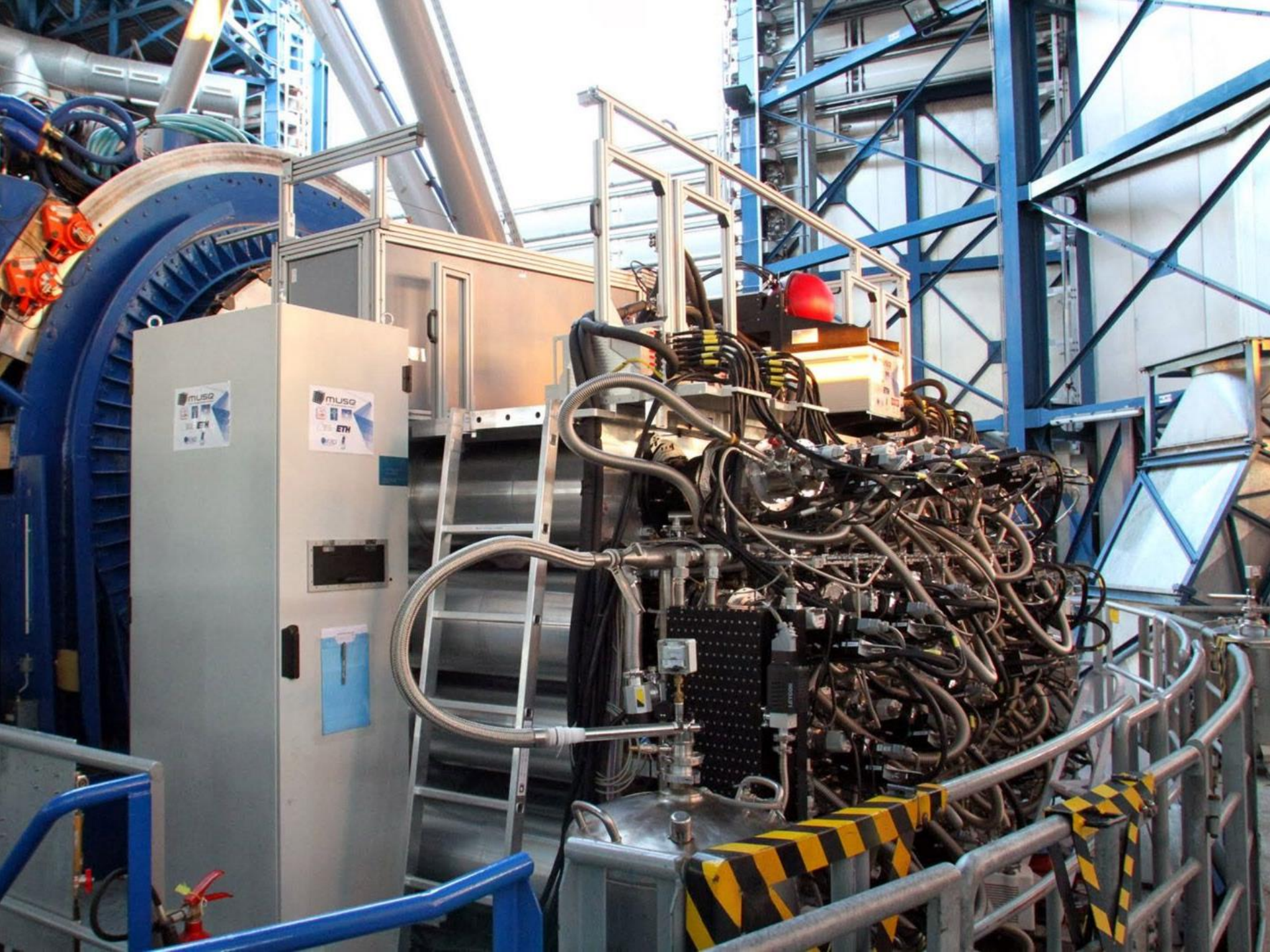
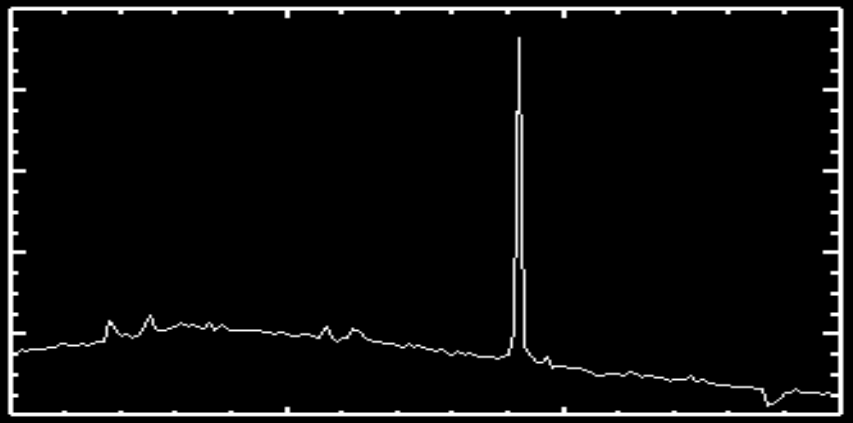
Martin M. Roth, AIP / Universität Potsdam
with credit to S. Kamann, P. Weilbacher, T.-O. Husser & MUSE Team

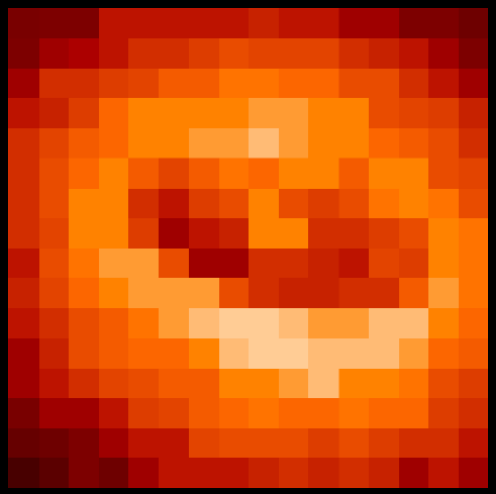
Outline

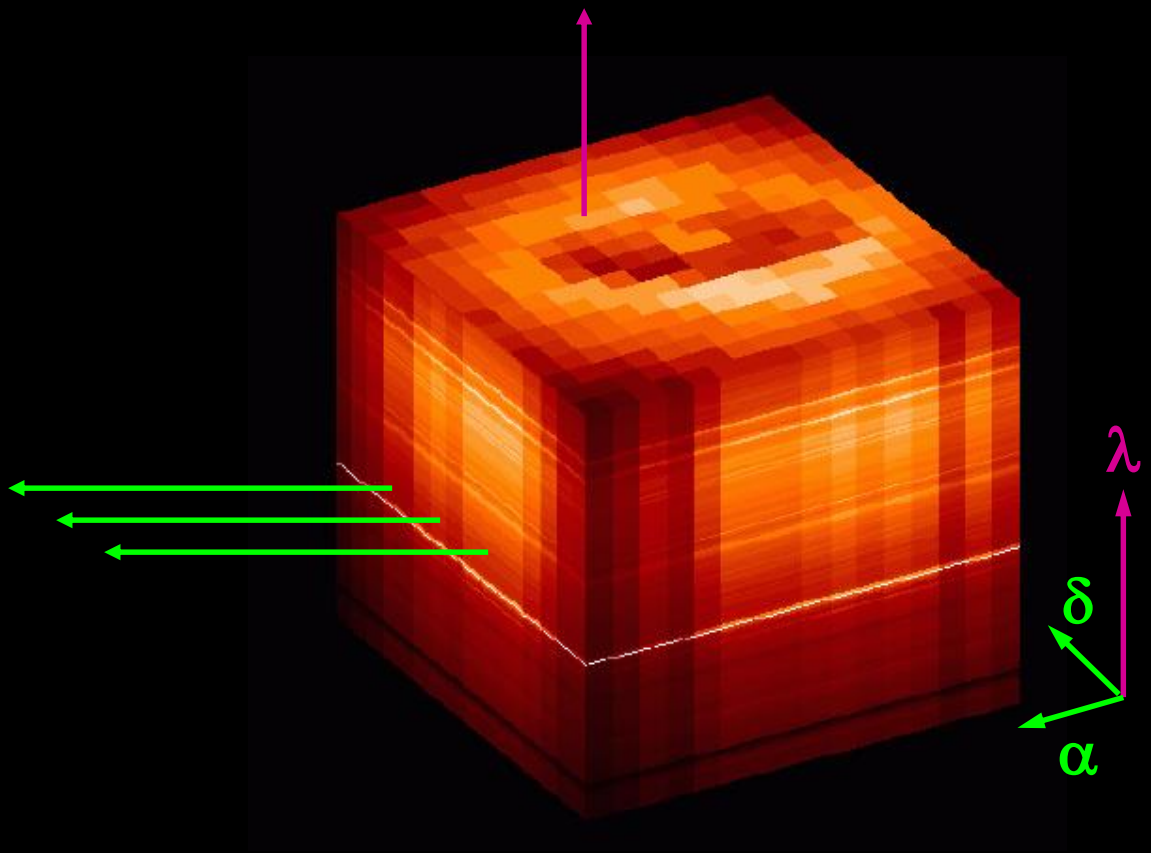
- Motivation
- MUSE results concerning DIG
- WIM in the Milky Way
- Summary & Conclusions


musa
ETH
musa
ETH

Integral Field ("3D") Spectroscopy

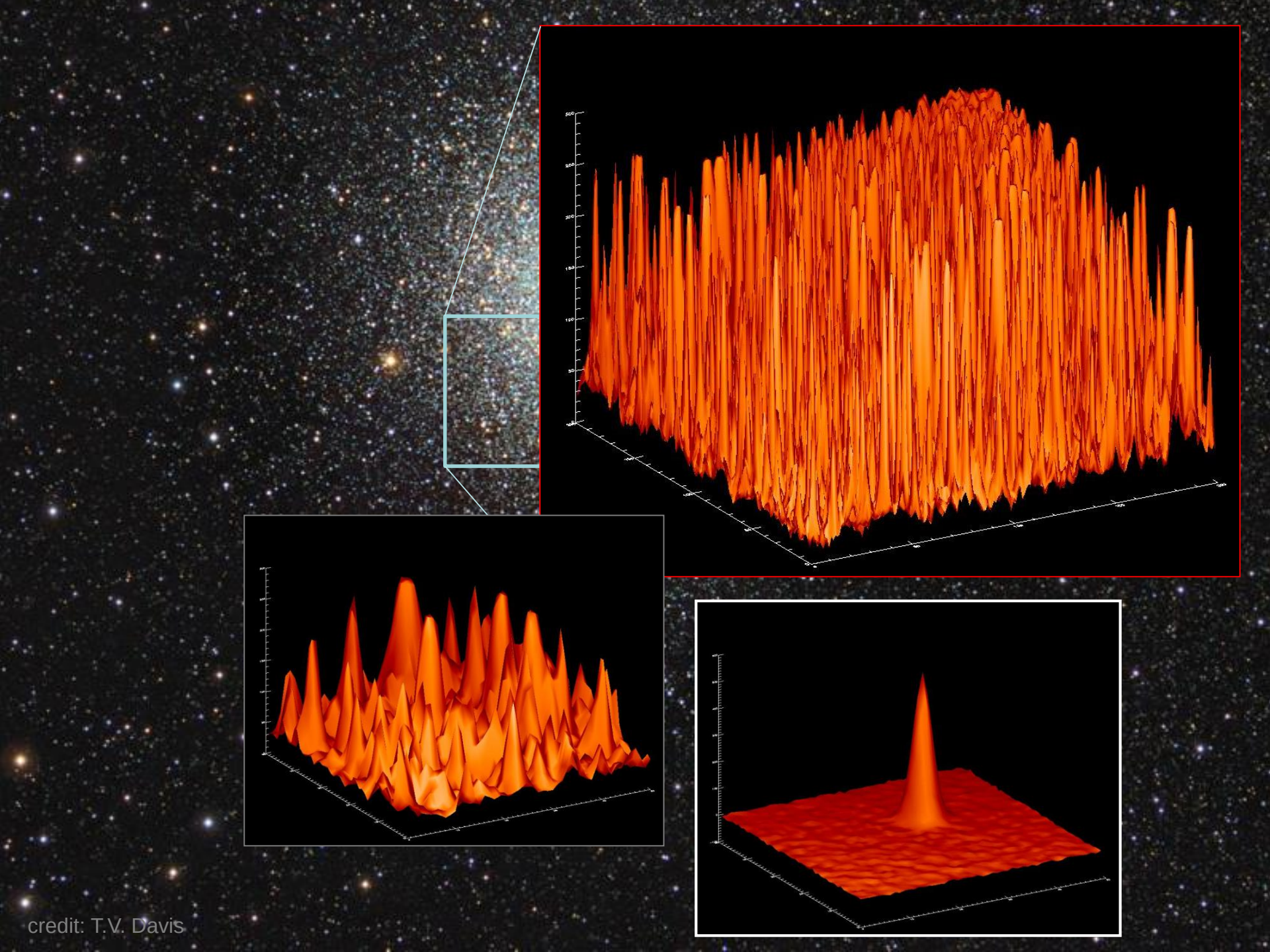






Motivation:

crowded field 3D spectroscopy

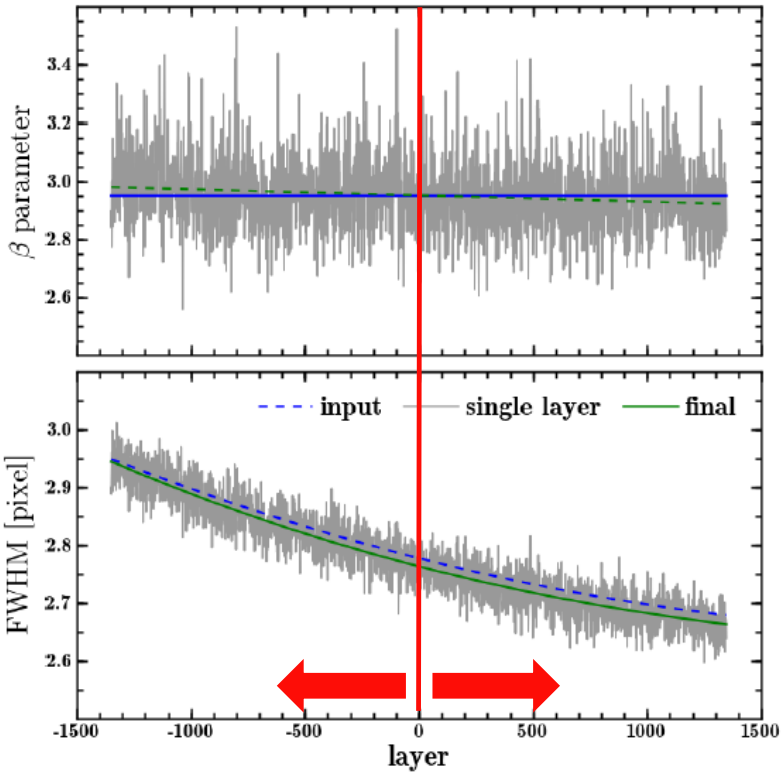


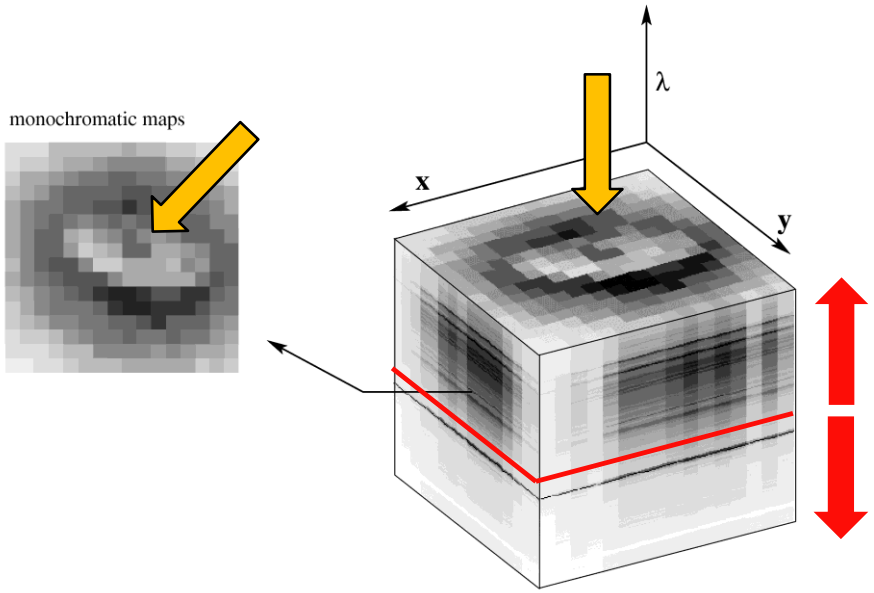
credit: T.V. Davis

PSF-fitting crowded field 3D spectroscopy

PampelMuse ©

Modelling the Point Spread Function (PSF):





Kamann (thesis, 2013)

PSF-fitting crowded field 3D spectroscopy

PampelMuse ©

important input data:

stellar centroids from HST images

Global Model:

