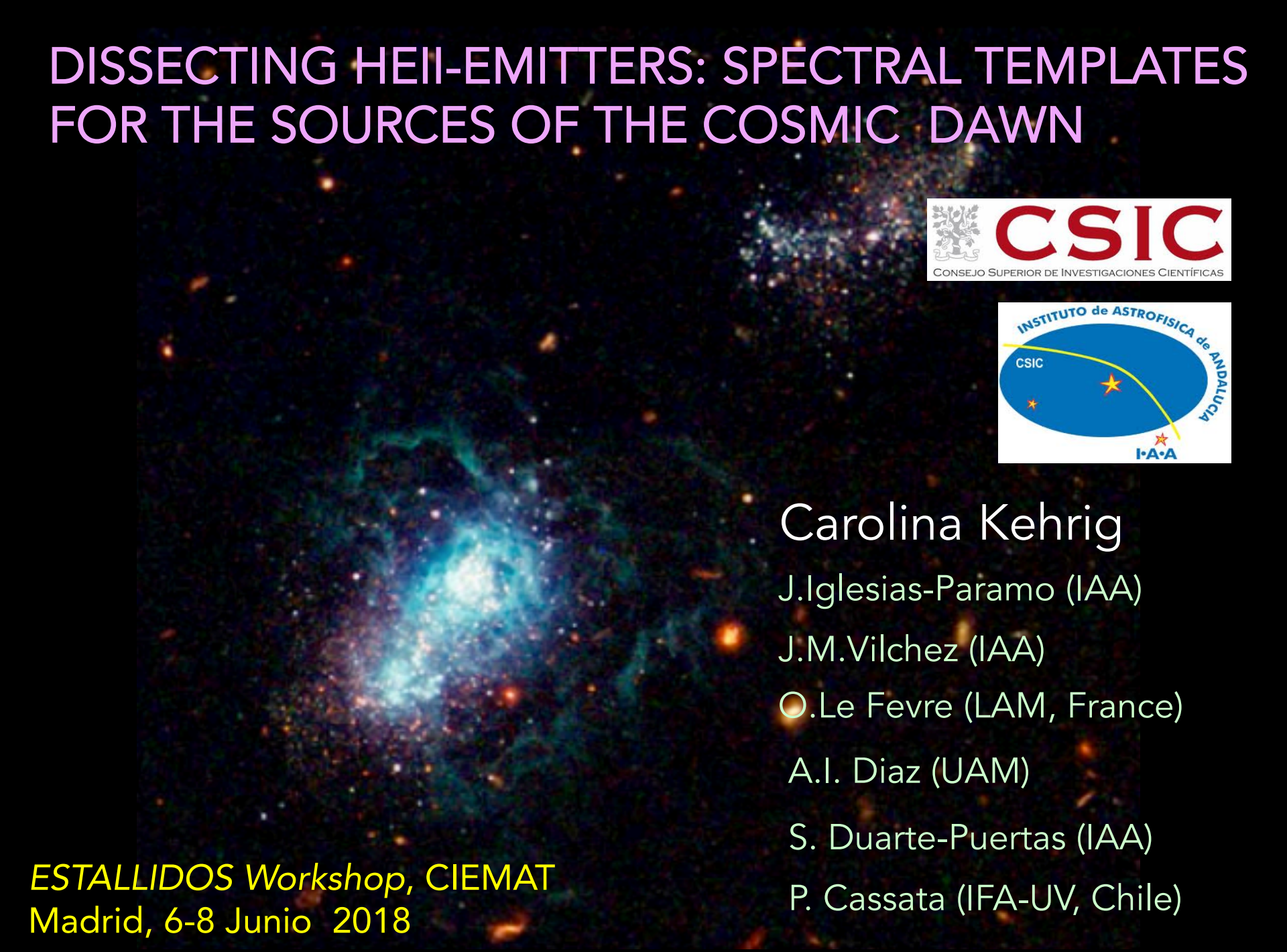
DISSECTING HEII-EMITTERS: SPECTRAL TEMPLATES FOR THE SOURCES OF THE COSMIC DAWN



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ESTALLIDOS Workshop, CIEMAT
Madrid, 6-8 Junio 2018

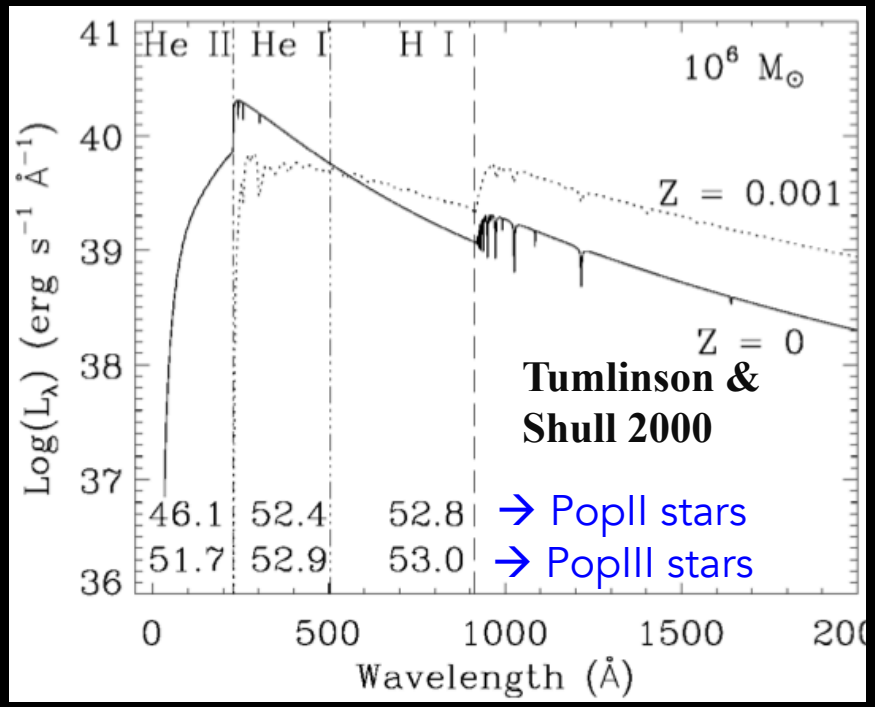
Why is the study of the HeII line relevant ?

✔ Nebular HeII emission (λ1640,4686 Å) is observed to be more frequent among SF galaxies at high-z than for local SF objects (e.g. Kehrig+2011; Cassata+2013;) and indicates extremely hard UV-emitting spectrum (E > 54 eV)

✔ Expected harder SED at the lower metallicities typical in the far-away Universe

Z	IMF	Q(H)	Q(HeI)	Q(HeII)
0.	A	46.98	46.75	45.54
0.	B	47.29	47.10	46.26
0.	C	47.98	47.80	47.05
10^{-7}	A	46.94	46.65	43.45
10^{-7}	B	47.30	47.06	45.61
10^{-7}	C	48.01	47.78	46.39
10^{-5}	A	46.90	46.55	42.39
10^{-5}	B	47.30	46.99	44.56
10^{-5}	C	48.02	47.73	45.35

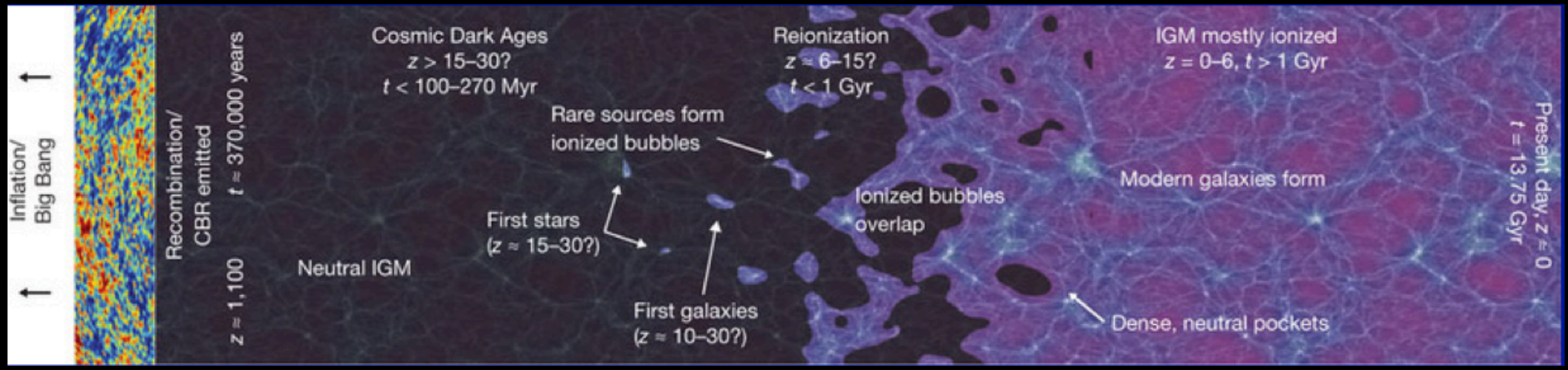
Schaerer (2003)
Q(X) [log(photon/s/$M_\odot$)]



Synthetic spectra of Population II and Population III clusters → PopIII stars can produce many HeII ionizing photons

Why is the study of the HeII line relevant ?

✔ High-ionization HeII line: window into the ionizing spectrum of metal-poor hot stars and one of the best tracers of PopIII stars (e.g., Schaerer 2003; Johnson+2009) → "first lights" that appear during the cosmic dawn (6 < z < 10)



The nature of the sources responsible for the Universe reionization is currently unconstrained and subject of considerable observational and theoretical efforts.

Searching for PopIII galaxies is one of the main science drivers for next-generation telescopes (e.g. JWST, ELT; Johnson 2010; Visbal+2015)

✔ The gas properties and stars necessary and sufficient to power such high-ionizing emission remains unclear in many cases; before interpreting z > 6 HeII-emitters and use HeII line to infer properties of distant starburst, it is crucial to understand the formation of HeII line at lower redshifts!

