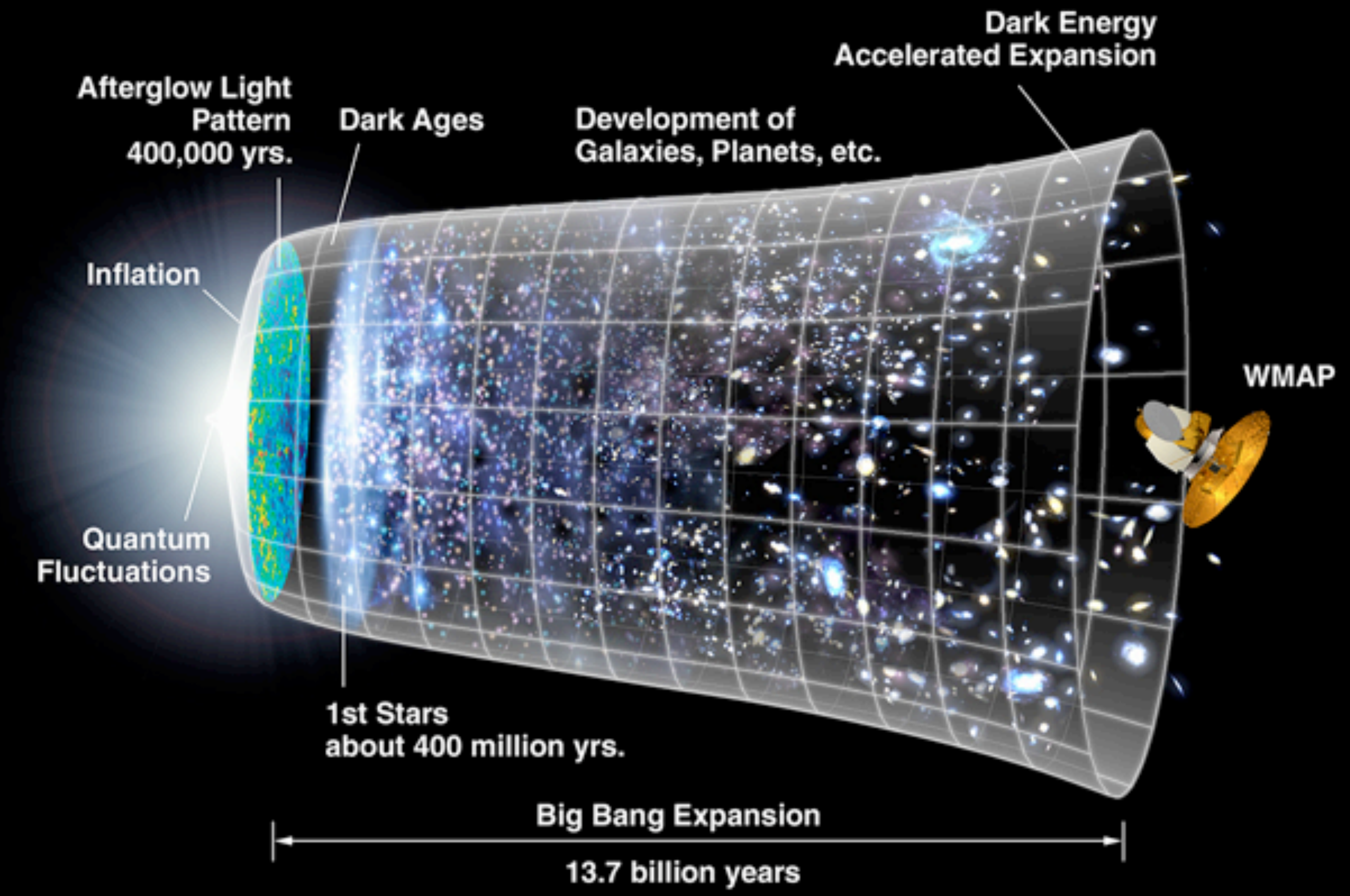
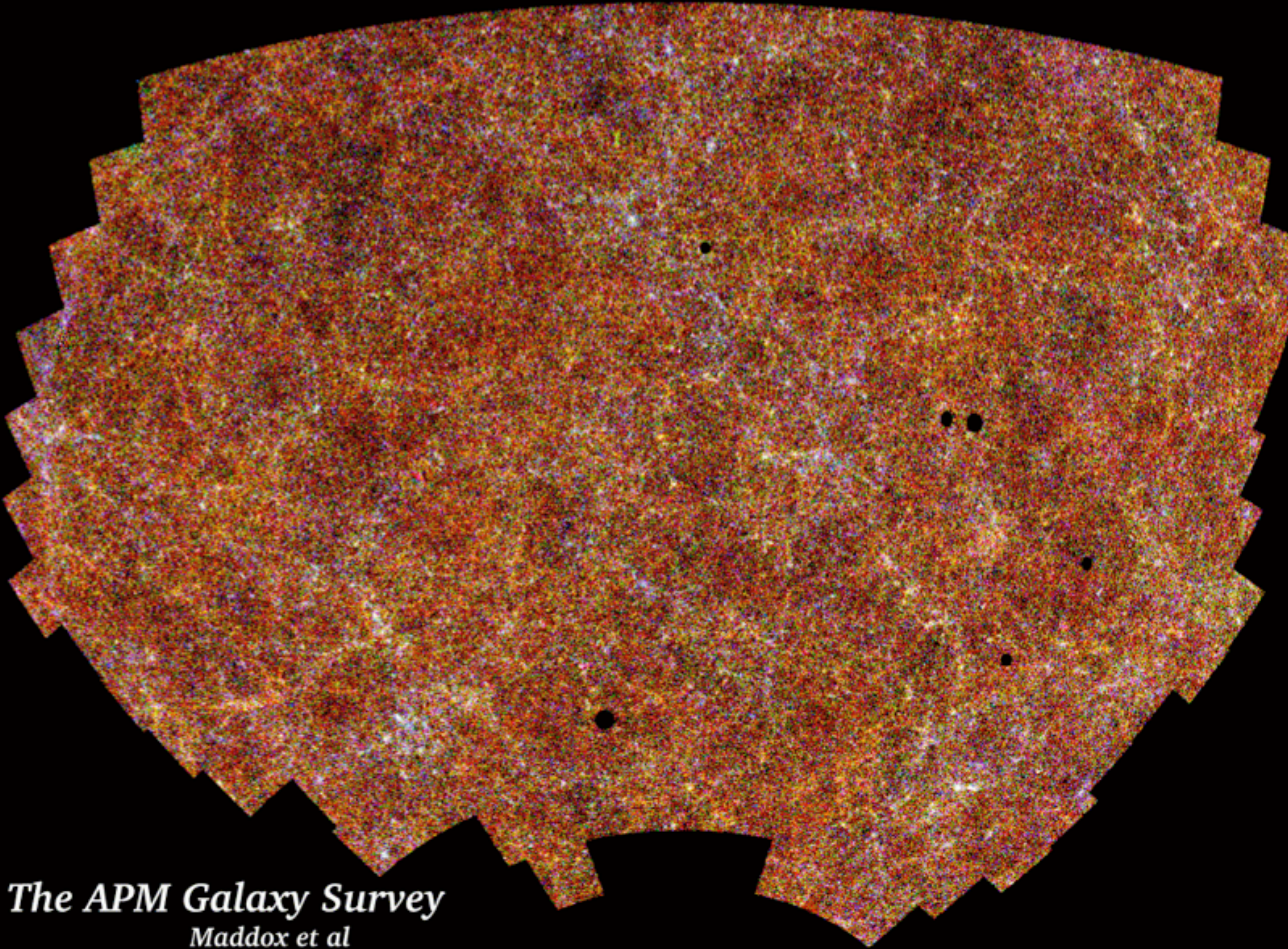
Massive galaxies at z~2 in the COSMOS-WIRCAM survey

H.J. McCracken and the COSMOS consortium

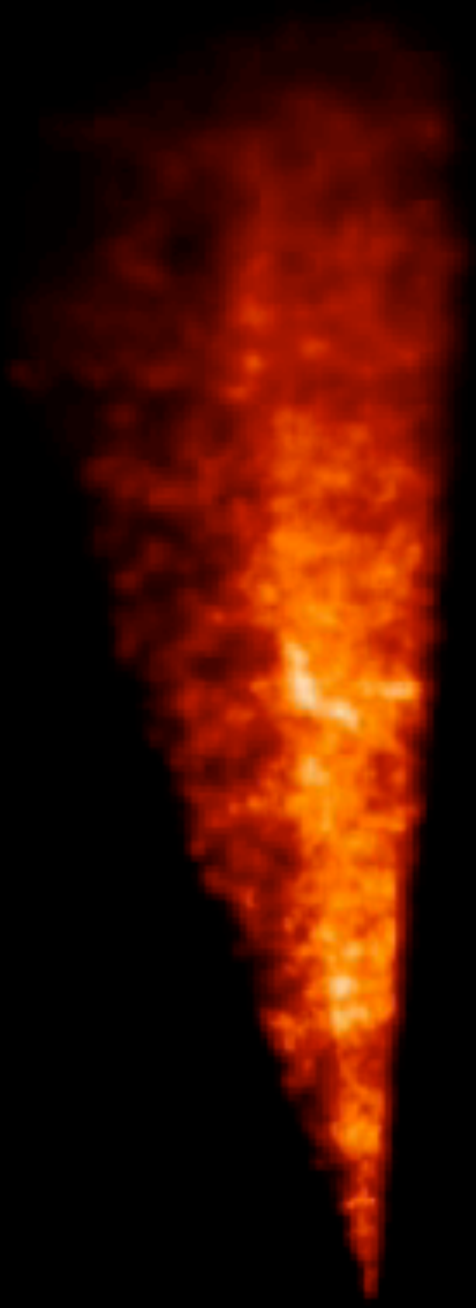


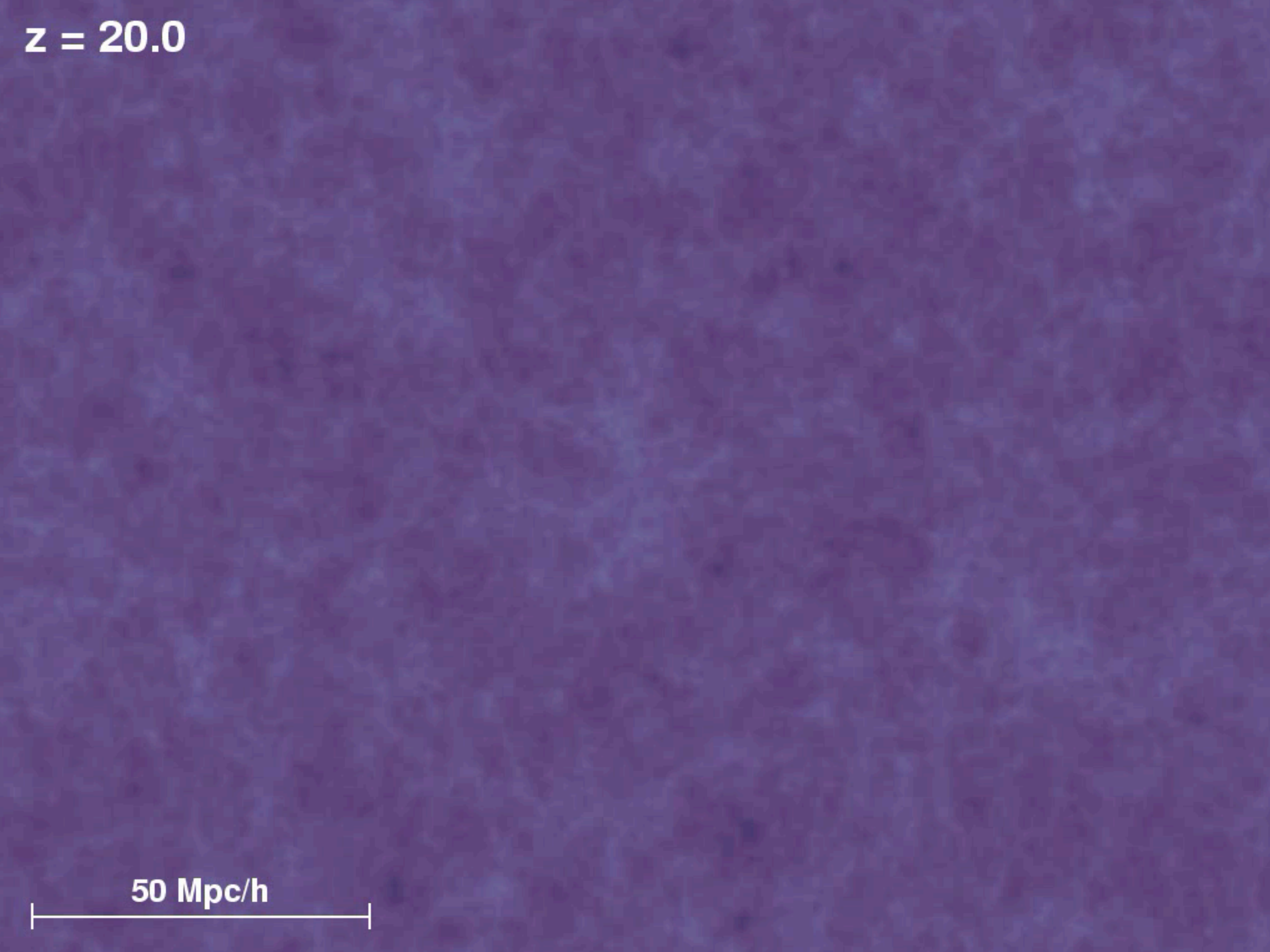
NASA/WMAP Science Team



The APM Galaxy Survey

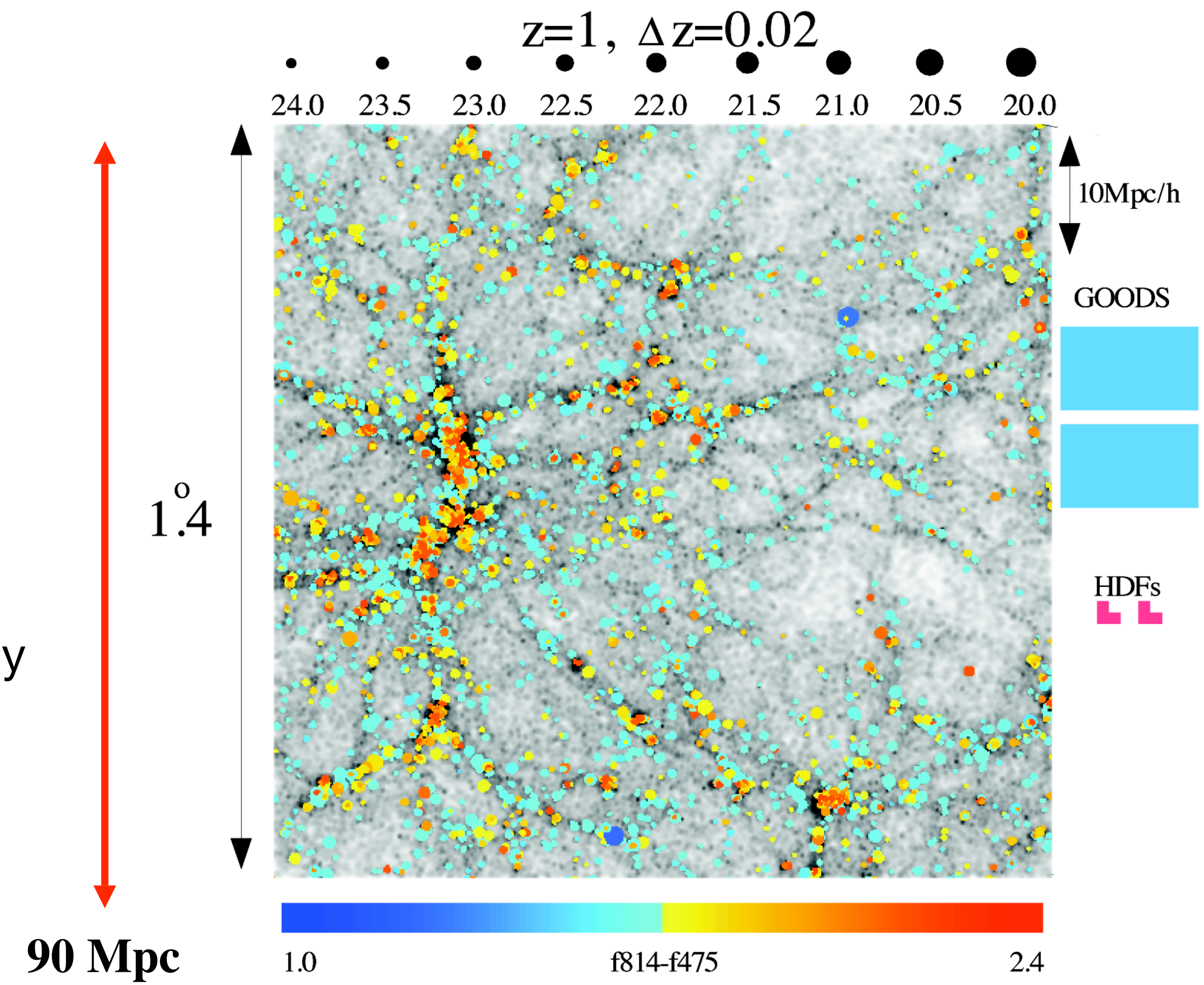
Maddox et al



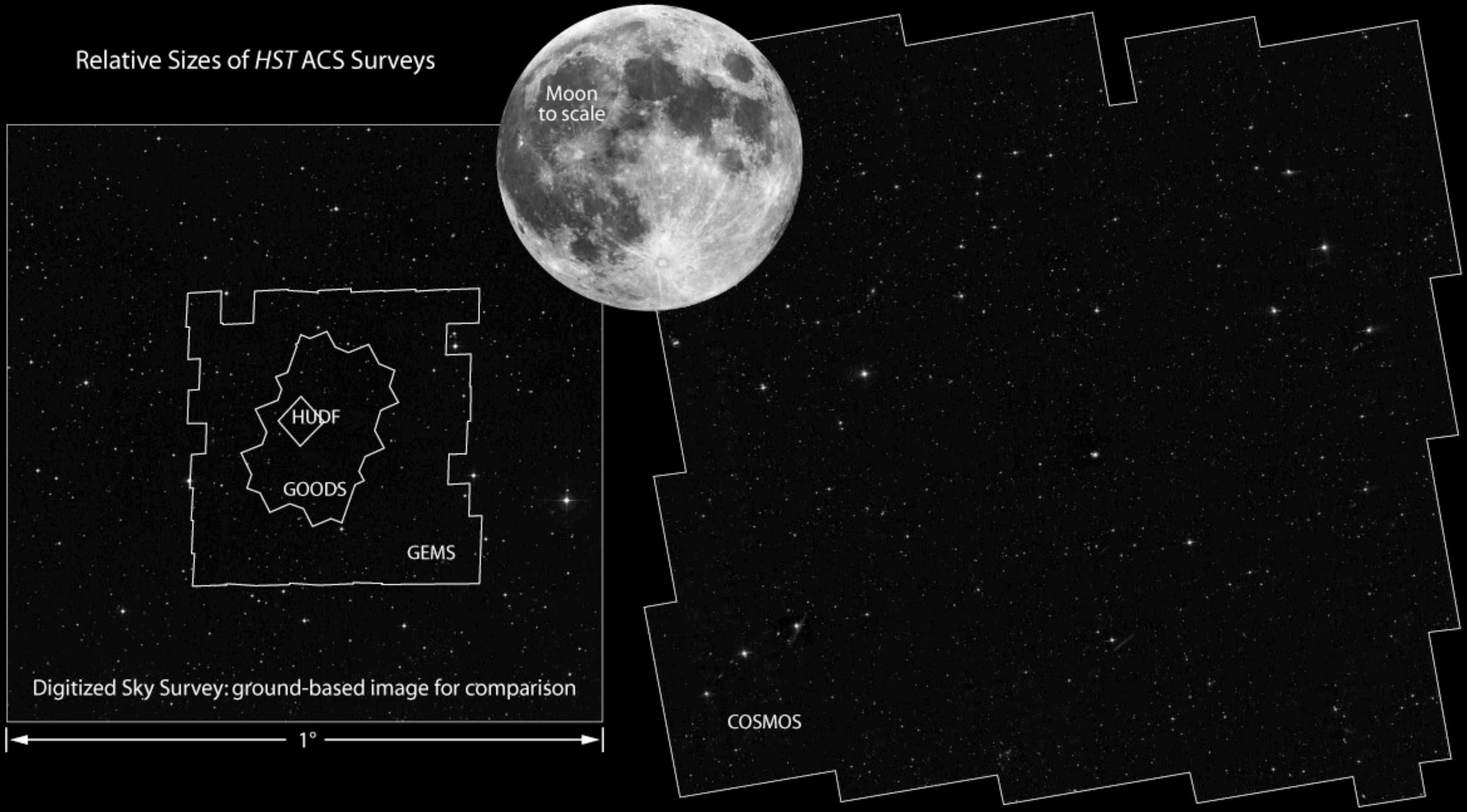

z = 20.0
50 Mpc/h

The COSMOS survey: probing structures at z~1

- How does the galaxy formation process depend on environment?
- How do structures evolve over cosmic time?
- What is the relationship between the dark matter and the luminous matter?
- Previous deep HST-based surveys were dominated by **cosmic variance** and did not probe a representative slice of the Universe
- COSMOS provides ACS morphologies

