Galaxy evolution: where, when, why? Clues from zCOSMOS

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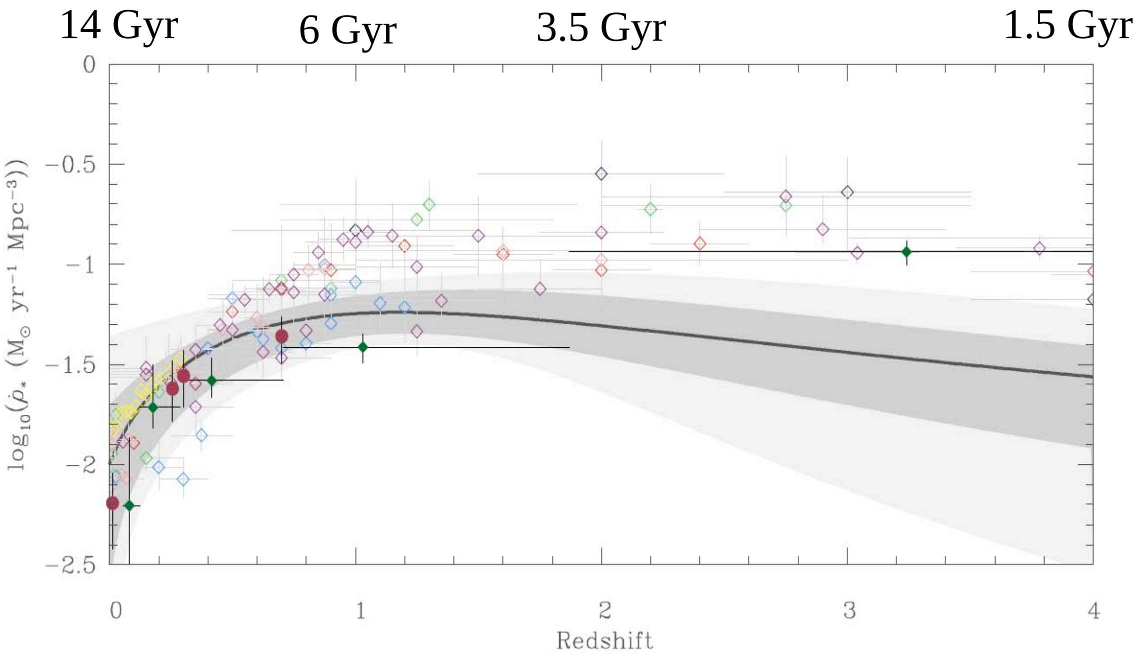
The context: evolution of star-formation in the Universe

Possible role(s) of the environment

COSMOS and zCOSMOS

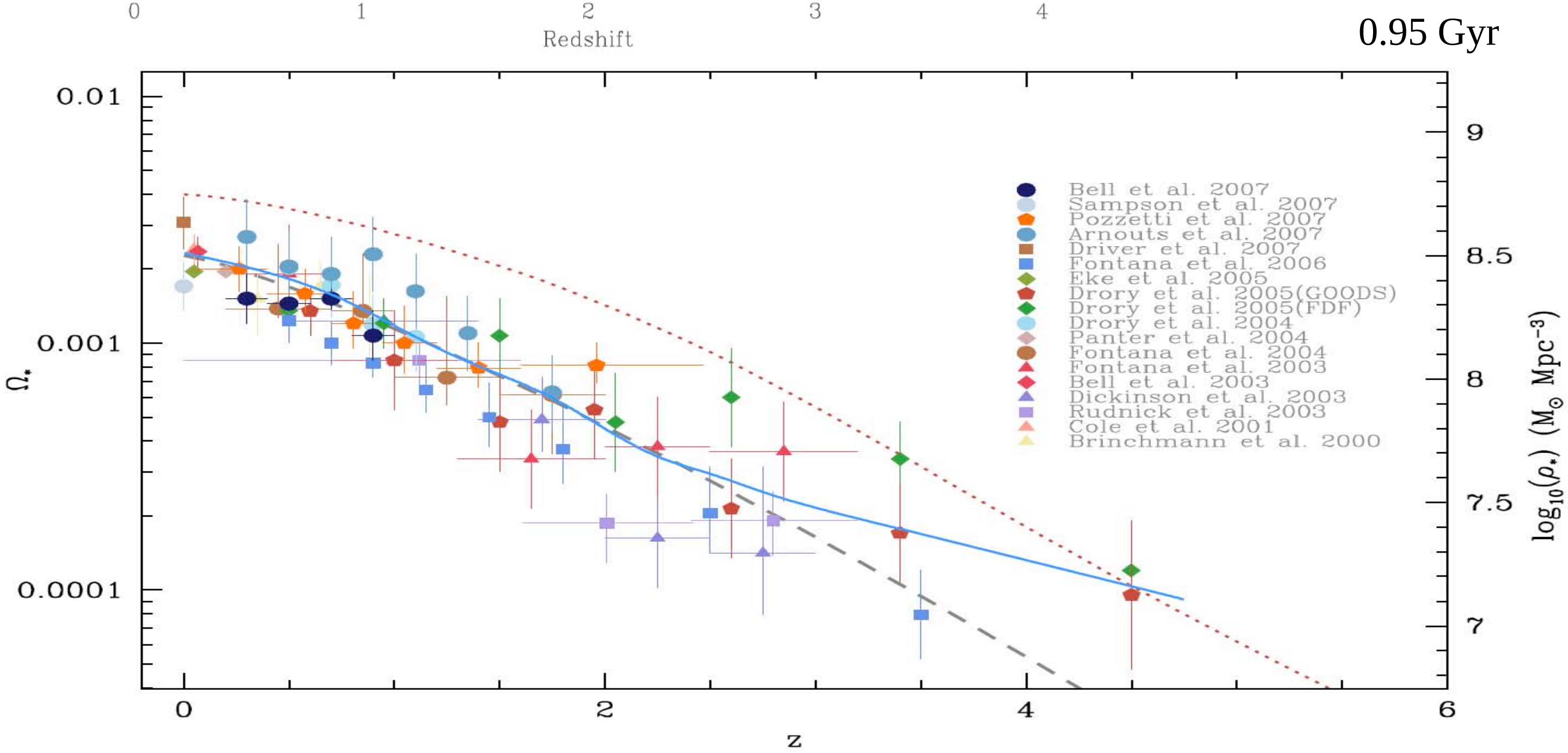
(a) $z < 1$ - disentangling Nature and Nurture

(b) $z \sim 2$ - new processes in galaxies

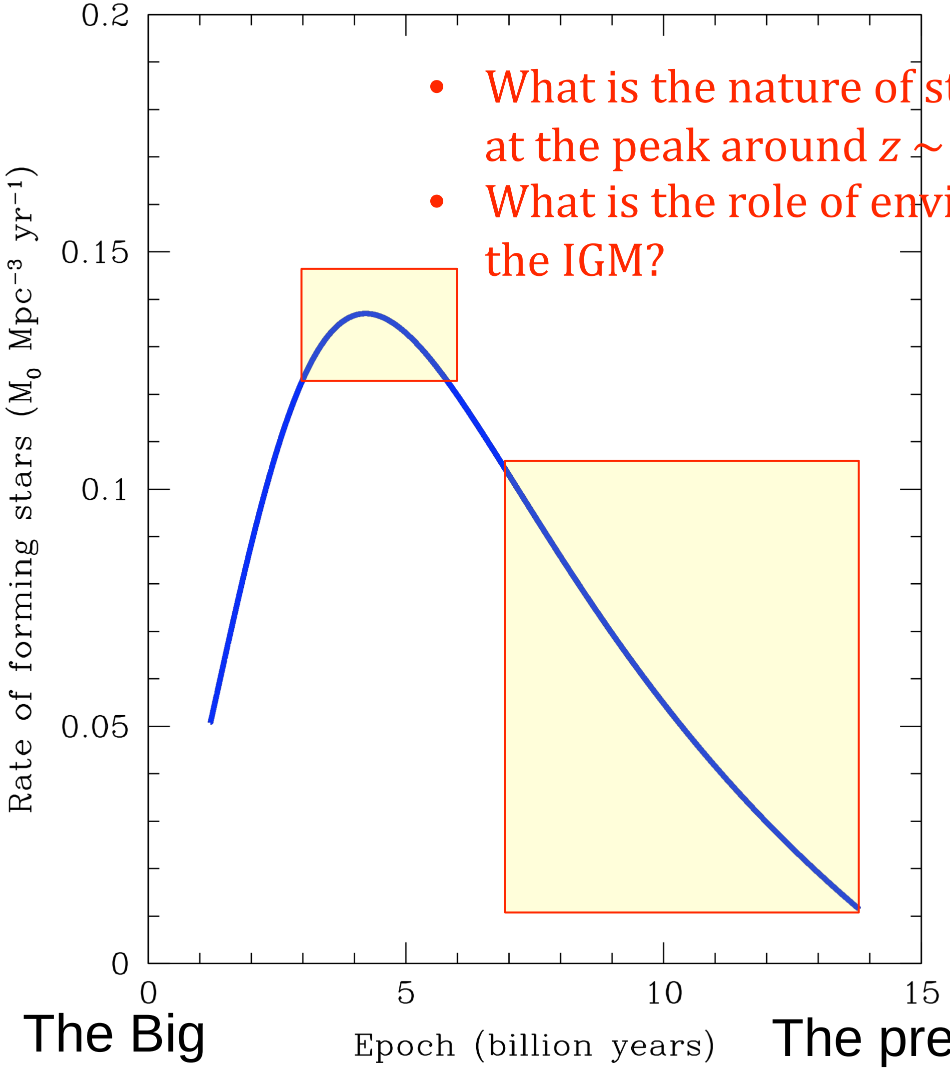


Overall consistency between global star-formation rate and stellar mass

e.g. Wilkins et al 2008



The history of star-formation in the Universe



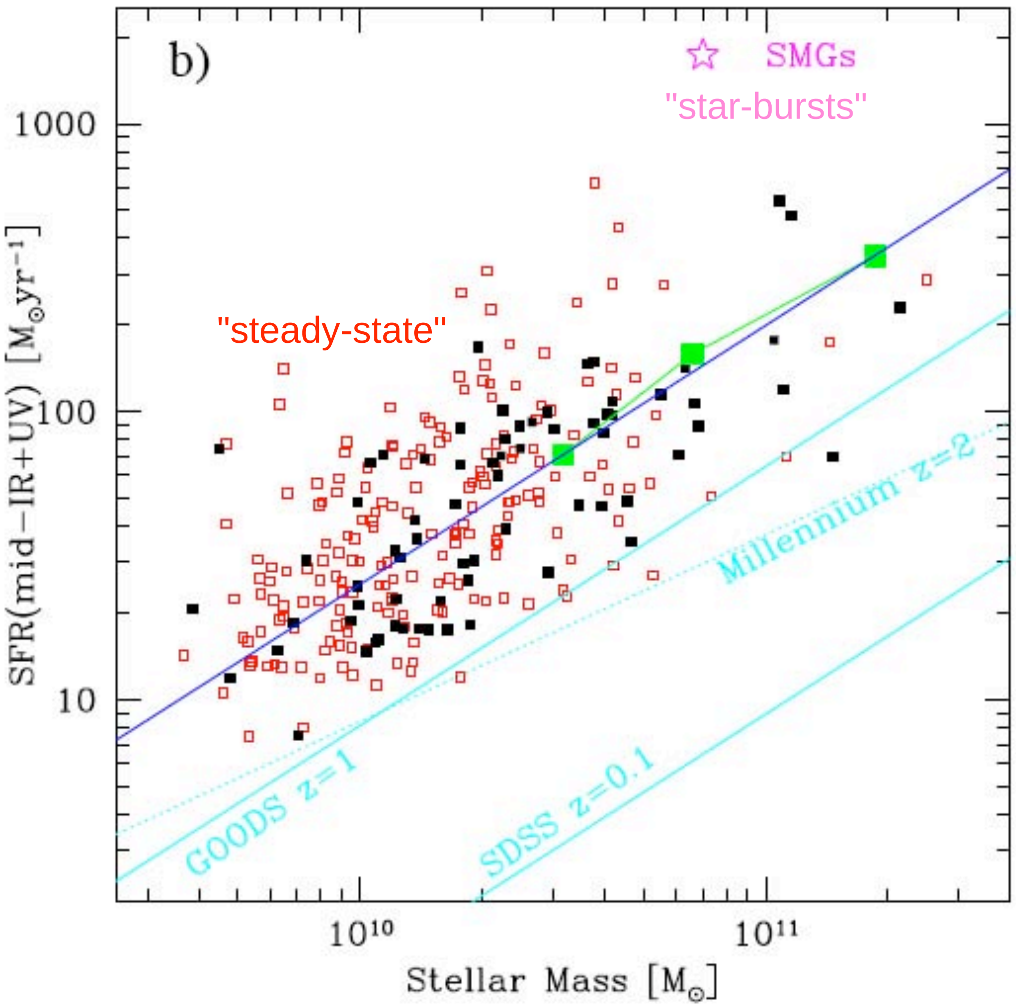
- What is the nature of star-formation at the peak around $z \sim 2$?
- What is the role of environment and the IGM?

The Big Bang

The present time

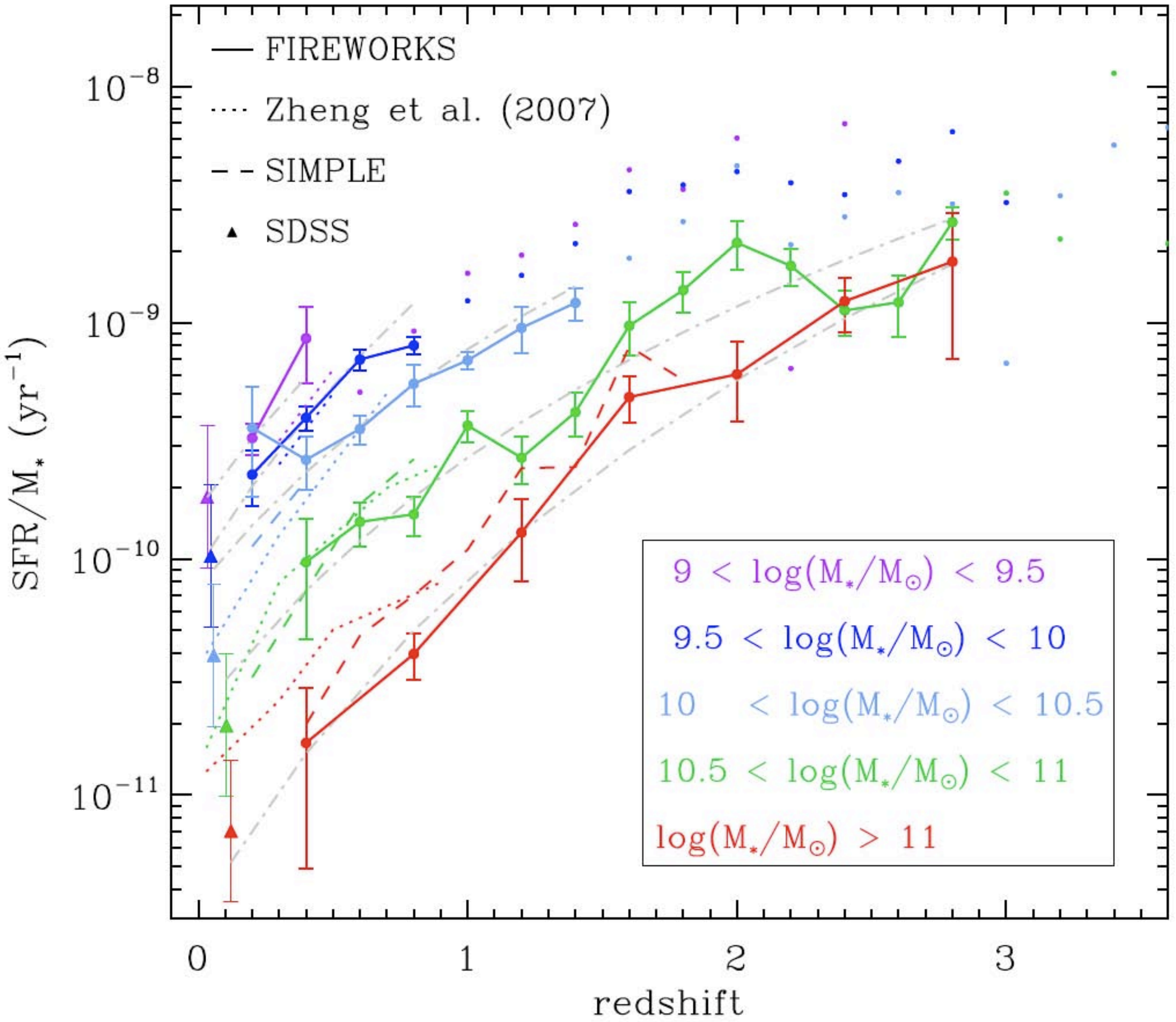
- What causes the decline in star-formation at late epochs $z < 1$
- What are the relative roles of mass and environment? ("Nature" vs. "Nurture")

