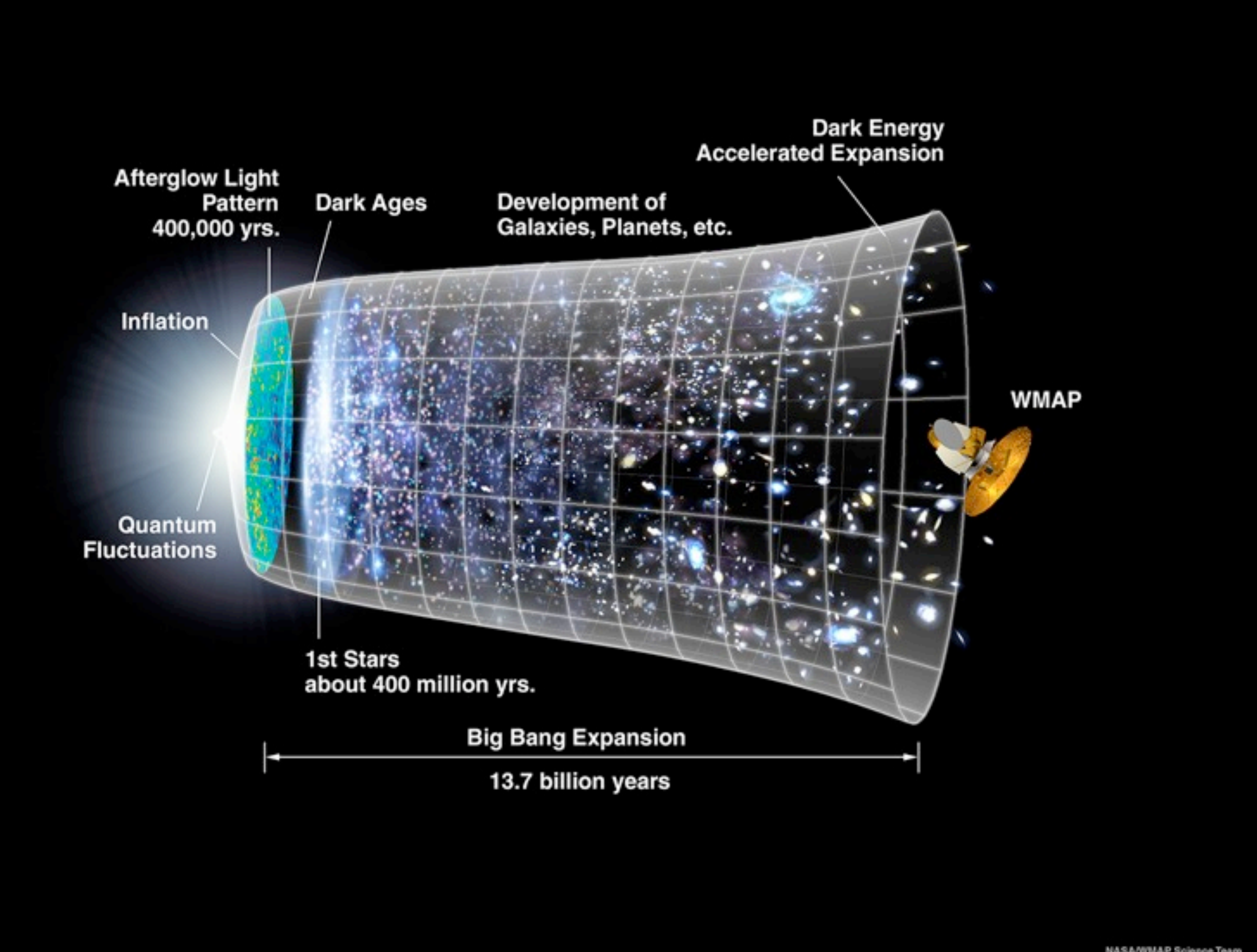
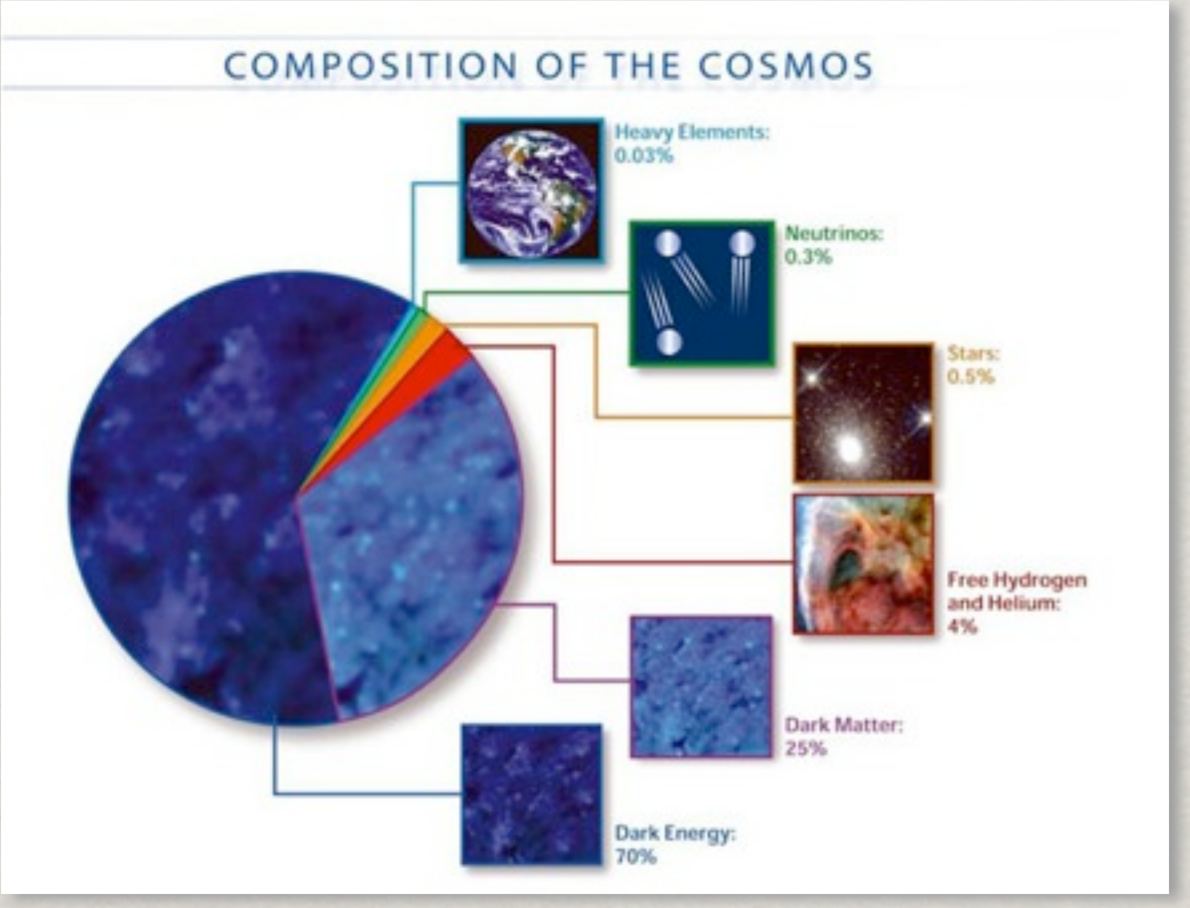
Massive galaxies at z~2 in the COSMOS-WIRCAM Ks band survey

Henry Joy McCracken

Institut d'Astrophysique de Paris

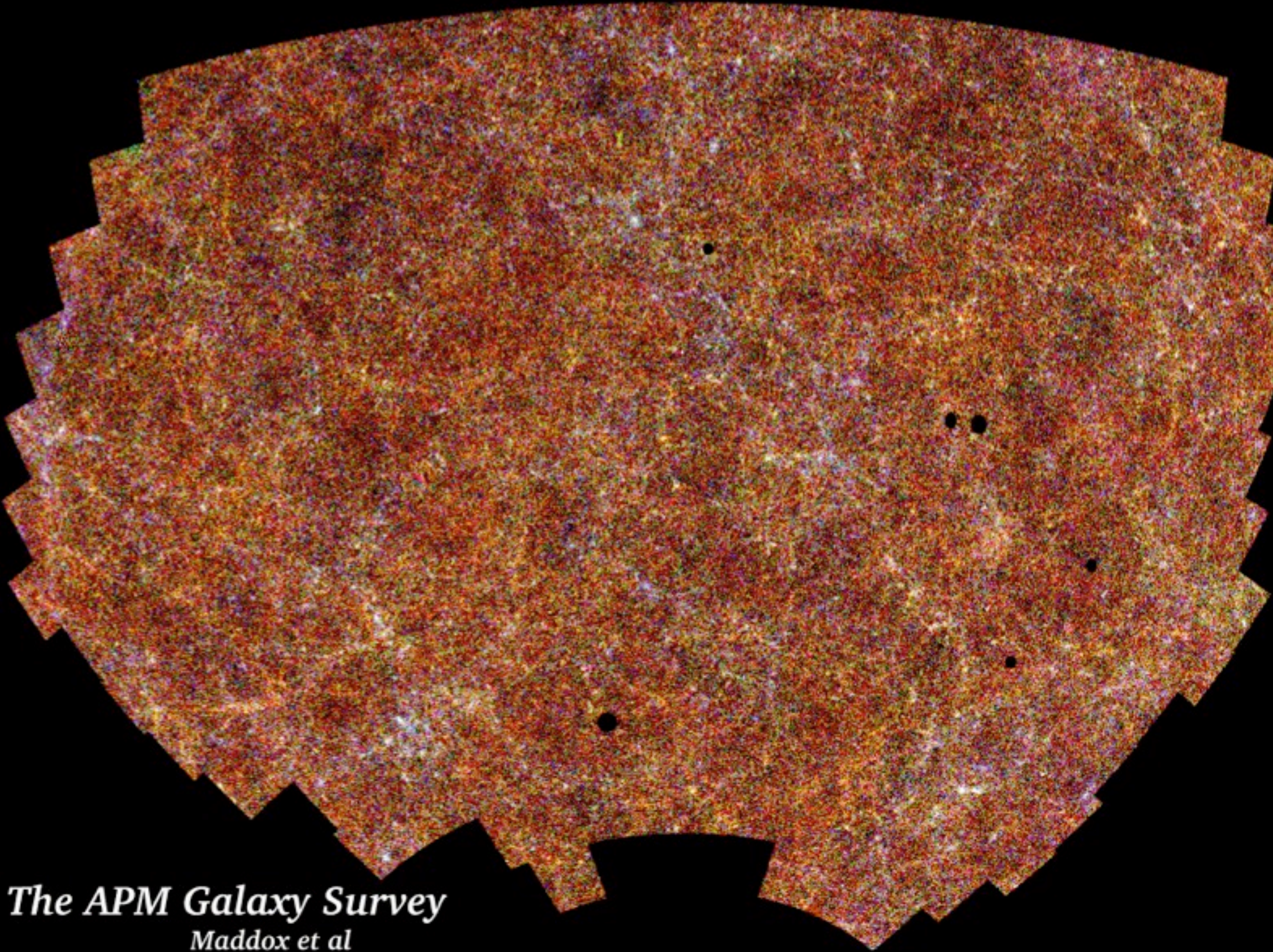

Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
400,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years

What the Universe is made of..



Luminous matter (like stars and galaxies) comprises less than 1% of the energy content of the Universe!

We don't know what the dark matter ***really*** is…
We don't know what the dark energy ***really*** is…
...but we know for sure … something is there!



The APM Galaxy Survey
Maddox et al

The COSMOS survey: probing structures at z~1

How does the galaxy formation process depend on environment?

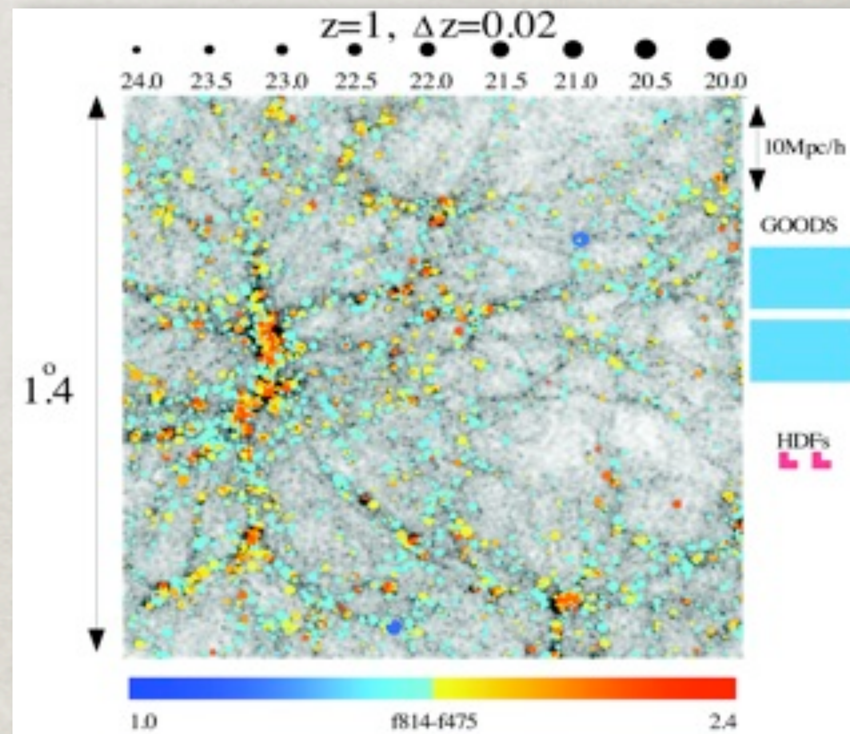
How do structures evolve over cosmic time?

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

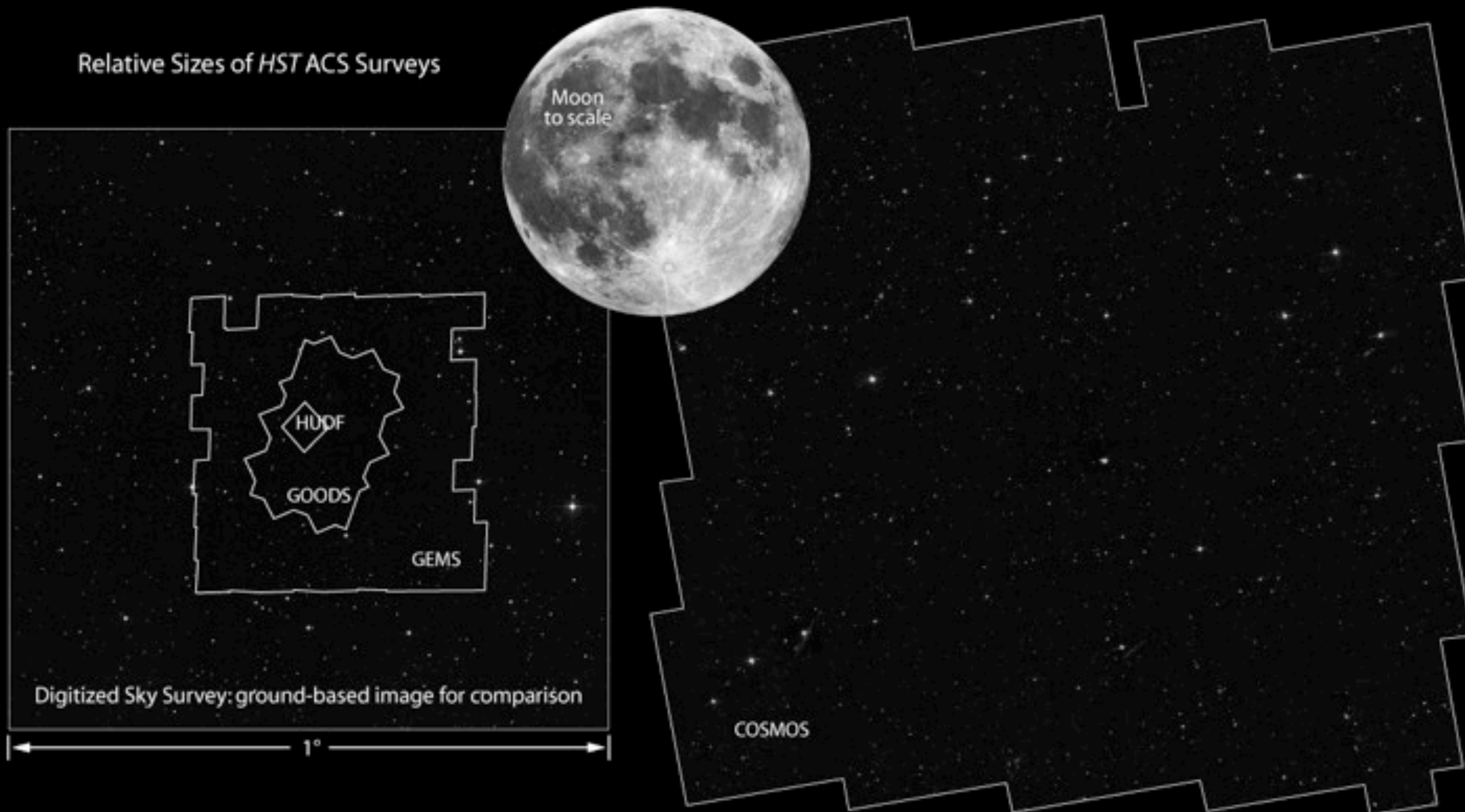
COSMOS provides ACS morphologies for all galaxies