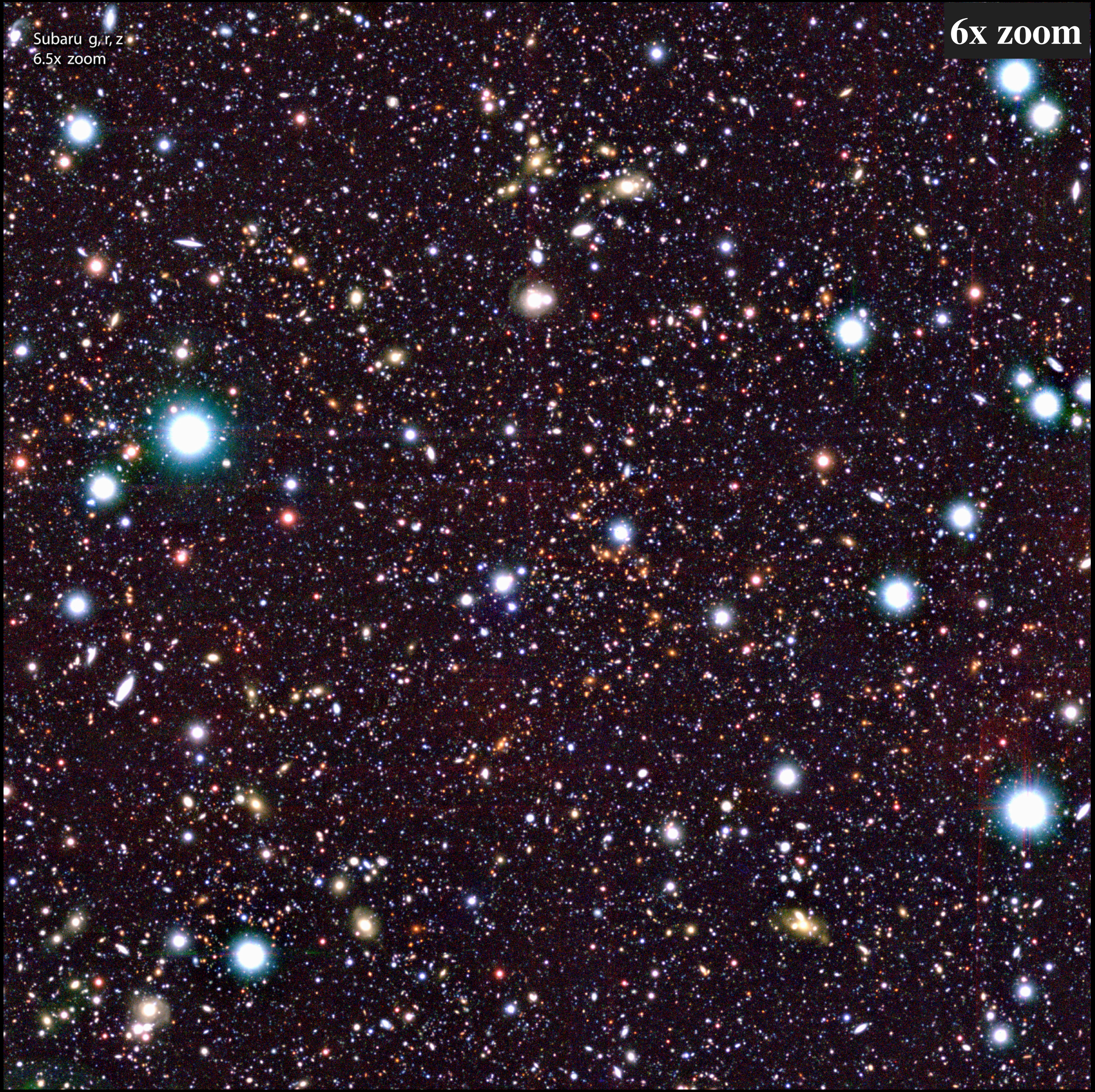


COSMOS: ACS (PI: N. Z. Scoville)



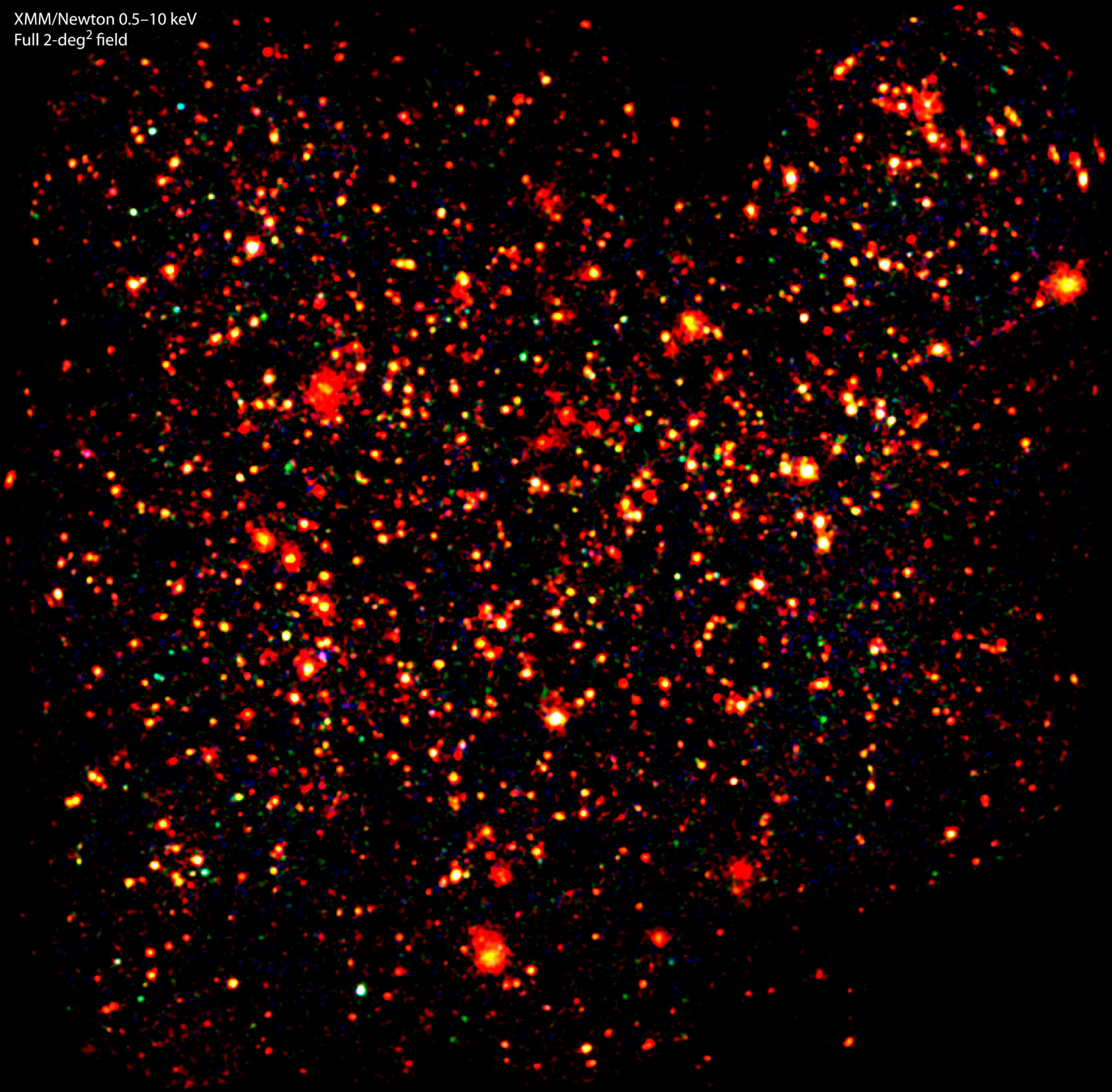
2 deg^2 : 9x larger than any previous HST image
575 orbits (10% of HST time for two years!)
9x larger than any previous HST image

Subaru 8m
PI: Y. Taniguchi
35 nights



Ultra-deep optical imaging;
35 broad and narrow bands

XMM
PI: G. Hasinger
1.4 Msec



X-ray bands
Diffuse emission: hot gas and clusters

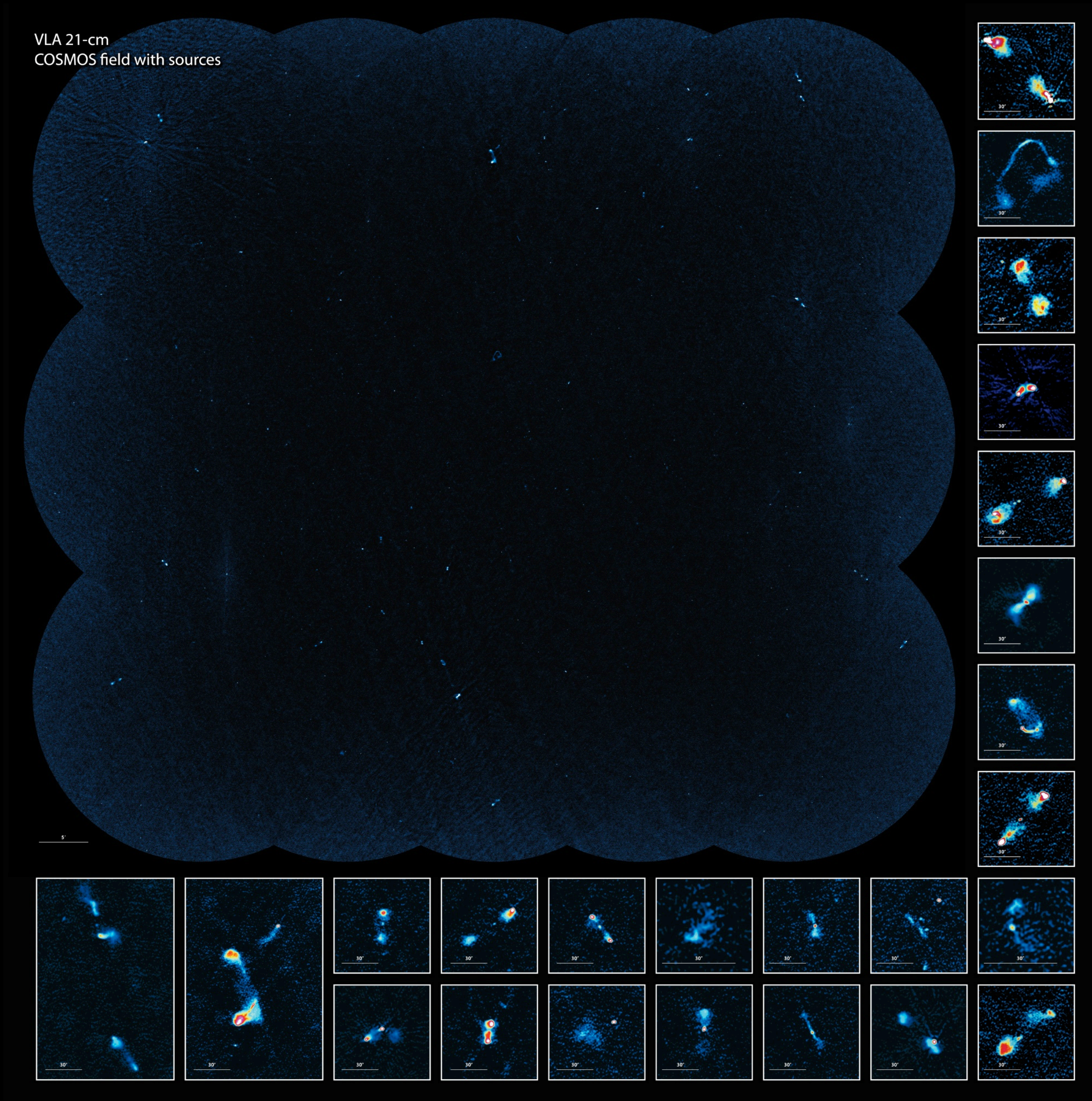
Spitzer IRAC
PI: D. Sanders
600hrs w/MIPS