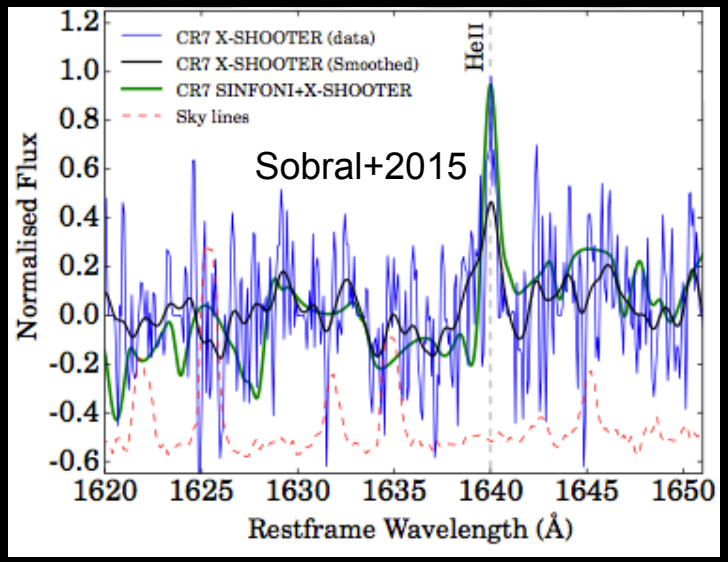
HeII ionization: the observational reality

✔ Sources of ionizing radiation (hot Wolf-Rayet (WR) stars, fast shocks, X-ray binaries) have been proposed to explain the HeII ionization in local star-forming systems (e.g., Garnett+1991; Schaerer 1996; Thuan & Izotov 2005; Gräfener & Vink 2015)

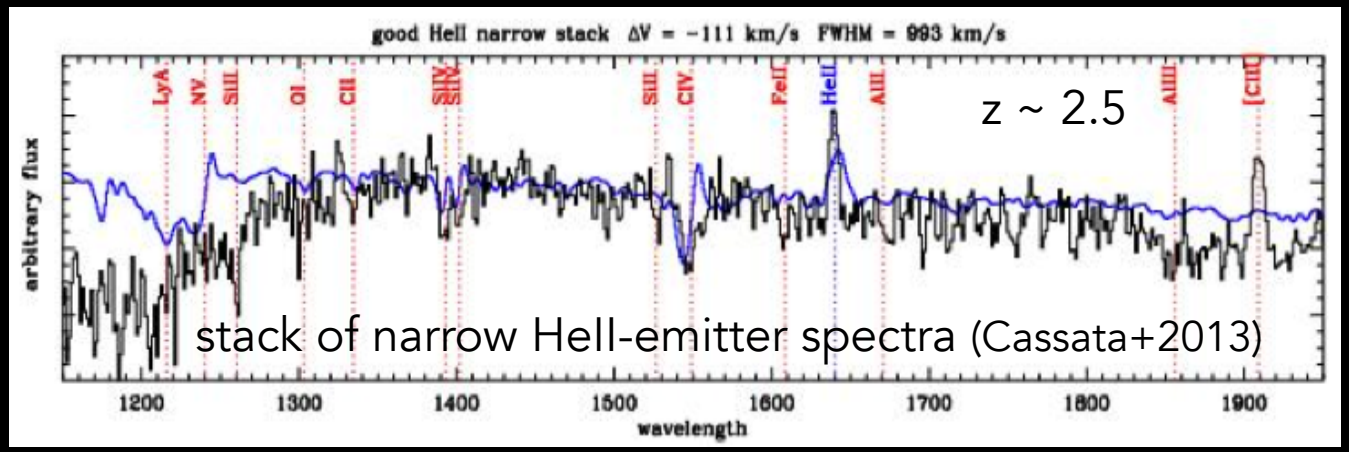
✔ Nebular HeII does not appear to be always associated with WRs and the origin of the HeII ionization in several SF objects remains unclear → (e.g. Guseva+2001; Shirazi & Brinchmann 2012; Kehrig+2013)

HeII ionization: The observational reality

Nebular HeII does not appear to be always associated with WRs → WRs cannot explain the HeII ionization in all cases, particularly at low metallicity (e.g. Guseva+2001; Shirazi & Brinchmann 2012; Kehrig+2013)



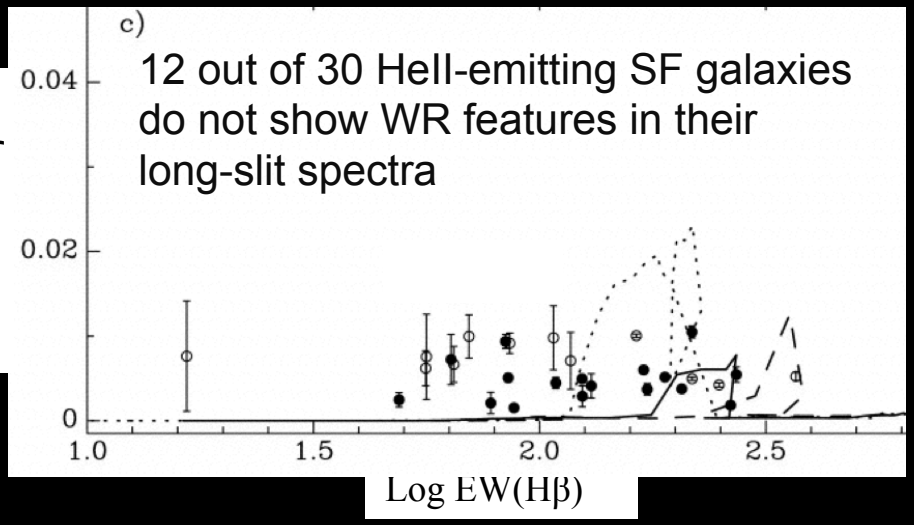
CR7 (the brightest Lyα emitter at z = 6.6): WR star interpretation is strongly disfavoured. PopIII stars or Black Hole ? (e.g. Sobral+2015; Agarwal+2017; Bowler+2017)



Stellar population models including WRs do not reproduce the properties of the narrow HeII emitters. Peculiar stellar population or popIII stars ? (see also Grafener & Vink 2015)

HeII ionization in the local Universe: The observational reality

Guseva et al. (2000)



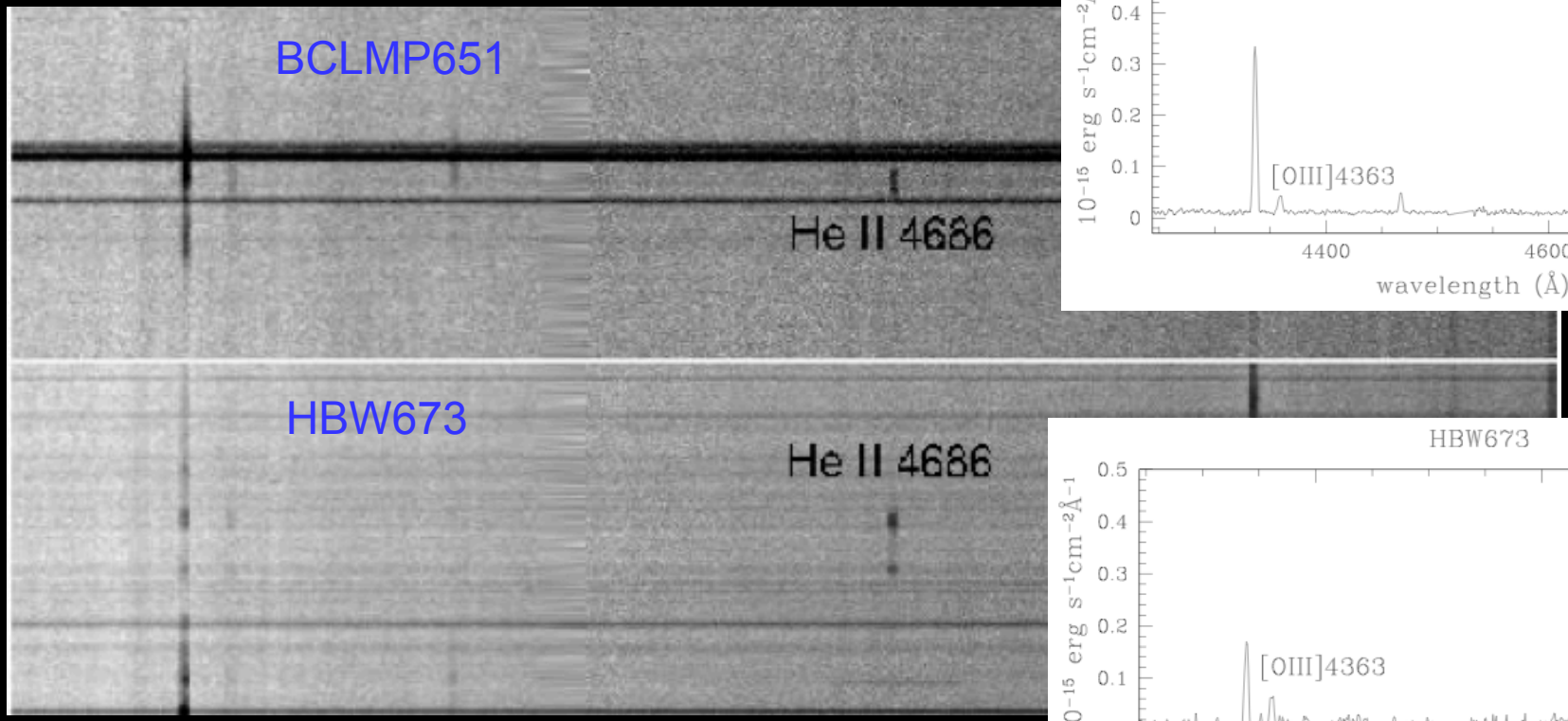
galaxies with detected and nondetected WR features are indistinguishable and other mechanisms for the origin of nebular HeII need to be invoked