$z \sim 2$



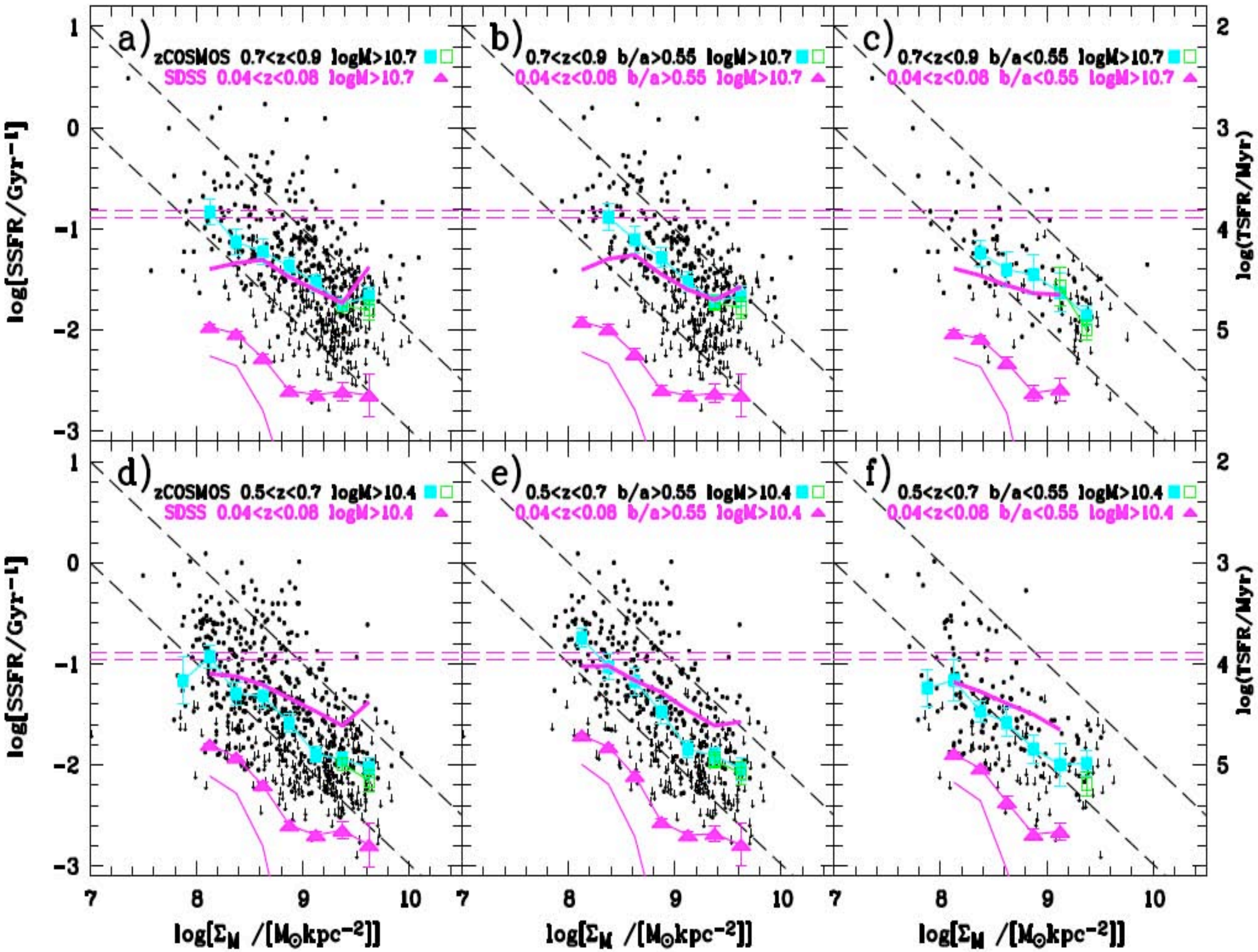
At all redshifts, star-formation rates are closely linked to existing stellar mass (sSFR) and change with epoch roughly uniformly across masses

Daddi et al, 2008, ApJ 670, 156
Elbaz et al 2007, A&A, 468, 33



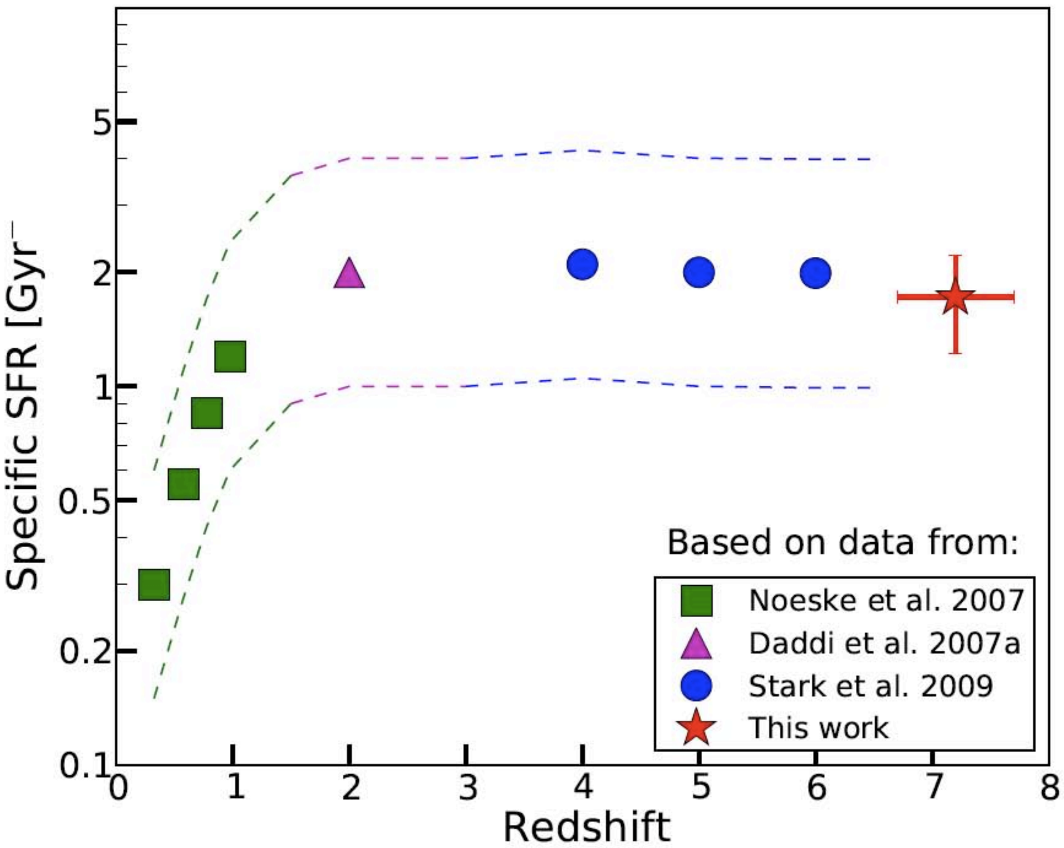
Damen et al, 2009, ApJ, 705, 617

Even internal relations of star-formation with e.g. stellar surface mass density seem to be just scaled up in star-formation



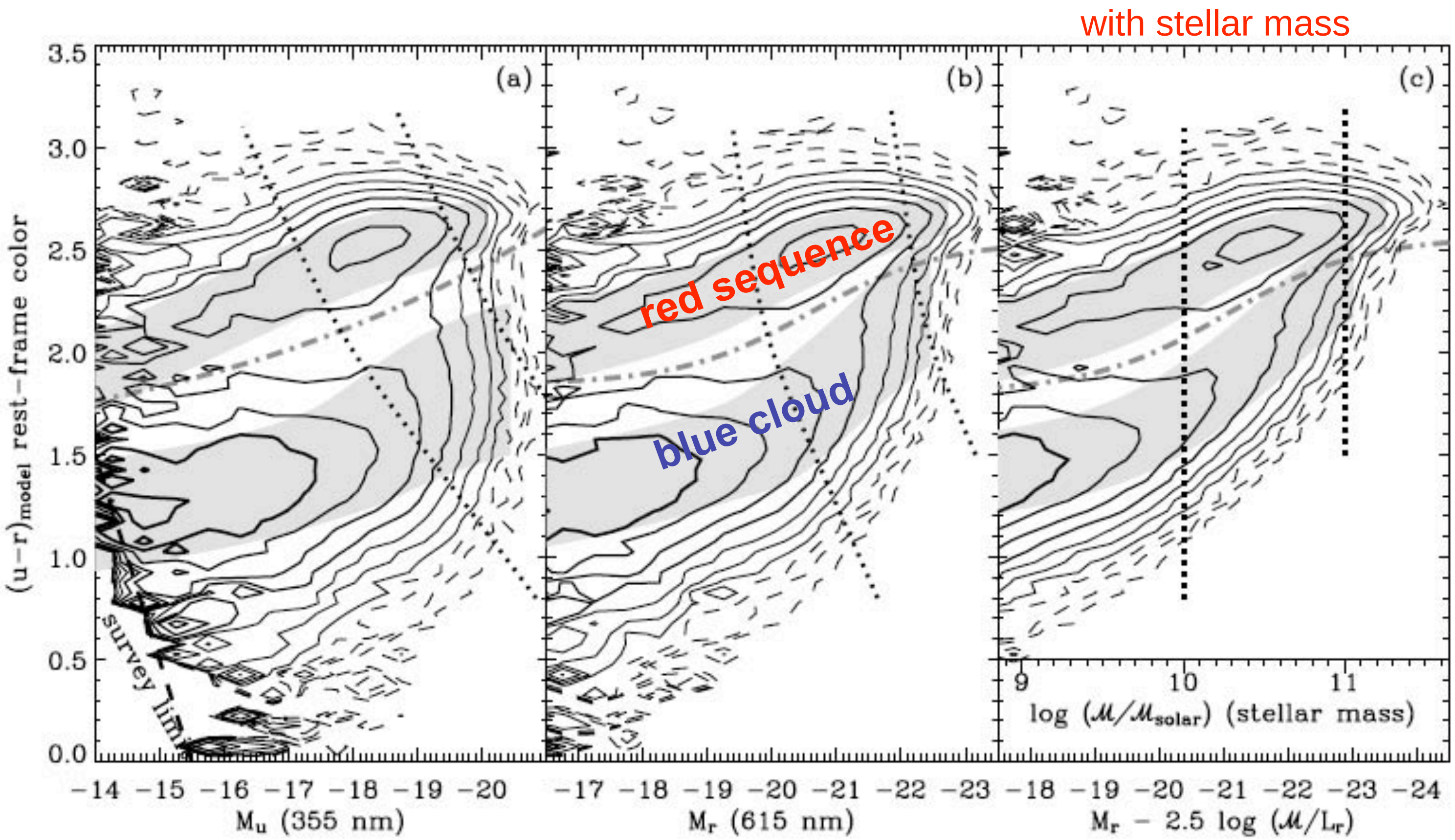
Maier et al (2009), ApJ 694, 1099

Evolution in sSFR at fixed mass ($5 \times 10^9 \, M_\odot$)



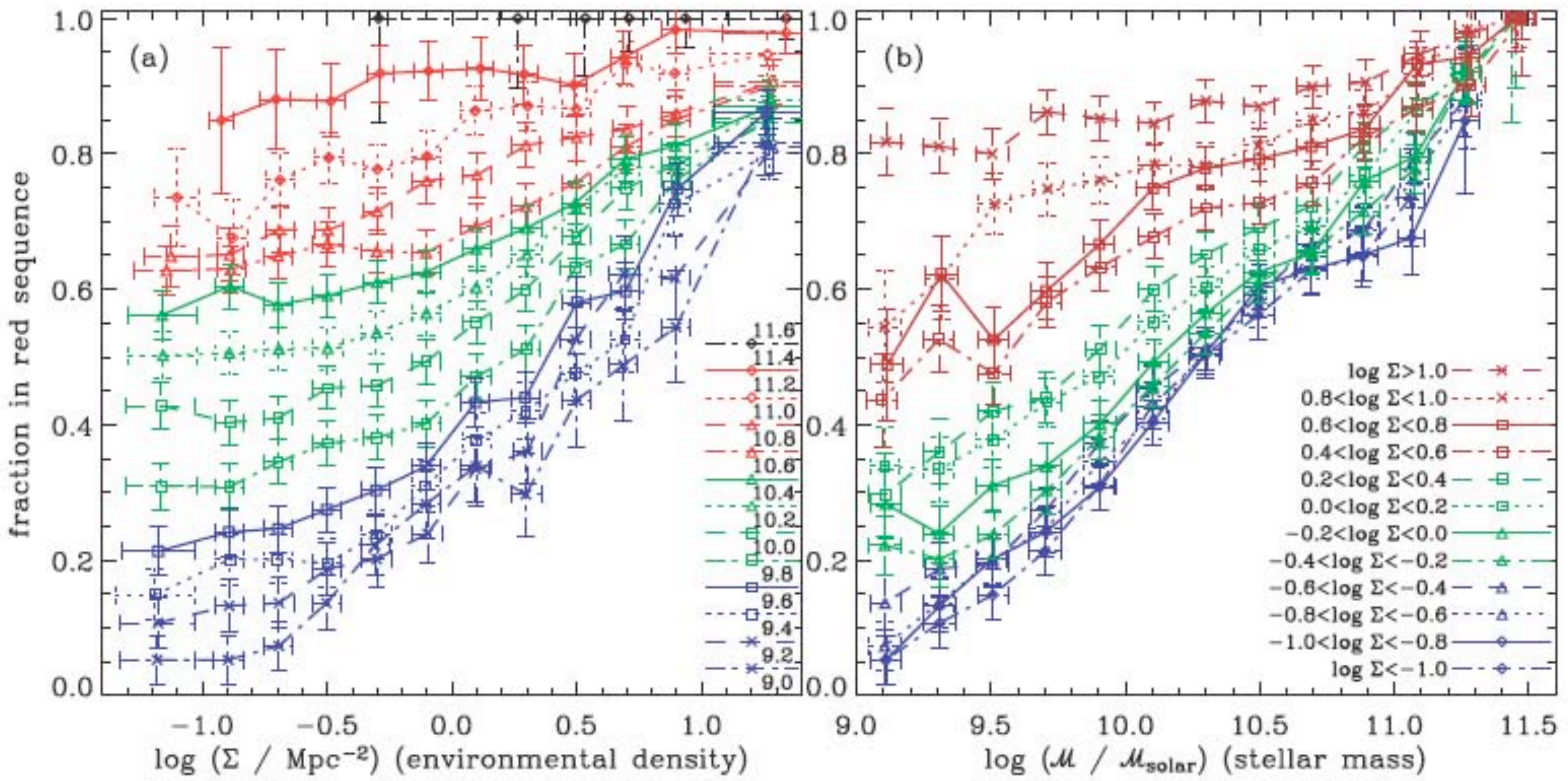
e.g. Gonzalez et al (2009)

Colour and mass in local SDSS



The red-sequence (passive galaxies) and the blue cloud (actively star-forming)

Colour, mass and environment in local SDSS



The relative roles of the environment ("Nurture" vs. e.g. mass ("Nature")

Note: Most stellar mass is in galaxies 10.5 < log (M/M_{sun}) < 11.0

Baldry et al 2006

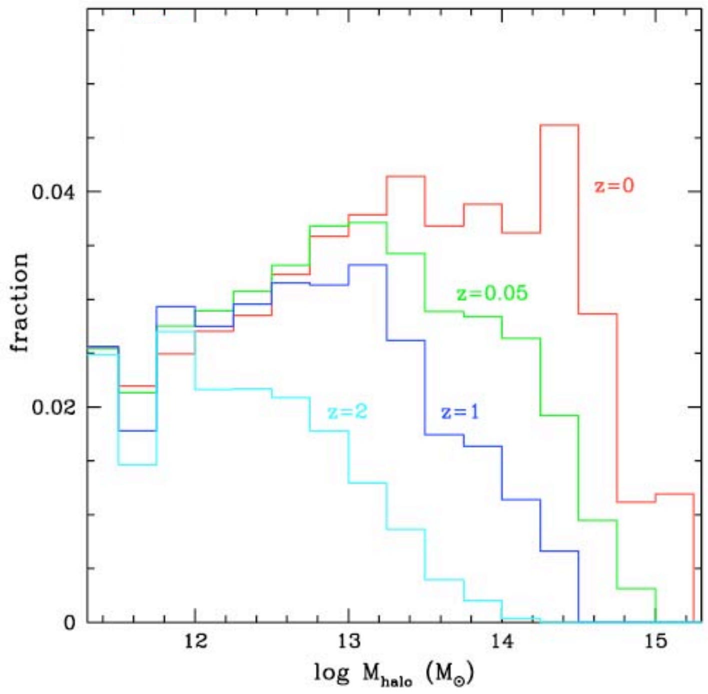
Ways for the environment to shape galaxy evolution

Collapse timescales (cosmological sequencing)

Dependence of various Dark Matter halo properties on environment

Baryonic processes acting via the environment

- Heating and cooling of gas (including Cold Flows)
- Ram-pressure stripping in the high pressure IGM
- Tidal disruption
- Harassment (high speed interactions)
- Mergers of galaxies
- Internal dynamical evolution triggered by interactions



Many of these will operate on the scale of galaxy groups, $13.5 < \log(M/M_\odot) < 14.5$, where most galaxies reside and where there is rapid evolution since $z \sim 2$

Lots of questions

- What causes the roughly constant sSFR in star-forming galaxies of wide range of masses at z > 2 (with quasi-exponential growth in mass), then the sharp decline at lower redshifts?
- How is mass built up in massive galaxies (in situ star formation, or mergers)?
- What causes most of the most massive galaxies to become passive?

  – supply of gas, termination of cold flows ?

  – mergers ?

  – AGN or other feedback processes ?

  – other environmental effects ?

