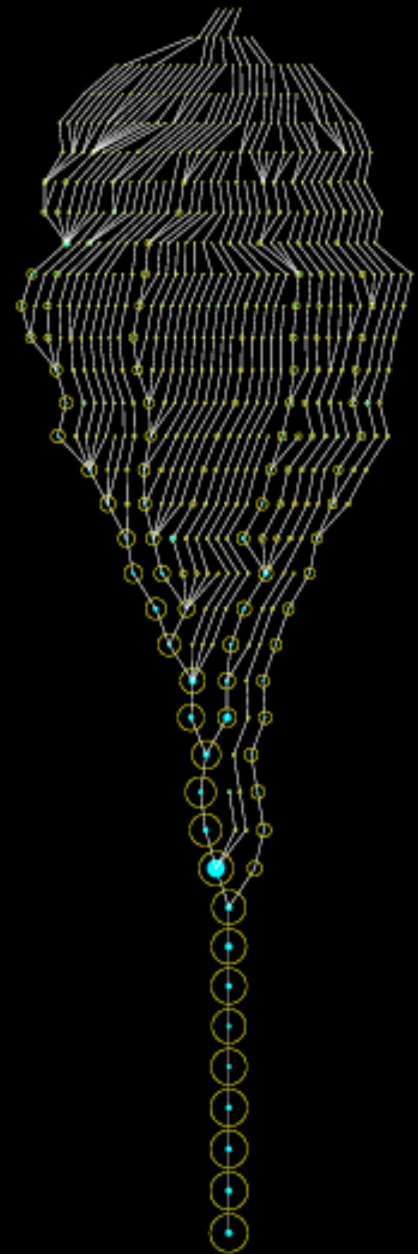




with thanks to T. Kimm, C. Maulbetsch, F. Fontanot, B. Moster (MPIA)
P. Hopkins, L. Hernquist, T.J. Cox, B. Robertson (CfA)
the GEMS team
the GOODS team
K. Noeske & the AEGIS team



Springel et al. 2006

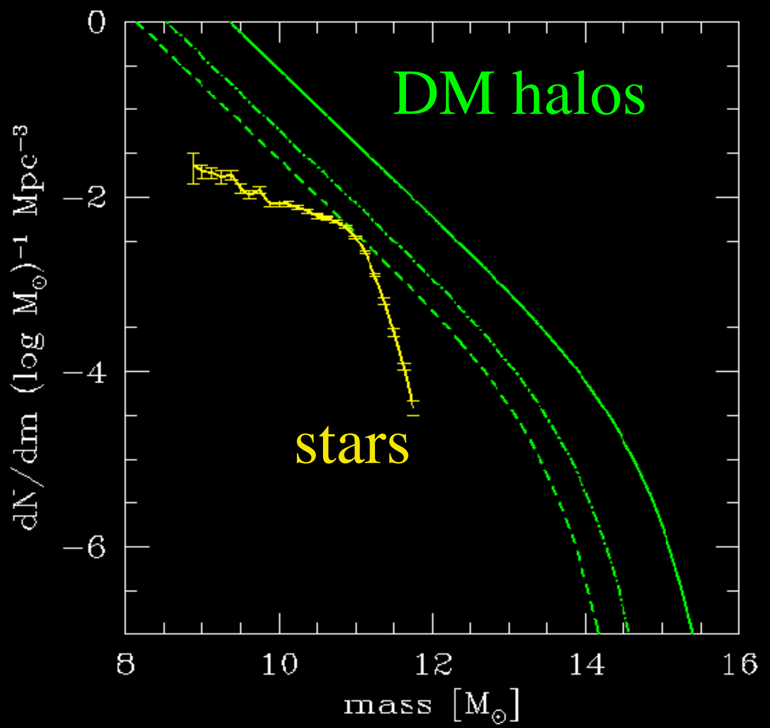


Wechsler et al. 2002

If we accept the basic paradigm of ΛCDM:

- cosmological parameters well constrained
- structure formation in dominant dark matter component accurately quantified
- formation history of dark matter halos represented by 'merger trees'

mapping dark matter to baryons



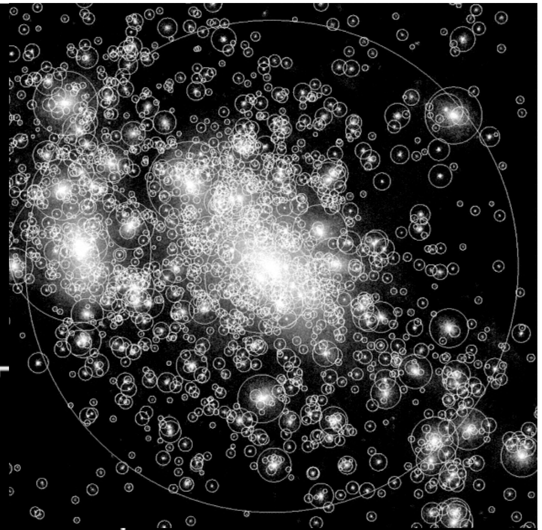
- in order to reconcile CDM (sub)halo mass function with galaxy LF or stellar MF, cooling/star formation must be inefficient overall
- baryon/DM ratio must be a strongly non-linear (& non-monotonic) function of halo mass

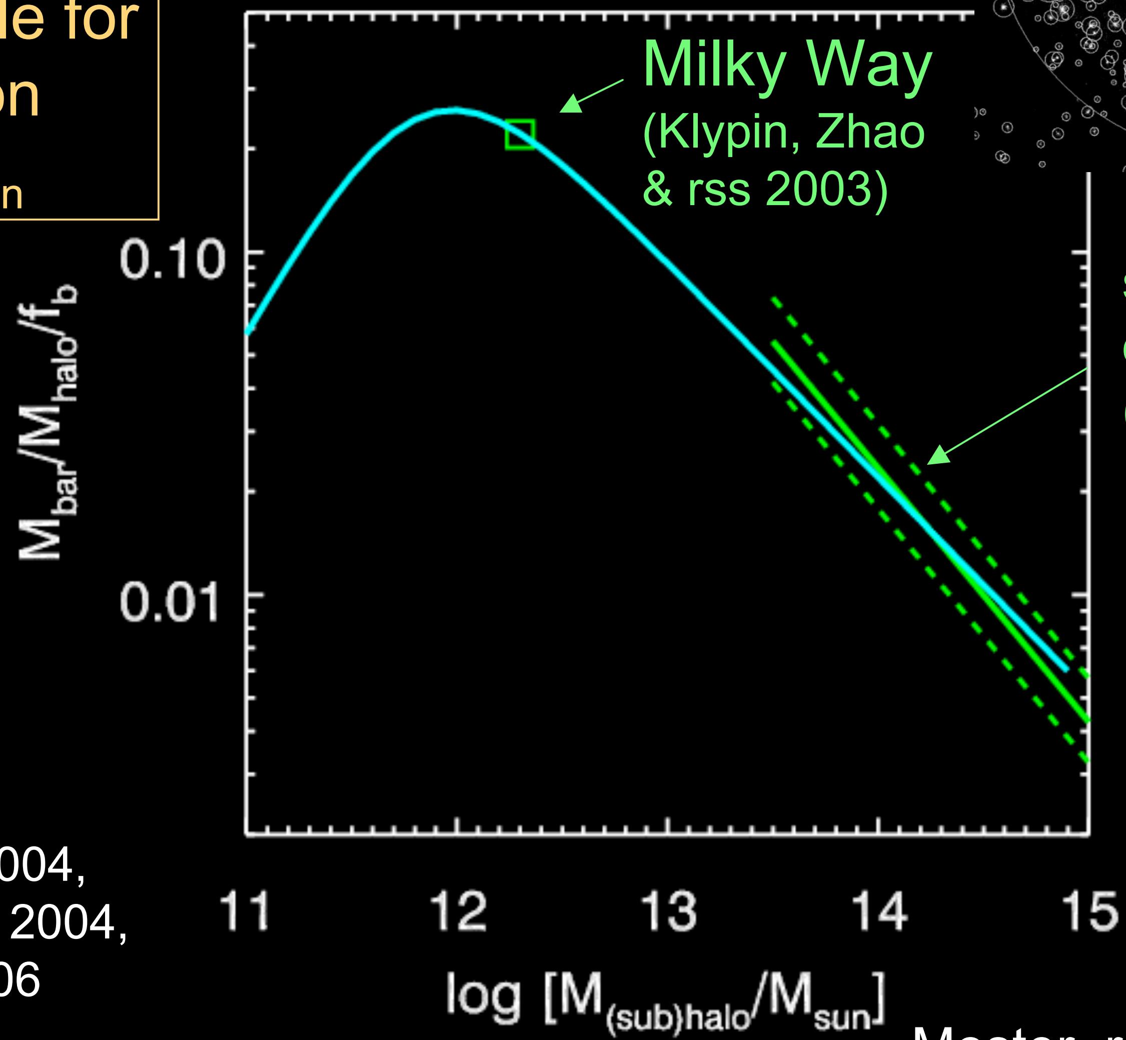
Somerville & Primack 1999; Benson et al. 2003

empirical mapping between halo mass & stellar mass

‘special’ scale for star formation $M_h \sim 10^{12}\ M_{sun}$

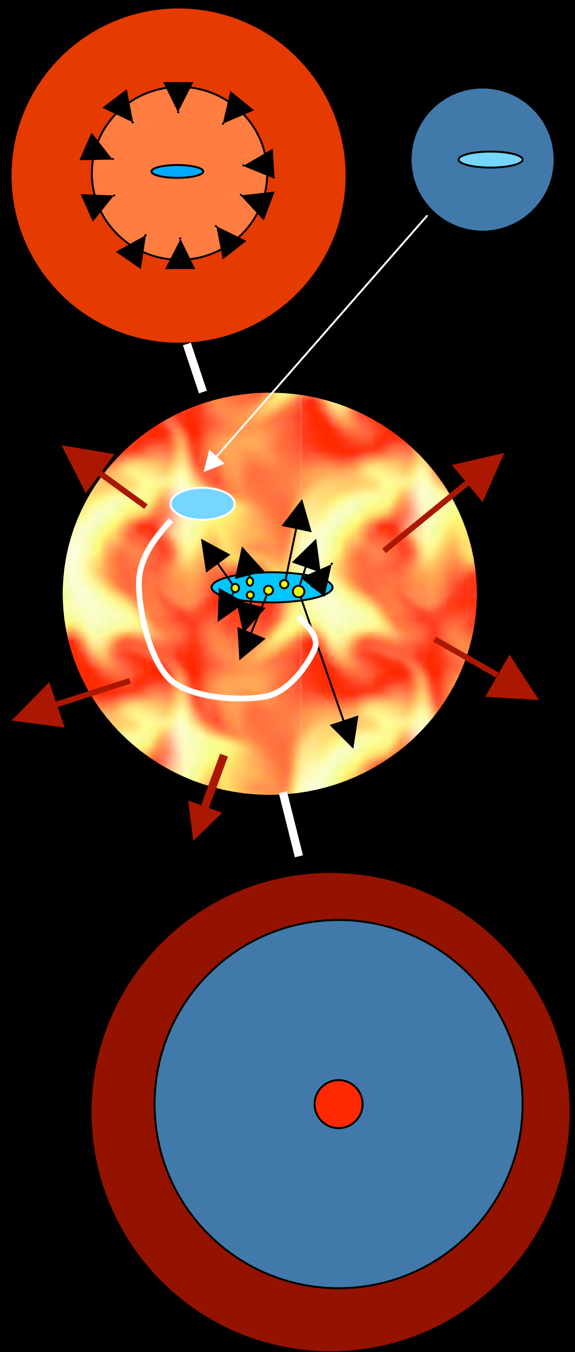
(we also match observed galaxy clustering as a function of stellar mass)





in the spirit of Kravtsov et al. 2004, Tatsitsiomi et al. 2004, Conroy et al. 2006

Moster, rss et al. in prep



galaxy formation in a CDM Universe

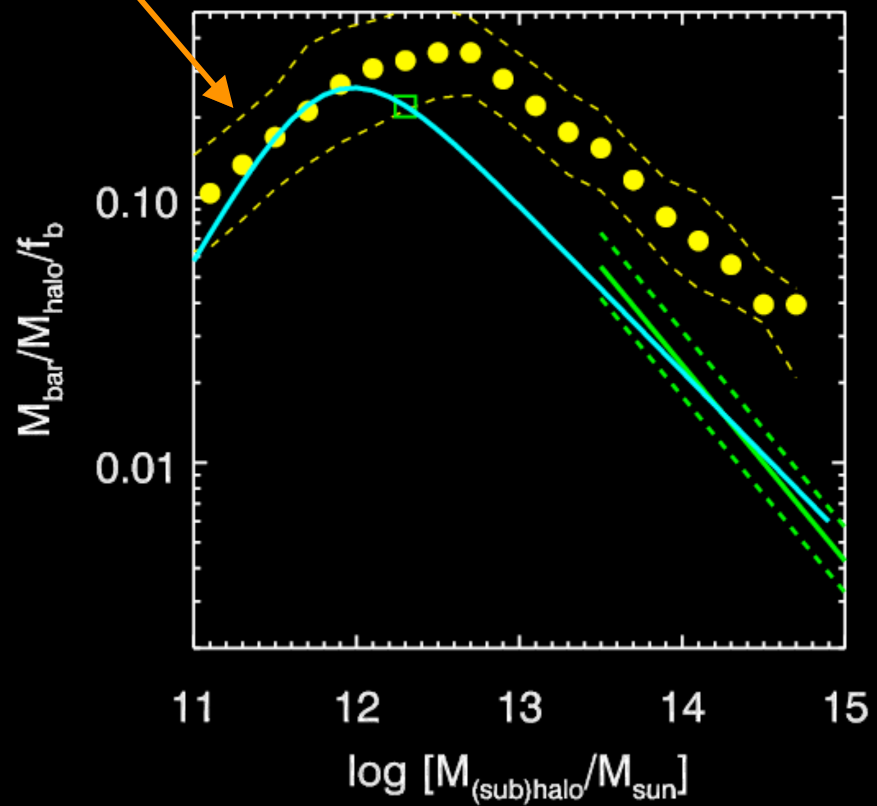
- gas is collisionally heated when perturbations 'turn around' and collapse to form gravitationally bound structures
- gas in halos cools via atomic line transitions (depends on density, temperature, and metallicity)
- cooled gas collapses to form a rotationally supported disk
- cold gas forms stars, with efficiency a function of gas density (e.g. Schmidt-Kennicutt Law)
- massive stars and SNae reheat (and expel?) cold gas
- galaxy mergers trigger bursts of star formation; 'major' mergers transform disks into spheroids

White & Frenk 1991; Kauffmann et al. 1993; Cole et al. 1994; Somerville & Primack 1999

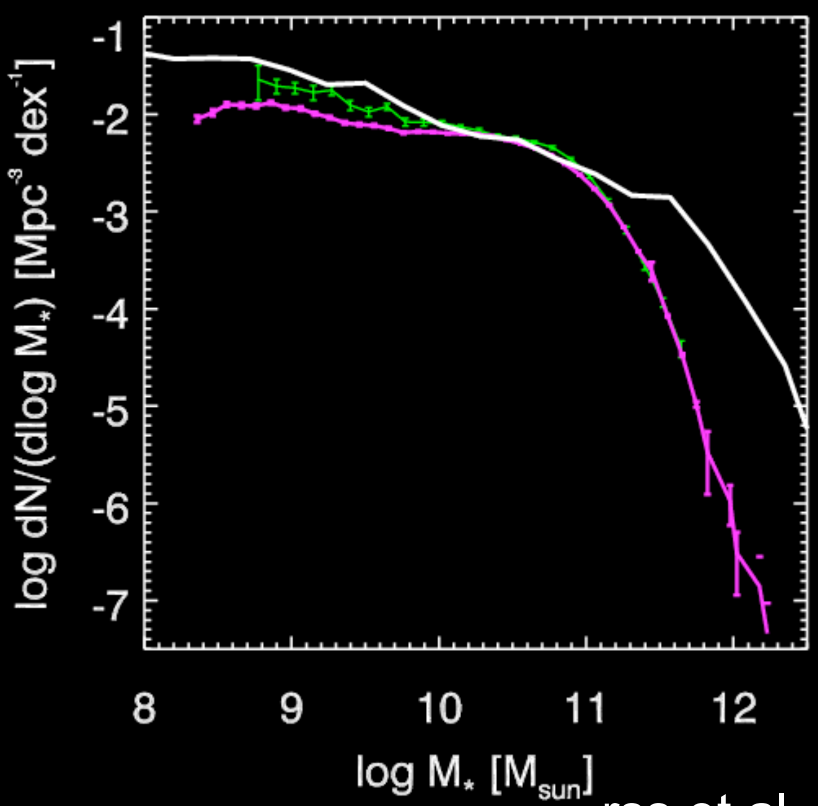
the galaxy overcooling problem

Somerville & Primack 1999; Cole et al. 2001; Kauffmann et al. 1999; Benson et al. 2003; Croton et al. 2006; *n.b. also seen in hydro sims*

baryons expelled by SN-driven winds



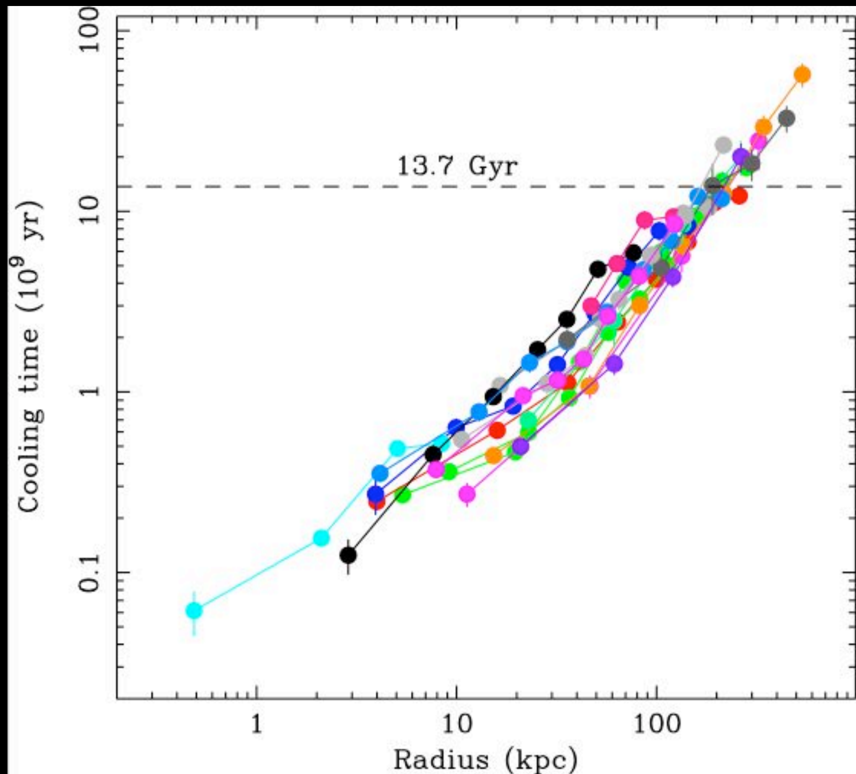
stellar mass function



rss et al. 2007

Cooling Flow Problem

- X-ray data allow us to determine density and temperature of ICM
- Cooling times in central regions short -- would expect significant cooling
- yet correspondingly large amounts of stars or cold gas not observed



Peterson & Fabian (2006)

old stars

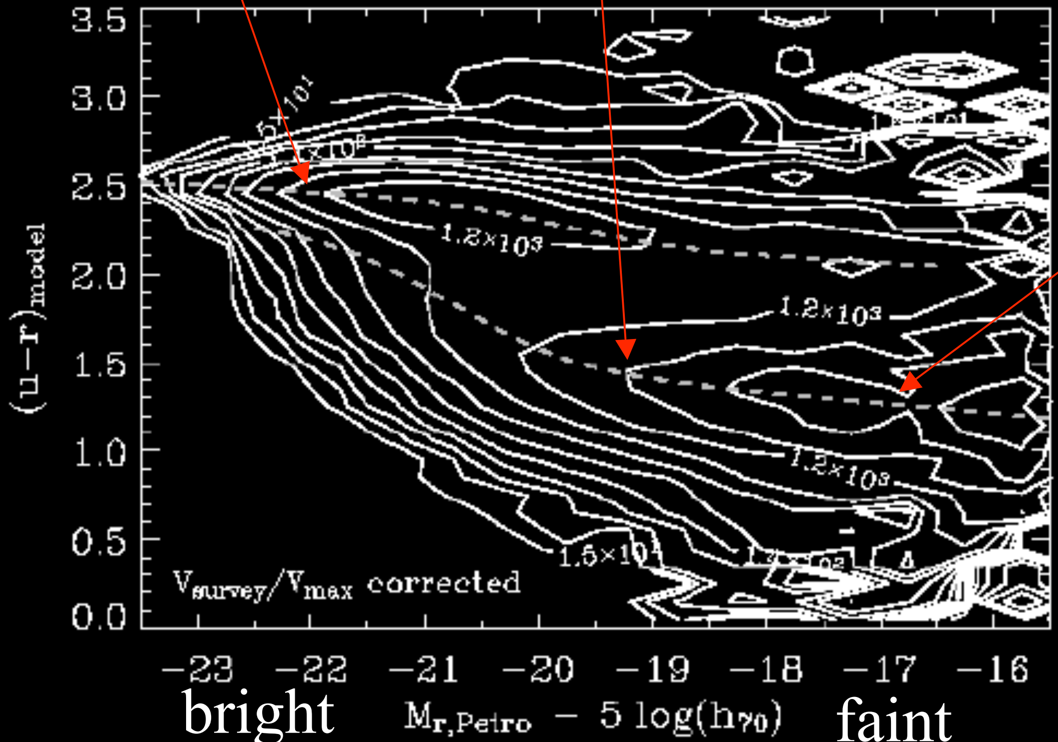
local universe: galaxies are bimodal in color, morphology, & structure

young stars

red

color

blue



bright faint

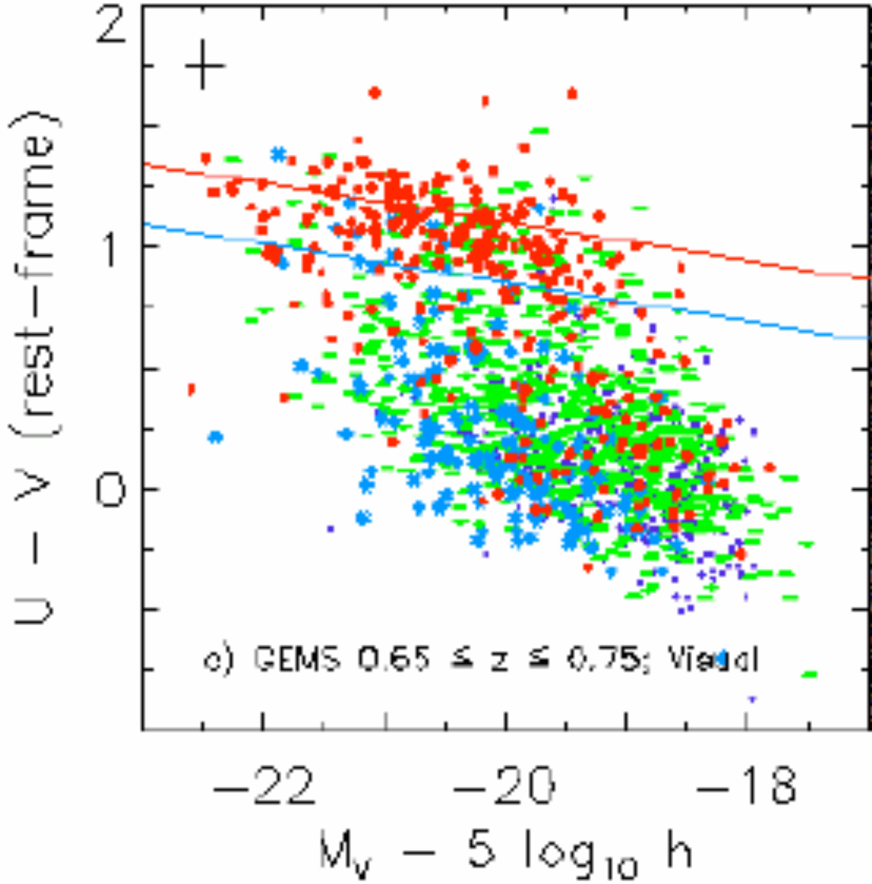
luminosity

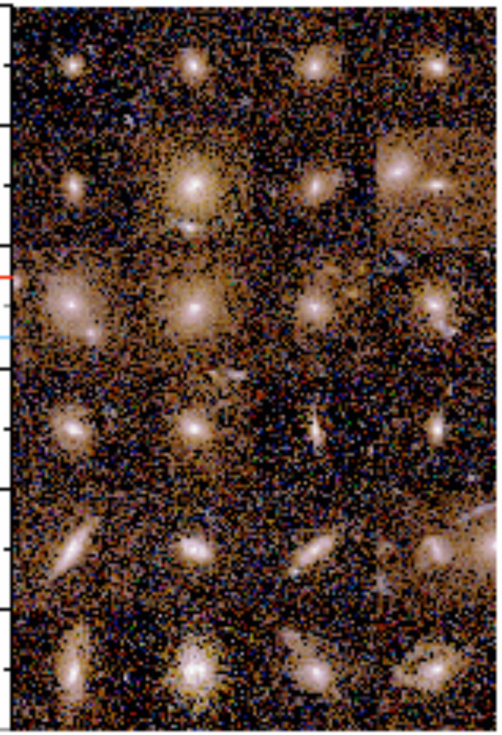
strong correlation between stellar mass & type

