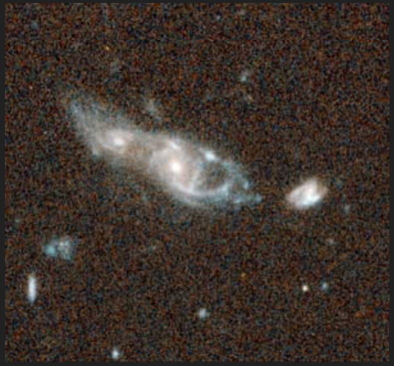
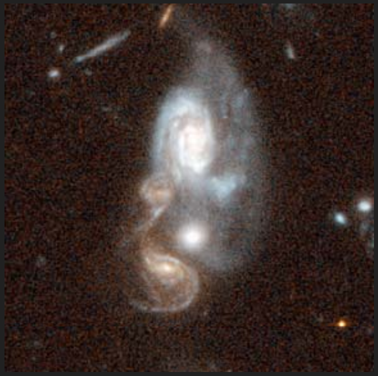
ON THE CO-EVOLUTION OF GALAXIES AND THEIR BLACK HOLES





rachel somerville

Max Planck Institute for Astronomy, Heidelberg

with thanks to E. Bell, X. Zheng, H.-W. Rix, & the GEMS team
P. Hopkins, B. Robertson, T.J. Cox, L. Hernquist, Y. Li

MERGERS AS DRIVERS OF GALAXY AND BH GROWTH

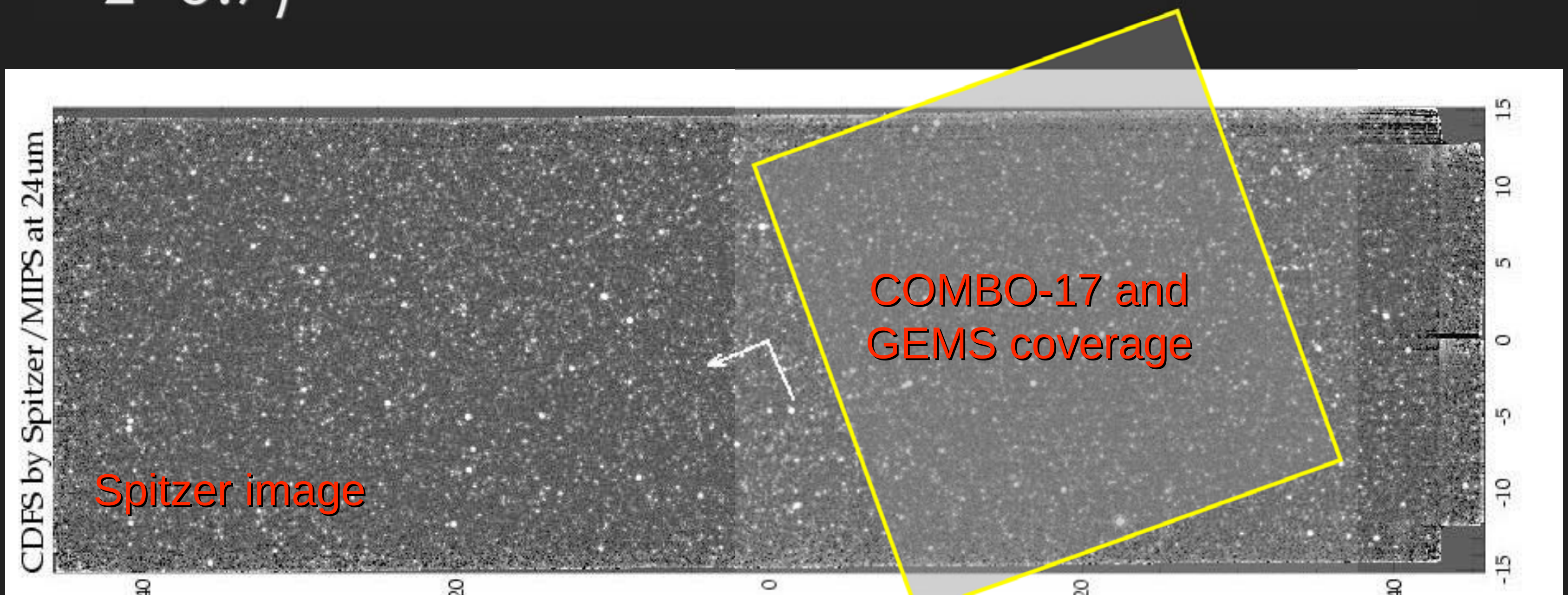
- triggers of powerful bursts of star formation?
- responsible for transforming disks into spheroids?
- drivers of gas into galactic nuclei, feeding the central BH, & producing an AGN?

QUESTIONS

- how significant are mergers in driving the characteristic rise and fall of the global SFR and downsizing?
- how significant are mergers in driving the characteristic rise and fall of BH accretion and downsizing?
- are observations of merger rates and QSO LF consistent with them being closely associated processes?

COMBO-17 + GEMS + SPITZER

- colors, photo-z, stellar masses to z~1 from COMBO-17; HST imaging from GEMS
- Spitzer 24μm data from the MIPS instrument team (83μJy --> $3M_{\odot}$ yr^{-1} at z~0.7)

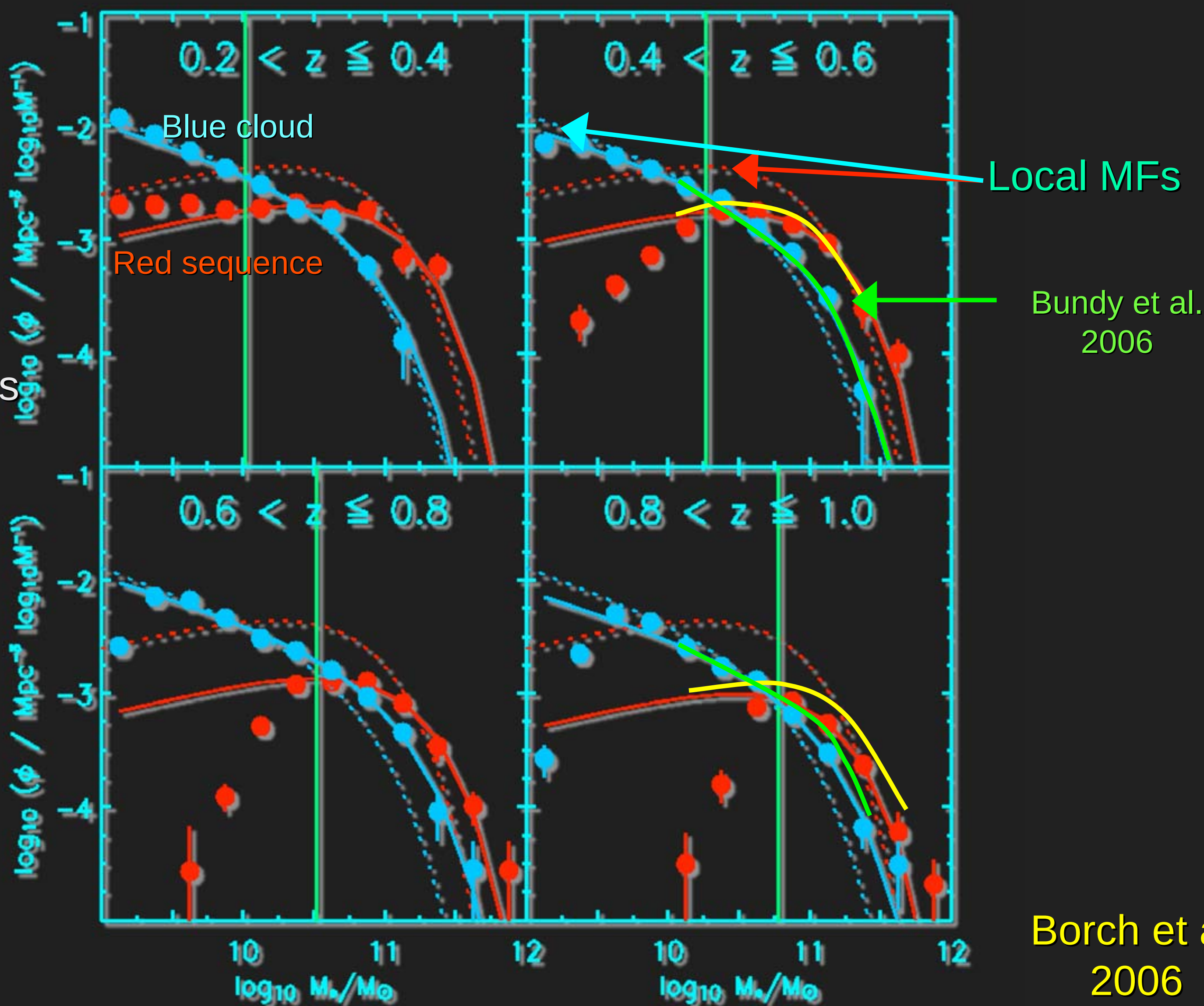


Rieke et al. 2004; data described in Papovich et al. 2004

Stellar mass function split by color

Weak evolution in MF of blue guys (~ disks)

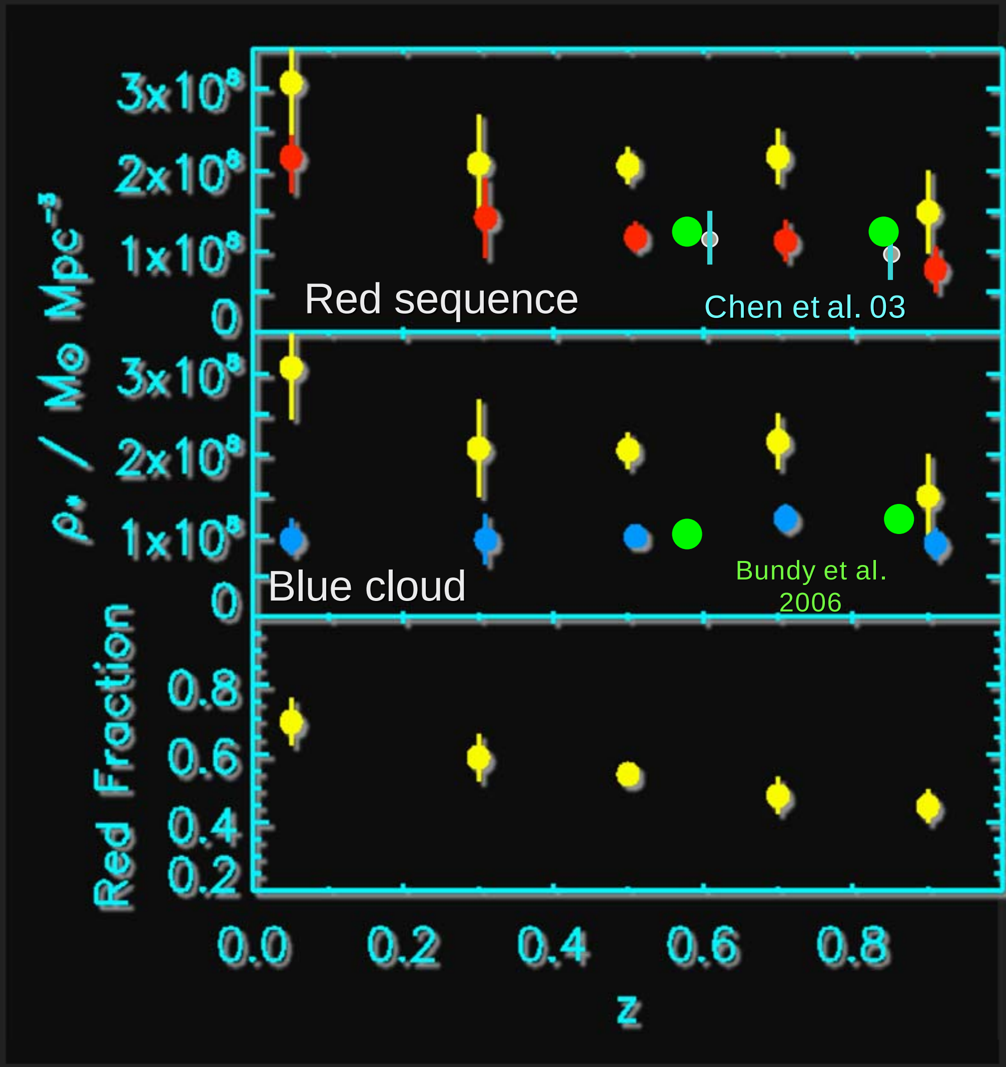
Strong evolution in red guys at L<2L* at least (~ spheroids)



Borch et al. 2006

GLOBAL STELLAR MASS EVOLUTION BY COLOR

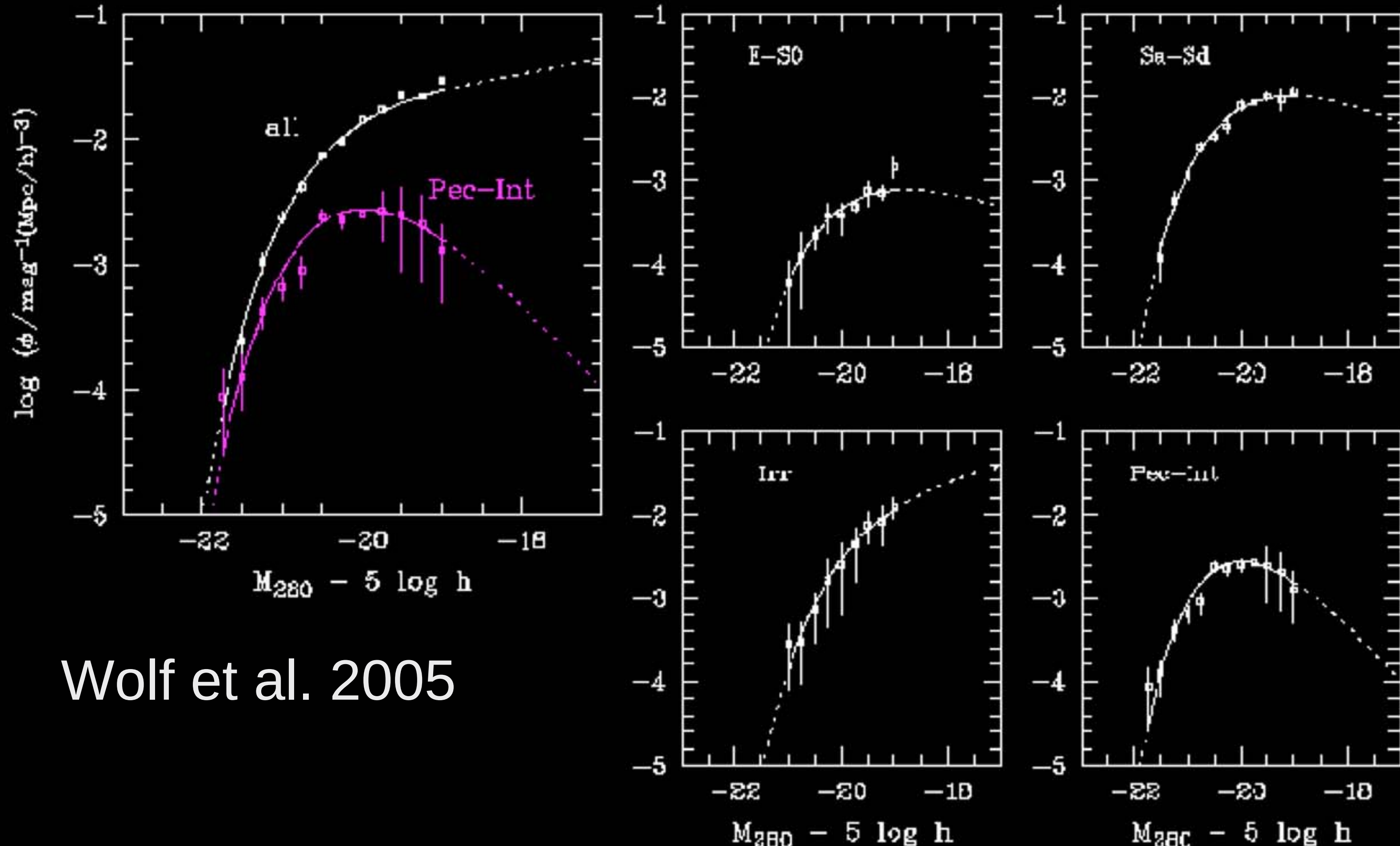
- stellar mass density in blue cloud ~constant since z~1
- stellar mass density in red sequence has increased by a factor of 2-3 since z~1



Borch et al. 2006

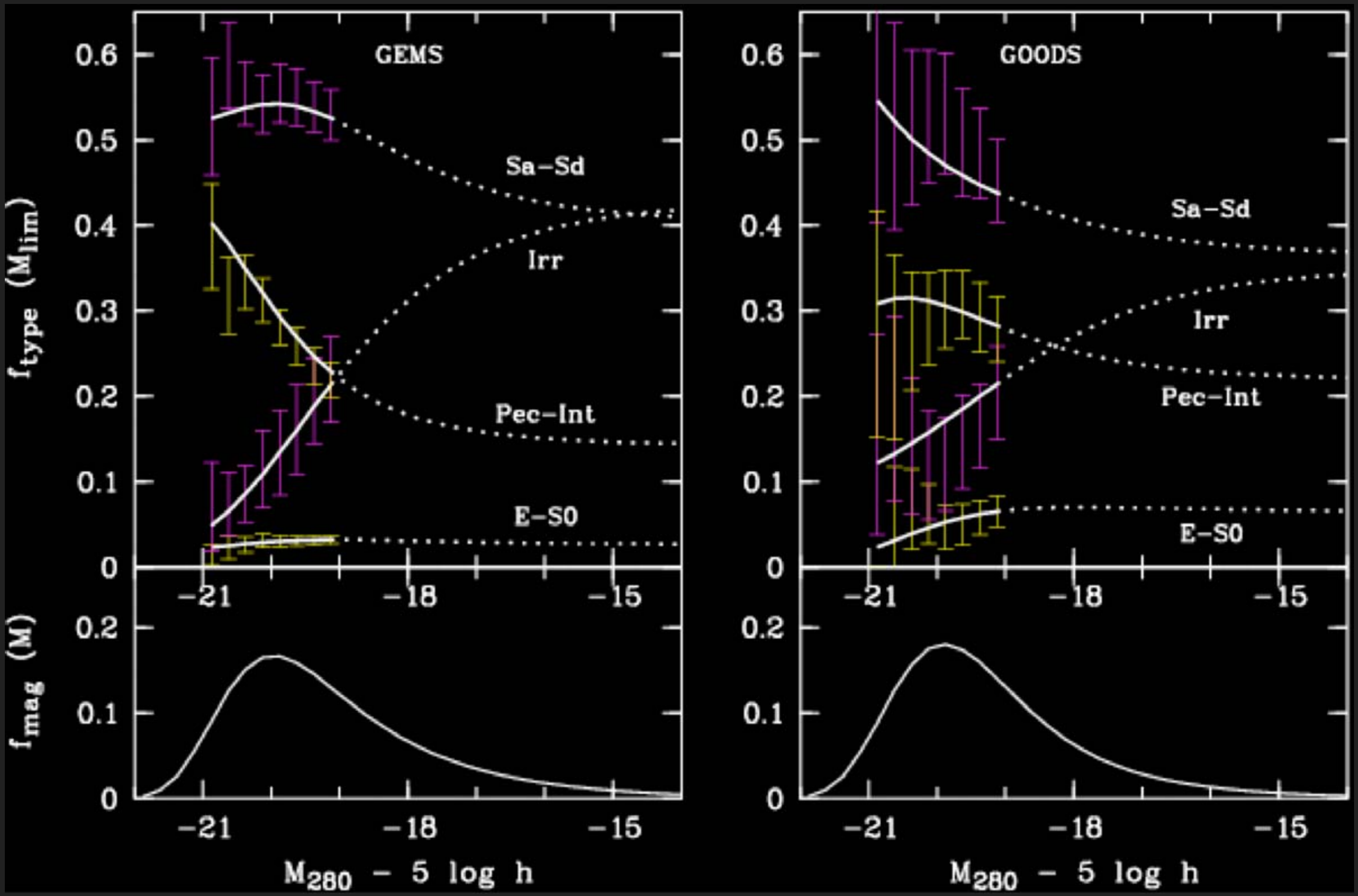
WHICH GALAXIES CONTRIBUTE TO THE UV LUMINOSITY DENSITY AT Z=0.7?