COSMOS

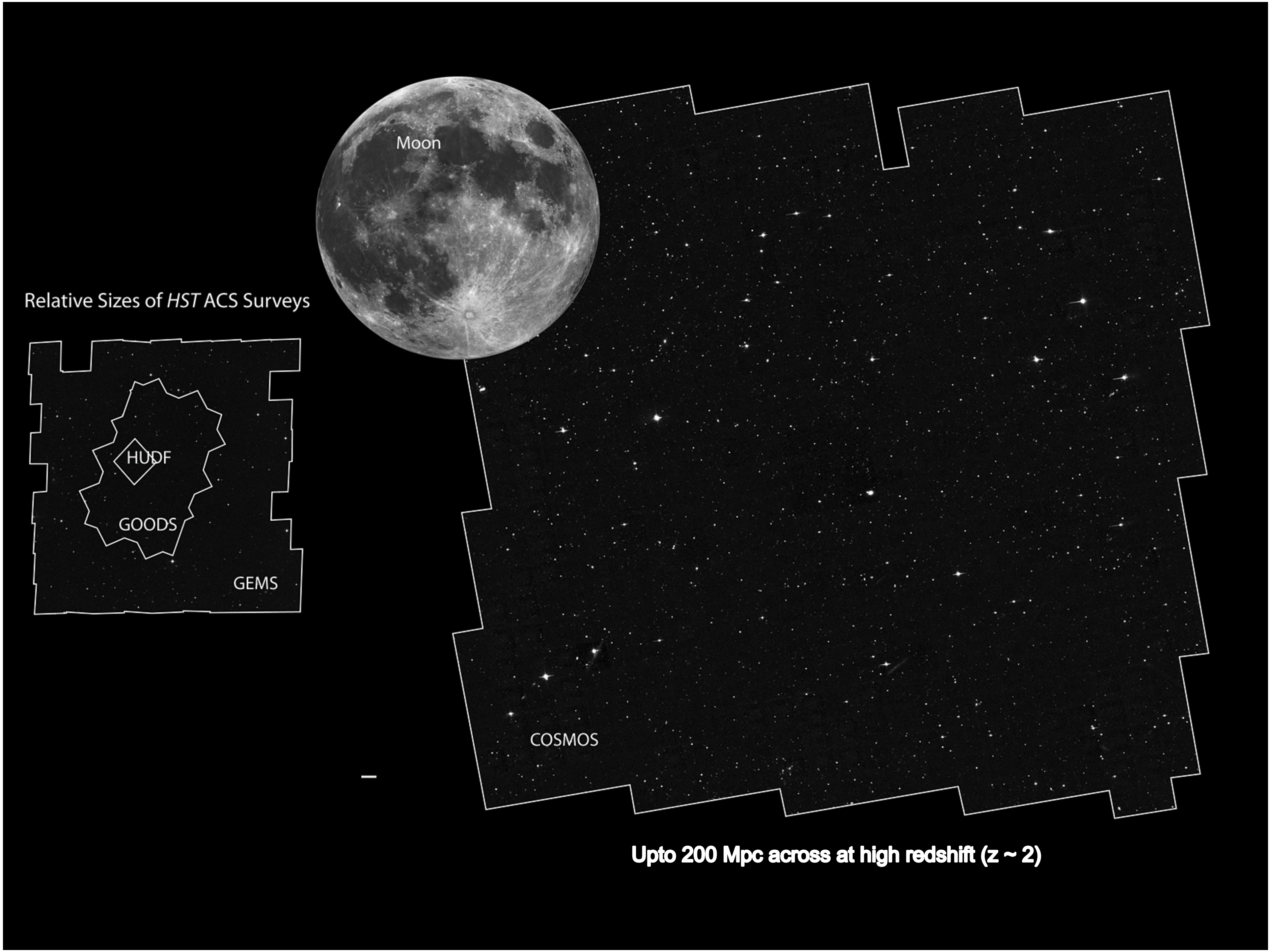
Global co-operative to study a single equatorial 2 deg^2 field (PI Scoville)

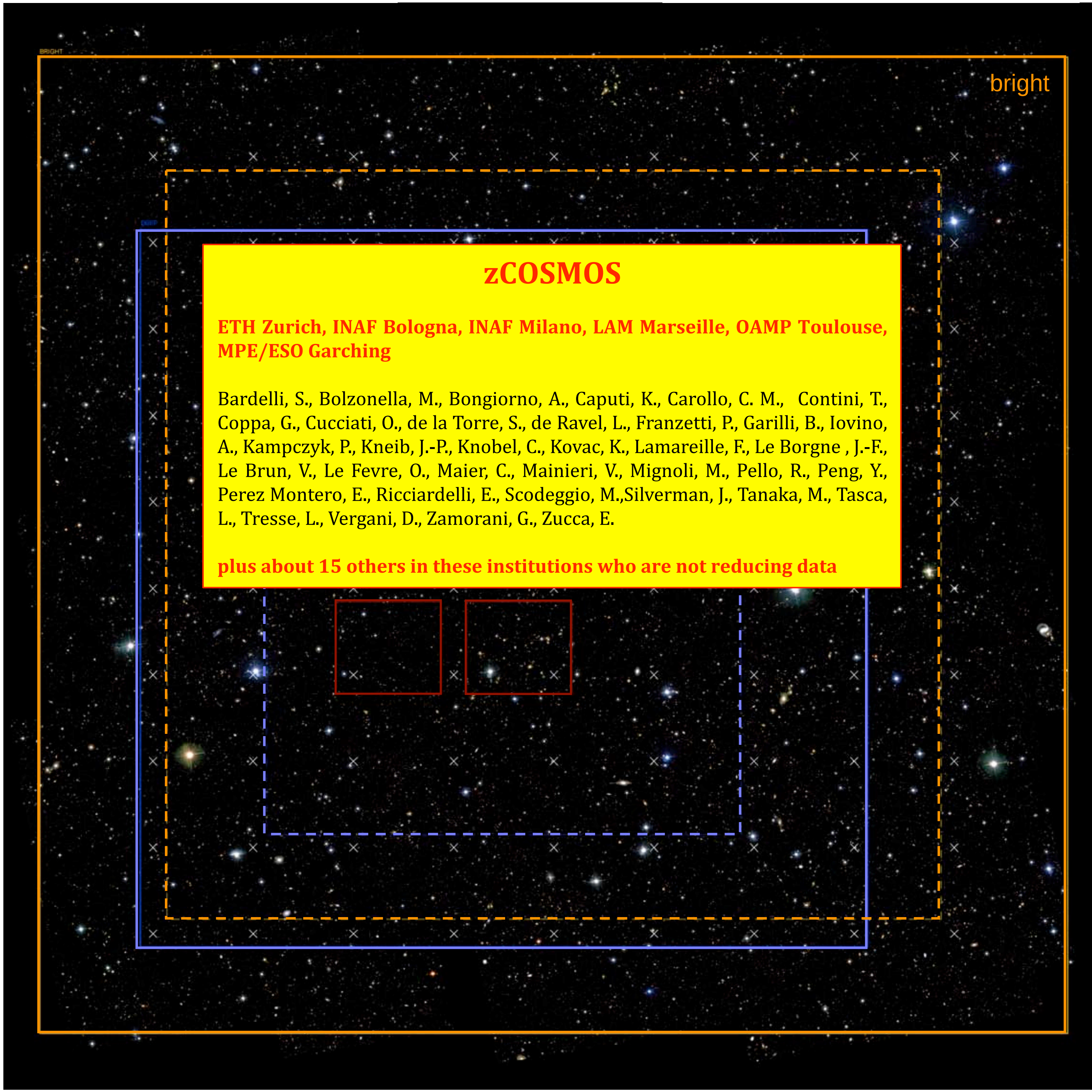
500,000 galaxies ($I_{AB} < 26$) in 10^8 Mpc^3 to z = 4

X-ray	XMM Newton and Chandra
UV	Galex
Optical	HST (814)
	Subaru multi-bands
	CFHT (U)
Near-IR	CFHT, UKIRT, NOAO
IR	Spitzer IRAC and MIPS
	Herschel GTO
Submm	Mambo+
Radio	VLA
Future:	eVLA, ALMA, Scuba-2, HST/WFC3

Note: Almost all data publicly available at IPAC

http://irsa.ipac.caltech.edu/data/COSMOS/


Relative Sizes of *HST* ACS Surveys
Moon
HUDF
GOODS
GEMS
COSMOS
Upto 200 Mpc across at high redshift (z ~ 2)



zCOSMOS

ETH Zurich, INAF Bologna, INAF Milano, LAM Marseille, OAMP Toulouse, MPE/ESO Garching

Bardelli, S., Bolzonella, M., Bongiorno, A., Caputi, K., Carollo, C. M., Contini, T., Coppa, G., Cucciati, O., de la Torre, S., de Ravel, L., Franzetti, P., Garilli, B., Iovino, A., Kampczyk, P., Kneib, J.-P., Knobel, C., Kovac, K., Lamareille, F., Le Borgne , J.-F., Le Brun, V., Le Fevre, O., Maier, C., Mainieri, V., Mignoli, M., Pello, R., Peng, Y., Perez Montero, E., Ricciardelli, E., Scodeggio, M.,Silverman, J., Tanaka, M., Tasca, L., Tresse, L., Vergani, D., Zamorani, G., Zucca, E.

plus about 15 others in these institutions who are not reducing data

zCOSMOS-bright

- $I_{AB} < 22.5$ (1 hr)
- $0.1 < z < 1.4$
- 70% sampling
- ~100 kms^{-1} accuracy
- about 18,000 redshifts

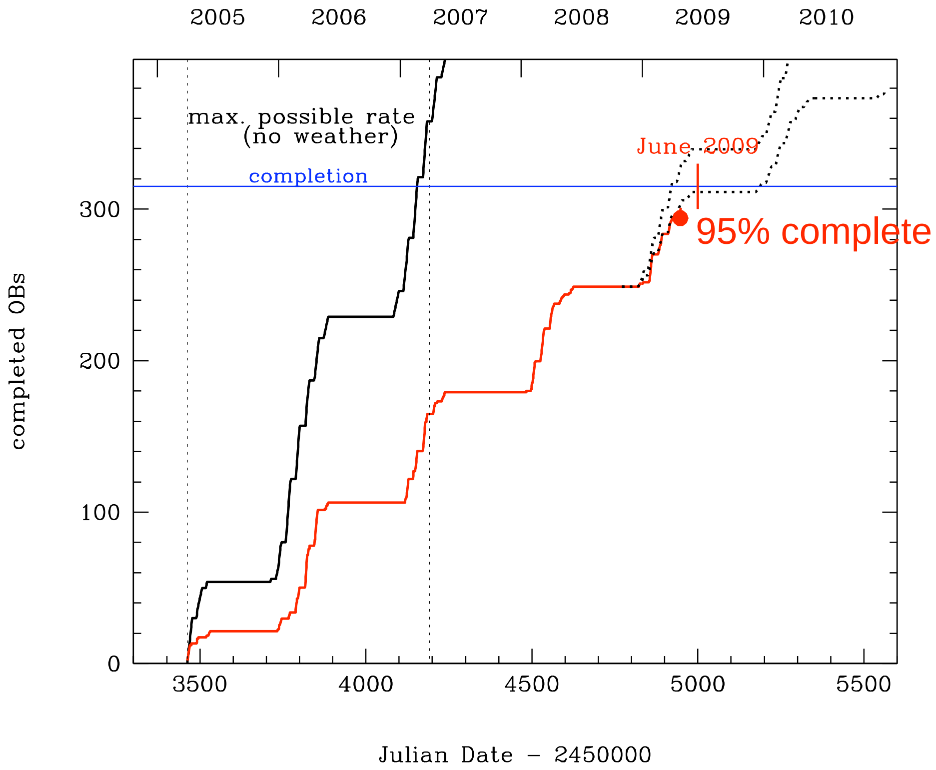
zCOSMOS-deep

- $B_{AB} < 25.25$ colour-selected (4.5 hr)
- $1.5 < z < 3$
- 70% sampling
- ~300 kms^{-1} accuracy
- about 4000 redshifts

Together: 600 hours of observation on VLT UT3

Particularly aimed at characterizing the <u>environment</u>

We've almost finished the observations after five years !



At least 10 FTE-years of data reduction and redshift identification

Bright (270 hrs)

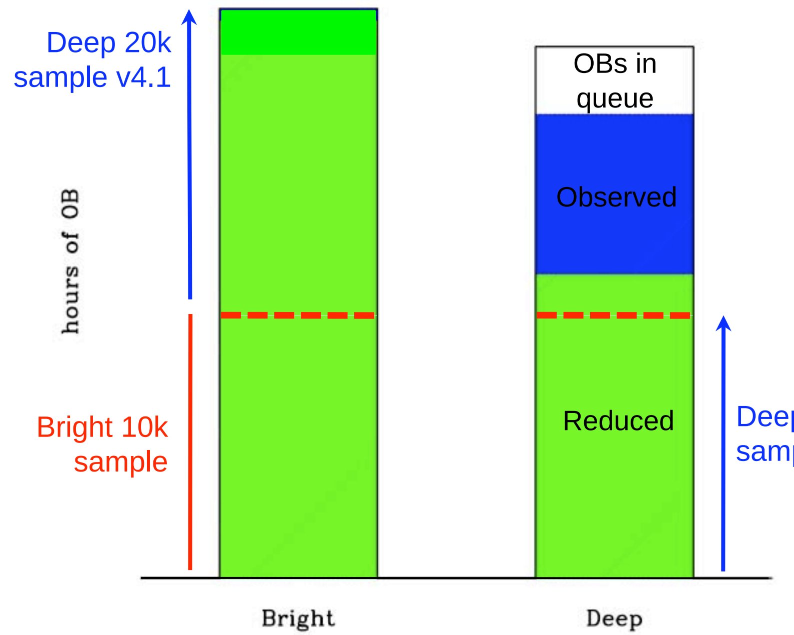
185/185 OBs observed (incl. 5 repeats) 100%

185/185 OBs reduced and reconciled 100%

Deep (252 hours)

110/126 OBs observed 87%

72/126 OBS reduced and reconciled 57%



Technical note: Photo-z now work extremely well

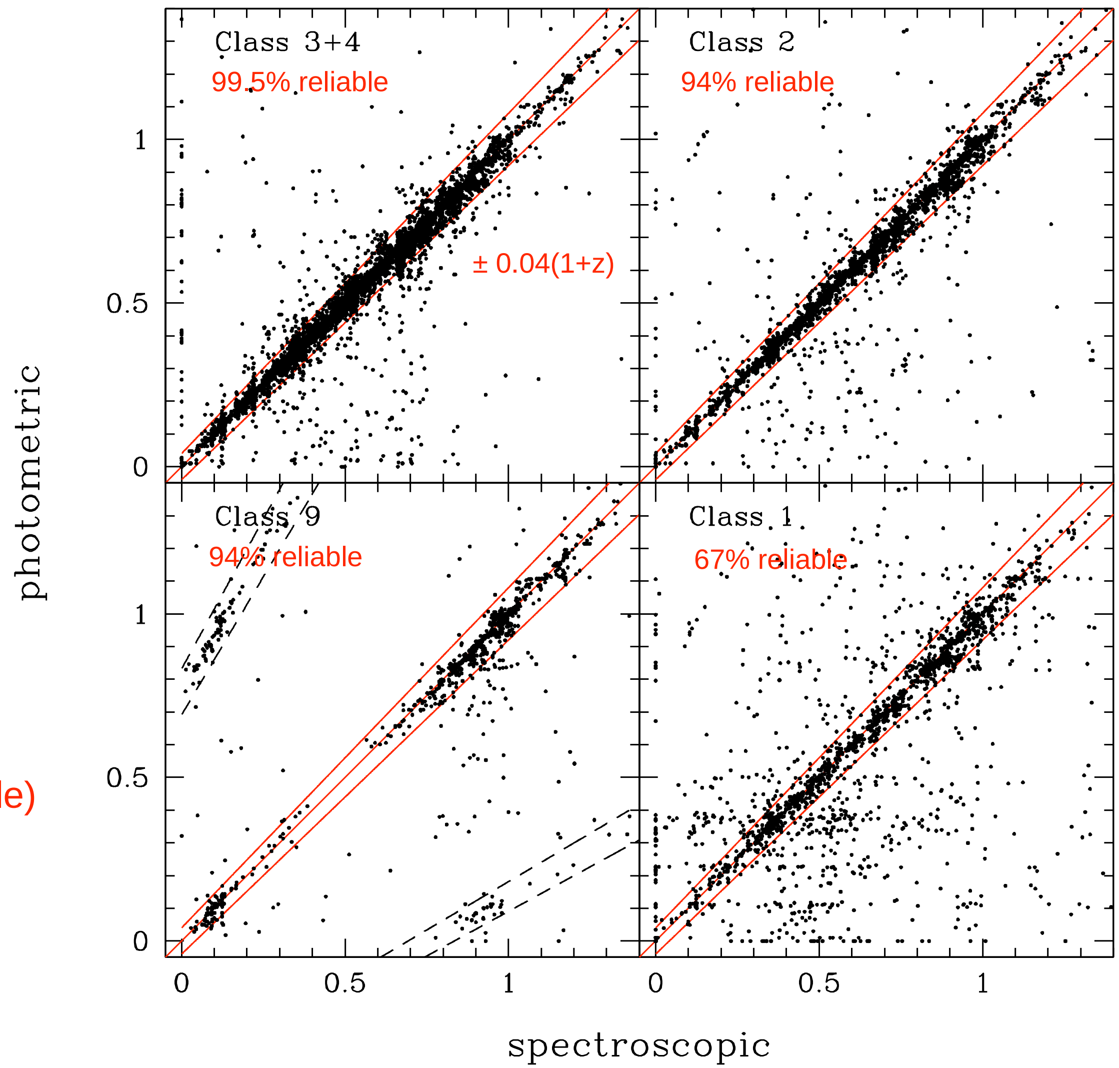
- COSMOS 30-band photometry
- relatively bright I < 22.5
- relatively low z < 1.4

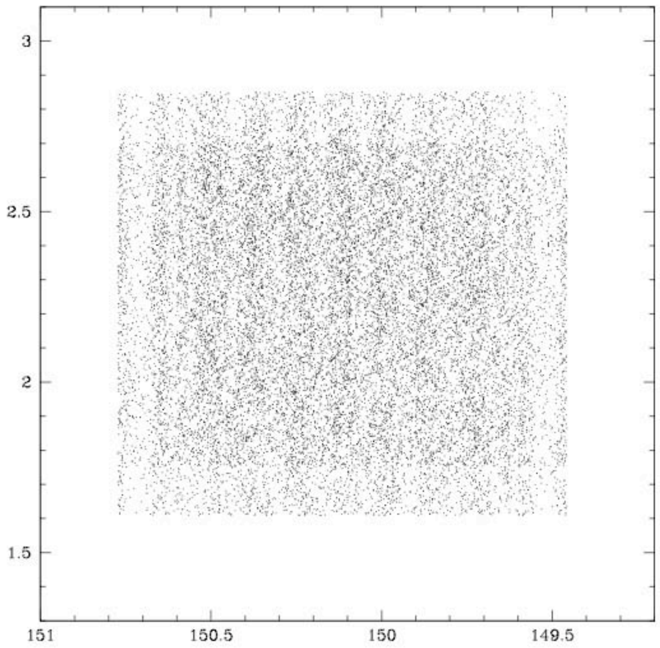
Based on LePhare and ZEBRA template-fitting codes

