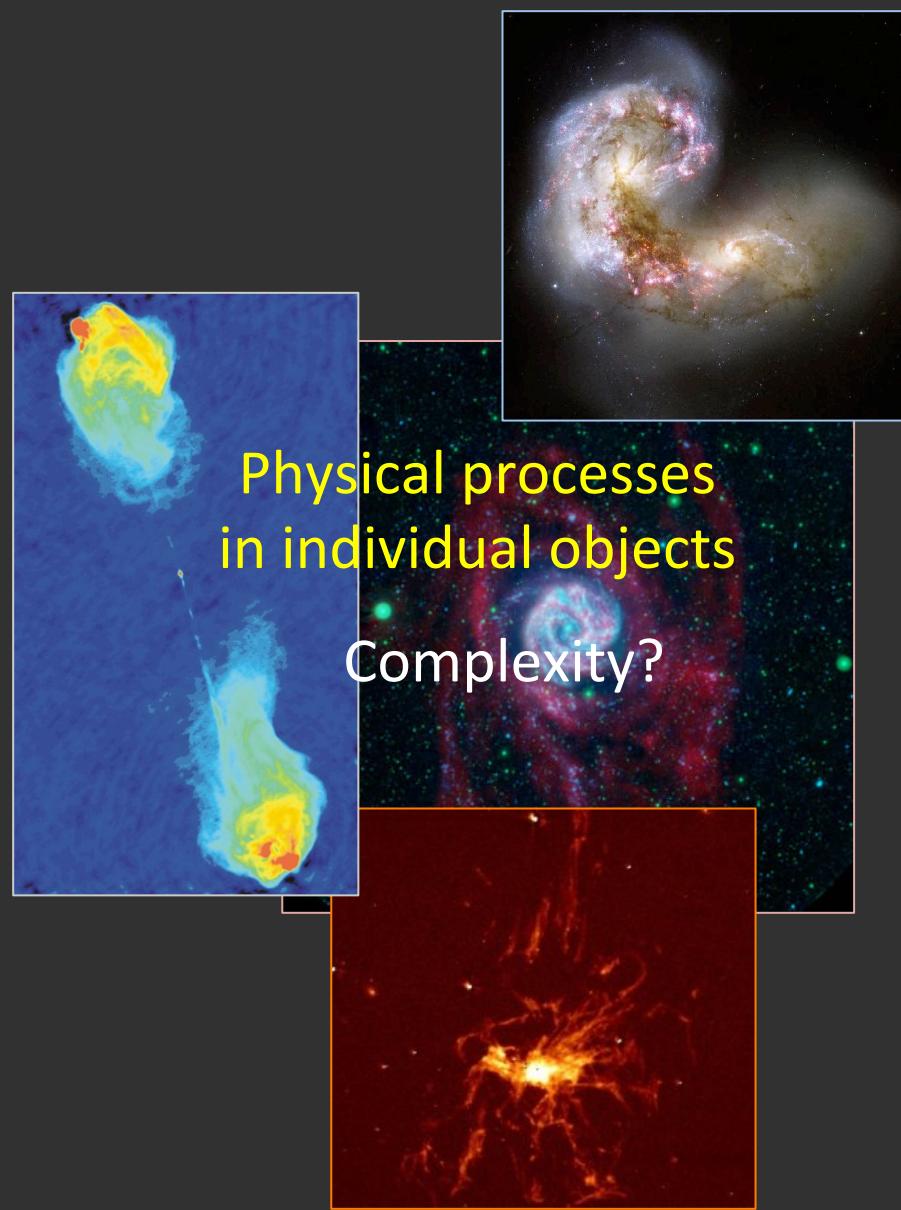


# The galaxy population over cosmic time: An observational view from large scale surveys

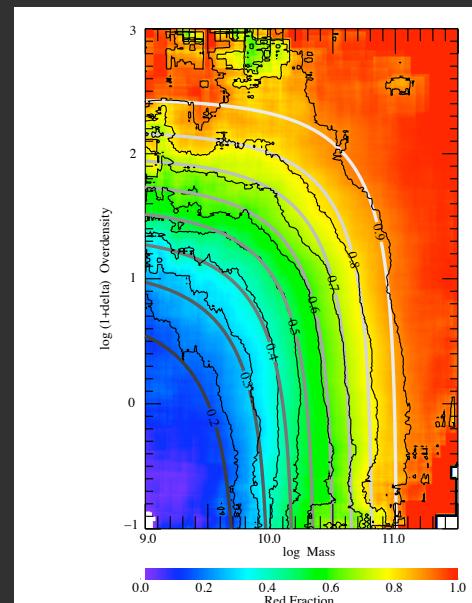
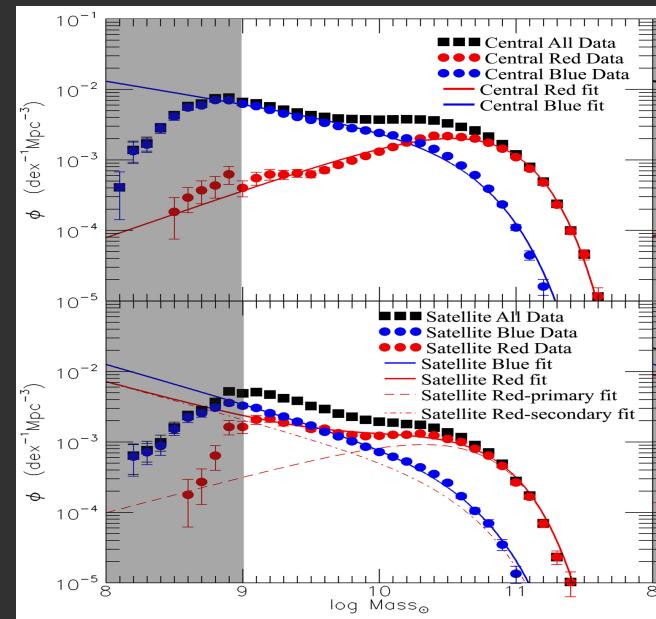
Simon Lilly, ETH Zurich

## Lecture 1: Getting the information

# Galaxy evolution: observational snapshots in time



The  
evolving  
population  
Simplicity?



# The galaxy population over cosmic time

Lecture 1: Getting the information: measurements on large numbers of galaxies at high redshifts

- Surveys
- Information from data

Lecture 2: Key observational results on the population

Lecture 3: Some phenomenological interpretation (PPPP)

- The Dead: The quenching of galaxies
- The Living: The control of star-formation and metallicity

Scope:

Observations that are available at high  $z$  for large numbers of galaxies

- no dynamics
- fairly massive galaxies  $10^{10} M_{\odot}$  in typical environments
- $z < 5$  (e.g. no reionization) and mostly  $z \sim 2$  and below
- nothing on AGN (see Tim Heckman's lectures)
- not enough on gas content and gas flows (see Reinhard Genzel, Romeel Dave etc).

## Part I: Imaging and spectroscopic surveys

# Galaxy evolution: snapshots in time

## What we want

Old stars

Optical/NIR

Young stars

ultraviolet

Obscured emission

mid- & far- IR

AGN

X-ray, radio

Gas ionized

Optical lines

atomic

Radio lines

molecular

sub-mm lines

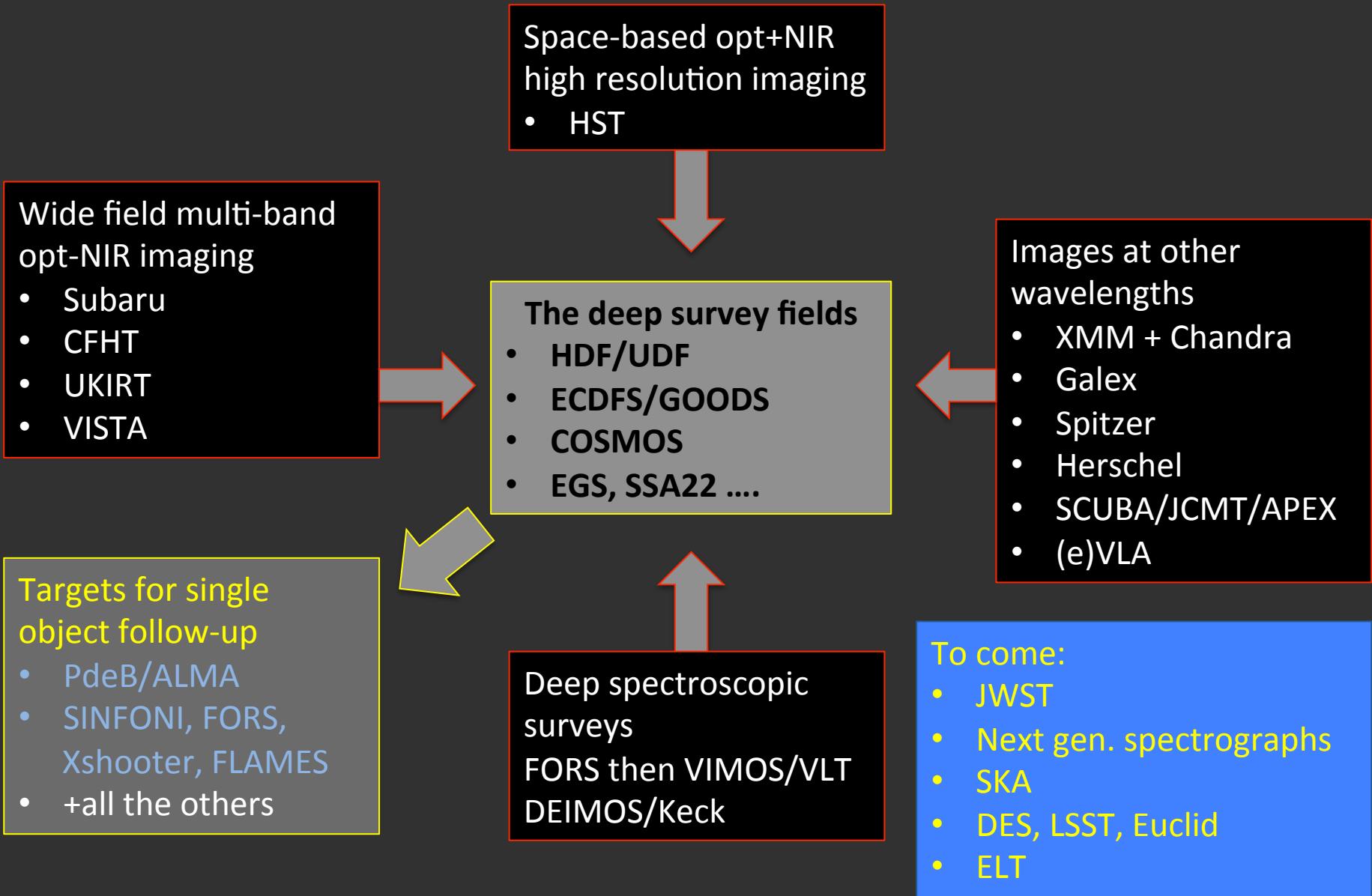
Inflow, outflow, rotation

kinematic of emission/absorption lines

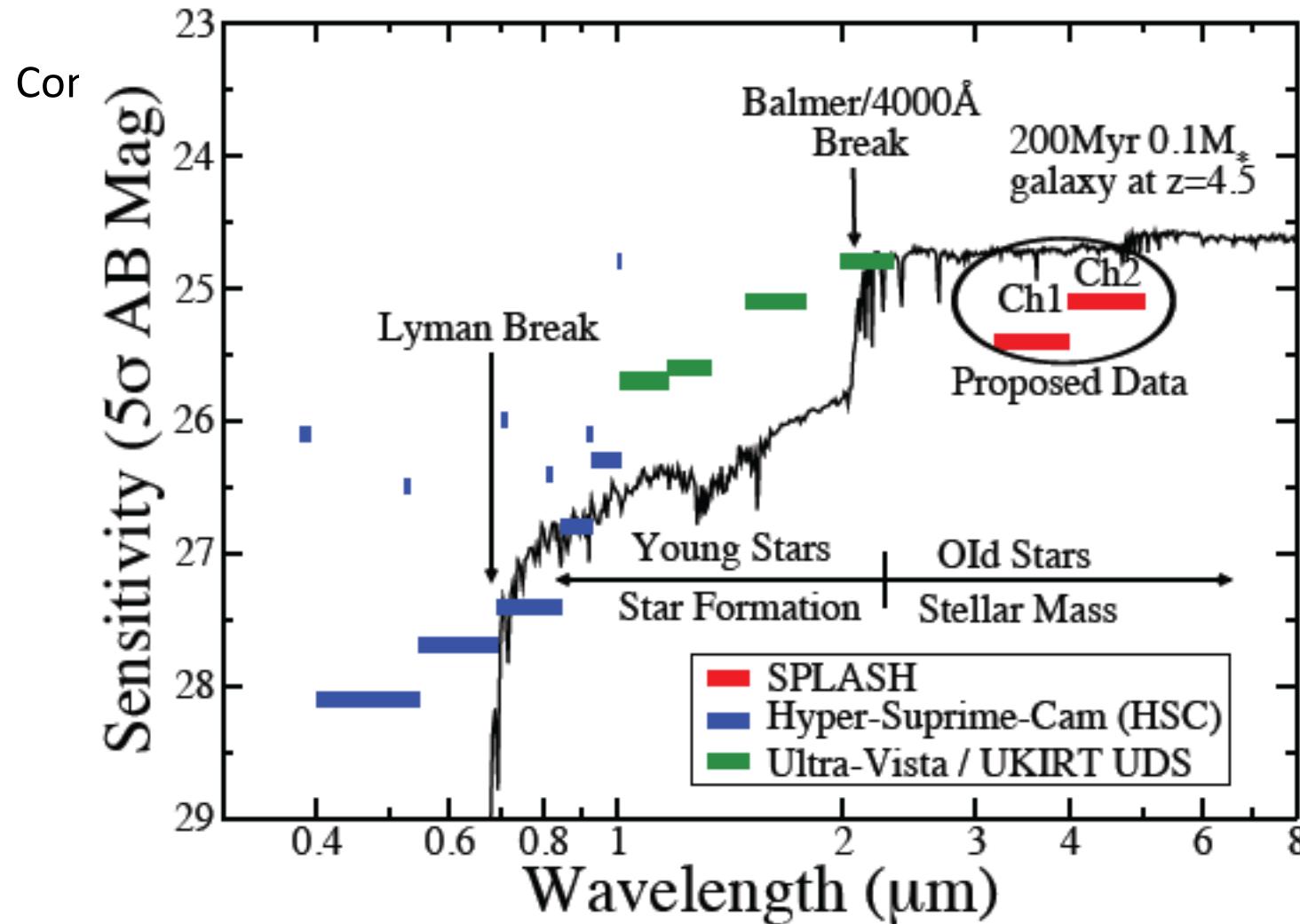
Dark matter environment

Dark matter proxies ?

