Morphology and ionization of He^+ nebula in NGC1569 using MEGARA at the GTC

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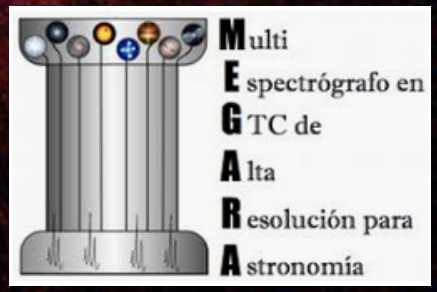
+ MEGARA team



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MEGARA-IFU detection of extended He II λ4686 nebular emission in the central region of NGC 1569 and its ionization budget

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Mayya et al. (2020) MNRAS 498, 1496 (11 October issue)

Ionization of He^+ by massive stars

E(He^+) = 54.4 eV = 228 Å

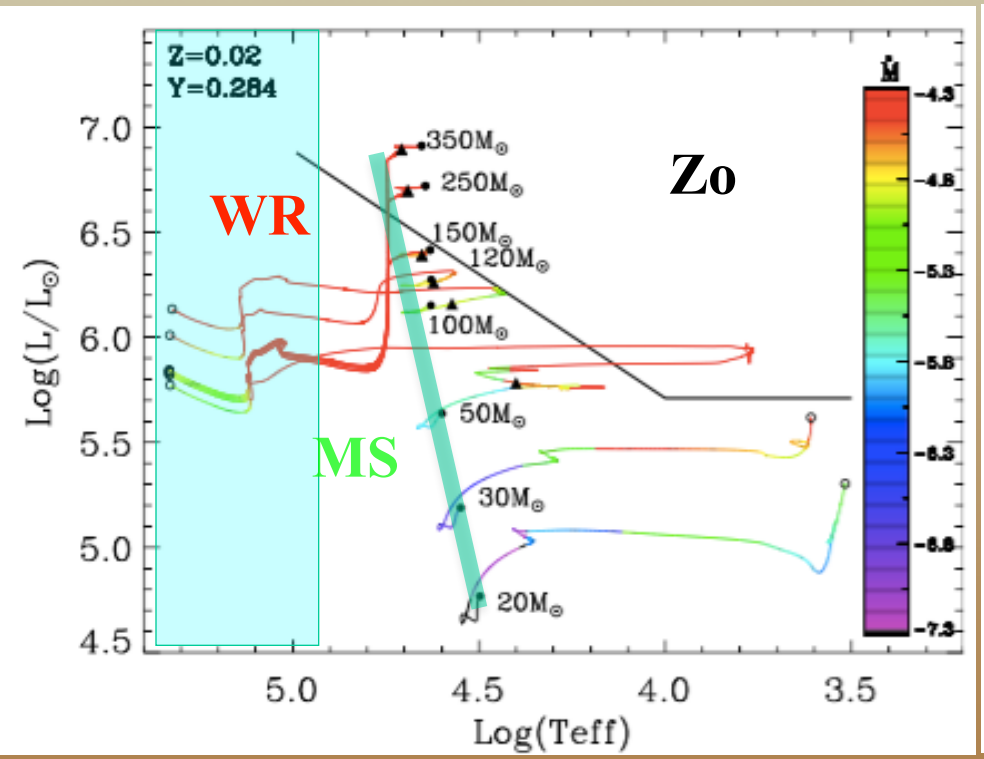
Requires T_{eff} > 60000 K

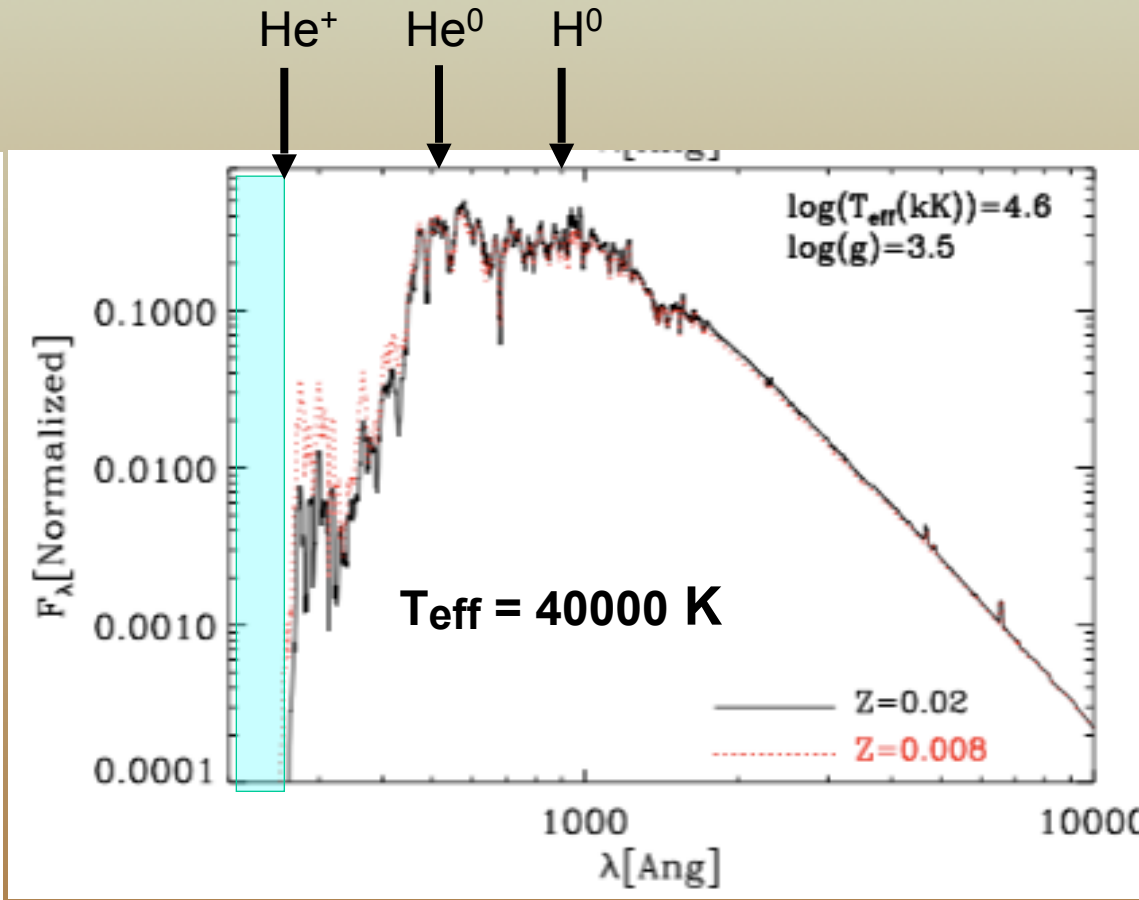
===> **main-sequence stars cannot ionize He^+ to He^{++}**

But, **Wolf Rayet stars are hot enough to ionize He^+**

WR Stars: M>25 $M_\odot$; t=3-5 Myr

Chen et al. 2015



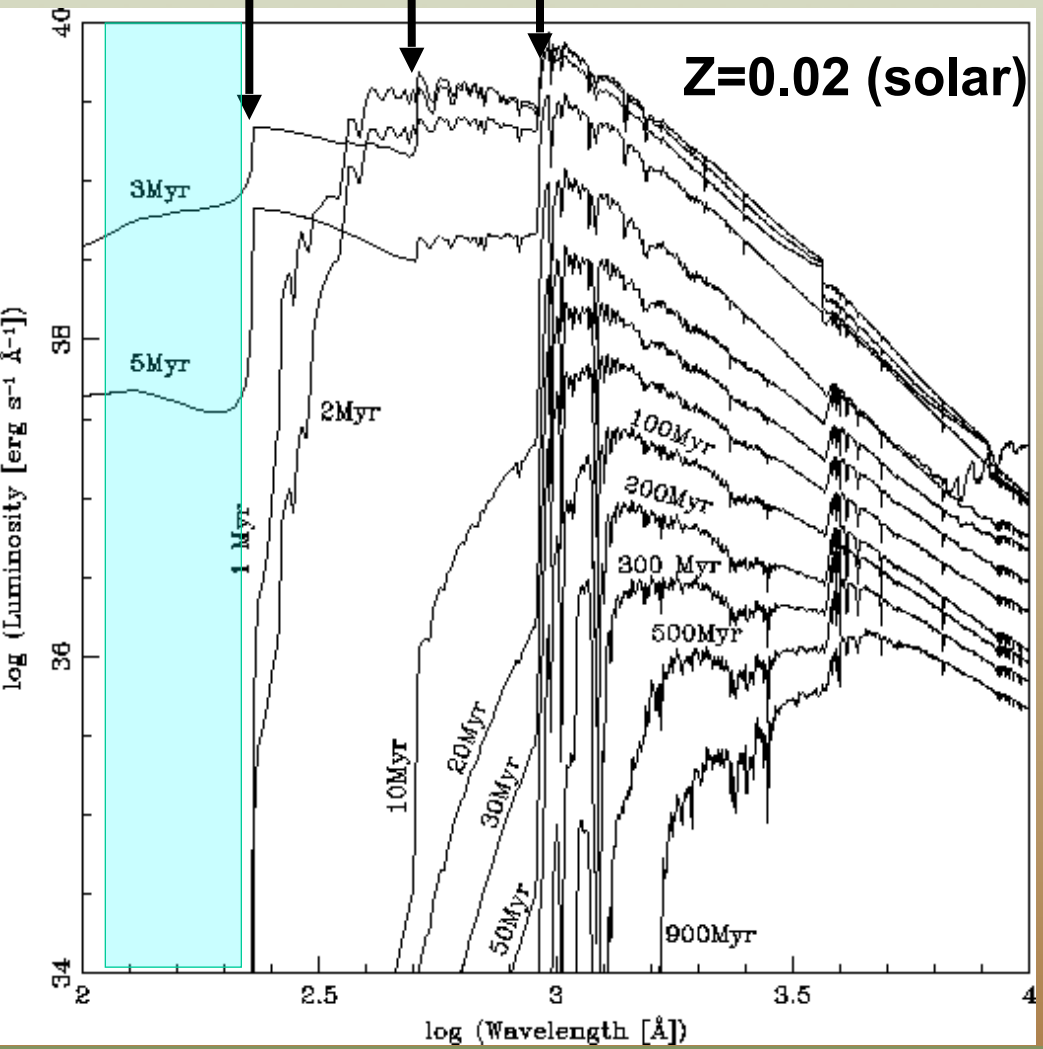


Ionization of He^+ in star-forming regions

Available only during WR phase (3-5 Myr)

He^+ He^0 H^0

STARBURST99
(Leitherer et al. 1999)



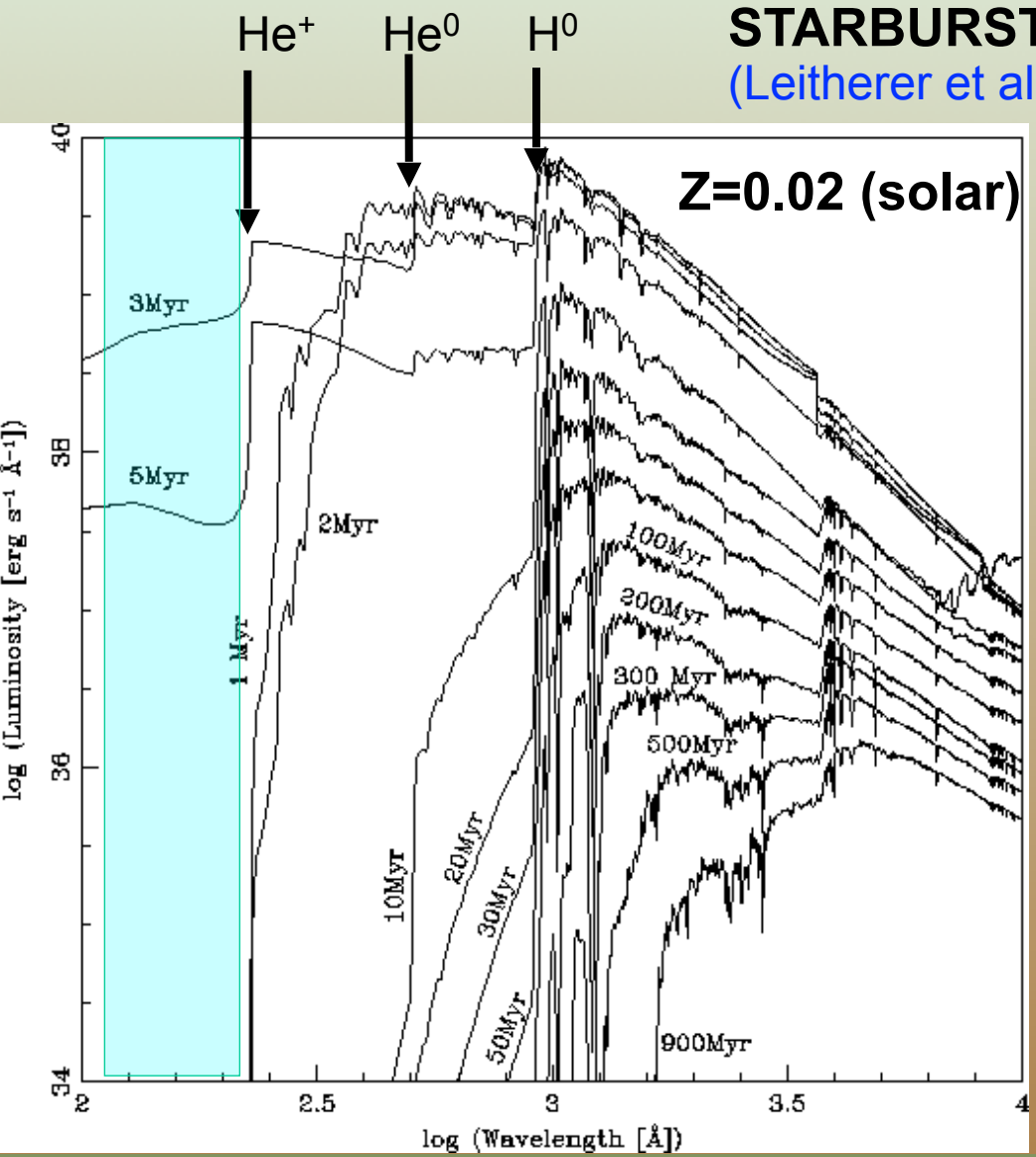
Ionization of He^+ in star-forming regions

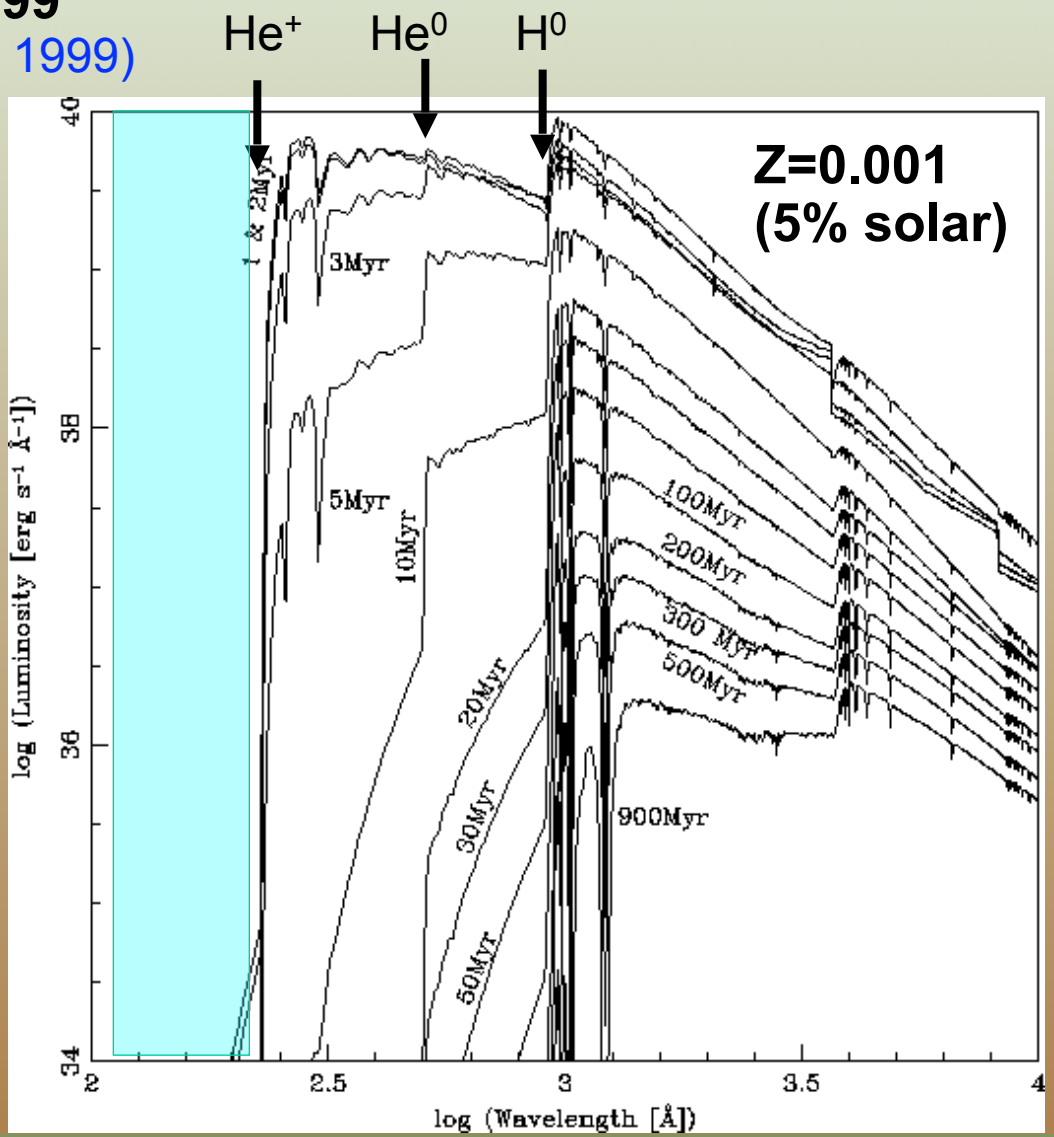
…and the metallicity dependence

Available only during WR phase (3-5 Myr) for Z>0.25

===> HeII4686 line is not expected in metal-poor (Z<0.25) galaxies

STARBURST99
(Leitherer et al. 1999)