VLA

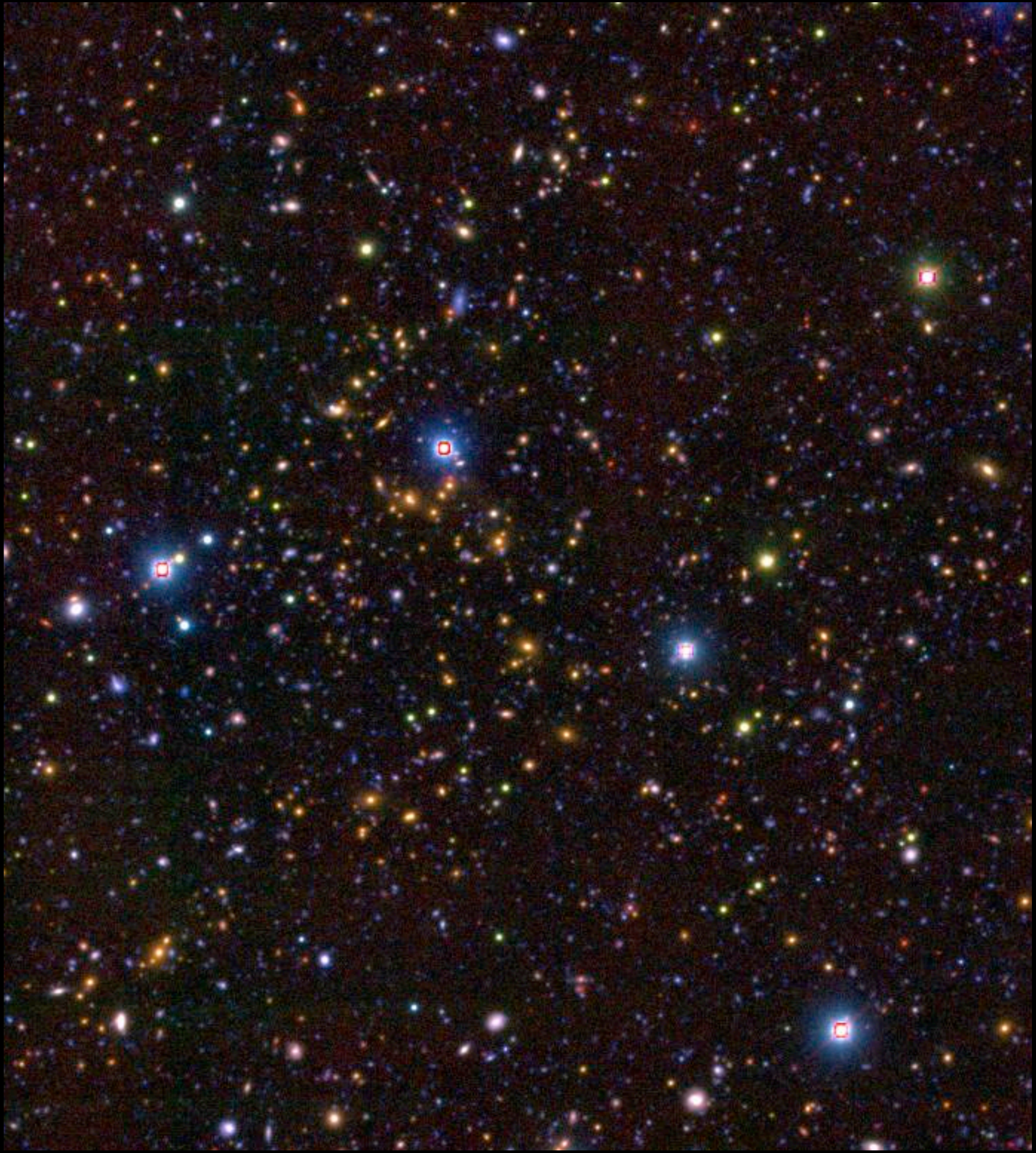
PI: E. Schinnerer

300hrs

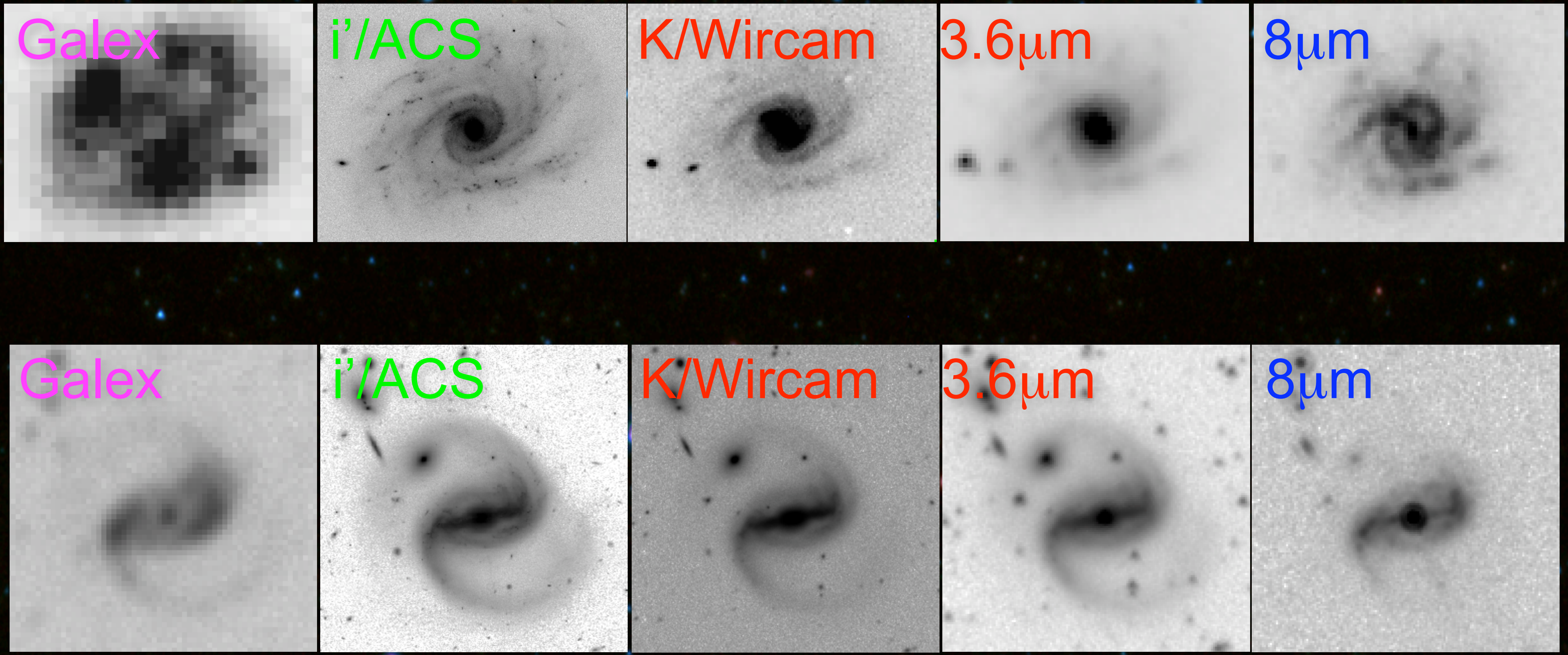
7-10 µJy



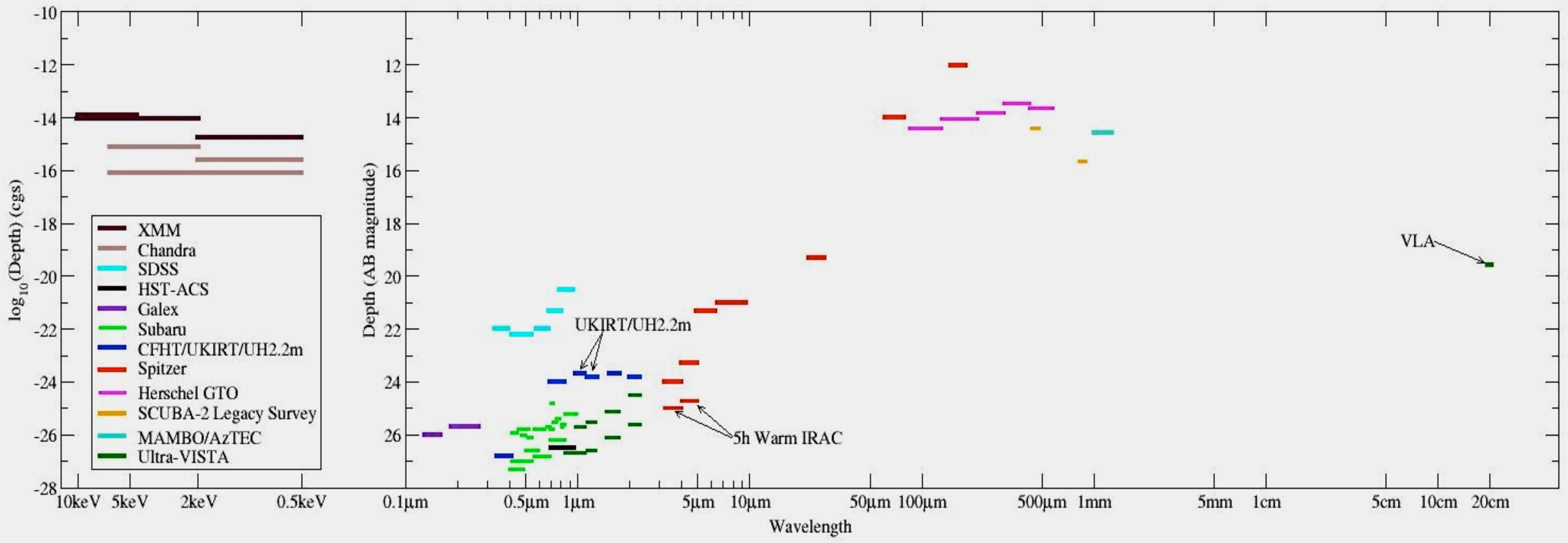
Near IR JHK
KAB~23.8 (5sig)
PIs: Sanders,
Willot, Kneib



3x size of UKIDSS UDS
0.5 mag. deeper

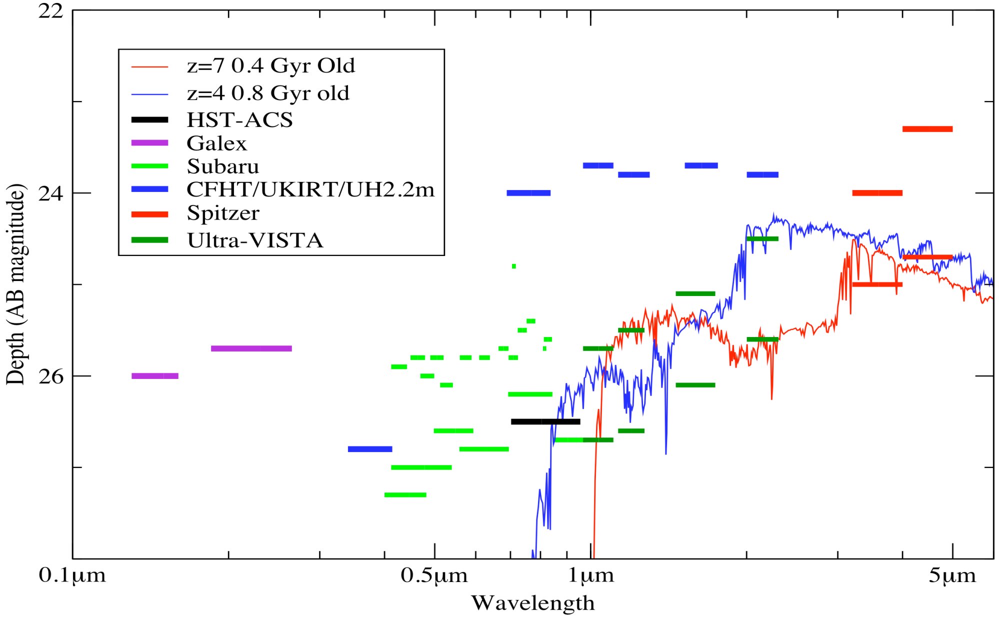

Galex
i'/ACS
K/Wircam
3.6μm
8μm
Galex
i'/ACS
K/Wircam
3.6μm
8μm

Summary of COSMOS multi-wavelength coverage



5 σ
3'' apert.

Capak et al. 08



Photometric redshifts: a cheap way to get galaxy distances (Ilbert et al. 2006,8 and Coupon et al. 08)

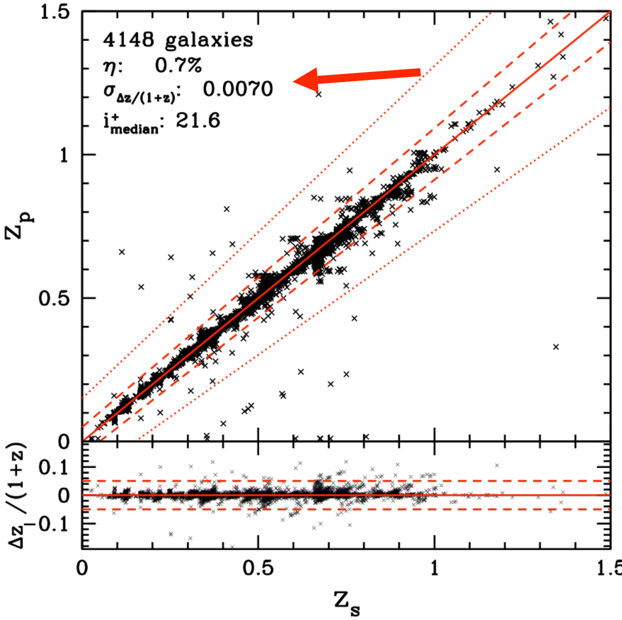
$$\chi^2(z,T,A) = \sum_{f=1}^{N_f} \left(\frac{F^f_{\rm obs} - A \times F^f_{\rm pred}(z,T)}{\sigma^f_{\rm obs}} \right)^2 ,$$

- “Photometric redshifts” are computed by comparing observed spectral energy distributions with a set of template SEDs.
    - For many years the accuracy of photometric redshifts was difficult to assess because of the lack of large (>10k objects) spectroscopic training sets (it turned out that a lot of photo-zeds computed without training sets were actually wrong!)
- Wide-field cameras with precise photometric calibration (like Megacam) combined with wide field spectrographs producing training sets of ~10k galaxies (like VIMOS) makes estimating photometric redshifts for millions of galaxies with percent-level accuracy possible

COSMOS 30-band photo-zeds (Ilbert et al. 08)

Bright (<22.5)

zCOSMOS bright i^+_{AB}<22.5

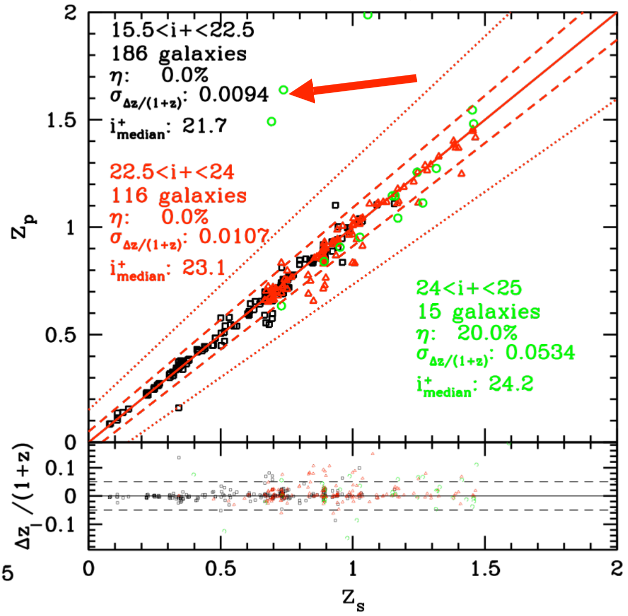


IR-selected

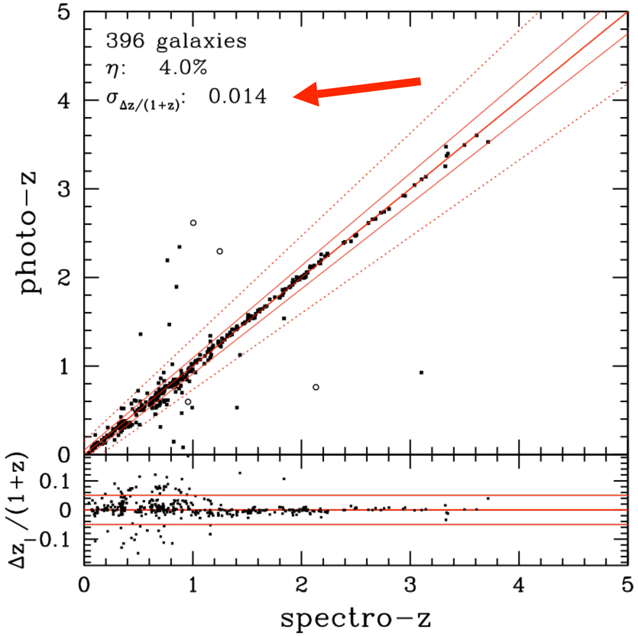
opt. faint (22.5 – 24)

24 – 25 mag I

Infrared selected ($F_{24\mu m}$> 60 μJy)

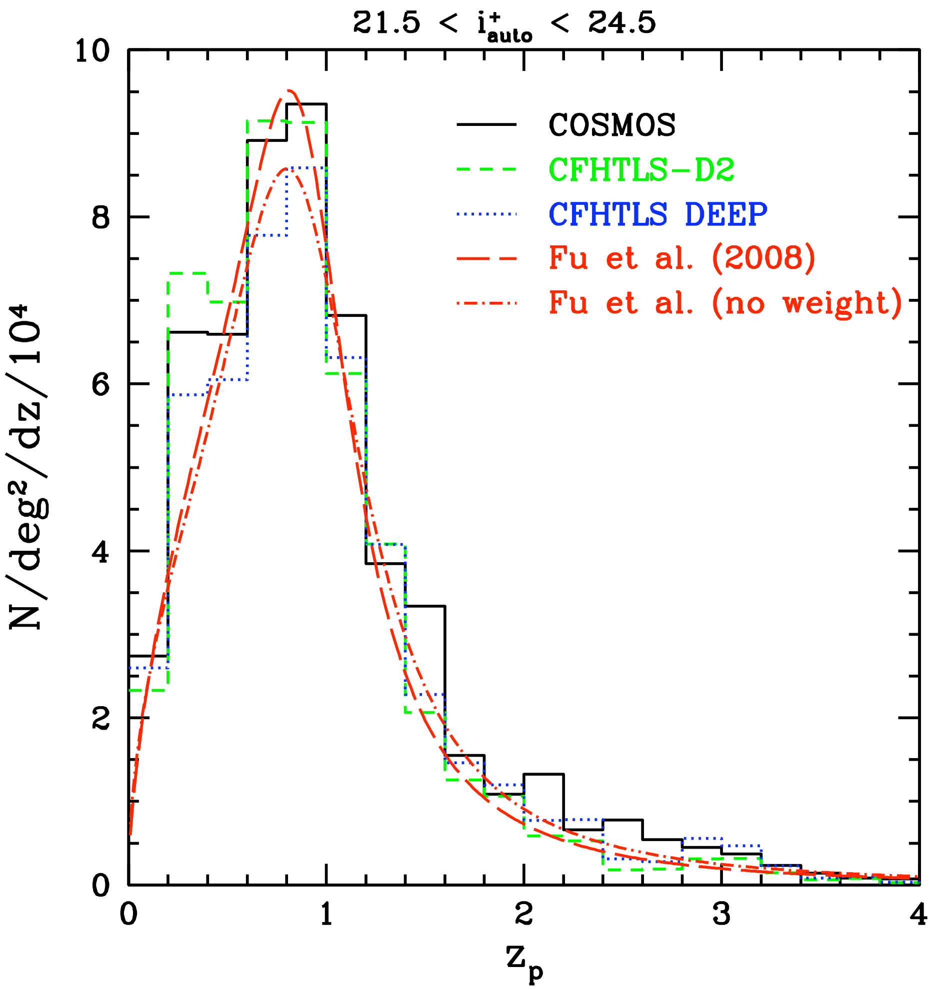


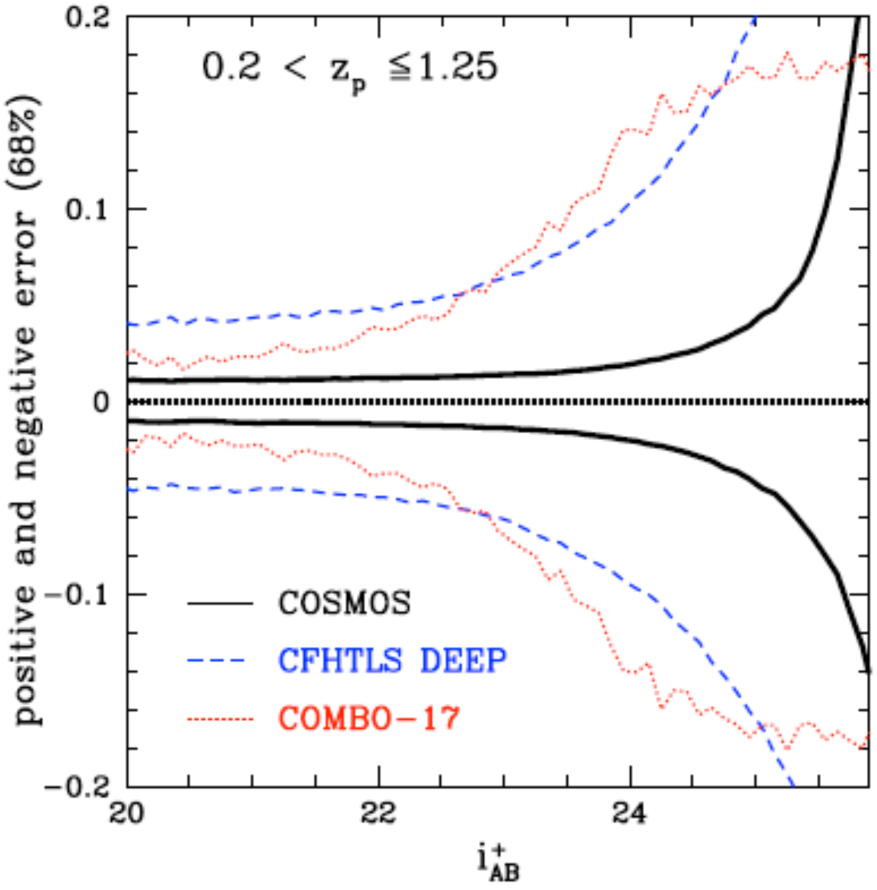
X-ray selected AGNs



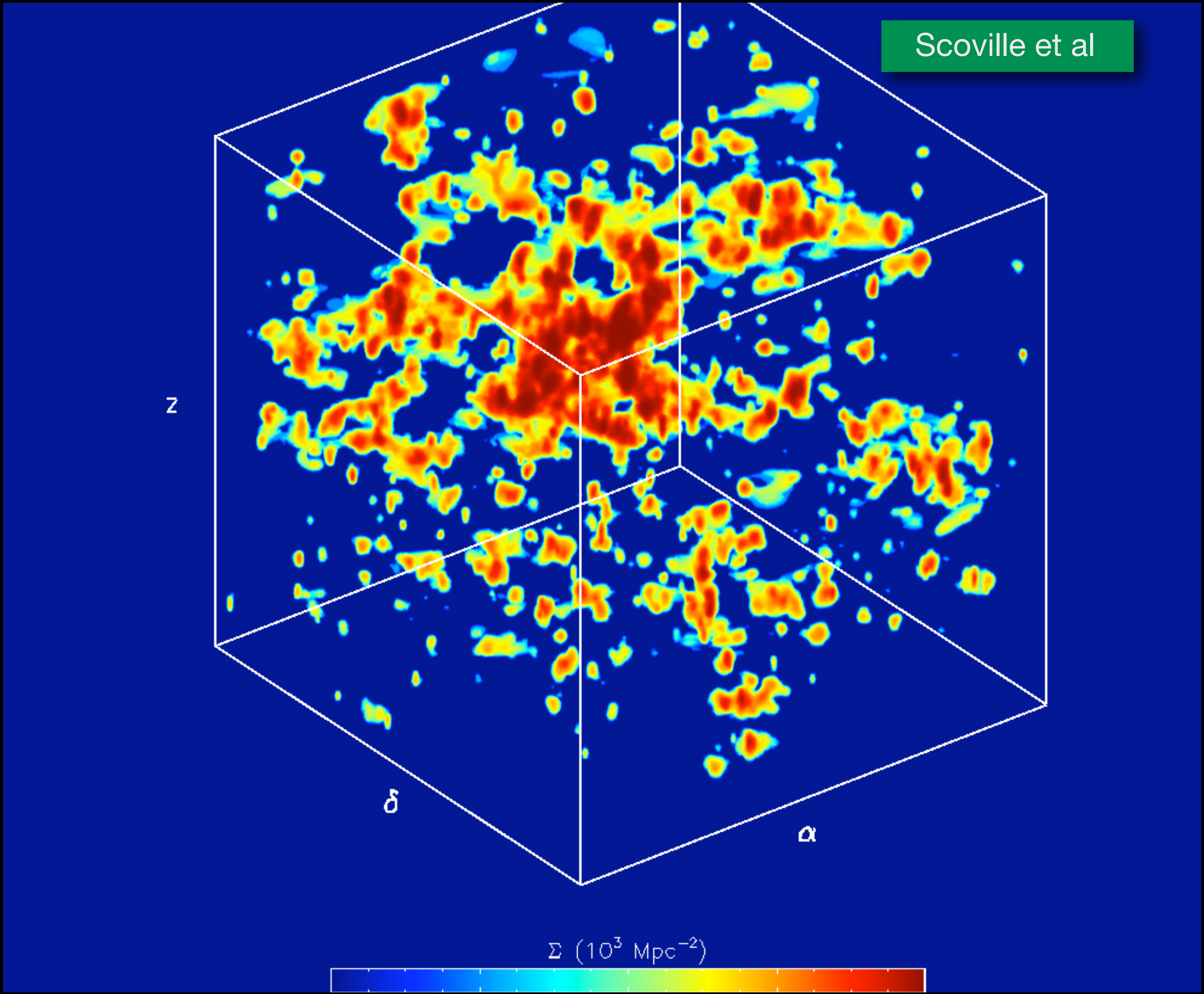
- ~0.7%-1% accuracy photometric redshifts over 0.2<z<1.2
- Large spectroscopic training sample: VLT/zCOSMOS (Lilly); also smaller samples from Magellan (Trump); and Keck (Capak)