SDSS

Baldry et al. 2003

red sequence, color bimodality, and the strong correlation with morphology persists to at least z~1-1.5

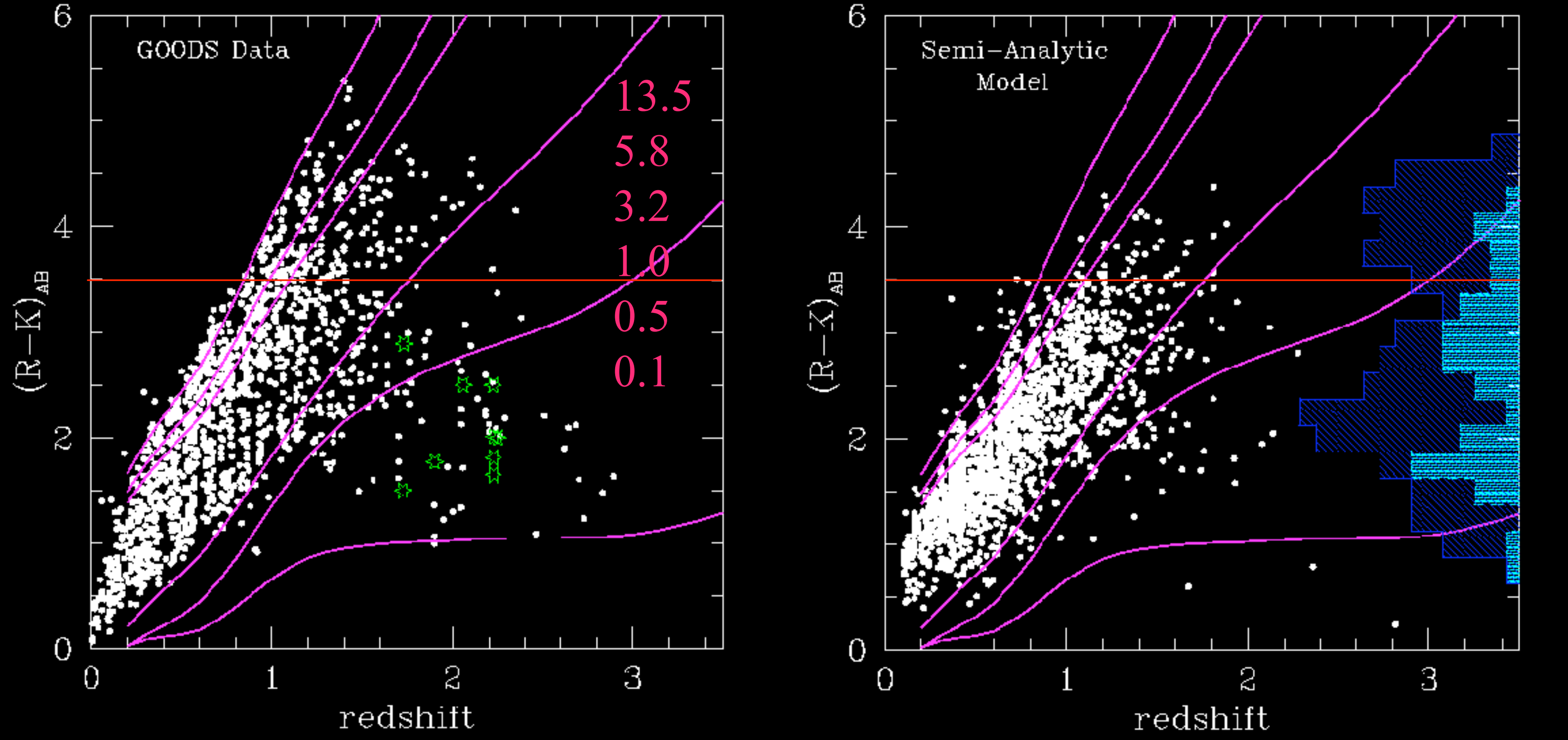




Bell et al. 2003

see also Faber et al. 2004

Pre-AGN FB models could not produce enough massive *red* (dead) galaxies



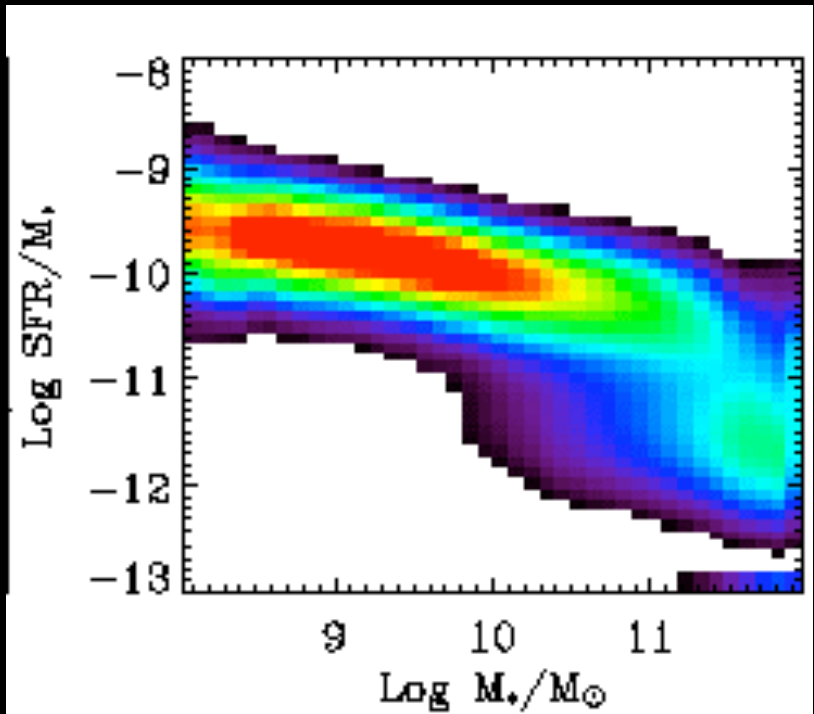
GOODS

$K_{AB}<22$

rss et al. 2004 GOODS ApJL

why are massive galaxies red/dead? quenching and the critical mass

specific star formation rate



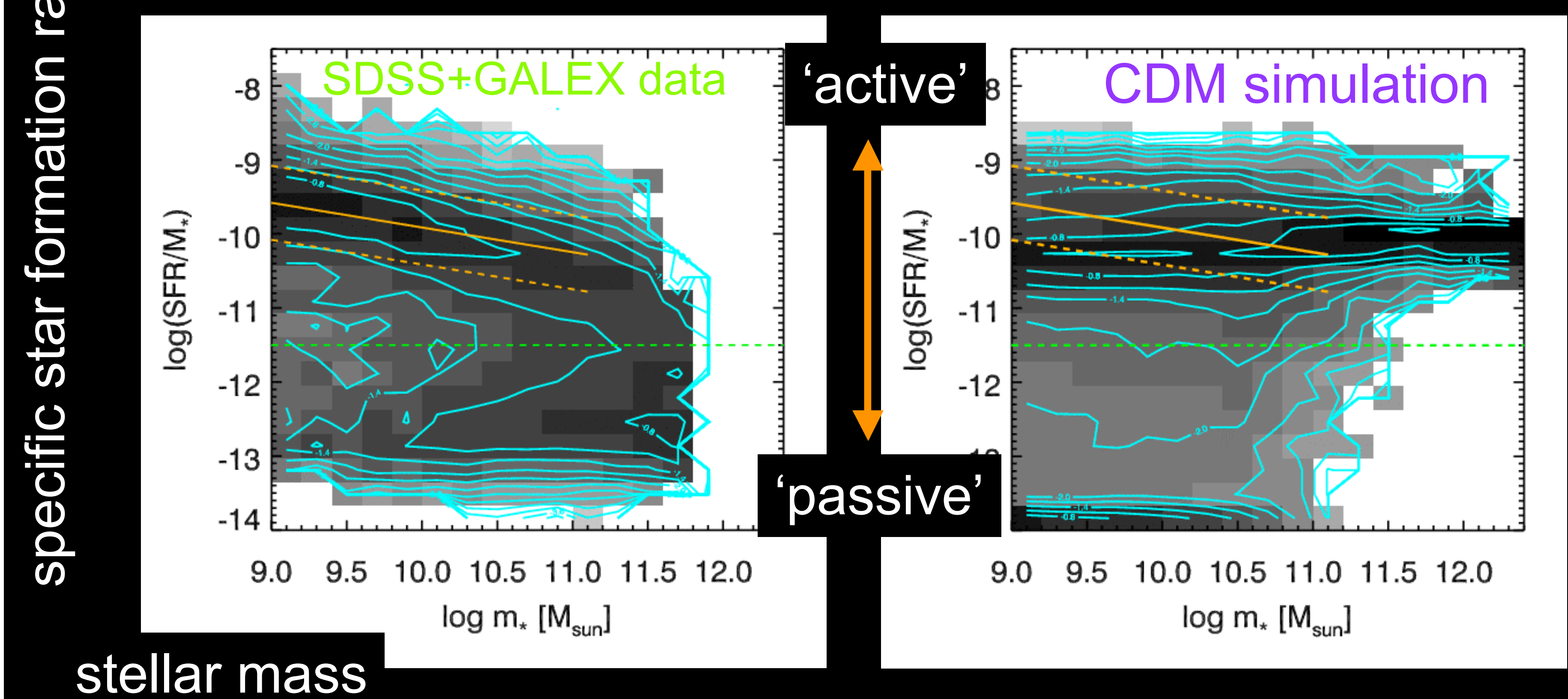
stellar mass

Brinchmann et al. 2003

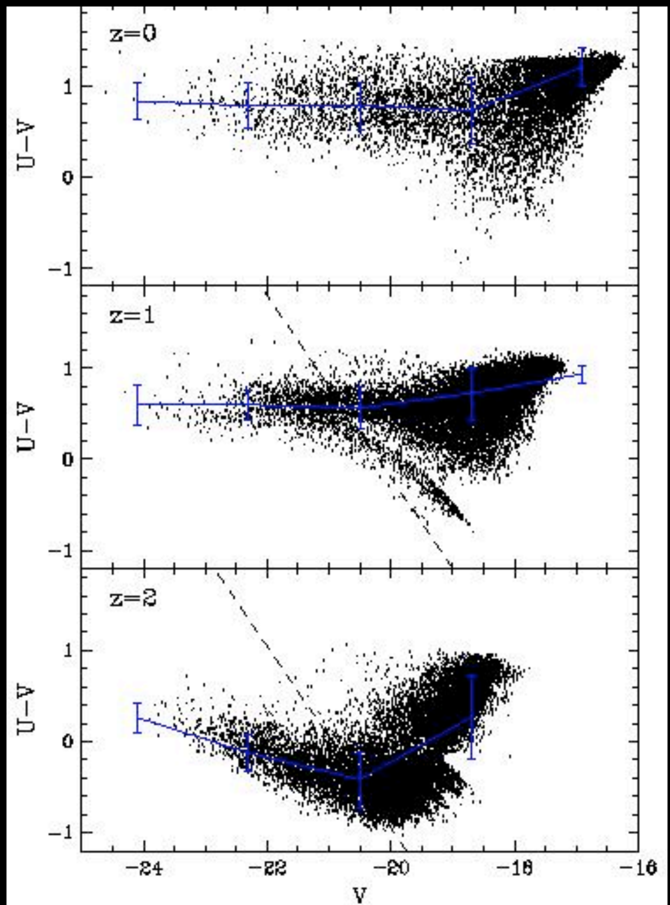
- most low-mass galaxies lie on a star forming ‘main sequence’
- appearance of ‘quenched’ galaxies above $m_* \sim m_{crit} \sim 3x10^{10}\ M_{sun}$
- m_{crit} also corresponds to the transition between disk- and spheroid-dominated galaxies (Kauffmann et al. 2003)
- seen to z~1.5-2 (Noeske et al. 2007; Bundy et al. 2006; Papovich et al. 2006; van Dokkum et al. 2006)

color-magnitude/ color bimodality problem:

massive galaxies in CDM simulations continue to accrete
cold gas and form stars-->too many massive blue disk galaxies
not enough massive red spheroid dominated galaxies
at all redshifts z<~2 (e.g. rss 2004)



color/bimodality problem: SPH simulations

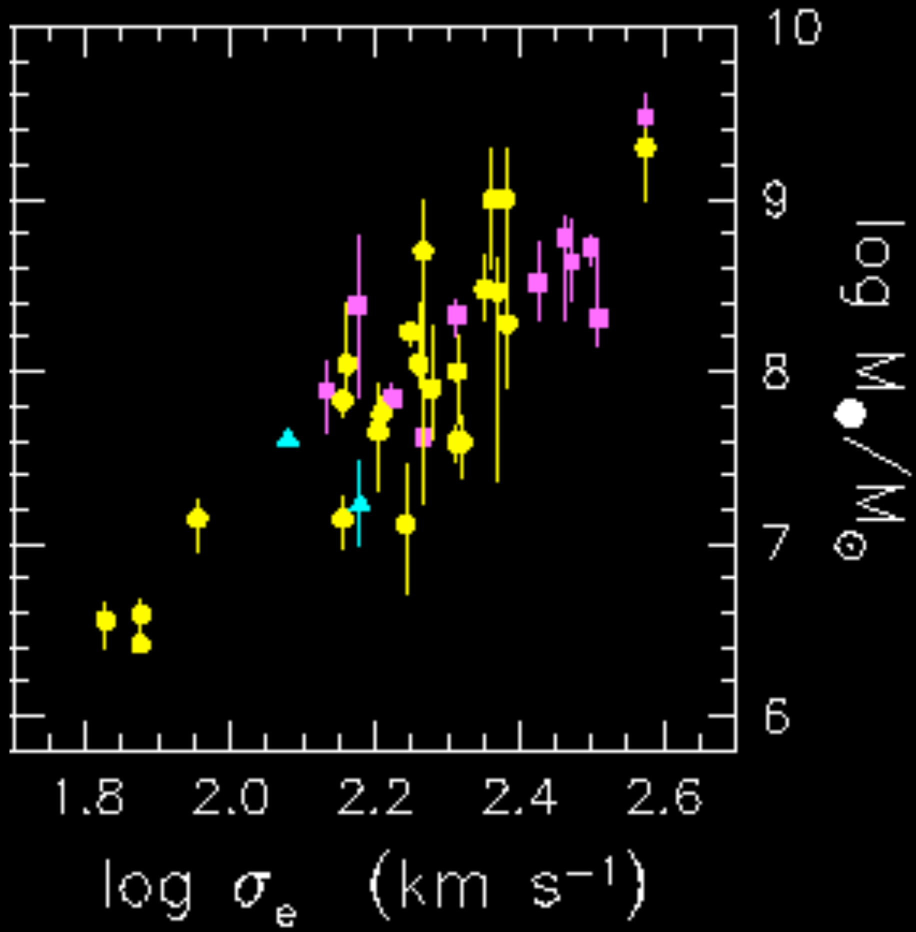


Dave et al., see also Nagamine et al.

- semi-analytic models & SPH simulations produced an inverted CM relation
- generically did not produce color bimodality

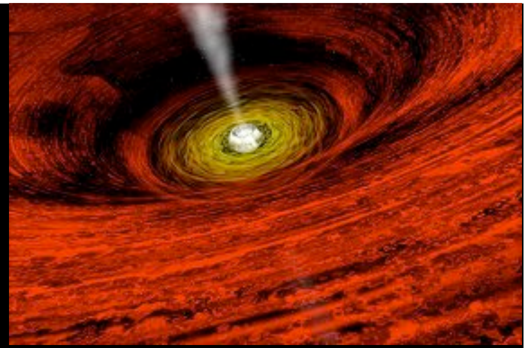
enter 'AGN feedback'...

- need mechanism to:
  - reduce/stop cooling in massive halos
  - quench star formation in massive galaxies
- n.b. stellar/SN feedback does not work
  - not enough energy
  - little/no star formation in the systems where the energy input is needed



Ferrarese & Merritt 2000
Gebhardt et al. 2000

AGN feedback 1: bright mode

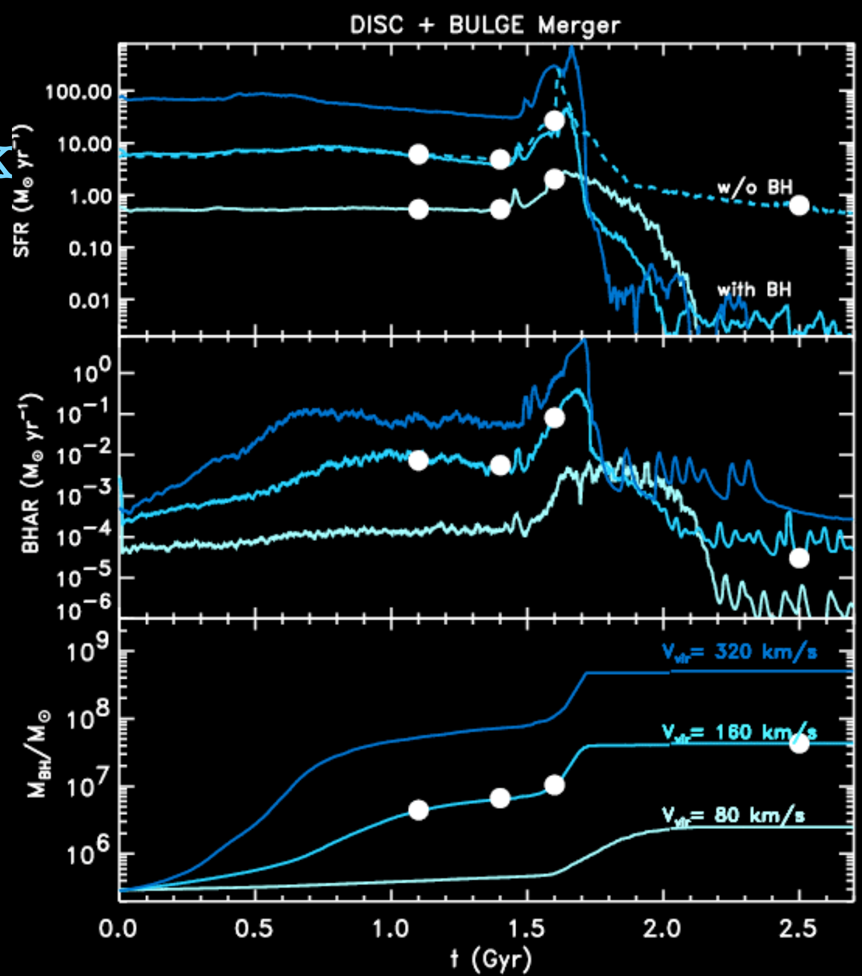


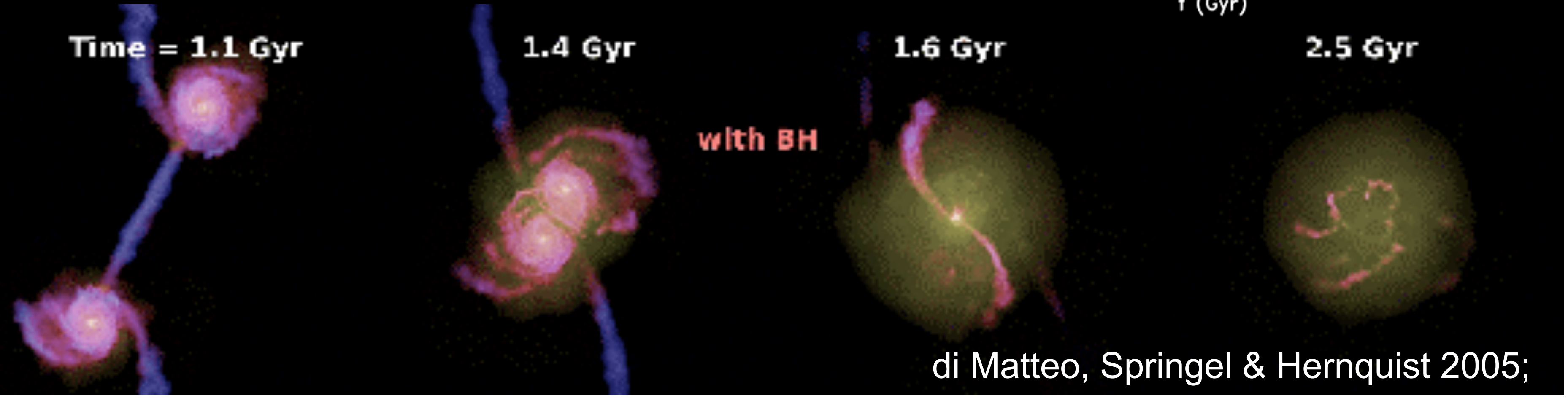
- optical/X-ray luminous AGN/QSO, produced during periods of efficient feeding (mergers?)
- high accretion rates (0.1-1 L_{Edd}), fueled by cold gas via thin accretion disk --> BH grows rapidly
- rare-->duty cycle short
- thermal coupling of AGN energy with ISM is probably fairly weak (<5%)