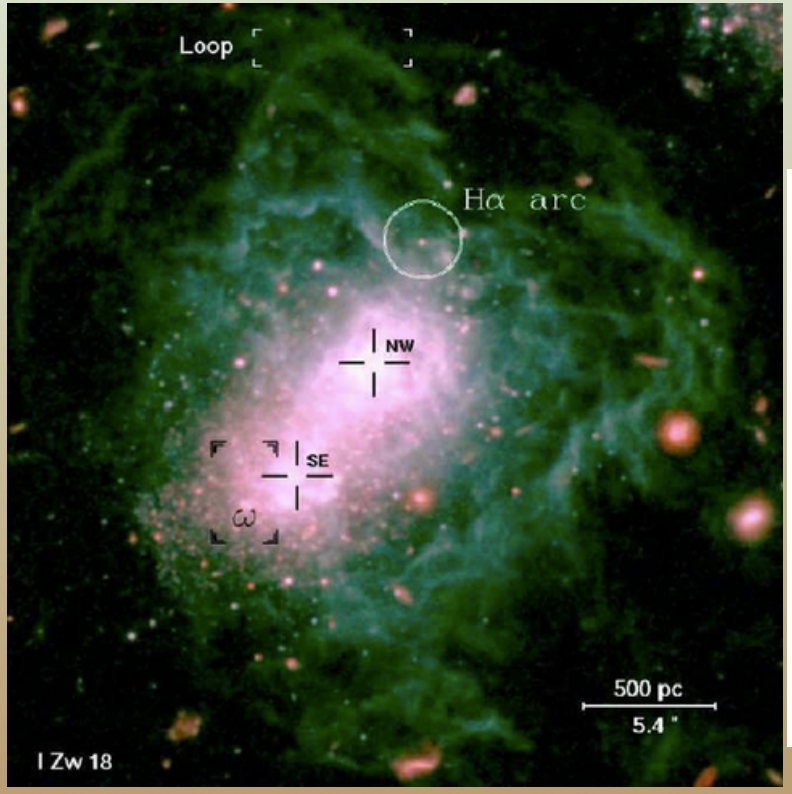
Detection of HeII4686 in I Zw 18

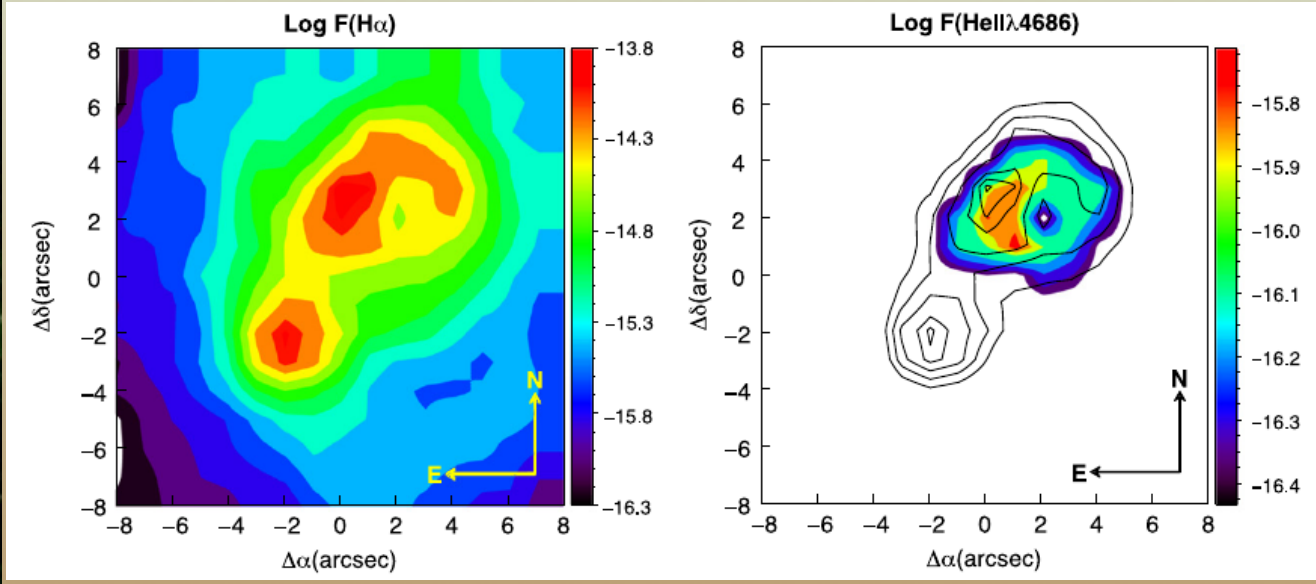
I Zw 18: Z=1/32 $Z_\odot$

$L(He^+) = 1.12 \times 10^{38}$ erg/s
$Q(He^+) = 1.33 \times 10^{50}$ ph/s

Kehrig et al. 2015

9 WC stars present
==> **~1/50 of observed Q(HeII)**





What is the source of ionization of the observed HeII4686 line in I Zw18?

The problem:

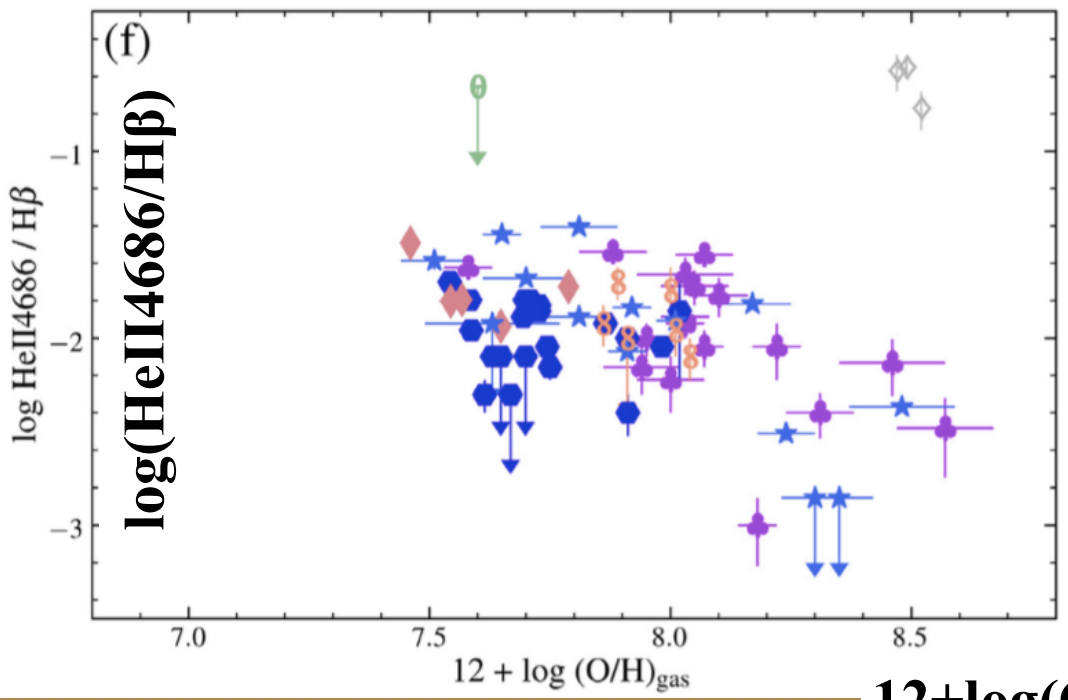
- I Zw 18 is not an exception!

- There is a trend of increasing HeII4686/Hβ with decreasing metallicity!!!

===> He^+ ionization budget problem at low metallicities

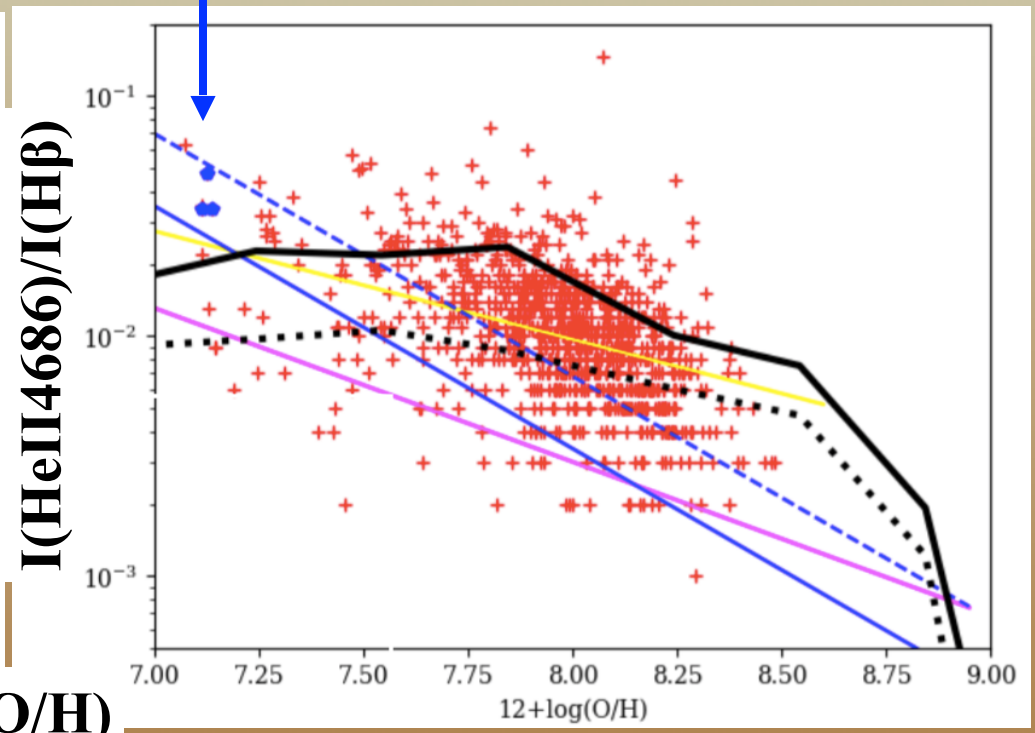
- **Other sources of HeII ionization: High mass X-ray binaries (HMXBs)?**

Plat et al. 2019



I Zw 18

Schaerer et al. 2019



12+log(O/H)

Formation scenarios of WR stars and HMXBs

Formation of WR stars: effect of rotation and binary

Leitherer et al. 2014

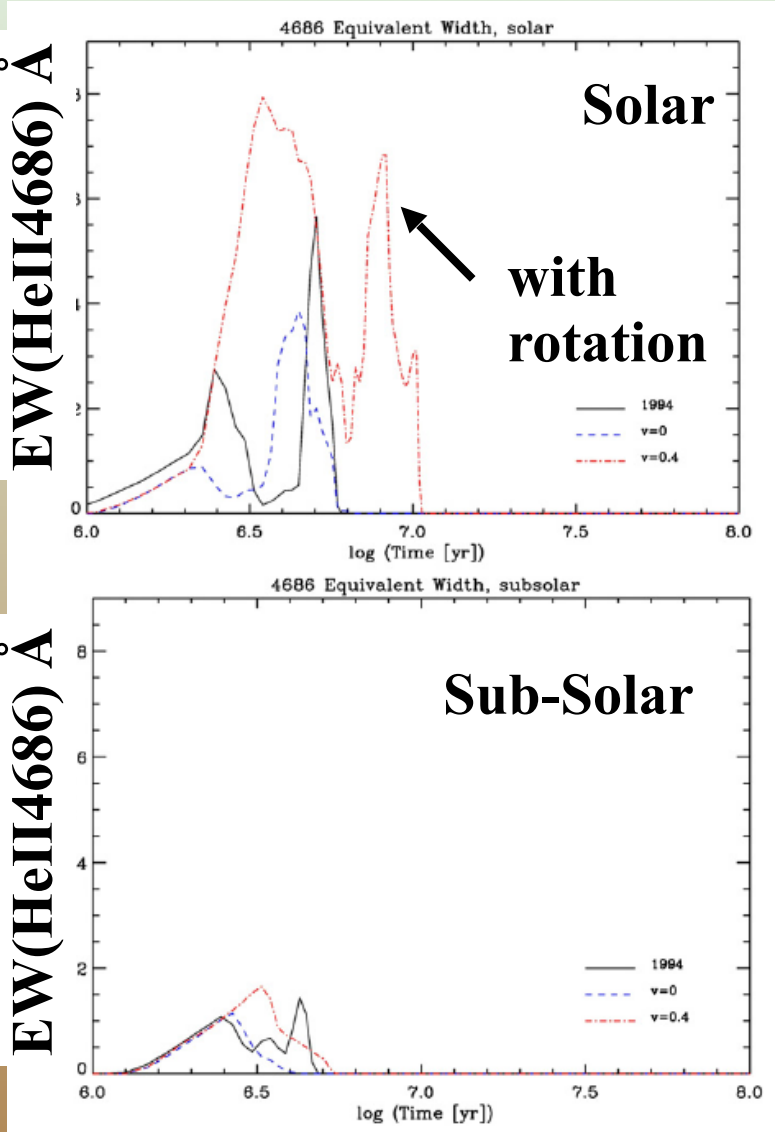
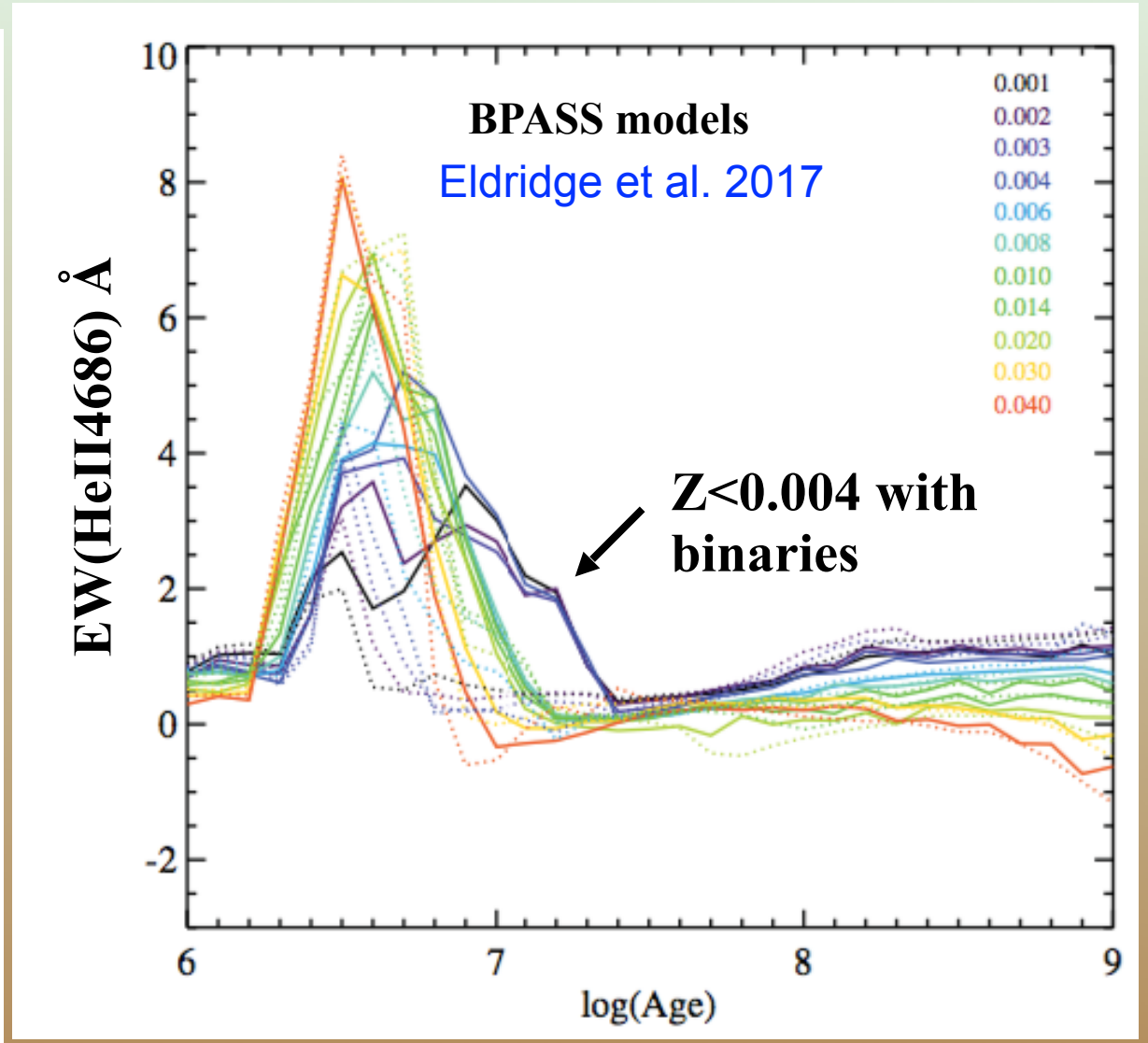