Extensive multi-band coverage



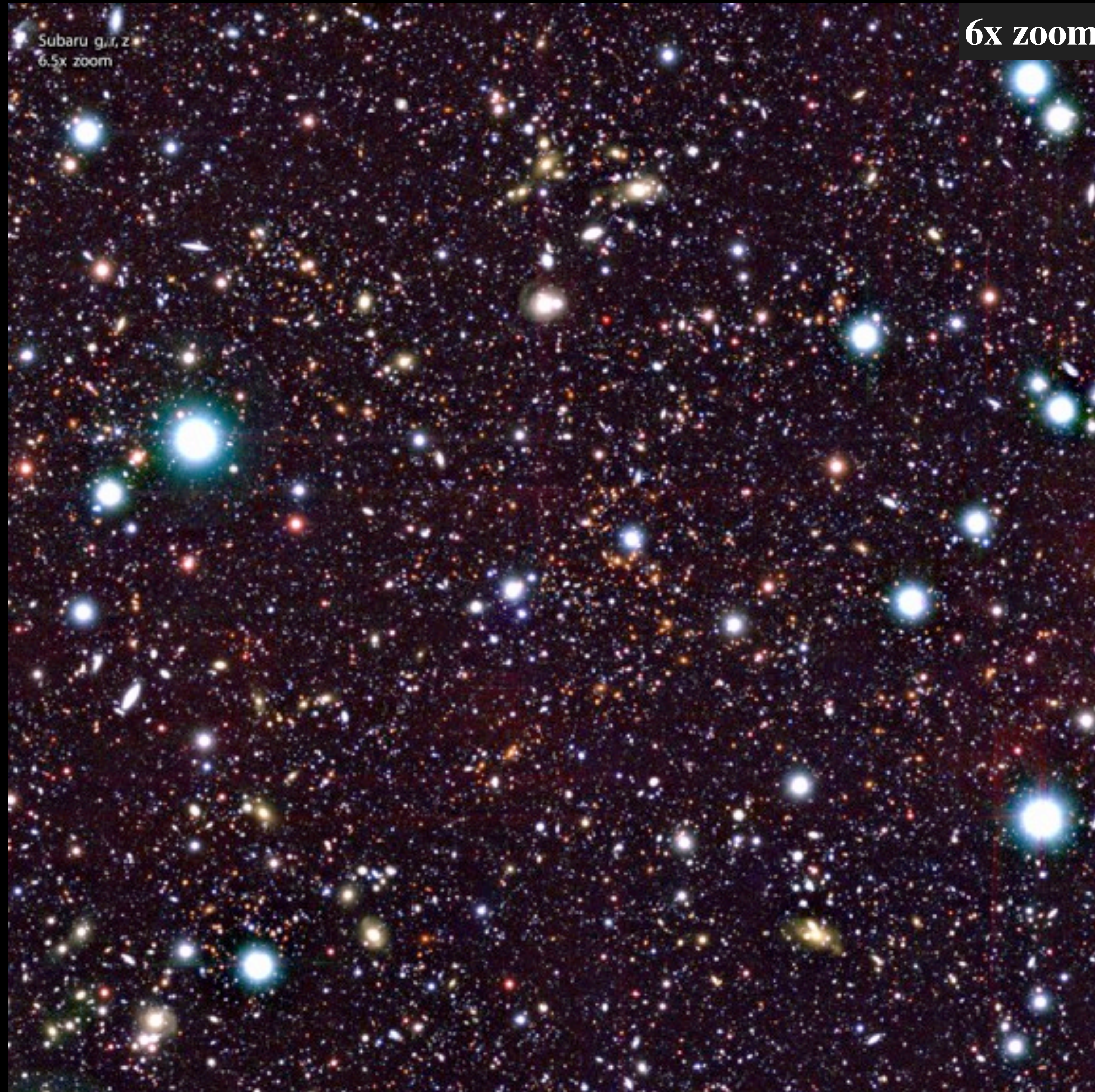
90 Mpc

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



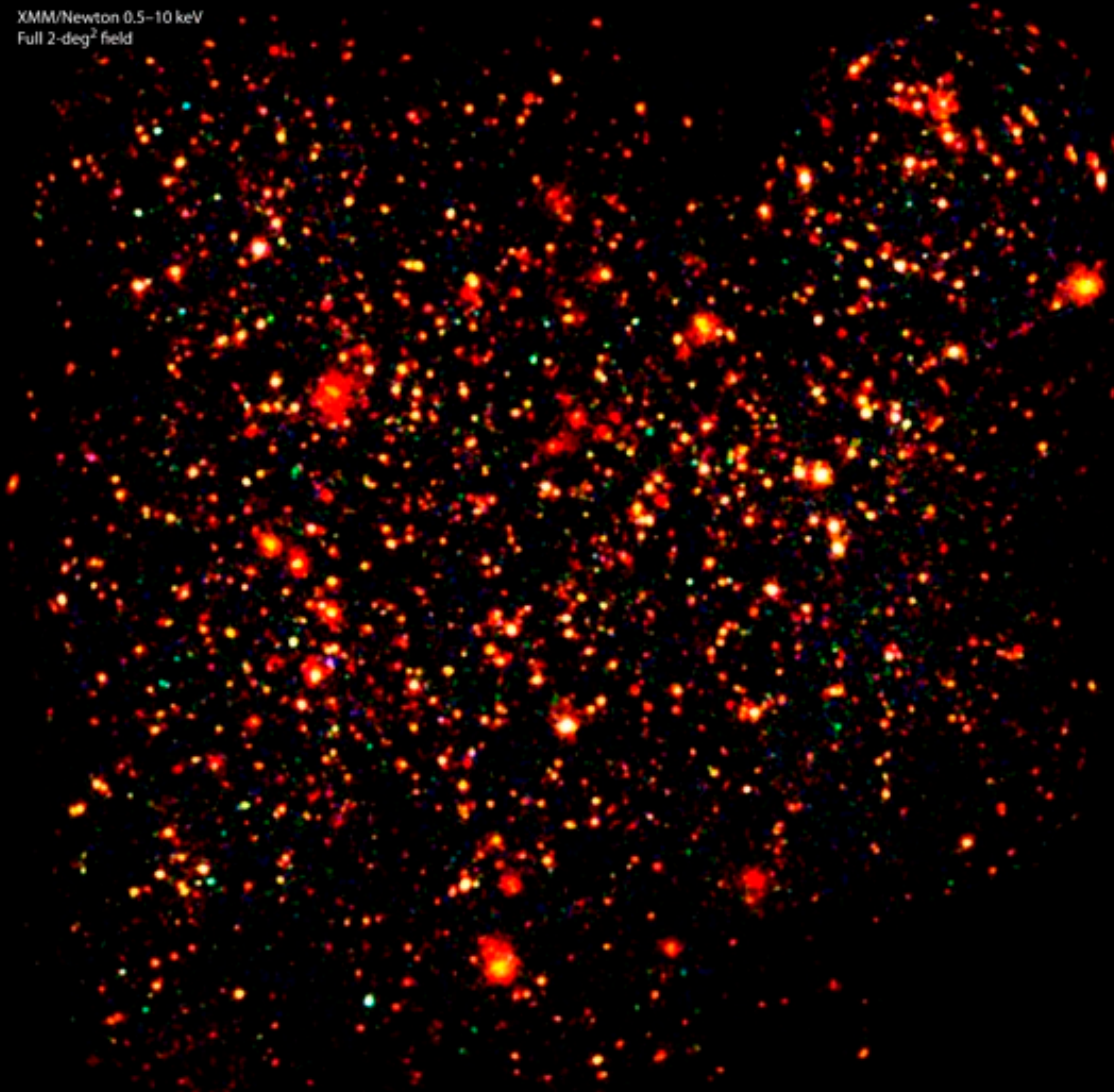
2 deg^2 : 9x larger than any previous HST image
575 orbits (10% of HST time for two years!)
9x larger than any previous HST image

Subaru 8m
PI: Y. Taniguchi
35 nights



Ultra-deep optical imaging;
35 broad and narrow bands

XMM
PI: G. Hasinger
1.4 Msec

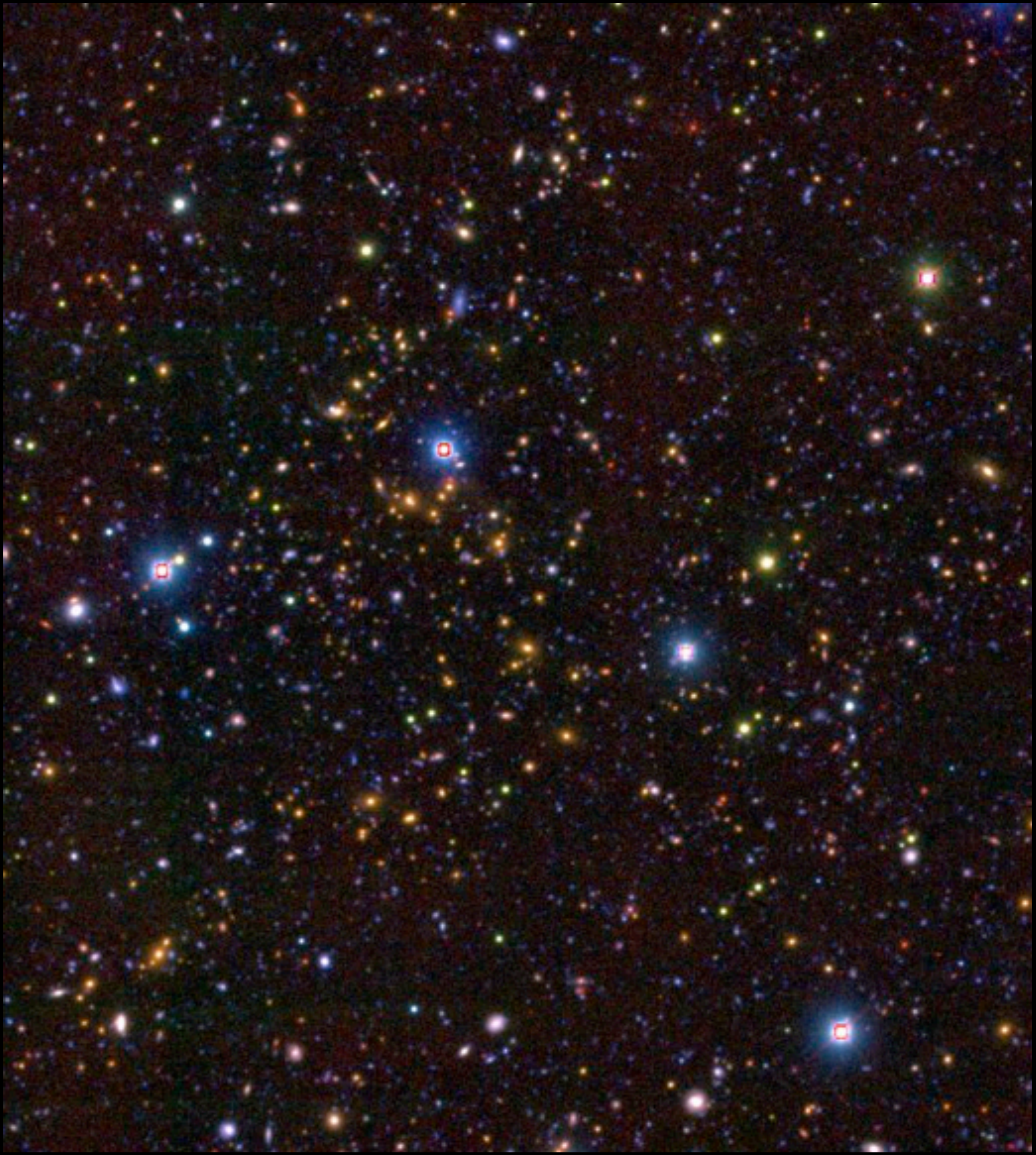


X-ray bands
Diffuse emission: hot gas and clusters

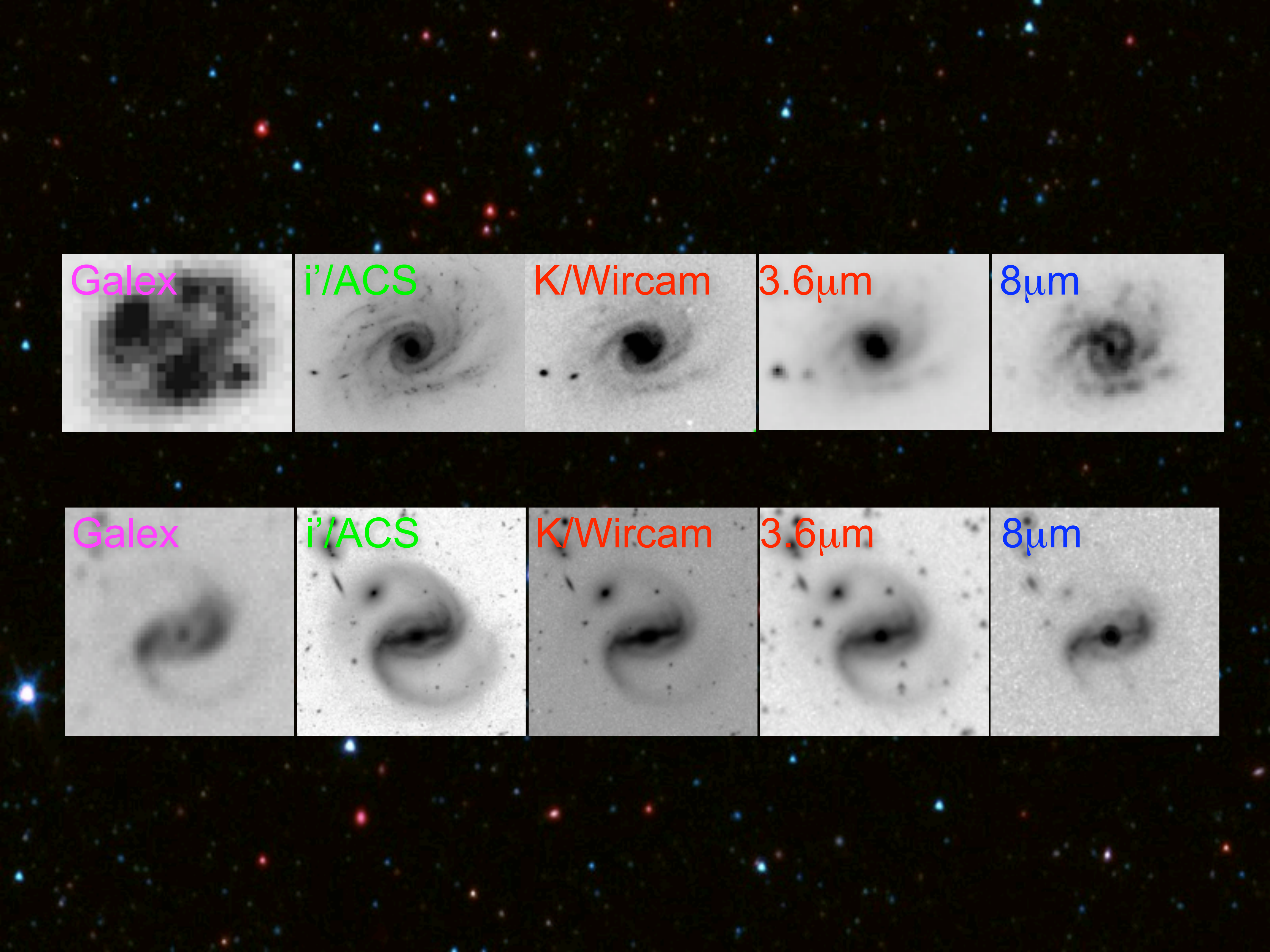
Spitzer IRAC
PI: D. Sanders
600hrs w/MIPS

VLA
PI: E. Schinnerer
300hrs
7-10 μJy

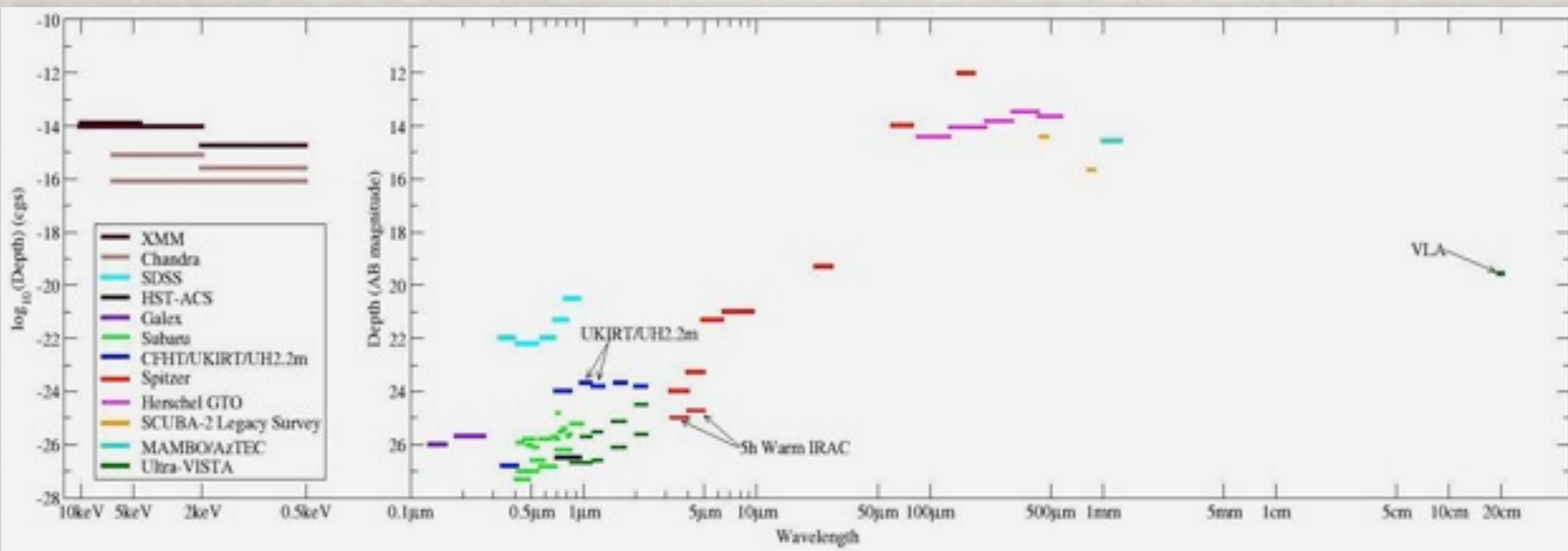
Near IR JHK
KAB~23.8 (5sig)
PIs: Sanders, Willot, Kneib