# The global high redshift “observatory system”

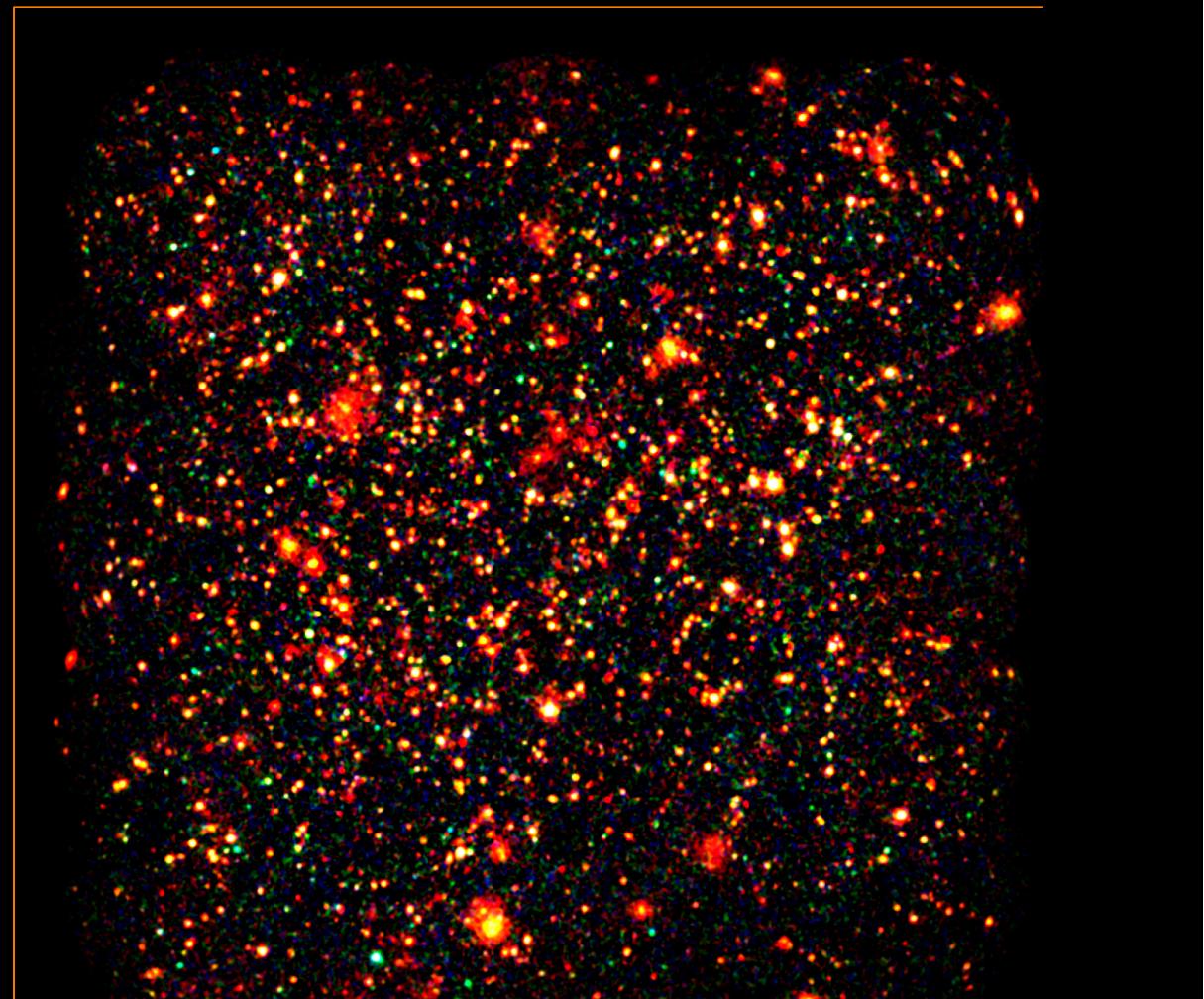
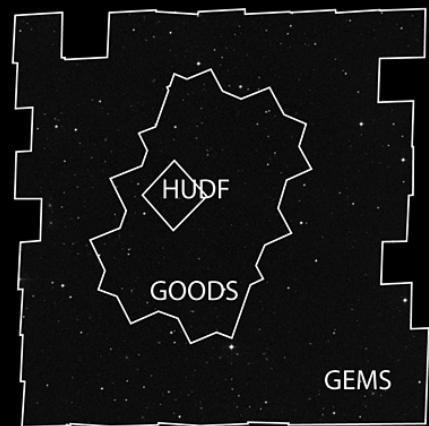


## Imaging surveys: example COSMOS

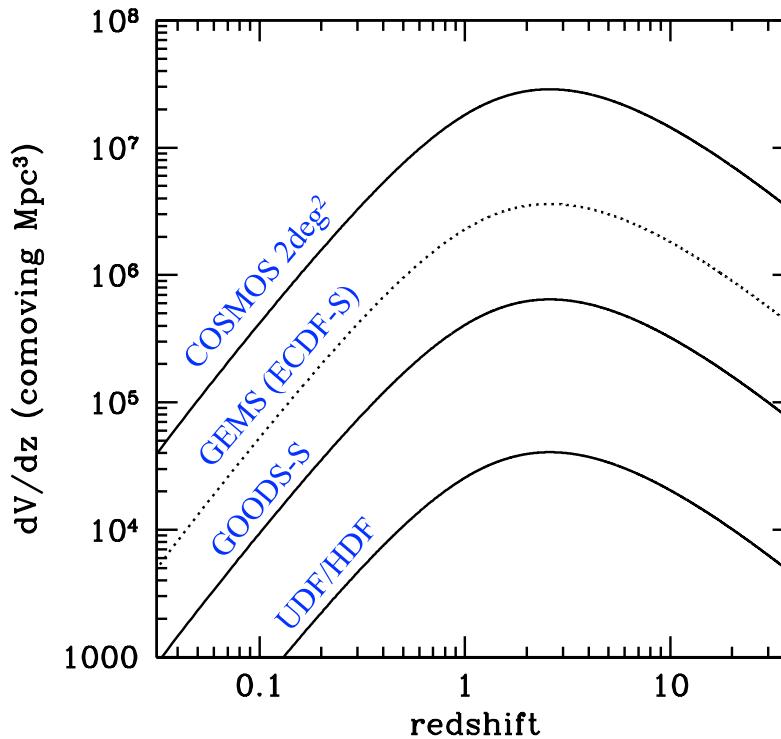
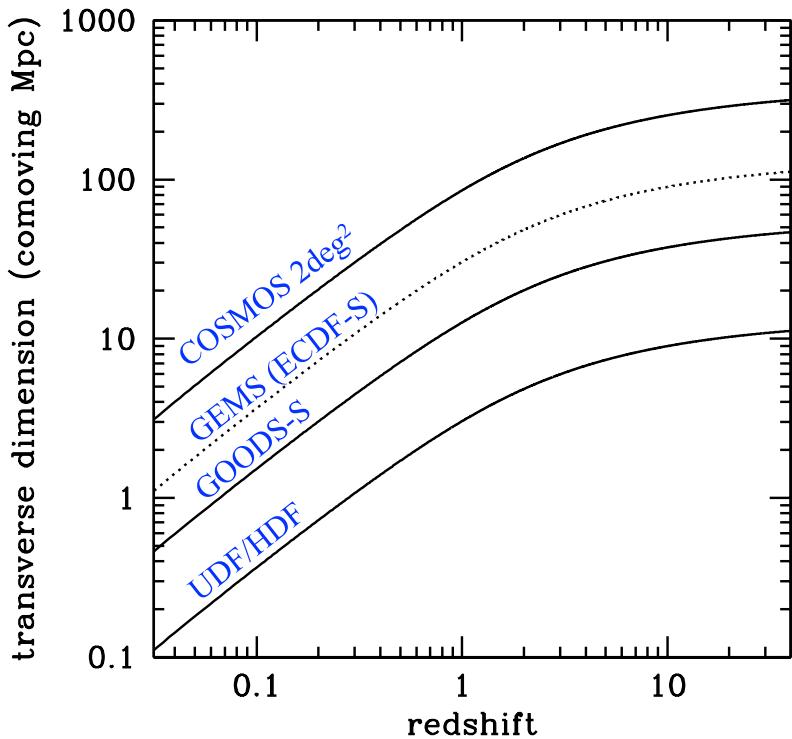


# COSMOS

Relative Sizes of *HST* ACS Surveys



# Surveyed regions are large but finite



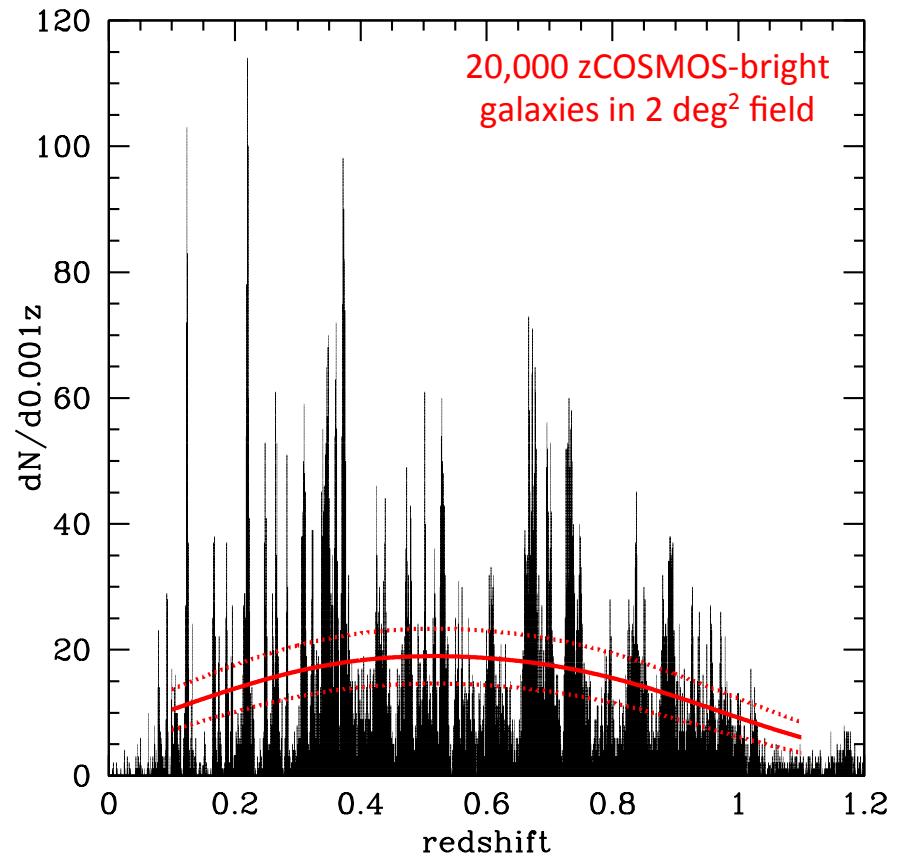
# Cosmic variance

See Trenti & Stiavelli 2008 ApJ 676, 767.  
Newman & Davis 2002, ApJ, 564, 567.  
Somerville et al 2004, ApJ, 600, L171.

Excess variance in the population  
(over Poisson) due to large scale  
structure within the survey volume:

- numbers of galaxies
- mean  $\langle z \rangle$
- types of galaxies?

Surveys are dominated by cosmic  
variance as soon as you see  
structure (in space or  $z$ ) at high  
significance



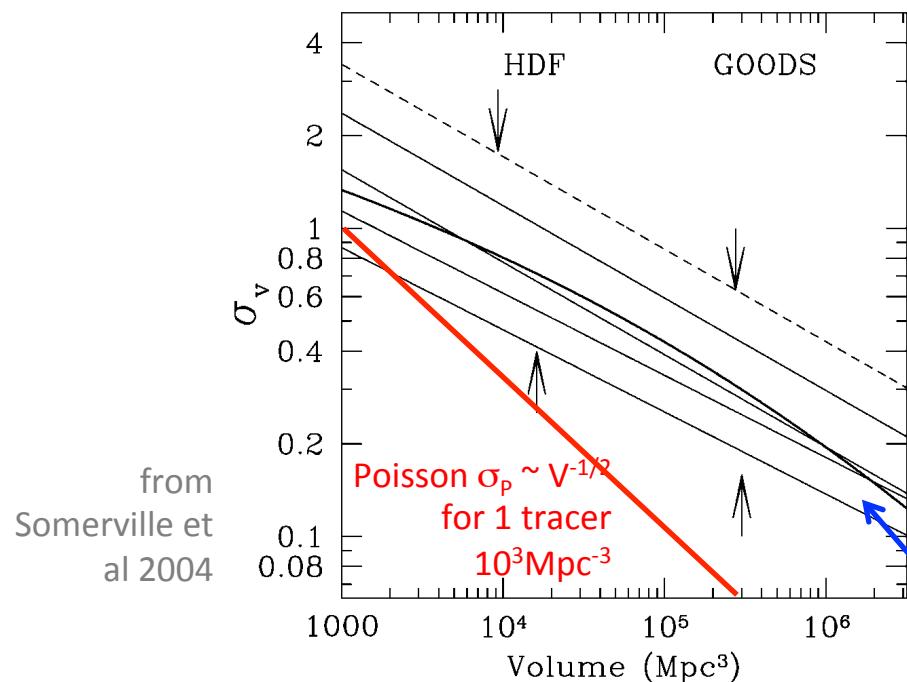
## Cosmic variance (2)

In terms of number of objects (simplest case)

$$\sigma_v^2 \equiv \frac{\langle N^2 \rangle - \langle N \rangle^2}{\langle N \rangle^2} - \frac{1}{\langle N \rangle}.$$

$$\sigma_v^2 = \frac{\int_V \int_V d^3x_1 d^3x_2 \xi(|\mathbf{x}_1 - \mathbf{x}_2|)}{\int_V \int_V d^3x_1 d^3x_2}$$

Larger fields have *smaller* CV but the CV is *larger* relative to Poisson variance



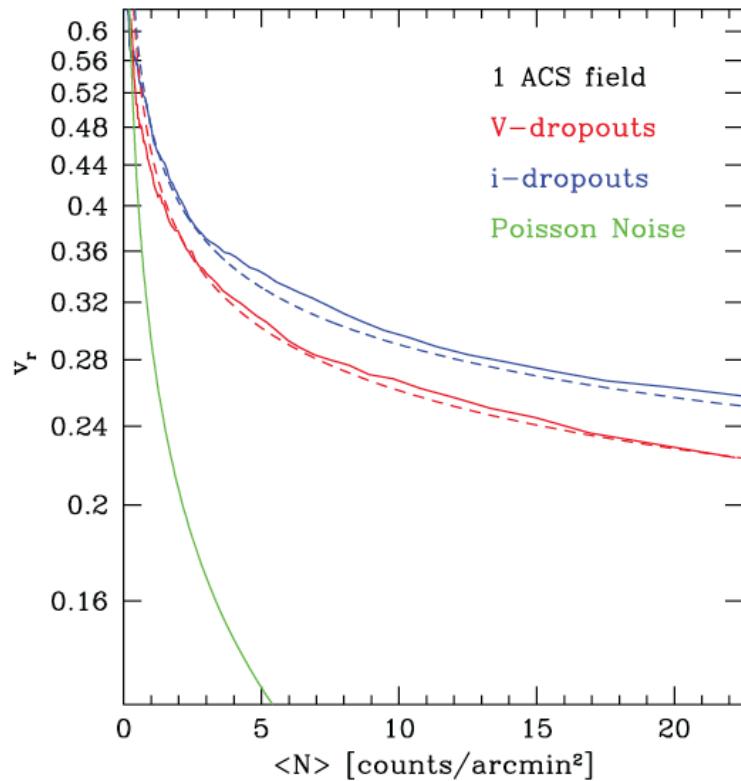
The only way to beat CV is to have many small (or sparse) fields, so you track the Poisson line  $\sigma_v \sim n^{-1/2}$

Also, note that sometimes you want to have CV because you want to study LSS!



Even the huge COSMOS field will have 10% variations per unit z  
 $\sigma_v$  for linear CDM spectrum (other lines for various bias)

## Cosmic variance (3)



Final example: doesn't matter how faint you go, you will never determine the number density of V-dropouts ( $z \sim 5$ ) and I-dropouts ( $z \sim 6$ ) to better than 25% from a single ACS field (from Trenti and Stiavelli)

## Aside (1): Confusion noise and the confusion limit

Some survey instruments have significantly poor resolution

JCMT (15m) at 850μm	15 arcsec
Herschel (3.5m) at 160μm	12 arcsec
Spitzer (0.8m) at 24μm	8 arcsec

Brightness and position of sources affected by fainter sources.

Usually: confusion noise is significant when 1 source per 40 beams.  
Not improved by more integration, only by better resolution.

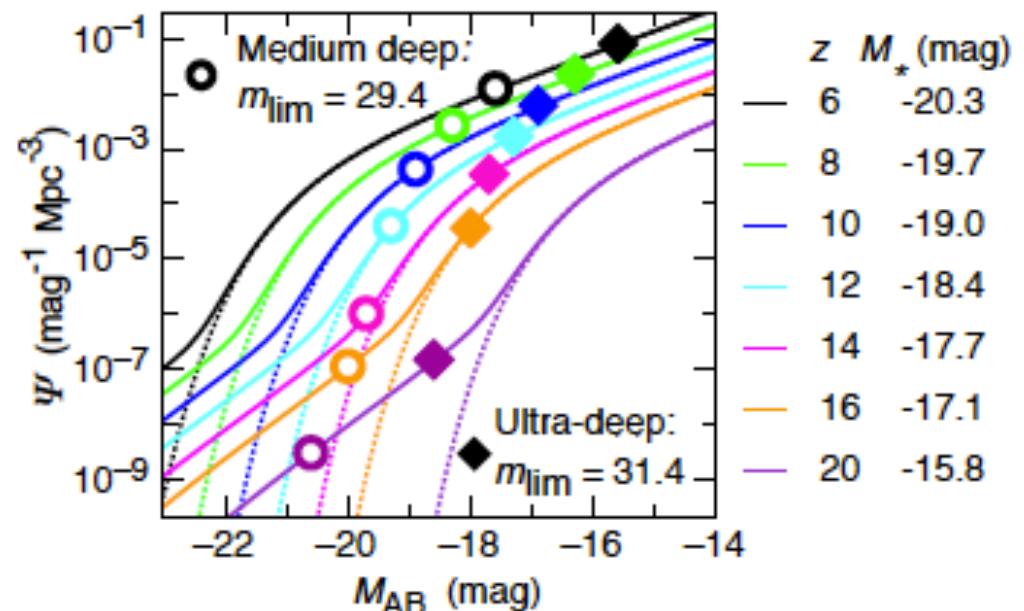
## Aside (2): Lensing bias

Cross-section for magnification  $\mu$  scales as  $\sigma(>\mu) \sim \mu^{-2}$  or  $\mu^{-5/2}$  (Blandford & Narayan 1986, Schneider & Weiss 1992)

If logarithmic slope of luminosity function  $\alpha = d\log\Phi/d\log L$  is steeper than this, then bright sources will be rare cases of high magnification

Certainly relevant for brightest sources found by Planck, Herschel, SPT etc.

May also be relevant for highest redshift faint galaxies (see Wyithe et al 2011, arXiv.1101.2291)



# Estimation of redshifts: photo-z

Purely photometric data may be used to estimate redshifts ( $R \sim 5$  “spectroscopy”)

## Training set approaches

Nearest-neighbour, Artificial neural net (ANN-z), Boosted decision trees (Arbor-z) etc.