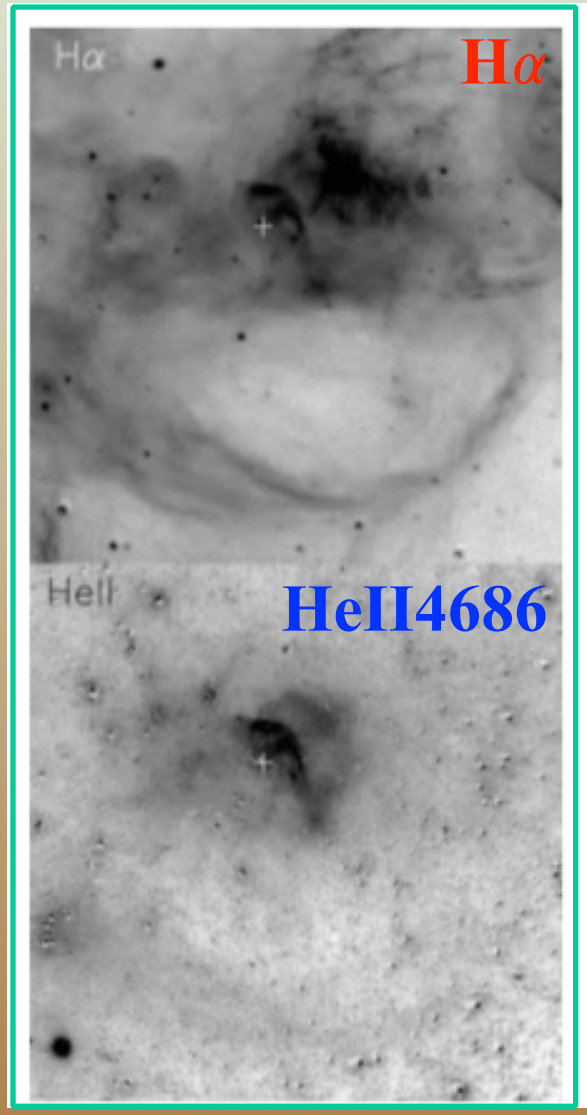
Figure 24. Equivalent width of stellar He II 4686 from W-R stars predicted by the 1994, v00, and v40 tracks at solar (top) and subsolar (bottom) chemical composition.



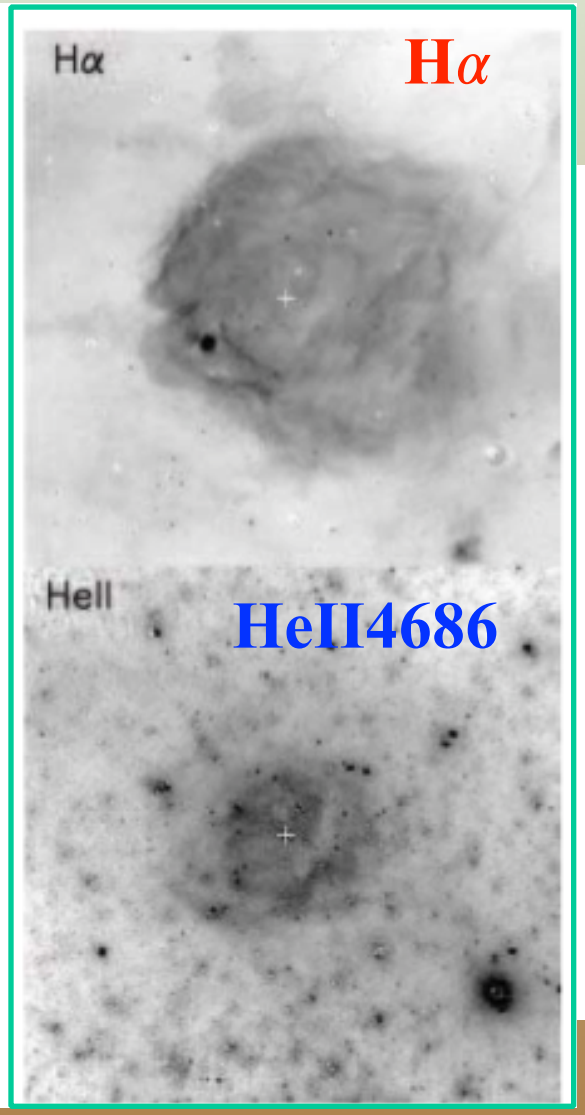
- **Rotation prolong the duration of WR phase at Z=Z⊙**
- **Binary stars prolong the duration of WR phase at Z < 0.004**

He^{++} nebula in nearby galaxies: morphology

N79 in the LMC
(WN2 star Br2)

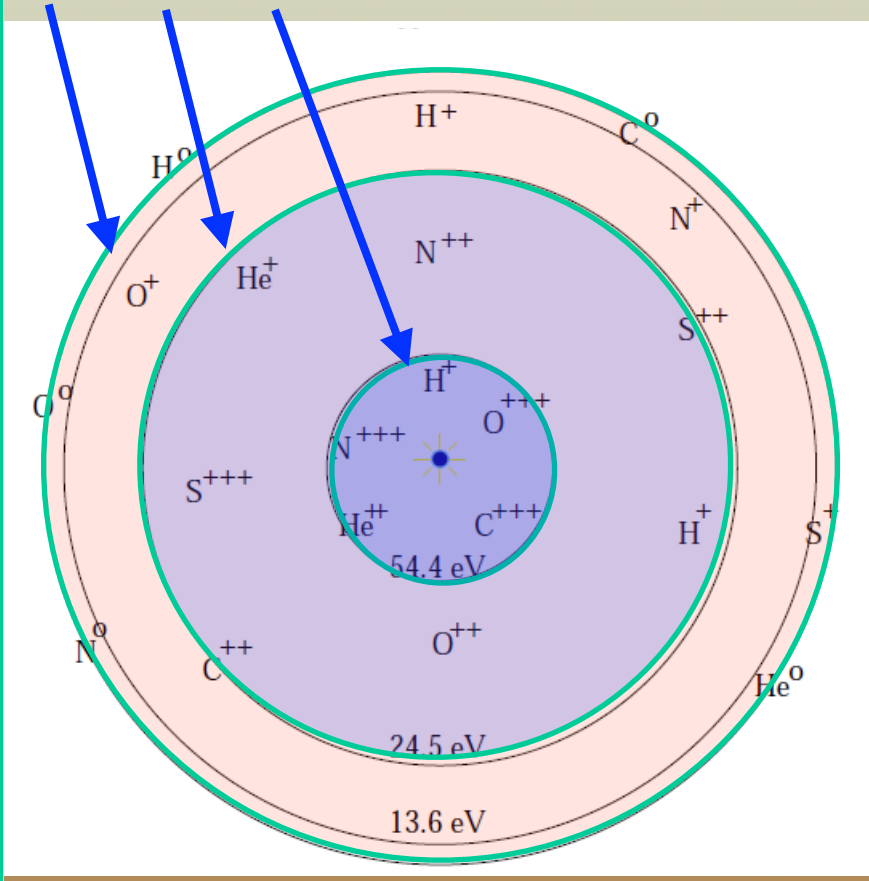


N76 in the SMC
(WN2 star AB7)



Chu 2016

H^+, He^+, He^{++} Stromgren Spheres

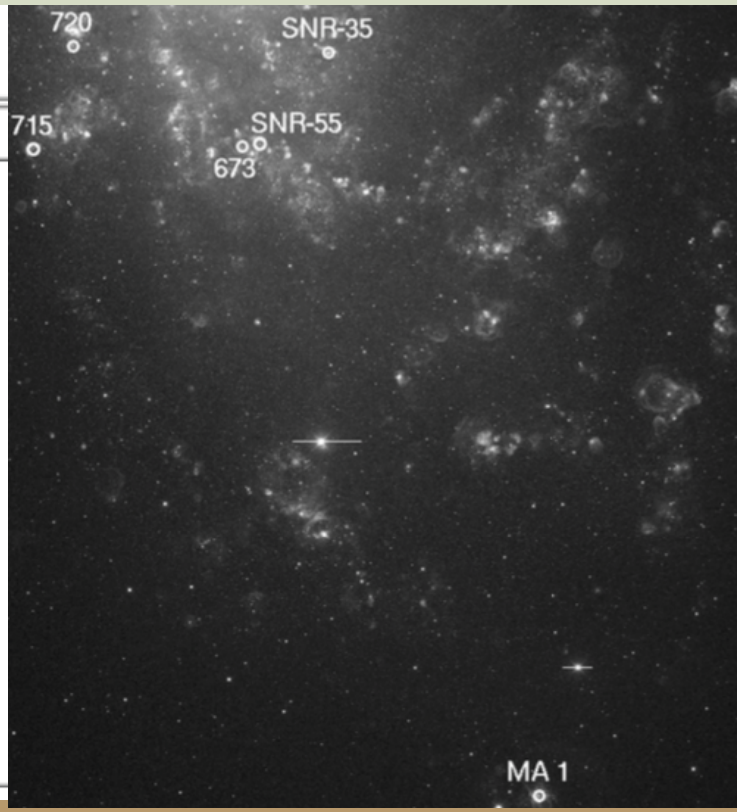


He++ nebula in nearby galaxies: morphology

M33 Kehrig et al. 2011

Table 9. HII regions with nebular He II emission in the Local Group.

Galaxy	Region	12+log(O/H)	Ionizing source	Spectral type
MW	G2.4+1.4	8.45	WR102	WO2
LMC	N44C	8.32	X-5?	X-ray Neb?
LMC	N159	8.36[a]	X-1	HMXB
LMC	N79	8.17-8.27	BAT99-2	WN2b(h)
LMC	N206	8.36	BAT99-49	WN4:b+O8V
SMC	N76	7.93	AB7	WN4+O6I(f)
SMC	NGC 249	8.11[a]	SMC-WR10	WN3ha
IC1613	S3	7.70		WO3
M 33	BCLMP38b	8.39	MC45	WC4
M 33	BCLMP90	8.50		no obvious hot star associated
M 33	C001Ab	8.61		no obvious hot star associated
M 33	BCLMP208f	8.07		no obvious hot star associated
M 33	BCLMP711a	8.28		no obvious hot star associated
M 33	MA 1	8.00	MC8	WNE
M 33	HBW673	8.66		no obvious hot star associated
M 33	BCLMP651	8.12		no obvious hot star associated



- **For MA1, HeII4686 line strength agrees with ionization from its central star (WNE)**
- **No obvious hot star associated with all HeIII nebulae!!!**

A case study: He^{++} nebula in NGC1569

F658N (R) =Hα
F814W (G)
F555W (B)
RGB HST image

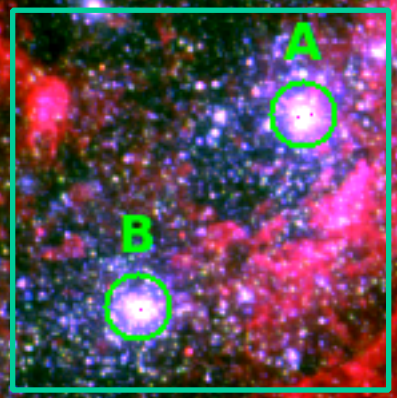
12+log(O/H) = 8.19
Kobulnicky & Skillman 1997
===> **Z ~ Zo/3 (~LMC)**

Distance = 3.1 Mpc
Grocholski et al. 2012

SSC	r_h (pc)	M_{vir} (10^5 M_o)	M_{phot}	Pop	Age Myr
A	2.7	6.0	7.6	O+WR	< 5
B	3.2	6.7	14	RSG	~15

Larsen et al. 2008, 2011
González-Delgado et al. 1997

SSCs A and B



10" = 150 pc

N
E

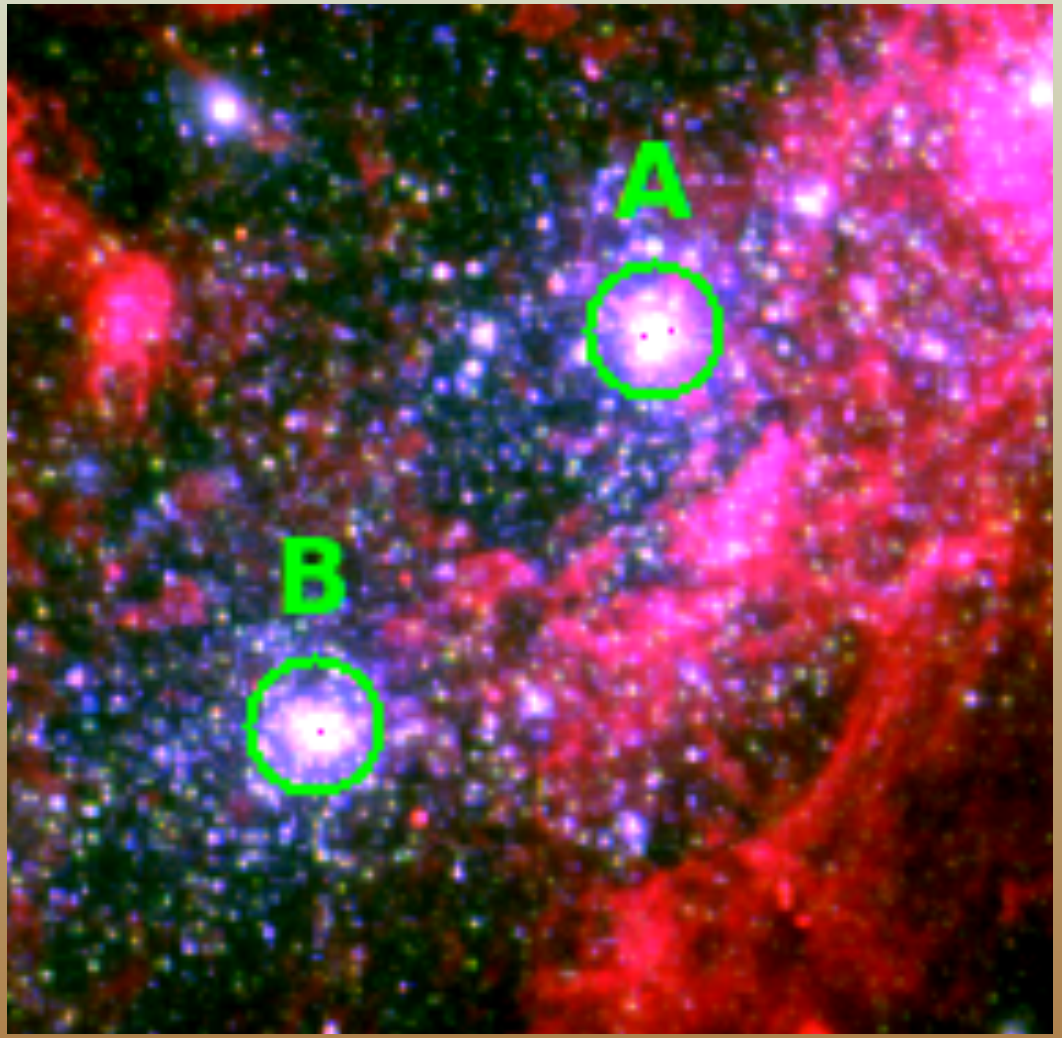
- Is there a He^{++} nebula around SSC-A?