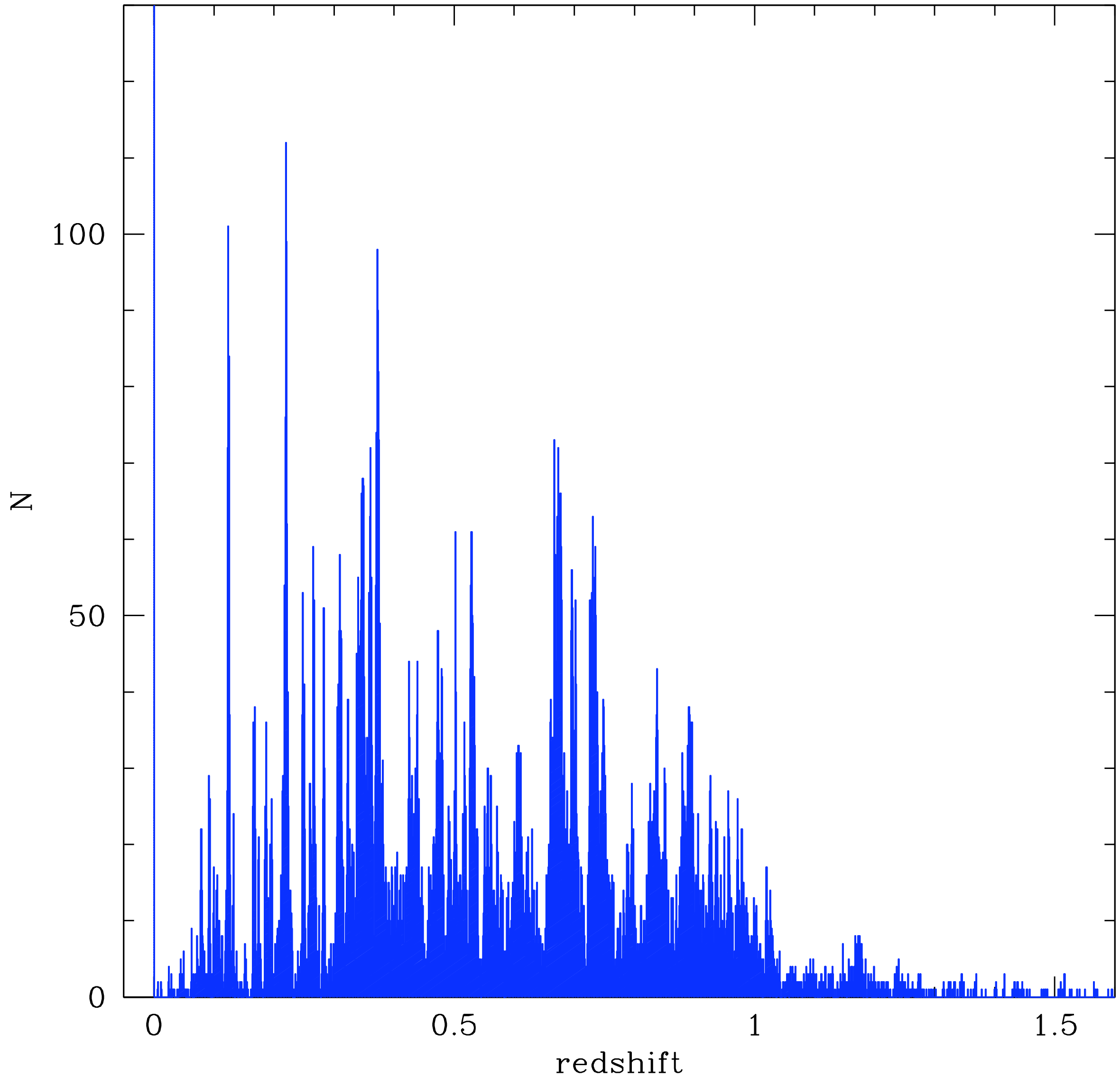
- "Floor" of 3-4% outliers even in most reliable spect-z, due to photometric problems in "masked" regions: otherwise failures < 1 %
- **σ_z ~ 0.01 (1+z)**
- Excellent correlation between photo-z consistency and spectroscopic repeatability

Use photo-z to tell us which of the less reliable redshifts are right (97% repeatable) and which are wrong (< 30% repeatable)

Sample at 0.5 < z < 0.8 is 95% complete with 99% reliability



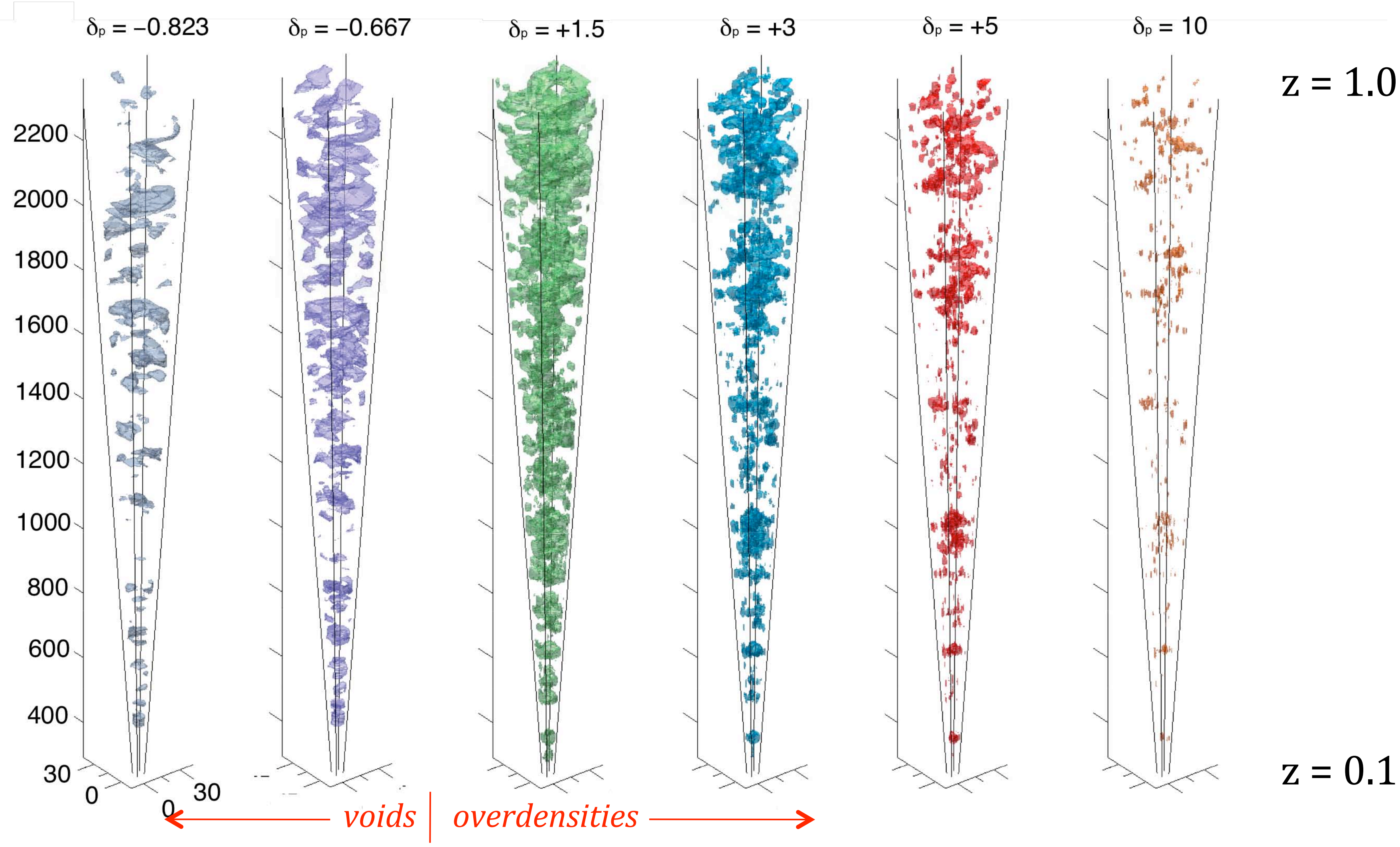




Bright sample: $I_{AB} < 22.5$

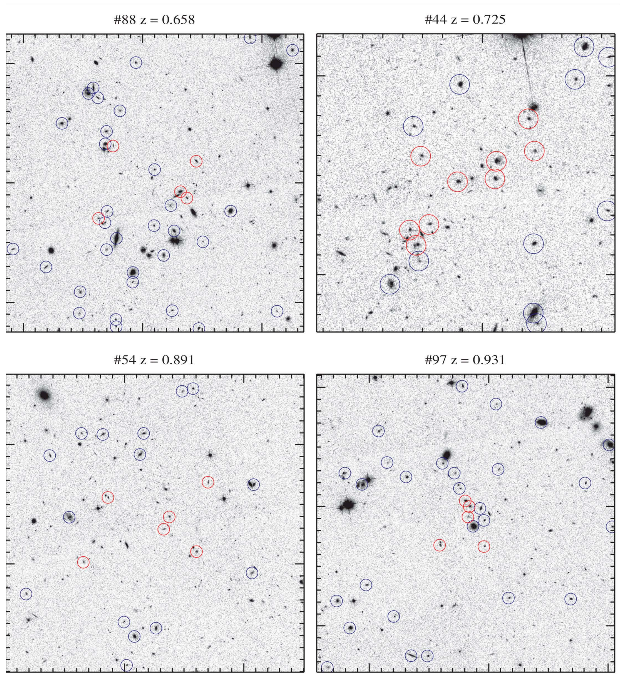
Note effects of large scale structure (a.k.a. cosmic variance) even in 100 Mpc transverse field

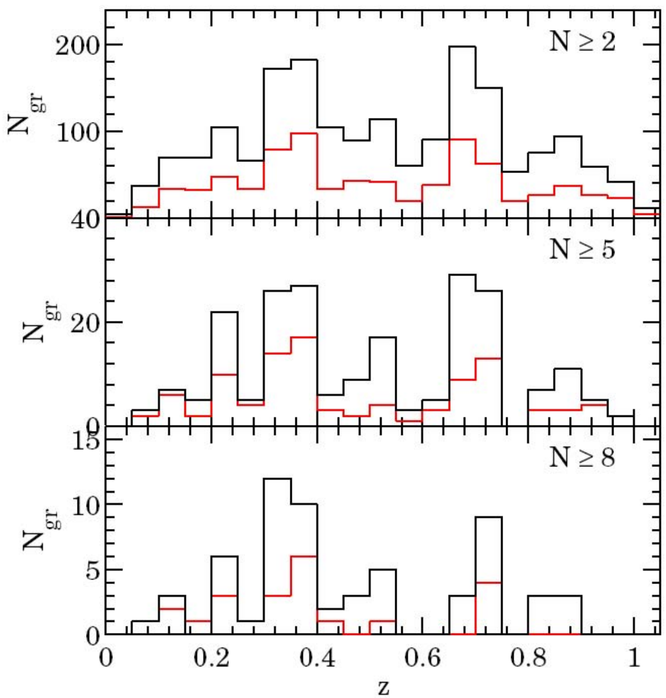
Characterizing environment to $z = 1$



zCOSMOS density field (spanning > 2 dex on Mpc-scales) constructed using **ZADE** – combining 10,000 spectro-z + 30,000 photo-z

(Kovac et al 2009, ApJ, astro-ph 0903.0349)





zCOSMOS group catalogue at z ≤ 1

High fidelity** groups using optimized "multi-pass" FoF+VDM algorithms
(Knobel et al 2009, ApJ 697, 1842).

In new 20k bright sample:

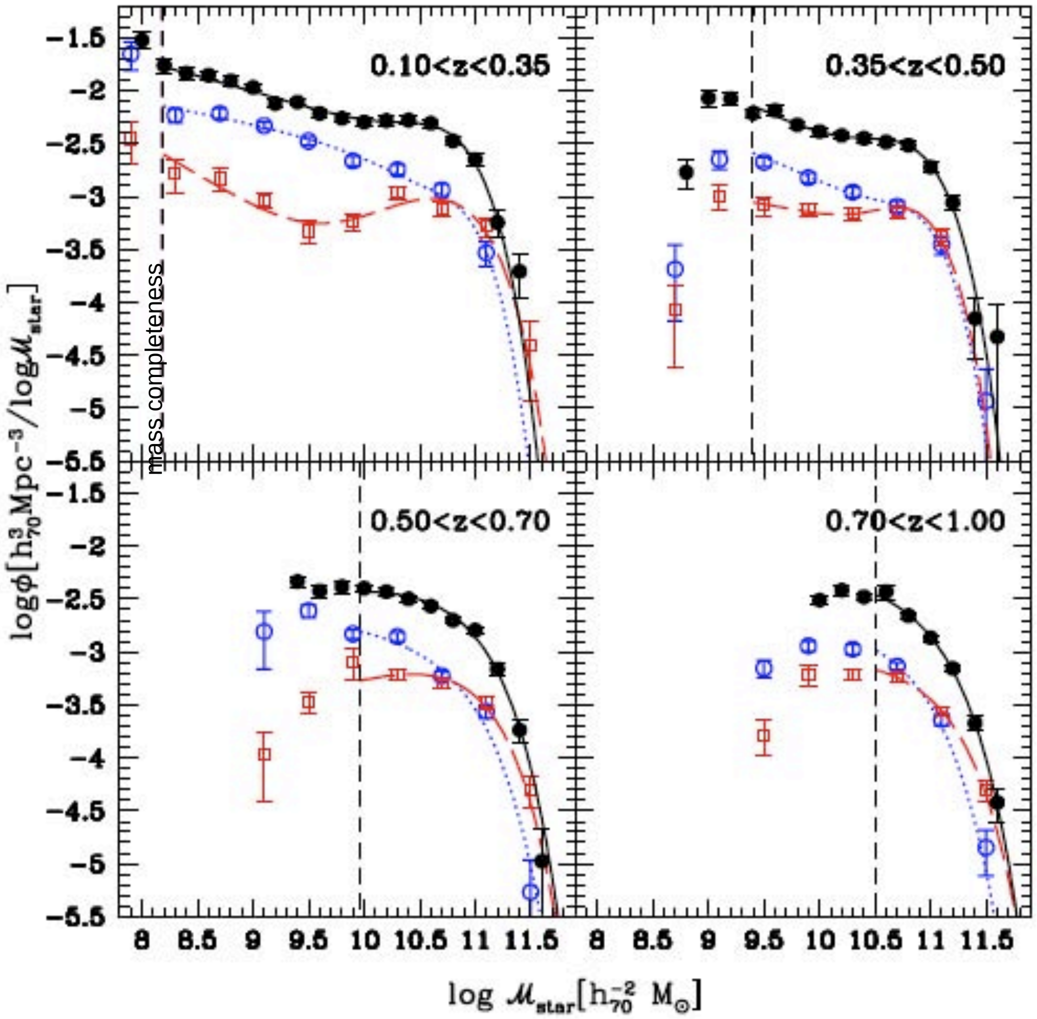
- almost 2000 groups (N ≥ 2) of which >200 have confirmed membership N > 5 .
- can assign group membership for 35% of galaxies at z = 0.3 and still 12% at z = 0.8
- Currently working to incorporate the 1/3 of sample with photo-z, plus go fainter with photo-z to examine central/satellite paradigm

** fidelity:

group completeness	81%
group purity	82%
member completeness	81%
interloper fraction	17%

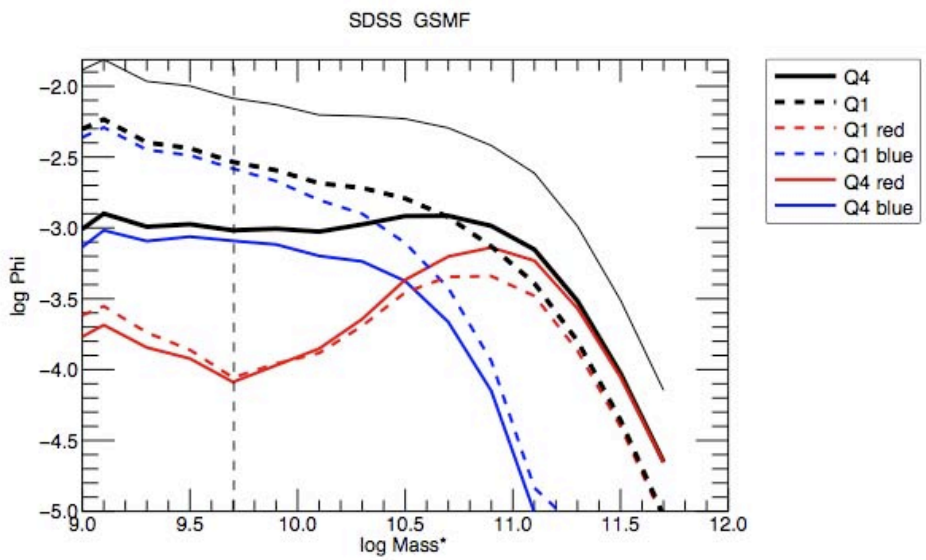
Different galaxy MF in different environments