Shirazy & Brinchmann (2012): 40% of the HeII-emitting SF galaxies from SDSS do not show WR signatures → lack of WR features does not seem to be a S/N issue

HeII ionization in the local Universe: The observational reality

The origin of the nebular HeII still remains difficult to understand in many cases

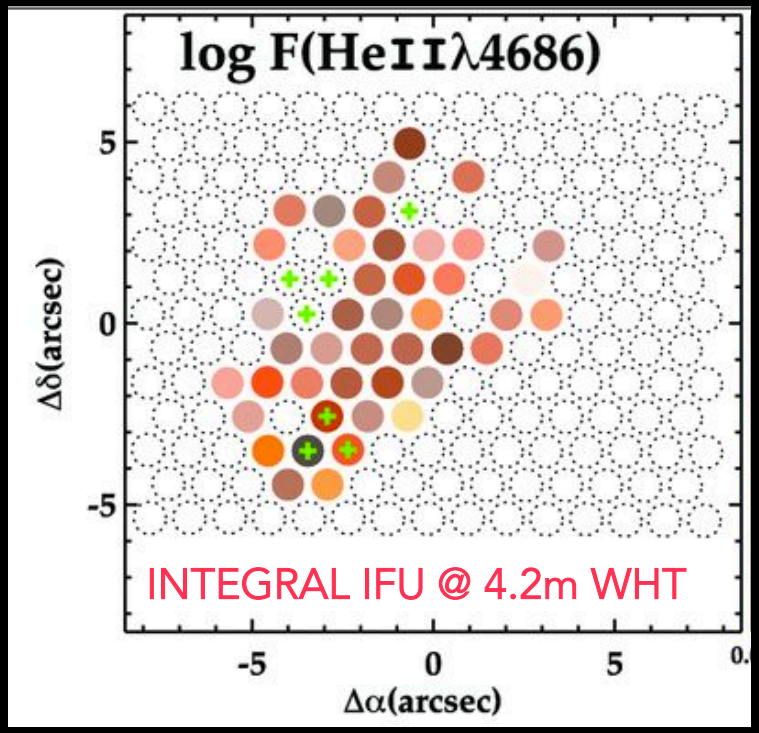
GMOS/GEMINI spectroscopy of HeII nebulae in M33 (Kehrig, Oey, Crowther+2011)



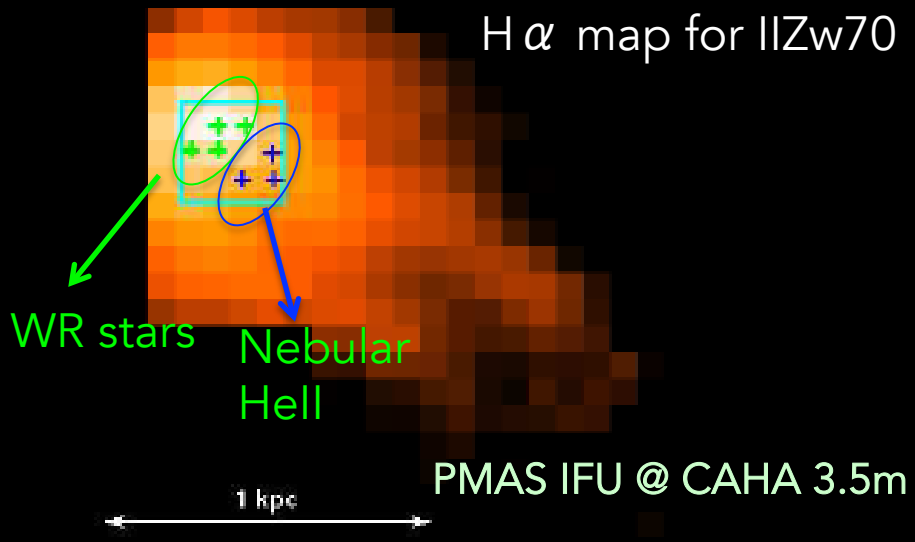
2 new HeII nebulae in M33 not associated with any hot massive star

HeII ionization in the local Universe from IFS

Mrk178 (Z ~ 10% $Z_\odot$) and IIZw70 (Z ~ 15% $Z_\odot$): HeII emission is extended and goes much beyond the location of WR stars



Kehrig,Vilchez+2013



Kehrig,Vilchez+2008

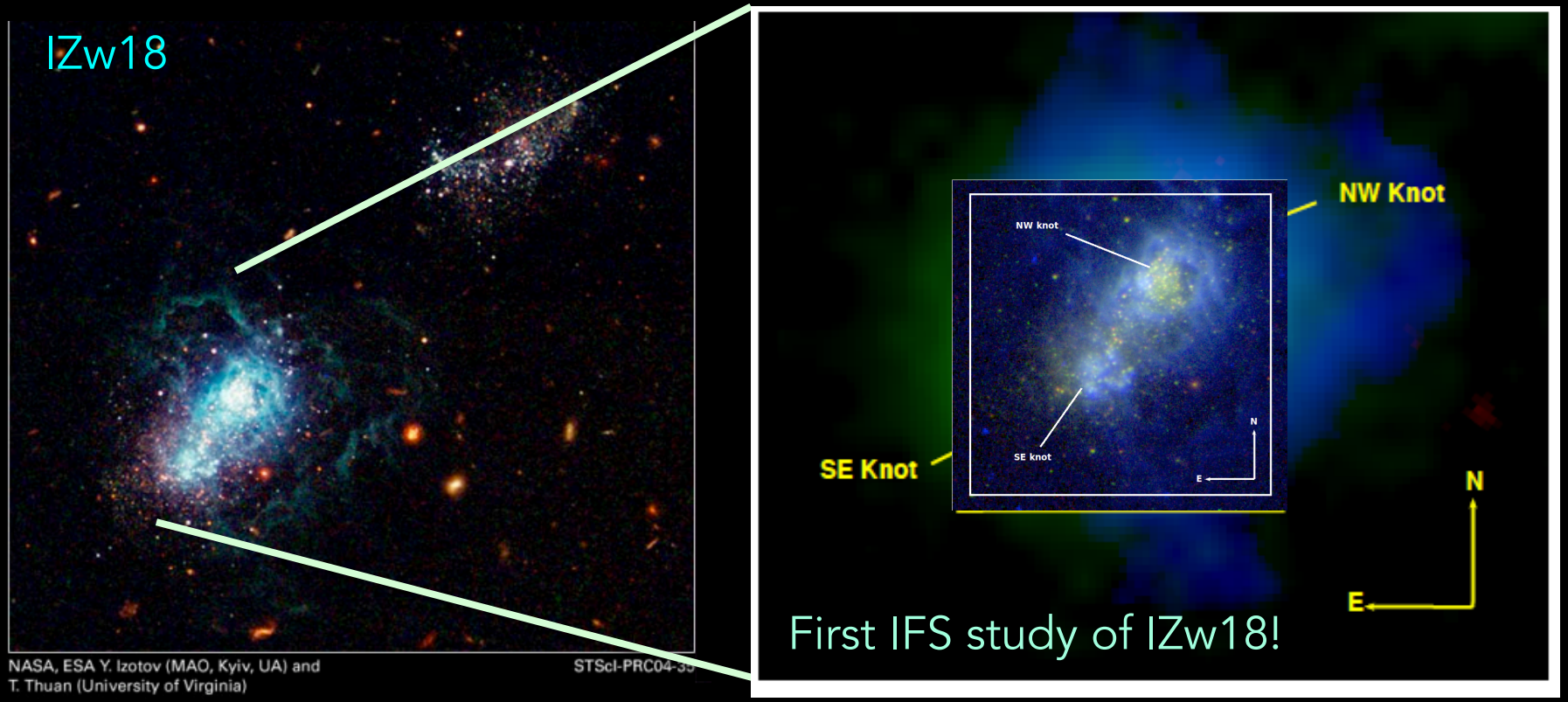
IFS: Spatial separation between WR stars and the HeII-emitting zone (see also Izotov+2006; Herenz+2017), and where the non-detection of WR features is unlikely to be an effect of the weakness of WR bumps (see also Shirazi & Brinchmann 2012)

The first IFS study of IZw18!

Kehrig, Vilchez et al. (2015,2016)

The nearby lowest-metallicity (Z~0.0004) SF galaxy and our best local analog of faraway starbursts (e.g. Skillman & Kennicutt 1993; Vilchez & Iglesias-Paramo 1998)

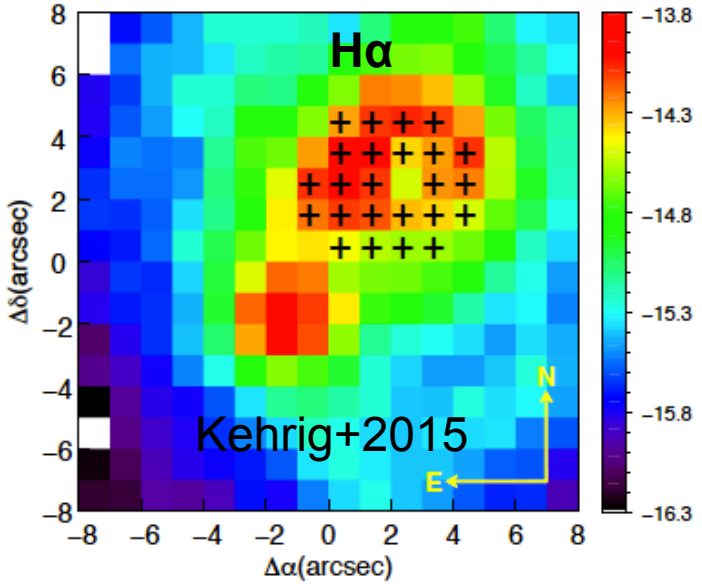
Natural local counterpart of distant HeII-emitters!

