Chemical Abundances at High z from Observations of Lensed Galaxies

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Summary

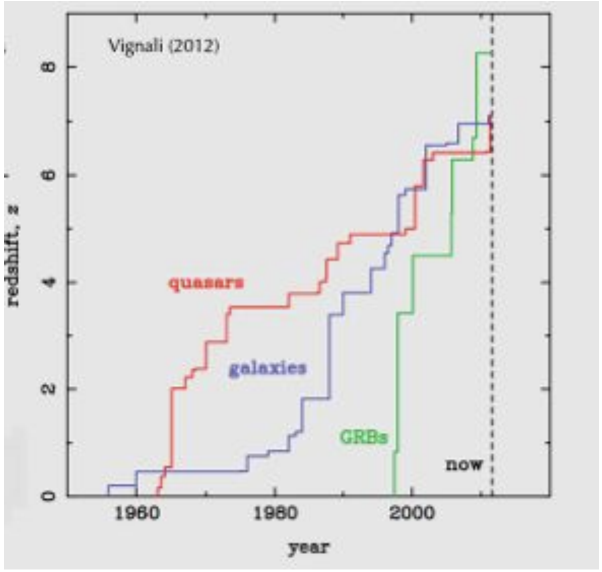
- *First observational evidence of gravitationally lensed galaxies (1986)*
- *Strong gravitational lensing as a unique tool to investigate key issues of astrophysics*
- *Lensed galaxies surveys*
- *Chemical abundances at high z from the study of lensed galaxies*

The discovery of the first gravitational arc: background

4m-class telescopes outside the USA started full operation in the late 70s (4m KittPeak 1974, AAT 1975, ESO 3.6 and CHFT 1978,); with CCD detector in the mid 80s.

In the pre ESO NTT era(<1989) poor image quality at a telescope considered almost as an act of God…. `difficult to detect faint, sharp features

In the mid 80s very few normal galaxies identified above z=1. Not many lensed/ lensing galaxies were expected



In view of the fact that the redshift of the Abell 370 arc is nearly twice that of the cluster, it is tempting to state with certainty the conclusion that this arc (as well as the one in Cl 2244) is a gravitational image of a background object, with the mass responsible for the imaging to be found within the cluster. However, we are continually reminded by colleagues that not all astronomers place unrestrained faith in the cosmological interpretation of redshift for extragalactic objects. Therefore,

Lynds & Petrosian, 1988 Ap.J.

Strong lensing of galaxies: the first observations

- *Toulouse group (**B.Fort,G. Soucail, Y.Mellier,etc**) observes a giant arc in cluster A370 in a program on clusters at CHFT (1985)*
- ***Soucail et al** A&A Letters,January87 (submitted on April 86) publish a photo of "a giant ring-like structure" at the centre of the A370 cluster*
- ***Lynds & Petrosian** in a communication at the AAS meeting in Pasadena in January 87 report the discovery of giant luminous arcs in the clusters A370 and 2242-02*
- ***Paczynski** (Nature, February 87), reports on Lynds & Petrosian as heard from TV news and people at the meeting. Shows pictures from KPNO 4m. Lists various interpretation as discussed at Princeton, favors gravitational lensing.*
- ***Soucail et al** 1987 (The Messenger and A & A) with the redshift of the arc from EFOSC+multislitspectra at the ESO 3.6m claim the discovery of "the first gravitational Einstein ring"*
- ***Lynds & Petrosian** 1988 photometry and spectroscopy, correct interpretation*

N.B. First multiple images of a QSO by Walsh et al. 1979 , correctly interpreted as a gravitational effect

The discovery of the first arc in A 370 (1986)

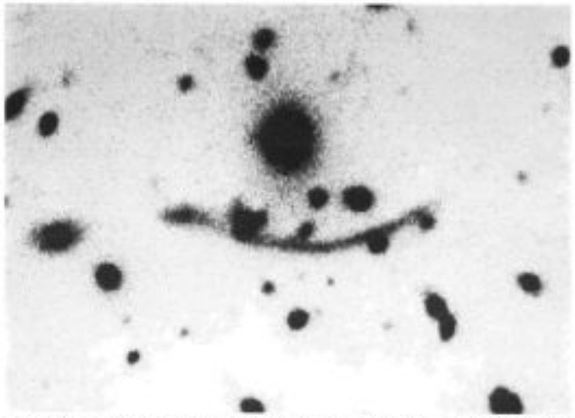
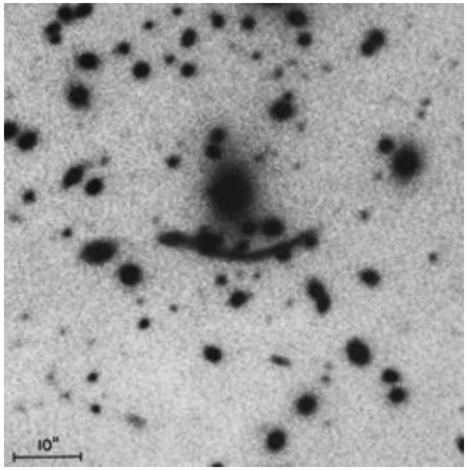
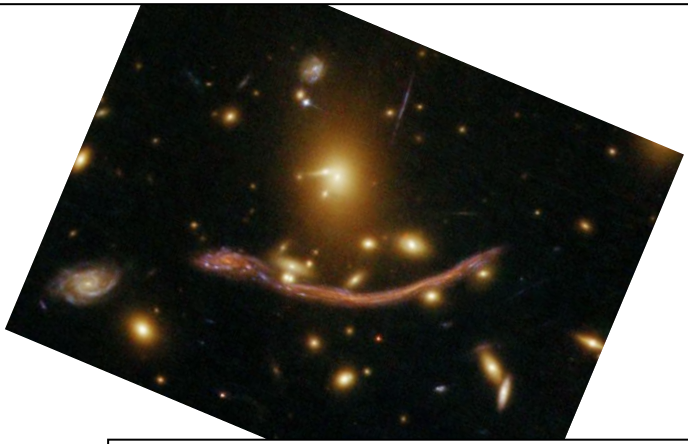


Figure 2: *The giant luminous arc in Abell 370. CFHT, 0.″2/pixel, 10 min., seeing 0.″7, November 25, 1986.*



3.6m CHFT, Soucail et al. AA 1987

4m Kitt Peak 1986 (RCA CCD)
Lynds & Petrosian



HST, ACS+WFC3 (2012) CLASH survey
(courtesy of P. Rosati)

Interpretations of the arc in A 370

*As discussed by **Lynds and Petrosian (1988)**:*

1. Disruption of a normal galaxy in the gravitational field of the massive cD or from an encounter of 2 galaxies (→ arcs in NGC 4038-39)
2. Light eco of a distant QSO outburst in intergalactic material
3. Non thermal optical jet (M87,3C273). *No strong radio source!*
4. Gravitational mark by an orbiting object
5. Cluster-centered explosion generating shock waves-induced star formation

6. Gravitational imaging of a background object by the cluster (as predicted by Zwicky 1937)

Explanations 1-5 not consistent with higher redshift (if cosmological) but ruled out by other properties of the arc as well.