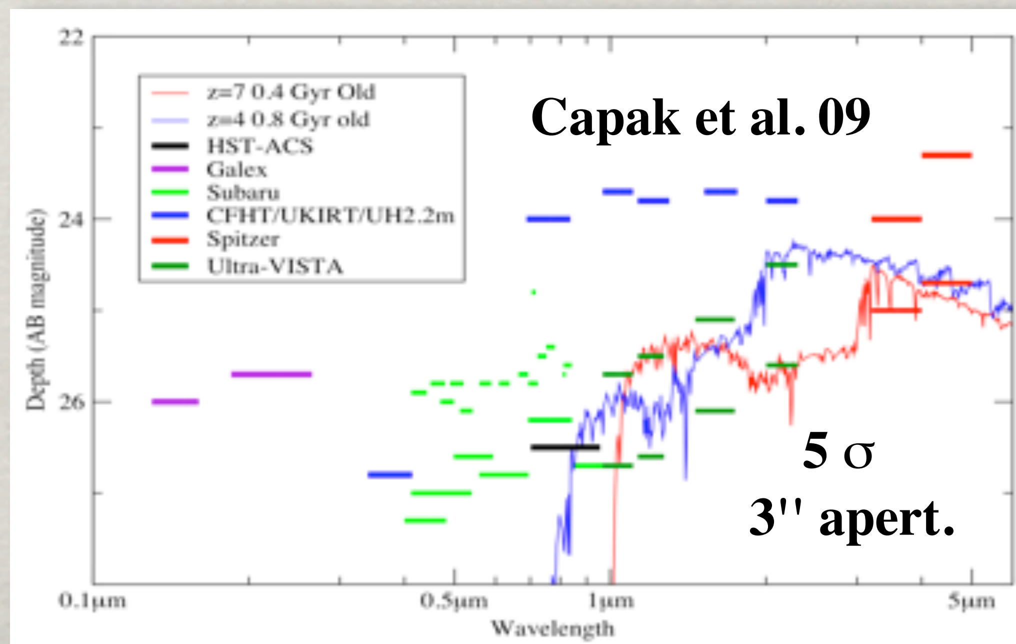


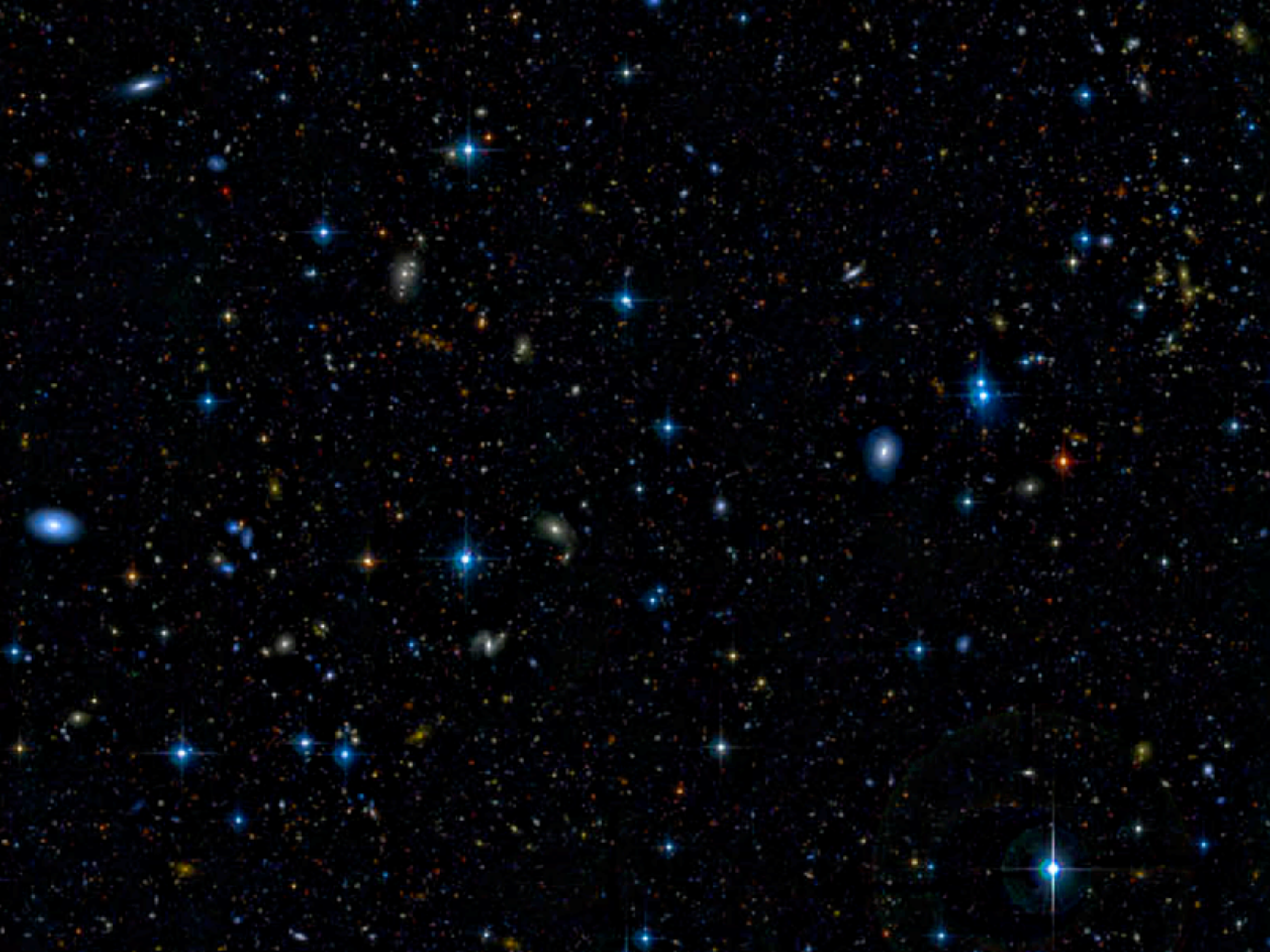
3x size of UKIDSS UDS
0.5 mag. deeper

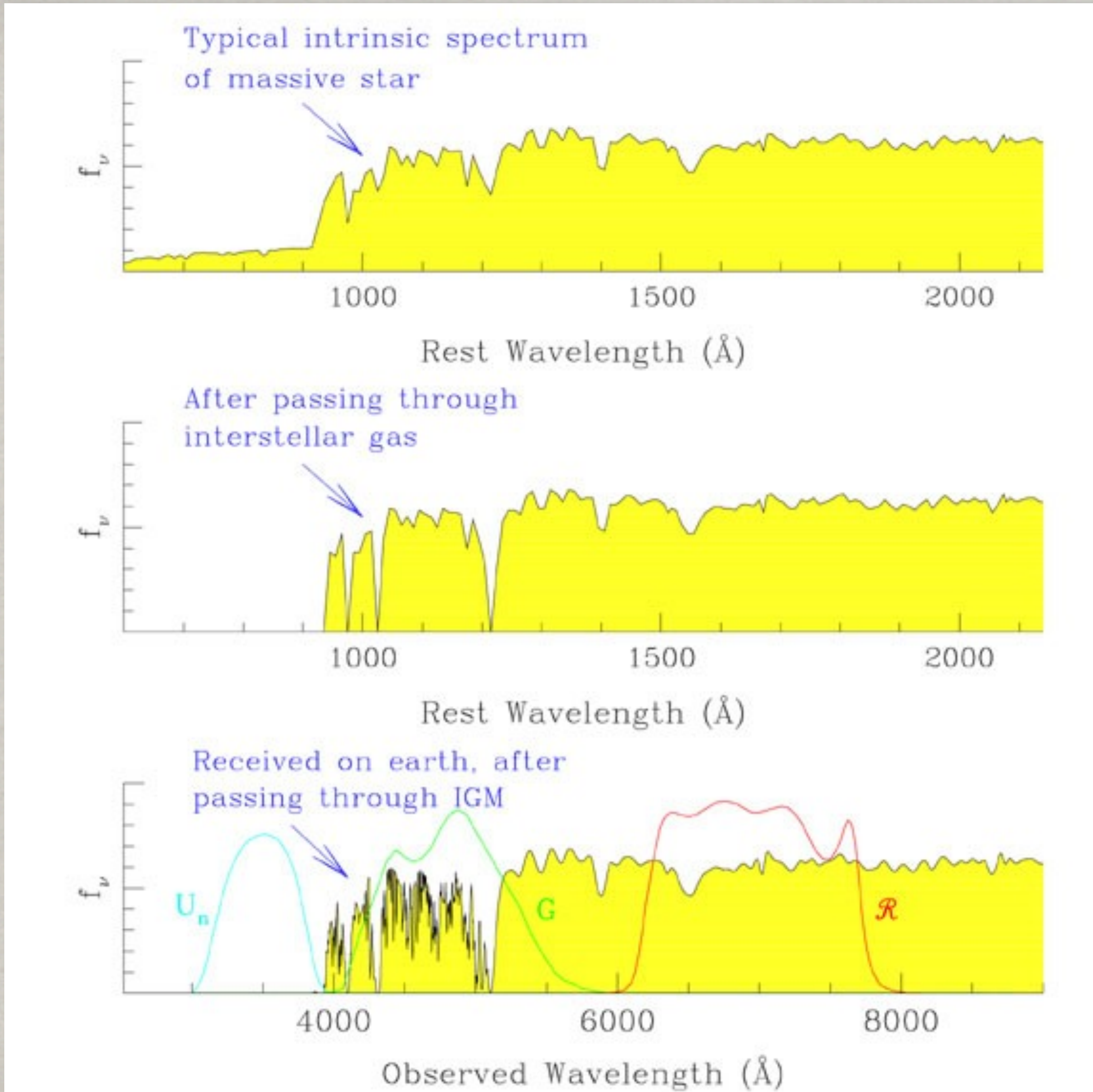

Galex
i'/ACS
K/Wircam
3.6μm
8μm
Galex
i'/ACS
K/Wircam
3.6μm
8μm

Summary of COSMOS multi-λ coverage








Typical intrinsic spectrum
of massive star
f_ν
1000
1500
2000
Rest Wavelength (Å)
After passing through
interstellar gas
f_ν
1000
1500
2000
Rest Wavelength (Å)
Received on earth, after
passing through IGM
f_ν
U_n
G
R
4000
6000
8000
Observed Wavelength (Å)

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

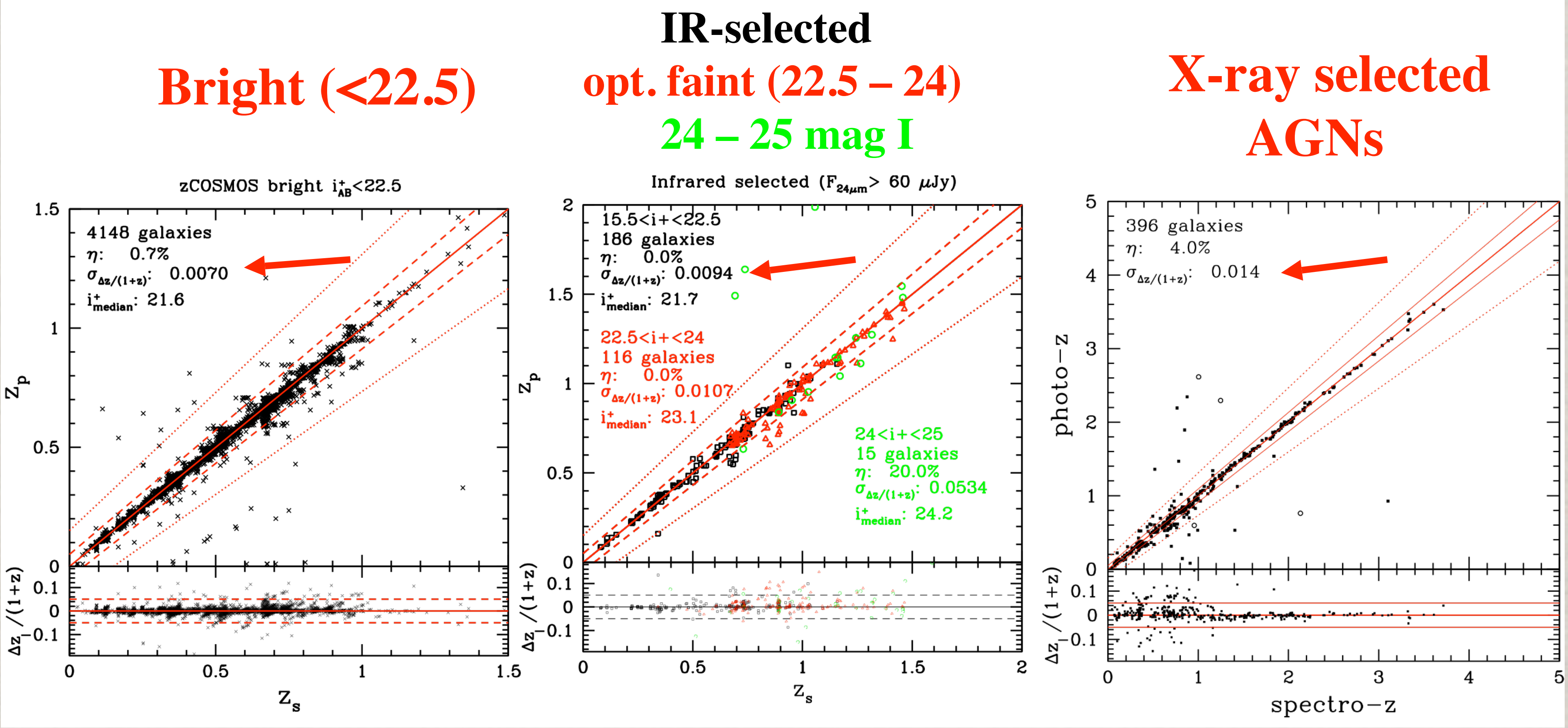
$$\chi^2(z, T, A) = \sum_{f=1}^{N_f} \left(\frac{F^f_{\rm obs} - A \times F^f_{\rm pred}(z, T)}{\sigma^f_{\rm obs}} \right)^2 ,$$

"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!)

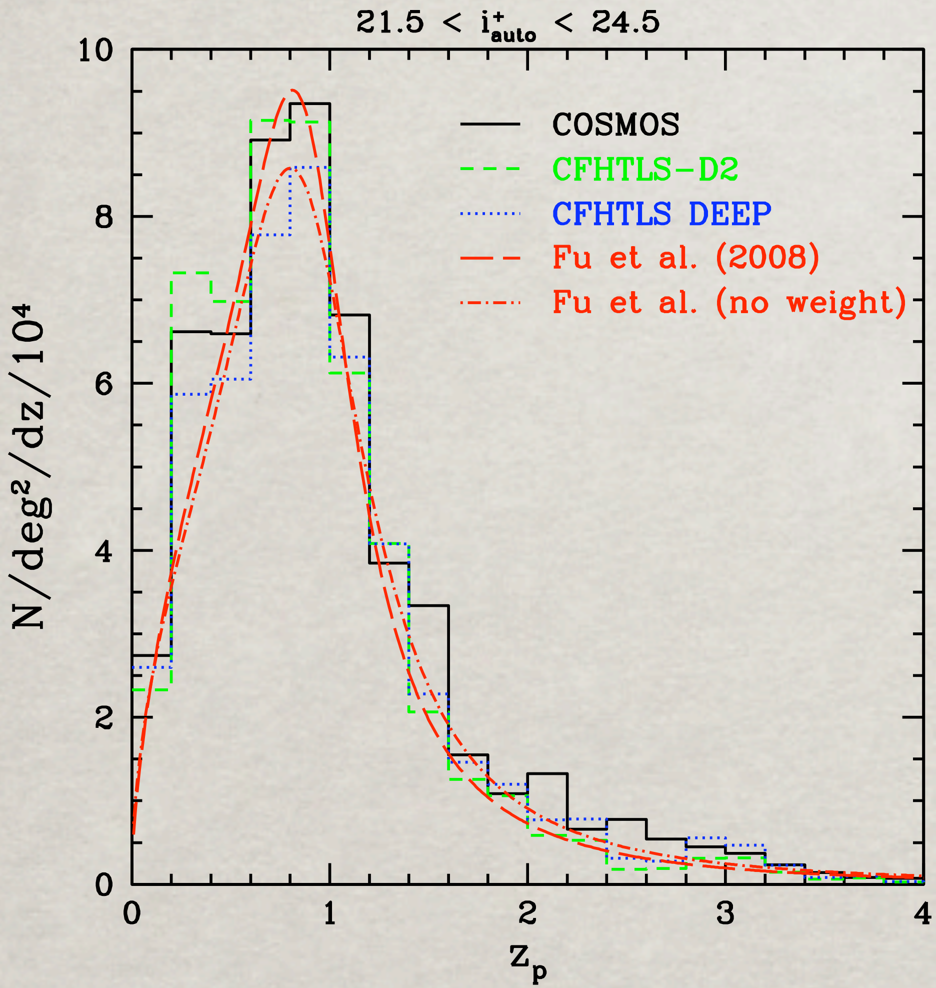
Wide-field cameras with precise photometric calibration (like Megacam) combined with wide field spectrographs producing training sets of ~10k galaxies (like VIMOS) makes estimating photometric redshifts for millions of galaxies with percent-level accuracy possible

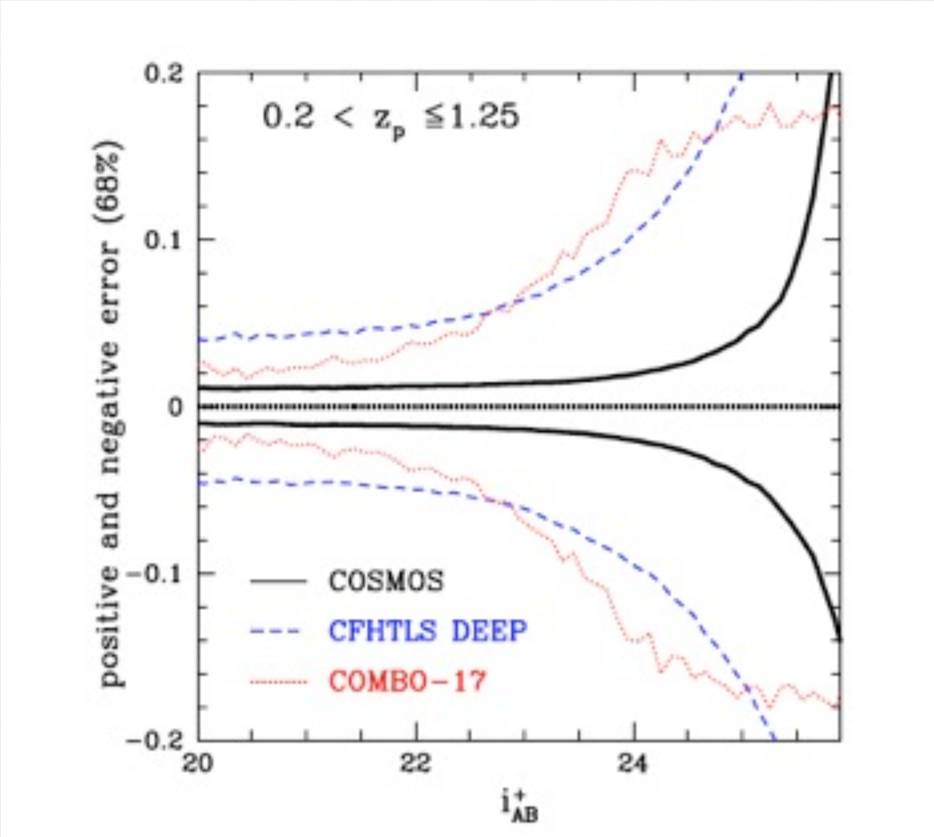
COSMOS 30-band phot-zeds (ilbert et al 08)