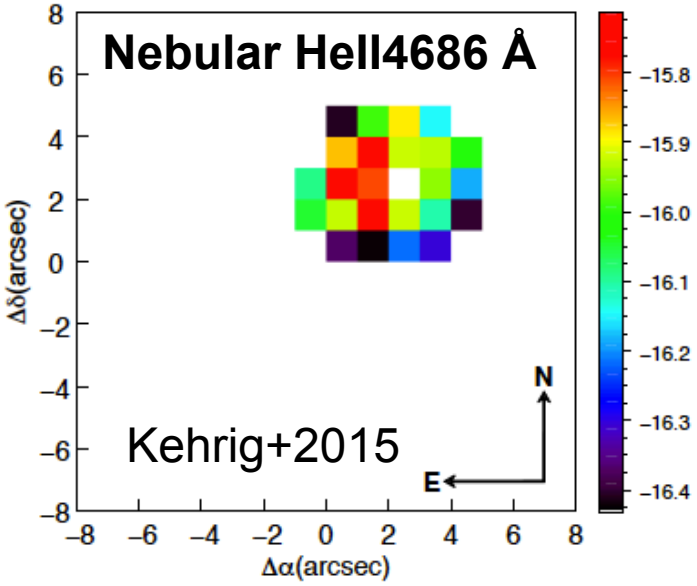


FOV ~ 1.4 kpc x 1.4 kpc

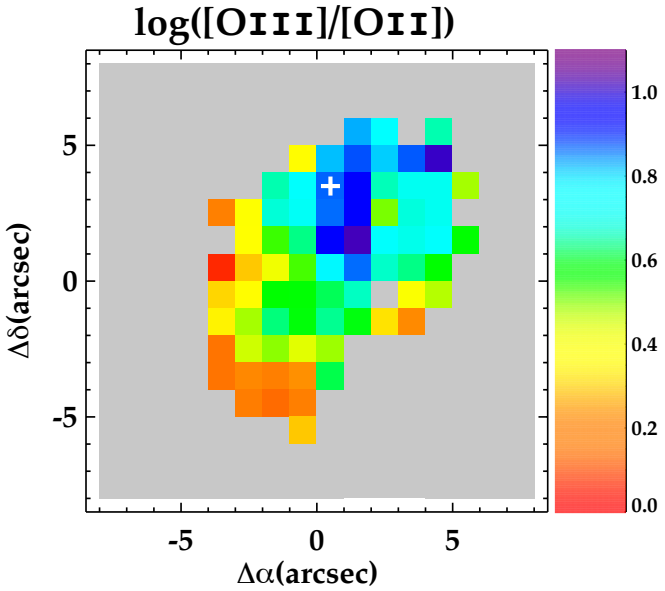
Optical spectra: PMAS IFU @ CAHA 3.5m telescope

We discovered a large nebular HeII4686-emitting region





1"/spaxel ~ 88 pc/ spaxel @ D=18.2 Mpc



NW knot and thereabouts:

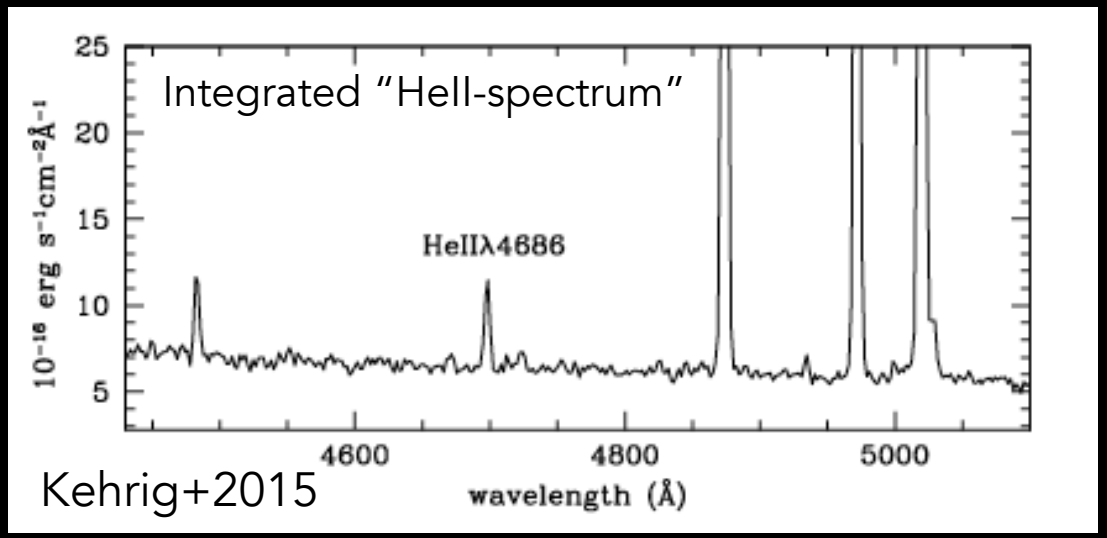
- ✔ Most of higher-Te[OIII] (> 22000 K) spaxels
- ✔ Higher excitation gas and ionization parameter
- ✔ Nebular HeII-emitting region

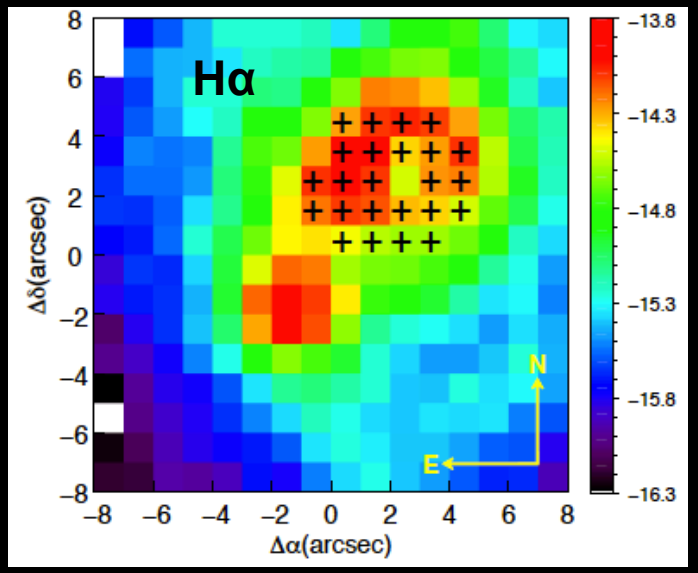
Existence of a harder radiation field

Our IFU data reveal for the first time: total spatial extent and precise location of the nebular HeII region, and the corresponding total HeII-ionizing flux in IZw18!

Kehrig, Vilchez+2015, ApJL

What is the main source powering nebular HeII emission in IZw18 ?





Total L(HeII4686)$_{obs}$ ➔ Q(HeII)$_{obs}$ = Total HeII-ionizing photon flux

Conventional HeII-ionizing sources (WRs, shocks, X-ray binaries) are not sufficient to explain the observed HeII emission in IZw18.

Peculiar very hot stars in IZw18 are required to explain the HeII ionization

metal-free ionizing stars (PopIII-like stars; Yoon+2012) ? (see also Senchyna+2017)

The extended HeIIλ4686 emission in the extremely metal-poor galaxy SBS 0335-052E seen with MUSE*

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Av. Vallarta No. 2602, C.P. 44130, Guadalajara, Jalisco, Mexico

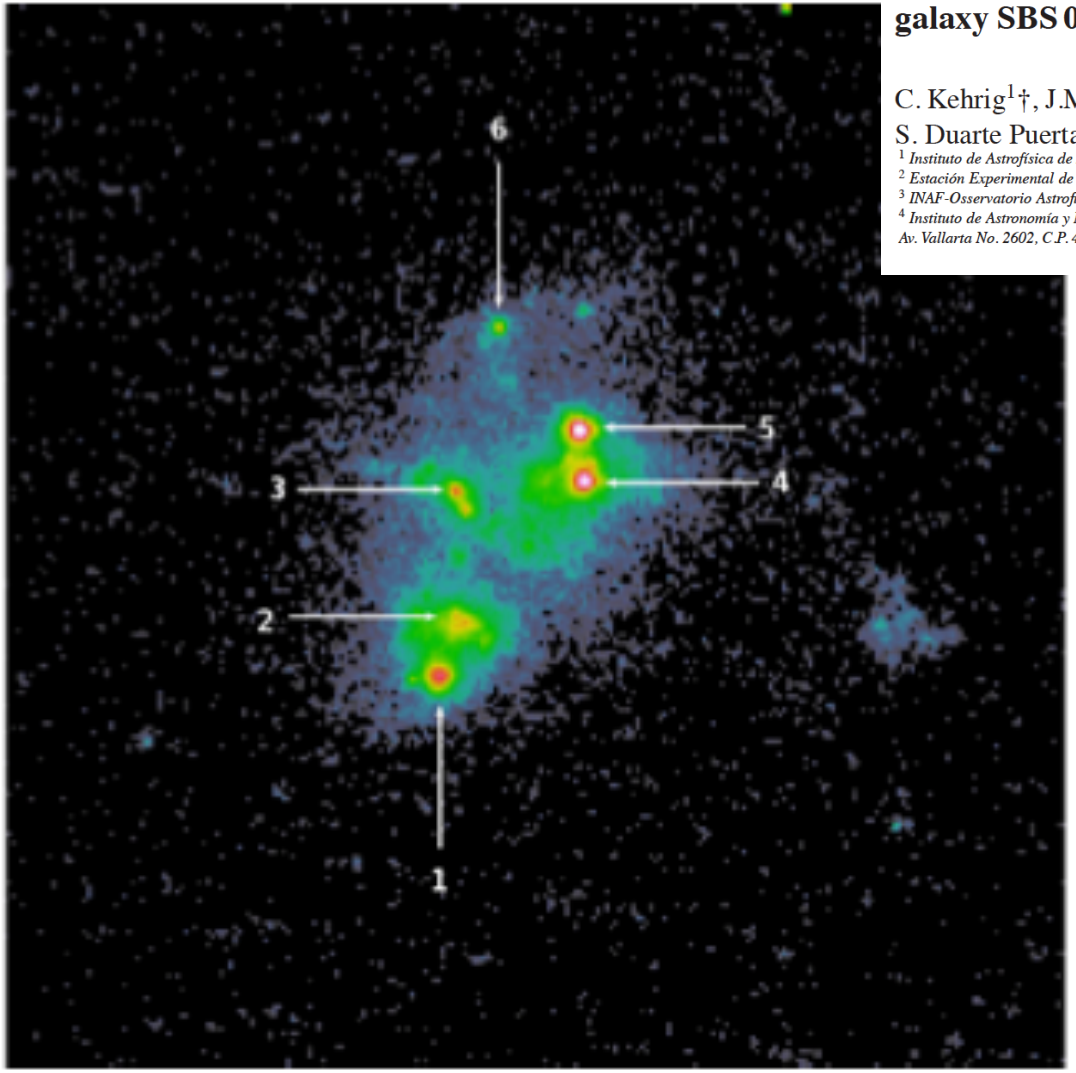


Figure 1. HST ACS/F220W archival image of SBS 0335-052E (HST Proposal ID 10575; PI: G.Östlin). The brightest SSCs as identified by Thuan et al. (1997) are labeled. The image is 6" × 6". North is up and east is to the left.