Interpretation 6 consistent with morphology and redshift , with doubts from lack of fully developed model of the gravitational effect

Strong gravitational lensing as a unique tool for astrophysics (1)

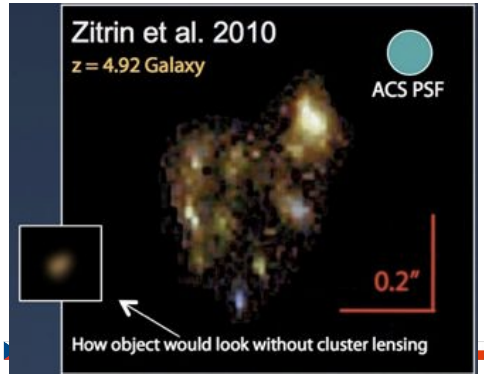
- *gravitational amplification provides the best view of intrinsically faint, highest redshift galaxies which would not be reachable with today's telescopes. Many spectroscopically confirmed beyond z=5*

Predicted by Zwicky (1937). Nottale & Hammer (1984)

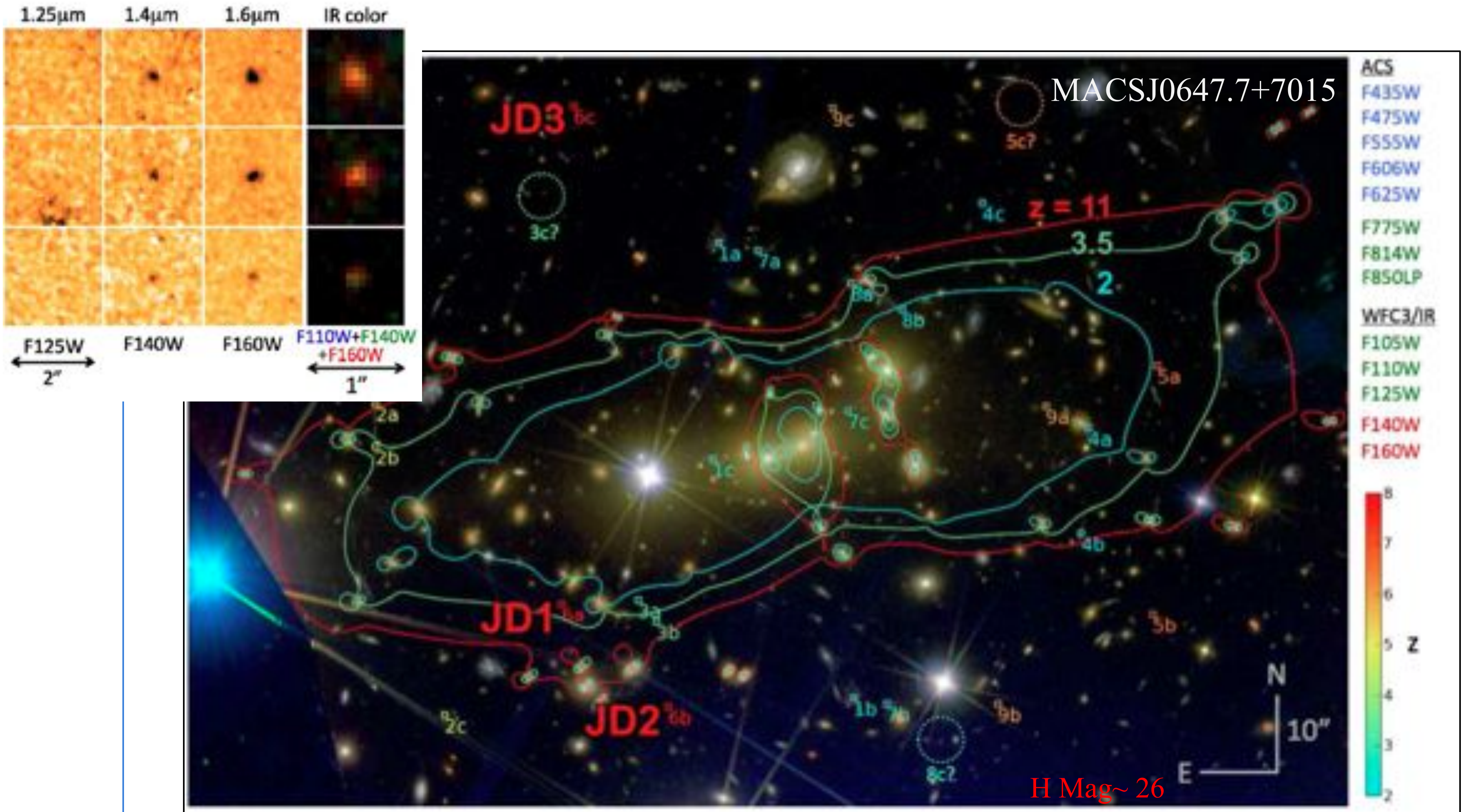
> (iii) One possible useful consequence of our calculations is that they suggest observational programs, e.g. for the detection of very distant objects like high redshift QSO or primeval galaxies.

- *for the brightest members of the population of high redshift, lensed galaxies it is possible with the amplification to obtain medium-high resolution spectra→ to perform detailed studies of gas abundances, stellar populations and IGM.*

- *When sufficient data on the multiple lensed images and the lensing galaxy are available, the morphology of the lensed galaxy can be reconstructed. Even gradients can be measured*



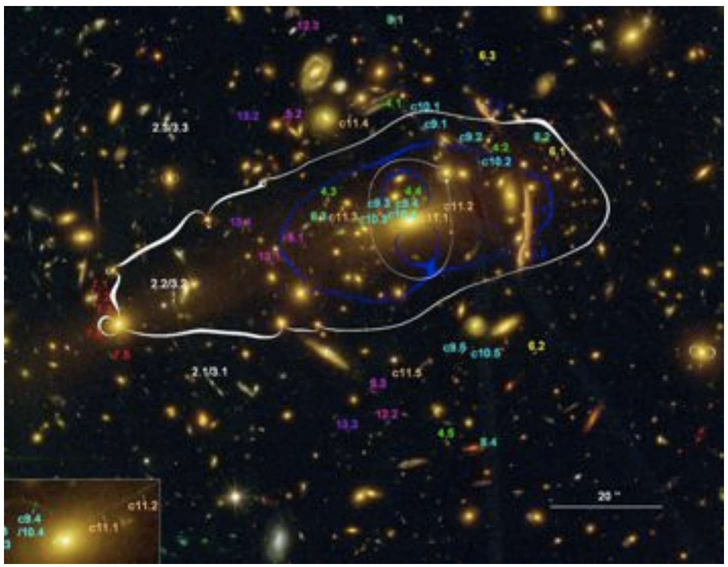
The most distant Continuum (broad band) detection at z_{phot} = 10.7



Coe et al. 2013

Strong gravitational lensing as a unique tool for astrophysics (2)

- *to understand the distribution of dark and luminous matter in massive galaxies and clusters for $5<R<3000$ kpc (see review by Hoekstra et al 2013)*



Zitrin et al. 2012

Constraining the mass distribution in MACS J1206.2−0847 (at z=0.44) from photometry and spectra of >50 images of lensed galaxies

to check consistency of arc statistics with ΛCDM paradigm and its prediction on matter aggregation mechanisms (number and mass of clusters at high z)

Surveys of lensed galaxies (1): cluster-galaxy

- CLASH: Cluster Lensing And Supernovae with Hubble- Postman et al.2012

Deep imaging with the ACS and WFC3 (16 bands) direction of 25 massive galaxy cluster + ground-based imagery and spectroscopy. Many clusters from the MACS survey of ROSAT, at z= 0,2-0.9