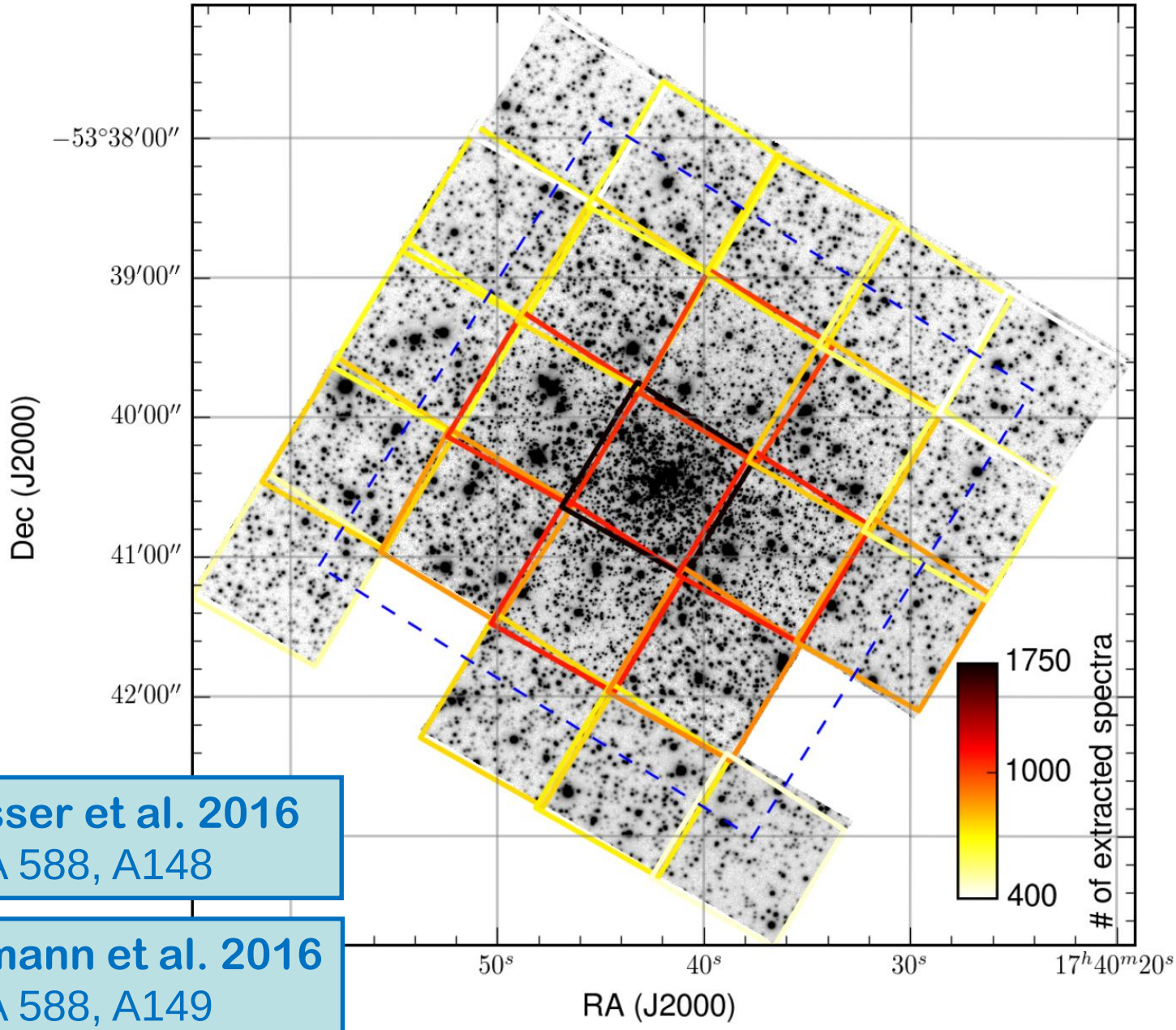
observed datacube: $\mathfrak{d}_{i,j,k}$

model datacube: $$\mathfrak{m}_{i,j,k} = \sum_n f_k^n \ \mathrm{psf}_{i,j,k}^n + \sum_m b_{i,j,k}^m$$

minimization: $$\chi^2 = \sum_{i,j,k} \frac{\left(\mathfrak{d}_{i,j,k} - \sum_n f_k^n \ \mathrm{psf}_{i,j,k}^n - \sum_m b_{i,j,k}^m\right)^2}{\sigma_{i,j,k}^2}$$

Kamann (thesis, 2013)

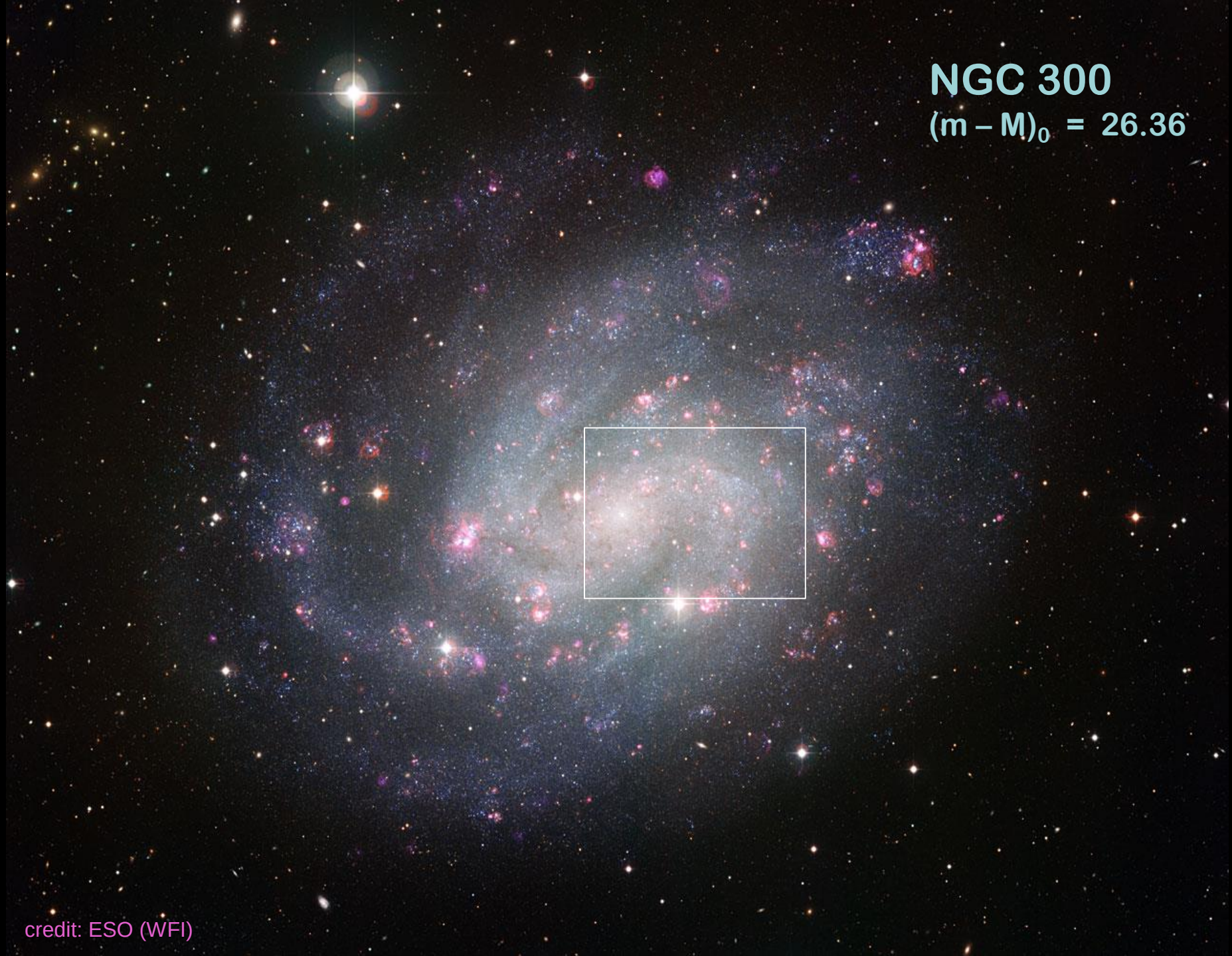
NGC6397

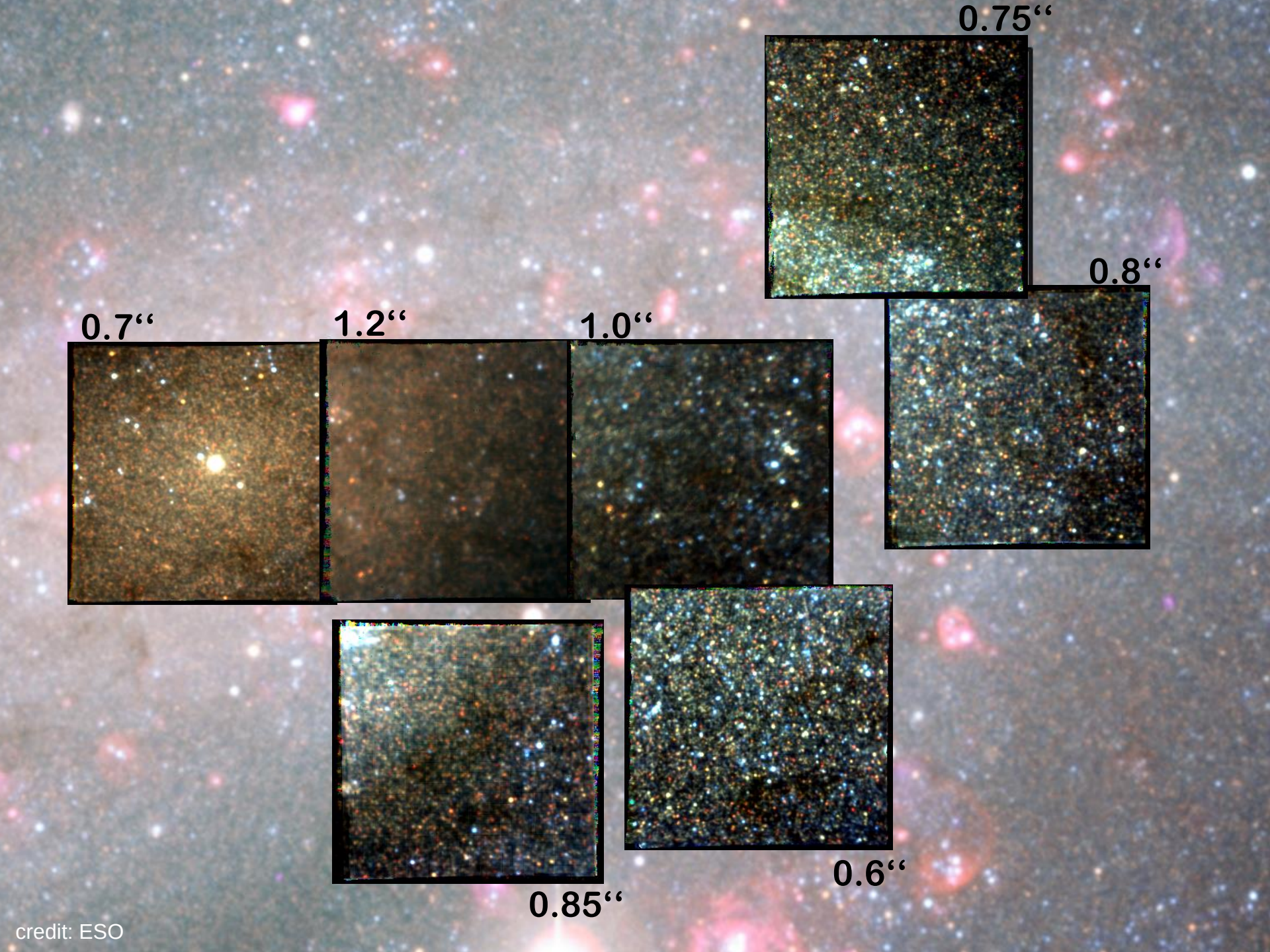


PMAS

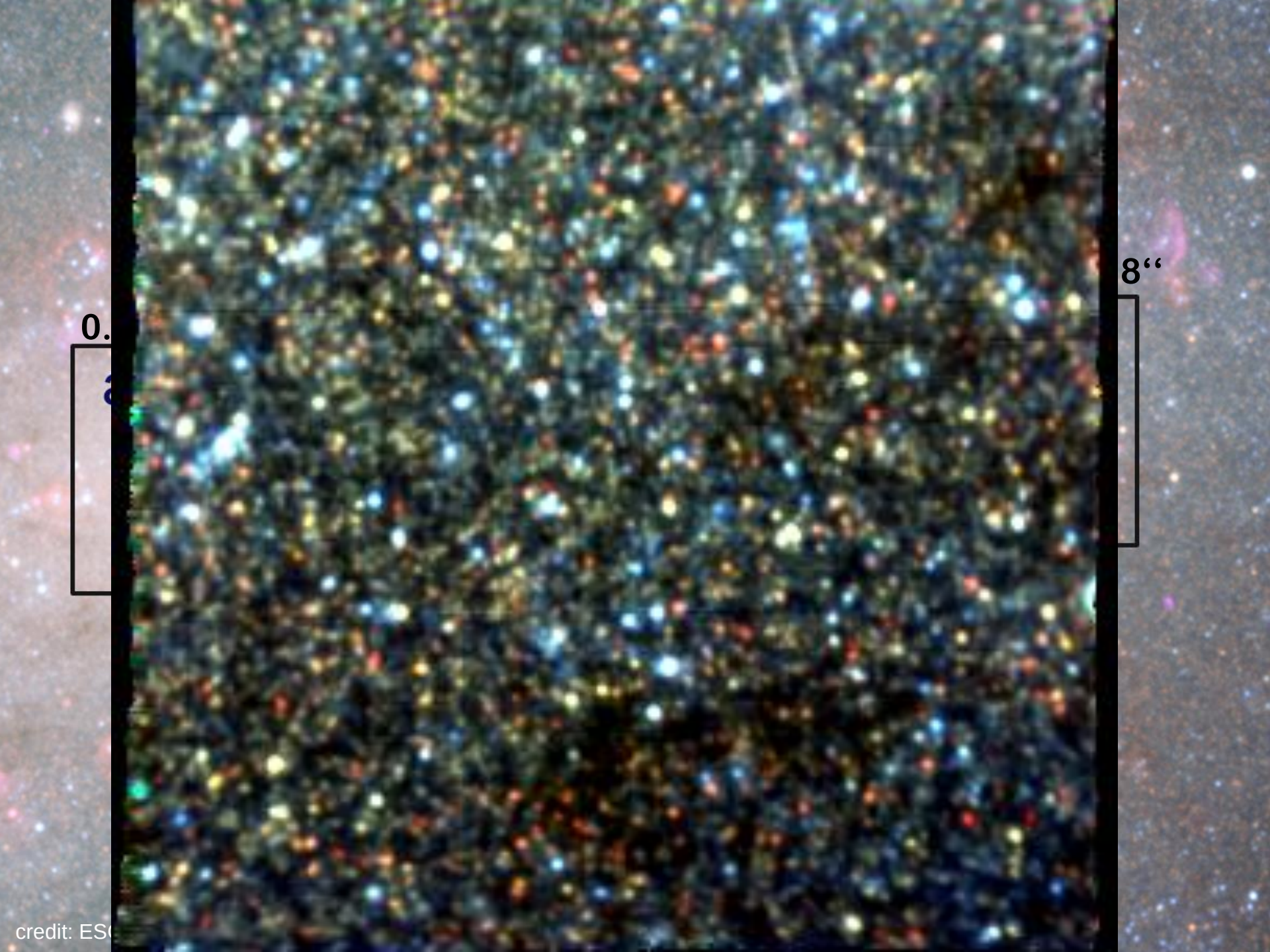
Husser et al. 2016
A&A 588, A148

Kamann et al. 2016
A&A 588, A149


NGC 300
$(m - M)_0 = 26.36$
credit: ESO (WFI)



credit: ESO


8“
credit: ESO

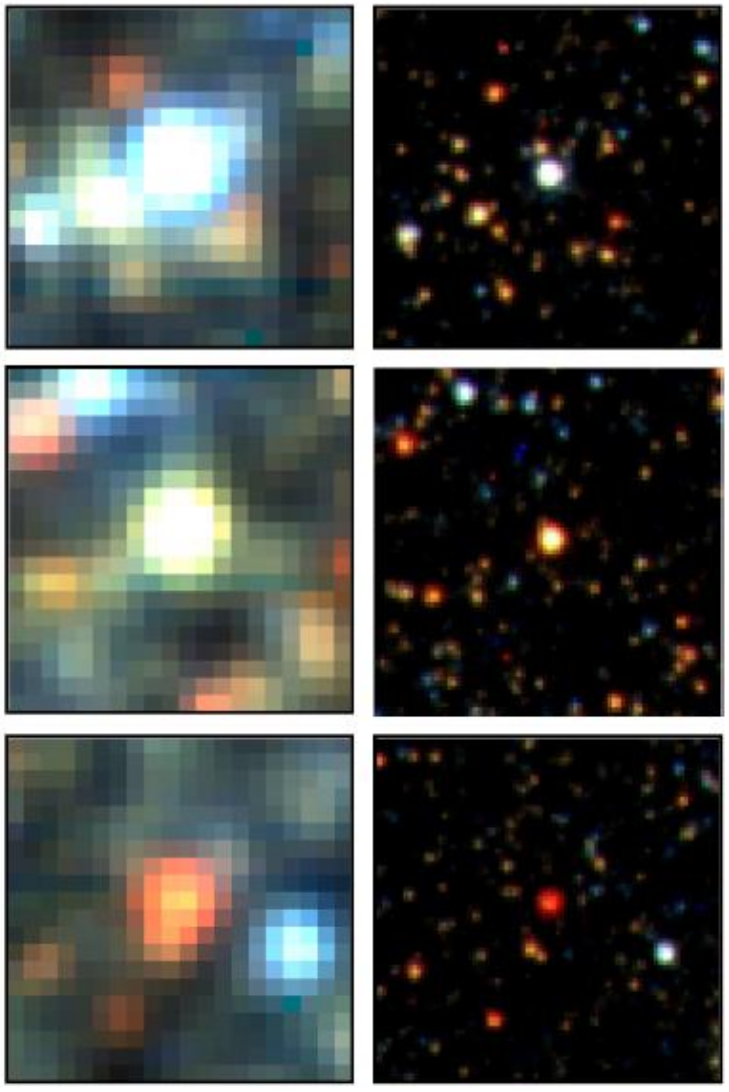
Data Analysis

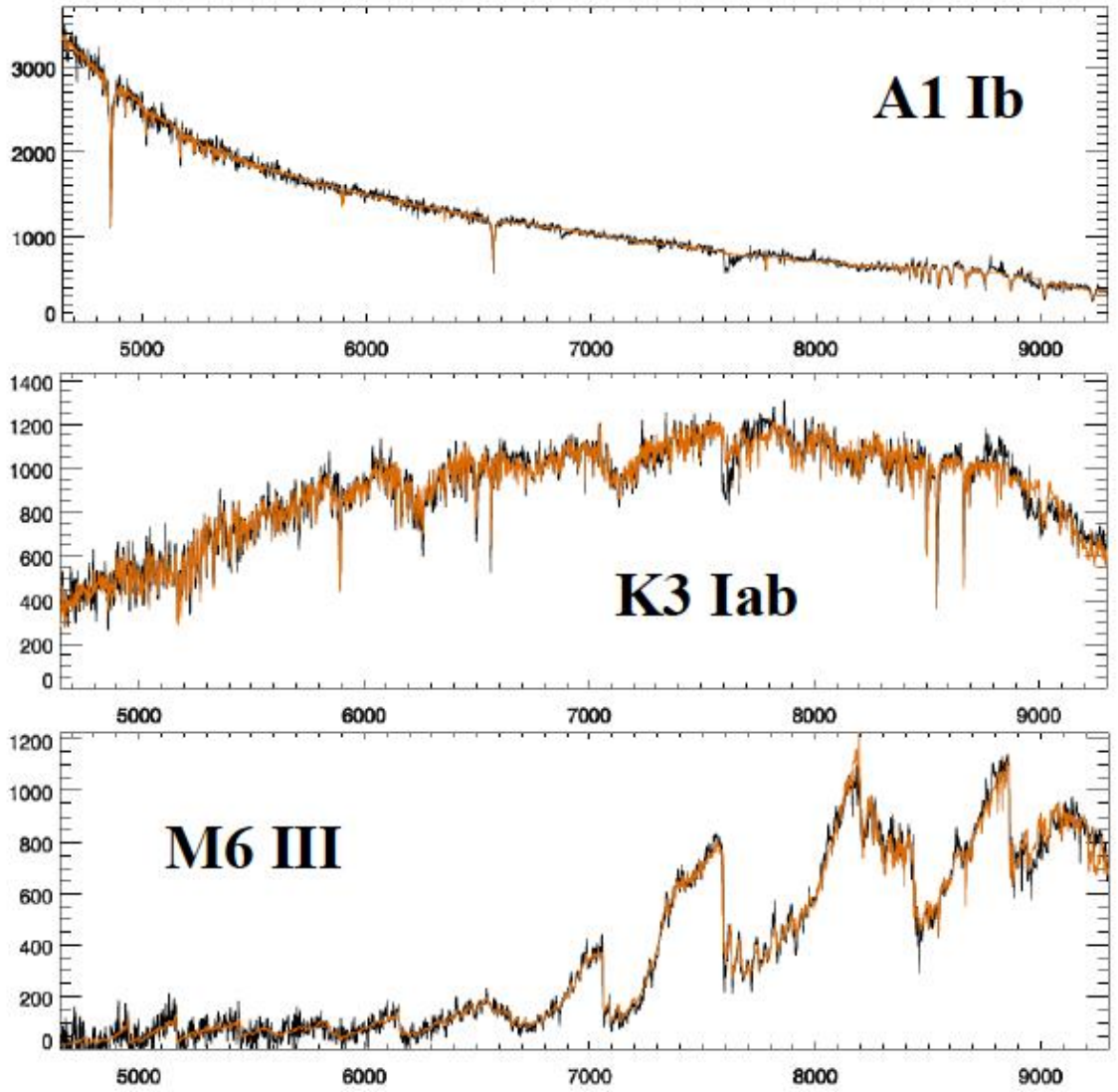
- HST photometry catalogue (ANGST)
- VRI images
  - from HST archive
  - MUSE images extracted from datacubes
- Extraction of spectra using PampelMuse
- Fields not covered by HST with DAOPHOT FIND
- Stars:
  - Spectral template fitting with ULYSS
  - Spectral library: MIUSCAT (MILES+CAT+indoU.S.)
  - Fitting with Göttingen Library GLIB
  - Photometry of MIUSCAT stars (SIMBAD)
  - Visual inspection → Teff, log g, vrad
- Emission line objects:
  - classification, flux,fwhm,vrad (p3d)

