UV & optical spectroscopy of extremely metal-poor galaxies: clues for interpreting distant galaxy observations

by A. Wofford (IAP, moving to UNAM, Mexico)

in collaboration with:

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NEOGAL

Galaxy pair I Zw 18 by HST ACS. It has an ionized-gas metal mass fraction (hereafter metallicity) of Z ~ 3% solar as gauged by O/H (Izotov+99; $12+\log(O/H)_{\odot}=8.69$, Asplund+09)

What are extremely metal poor / deficient galaxies (XMPGs / XMDGs)?

- nearby, actively star-forming galaxies of low stellar mass ($\log M_\star / M_\odot = 6 - 10$), which are dynamically primitive, i.e., still forming their disk
- arbitrarily defined to have ionized-gas with O/H ≤ 10% solar (Kunth & Östlin 00) and observed to have O/H as low as ~3% solar or $Z \sim 4 \times 10^{-4}$ (Sánchez-Alméida+16)
- unfortunately, too far away to study individual massive stars => large uncertainties in models of the evolution of massive stars at low Z
- may contain an old stellar population, e.g., I Zw 18 contains RGB stars which formed at least 1 Gyr ago (Annibali+13)

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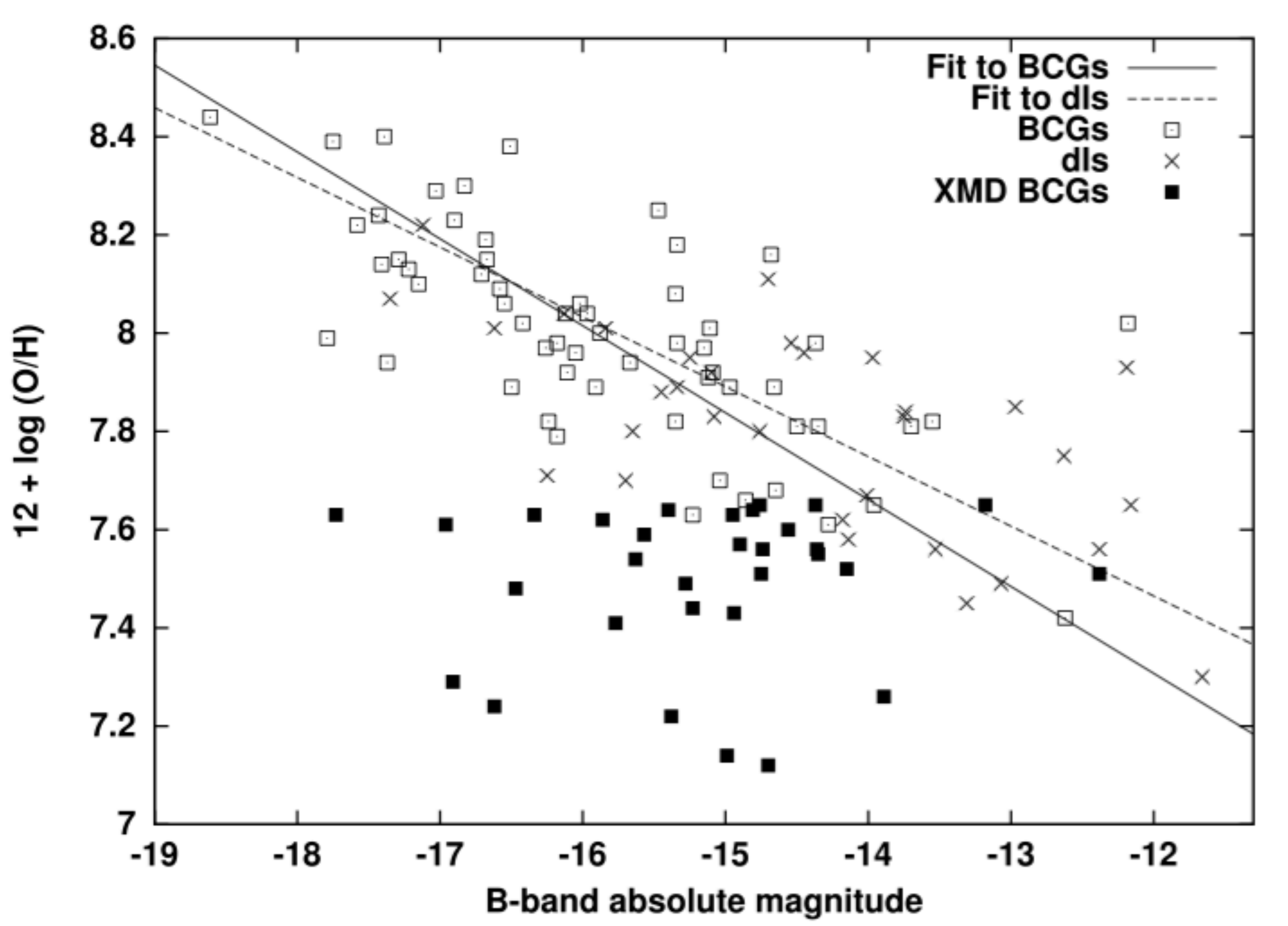
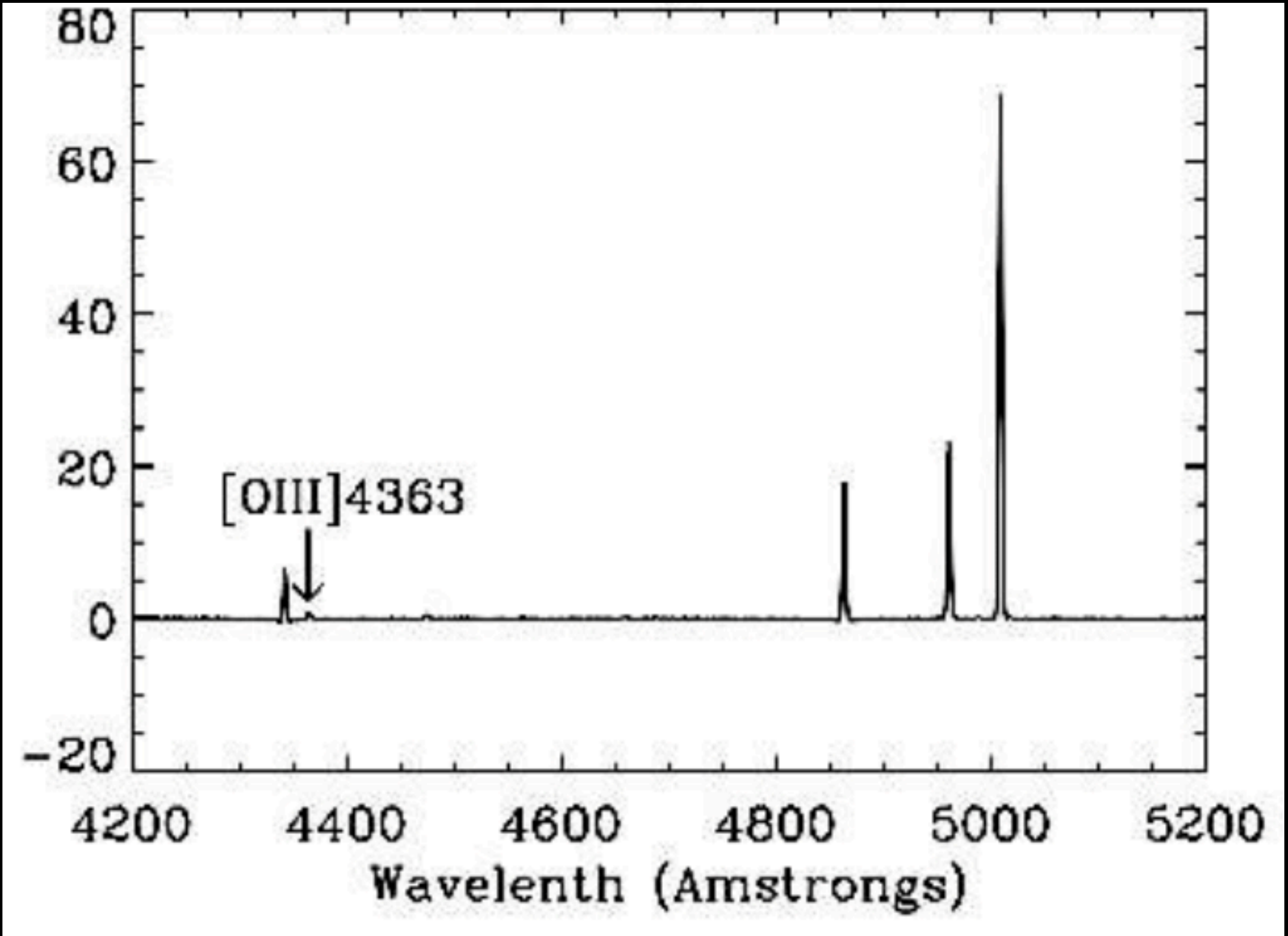
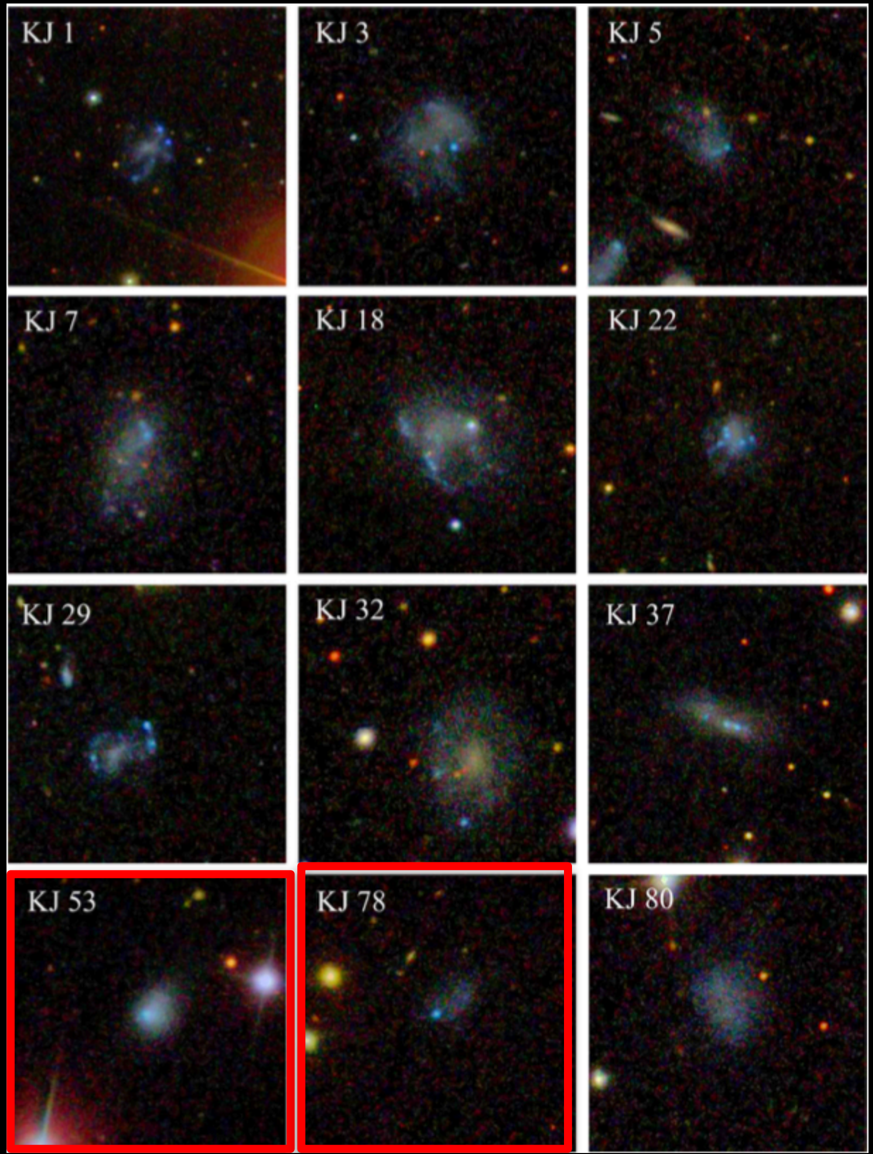
Some have significantly lower O/H than expected from their mass according to the L–Z or $M_{\star}$–Z relations of BCGs/dIs (Etka & Chengalur 10) => challenge for models of the chemical evolution of galaxies. Is this due to 1) a low time-averaged SFR, 2) preferential outflow of metal-enriched gas, 3) infall of pristine gas?