Strengths: Fully empirical

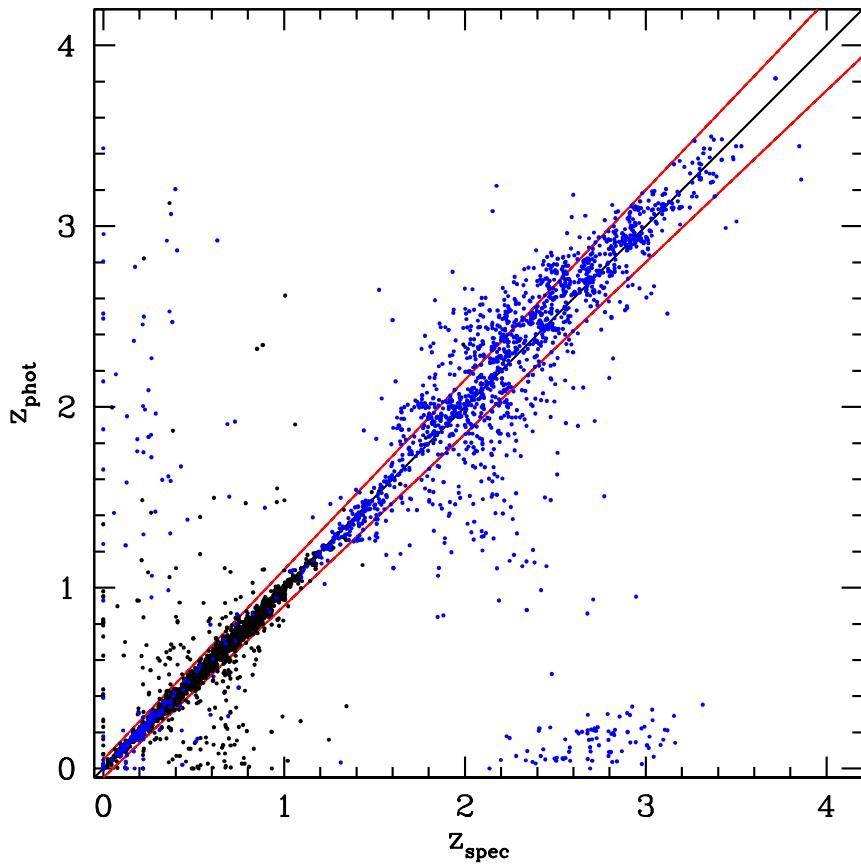
Weaknesses: Dependent on training set (completeness in redshift and type, CV etc).

## Template fitting approaches

Strengths: Robust to deficiencies in spectroscopic sets, easily incorporates knowledge of astrophysical effects (redshift, reddening etc).

Weaknesses: Dependent on templates

# Practical performance of photo-z



State of the art in photo-z

COSMOS 30-band from GALEX-UV to Spitzer 3.8 $\mu$ m (Ilbert et al 2010)

Comparison with highly reliable zCOSMOS redshifts

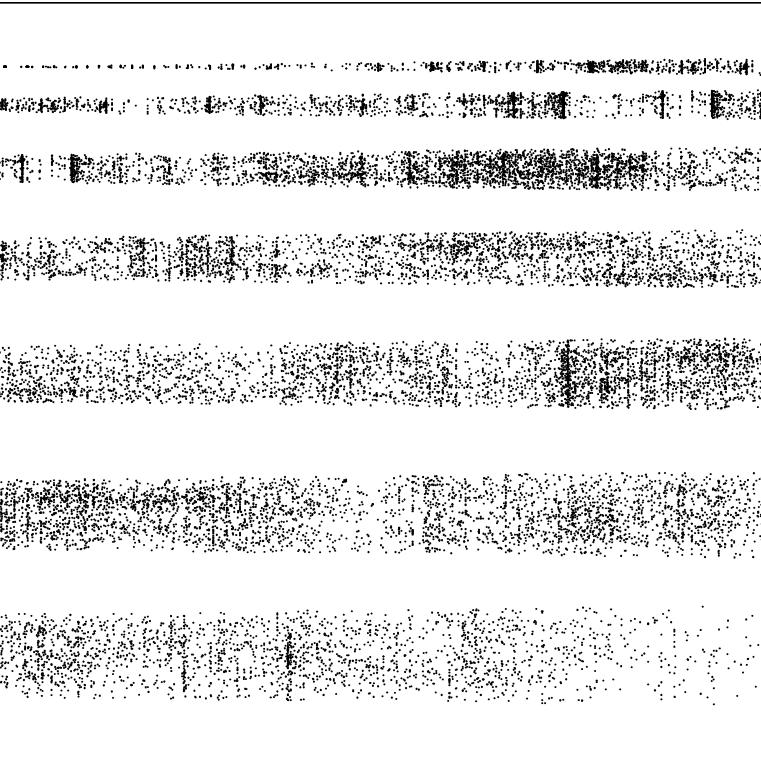
$$\begin{array}{ll} I_{AB} < 22.5 & \sigma_z \sim 0.01(1+z) \\ B_{AB} < 25.25 & f_{\text{out}} \sim 1\% \\ & \sigma_z \sim 0.03(1+z) \\ & f_{\text{out}} \sim 10\% \end{array}$$

Why do photo-z work so well? Limited range of galaxy spectral energy distributions.

- 1<sup>st</sup> three eigenspectra contain 98% of variance (see e.g. Connolly et al 1995, Yip et al 2004)
- About 3 degrees of freedom in 10,000 photo-z templates (Bordoloi et al 2010).

# Why spectroscopic redshifts matter

COSMOS comoving cone from  $z = 0$  to  $z = 1$



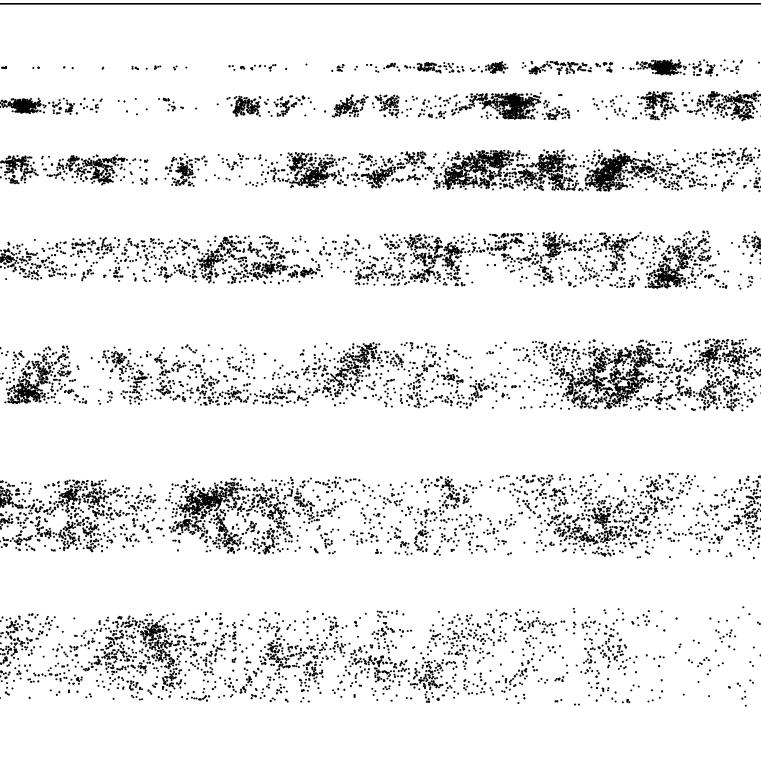
300 Mpc

The need for spectroscopic redshifts:  
structure in the Universe

$z_{\text{COSMOS}}$  between  $0 < z < 1$   
with COSMOS 30-band photo-z

# Why spectroscopic redshifts matter

COSMOS comoving cone from  $z = 0$  to  $z = 1$

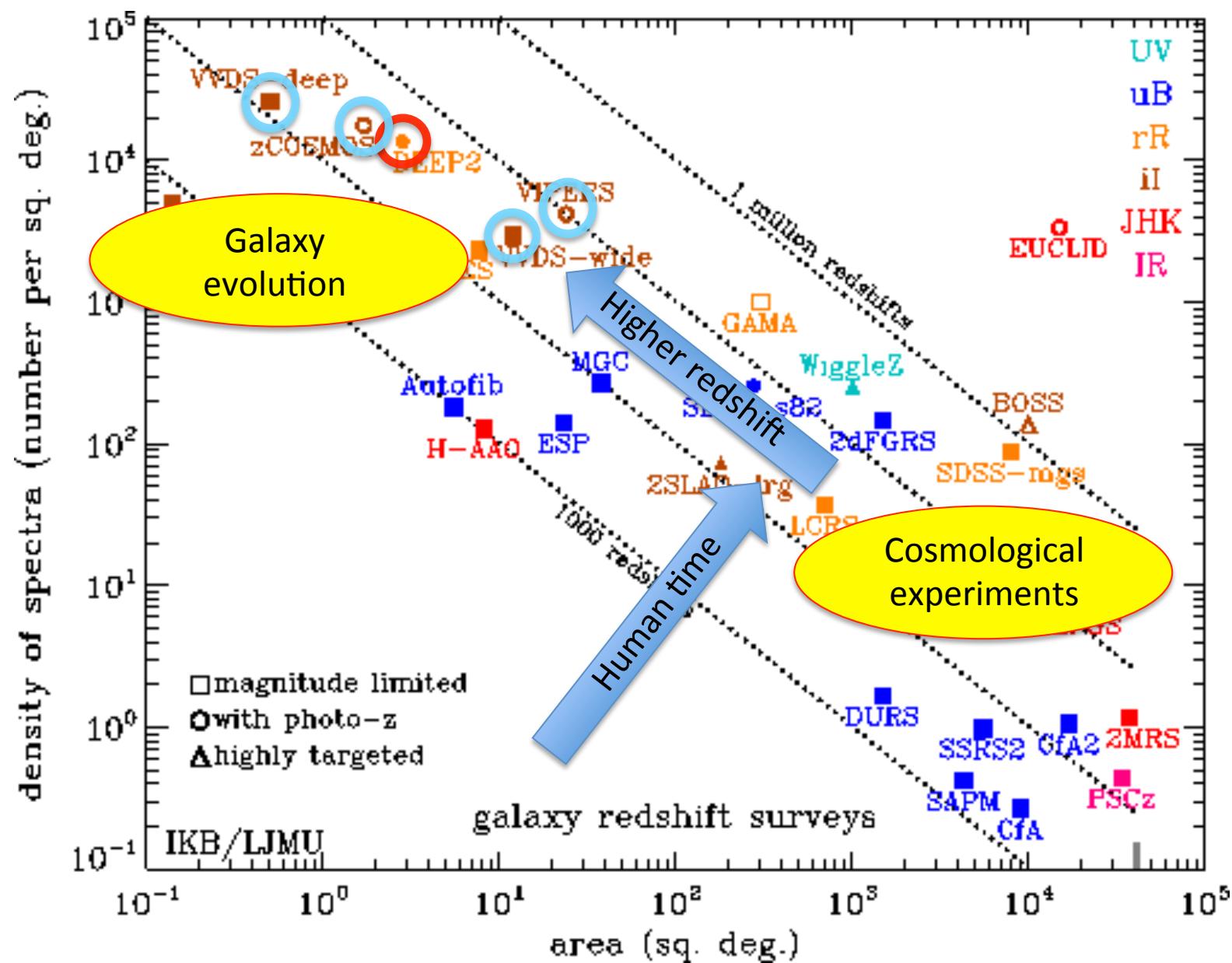


300 Mpc

The need for spectroscopic redshifts:  
structure in the Universe

$z_{\text{COSMOS}}$  between  $0 < z < 1$   
with  $z_{\text{COSMOS}}$  spectro-z

# Galaxy redshift surveys (courtesy of Ivan Baldry)



# Survey spectroscopy

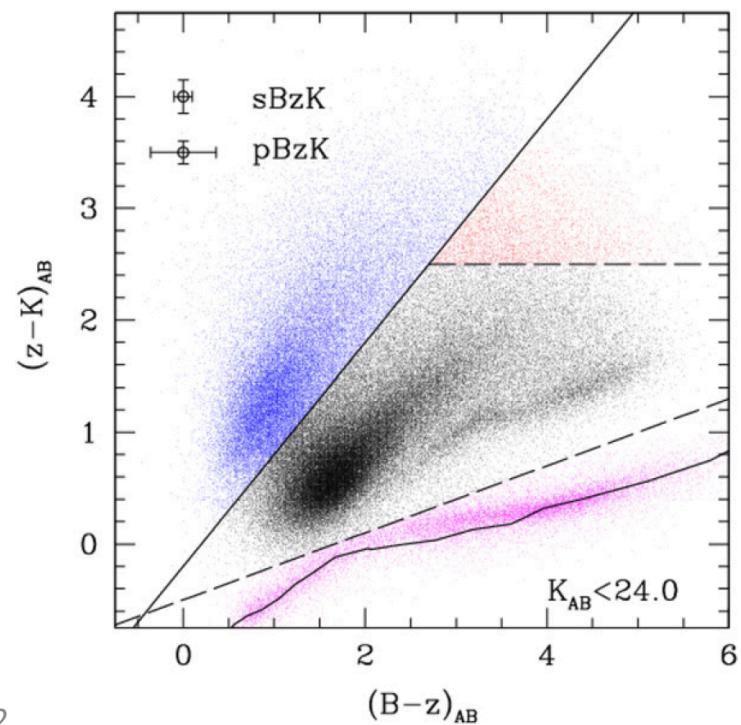
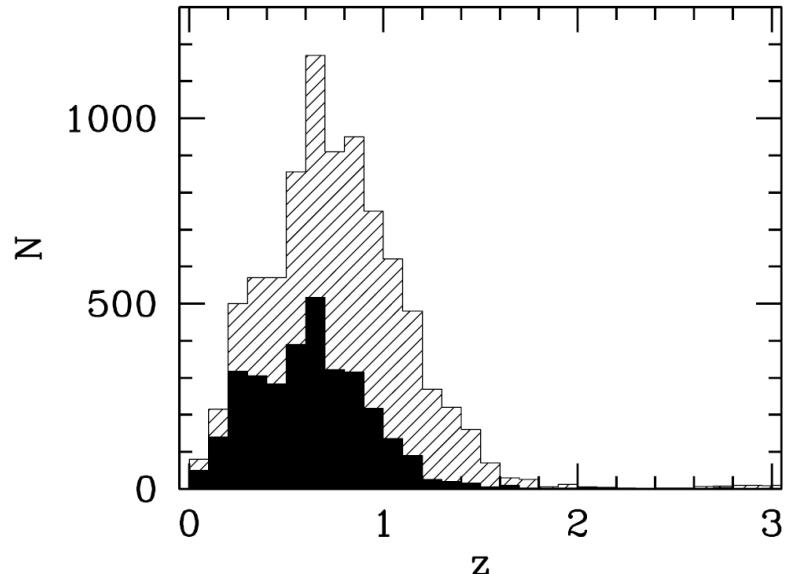
In practice:

Magnitude-selected (e.g.  $I_{AB}$ ) out to  $z \sim 1$ .