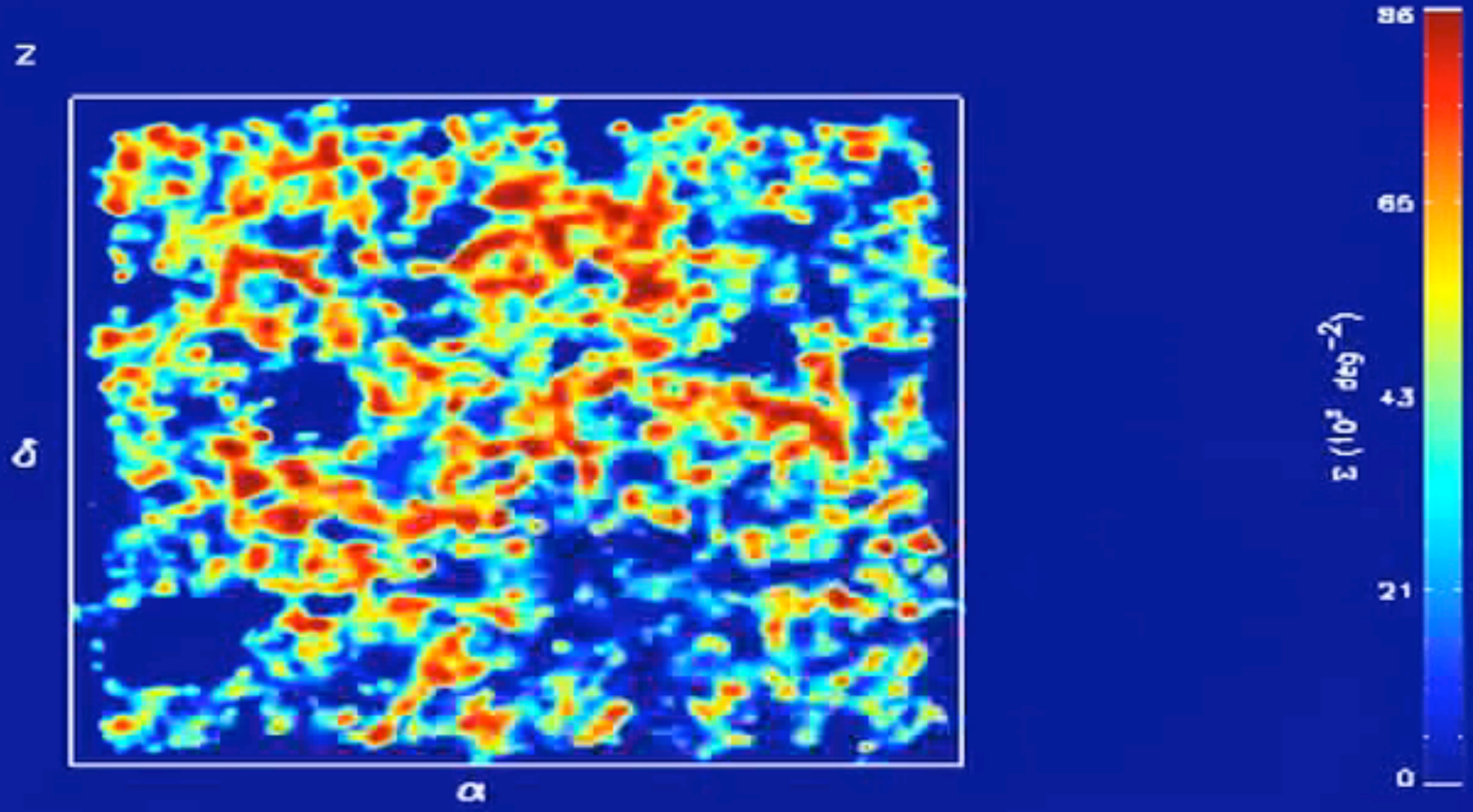
N(z) and photometric redshift accuracy



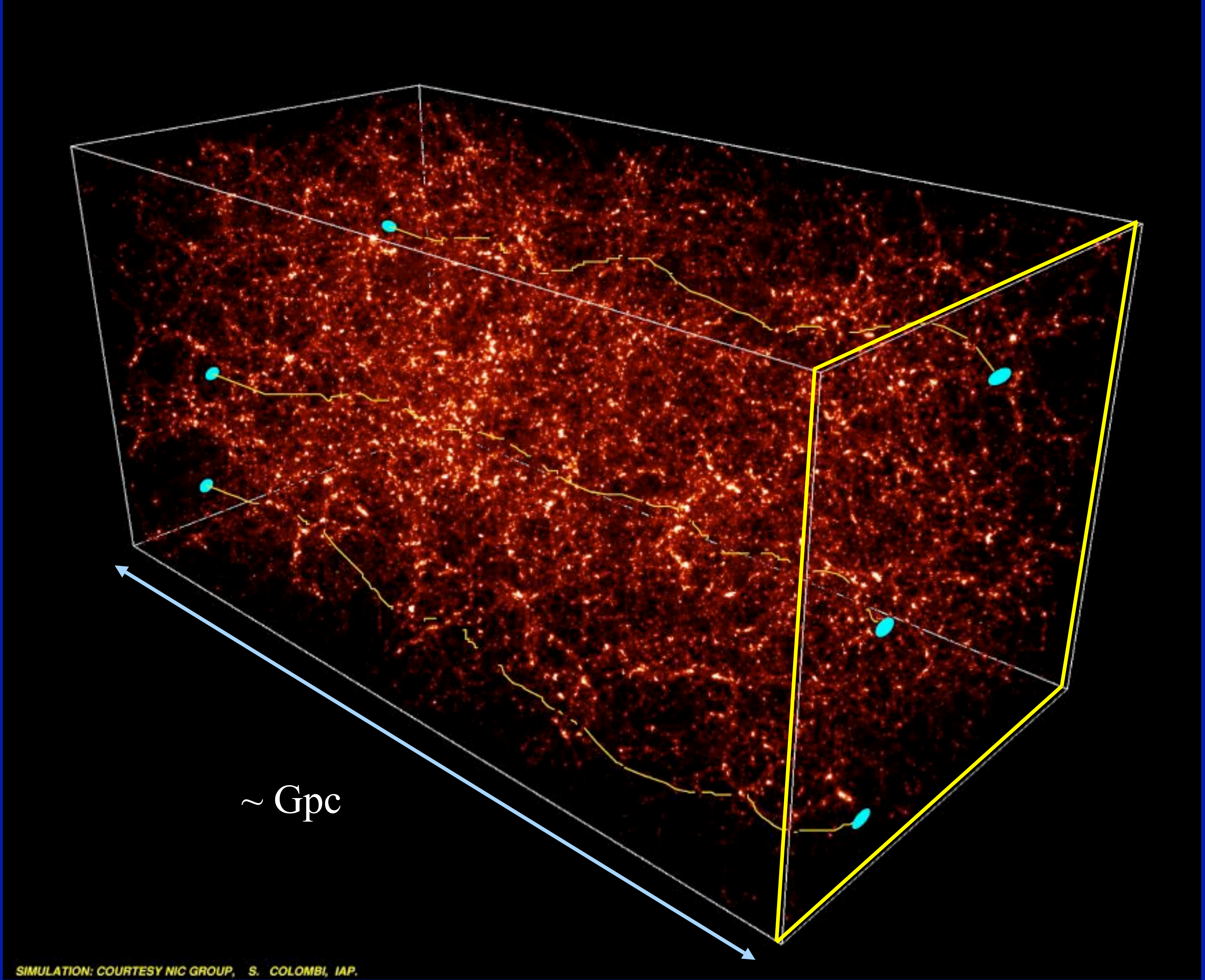


Scoville et al



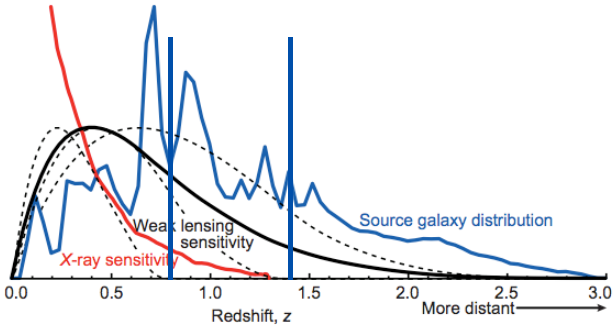

z
δ
α
86
65
43
21
0
Σ (10³ deg⁻²)

Cosmic shear : propagation of light through the cosmic web

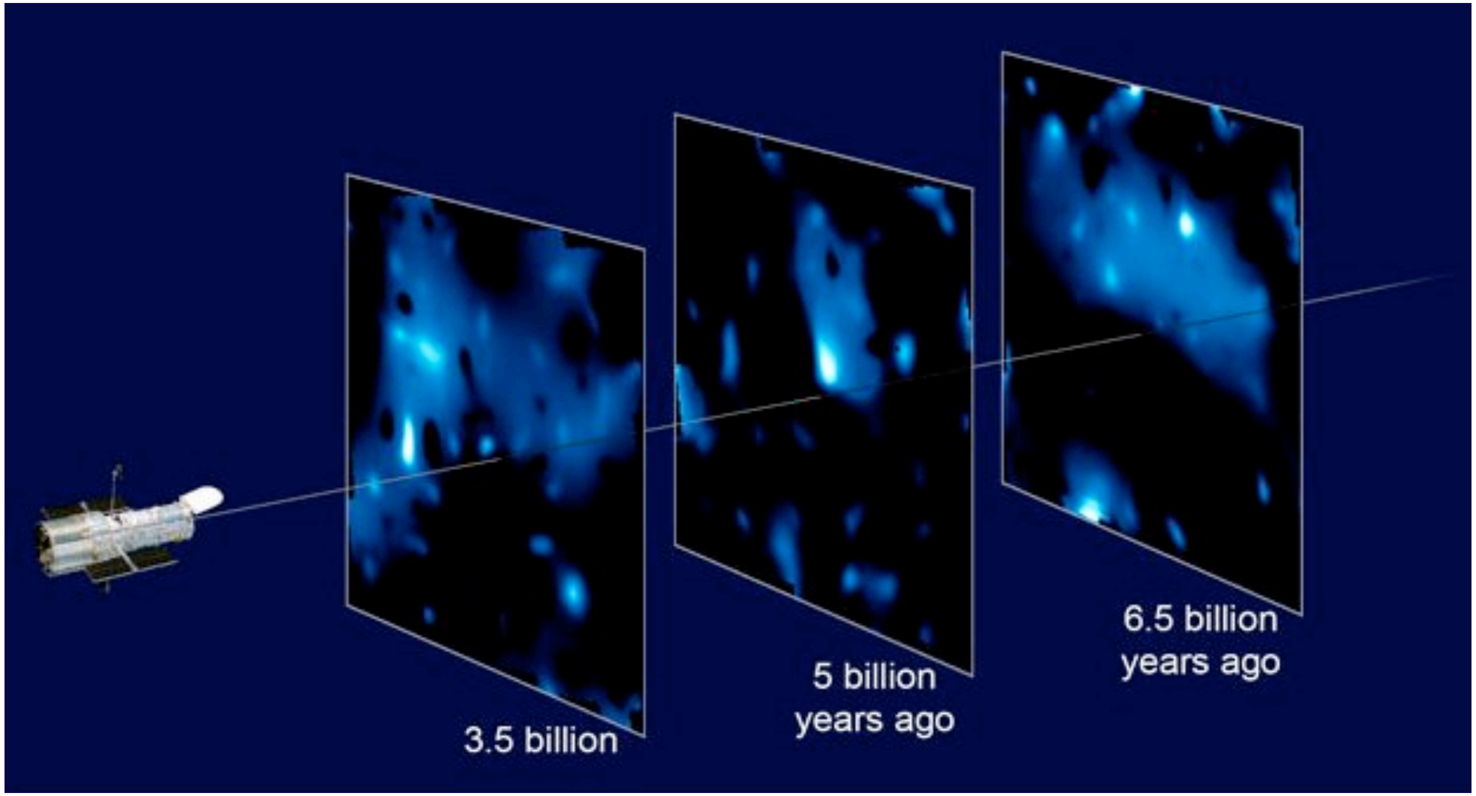


SIMULATION: COURTESY NIC GROUP, S. COLOMBI, IAP.

Mapping the distribution of dark matter (Massey et al., Nature)



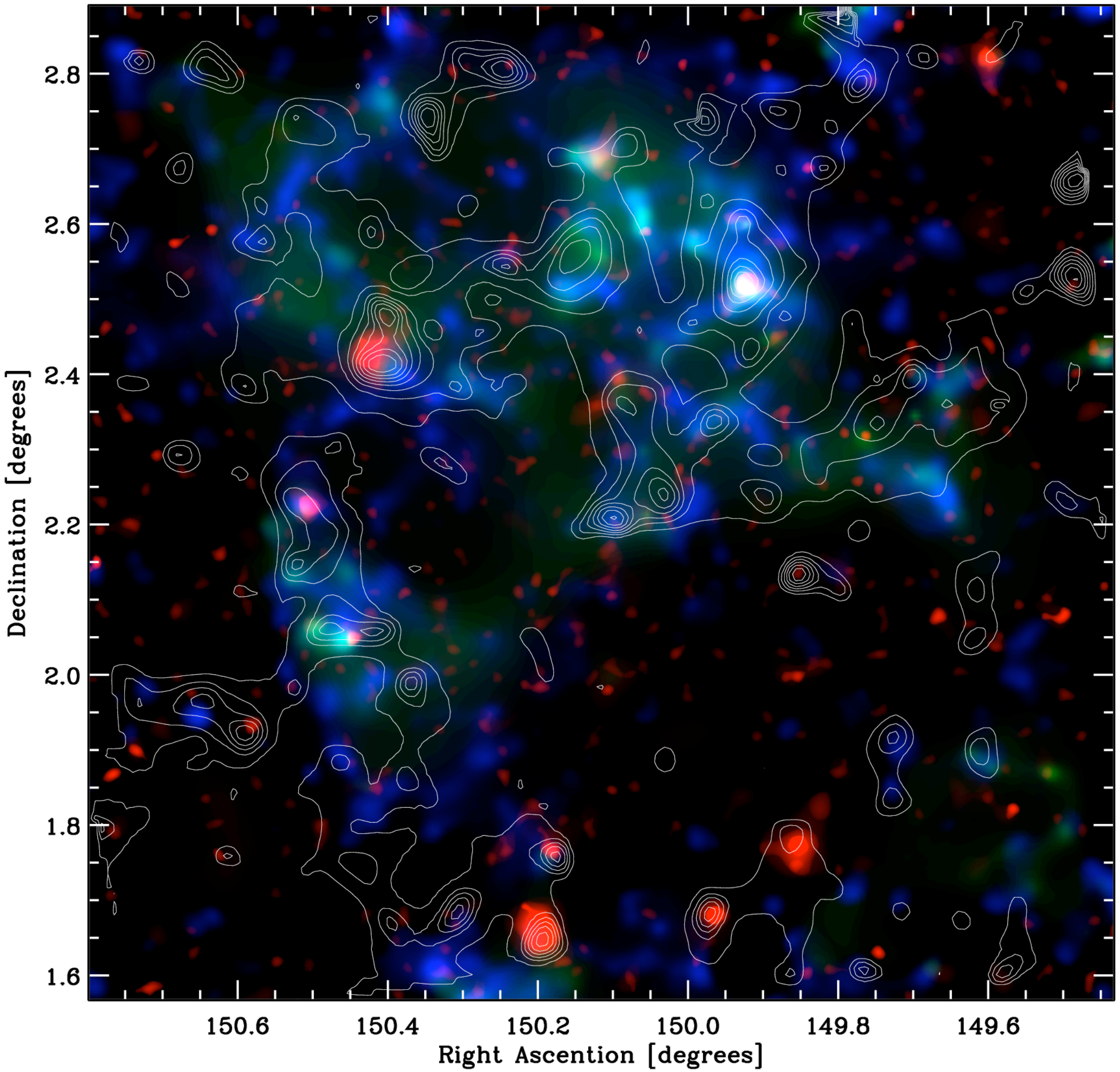
- COSMOS represents a unique combination of multi-wavelength data and ACS morphologies
- Shape measurements can tell us where the dark matter is
- Photo-zeds allow us to ‘slice’ the dark matter distribution