- ~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 photo-zed accuracy



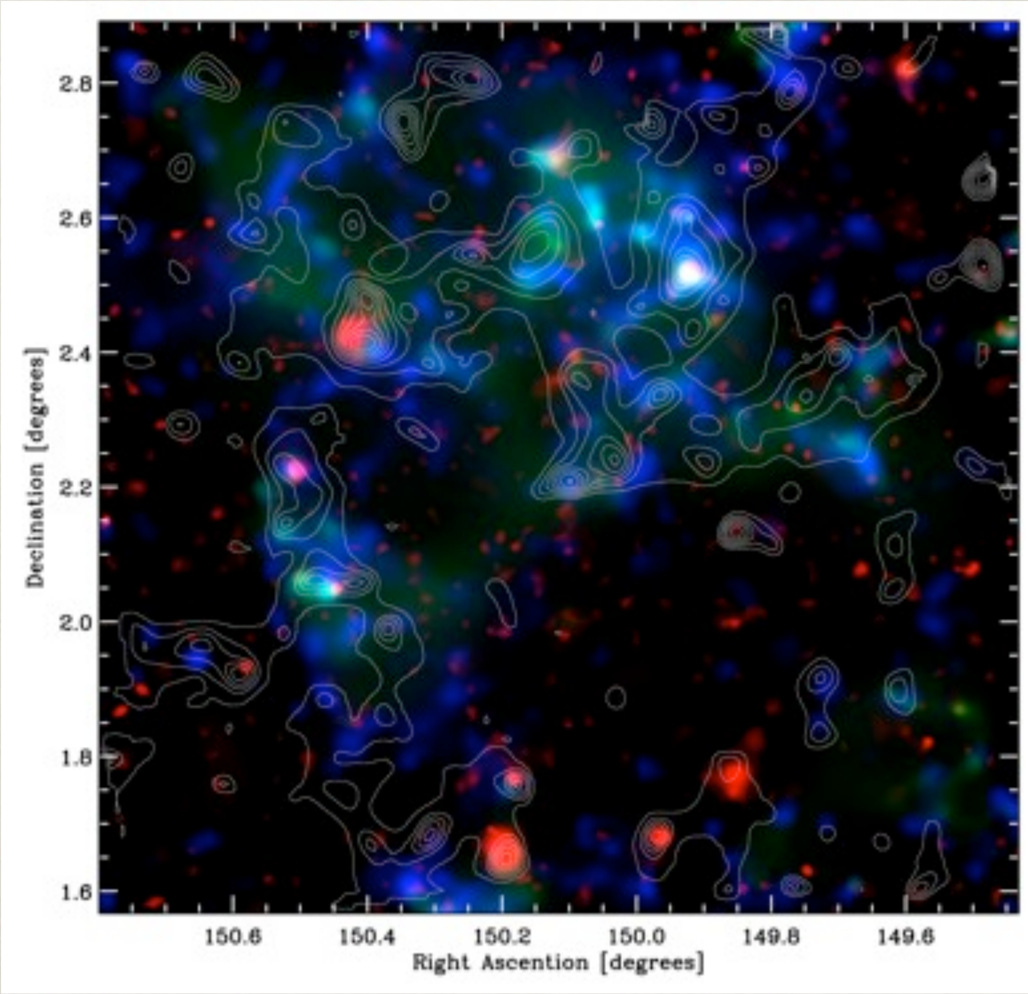


The COSMOS mass / galaxy map

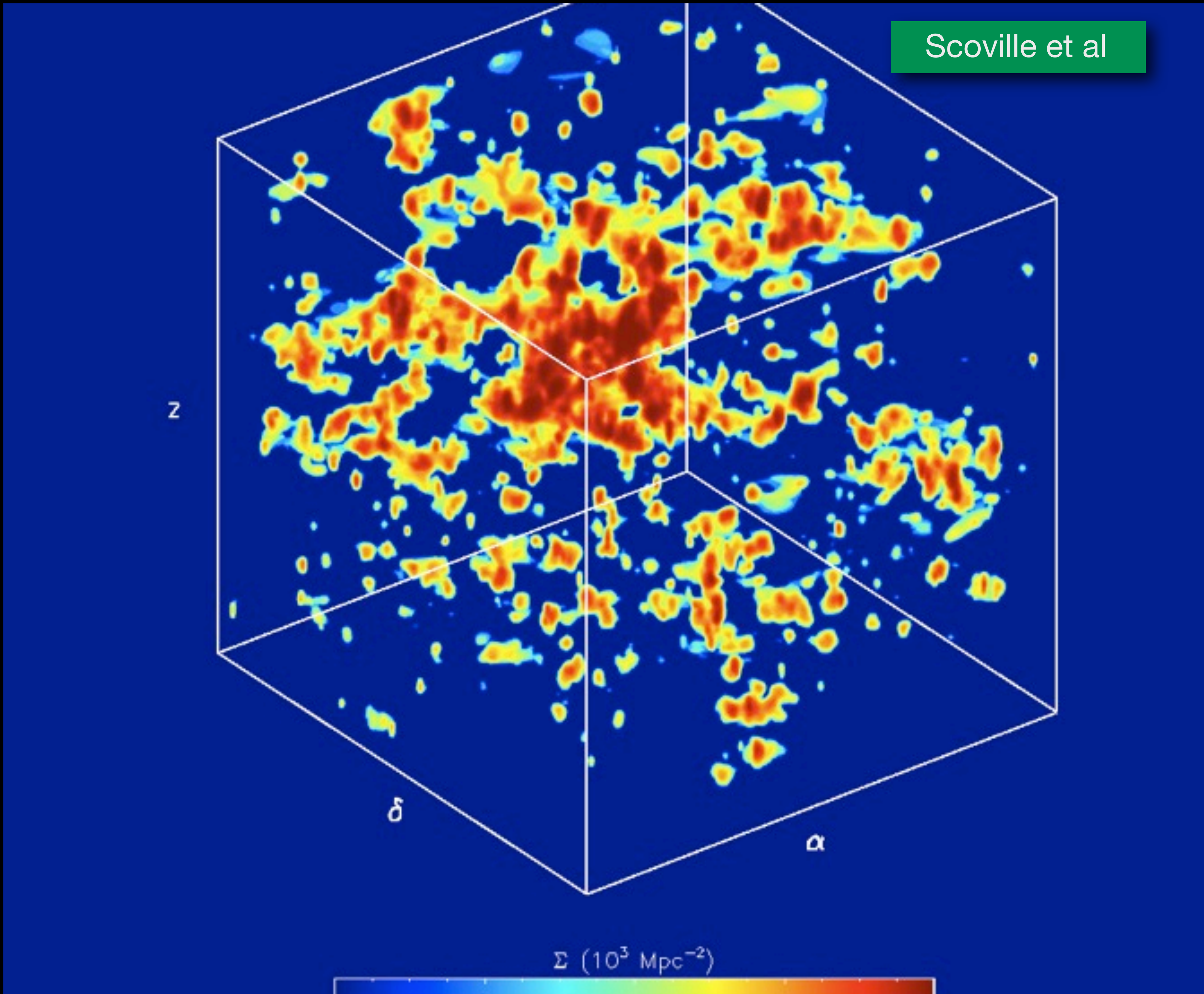
Blue: galaxies

Red: x-ray emission

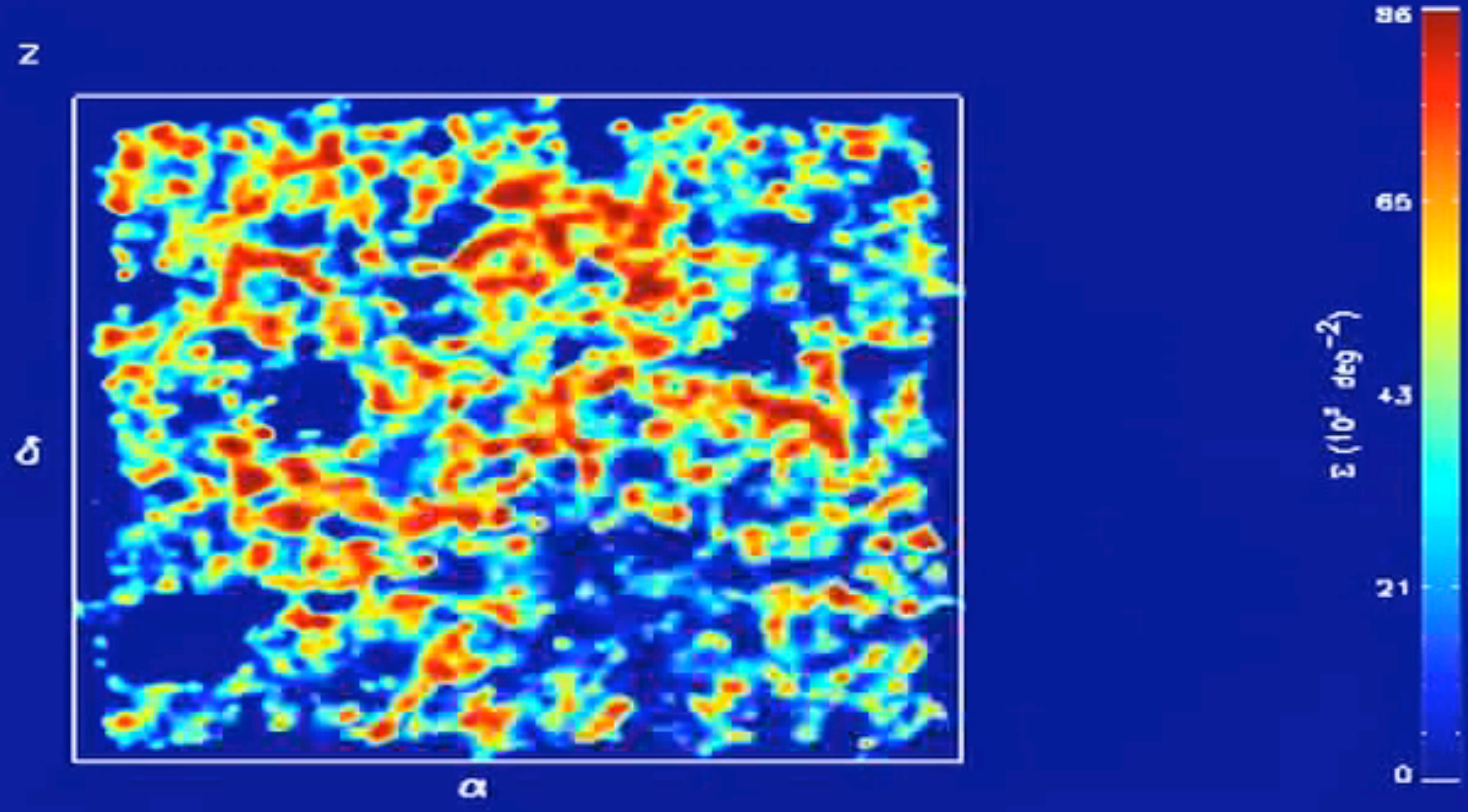
Contours: Dark matter lensing map



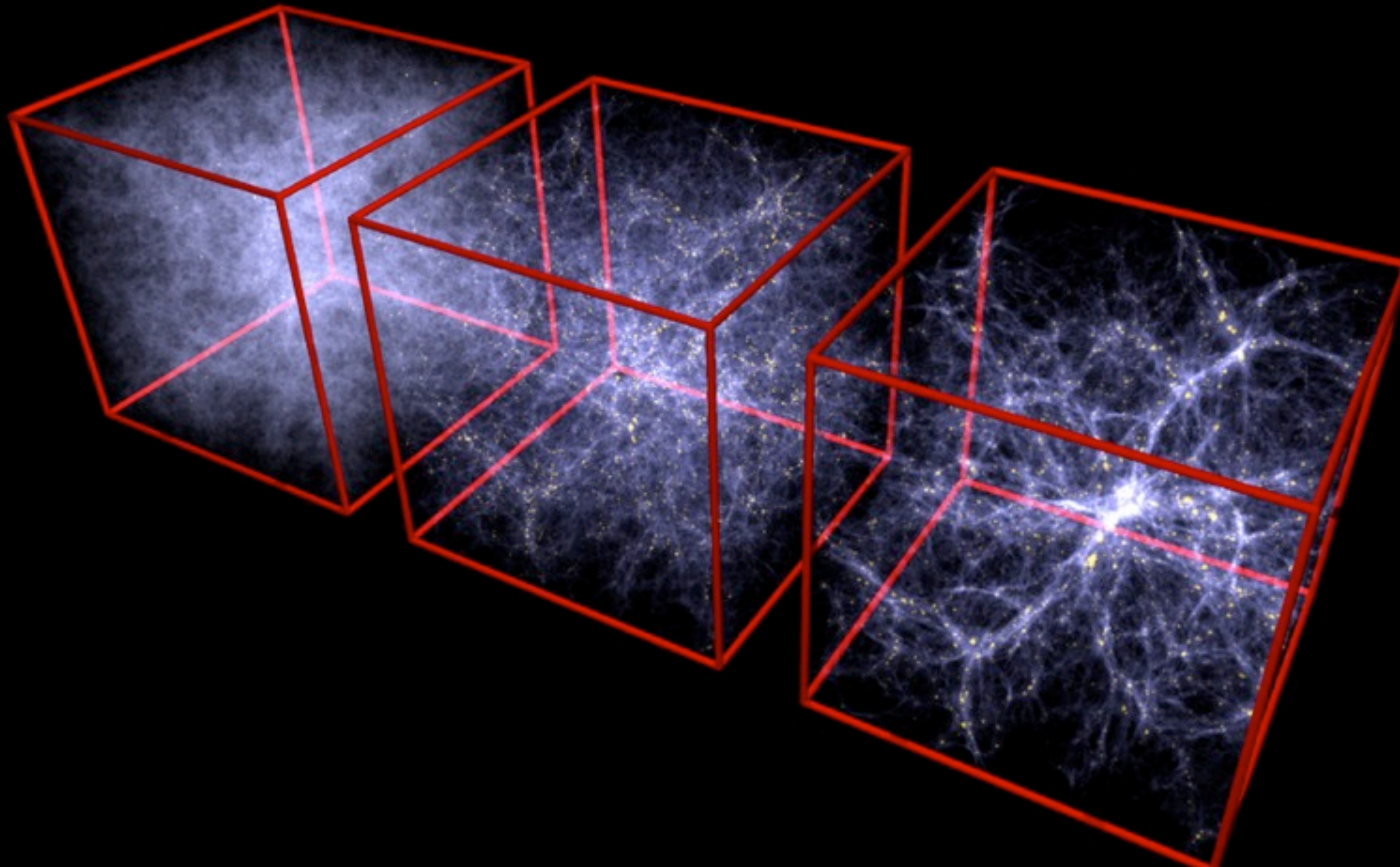
Only possible thanks to the combination of ACS morphologies, precise photo-zeds and deep X-ray images