Galactic Stellar Mass Functions in lowest and highest density quartiles

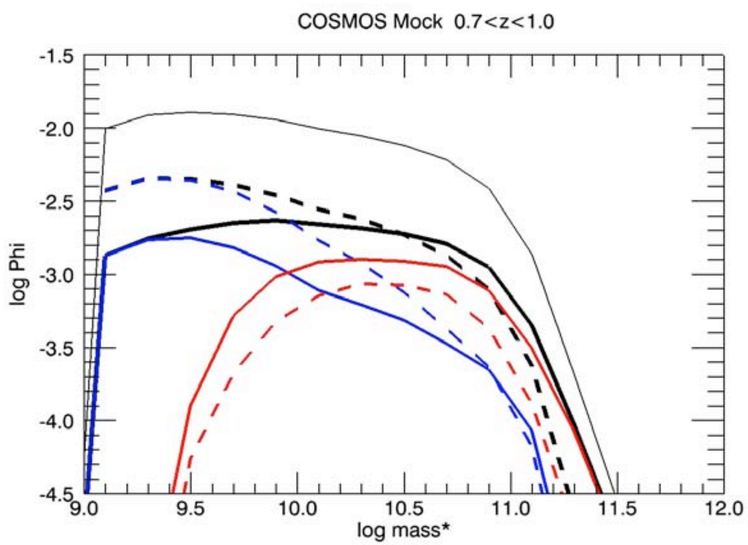


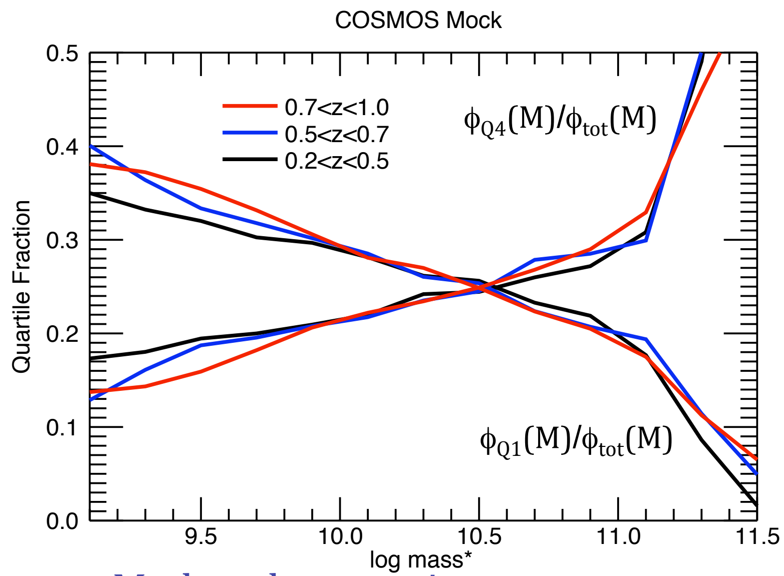
Bolzonella et al (2009)
arXiv:0907.0013

Also seen locally in SDSS and in COSMOS SAM-based mocks



- "Nature" vs. "Nurture" issue becomes more complicated if mass anyway varies with environment.
- Given that GSMF is *f* (density), the density effects seen in luminosity-selected samples (and broad mass bins) may be due to the underlying mass effect plus different relative numbers of high and low mass galaxies in different environments

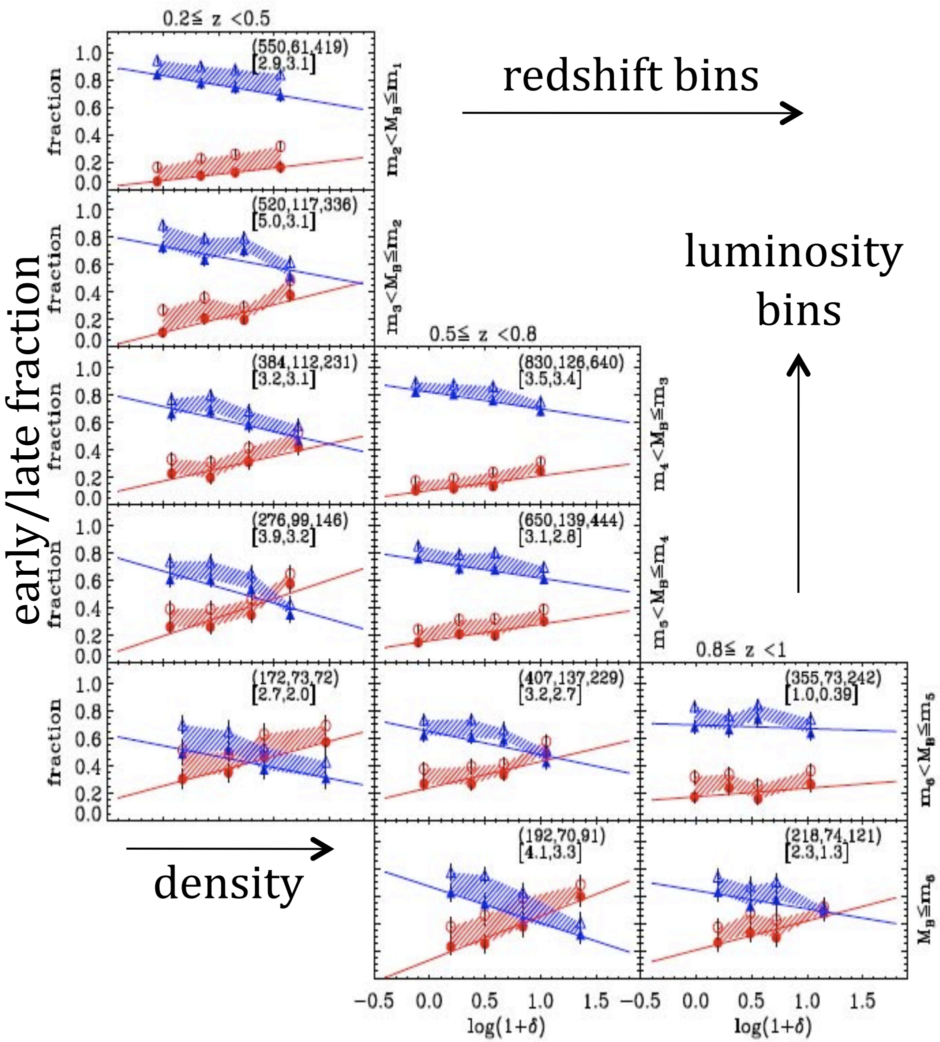


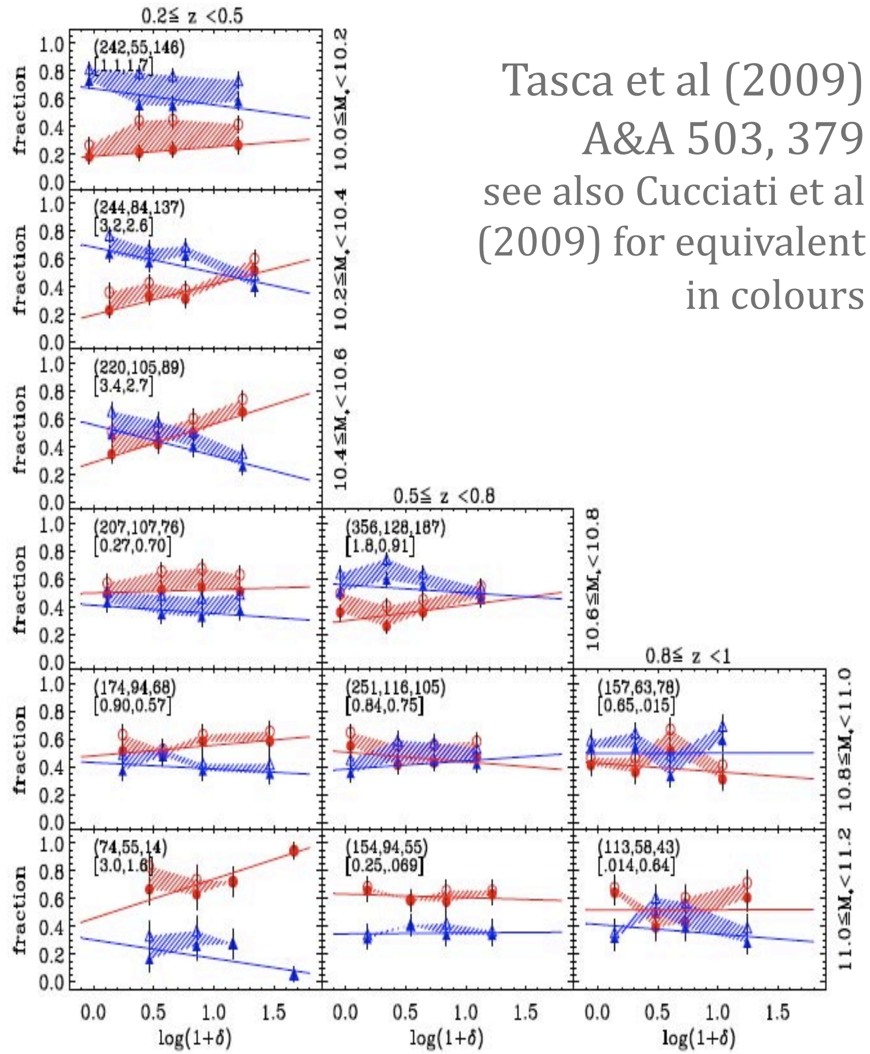


Modest decrease in mass segregation with epoch in mocks

Peng et al (in prep)

From luminosity-bins to mass-bins





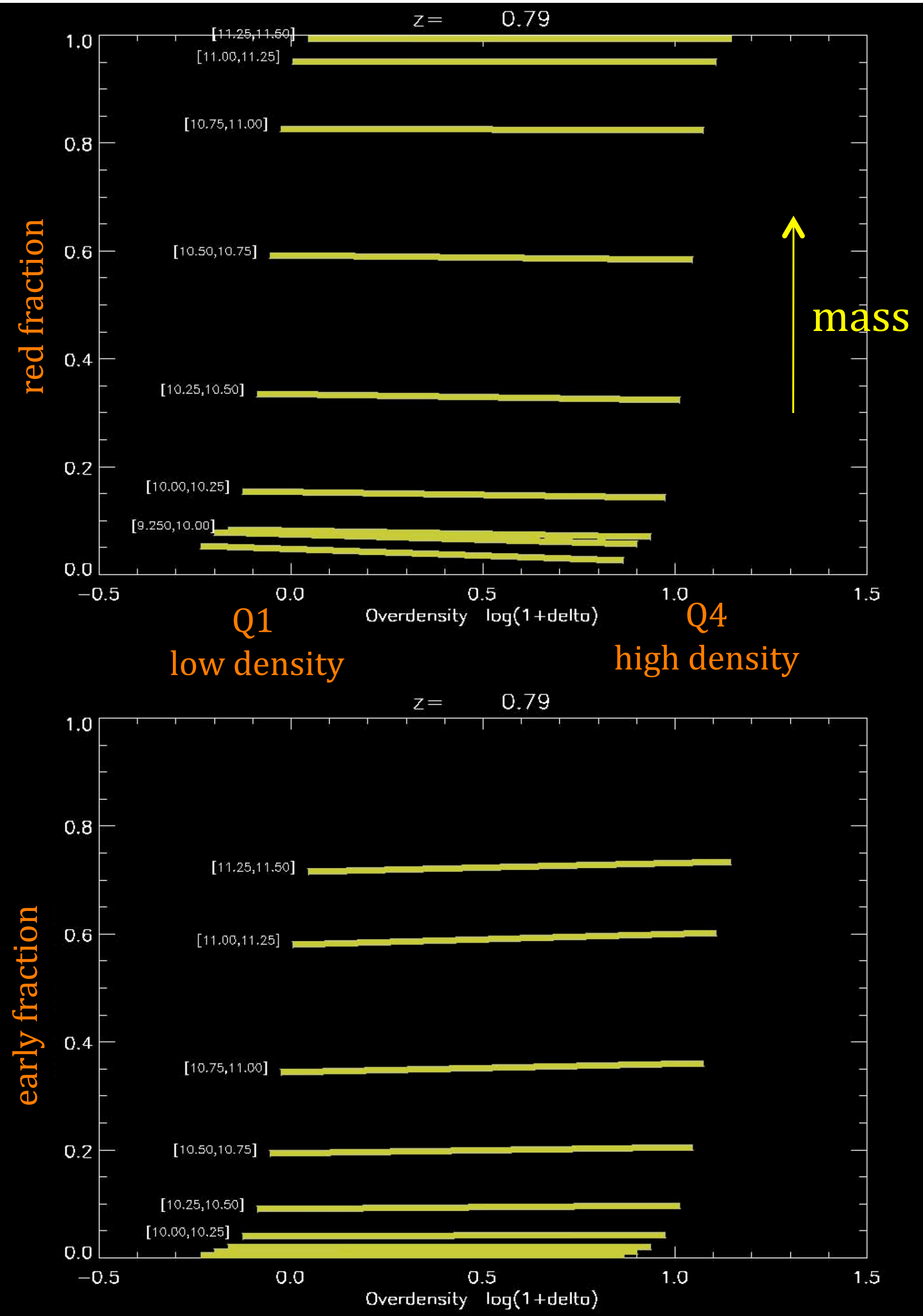
Tasca et al (2009)
A&A 503, 379
see also Cucciati et al (2009) for equivalent in colours

Strong morphology-density relation in luminosity-binned samples....

.... largely disappears in constant mass bins (@ log M > 10.6 and higher z)

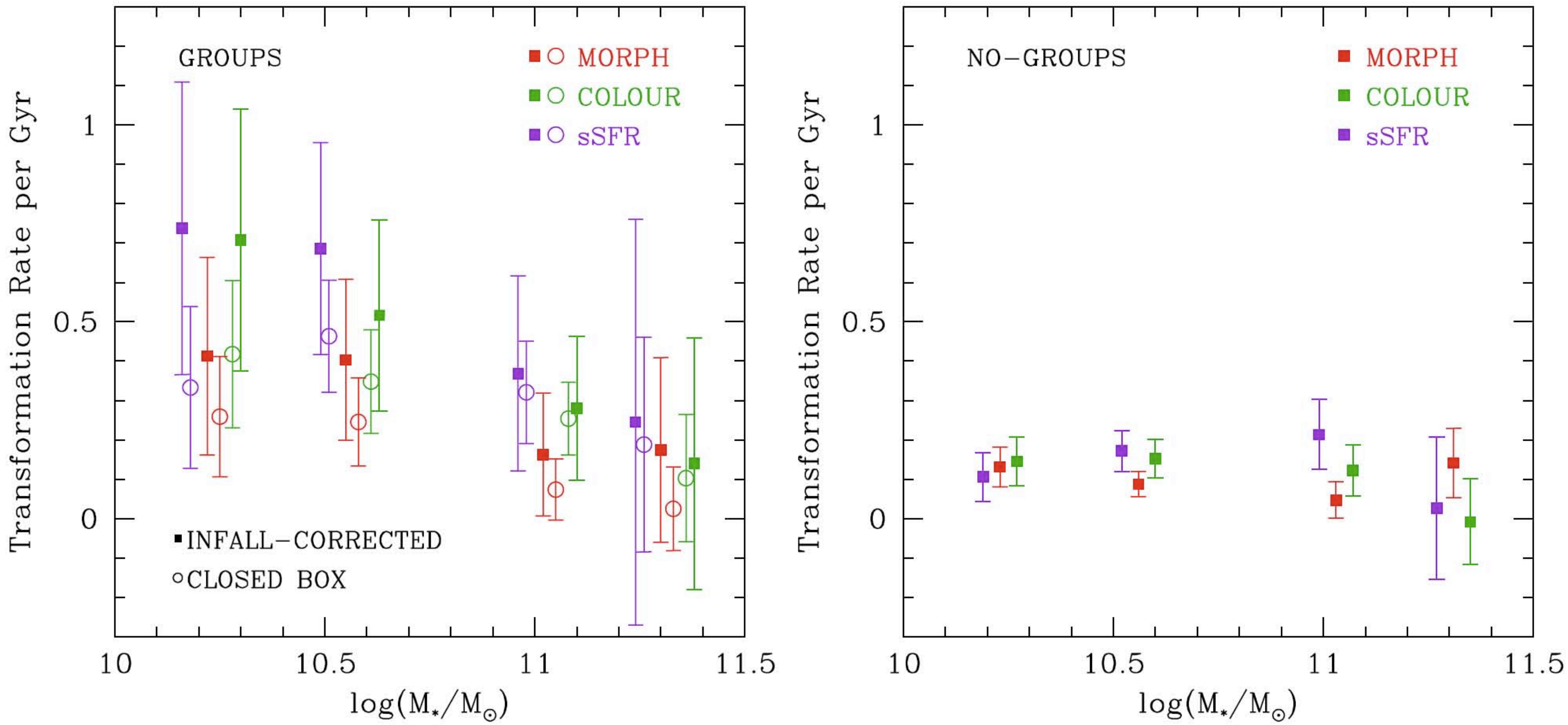
Summary of galaxy evolution as *f*(environment) since $z = 1$

- Galaxy stellar mass function is a function of environment. This complicates Nature vs. Nurture, and makes samples with range of Mass prone to quite spurious environmental trends
- At a <u>fixed</u> mass, the colour- and morphology-density relations are rather weak, especially for high masses ($>10^{10.5}$) and $z > 0.5$, and largely disappear by $z = 1$.
- Thereafter, the effects of environment develop over time but appear to be secondary to *mass*: i.e. at $z \sim 0.5$, the full range of environments is equivalent to $\Delta t \sim 2$ Gyr or $\Delta M \sim 0.2$ dex.
- Not yet clear whether due to passage of time, or involvement of susceptible masses? Merger rate in different environments ?