Di Matteo, Springel & Hernquist 2005

Hydrodynamic simulations of galaxy mergers including black hole growth and feedback

- self-regulated BH growth, reproducing M_{BH}-σ relation (di Matteo et al. 2004)
- AGN-driven wind removes residual cold gas at the end of the merger, leading to lower SFR and redder colors in the spheroidal remnant (Springel et al. 2004)
- characteristic AGN ‘lightcurve’

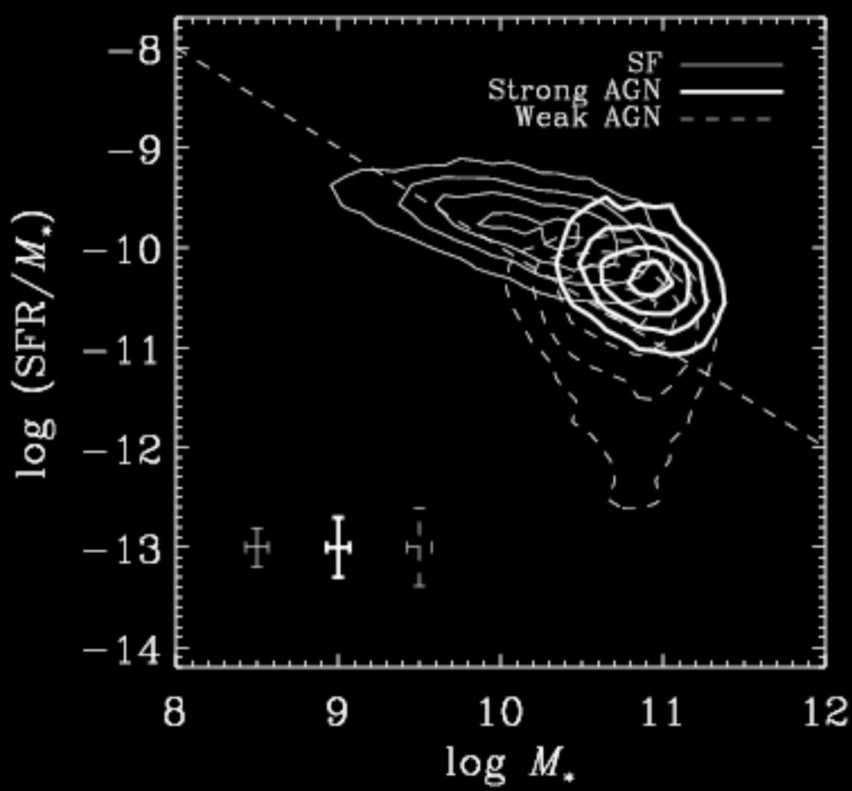




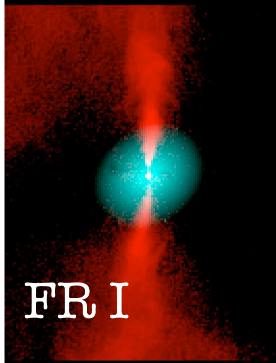
di Matteo, Springel & Hernquist 2005;

circumstantial evidence that AGN are associated with quenching of SF…

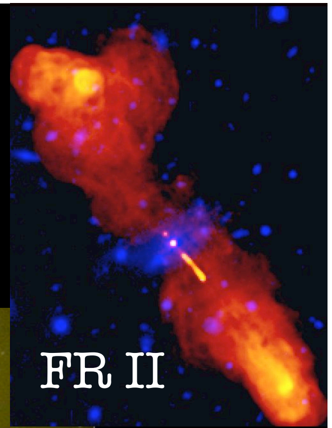
- weak AGN at z=0 live in massive, spheroids with young stellar pops; many are post-starburst (Kauffmann et al. 2003)
- strong correlation of σ with color; almost all 'green valley' galaxies host weak AGN (Kaviraj et al. 2006; Kauffmann et al. 2006; Salim et al. 2007)
- similar results seen for AGN to z~1 (GEMS; Sanchez et al. 2004; AEGIS; Pierce et al. 2006)



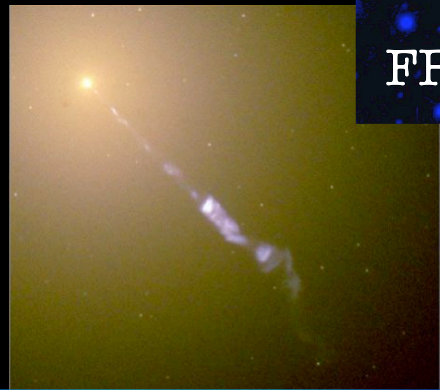
Salim et al. 2007

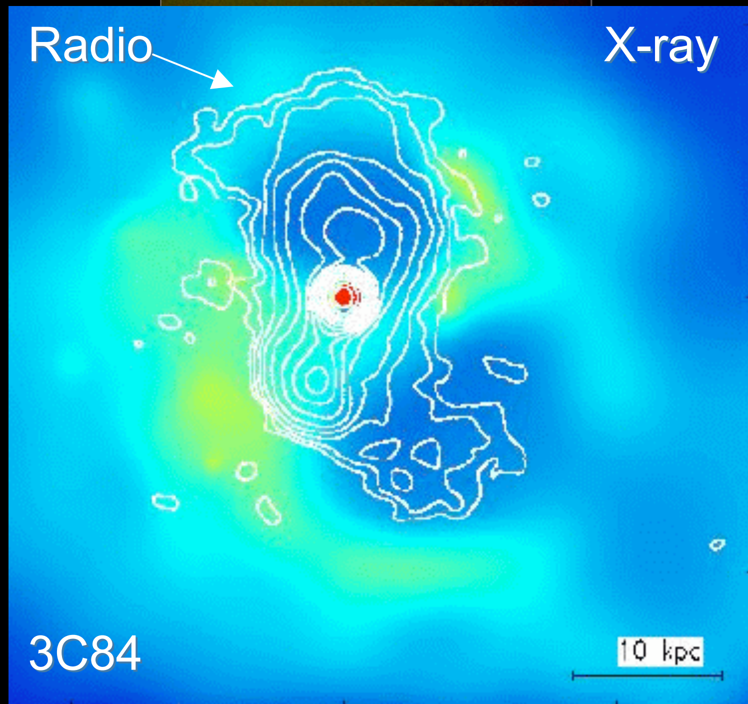


AGN feedback 2: Radio Mode



- many massive galaxies are 'radio loud'
- radio activity believed to be associated with BH's in 'low accretion state' (low Eddington ratio, $<10^{-3}$) -- (spherical, Bondi accretion or ADAF?)
- jets often associated with cavities visible in X-ray images
- coupling of jet energy with hot gas very efficient

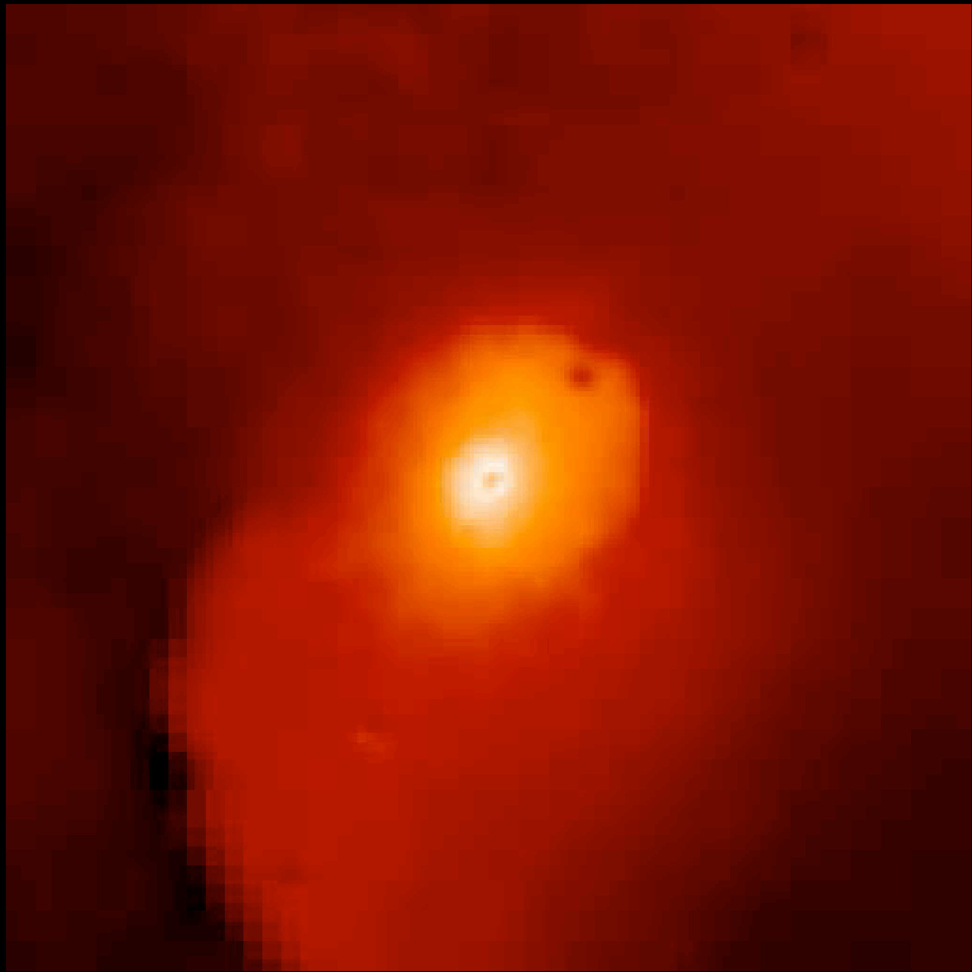




effervescent heating

- intermittent jet with a duty cycle of ~10^7 yr leads to efficient heating of a large fraction of the cluster gas (Ruszkowski et al. 2004)
- combination of sound waves, weak shocks and bubble-ICM interface
- heating rate may be able to balance radiative cooling for reasonable input luminosities

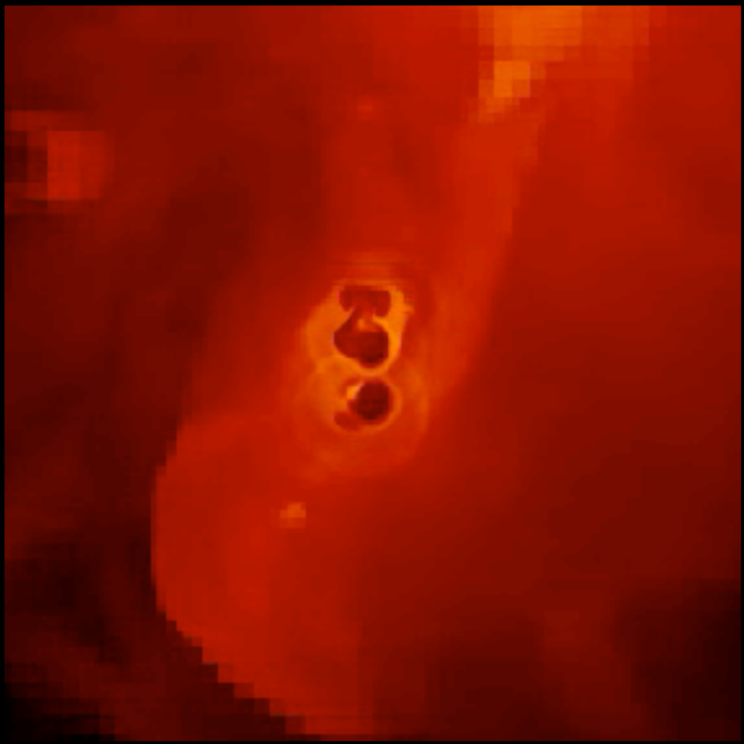
see also Reynolds et al. (2002; 2005)
Vernaleo & Reynolds (2006, 2007)
Sijacki & Springel 2005



Bruggen, Ruszkowski & Hallen 2005

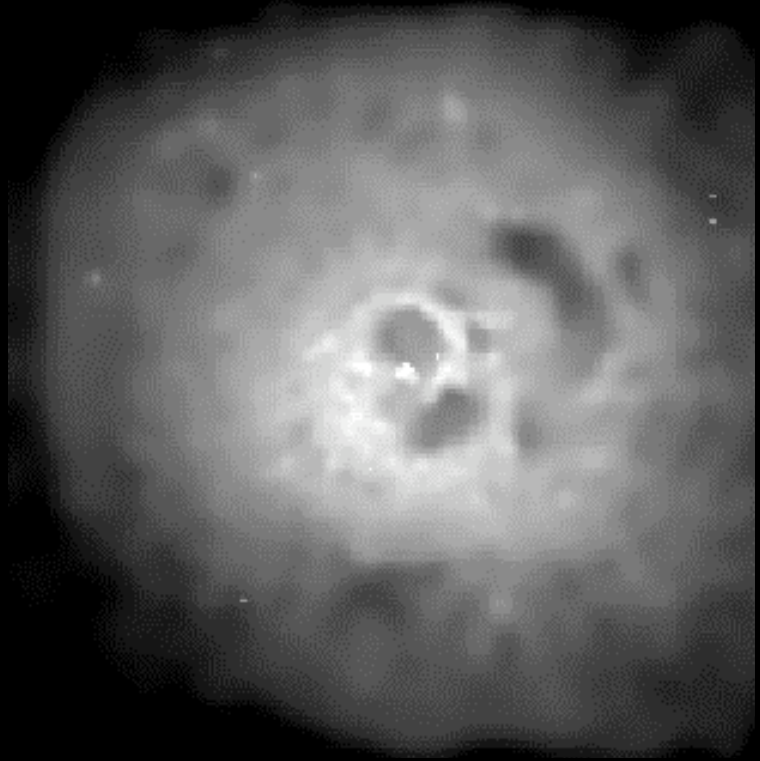
- simulations produce cavities and 'cold fronts' that look similar to those seen in X-ray images of clusters

simulation of heating by a jet



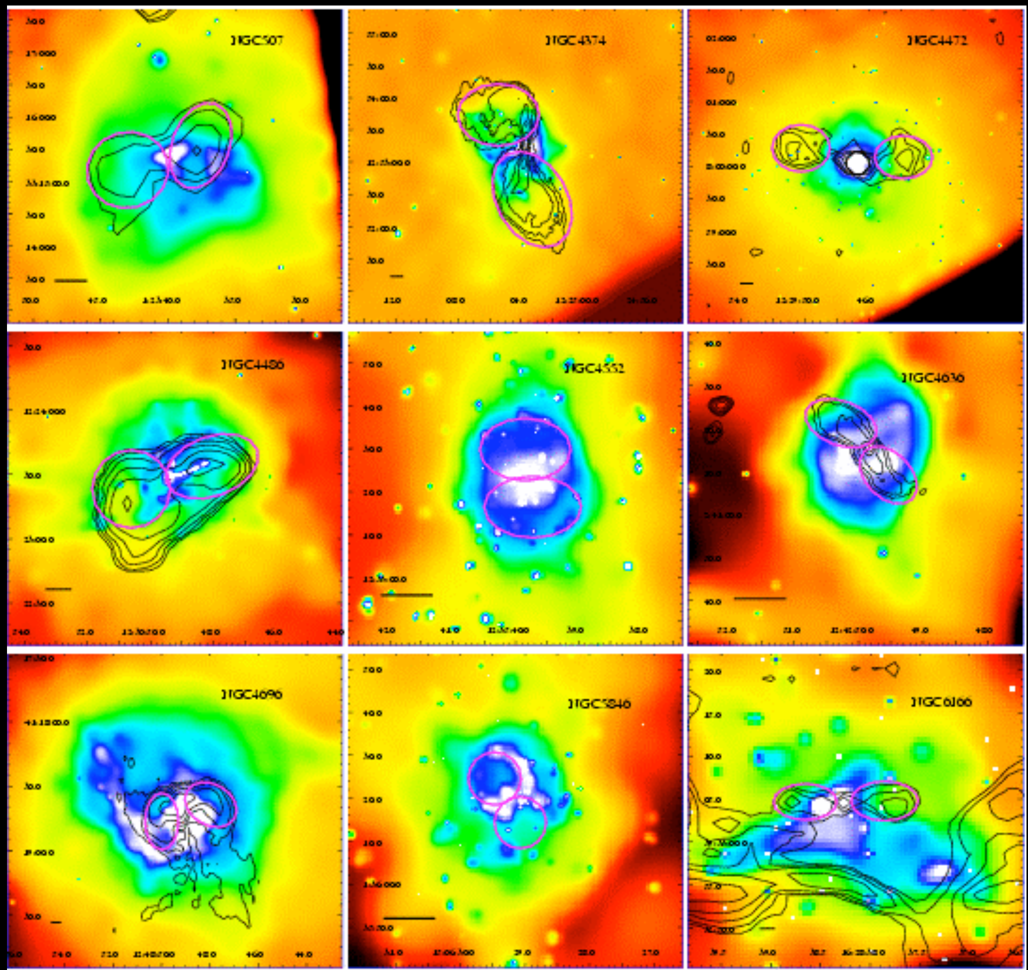
Bruggen, Ruszkowski & Hallen 2005

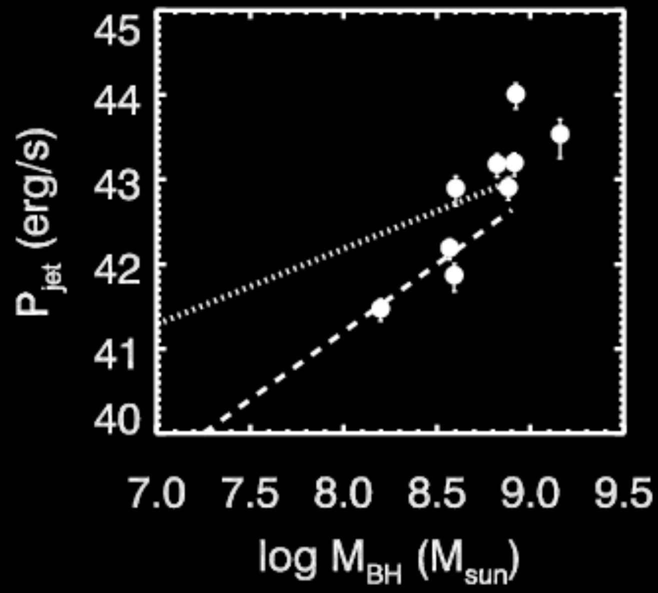
Chandra image of hot gas in real cluster



Fabian et al.

