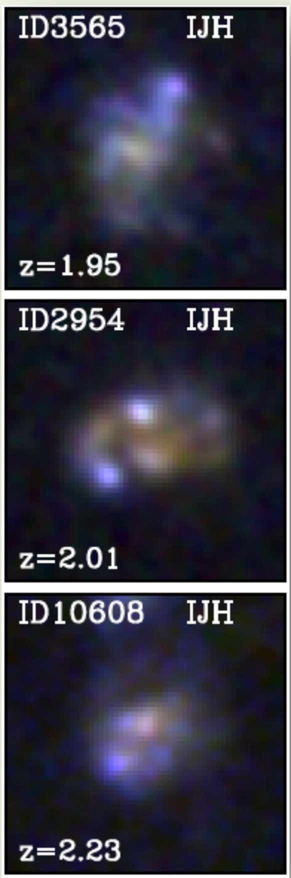
Properties of strong gravitational lensed galaxies

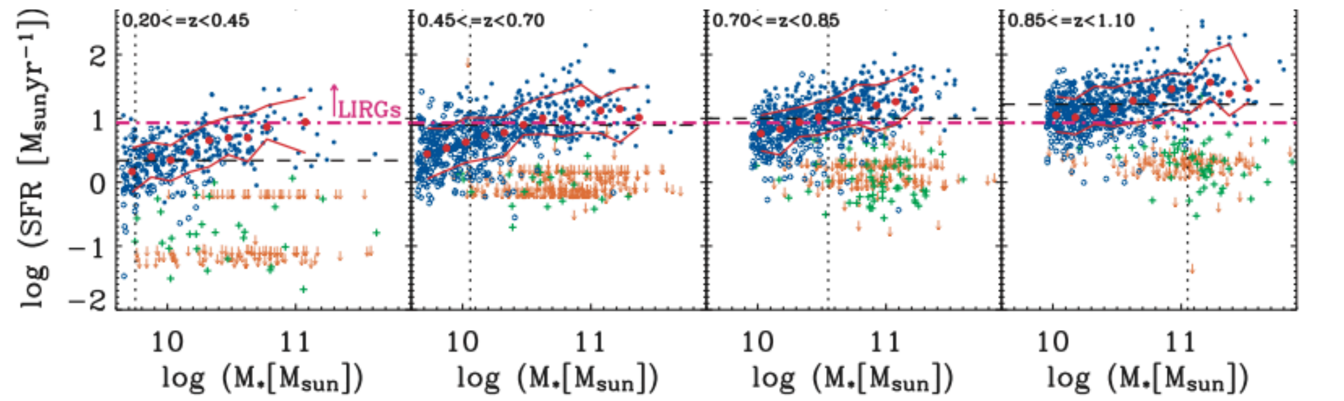
Lise Christensen
Dark Cosmology Centre,
Niels Bohr Institute, Copenhagen

Properties of z>2 star forming galaxies



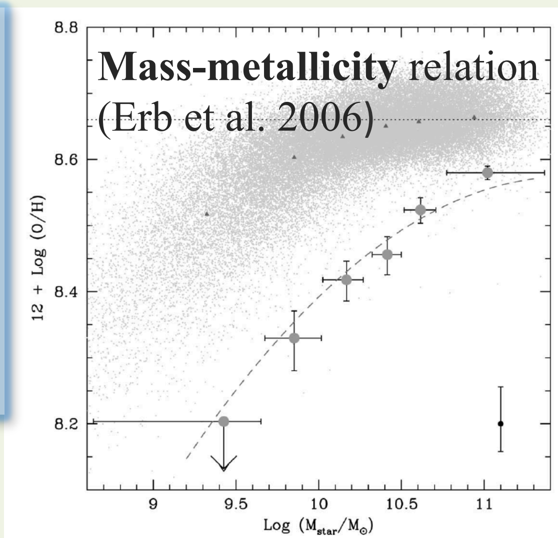
Hubble sequence in place
At z~2 (Wuyts, S. et al. 2011)=
Age of the universe~ 3.3 Gyr

Main sequence for star forming galaxies (Noeske et al. 2007)

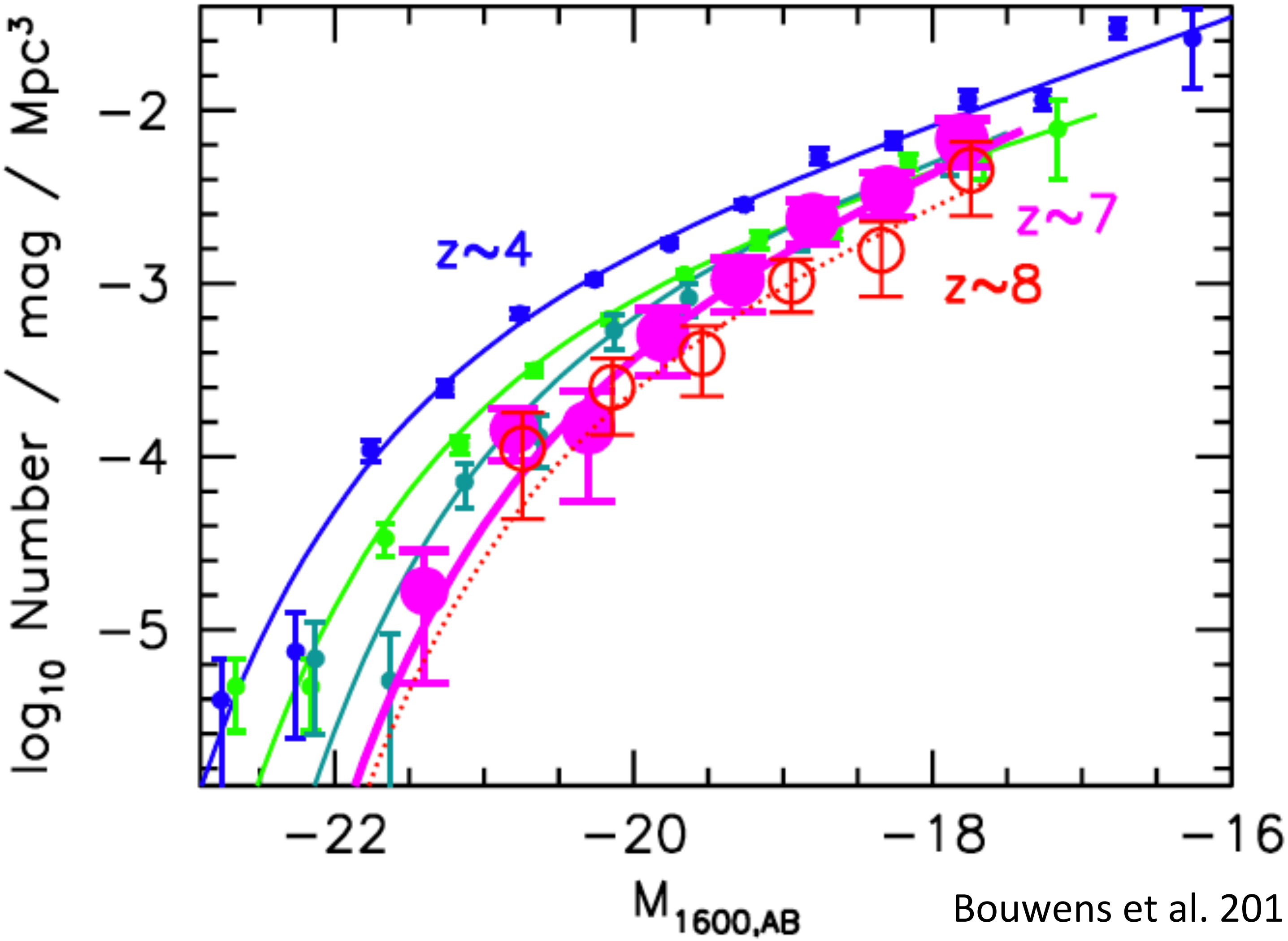


- Based on high-mass galaxies
- How do galaxies build up their mass?
- Nature of the low mass galaxies at high-z?

Mass-metallicity relation (Erb et al. 2006)



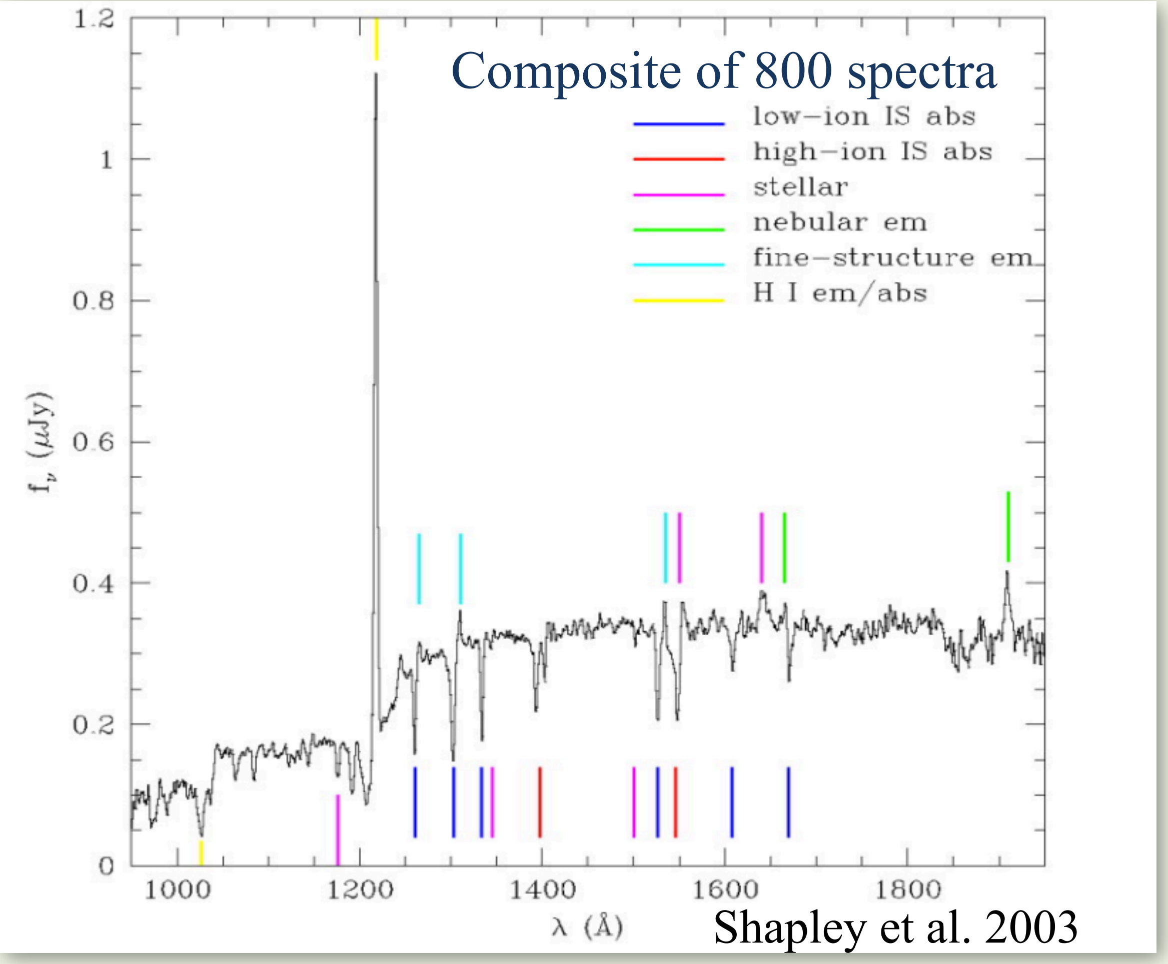
High-z galaxy luminosity functions



Bouwens et al. 2011

A typical z~3 galaxy spectrum

- Bright (*R* < 25.5 mag) - small dynamical range
- Stellar masses ~>10^{10} Msun
- Metal rich (> half solar)
- High star-formation rates (10-1000 Msun / yr)