The COSMOS mass / galaxy map

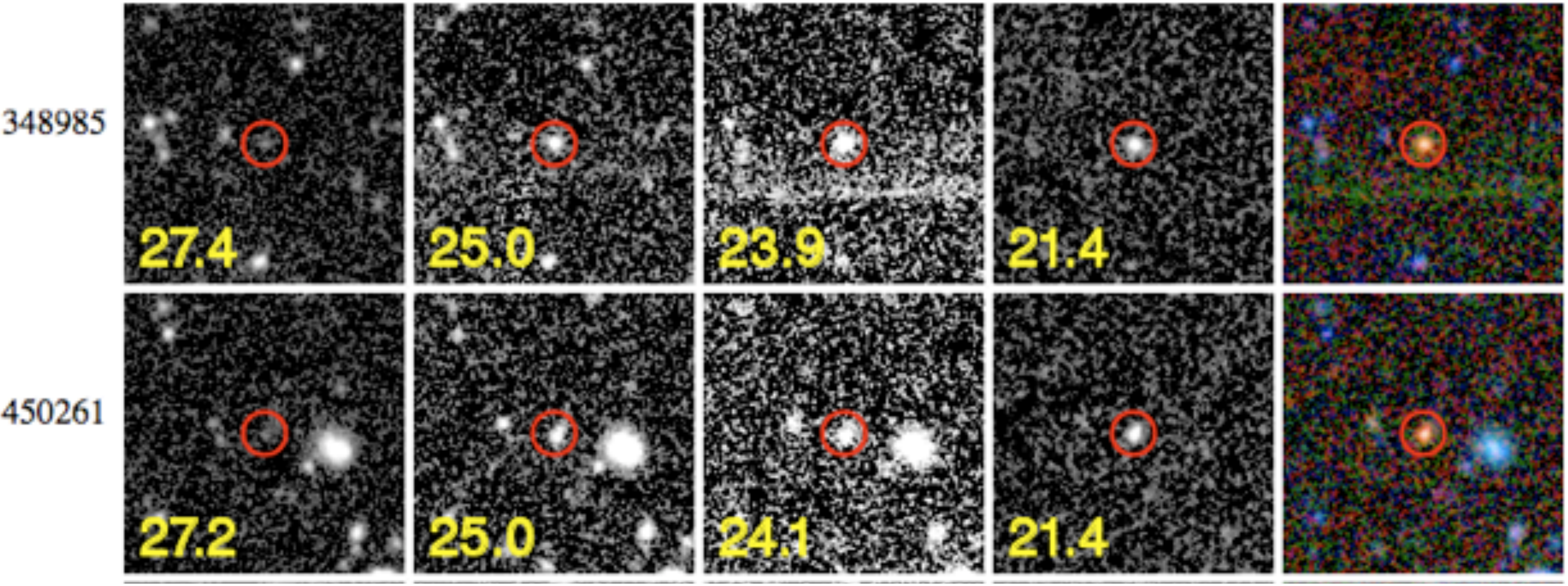
- Blue: galaxies
- Red: x-ray emission
- Contours: Dark matter lensing map

- Only possible thanks to the combination of ACS morphologies, precise photo-zeds and deep X-ray images



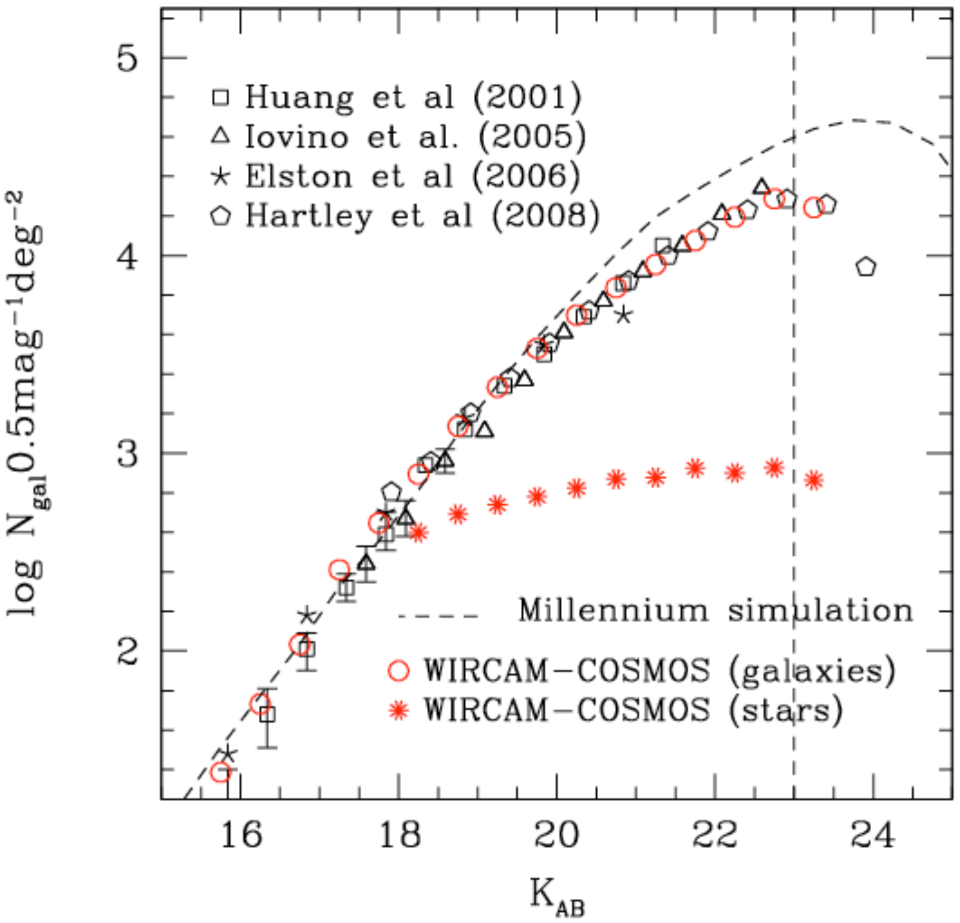
Why we need K-selected catalogues

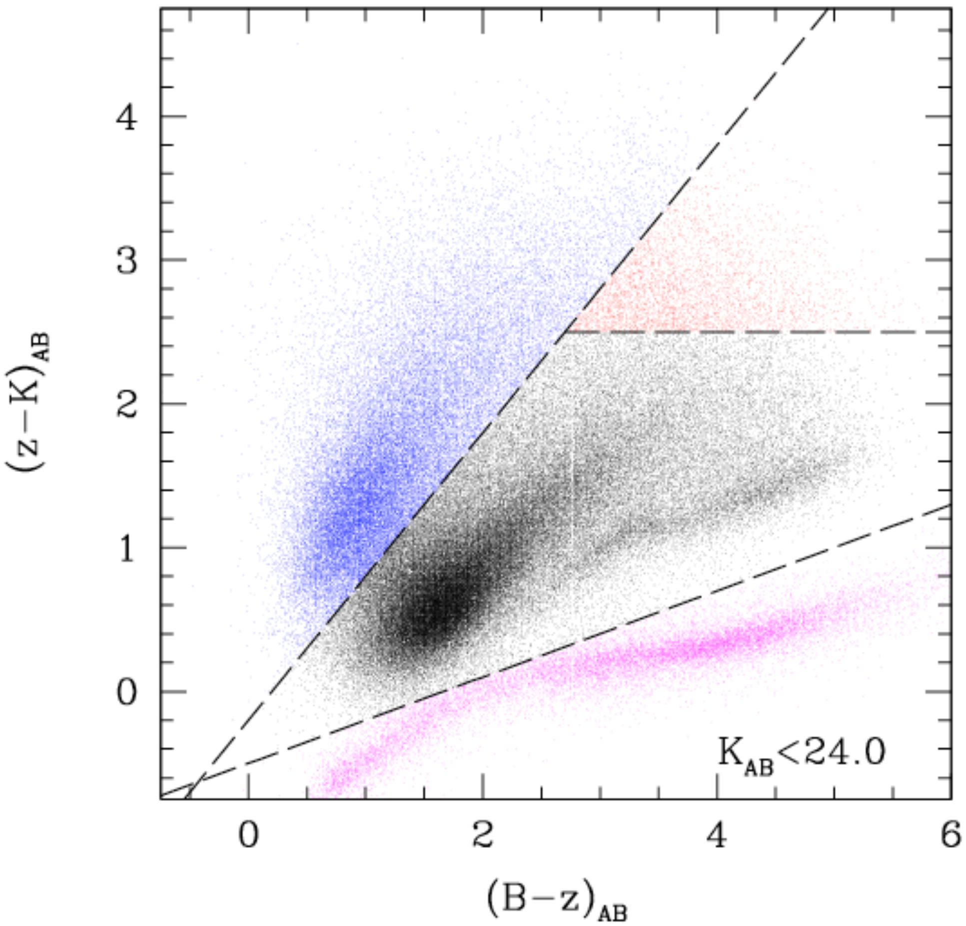
- Optical surveys cannot detect dust-obscured galaxies
- Near-IR selected can detect old, passive galaxies; these pose the most problems for our current theories of galaxy formation!
- Optically-selected samples provide a poor estimate of the underlying stellar mass (they probe the rest-frame UV) at z>1.



- At the faint end there is now very good agreement between surveys
- BzK diagram is a relatively model-invariant way to select passive / star forming populations

The K-selected galaxy population in COSMOS





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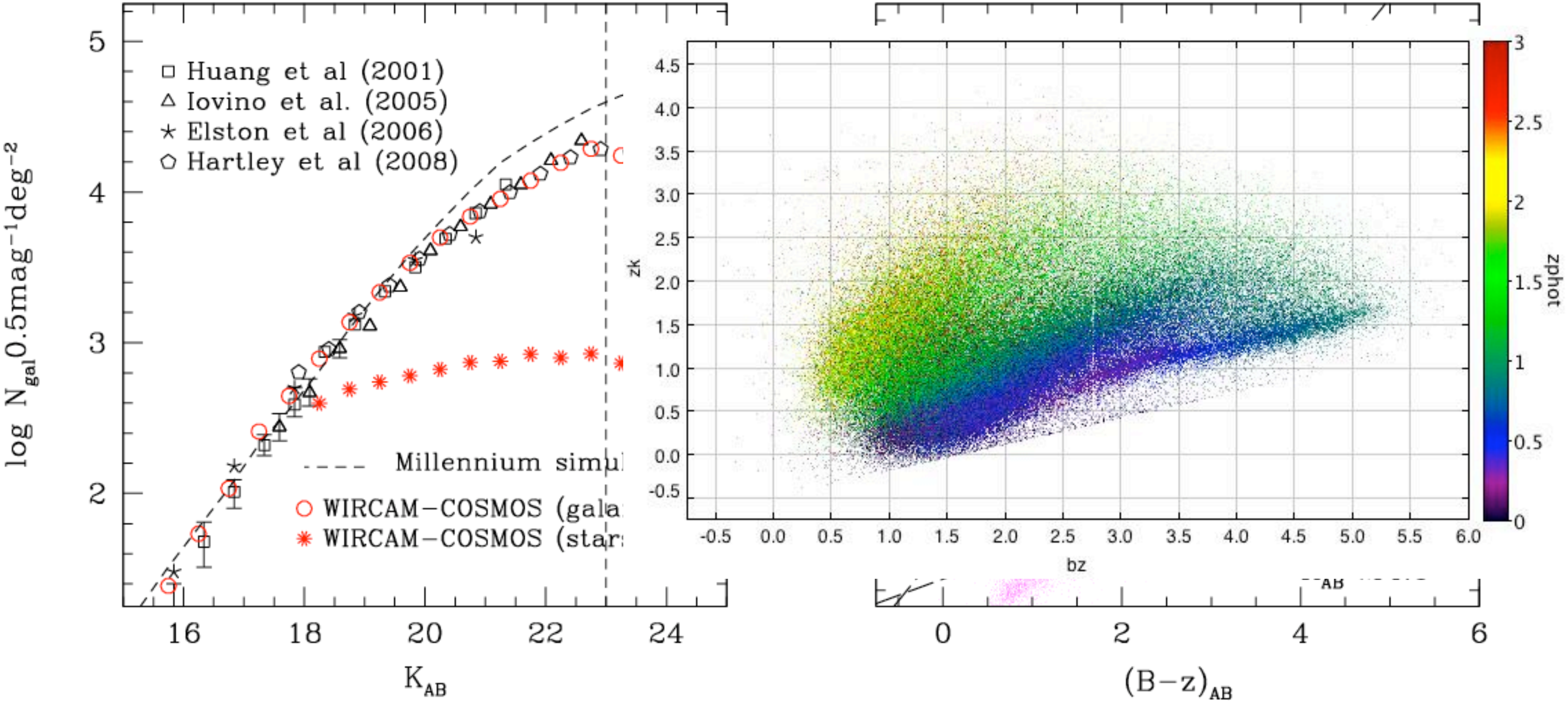

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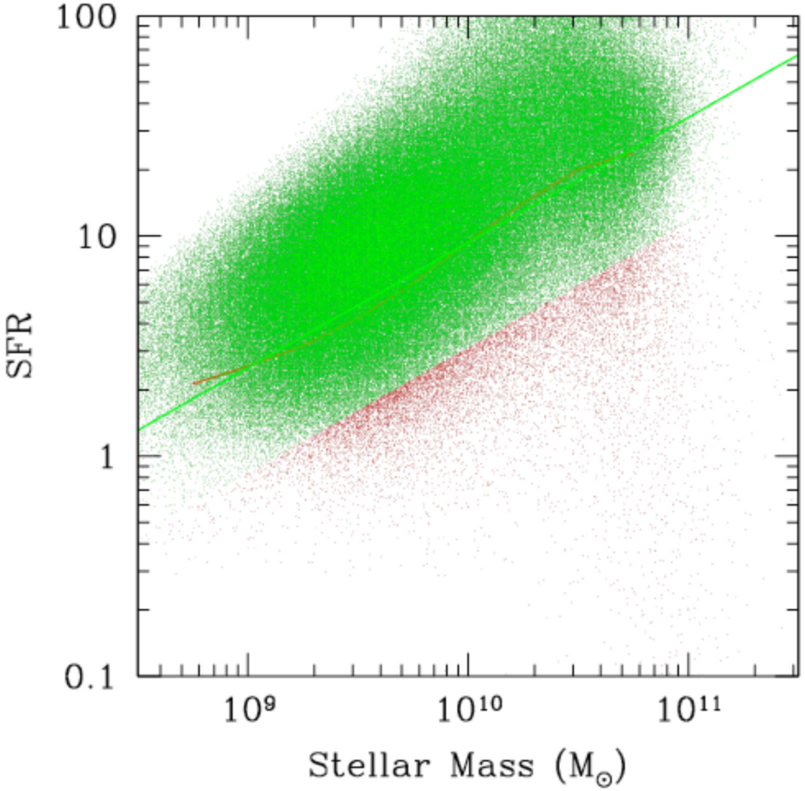
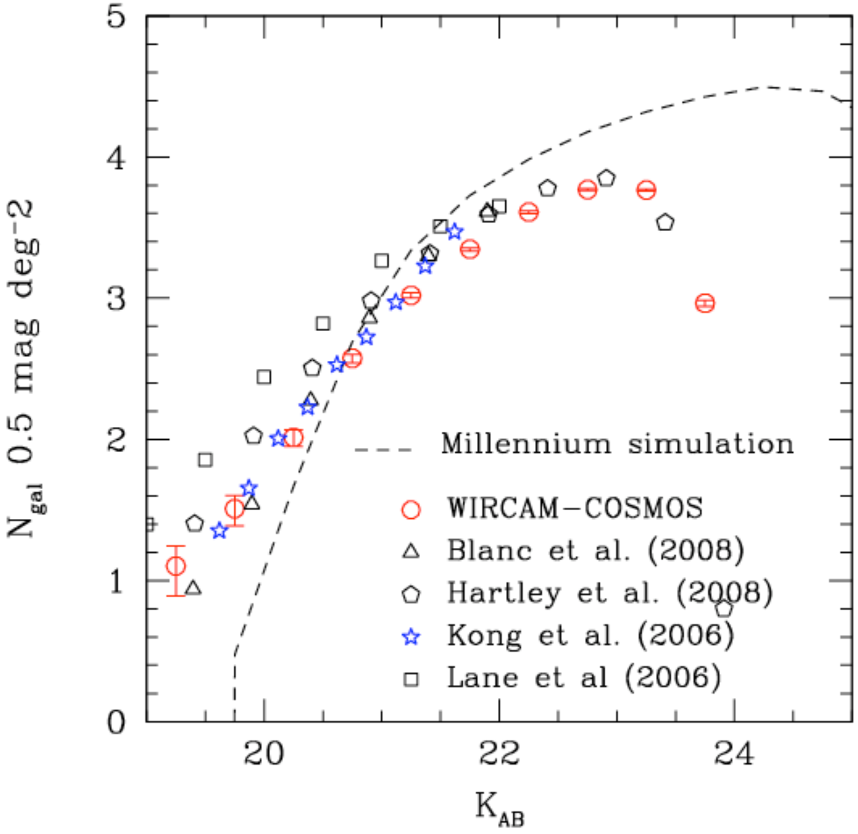
The star-forming galaxy population at z~2

Millennium simulation

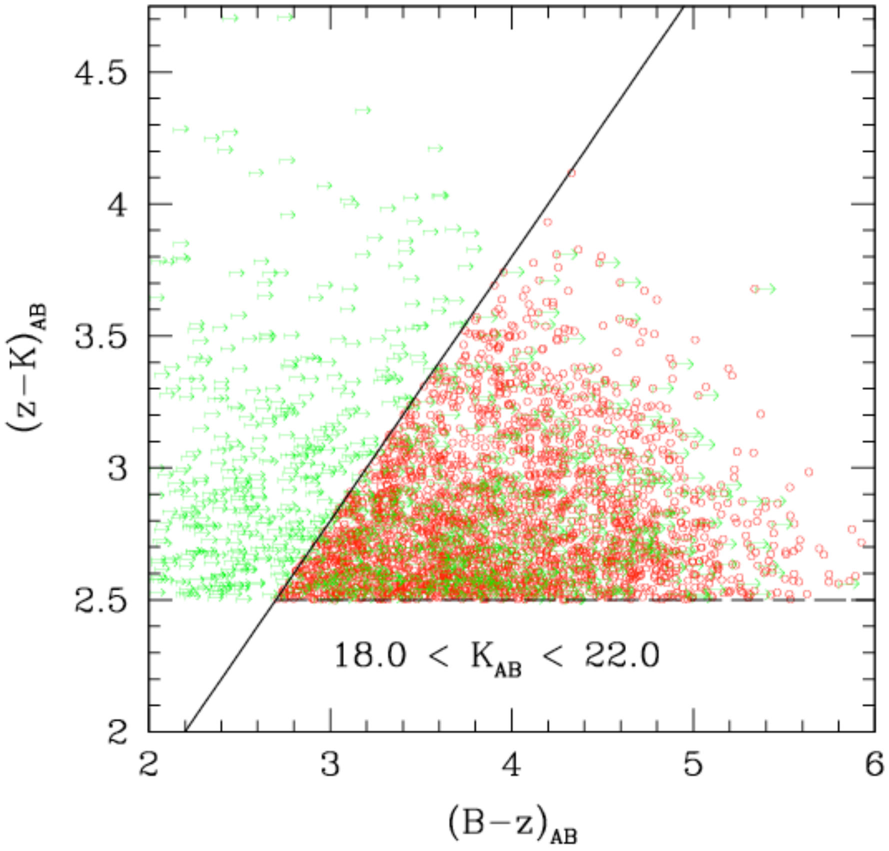


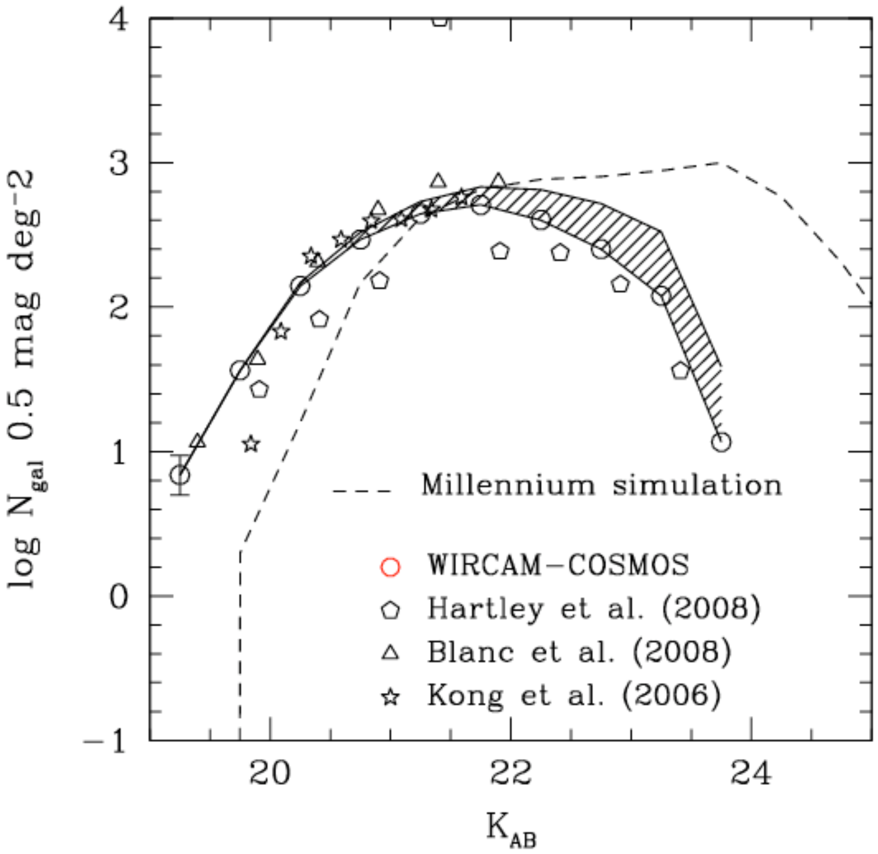
star-forming galaxies



- “BzK” diagram is a highly efficient way to select SF galaxies at z~2
- Millennium simulation **over-predicts** the number of faint galaxies.