There is no young cluster more massive than SSC-A in the MW or the Local group galaxies

A case study: He^{++} nebula in NGC1569

Specific goals of our study

- Is there a He^{++} nebula around SSC-A?
- Is there a He^{+} ionization budget problem at the metallicity of NGC1569?



MEGARA at the 10.4-m GTC

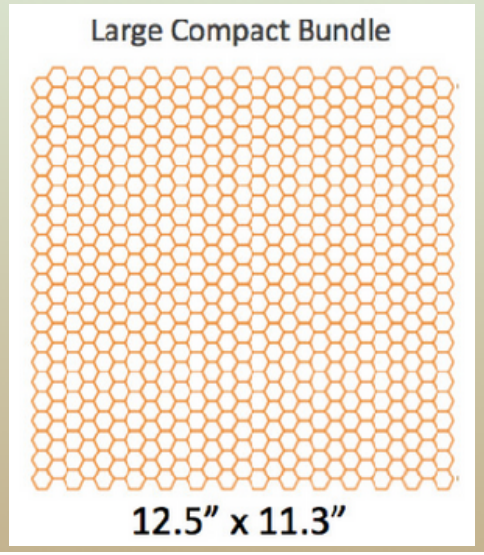
http://www.gtc.iac.es/instruments/megara/megara.php

Installed at the GTC (La Palma) in August 2017

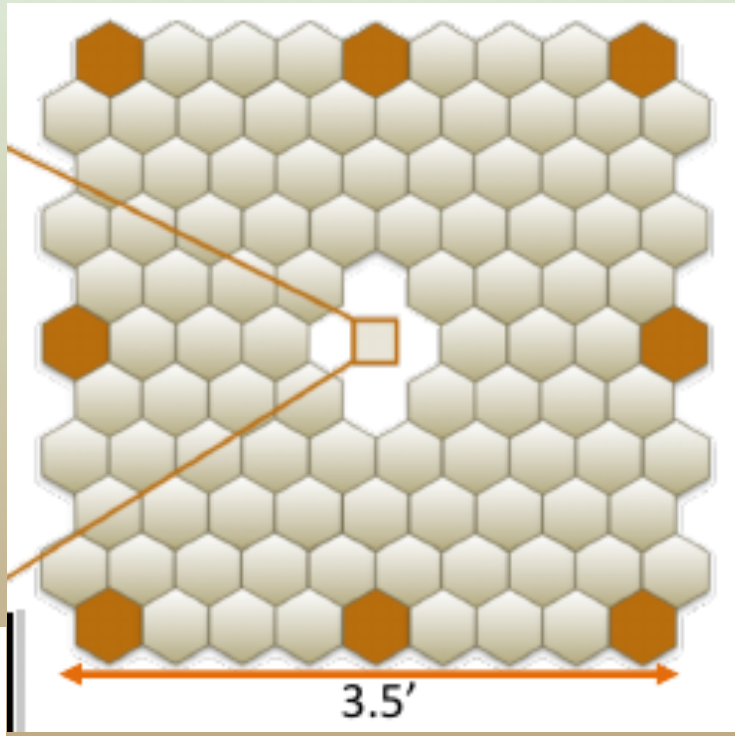
PI: Armando Gil de Paz

623 fibers (IFU)
(56 sky fibers)
92 positions (MOS)

IFU mode



MOS mode



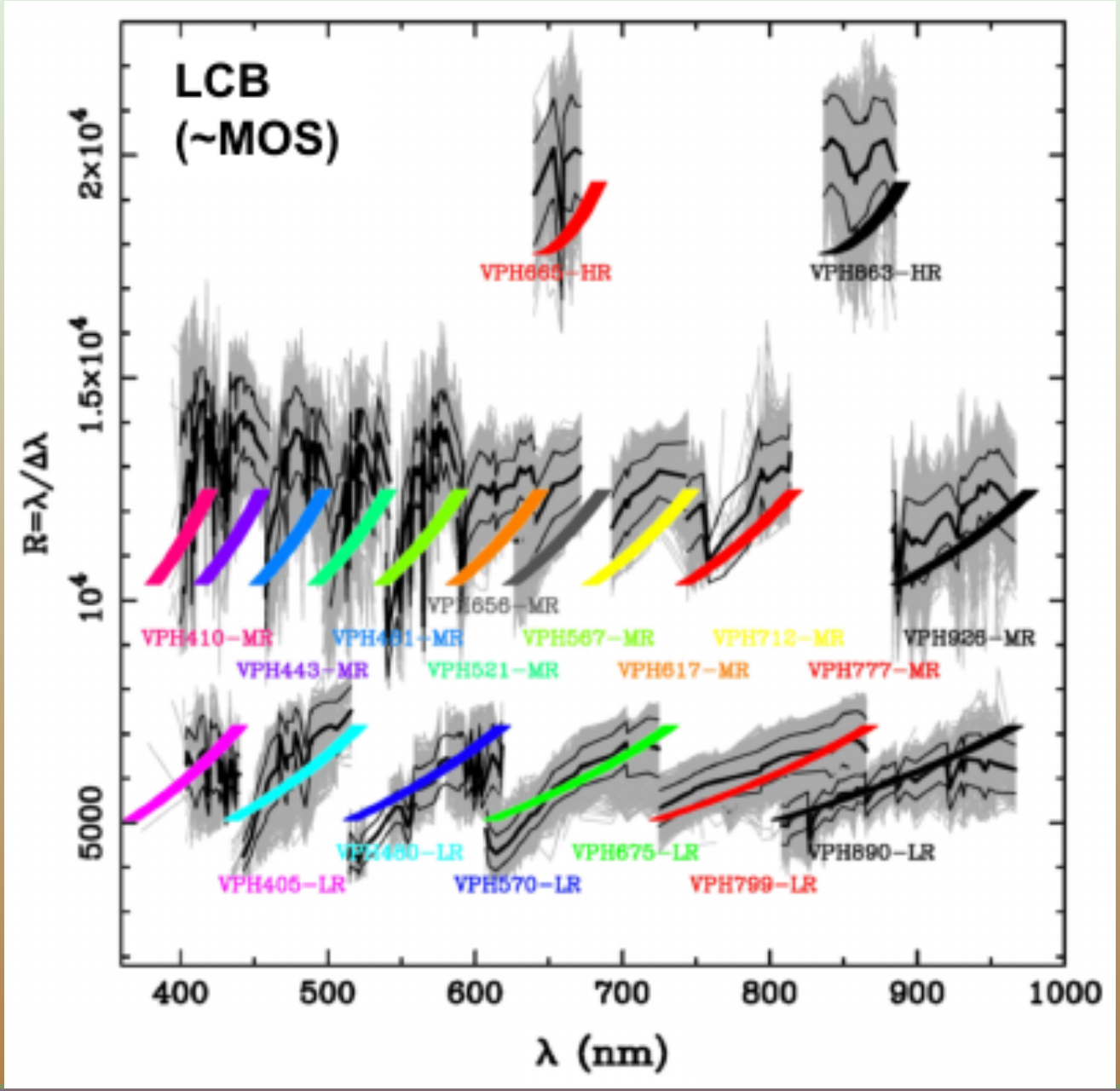
	IFU	MOS
Field of View	12.5 x 11.3 arcsec^2	3.5 x 3.5 arcmin^2
Spaxel size	0.62 arcsec	
Sampling (1D FWHM)	3.6 pix	
LR VPHs	R(λ/Δλ) ~ 5 500	
MR VPHs	R(λ/Δλ) ~ 12 000	
HR VPHs	R(λ/Δλ) ~ 20 000	

Optical components and cryostat fabricated at INAOE laboratories

INAOE has ~150 hrs of Guaranteed Time

Resolution and spectral coverage

Hα CaT



R=18000 (Δλ~ 0.3 Å)

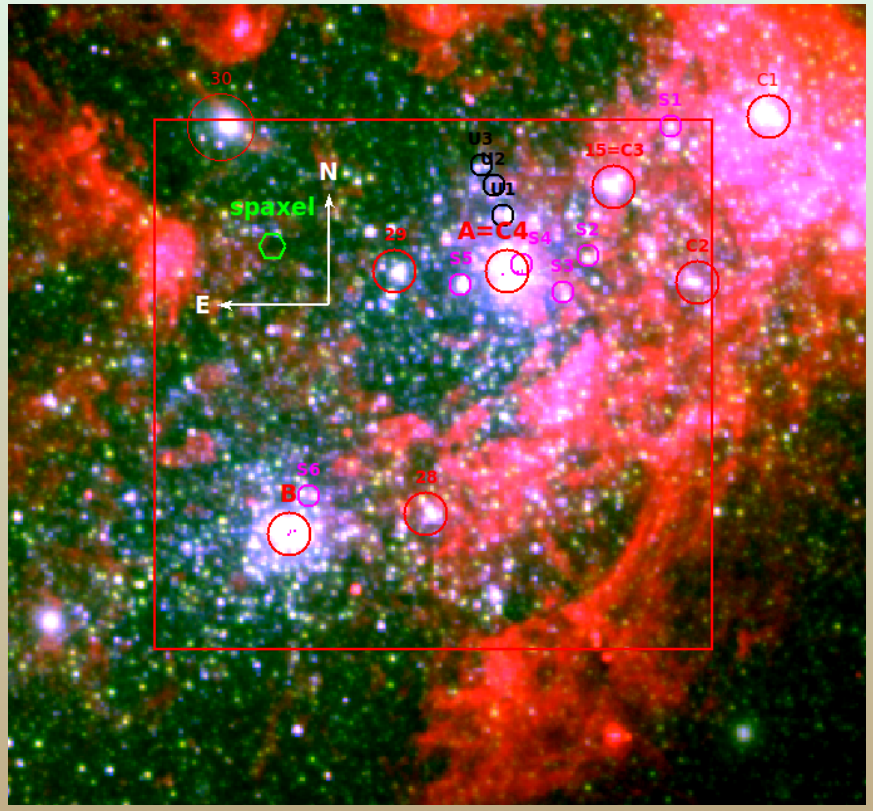
R=12000 (Δλ~ 0.5 Å)

R=6000 (Δλ~ 1 Å)

MEGARA/IFU observations of NGC1569

Observations

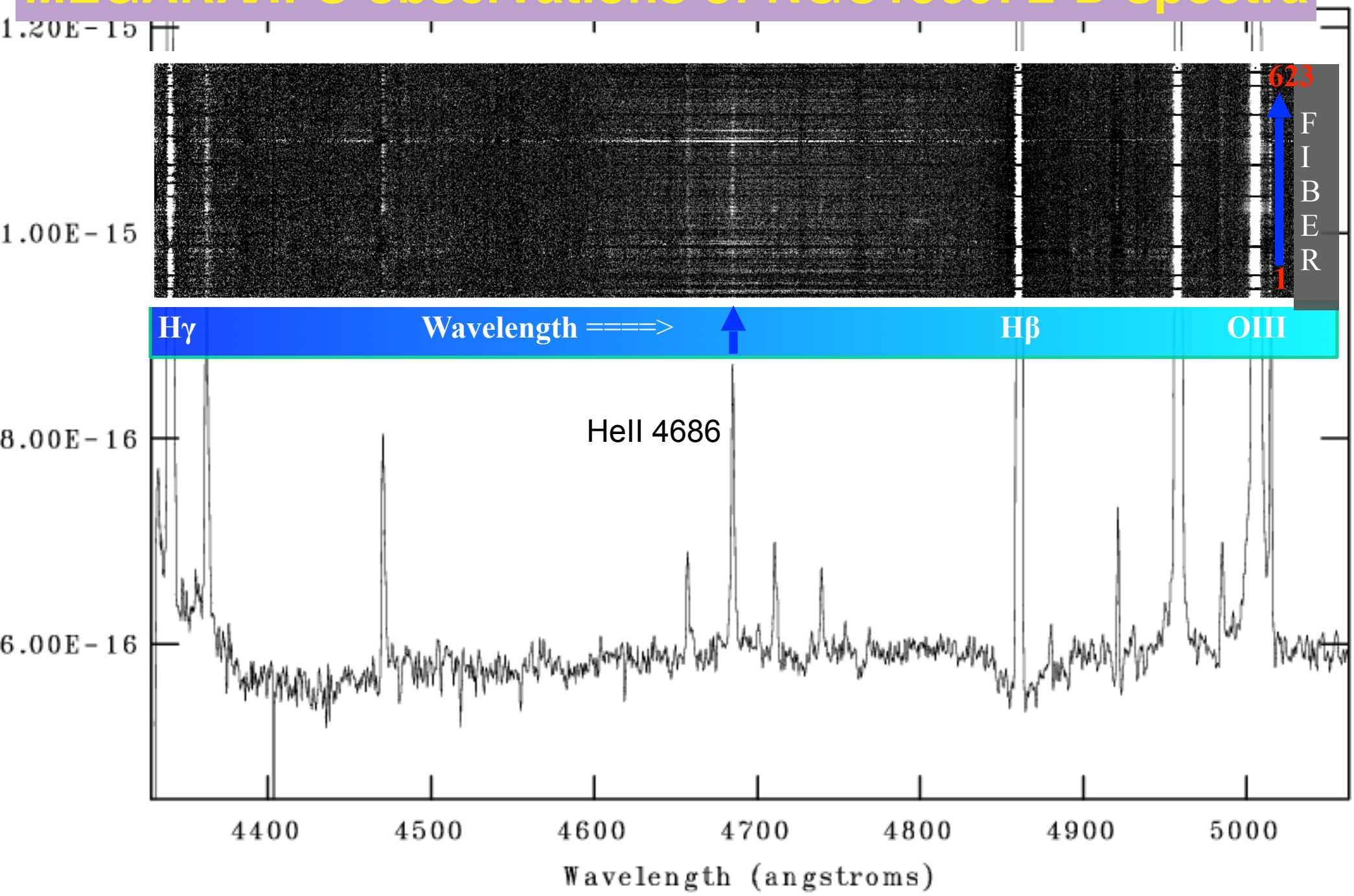
- IFU mode (567 object + 56 sky spectra)
- Exposure = 3 x 1200 sec
- Grating (VPH): LR-B (4330-5200 A)
- Seeing ~ 0.9”
- Dark and photometric sky conditions
- Date of observations: January 2019
- Gauranteed time observations