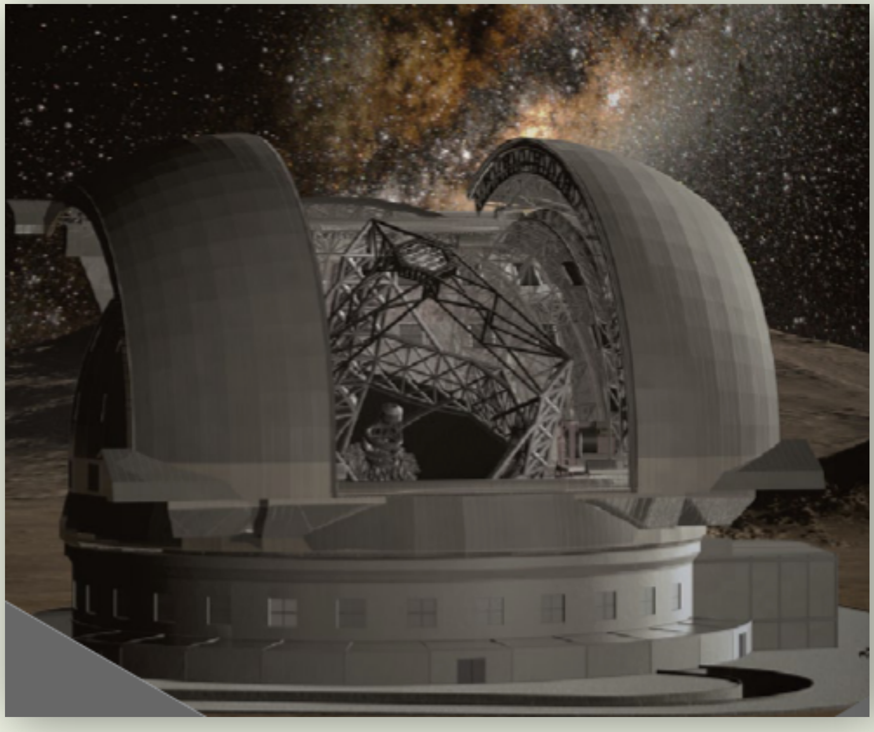


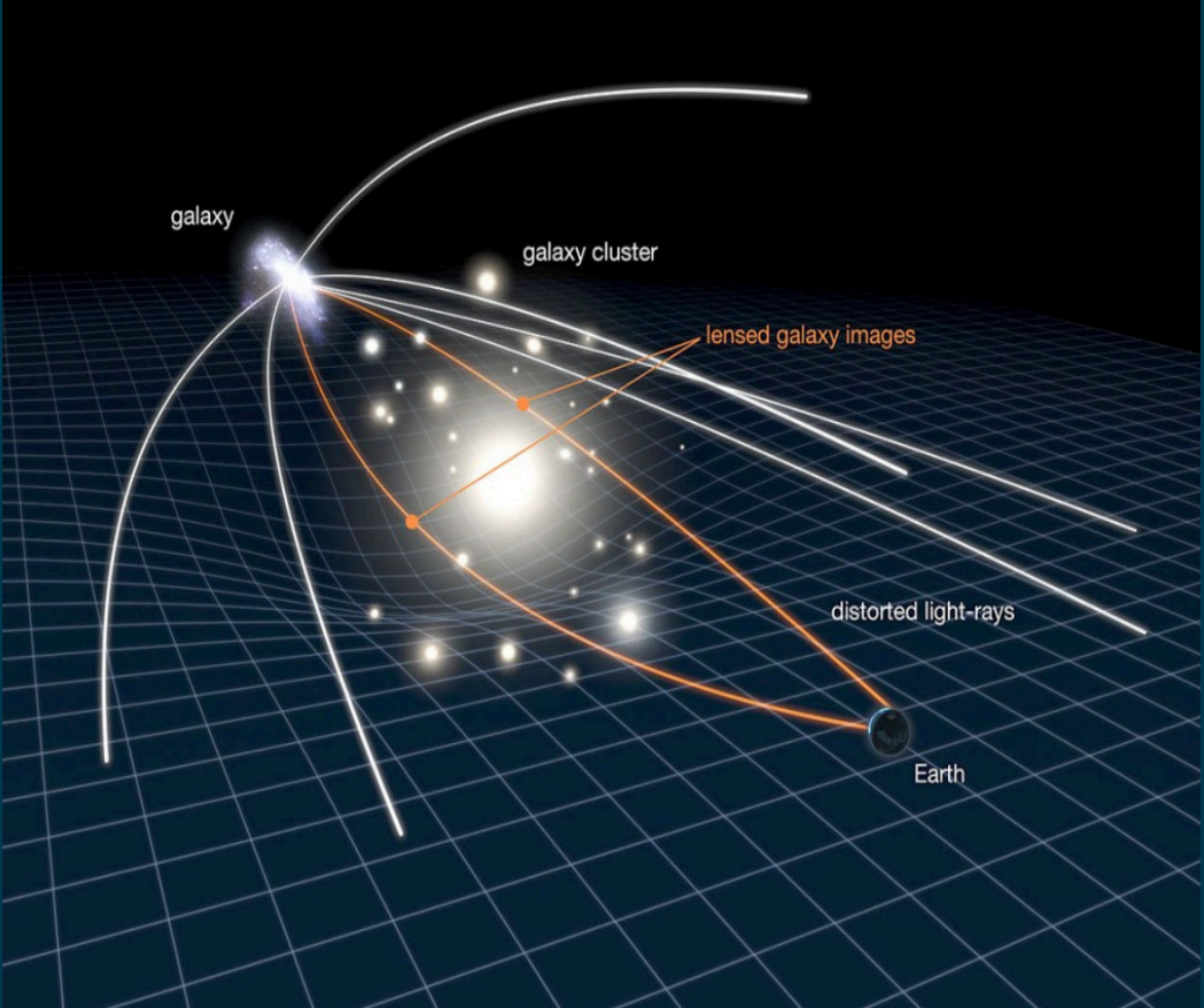
Shapley et al. 2003
Steidel et al. 2010

High-resolution galaxy spectra

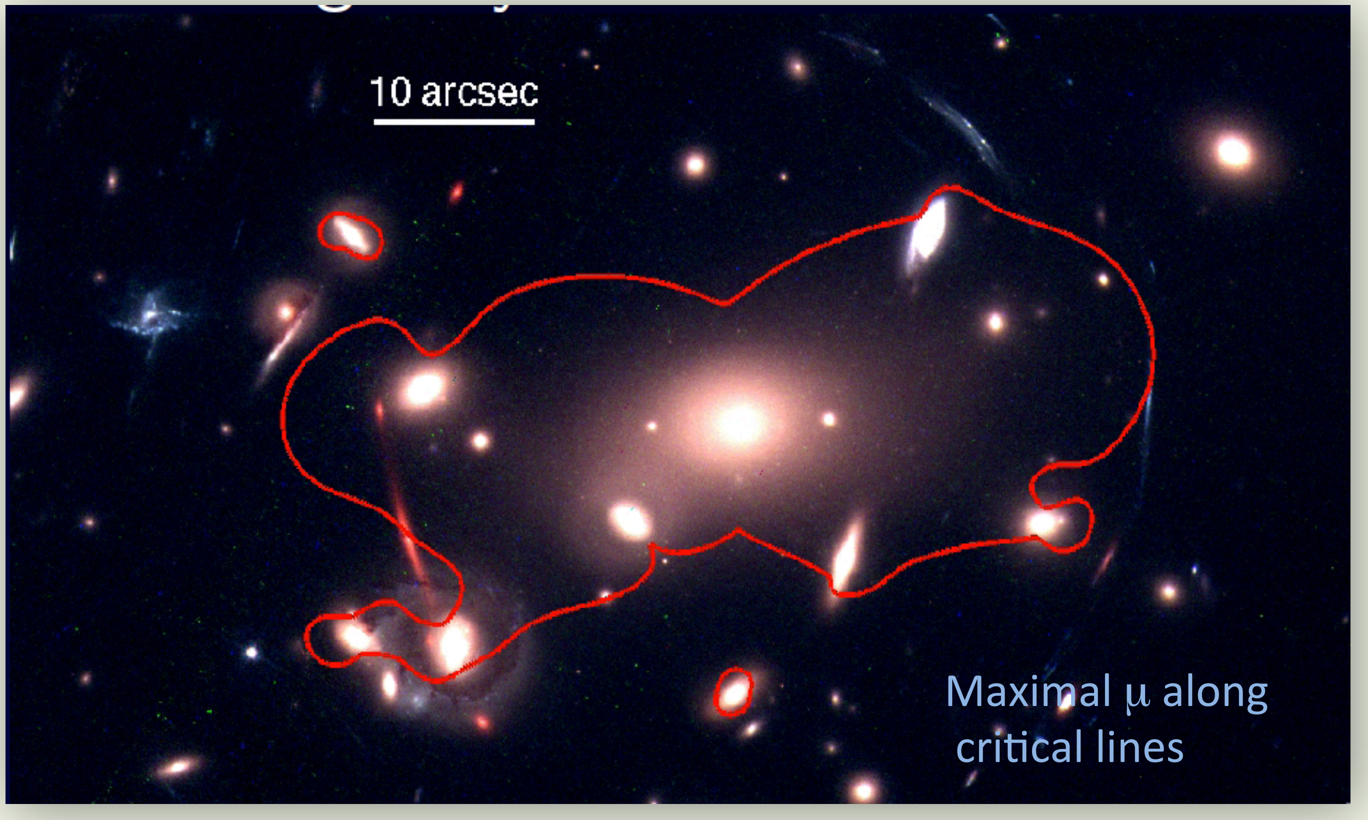
Observations of a single R=25 mag galaxy with high spectral resolution at a decent S/N takes > 100 hours at an 8m class telescope.

Wait for this?




galaxy
galaxy cluster
lensed galaxy images
distorted light-rays
Earth

Gravitational magnification



A lens model is needed to determine the magnification μ (10−50)

We can observe galaxies intrinsically 2-4 magnitudes fainter

Strong Lensing Surveys

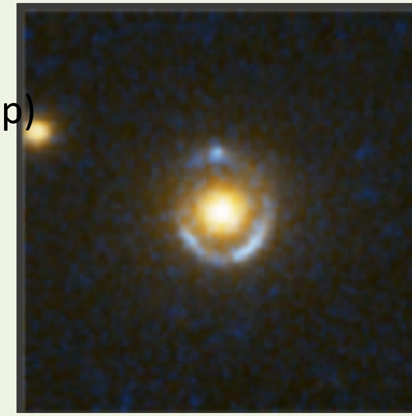
Cluster lenses
HST:

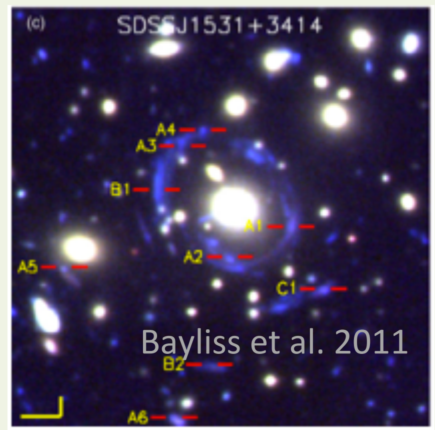
- CLASH : 524 orbits on 25 clusters
  16 filters (Postman et al. 2012)
- Frontier fields : 560 orbits on 4 clusters

Galaxy lenses
SDSS:

- SLACS (HST follow-up)
- BELLS

(Bolton et al. 2006)





Bayliss et al. 2011

- SGAS : giant arcs

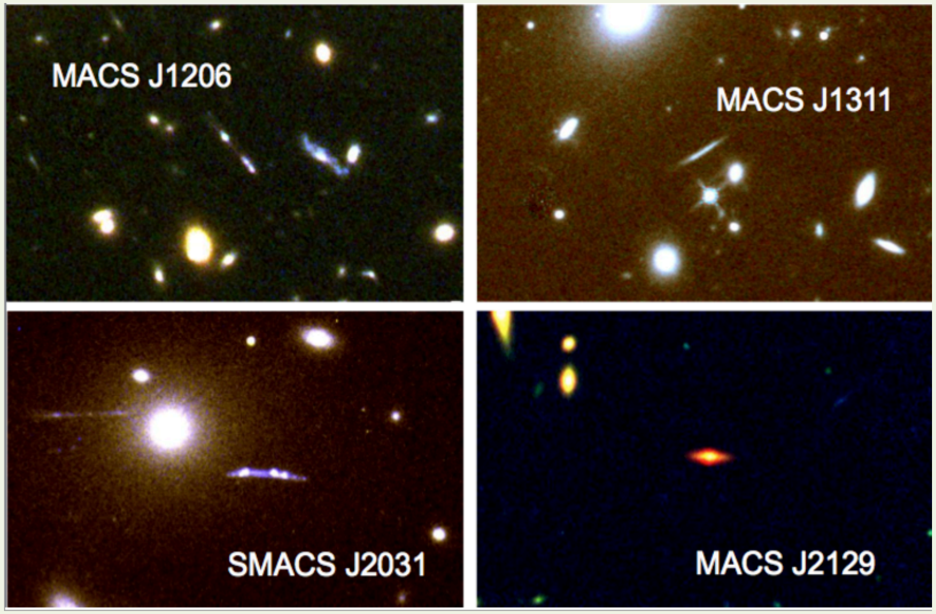
(Hennawi et al. 2008)

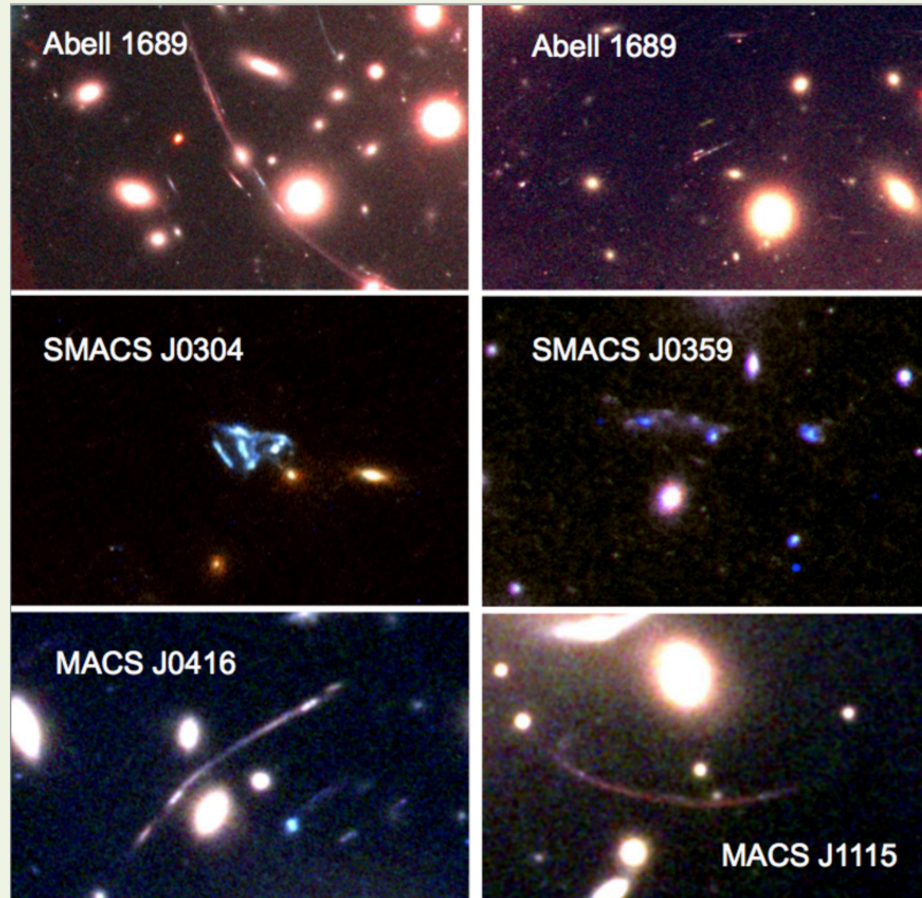
- CASSOWARY

(Belokurov et al. 2007)

Stark et al. 2013

X-shooter 1hr Snapshots of gravitational lensed galaxies





GTO snapshot project

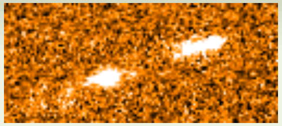
- ❖ Measure redshifts of background source galaxies (mag = 22-25)
- ❖ Improve lens models, + properties of source galaxies

10 clusters. Spectra of 12 arcs:

- ❖ Magnification factors: 5 – 40
- ❖ Redshifts for 12 lensed galaxies: $1 < z < 6$