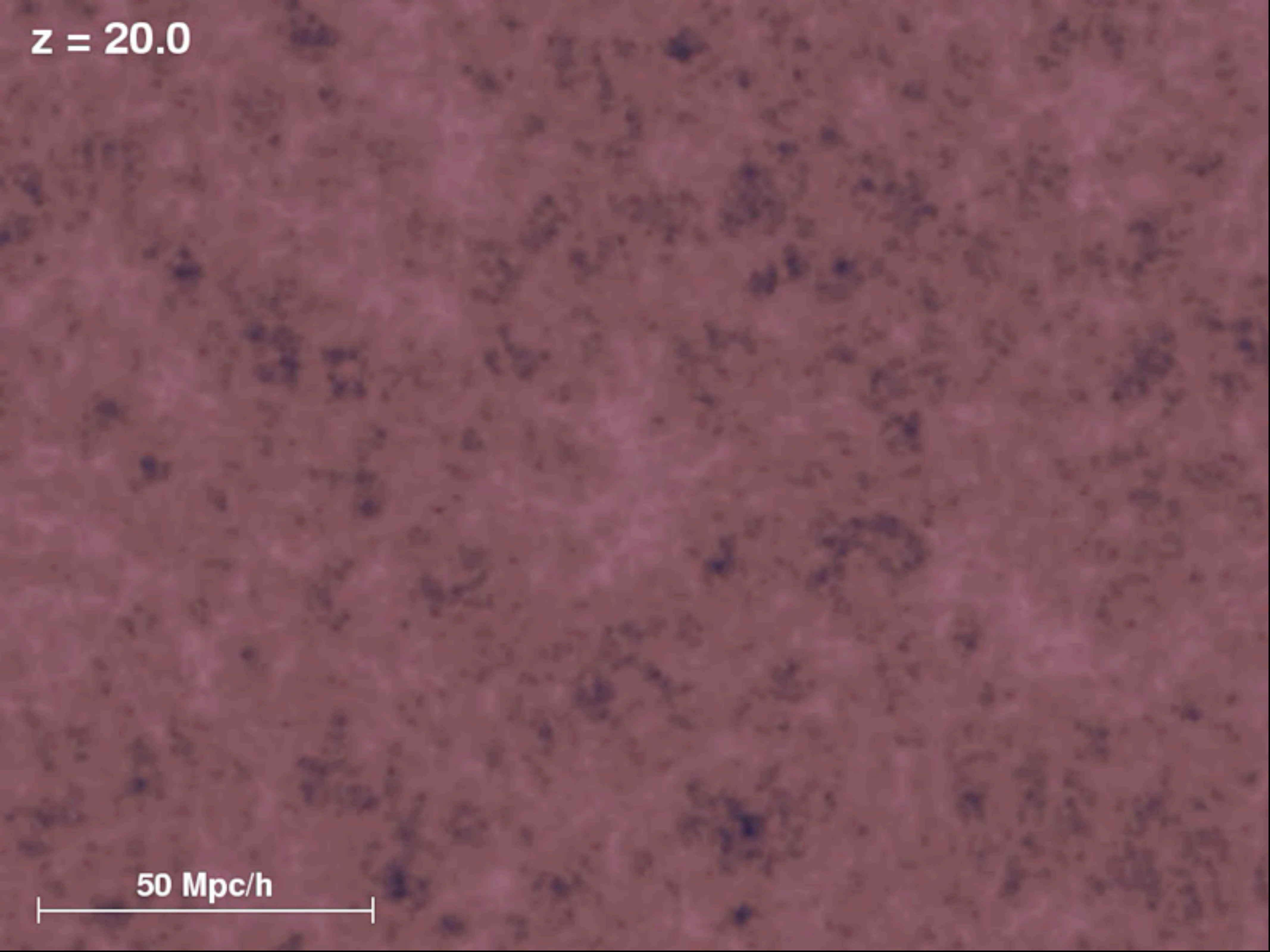


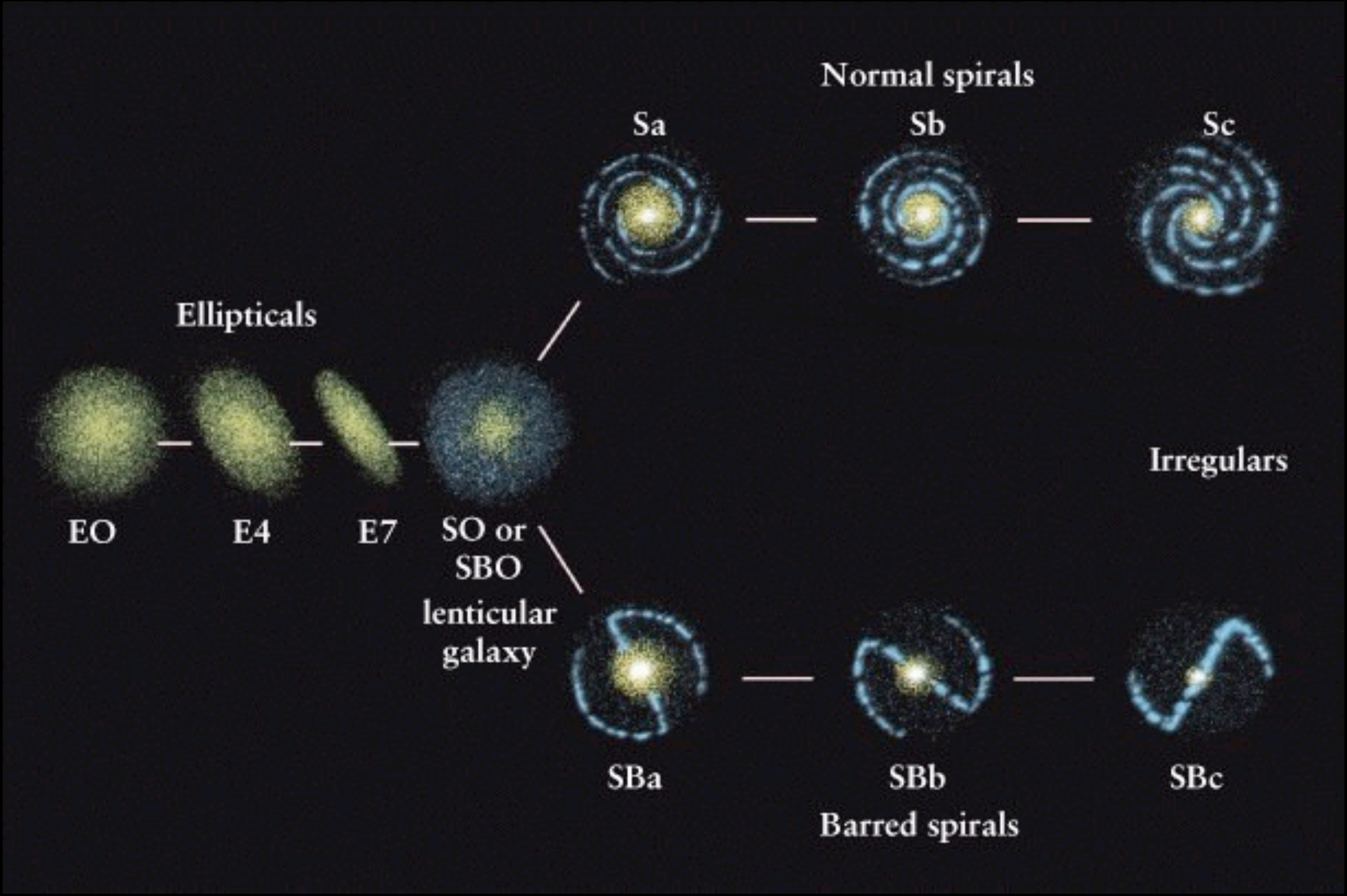
Scoville et al
z
δ
α
Σ (10³ Mpc⁻²)



z
δ
α
96
65
43
21
0
Σ (10² deg⁻²)




z = 20.0
50 Mpc/h


Normal spirals
Sa
Sb
Sc
Ellipticals
Irregulars
EO
E4
E7
SO or
SBO
lenticular
galaxy
SBa
SBb
SBc
Barred spirals

But how do galaxies form?

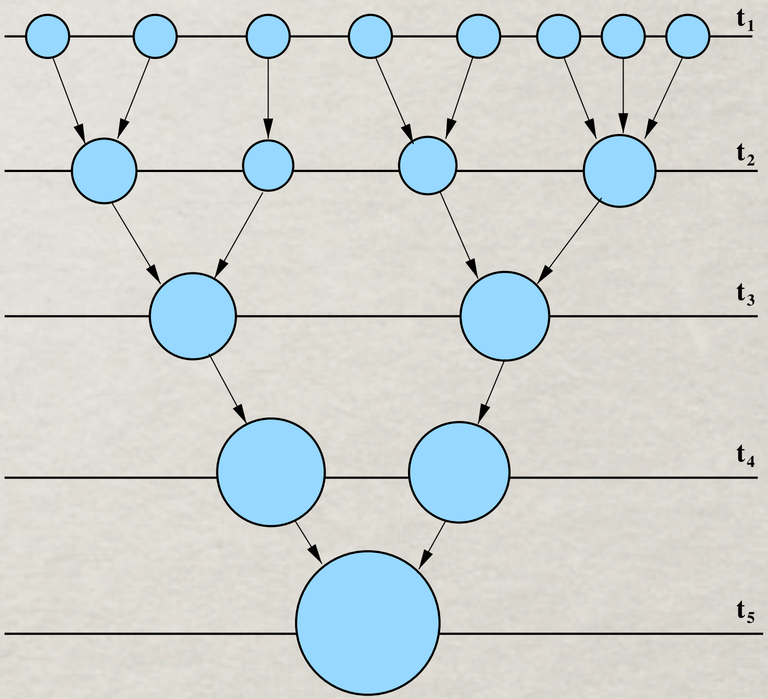
Smallest haloes form first

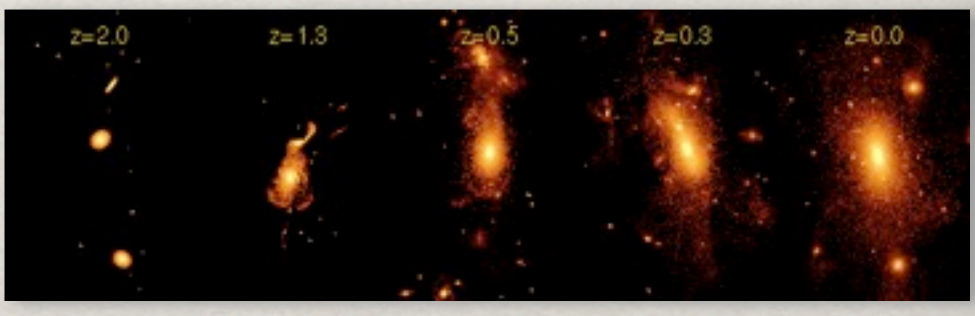
Haloes of dark matter accrete and grow under the action of gravity

Baryonic matter gathers in these potential wells and forms stars and galaxies

Smallest galaxies form first

There should be very few massive galaxies early in the Universe...

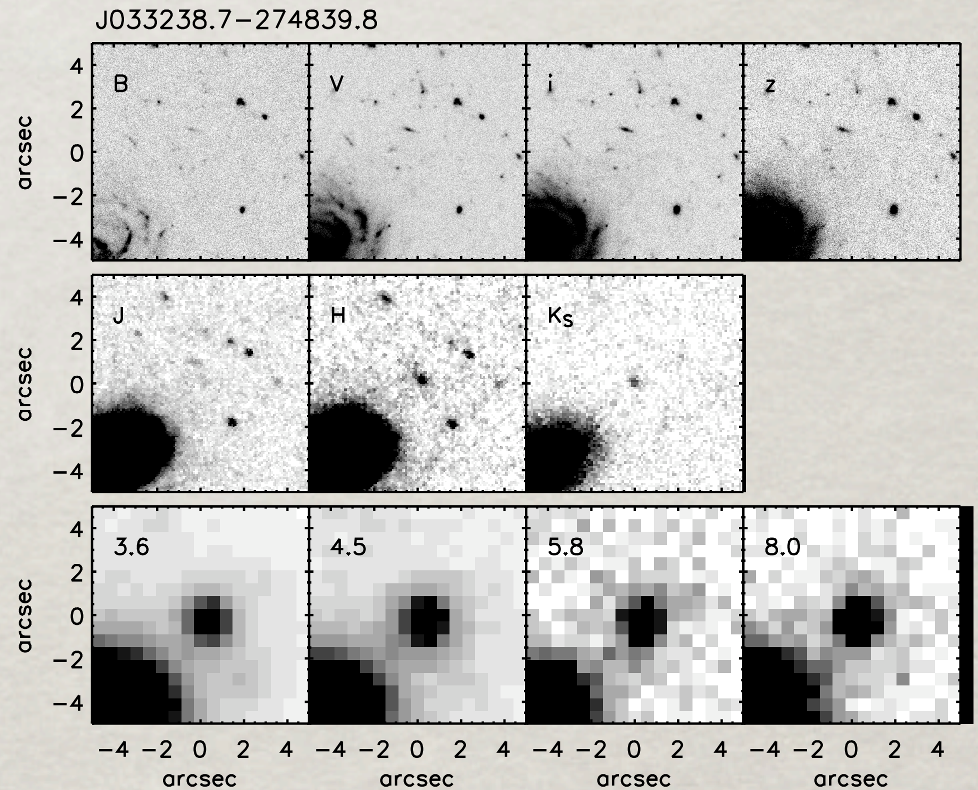




Formation of an elliptical galaxy by merging

Witnessing the formation of the first galaxies?

The case of HUDF-J2



This galaxy is a “J-dropout” and has colours consistent with being very old and massive -- but we see it only a few million years after the big bang!

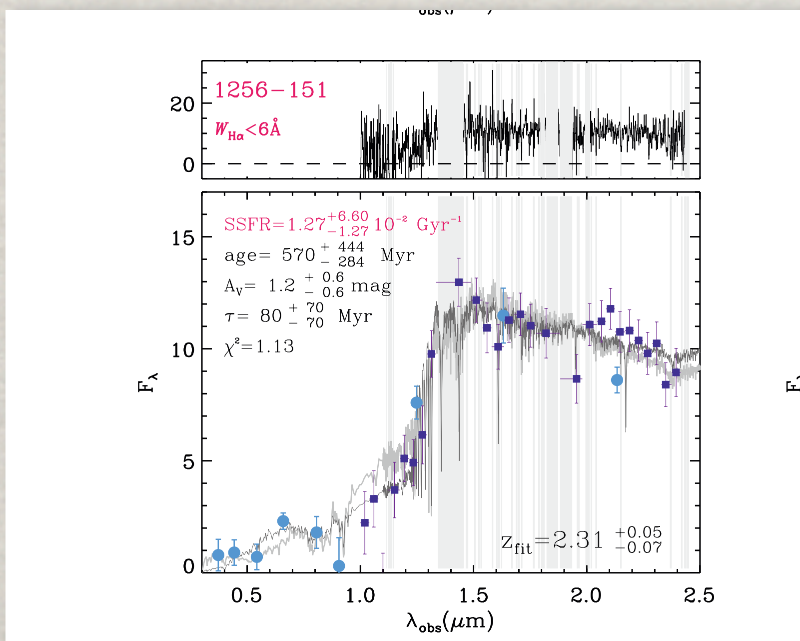
However, we really need to have larger surveys with many more galaxies!

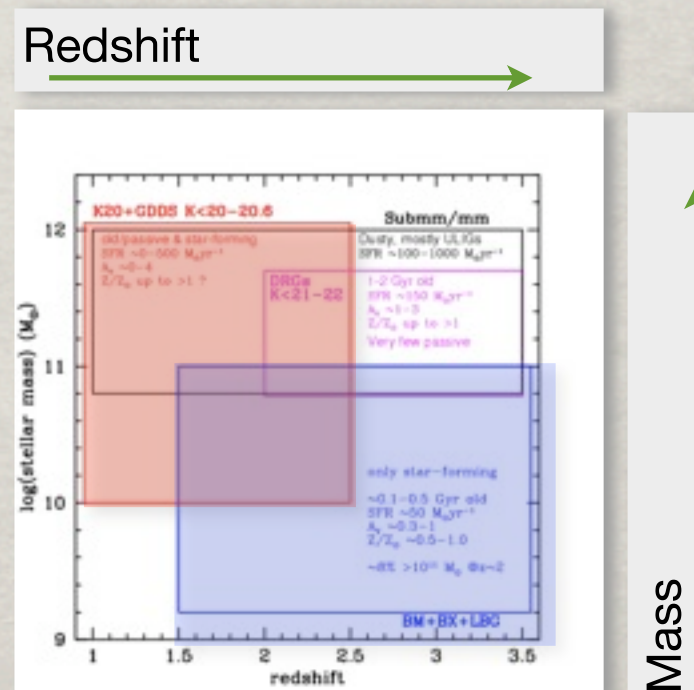
What NIR surveys can tell us

Near-infrared surveys can find the oldest galaxies, most massive objects in the Universe

Near-infrared surveys are sensitive “passively evolving” galaxies, i.e., galaxies where only stellar evolution is occurring

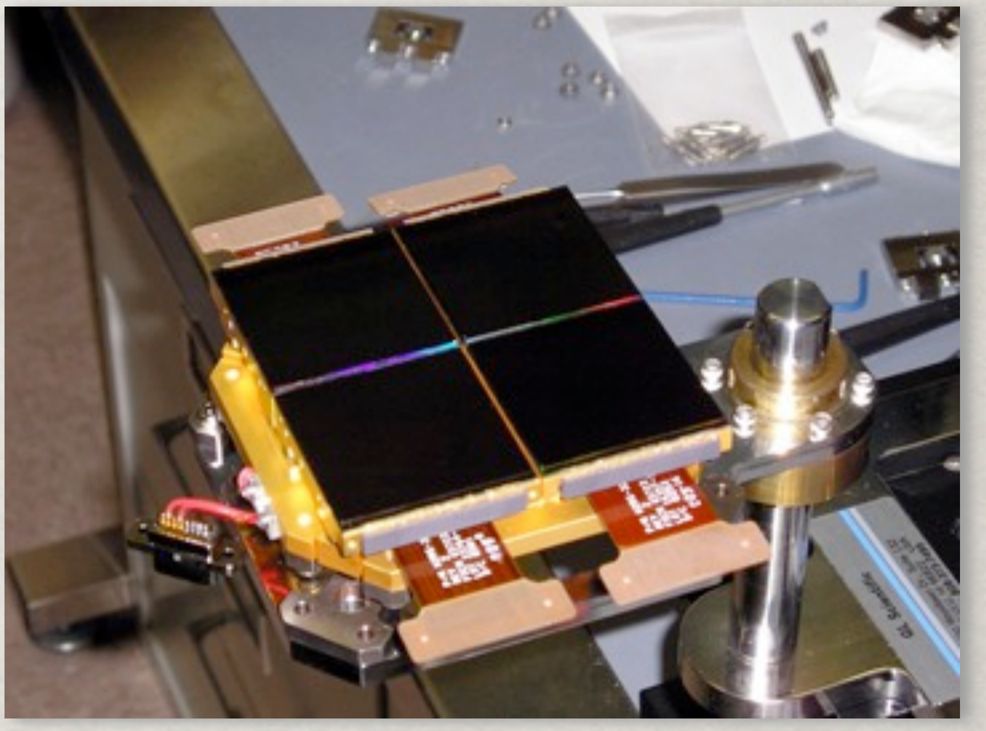
Directly probes the underlying stellar mass





A large Near-IR survey at CFHT

We used WIRCAM to cover the entire COSMOS field in near-infrared Ks.