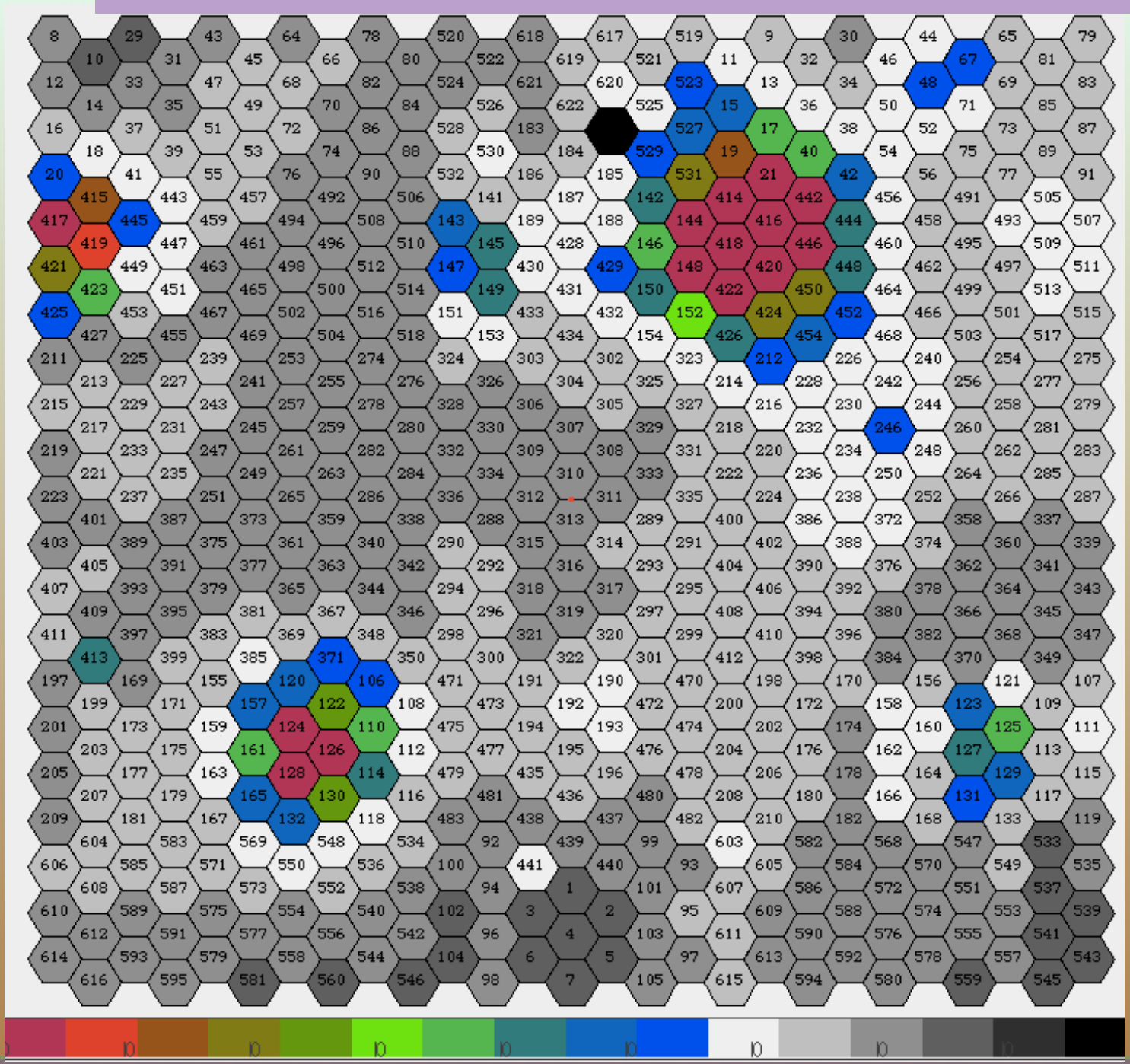
Data Reduction and analysis

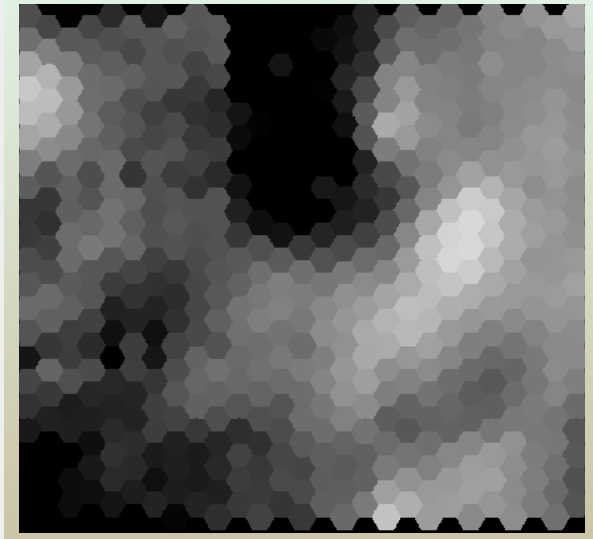
- Primary Data Reduction using MEGARA pipeline
  ===>Wavelength and flux calibrated, sky-subtracted 2-D spectral image
- Data cube creation using python script (Javier Zaragoza)
- Data analysis and narrow-band image using IRAF-based scripts (Mayya)

MEGARA/IFU observations of NGC1569: 2-D spectra



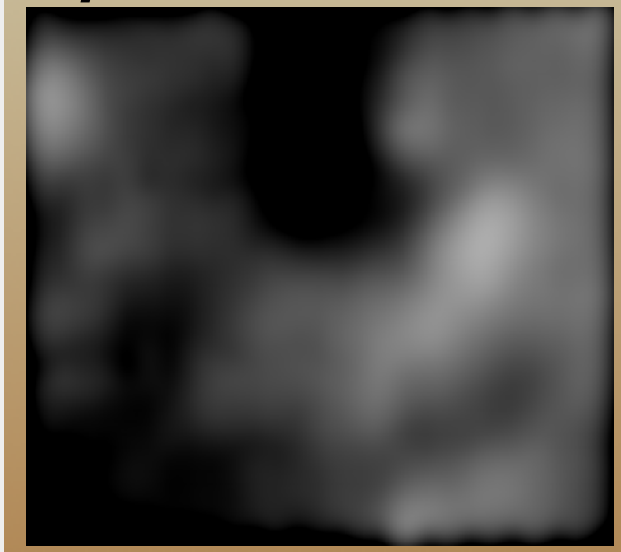
MEGARA/IFU observations of NGC1569: image



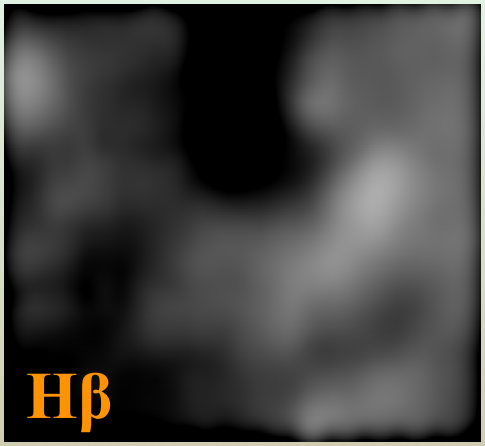


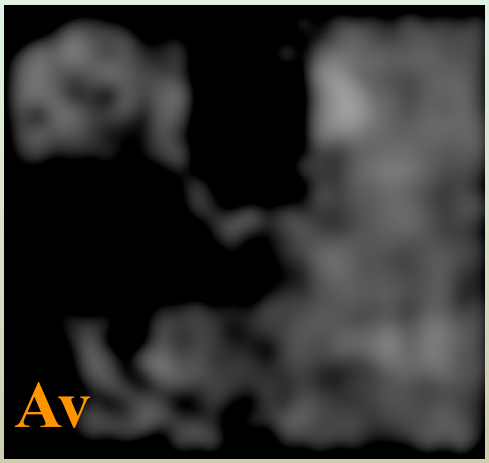
Hβ-original MEGARA fibers

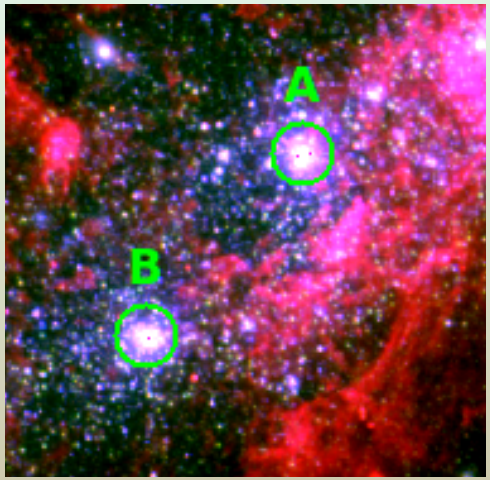
Hβ-smoothed by the PSF

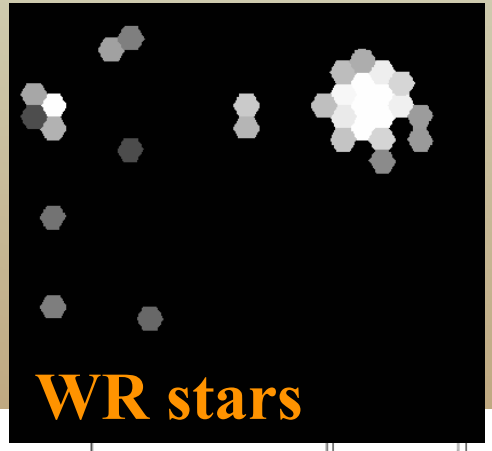


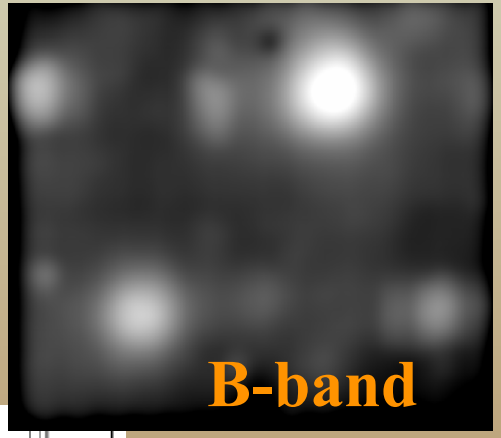
MEGARA/IFU images at selected wavelengths

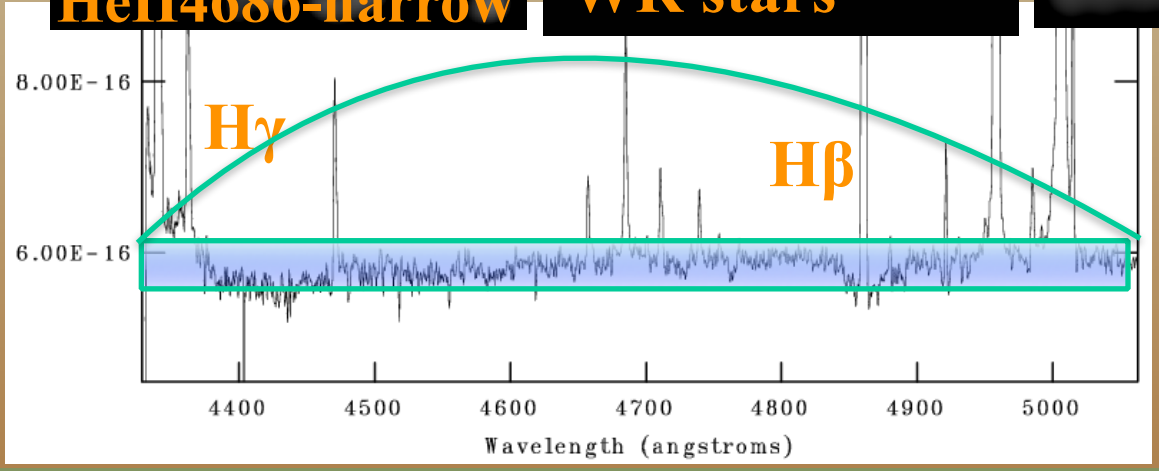










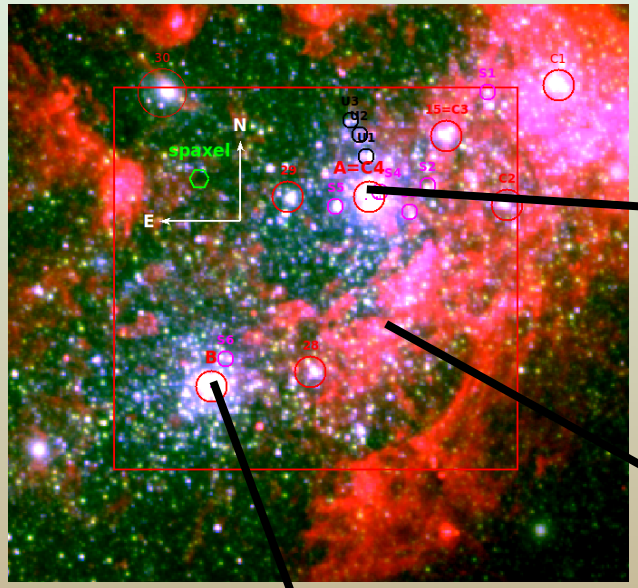


Av - using Balmer decrement for photo-ionized nebulae

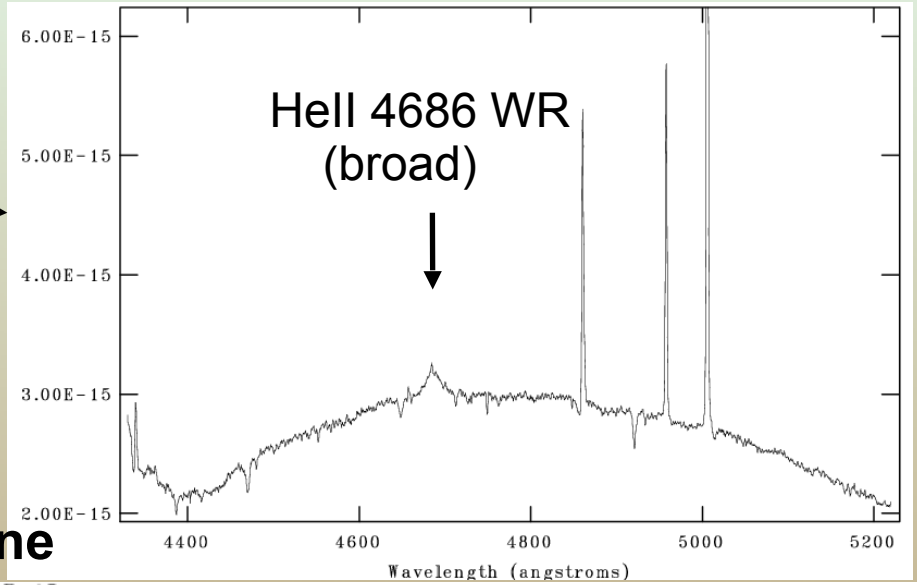
B-band: by integrating the spectra over the filter response curve

MEGARA/IFU sample spectra

How to distinguish WR stars from nebula?