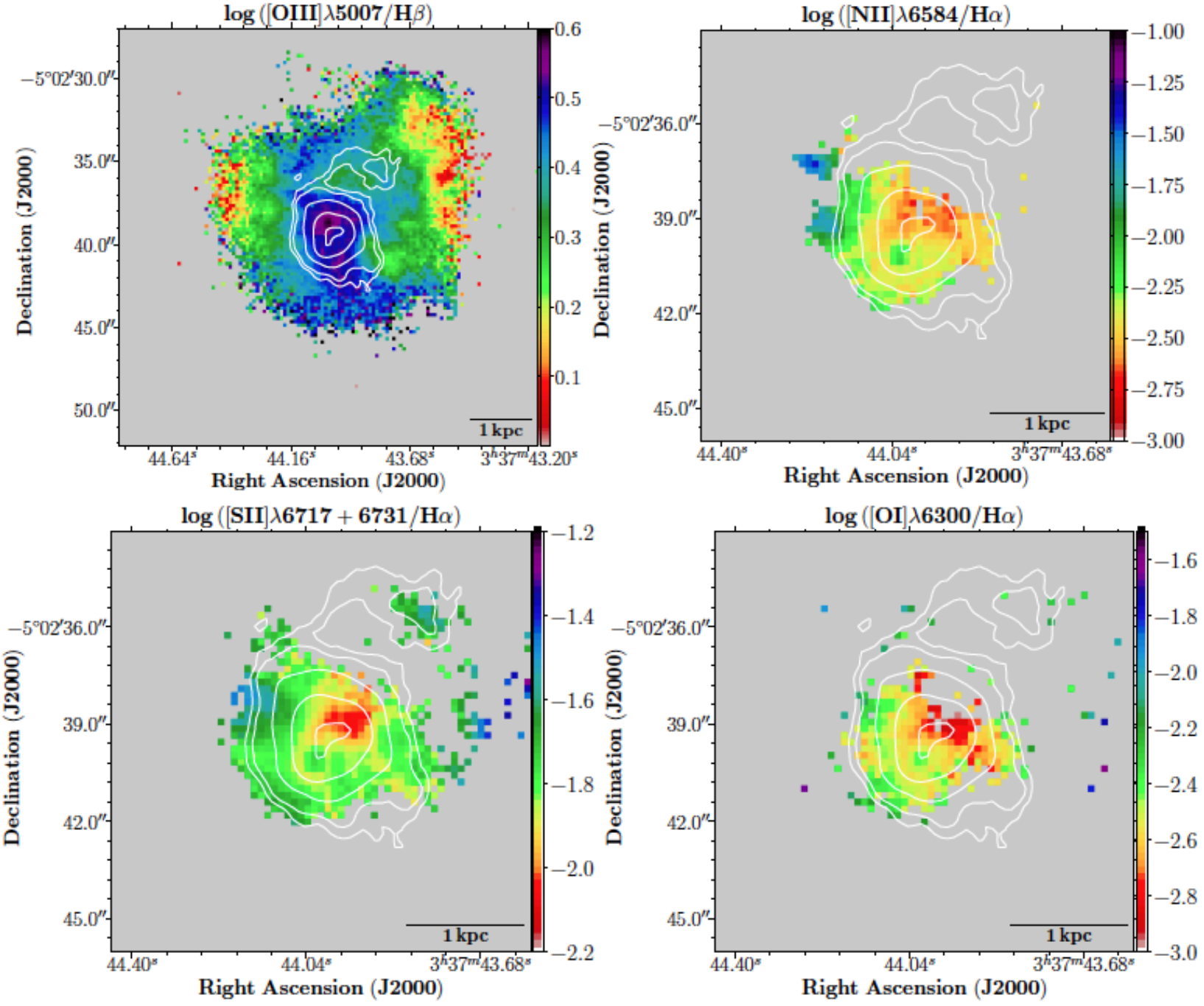
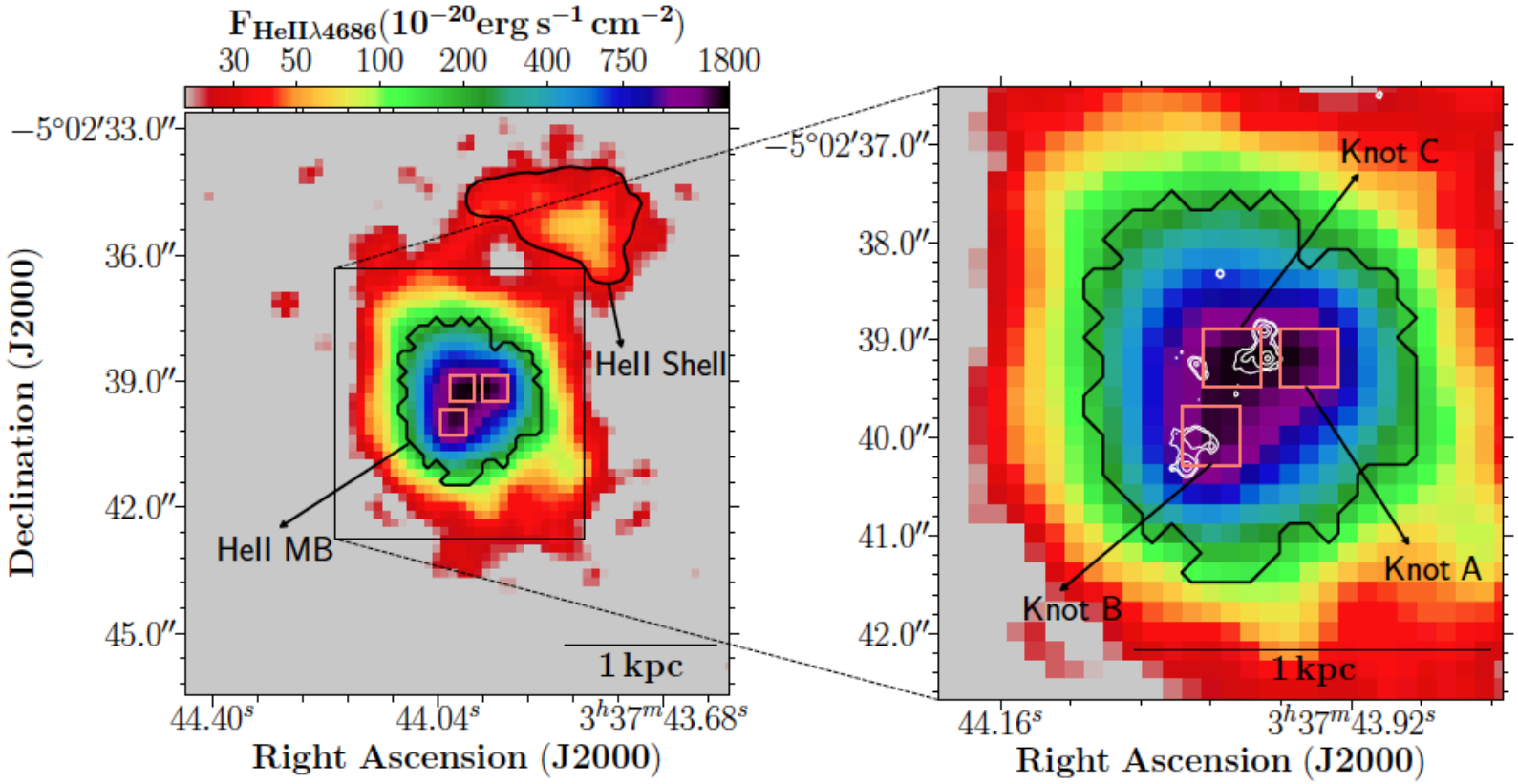


Figure 7. Line ratio maps of SBS 0335-052E: [OIII]λ5007/Hβ, [NII]λ6584/Hα, [SII]λ6717,6731/Hα, [OI]λ6300/Hα. Only line fluxes with S/N (per pixel) >


$F_{HeII\lambda4686}(10^{-20}erg\,s^{-1}\,cm^{-2})$
30 50 100 200 400 750 1800
−5°02′33.0″
36.0″
39.0″
42.0″
45.0″
Declination (J2000)
HeII Shell
HeII MB
1 kpc
44.40s
44.04s
3h37m43.68s
Right Ascension (J2000)
−5°02′37.0″
38.0″
39.0″
40.0″
41.0″
42.0″
Knot C
Knot A
Knot B
1 kpc
44.16s
3h37m43.92s
Right Ascension (J2000)