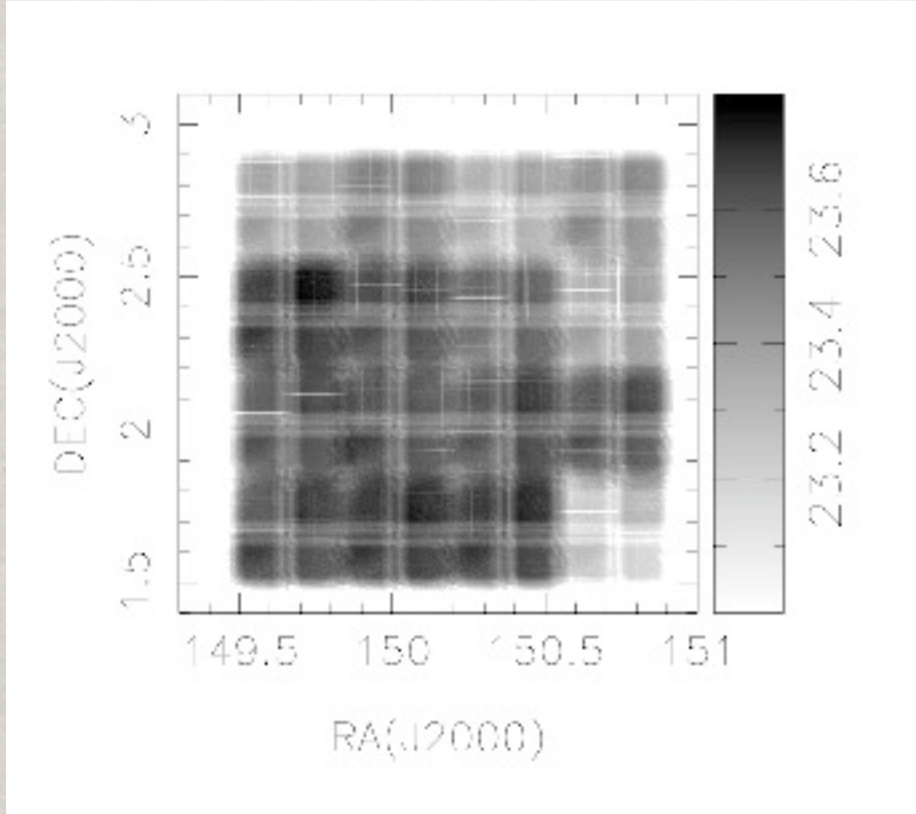


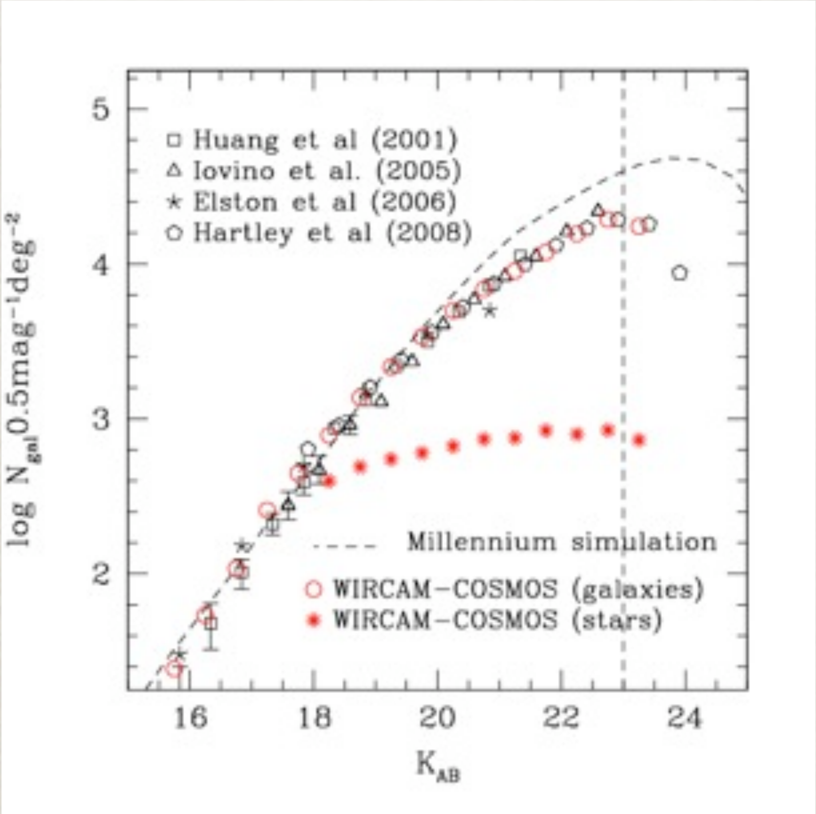
The WIRCAM near-infrared camera

Canada-France Hawaii telescope

The largest, deepest Near-IR survey to date

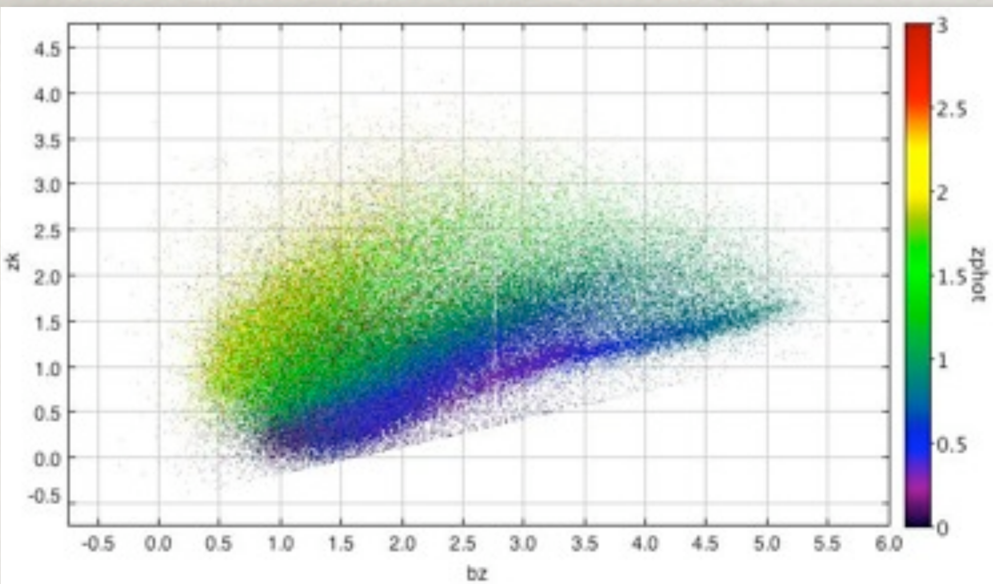
WIRDS-COSMOS data

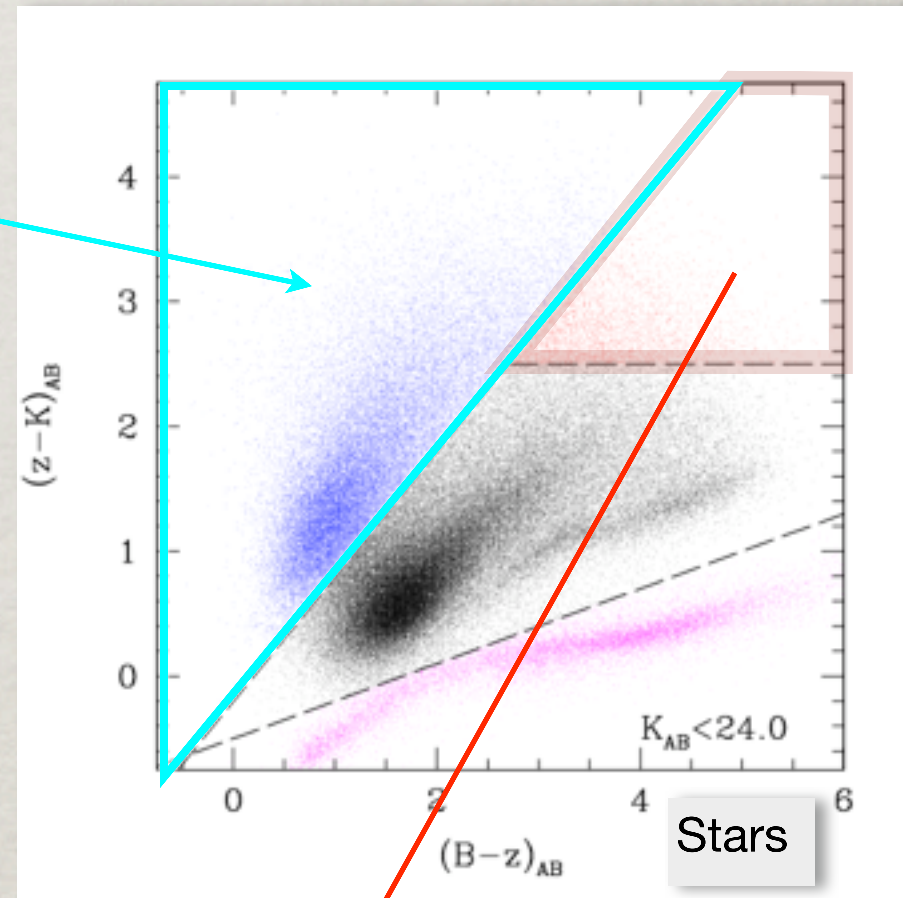




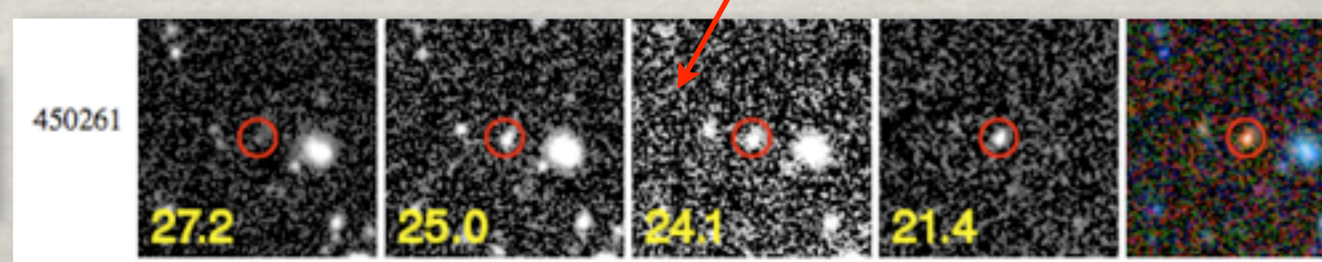
COSMOS Optical-Near-IR diagram

“Star-forming” BzK galaxies



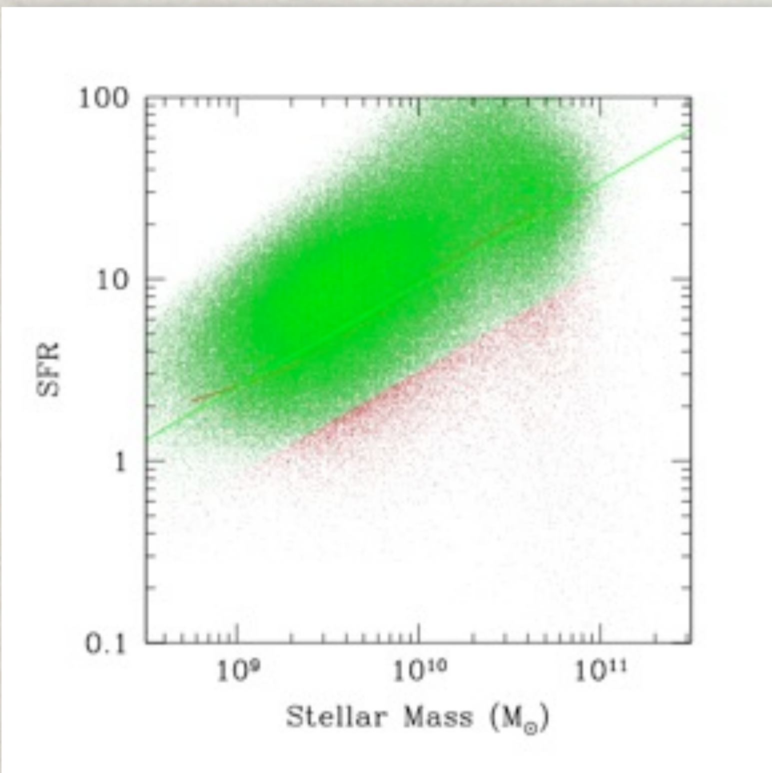


Passive galaxy in COSMOS survey

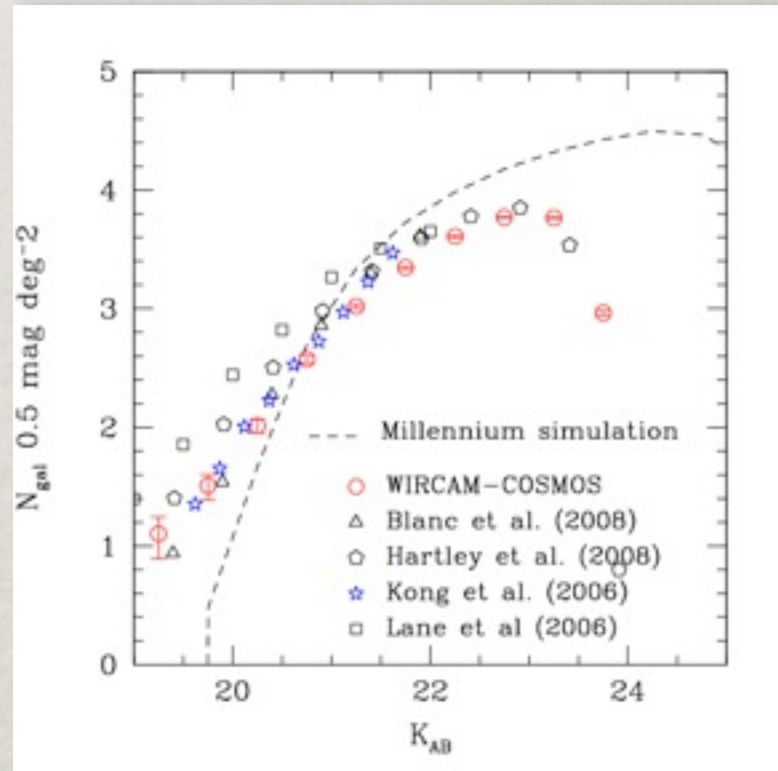


Star-forming galaxy candidates?

Millenium simulation

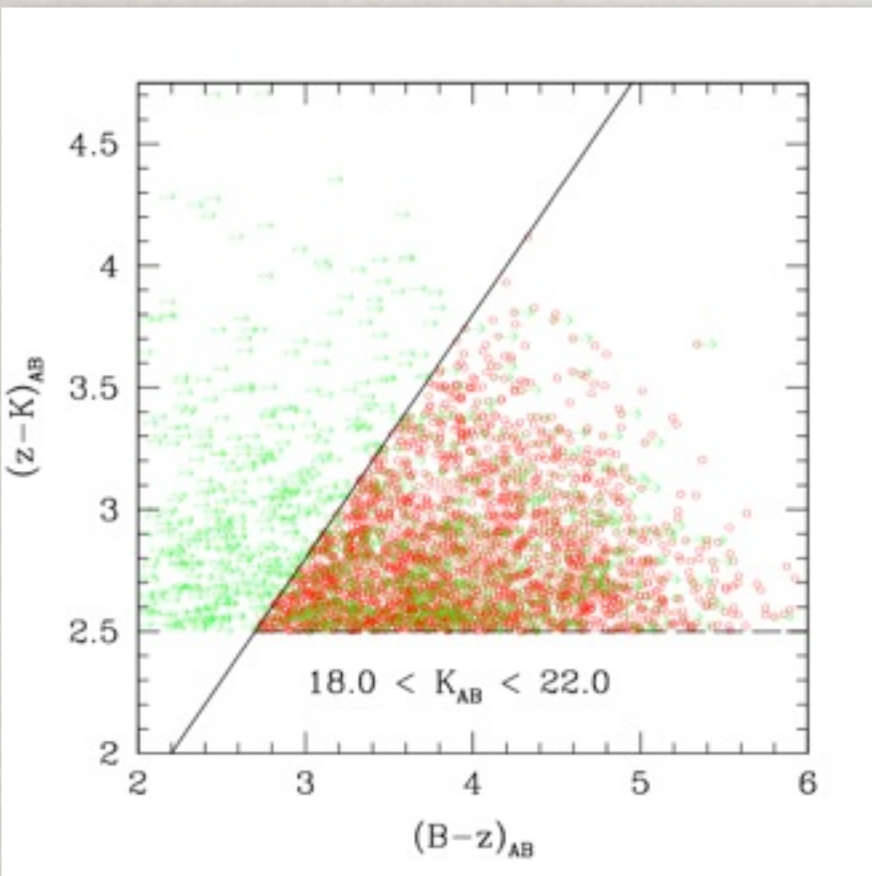


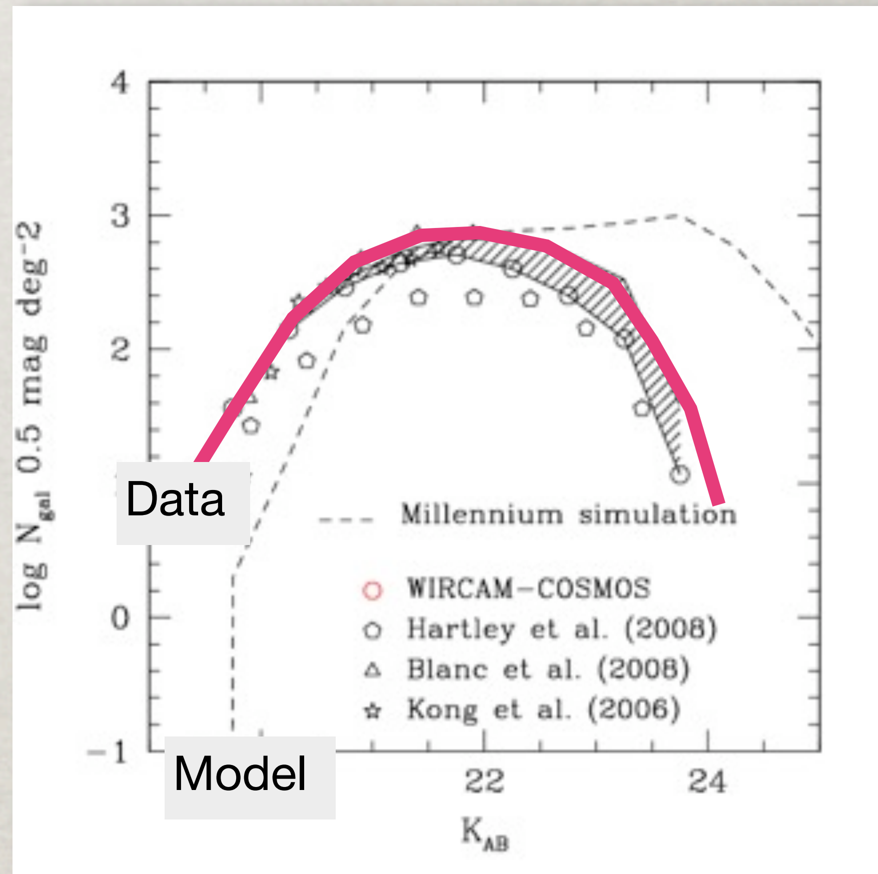
Star-forming BzK



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

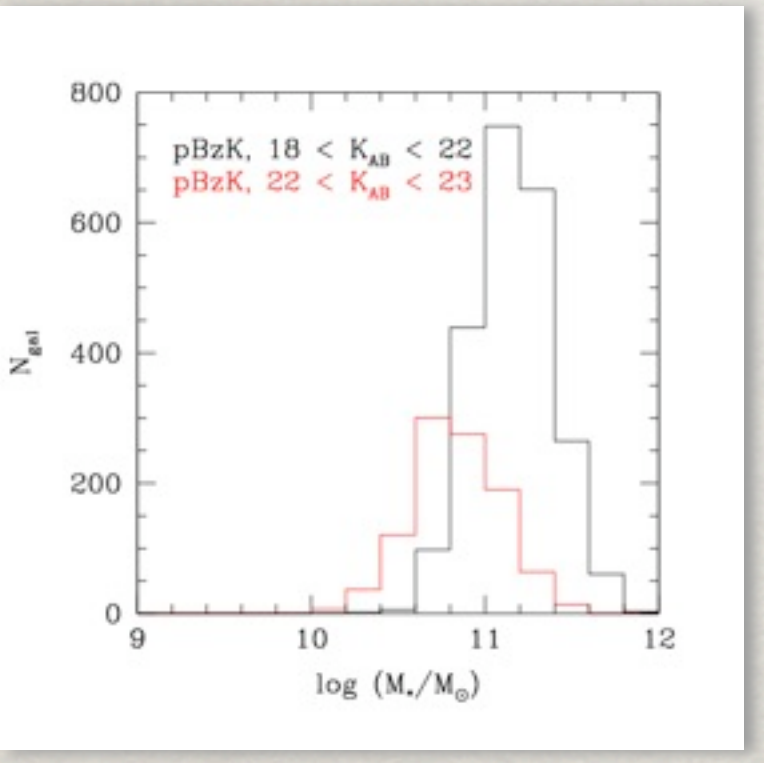
Number counts of passive BzK

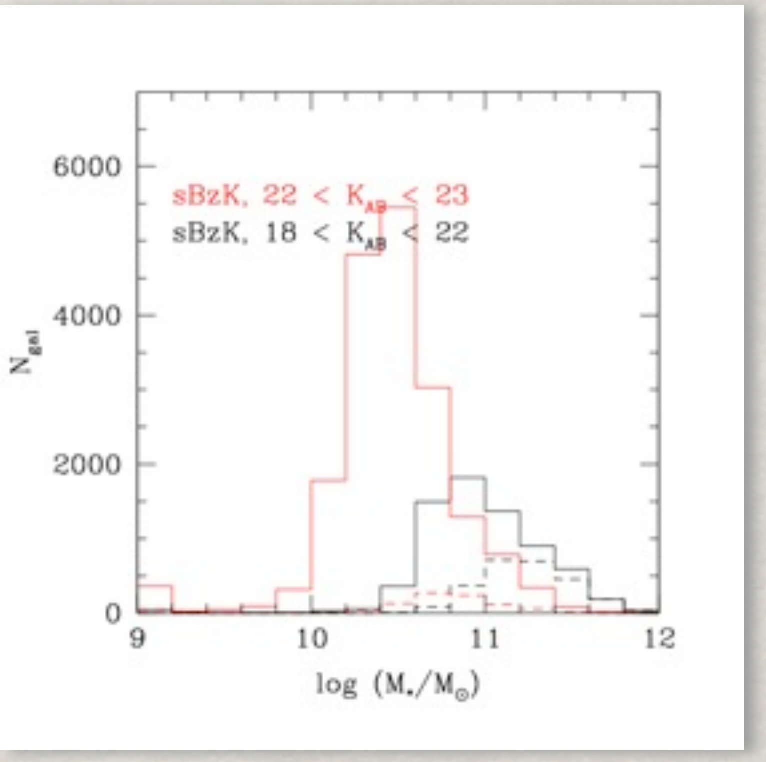




- We clearly see a **turn-over** in the counts of passive galaxies which cannot be explained by sample incompleteness
- The millennium simulation under-predicts the number of bright galaxies