Need colour selection to effectively isolate high- $z$  galaxies  
 $z > 1$  (esp. until NIR MOS)

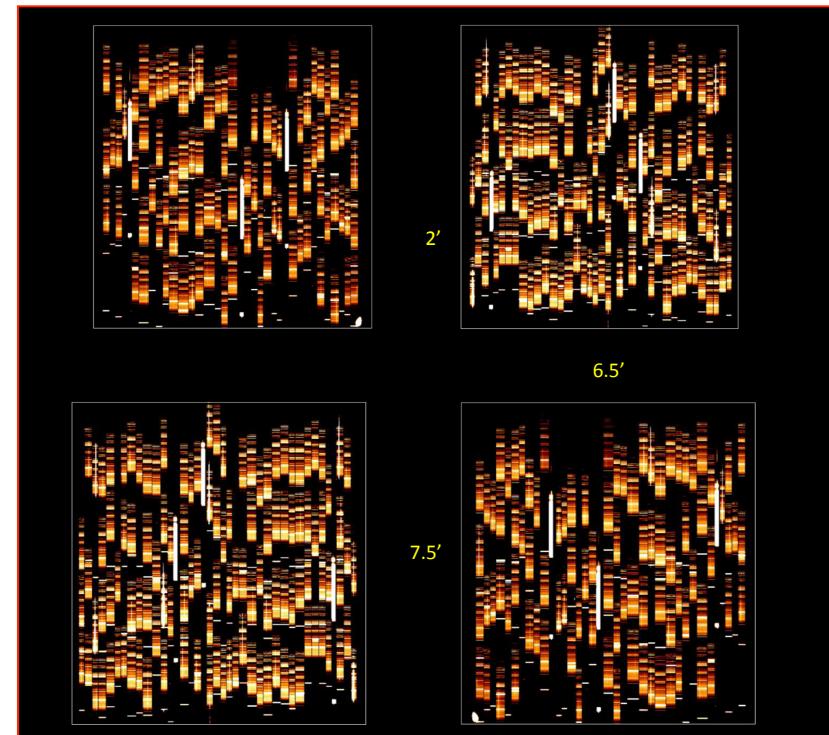
- ugr BM-, BX- “dropout”
- BzK

N.B. Careful choice of sampling rate and targeted success rate dictated by science goals



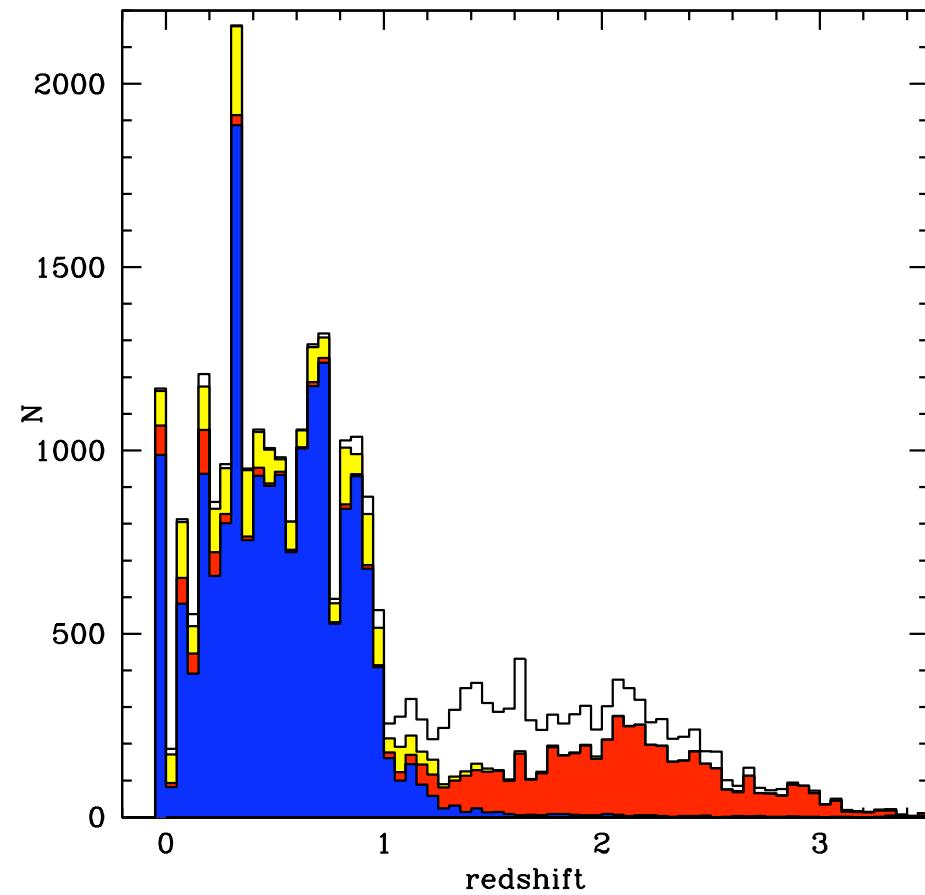
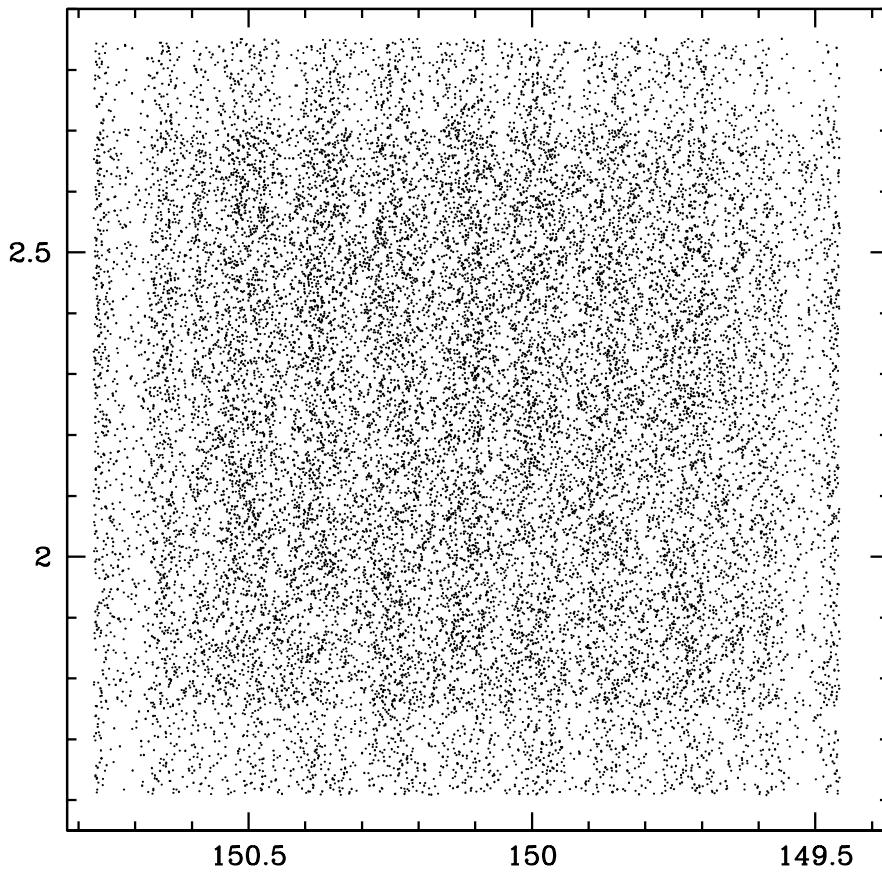
	fields	selection	N <sub>galaxies</sub>	sampling	success
VVDS	$4 \times 4 \text{ deg}^2$	$I_{AB} < 22.5$	35,000	~15%	~ 80%
	$2 \times 2 \text{ deg}^2$	$I_{AB} < 24$	12,000	<10%	
	$1 \times 2 \text{ deg}^2$	$I_{AB} < 24.5$	1,000	<10%	
DEEP-2	$4 \times 1 \text{ deg}^2$	$BRI + R_{AB} < 24$	35,000 @ $0.8 < z < 1.4$	~60%	75%
zCOSMOS	$1 \times 2 \text{ deg}^2$	$I_{AB} < 22.5$	20,000 @ $0 < z < 1.2$	~70%	85%
		$gzK + B_{AB} < 25.5$	5,000 @ $1.5 < z < 3$	~70%	30-80%

- Generally with multi-slit spectrographs, e.g. VIMOS on VLT, DEIMOS on Keck.
- Can fibres work below sky?
- Badly need effective NIR multi-object spectrograph
  - FMOS (fibres)
  - MOSFIRE (slits)
  - KMOS (optical probes)



## **zCOSMOS**

- 20,000 galaxies  $I_{\text{AB}} < 22.5$  @  $0.1 < z < 1.4$  over  $2 \text{ deg}^2$
- 5,000 galaxies  $BzK$  &  $ugr$   $B_{\text{AB}} < 25.25$  @  $1.4 < z < 3.0$  in central  $1 \text{ deg}^2$

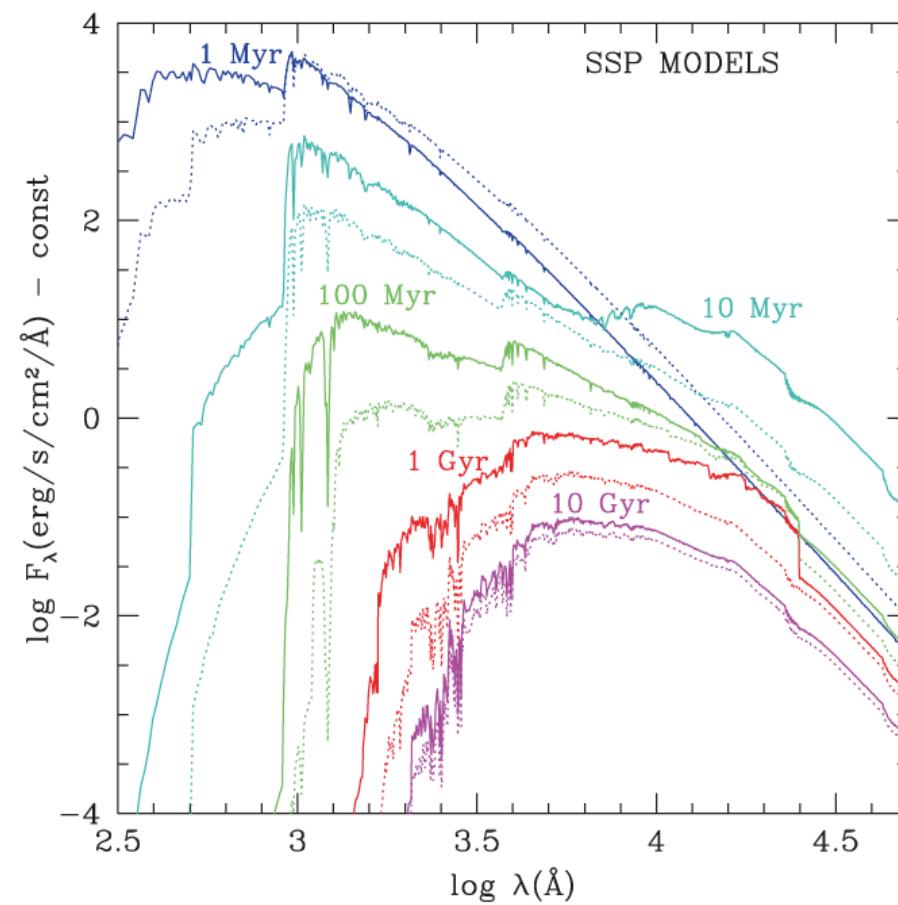
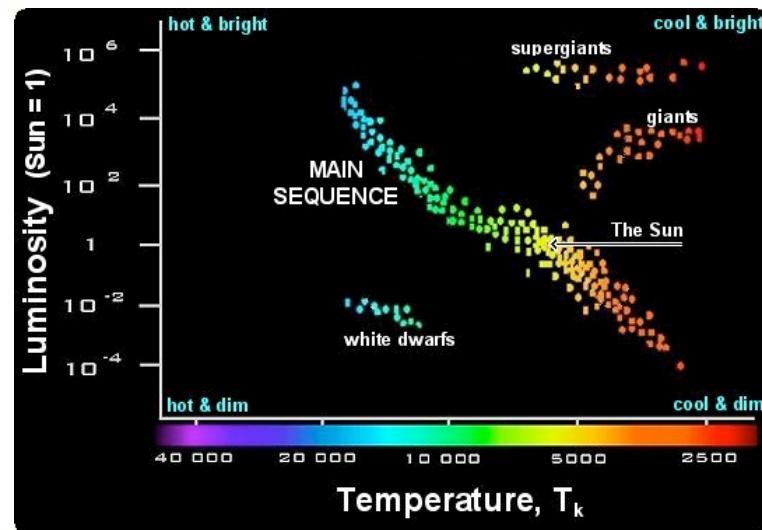


## Part II: Information from data

# Stellar masses and star-formation rates

Stellar population models

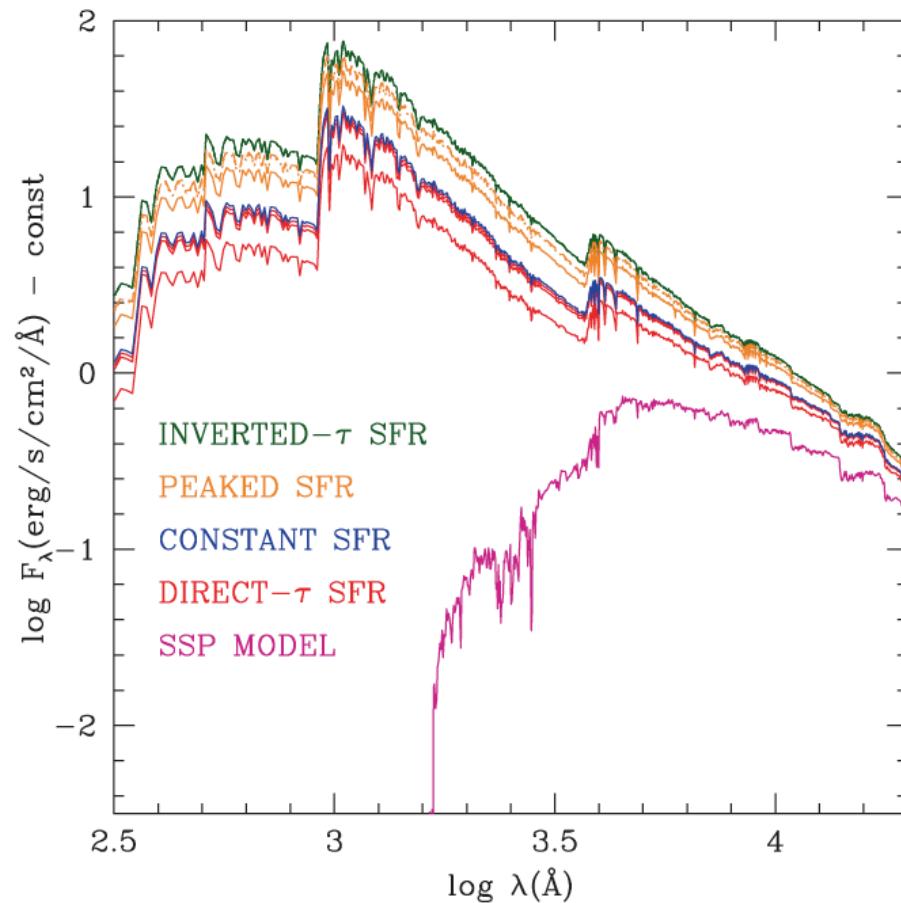
See: Jakob Walcher's website: <http://www.sedfitting.org/SED08/Welcome.html>  
Laura Greggio & Alvio Renzini: "Stellar Populations", Wiley 2011.



# Star-formation rates

The only measurement of SFR is to count stars in a star-forming region.  
Everything else is an estimate, often simply empirically calibrated.

Best estimate is ultraviolet luminosity (e.g. 1500 Å) which is dominated by young massive stars and does not reflect previous star-formation history



## Star-formation rate estimates (1)

Shape of ultraviolet spectrum  
also does not depend on i.m.f..

But the total mass of stars being  
formed does depend on i.m.f.,  
because mass is dominated by  
much lower mass stars.

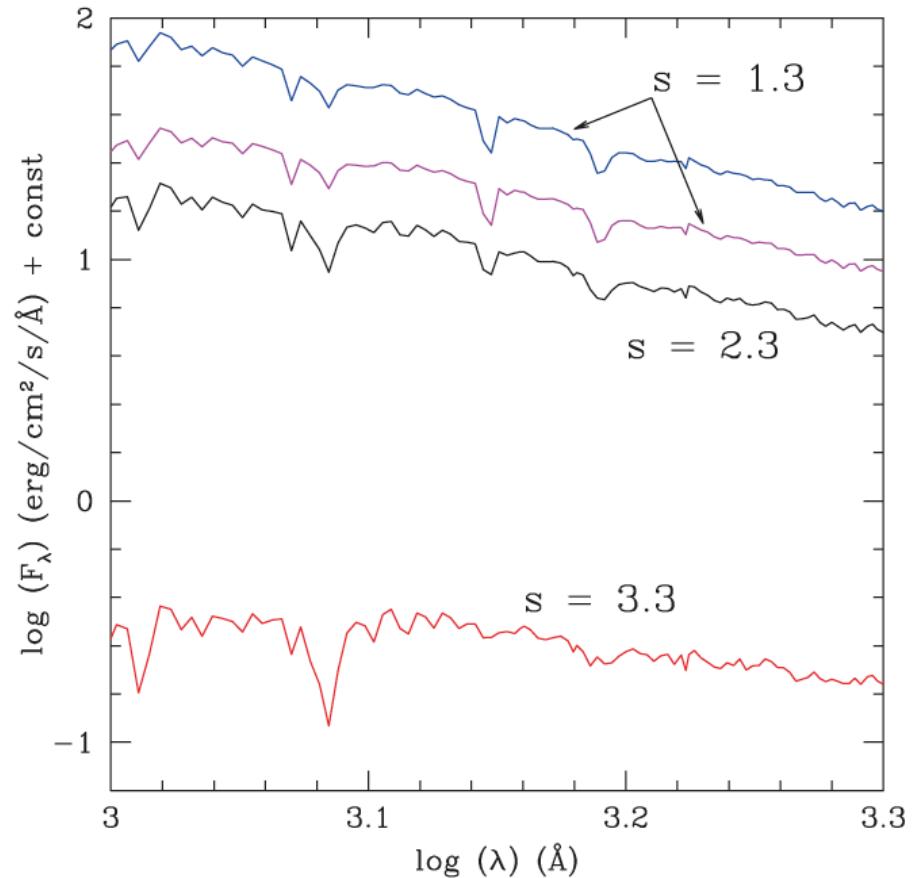
$$\left(\frac{dN}{dm}\right) \propto m^{-(1+x)}$$

Salpeter imf  $x = 1.35$

$$\text{SFR} (M_{\odot} \text{yr}^{-1}) \simeq 1.13 \times 10^{-28} L_{1500}^{\circ} (\text{erg s}^{-1} \text{Hz}^{-1})$$

i.m.f. with flatter slope below  $0.5 M_{\odot}$

$$8.5 \times 10^{-29}$$



## Effect of dust absorption and extinction

Ultraviolet radiation is strongly absorbed by dust.