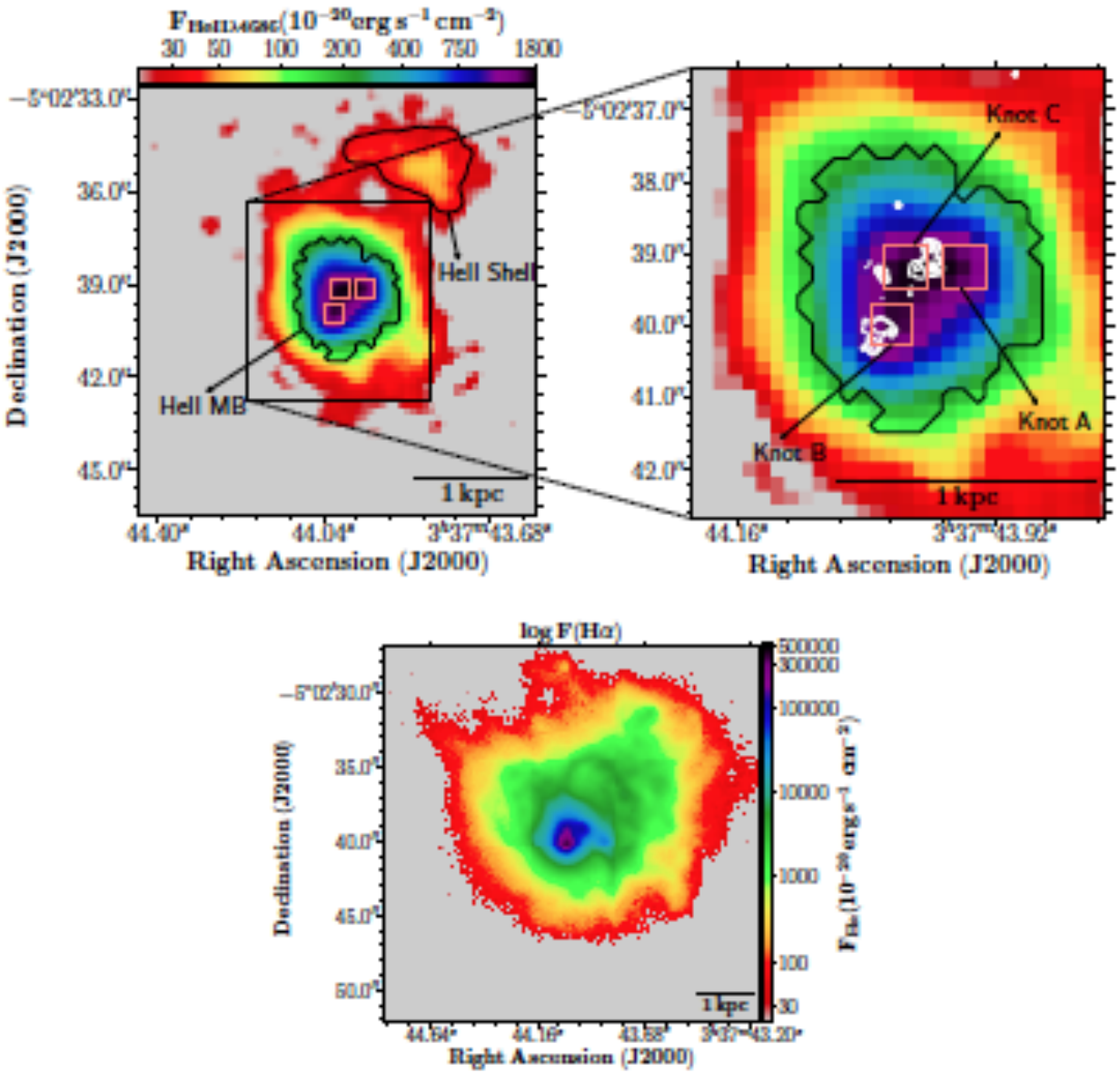
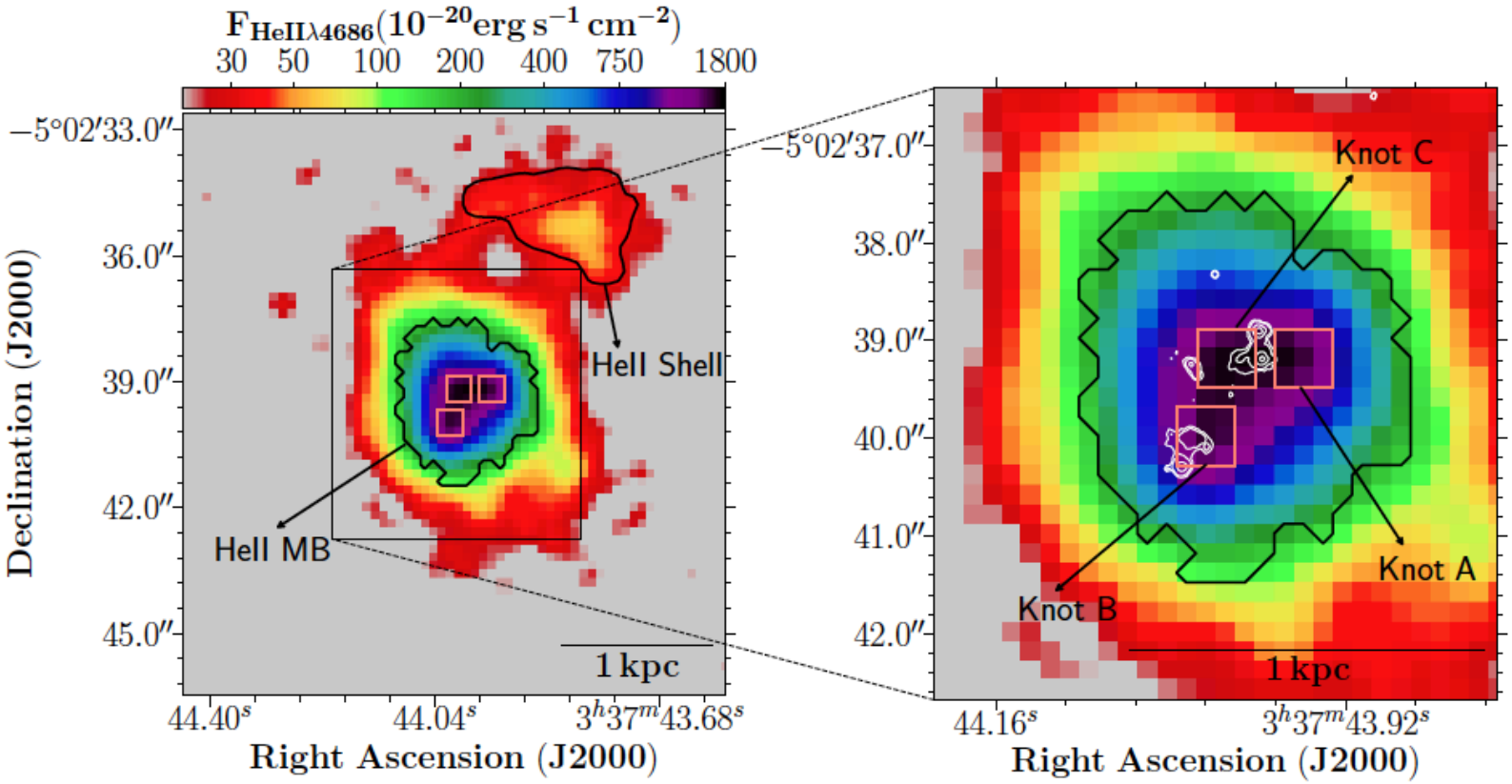
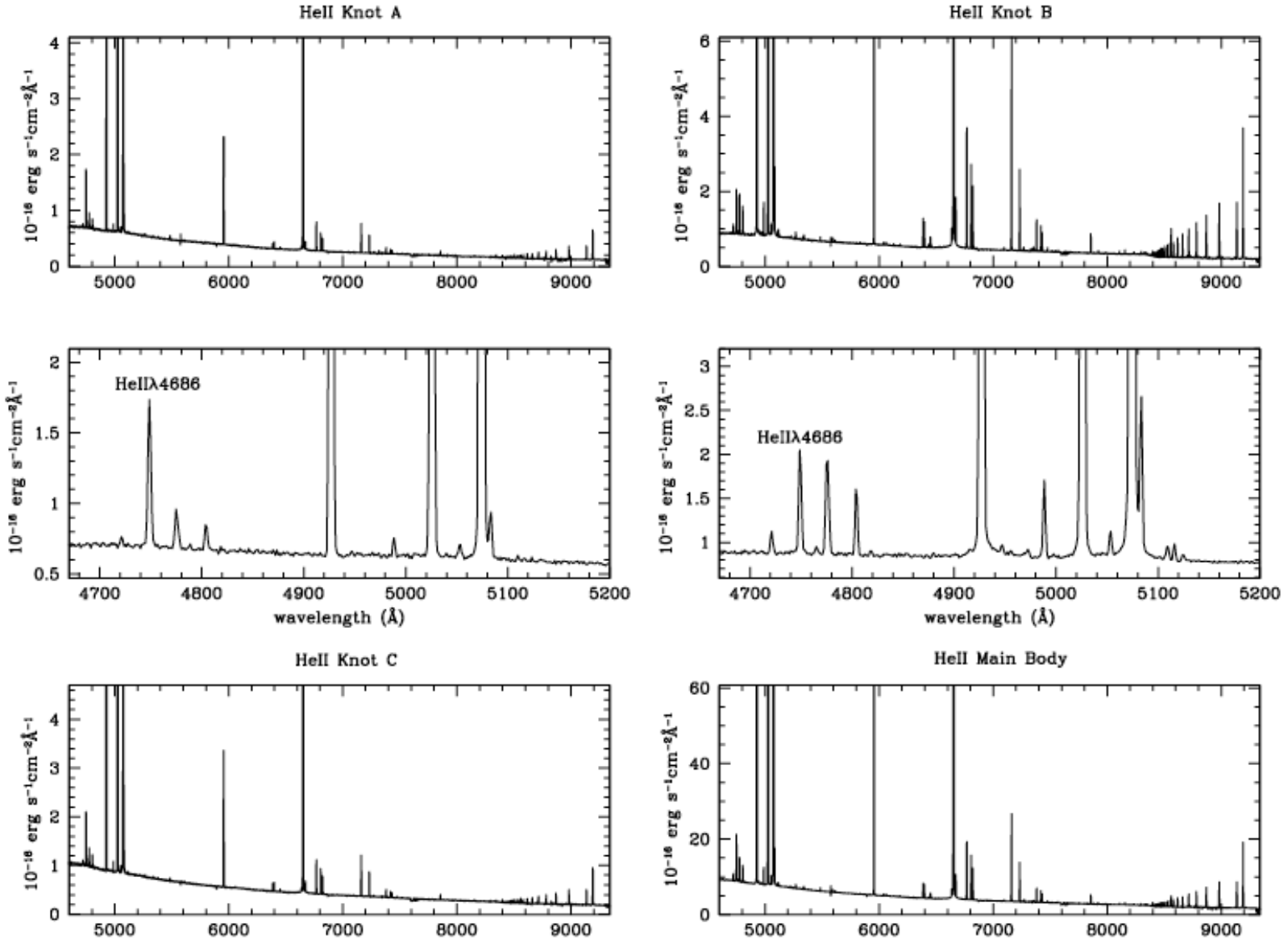