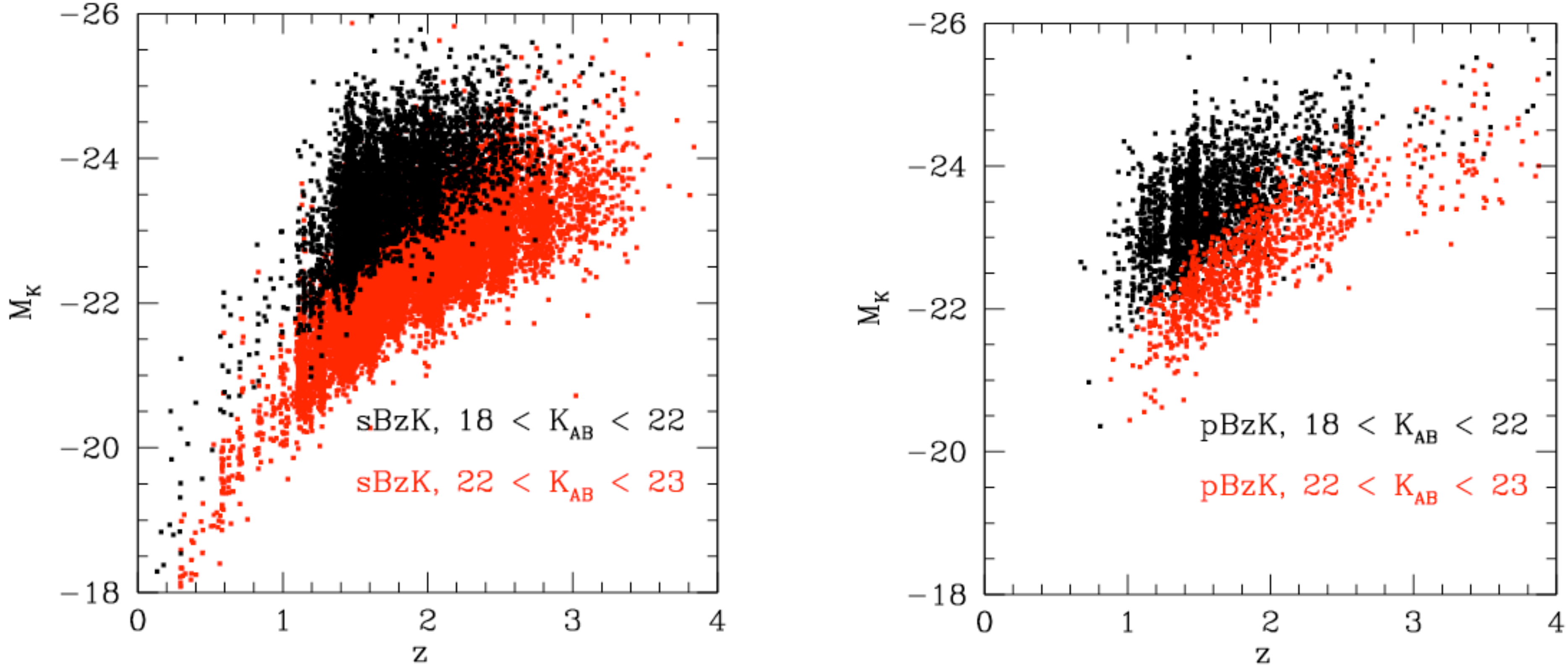
Counts of passive galaxies





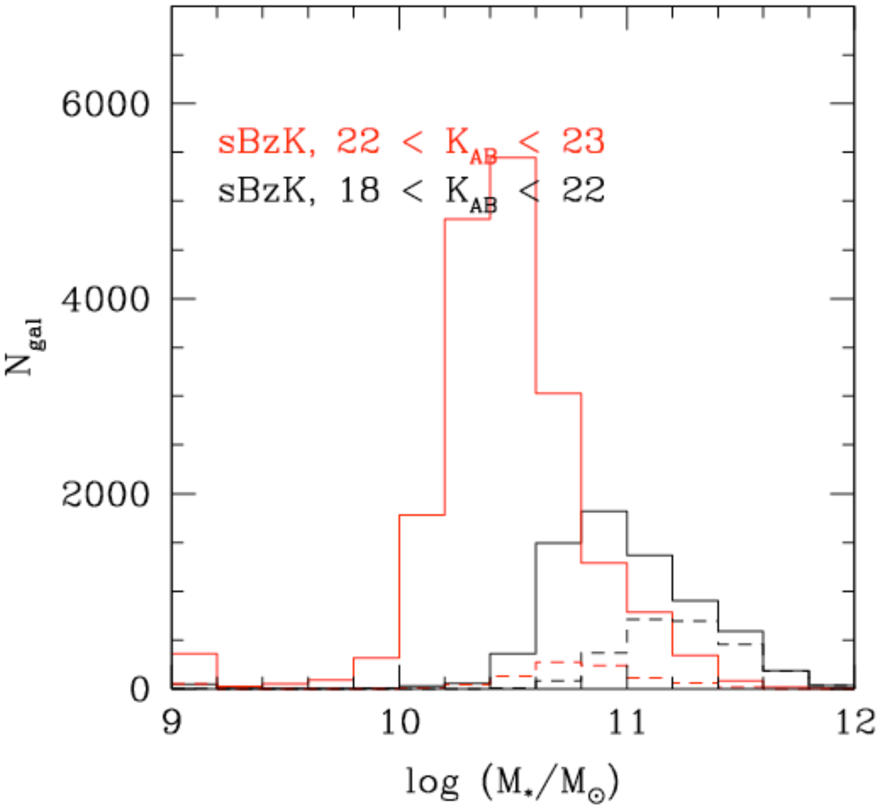
- We clearly see a turn-over in the counts of passive galaxies which cannot be explained by sample incompleteness
- The millennium simulation under-predicts the number of bright galaxies

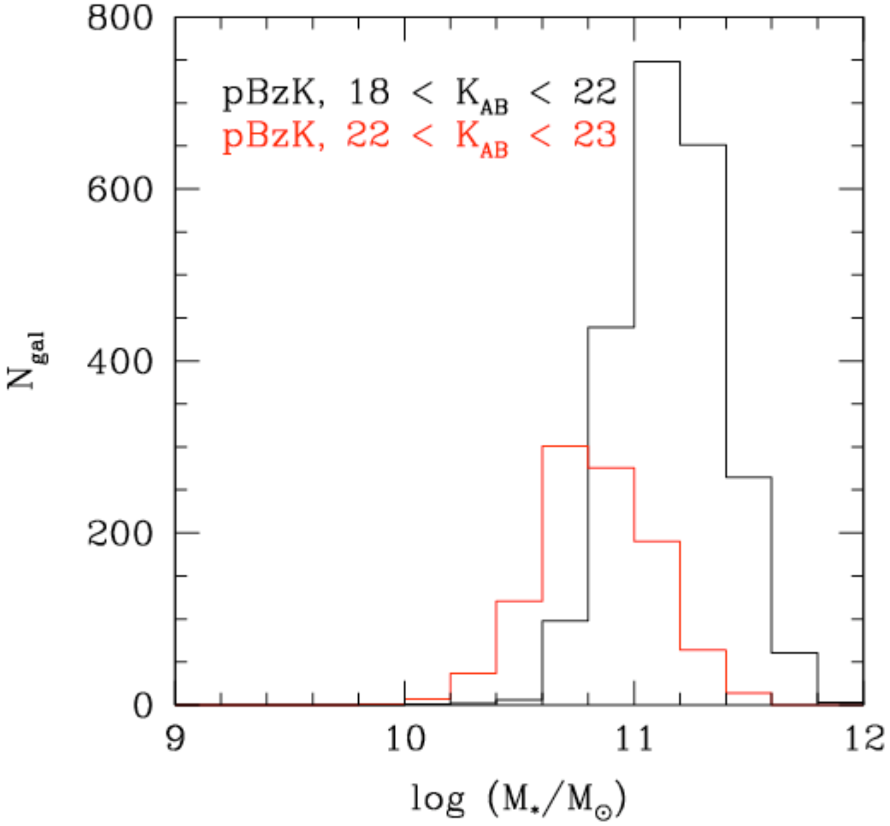
Absolute magnitudes of quiescent and star-forming galaxies



- Redshift selection function is relatively sharp
- We can use the Arnouts et al 2008 empirical relation to derive the stellar mass

Stellar masses of the pbzk / sbzk population





- Passive galaxy population is much more massive than the star-forming population

A word on two-point correlation functions...

- Two-point correlation functions give the excess probability for finding a neighbour a distance r from a given galaxy:

- w(θ) is the simply the projection of xi(r) on the sky and depends (amongst other things) on the source redshift distribution (see later)
- xi(r) can be calculated exactly for dark matter
- The relation between the clustering of the dark matter and that of the luminous matter can tell us something about the “bias” or the galaxy formation -- this is either
- How does galaxy clustering depend on physical properties and environment?
- The passive BzK galaxy population represents and ideal “extreme” galaxy population

A word on two-point correlation functions...

- Two-point correlation functions give the excess probability for finding a neighbour a distance r from a given galaxy:

$$\delta P = n^2 \delta V_1 \delta V_2 [1 + \xi(r_{12})]$$

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Galaxy clustering compared to dark matter

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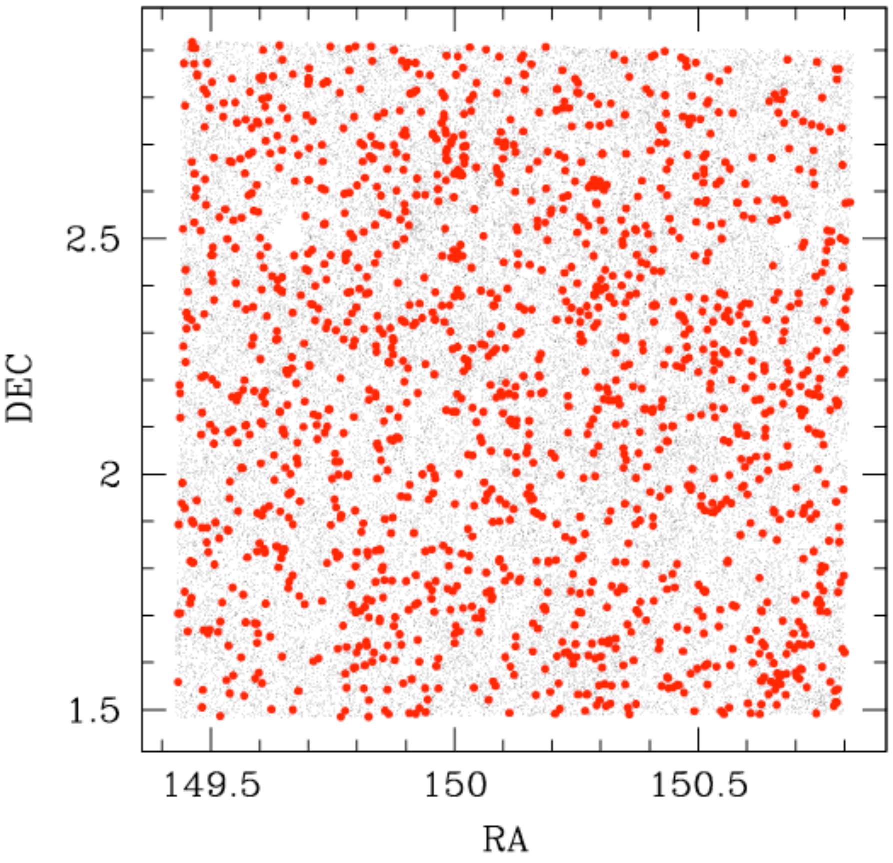
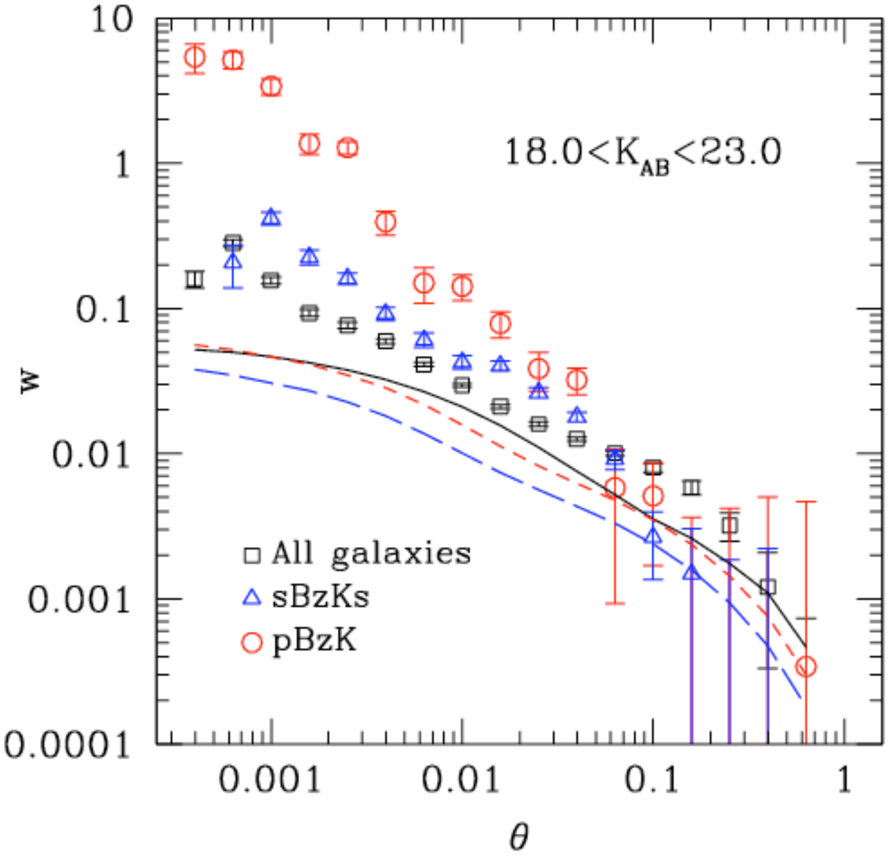
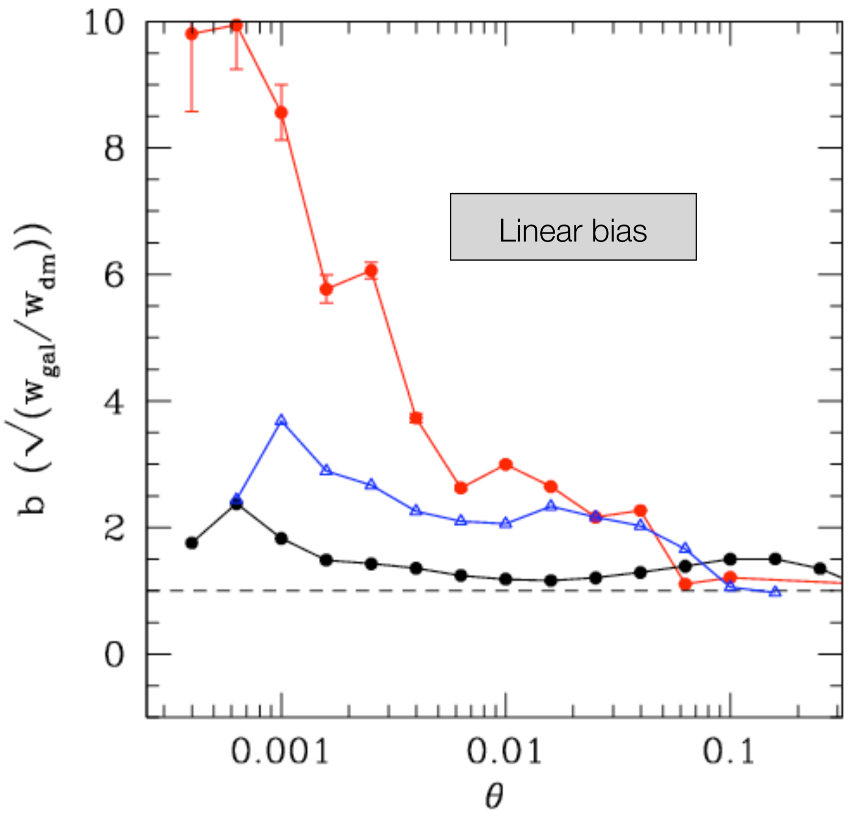