► Catalogue

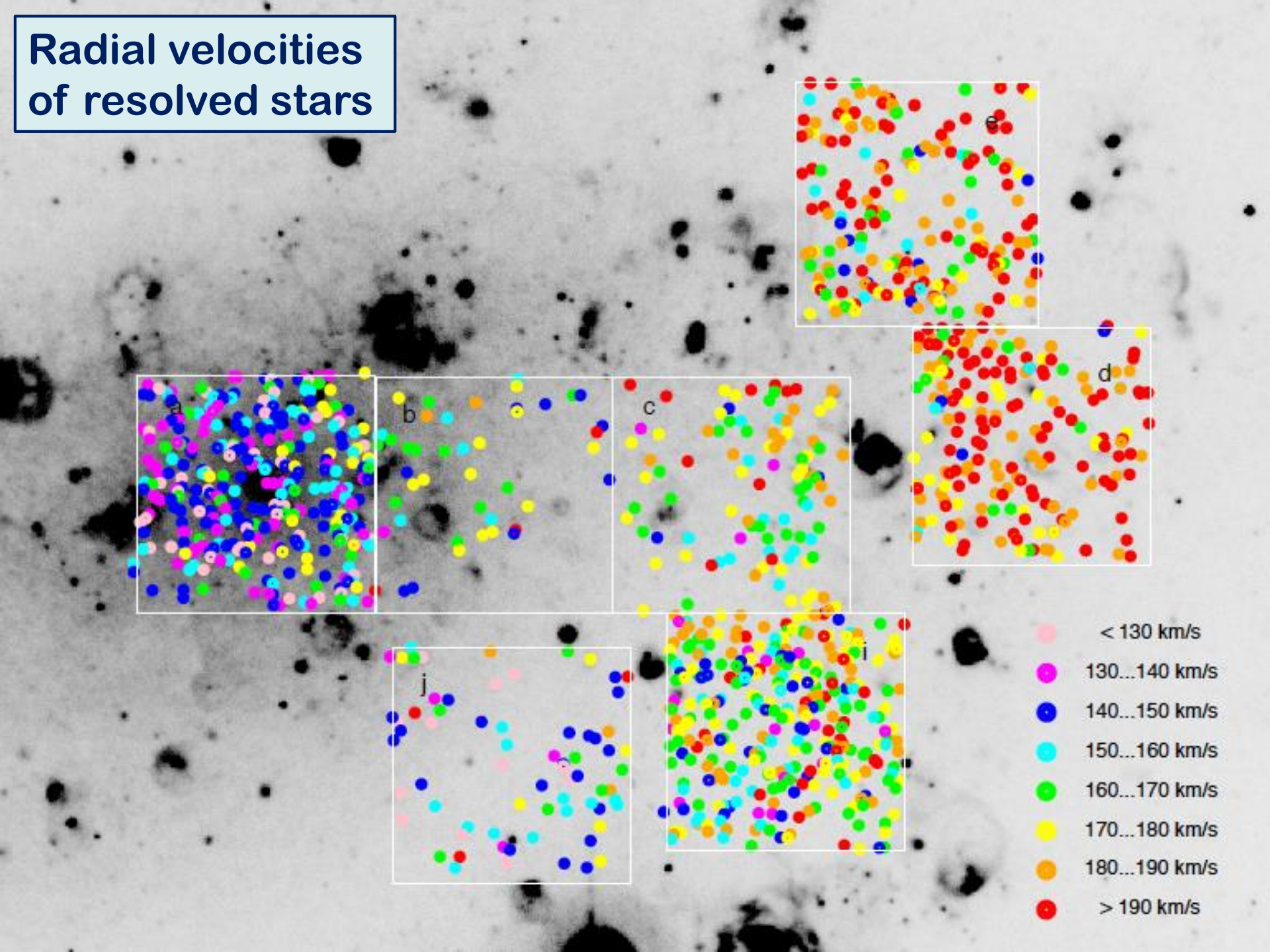
► Atlas

Example spectra:





Radial velocities of resolved stars



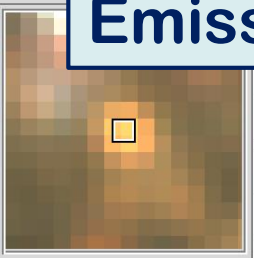
Summary (from 9 hrs exposure time)

	a	b	c	d12	e1	i	j	
Seeing	0.7“	1.2“	1.0“	0.8“	0.75“	0.6“	0.85“	
PN	5	7	6	4	9	3	2	36
PN candidates	4	0	0	1	4	0	0	9
HII regions	10	11	5	13	4	13	5	61
cHII regions [1)]	8	4	5	19	5	2	8	51
SNR	14	5	3	5	3	6	2	38
emStars [2)]	18	4	4	15	30	**40**	7	118
bgr. Galaxies [3)]	4	3	1	6	2	8	4	28
Stars [4)]	445:	77:	152:	265:	299:	**517**	91:	1846

1) compact HII regions
2) emission line stars
3) background galaxies
4) stars with spectral type

MUSE results concerning DIG

Emission line objects



Datei
field_a_stars.png
Objekt

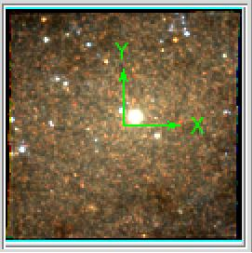
Wert
r 255
g 220
b 113

WCS

Physikalisch
X 85.690
Y 206.803

Bild
X 85.690
Y 206.803

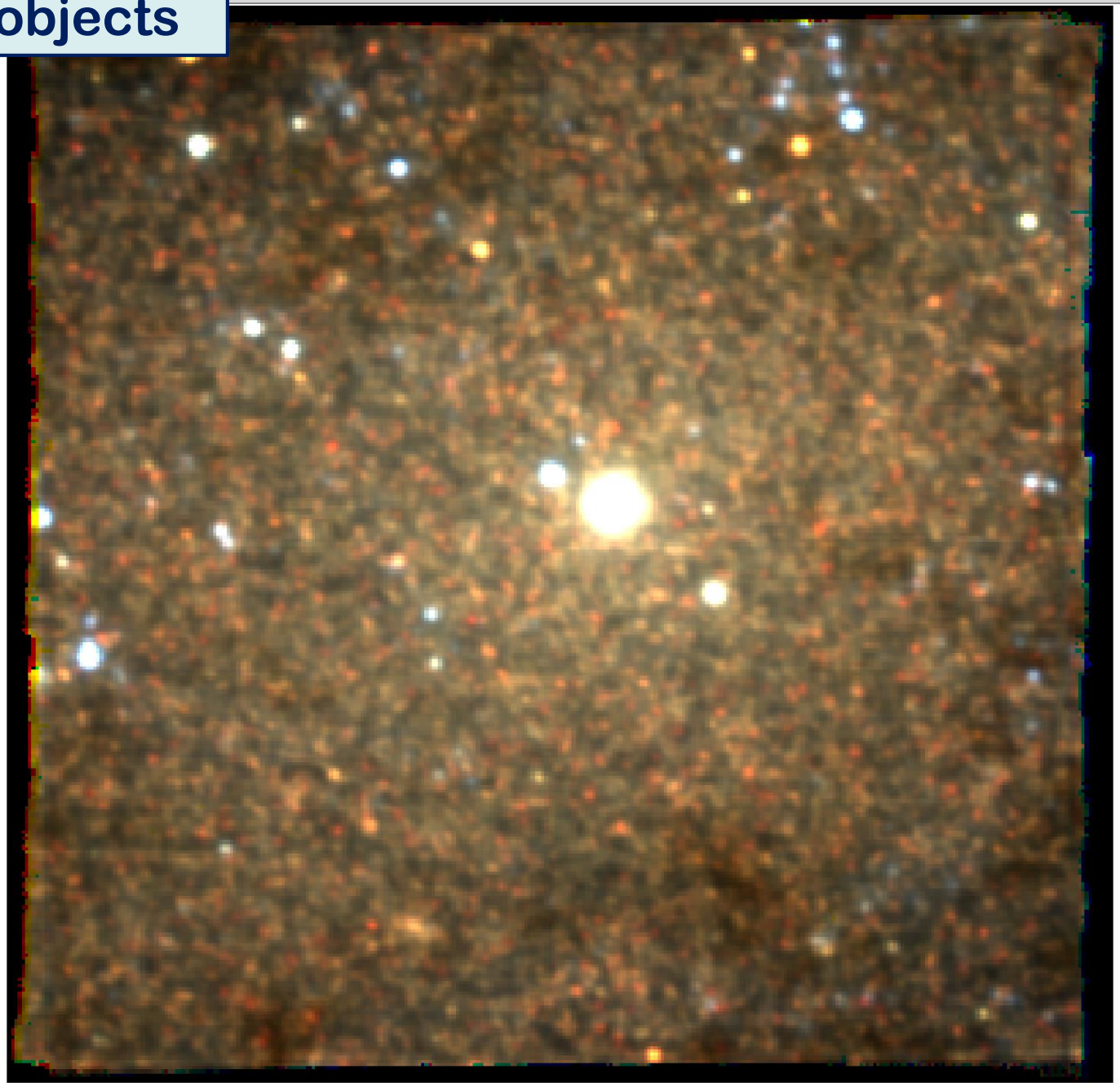
Rahmen 2
x 2.254
° 0.000



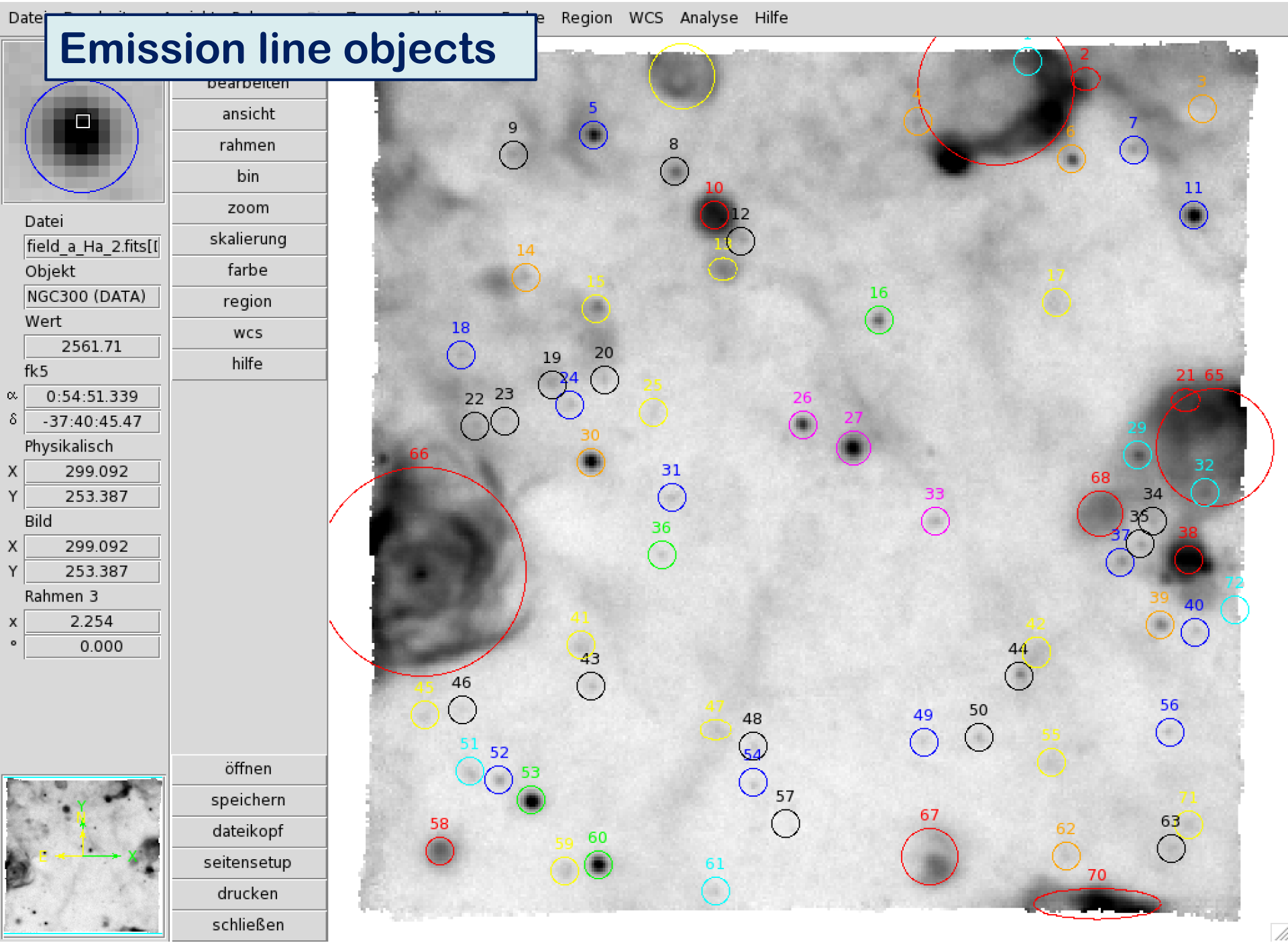
Datei Region WCS Analyse Hilfe

bearbeiten
ansicht
rahmen
bin
zoom
skalierung
farbe
region
wcs
hilfe

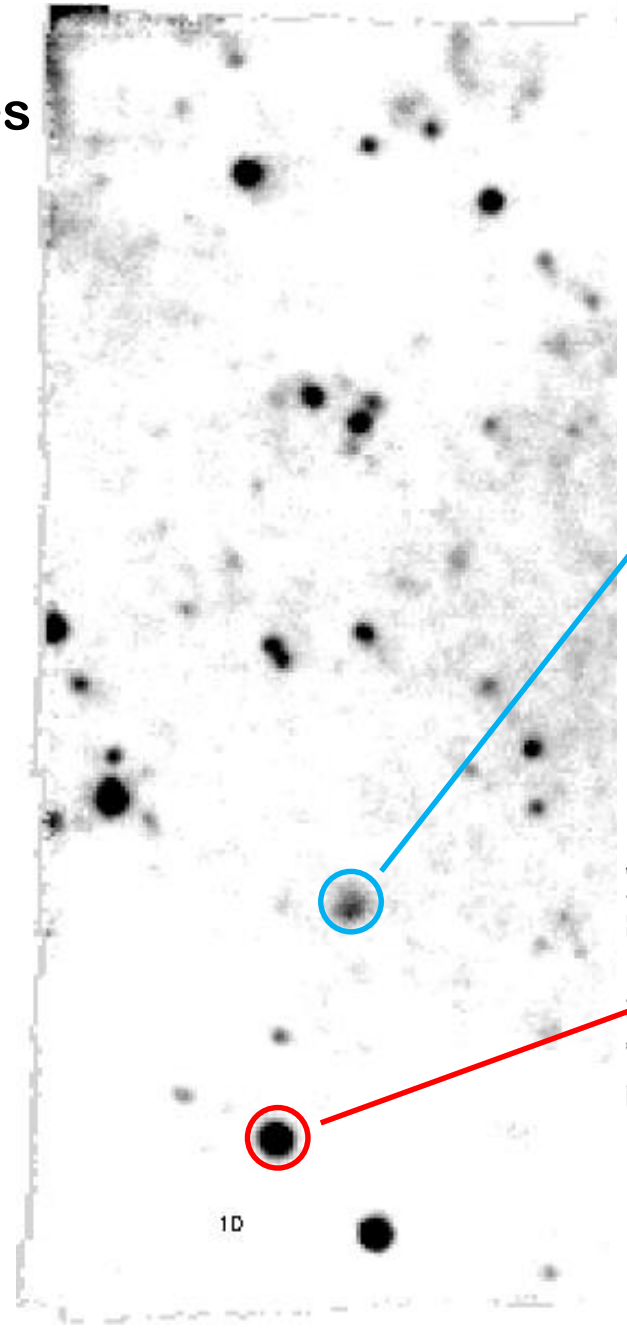
öffnen
speichern
dateikopf
seitensetup
drucken
schließen