Figure 3. *Top row*: The HeII λ4686 map in two different scales showing the boundaries of the areas that we use to create the integrated spectra of the HeII-emitting regions: HeII shell, HeII main body, and HeII knots A,B,C (see text and table 1 for details); in the top-right panel the white lines mark the location of the brightest SSCs of SBS 0335-052E (see Fig.1). *Bottom row*: The Hα map showing only the spaxels with Hα S/N (per pixel) > 10. North is up and east to the left.


F_HeIIλ4686(10^−20 erg s^−1 cm^−2)
30 50 100 200 400 750 1800
−5°02′33.0″
36.0″
39.0″
42.0″
45.0″
Declination (J2000)
HeII Shell
HeII MB
1 kpc
44.40^s
44.04^s
3^h37^m43.68^s
Right Ascension (J2000)
−5°02′37.0″
38.0″
39.0″
40.0″
41.0″
42.0″
Knot C
Knot A
Knot B
1 kpc
44.16^s
3^h37^m43.92^s
Right Ascension (J2000)


HeII Knot A
HeII Knot B
HeIIλ4686
HeIIλ4686
wavelength (Å)
wavelength (Å)
HeII Knot C
HeII Main Body
10^{-16} erg s^{-1}cm^{-2}Å^{-1}

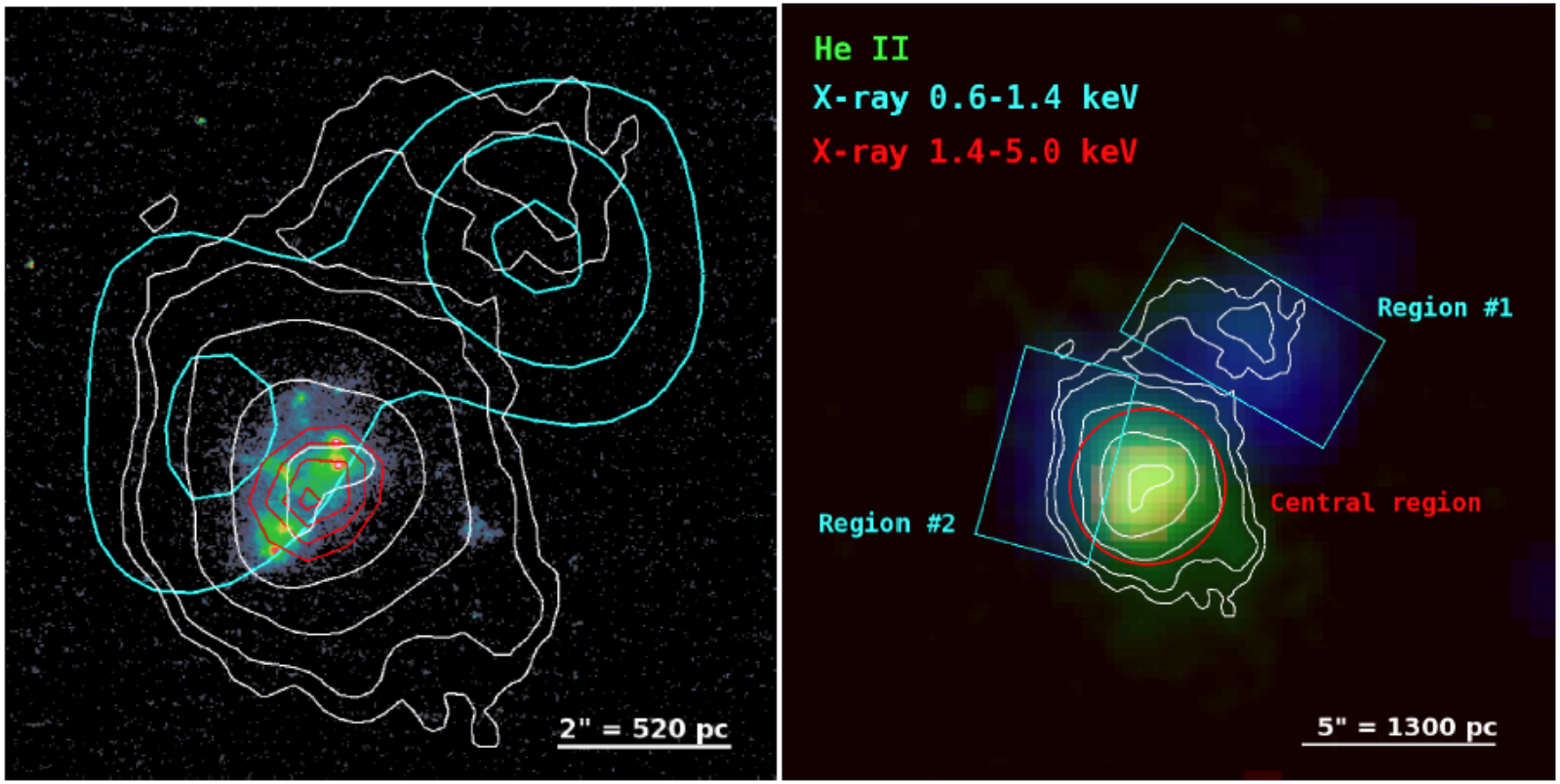


Figure 5. Left panel: Soft (cyan lines) and hard (red lines) X-ray contours overlaid on the HST ACS/F220W image of SBS 0335-052E. Right panel: Colour composite image of SBS 0335-052E in three bandpasses (blue = soft X-rays, red = hard X-rays, green = HeIIλ4686 flux image). In both panels, the white curves represent the isocontours of the HeIIλ4686 emission line flux. North is up and east is to the left.

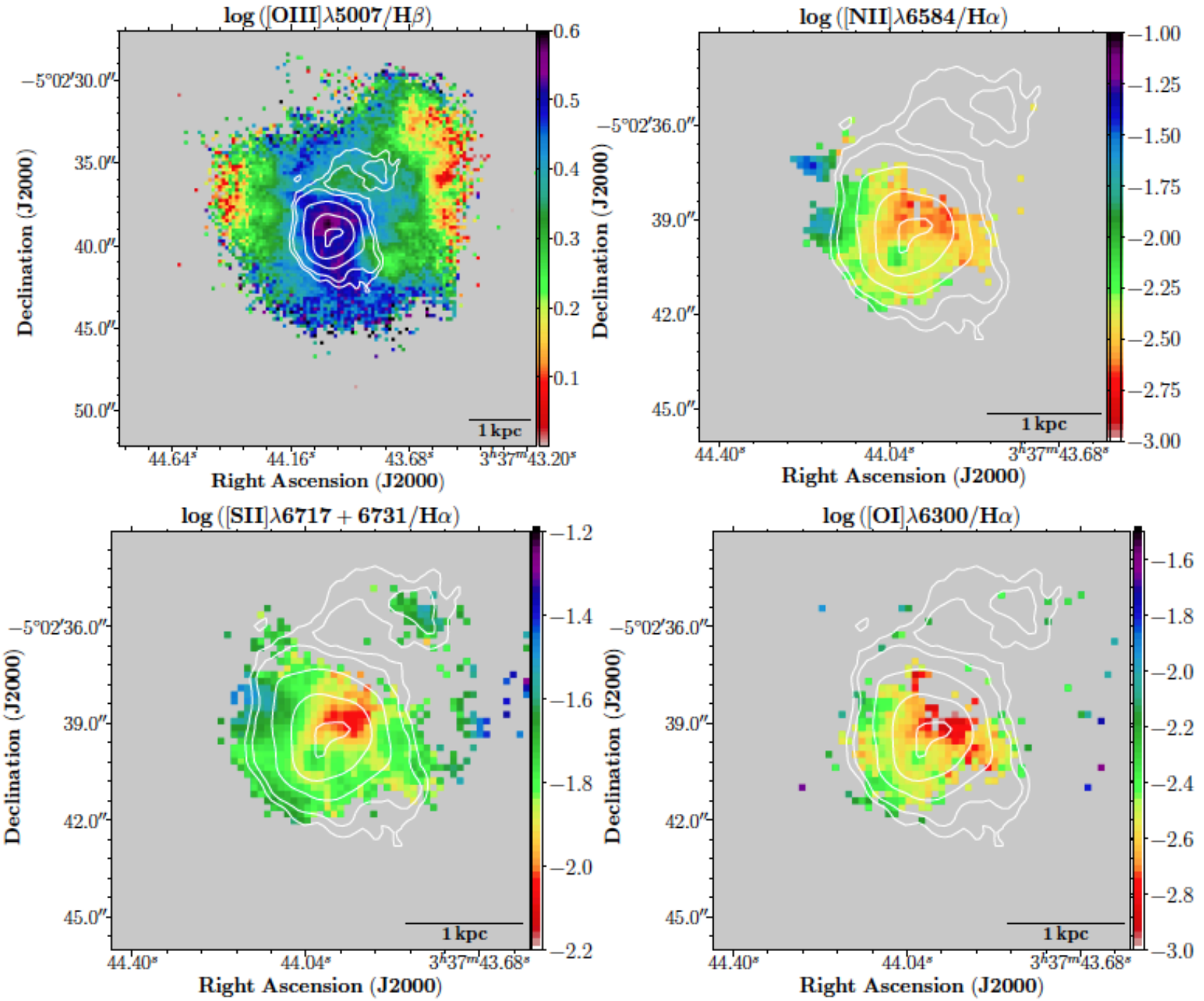


Figure 7. Line ratio maps of SBS 0335-052E: [OIII]λ5007/Hβ, [NII]λ6584/Hα, [SII]λ6717,6731/Hα, [OI]λ6300/Hα. Only line fluxes with S/N (per pixel) >