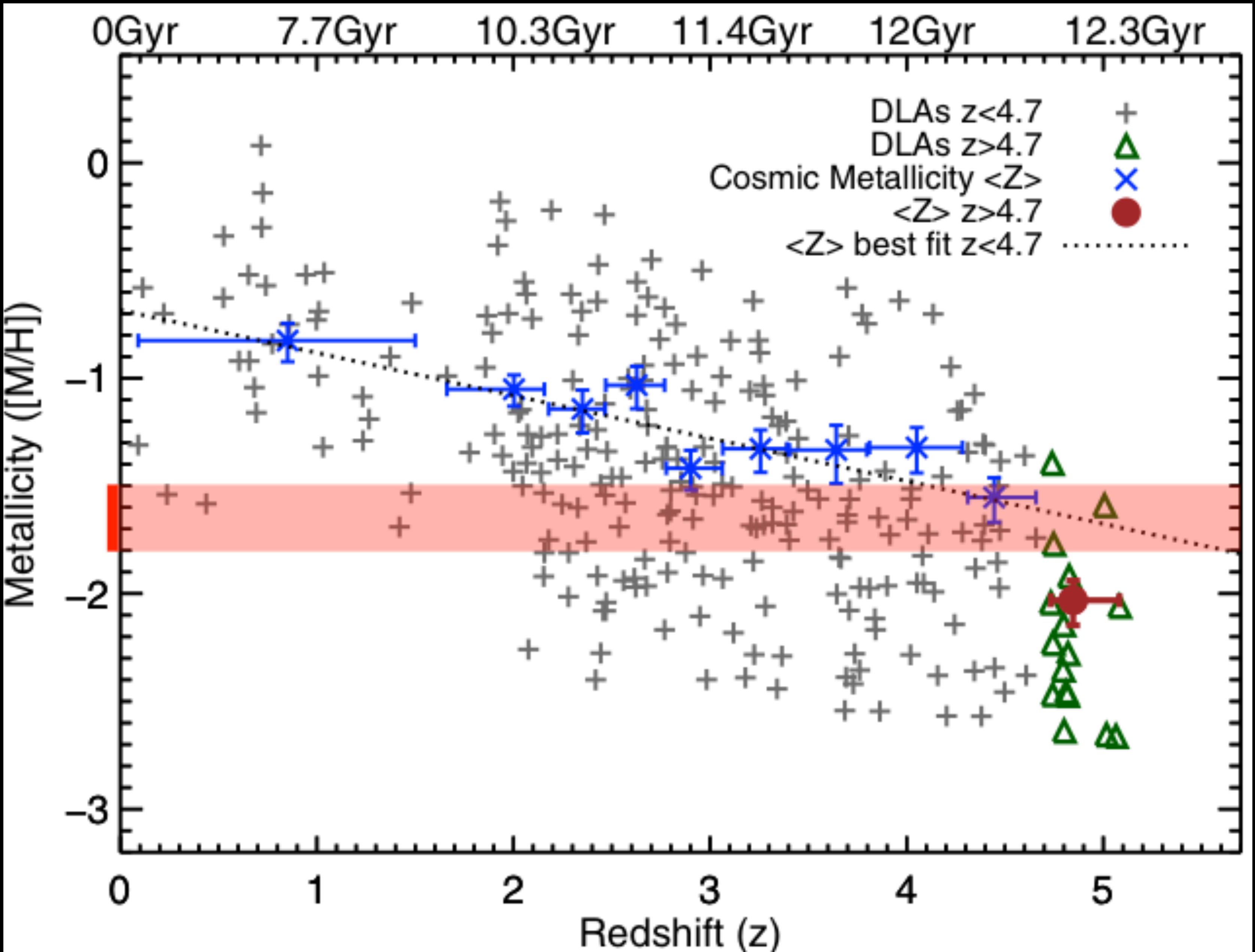
XMPGs are uncommon in emission-line based surveys
They represent 0.01% of emission-line galaxies in SDSS DR7 where candidates are found via strong [O III] 4363 emission
⇔ high Te ⇔ gas cannot cool due to low metal content



XMPGs are also found via morphology-based searches
James+15, who target faint blue systems with H II regions embedded in a diffuse continuum, found two XMPGs out of their sample of 12 followed spectroscopically.



For reference, XMPGs w/ Z~2-3% solar (red band) match metallicities measured in DLAs out to z~5. Showing fig. 3 of Rafelski+14.



Importance of XMPGs beyond z~5

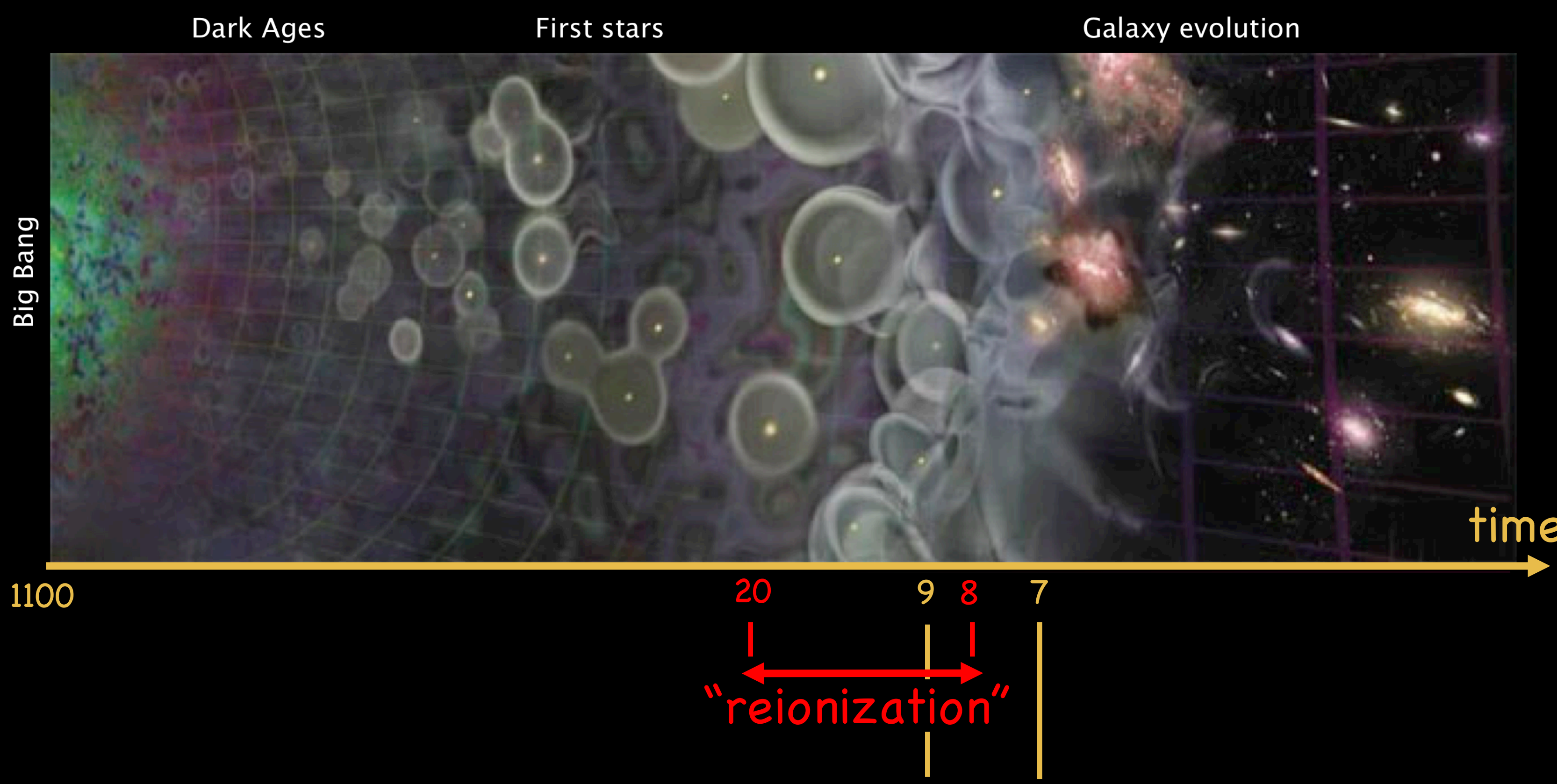
It just takes a few pair-instability supernovae to reach a metallicity of Z ~ 2% solar by z ~ 7 (Wise+12)

=> unlikely that we will ever see genuine primordial galaxies with $Z / Z_{\odot} \sim 0$

Since XMPGs w/ Z~3% solar are "chemically un-enriched", their detailed study is what is needed to learn about how low metallicity determines the properties of distant chemically un-enriched distant galaxies

JWST NIRSpec will detect the rest-frame UV of thousands of galaxies at z ~ 10 – 15,

during the epoch of "reionization"



rest-frame UV emission lines detected out to z~7-9 (e.g., Oesch +15 & Stark+16)

Examples of what can be learned from rest-frame UV emission lines from the integrated light of distant galaxies:

He II 1640: *a main tool* to trace peculiar massive stars, since He II 4686, which is traditionally used for this purpose, will be unavailable

- Peculiar stars are Pop III stars or stars with masses above canonical limit of 120 $M_\odot$

C IV 1550 / C III] 1909: hardness of ionizing continuum

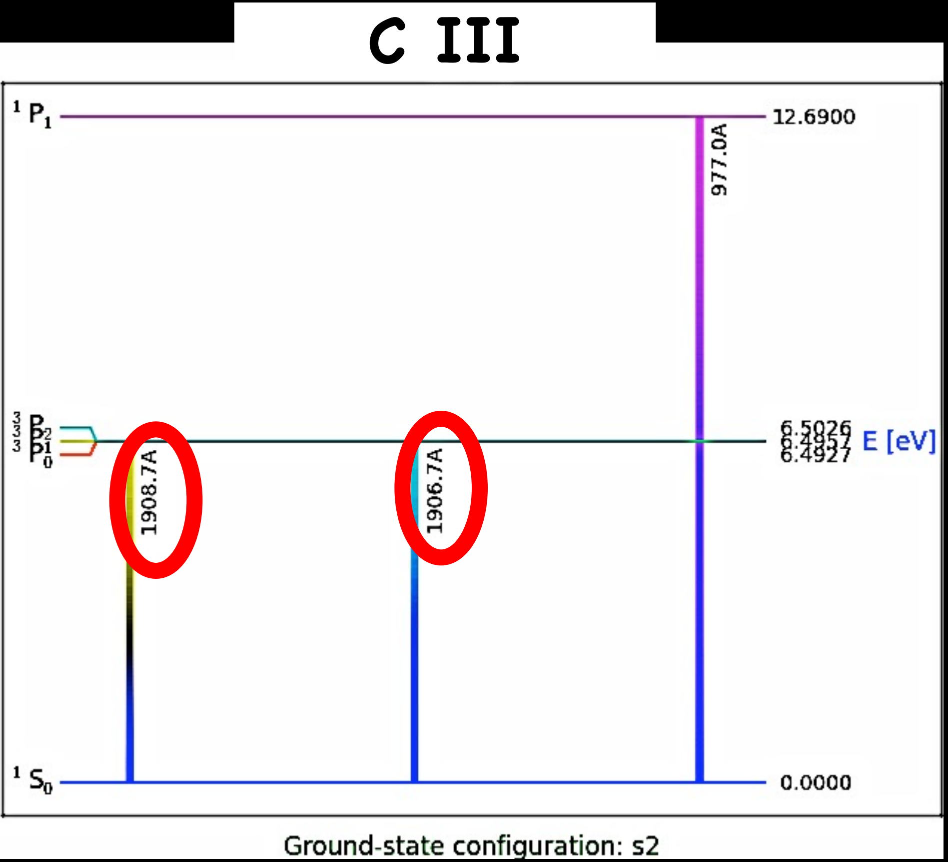
- C I => C III takes 24.4 eV
- C I => C IV takes 47.9 eV

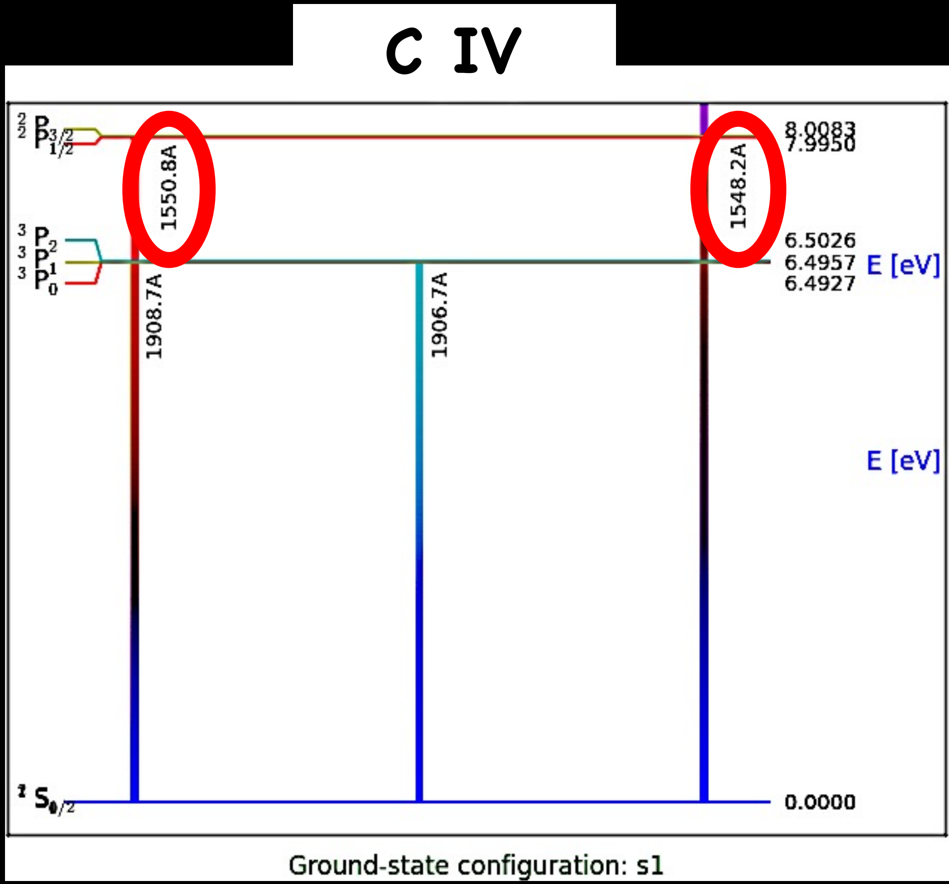
C III] / O III] / Si III]: C / O / Si abundances (O III] lines can be as strong as He II 1640)

Line ratios which are sensitive to the gas density

[C III] 1907 / C III] 1909

C IV 1548 / C IV 1551





What are the uses of UV spectroscopy of XMPGs with Z~3% solar?