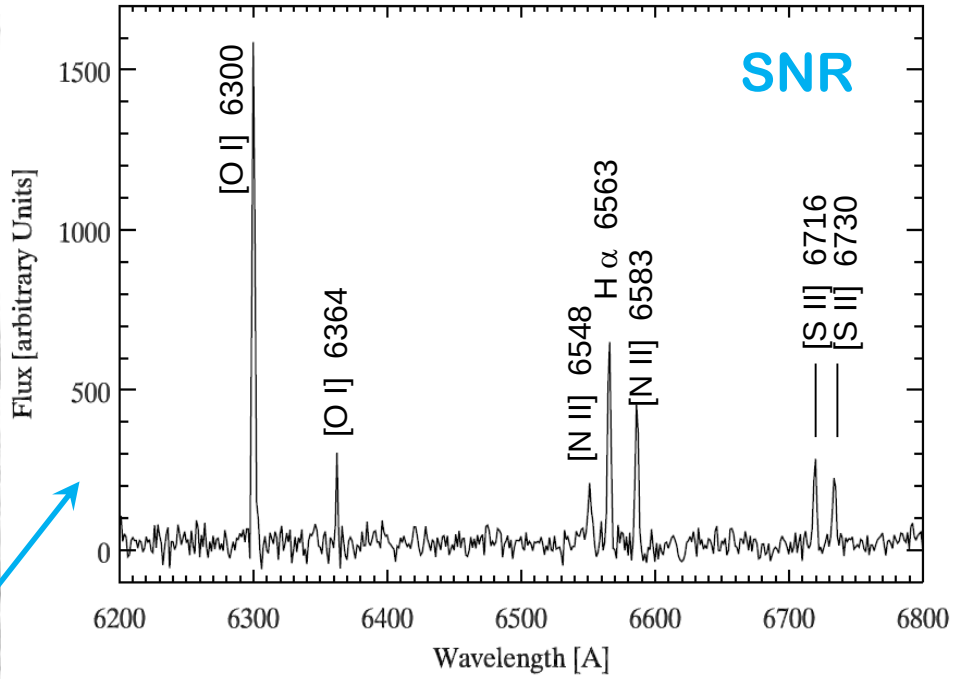


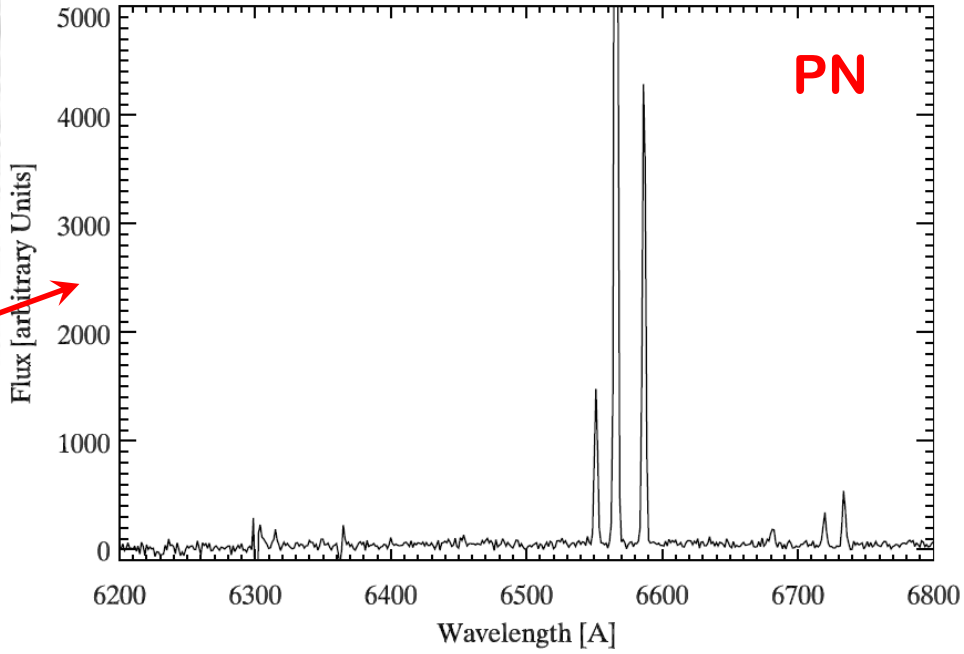
Emission line objects

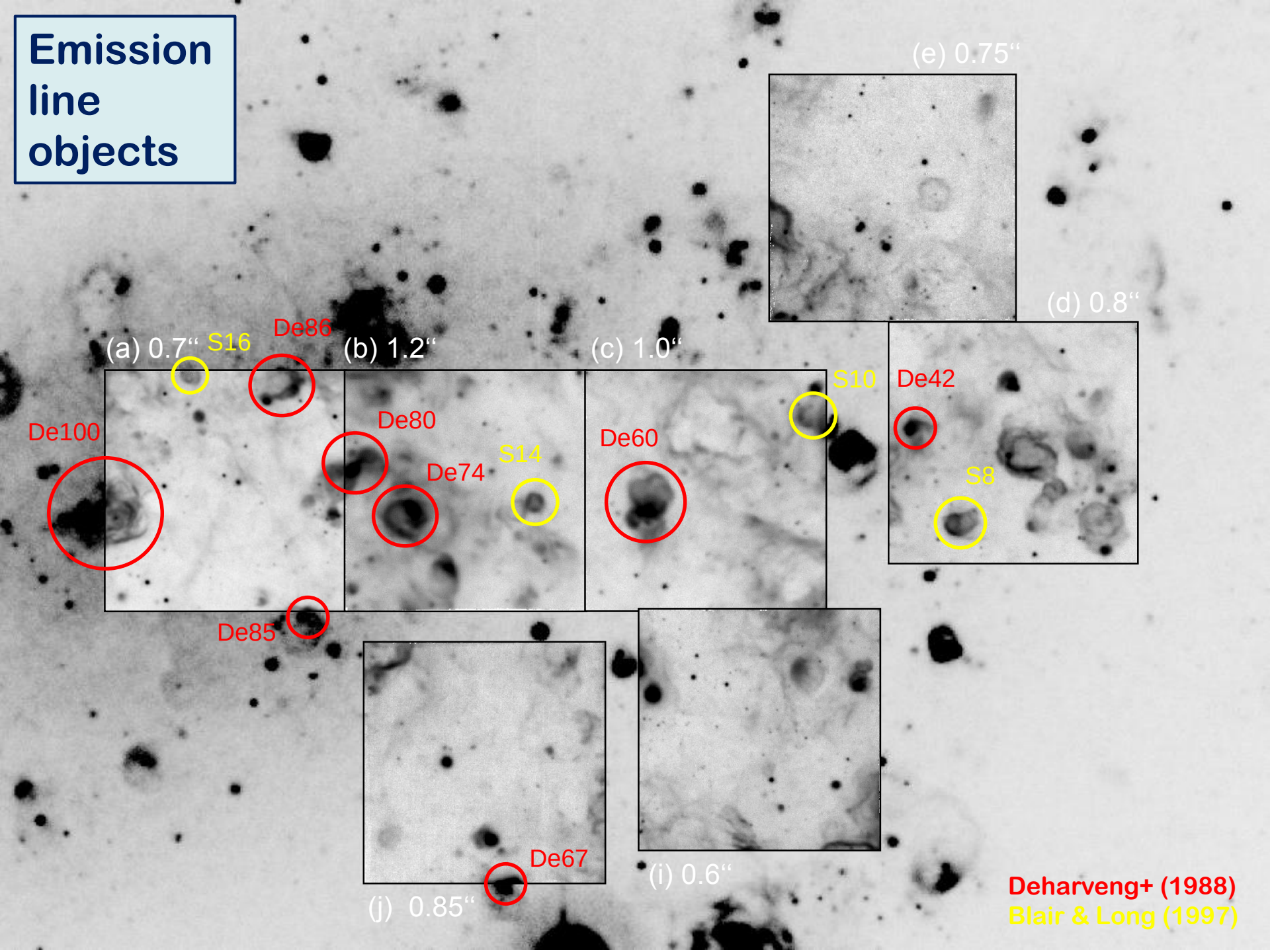


SNR candidates in field (a)

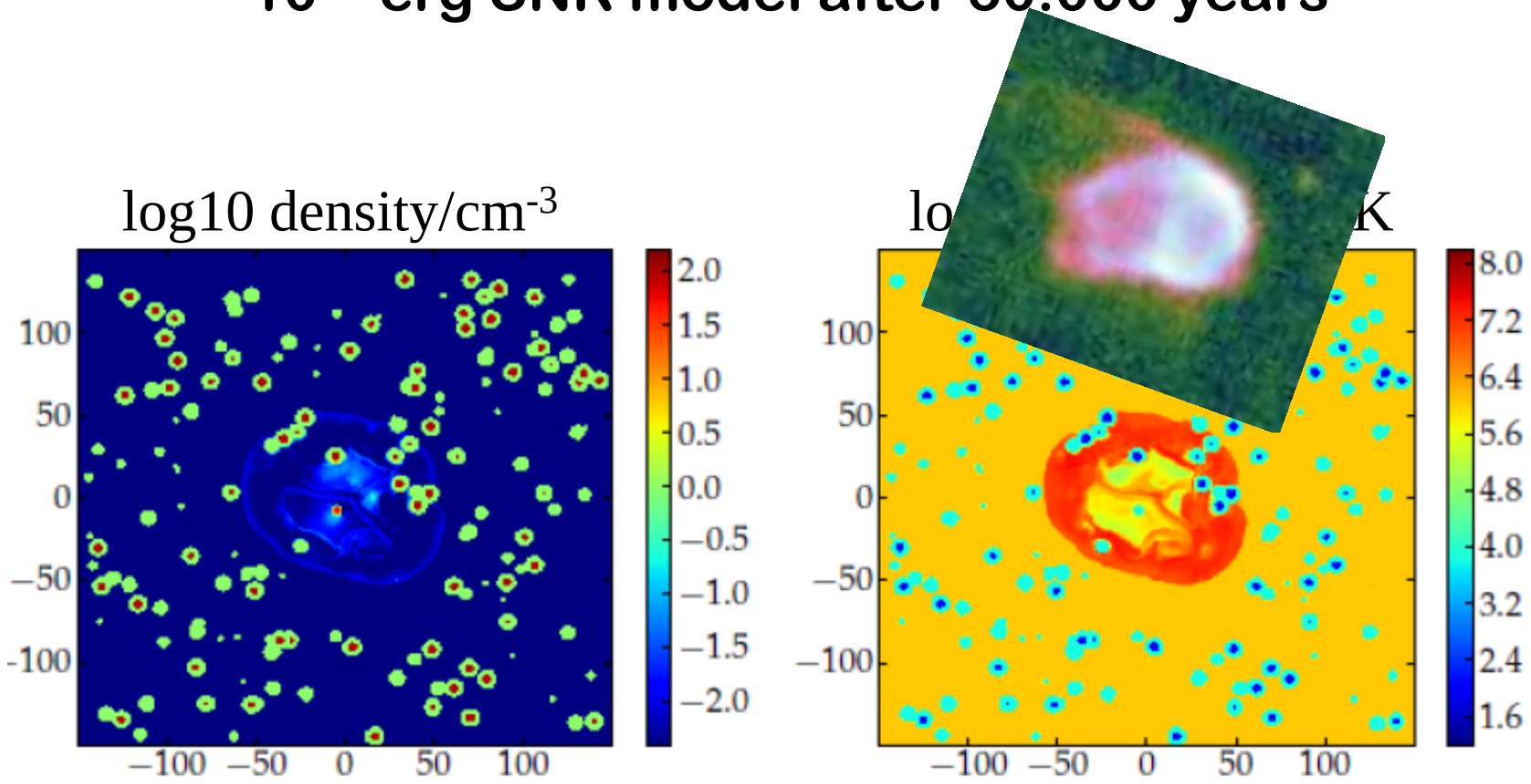






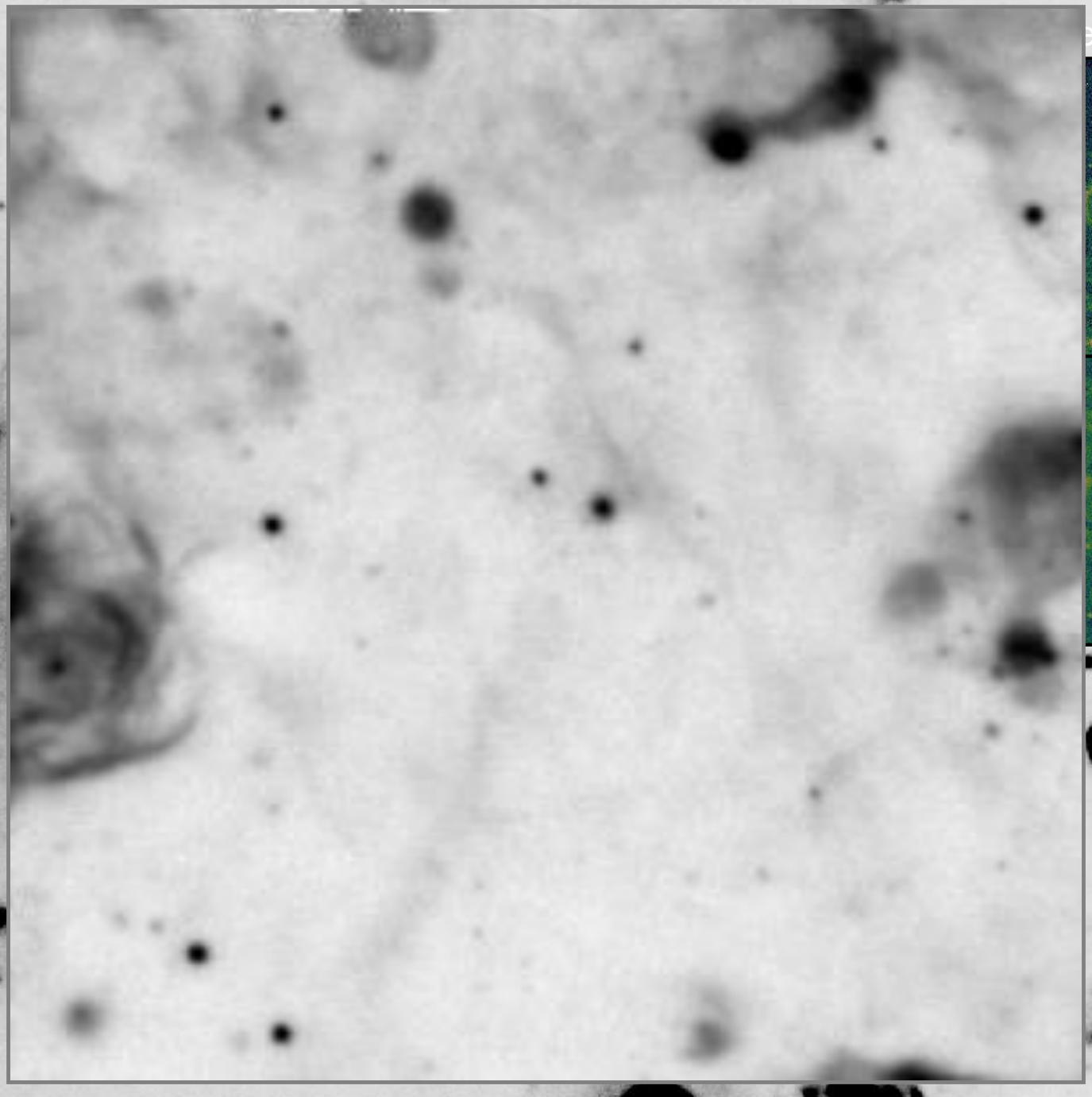

Emission line objects
(e) 0.75“
(d) 0.8“
(a) 0.7“
S16
De86
(b) 1.2“
(c) 1.0“
S10
De42
De100
De80
De74
S14
De60
S8
De85
De67
(i) 0.6“
(j) 0.85“
Deharveng+ (1988)
Blair & Long (1997)

10^{51} erg SNR model after 30.000 years

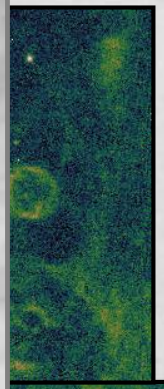


Li, M., Ostriker, J.~P., Cen, R., Bryan, G.~L., & Naab, T. 2015, ApJ 814, 4

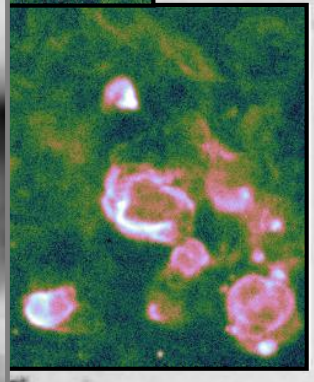
Yadav et al. 2017, Supernovae under microscope: how supernovae overlap to form superbubbles, MNRAS 465, 1720
Filipovic et al. 2016: Supernova remnants in the Magellanic Clouds, 2016arXiv160401458