Either (1): Correct the ultraviolet luminosity and use previous formula. Amount of absorption can be estimated from change of slope of ultraviolet (since that is constant). Requires extinction curve, e.g. Calzetti 2001 PASP 113, 1449

$$\frac{\mathcal{F}_\lambda}{\mathcal{F}_\lambda^o} = 10^{-[0.91E(B-V)k(\lambda)]} \quad k(\lambda) = 1.17 \left( -2.156 + \frac{1.509}{\lambda} - \frac{0.198}{\lambda^2} + \frac{0.011}{\lambda^3} \right) + 1.78$$

Or (2): Measure the re-radiated emission at infrared wavelengths. Caveat: Need broad spectrum of flux measurements, plus worry about other sources of absorbed light (old stars, AGN etc.).

$$\text{SFR} (M_\odot \text{yr}^{-1}) \simeq 4.5 \times 10^{-44} L_{\text{FIR}} (\text{erg s}^{-1})$$

and add them together, using observed ultraviolet luminosity

$$\text{SFR} (M_\odot \text{yr}^{-1}) \simeq 1.13 \times 10^{-28} L_{1500} + 4.5 \times 10^{-44} L_{\text{FIR}}$$

## Star-formation rate estimates (2)

Other proxies for ultraviolet luminosity:

H $\alpha$  6563 recombination line from photo-ionized Hydrogen in HII regions. Empirical calibration

$$\text{SFR} (M_{\odot} \text{yr}^{-1}) \simeq 5 \times 10^{-42} L_{\text{H}\alpha}^{\circ} (\text{erg s}^{-1})$$

Need to correct for (moderate) absorption of H $\alpha$  (higher than continuum)

$$E(B - V)_{\text{lines}} \simeq \frac{E(B - V)_{\text{cont}}}{0.44}$$

If H $\alpha$  not available (often the case at  $z > 0.5$ ), must use other lines, e.g. [OII] 3727. Can use empirical correction for reddening based on luminosity?

$$\text{SFR} (M_{\odot} \text{yr}^{-1}) \simeq 2.36 \times 10^{-41} L_{[\text{OII}]} \left( \frac{L_B}{10^{10} L_{B,\odot}} \right)^{0.49}$$

## Star-formation rate estimates (3)

Other proxies of star-formation:

Radio continuum: Good correlation with LFIR. Due to cosmic rays from supernovae?

$$\text{SFR} (M_{\odot} \text{ yr}^{-1}) \simeq 2.2 \times 10^{-40} L_{0.5-2 \text{ keV}} (\text{erg s}^{-1})$$

Soft X-ray luminosity: X-ray binaries involving massive stars

$$\text{SFR} (M_{\odot} \text{ yr}^{-1}) \simeq 5.9 \times 10^{-22} L_{1.4 \text{ GHz}} (\text{erg s}^{-1} \text{ Hz}^{-1})$$

# Stellar masses

Which “stellar mass” are we talking about? Different equally valid definitions are used

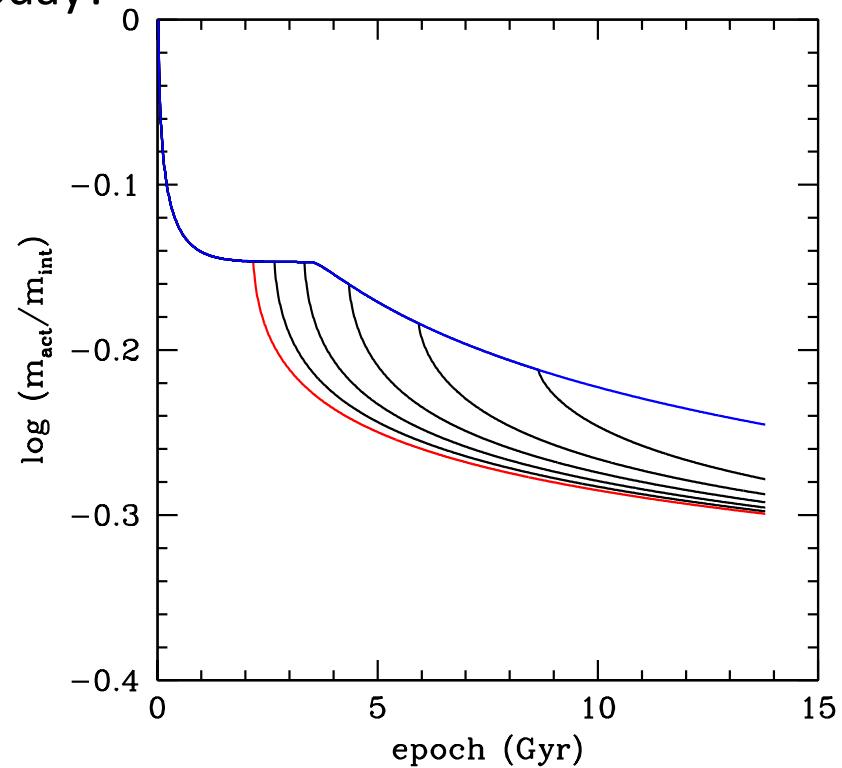
- Mass of stars that have been formed,  $m_{\text{int}}$ ?
- Mass of stars that are still burning at time  $t$ ,  $m_{\text{act}}$ ?
- + add in the stellar remnants (WD, NS, BH)?
- Mass of stars that will still be burning today?

Differences are not negligible and may matter.

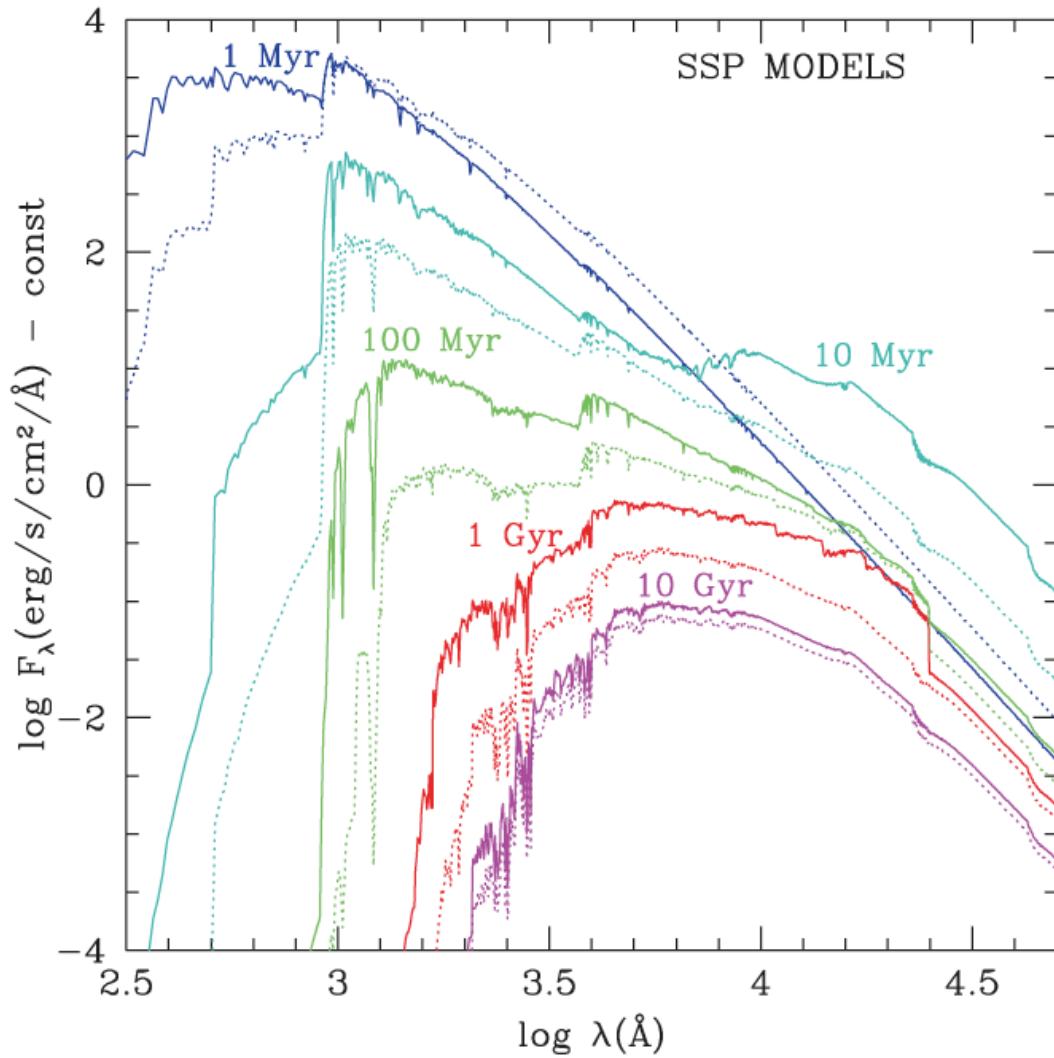
If you want to use the sSFR to give the e-fold time of the stellar mass, then use

$$sSFR = \frac{SFR}{m_{\text{int}}} \sim (1 - R) \frac{SFR}{m_{\text{act}}}$$

What most  
observers quote



# Stellar mass estimates from SED fits



As discussed before, ultraviolet dominated by young stars → info on SFR not  $m_{\text{star}}$ .

Note that the CW that “the NIR traces stellar mass” is not really true: NIR traces RGB population, i.e. MS turn-off stars.

$$L \sim < L_g \tau_g > \left( \frac{dN}{dm} \right) \left( \frac{dm_{TO}}{dt} \right)$$

$$\frac{d \ln L}{d \ln t} \sim -1 + 0.3x \sim -1$$

Factor of ten decline between 1 Gyr and 10 Gyr.

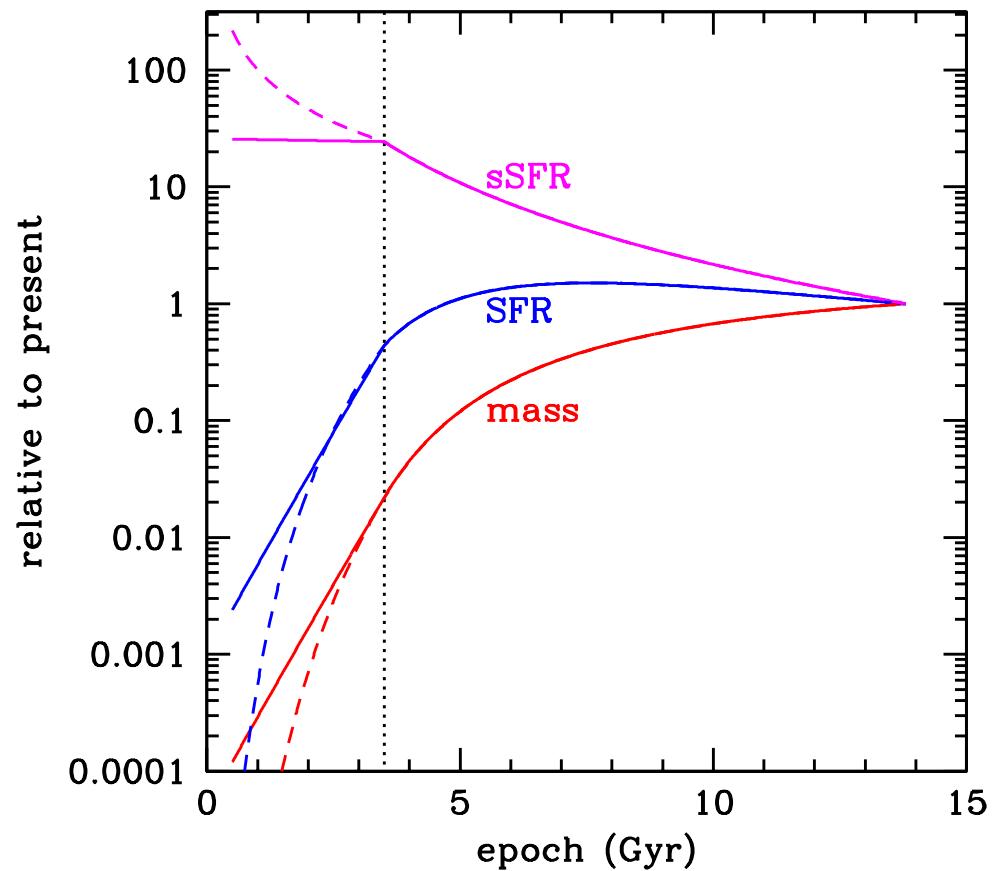
# Stellar masses from SED fits (1)

Outputs of SED-fitting  
depend on assumed SFR  
histories

“Conventional” (since 1980s) to  
use exponentially decaying SFR

$$SFR \propto e^{-\frac{t}{\tau}}$$

Possibly OK at  $z < 1$ , likely to  
be completely wrong at high  
redshift



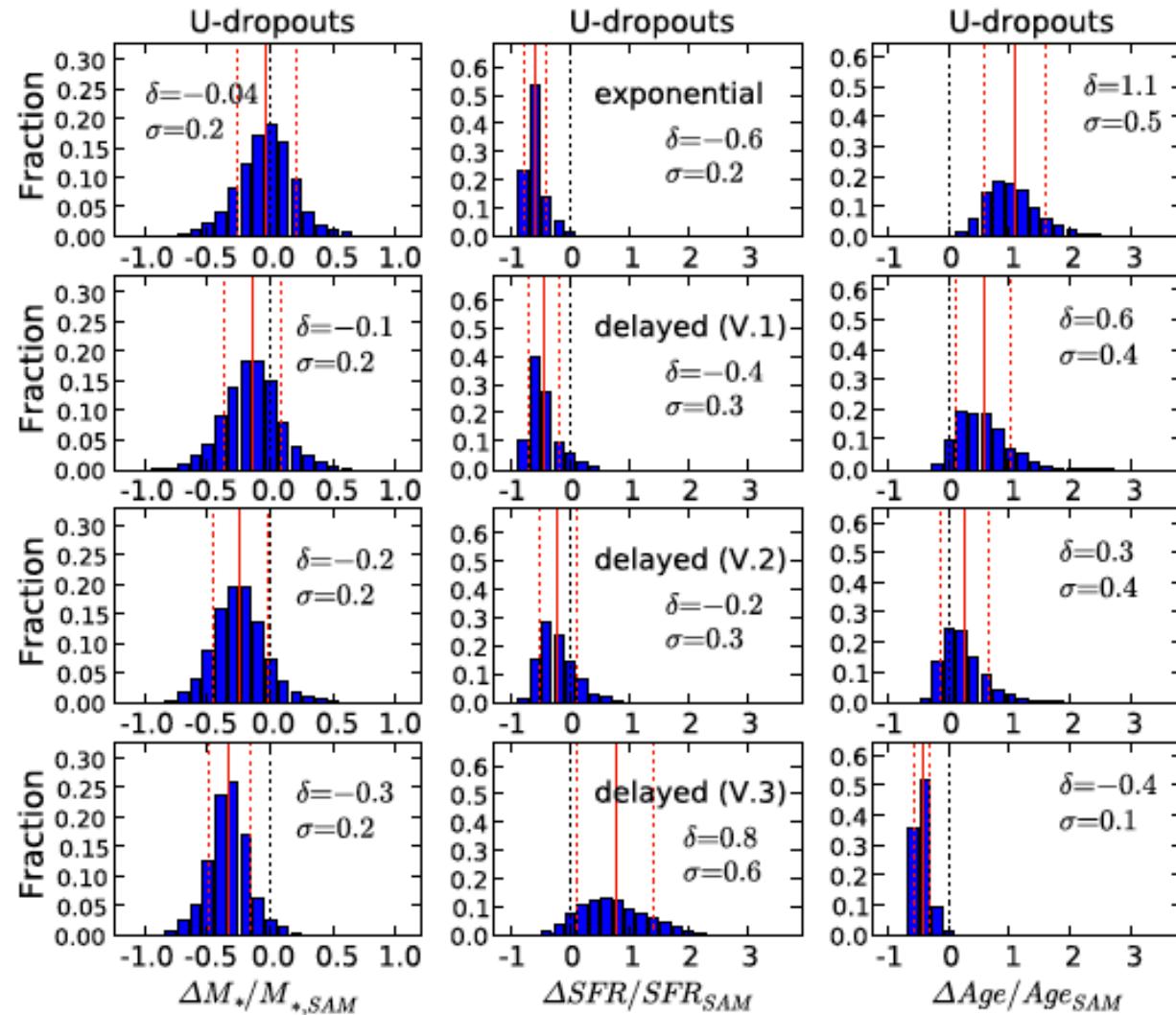
## Stellar masses from SED fits (2)

Outputs of SED-fitting  
depend on assumed SFR  
histories

Effects are not negligible  
- see Lee et al, 2010, ApJ,  
725, 1644

Generally stellar masses  
are the most robust, then  
SFR and finally age.