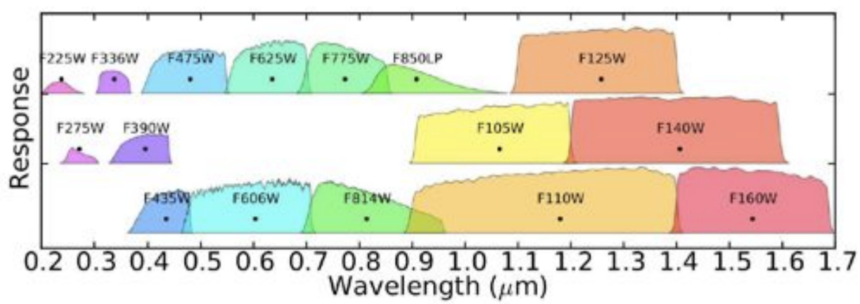


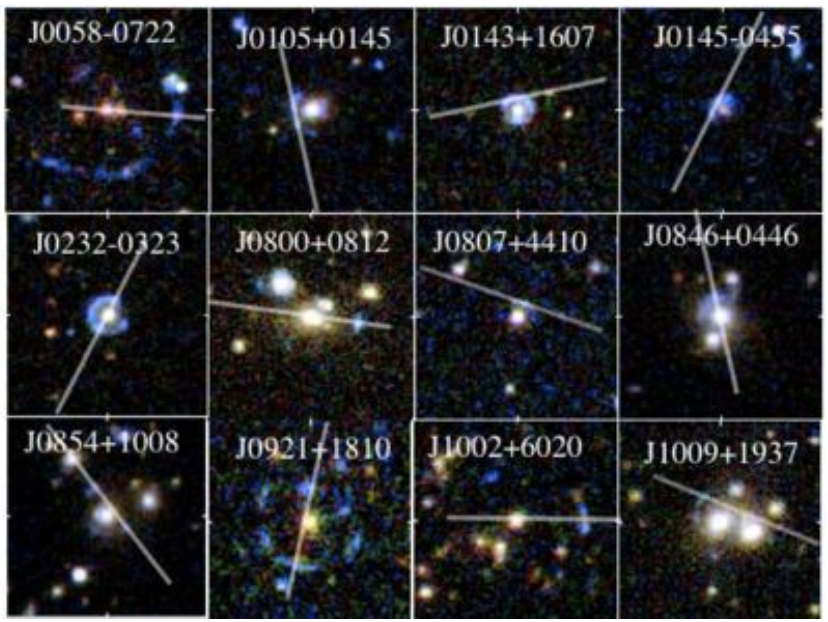
Fig. 1: The HST filter set used by CLASH, showing the transmission as a function of wavelength from UV to NIR.

Galaxy cluster MACJS1206 (z = 0.4385) imaged with *HST/ACS/WFC3*.

- SGAS (Bayliff et al.2011) search for giant arcs in the direction of clusters identified from SLOAN. 37 clusters identified, HST follow-up

Surveys of lensed galaxies (2): galaxy-galaxy
(high z SF galaxy lensed by foreground elliptical)

- CASSOWARY: Search for objects in SLOAN catalogue (early type galaxy + nearby blue objects at separations up to 10 arcsec) and confirmatory spectra at a large telescope



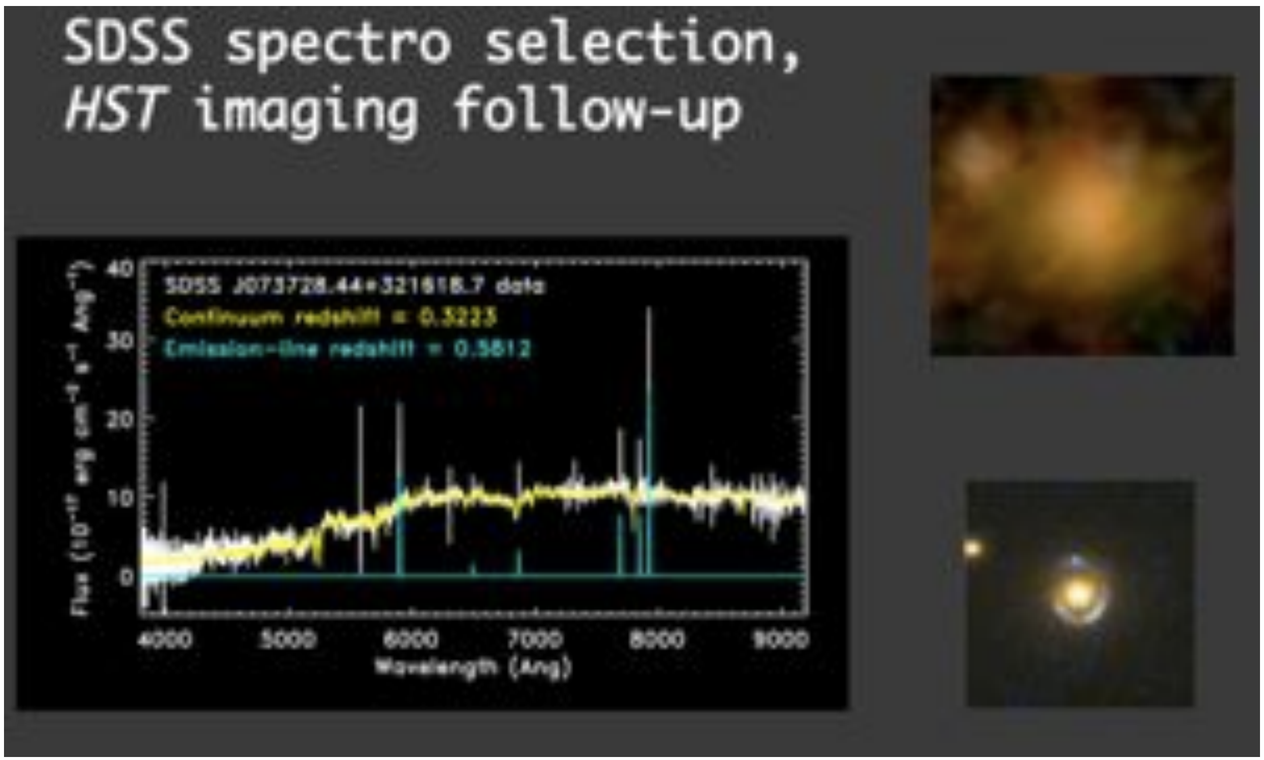
Bielukorov et al (2009)

Stark et al (2013)

SDSS imaging (40x40 arcsec)

Surveys of lensed galaxies (3): galaxy-galaxy

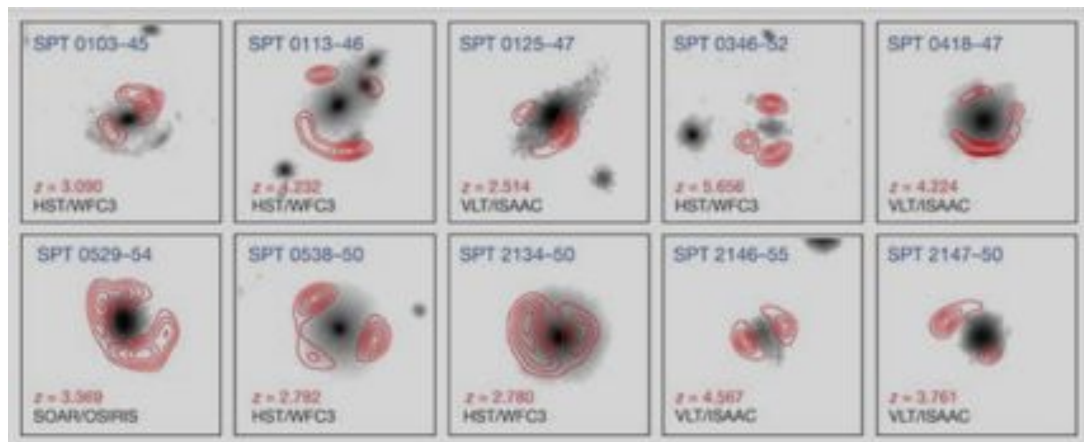
- SLACS (Bolton et al 2006) : starting from SLOAN spectroscopic database, candidates with mixed spectrum + ACS for confirmation



Surveys of lensed galaxies (4): galaxy-galaxy

- Dusty starburst lensed galaxies from mm surveys with SPT and follow up observations (imaging and spectroscopy)with ALMA .