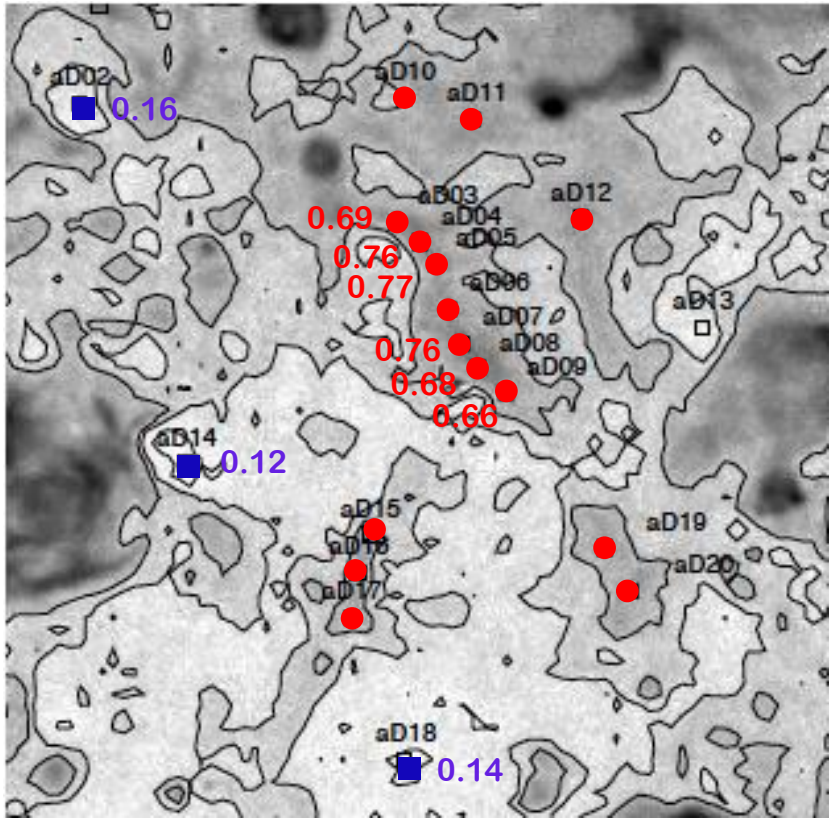
e) 0.75“



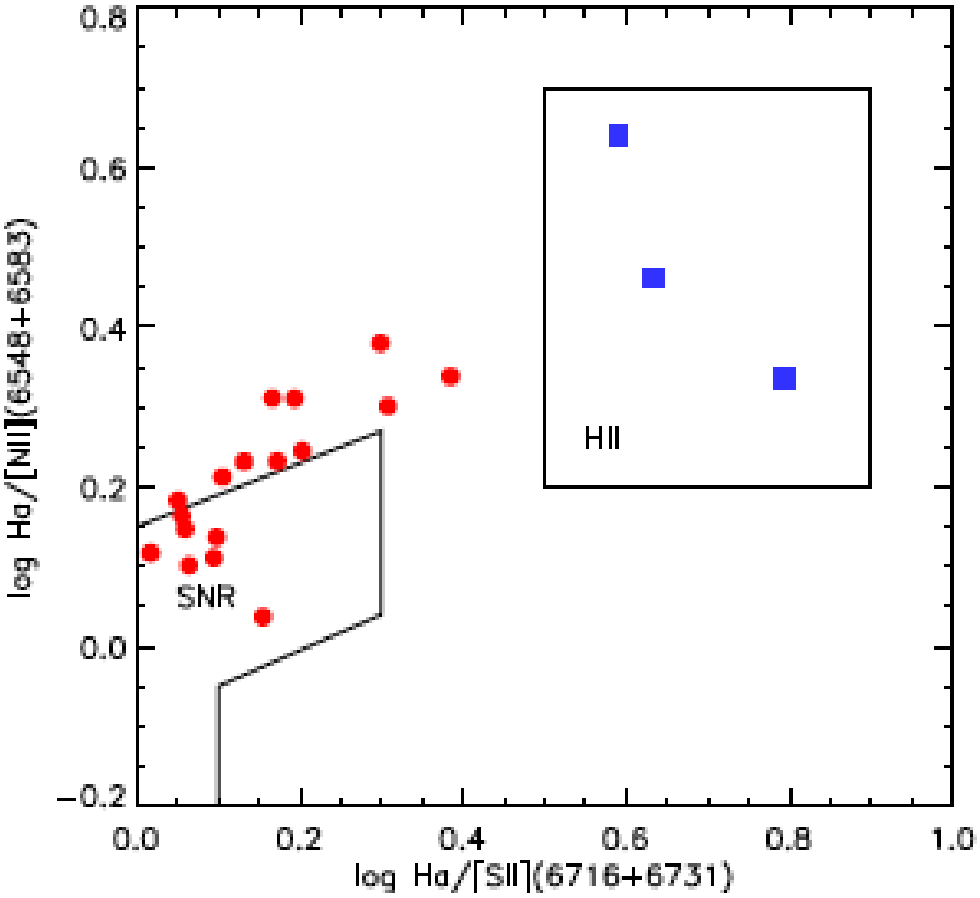
(d) 0.8“



nuclear region Field (a) in [SII]



diagnostic diagram (Sabbadin et al. 1977)



integrated flux over filaments vs. open areas:

shocked: 1.1e-14 cgs

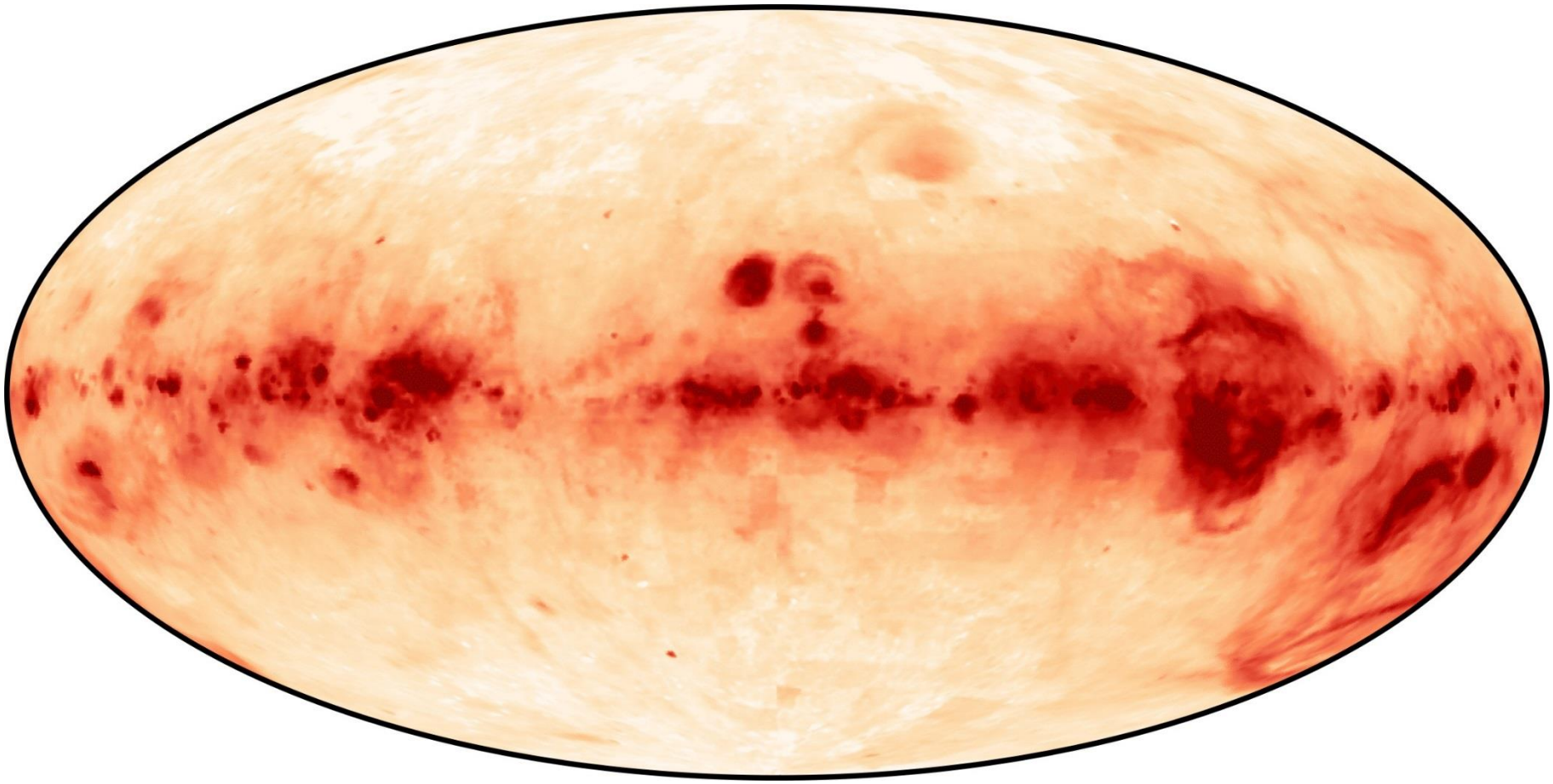
photoionized: 0.8e-14 cgs

WIM in the Milky Way

Wisconsin H-Alpha Mapper (WHAM)

WHAM at Cerro Tololo

Hα all-sky map (WHAM)



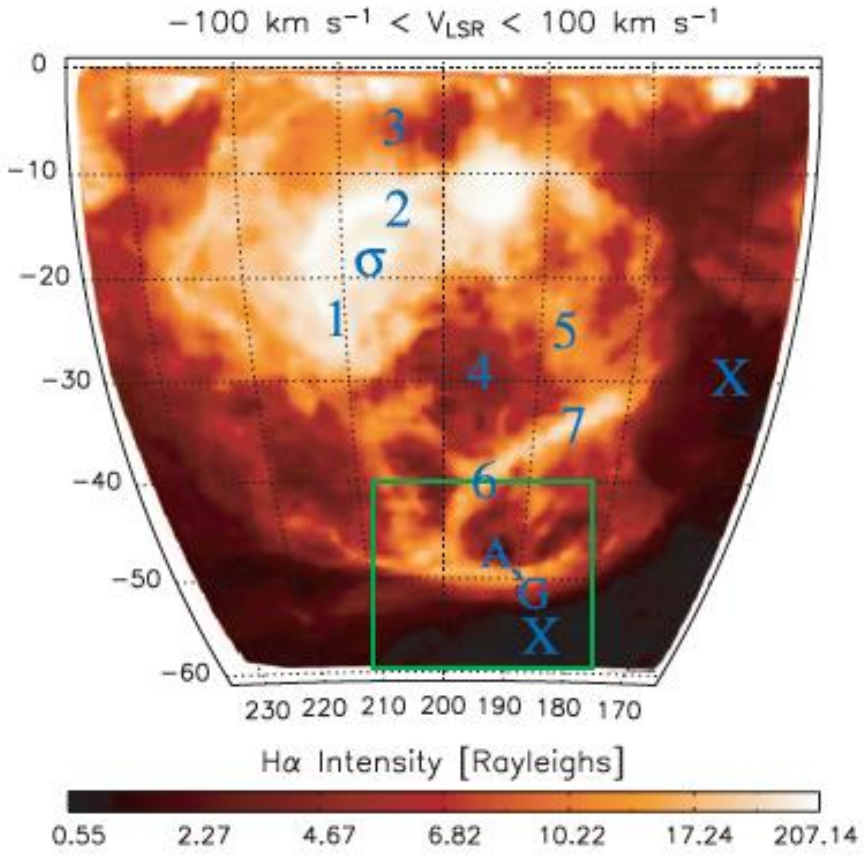
Origin of warm ionized gas (WIM) in the galaxy

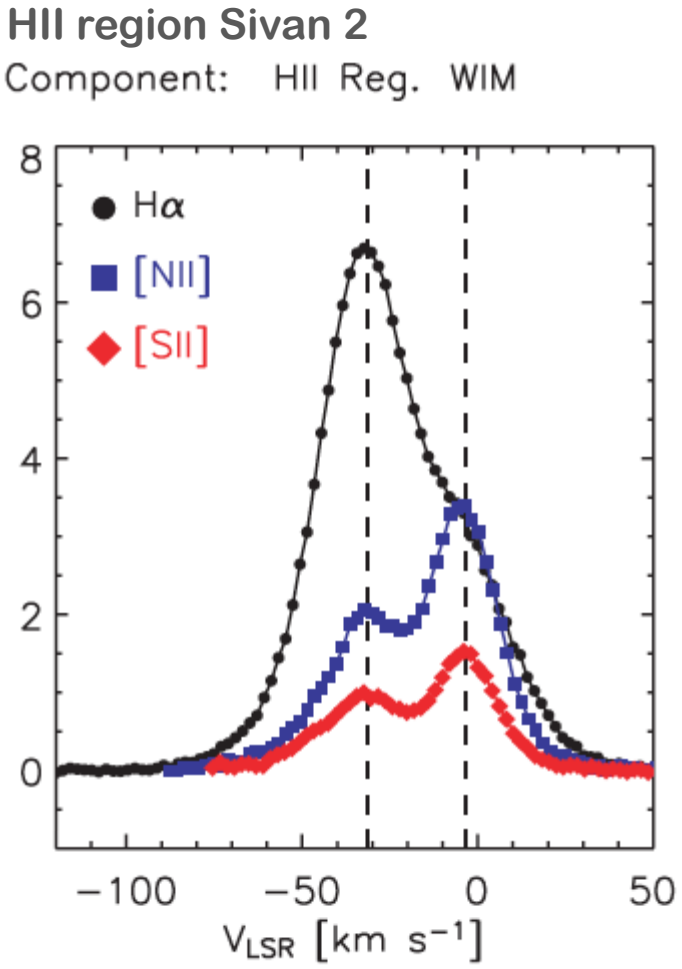
Haffner et al. (2003) summarize:

- ionization across hundreds of pc due to O stars, enabled by superbubbles, chimneys, worms (Norman 1991, Koo et al. 1992)
- Lyman continuum from O stars leaking out of HII regions and between HI clouds (Miller & Cox 1993, Dove & Shull 1994, Dove et al. 2000)
- surface of neutral clouds bathed in a hot medium (McKee & Ostriker 1977)
- HII mixed with neutral hydrogen (Spitzer & Fitzpatrick 1993, Scamia 1990)
- photoionization from old cooling SNR (Slavin et al. 2000)
- source other than photoionization (Haffner et al. 1999, Reynolds et al. 1999)

Orion Eridanus Superbubble (Madsen et al. 2006)

~280 pc diameter

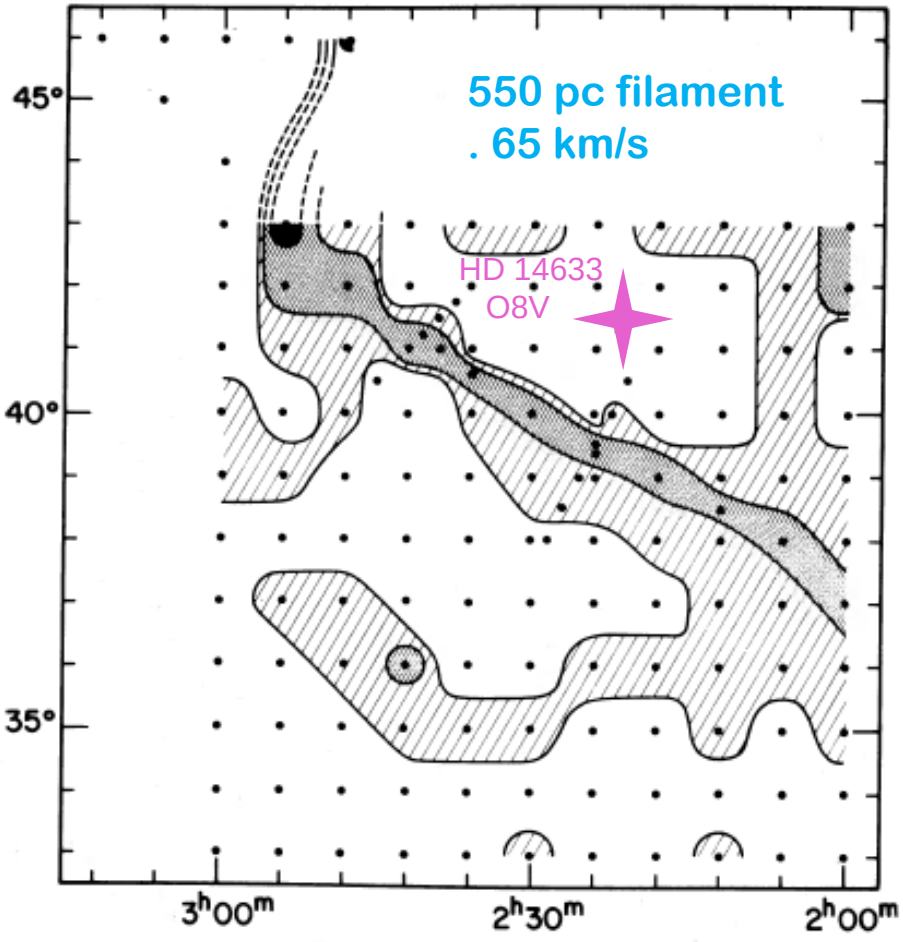


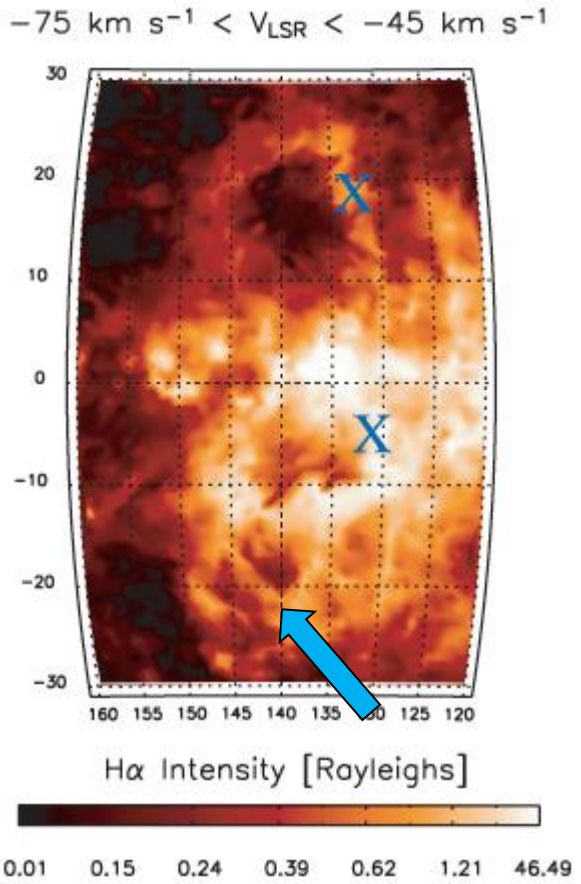


► **ionization of bubble interior and filaments/walls compatible with O star UV flux, shock ionization negligible (Reynolds & Ogden 1979)**

Perseus Superbubble (Madsen et al. 2006)

2000 pc x 800 pc





- consistent with models of a moderate velocity (50-90 km s^{-1}) shock propagating through a low-density (0.3 cm^{-3}) ambient medium (Ogden & Reynolds 1985)

Summary

(1) Crowded field 3D spectroscopy works even
at distances of nearby galaxies

(2) MUSE is extremely efficient to discover emission line objects

(3) We find low surface brightness filamentary structures
with line ratios typical for shock excitation

(4) What is the ionization source?