1. Find and test UV diagnostics for disentangling various sources of ionization (massive stars, AGN, shocks)
2. Test different model flavors of the integrated light of young galaxies (e.g., with interacting binaries & masses up to 300 $M_{\odot}$)
3. Calibrate low-Z model spectra of the integrated light of stars + gas + dust. A model is well calibrated when it can reproduce the observed continuum and emission lines without any fudge factors.
4. Determine how metallicity affects galaxy properties such as:

- C/O ratio
- attenuation due to dust
- upper stellar initial mass function
- star formation rate

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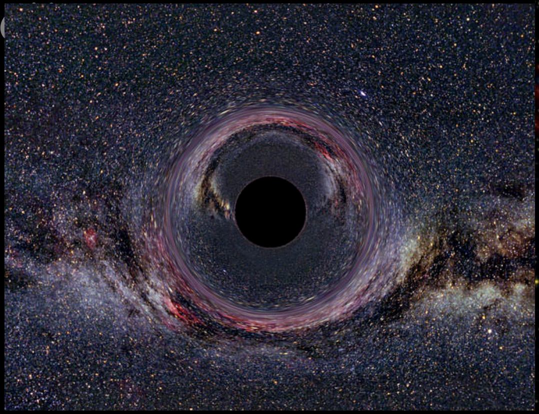

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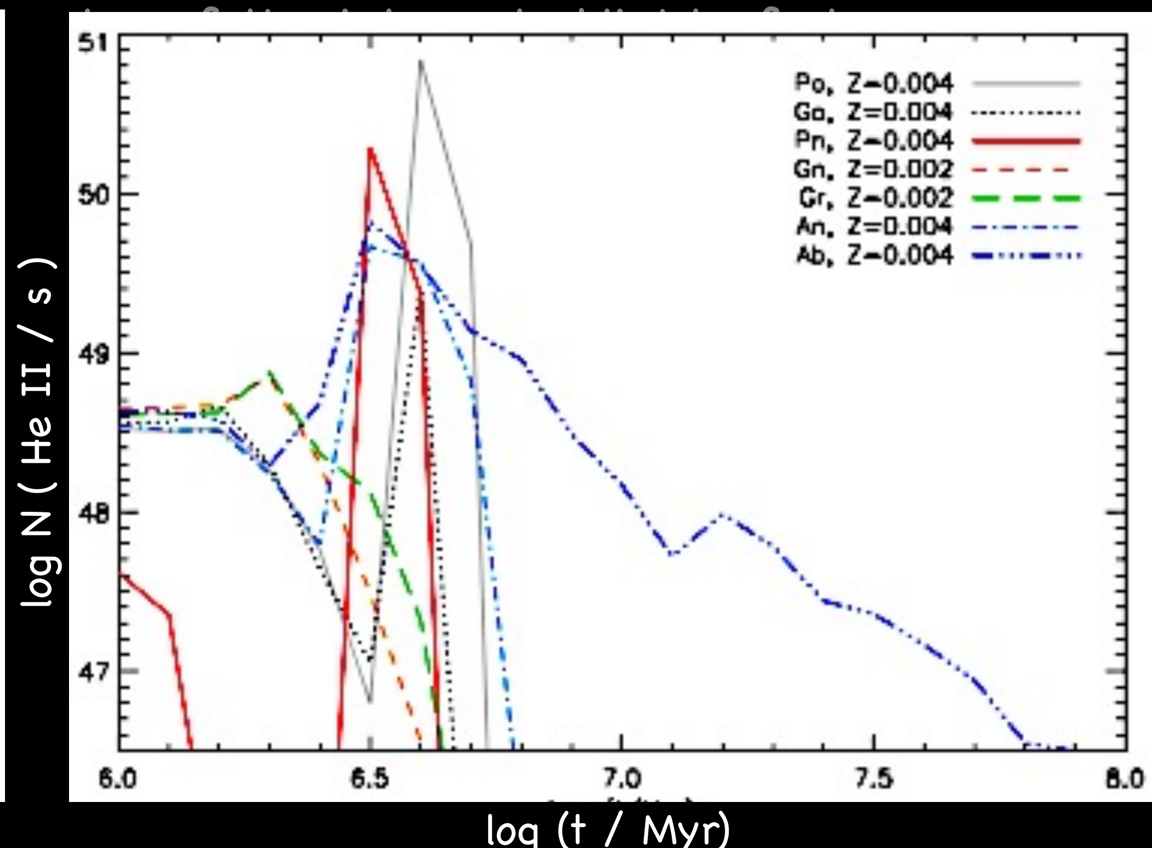
In **Wofford+16** we found that at Z=1/5 solar Geneva rotating (Gr) and BPASS binary (Ab) models have higher ionization rates and that binary models sustain these rates for longer times relative to single non-rotating models



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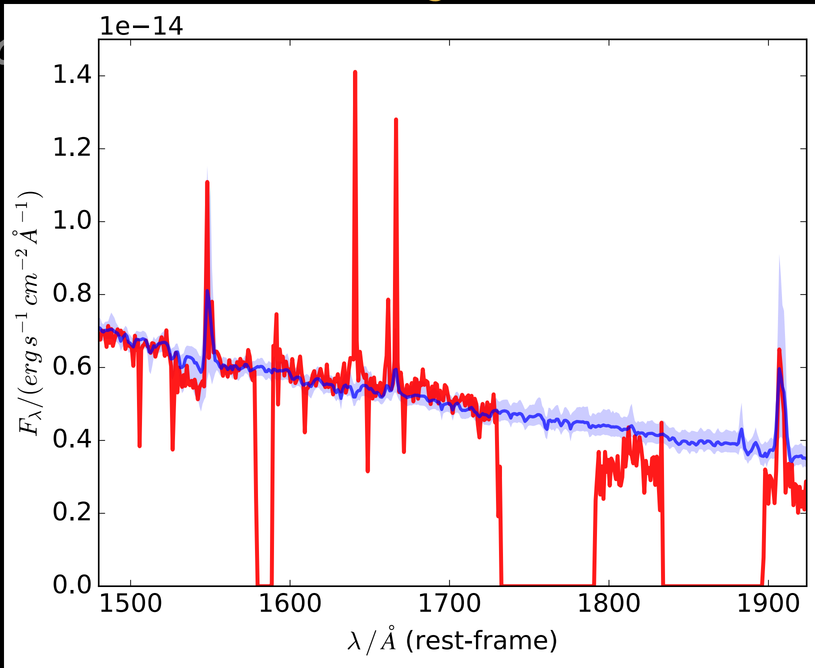

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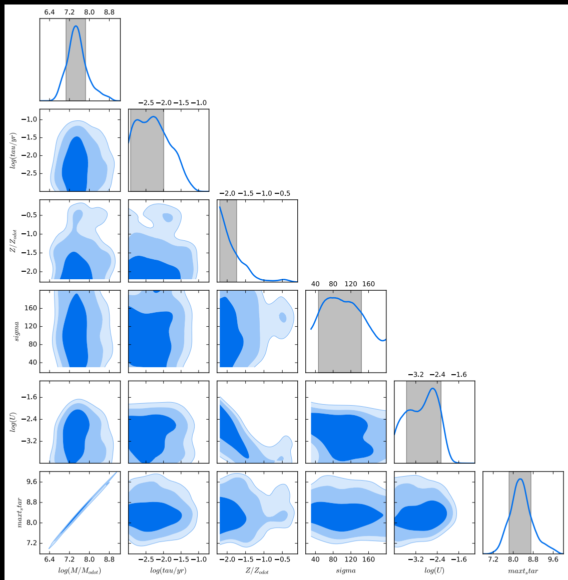

What is the status of rest-frame UV spectroscopy of XMPGs with Z~3% solar?

Currently, spatially and spectrally resolved rest-frame UV observations of XMPGs w/ Z~3% solar are still scarce. This is because...

- until recently, we only knew a couple of galaxies with Z ~ 2-3% solar in the local universe
- previous UV spectrographs covered such galaxies with large apertures, e.g., IUE 10"x20" or FUSE 30"x30"; or lower spectral resolutions, e.g., FOS G190H FWHM~1.45 Å, IUE SWP FWHM~3-8 Å
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HST Cosmic Origins Spectrograph (COS) UV spectroscopy

Used r=1.25″ circular aperture and G160M + G185M gratings (FWHM~20 km/s) to obtain rest-frame 1420 to 1920 Å coverage (w/ some gaps) for 3 SF regions in 3 XMPGs:

1) UGC 5340-1 (12+log(O/H)=7.23, $Z/Z_\odot$~1/29; no previous UV spectrum)

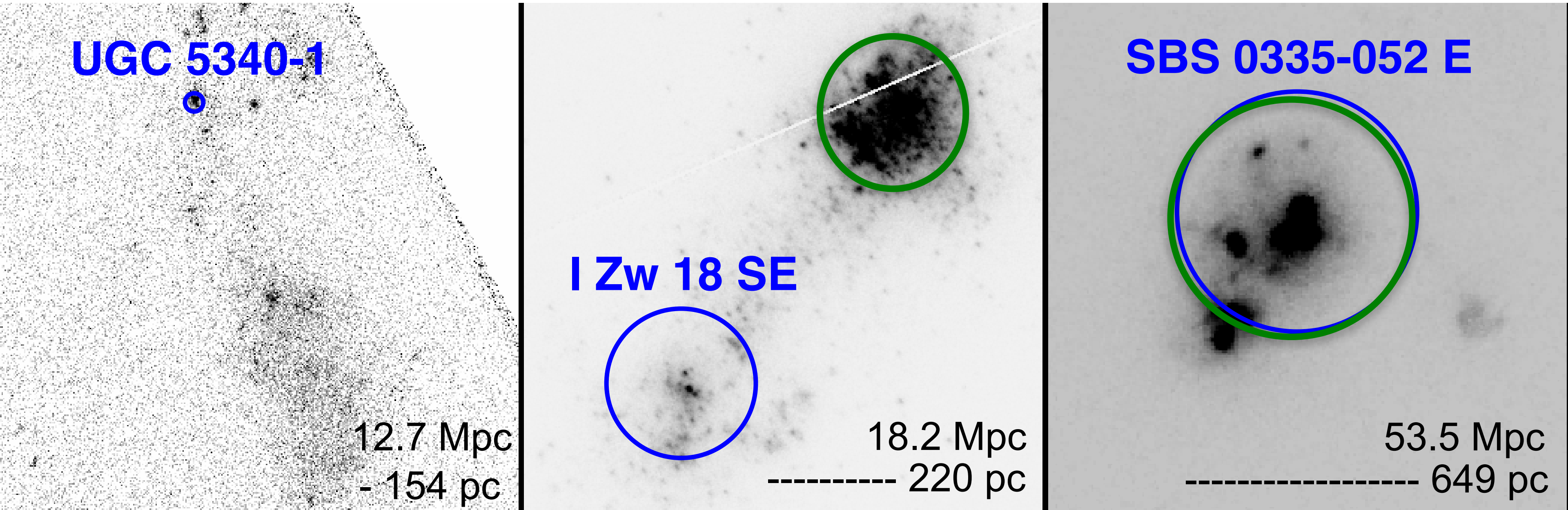
2) I Zw 18 SE (12+log(O/H)=7.18, $Z/Z_\odot$~1/32; IUE 10″x20″ SWP, FOS r=1″ G190H)