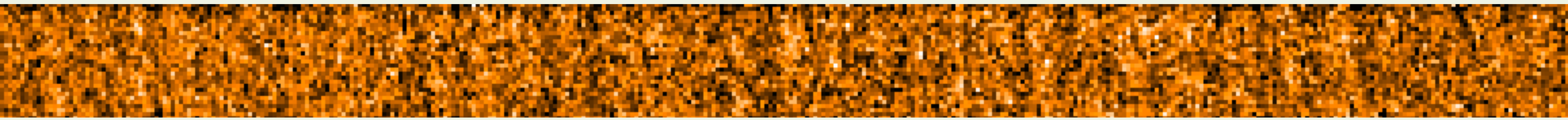
(Christensen et al. 2012a,b; 2013)

Faint galaxy spectra

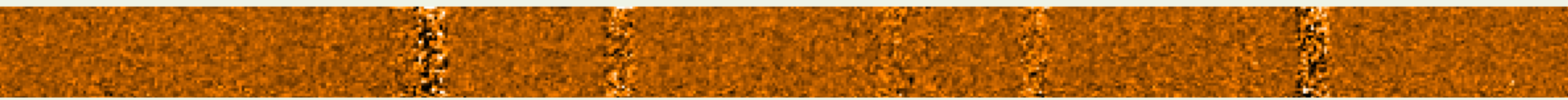


ACS, F606W of MACS 1206 cluster arc ID 1.1, 1.2

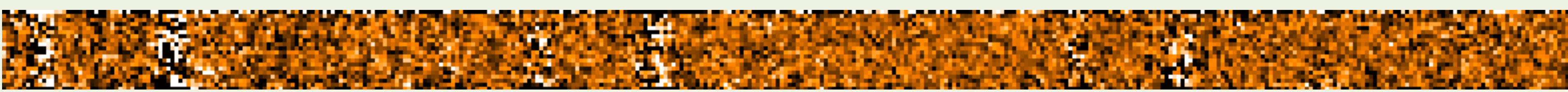
B=25.1 mag



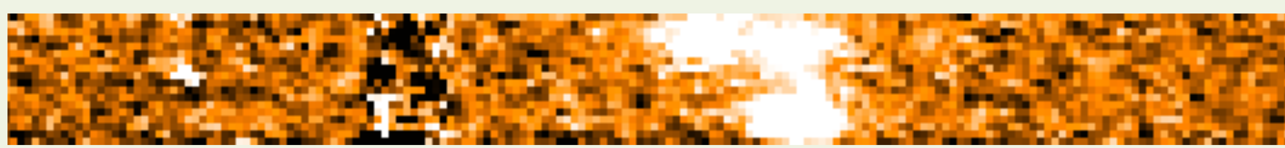
r =24.5 mag



J=24.4 mag



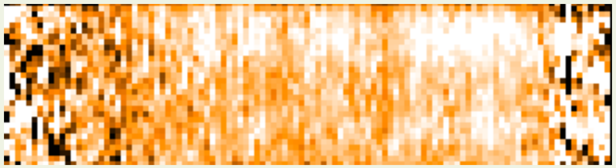
And a single emission line in the K-band: Flux ~$3x10^{-16}$ erg/s/cm2



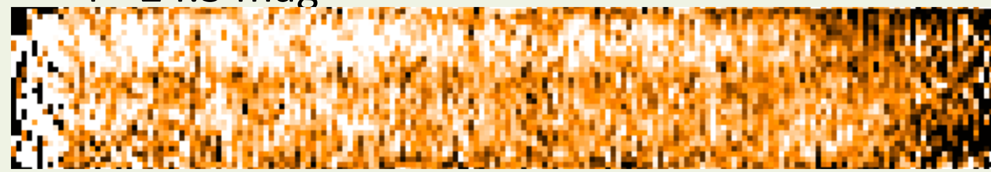
Faint galaxy spectra

Bin by a factor of 10-500 , weighted with errors:

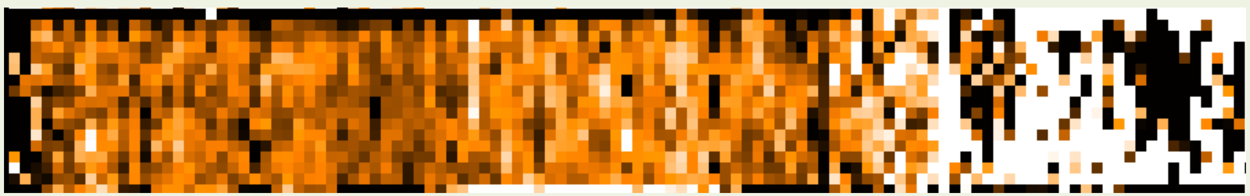
B=25.1 mag

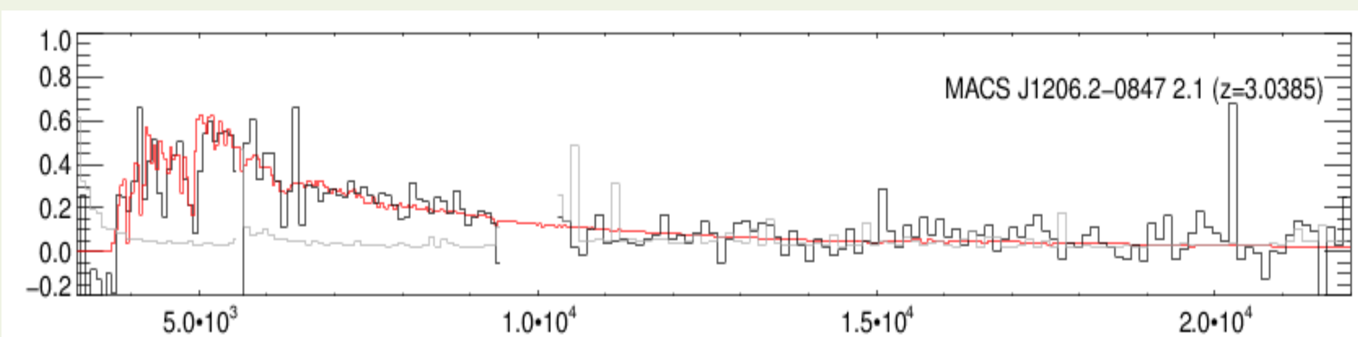


r =24.5 mag



J=24.4 mag





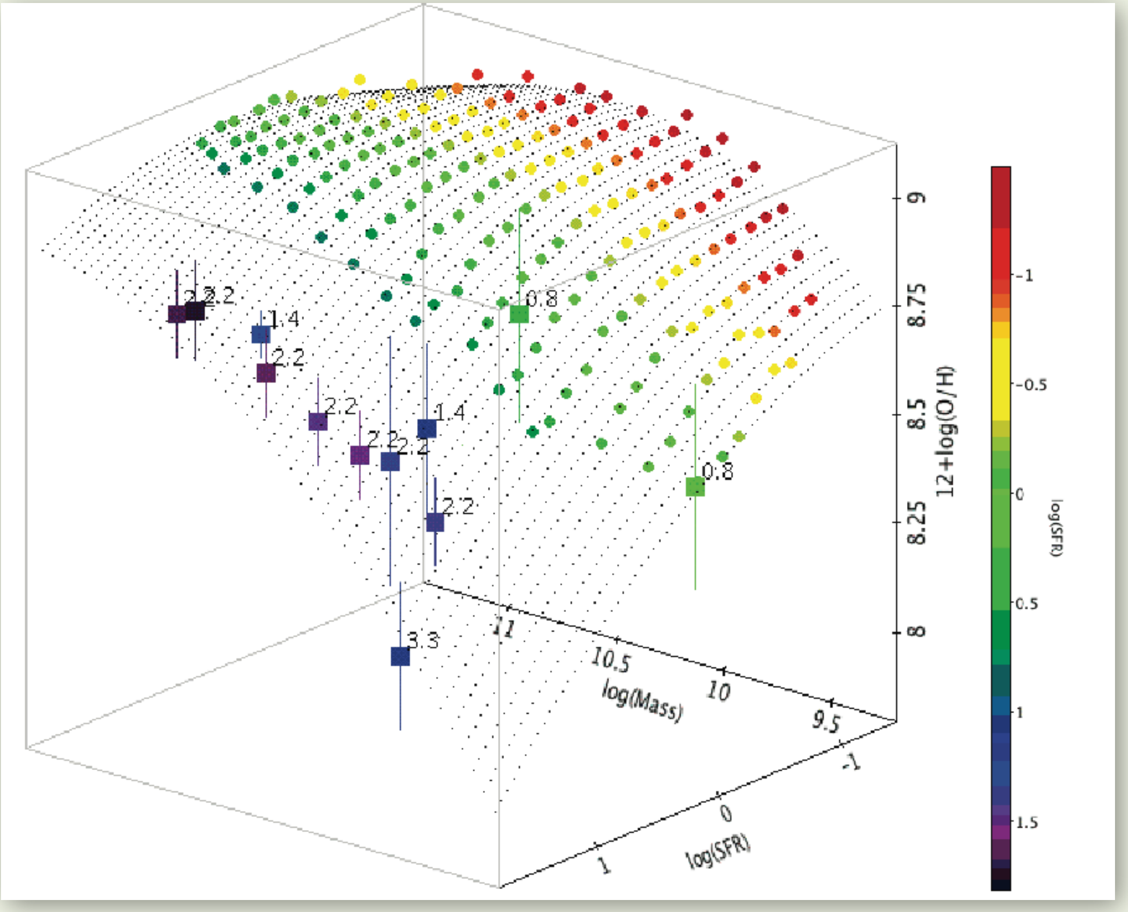
Spectral SED fit:

- Stellar mass
- Stellar population age
- Star formation rate
- Intrinsic reddening

Emission lines:

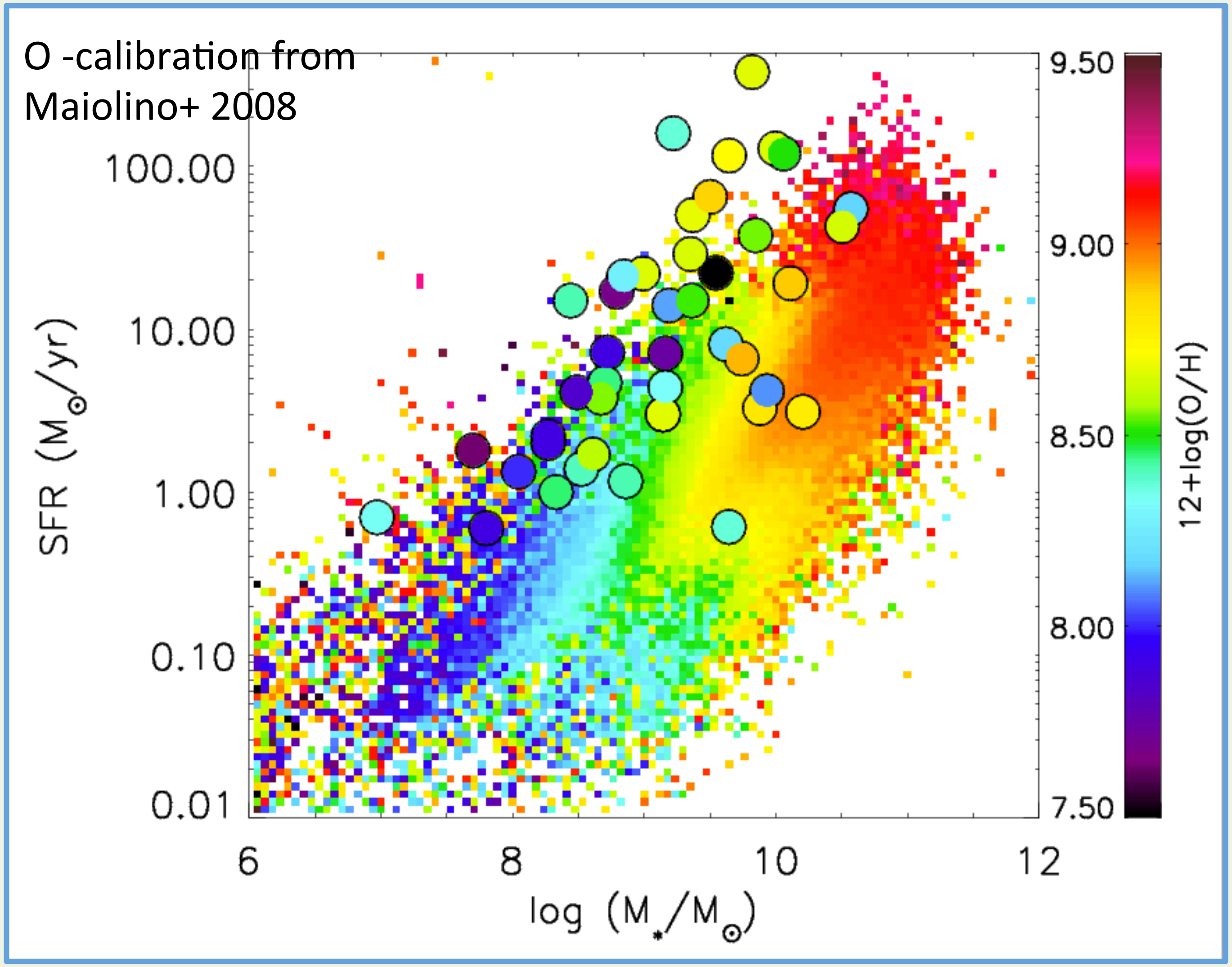
- SFRs
- O abundance
- reddening

Scaling relations:
Fundamental SFR-M*-O/H relation



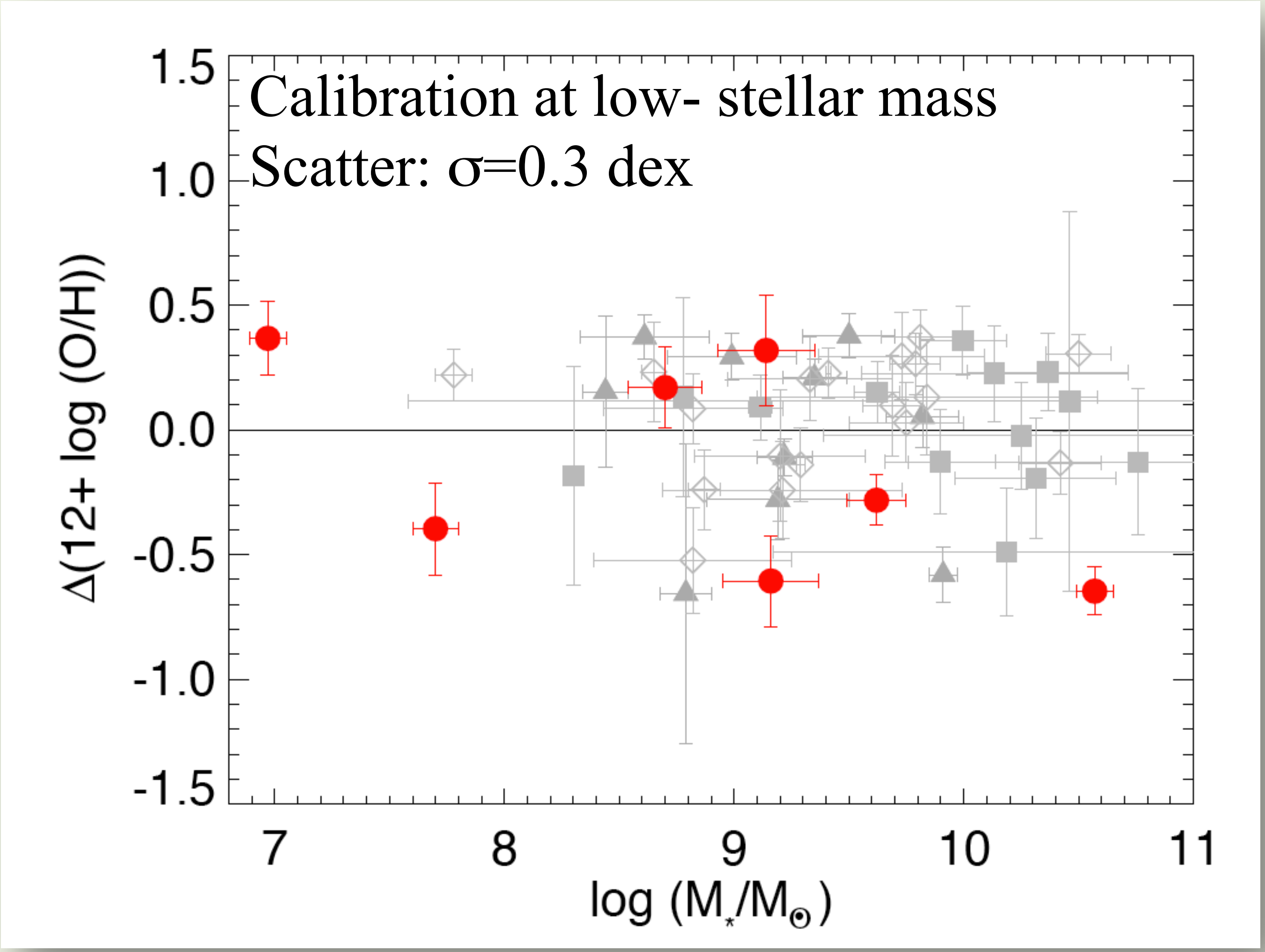
Based on largely low-z, high-mass, high metallicity galaxies (Laura-Lopez et al. 2010; Mannucci et al. 2010, 2011

Scaling relations: Fundamental SFR-M*-O/H relation



Scaling relations: Fundamental SFR-M*-O/H relation

Offset from fundamental relation



Data from : Christensen et al. 2012; Richard et al 2011, Wuyts et al. 2012, Belli et al. 2013

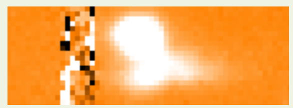
Direct measure: Oxygen abundance

Direct, temperature sensitive measure (Aller 1984; Izotov et al 2006):

[OIII] 4959

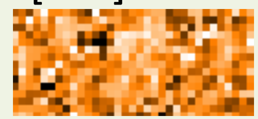
+

[OIII] 5007

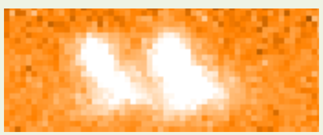


/

[OIII] 4363



→ temperature

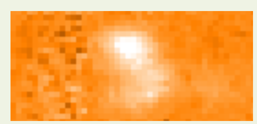


[OII] 3727,3729 flux ratio → Electron density

temperature
density

, O lines ,

Hbeta



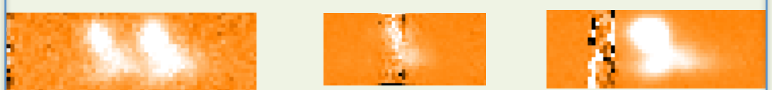
→ O abundance

Compare abundance to the sun : 12+log(O/H)=8.69
(Asplund 2009)

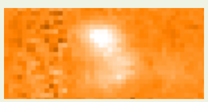
Indirect measure: Oxygen abundance strong emission line diagnostics: R_{23}

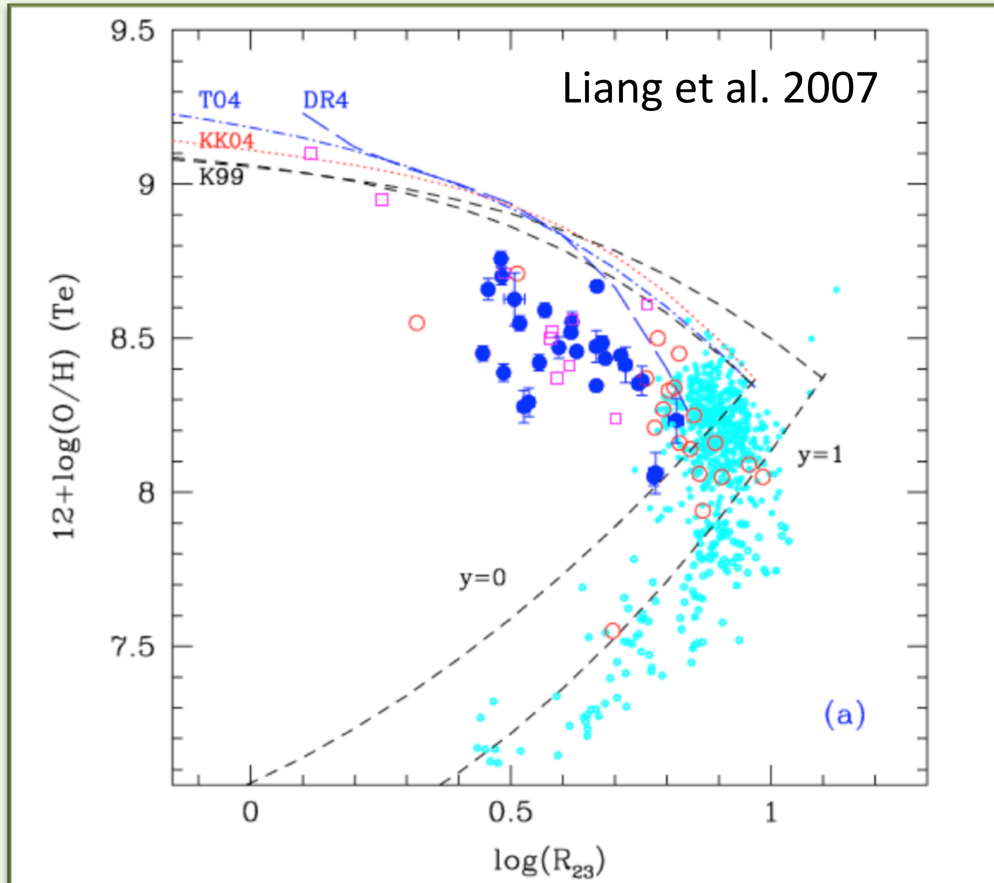
R_{23}=

[OII] 3727 + [OIII] 4959 + [OIII] 5007



Hbeta

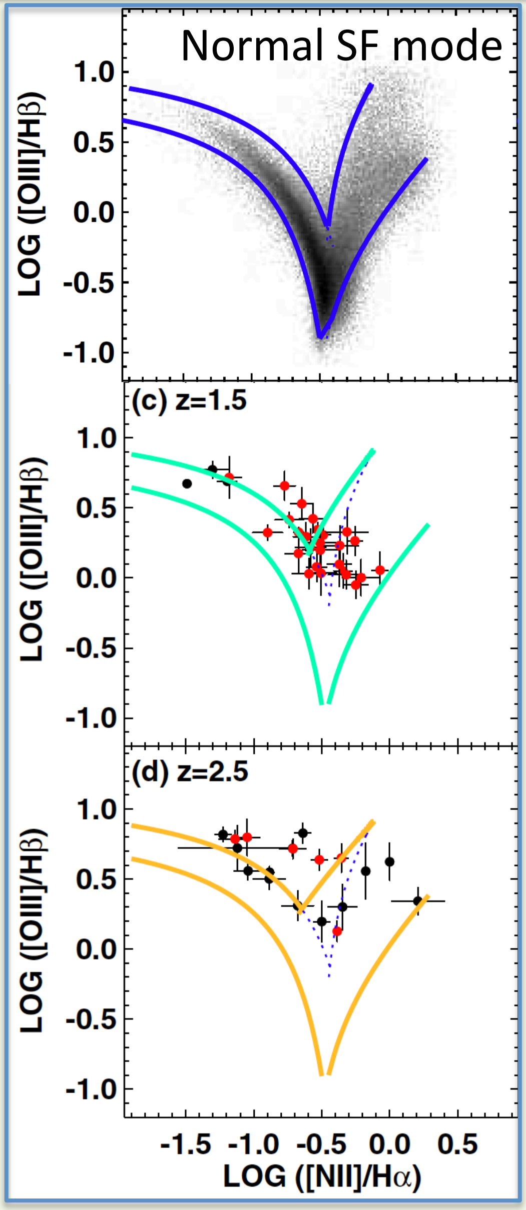


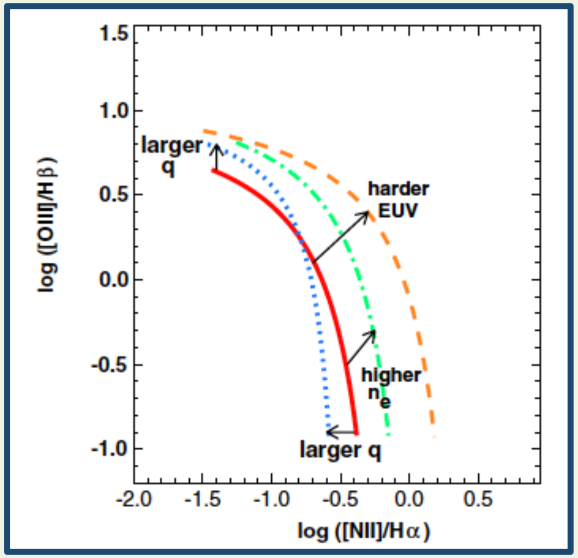


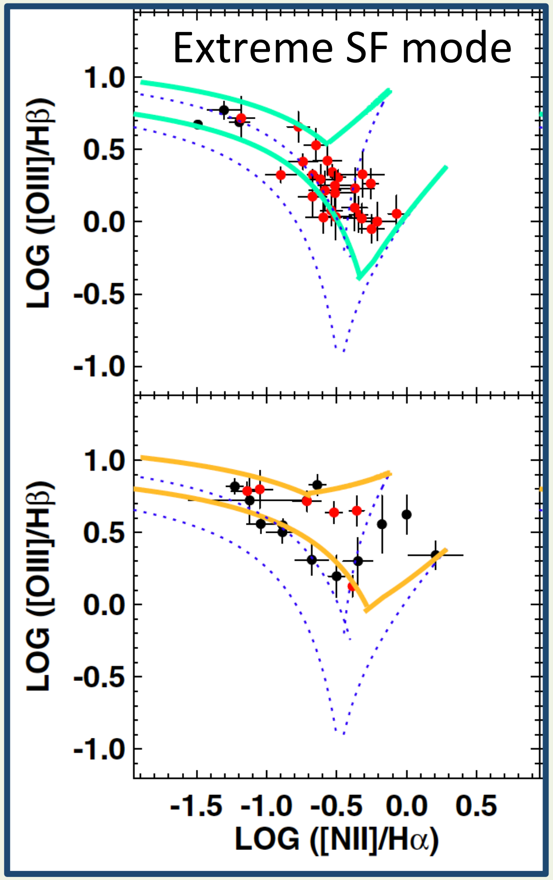
Problems:

- ❖ R_{23} is double valued
- ❖ It is calibrated at low-z
- ❖ Can we trust it at high-z?

STRONG LINE DIAGNOSTICS AT HIGH-Z





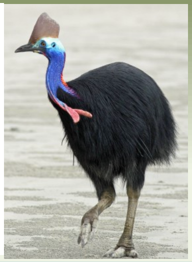


Kewley et al. 2013a,b

CASSOWARY

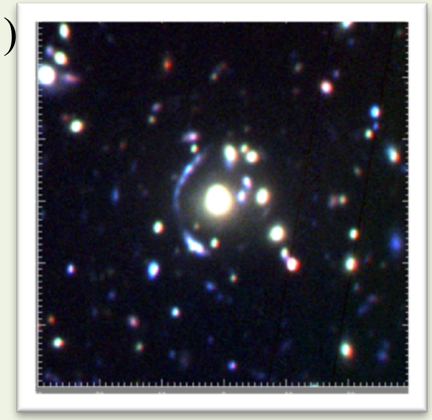
Cambridge **A**nd **S**loan **S**urvey **O**f **W**ide **AR**cs in the sk**Y**

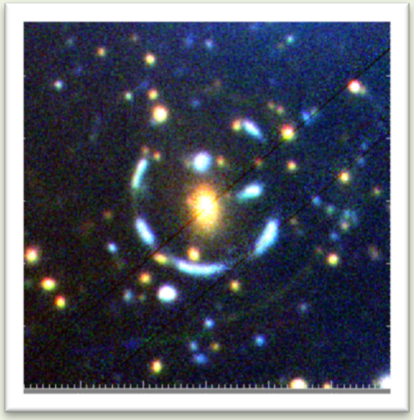
The Cassowary is the second largest flightless bird on the planet.