  Vieira et al (2013), Hezaveh et al (2013)



COMING: PLANCK clusters, Herschel luminous millimeter galaxy, KIDS at ESO VST. GLASS (Grism Lens-Amplified Survey from Space) , FRONTIER FIELDS Clusters (2 mag deeper than CLASH), ROSITA satellite

How many extragalactic lensed galaxies we know?

Table 1 Secure cases of multiple-imaging gravitational lenses

Source	z_s	z_d	θ_{max}
Multiple Quasars			
Q0957+561AB	1.41	0.36	6.1"
Q0142−100AB	2.72	0.49	2.2"
Q2016+112ABC	3.27	1.01	3.8"
Q0414+053ABCD	2.63	?	3"
Q1115+080A,A,BC	1.72	?	2.3"
H1413+117ABCD	2.55	?	1.1"
Q2237+031ABCD	1.69	0.039	1.8"
Arcs			
Abell 370	0.72	0.37	
Abell 963	0.77	0.21	
Abell 1352	?	0.28	
Abell 1525	?	0.26	
Abell 1689	?	0.18	
Abell 2163	?	0.17	
Abell 2218	?	0.17	
Abell 2390	0.92	0.23	
Cl 0024+17	?	0.39	
Cl 0302+17	?	0.42	
Cl 0500−24	0.91	0.32	
Cl 1409+52	?	0.46	
Cl 2244−02	2.23	0.33	
Radio Rings			
MG1131+0456	?	?	2.2"
0218+357	?	?	0.3"
MG1549+3047	?	0.11	1.8"
MG1634+1346	1.75	0.25	2.1"
1830−211	?	?	1.0"

← Known gravitational lensed objects in the review of Blandford and Narajan (1992)

Today more than 300 lensed galaxies have been identified (of which ≈100 giant arcs behind clusters)

Many thousands expected from the already approved surveys

Galaxy types in the lensed high z galaxy sample

- **Star forming galaxies**

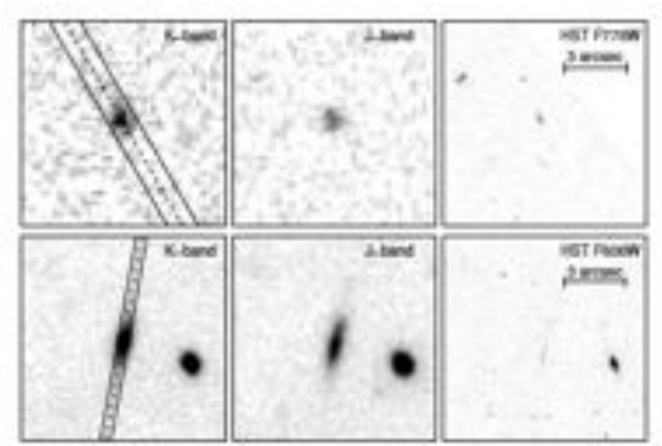
  Most of the identified lensed galaxies are gas-rich, star forming galaxies.

  Strong selection effects: (1) many surveys look for "blue" objects close to a red galaxy; (2) it is easier to get a confirmation redshift from an emission line spectrum

- **Quiescent galaxies at z≈2:**

  Just brightest could be studied so far.

  Two candidates selected in the direction of clusters. Spectra used to determine age, mass. Geier et al (2013)



Chemical evolution from lensed galaxies: seed papers (1)

Pettini et al (2000,2002)

The first to study in detail a Lyman break-> star forming galaxy at z>2.

MS 1512-cb58 (z=2.72), serendipity discovery in the direction of a cluster at z=0.37. Magnification~ 30.

Rest frame UV spectrum (from the Keck optical spectrum, R= 1500-3000)

Rest frame UV spectrum (from Keck ESI, R=5200)

RESULTS:

UV spectral properties similar to those of nearby star-forming galaxies and spectral synthesis models based on libraries of O and B stars can reproduce accurately the integrated stellar spectrum.

The P Cygni profiles of C IV and N V are best matched by continuous star formation with a Salpeter initial mass function (IMF) extending beyond $M_{\odot}$ 50

$Z \sim 1/3\, Z_{\odot}$, definitely more metal-enriched than DLA at same z

Mass loss rate up to 225 $M_{\odot}$/ year

Chemical evolution from lensed galaxies: seed papers (2)

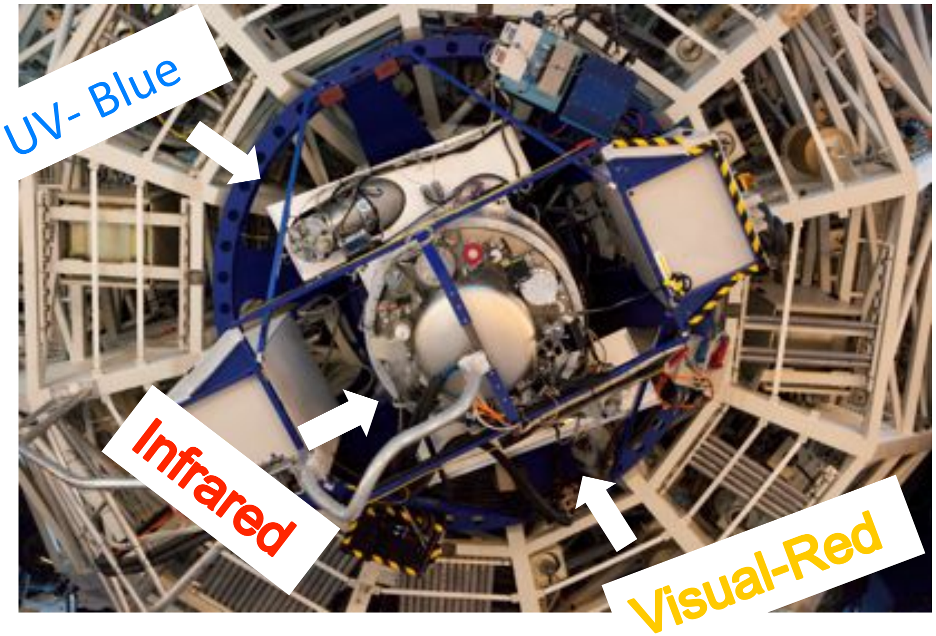
Fosbury et al (2003) : detailed spectroscopic study at Keck (optical and NIR) of the Lynx galaxy at z=3.357- a lensed galaxy discovered in a multi-wavelength study of a ROSAT cluster at z=0.570. Magnification ~10.

RESULTS:

Emission lines, rest-frame UV continuum, Pcygni profile of Lyα and CIV point to cluster of very hot O stars (M up to 140 M⊙ , pop III?)