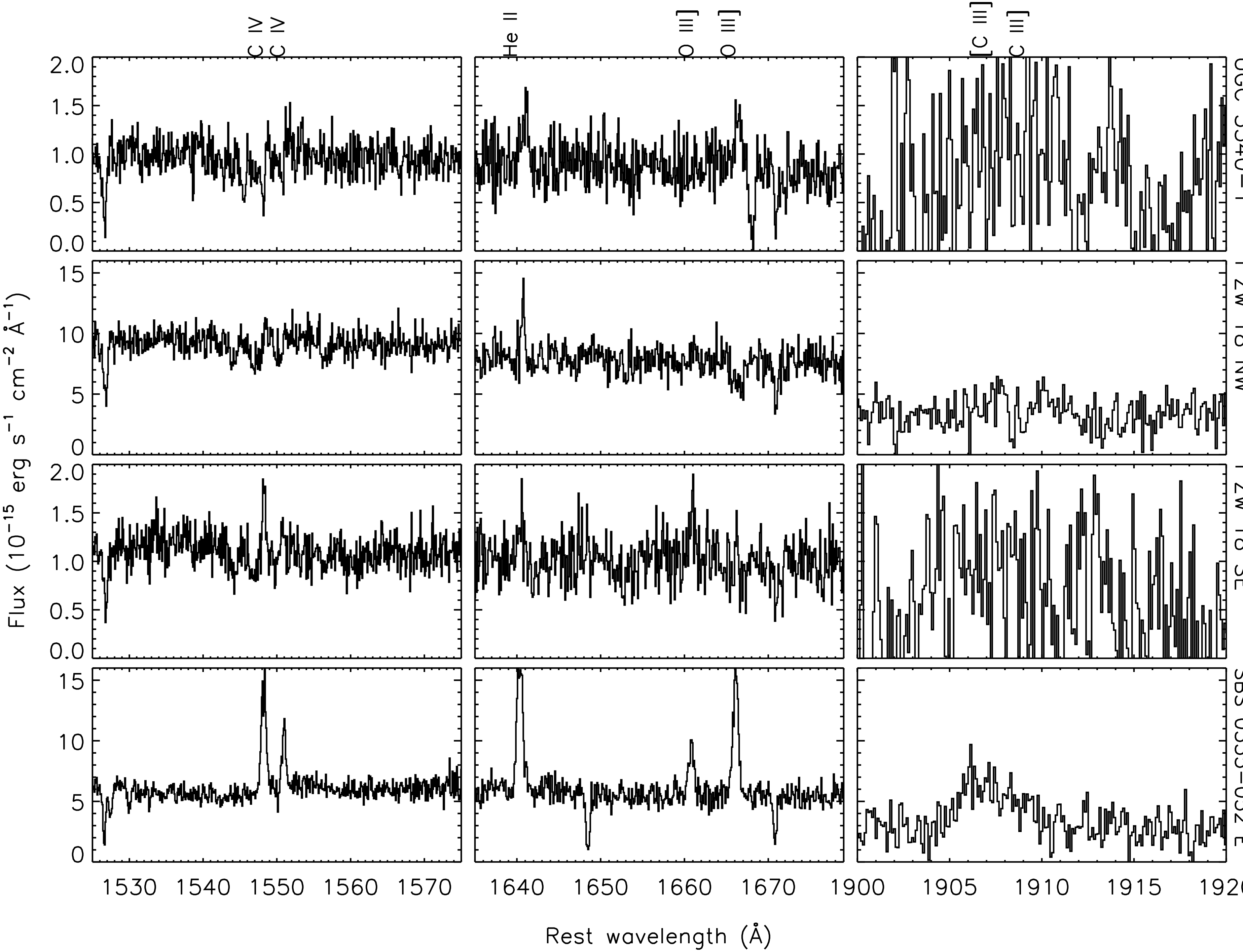
this added to the data for:

I Zw 18 NW (12+log(O/H)=7.17, $Z/Z_\odot$~1/33; IUE, FOS, COS G130M, G160M, G185M)

3) SBS 0335-052 E (12+log(O/H)=7.33, $Z/Z_\odot$~1/23; FUSE, IUE, G190H, COS G130M)

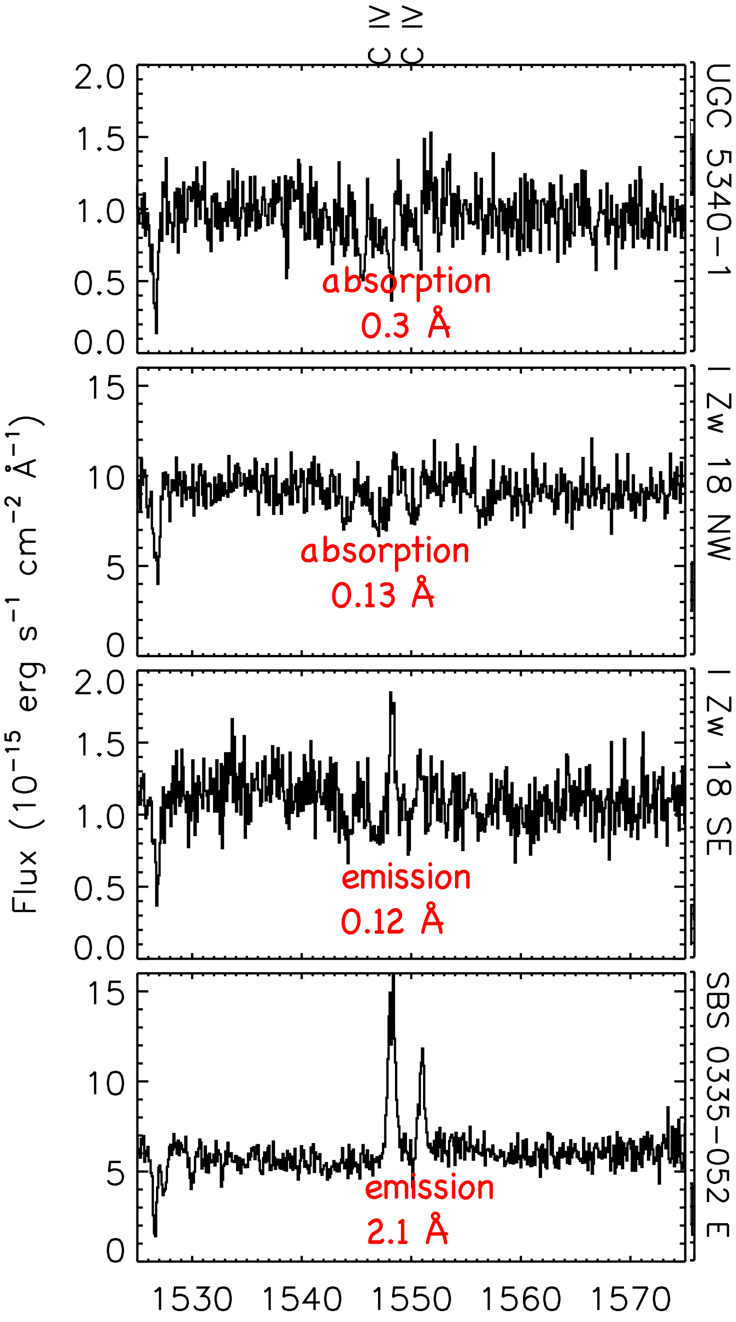
UV image with COS r=2.5″ circular aperture overlaid



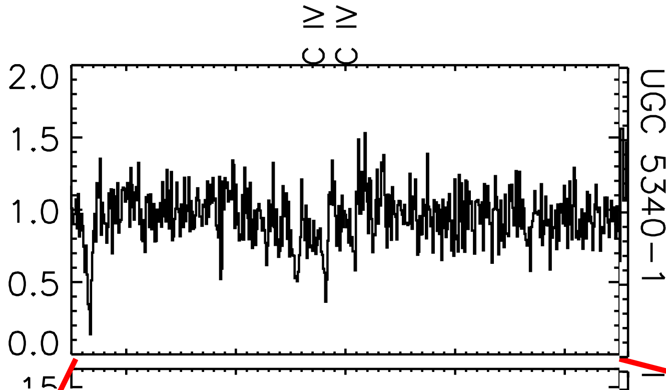


C IV
C IV
He II
O III]
O III]
[C III]
C III]
UGC 5340−1
I Zw 18 NW
I Zw 18 SE
SBS 0335−052 E
Flux (10^{-15} erg s^{-1} cm^{-2} Å^{-1})
Rest wavelength (Å)