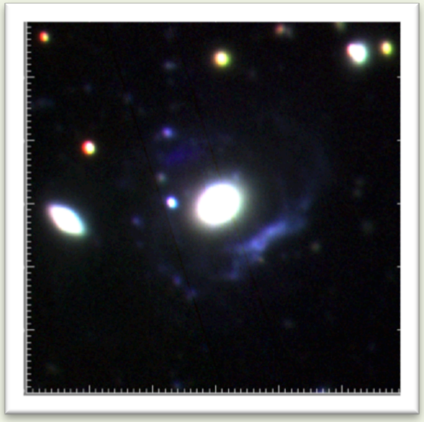


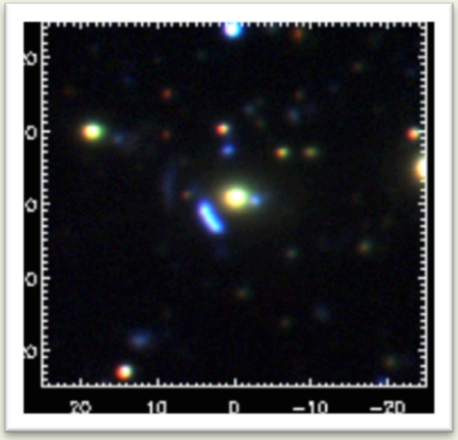
~100 candidate lensed galaxies found in images from the Sloan Digital Sky Survey (Belokurov et al. 2007)

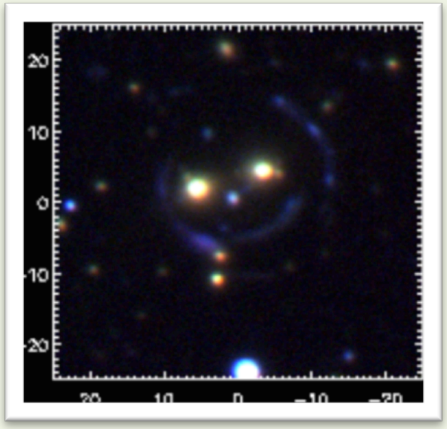
- ✧ 1/2 spectroscopically confirmed (Stark et al. 2013)
- ✧ Gemini follow up imaging (2011)
- ✧ NOT imaging (start 2013) (69 targets)
- ✧ X-shooter data for 6 sources.

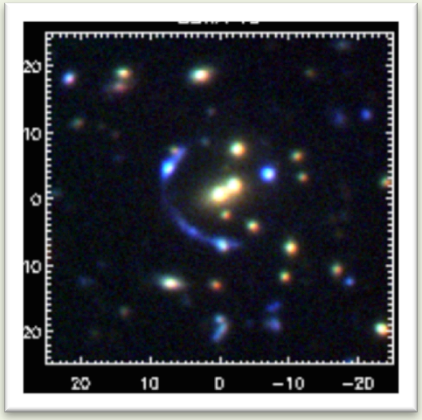












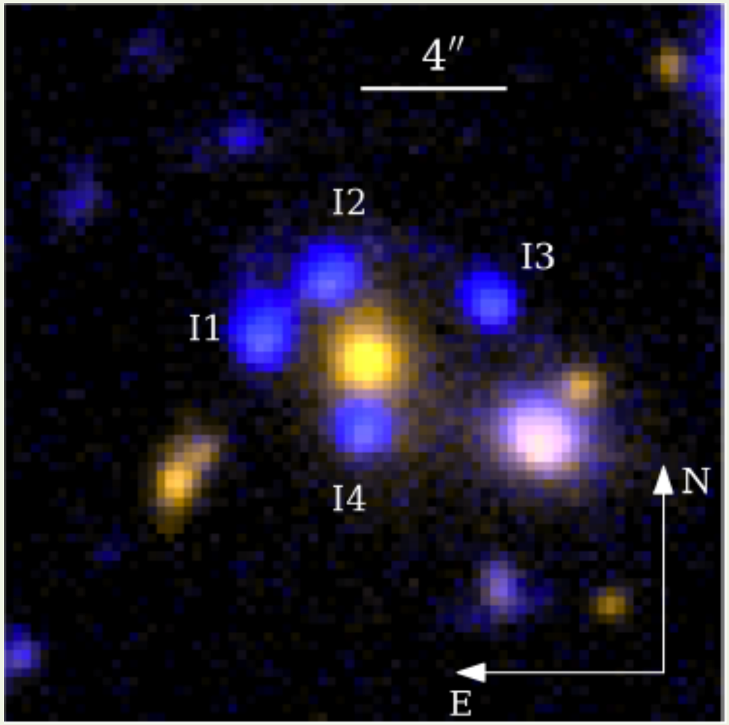
Cassowary 20 : a high-z Einstein cross

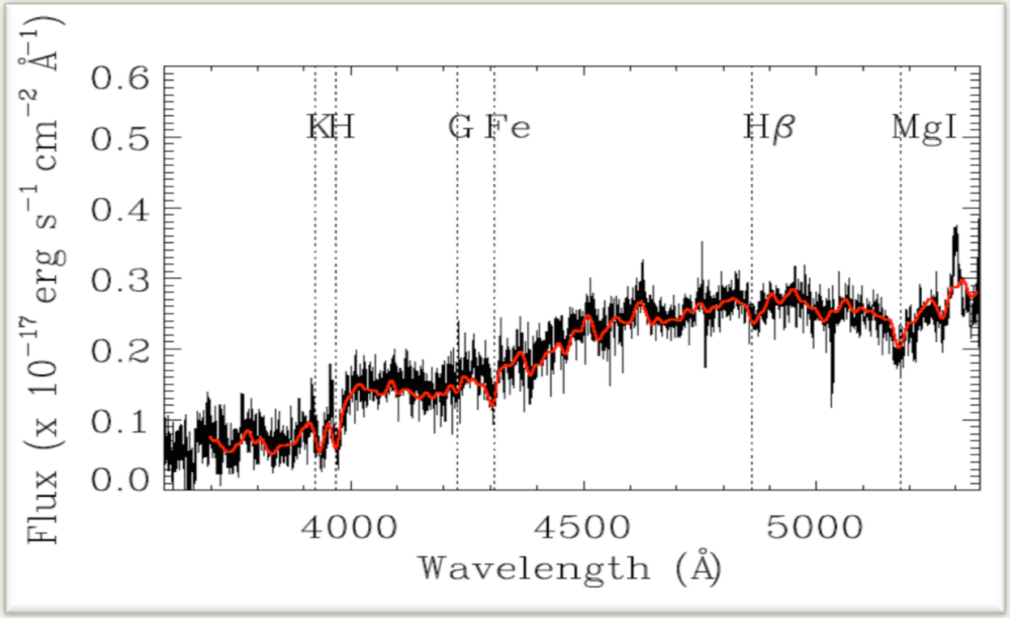
Source: 2L* galaxy at z=1.43

- total magnification factor 11.5
- SFR = 5 M/yr (Ha) 10 M/yr (UV)

Oxygen abundance (diagnostics vary):

- Direct OIII] 1666 : 12+log(O/H) = 7.84 ± 0.17
- R23 : 12+log(O/H) = 7.96 ± 0.11
- N2 : 12+log(O/H) = 7.91 ± 0.09





Lens galaxy

- Massive lens galaxy at z=0.7
- velocity dispersion ~500 km/s

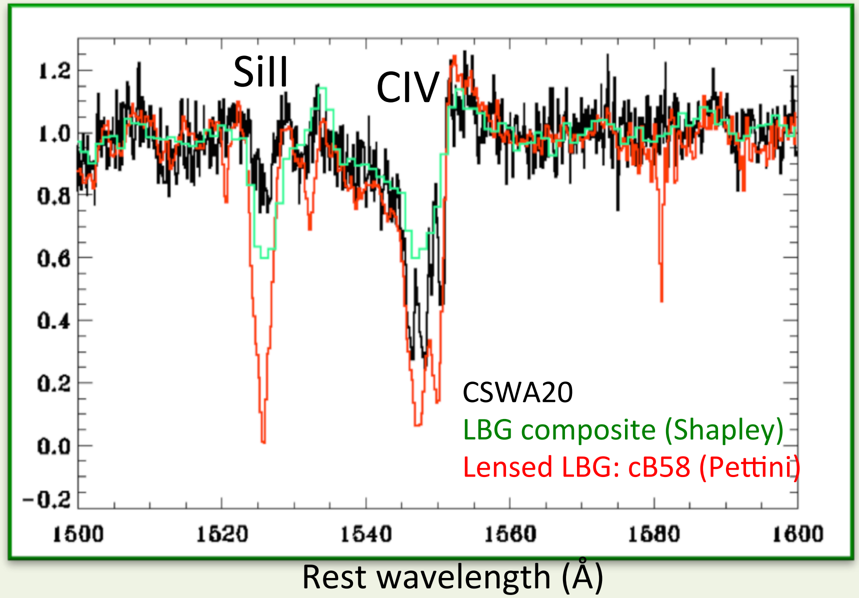
Pettini et al. 2010, James et al. 2013

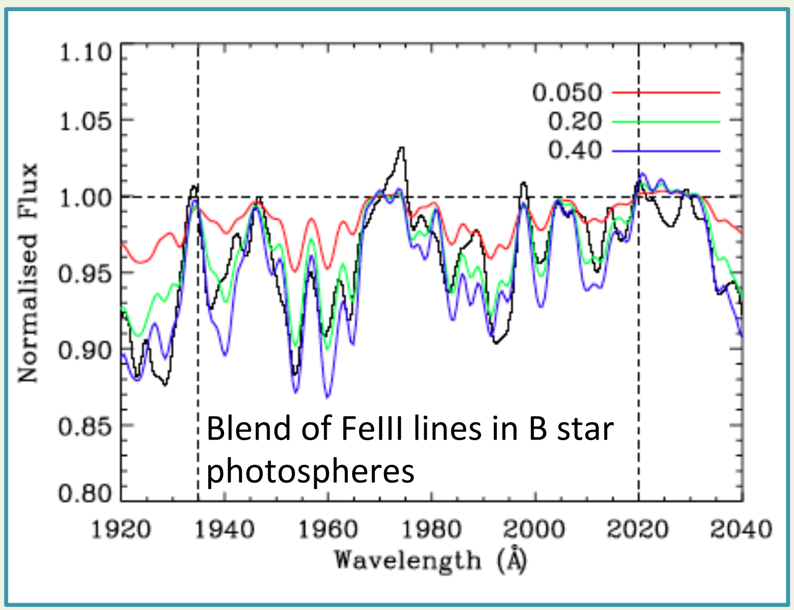
CSWA 20 – Stellar diagnostics

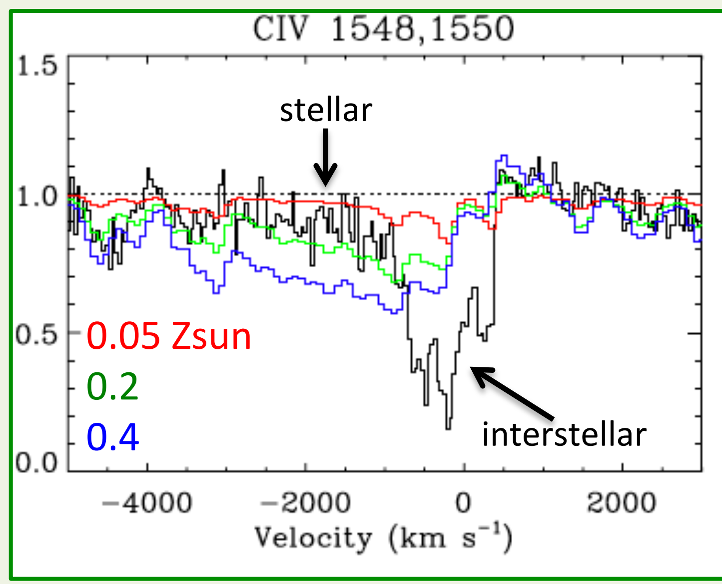
Stellar metallicities:

– CIV P-cygni profile from winds of O stars: ~0.1Z

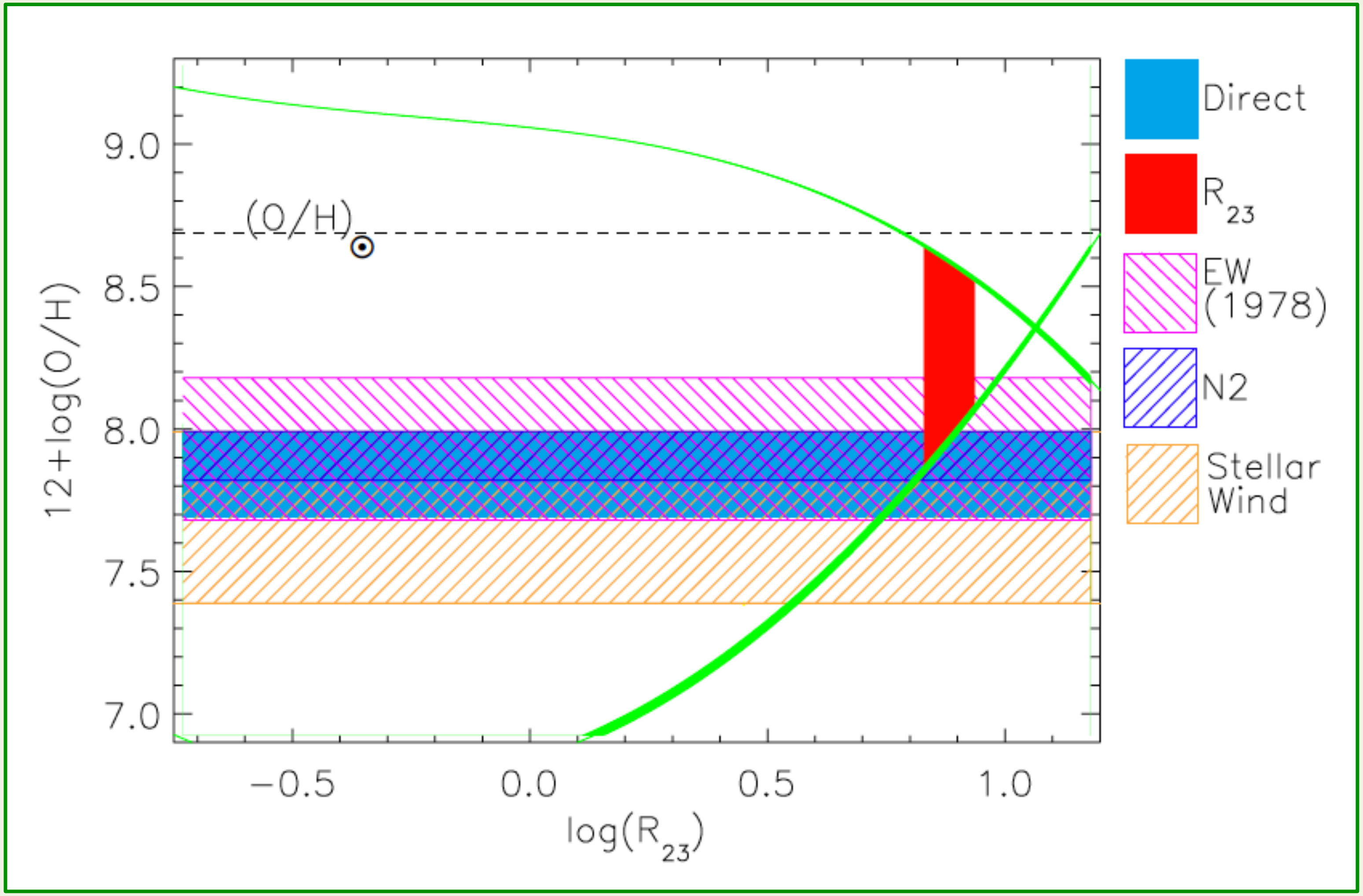
– Fe III 1978 index: ~0.1Z





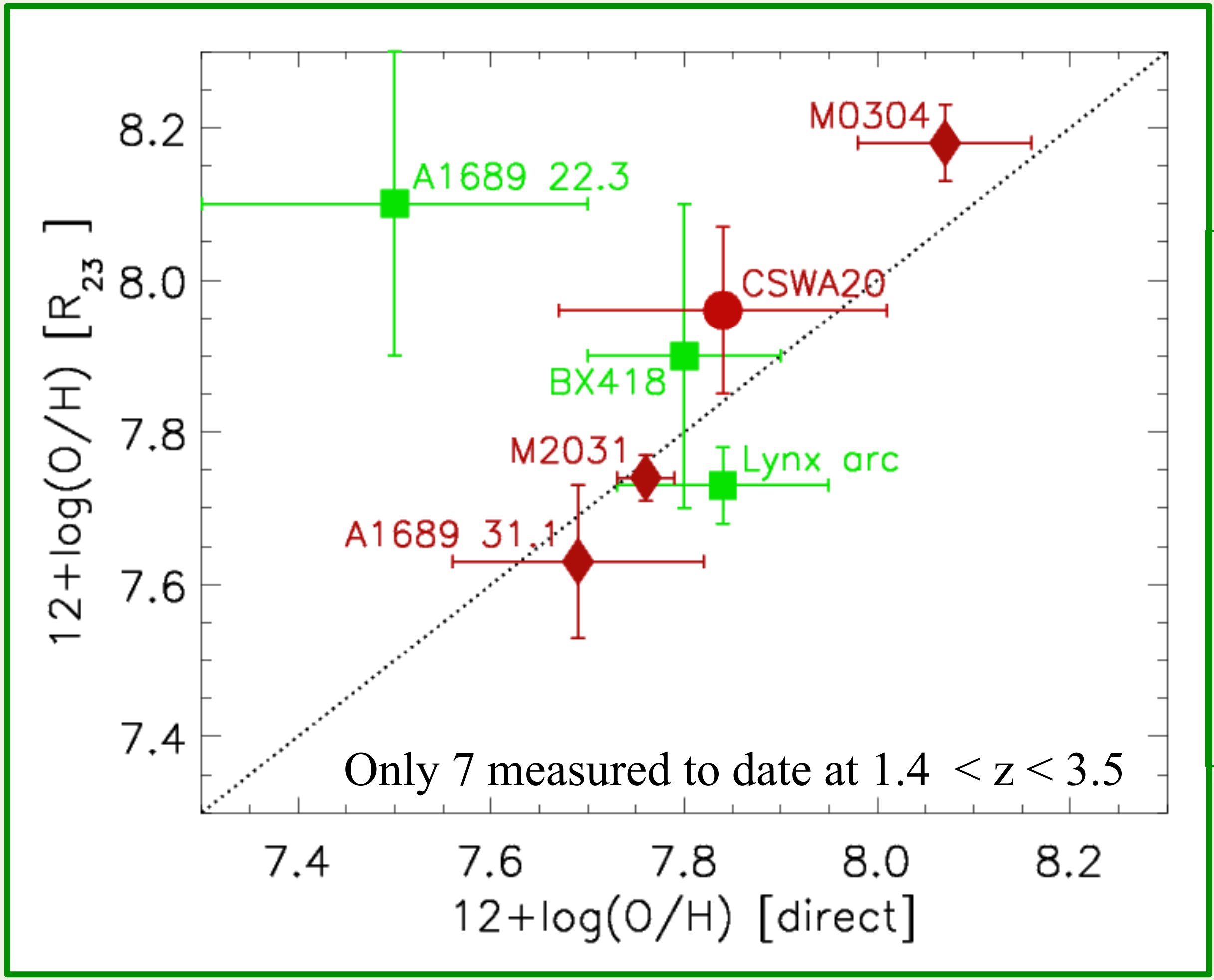


CSWA 20 – FIVE DIAGNOSTICS



James, Pettini, Christensen, 2013, MNRAS submitted

Direct vs. strong line diagnostics

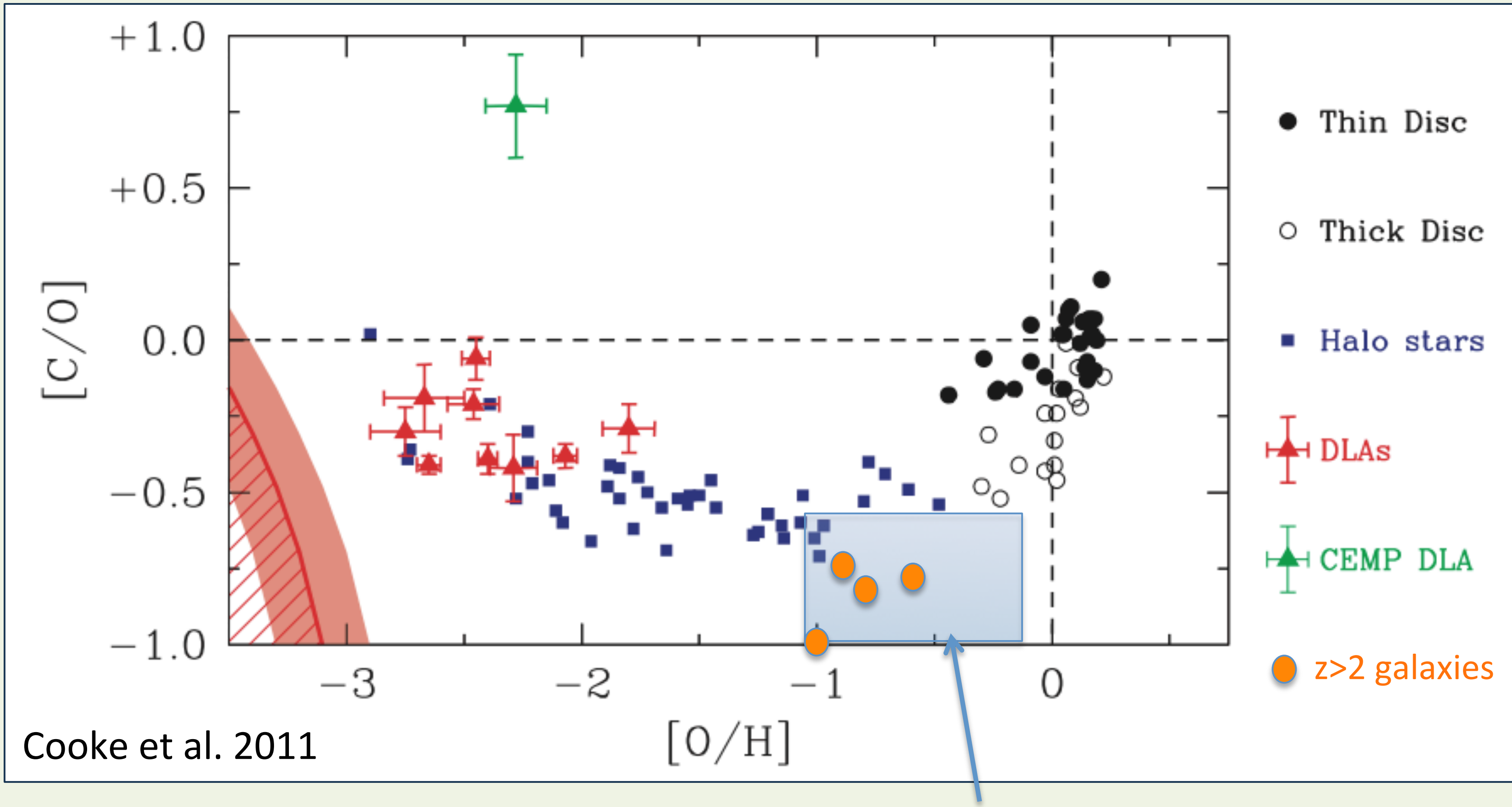


4 X-shooter galaxies:
-Christensen et al. 2012
-James et al. 2013

R23 calibrations correcting for the ionisation parameter

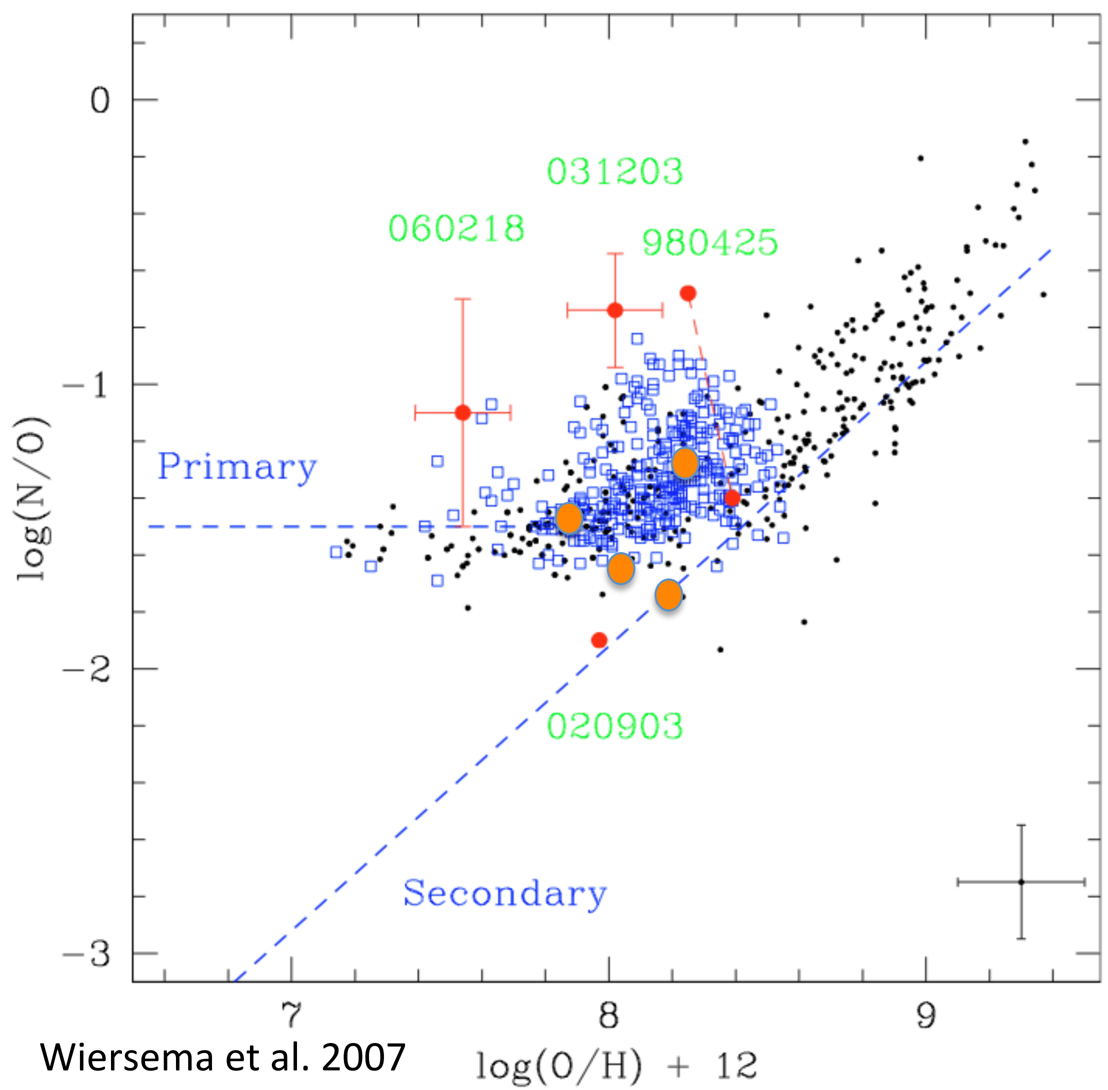
- Erb et al. 2010
- Yuan et al. 2009
- Villar-Martin et al. 2004

C/O Abundance ratio



Local dwarf irregulars (Garnett+95)