Metallicity~ 0.05 solar, overabundance of silicon,

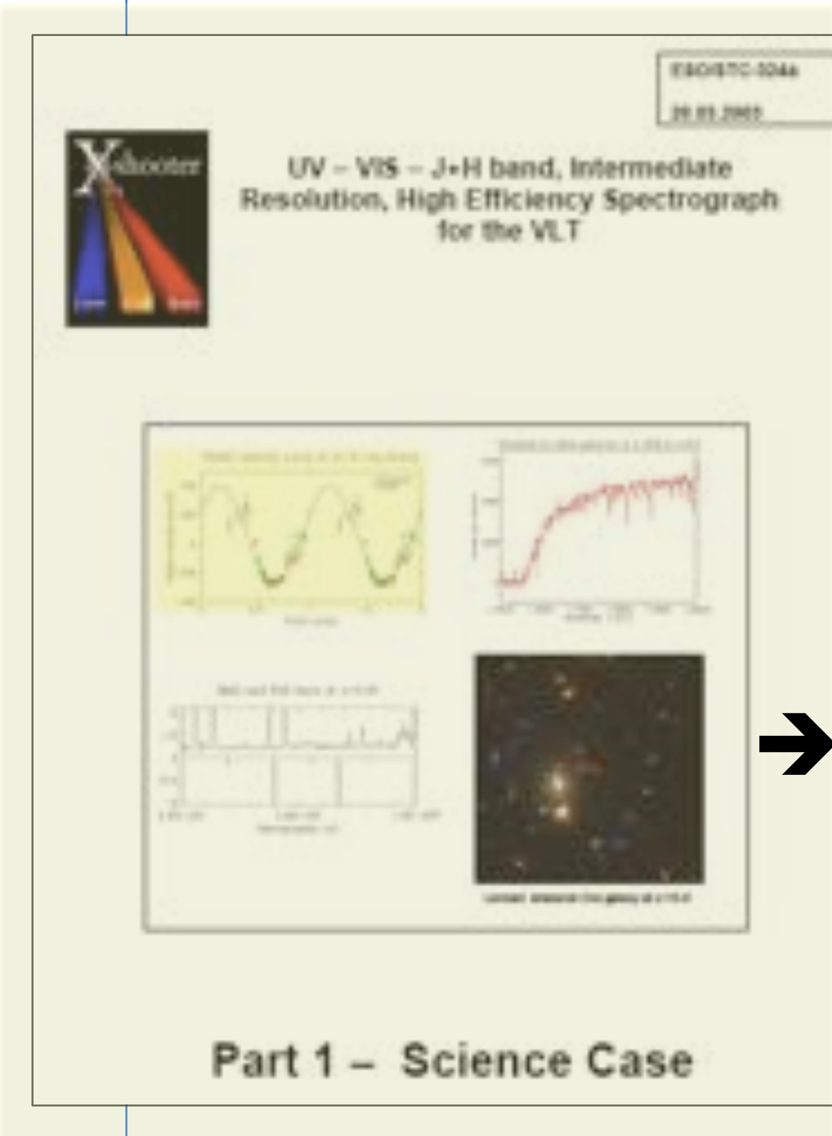
X-shooter: a new VLT instrument best suited for the study of lensed galaxies



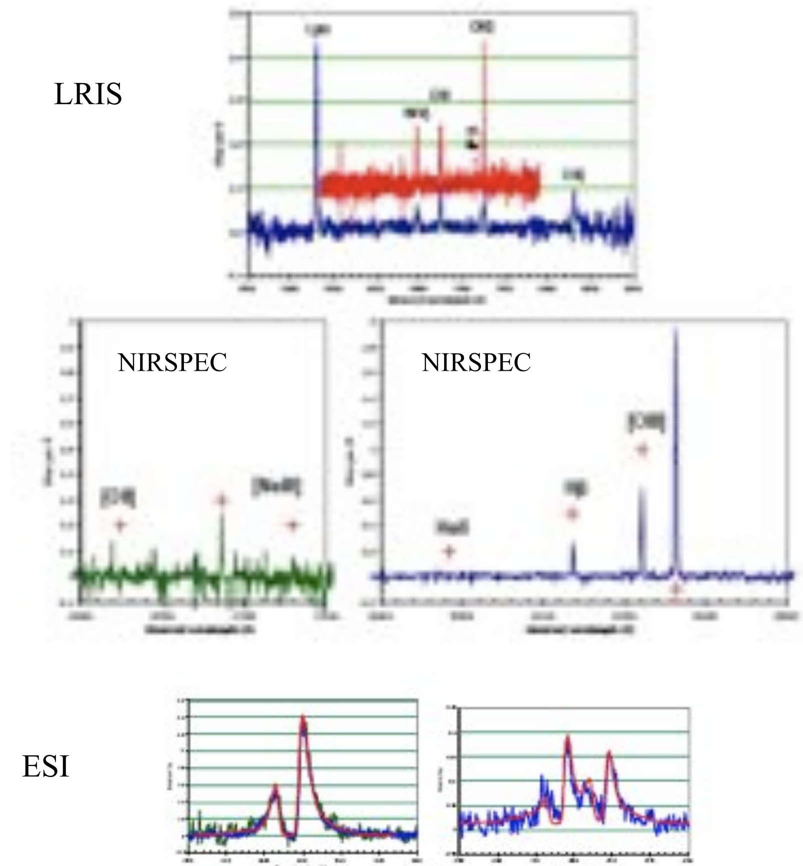
- Operating from October 2009. Built by a Consortium of ESO and institutes from Denmark, France , Italy and the Netherland

- 3 fixed format echelle spectrographs which operate in parallel and deliver an intermediate resolution spectrum of the target from 300 to 2400 nm

Lensed galaxies: key science case of the X-shooter (2003)

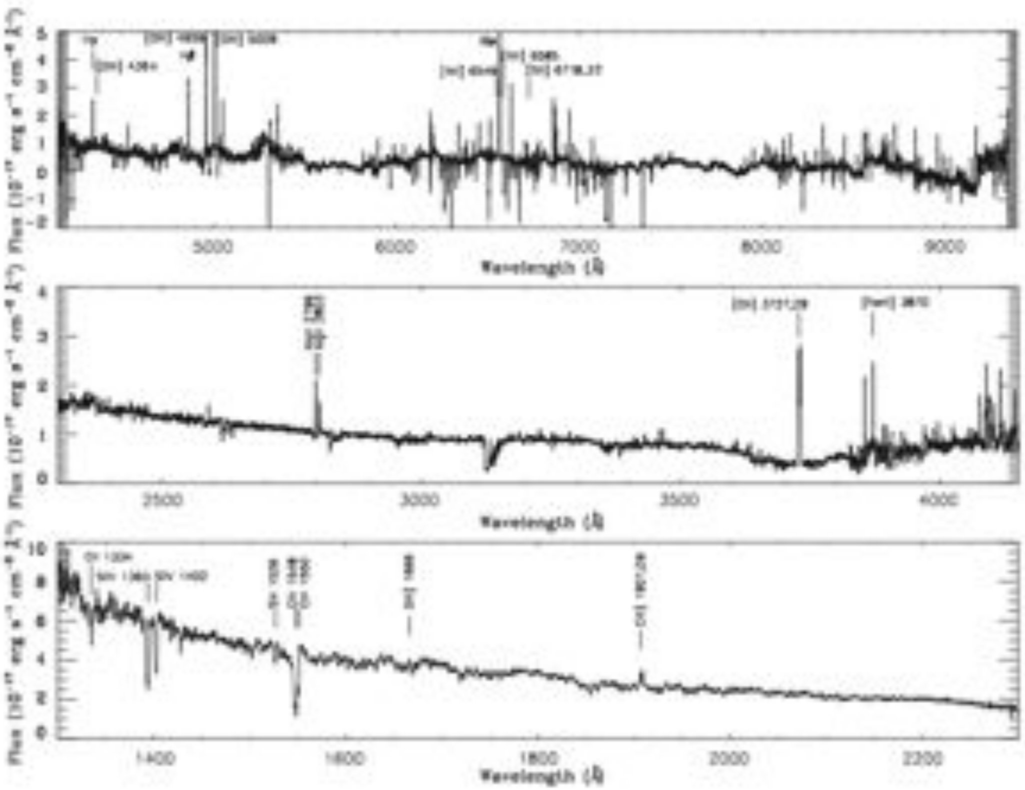


The Lynx arc (a lensed emission line galaxy at z=3.4, Fosbury et al 2003): an example of an ideal target for X-shooter observations