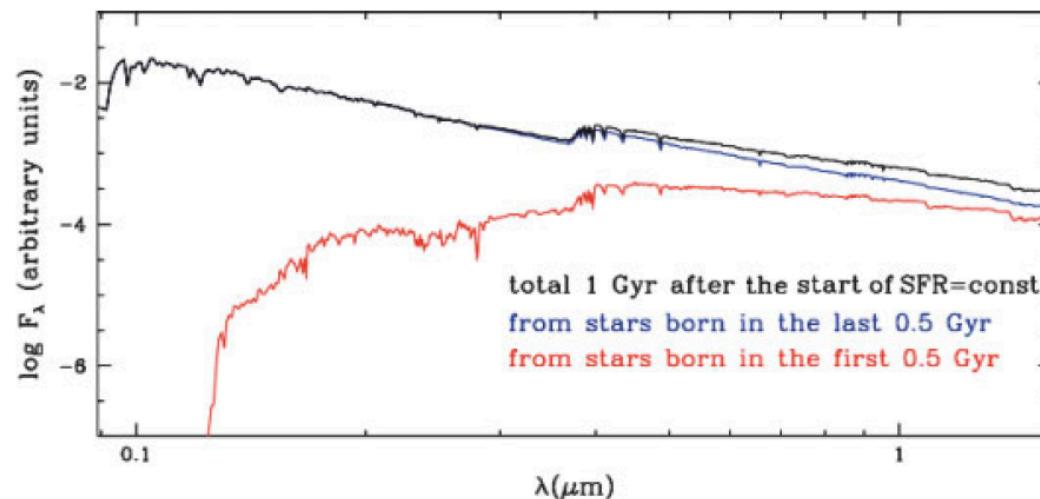
Lee et al 2010 ApJ, 725, 1644



## Why integrated stellar population “ages” are usually underestimated

If SFR is rising with time, or more or less constant, the young stars make significant contribution to even the NIR light.

This biases “age” to younger ages.



# Metallicities

## Potentially key diagnostic of baryon cycling

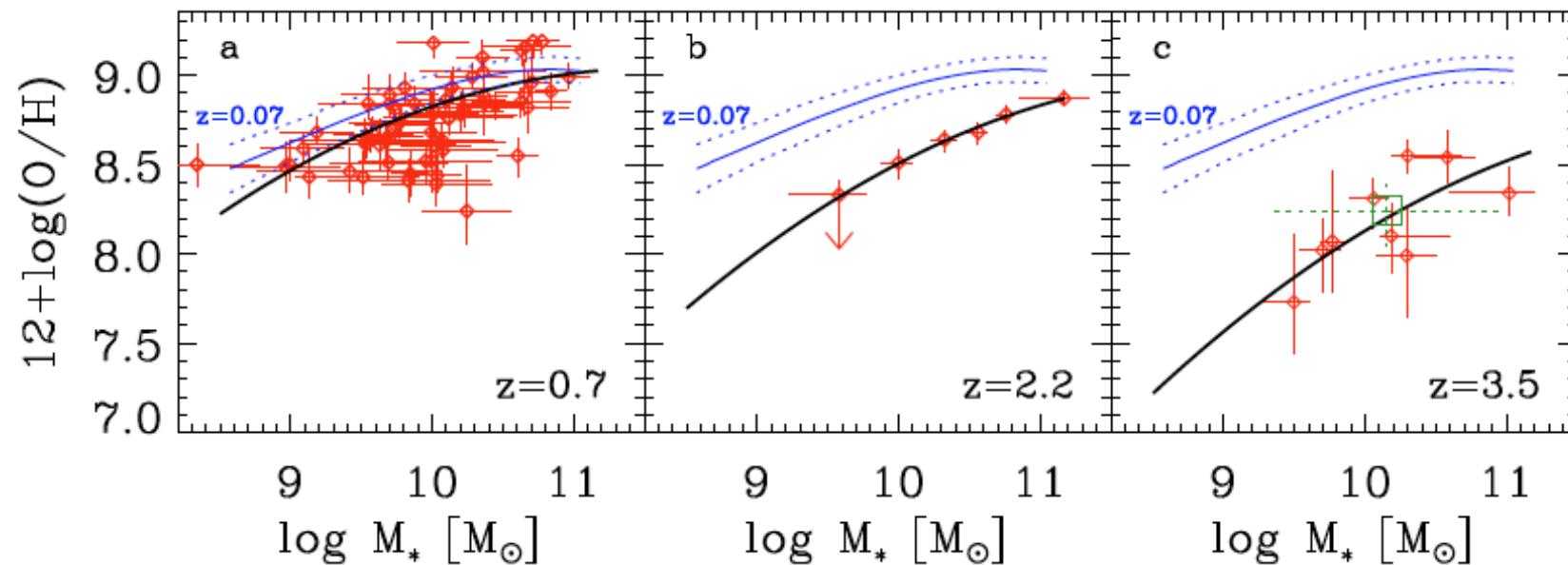
Stellar metallicities can be reasonably well determined with high S/N spectra (not possible at high redshift).

Gas phase metallicities are much less certain (less well-constrained physical conditions – density, temperature, ionization parameter, reddening etc.

At high redshift, even measurements of all the bright lines become difficult. There are only a handful of galaxies with [OII] 3727, [OIII] 5007, H $\alpha$ , H $\beta$ , NII 6583.

# Metallicities

From Maiolino et al 2008, A&A 488, 463.



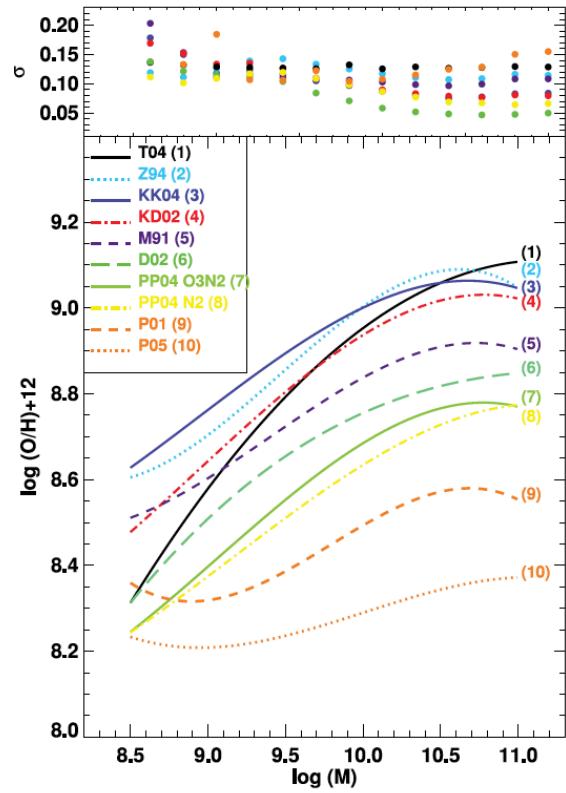
At high redshift, even measurements of all the bright lines become difficult. There are only a handful of galaxies with [OII] 3727, [OIII] 5007, H $\alpha$ , H $\beta$ , NII 6583.

# From Kewley & Ellison 2008, ApJ 681, 1183

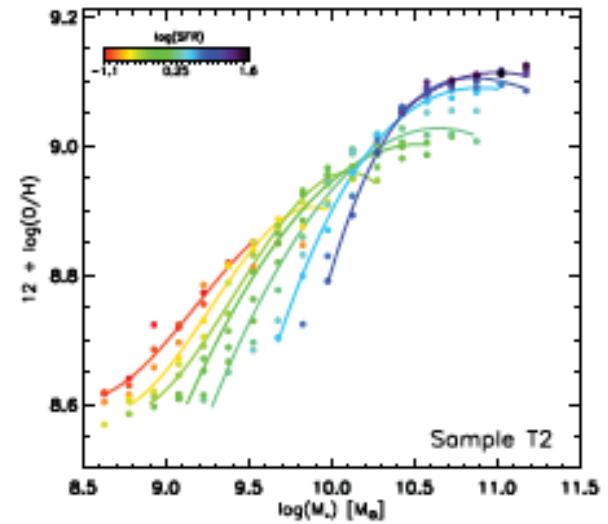
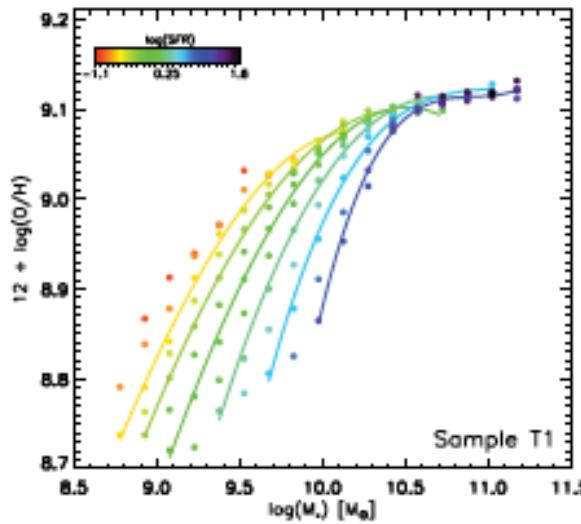
TABLE 1  
COMPARISON OF THE 10 METALLICITY CALIBRATIONS

Number	ID	Emission Lines	Calibration Class	References
1.....	T04 <sup>a</sup>	[O II], H $\beta$ , [O III], H $\alpha$ , [N II], [S II]	Theoretical	T04
2.....	Z94	$R_{23}$	Theoretical	Z94
3.....	KK04	$R_{23}$ , [O III]/[O II]	Theoretical	KK04
4.....	KD02	[N II]/[O II], $R_{23}$ , [O III]/[O II]	Theoretical	KD02
5.....	M91	$R_{23}$ , [O III]/[O II]	Theoretical	M91
6.....	D02	[N II]/H $\alpha$	Combined	D02
7.....	PP04	[N II]/H $\alpha$ , [O III]/H $\beta$	Empirical	PP04
8.....	PP04	[N II]/H $\alpha$	Empirical	PP04
9.....	P01, P05	$R_{23}$ , [O III]/[O II]	Empirical	P01; P05
10.....	$T_e$	[O III] $\lambda$ 4363, [O III] $\lambda\lambda$ 4959, 5007	Direct	Aller (1984); Stasińska (2005); Izotov et al. (2006a)

<sup>a</sup> The T04 method uses a statistical technique to calculate the probability distribution of an object having a particular metallicity based on model fits to the [O II], H $\beta$ , [O III], H $\alpha$ , [N II], and [S II] emission lines.



Again, the differences matter...



# Sizes, structures and morphologies (1)

## “Size”

Tells us typical stellar densities (for a given mass)

- Half-light radius
- Second-moment of light distribution

## “Morphology”

Tells us (3-d)bulge-to-(2-d)disk ratio: information on what has happened to the galaxy.

## “Structure”

The profile or concentration of the projected light distribution

- Sersic  $n$
- Concentration
- $M_{20}$

What exactly is “structure” telling us?

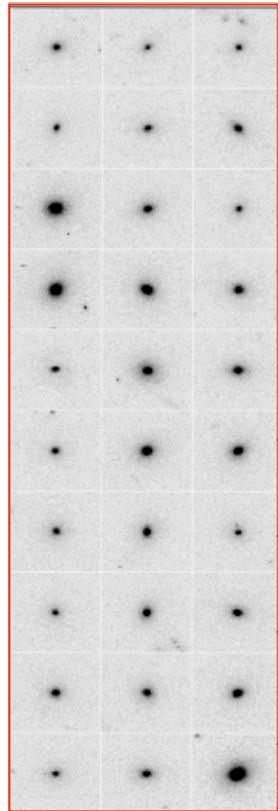
$$\ln \mu = \ln \mu_0 - kr^{1/n}$$

$$0.5 < n < 10$$

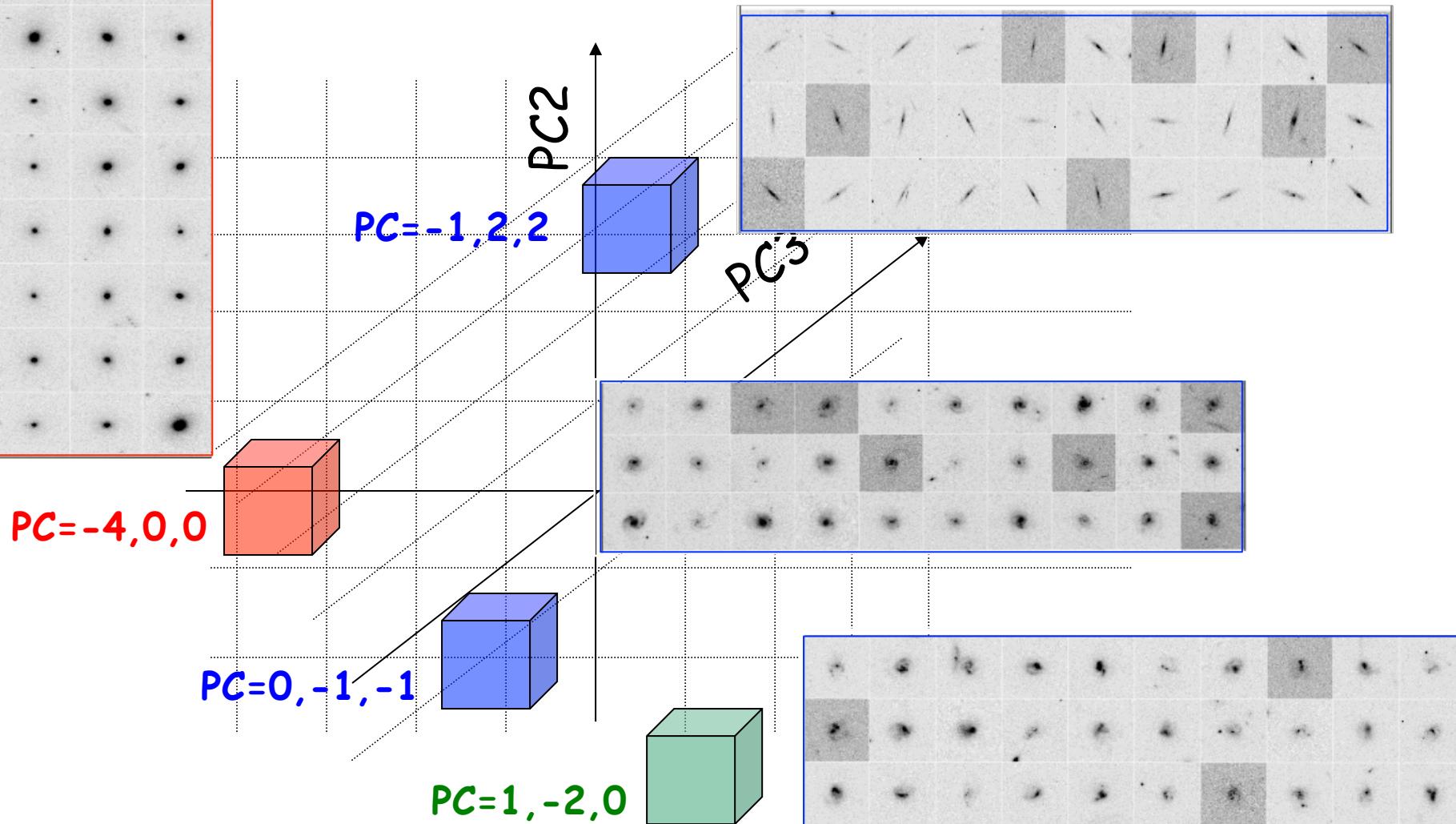
$n = 1$  exponential (“disk”)

$n = 4$  de Vaucouleurs (“spheroid”)

All of these have observational issues with surface brightness thresholds and convolution by PSF, requiring careful correction (see e.g. Cibinel et al, arXiv 1206.6108



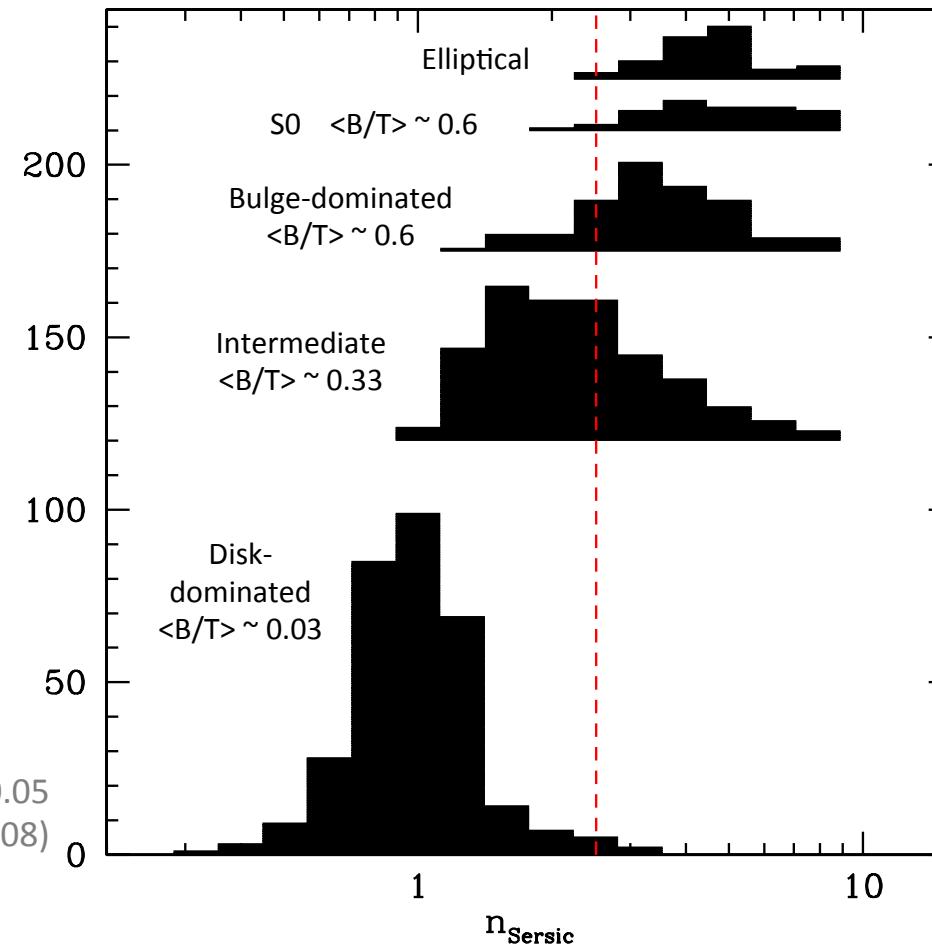
**ZEST** machine morphological classifier: Scarlata et al 2006 ApJ 172, 406  
PC-analysis of [Concentration](#), [M20](#), [Gini](#), [Ellipticity](#), [Asymmetry](#)  
90% of variance in first three PC components as applied to 56,000  
COSMOS galaxies at  $I_{AB} < 24$



# “Structure” is not the same as “morphology”

More than 50% of  $n > 2.5$  galaxies have significant disk components.