(5) Excellent case for an ESO Large Program Proposal,
a Public Survey

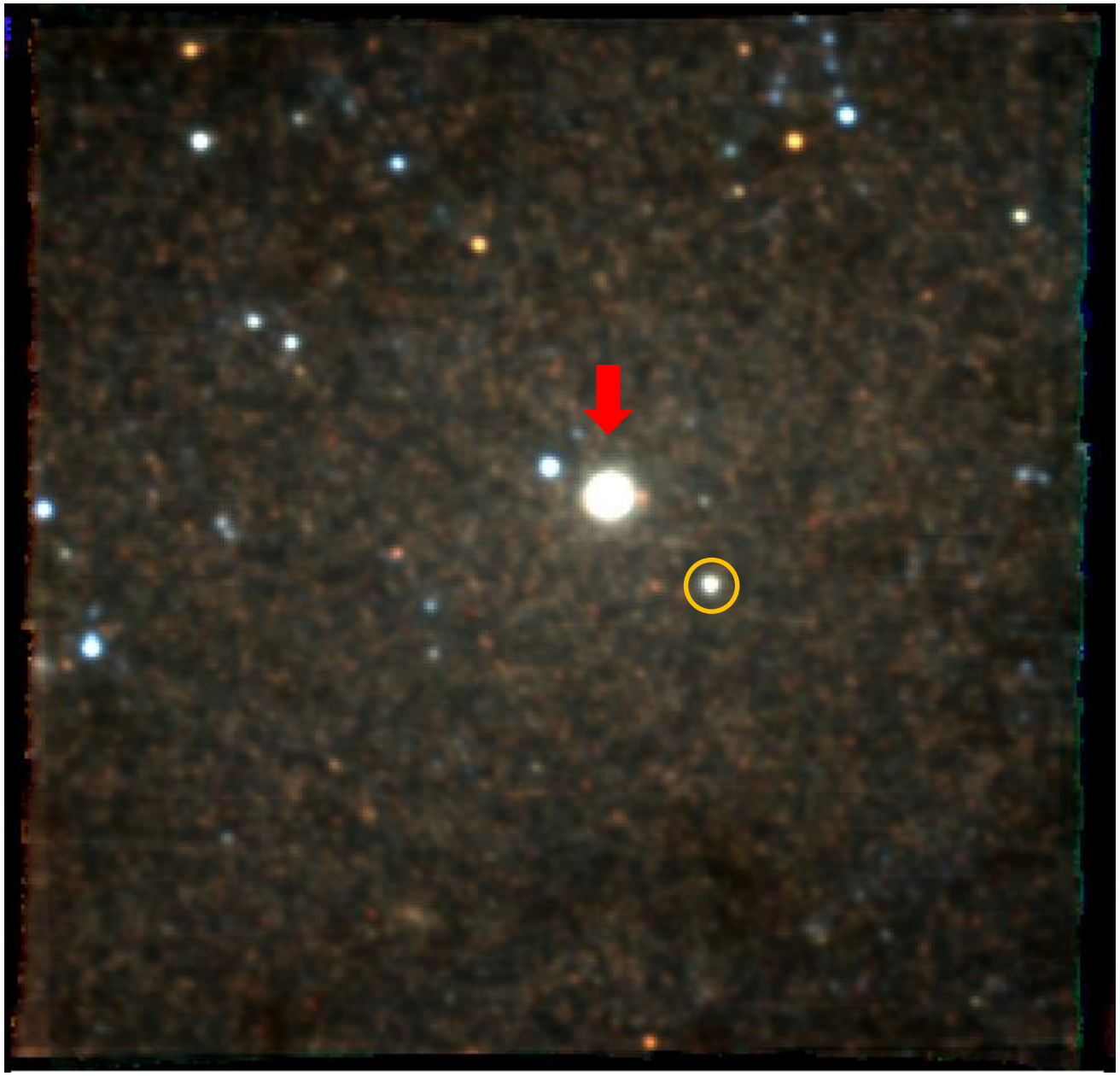
Acknowledgements

BMBF Verbundforschung Astrophysik
Projektträger PT-DESY:

various grants:
PMAS
ULTROS
MUSE
ERASMUS-F
ELT-MOS

Deutsche Forschungsgemeinschaft:
Calar Alto travel grants

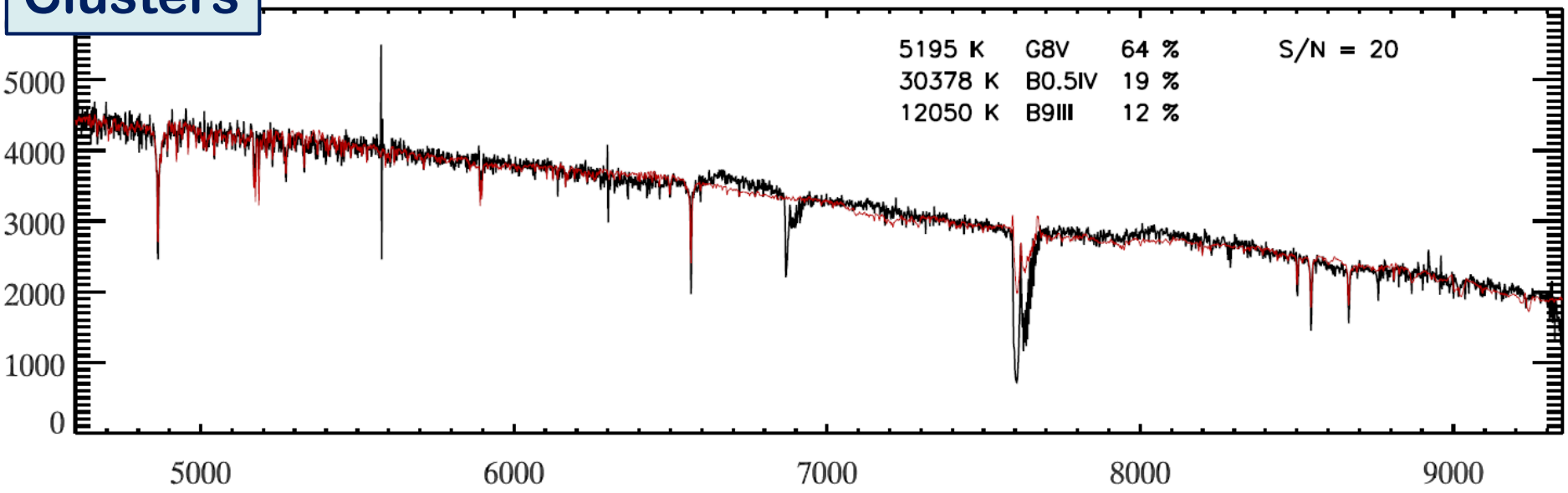
Clusters



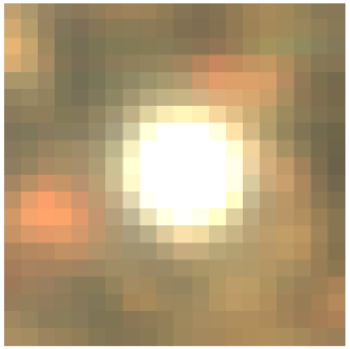
nuclear star cluster:
multiple star formation episodes
(Walcher et al. 2006)

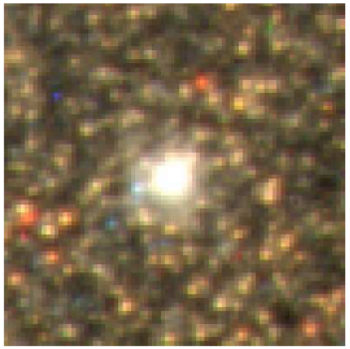
Clusters

No. 205 ID 350



xc,yc: 206.3 142.10
mag: 21.00
ra: 13 43 14
dec: −37 41 8
fwhm: 2.9 spaxels
vrad: 119 +/− 3 (MIUSCAT)
vrad: 135 +/− 2 (GLIB), vtell: −4+/−1





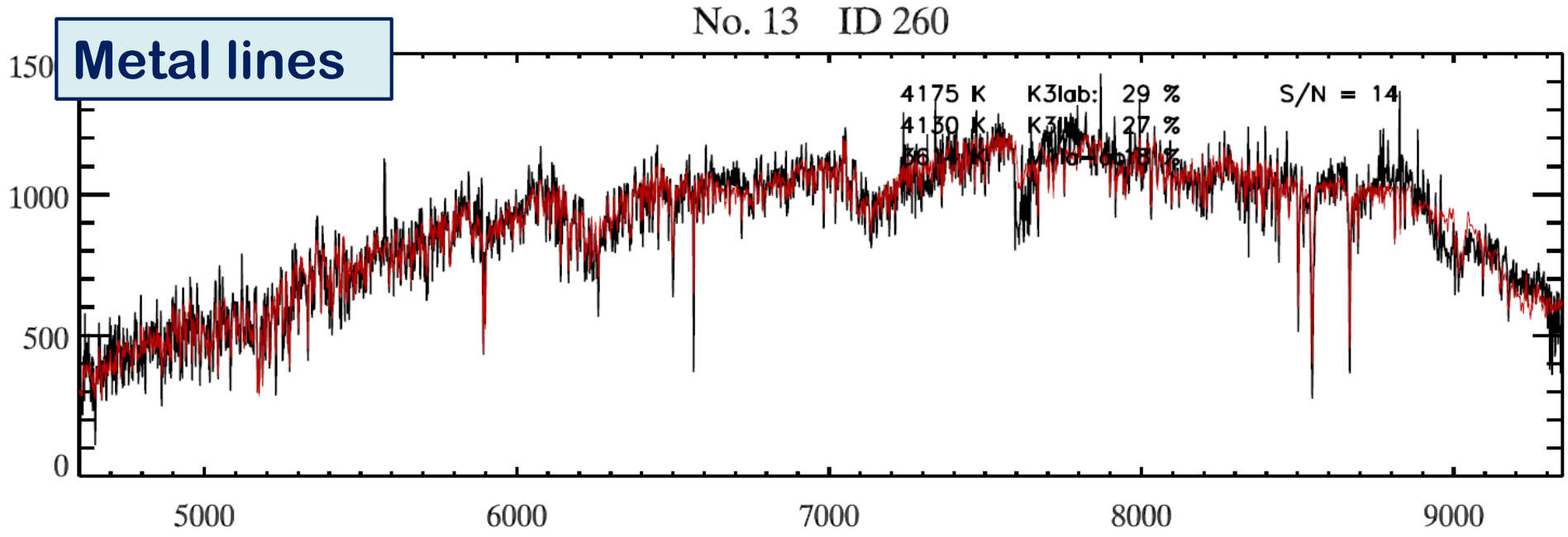
7 components contributing to fit:

MIUSCAT	Teff	log g	[Fe/H]	Qu	%	Star	type	R@2Mpc
iu314V	5195	4.50	−0.88	10	64	HD064606	G8V	31.85
iu345V	30378	4.31	−0.26	10	19	HD034816	B0.5IV	23.69
iu160V	12050	3.90	−0.43	100	12	HD175640	B9III	26.61
iu399V	11846	3.76	0.520	100	3	HD224801	B9p...	26.37
iu350V	8910	3.76	−0.02	1	1	HD040183	A2IV+...	26.20
iu086V	3000	0.00	−0.58	100	1	HD126327	M7.5	24.93
iu460V	3166	−0.1	−0.13	100	1	HD078712	M6IIIlase	23.69

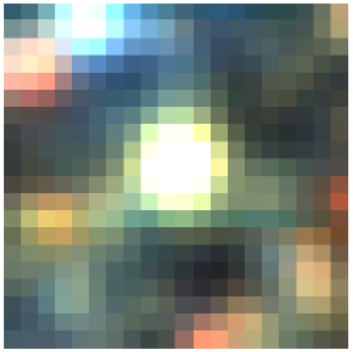
GLIB:	5835	3.74	−1.02
errors:	22	0.09	0.029

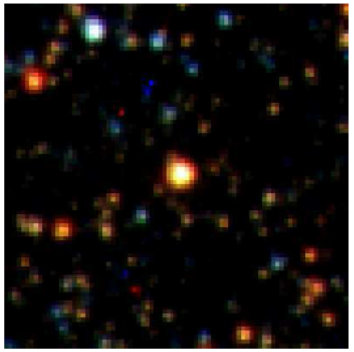
BLEND: 0

Metal lines



xc,yc: 199.7 215.1
mag: 21.38
ra: 13 40 26
dec: −37 41 54
fwhm: 2.6 spaxels
vrad: 170 +/− 17 (MIUSCAT)
vrad: 173 +/− 1 (GLIB), vtell: −15+/−2

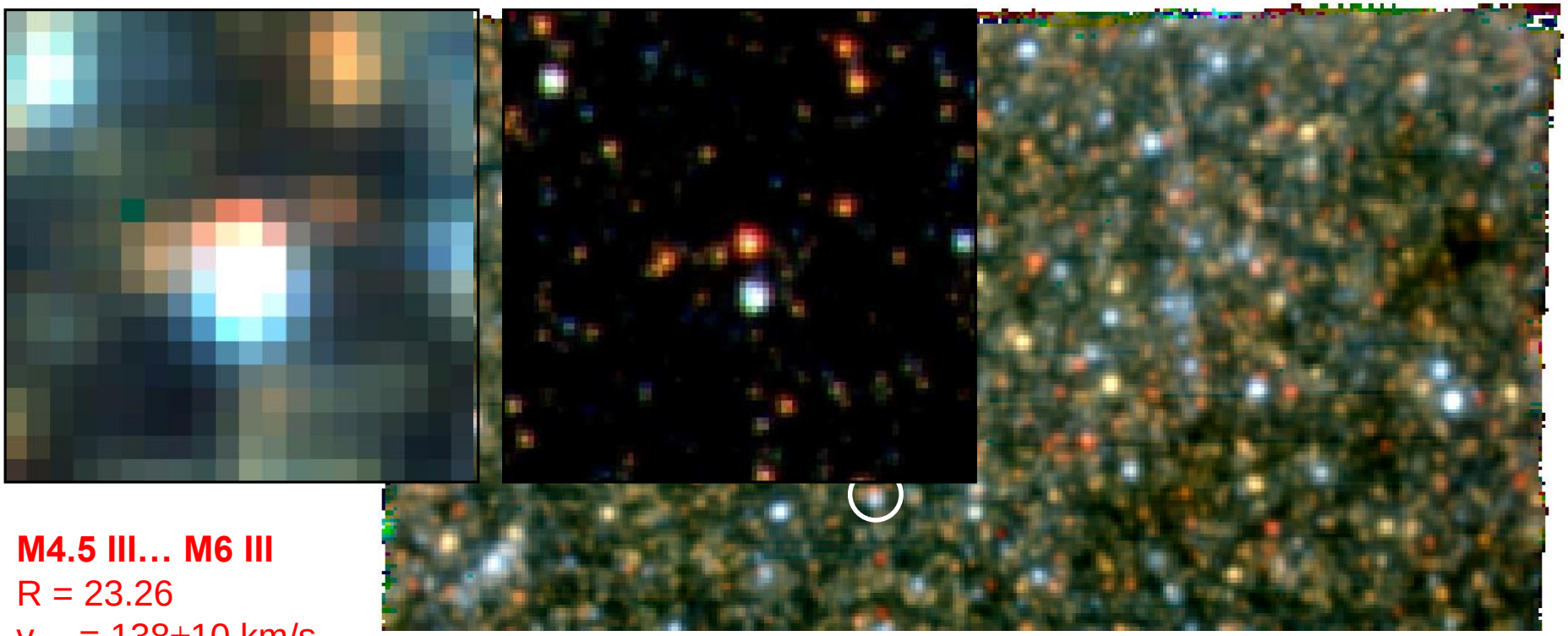




9 components contributing to fit:

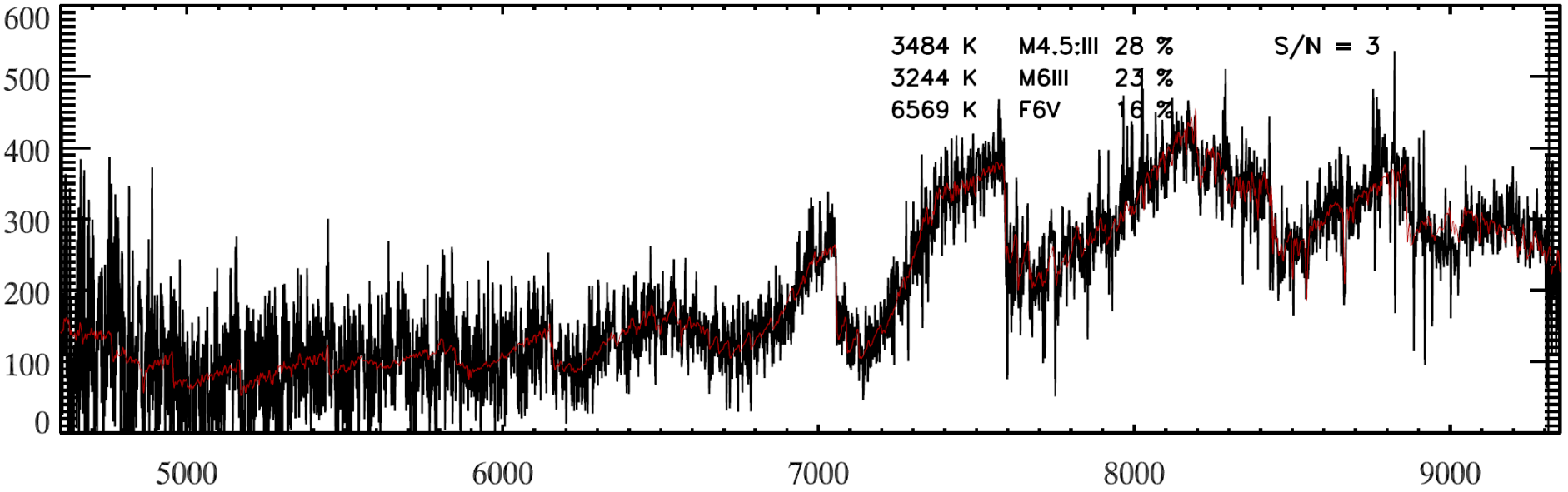
MIUSCAT	Teff	log g	[Fe/H]	Qu	%	Star	type	R@2Mpc
iu409V	4175	0.84	−0.31	10	29	HD004817	K3Iab:	18.33
iu247V	4130	1.81	0.230	100	27	HD124547	K3III	24.43
iu177V	3614	0.00	−0.42	100	18	HD042543	M1Ia−ab	21.12
iu234V	4000	0.70	−0.36	10	8	HD042475	M1Iab:	21.12
iu428V	3971	1.25	−0.14	10	7	HD039283	A2V	25.79
iu190V	4379	1.37	0.110	100	6	HD110014	K2III	28.04
iu093V	3895	1.41	−0.01	100	3	HD139669	K5III	22.82
iu170V	4400	2.19	0.100	10	2	HD005848	K2II−III	25.05
iu436V	3410	0.94	−0.02	10	1	HD044478	M3III	23.40
GLIB:	3878	2.56	−0.33					
errors:	7	0.00	0.022					