Transformation rates

$$rate = \frac{1}{f_P}\frac{df_P}{dt}$$

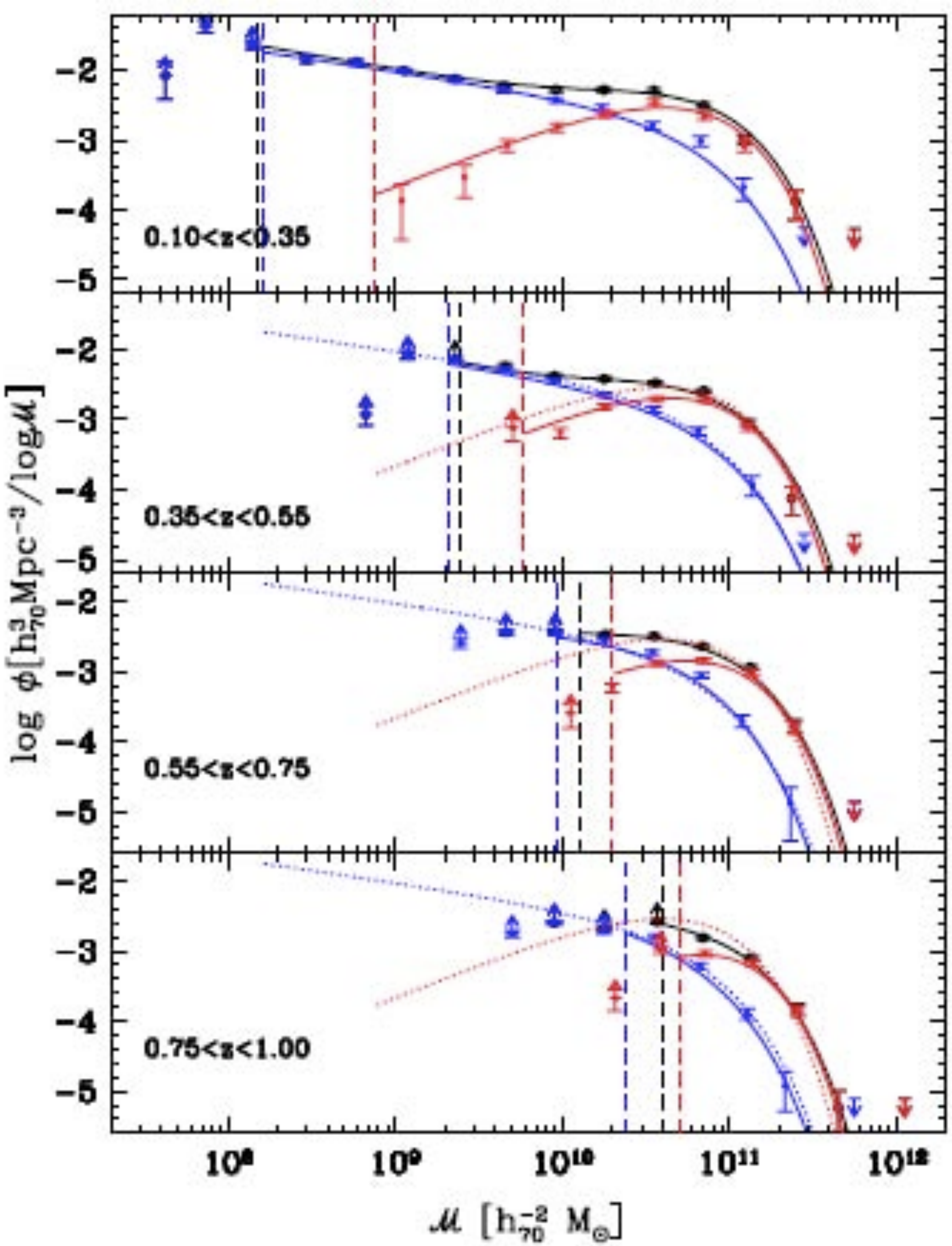


- Transformation rate is substantially faster in groups
- Rate is faster in colour and/or star-formation activity than in morphology
- Rate is faster (in groups) for lower mass galaxies

Is this linked to the environment (and luminosity) dependence of merging rates?

Kovac et al (2009)
arXiv:0909.2032
see also Iovino et al (2009)

But is this the right way to think about it?



Constancy of mass function of star-forming galaxies

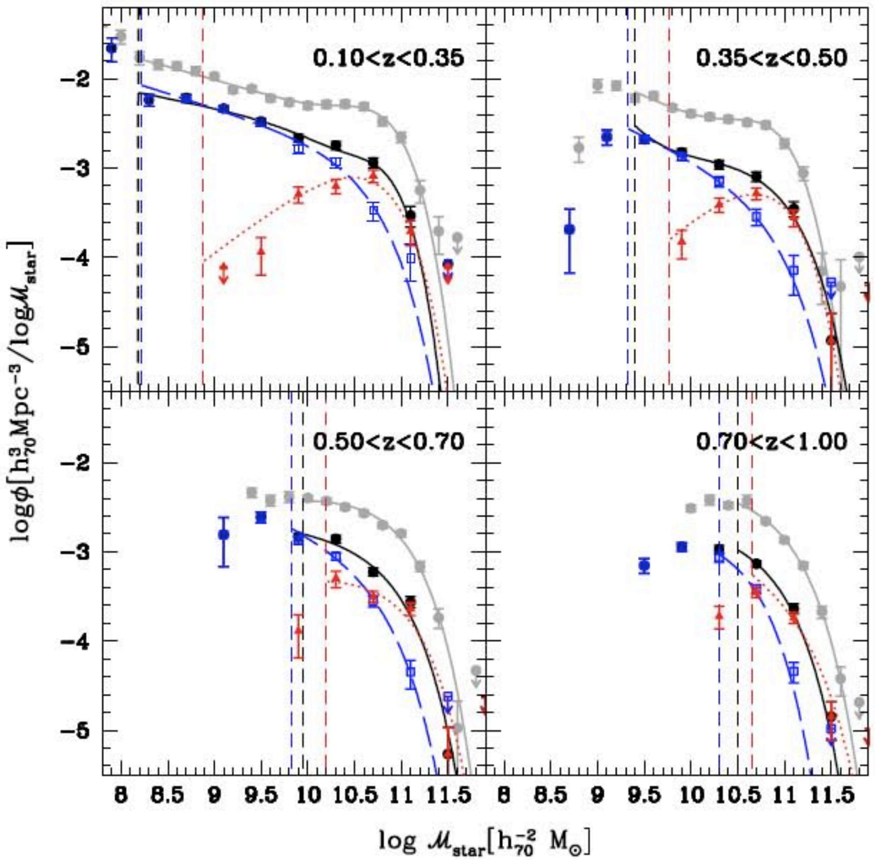
Global rise in SFRD is due to uniform increase in SSFR of "all" galaxies

Build-up of red population rather than "passification"

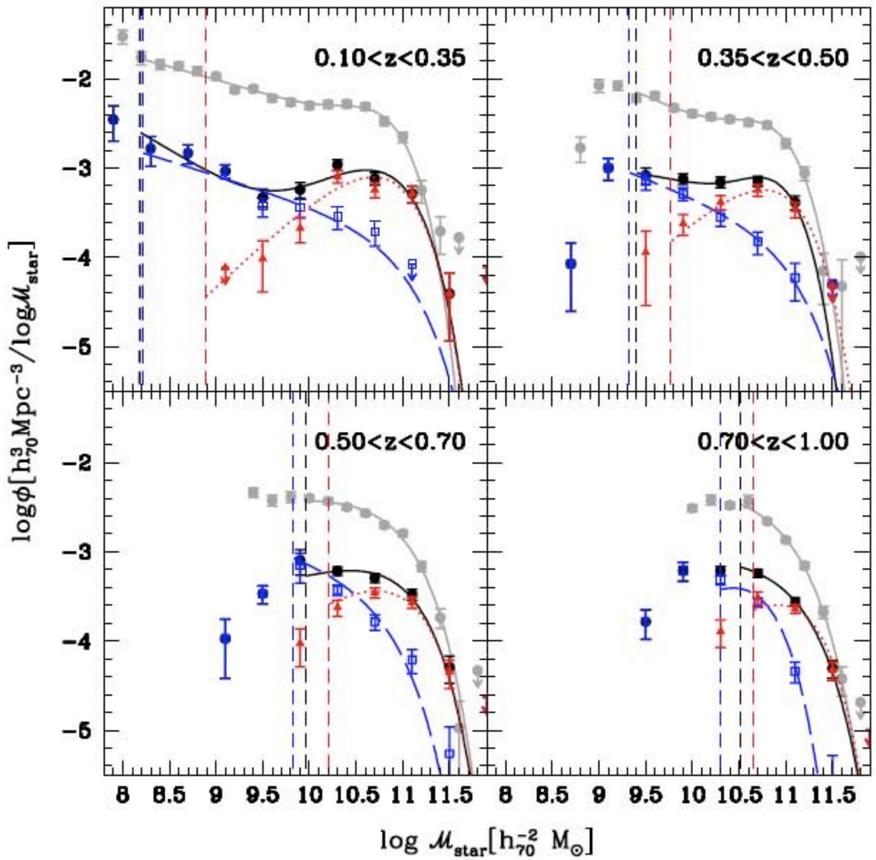
Pozzetti et al (2009)
Bolzonella et al (2009)

Different galaxy MF are due to different proportions of "universal" blue and red MF in different environments

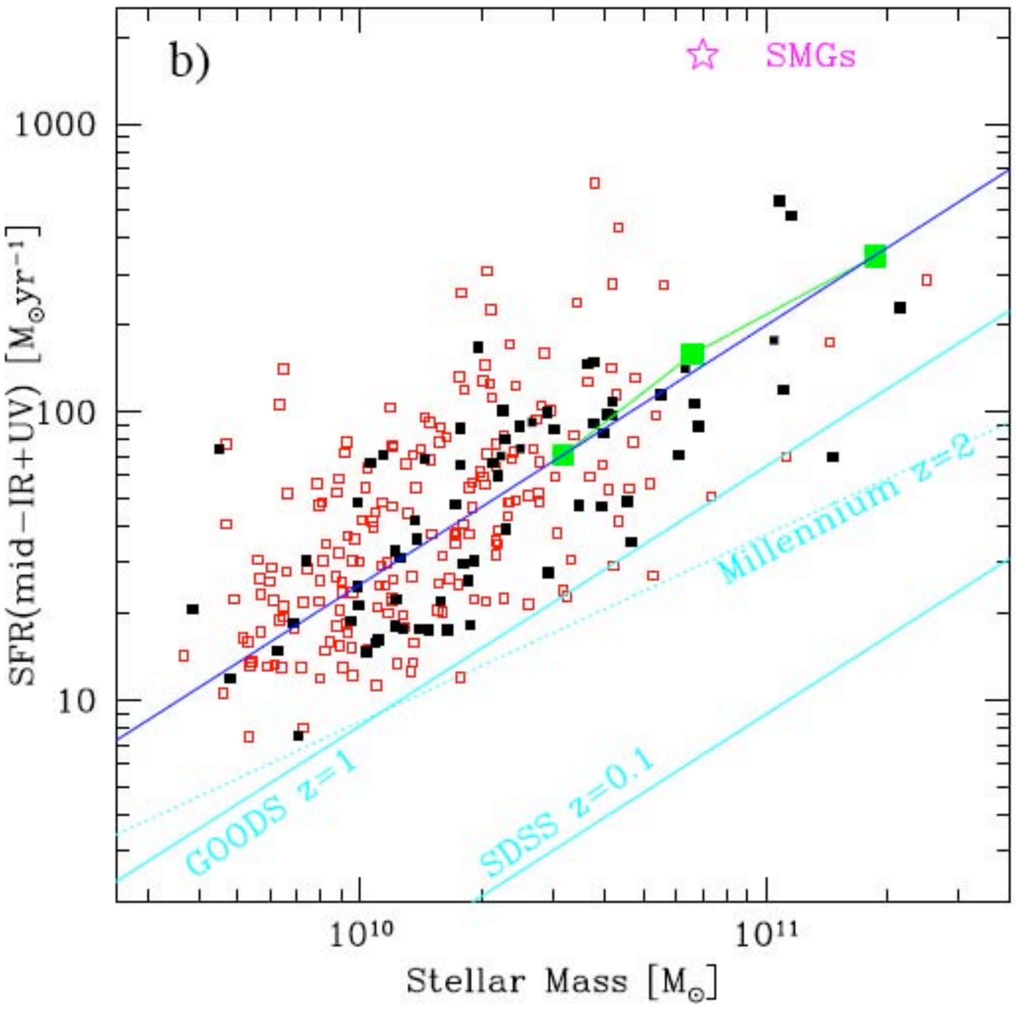
Q1 low density, blue and red galaxies



Q4 high density, blue and red galaxies



Bolzonella et al (2009)
arXiv:0907.0013

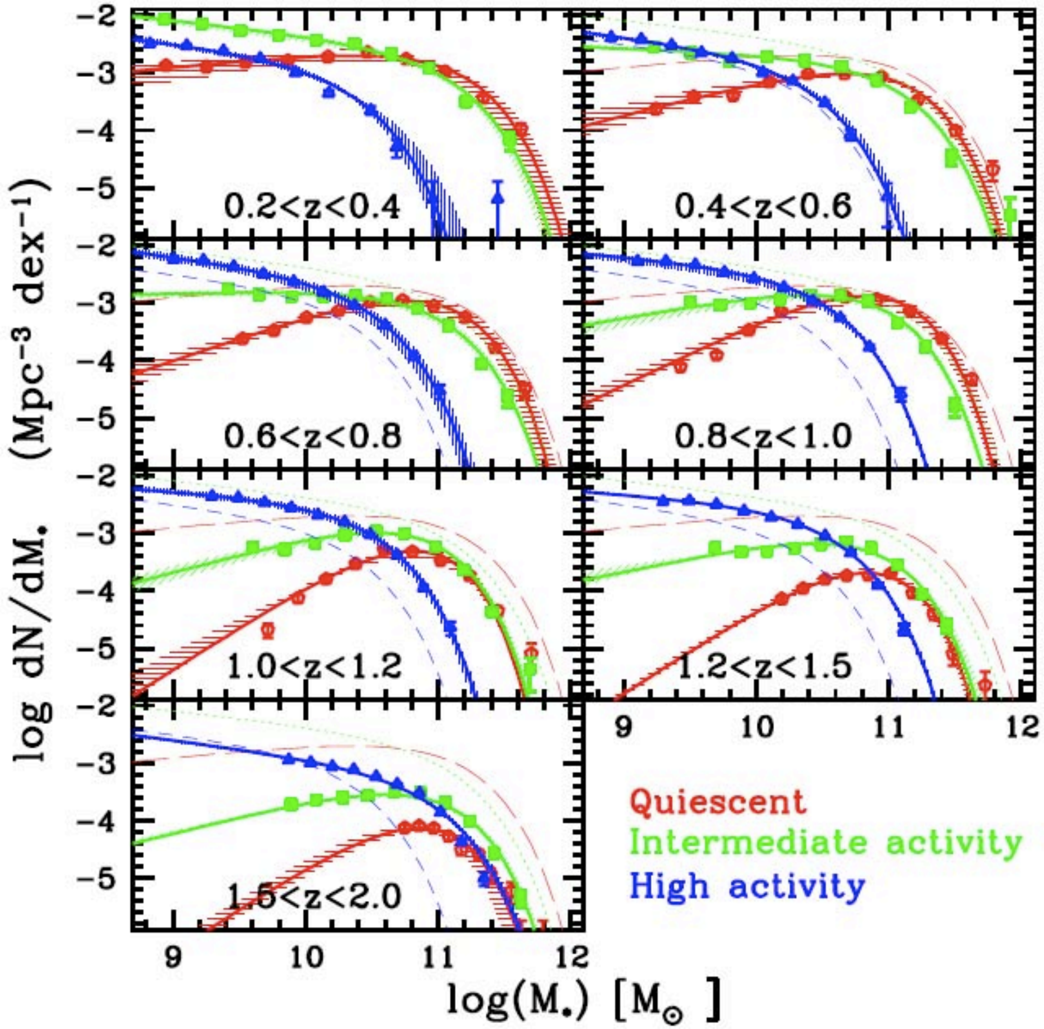


At z = 2, the masses of star-forming galaxies are still modest.

What is remarkable is their high SFR, → SSFR ~ 2.5 Gyr^{-1}, and the high fraction (50%) forming stars - c.f. τ = 3.4 Gyr at z = 2

Daddi et al, 2008, ApJ 670, 156

The "universal" shape of GSMFs back to z = 2?

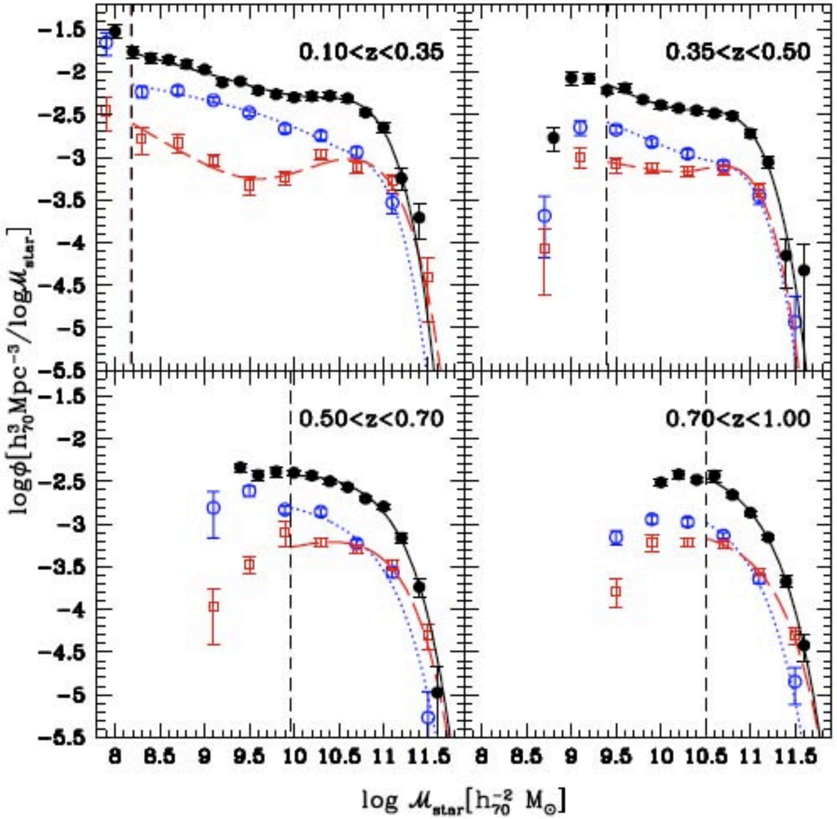


Down-sizing is more about the <u>level</u> of activity in star-forming galaxies, than about changes in the <u>characteristic masses</u> of star-forming galaxies

Why is this?