Data from  $\sim 700$  ZENS group galaxies at  $z \sim 0.05$   
(Cibinel et al 2012, arXiv 1206.6108)



# Environment

What do we mean, or want, by “environment”?

- (a) Local density (of galaxies)
- (b) Group-centric distance
- (c) Central in its halo or satellite
- (d) Group halo mass
- (e) Location in the larger cosmic web

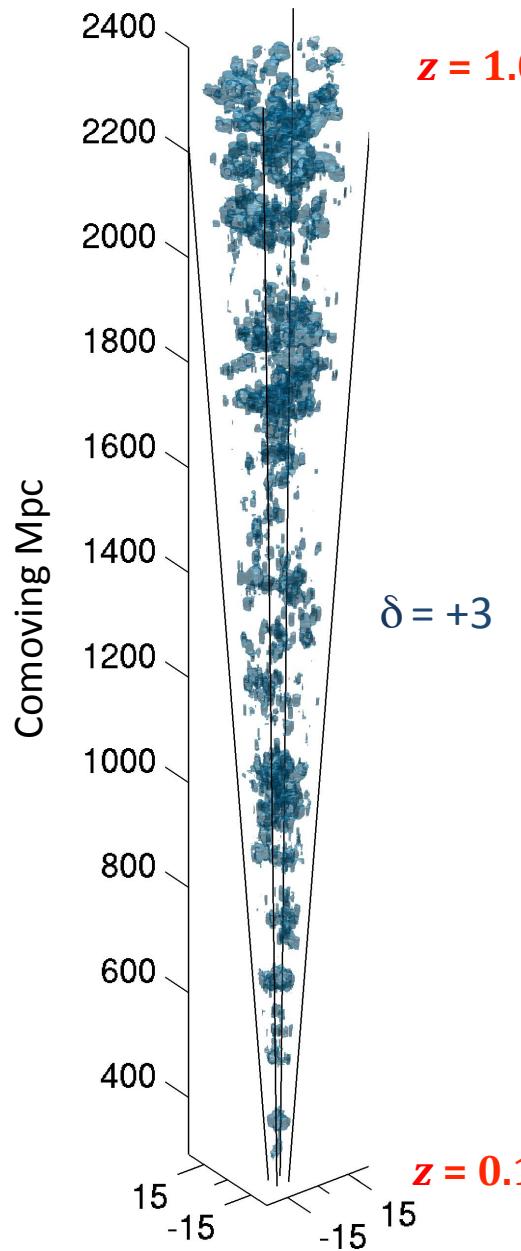
Spectroscopic redshifts (with high sampling rates) yield reasonable density fields and group catalogues, potentially yielding all of these quantities.

# Centrals and satellites

Difficulties of defining centrals and satellites even at low redshift: from ZENS survey  
 (Cibinel et al 2012, arXiv1206.6108 )

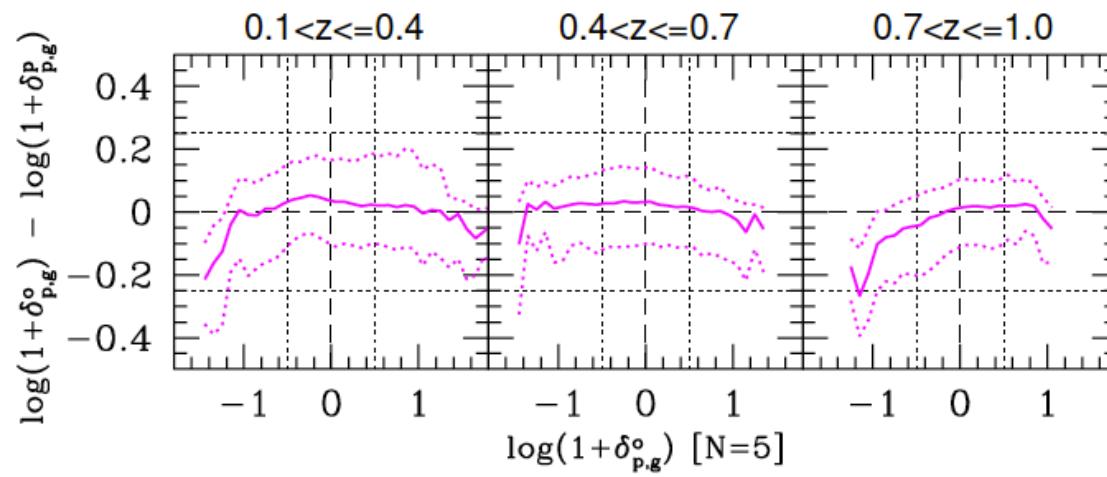


40% of ZENS/2PIGG at low z groups do not have an unambiguously defined central.  
 20% are probably benign (incompleteness), 20% of groups are unrelaxed.



## Density field at high redshifts

Over-density-field  $\delta = \delta\rho/\rho$  in COSMOS  
based on 5NN in volume limited sample (typically  
samples density on 1 Mpc scales)



Kovac et al 2010, ApJ 708, 505

Choices for constructing continuous  $\delta(\theta, \phi, z)$  from galaxy point survey  $\{\theta_i, \phi_i, \zeta_i\}$ .

Looked at:

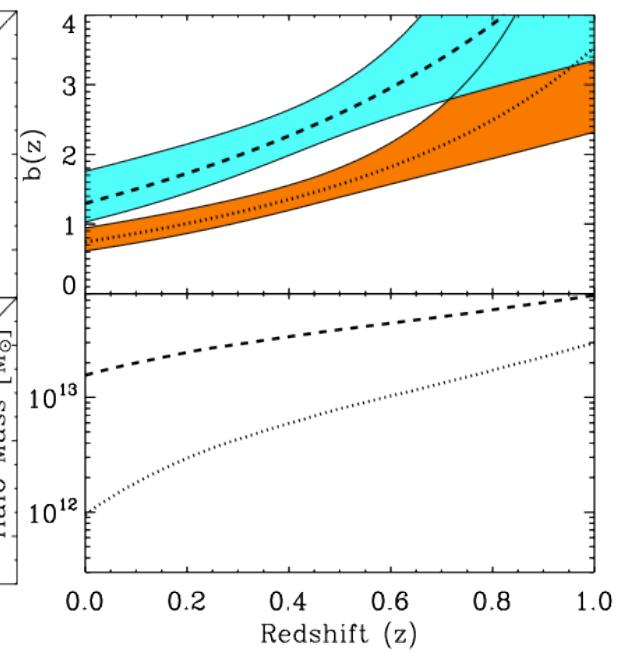
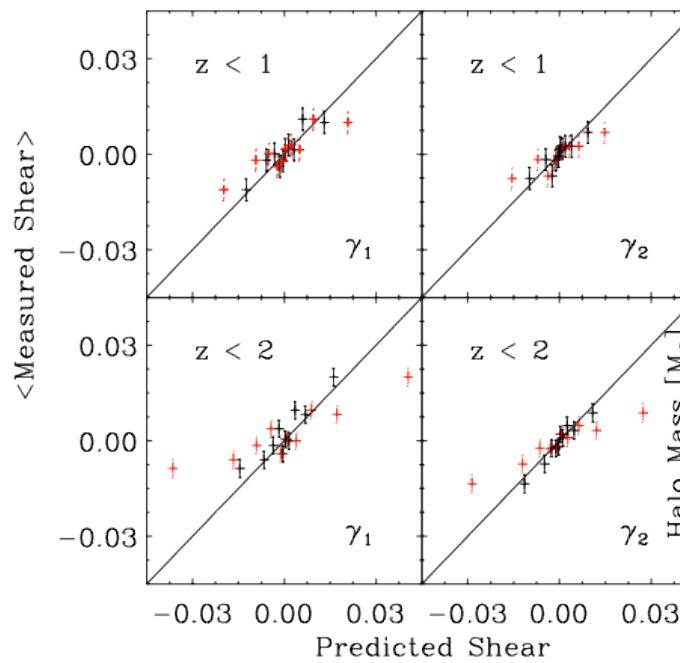
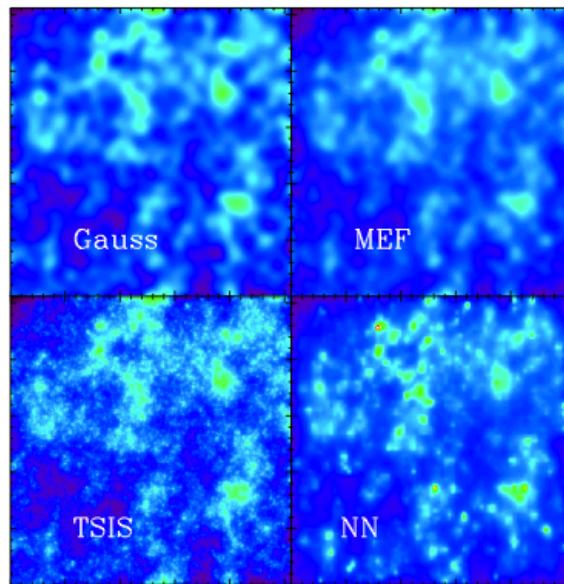
- Gaussian smooth (1.2 arcmin)?
- Multiscale Entropy filter?
- Truncated isothermal spheres?
- Nearest Neighbour?

$$\{\theta_i, \phi_i, z_i\} \xrightarrow{\chi} \delta_\chi^g(\theta, \phi, z)$$

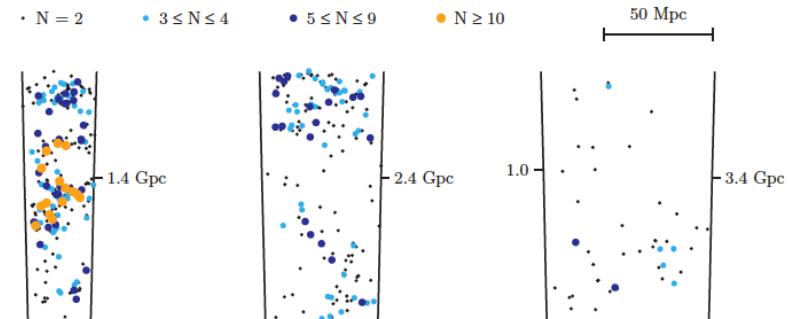
$$\delta_\chi^g = b_\chi \delta^m$$

$$= b_1(z) \delta^m + b_2(z) [\delta^m]^2$$

From Amara et al, 2012, 424, 553



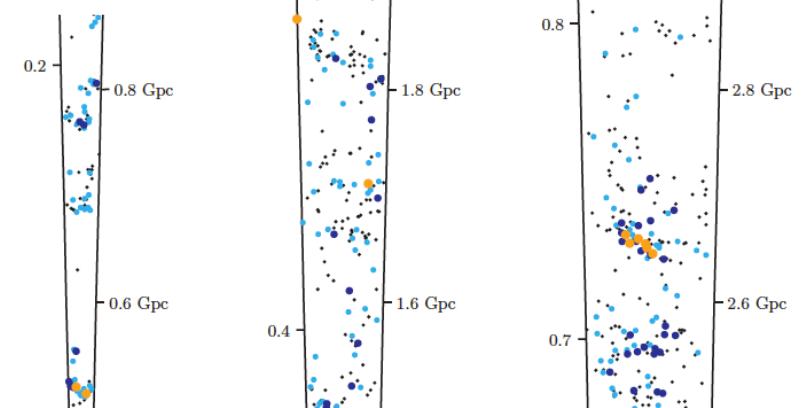
# Groups at high redshift



## Catalogues of groups at high redshift

	VVDS-02 Cucciati et al (2010)	DEEP-2 Gerke et al (2012)	zCOSMOS Knobel et al (2012)
N <sub>gal</sub>	6600	35,000	18,000
N with N > 3	144	706	566
<z>	0.6	0.75	0.5
Purity	50%	60%	83%
Completeness	60%	70%	83%

zCOSMOS: central/satellite division with purities of 84% (centrals) and 74% (satellites)



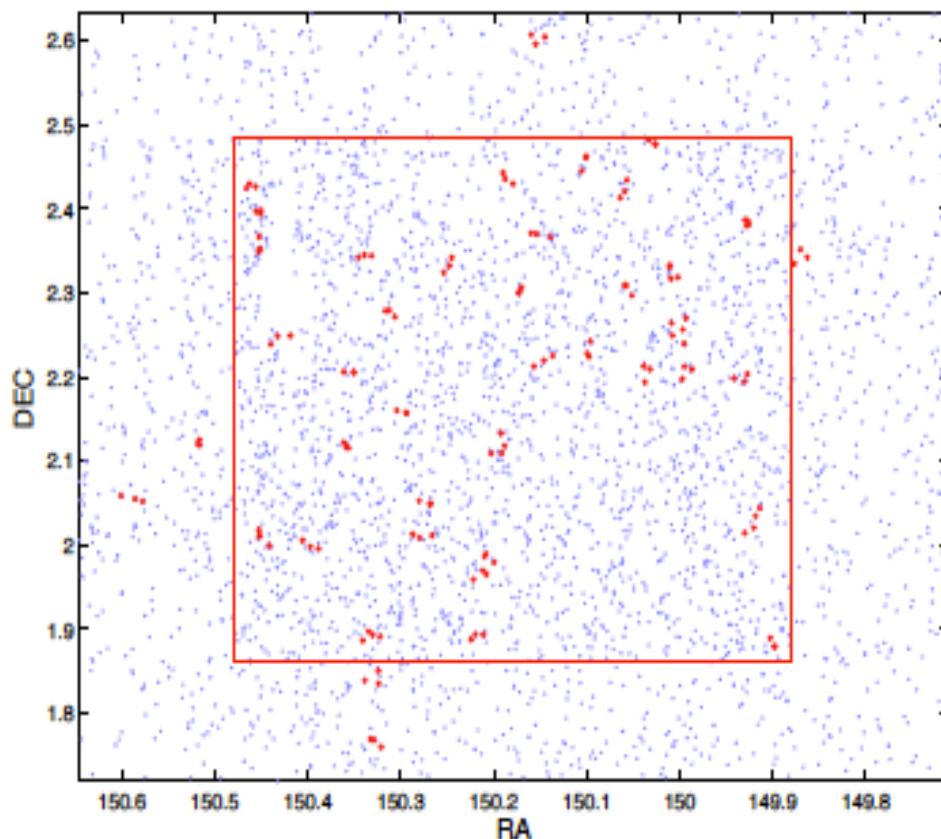
## Groups at very high redshift

Harder: generally lower sampling densities and groups are just forming

42 “proto-groups”\*\* at  $1.8 < z < 3$  in zCOSMOS-deep

Diener et al (2012, in press)