0.65<z<0.75



Wolf et al. 2005

CONTRIBUTIONS TO GLOBAL SFR BUDGET BY TYPE AT Z=0.7

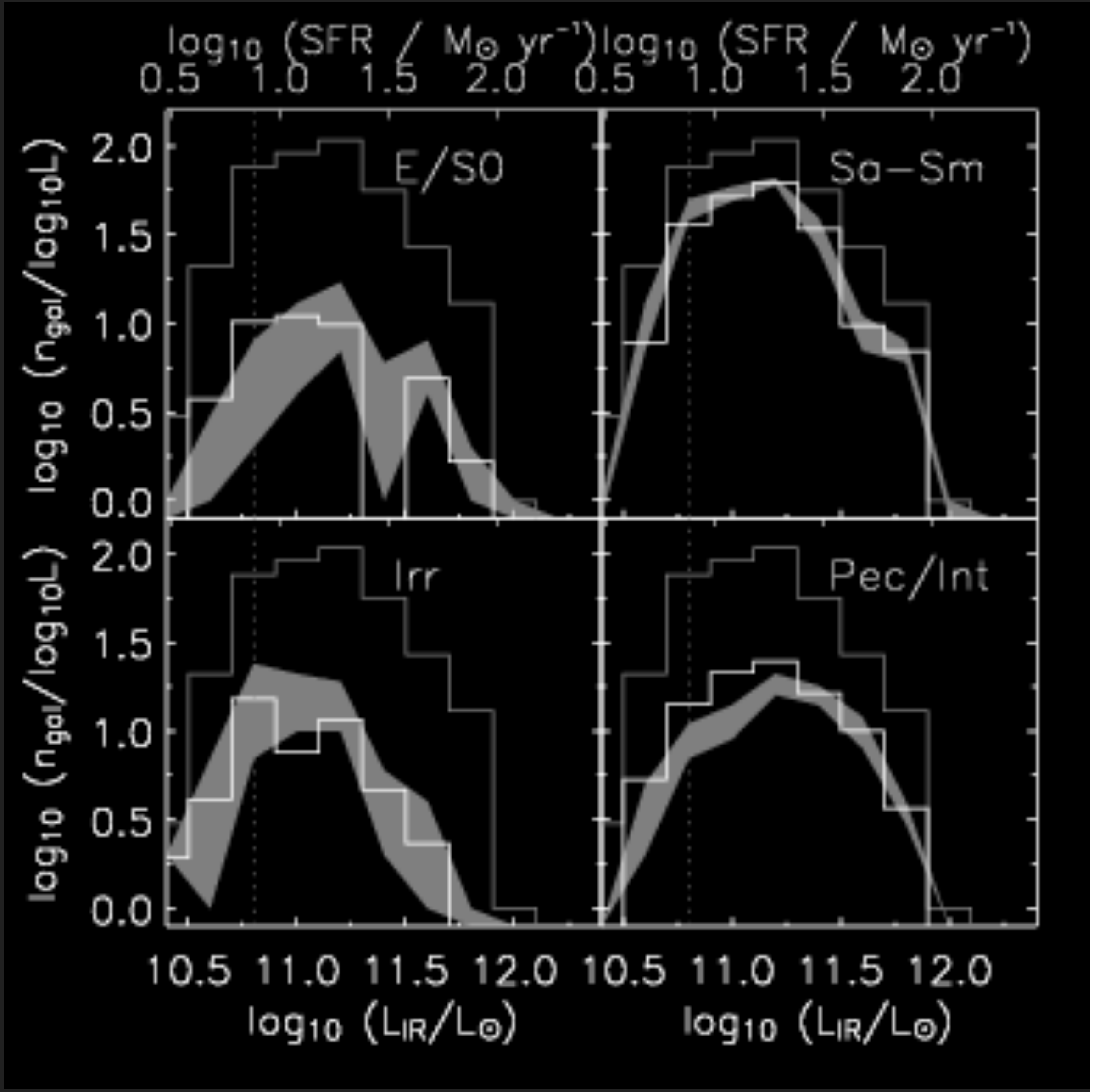


Wolf et al. 2004

THE IR VIEW

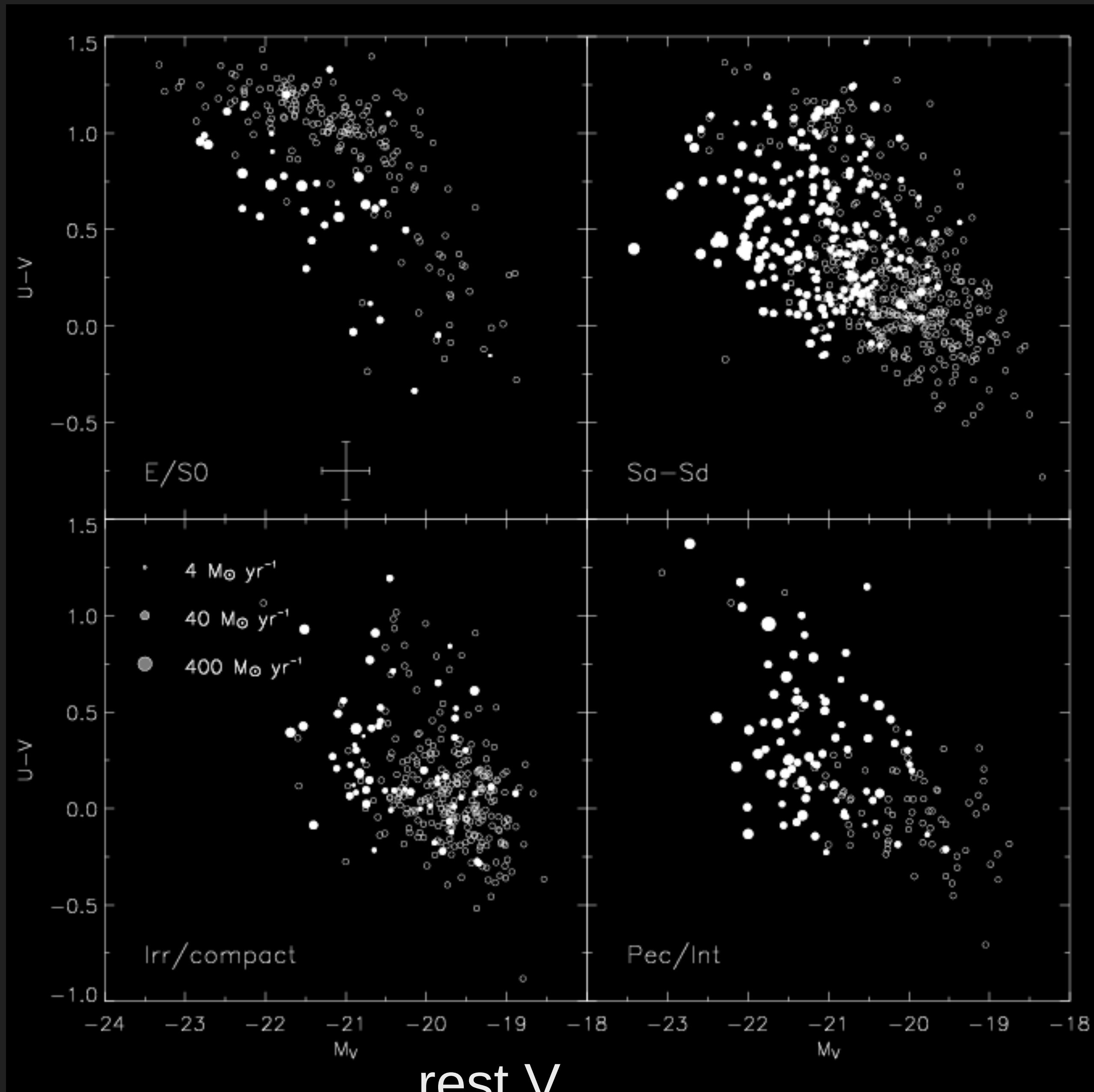
at z=0.7:

- Red E/S0s are non-star-forming
- Most SF is in large spirals
- 20-30% of total SF at z=0.7 in manifestly interacting systems



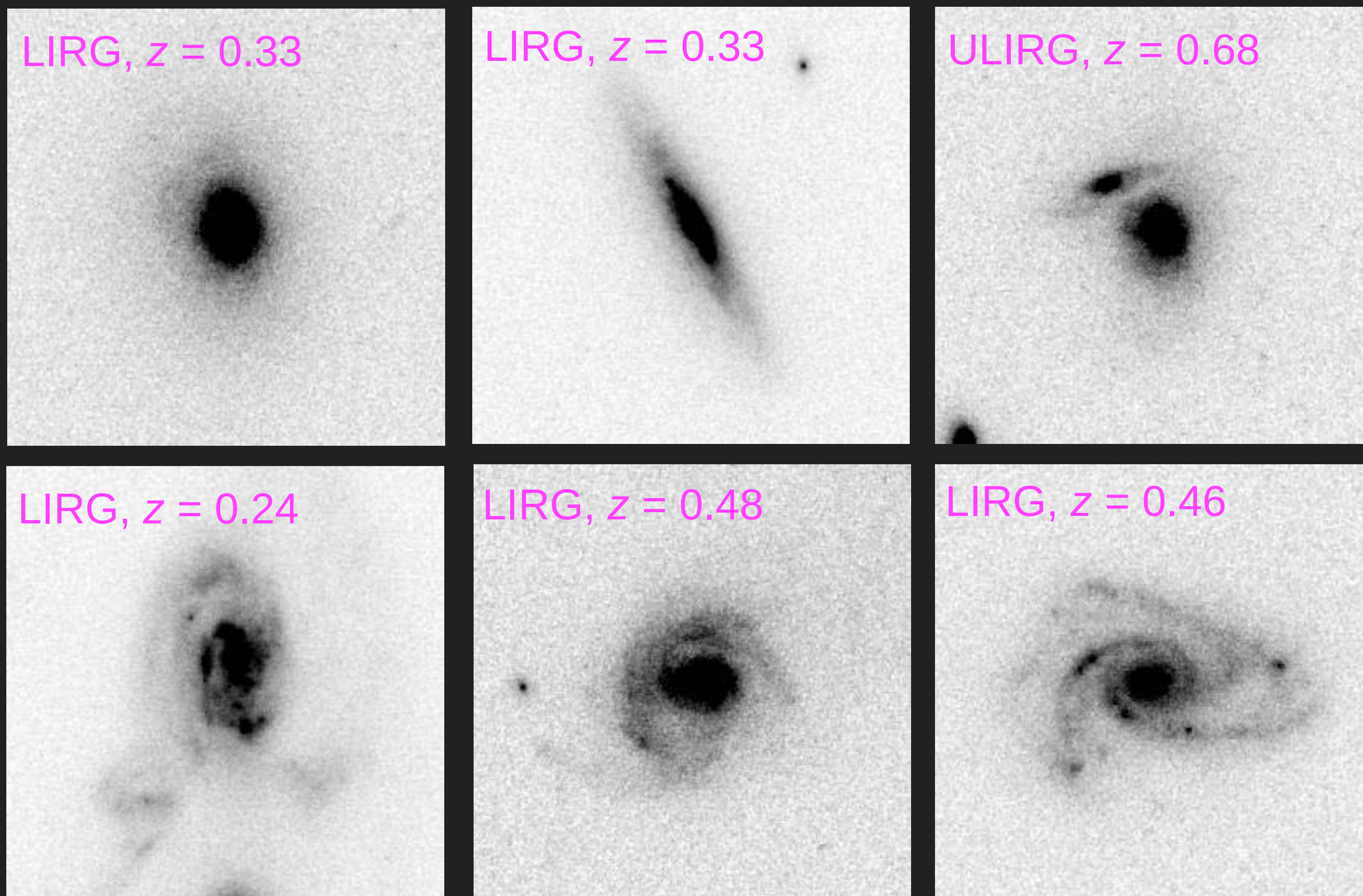
Bell et al. 2005

U-V


E/S0
Sa−Sd
Irr/compact
Pec/Int
4 M⊙ yr⁻¹
40 M⊙ yr⁻¹
400 M⊙ yr⁻¹
U−V
U−V
Mv
Mv
1.5
1.0
0.5
0.0
−0.5
−1.0
−24
−23
−22
−21
−20
−19
−18

rest V

Most IR luminous galaxies in GEMS are relatively normal looking spirals

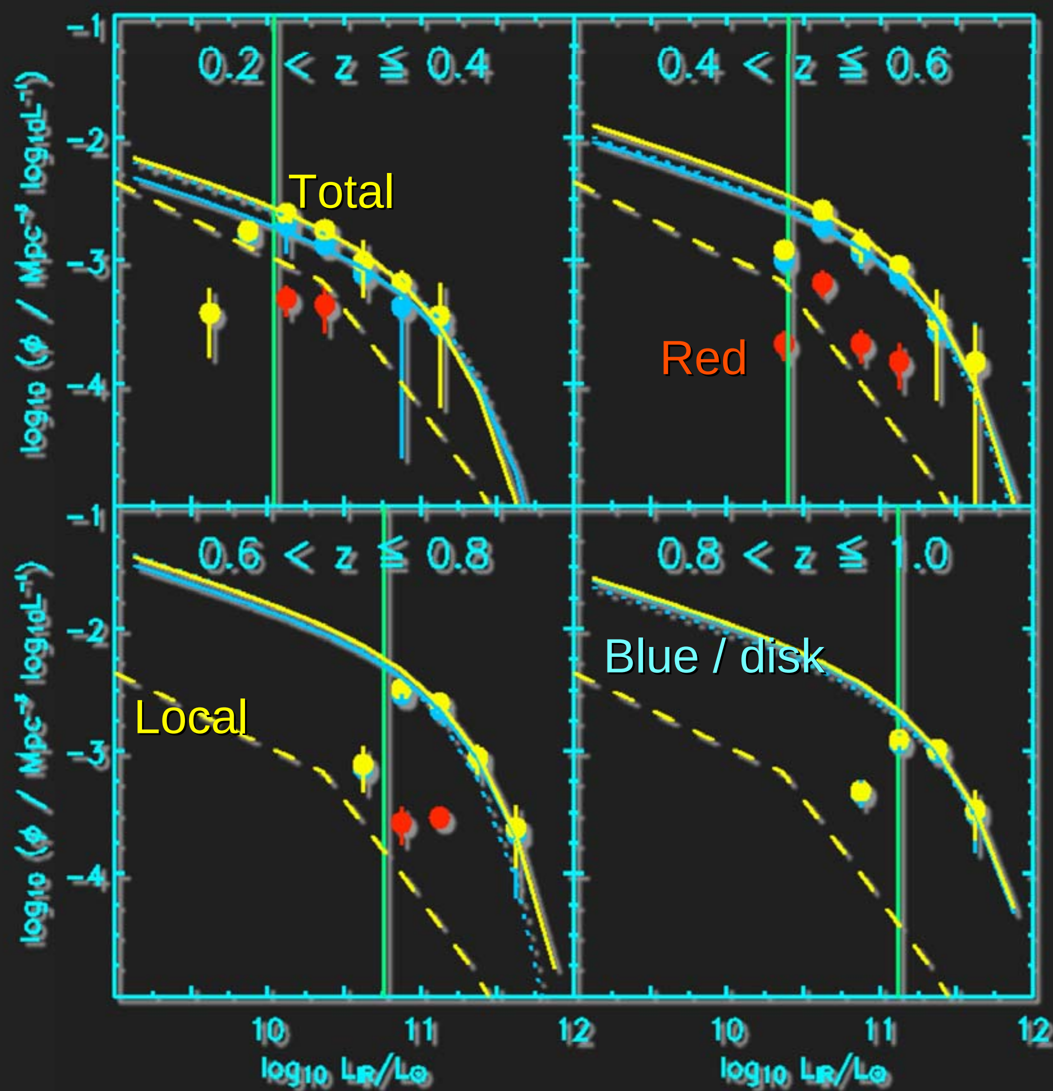


Evolution of IR LF

IR LF very strongly evolving

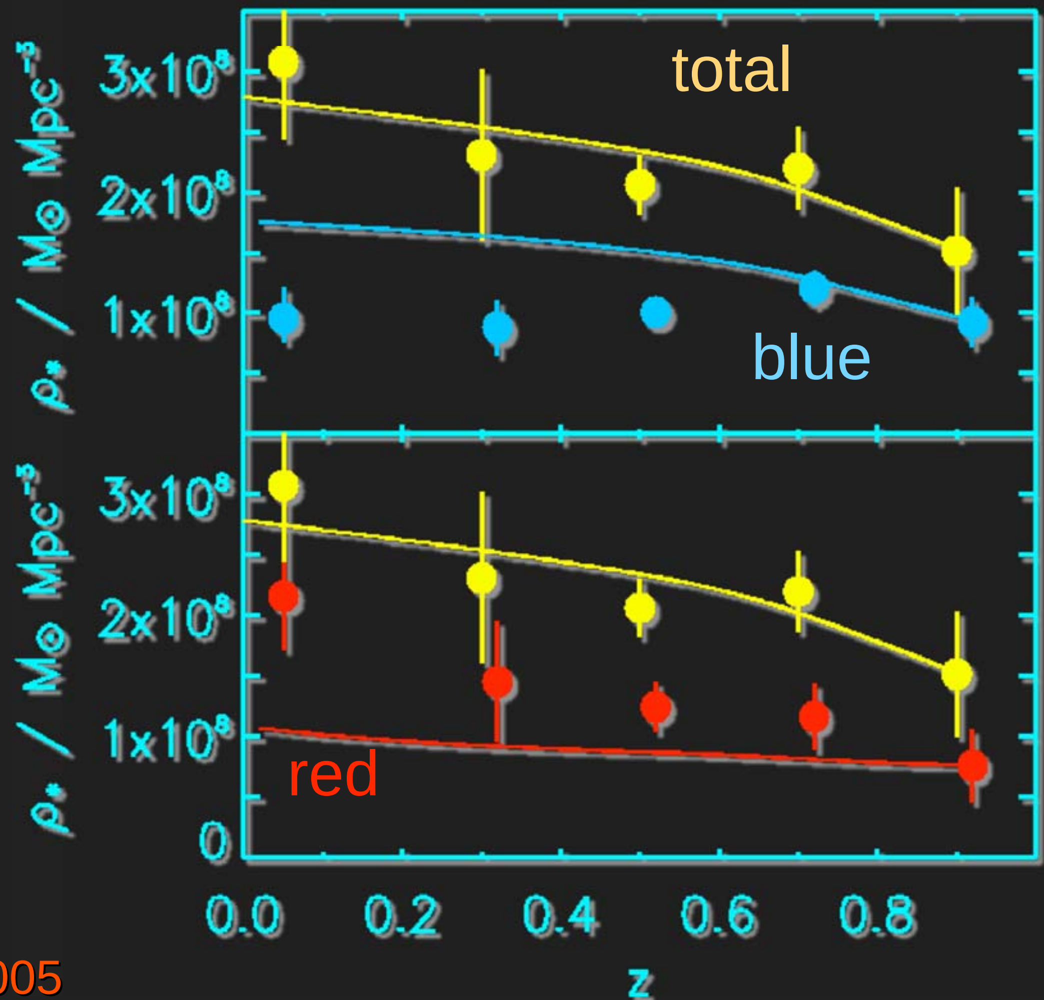
Almost all SF is in blue disks

Le Floc'h et al. 2005
Bell et al. 2005



SF and mass assembly split by color

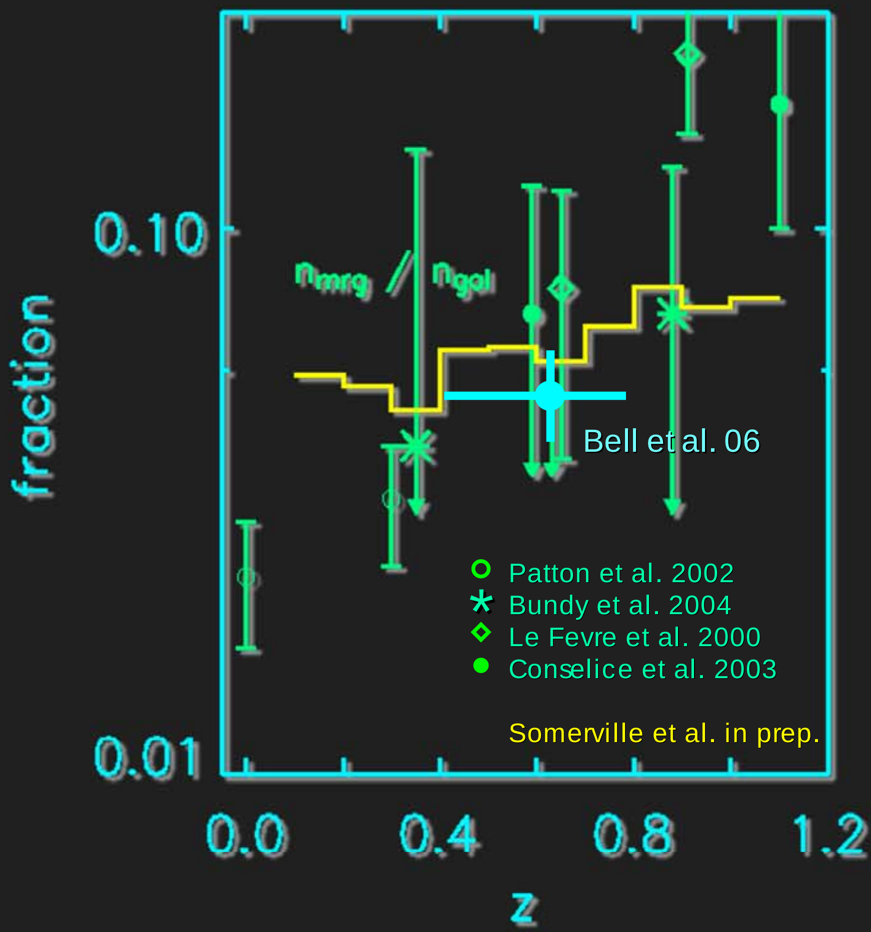
- compare integrated SFR with observed growth in stellar mass
- most star formation is in blues, but their mass density does not grow!
- need a process that moves galaxies from blue to red pile...



Bell et al., in prep.; Le Floc'h et al. 2005

MERGERS?