X-ray bubbles as ‘calorimeters’

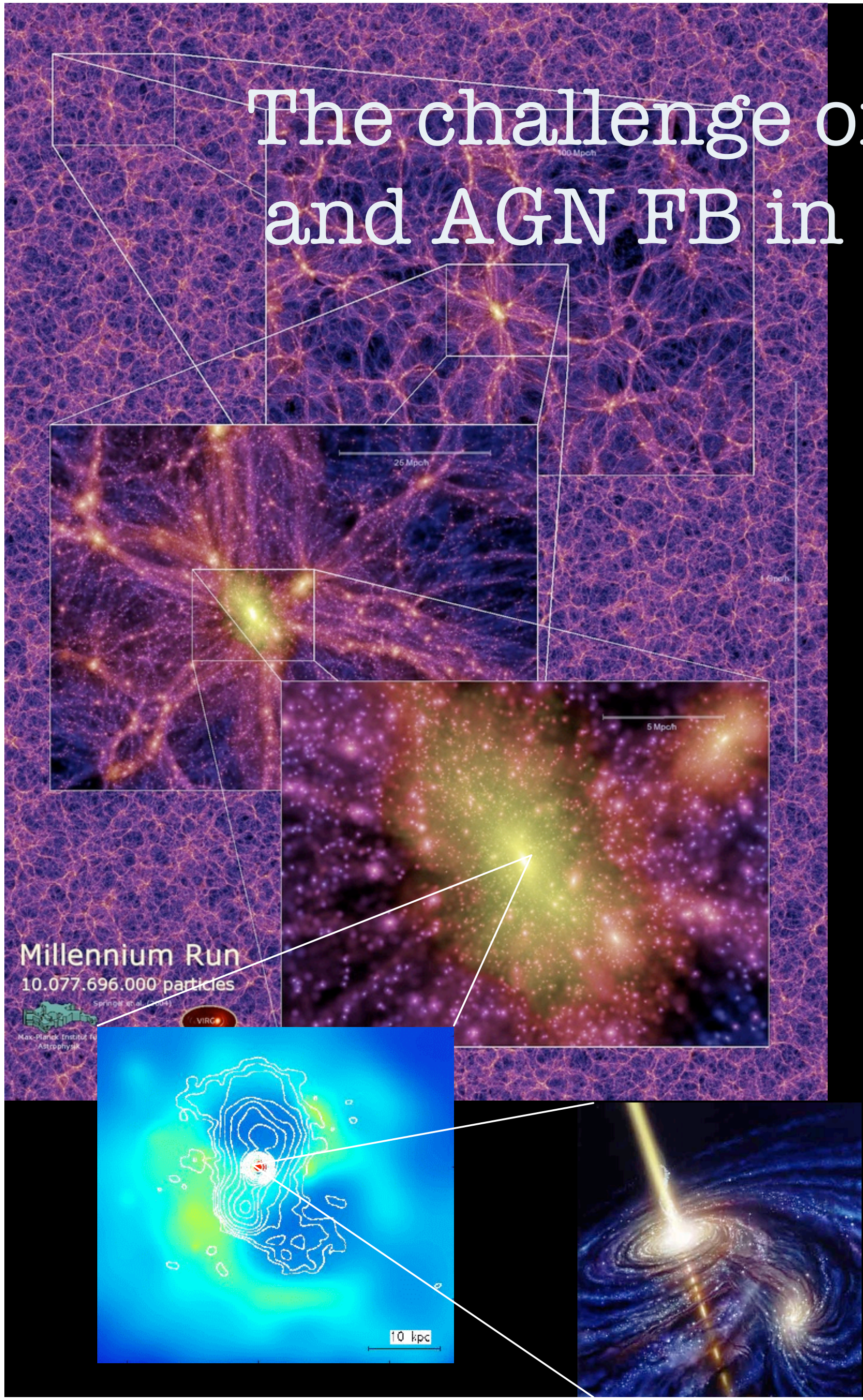




jet power (measured via bubble energy) scales with BH mass
(n.b. ‘PV’ argument may underestimate energy e.g. Binney et al. 2007)

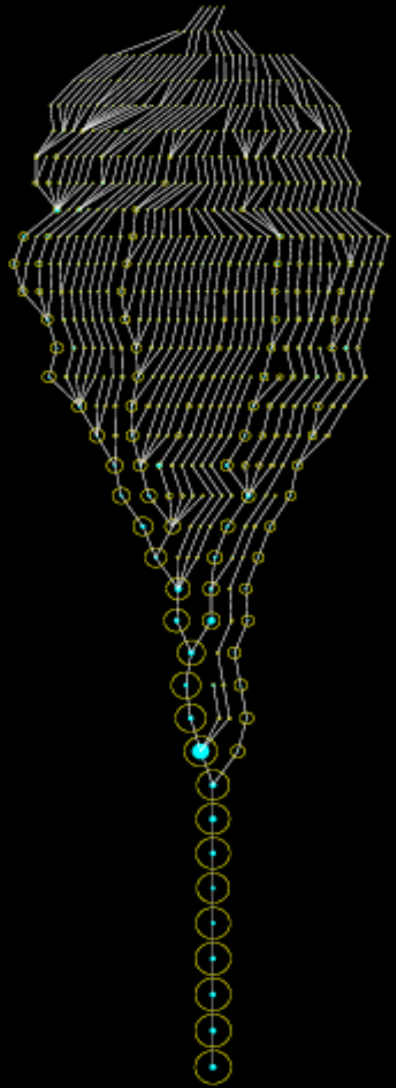
Allen et al. 2006
Best et al. 2006
see also Birzan et al. 2004

The challenge of simulating BH growth and AGN FB in a cosmological context



- dynamic range:
  - Gpc (luminous QSO)
  - few 100 Mpc (LSS)
  - 10's of kpc (ICM, jets)
  - sub-kpc (star formation, stellar FB)
  - few 100 pc (nuclear gas inflows, starbursts, AGN feeding, winds)
  - pc & sub-pc (accretion disk, BH mergers, etc)
- poorly understood physics (B-fields, conduction, cosmic ray pressure, turbulence, feeding problem, ...)

NEW Self-consistent model for the co-evolution of galaxies, black holes, and AGN



- top-level halos start with a ~100 M_{sun} seed BH
- mergers trigger bursts of star formation and accretion onto BH; efficiency and timescale parameterized based on hydrodynamical merger simulations (μ, B/T, V_c, f_g, z; Cox et al., Robertson et al.)
- BH accrete at Eddington until they reach 'critical mass', then enter 'blowout' (power-law decline) phase

$$dm_{acc}/dt = \dot{m}_{Edd}/[1+(t/t_Q)^{\beta}]$$

- energy released by accretion drives a wind
- BH merge when their galaxies merge; mass is conserved

rss, Hopkins, Hernquist, Cox, Robertson et al. 2007

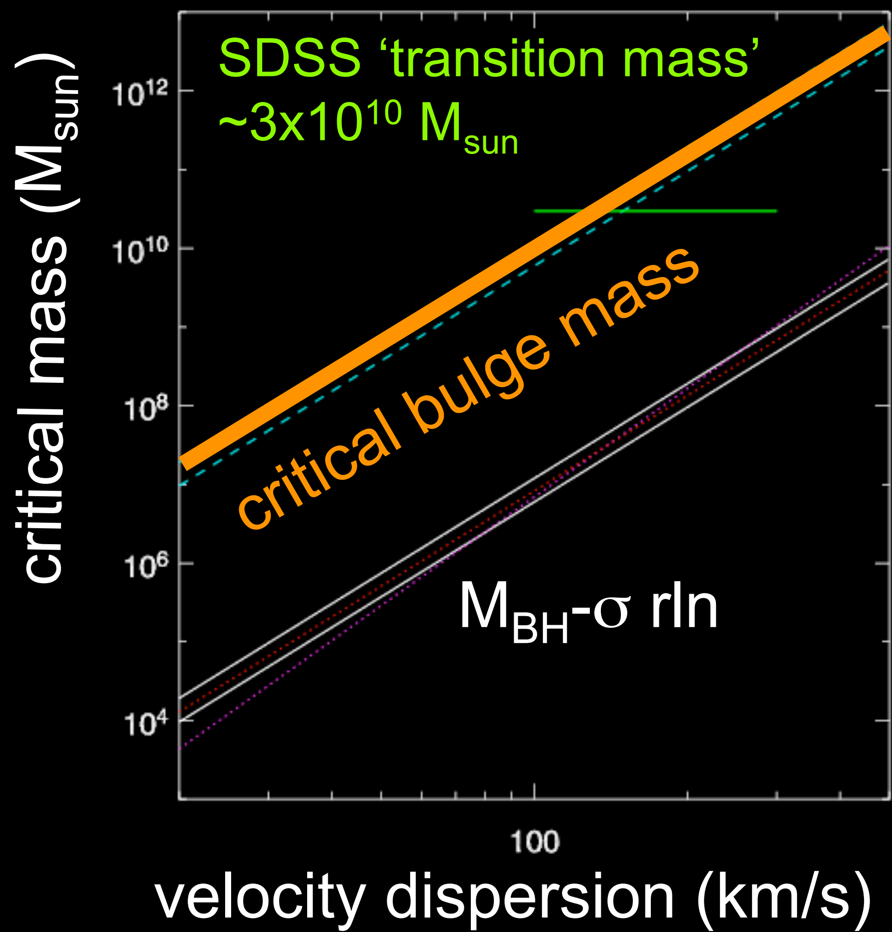
momentum-driven winds: critical mass

$$L_{crit} = \frac{4 f_g c}{G} \sigma^4$$

Murray, Quataert & Thompson 2004

$$L_\bullet = \eta_{Edd} L_{Edd}$$

$$M_{\bullet,crit} / M_{sun} = 0.12 \eta_{Edd}^{-1} \left(\frac{f_g}{0.1} \right) \left(\frac{\sigma}{km/s} \right)^4$$



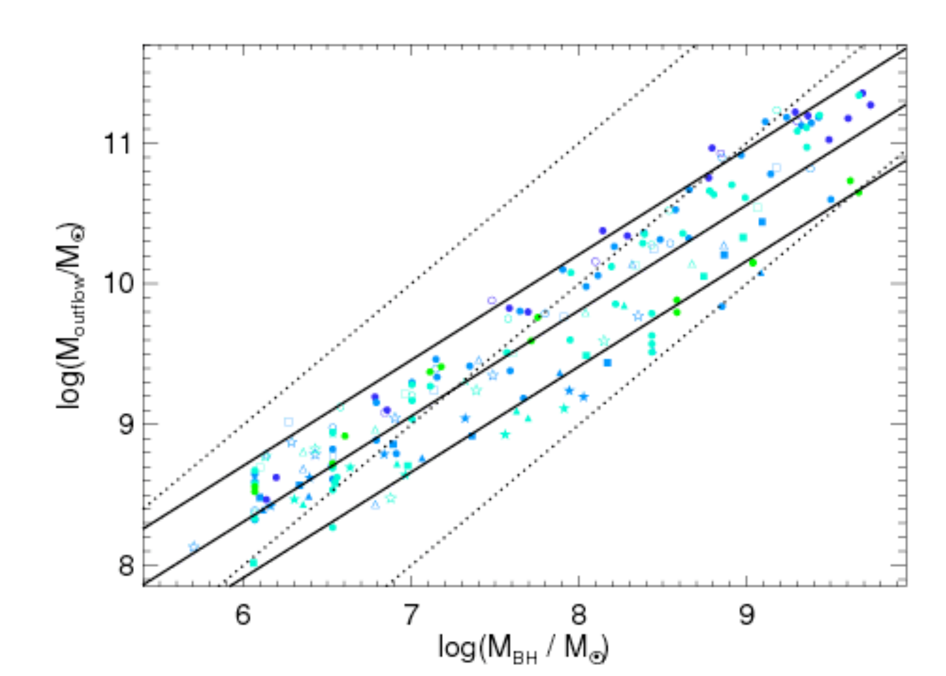
rss et al. 2007

momentum-driven winds: galactic outflows

$$\frac{\varepsilon_{wind} E_{BH}}{c} = M_{out} v_{esc}$$

$$E_{BH} = \eta \frac{dm_{acc}}{dt} c^2$$

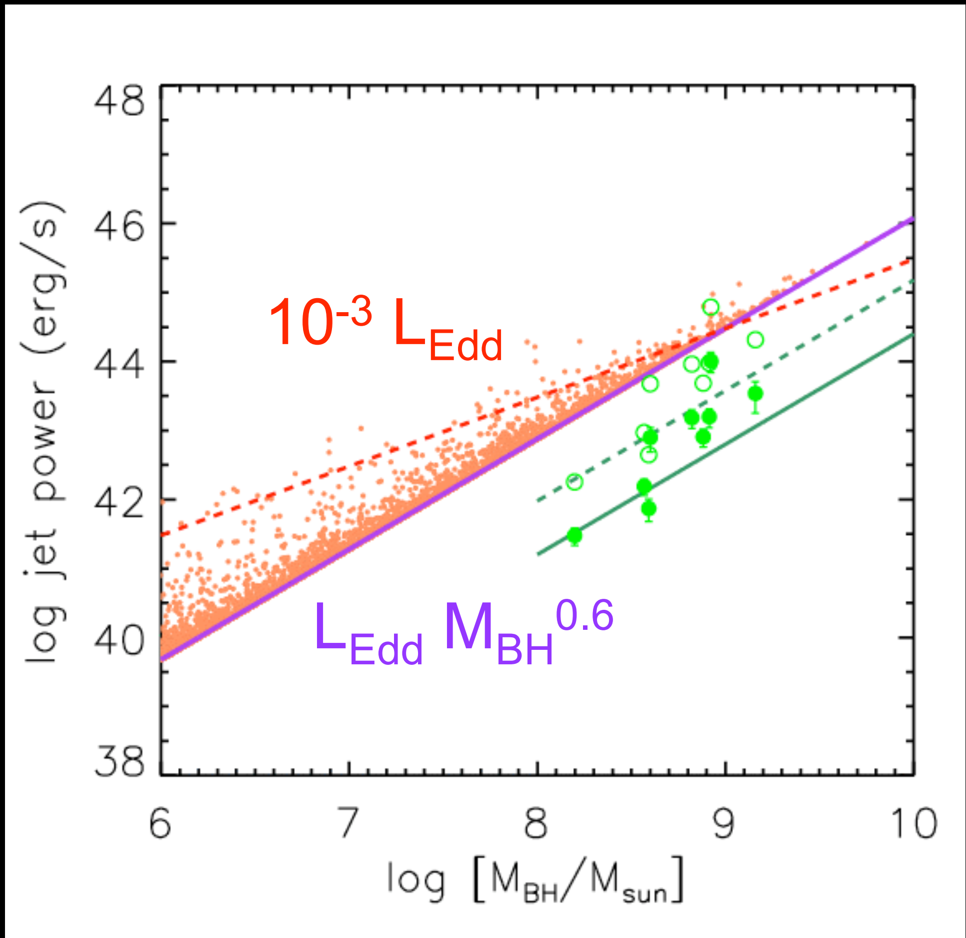
$$\frac{dM_{out}}{dt} = \varepsilon_{wind} \eta \frac{c}{v_{esc}} \frac{dm_{acc}}{dt}$$



from hydrodynamic simulations of merging galaxies (Springel, di Matteo & Hernquist; Hopkins et al.)

rss, Hopkins, Hernquist, Robertson, Cox et al. 2007

“radio mode” heating



- assume continuous ‘Bondi-like’ accretion

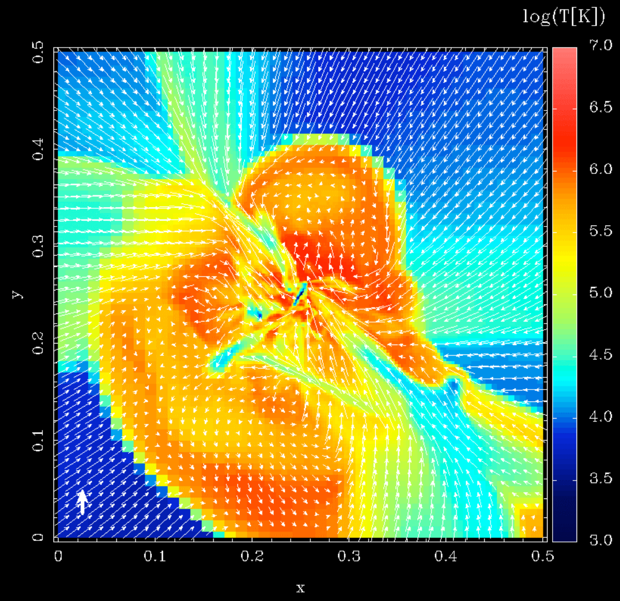
$$\dot{m}_{acc,R} = f_{Edd,R} L_{Edd} M_{BH}^{\alpha_R}$$

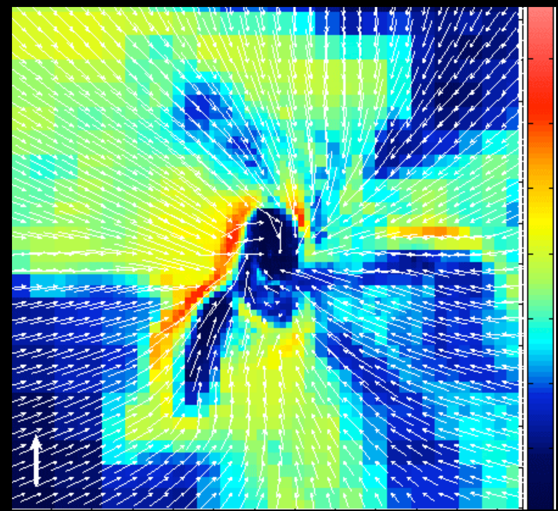
- fixed fraction κ of released energy in kinetic form (jet)

Allen et al. clusters; Best et al. study w/ factor 6 boost (Binney et al. 2007)

hot vs. cold flows

- when $r_{cool}<r_{ff}$, gas is shock heated to virial temperature then cools in a “cooling flow”
- when $r_{cool}>r_{ff}$, gas never shock heats, “falls in cold”
- halos with primarily cold vs. hot flows separated by a critical mass of few x 10^{11}-10^{12} M_{sun} (e.g. Birnboim & Dekel 2003; Keres et al. 2004)
- heating by radio jets may only be effective when a quasi-static hot gas halo is present (i.e. in large mass halos; Cattaneo et al. 2006)

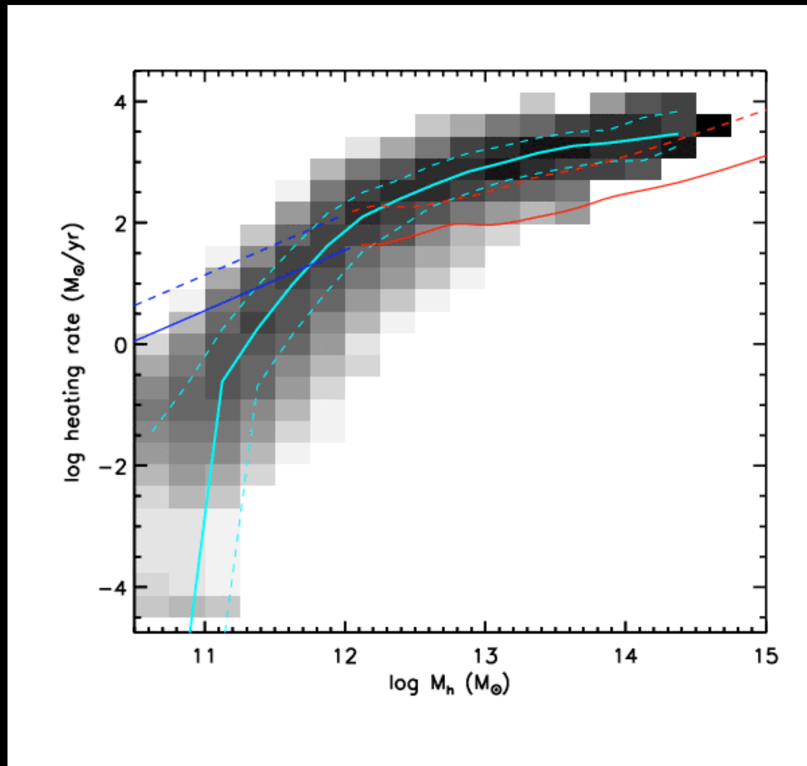




Kravtsov et al.

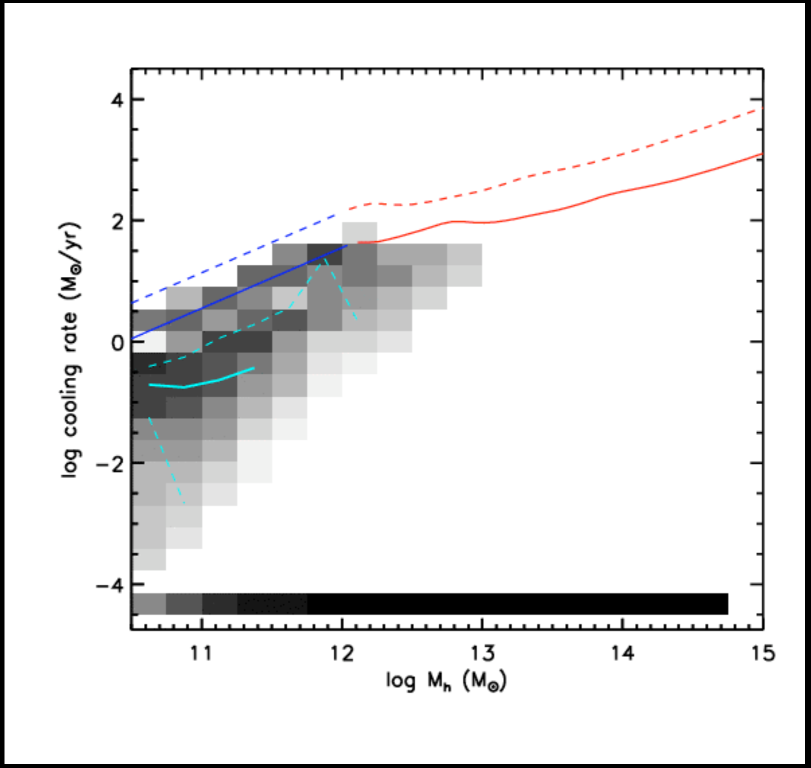
radio mode heating

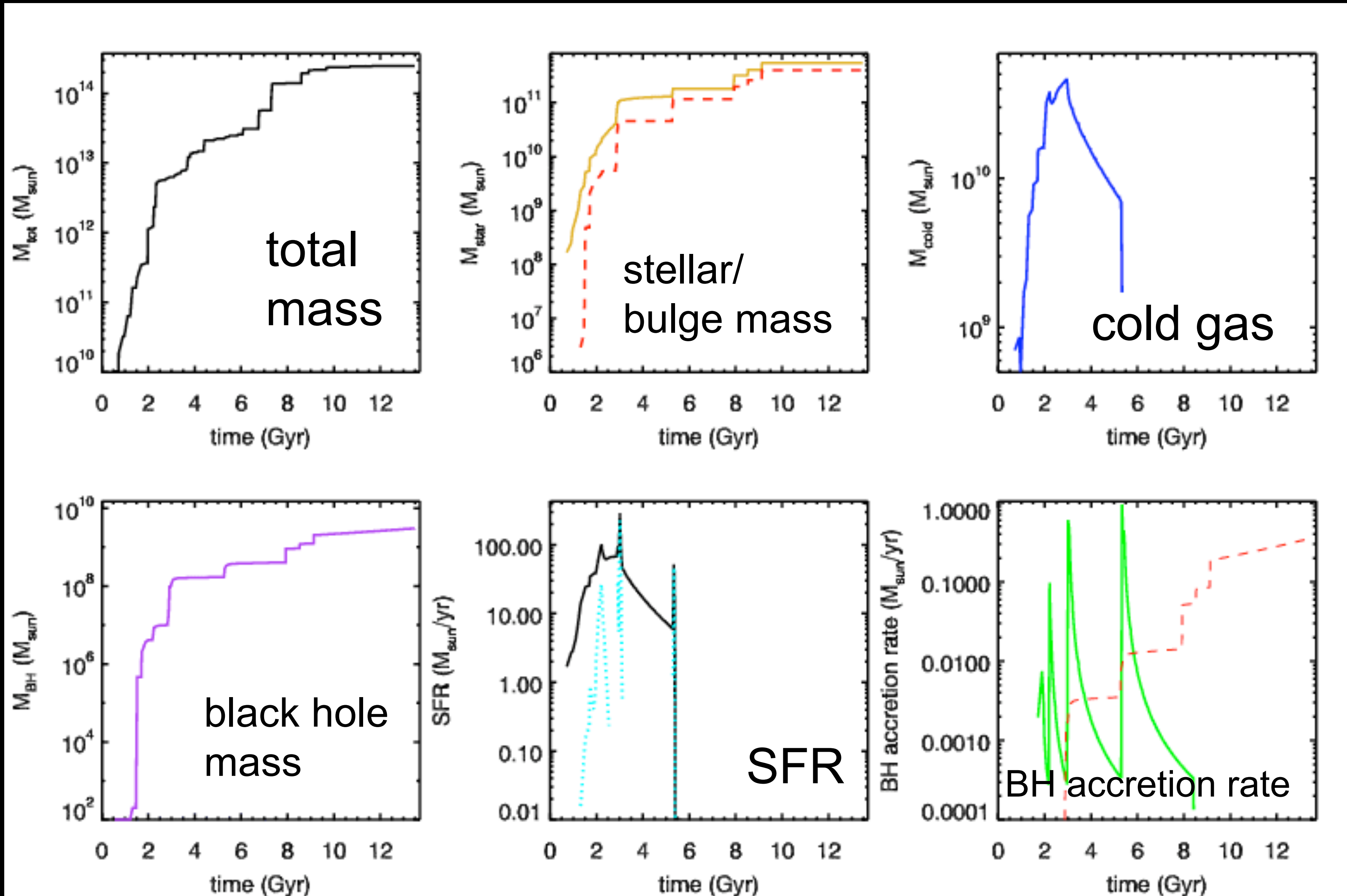
- predicted heating rate is subtracted from cooling rate at each timestep *in which cooling is from a quasi-static hot halo*
- ‘cold mode’ cooling is unaffected