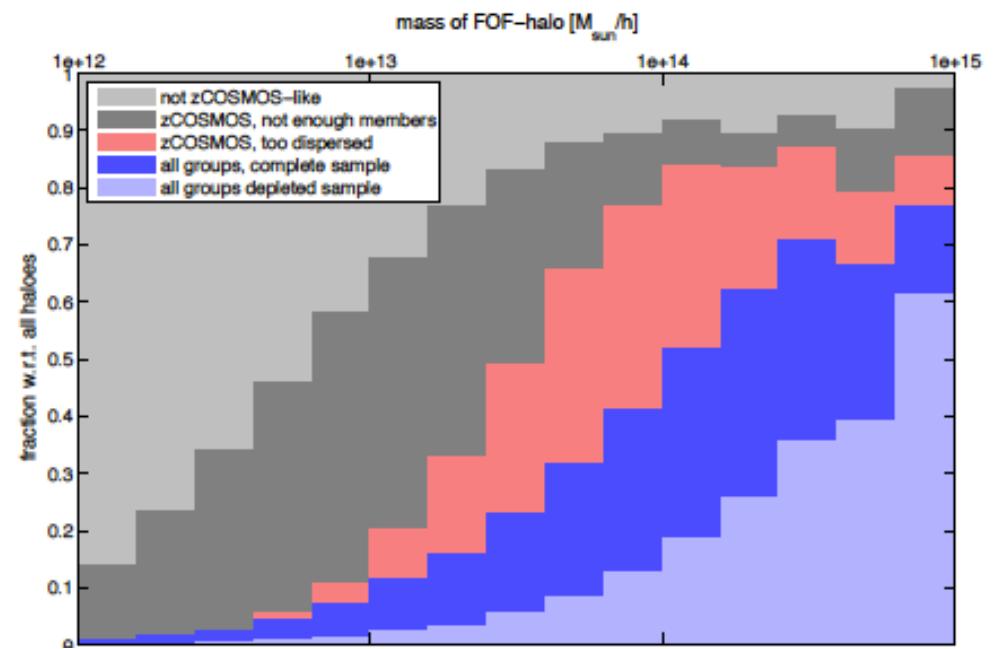
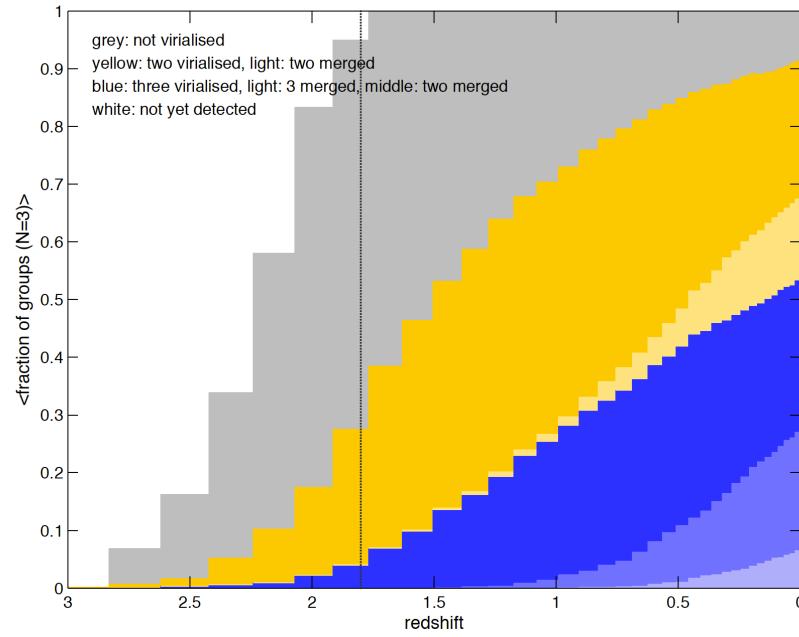
\*\*Defined as 3 or more objects with  $\Delta r_{\text{phys}} < 500 \text{ kpc}$  and  $\Delta v < 700 \text{ km s}^{-1}$



What are they and what will they become?

Millennium simulations yield roughly the right number.

Almost none of the members are in the same halo at the epoch we observe them



When, if ever, do the  $z \sim 2.5$  structures form into groups

What fraction of today's groups/clusters are represented by the detected  $z \sim 2.5$  structures

# Halo masses

High halo masses ( $m > 10^{14} M_\odot$ )

- Kinematics of galaxies
- X-ray emitting gas (hydrostatic equilibrium)
- Strong and weak gravitational lensing on individual objects

These all become less practical at lower halo masses

Groups calibrated via optical luminosity

Yang et al 2007, ApJ, 671, 153

Eke et al 2004 MNRAS 355 769

Knobel et al 2012, ApJ, 753, 121

Stacked weak lensing analysis

Mandelbaum et al 2006, 372, 758

Leauthaud et al 2012, ApJ 744, 159

Other statistical techniques based on DM theory

- Halo-occupation distribution (HOD)
- Abundance matching

# Galaxy mergers

A key quantity in a hierarchical Universe: what is in-situ sSFR compared with mass brought in by mergers (sMMR)?

Two approaches:

- (a) Morphologically disturbed objects:: Requires knowledge of how long the recognizable phase lasts.

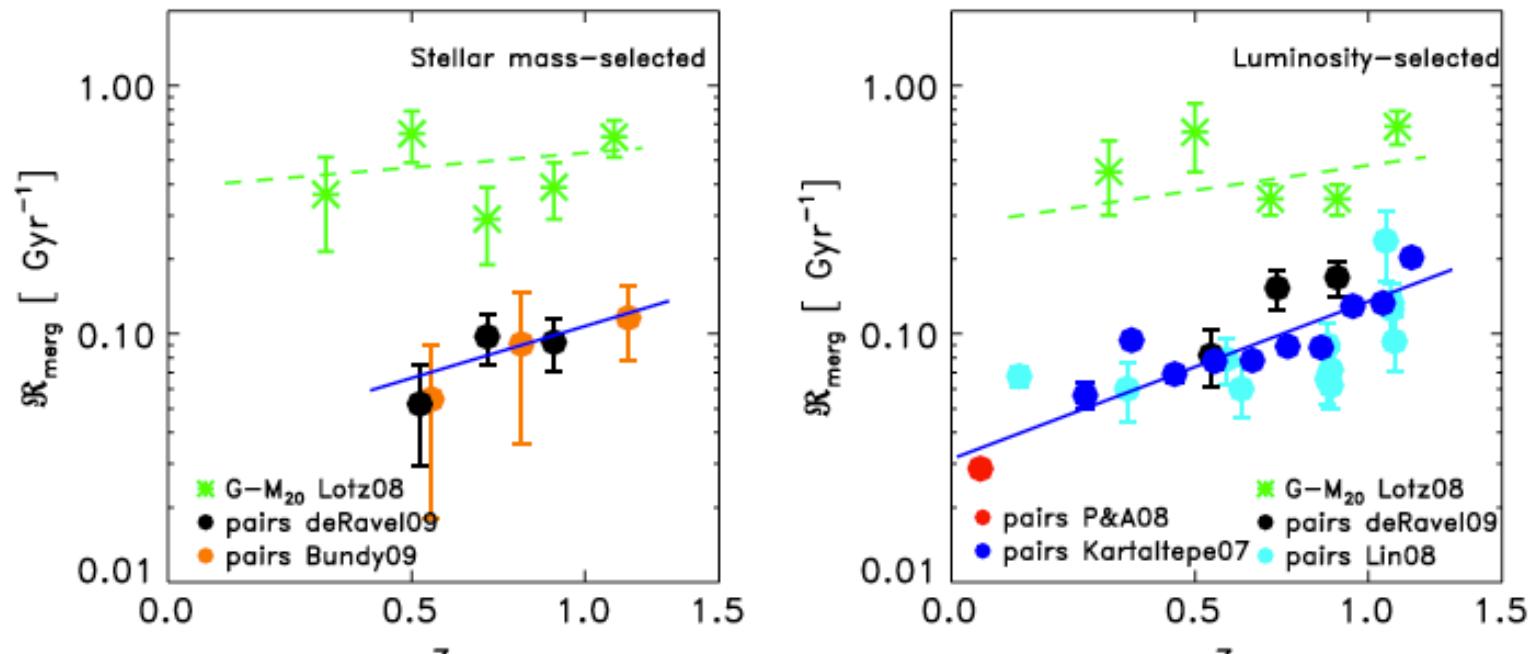
$$\text{Rate} = \frac{f_m}{t_m}$$

- (b) Pairs of objects (imaging with projection correction or spectroscopic with  $\Delta v$  criterion) : Requires knowledge of what fraction of pairs will merge in unit time (from SAM-type simulations)

$$\text{Rate} = 0.5 f_{pair} P(0)$$

With  $P(t) dt$  the probability distribution of when a given pair will merge

see Lotz et al, 2011, ApJ, 742, 103



### Major Merger Rates Per Galaxy (Gyr $^{-1}$ )

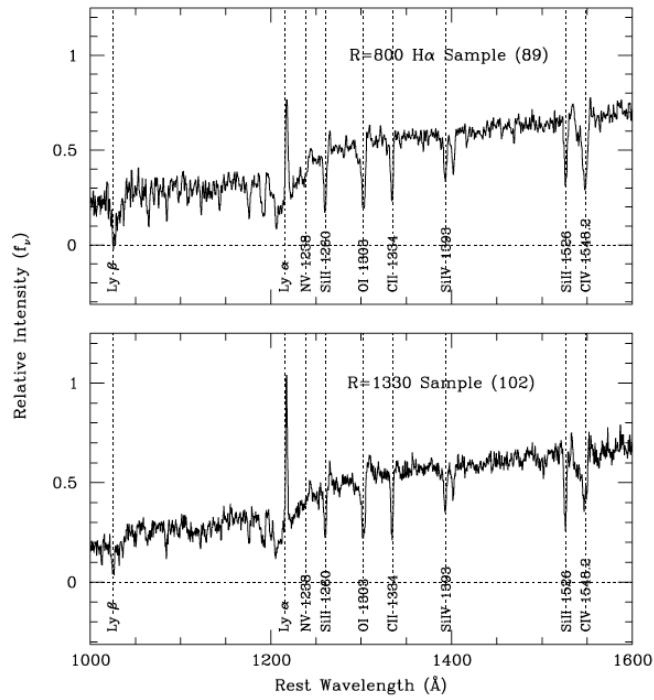
$\mathfrak{R}_{\text{pairs}, M_{\text{star}}}(z)$	1:1–1:4	$(0.03 \pm 0.01)(1 + z)^{+1.7 \pm 1.3}$
$\mathfrak{R}_{\text{pairs}, \text{PLE}}(z)$	...	$(0.03 \pm 0.01)(1 + z)^{+2.11 \pm 0.2}$
$\mathfrak{R}_{\text{pairs}, n_{\text{gal}}}(z)$	...	$(0.016 \pm 0.001)(1 + z)^{+3.0 \pm 0.3}$

## Gas content, gas inflows, gas outflows

Again, we have limited information at high redshift:

- HII easy to detect ( $\text{H}\alpha$  etc).
- HI detectable only in absorption ( $\text{Ly}\alpha$ )  
with some prospect for fluorescent emission
- $\text{H}_2$  undetectable but can use other molecules as proxies (e.g. CO),  
converted with the X-factor
- Metal absorption lines (e.g MgII, CIV) primarily low T material.

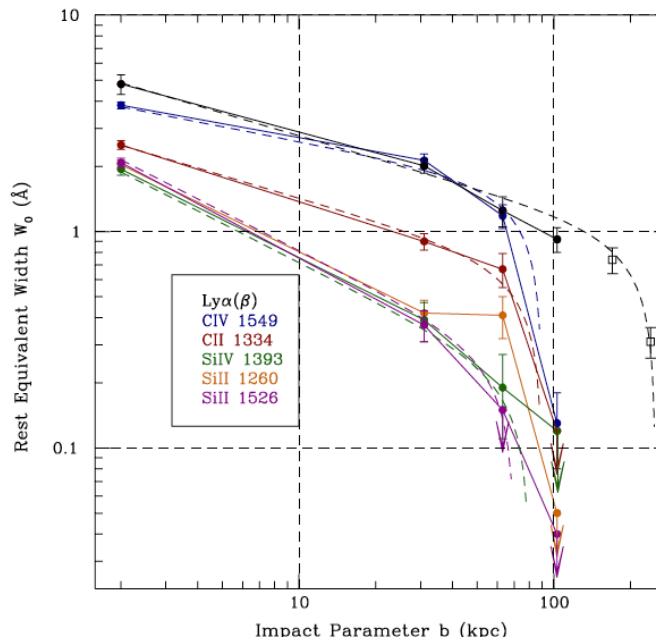
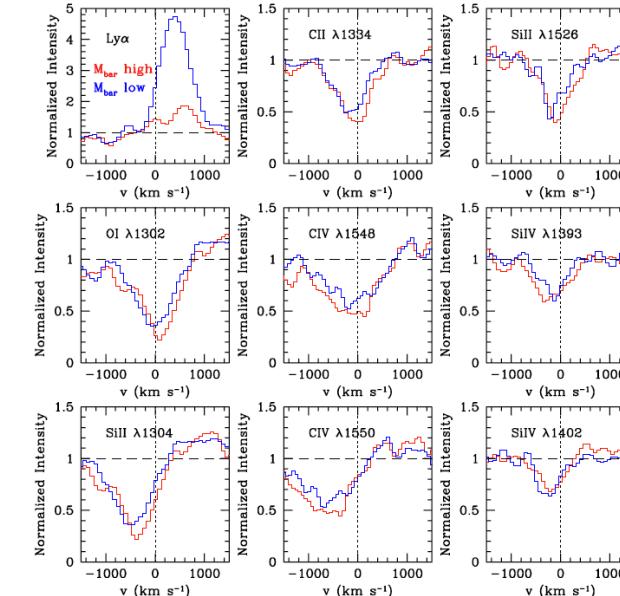
# Gas content, gas inflows, gas outflows



Stacked spectra of  $\sim 100$   $z \sim 2$  galaxies

From Steidel et al 2010, ApJ 717, 289

Velocity distribution down-the-barrel



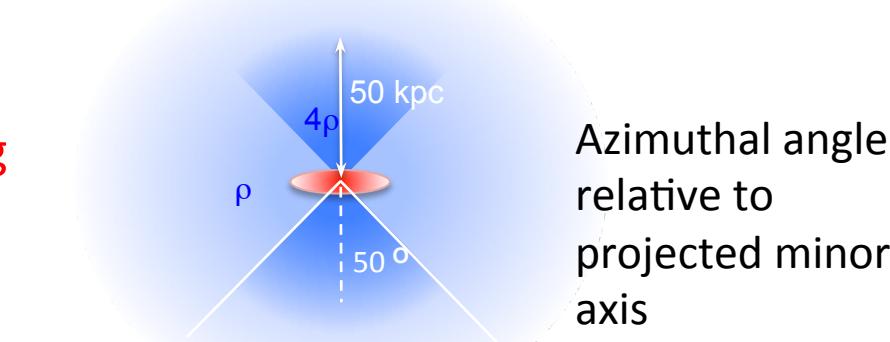
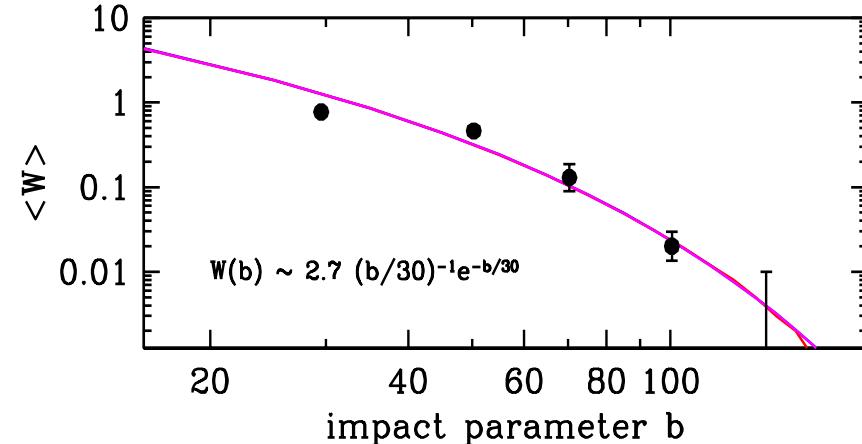
# Mapping of MgII around galaxies at $0.5 < z < 0.9$

(Bordoloi et al 2011)

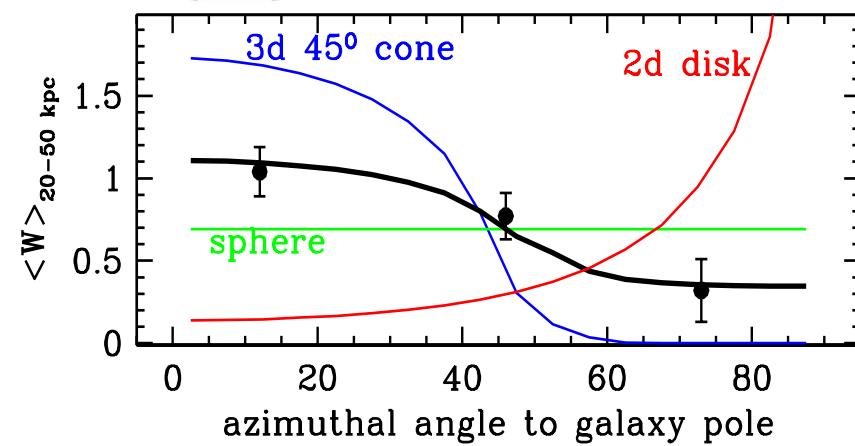
Stacked spectra of about 5200  $B \sim 25$  zCOSMOS galaxies lying behind ( $z > 1.2$ ) about 4000  $0.5 < z < 0.9$  galaxies with  $b < 200$  kpc

Bipolar geometry suggests outflowing material entrained in star-formation driven wind

Total mass loss including hot component?



Azimuthal angle  
relative to  
projected minor  
axis



## Summary messages:

- Observations have progressed dramatically in the last 20 years
- Survey design matters. You get what you get.
- But are still incomplete or indirect in some key areas
  - dark matter haloes
  - gas at high redshift
- And there are significant systematic uncertainties ( $\sim 0.3$  dex) in many key quantities
  - Stellar masses
  - Star-formation rates
  - Metallicities

Many of these need continued classical “astronomy” work to check and clarify empirical relations