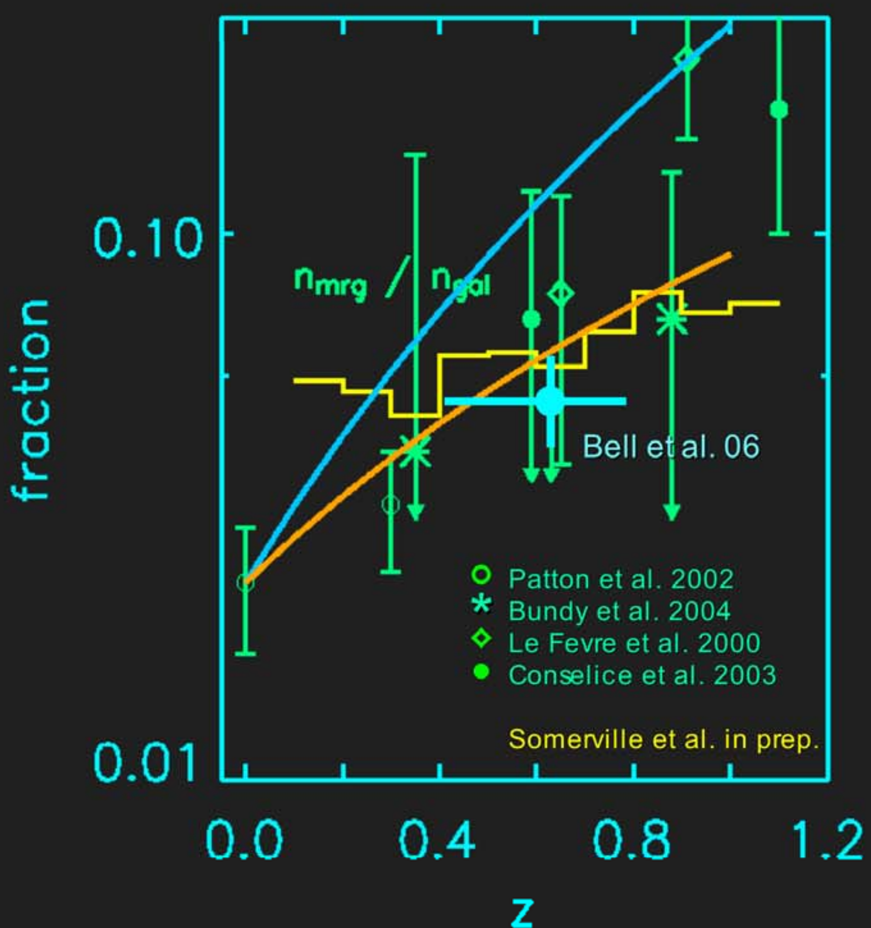
- direct measure of merger fraction from close pair fraction in COMBO
- agrees fairly well with other results from *mass-selected* samples; SAM



Bell, Phelps, rss et al. 2006

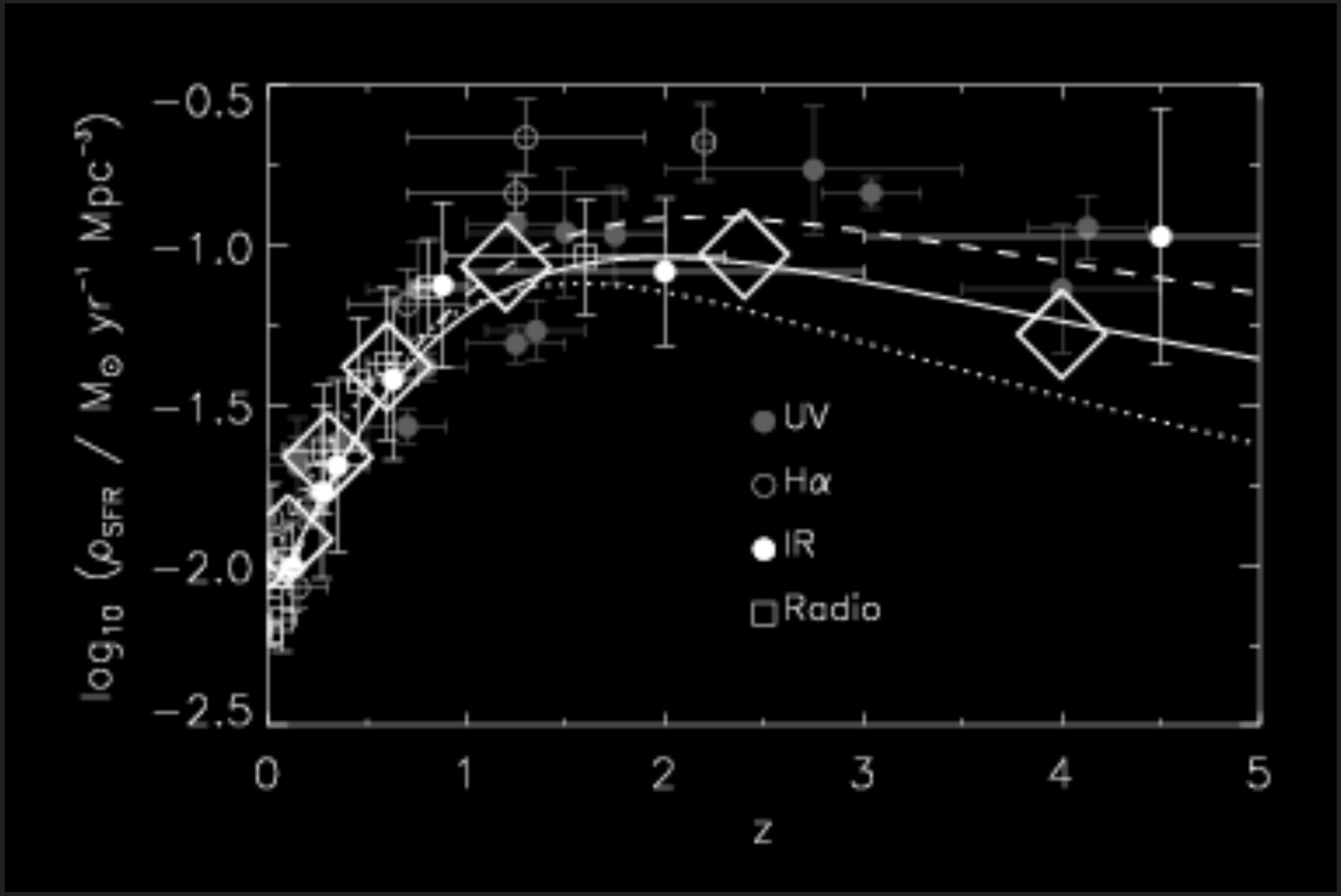
Mergers?

- implied 'transformation' rate is higher, and steeper, than the 'direct' estimates of merger rate
- n.b. keep in mind merger rates are hard to measure by any means!



Bell, Phelps, rss et al. 2006

CO-EVOLUTION OF GLOBAL ACCRETION RATES



diamonds = accretion rate based on hard X-ray LF x $\rho_{BH}(z=0)/\rho_{*,sph}(z=0)$ ~2000

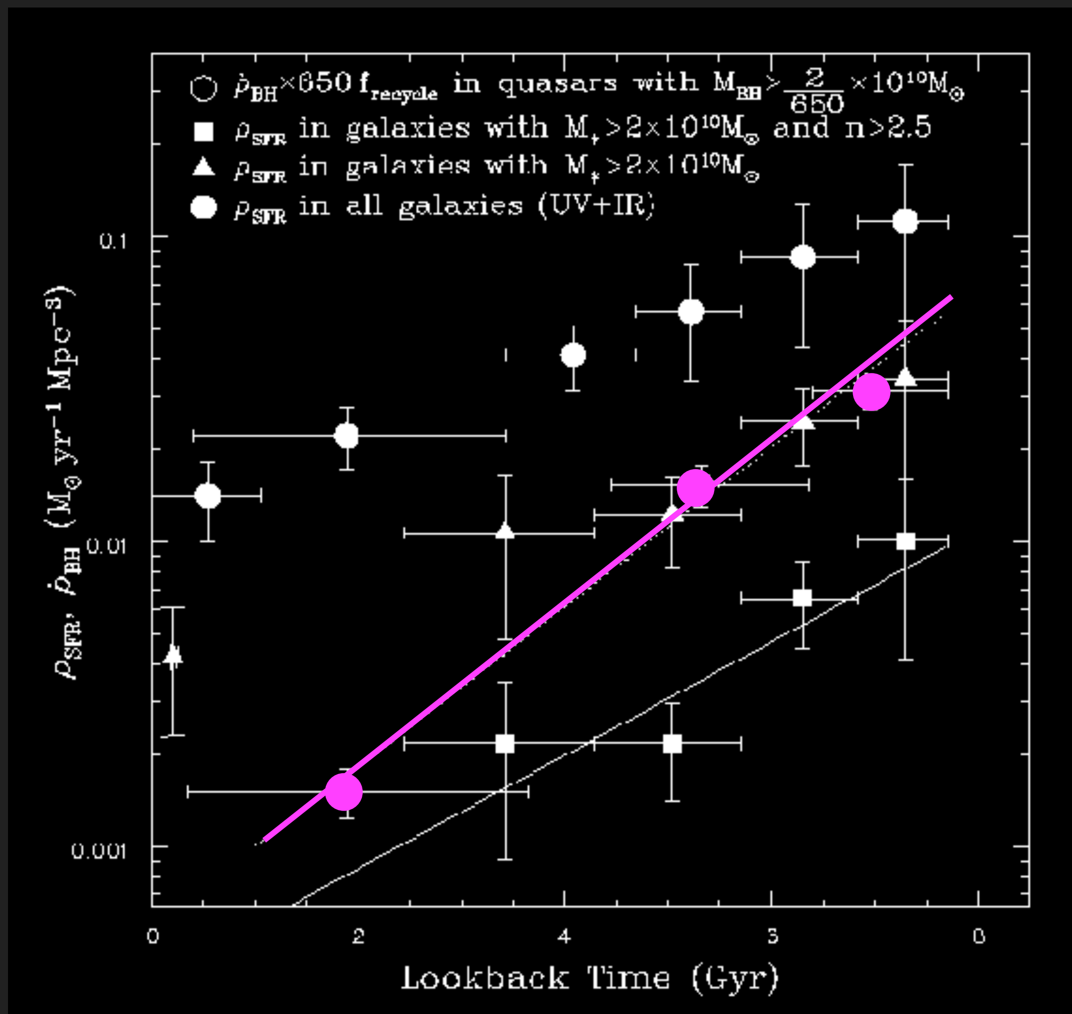
Zheng, Bell, rss, Rix, Jahnke et al. in prep

CO-EVOLUTION IN MASS AND ACCRETION RATE

SFR in all galaxies is too much...

SFR in (all) massive galaxies is about right

SFR in massive spheroids not enough

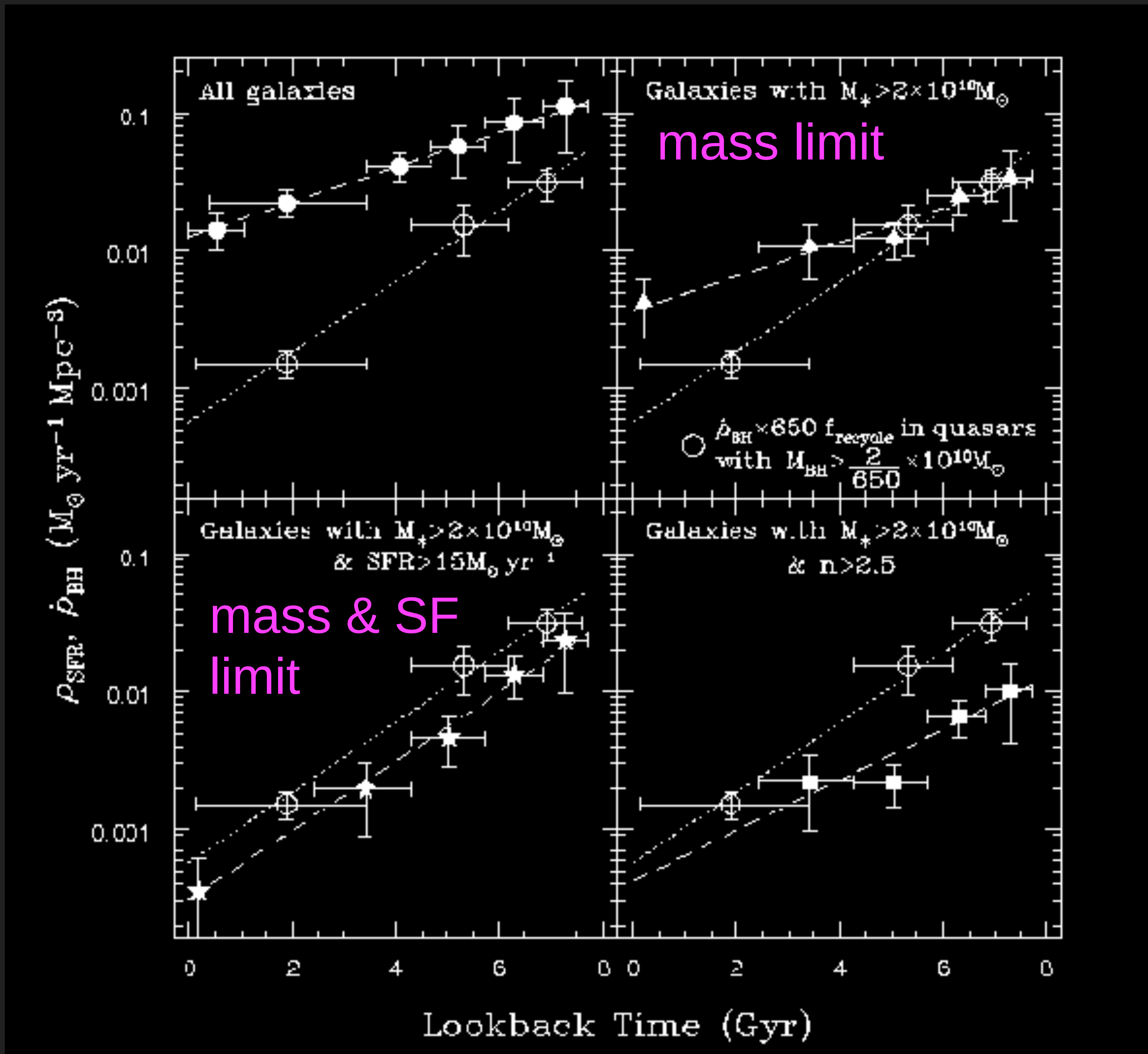


accretion onto massive BH assuming distribution of L/L_{Edd} from Kollmeier et al.

Zheng et al. in prep

CO-EVOLUTION BY MASS AND ACCRETION RATE

- take LF of optical QSOs.
  - convert L_{obs} to L_{bol} using standard bolometric corrections.
  - L_{bol} --> accretion rate assuming efficiency of conversion of rest mass to energy of 10%
  - convert L_{bol} to M_{BH} using distribution from Kollmeier et al. 2006 based on linewidths ($\langle L_{bol}/L_{Edd} \rangle \sim 0.25$, $\sigma \sim 0.3$ dex)
  - plot accretion rate contributed by BH above a given mass limit



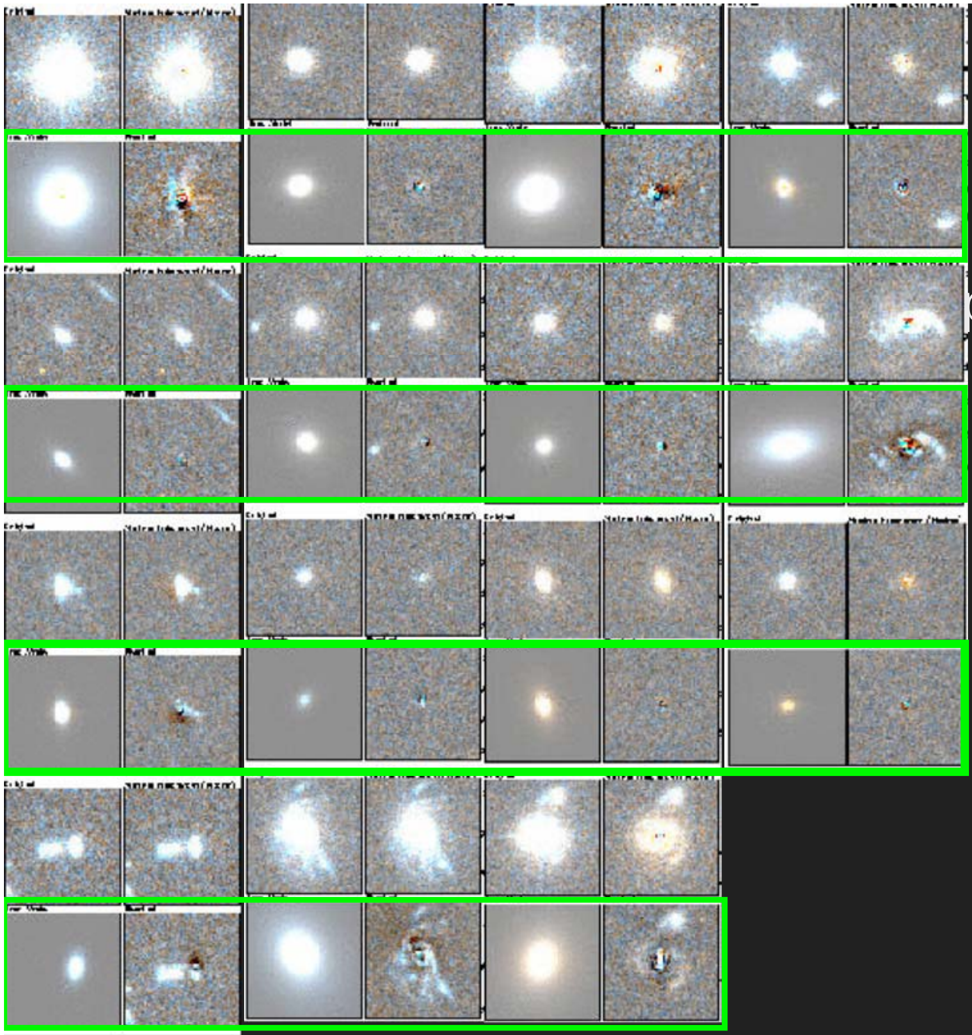
open circles: black hole accretion

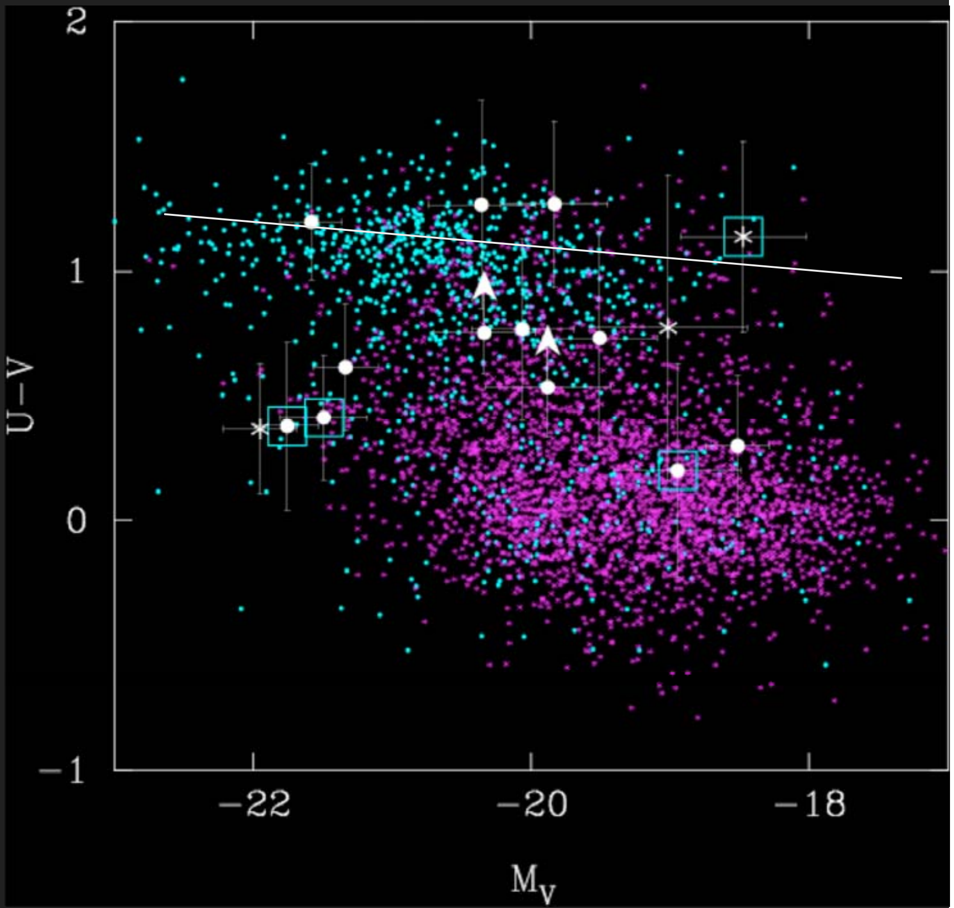
filled: star formation

Zheng, Bell, rss, Rix, Jahnke et al. in prep.

AGN host morphologies in GEMS:

-4/15 appear to be mergers
-2/15 have exponential profiles (n<2.5)
-majority have deV-like (n>2.5) profiles