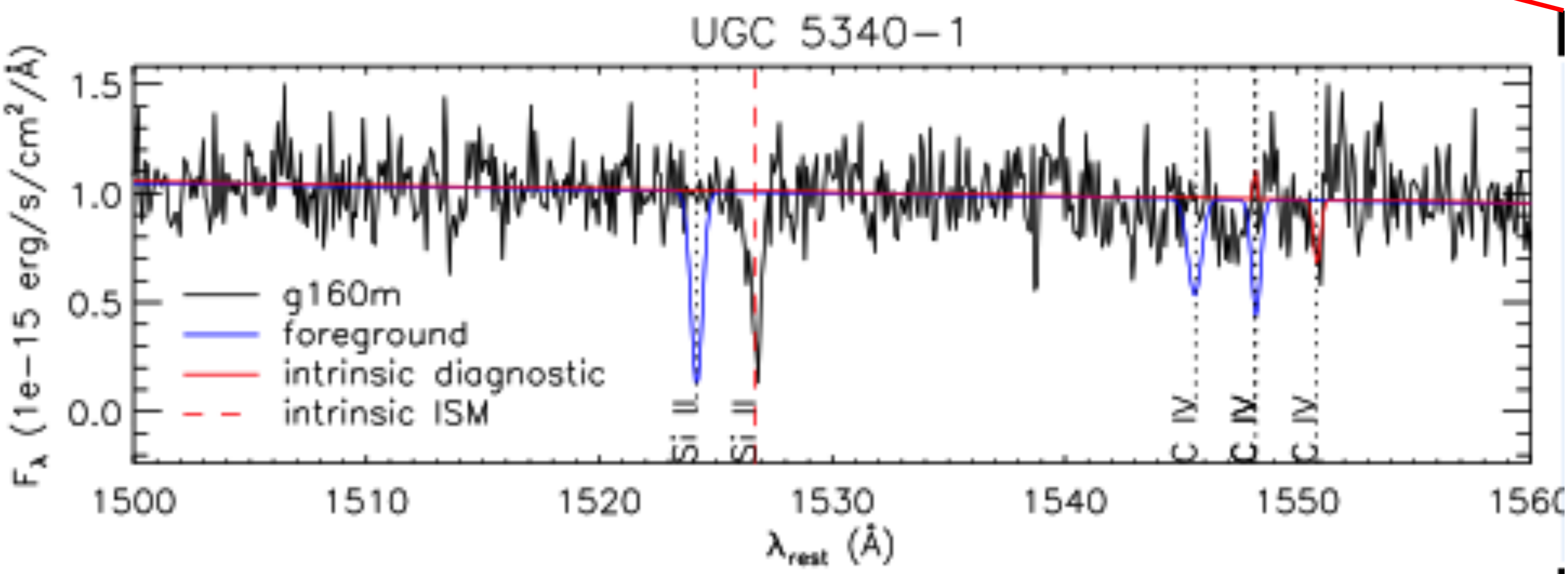
C IV 1548 + 1551



C IV 1548 + 1551

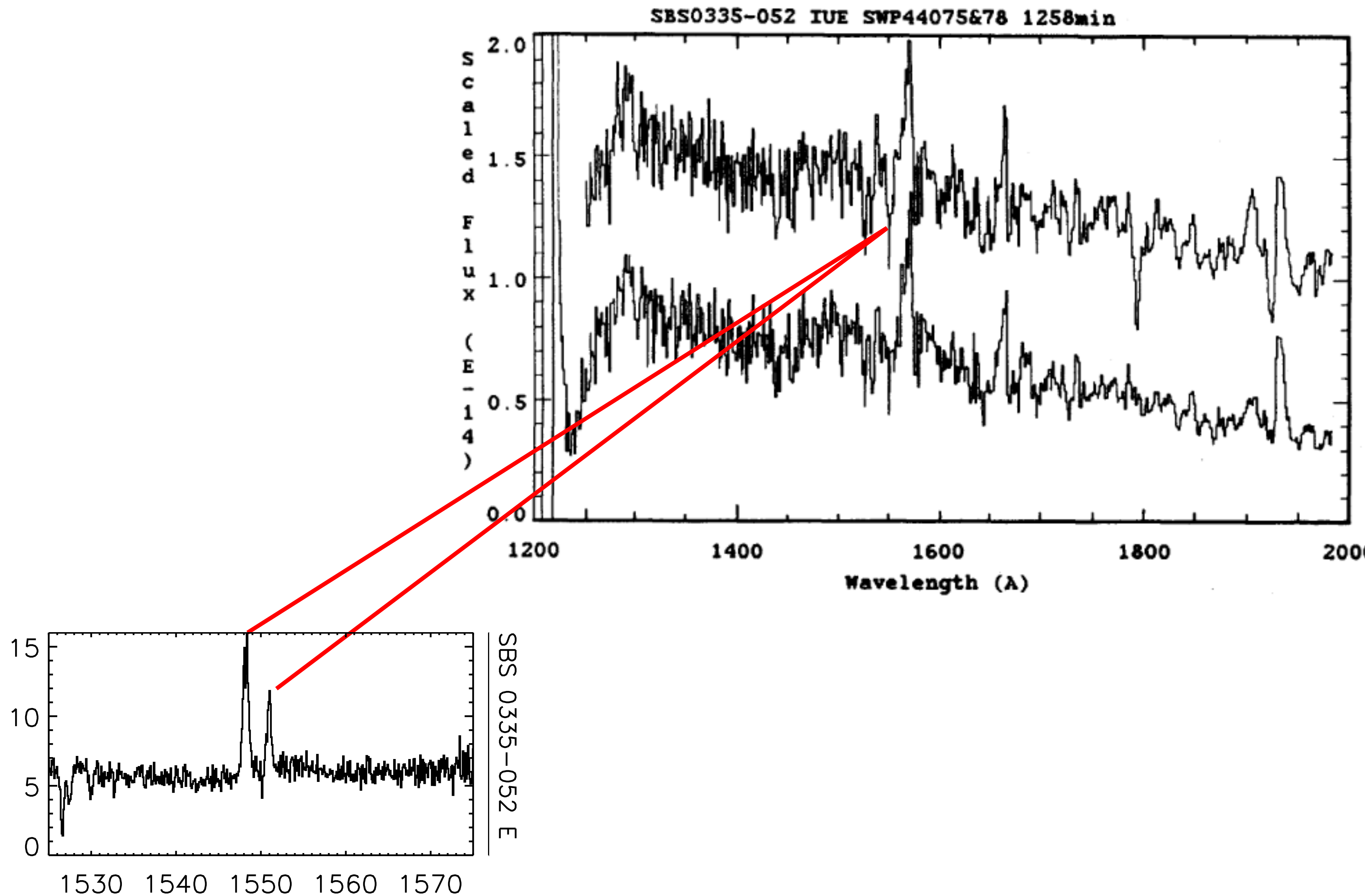


C IV 1548 is contaminated with
C IV 1551 from the MW

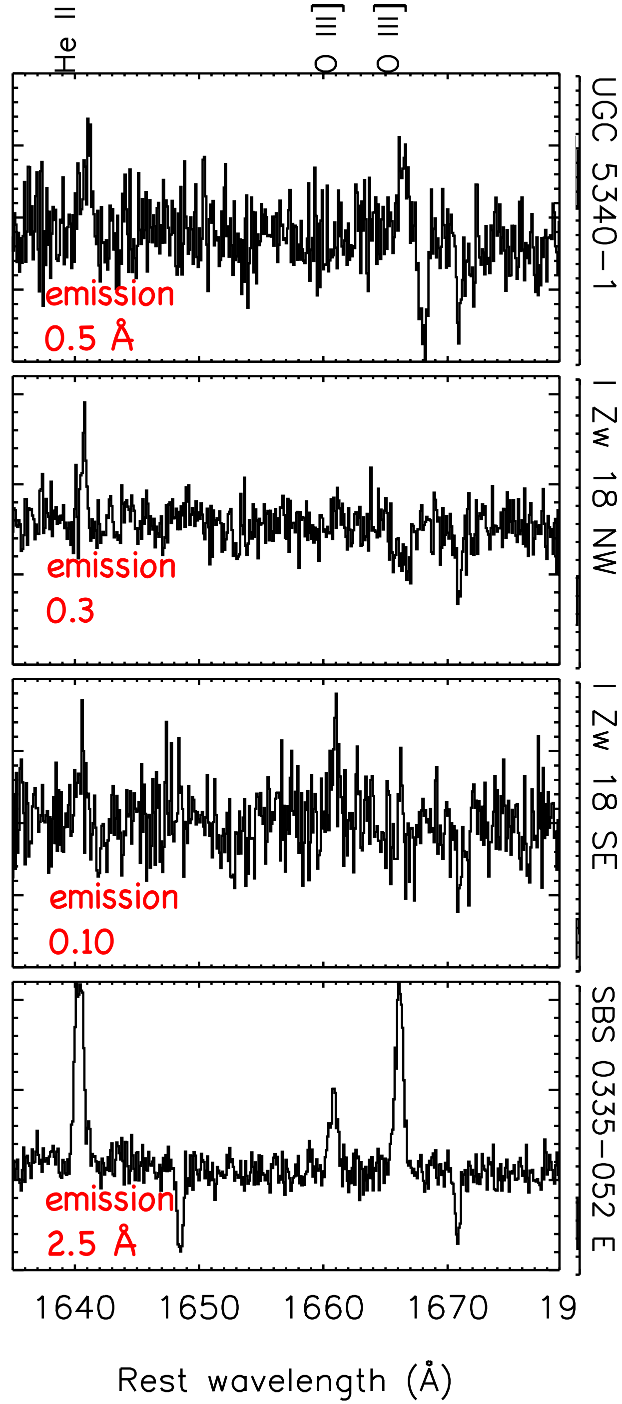


C IV 1548 + 1551

(SWP44075-646min & SWP44078-612min). The top spectrum is the result and the bottom is an improved spectrum obtained using the slit-weighted optimal extraction scheme. Note the broad CIVλ1549 emission (redshifted by 20Å). (Dufour+93)



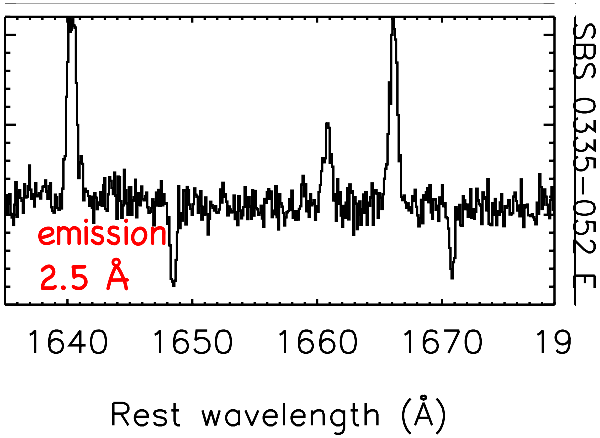
He II 1640

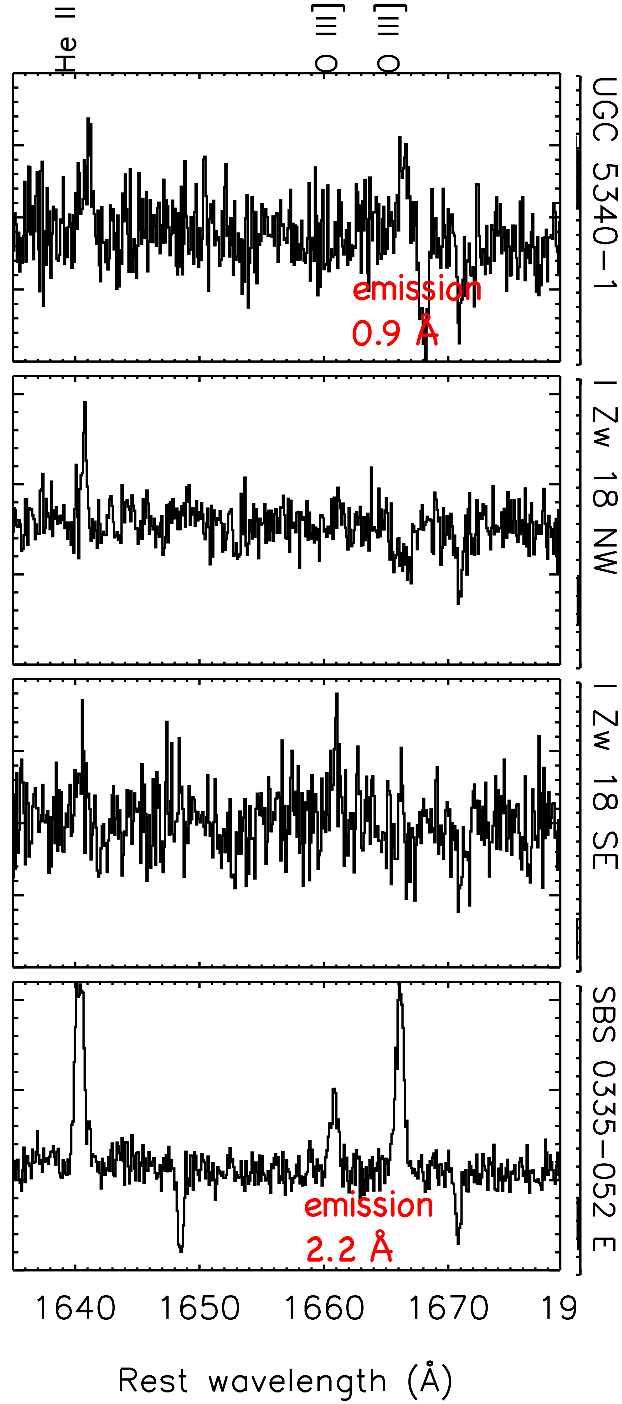


He II
O III]
O III]
UGC 5340−1
emission
0.5 Å
I Zw 18 NW
emission
0.3
I Zw 18 SE
emission
0.10
SBS 0335−052 E
emission
2.5 Å
1640
1650
1660
1670
19
Rest wavelength (Å)

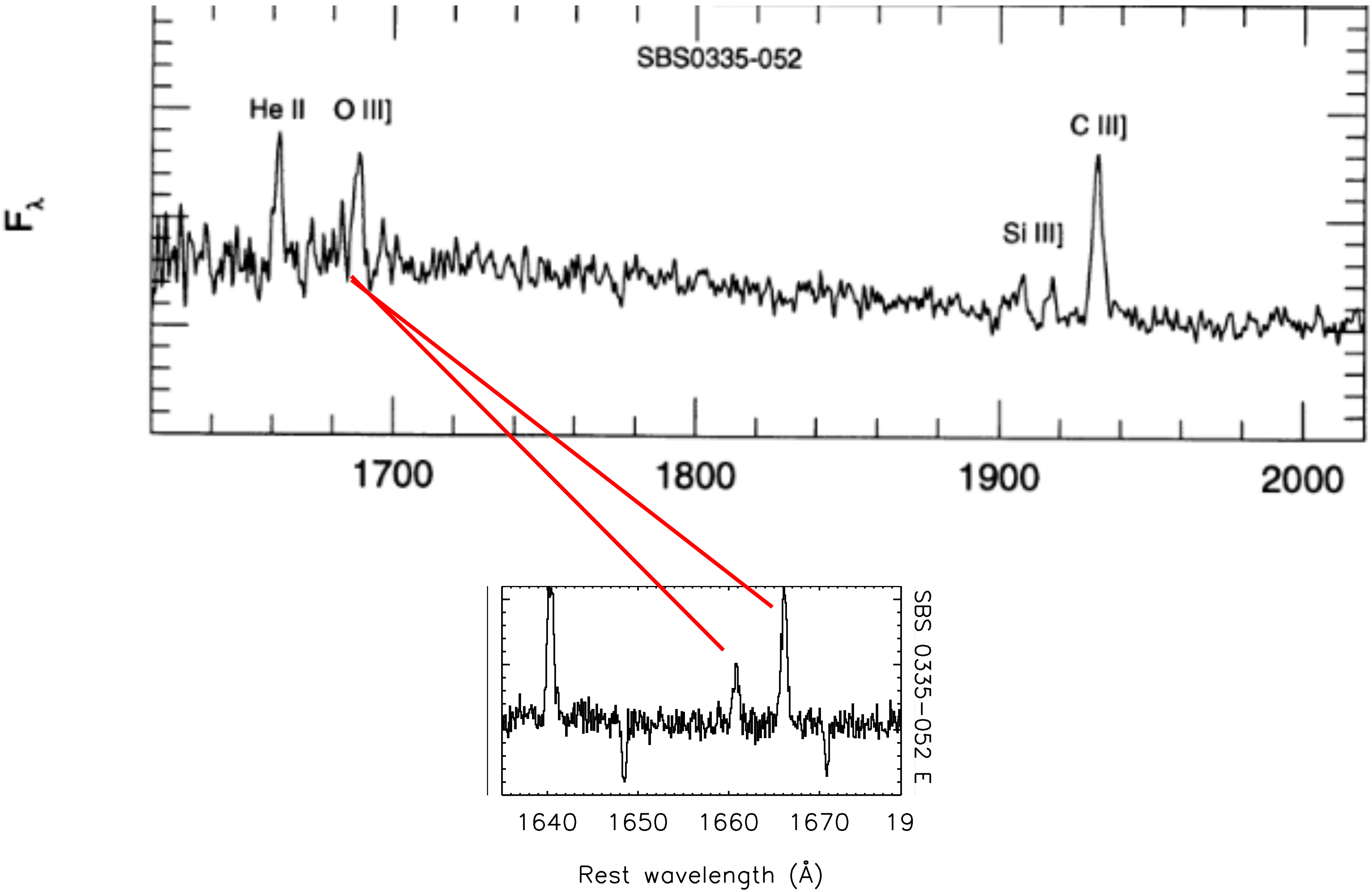
Preliminary models of the integrated light of stars + gas,
including models with binaries and with 300 $M_{\odot}$ stars
have a hard time reproducing the EW(He II) of SBS