radio mode heating

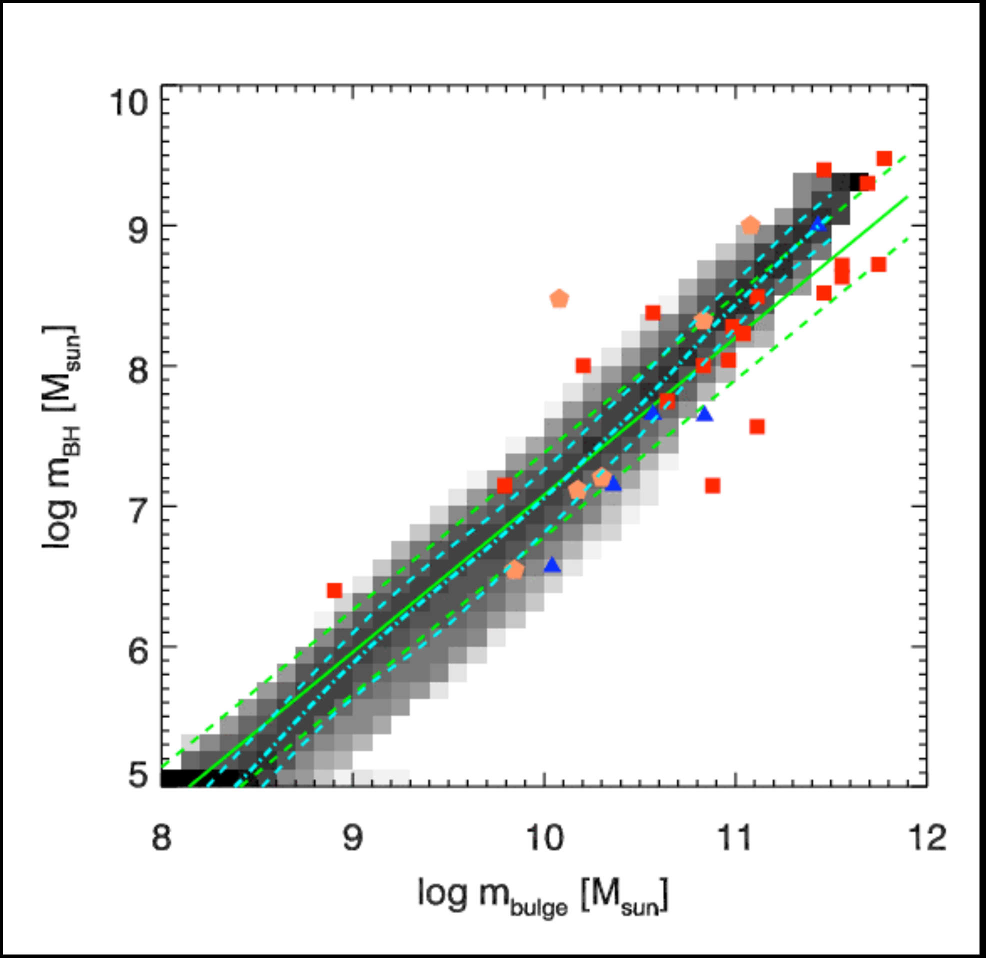
- energy is sufficient to offset cooling in massive halos




total mass
stellar/
bulge mass
cold gas
black hole
mass
SFR
BH accretion rate
M_{tot} (M_{sun})
M_{star} (M_{sun})
M_{cold} (M_{sun})
M_{BH} (M_{sun})
SFR (M_{sun}/yr)
BH accretion rate (M_{sun}/yr)
time (Gyr)
time (Gyr)
time (Gyr)
time (Gyr)
time (Gyr)
time (Gyr)

predicted M_{BH}-M_{bulge} relationship

in our model, arises from 'bright mode' feedback



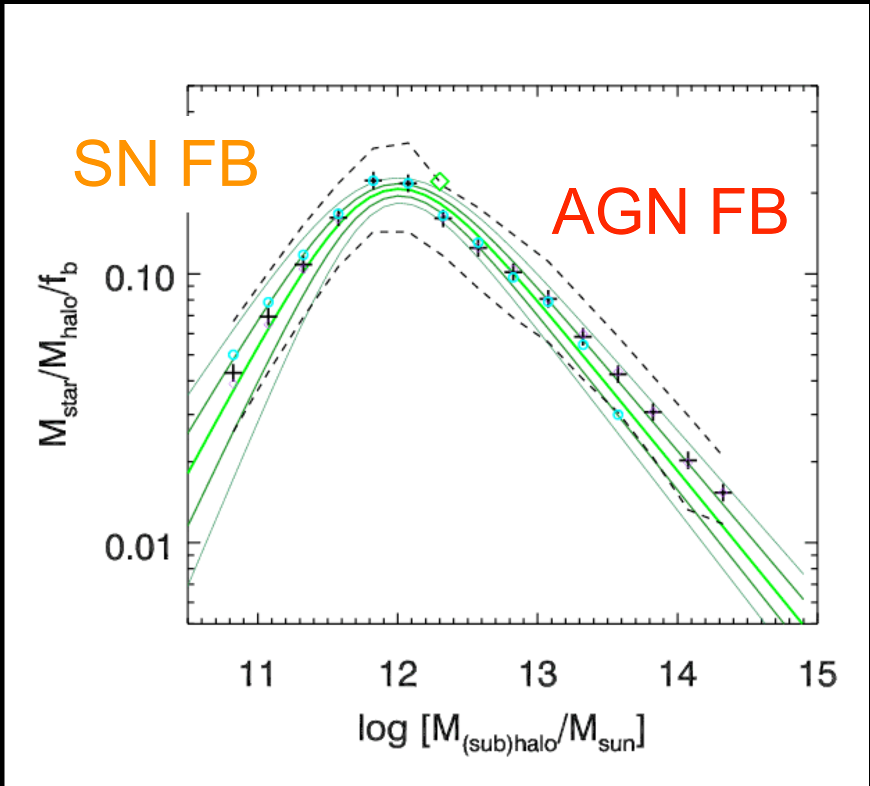
matches slope & scatter of observed relation

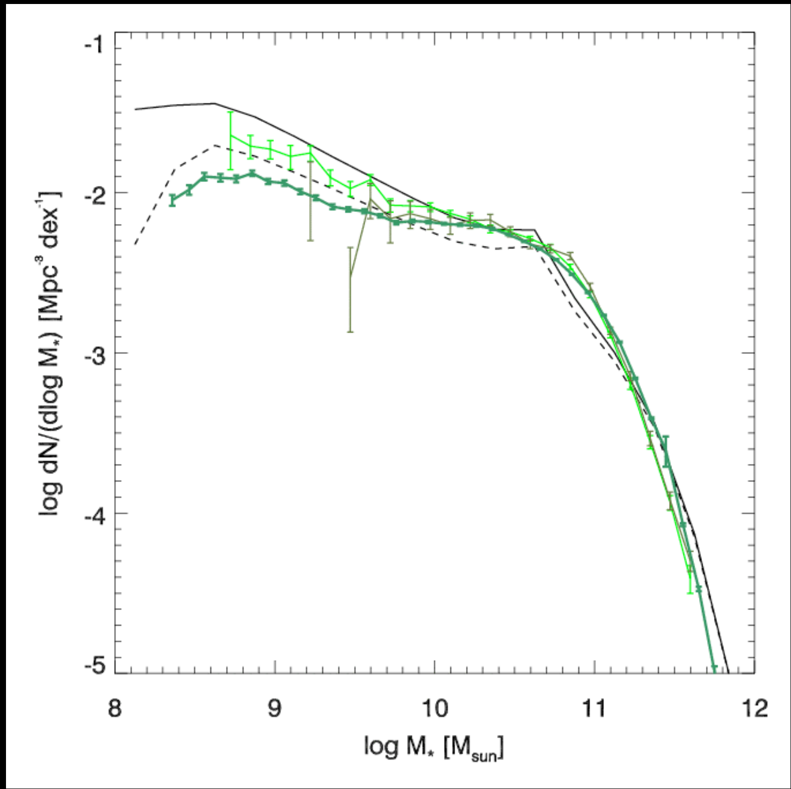
large symbols:
Haering & Rix data
green: H&R fit + scatter
intrinsic scatter: 0.3 dex

cyan: predicted median, 10th, & 90th percentile
predicted scatter: ~0.15 dex

rss et al. 2007

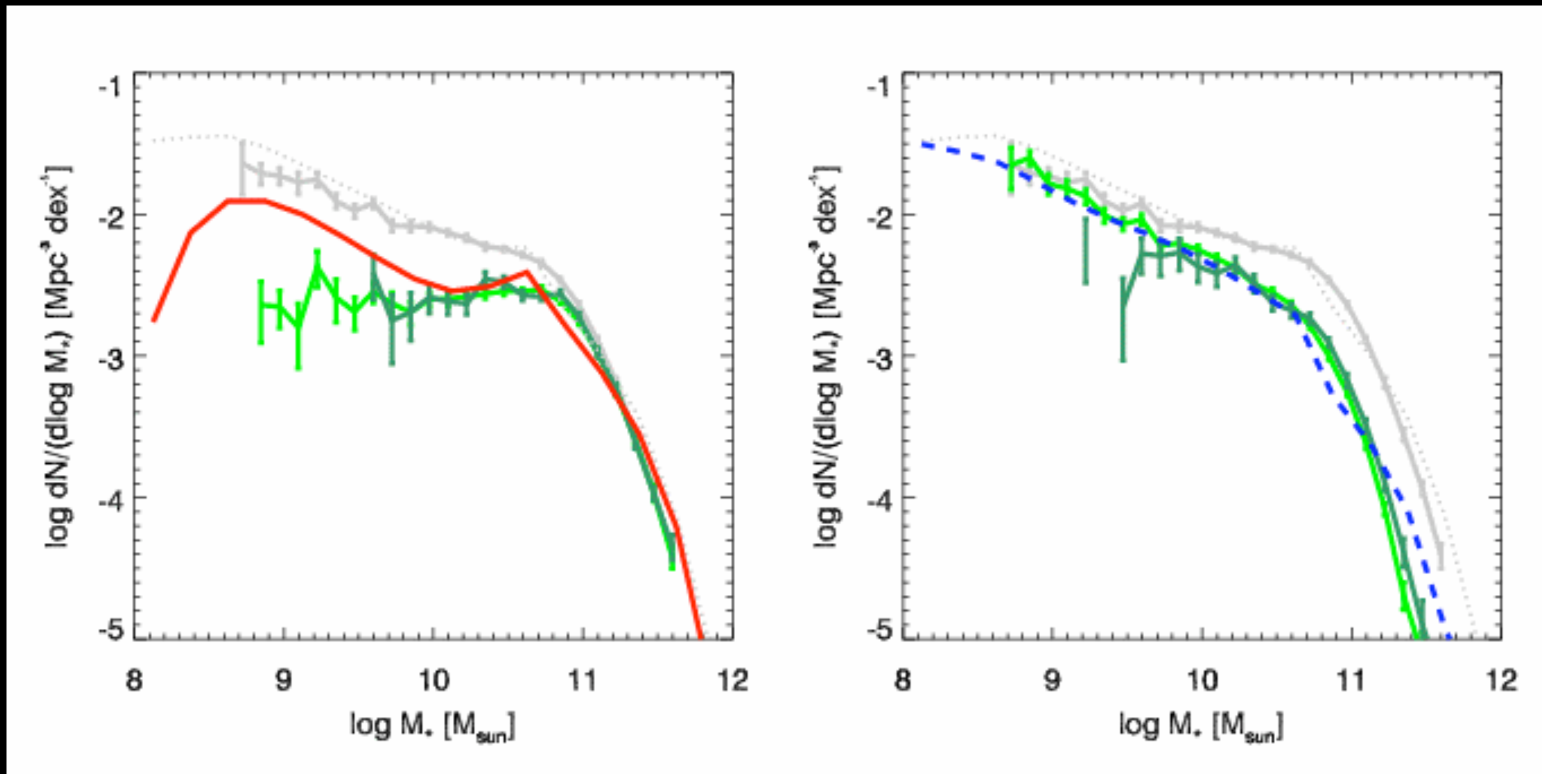
implementing the heating term leads to a much-improved galaxy mass/luminosity function at z~0





rss et al. 2007

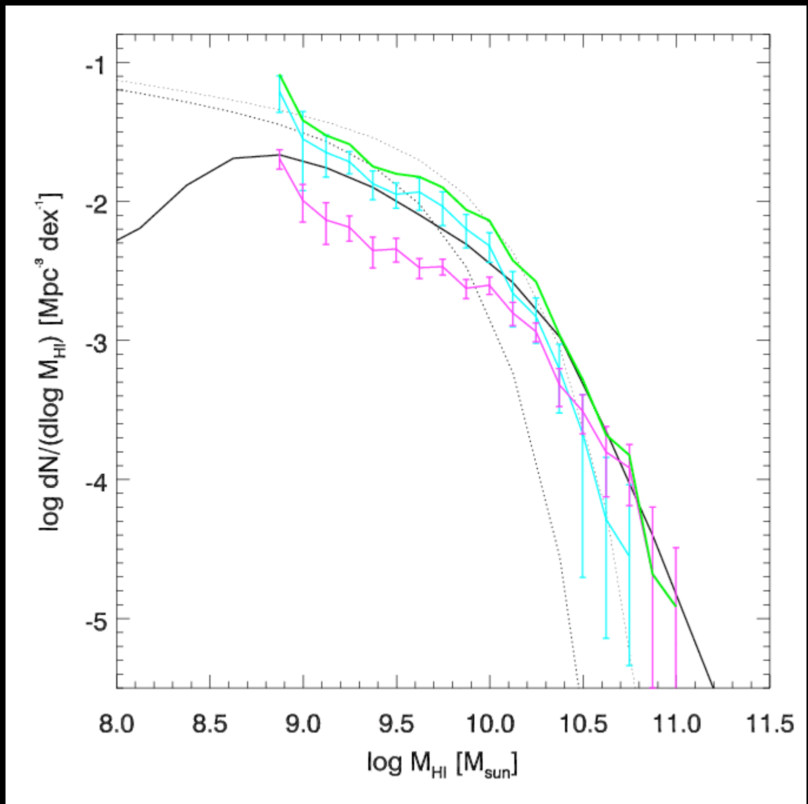
stellar mass function by type



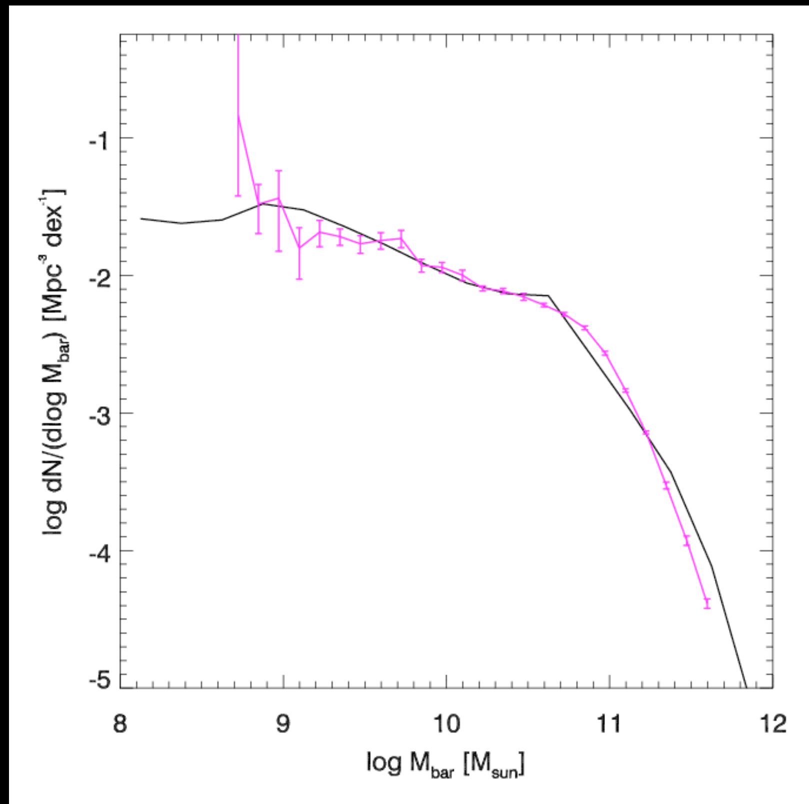
rss et al. 2007

baryonic mass function

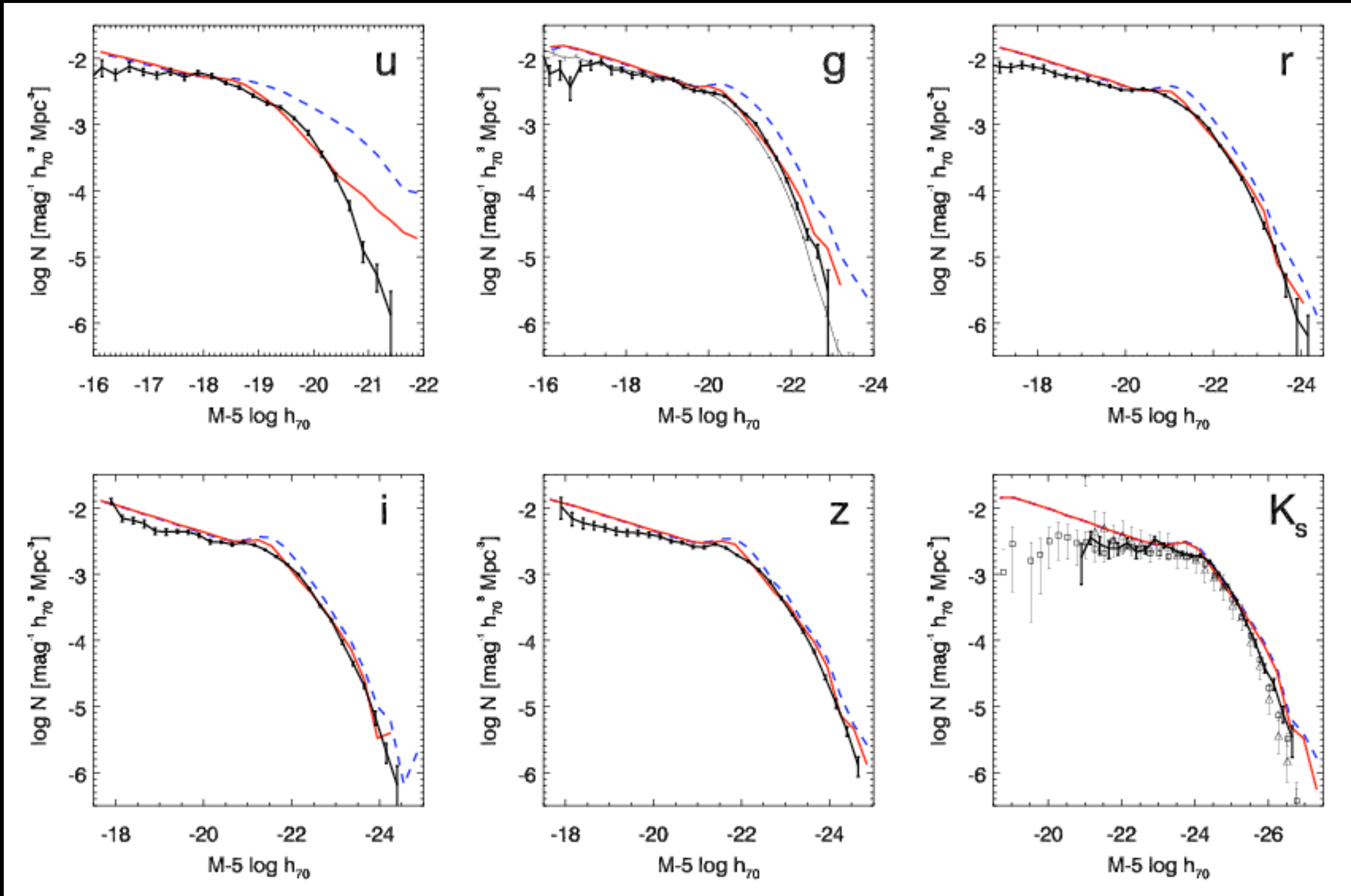
cold gas ($H_I + H_2$)