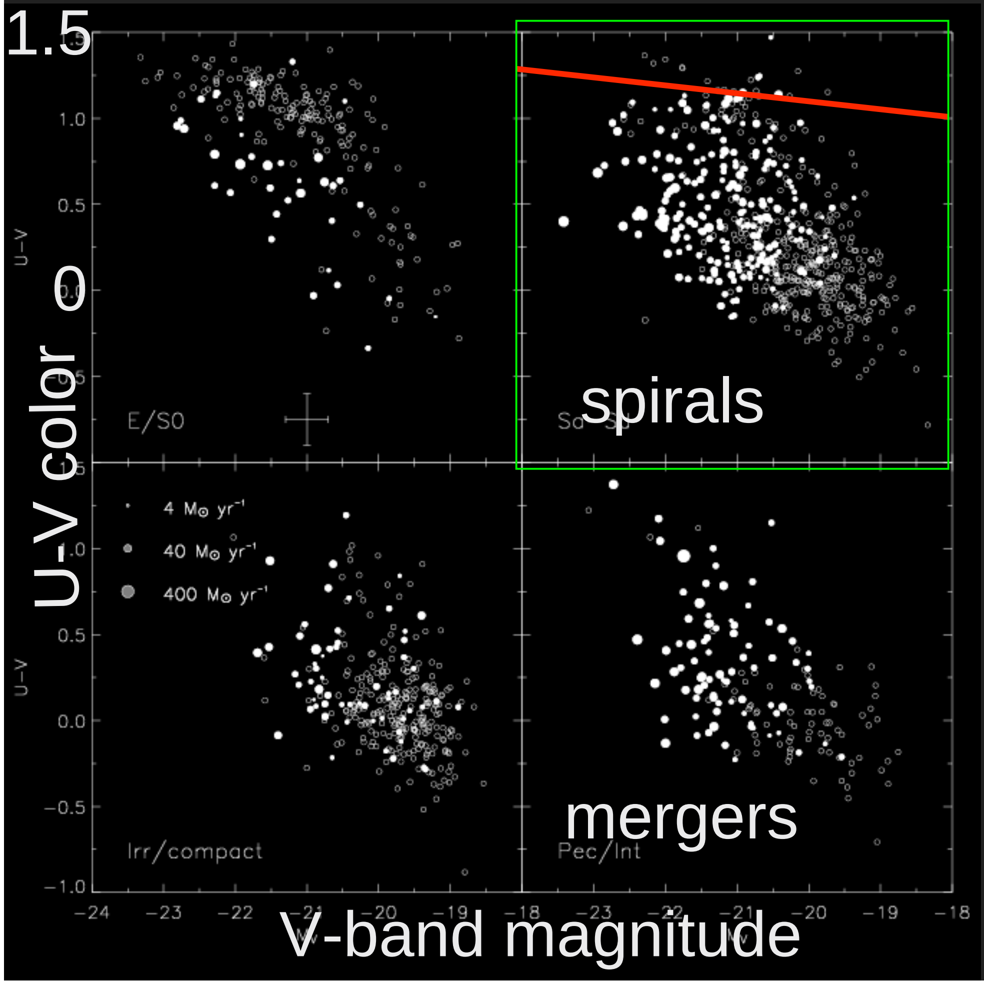


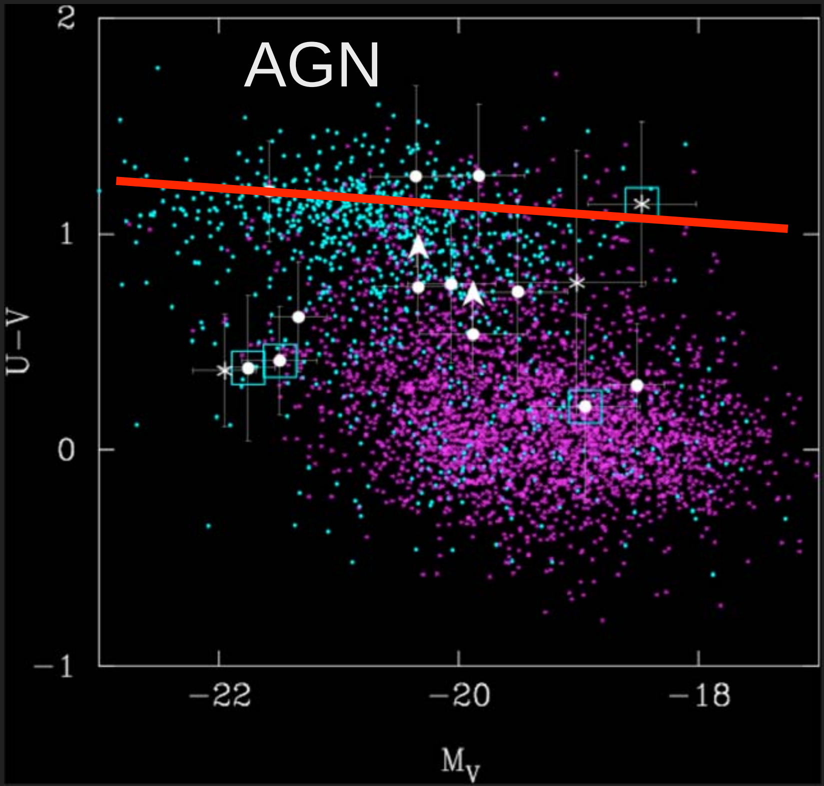


Sanchez et al. 2004

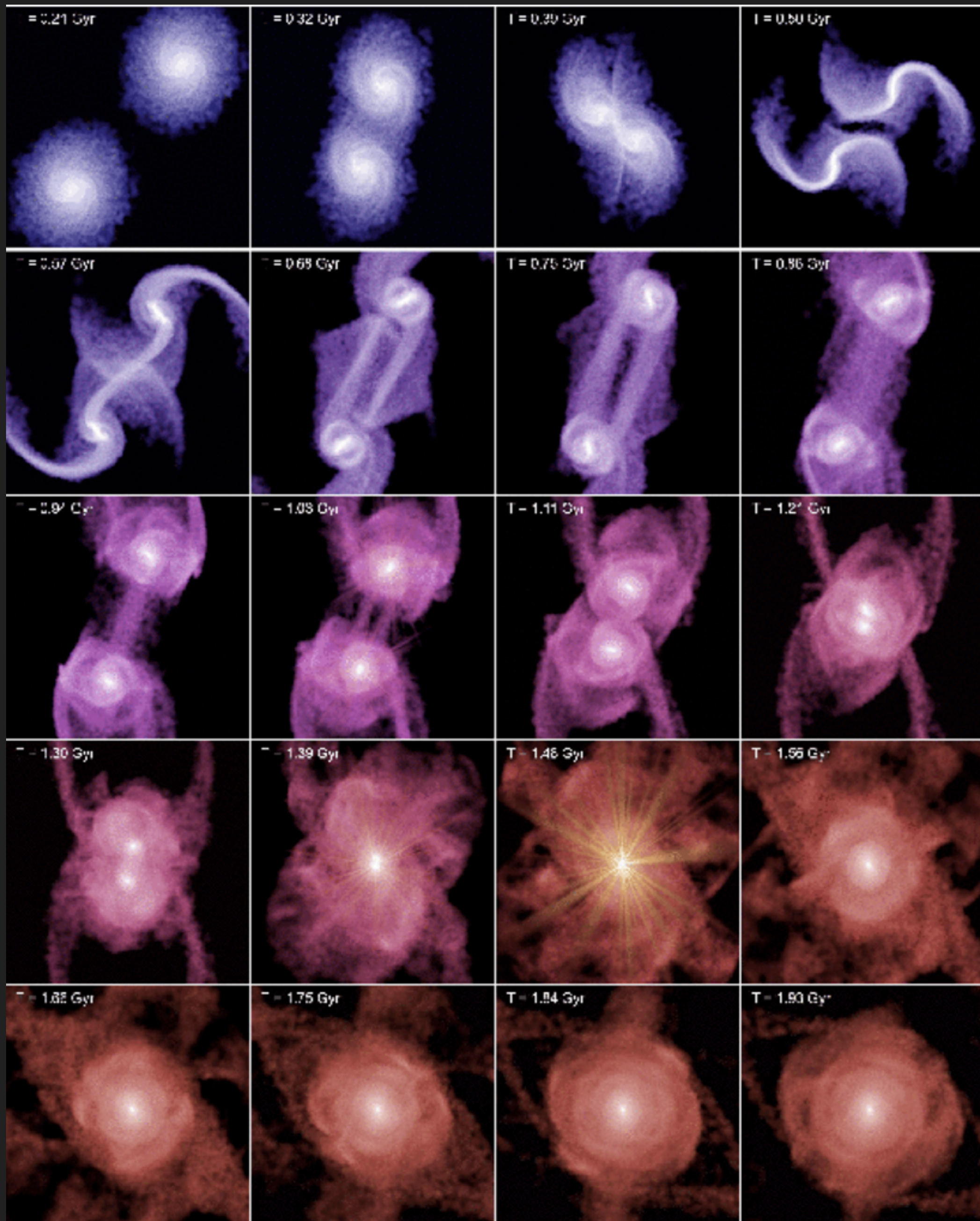
COLORS OF STAR FORMING GALAXIES VS. AGN HOSTS

galaxies z=0.7





Sanchez et al. 2004
Bell et al. 2005

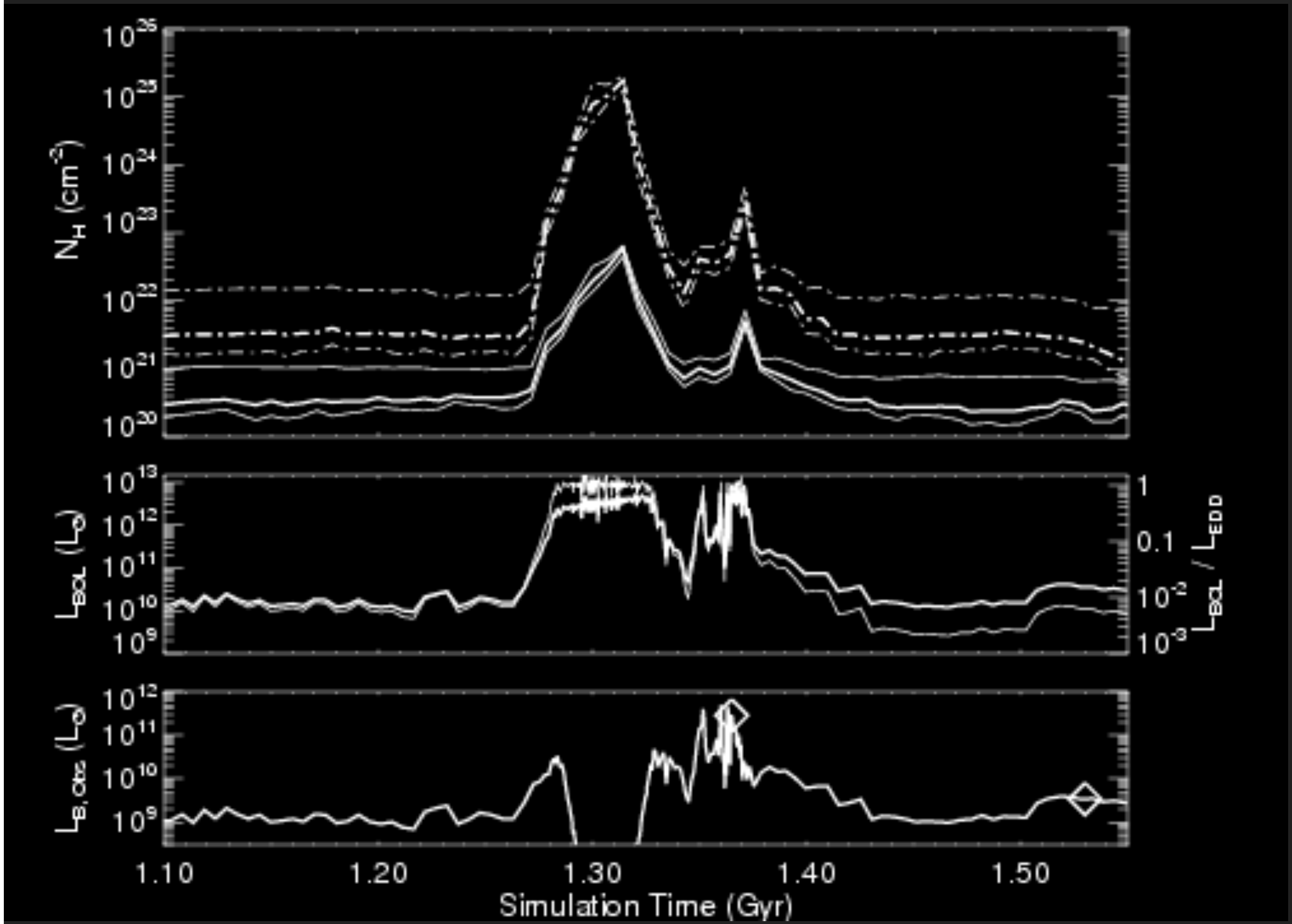


Hydrodynamic simulations of galaxy mergers including black hole growth and feedback

-sub-grid model of SF in multi-phase ISM
-Bondi accretion onto central BH
-thermal energy from stars and AGN returned to ISM

di Matteo, Springel & Hernquist
Springel, di Matteo & Hernquist
Robertson et al.
Hopkins et al.

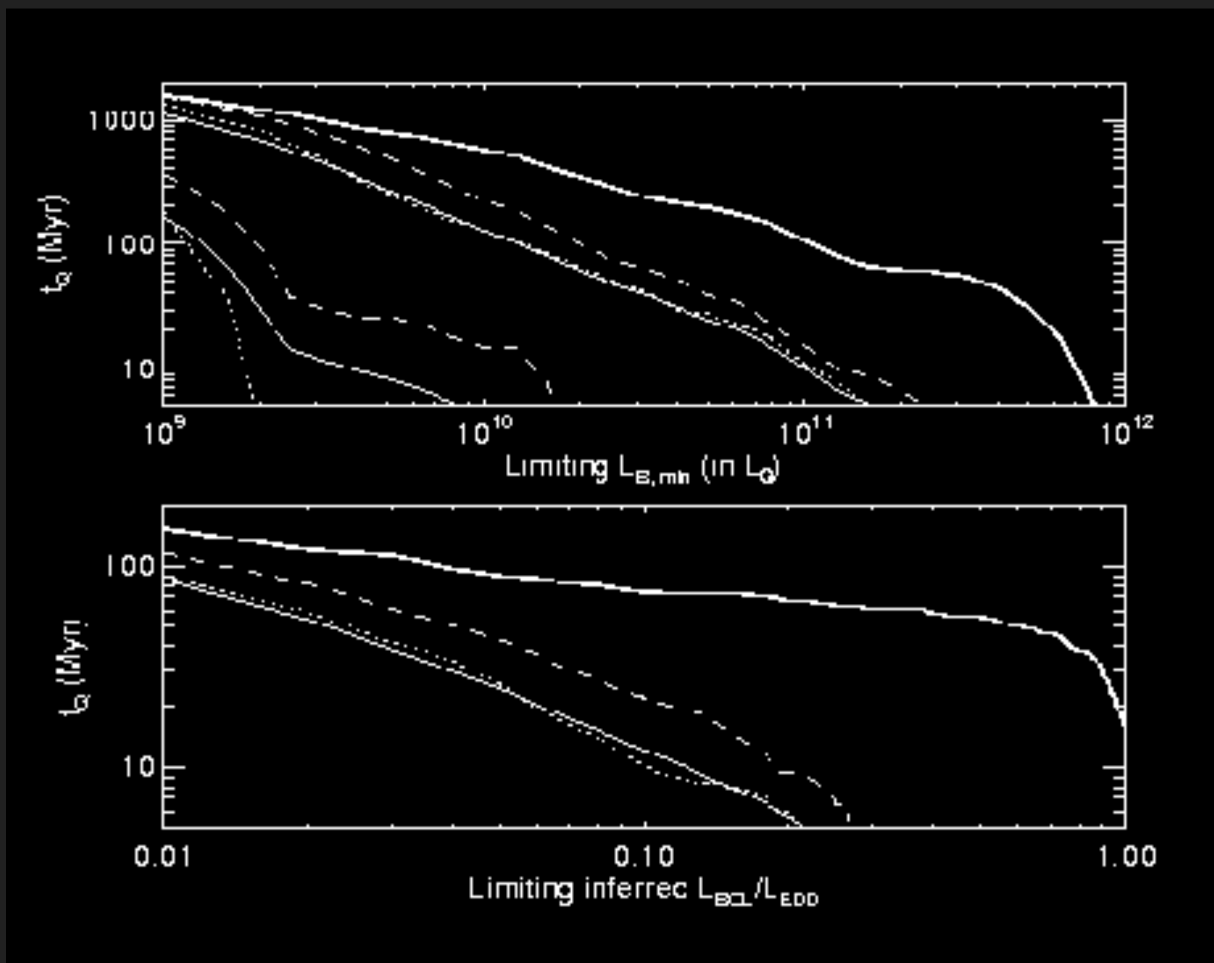
CHARACTERISTIC QSO LIGHTCURVES



-QSO accretes at << L_{edd} over most of its lifetime
-'visibility time' much longer at faint luminosities
-obscuration is largest during peak of accretion
-optical QSO becomes visible during 'blowout' phase

Hopkins et al. 2005

PARAMETERIZATION OF LIGHTCURVES



differential time spent in a given logarithmic luminosity interval: $dt/d\log(L) = t_Q\ (L/L_Q)^{\alpha} \exp[-L/L_Q]$ where L_Q propto peak lum or final BH mass, α~const

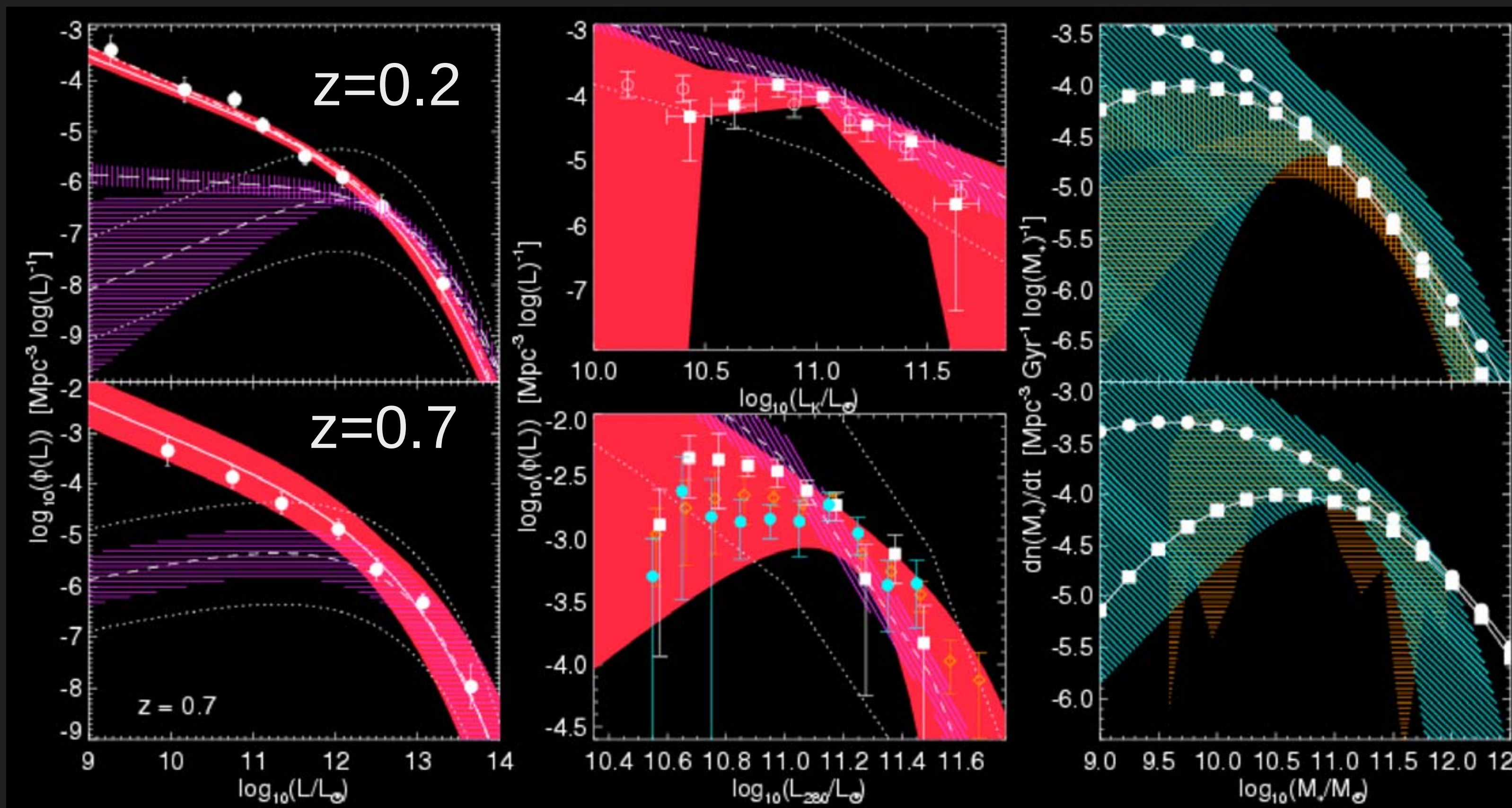
Hopkins et al. 2005

MAPPING THE OBSERVED MERGER LF AND QSO LF

- we can use these parameterizations of starburst & QSO lightcurves to compute statistical mappings between QSO luminosity functions, LF or mass function of merging galaxies, galaxy-galaxy merger rate, host luminosity, etc.

Hopkins, rss, Hernquist, Cox, Robertson & Li 2006

observations: hard X-ray QSO LF (Ueda et al. 2003)
merger LF at z=0.2 from 2MASS (Xu et al.) & z=0.7 from GEMS



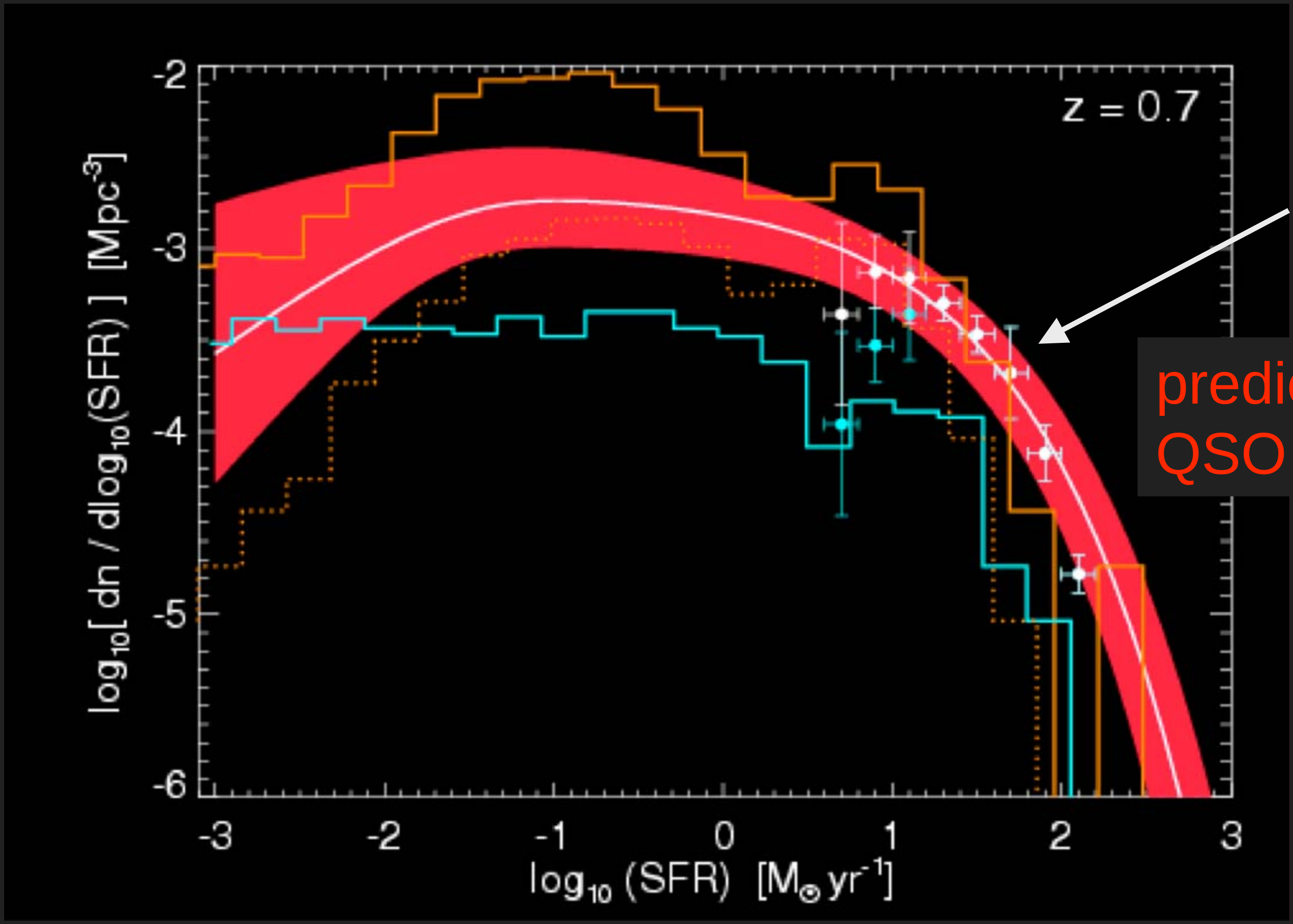
QSO LF predicted from observed merger LF