=> not quite ready to study peculiar stars at z>10



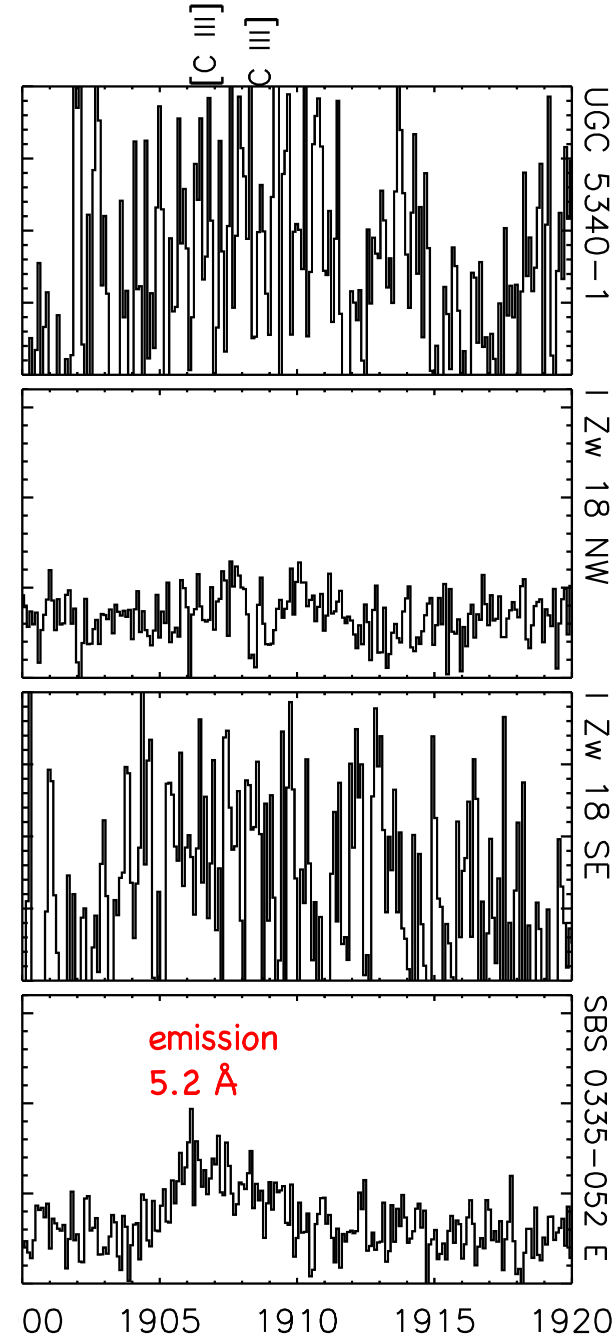

He II
O III]
O III]
UGC 5340−1
emission
0.9 Å
I Zw 18 NW
I Zw 18 SE
SBS 0335−052 E
emission
2.2 Å
1640
1650
1660
1670
19
Rest wavelength (Å)

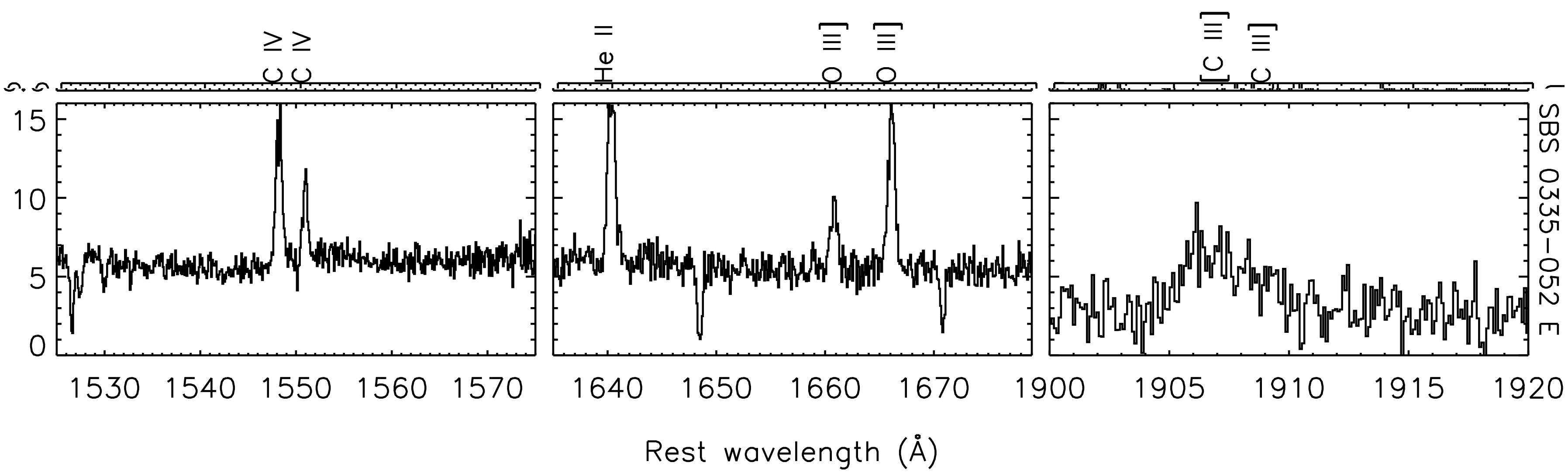
Faint Object Spectrograph, 1″ circular aperture, G190H, FWHM~3 Å, smoothed w/ 3 point Gaussian (Garnett+95)



Unfortunately, G185M observations of [CIII] 1907 + CIII] 1909 have low SNR for 3 regions in 2 galaxies. Also a grating with currently a wavelength calibration issue.

SBS…E has EW=5.2 Å
Is this comparable to z~6-7 galaxies once uncertainty in the continuum taken into consideration?





C IV
C IV
He II
O III]
O III]
[C III]
C III]
SBS 0335−052 E
0
5
10
15
1530
1540
1550
1560
1570
1640
1650
1660
1670
1900
1905
1910
1915
1920
Rest wavelength (Å)

SBS 0335-052 is a galaxy pair

SBS0335-052 E is the eastern component

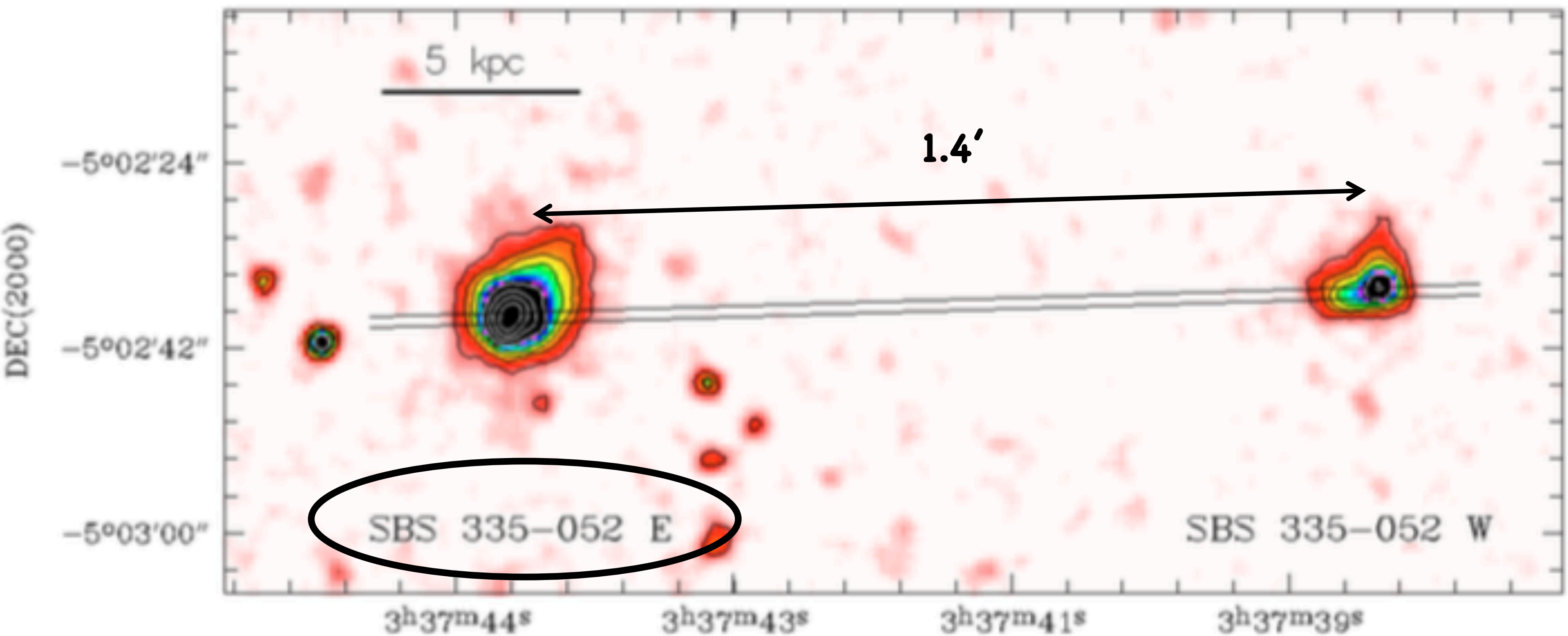
It has:

Stellar mass = $8 \times 10^7\ M_\odot$ | Gas mass = $2.1 \times 10^9\ M_\odot$ |

Dynamical mass = $9 \times 10^9\ M_\odot$ (Pustilnik+01)

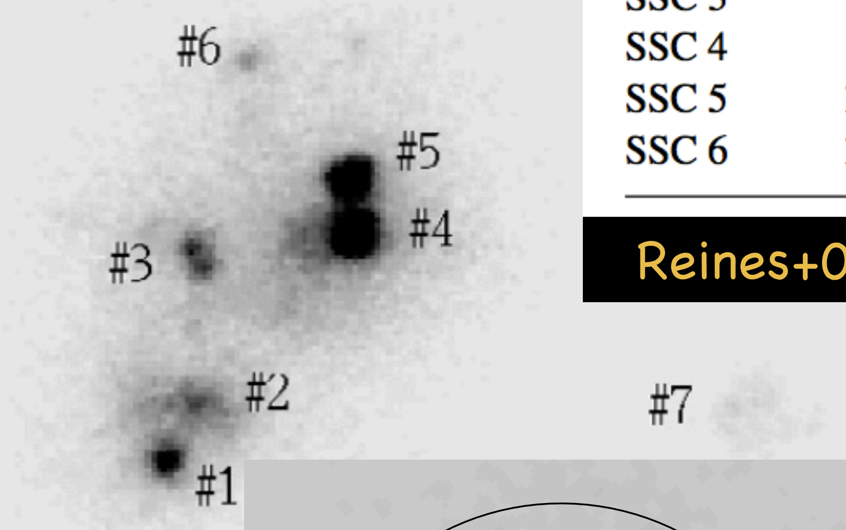
Dust mass = $3.8 \times 10^4\ M_\odot$ (Hunt+14, via ALMA)

Below: 2.2 m Calar Alto B-image(Izotov+99)



SBS 0335-052E

HST ACS UV image with star clusters labeled (Izotov+06)



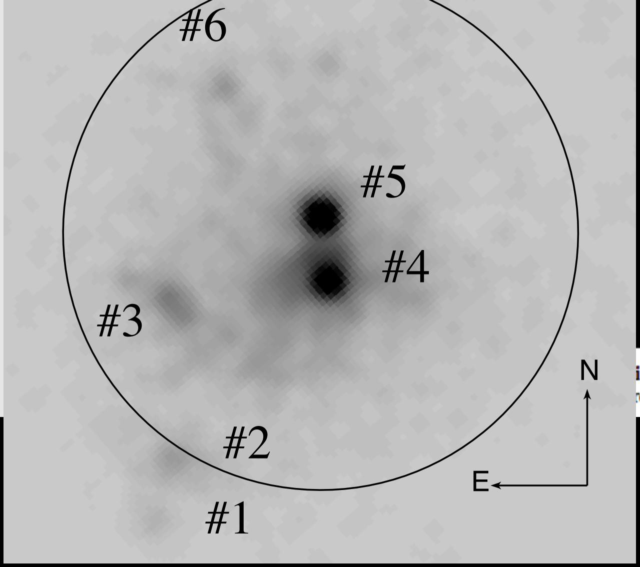
Properties from SED Fitting

Source	Age (Myr)	Mass ($10^6\ M_\odot$)	A_V (mag)
SSC 1	$\lesssim 3^a$	1.0(0.1)	0.5(0.1)
SSC 2	$\lesssim 3^a$	1.1(0.1)	0.5(0.1)
SSC 3	5.7(3.8)	0.4(0.2)	0.2(0.1)
SSC 4	$\lesssim 3^{a,b}$	1.1(0.1)	0.1(0.1)
SSC 5	11.8(1.1)	1.8(0.2)	0.0(0.1)
SSC 6	12.2(3.2)	0.2(0.1)	0.1(0.1)