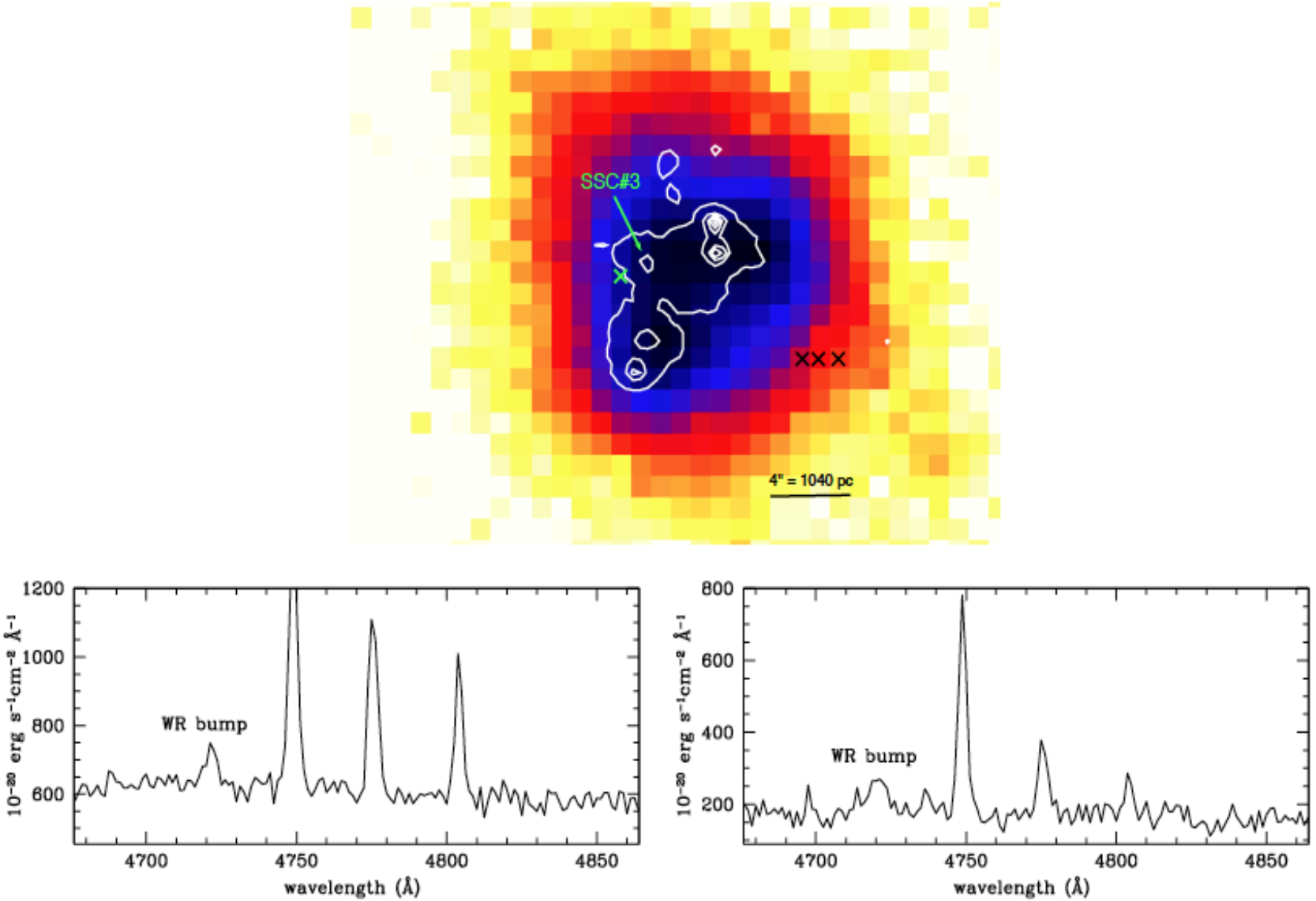


Figure 8. *Top panel*: Nebular HeIIλ4686 map centered on the massive young SSCs whose positions are represented by the white countours. The crosses indicate the location of the WR knots detected in this work. *Bottom row*: spectra showing the WR bumps. *Bottom-left panel*: spectrum of the spaxel nearby SSC#3, indicated by the green cross in the *top panel*; *Bottom-right panel*: spectrum obtained by adding the emission from the 3 spaxels marked with black crosses in the *top panel*.

IMF [a]	Z ($Z/Z_\odot$) [b]	Q(HeII) photon s^{-1}	
		Single	Binary
imf100-100[c]	10^{-5} (0.05 %)	1.40×10^{49}	7.89×10^{50}
	10^{-4} (0.5 %)	6.45×10^{48}	3.40×10^{50}
	0.001 (5 %)	5.05×10^{46}	2.18×10^{49}
imf100-300[c]	10^{-5} (0.05 %)	1.20×10^{49}	7.37×10^{50}
	10^{-4} (0.5 %)	6.16×10^{48}	3.48×10^{50}
	0.001 (5 %)	4.30×10^{46}	2.39×10^{49}
imf135all-100[d]	10^{-5} (0.05 %)	5.01×10^{48}	2.09×10^{50}
	10^{-4} (0.5 %)	2.29×10^{48}	8.97×10^{49}
	0.001 (5 %)	1.77×10^{46}	5.94×10^{48}
imf135-100[e]	10^{-5} (0.05 %)	6.87×10^{48}	2.71×10^{50}
	10^{-4} (0.5 %)	3.10×10^{48}	1.16×10^{50}
	0.001 (5 %)	2.40×10^{46}	7.68×10^{48}
imf135-300[e]	10^{-5} (0.05 %)	6.59×10^{48}	2.79×10^{50}
	10^{-4} (0.5 %)	2.98×10^{48}	1.27×10^{50}
	0.001 (5 %)	2.30×10^{46}	8.99×10^{48}
imf170-100[f]	10^{-5} (0.05 %)	2.60×10^{48}	7.22×10^{49}
	10^{-4} (0.5 %)	1.16×10^{48}	3.07×10^{49}
	0.001 (5 %)	8.77×10^{45}	2.13×10^{48}
imf170-300[f]	10^{-5} (0.05 %)	2.58×10^{48}	7.62×10^{49}
	10^{-4} (0.5 %)	1.15×10^{48}	3.43×10^{49}
	0.001 (5 %)	8.70×10^{45}	2.46×10^{48}

[a] IMFs are labelled following the BPASSv2.1 designation (Eldridge et al. 2017)

[b] BPASS models assume $Z_\odot$=0.02 for consistency with their empirical mass-loss rates which were scaled from this value.

[c] imf100-100: α_1=-1.30 (0.1-0.5 $M_\odot$), α_2=-2.00 (0.5-100 $M_\odot$); imf100-300: as imf100-100 but with M_{up}=300 $M_\odot$

[d] Salpeter IMF with M_{up}=100 $M_\odot$

[e] These are the default IMFs recommended by Eldridge et al. (2017); imf135-100: α_1=-1.30 (0.1-0.5 $M_\odot$), α_2=-2.35 (0.5-100 $M_\odot$); imf135-300: as imf135-100 but with M_{up}=300 $M_\odot$

[f] imf170-100: α_1=-1.30 (0.1-0.5 $M_\odot$), α_2=-2.70 (0.5-100 $M_\odot$); imf170-300: as imf170-100 but withM_{up}=300 $M_\odot$

emission. For the first time, using the derived SBS 0335-052E integrated spectrum, we recovered the entire nebular HeII emission and compute the corresponding total HeII-ionization budget, $Q(HeII)_{int} \approx 3.17 \times 10^{51}$ photon s^{-1}. As we showed in Kehrig et al. (2015),

SBS 0335-052E, one of the most metal-poor ($Z \sim 3$-$4\%\ Z_{\odot}$) HeII-emitter starbursts known in the nearby universe, is studied using optical VLT/MUSE spectroscopic and Chandra X-ray observations. We spatially resolved the spectral map of the nebular HeIIλ4686 emission from which we derived for the first time the total HeII-ionizing energy budget of SBS 0335-052E. The nebular HeII line is indicative of a quite hard ionizing spectrum with photon energies > 4 Ryd, and is observed to be more common at high-z than locally. Our study rules out a significant contribution from X-ray sources and shocks to the HeII photoionization budget, indicating that the He^{+} excitation is mainly due to hot stellar continua. We discovered a new WR knot, but we also discard single WR stars as the main responsible for the HeII ionization. By comparing observations with current models, we found that the HeII-ionization budget of SBS 0335-052E can only be produced by either single, rotating metal-free stars or a binary population with $Z \sim 10^{-5}$ and a 'top-heavy' IMF. This discrepancy between the metallicity of such stars and that of the HII regions in SBS 0335-052E is similar to results obtained by Kehrig et al. (2015) for the very metal-deficient HeII-emitting galaxy

Our HeII emitters → unique sample of counterparts to the long-sought-for sources of cosmic reionization and fundamental guidance for the interpretation of upcoming rest-frame UV galaxy spectra at high-z

This project presents a novel approach to be performed using the GTC MEGARA-IFU which offers the only opportunity to perform this project in the foreseeable future!

Thank you