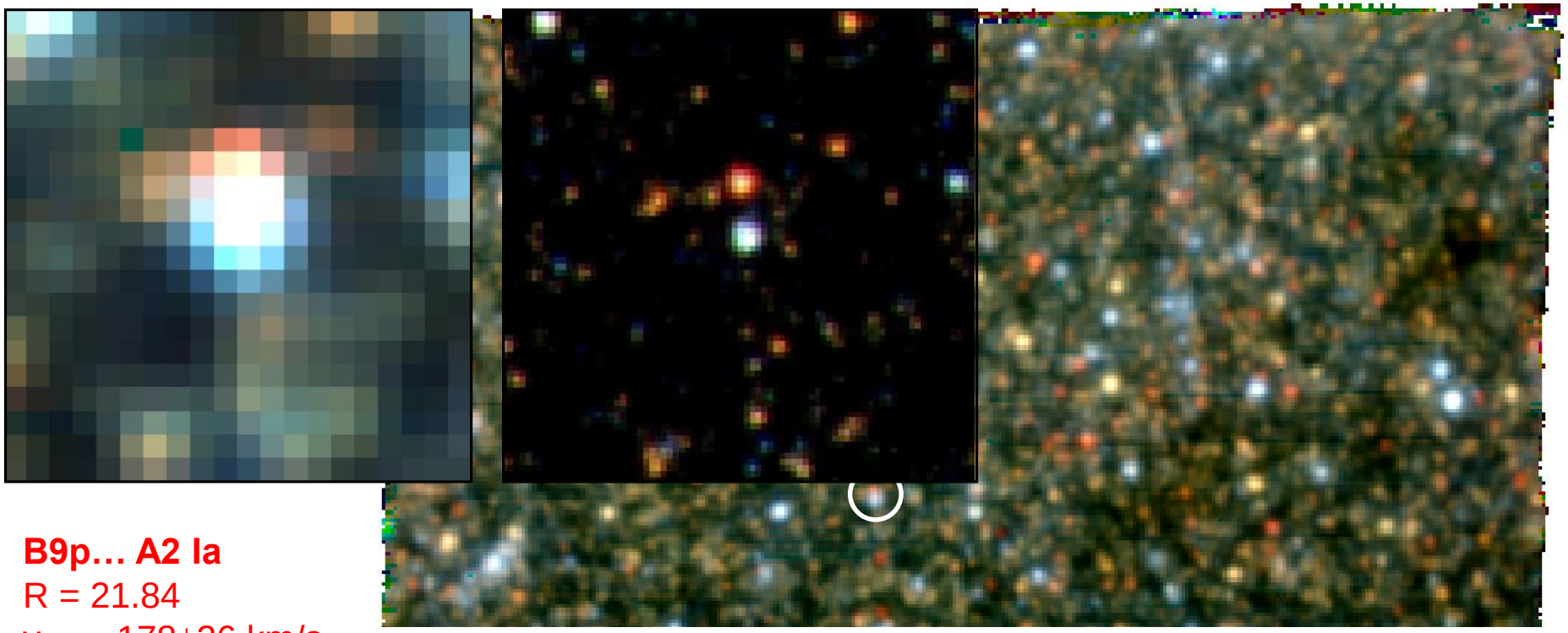
BLEND: 1



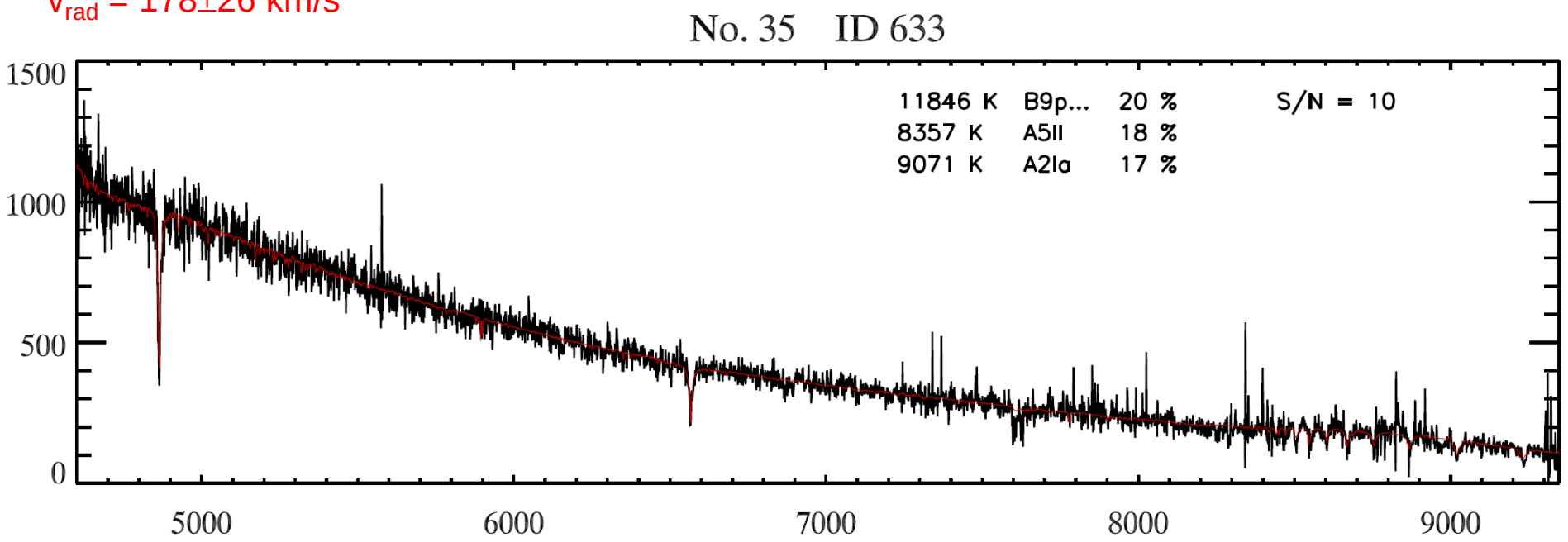
M4.5 III… M6 III
R = 23.26
v_{rad} = 138±10 km/s