merger LF from observed QSO LF

inferred (gas rich) merger mass function

Hopkins, rss, Hernquist, Cox, Robertson & Li 2006

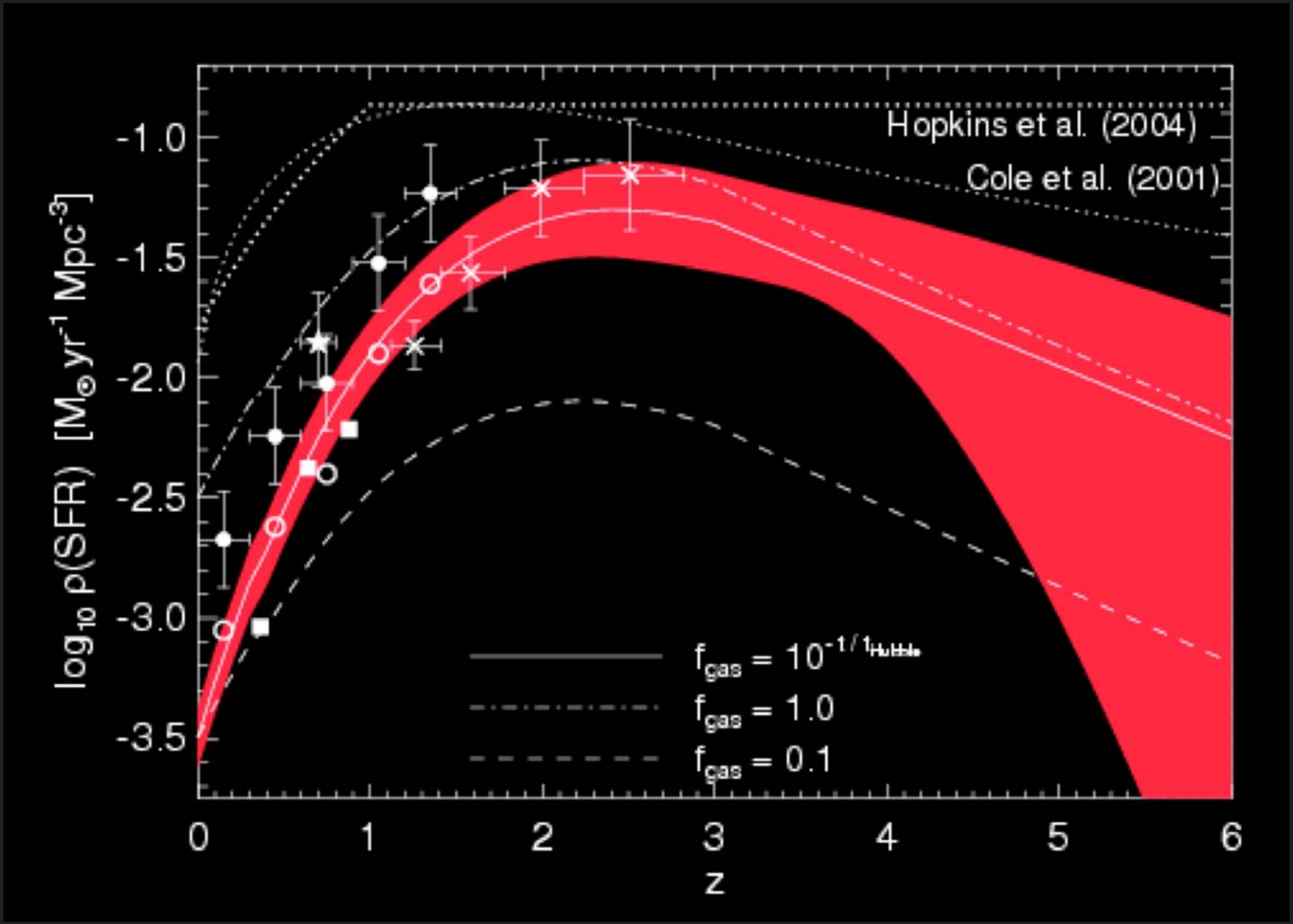
star formation rate function of mergers



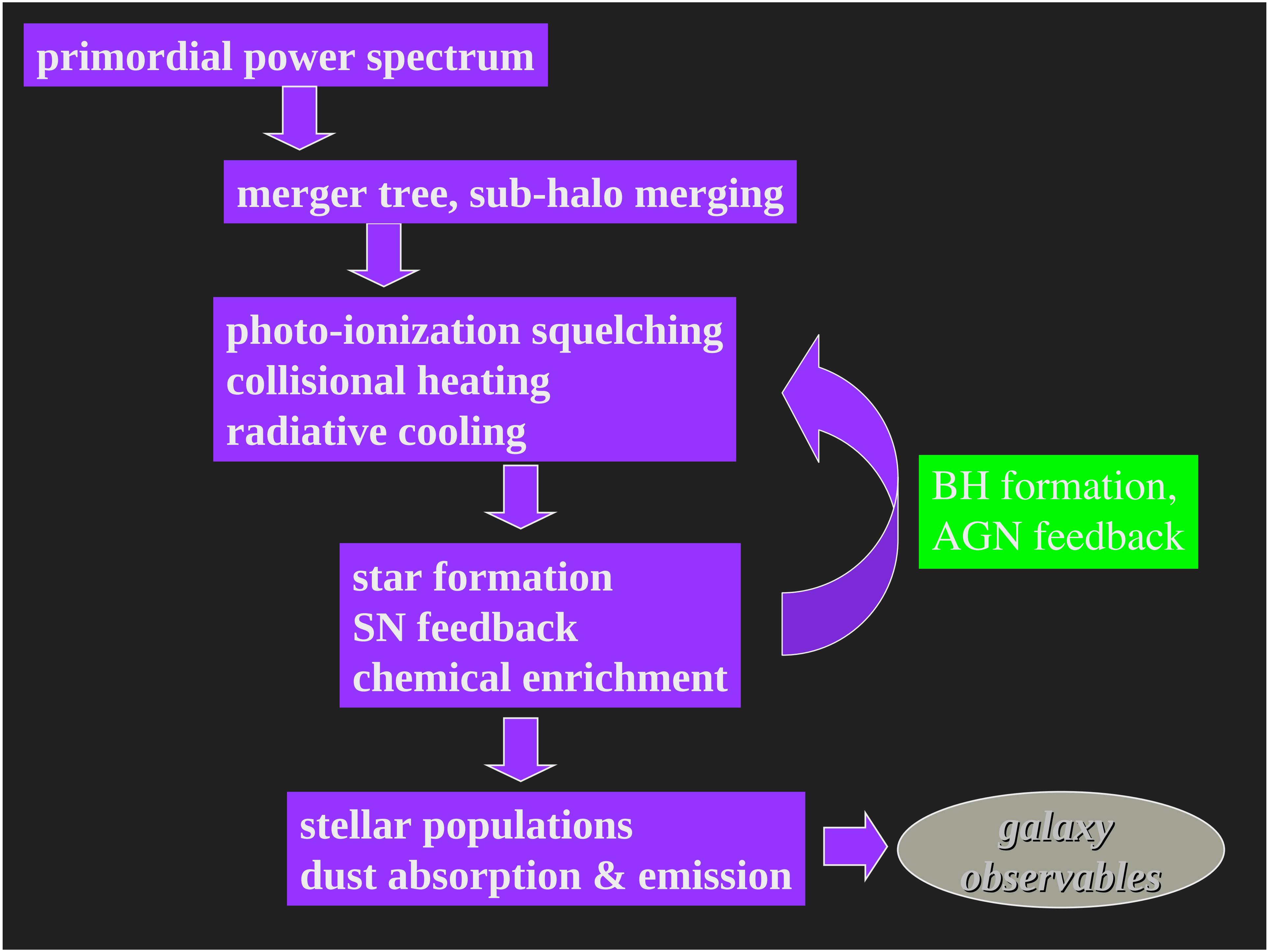
GEMS mergers

predicted from QSO LF

mergers contribute ~1% to the global SFR at z=0, 15-25% at z~1, 30-50% at z~2



Hopkins, rss et al. 2006

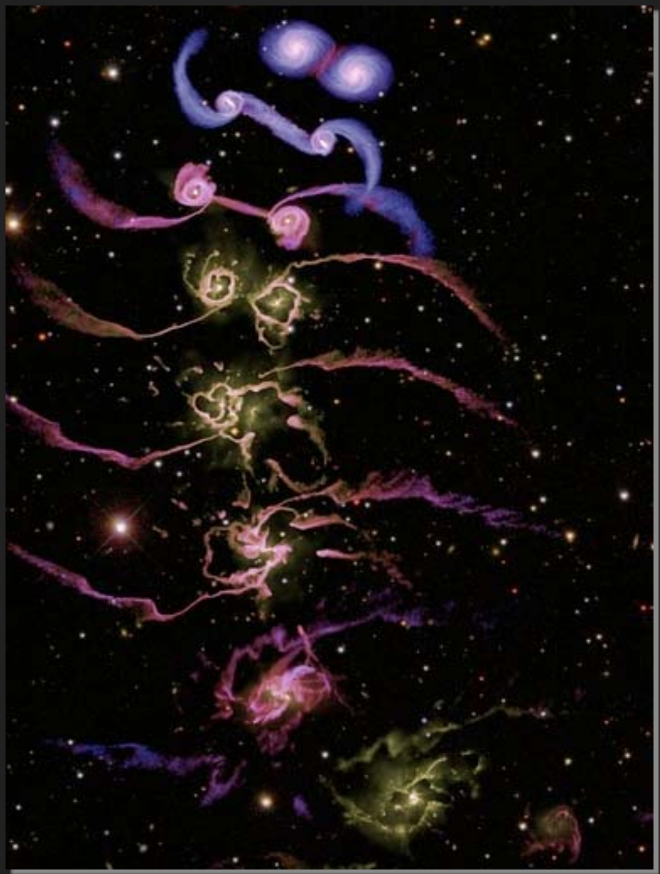

primordial power spectrum
merger tree, sub-halo merging
photo-ionization squelching
collisional heating
radiative cooling
star formation
SN feedback
chemical enrichment
BH formation,
AGN feedback
stellar populations
dust absorption & emission
galaxy
observables

THE NEED FOR AGN FEEDBACK IN COSMOLOGICAL MODELS

- overcooling problem: too large a fraction of gas cools into galaxies; huge excess of ultra-massive/luminous blue galaxies at z~0
- inverted color-magnitude relation & mass-age relation; dearth of massive red galaxies at high redshift
- weak or no color bimodality
- decrease in number density of luminous QSOs; AGN ‘downsizing’

AGN FEEDBACK MECHANISMS I

- during periods of efficient feeding (associated w/ merger?) we produce a luminous AGN/QSO
- thermal coupling of AGN energy with ISM is probably fairly weak (5%?), and duty cycle short
- BH growth self-regulated (produces M_{BH}-σ relation)
- AGN can drive a wind that 'sweeps up' galaxy



Di Matteo, Springel & Hernquist 2005

AGN feedback mechanisms II

- periods of low accretion efficiency (ADAF?) associated with jet formation
- energy couples with gas very efficiently (~100%?) and duty cycle is long
- resulting bubbles look similar to those seen in Chandra images of some clusters

QuickTime™ and a
decompressor
are needed to see this picture.

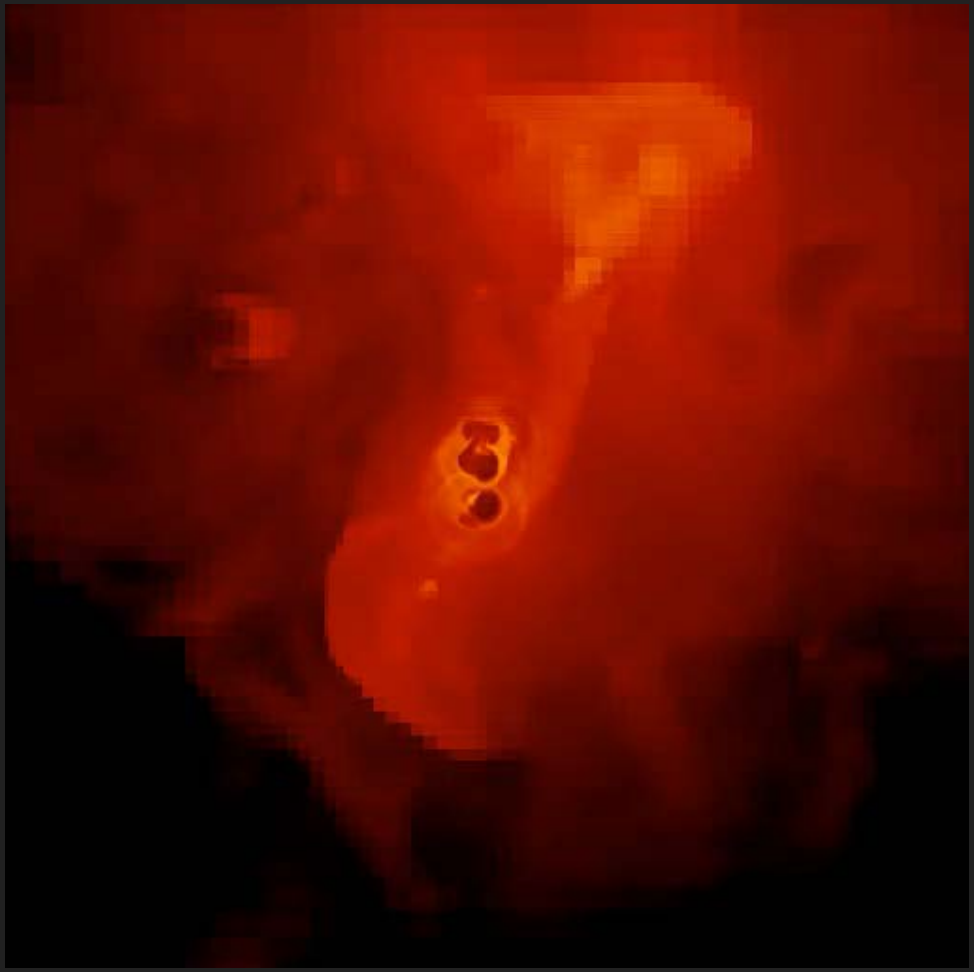
Bruggen, Ruszkowski & Hallen 2005

AGN FEEDBACK III

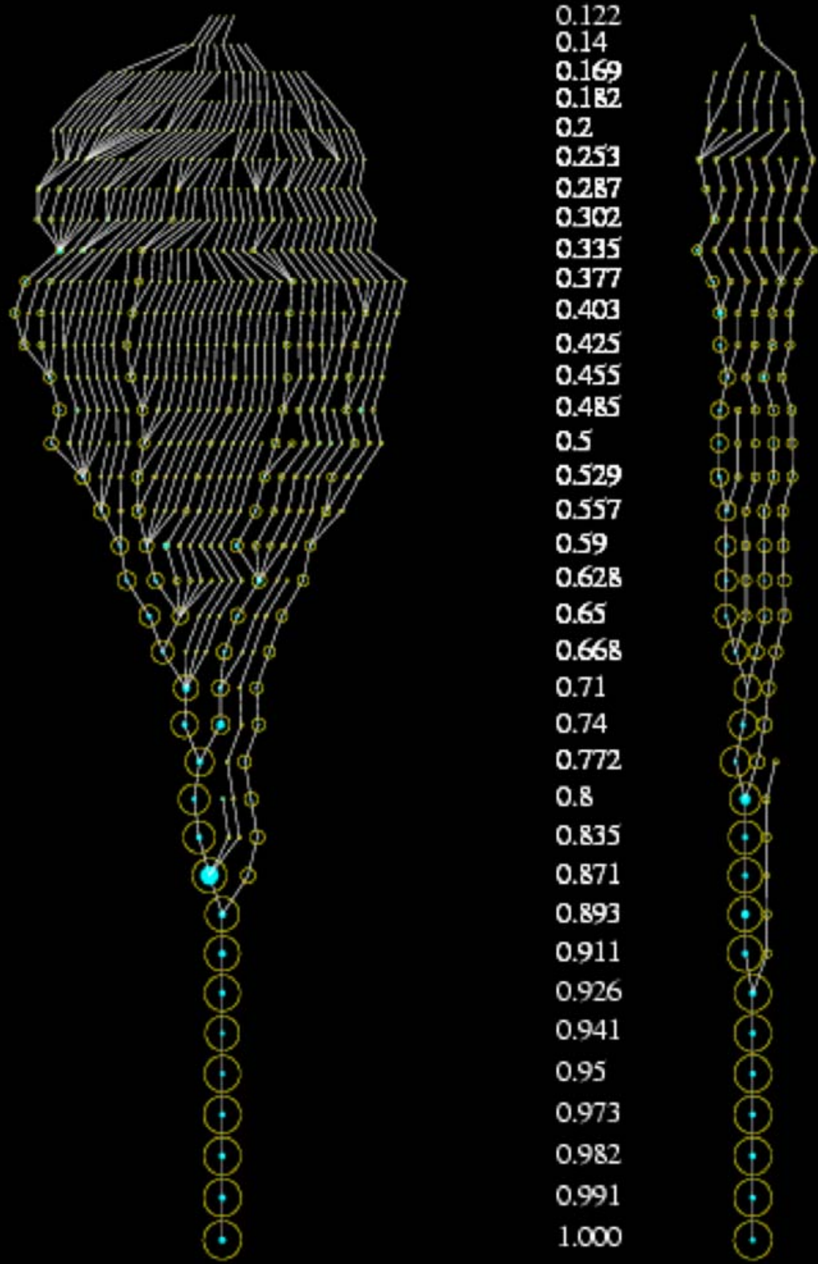
- below a critical halo mass ~few x 10^{11}-10^{12} M_{sun}, infalling gas never shock heats to the virial temperature but ‘falls in cold’
- above this critical mass, gas shock heats to form a hot halo, then cools in a ‘cooling flow’ (Birnboim & Dekel, Keres et al.)
- ‘radio mode’ feedback only affects hot mode cooling (Cattaneo et al., Croton et al., Bower et al.)

‘Effervescent’ heating by giant radio jets

- recent work suggests even columnated jets can heat a large filling factor of ICM
- resulting bubbles look similar to those seen in Chandra images of some clusters



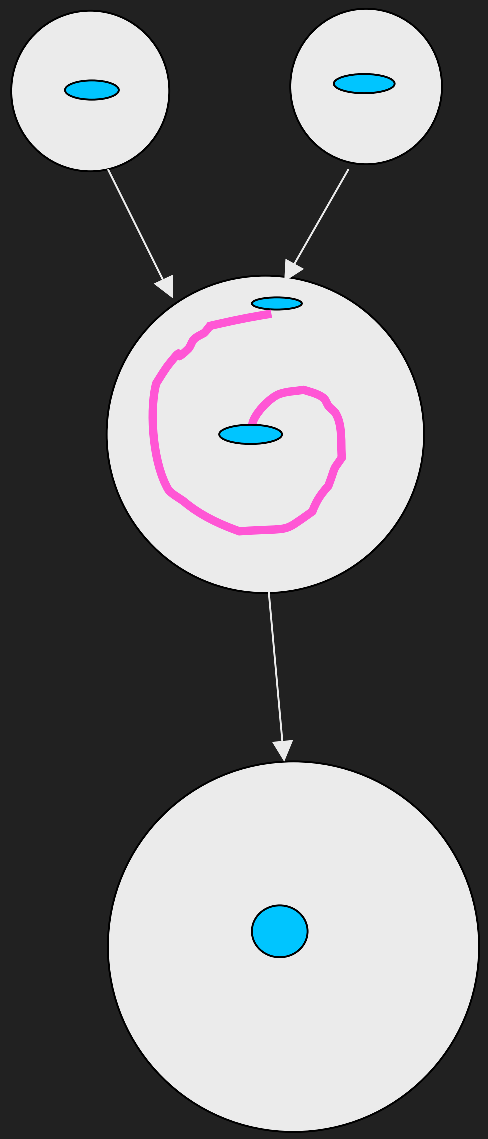
Bruggen, Ruszkowski & Hallen 2005



Modelling AGN and BH growth in a Hierarchical Cosmological context

-each top level halo seeded with a 100 M_{sun} BH

-cooling, quiescent star formation, chemical evolution and supernova feedback modelled within each galaxy

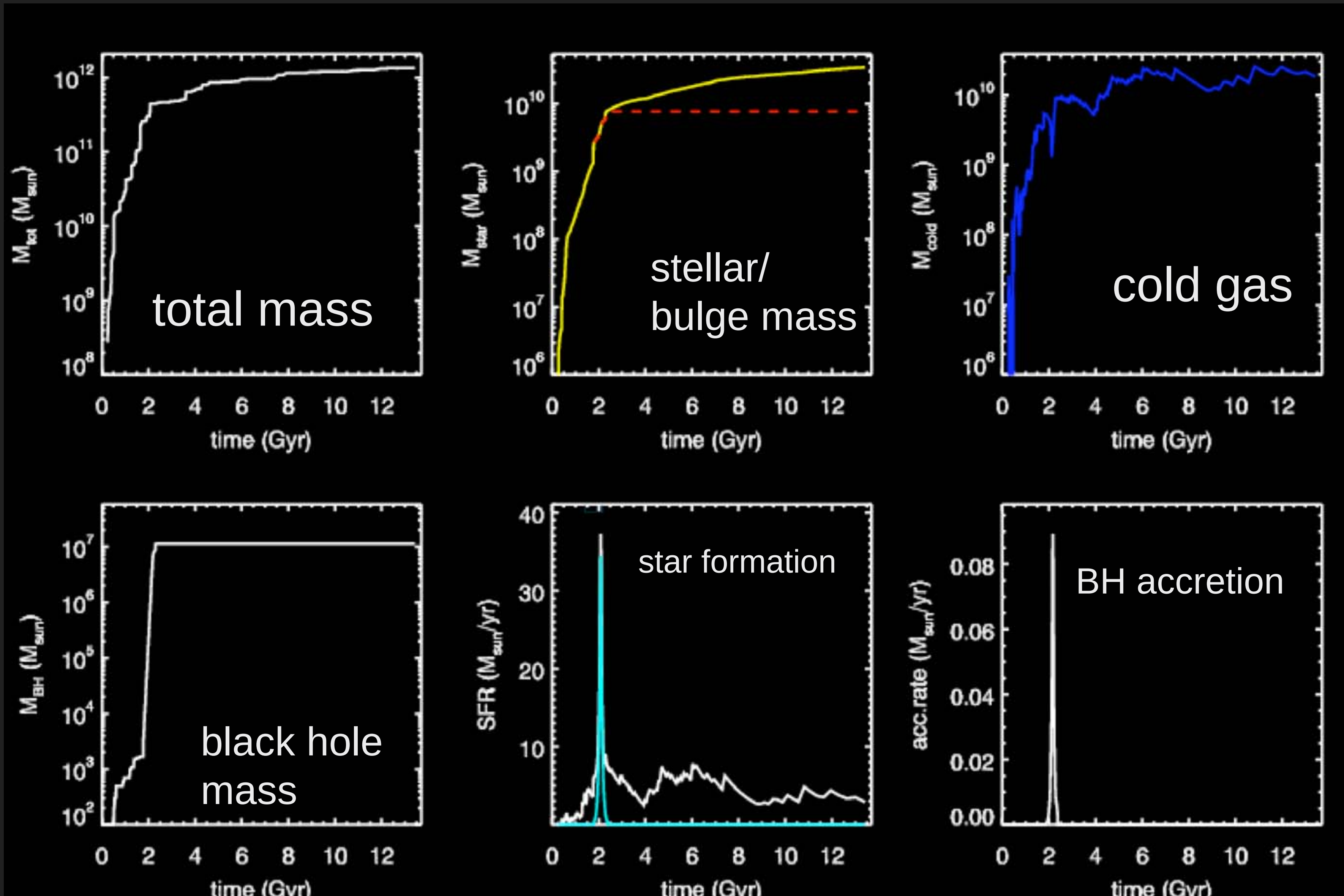


- merging of galaxies within DM halos via dynamical friction
- mergers trigger bursts of star formation and accretion onto BH; efficiency and timescale parameterized based on hydro merger simulations (μ, B/T, V_c, f_g, z; Cox et al., Robertson et al.)
- BH accrete at Eddington until they reach 'critical mass', then enter 'blowout' (power-law decline) phase