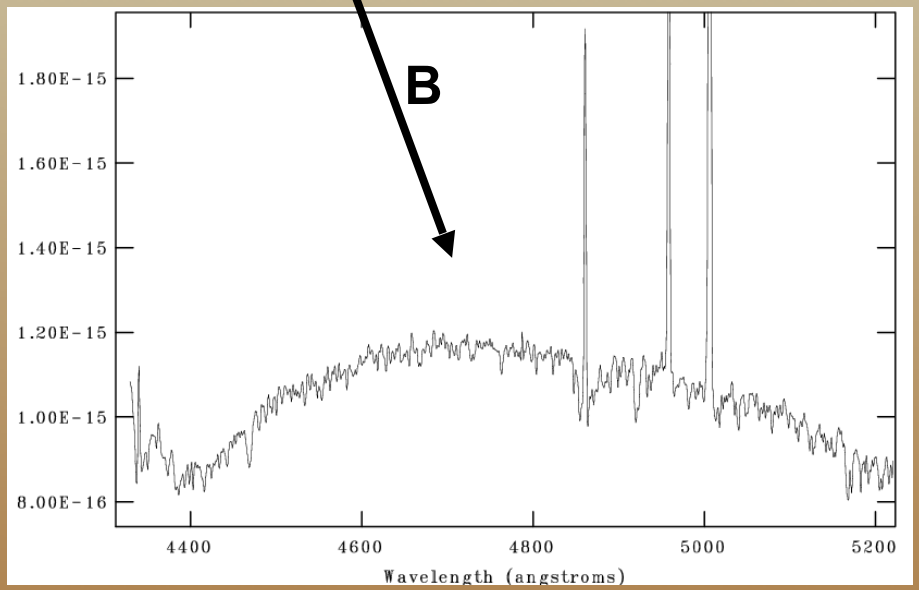


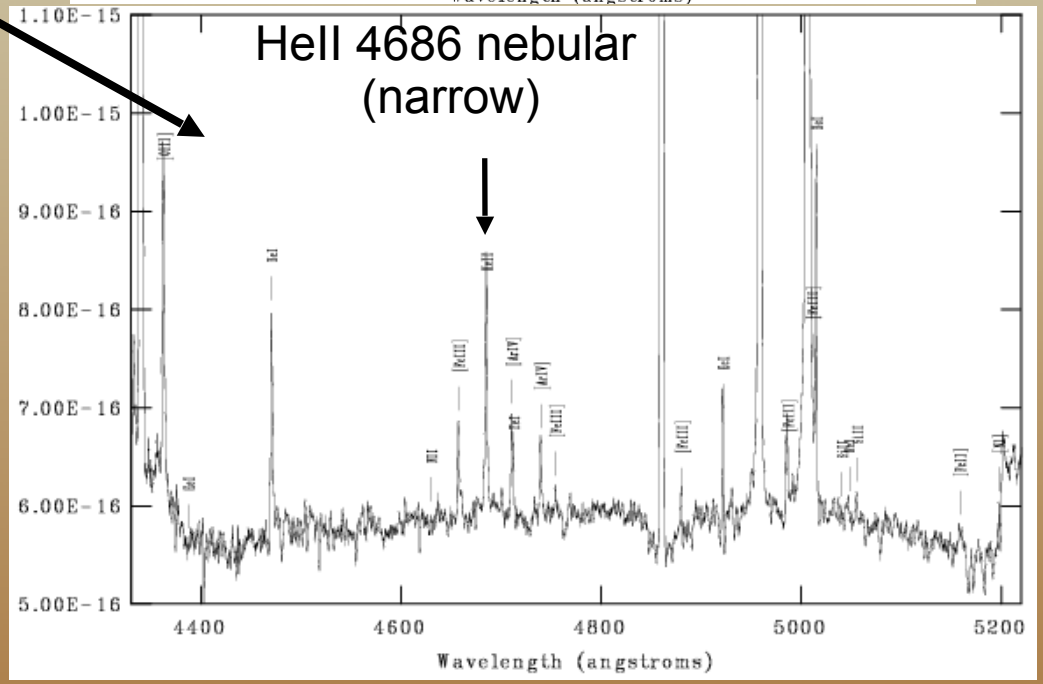
A



Nebular zone

B



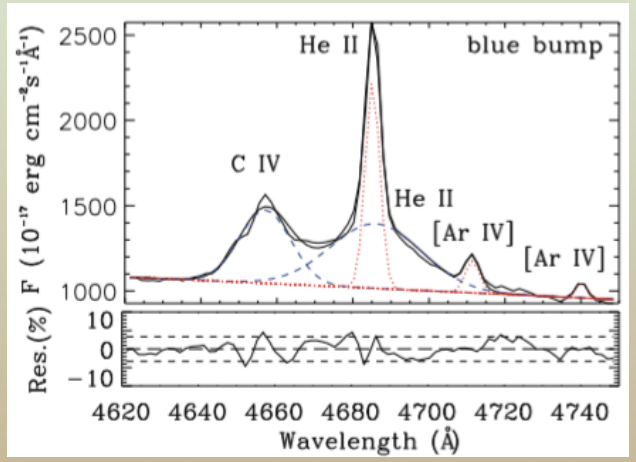


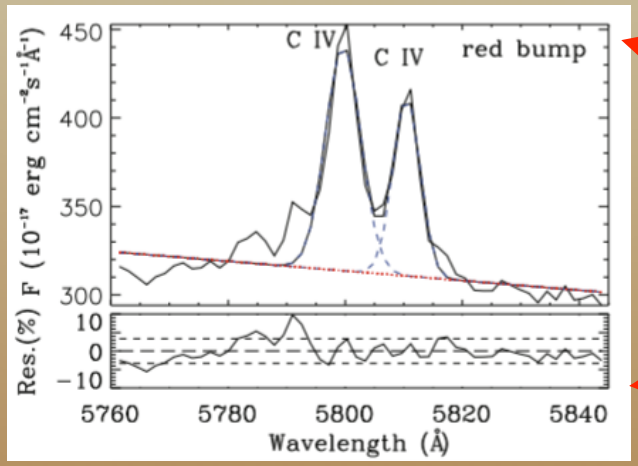
Tracers of He++ nebula and WR stars

How to identify WR stars?

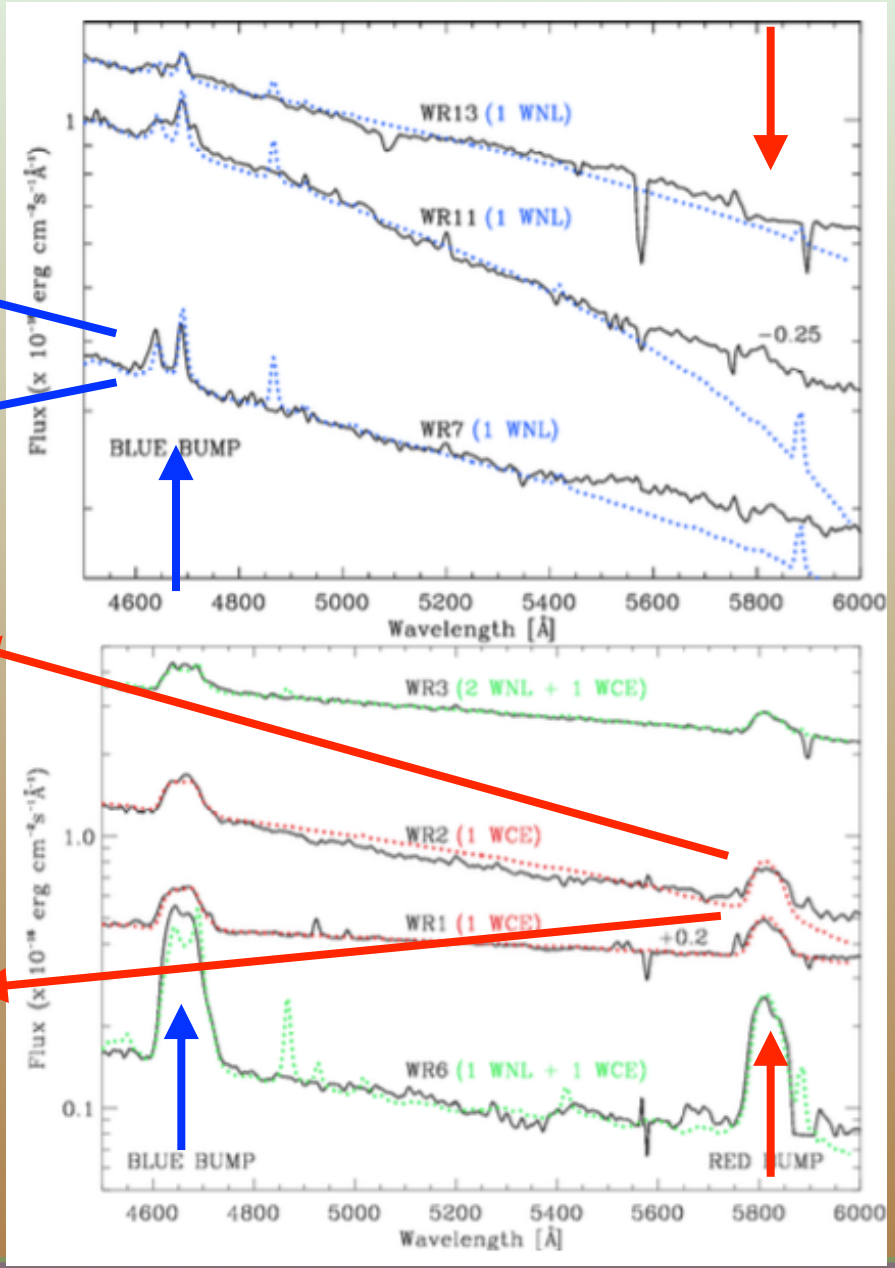
WR stars: blue and red bumps

Gómez-González et al. 2020b (NGC2371)





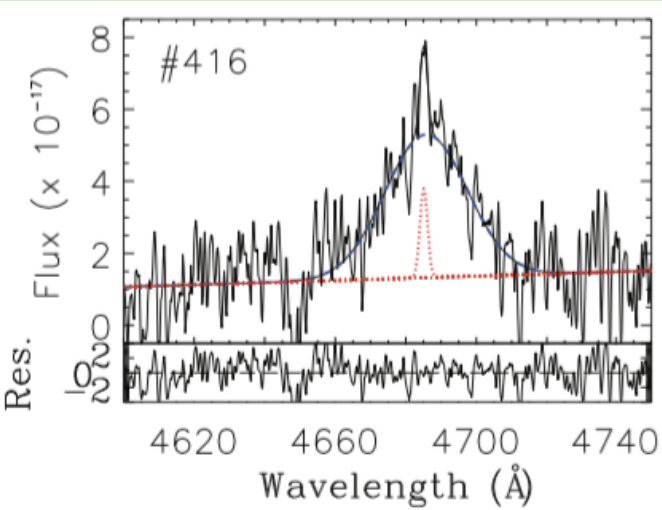
Gómez-González et al. 2016, 2020a (M81)

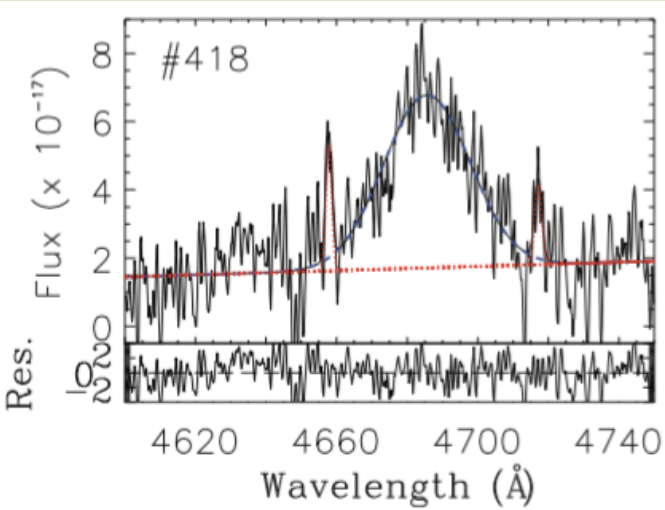


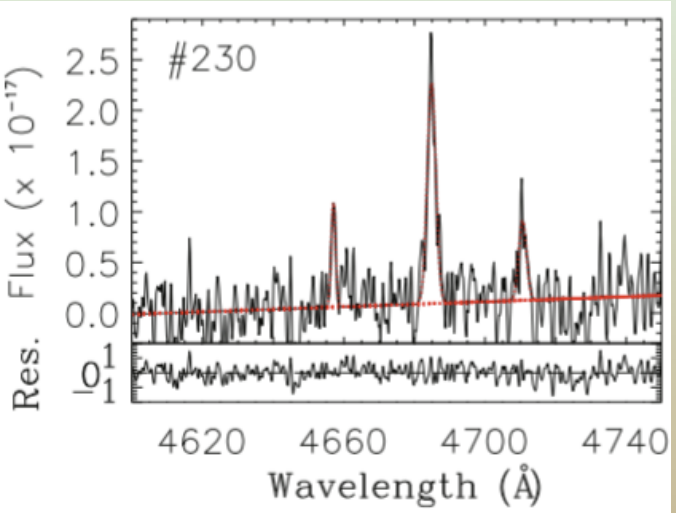
Hell 4686 broad feature ===> WR stars

Automatic identification of HeII4686 narrow and broad features

Multi-Gaussian Analysis of HeII 4686 feature in every fiber spectrum







WR + HeII nebular | **Only WR** | **Only HeII nebular**

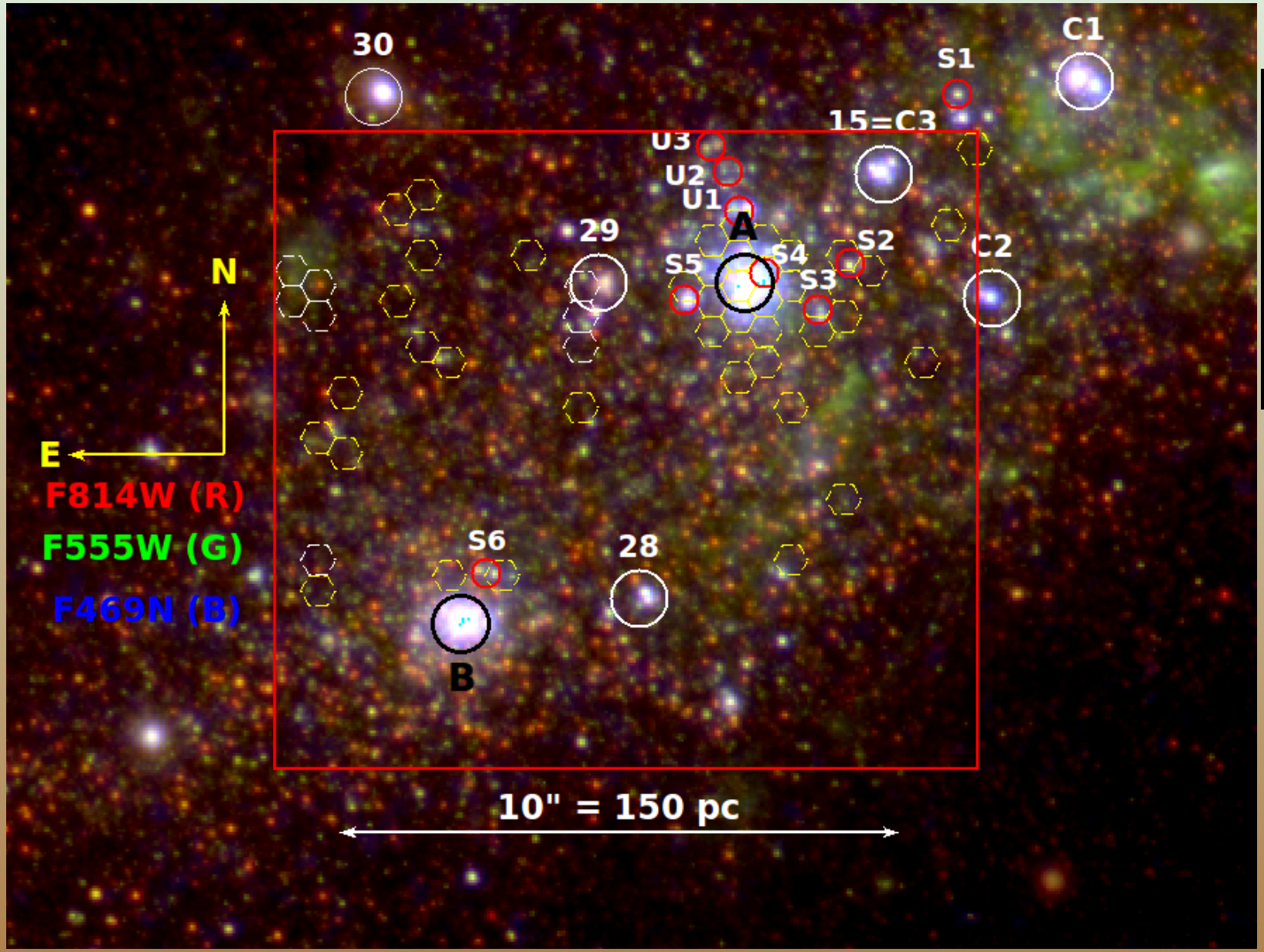
WR (FWHM > 6 Å): 49 fibers

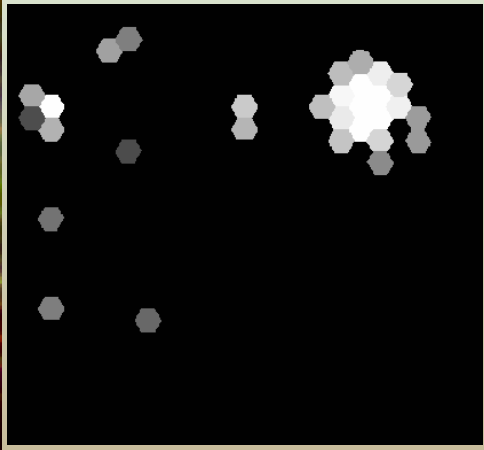
- 18 belong to SSC-A
- the rest are fibers with cross-talk with fibers of SSC-A or limiting fluxes
- Broad component corresponds to He+ ion (no NIII, CIII-CIV lines)
  ===> WNL type

Nebula (FWHM ~ 2 Å): 262 fibers

The fiber fluxes in each component are used to produce maps of WR positions and HeII nebula