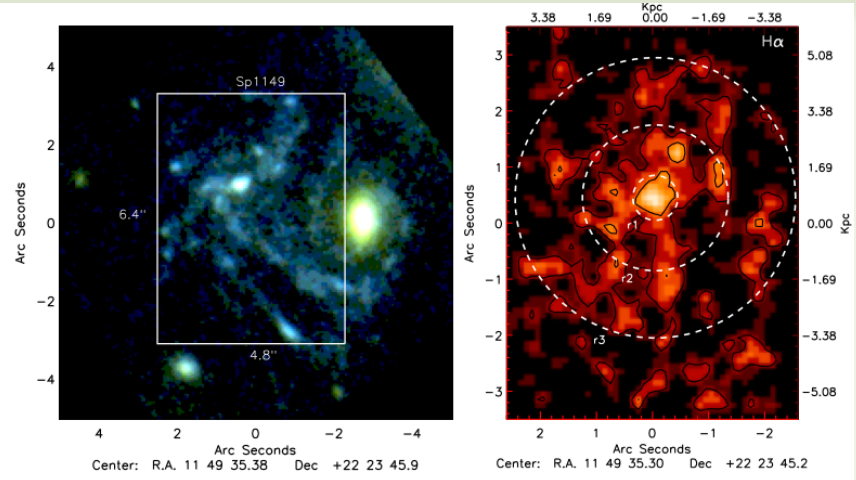
N/O Abundance ratio



Wiersema et al. 2007

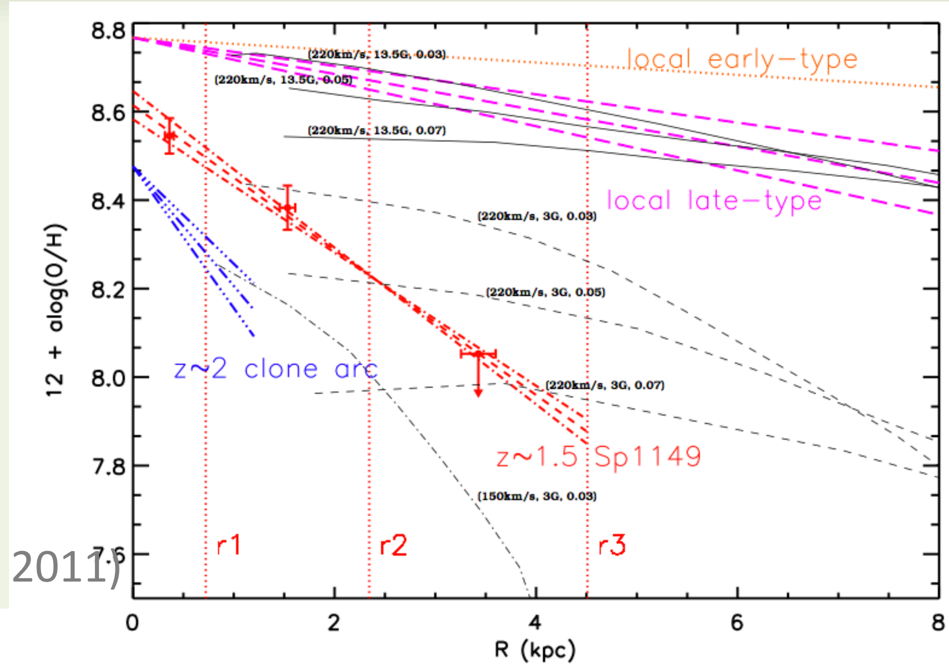
z>2 galaxies

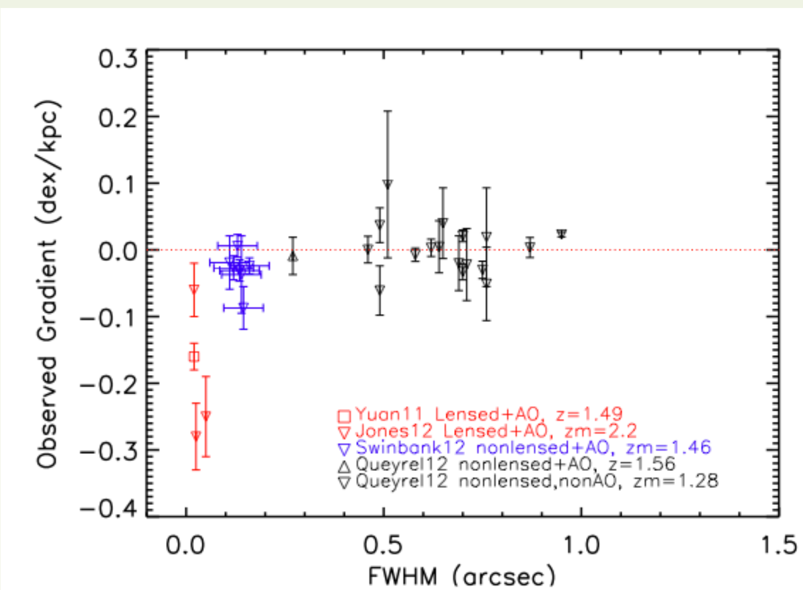
METALLICITY GRADIENTS



Keck/OSIRIS AO data of a z~1.5 galaxy.

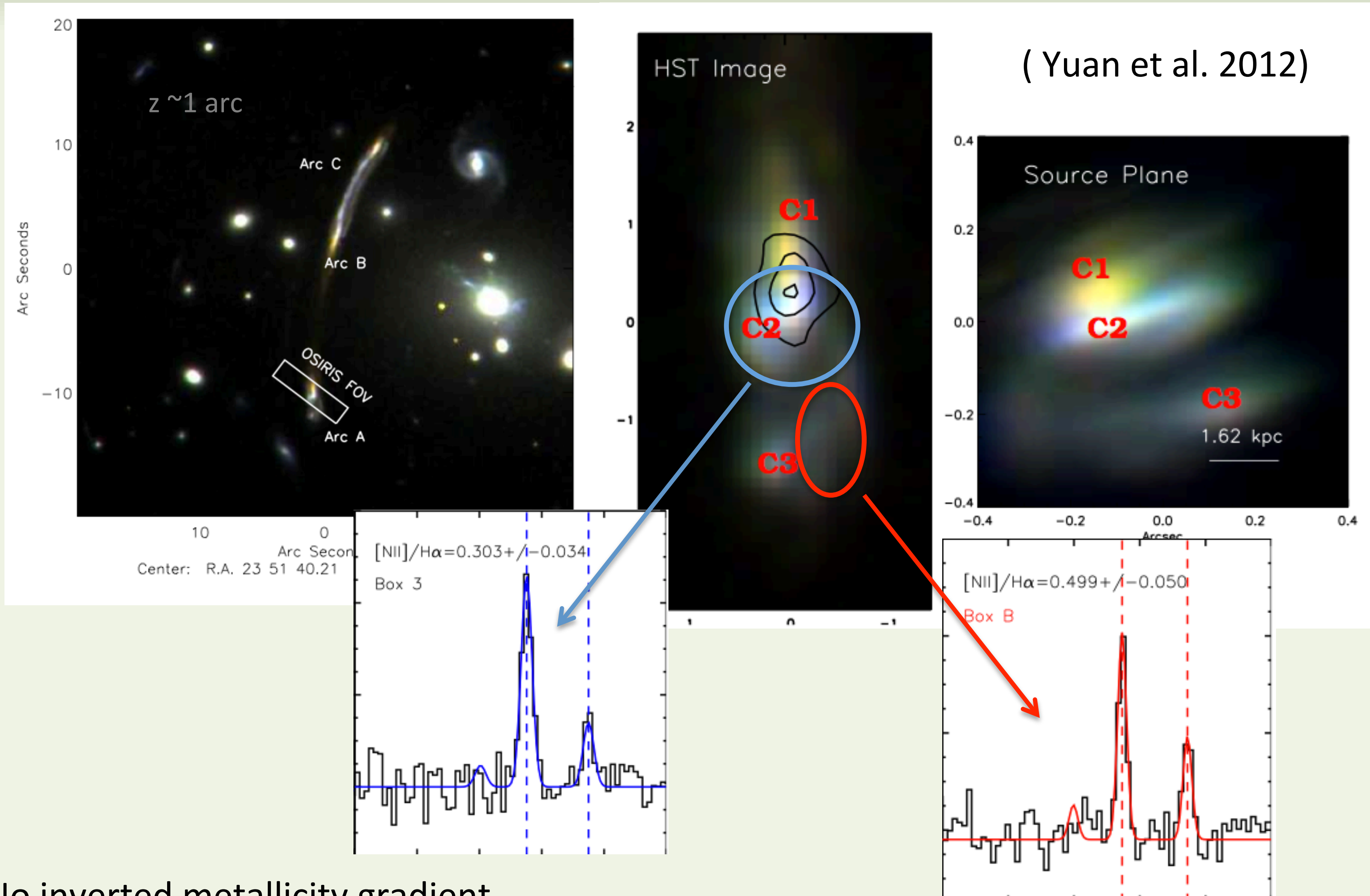
12+log(O/H) from N2 = f([NII])/f(Hα) (Yuan et al 2011)





Gradients are underestimated
if we do not have pc scale
spatial resolution (Yuan et al. 2013)

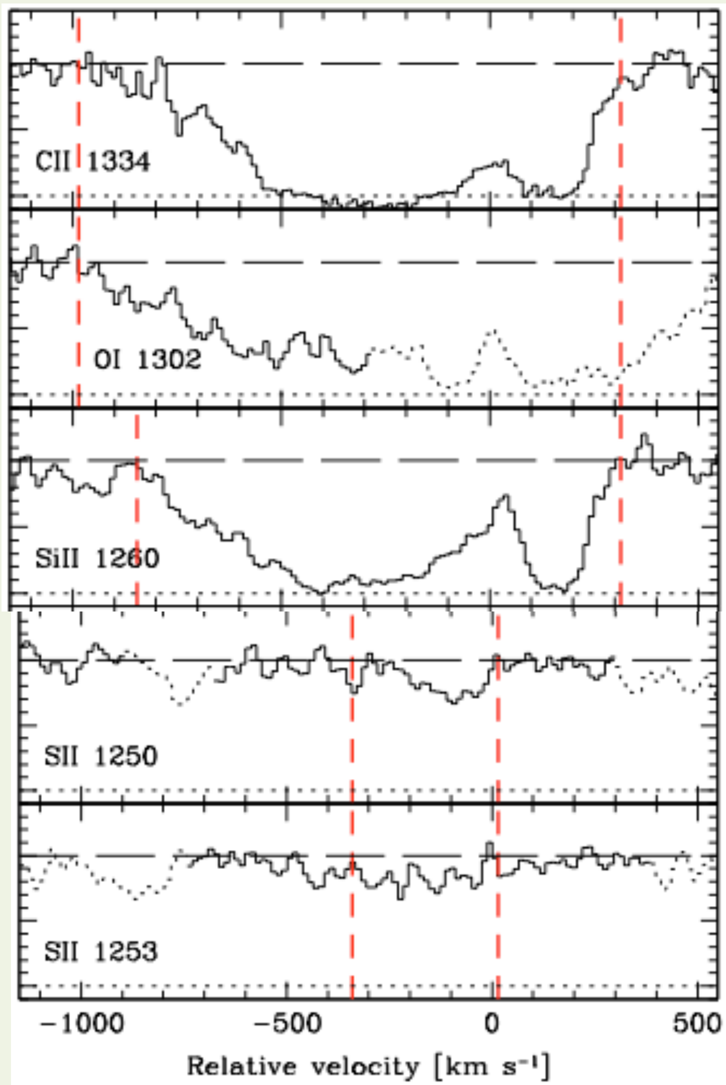
Metallicity gradients



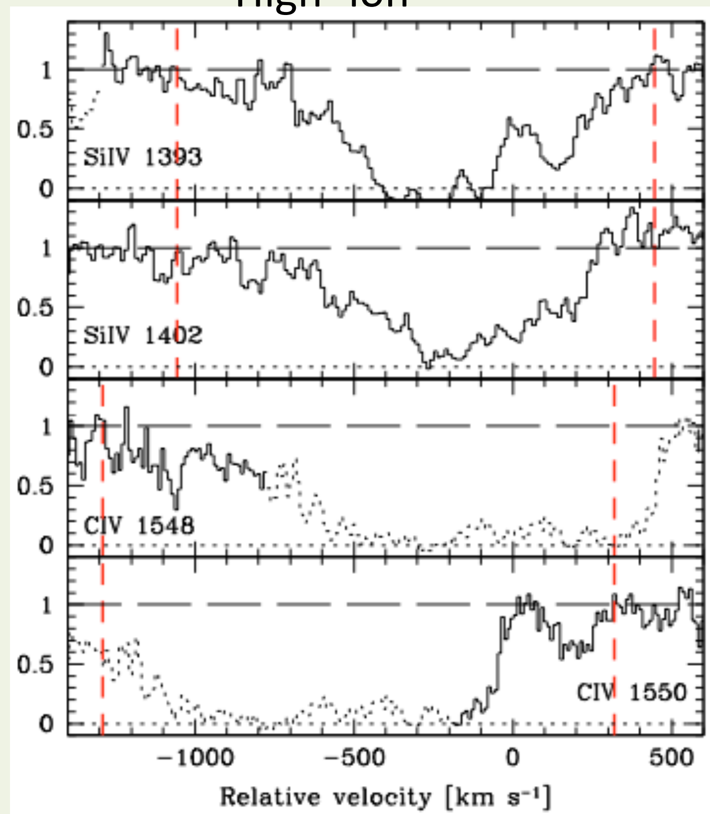
No inverted metallicity gradient,
but rather a shock excitation by outflows.