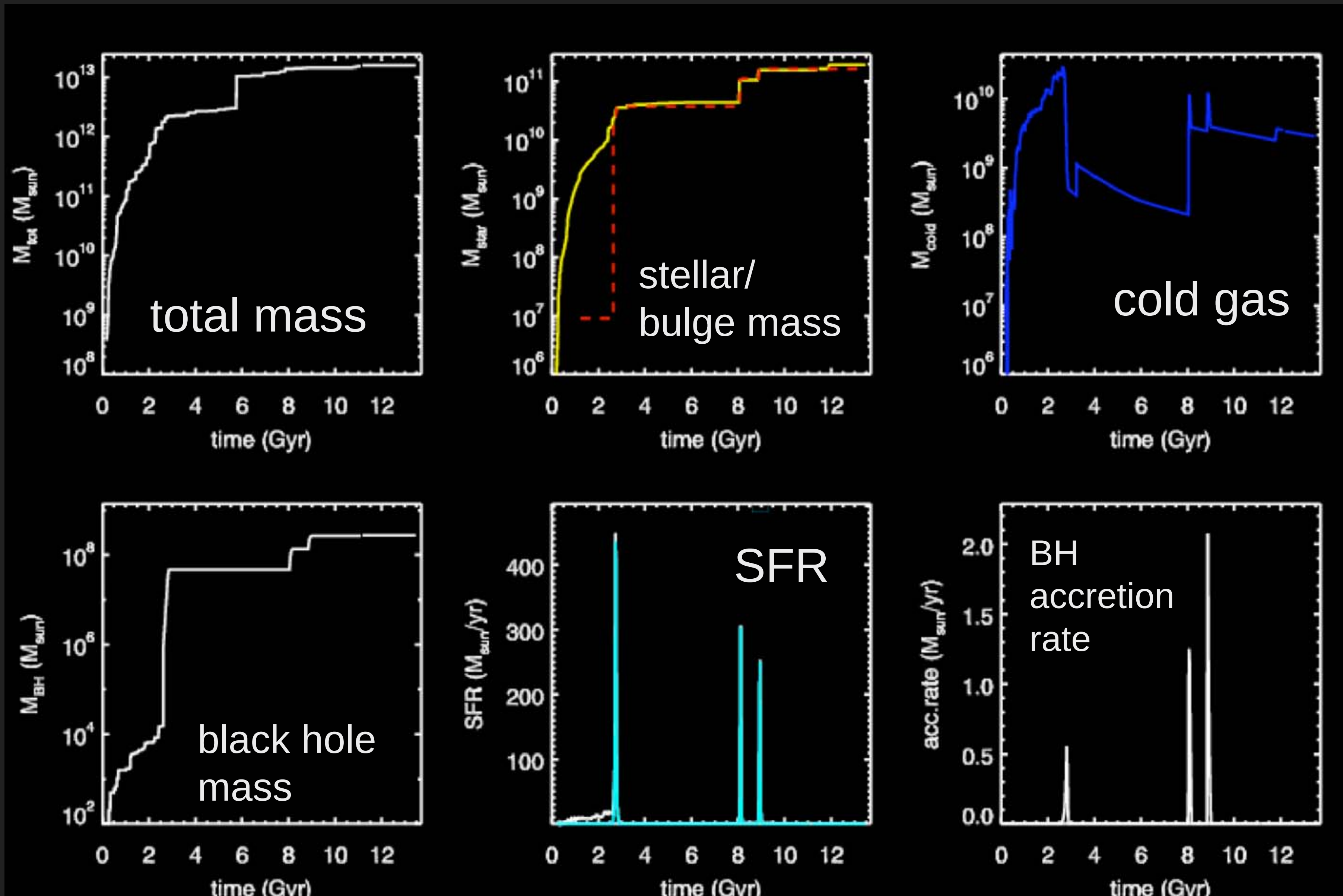
$$dm_{acc}/dt = m_{Edd}/[1+(t/t_Q)^{\beta}]$$

(Hopkins et al. 2005)

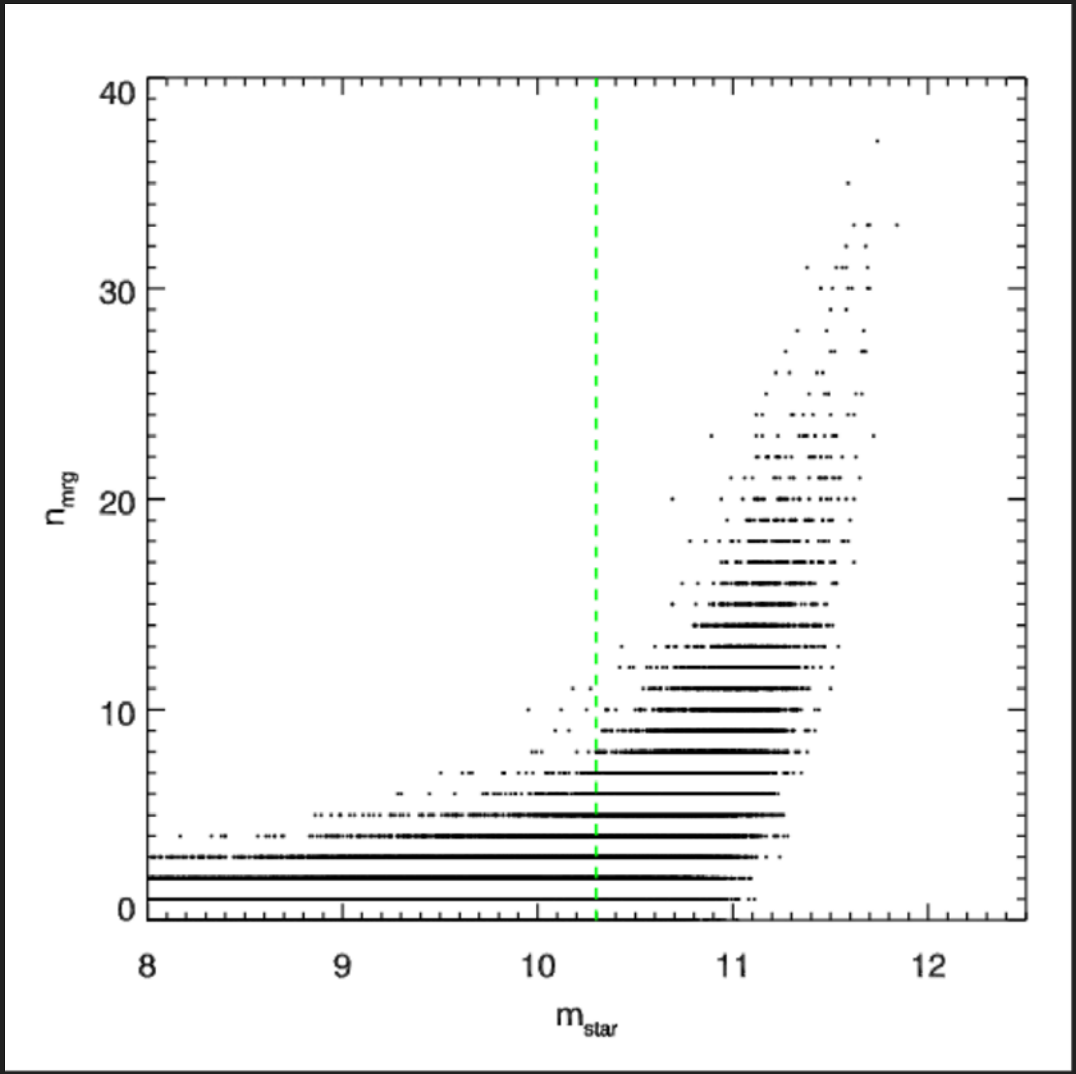
further star formation is suppressed as long as $m_{BH} > m_{crit}$



log M_h = 12.1, lg m*=10.6, m_r=-20.6, lg M_{BH}=7 B/T=0.22

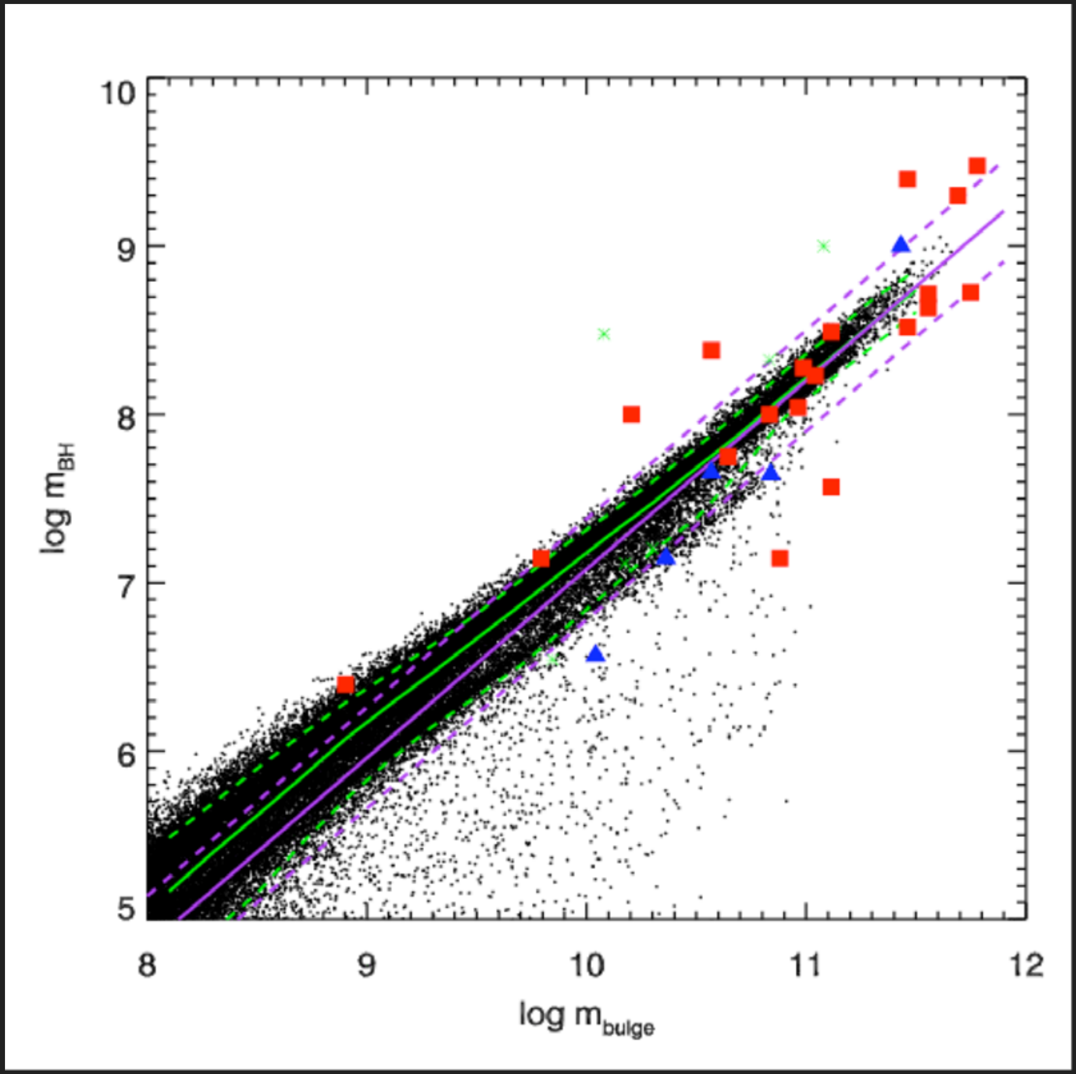


log M_h = 13.2, lg m*=11.3, m_r=-21.8, lg M_{BH}=8.4 B/T=0.9



-number of major mergers experienced over a galaxy’s history is a strong function of mass

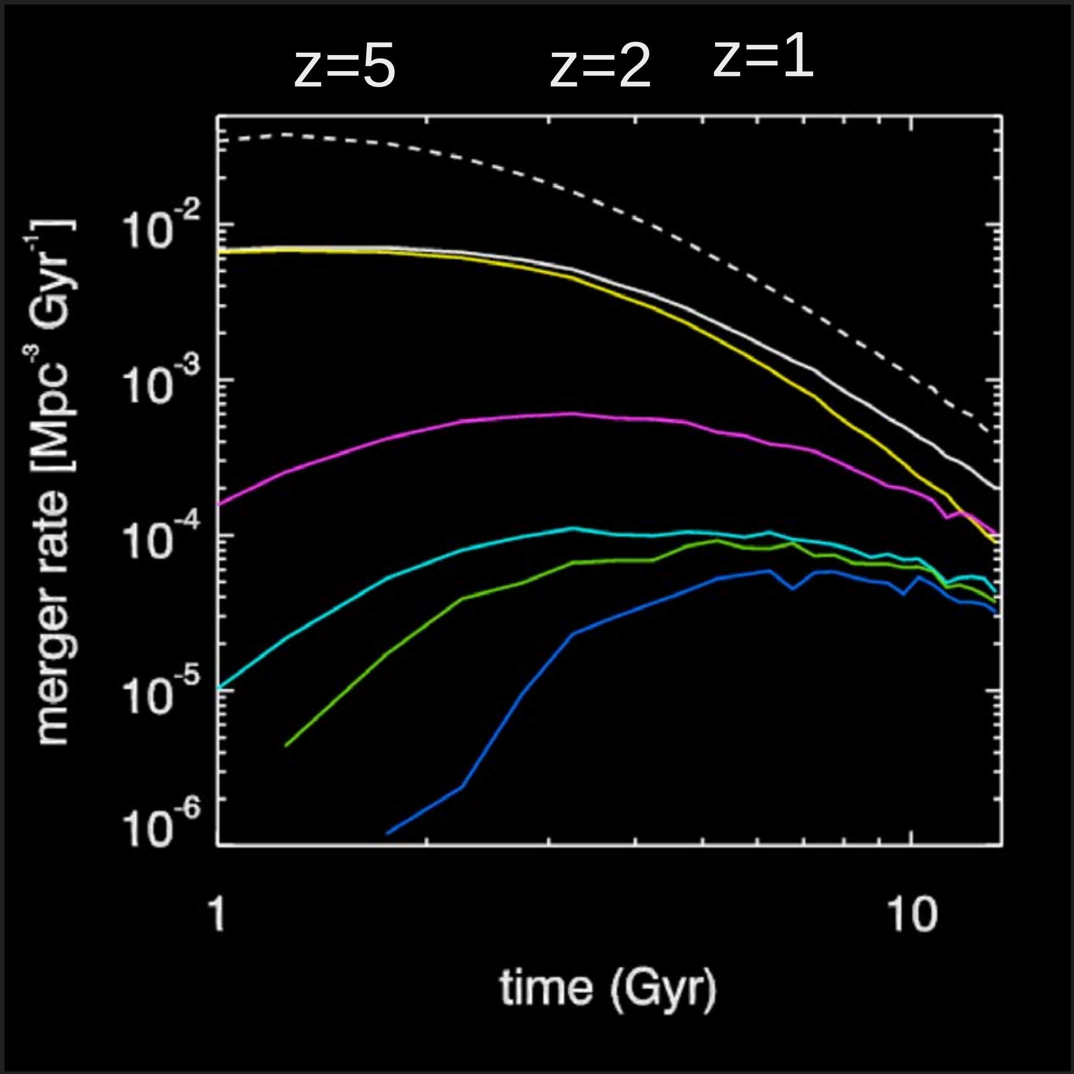
PREDICTED M_{BH}-M_{BULGE} RELATIONSHIP



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

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

MERGER RATES



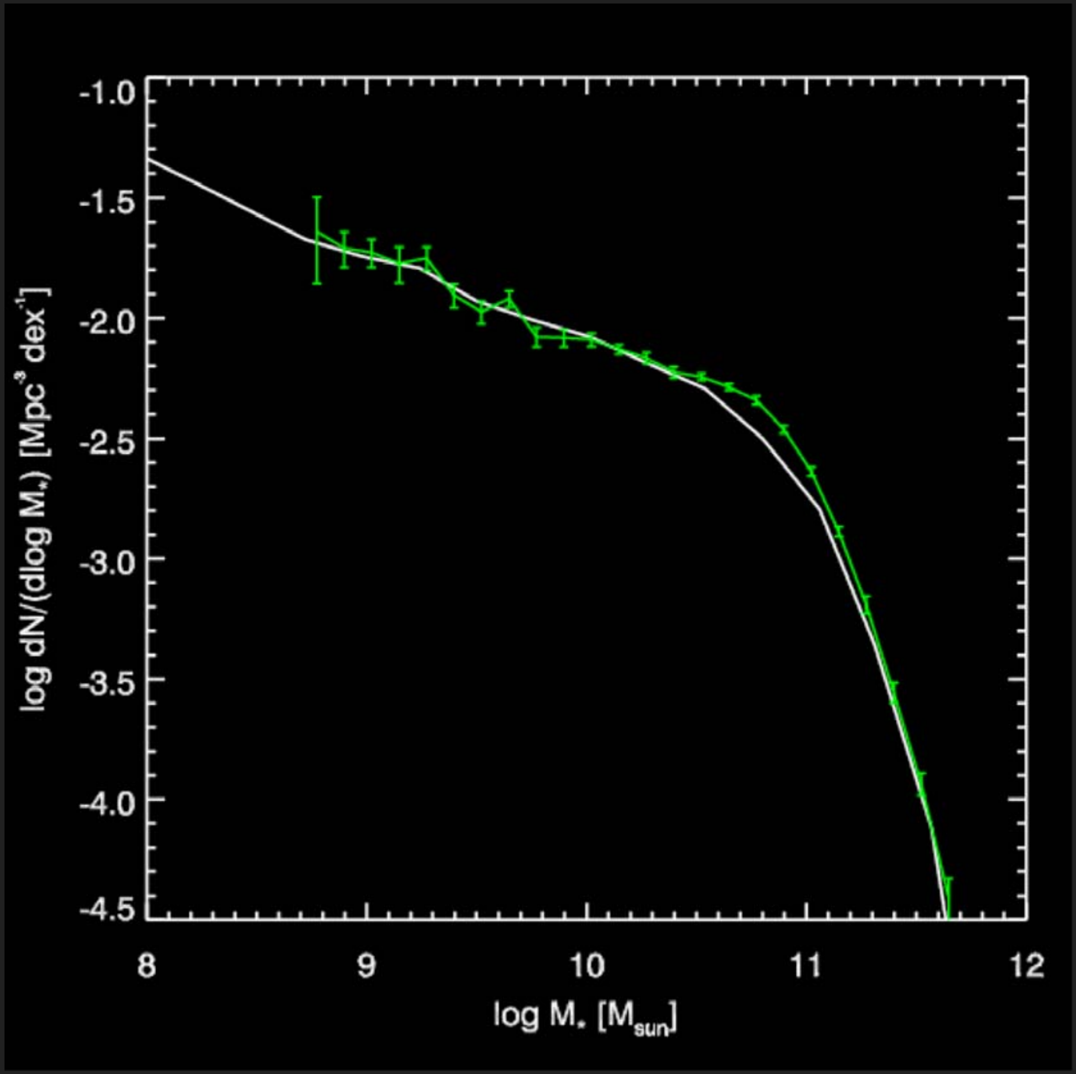
m_1/m_2 >0.1
m_1/m_2 > 0.25

S-S major mergers
S-E major mergers
E-E major mergers

major mergers with two BH $M_{bh}>10^6$ M_{sun}

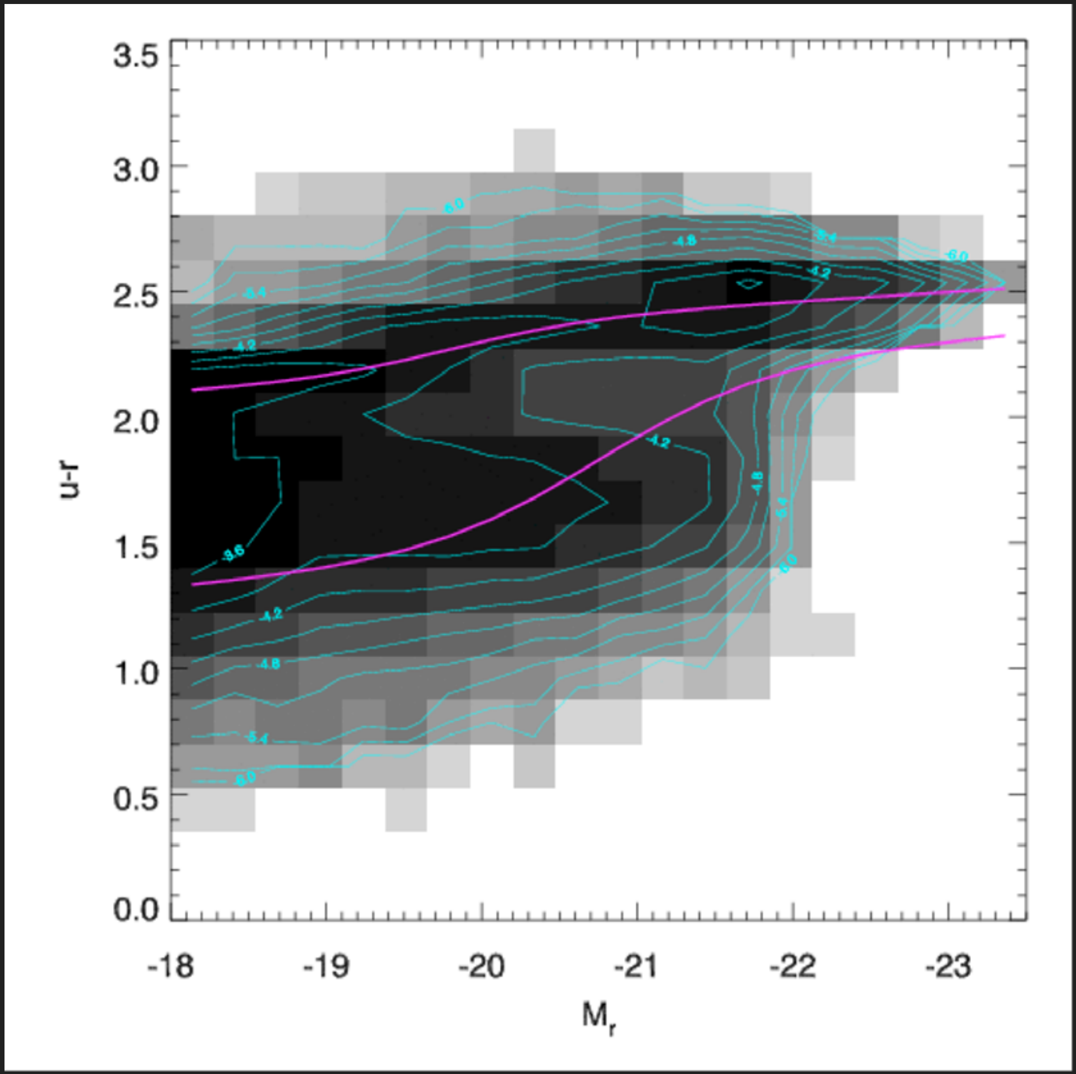
major mergers with $m_*>2.5\times10^{10}$ M_{sun}