Stellar masses for star-forming BzK





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

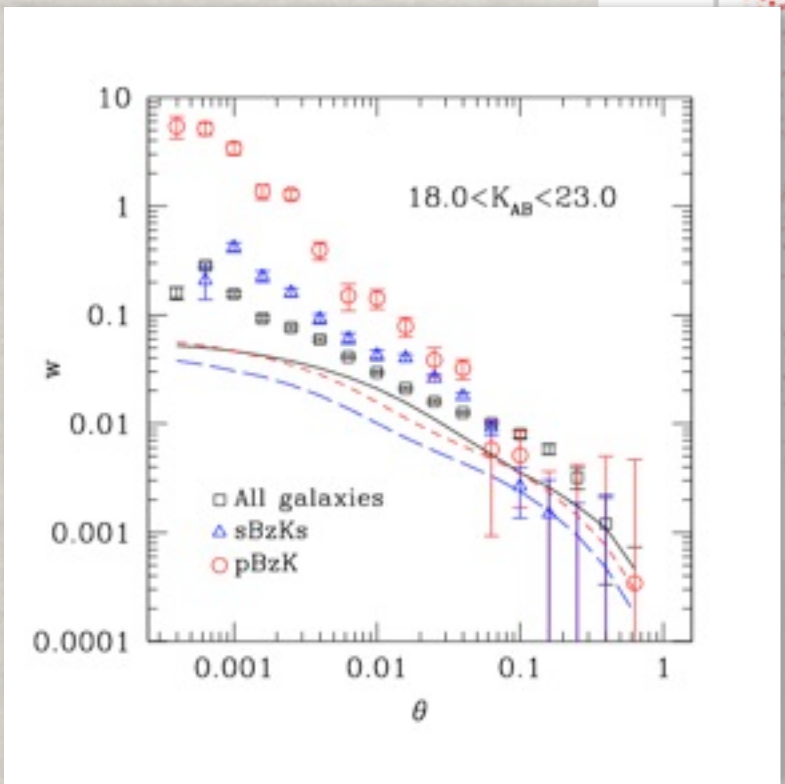
A word on two-point correlation functions...

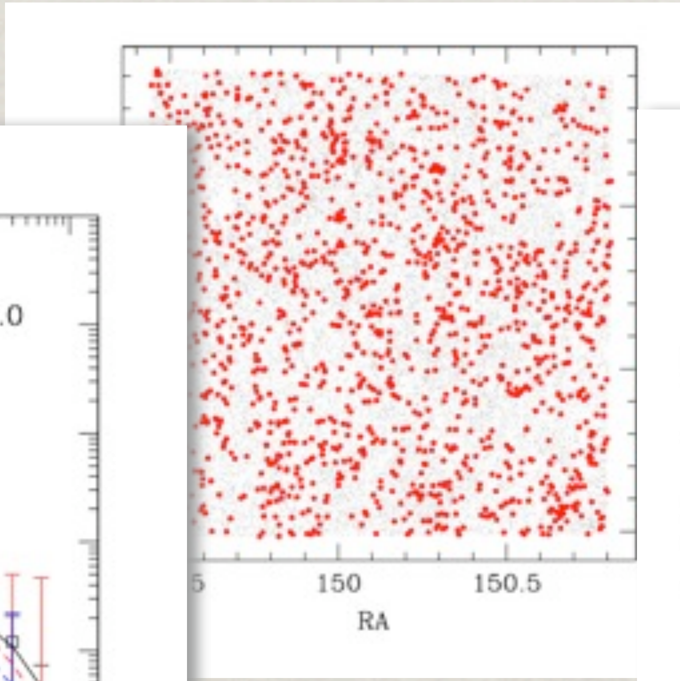
Two-point correlation functions give the excess probability for finding a neighbour a distance r from a given galaxy:

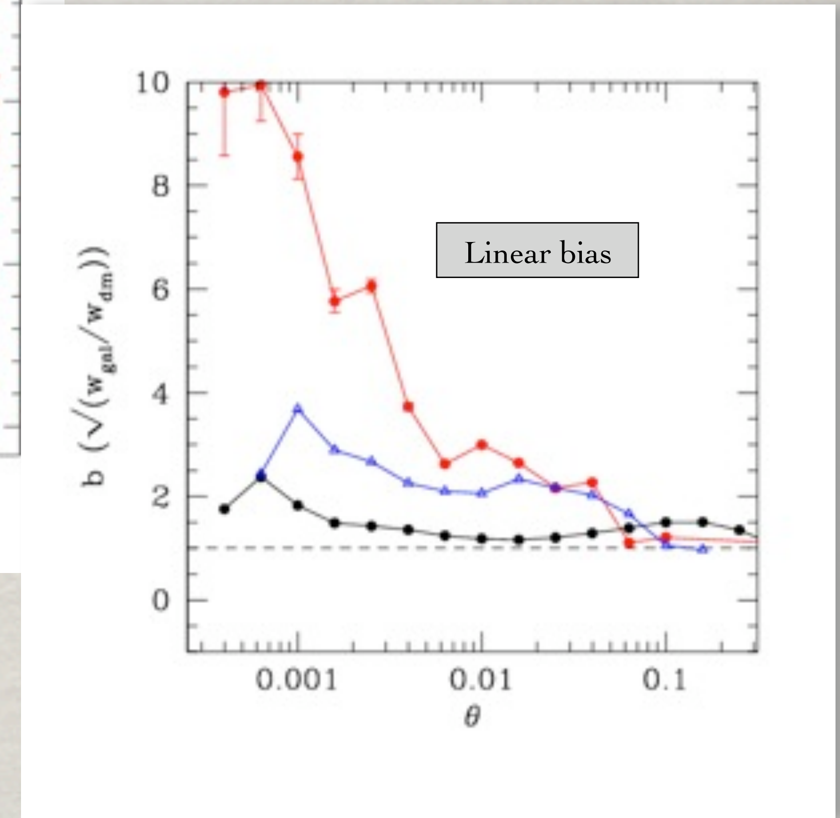
$$\delta P = n^2 \delta V_1 \delta V_2 [1 + \xi(r_{12})]$$

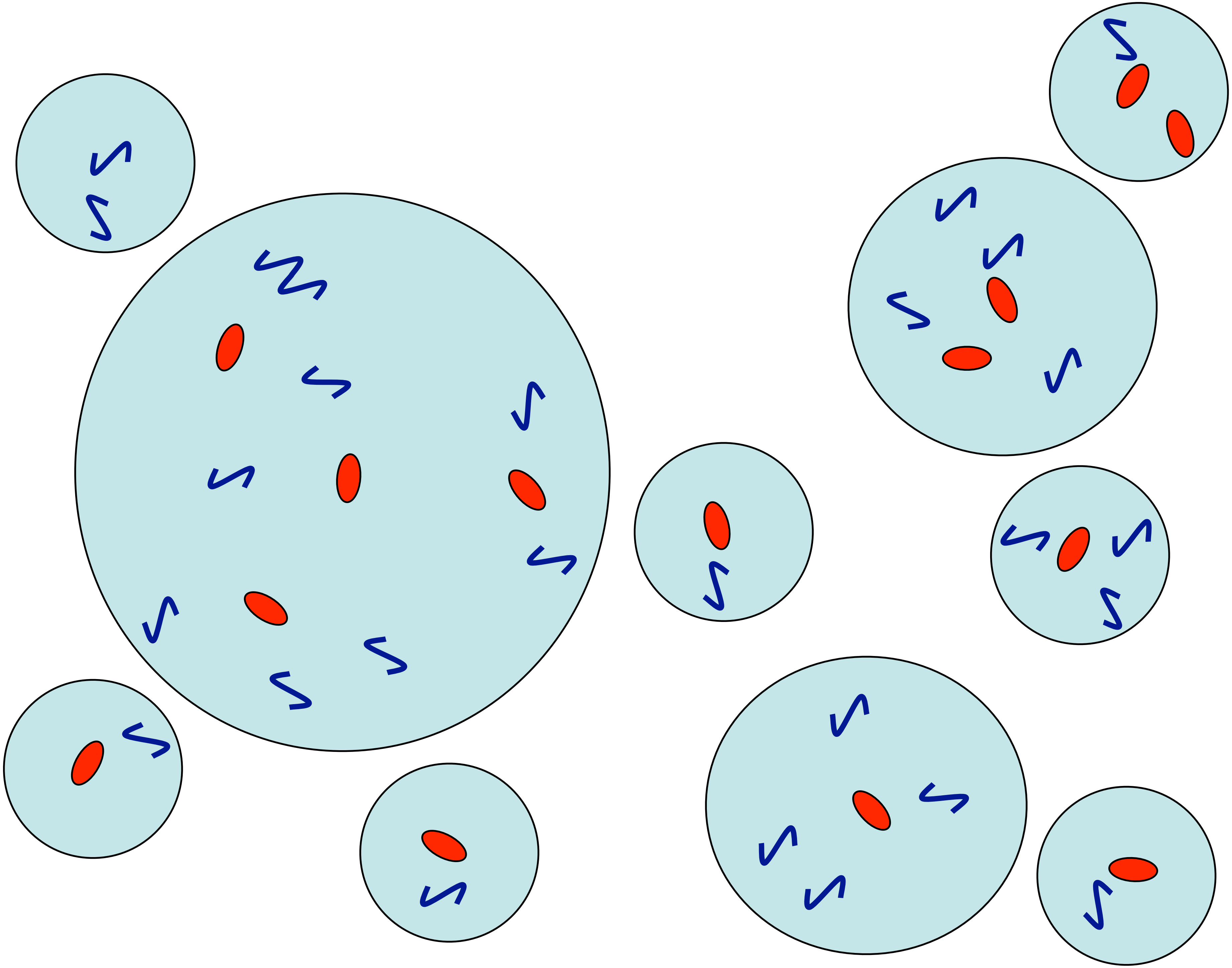
- w(θ) is the simply the projection of xi(r) on the sky and depends (amongst other things) on the source redshift distribution (see later)
- xi(r) can be calculated exactly for dark matter
- The relation between the clustering of the dark matter and that of the luminous matter can tell us something about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

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’

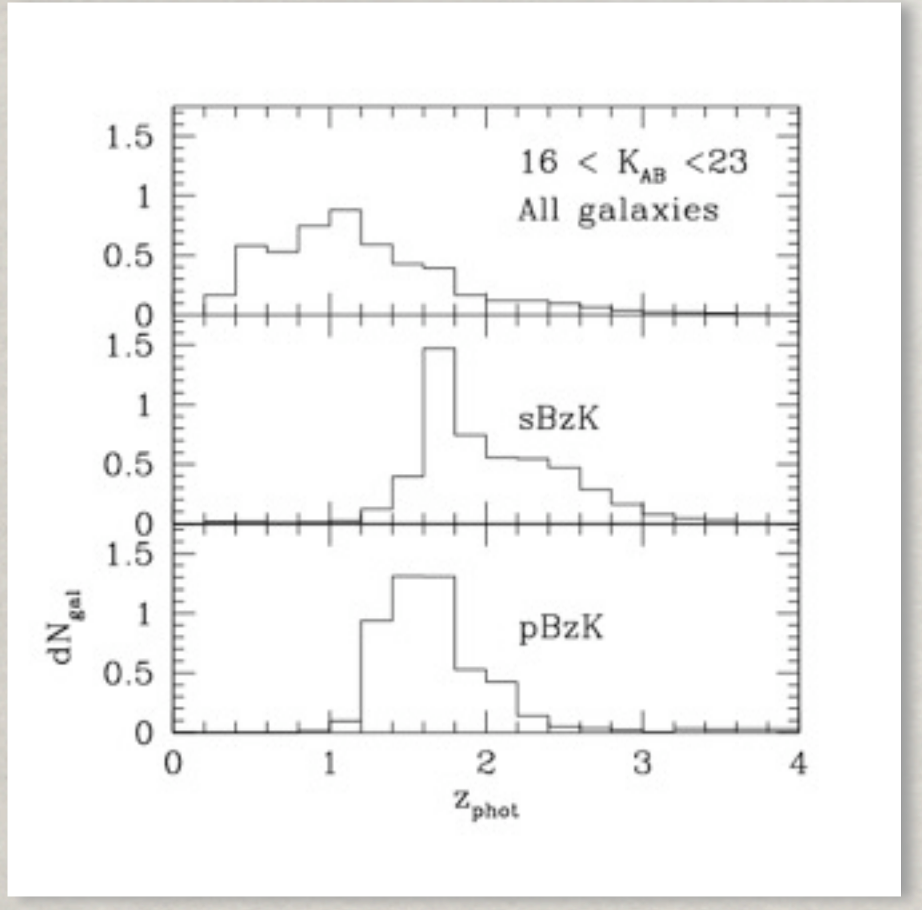
How to compute galaxy clustering using the halo model

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.**

Redshift distributions

Halo model must also reproduce the observed number density of galaxies



These redshift selection functions come from the accurate photo-zeds presented in Ilbert et al. 2008

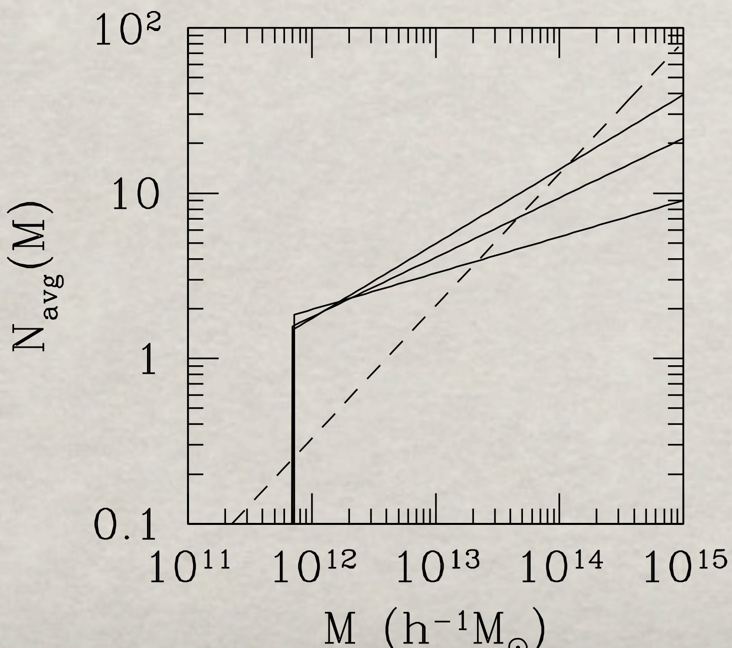
Deep IRAC and *JK* means we can compute accurate photo-zeds between 1<z<2