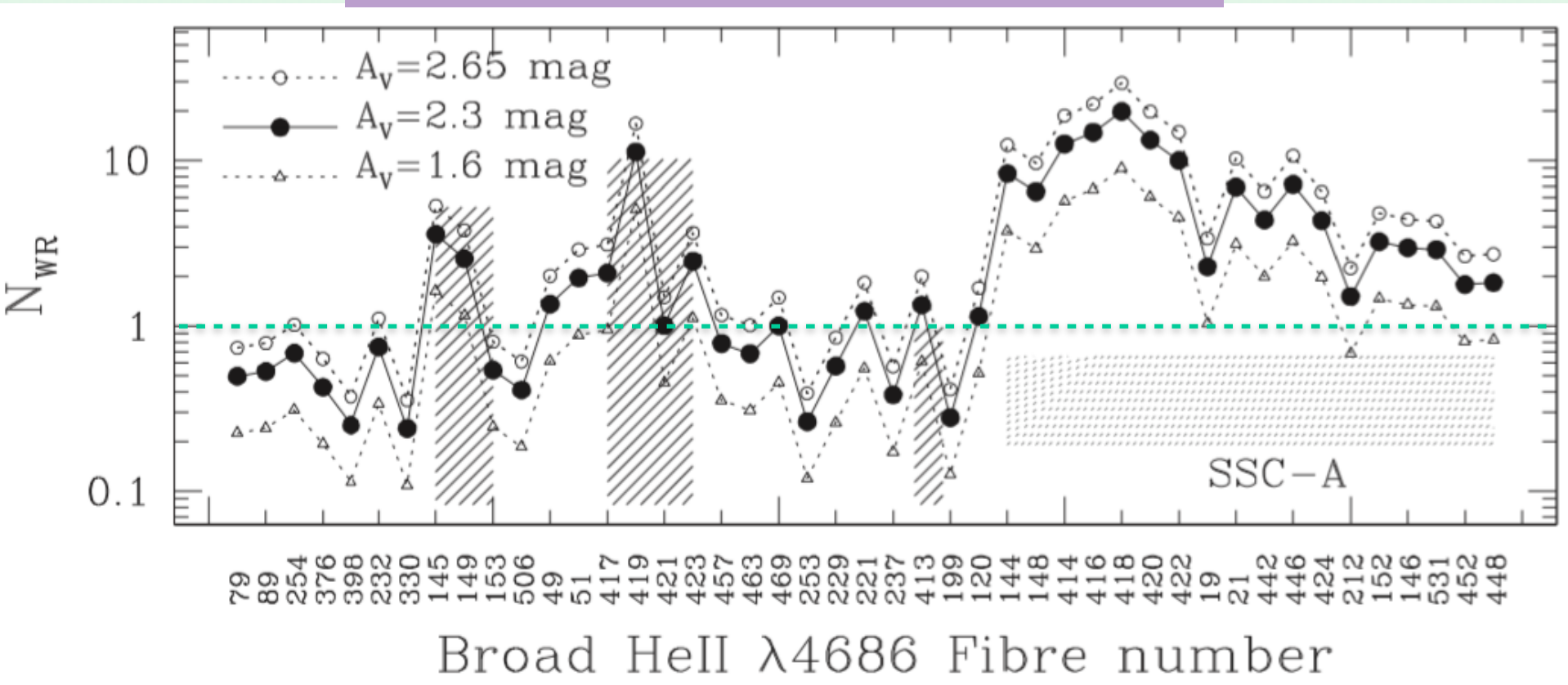
Spatial location of broad HeII4686 line - WR candidates





All reliable detections belong to SSC-A

Number of WR stars in each fiber



L(HeII4686) of WNL type WR star = 1.22×10^{36} erg/s López-Sánchez and Esteban 2010

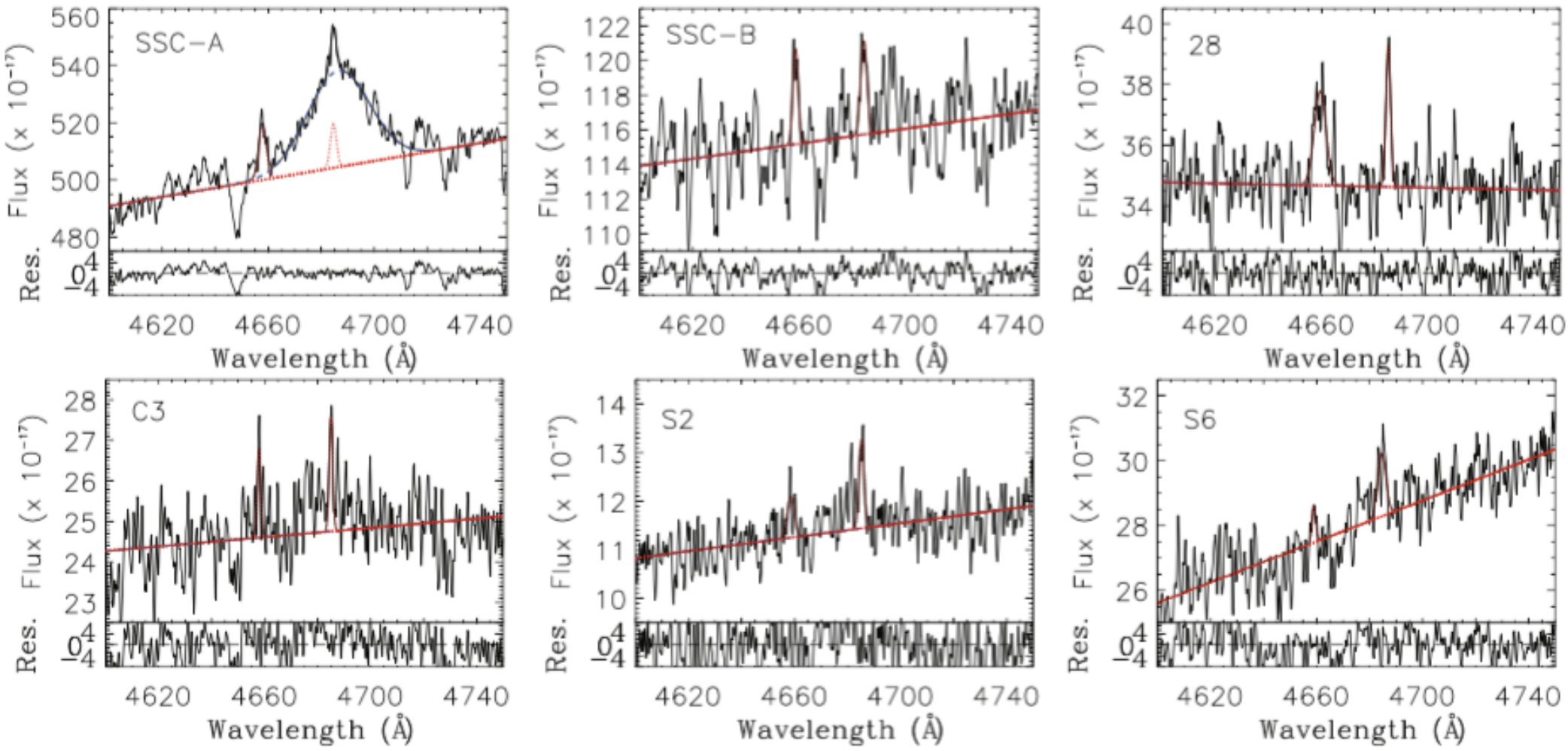
N_{WR} = L(HeII4686)/1.22×10^{36} erg/s

N_{WR}(SSC-A)= 124+/- 11 (Av=2.3 mag i.e Av mean continuum)
= 56 +/- 7 (Av = 1.6 mag i.e. the Galactic extinction) (Devost et al. 1997)
= 186 +/- 13 (Av=2.65 mag i.e. Av mean nebular

The N_{WR} is in agreement with that reported by González-Delgado et al. 1997

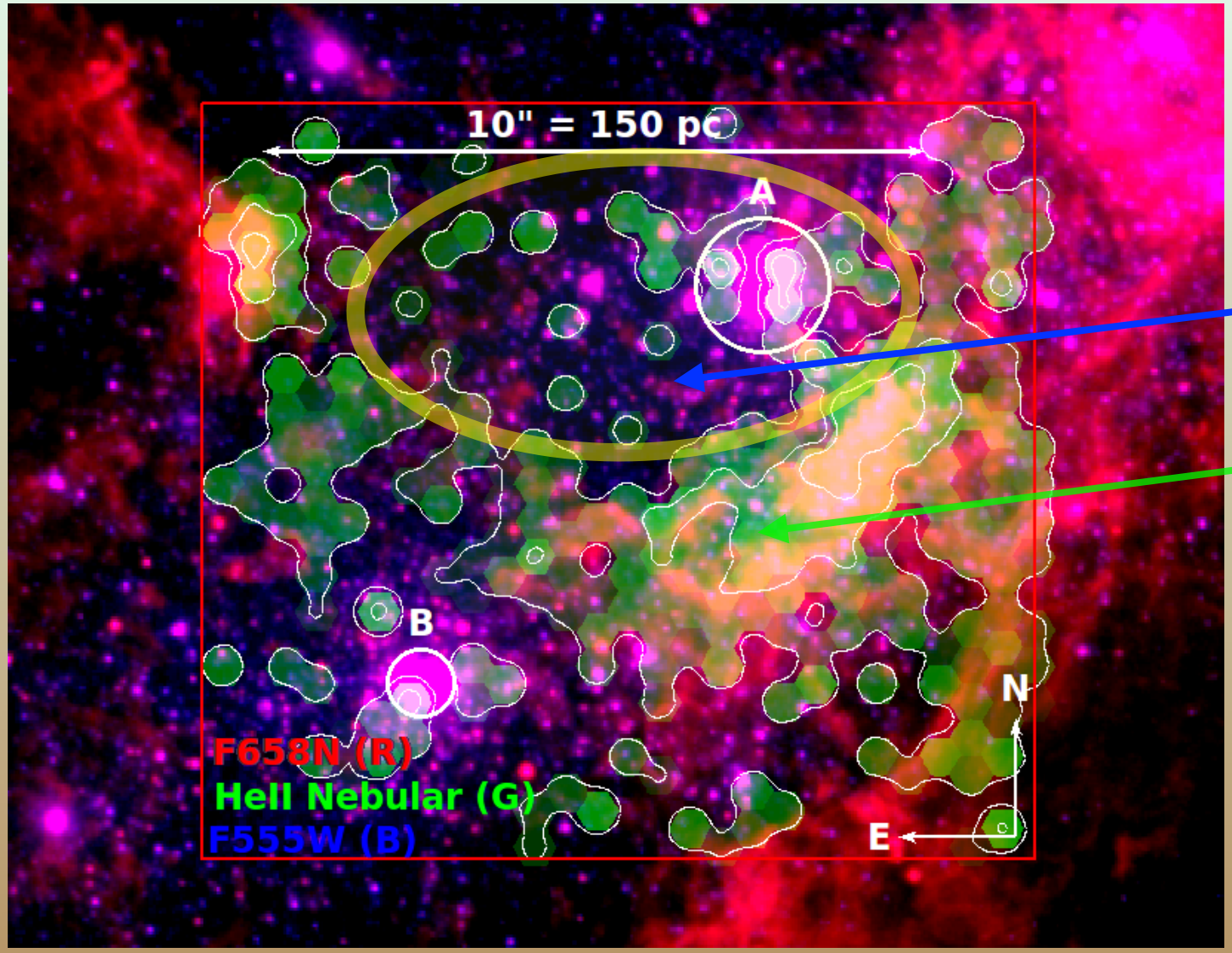
Other candidate-WR stars in the FoV

- **SSC-B, cluster #28**
- **candidate WRs from HST F469N-excess continuum sources** (Buckalew et al. 2000)



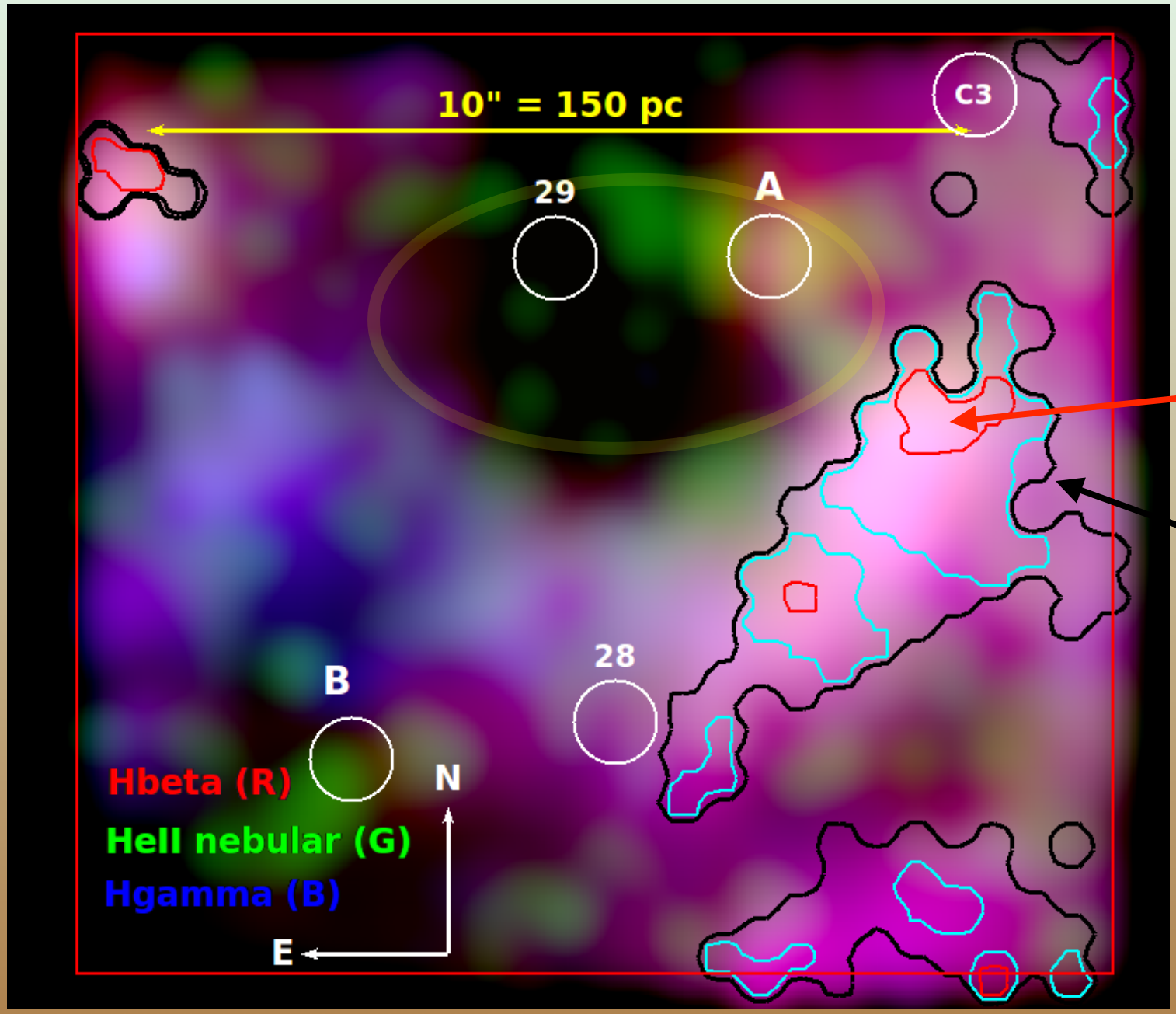
- **SSC-A is the only location of WR stars in our FoV**
- **We confirm the absence of WR stars in SSC-B**

Spatial location of narrow HeII4686 line - He^{++} nebula



- He^{++} nebula follows the H^{+} nebula in its morphology
- A crescent-shaped nebula of diameter of 150 pc off-centered from SSC-A
- No nebular emission within 40 pc of SSC-A ===> a WR bubble

H^+, He^{++} nebulae and extinction map



Av>4 mag

Av=1.6 mag

Observed vs SSP properties

$$\frac{Q(\mathrm{He}^+)}{\mathrm{photon\ s}^{-1}} = \frac{L(\mathrm{He\,II}\lambda4686)}{E_{\lambda4686}} \times \frac{\alpha_B(\mathrm{He}^+)}{\alpha_{\mathrm{eff}}(\mathrm{He\,II}\lambda4686)} = 1.02 \times 10^{48} \frac{L(\mathrm{He\,II}\lambda4686)}{10^{36}\ \mathrm{erg\ s}^{-1}},$$

$$\frac{Q(\mathrm{H}^0)}{\mathrm{photon\ s}^{-1}} = 2.10 \times 10^{48} \frac{L(\mathrm{H}\,\beta)}{10^{36}\ \mathrm{erg\ s}^{-1}},$$