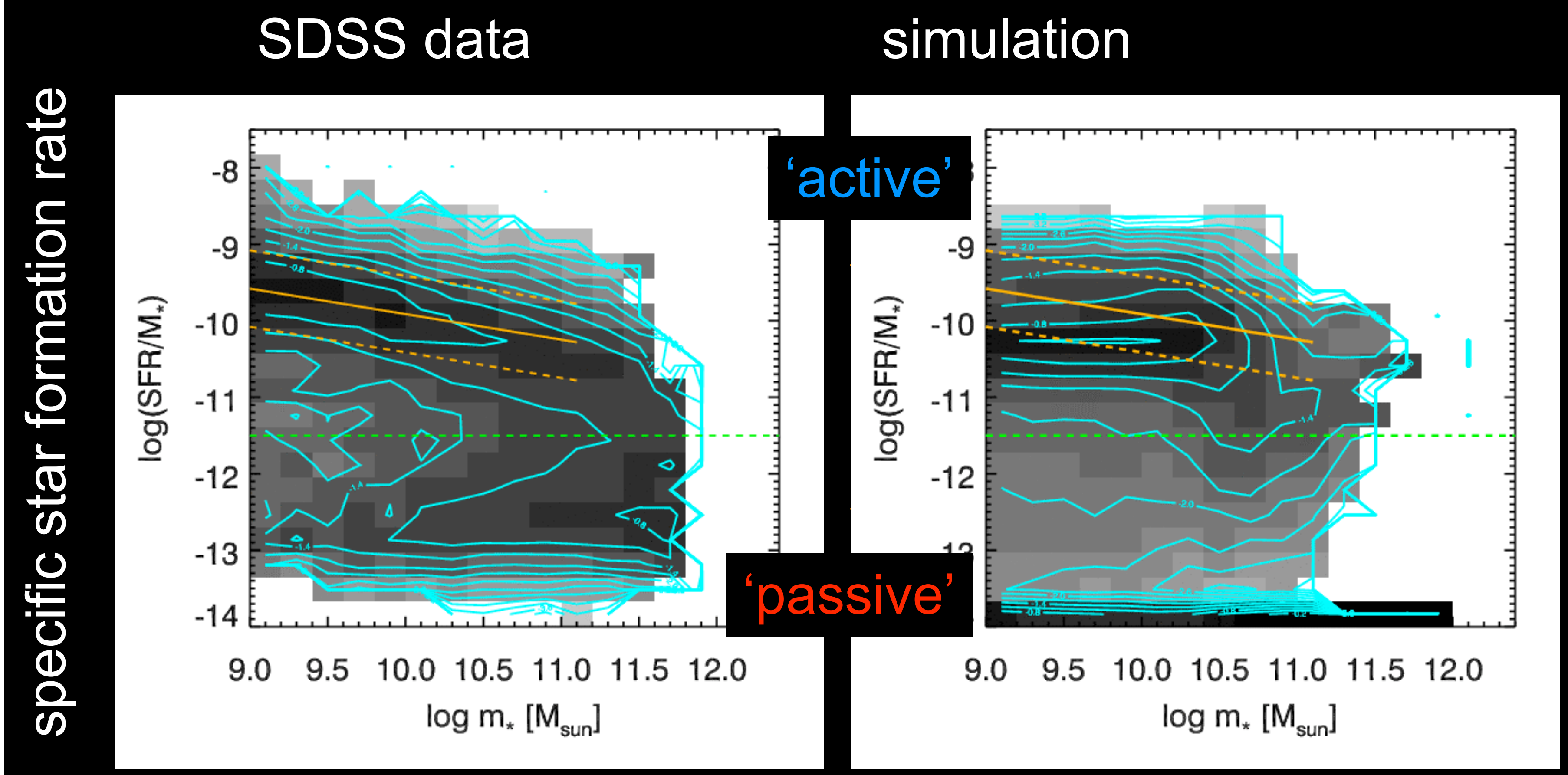
stars plus cold gas



luminosity functions

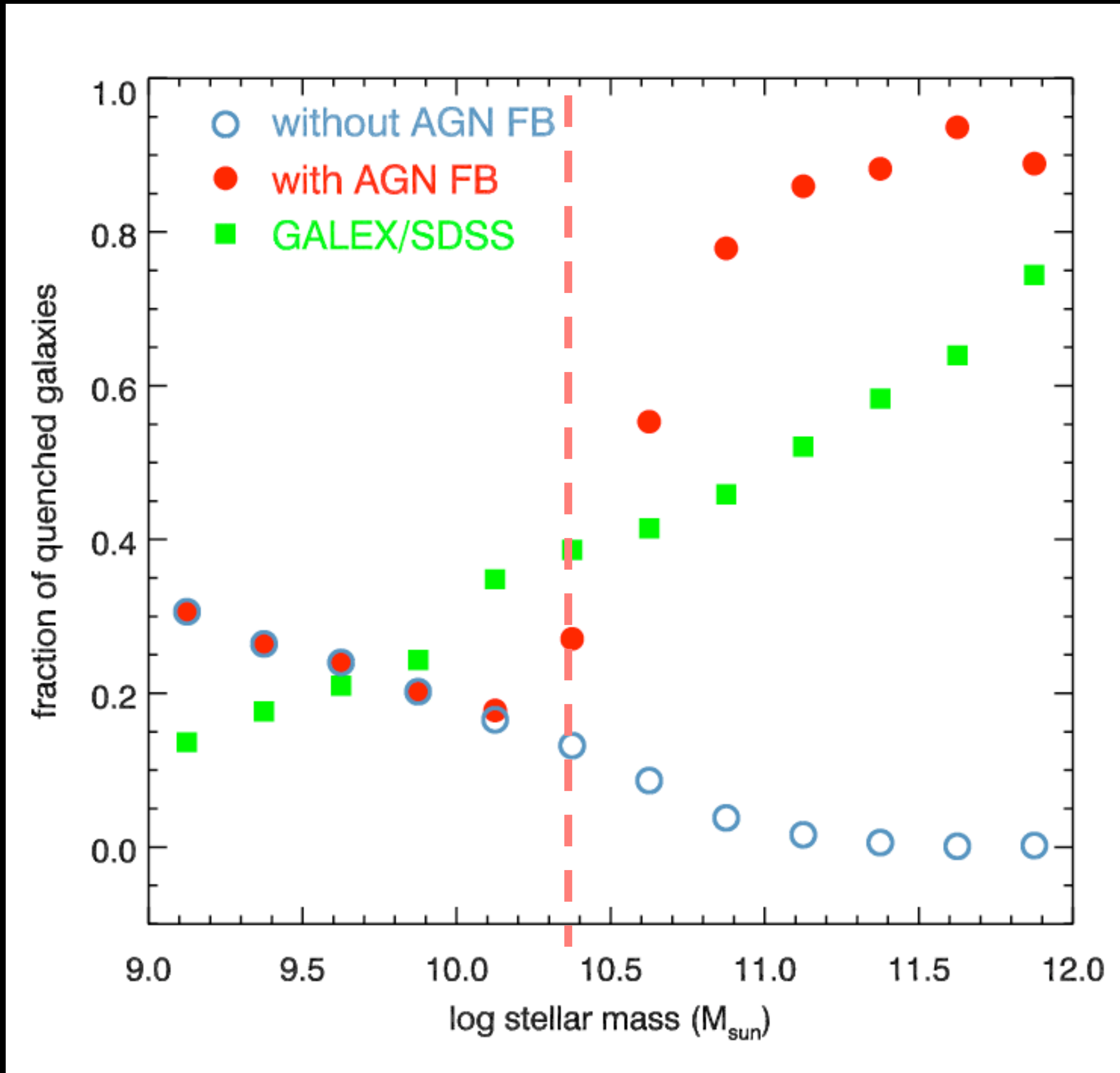


massive galaxies are quenched



massive galaxies are quenched

fraction of quenched galaxies

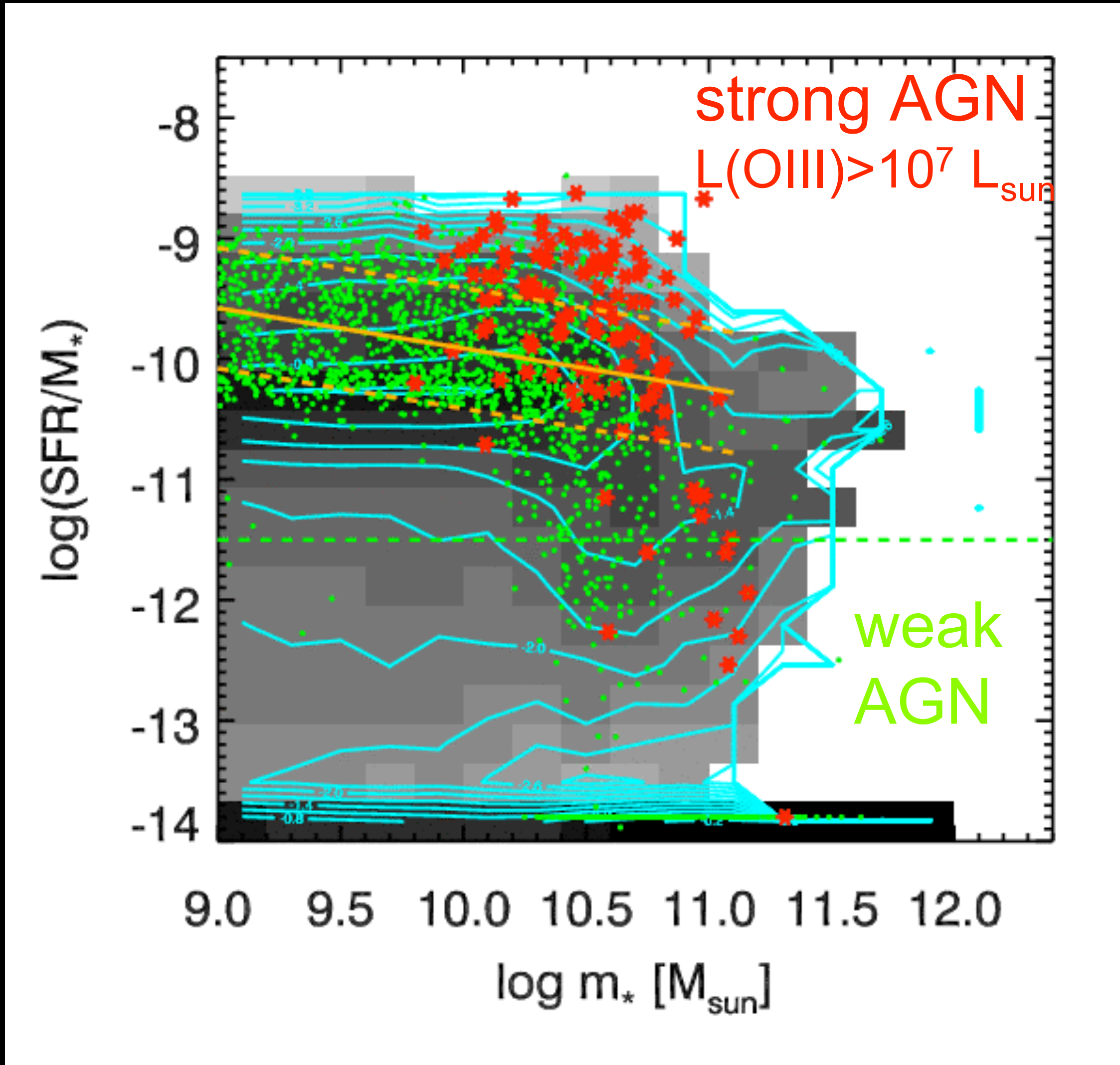


log stellar mass

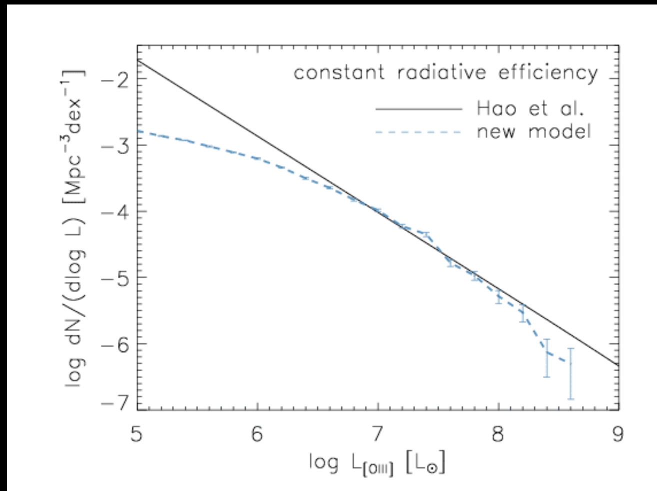
- the transition from active to quenched galaxies occurs at the right stellar mass scale ~3 x 10^{10} M_{sun} (Kauffmann et al.)

- some indication of 'over-quenching'

quenching caught in the act?

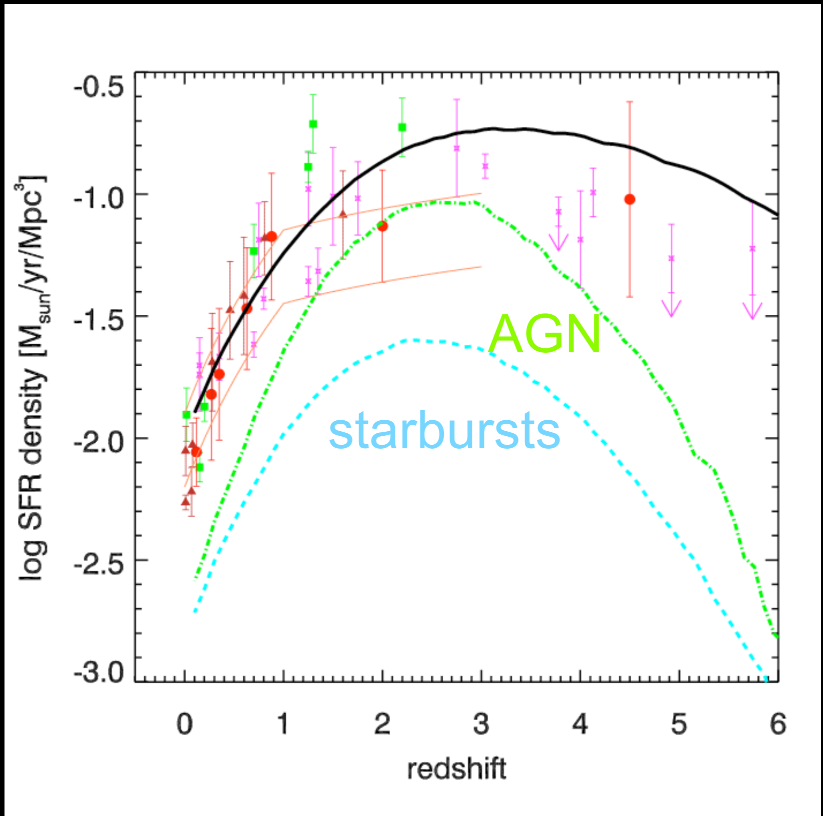


'strong' AGN occur in the most massive galaxies that still have star formation...
in qualitative agreement with observations (e.g. Kauffmann et al. 2003, Salim et al. 2007

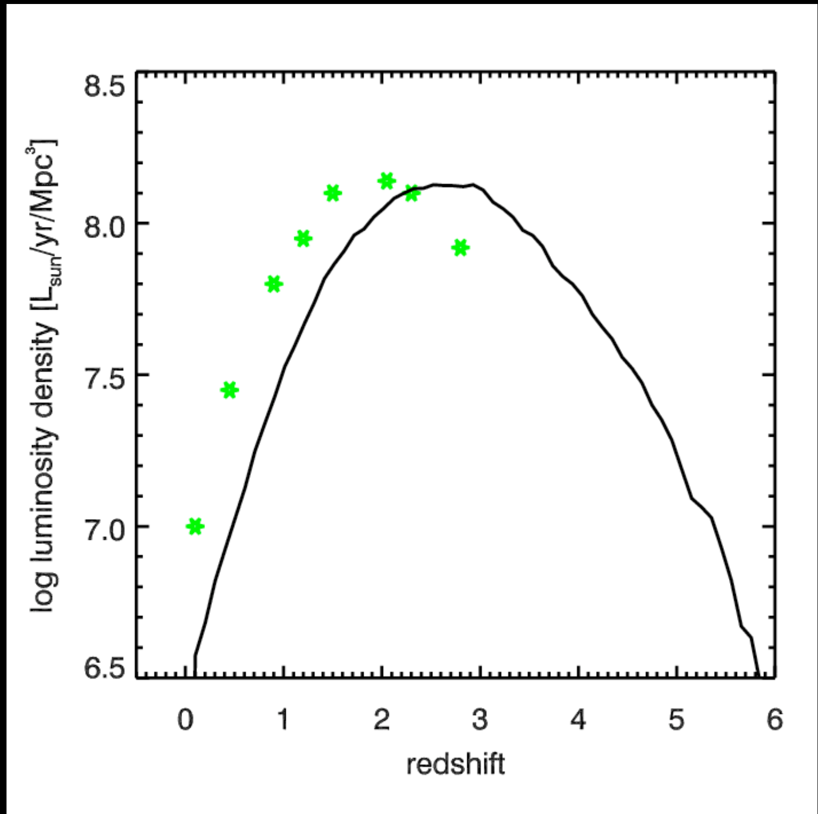


history of star formation and black hole accretion

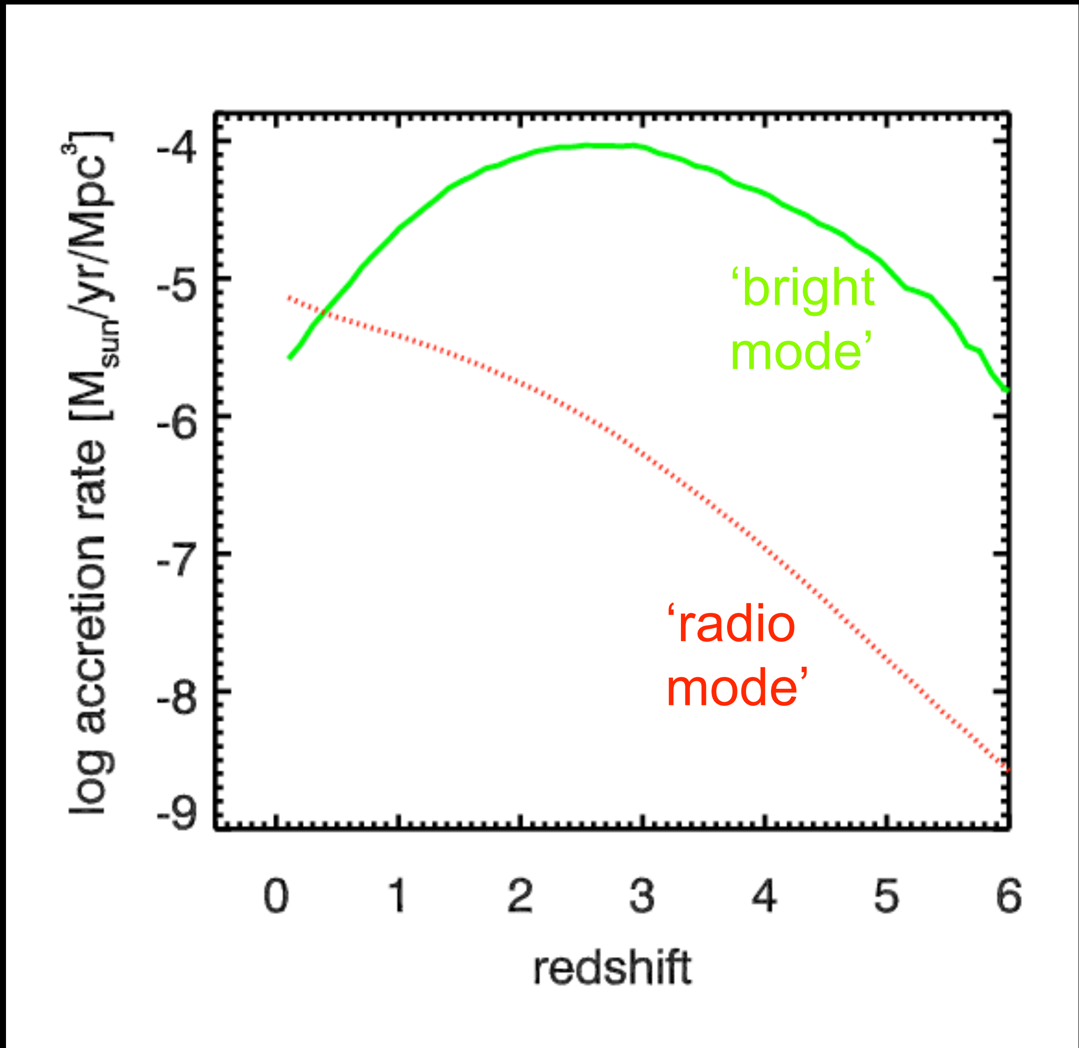
star formation history



QSO luminosity density



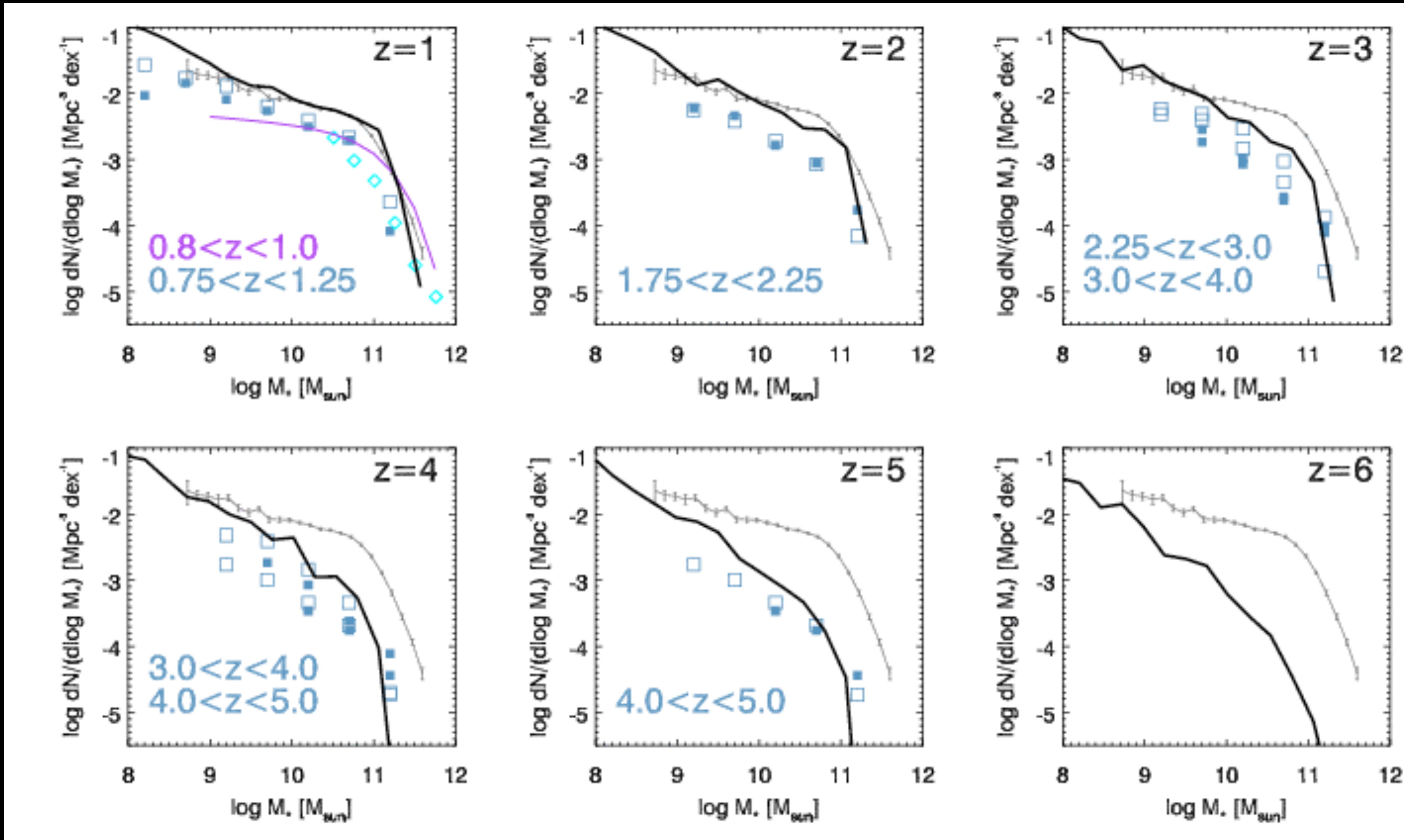
“bright” vs. “radio” mode accretion



BH growth over most of cosmic history is dominated by bright mode, in agreement with Soltan arguments

radio mode becomes more important at late times (z<1)