Lensed galaxies observed with the X-shooter at the VLT

taking advantage of the wide spectral coverage



UV to red rest frame spectrum of CSWR 20 at z=1.45

James, Pettini, Christensen et al. (2013)

Lensed galaxies with the X-shooter at the VLT ?

ESO VLT instrument refereed publications for the period 1.2011-8.2013

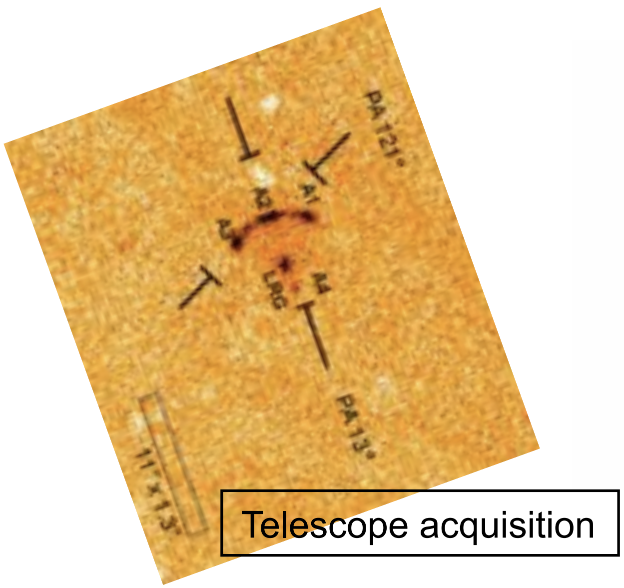
Instrument	Papers -all	Papers-Lensing
ISAAC	34	-
FORS2	69	9
UVES	126	1
NACO	60	3
FLAMES	87	-
VIMOS	67	5
SINFONI	74	-
X-SHOOTER	109	11

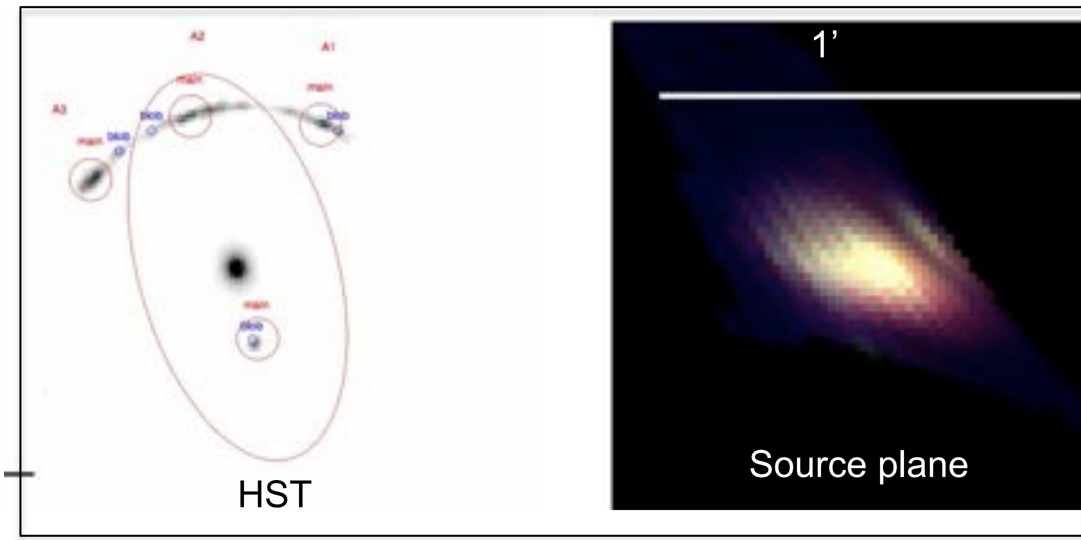
Abundances at high z from lensed galaxies (1)

Detailed study of the physical properties of the “**8 o’clock arc”, a star forming galaxy at z=2.73** (Dessauges-Zavadsky, D’Odorico et al.; 2010,2011)

X-shooter UV,optical and NIR spectra covering rest frame Lyα -Hα ,

HST imaging used for the gravitational lensing model





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MEASUREMENTS:

emission lines, stellar absorption lines and continuum, Interstellar absorptions

RESULTS:

-resolved in a main body and a large H II region

- masses (star+gas) $2x10^{10}$ $M_\odot$ and $2x10^{9}$ $M_\odot$ respectively

- gas content 70%; SFR ~ 200 $M_\odot$/ yr, age 40 Myr

- mean metallicity Z= 0.65 $Z_\odot$ (from SED, emission line ratios, IM)

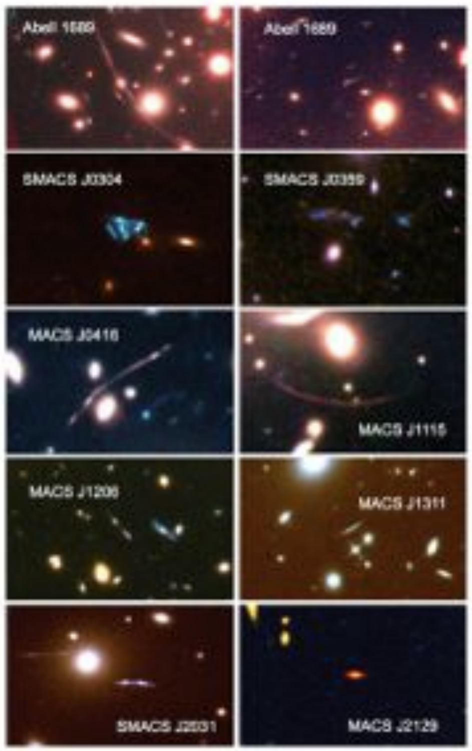
- evidence of outflow at 120 km/s from Lyα profile and Δv emission-absorption lines

CONCLUSION:

A young galaxy with an intense star formation which has already enriched in a significant way its IM

Abundances at high z from lensed galaxies (2)

Survey of 12 lensed galaxies with the X-shooter
Christensen et al. 2012. Targets selected on HST images of MACS clusters