Reines+08, using HST photometry

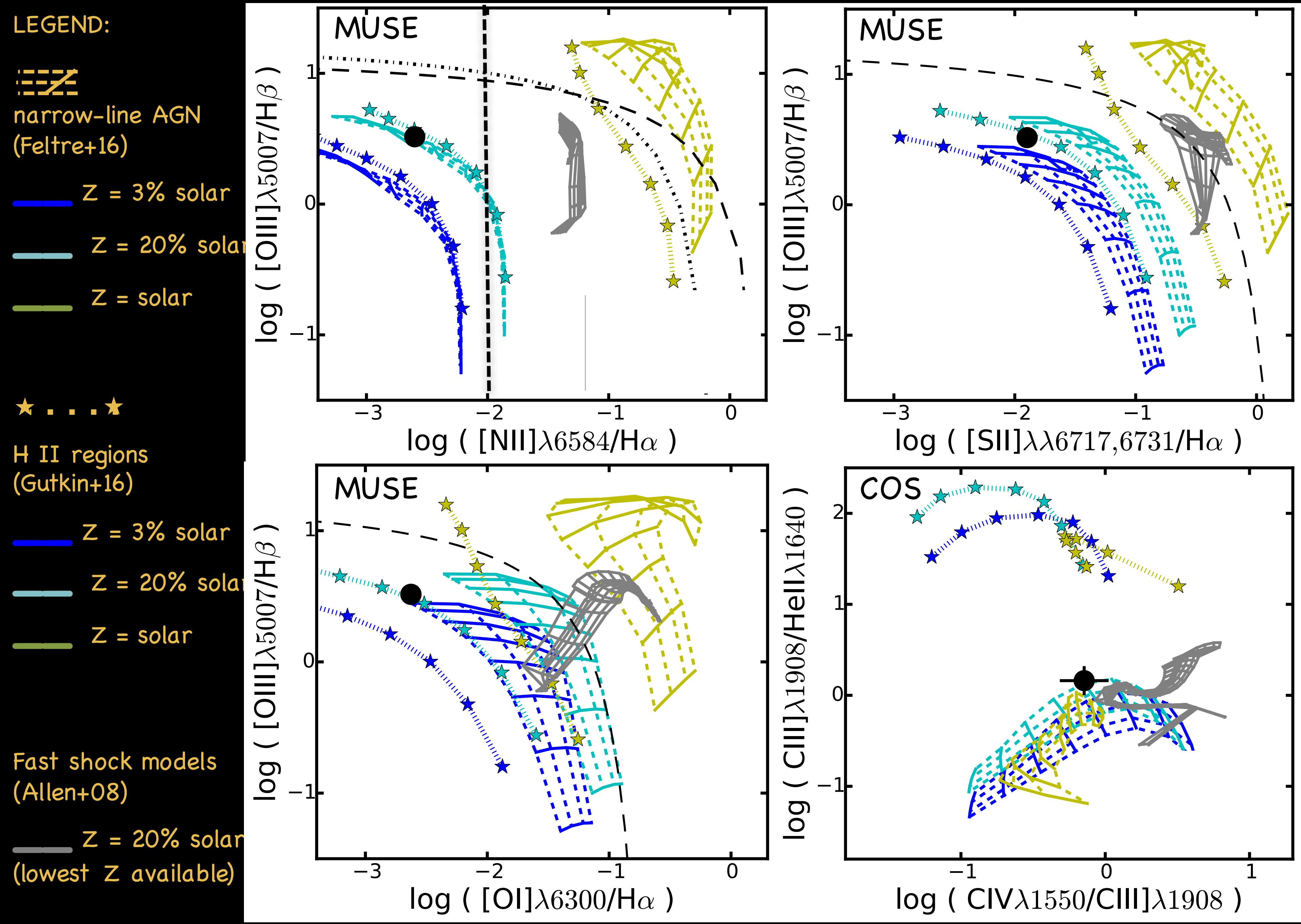
igure 3. NICMOS three-color image: F160W (~H) in blue, F205W (~K) in reen, and Paα (continuum subtracted) in red.

COS footprint

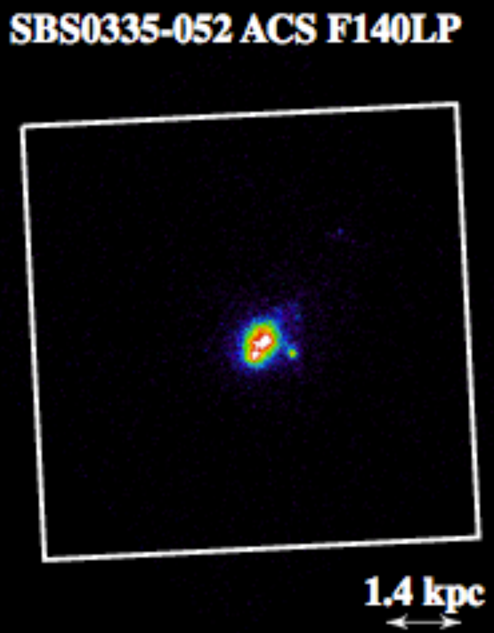


NICMOS 3-color image
continuum subtracted Paα

MUSE (PI Hayes) and COS (PI Wofford) obs. of SBS-E overlaid on diagnostic diagrams



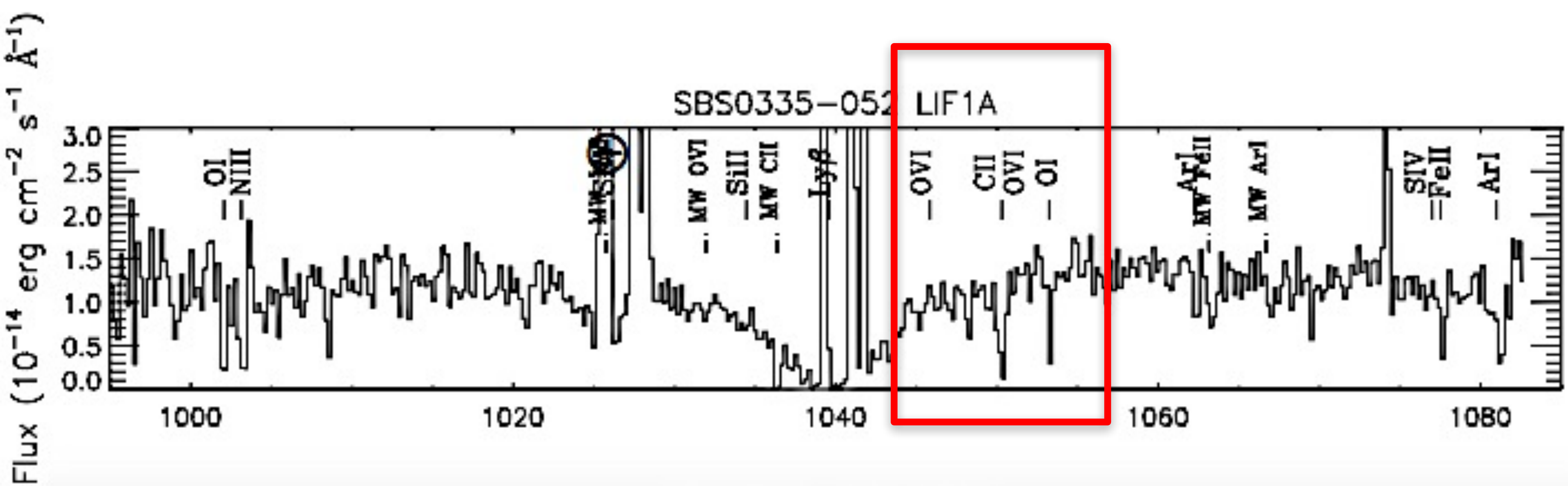
Shocks:



Caviat about shock models previously shown: lowest metallicity for which fast radiative shock models exist is 1/5 solar

No O VI emission from shocks in FUSE spectrum (Grimes+09)

Is this sufficient to rule out shocks as the source of high ionization lines?



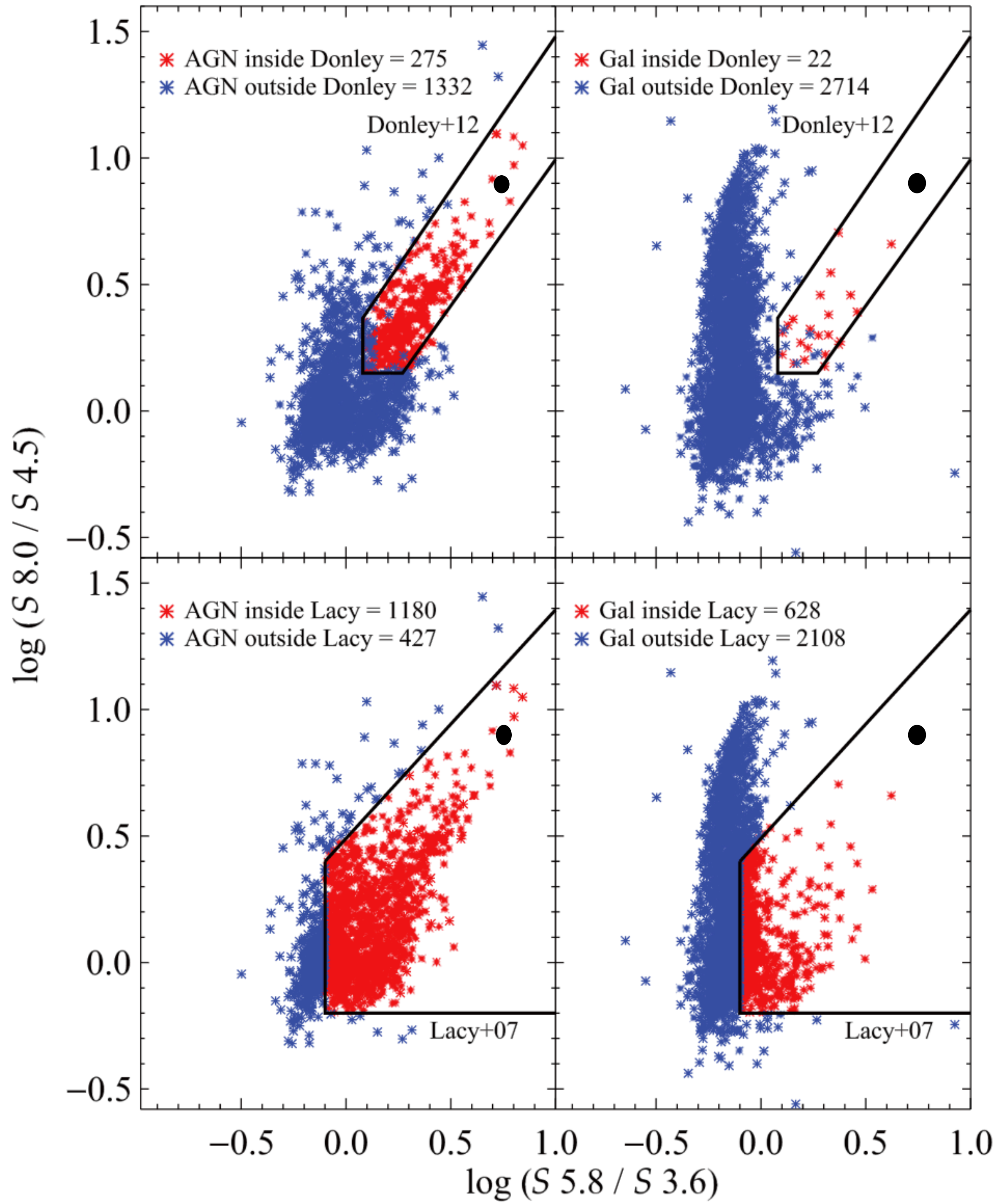
AGN

Fig. 7 of Delvecchio+14 showing Spitzer mid-IR color-color diagrams

Wedges are the AGN selection criteria of Donley+12 (top) and Lacy+07 (bottom)

We overlay SBS 0335-052E (black dot)

Using any of the wedges, SBS 0335-052 E would be selected as an AGN!!!



AGN continued...

Fig. 1 of Houck+04 showing Spitzer IRS spectrum of SBS (solid curve).

"If the spectrum of this very low-metallicity galaxy is representative of star-forming galaxies at higher redshifts, it may be difficult to distinguish them from active galactic nuclei, which also show relatively featureless flat spectra in the mid-IR."