Ilbert et al (2009)
arXiv: 0903.0102

What about the GSMF ?



e.g. Abbas and Sheth (2007) – halo mass function as f(large scale environment)

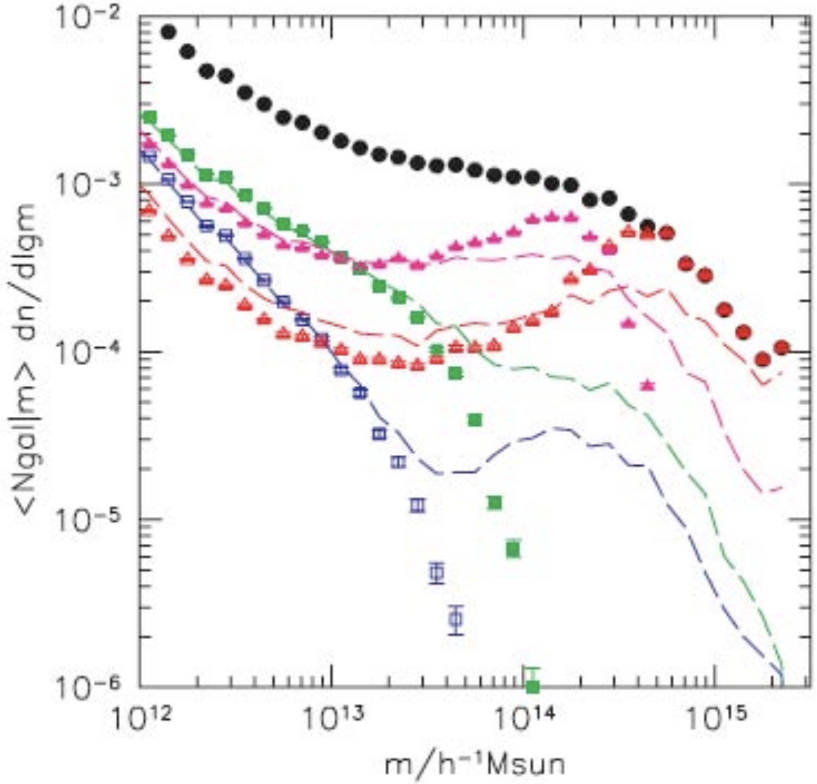
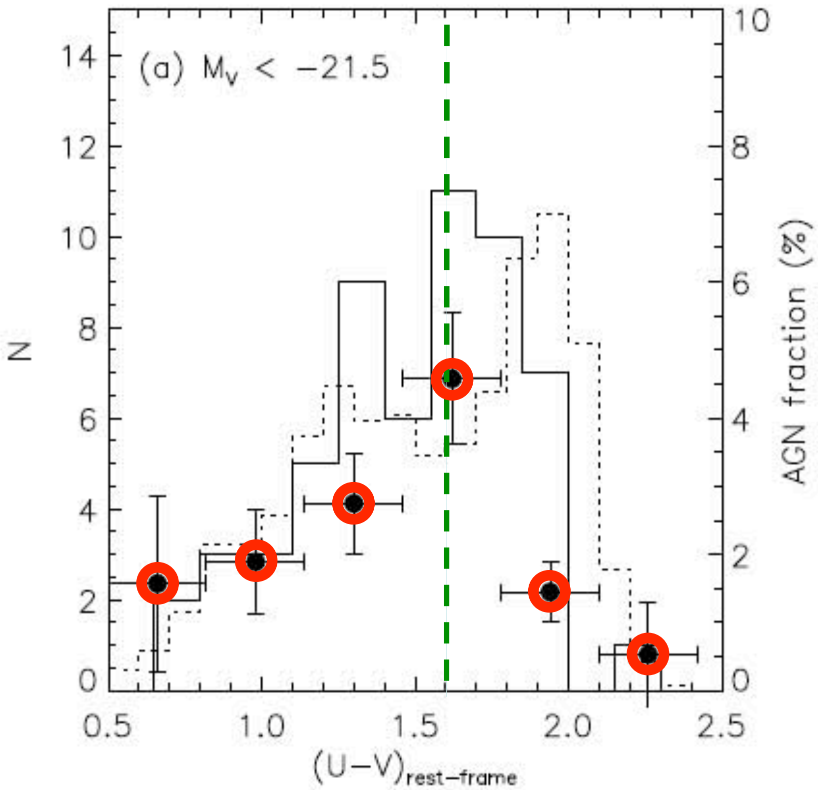
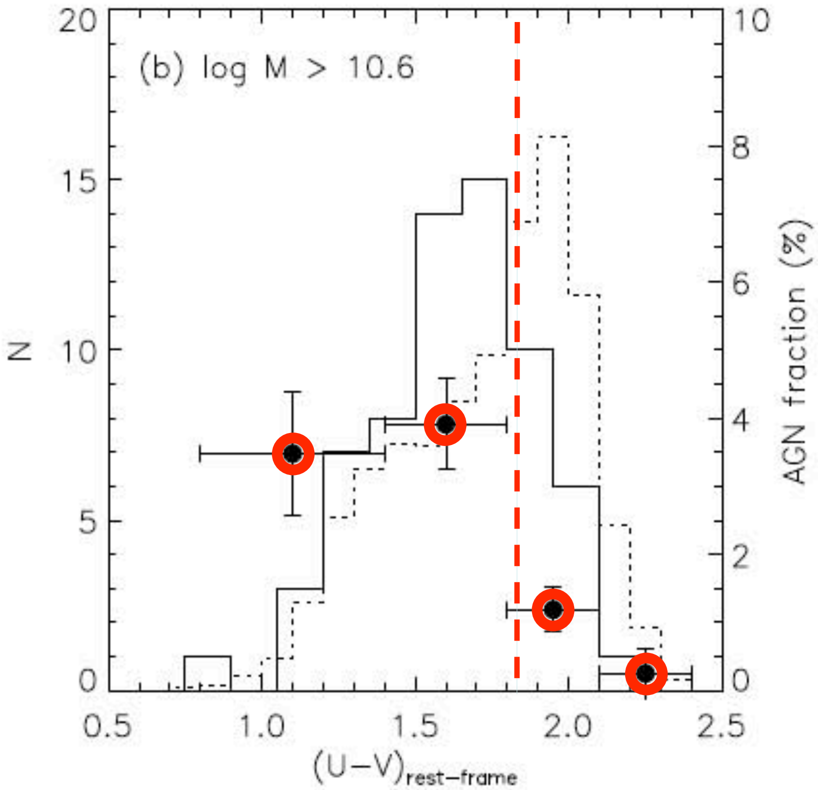


Figure 4. Galaxy-weighted halo mass function as a function of environment in our mock catalogue. Filled circles show this quantity when all galaxies in the mock catalogue are included. The other sets of symbols show this quantity when only galaxies in specific bins in environment are used. These

Importance of star-formation and mass in X-ray selected low luminosity AGN



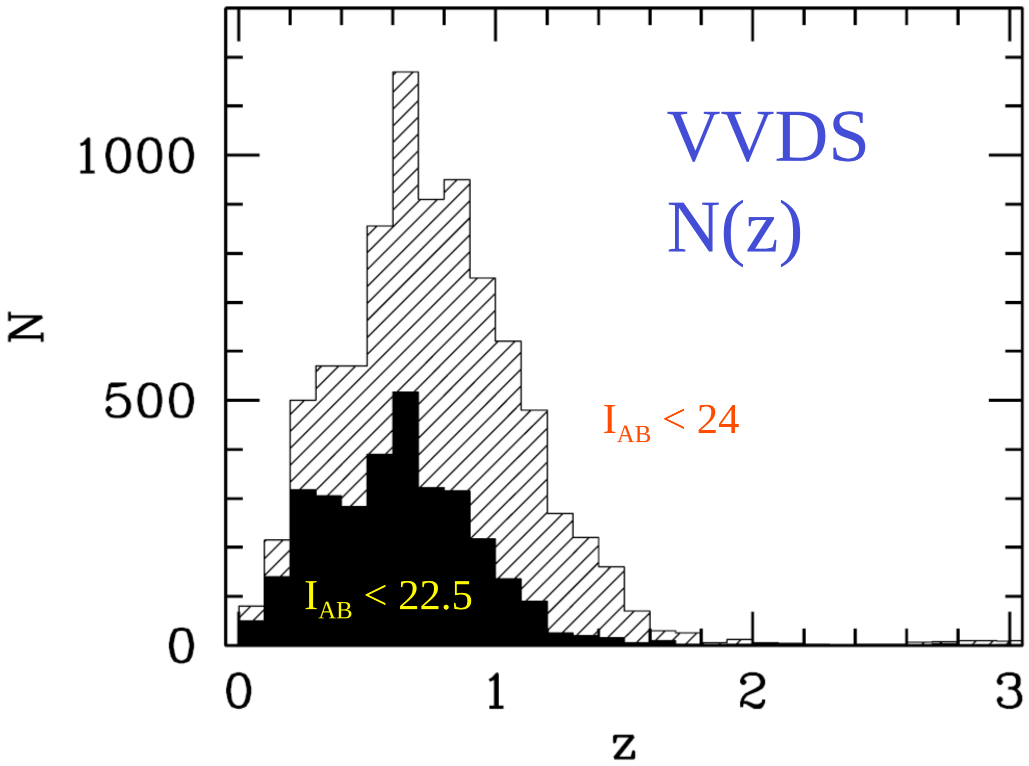
preferentially in green valley?
(luminosity-selected)



or a step-function with star-formation
(mass-selected)?

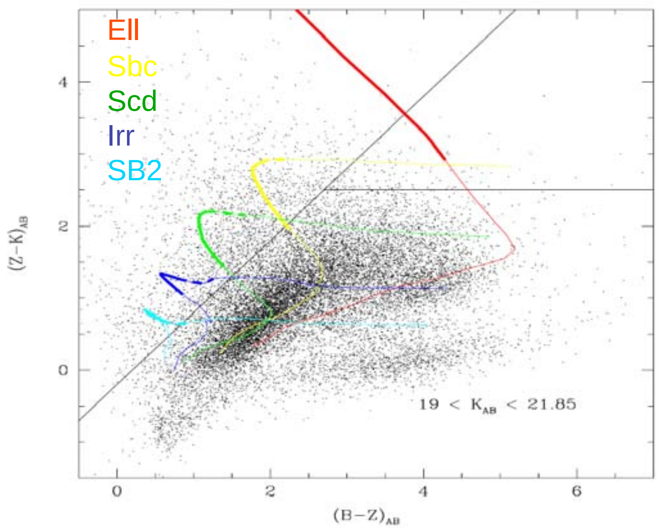
AGN also occupy the same environments as non-AGN once you select equally massive galaxies with on-going star-formation

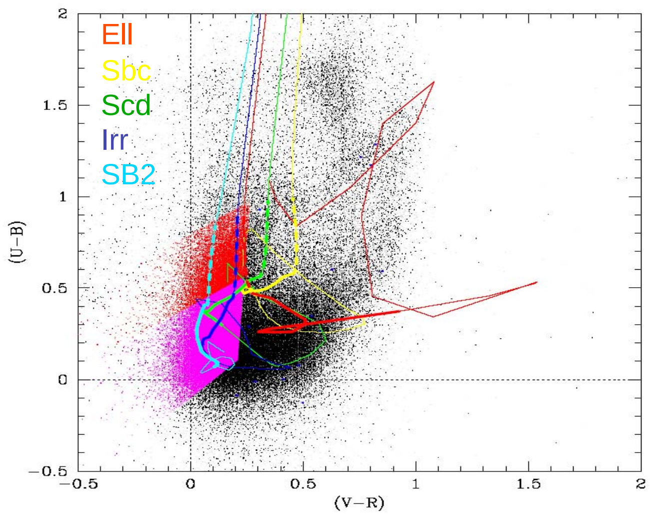
Silverman et al (2009ab)
ApJ, 695, 171
ApJ, 696, 396



zCOSMOS-deep 1.4 < z < 3:

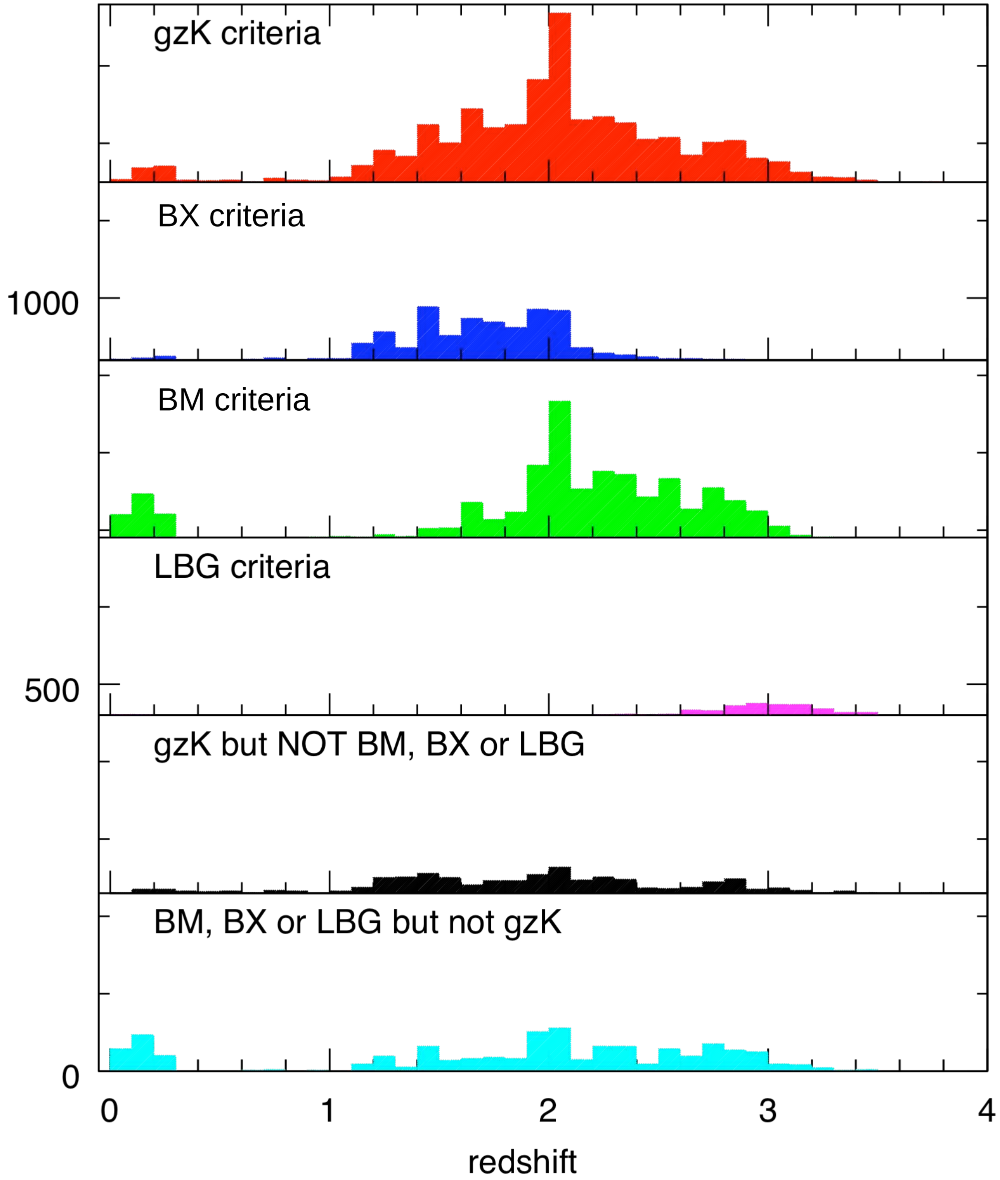
need selection to isolate tail of N(*z*) at AB ~25 (well-defined and reproducible colour-colour criteria)