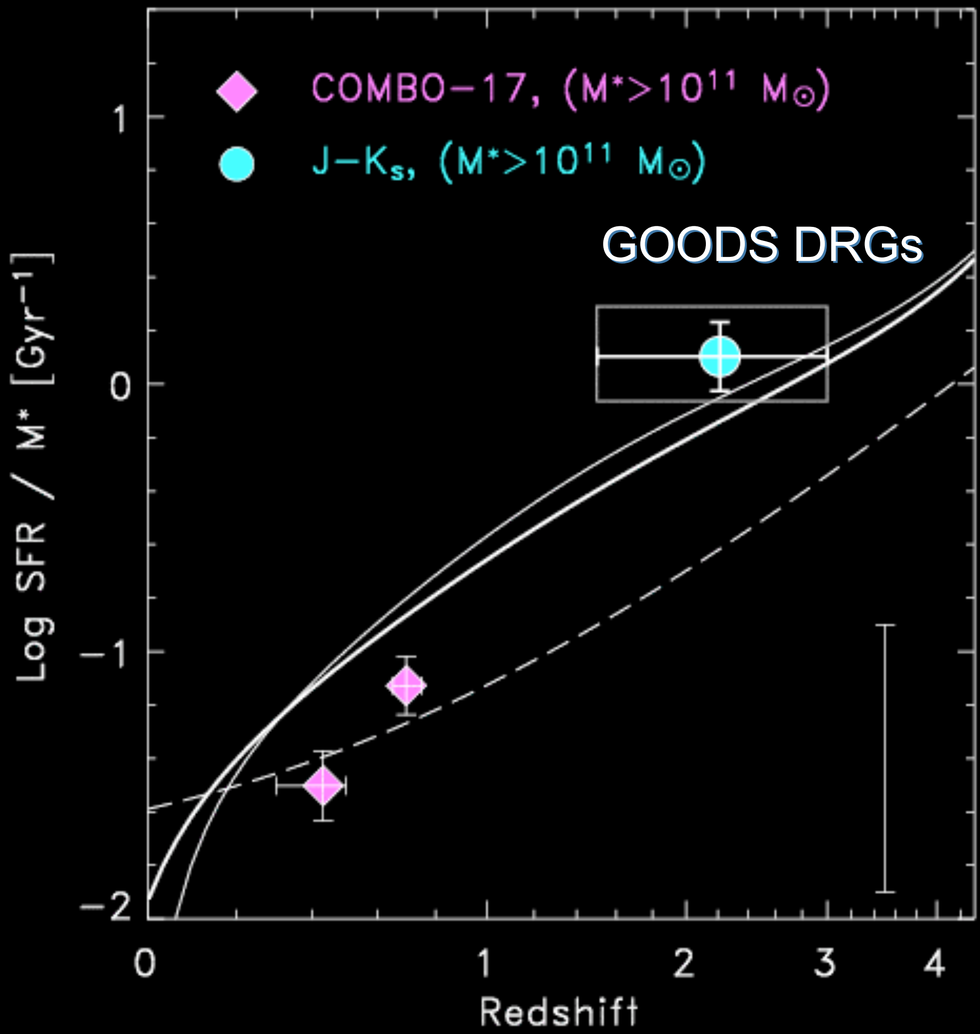
stellar mass function evolution



data from Borch et al. (COMBO-17);
Drory et al. (MUNICS, GOODS, FDF)

rss et al. in prep

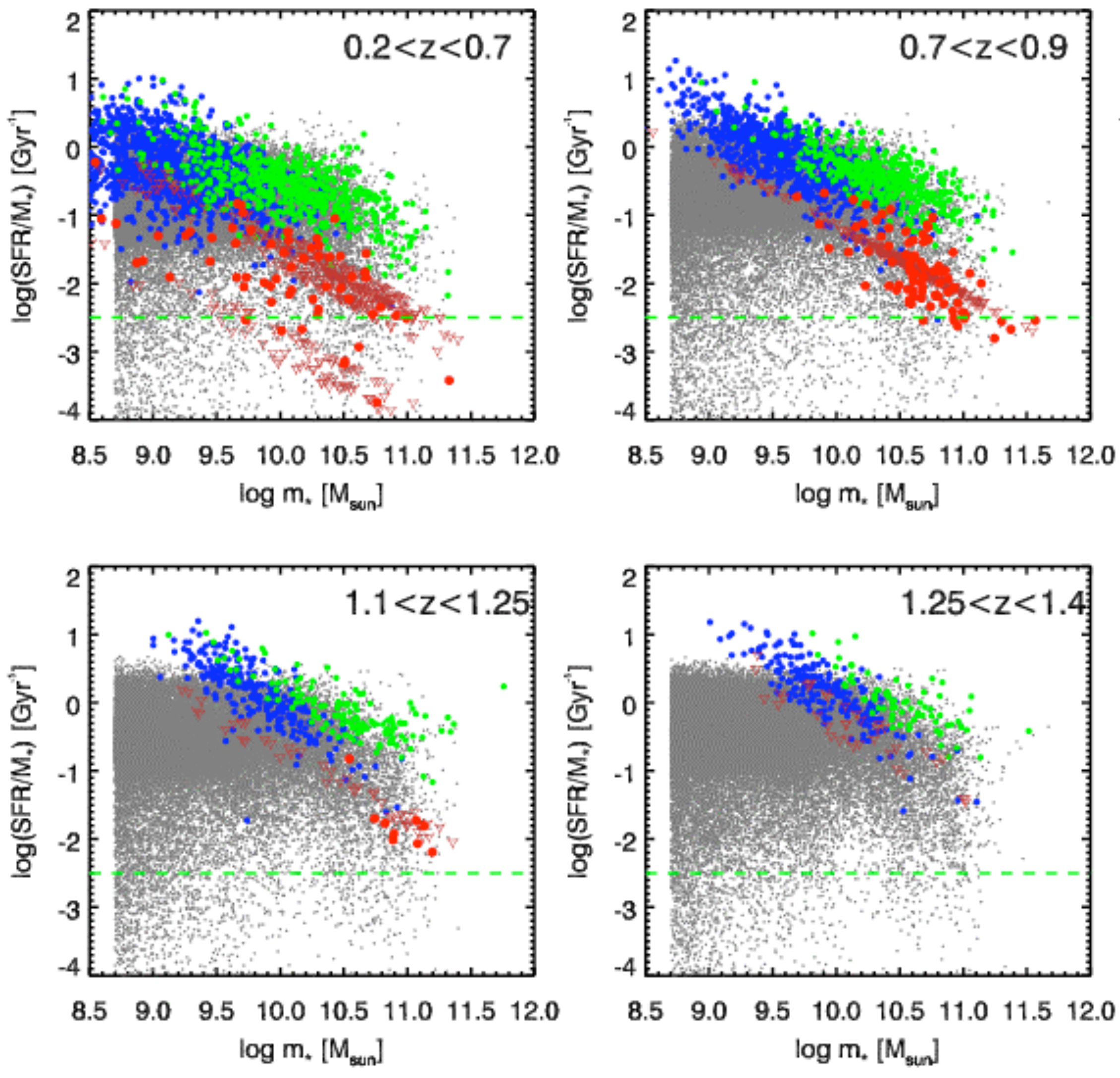
quenching of massive galaxies



massive galaxies were more actively star forming in the past

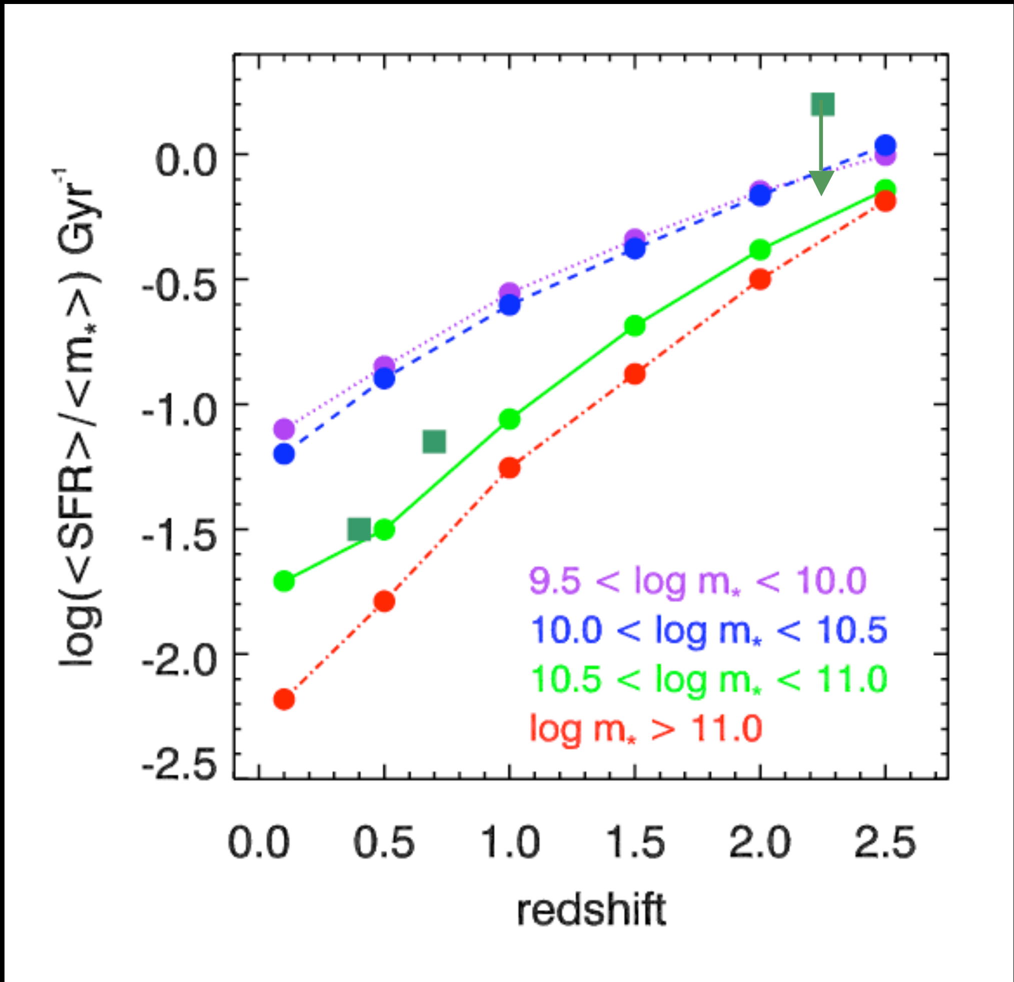
Papovich et al. 2005

‘staged’ star formation



data from AEGIS
Noeske et al. (2007)

downsizing?

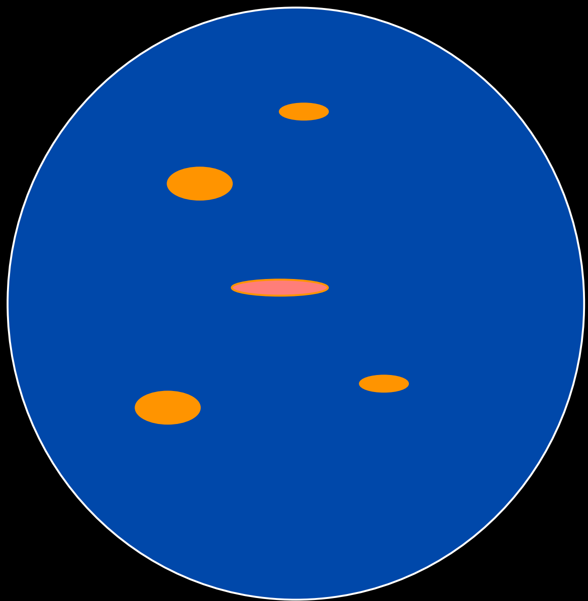


- more rapid decline in SSFR for massive galaxies (but only mildly; Zheng et al. 2007)

- overall decline due to gas consumption, plus quenching for massive objects

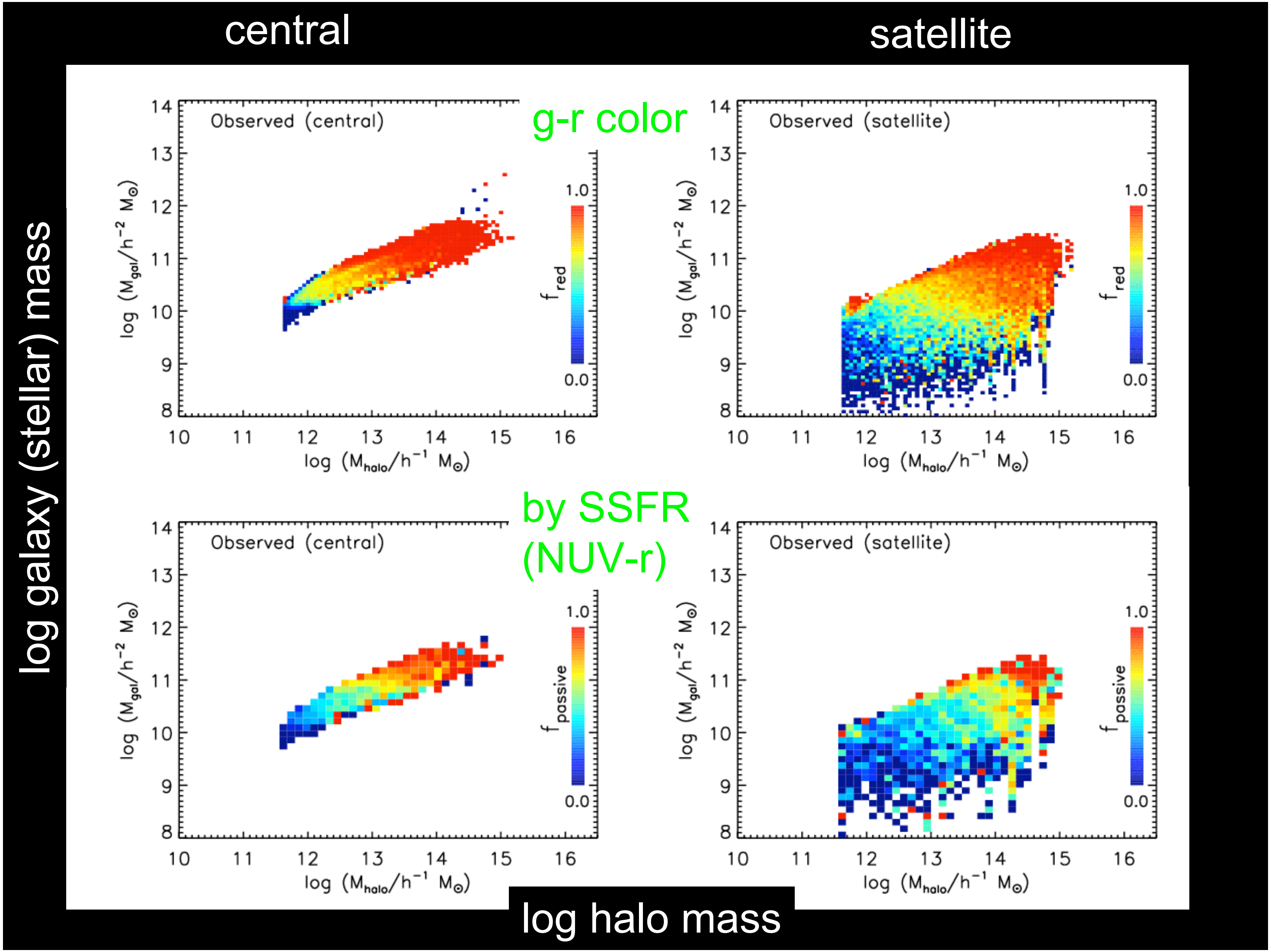
- SFR estimates at z~2 contaminated by AGN?

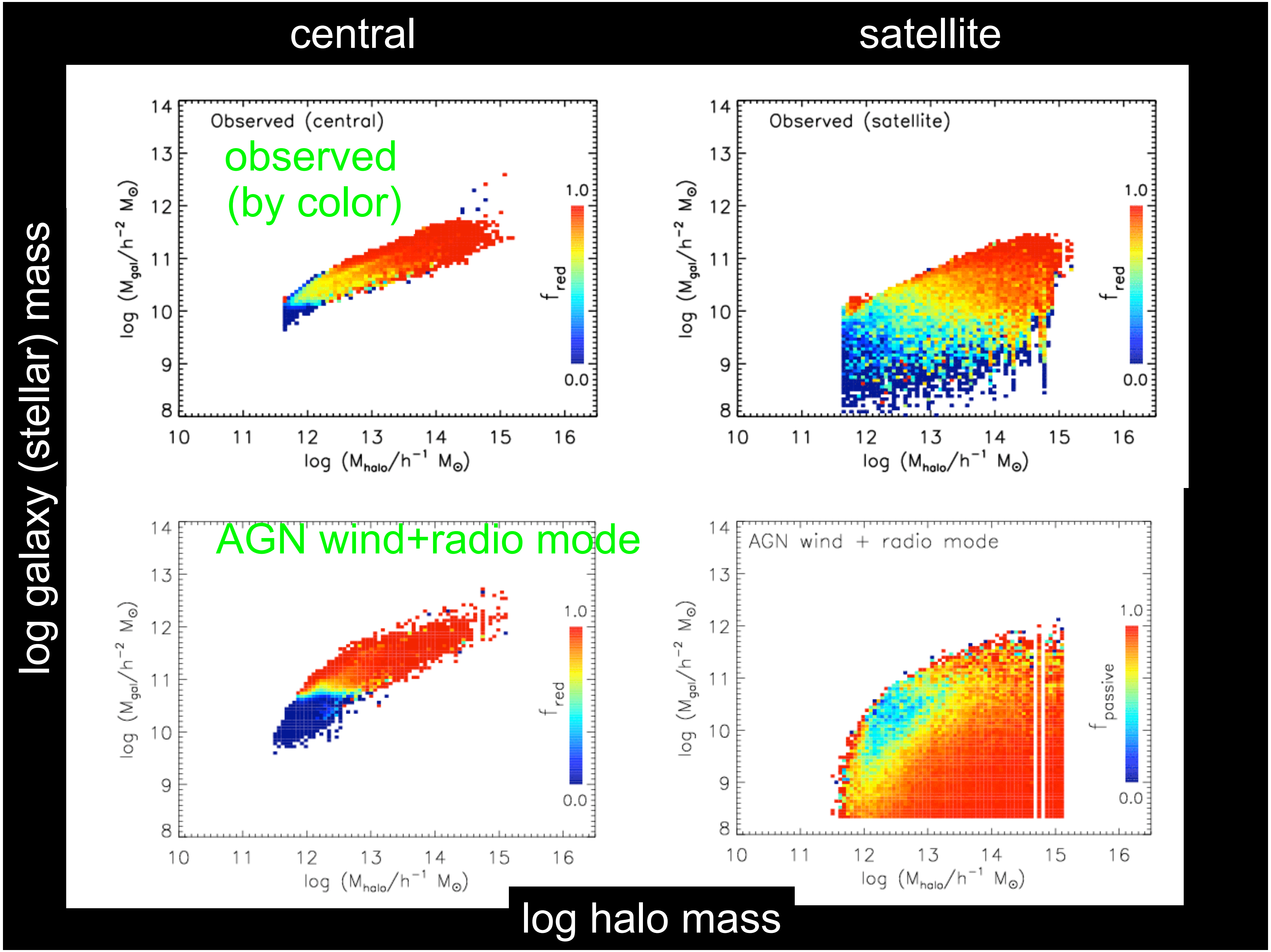
SF quenching as a function of galaxy mass and environment



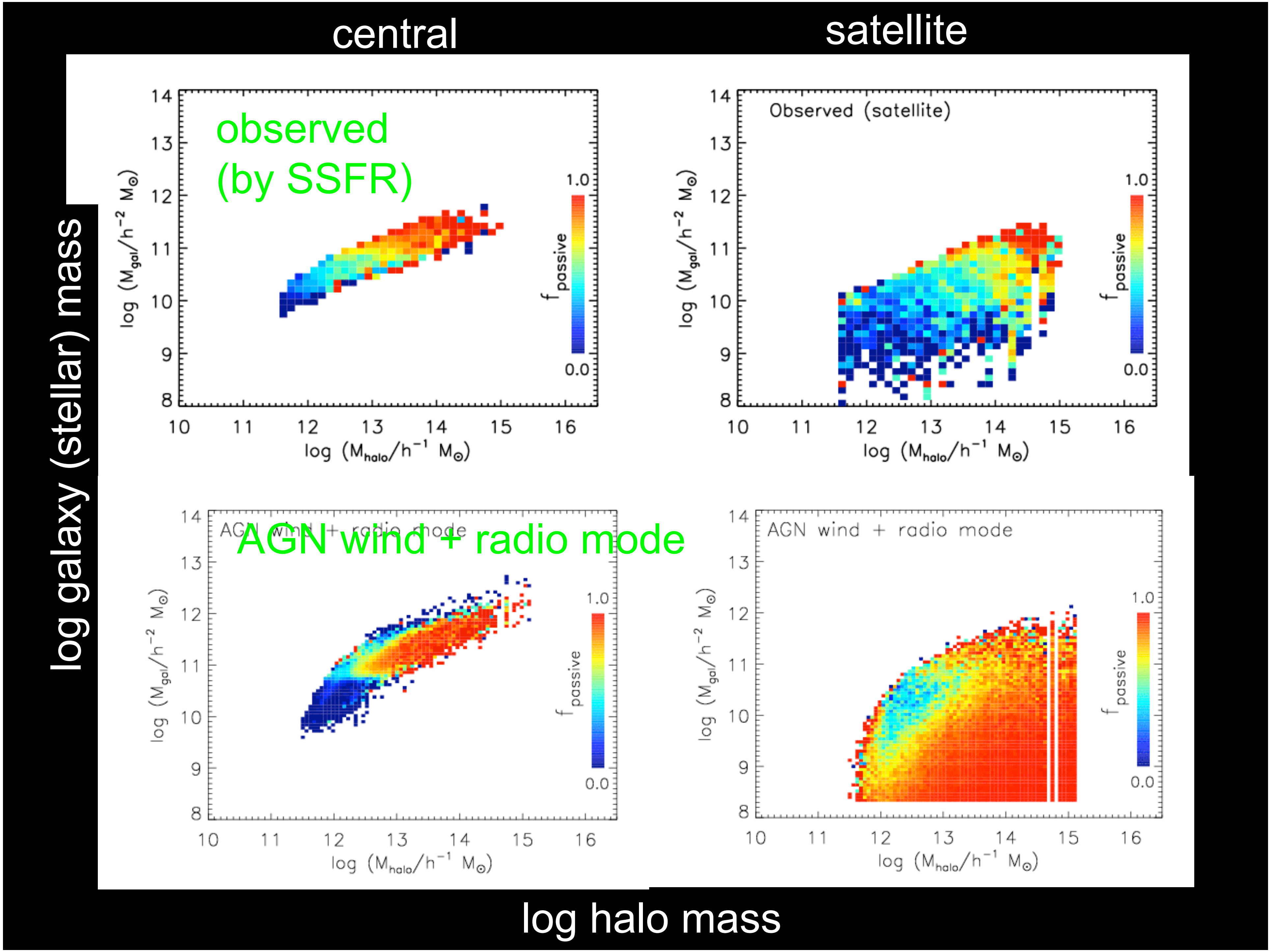
- make use of SDSS DR5 group catalog (van den Bosch & collaborators)
  - galaxies assigned to groups using FOF
  - halo masses estimated
  - central and satellite galaxies identified
- also make use of SFR from GALEX-matched sample (Salim et al.)