Absorption metallicities + outflows

Low-ion



High -ion



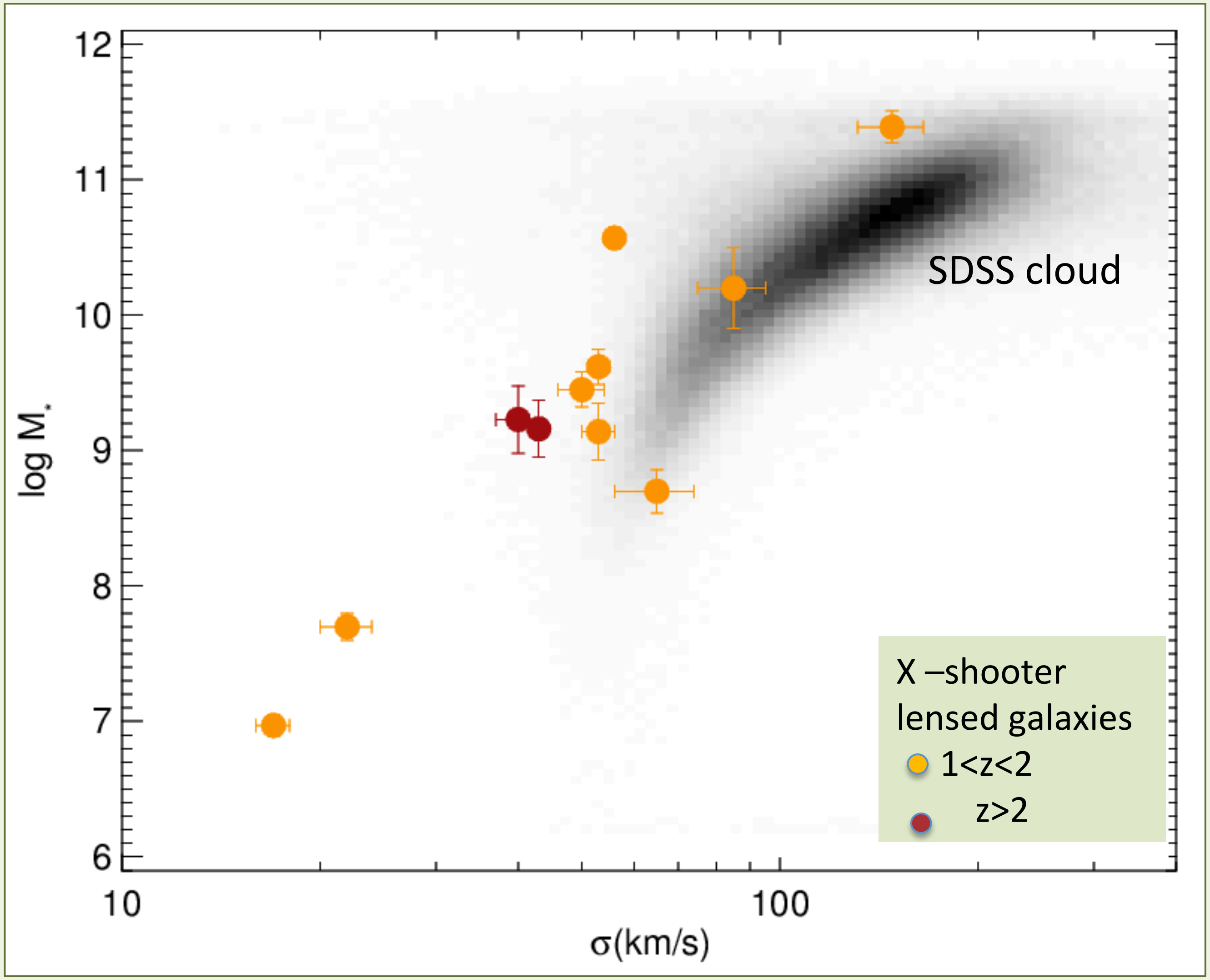
o’clock arc:

- Stellar metallicity : Z = 0.8 * solar
- O Abundance = 0.4-0.9 solar

Dessauges-Zavadsky et al. 2010, 2011

Stellar mass Tully-Fischer relation

M* from SED fits



Velocity dispersion from emission line widths

Stellar mass Tully-Fischer relation

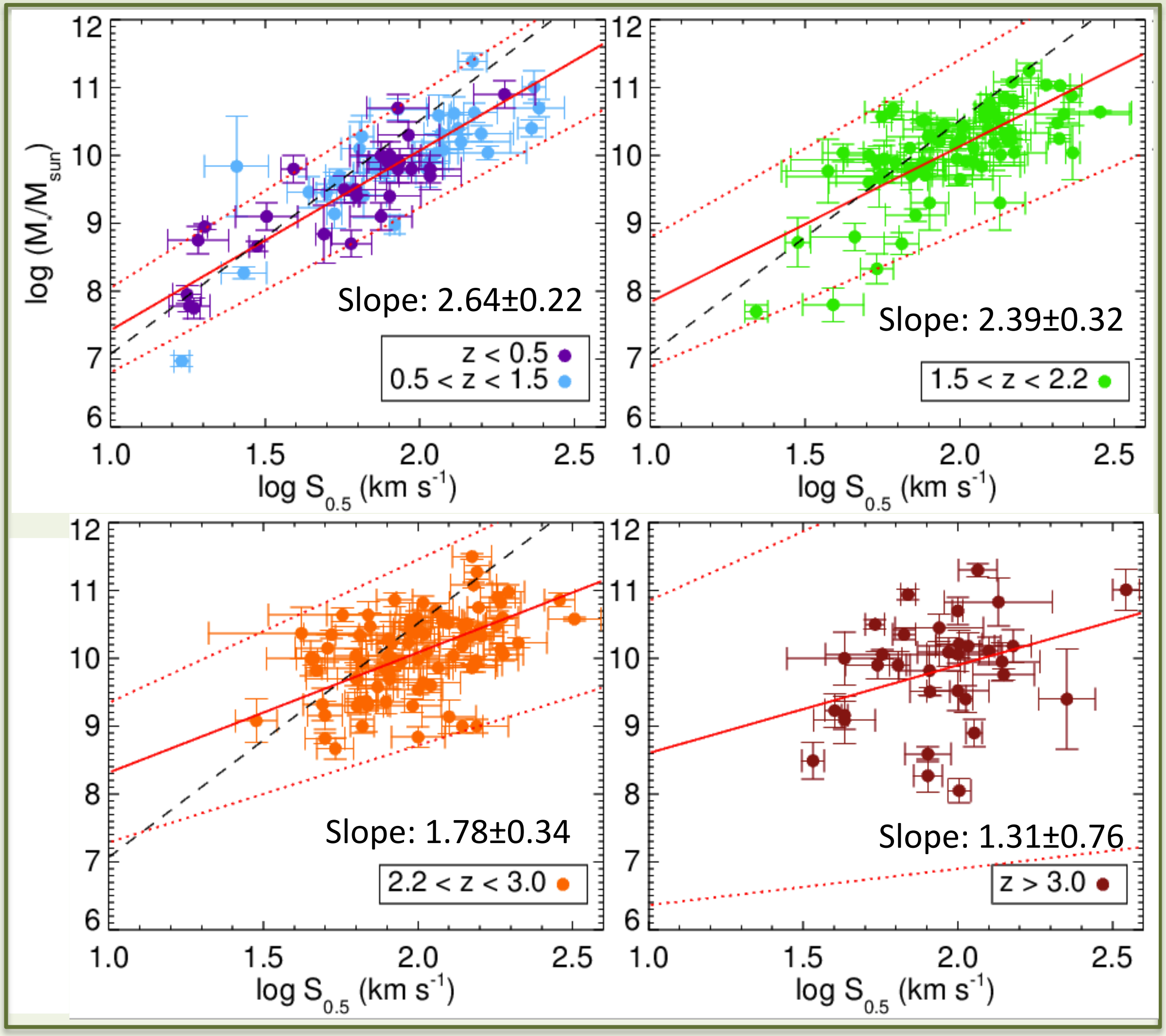
Galaxy samples (0<z<5):

- 160 lum. selected (limited range in M*)

- 45 lensed
- 20 GRB hosts
- 3 SN hosts
- 3 DLA hosts
- 7 Lya emitters

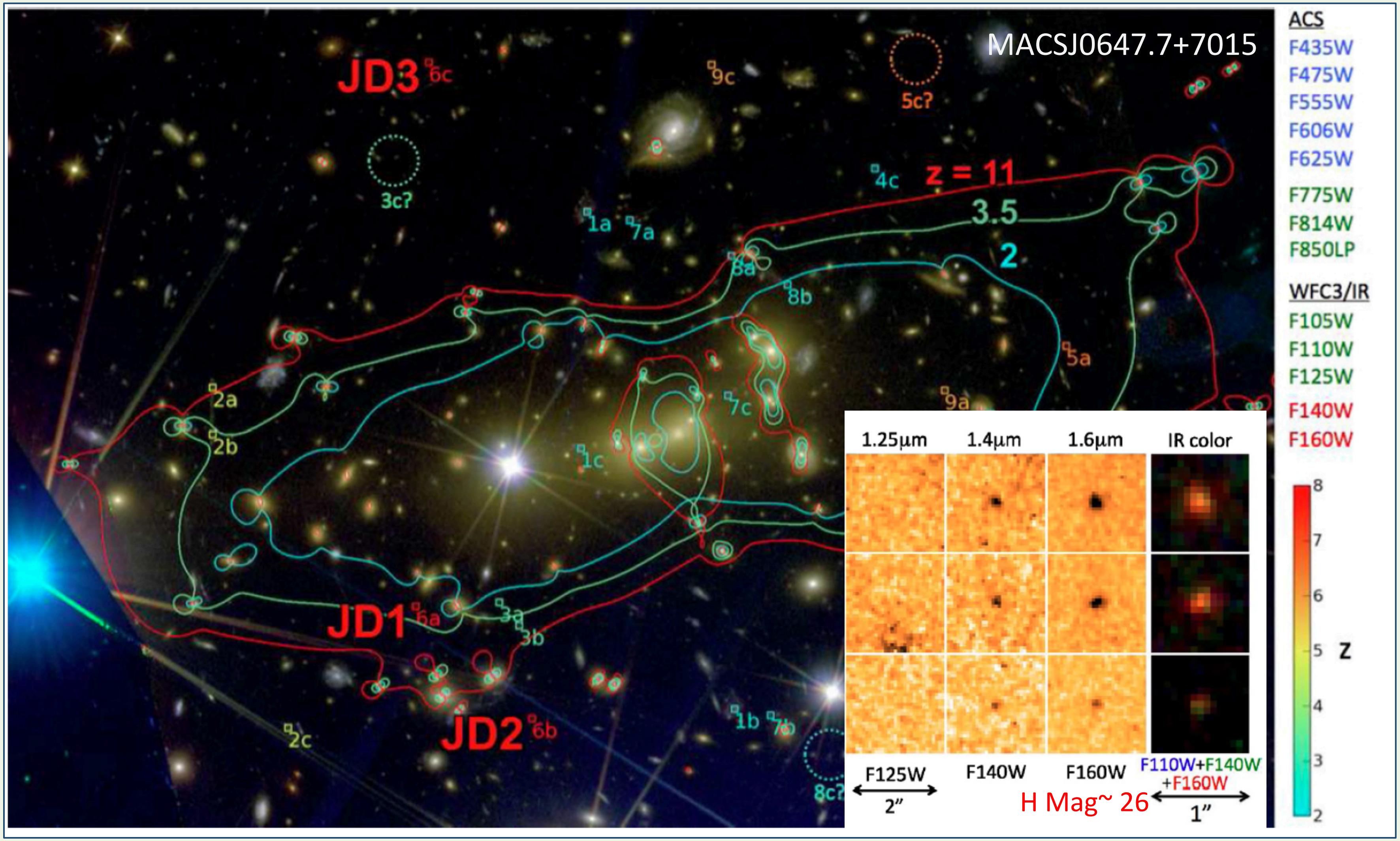
Dashed line: z~1 galaxies (Kassin et al. 2007)

Linear fit with MCMC code, linmax_err (Kelly 2007)



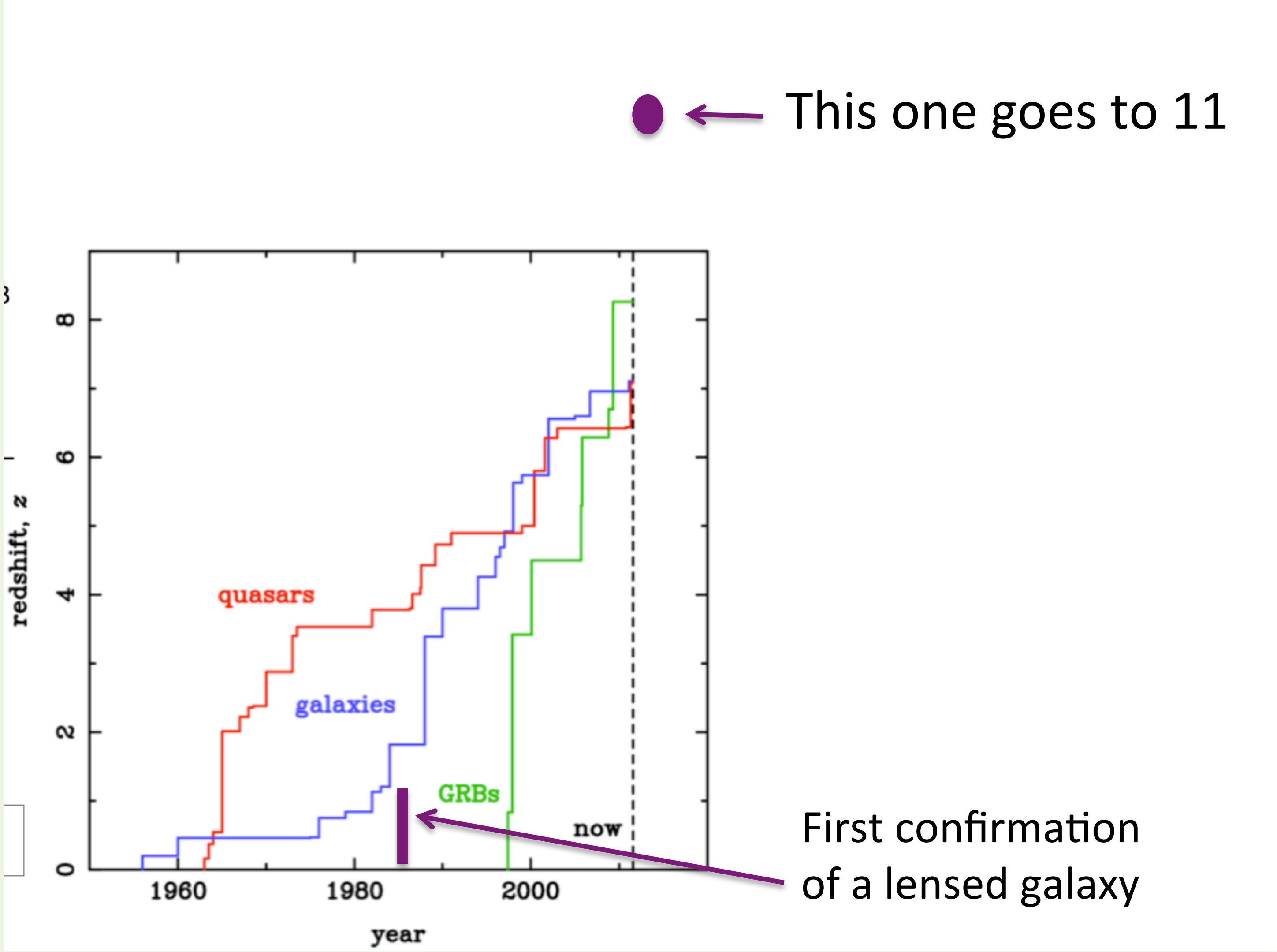
(work in progress)

The most distant Continuum (broad band) detection at z_{phot} = 10.7



Coe et al. 2013

The most distant galaxy detected?



Summary

- Extend scaling relations to low-stellar masses: Lensed galaxies follow the FMZ relation, stellar mass TF relation
- Strong line diagnostics (R_{23}) valid at $z > 2$. Correct for the ionisation parameter
- Be aware of interpreting abundance gradients and cases of shock ionisations
- Abundance ratios probe rapid enrichment from massive stars
- Locate the most distant galaxies at $z > 10$.