STELLAR MASS FUNCTION



predicted color-magnitude relation z=0

u-r color



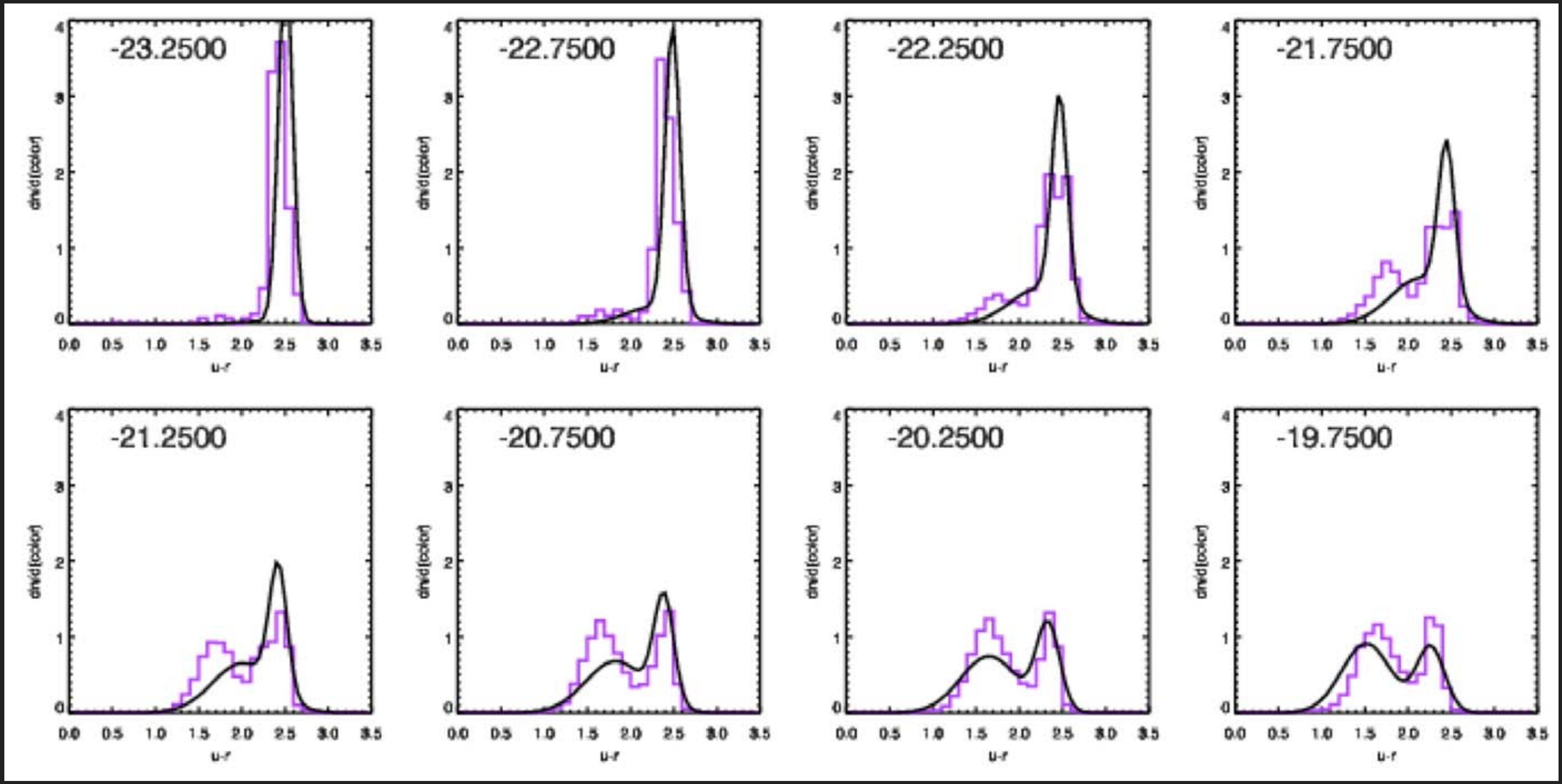
Baldry et al. red sequence and blue cloud

r-band magnitude

COLOR DISTRIBUTIONS

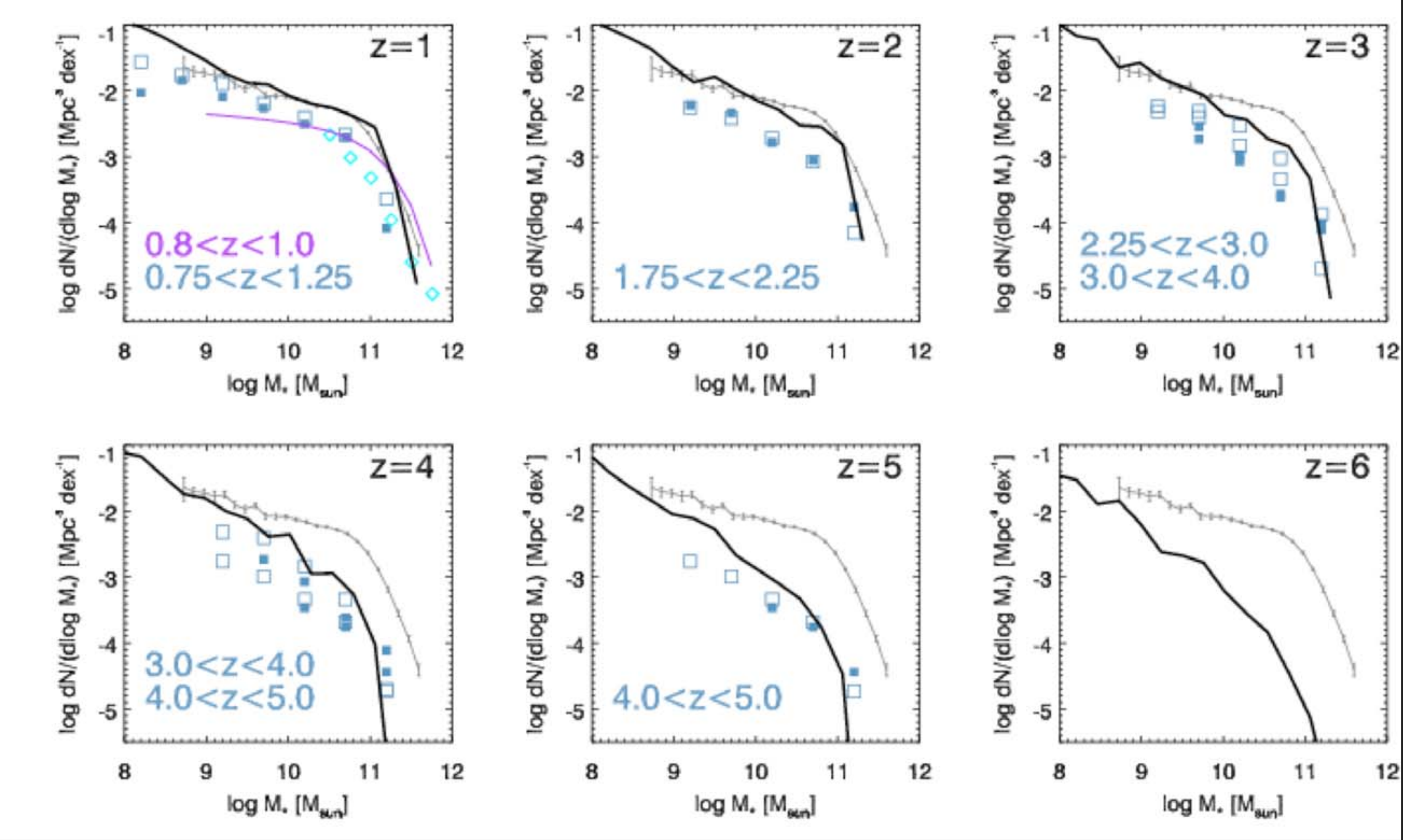
black=Baldry et al. SDSS;
purple=model

with AGN feedback



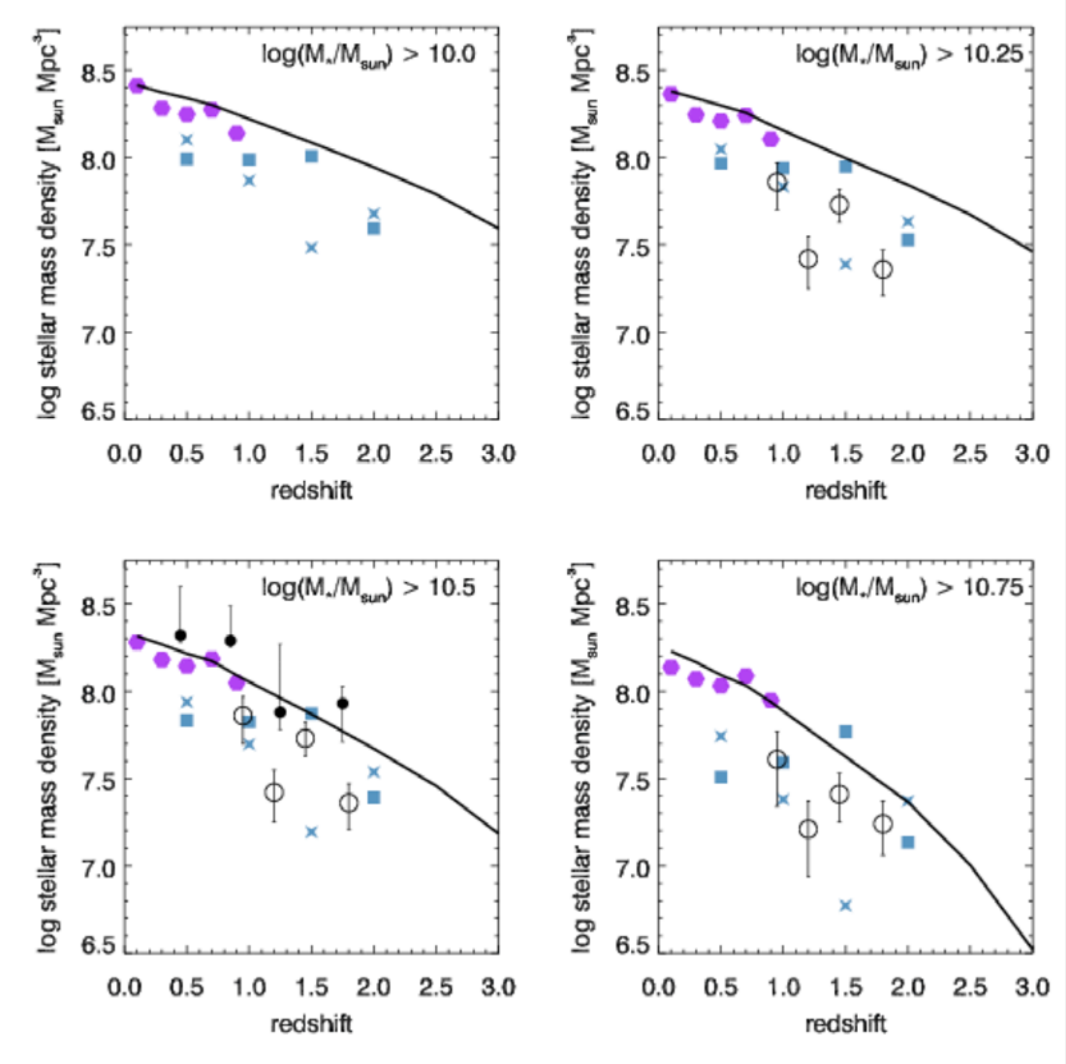
u-r

STELLAR MASS FUNCTION EVOLUTION



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

MASS-ASSEMBLY

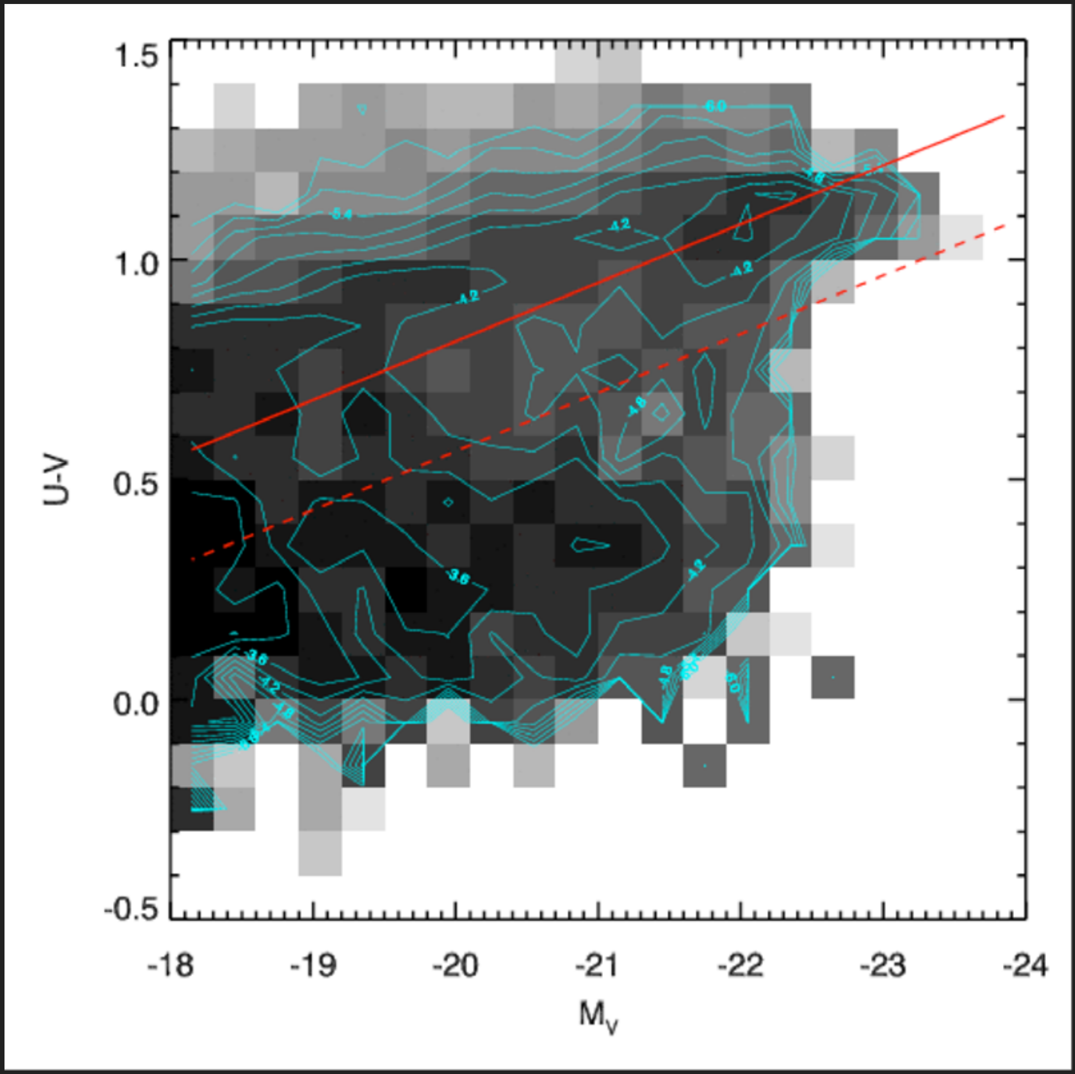


still produce (at least) enough massive galaxies at all redshifts where we have observations

data from
Borch et al. (COMBO-17)
Drory et al. (GOODS, FDF)
Glazebrook et al. (GDDS)
Fontana et al. (K20)

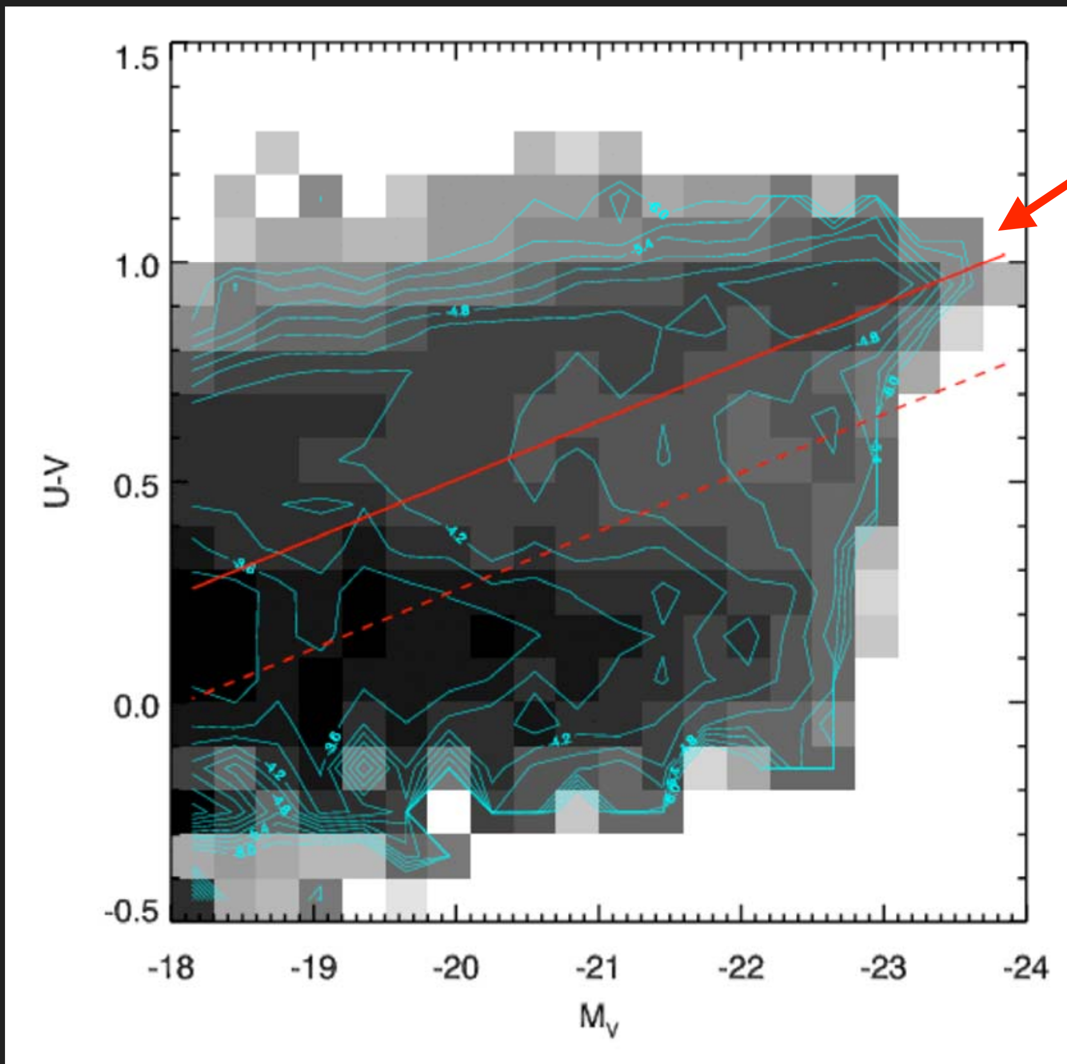
rss et al. in prep

z=1 rest-frame color-magnitude relation

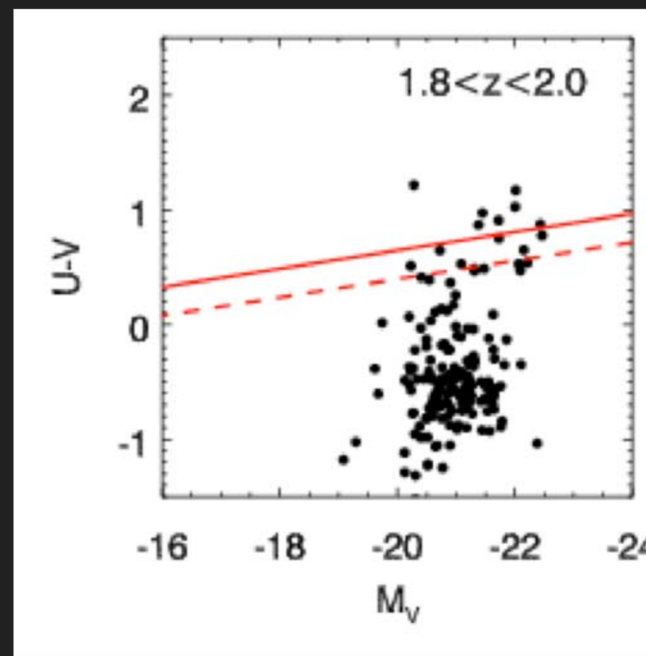


COMBO-17
red sequence
(Bell et al.)

z=2 rest-frame color-magnitude relation

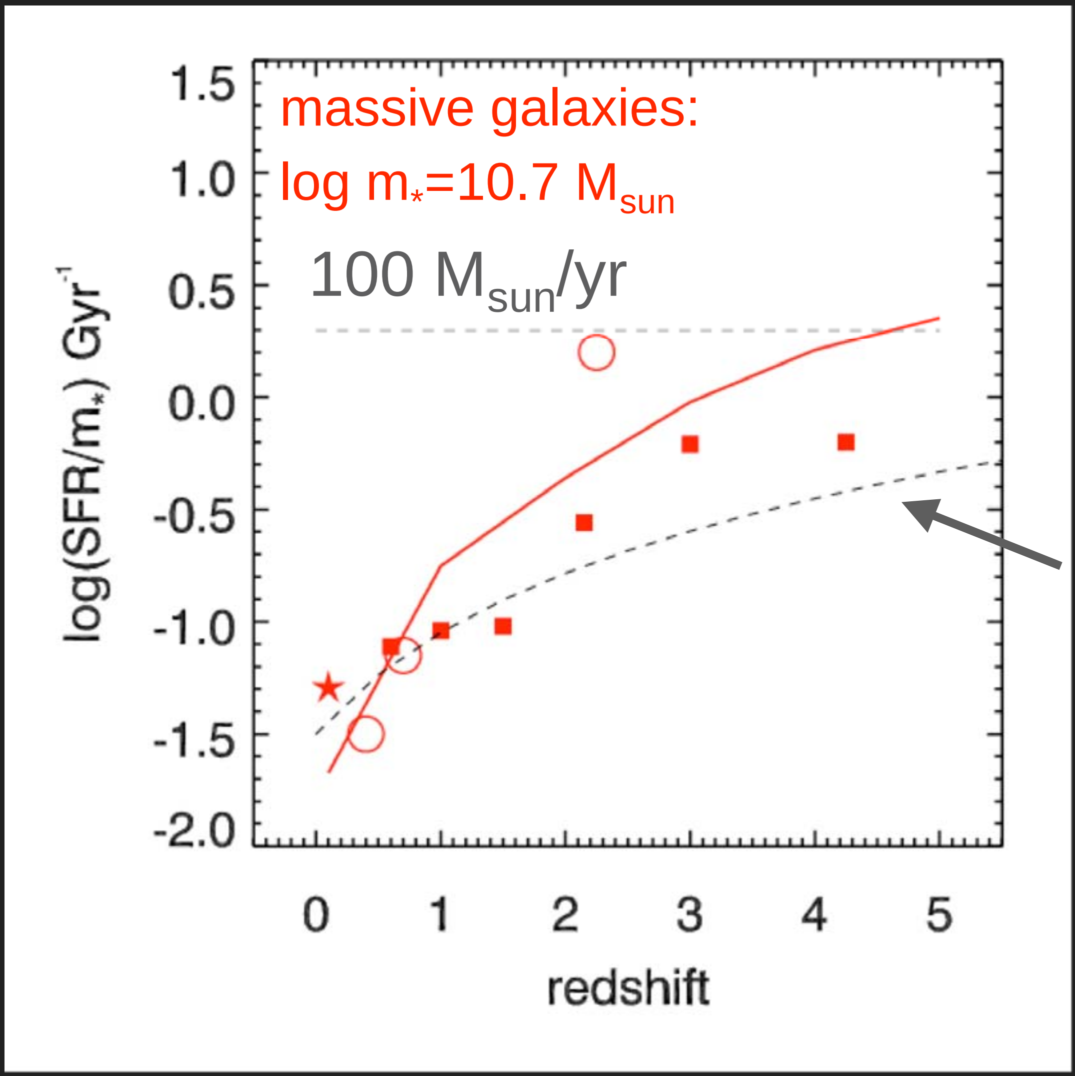


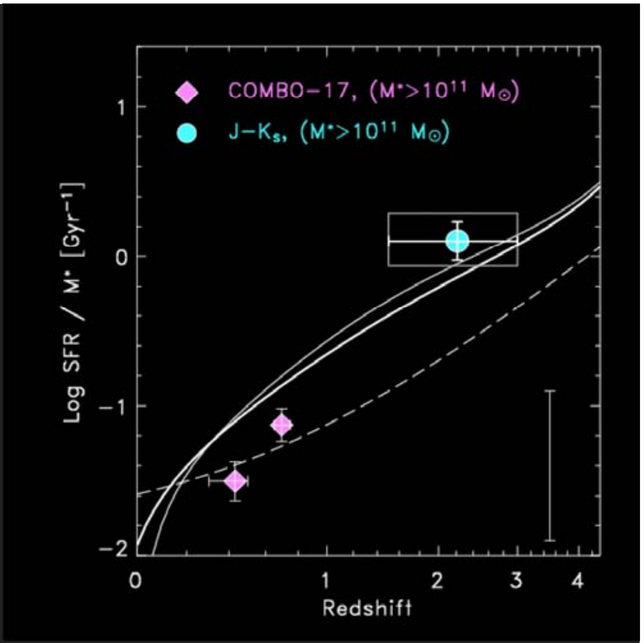
extrapolated COMBO-17
red sequence line



GOODS data

DOWNSIZING?