Case B: Osterbrock & Ferland 2006

Global ionizing photon rate implied by the nebular emission in NGC1569

$Q(H^0)$ = 1x10^{52} photon/s
$Q(He^{++})$ = 1x10^{50} photon/s

I(HeII4686)/I(Hβ) = 0.02
EW(Hβ) = 75 - 160 Å

Simple Stellar Population (SSP) models

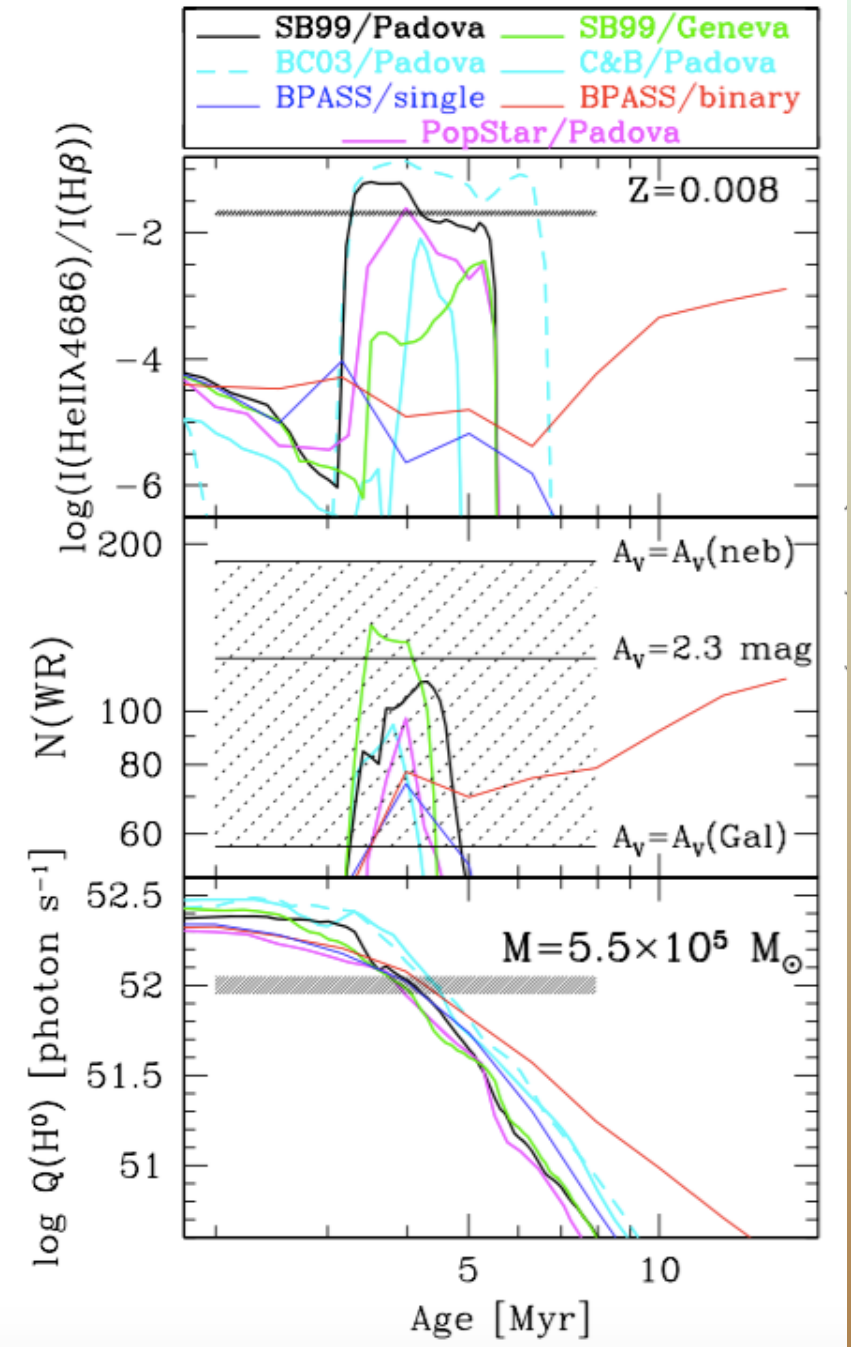
SSP code ID	WR model + atmosphere
(1)	(2)
SB99/Padova	Padova1994+CMFGEN
SB99/Geneva	Geneva1994+CMFGEN
PopStar/Padova	Padova1994+CMFGEN
BC03/Padova	Padova1994+POWR
C&B/Padova	Padova2015+POWR
BPASS/single	Cambridge+POWR
BPASS/binary	Cambridge+POWR

Leitherer et al. 1999
Leitherer et al. 1999
Mollá, García-Vargas, Bressan A. 2009
Bruzual & Charlot 2003
Charlot & Bruzual 2020
Eldridge et al. 2017
Eldridge et al. 2017

Kroupa IMF: 0.15-100 $M_\odot$

Most recent models downloaded from the respective web-sites

Observed vs SSP properties



SSP code ID	WR model + atmosphere	Comments
(1)	(2)	(9)
SB99/Padova	Padova1994+CMFGEN	Good fit
SB99/Geneva	Geneva1994+CMFGEN	I(He II)/I(H β) too low
PopStar/Padova	Padova1994+CMFGEN	Good fit
BC03/Padova	Padova1994+POWR	Good fit
C&B/Padova	Padova2015+POWR	Marginal fit
BPASS/single	Cambridge+POWR	I(He II)/I(H β) too low
BPASS/binary	Cambridge+POWR	I(He II)/I(H β) too low
SSC-A	Observed or inferred	$(5.5 \pm 0.5) \times 10^5$ $M_\odot$

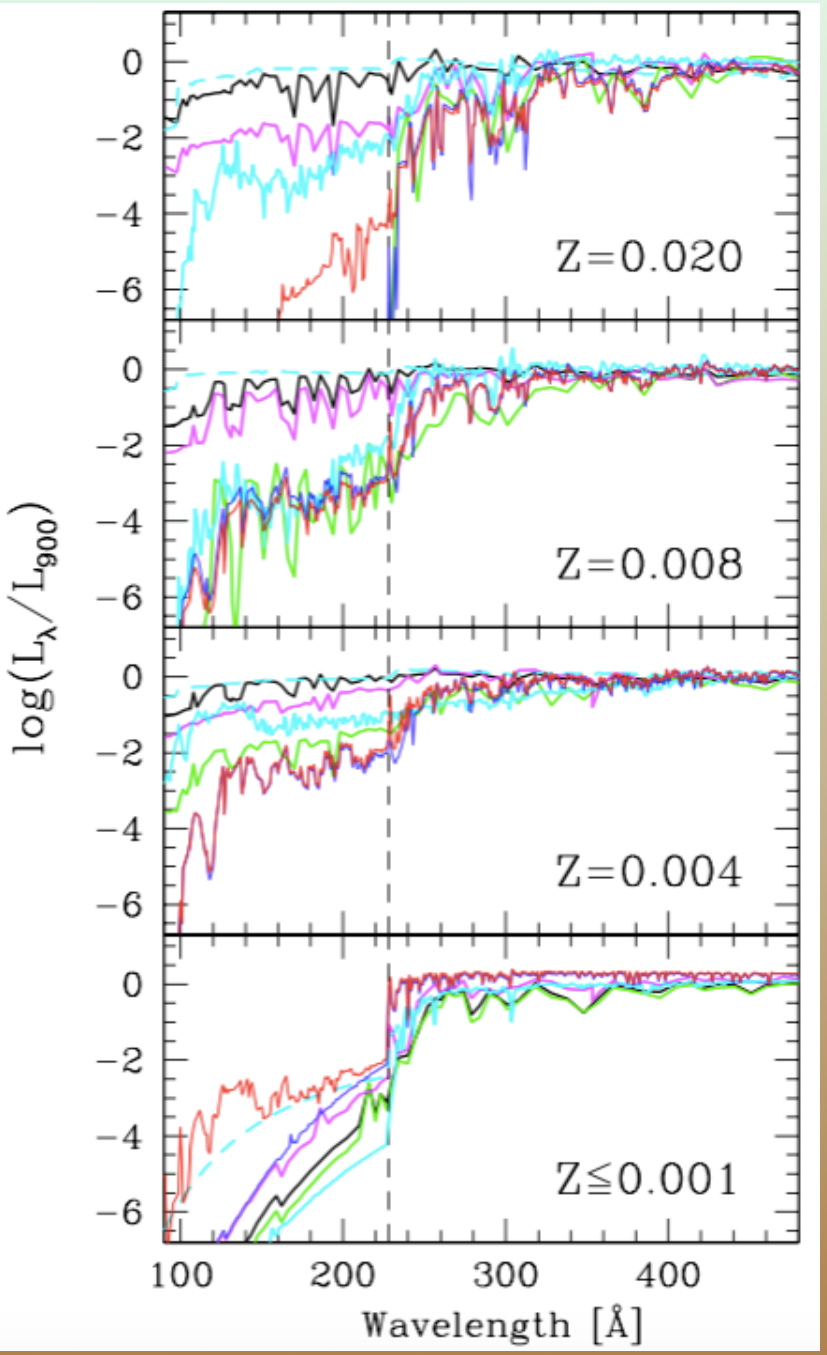
- **SSPs involving Padova tracks reproduce the observed values at**

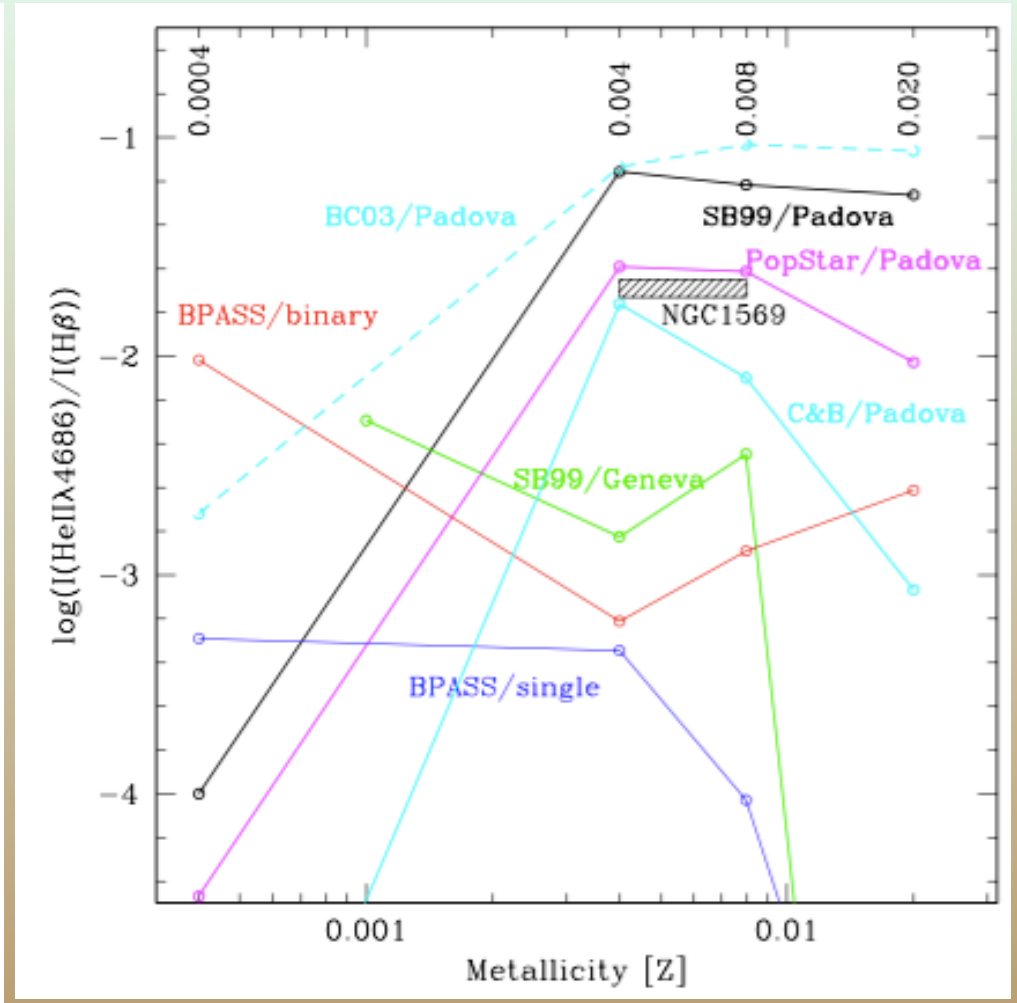
  age = 4.0+/-0.5 Myr
  mass = 5.5x10^5 M⊙

- **Other models underestimate the HeII4686 line strength**

- **The derived age and mass of SSC-A are in agreement with previous determinations** (Larsen et al. 2008, 2011)

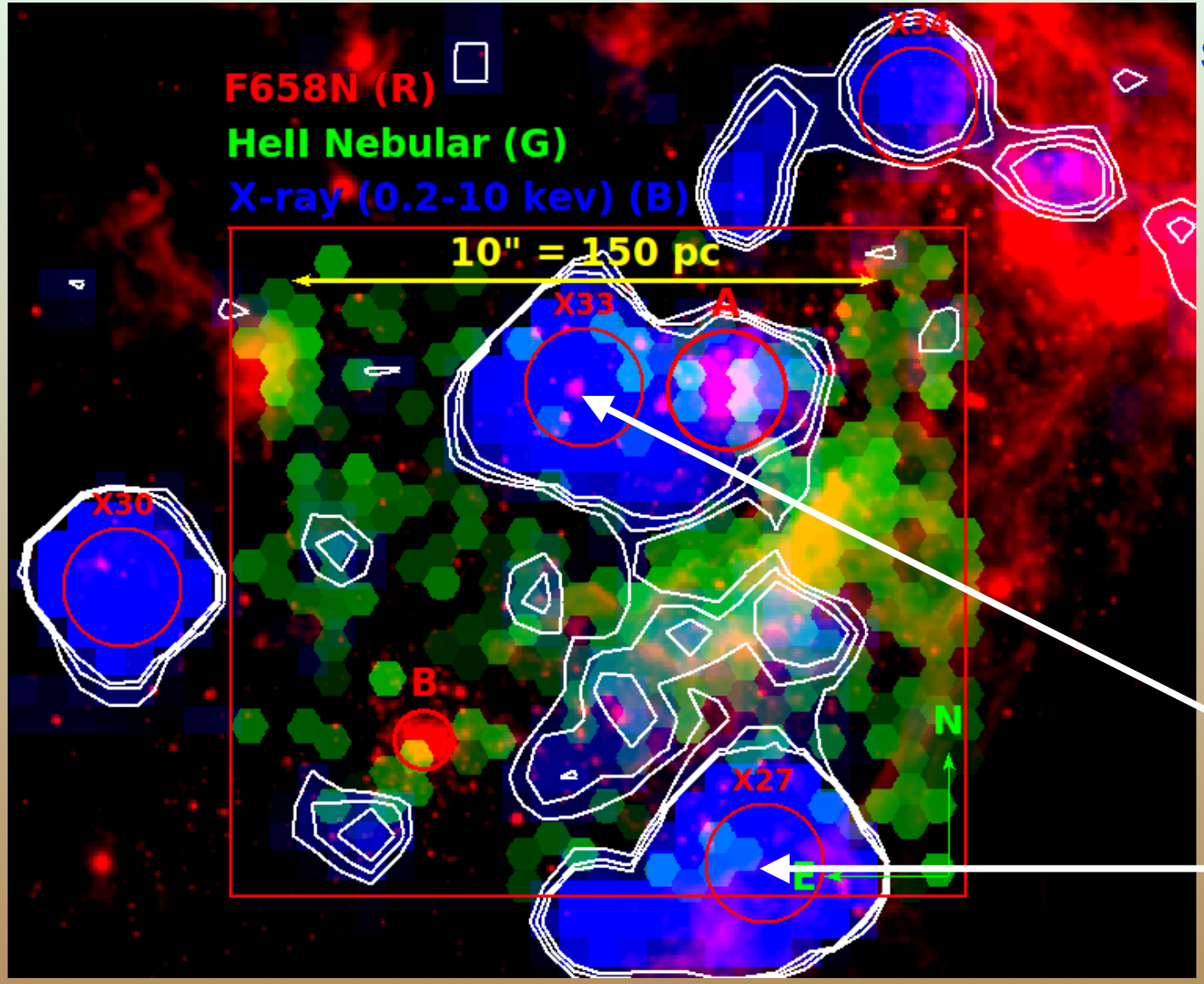
HeII4686/Hβ ratio vs metallicity: the ionization budget problem





- **Binary models produce the correct trend at low Z, but ratios are too small at high Z**
- **SSPs involving Padova tracks have the highest ratios for Z>0.004**
- **Other SSPs underestimate the ratio at all Z**

X-ray emission in NGC1569



Sánchez-Cruces et al. 2015

- **Diffuse soft X-ray emission is weak in the He^{++} nebula**
- **Hard X-ray point sources are too located far from He^{++} nebula**

Star cluster

X-ray binary

Chandra/ACIS image(0.2–10 keV band) in blue colour and white contours

Summary

- We used MEGARA/IFU at the GTC to map the He++ nebula and the WR stars in NGC1569
- We detect extended HeII4686 nebular emission from a crescent-shaped structure around SSC-A.
- We infer 124 WR stars of WNL type in SSC-A
- SSP models of age=4 Myr, mass 5.5×10^5 $M_\odot$ reproduce all the observed values
- Thus, the HeII ionization in NGC1569 is by WR stars and there is no requirement for other ionizing sources

Thanks