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

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

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

Computing w from the HOD model - II

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

1-halo power spectrum

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

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

2-halo power spectrum

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

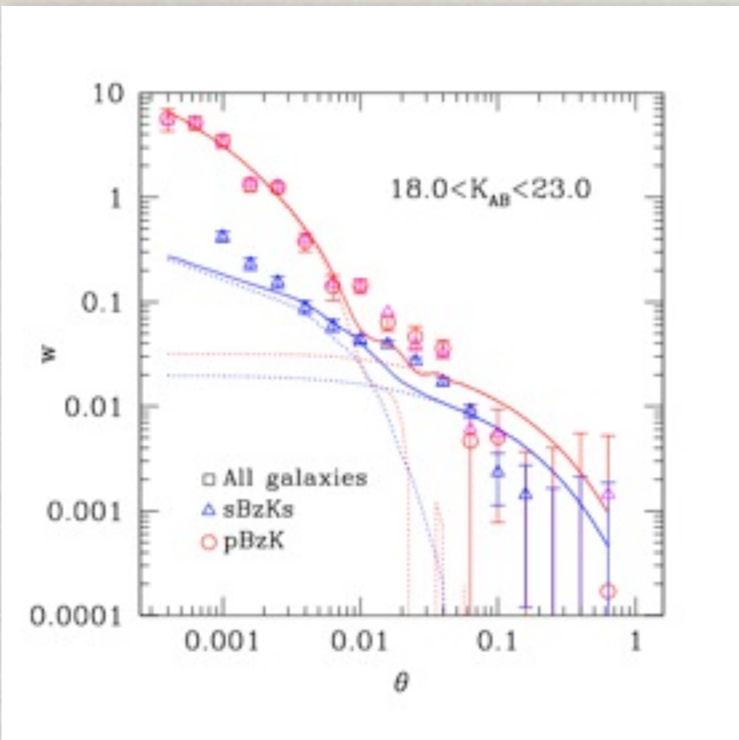
$$P_g(k) = P_g^{1h}(k) + P_g^{2h}(k).$$

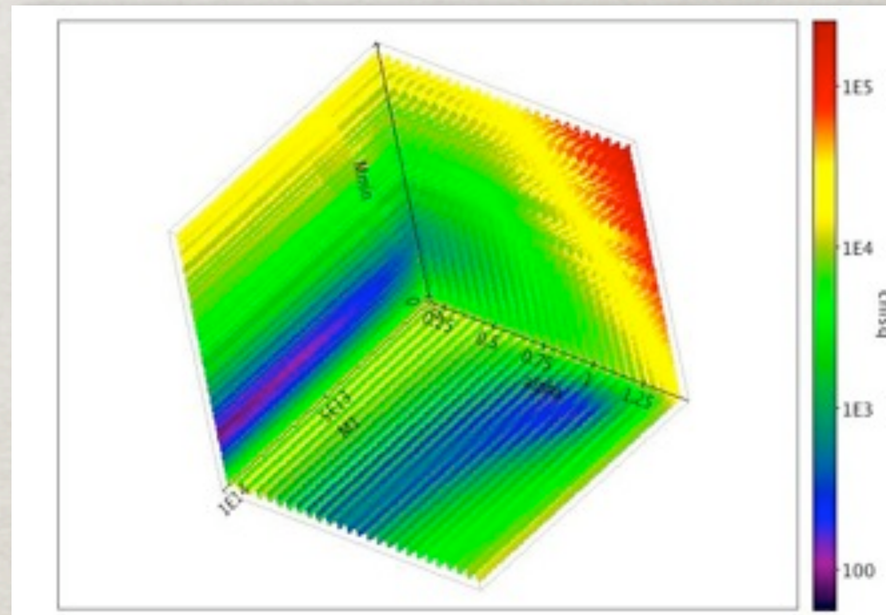
total power spectrum

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

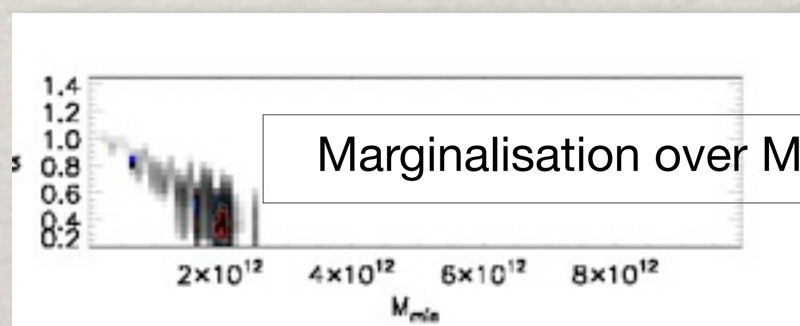
Results for the passsive BzK population

3-parameter space





“M1” parameter is poorly constrained by our data



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:

$$b_g(>M_{\rm min}) \equiv \frac{\int dM\, n_{\rm halo}(M) N_g(M) b(M)}{\int dM\, n_{\rm halo}(M) N_g(M)}.$$

Average halo bias

$$\langle M_{\rm host} \rangle = \frac{\int_{M_{\rm min}}^{\infty} dM\, M\, N_g(M) n_{\rm halo}(M)}{\int_{M_{\rm min}}^{\infty} dM\, N_g(M) n_{\rm halo}(M)},$$

Average halo mass

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

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

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)

Conclusions and summary

Number counts of passive galaxies turn at KAB~22

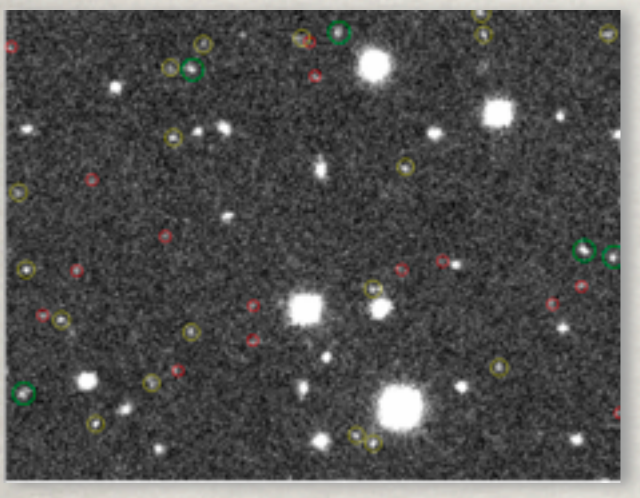
At z~2, counts of bright passive galaxies galaxies are underpredicted by the millennium simulation; bright galaxies are already “in place”

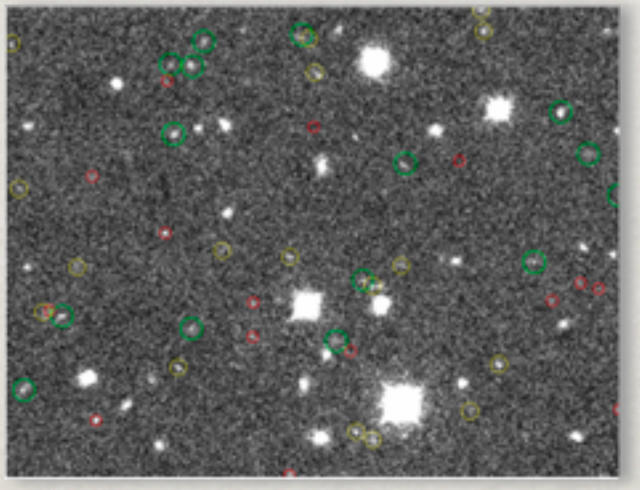
Using a “halo occupation model” we are able estimate the approximate masses of the haloes which host this passive (and star-forming) galaxy population

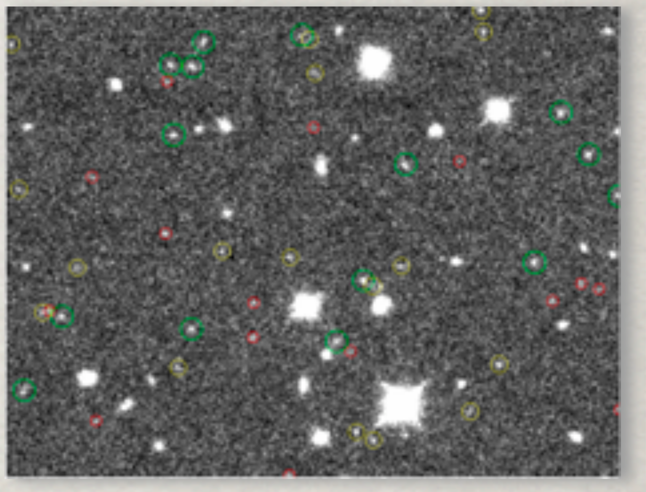
Using the K-band rest-frame absolute luminosity we can estimate the total mass in stars for the passive and star-forming galaxy populations.

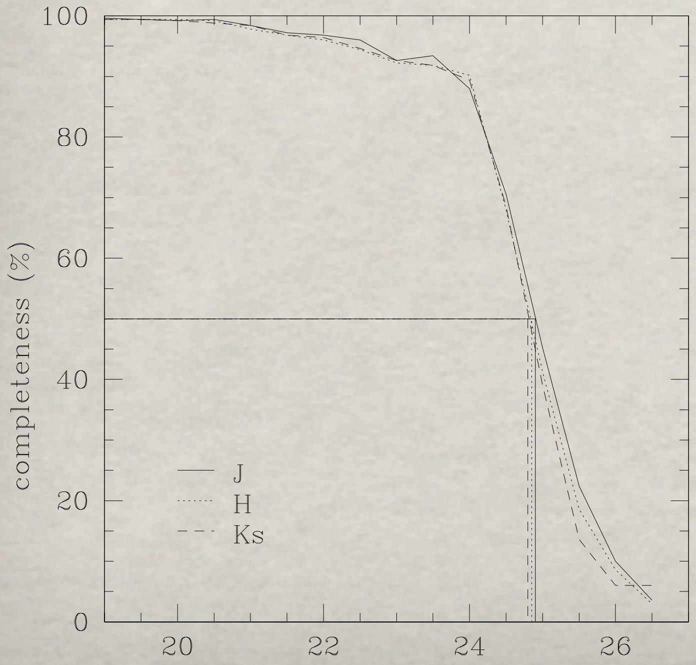
Studies with photometric redshifts (Ilbert et al.) confirm the general trend that most mass build-up takes place in the faint end of the passive galaxy population. The bright end of the passive galaxy mass function is already in place at z~2.

WIRDS data release: JHK data for the CFHTLS (Bielby et al.)









- Green = 23.0<JHK<23.5
- Yellow = 23.5<JHK<24.0
- Red = 24.0<JHK<24.5

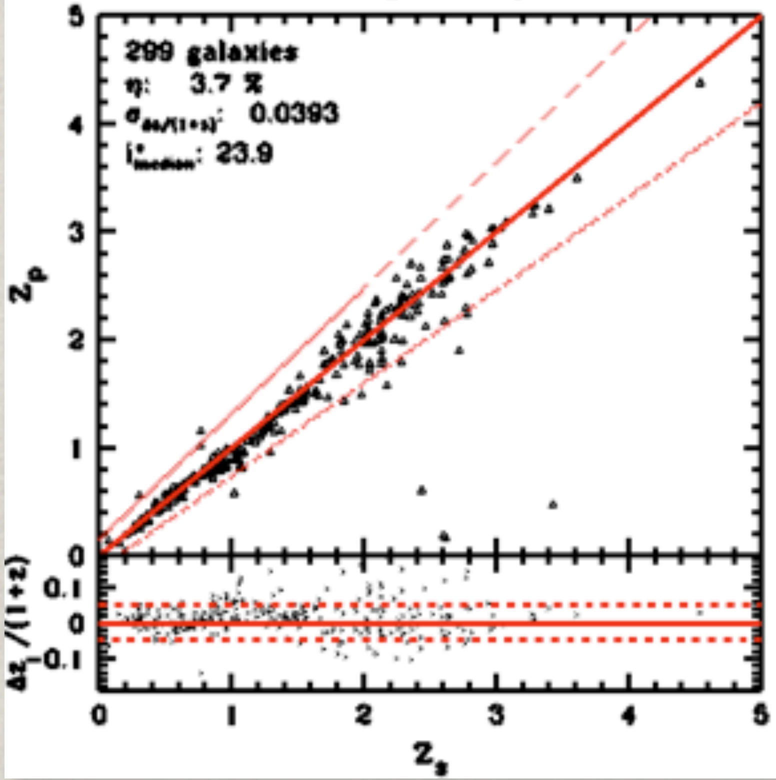
Very deep *JHK* on D1 CFHTLS field. 0.6” seeing.

The public release will include images, *gri-chisquared*-selected *K-selected* catalogues

The area overlaps with VVDS Ultra-deep survey

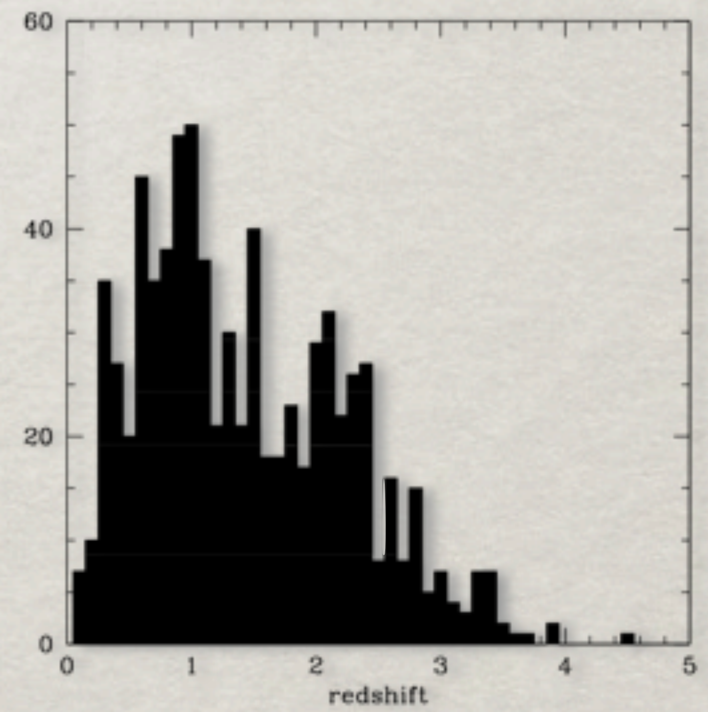
The VVDS “Ultra-deep” survey

Ilbert et al photo-zeds



ugrizk(CFHTLS) + JHK(wirds)

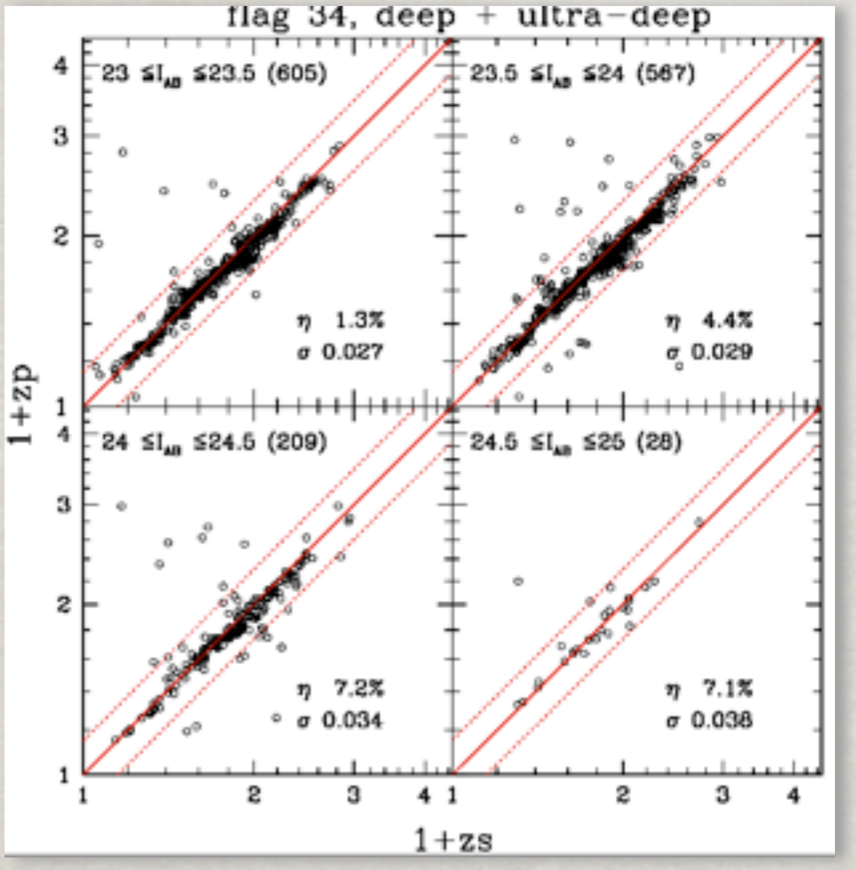
The “Ultra Deep” (OLF et al) is a magnitude limited IAB<24.75 spectroscopic survey using VIMOS on the CFHTLS-D1

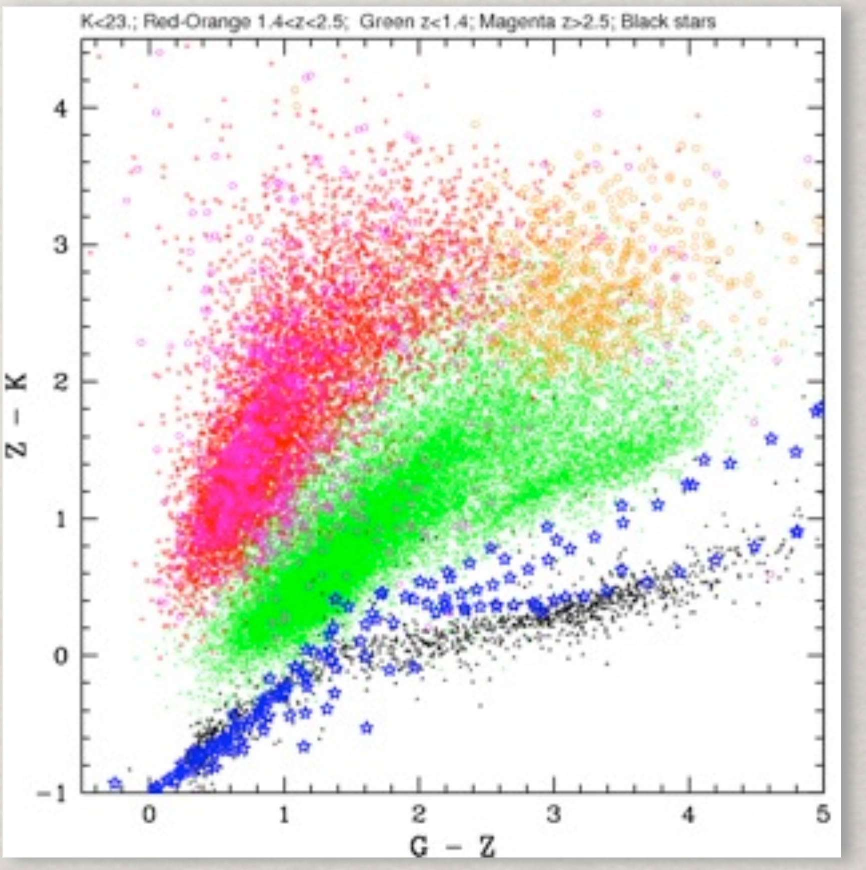


- Do the colour-colour selection criteria contain a representative survey of the Universe?

Photo-zeds for the Ultra-deep sample

Do the colour-colour selection criteria contain a representative survey of the Universe?





- Addition of near-infrared data greatly reduces the numbers of outliers and catastrophic failures in the redshift range 1<z<2