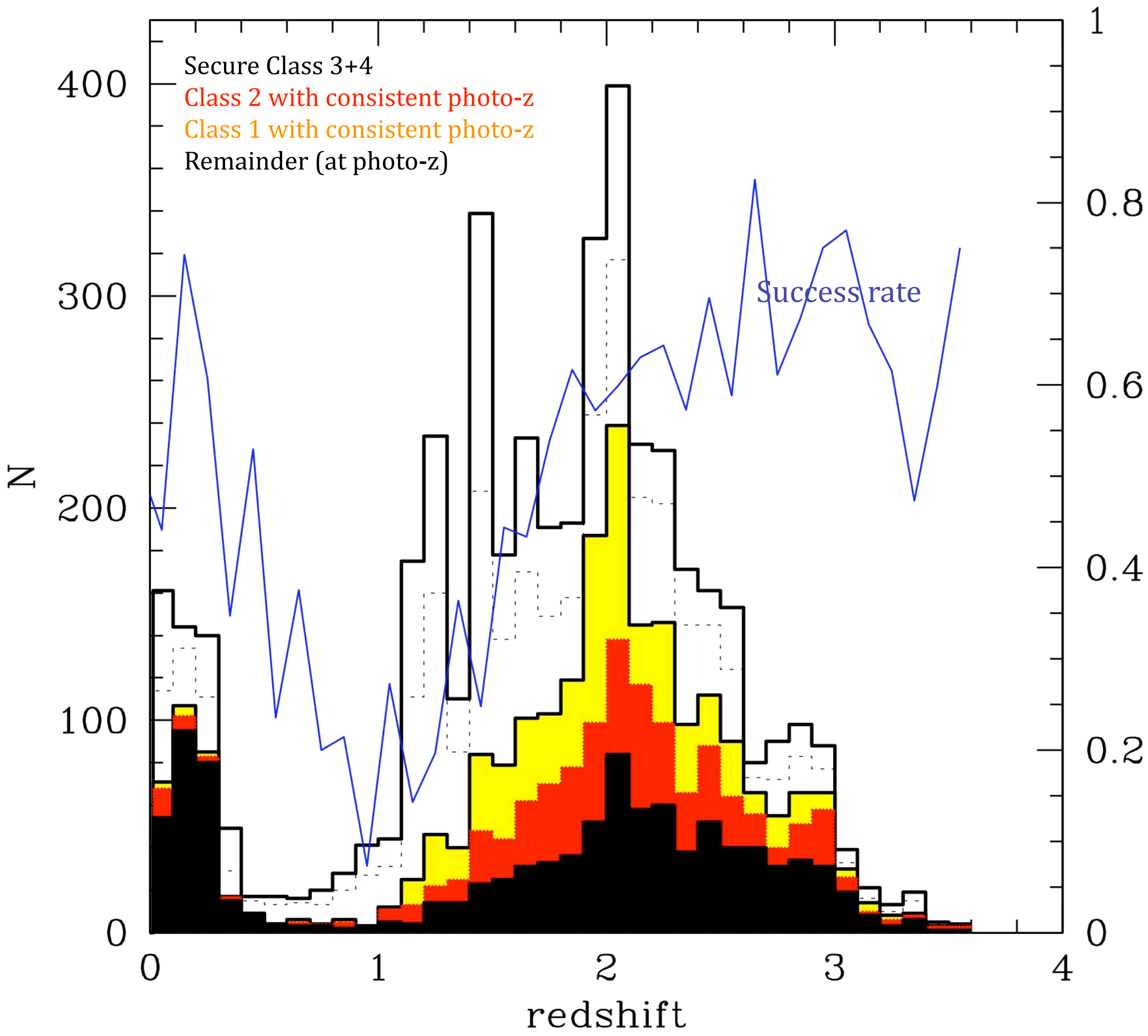


Use union of gzK ($K_{AB} < 23.5$) and Steidel BM/BX/LBG criteria

gzK and ugr colour selection work well



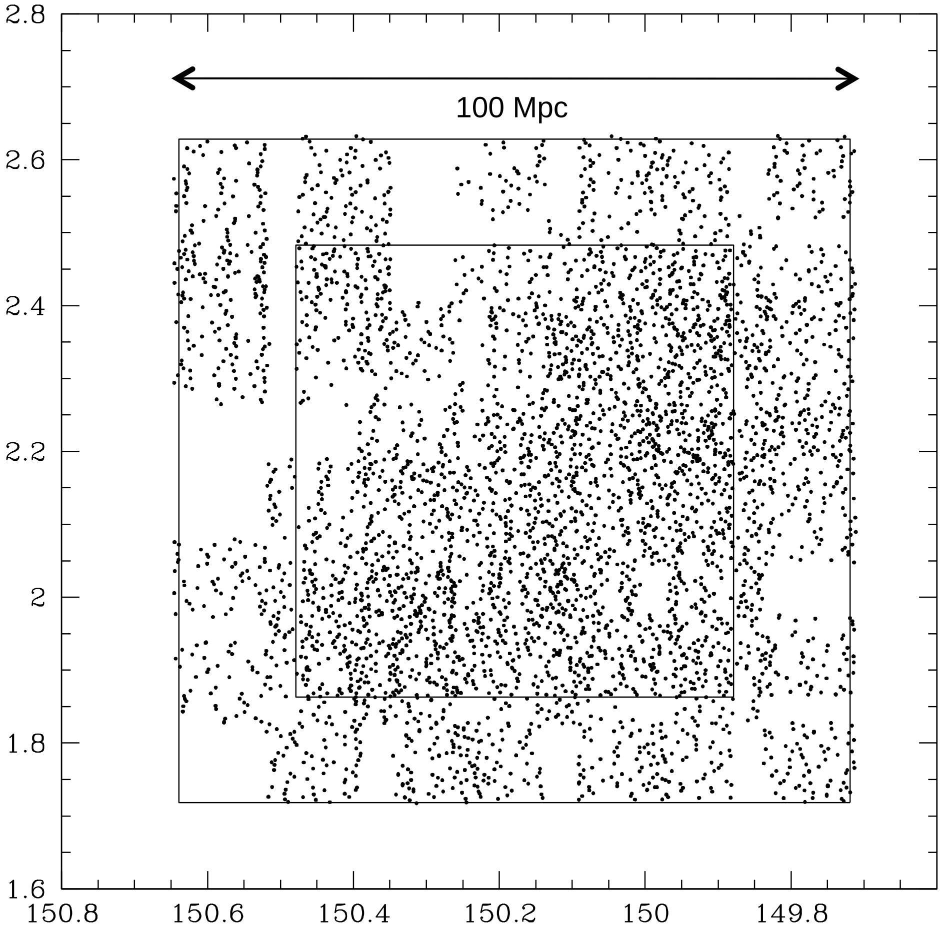
- Colour-selections are working as expected
- Sample is mostly selected by both gzK and BX/BM/LBG criteria with only a minority only one or the other

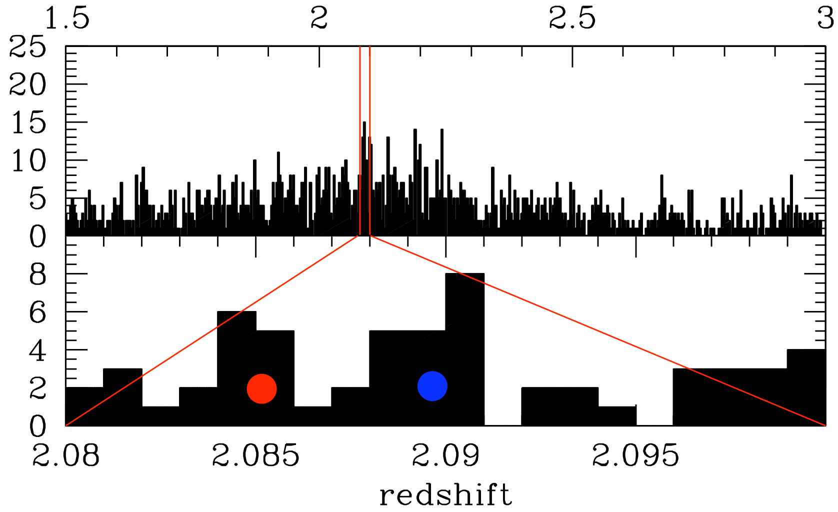


- Spectra cover 3600 < λ < 6800 A at R ~ 200
- Currently 2000 usable redshifts at 1.0 < z < 3.5 (should get to 4000 by end of program)
- Redshift success rate varies with redshift and is about 66% at $z > 1.9$.

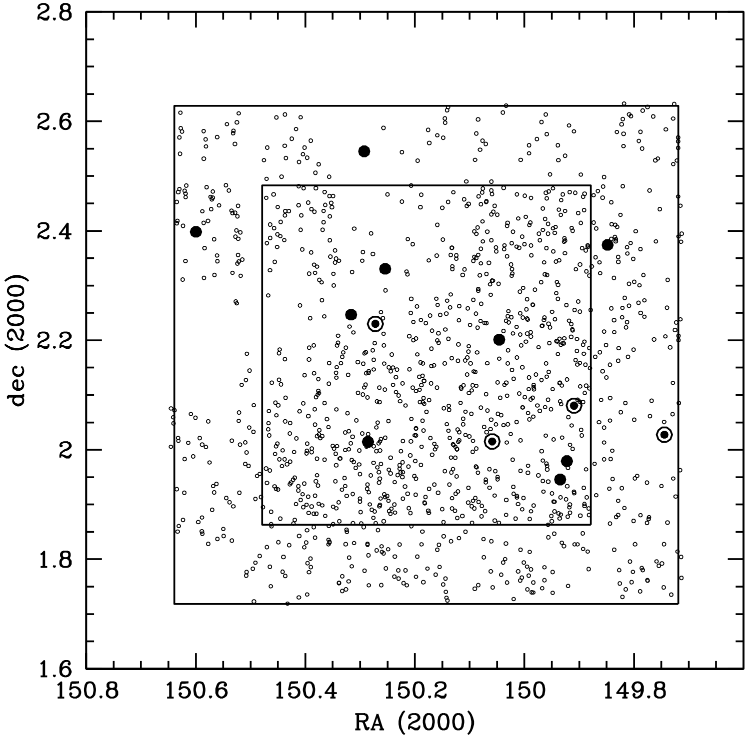
Towards environmental measures in zCOSMOS-deep

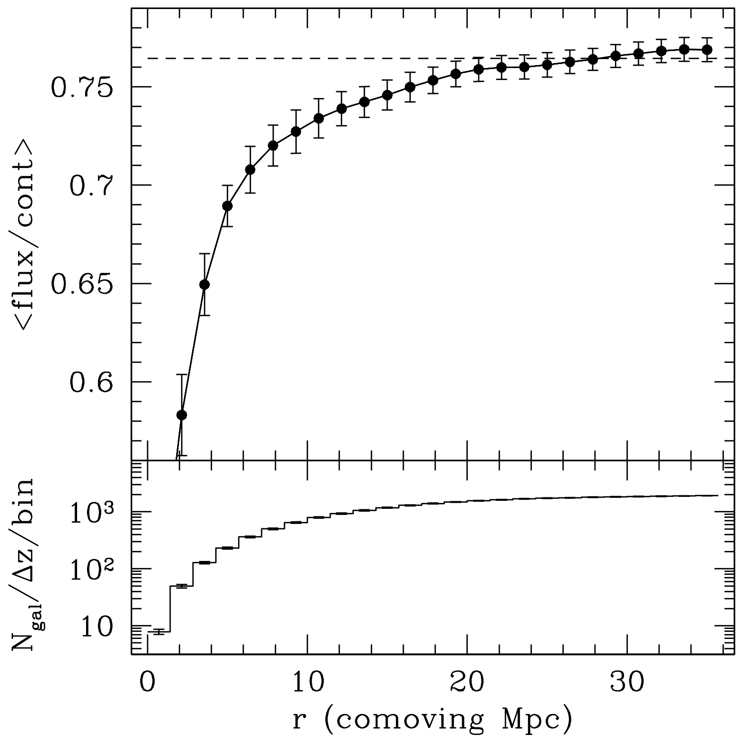
Current sampling is inhomogeneous….

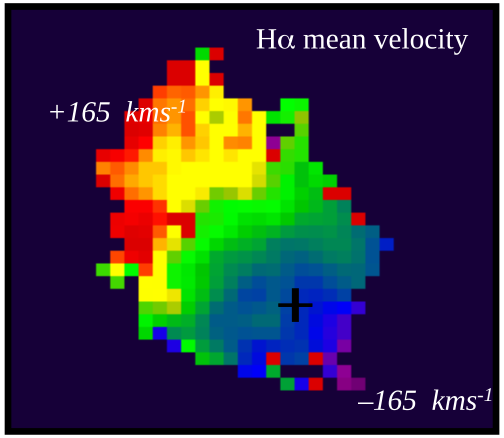


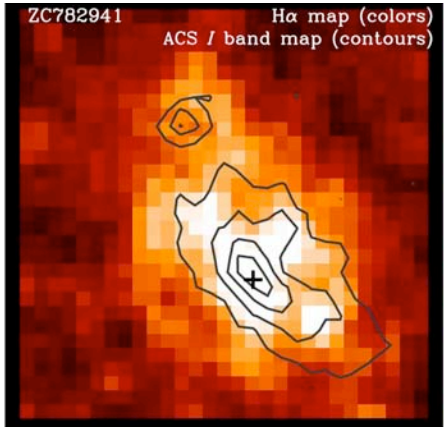


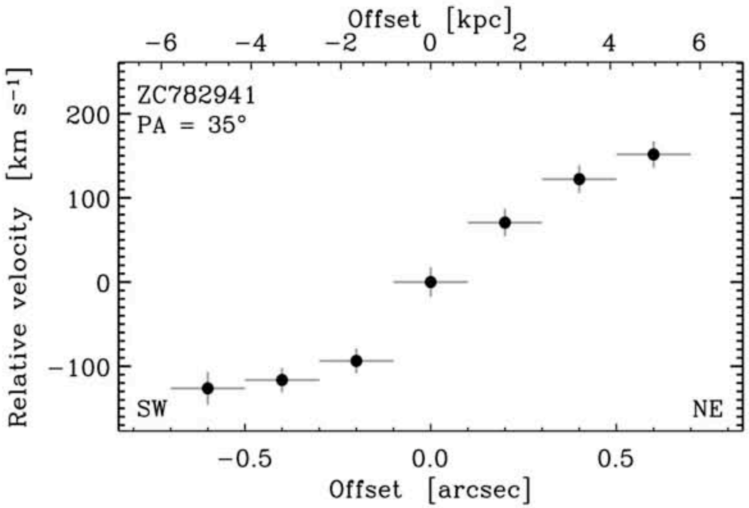
The future: High resolution spectra (UVES + XShooter?) of 2.3 < z < 2.8 quasars for IGM tomography through the 1.8 < z < 2.7 100×100×1000 Mpc^3 volume

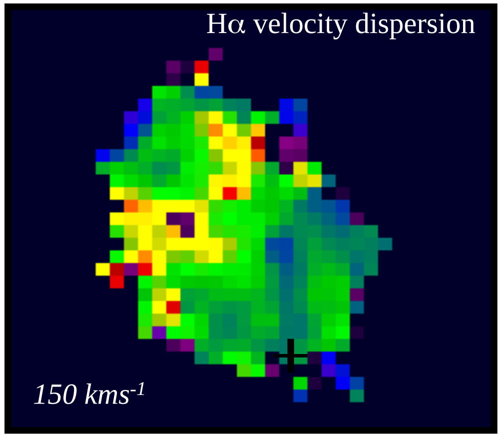


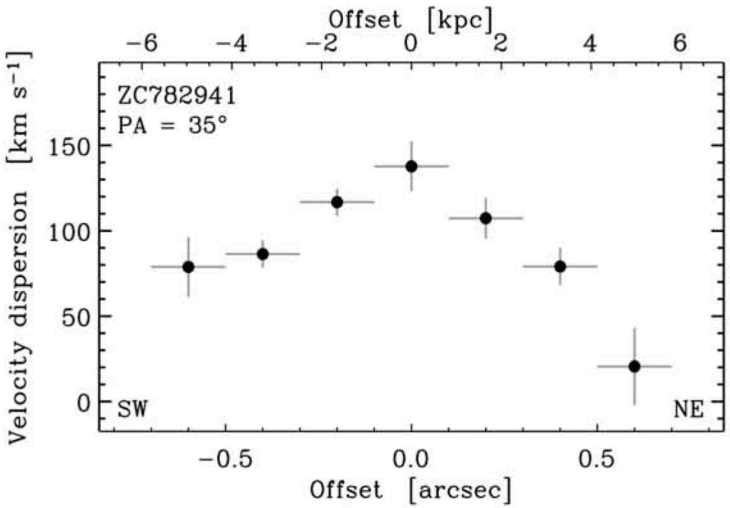










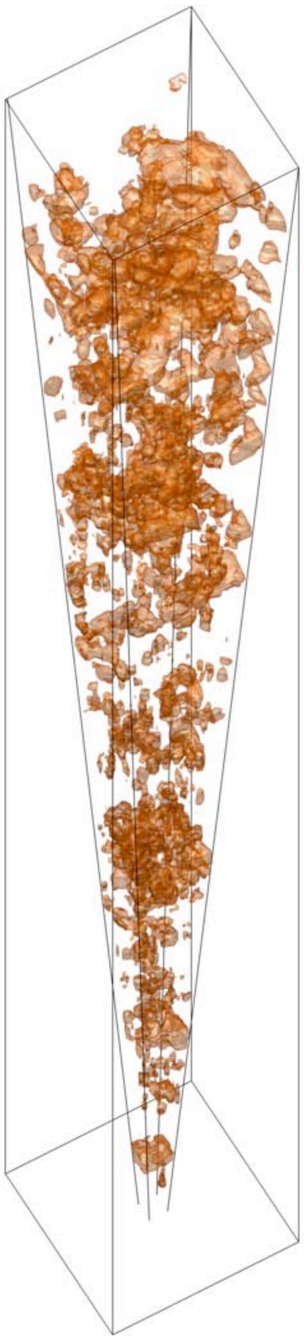


v_c=260 kms^{-1}
σ_{1d} = 135 kms^{-1}
$r_{1/2}$ = 3.0 kpc

$M_{dyn} = 5 \times 10^{10}\ M_\odot$
j = 800 kms^{-1} kpc
SFR (Hα) ~ 60 $M_\odot\ yr^{-1}$ $\rightarrow \tau \sim 10^9$ yr

A large galactic disk at z = 2.18

Gas-rich, turbulent, "blobby" disks with high SFR due to high volume cold flows, disk fragmentation and secular evolution? (Genzel et al 2008)



Summary

COSMOS and zCOSMOS in particular are enabling detailed studies of the links between the formation and evolution of galaxies and their environment.

At $0 < z < 1$:

- Galaxy properties and their evolution with time are clearly very dependent on mass and epoch.
- The Nature vs. Nurture debate is complicated by the clear dependence of galactic mass on environment, which also produces strong "artifical" effects with environment in samples that contain a range of masses (e.g. at fixed L, or even samples above a mass threshold)
- But, the environment also has an effect (at fixed M) but at a weaker level, equivalent to a couple of Gyr of cosmic time and/or 0.25 dex in mass, at z ~ 0.5, over the full range of environments
- The importance of environment (at fixed mass) grows with time due to a faster "transition rate" in dense environments at z < 1, especially clearly seen in groups.

At z ~ 2:

- Massive gas-rich disks display different properties to those today, turbulence, dynamical instabilities etc.
- Environmental effects will soon be explorable