Taysun Kimm with rss, Fontanot, van den Bosch, Bell, Yi, Salim +

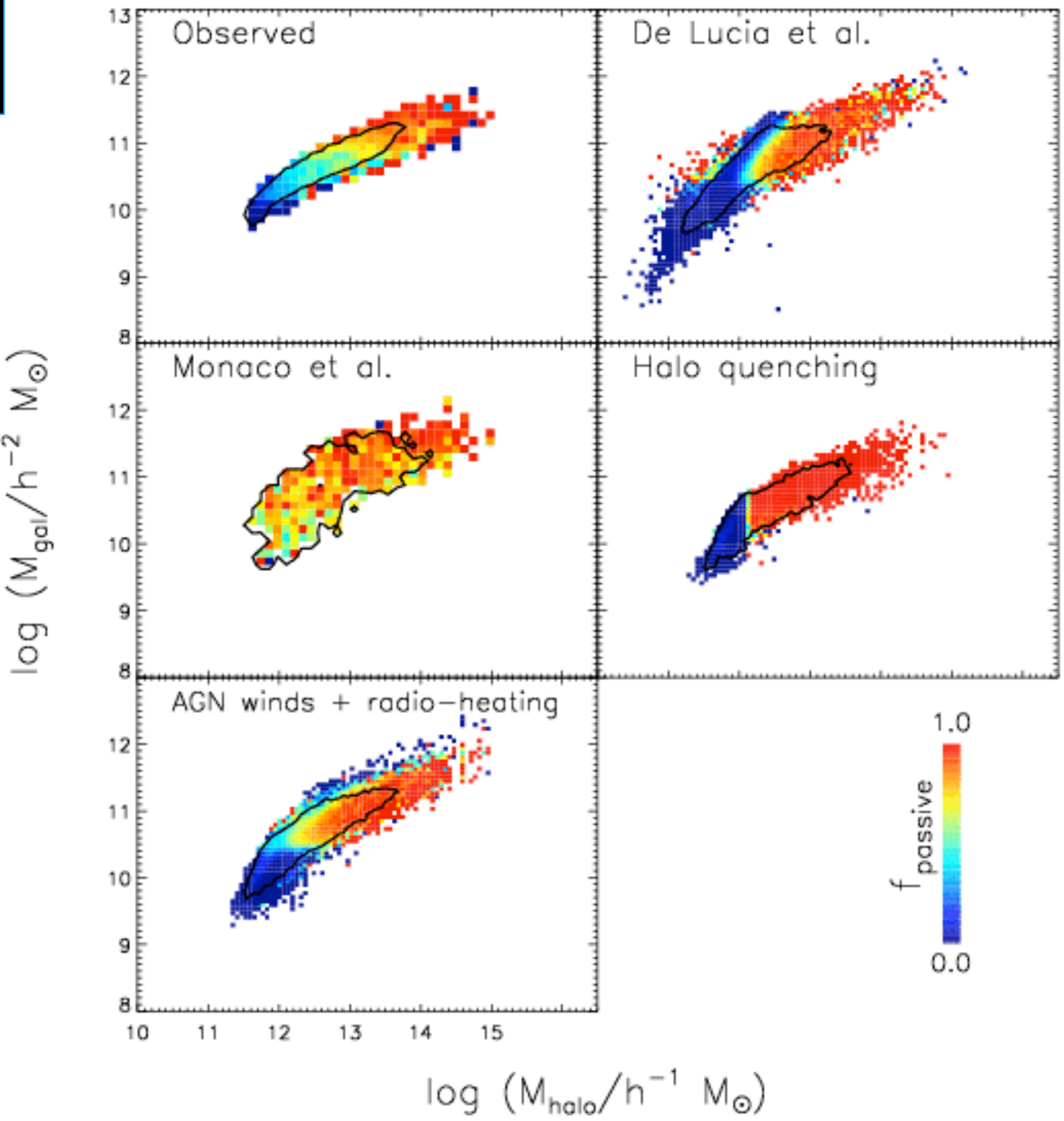

central
satellite
g-r color
by SSFR
(NUV-r)
log galaxy (stellar) mass
log halo mass
Observed (central)
Observed (satellite)
log (M_gal/h^-2 M_⊙)
log (M_halo/h^-1 M_⊙)
f_red
f_passive
1.0
0.0



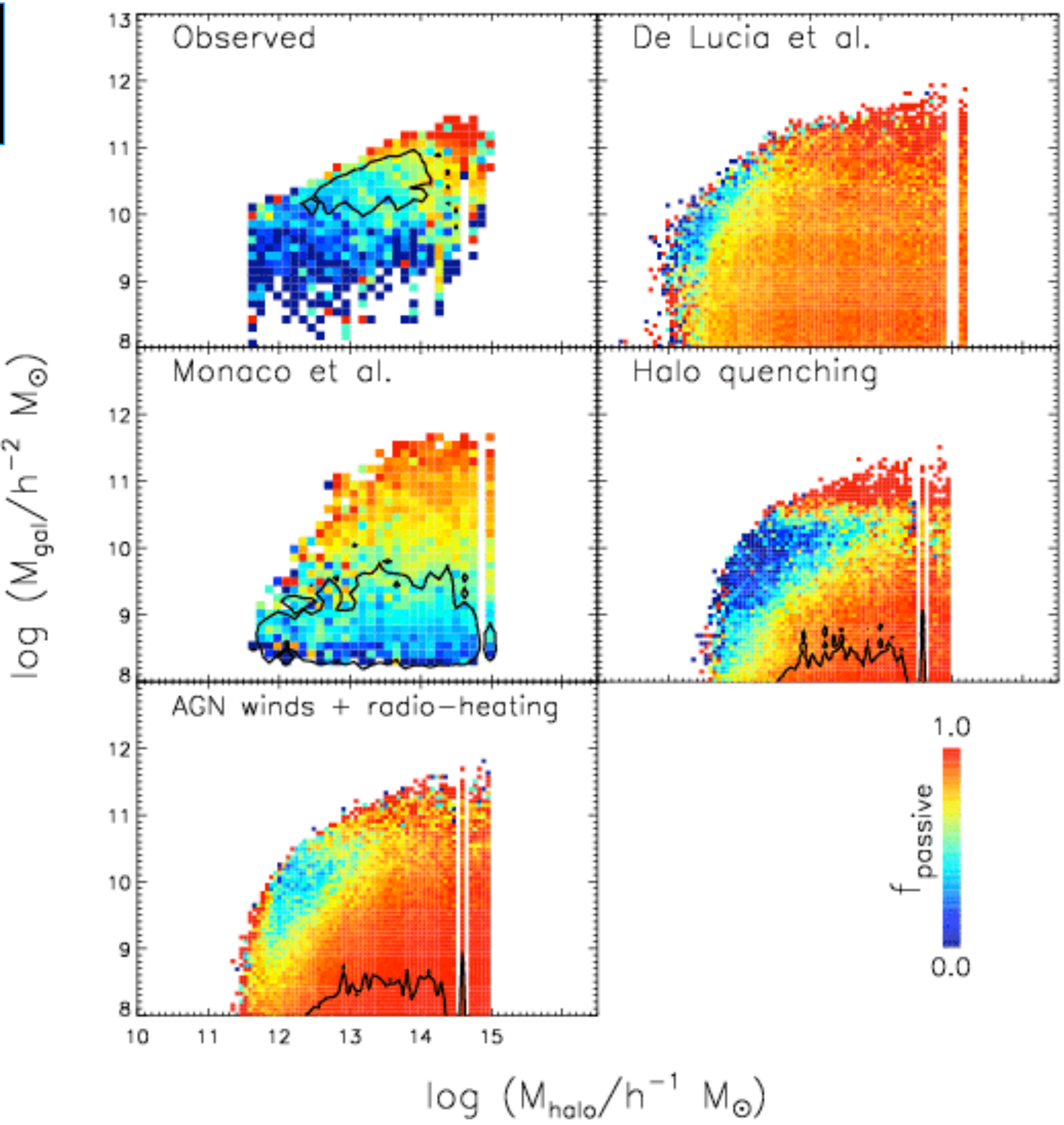
central
satellite
log galaxy (stellar) mass
Observed (central)
observed
(by color)
Observed (satellite)
AGN wind+radio mode
AGN wind + radio mode
log (M_gal/h^-2 M_⊙)
log (M_halo/h^-1 M_⊙)
f_red
f_passive
log halo mass


central
satellite
observed
(by SSFR)
Observed (satellite)
AGN wind + radio mode
AGN wind + radio mode
log galaxy (stellar) mass
log halo mass
log (M_{gal}/h^{-2} $M_\odot$)
log (M_{halo}/h^{-1} $M_\odot$)
$f_{passive}$
1.0
0.0

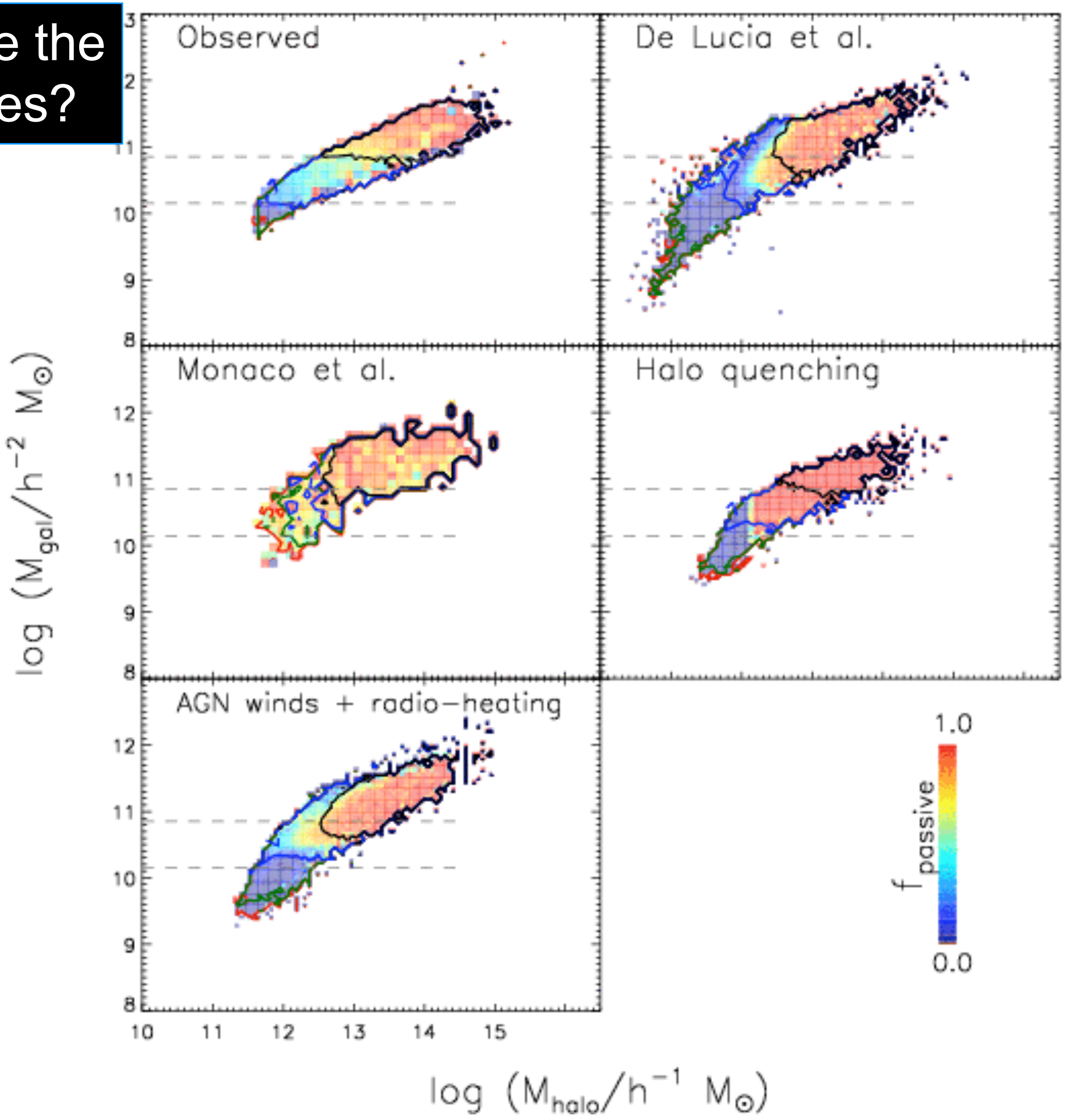
central galaxies



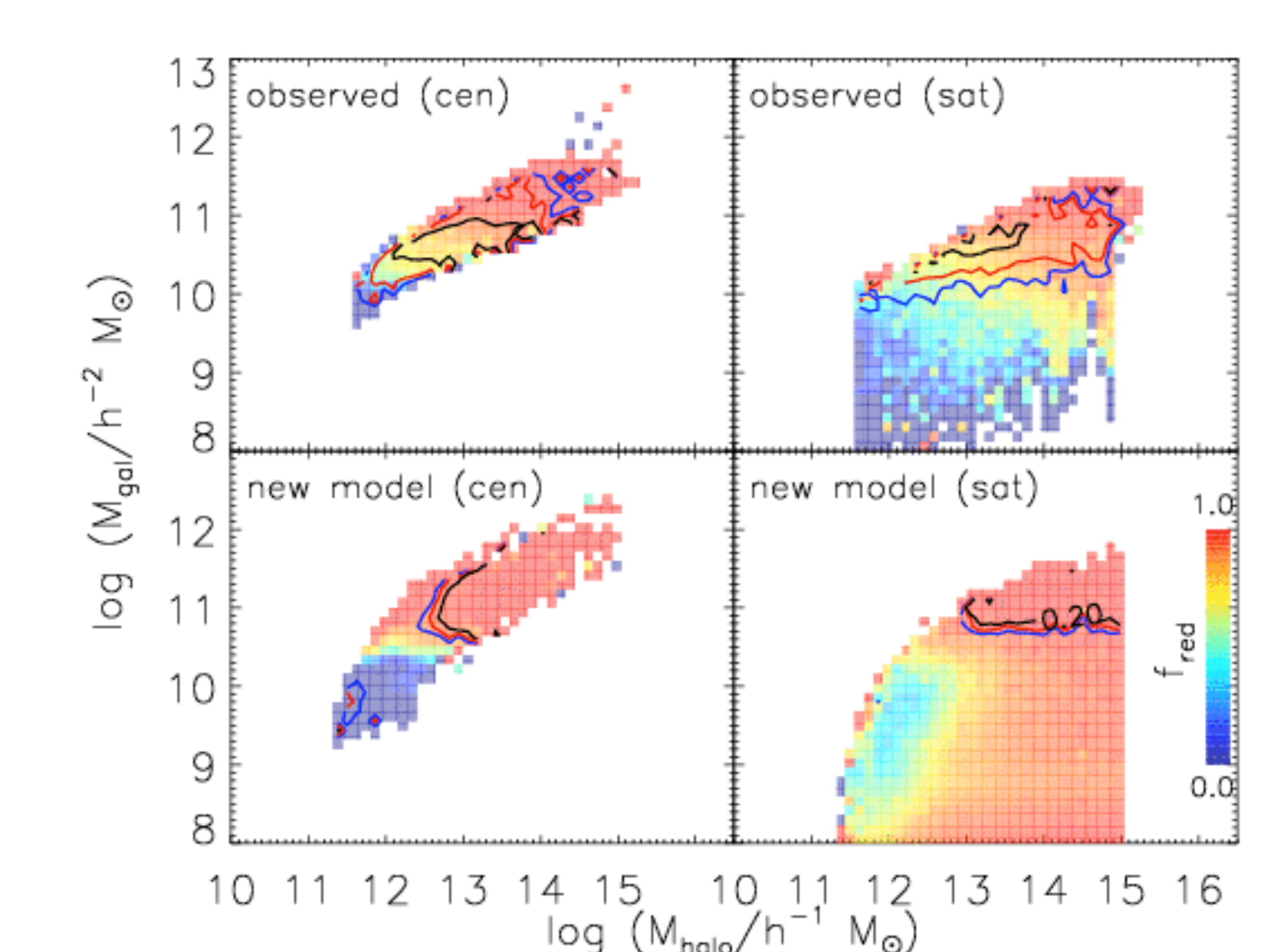
satellite galaxies



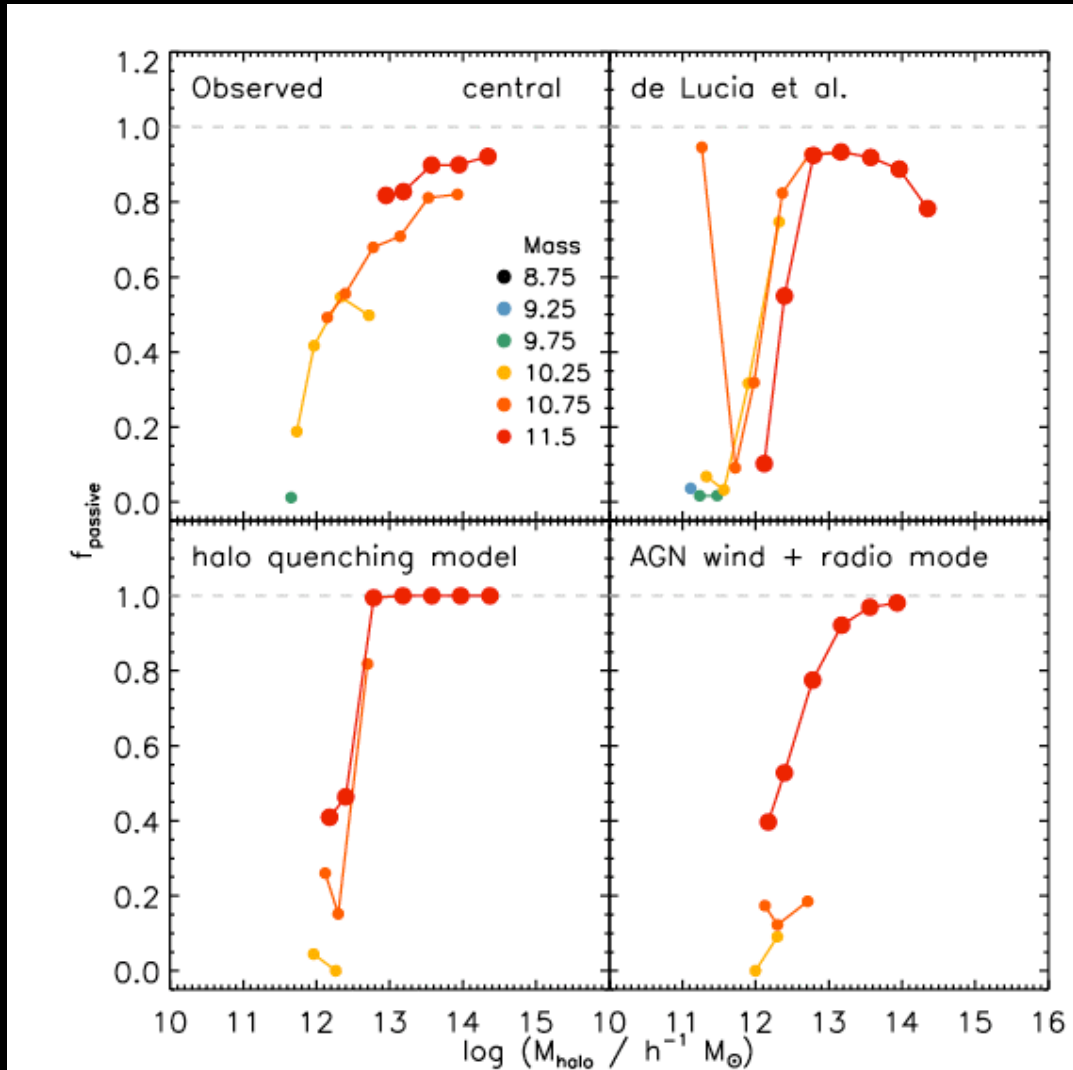
where are the black holes?



where are the AGN?



fraction of quenched galaxies



halo mass

Summary

- ‘old’ CDM-based galaxy formation models suffered from a set of interlinked problems
  - overcooling/cooling flow problem & obese galaxies
  - color-magnitude/color bimodality problems at high and low redshift
- Two kinds of AGN feedback are important:
  - “bright mode” feedback may regulate BH formation & temporarily quench star formation, but is not a viable ‘maintenance’ mechanism
  - low-accretion rate ‘radio mode’ FB a promising mechanism for counteracting cooling flows over long time scales
  - combined effects of strangulation plus winds quenches star formation in massive galaxies
- downsizing and “staged” star formation: massive galaxies ok, low-mass galaxies a problem. ditto AGN.
- studying demographics and habitats of quenched galaxies, massive BH and AGN activity a very promising way to constrain models