Strong emission lines measured in 3 targets with $2 \leq z \leq 3.5$

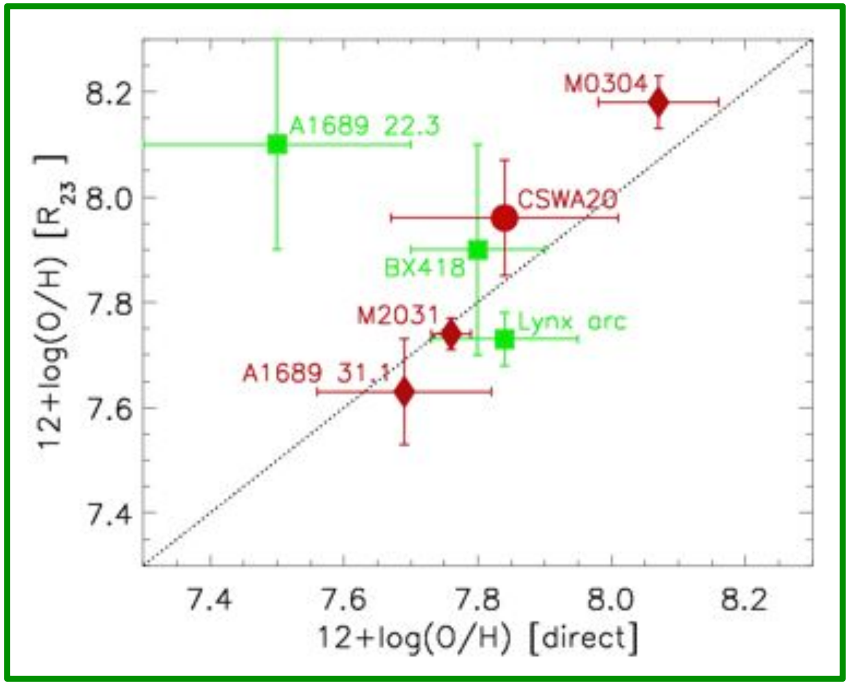
Detection of the [OIII] auroral line at 4363 Å provides a direct measure of the O abundance (~ 0.1 $Z_\odot$)

Carbon and Nitrogen ratios relative to Oxigen subsolar

Modest outflow velocities (<100 km/sec) from Lyα profile

Abundances at high z from lensed galaxies (2)

DIRECT ABUNDANCE MEASUREMENTS
versus STRONG LINE RATIO ESTIMATES



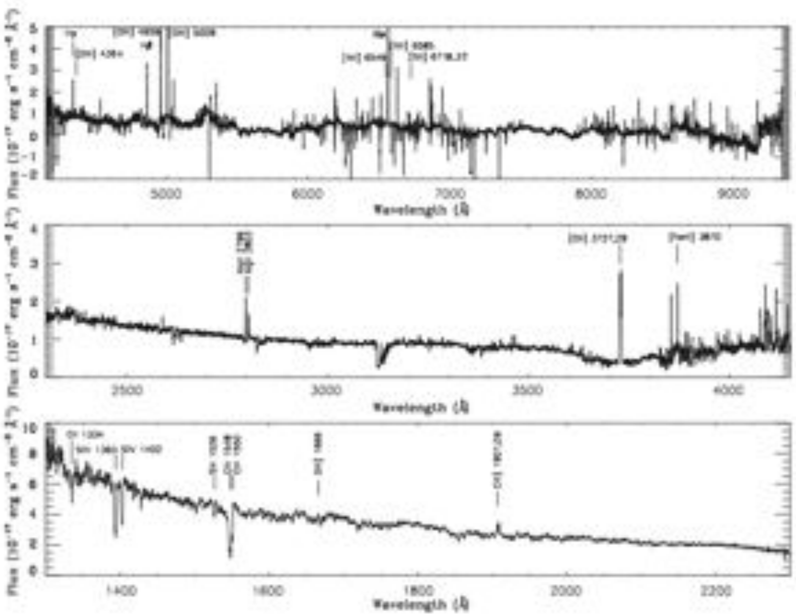
4 X-shooter galaxies:
-Christensen et al. 2012,13
-James et al. 2013
+
- Erb et al. 2010
- Yuan et al. 2009
- Villar-Martin et al. 2004

Only 7 high z measurements (1.4 < z < 3.5)

Abundances at high z from lensed galaxies (3)

A detailed study of the galaxy Cassowary 20 (z=1.43) lensed by a massive foreground galaxy at z=0.74

James, Pettini, Christensen et al. (2013)



RESULTS
:
SFR ~ 6-12 M⊙/yr from Hα and UV continuum

Oxigen abundance 1/7 solar, Carbon 1/50 solar

Outflow from ISM with speeds up to 750 km/s from

Stellar mass estimate from SED 1×10^{10} $M_\odot$

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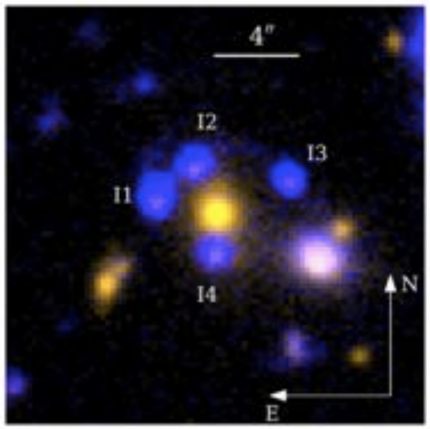
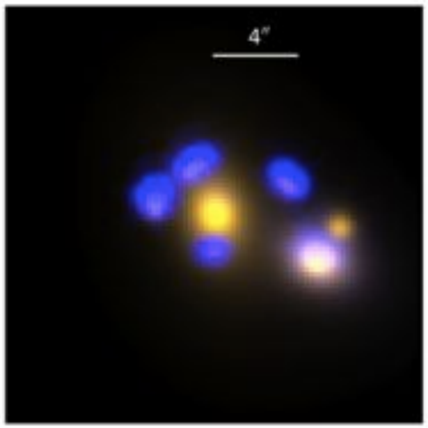
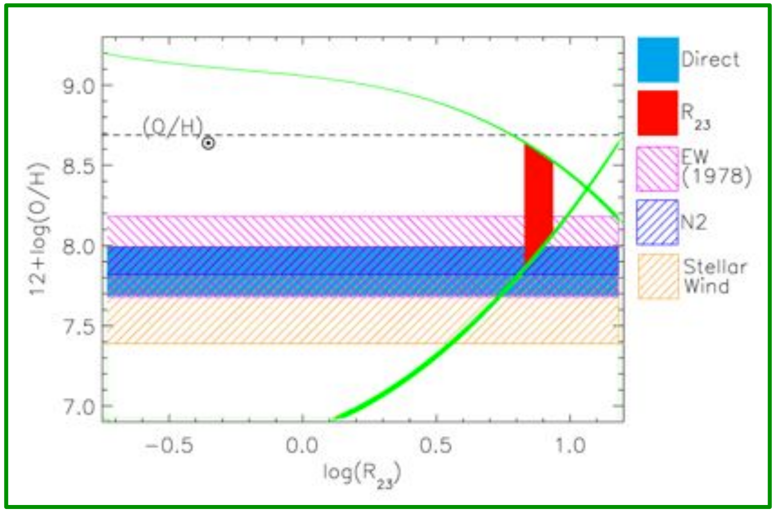
James, Pettini, Christensen et al. (2013) submitted





Two color composite of Cassowary 20 from exposures at the W. Herschel telescope, with the four lensed images of the galaxy(left). Gravitational lensing model of the same field (right).

5 independent oxigen abundance estimates versus the strong lines ratio R_{23} (([O iii] λλ5008.24,4960.30 + [O ii] λλ3727.09,3729.88) to Hβλ4862.69 (Pagel et al. 1979).