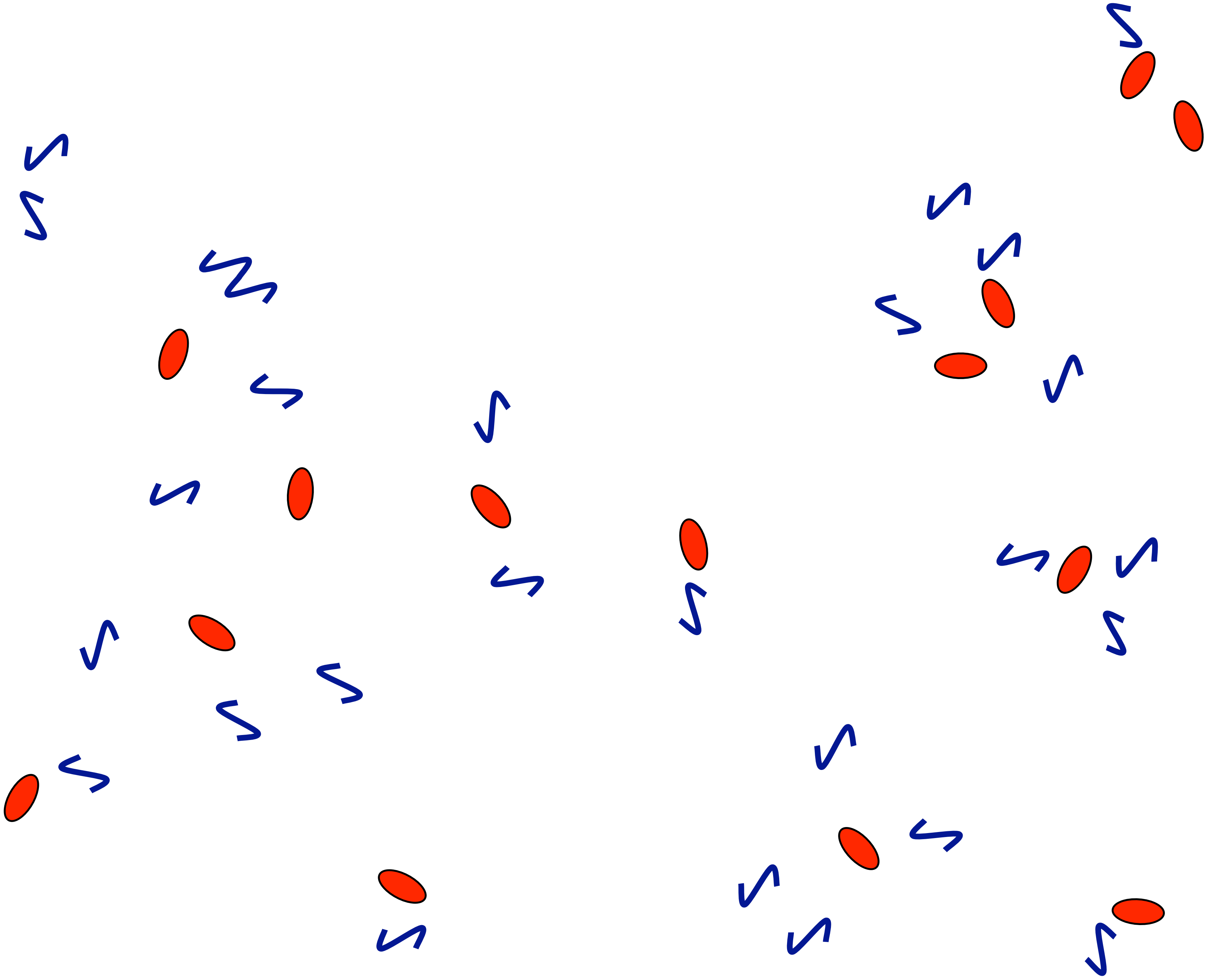
Galaxy clustering compared to dark matter

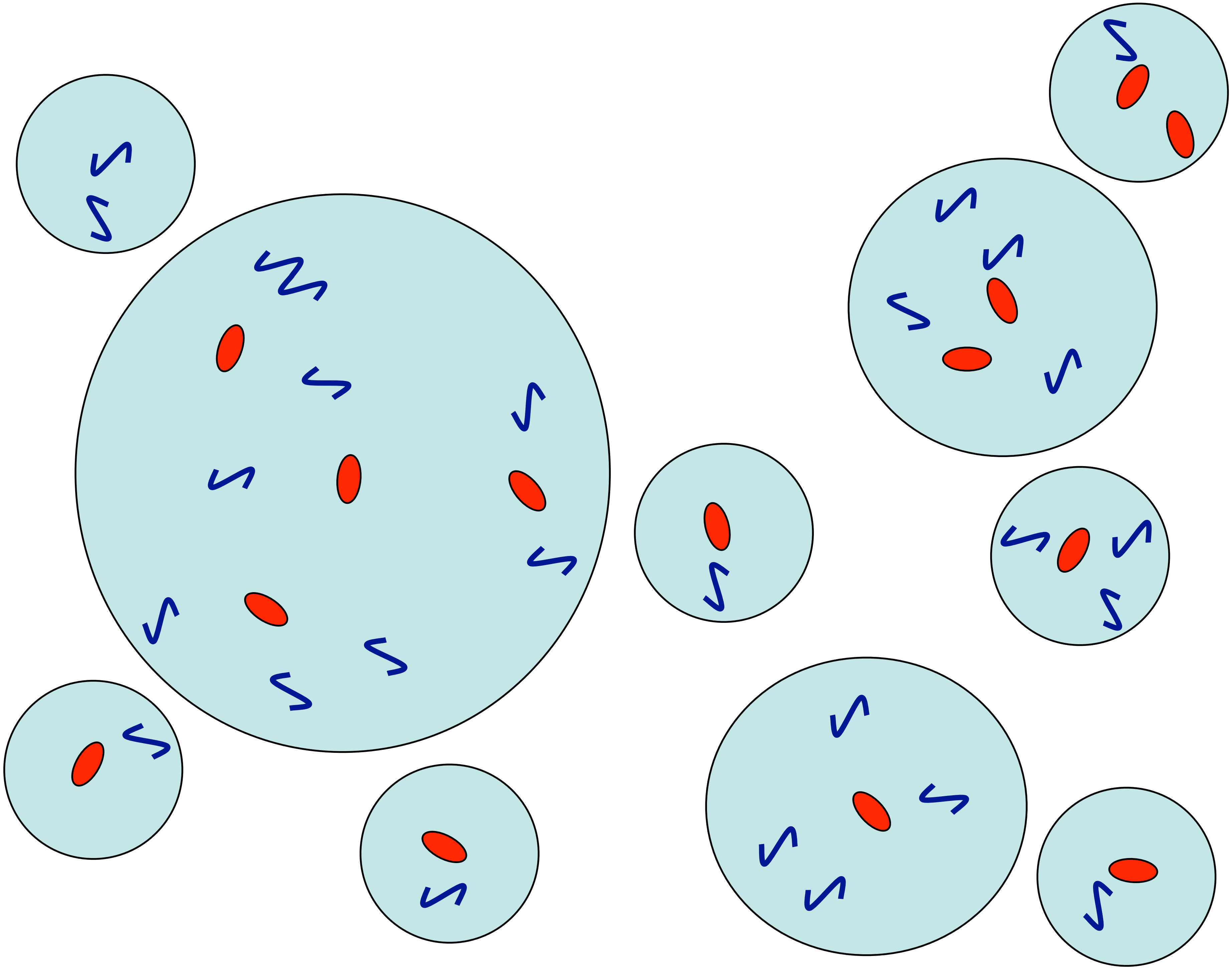




The halo model of galaxy clustering (with M. Kilbinger)

- Until recently, there were only two ways to model galaxy clustering: either a very technique based on generating a set of redshift distributions based on luminosity evolution models; or a much more complicated method based on “semi-analytical” models which ‘paint’ galaxies on the underlying dark matter.
- “Halo models” provide a phenomenological model to model galaxy clustering in the **non-linear regime.**
- The number and mass of dark matter halos as a function of halo mass can now be **reliably and rapidly calculated**
- Clustering measurements can provide a **powerful constraint** on how the hosting dark matter halo depends on galaxy type
- We would expect sBzK and pBzK galaxies to have quite different properties; they represent ideal ‘test cases’





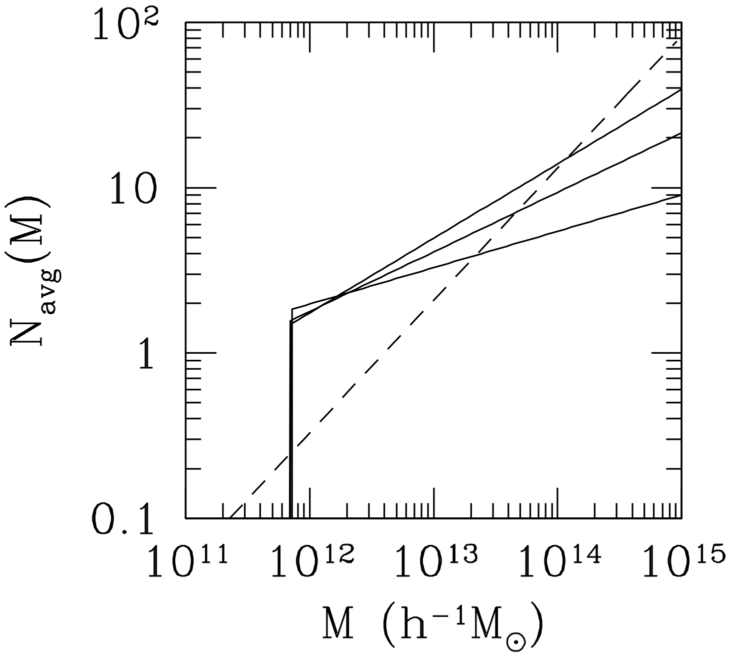
How to compute galaxy clustering using the halo model

- Three ingredients are necessary to generate a prediction of w, the projected two-point correlation function:

1. **An accurate representation of the non-linear power spectrum of dark matter, the density profile of dark matter haloes and the number of dark matter haloes as a function of halo mass**
2. **A prescription ("guess") for how the numbers of galaxies and pairs of galaxies which inhabit each dark matter halo depend on the halo mass.**
3. **Knowledge of the redshift selection function for each sample.**

Computing halo parameters

- Halo mass functions and halo profiles can be estimated from n-body simulations.
- The “halo model” tells us how many galaxies are in each halo of dark matter.
- For the time being we will try a very simple model for how haloes occupy dark matter haloes:



$$N_g(M) = \begin{cases} (M/M_1)^\alpha & \text{for } M > M_{\min}, \\ 0 & \text{for } M < M_{\min}. \end{cases}$$

Number of galaxies per halo

$$P_{\mathrm{g}}^{1\mathrm{h}}(k) = \frac{1}{(2\pi)^3 n_{\mathrm{g},z}^2} \int \mathrm{d}M\, n_{\mathrm{halo}}(M) \langle N_{\mathrm{g}}(N_{\mathrm{g}}-1)\rangle(M) |y(k, M)|^{p}.$$

1-halo power spectrum

- The one-halo term depends on galaxy pairs inside a give halo

$$P_{\mathrm{g}}^{2\mathrm{h}}(k) = P_{\mathrm{lin}}(k) \left[\frac{1}{n_{\mathrm{g},z}} \int \mathrm{d}M\, n_{\mathrm{halo}}(M) N_{\mathrm{g}}(M) b(M) y(k, M) \right]^2,$$

2-halo power spectrum

- The two-halo term depends on the halo-halo clustering and the linear bias

$$P_{\mathrm{g}}(k) = P_{\mathrm{g}}^{1\mathrm{h}}(k) + P_{\mathrm{g}}^{2\mathrm{h}}(k).$$

total power spectrum

$$\omega(\theta) = \int \mathrm{d}r q^2(r) \int \frac{\mathrm{d}k}{2\pi} k P_{\mathrm{g}}(k, r) J_0(f_K(r)\theta k),$$

Computing w from the HOD model - II

$$P_g^{1h}(k) = \frac{1}{(2\pi)^3 n_{g,z}^2} \int \mathrm{d}M n_{\mathrm{halo}}(M) \langle N_g(N_g-1)\rangle(M) |y(k, M)|^p .$$

1-halo power spectrum

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2-halo power spectrum

- The two-halo term depends on the halo-halo clustering and the linear bias

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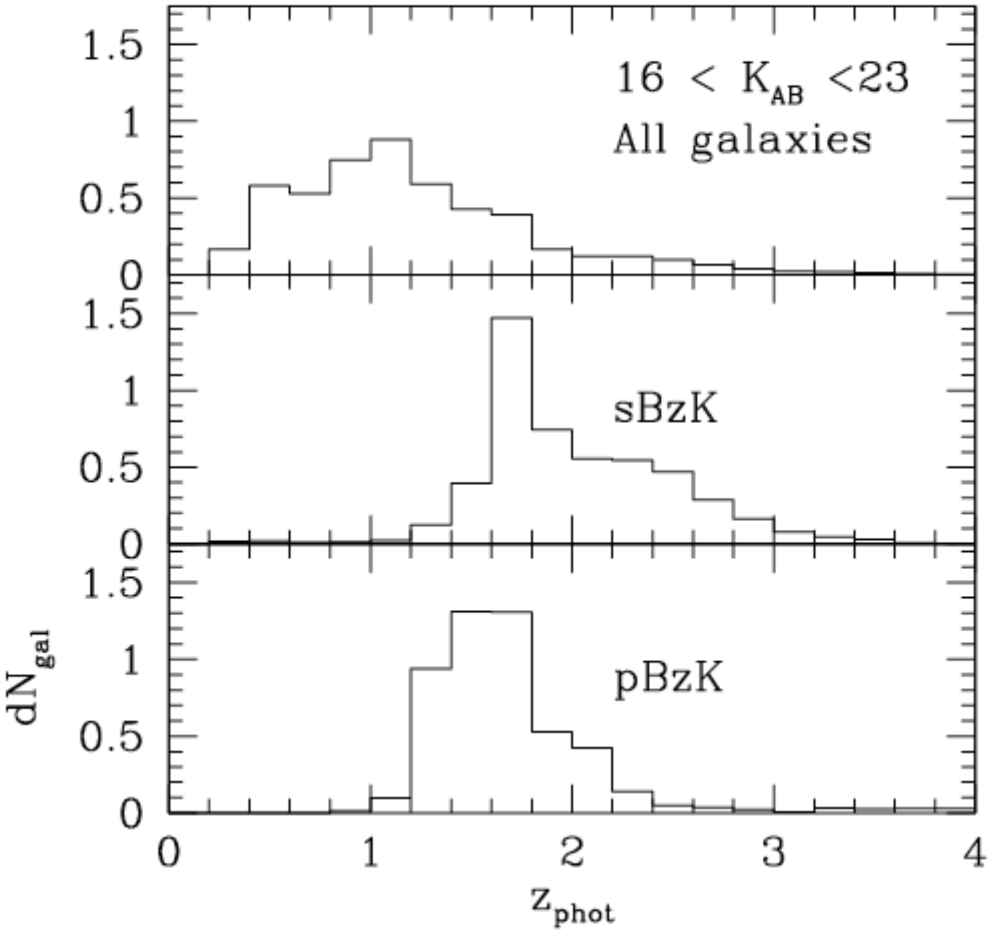
total power spectrum

$$\omega(\theta) = \int \mathrm{d}r q^2(r) \int \frac{\mathrm{d}k}{2\pi} k P_g(k, r) J_0(f_K(r)\theta k),$$

Redshift selection functions

- These redshift selection functions come from the accurate photo-zeds presented in Ilbert et al. 2008
- Deep IRAC and JK means we can compute accurate photo-zeds between 1<z<2

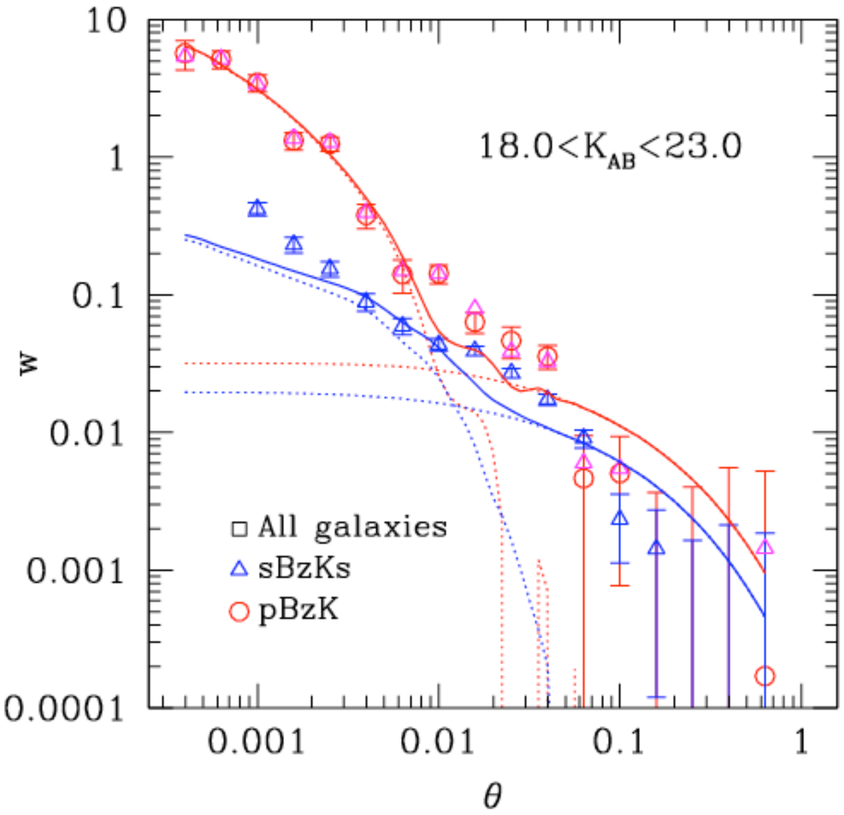


$$3.4 \times 10^{-3} h^3 \mathrm{Mpc}^{-3}$$

$$10^{-4} h^3 \mathrm{Mpc}^{-3}$$

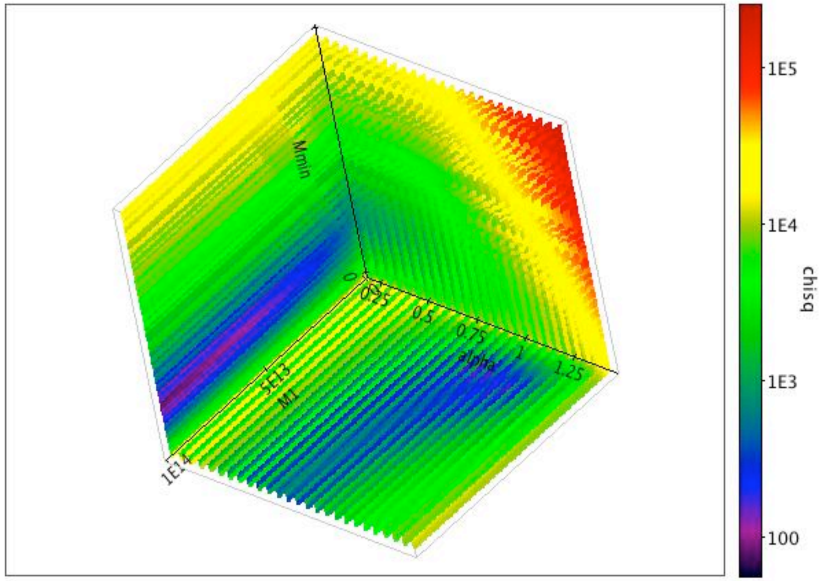
- Halo model must also reproduce the observed number density of galaxies