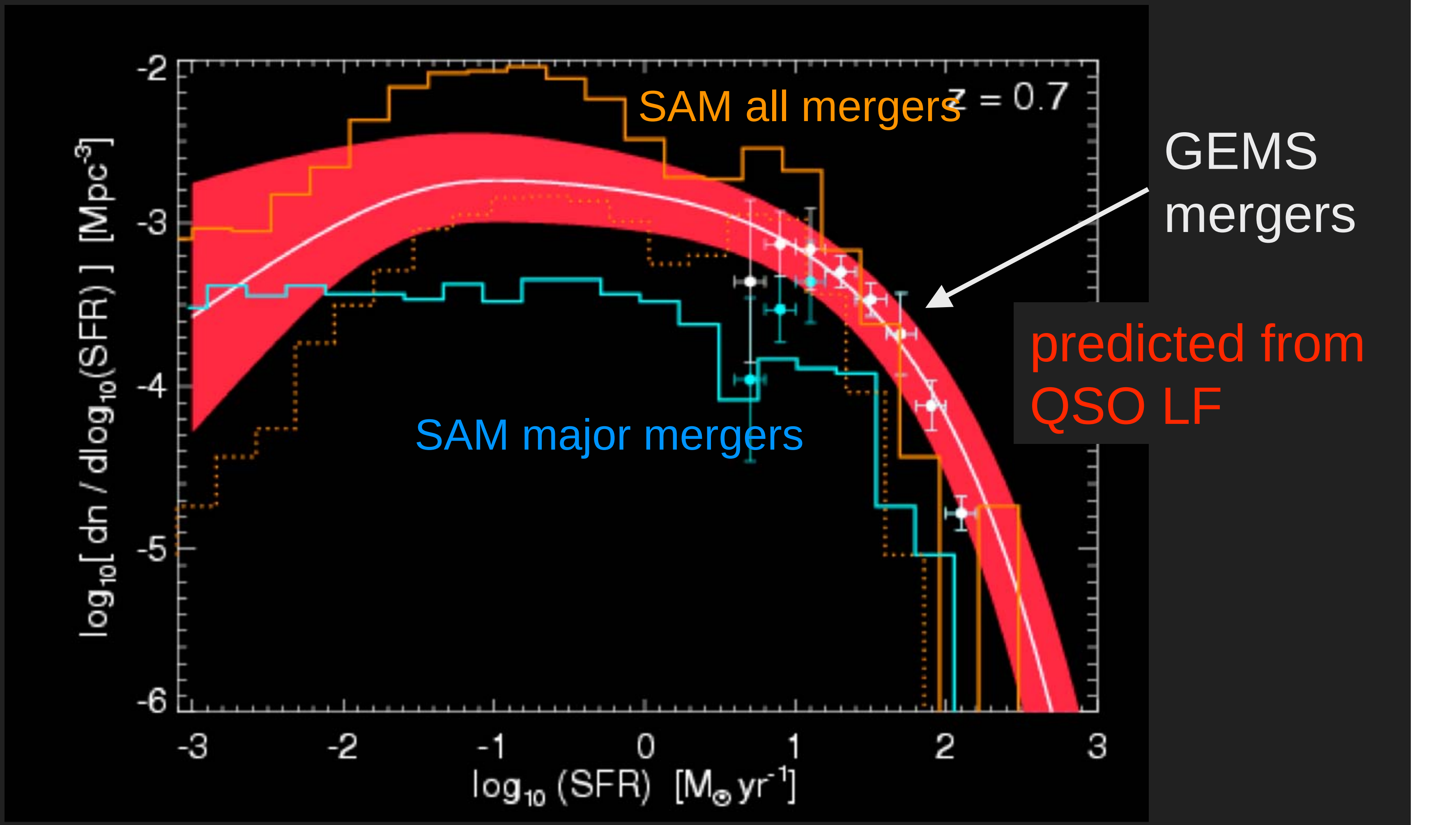




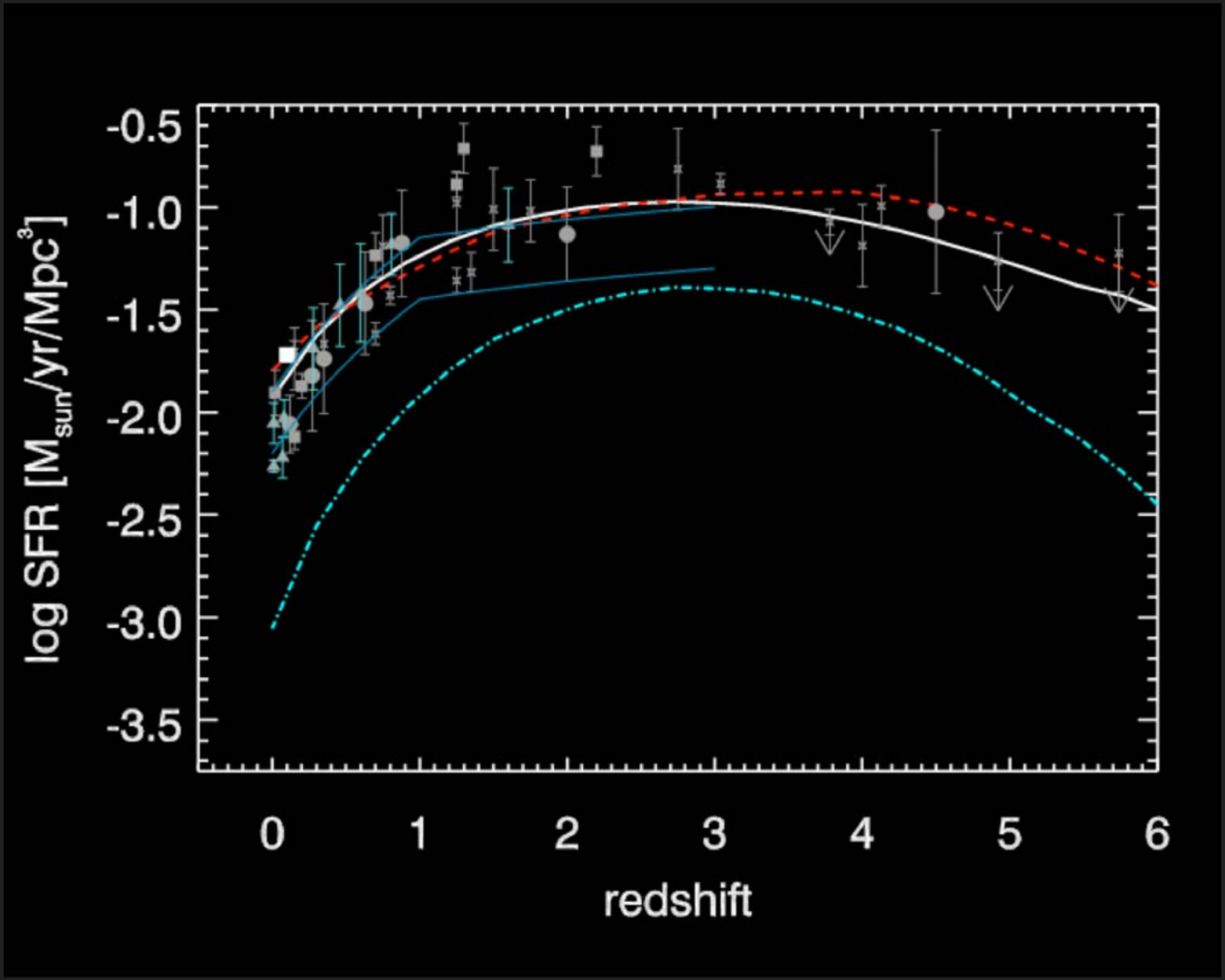
expected downsizing for Kennicutt + constant gas fraction

data from
Feulner et al.
Papovich et al.
Brinchmann et al. (z=0)

star formation rate function of mergers



SFR and BH accretion history in SAM



accretion rate x2000

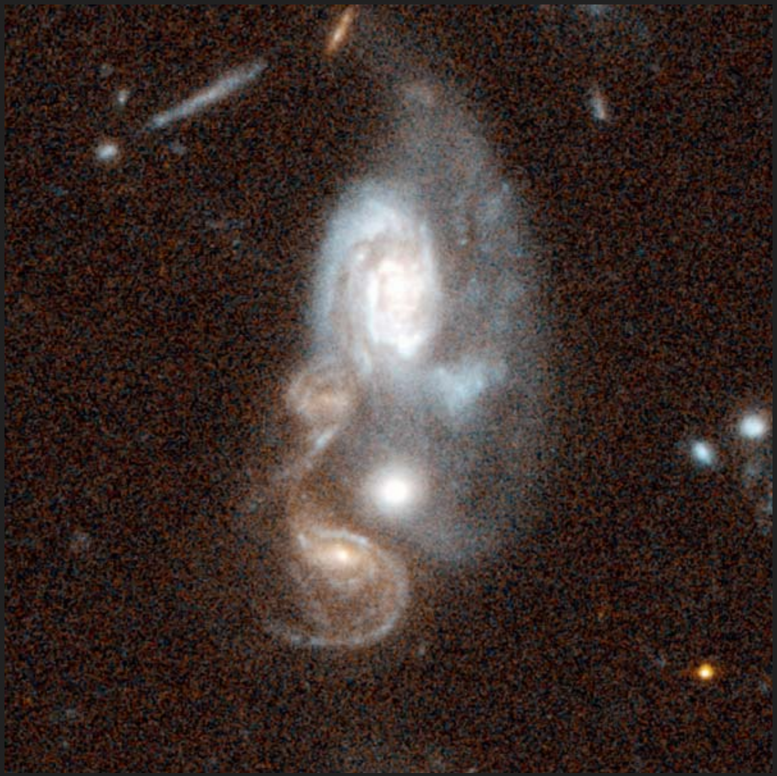
SF in major mergers

CONCLUSIONS

- decline in accretion activity onto the most massive BH and decline of SF activity in the most massive galaxies track each other in a manner consistent with ‘strict’ co-evolution
- decline in the global SFR since z~1 only about 1/3 due to declining merger rate
- only about 1/3 of the red-blue transition since z~1 due to mergers
- decline in QSO activity since z~1 consistent with observed decline in merger rate at all (observable) luminosities

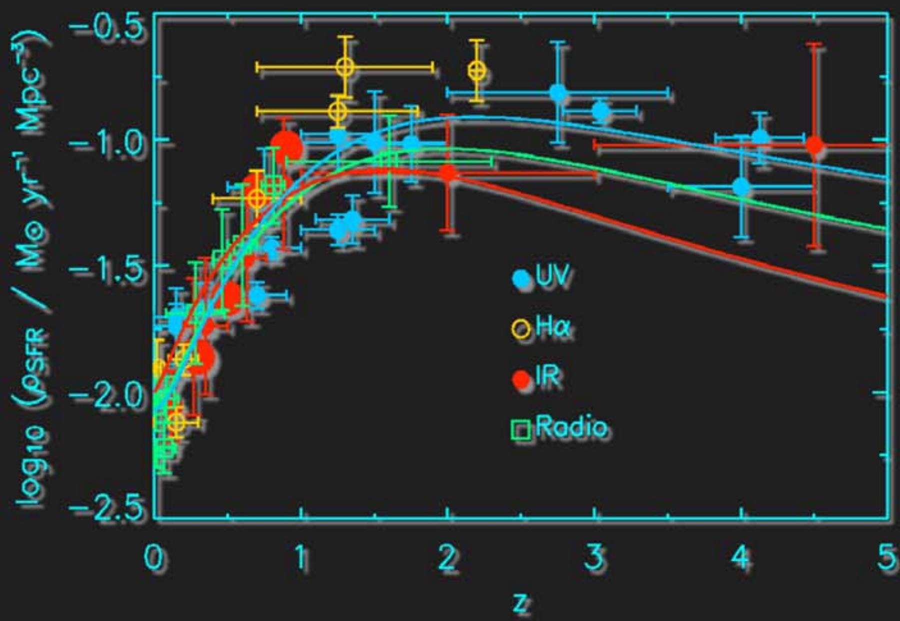
OPEN QUESTIONS

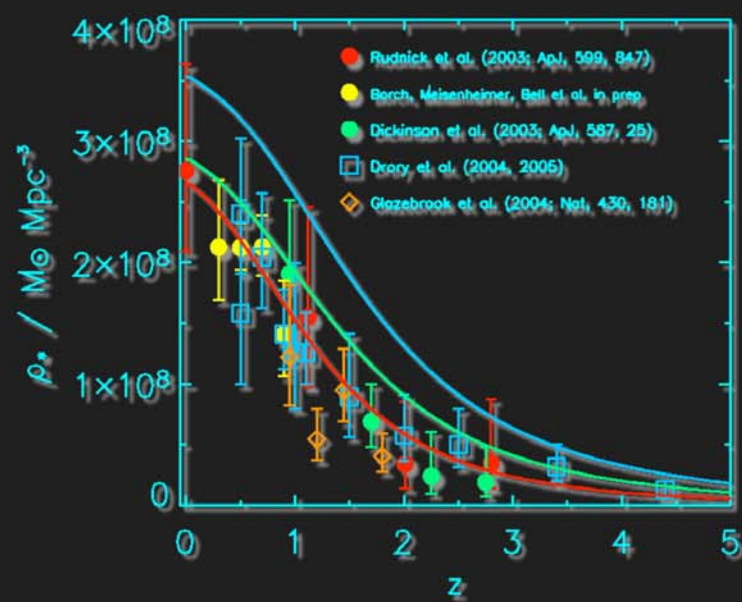
- we know that the sites of active star formation and BH accretion are not occurring in the same objects at (exactly) the same time
- why then do the *global* SFR and BH accretion rate, and even the mass-limited quantities, track each other so well?
- low-level accretion that tracks 'quiescent' star formation?
- both regulated by global gas supply?





SFR vs. SFH

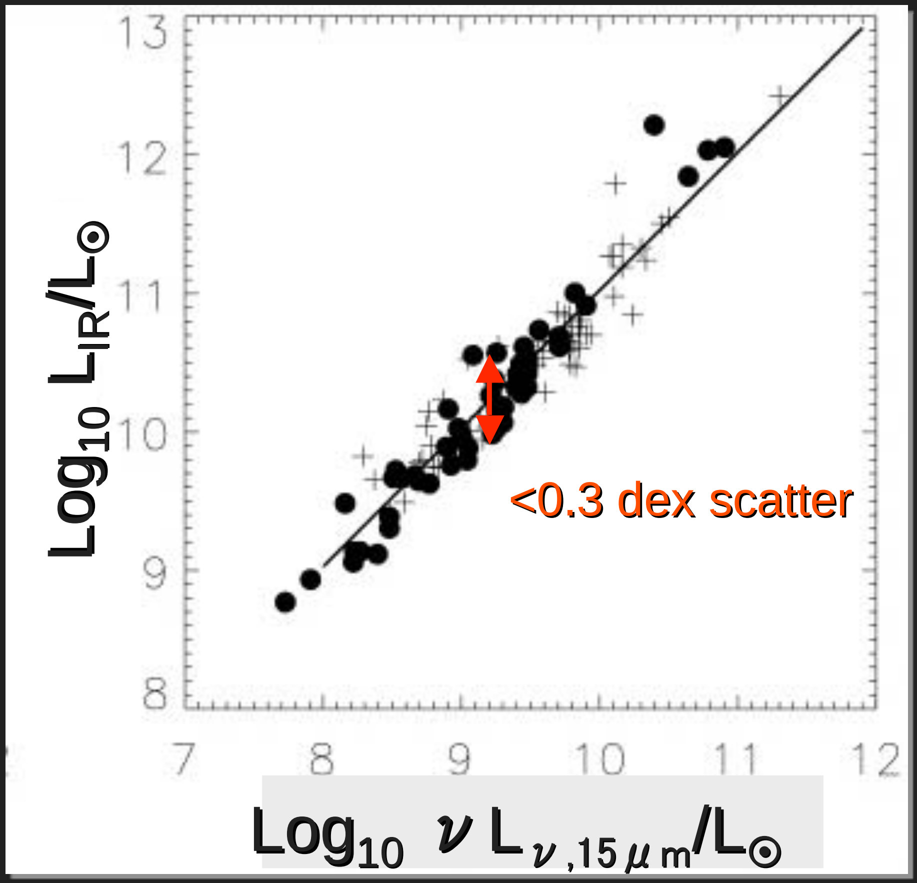




Borch et al. 2006

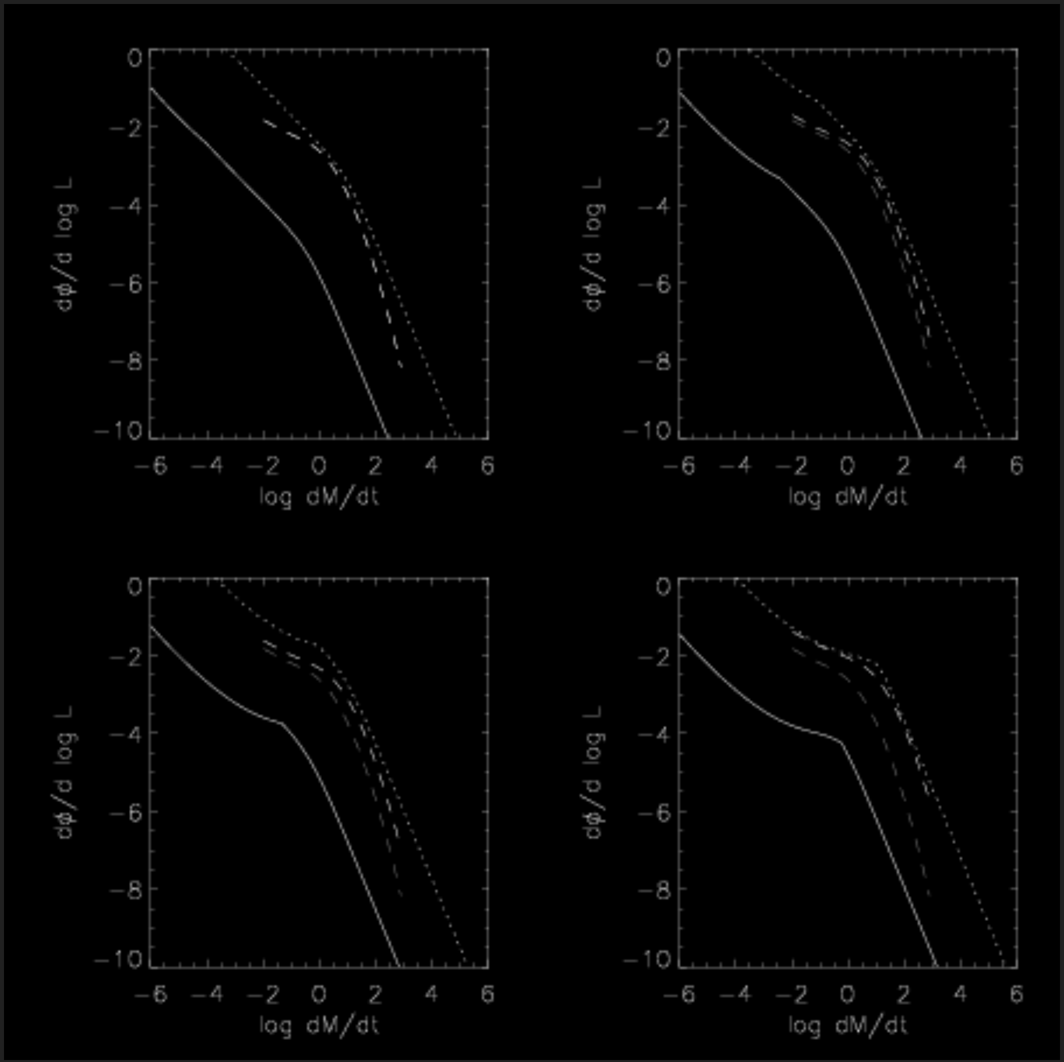
IR luminosity from 24μm flux

- Rest-frame 12-15μm correlates strongly with total IR luminosity in the local Universe, with < x2 scatter
- Will be able to test IR flux estimates with Spitzer 70,160μm, Apex 350μm and 870μm and Herschel PACS and SPIRE



Chary & Elbaz 2001; Papovich & Bell 2002;
See also Dale et al. 2005

CO-EVOLUTION OF DOWNSIZING



Zheng et al. in prep