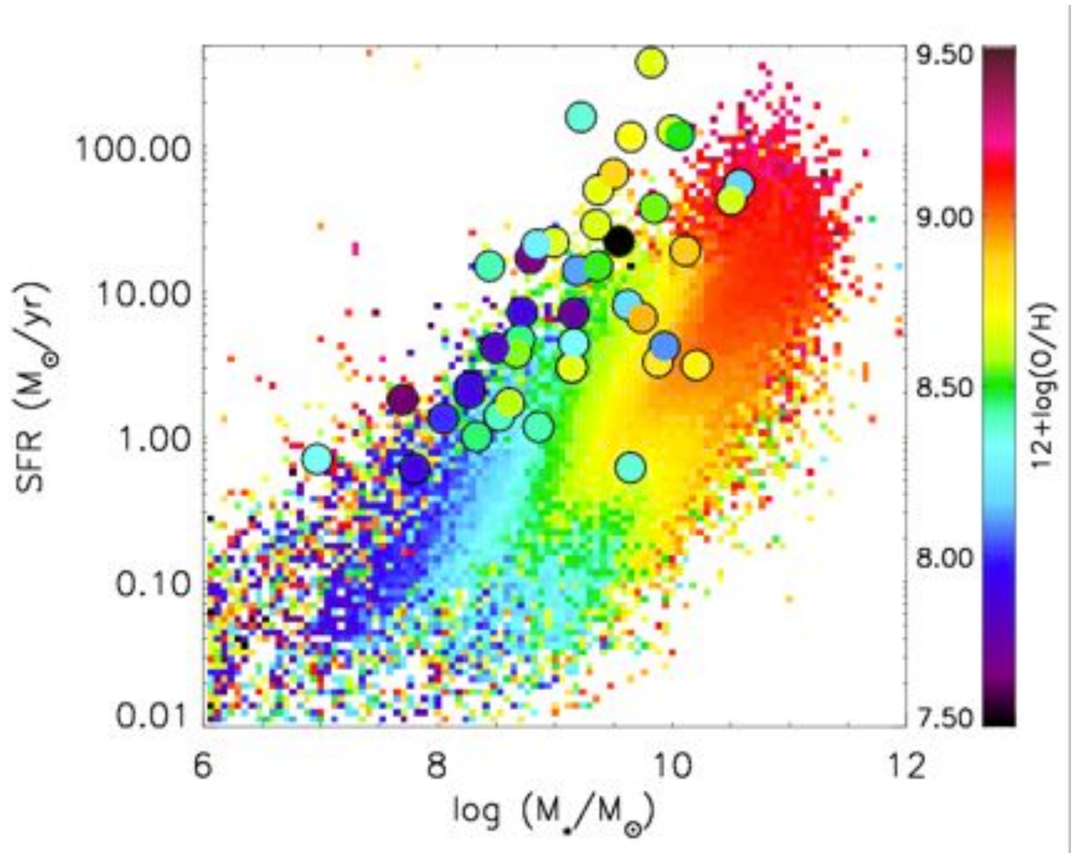
Fundamental relation SFR-Mass-Metallicity : the role of lensed galaxies

- *Detailed studies of the galaxies with M≈ M⁎ are made possible at z=1-4 by the gravitational amplification.*
- *They can be used to verify the validity of the fundamental relation (Mannucci et al 2009 and subsequent versions) at* ***early epochs and down to small masses and SFRs.***

Provided that there are sufficient data to properly model the amplification

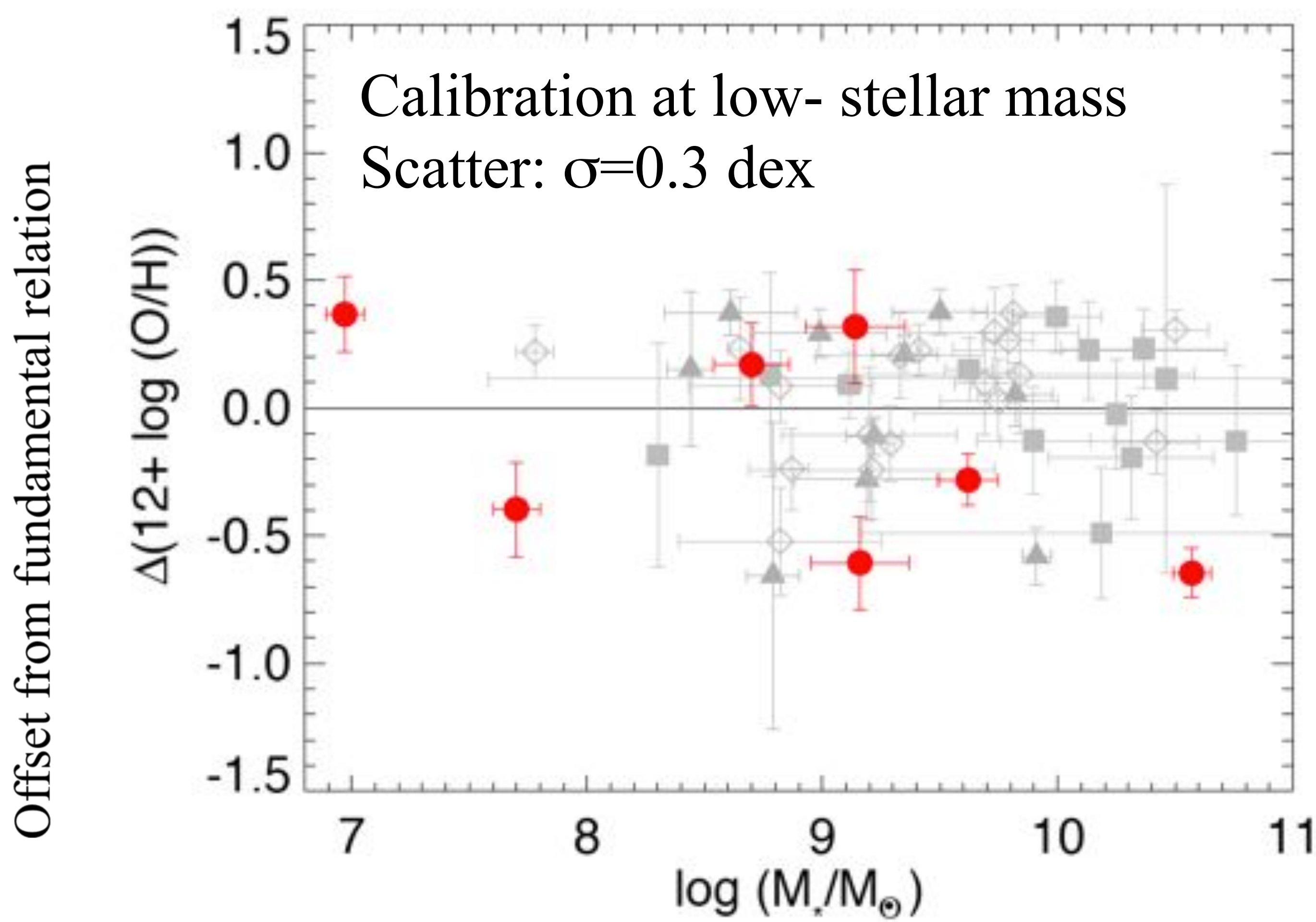
See for most recent modeling Daylan et al.2013;
Lilly, Carollo, Renzini et al. Ap.J. (2013) ;

Fundamental relation SFR-Mass-Metallicity : high z data points from lensed galaxies (1)



Christensen et al. The Messenger, 2013

1 < z <4 galaxies versus the fundamental SFR-M*-O/H relation at low redshift



Christensen et al. 2012(red dots), Wuyts et al. 2012; Belli et al. 2013

Thank you