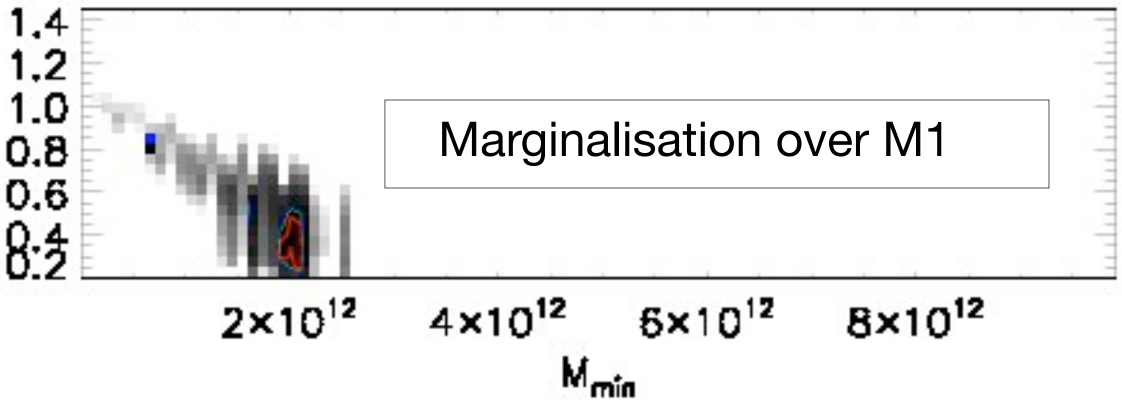
Results for passive BzK population



“M1” parameter is poorly constrained by our data

3-parameter space





Marginalisation over M1

Derived halo properties

Once we have derived the values of alpha, M1 and Mmin from the halo model which best match the observed surface density of galaxies and measured correlation function we can derive these additional parameters:

$$b_{\mathrm{g}}(>M_{\mathrm{min}}) \equiv \frac{\int \mathrm{d}M\, n_{\mathrm{halo}}(M) N_{\mathrm{g}}(M) b(M)}{\int \mathrm{d}M\, n_{\mathrm{halo}}(M) N_{\mathrm{g}}(M)}.$$

Average halo bias

$$\langle M_{\mathrm{host}} \rangle = \frac{\int_{M_{\mathrm{min}}}^{\infty} \mathrm{d}M\, M\, N_{\mathrm{g}}(M) n_{\mathrm{halo}}(M)}{\int_{M_{\mathrm{min}}}^{\infty} \mathrm{d}M\, N_{\mathrm{g}}(M) n_{\mathrm{halo}}(M)},$$

Average halo mass

$3.12 \times 10^{12} M_{\odot}$ (sBzK)

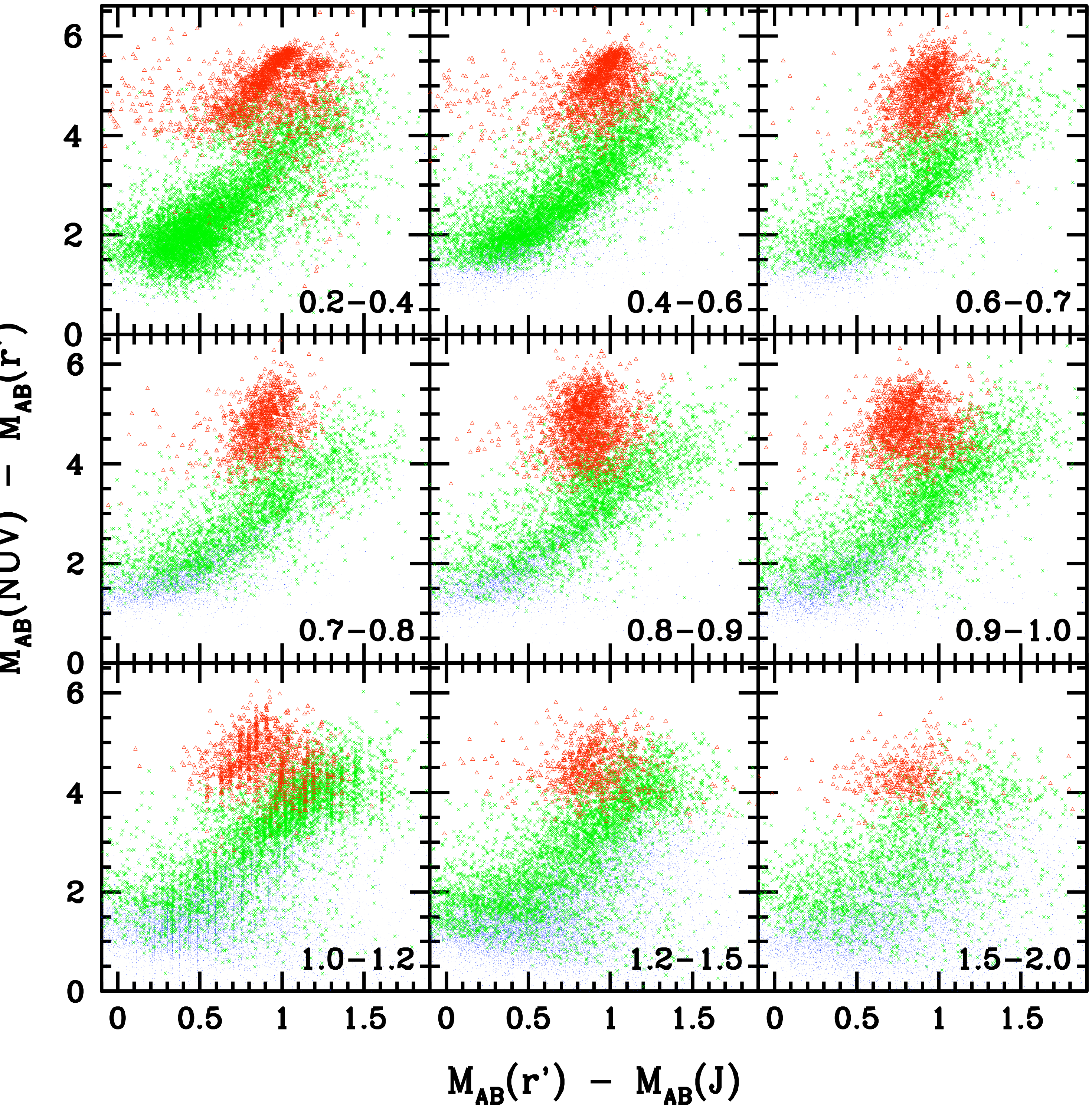
$9.15 \times 10^{12} M_{\odot}$ (pBzK)

3.154e+12 1/h Msun Halo mass for sbzk

Average bias: around 2

Average number of galaxies per halo: 10^-3 (pbzk)

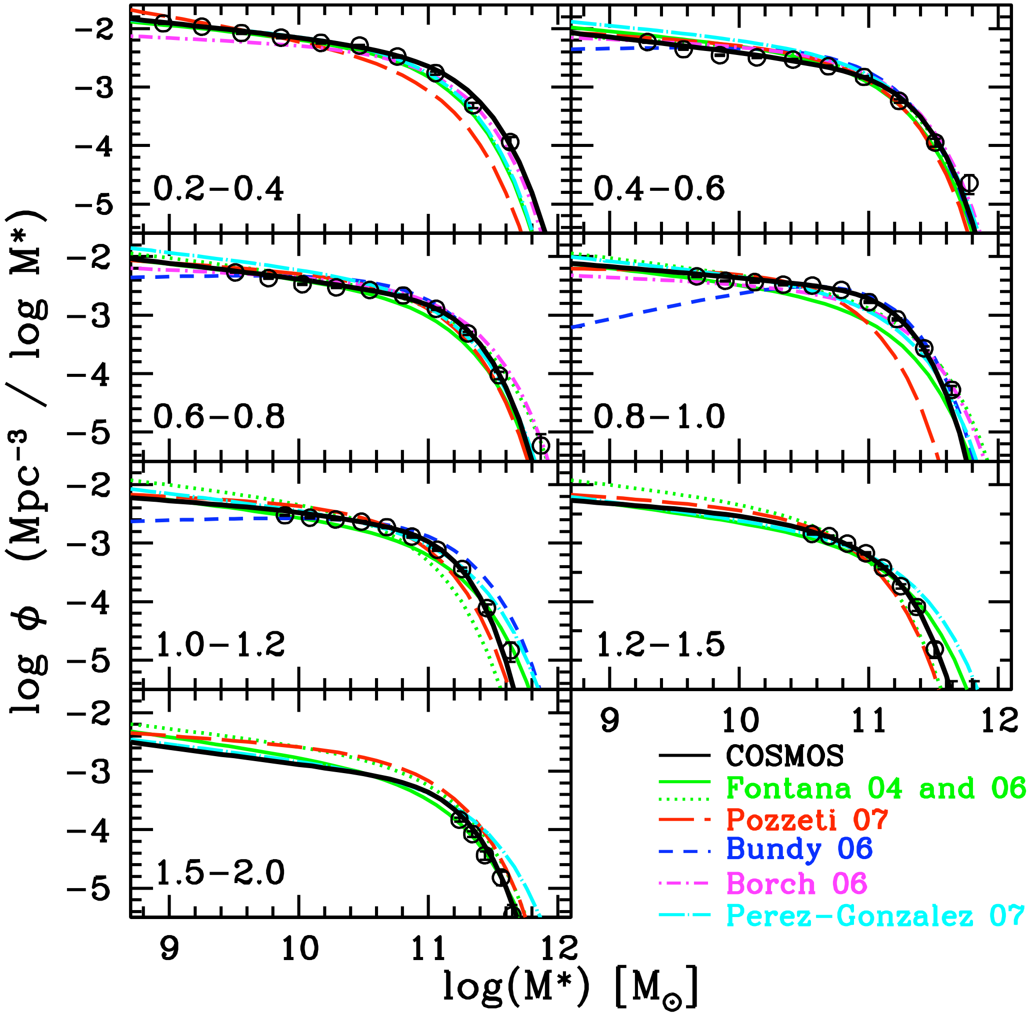
Average number of galaxies per halo: 10^-1 (sbzk)



optical-infrared colours rest-frame absolute colours from Ilbert et al. 2008

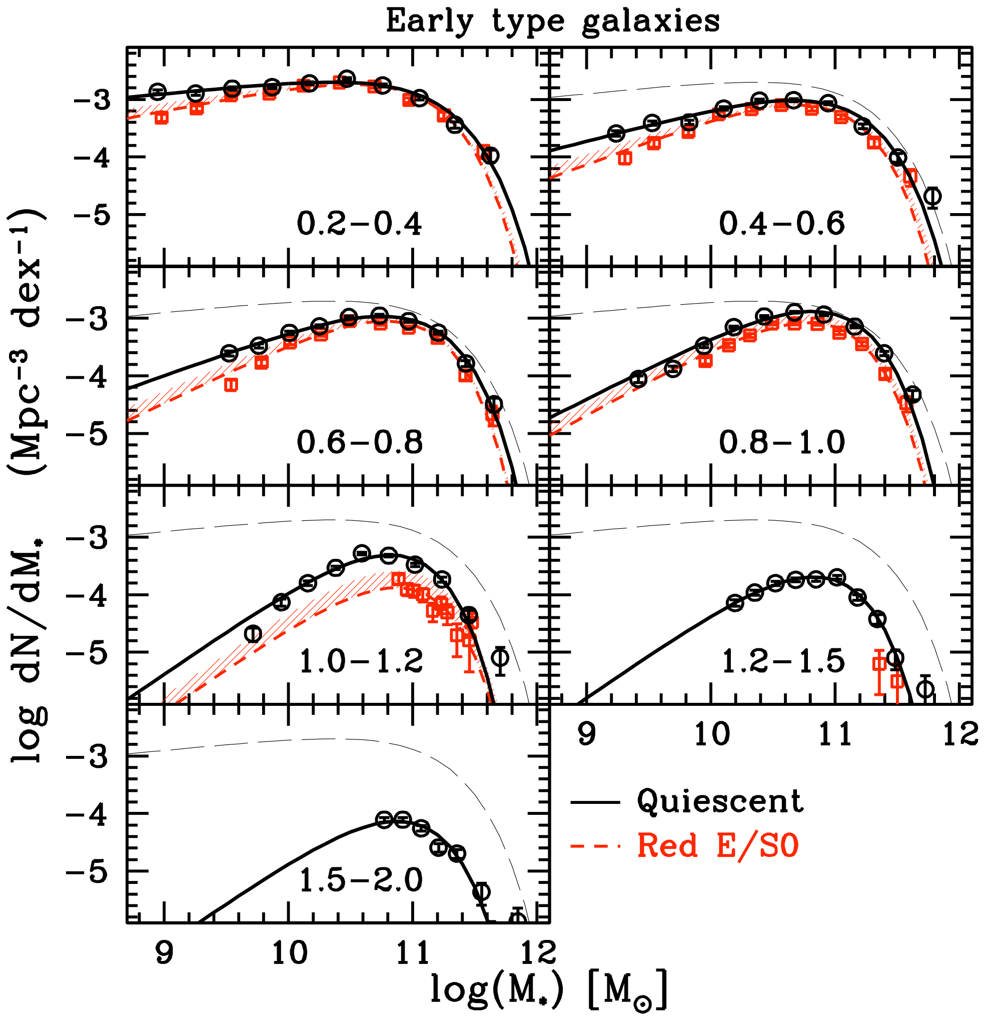
Mass function in COSMOS: or, when did galaxies form (Ilbert et al.)

- We can use our unique multi-band, highly-accurate photo-zeds to derive **stellar masses** for all galaxies using stellar population synthesis models
- By selecting galaxies in **IRAC**-mid infrared bands we can follow the evolution of mass-build up between 0.2<z<2.0 with the largest sample to date
- Our faint flux limit means we can accurately constraint the **faint end slope** of our mass functions

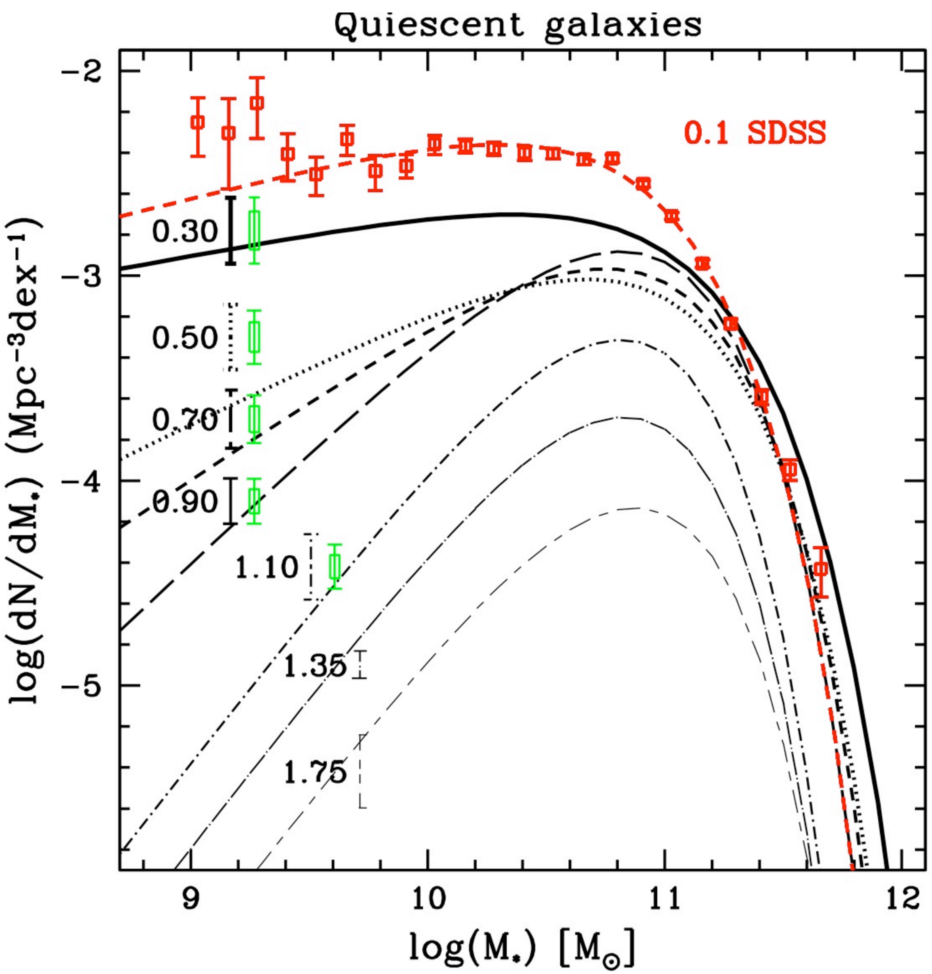


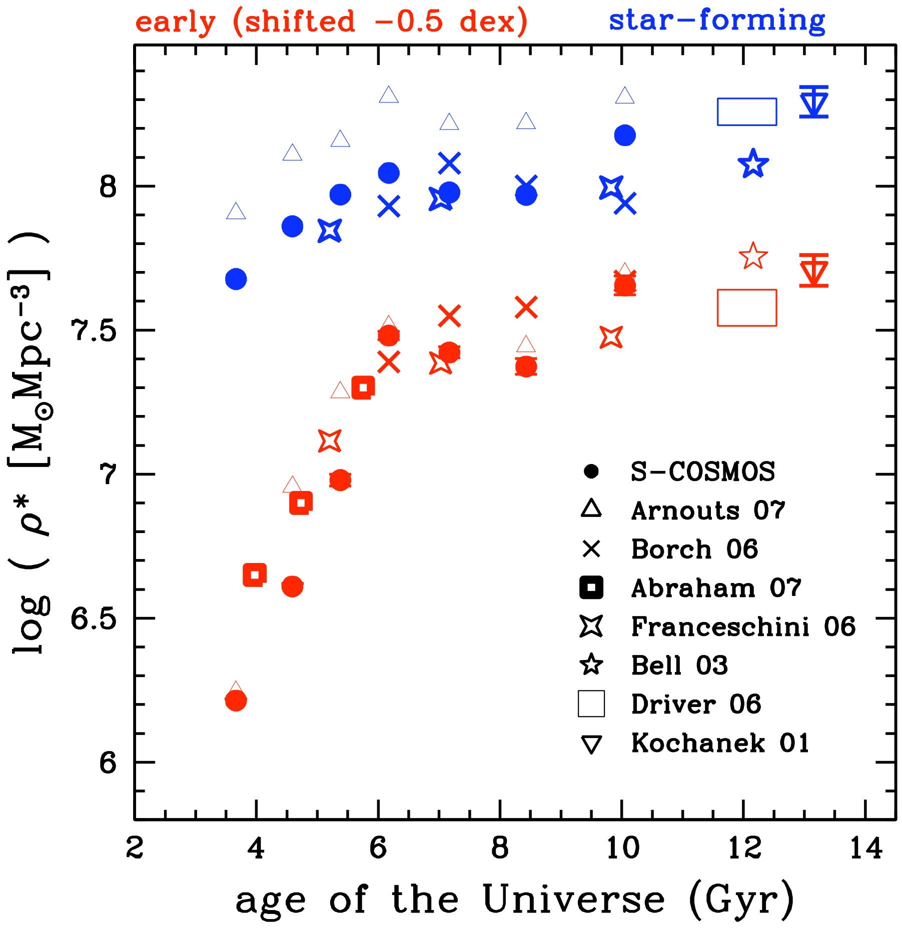
Evolution of the mass function of elliptical galaxies

- The bright end of the elliptical mass function is already in place at z~2
- Significant evolution takes place in the faint-end slope between 0.2<z<2.



Evolution of the faint-end slope of elliptical galaxies





- Very rapid evolution of the faint end of the mass function
- Massive galaxies are already in place by z~2; the bright end of the LF does not evolve

Conclusions and summary

- Number counts of passive galaxies turn at KAB~22
- At z~2, counts of bright passive galaxies galaxies are underpredicted by the millennium simulation; bright galaxies are already “in place”
- Using a “halo occupation model” we are able estimate the approximate masses of the haloes which host this passive (and star-forming) galaxy population
- Using the K-band rest-frame absolute luminosity we can estimate the total mass in stars for the passive and star-forming galaxy populations.
- Studies with photometric redshifts (Ilbert et al.) confirm the general trend that most mass build-up takes place in the faint end of the passive galaxy population. The bright end of the passive galaxy mass function is already in place at z~2.

Prospective!