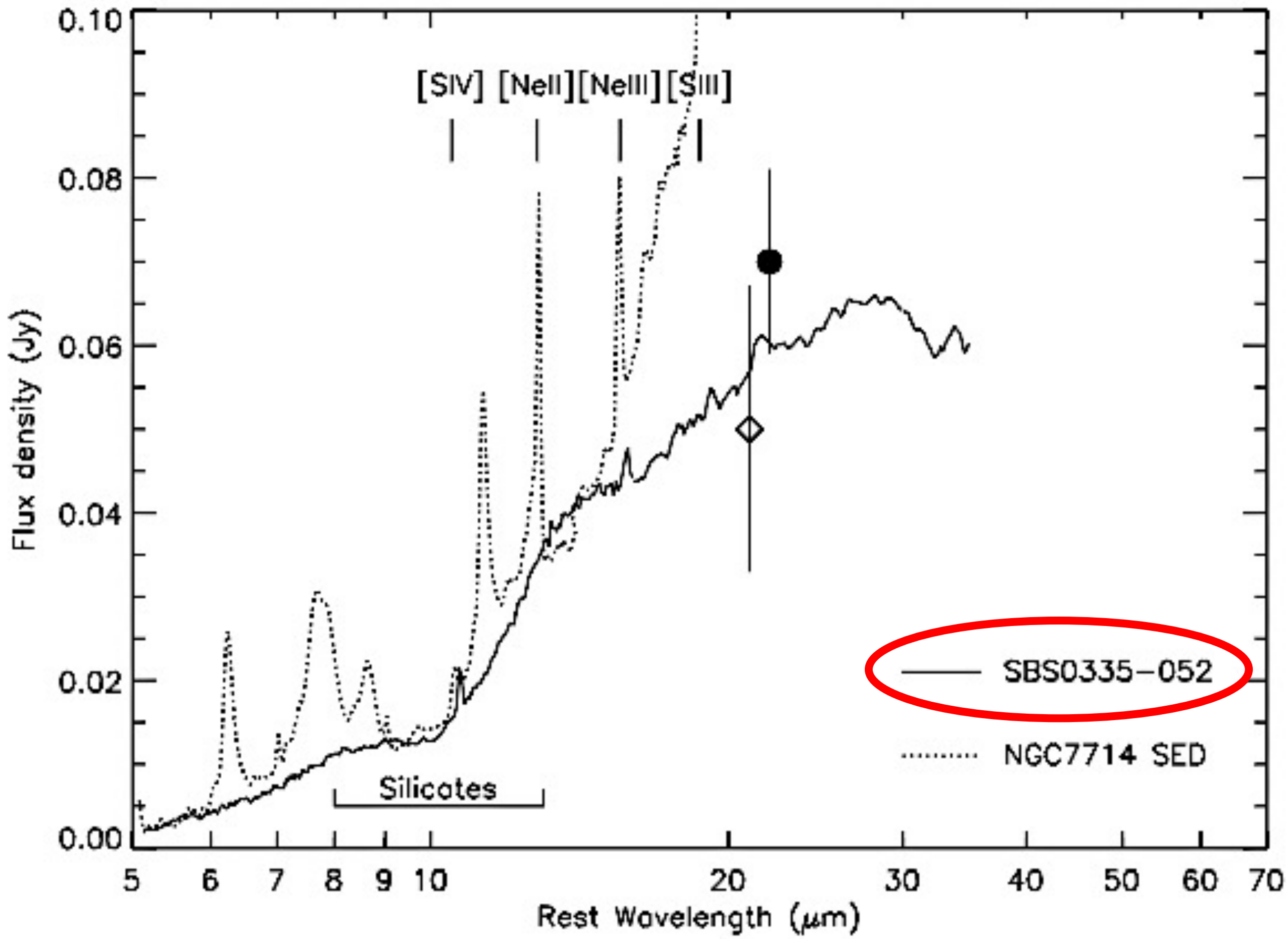
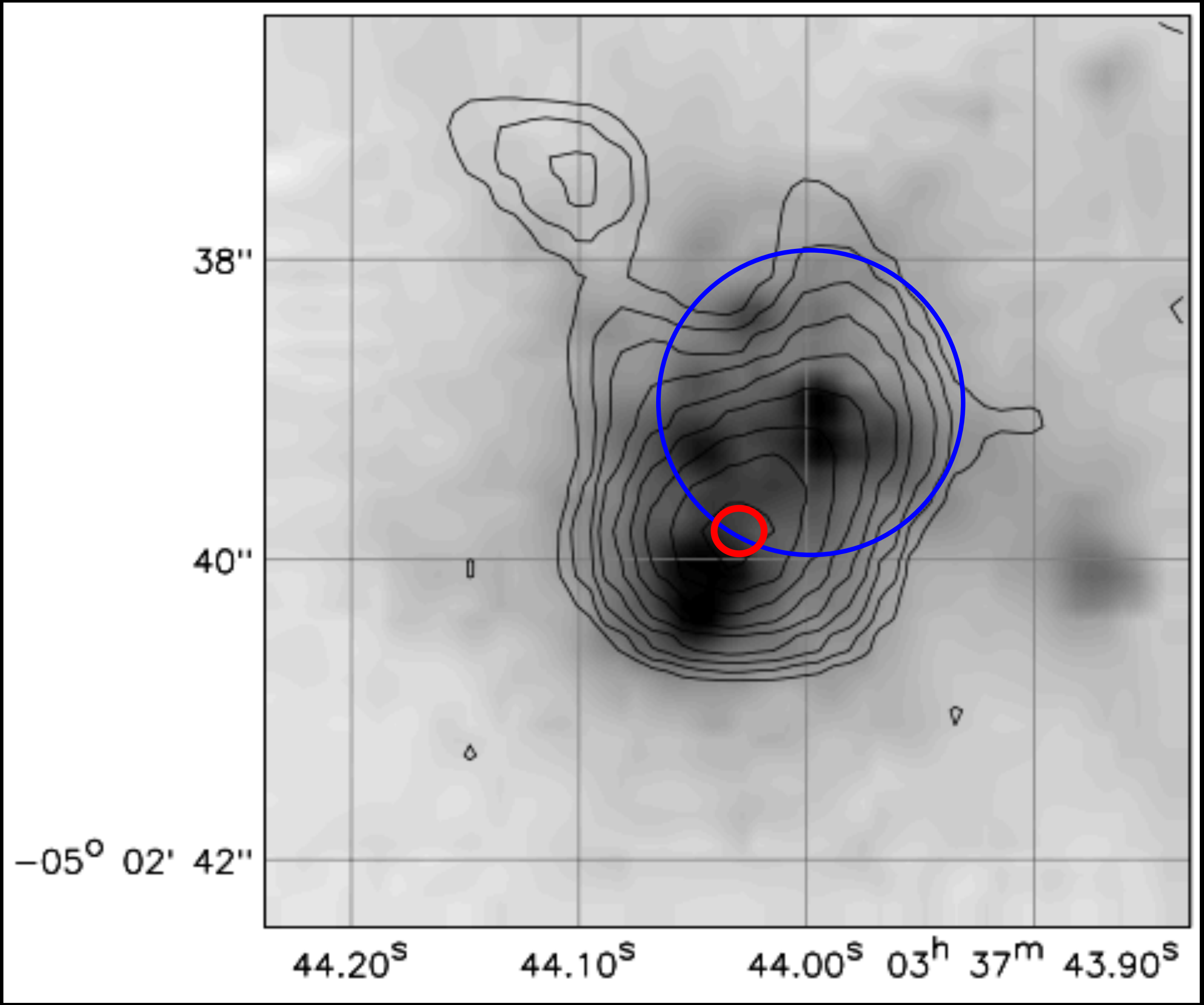


FIG. 1.—IRS low-resolution spectrum of SBS 0335−052 is presented (*solid line*) along with the spectrum of NGC 7714 (*dotted line*) from Brandl et al. (2004). The spectrum of NGC 7714 has been divided by 9.53 so that its 14 μm flux density matches that of SBS 0335−052. Note the complete lack of PAHs in the spectrum of SBS 0335−052 as well as the spectrum peak at ~30 μm (see § 3.1). The solid circle is our 22 μm peak-up photometric point, while the diamond corresponds to the 21 μm Gemini point from Plante & Sauvage (2002).

SBS 0335-052 E hosts x-ray binaries

Chandra X-ray contours on HST WFPC2 F569W image.

There is an X-ray point source located 0.3" N of SSC 2 (Izotov+04).

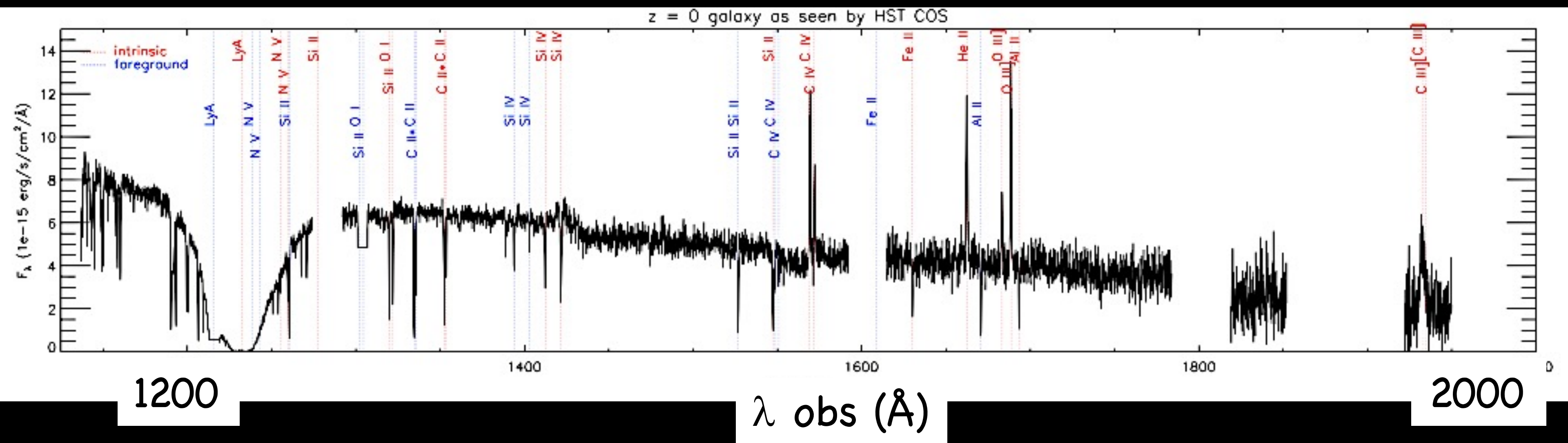


HST COS G130M + G160M + G185M spectrum of SBS 0335-052 E from ~1150 to ~1950 Å

Intrinsic lines have red IDs

Foreground lines have blue IDs

There are gaps between gratings

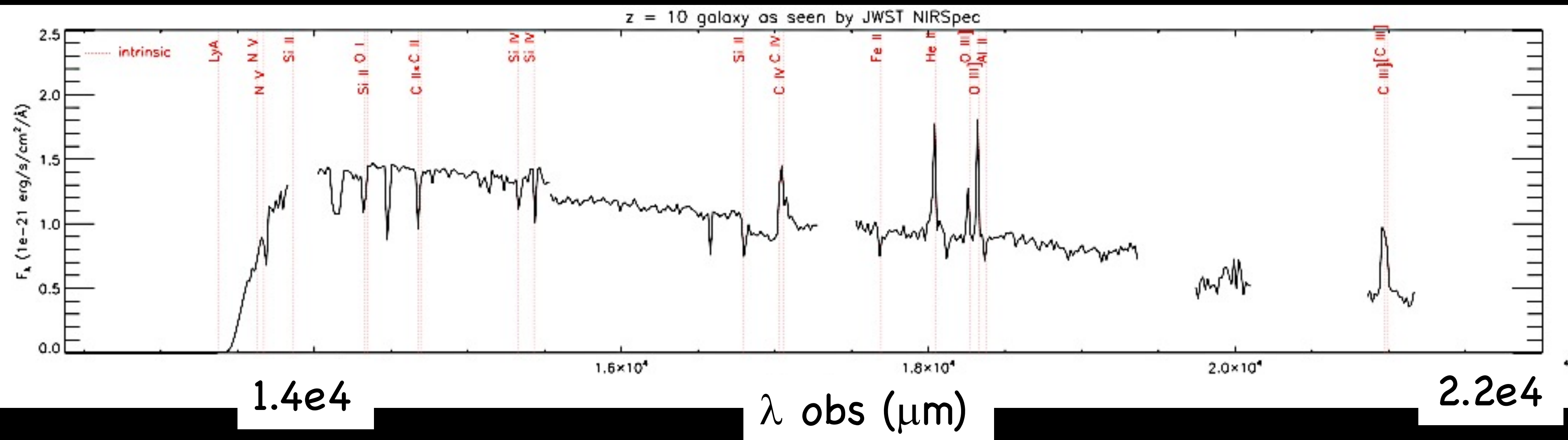


(PI, Aloisi)

(PI, Wofford)

Simulated JWST NIRSpec view of SBS at z=10

Intrinsic lines are marked with red vertical lines.



Obtained by: redshifting spectrum of SBS to z=10; diluting flux using the luminosity distance for cosmological parameters H_o=69.6, Ω_M=0.286, Ω_{vac}=0.714, and z=10; accounting for IGM absorption of UV photons using Madau (1995) attenuation; binning to the NIRSpec prism resolution of R~100 or FWHM=15.5 Å at 1550*(1+z) Å. The NIRSpec MSA prototype ETC assumes a point source centered in an open MSA shutter (0.2"x0.45") with background from two adjacent open shutters. The C IV blend at ~1.7 μm would be detected with S/N=6 per resolution element with an exposure time of 10^5 s.

Summary

At $Z \sim 3\%$ solar, C IV seen in absorption (no P-Cygni) and emission.

Reproducing observed EW of He II 1640 currently a challenge for pop. synthesis models (w/ and w/o binaries). Not quite ready to study peculiar massive stars via this line at higher z.

SBS 0335-052 E: MUSE optical line ratios consistent w/ H II regions & narrow-line AGN models. COS UV and Spitzer IR observations consistent exclusively w/ narrow-line AGN models. No evidence from continuum cm-observations for an AGN at location of COS aperture.

Other possibilities that we would like to explore in the SED models:

- x-ray binaries (SBS hosts a ULX at edge of COS aperture)
- lower metallicity shocks (lowest models currently available are Z~20% solar)

TAC: $Z \sim 2$-3% solar is the lowest metallicity which is measured in the ionized gas of nearby galaxies. XMPGs w/ this Z are *what is needed* to learn about how low metallicity determines the properties of galaxies.

Existing sample of UV spectra for such XMPGs includes only 4 SF regions in 3 galaxies. This is highly insufficient!!!

-3 SF have low SNR in observation of C III] 1909

- 1 galaxy has C IV 1548 affected by foreground contamination