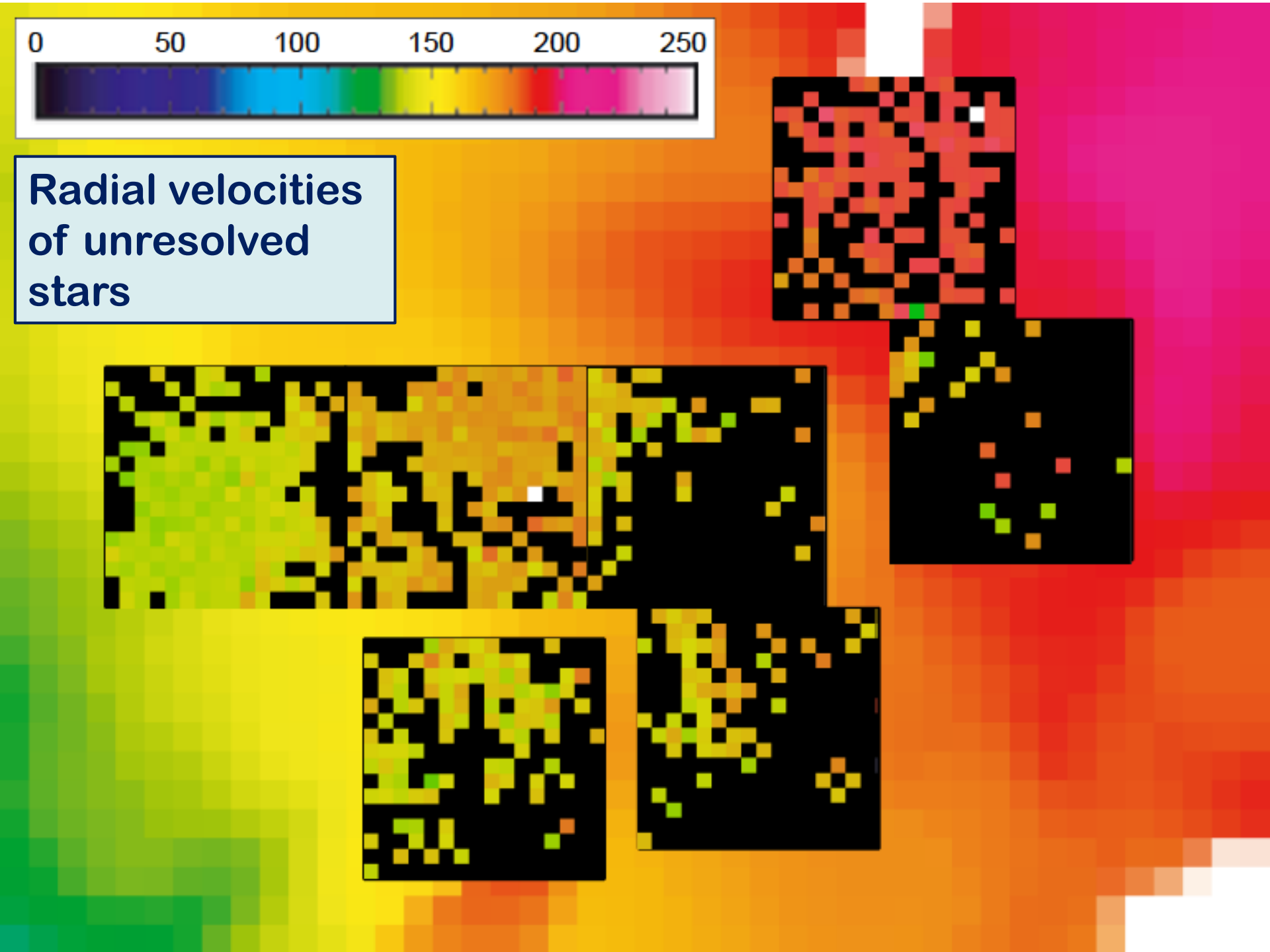
No. 83 ID 1539

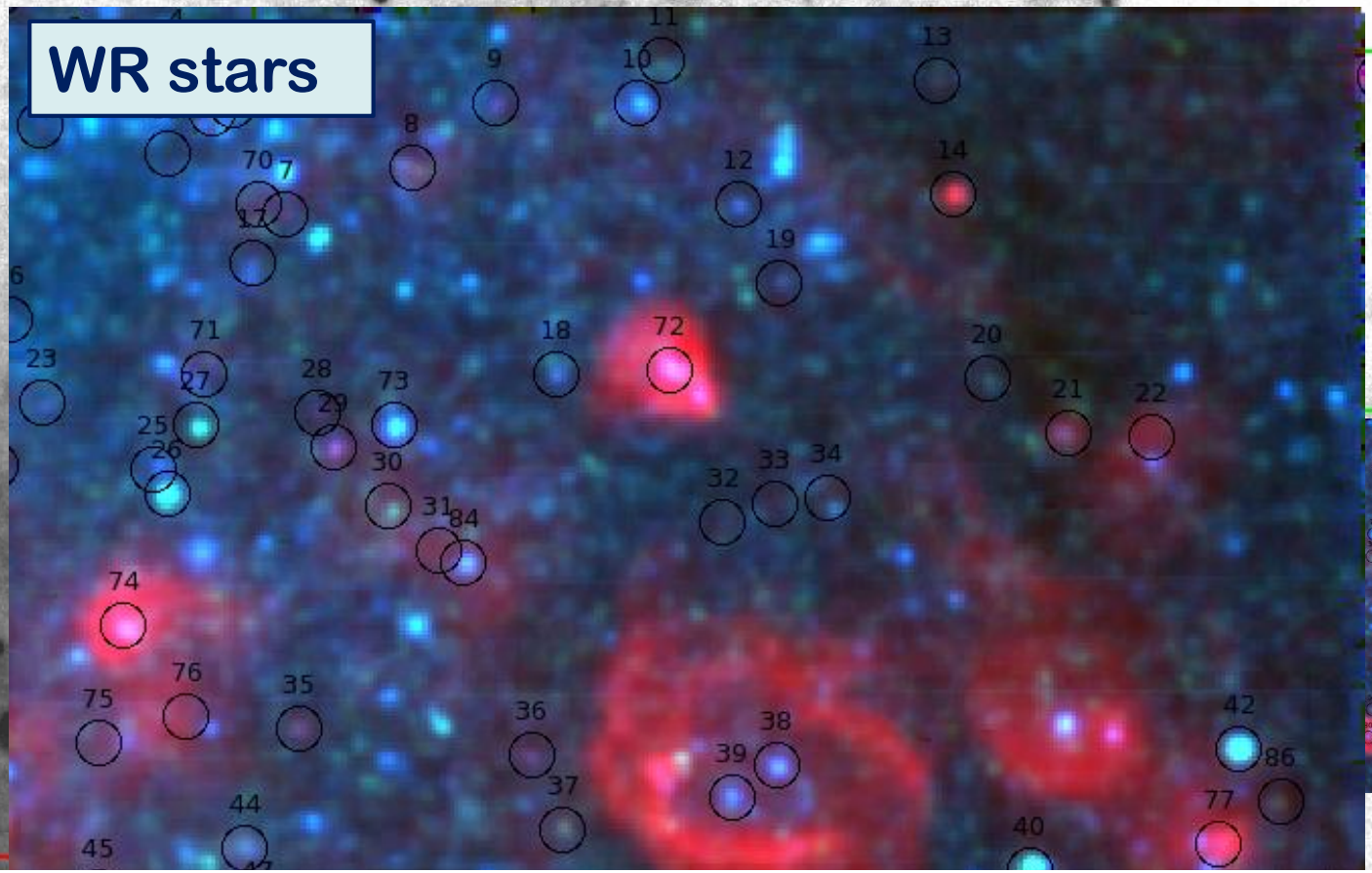


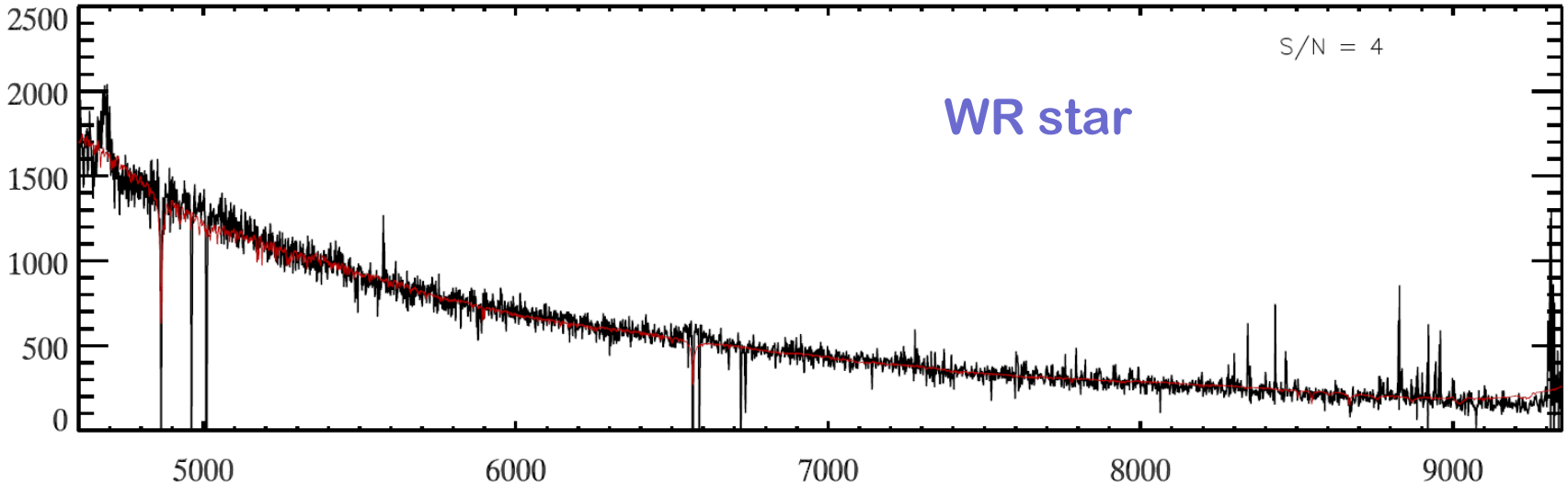


B9p… A2 Ia
R = 21.84
v_{rad} = 178±26 km/s



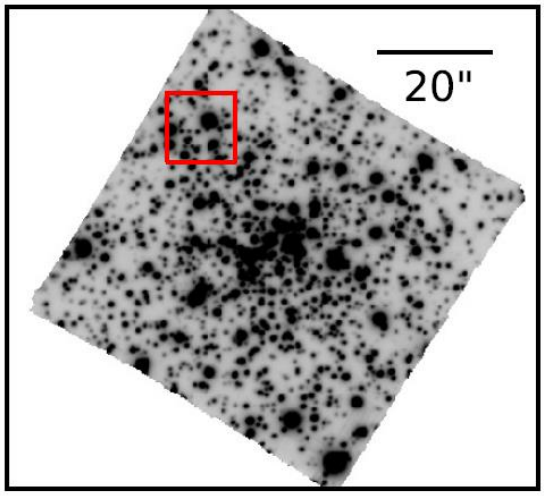

0
50
100
150
200
250
Radial velocities of unresolved stars

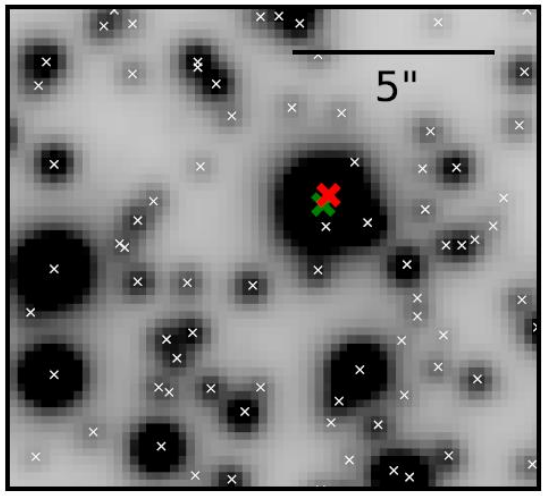

WR stars
e

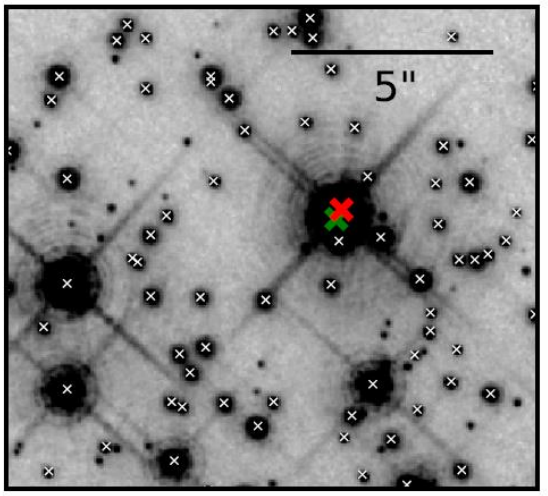

S/N = 4
WR star
2500
2000
1500
1000
500
0
5000
6000
7000
8000
9000

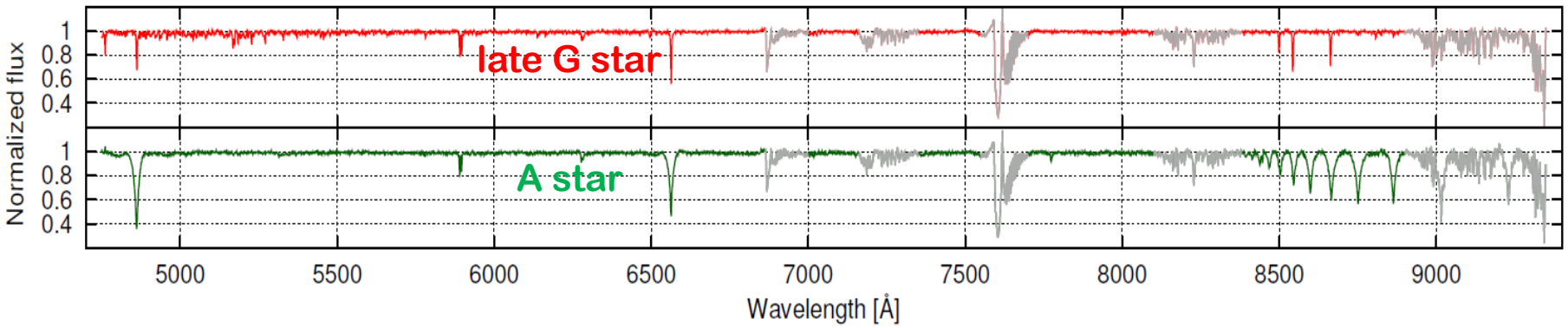
NGC6397

→ deblending spectra with PampelMuse

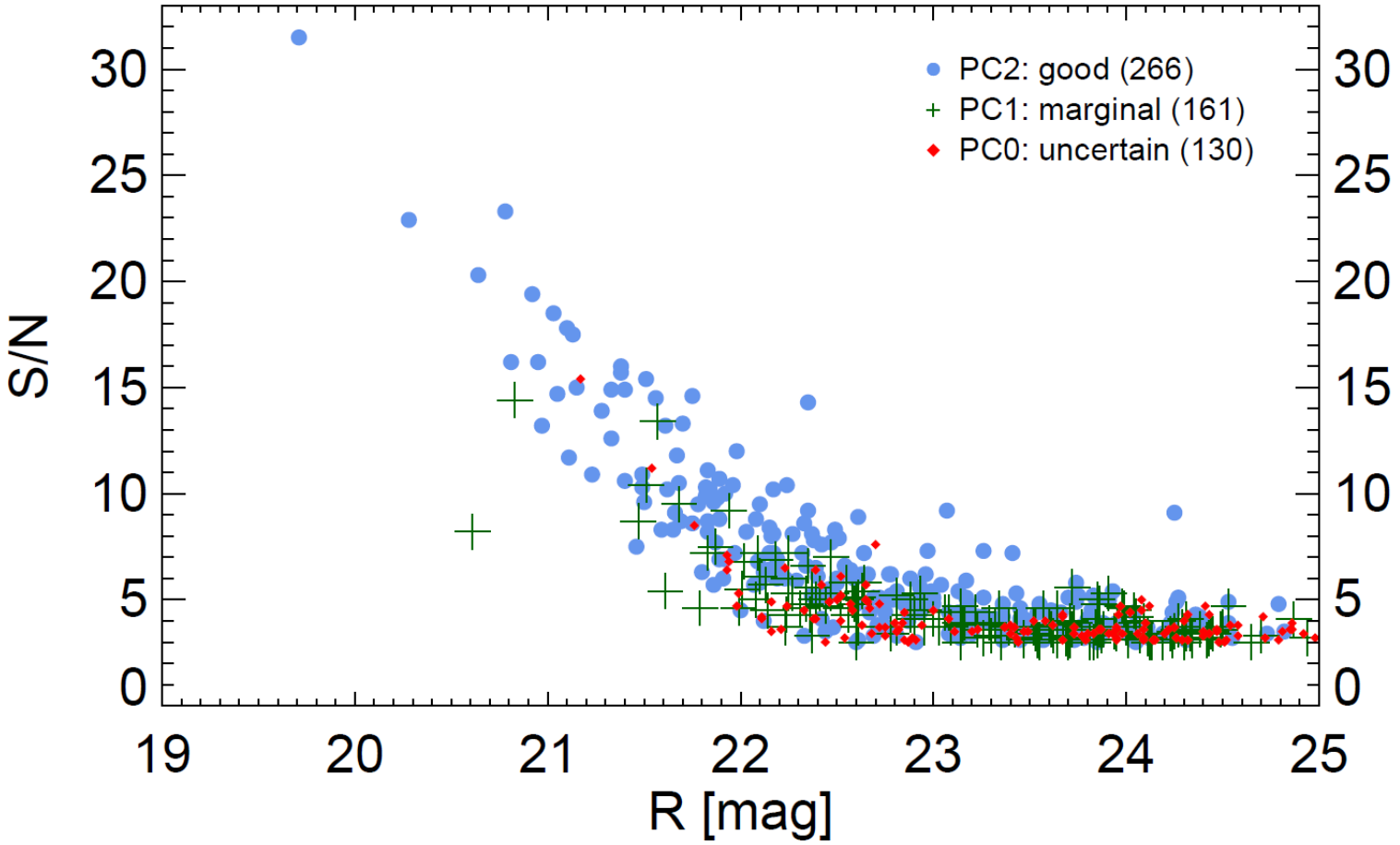




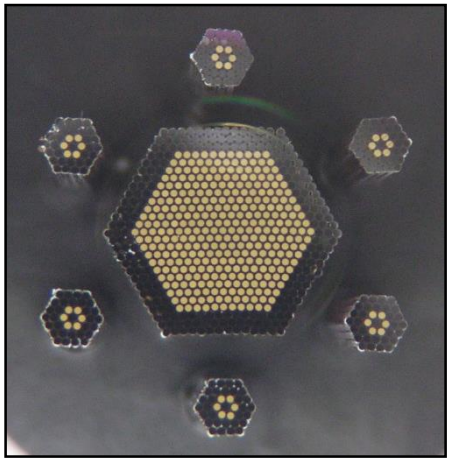




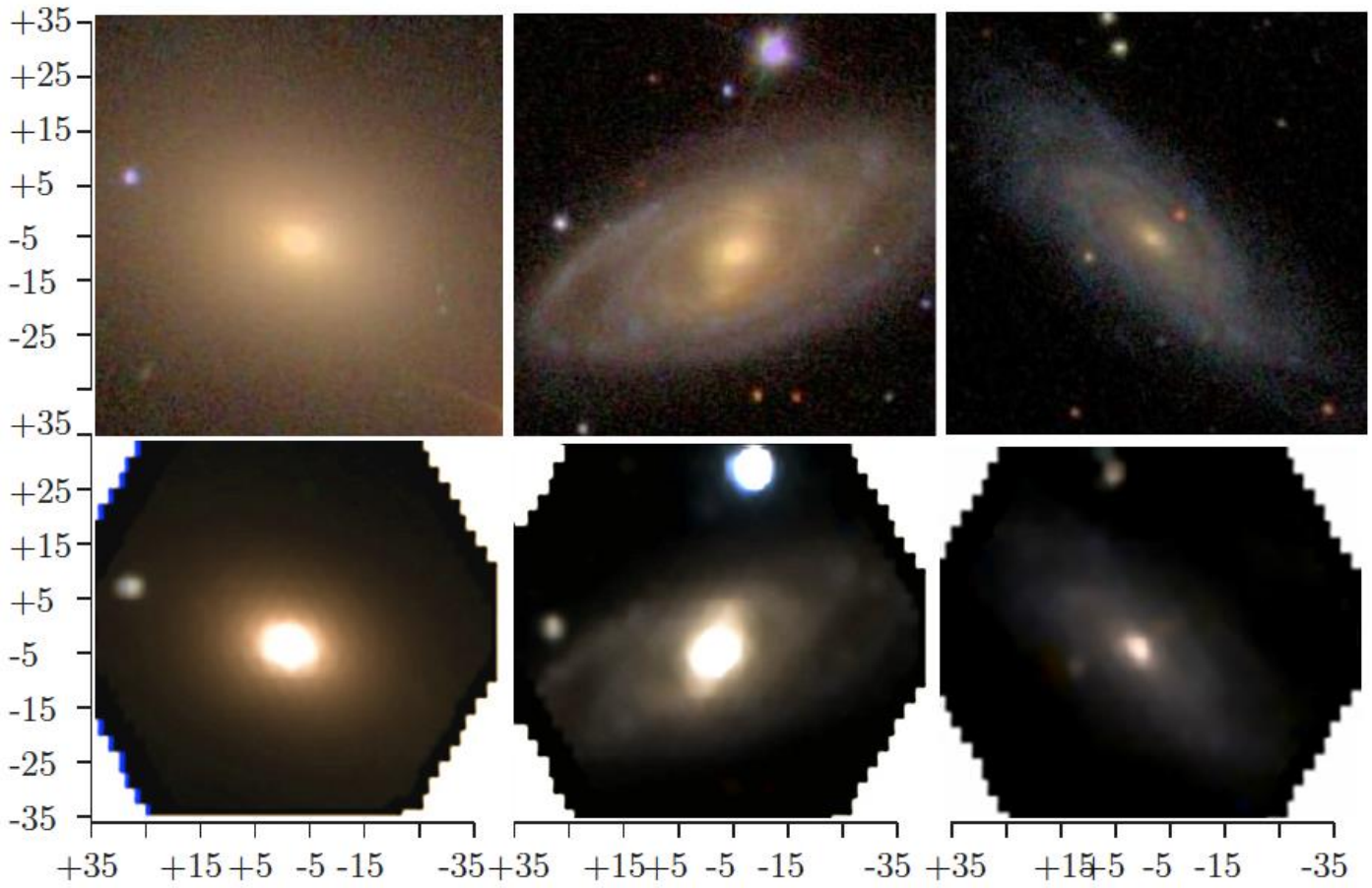
Completeness

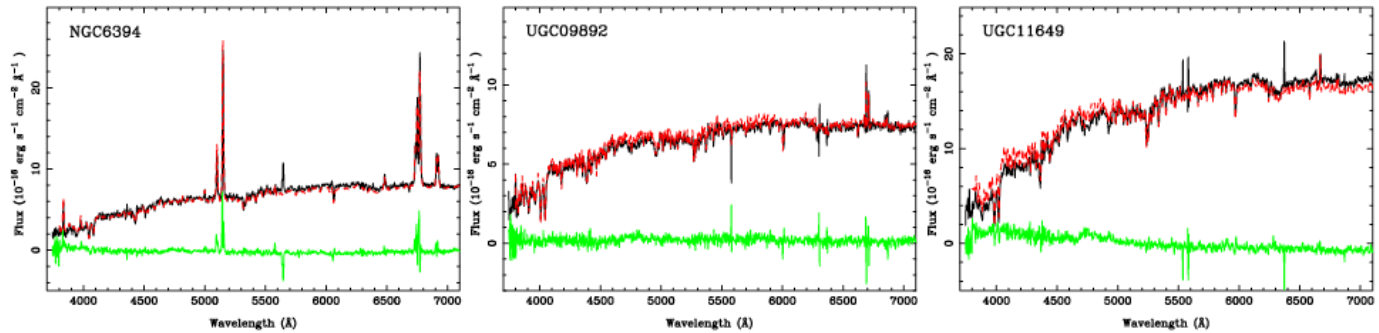


Integral Field Spectroscopy



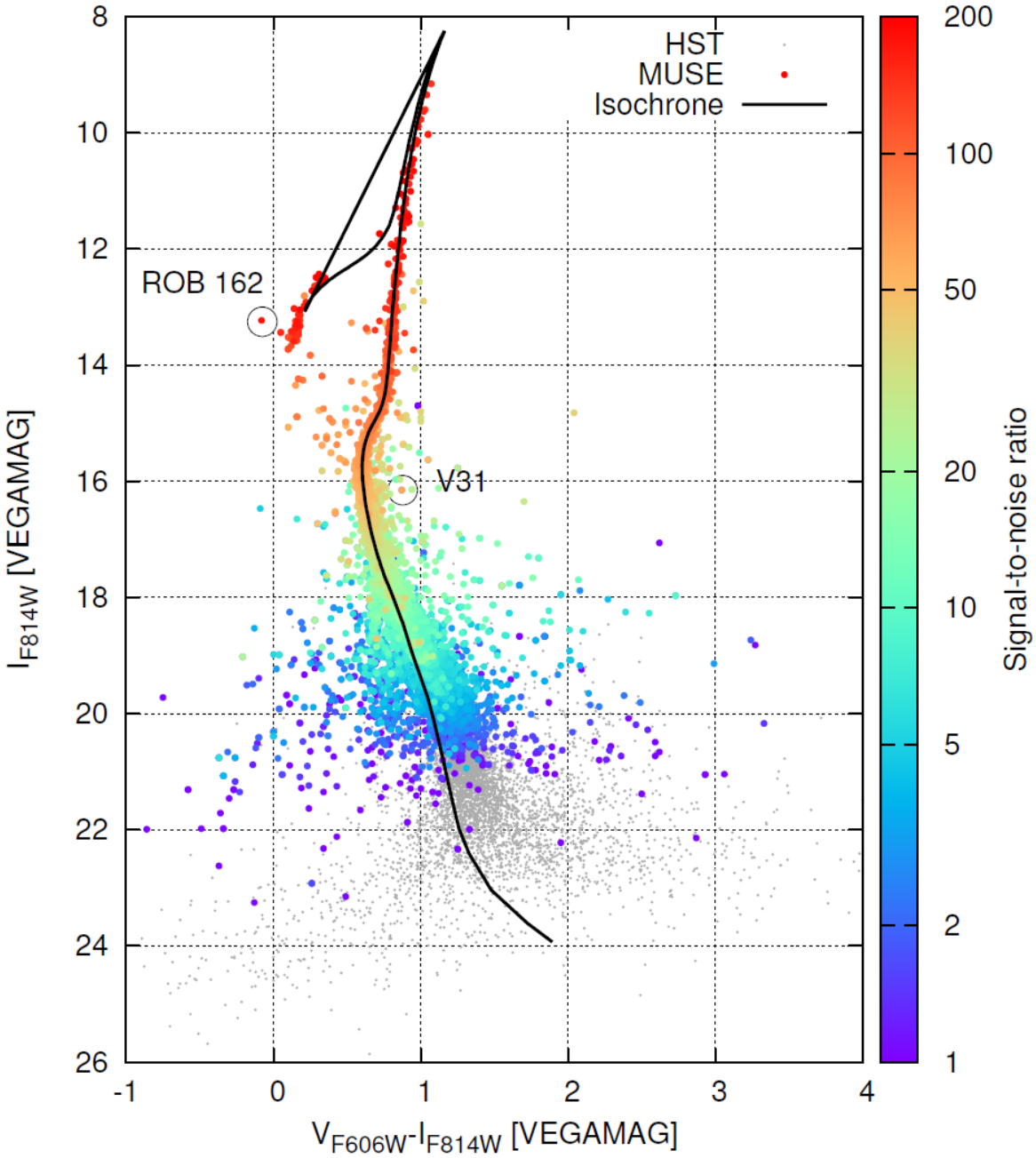
CALIFA Survey
(Sanchez et al. 2012)



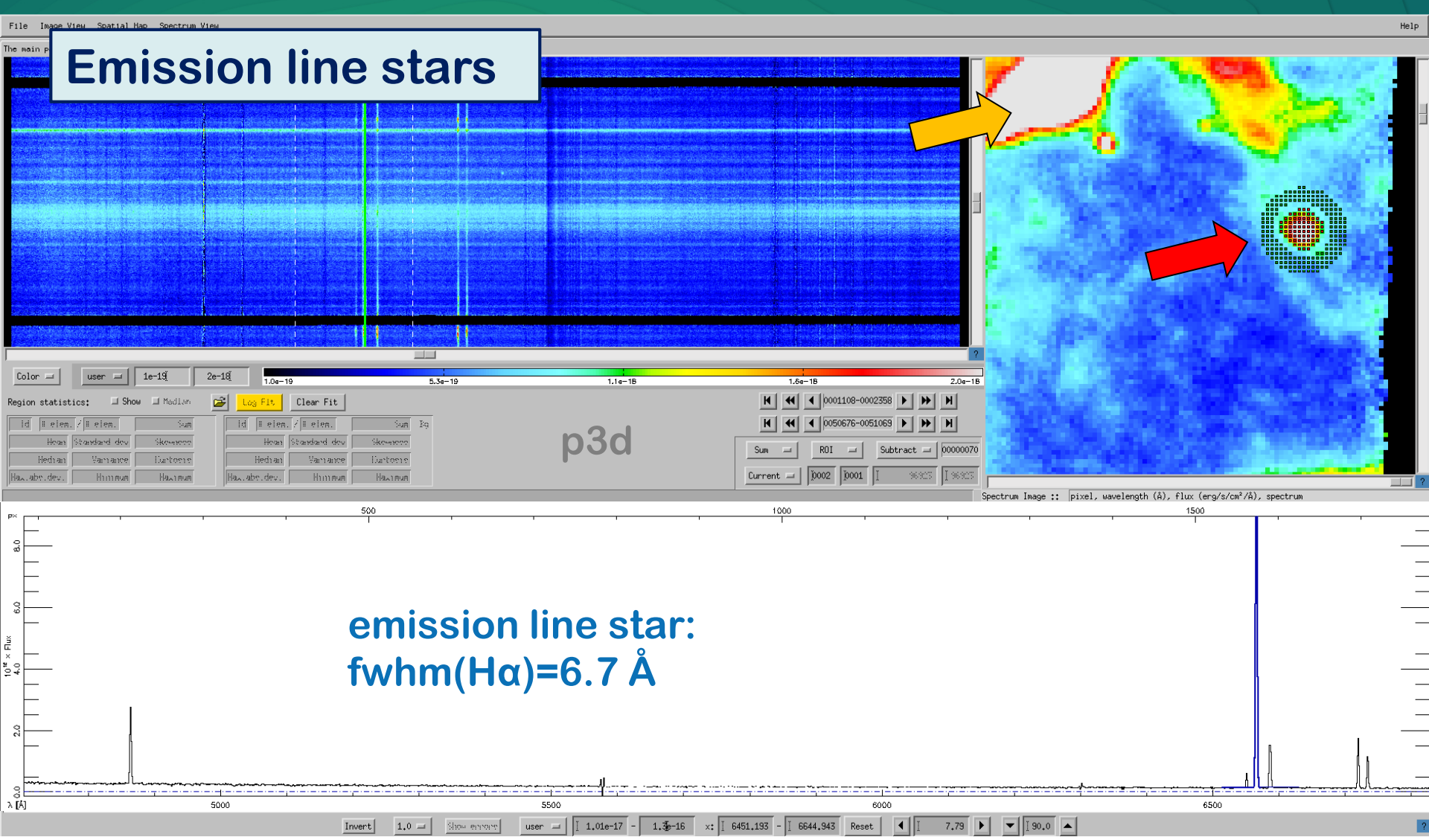



NGC 6397
$(m - M)_0 = 11.90$
credit: ESO (WFI)

NGC6397


HST
MUSE
Isochrone
ROB 162
V31
I_{F814W} [VEGAMAG]
V_{F606W}-I_{F814W} [VEGAMAG]
Signal-to-noise ratio
8
10
12
14
16
18
20
22
24
26
-1
0
1
2
3
4
200
100
50
20
10
5
2
1

Emission line stars

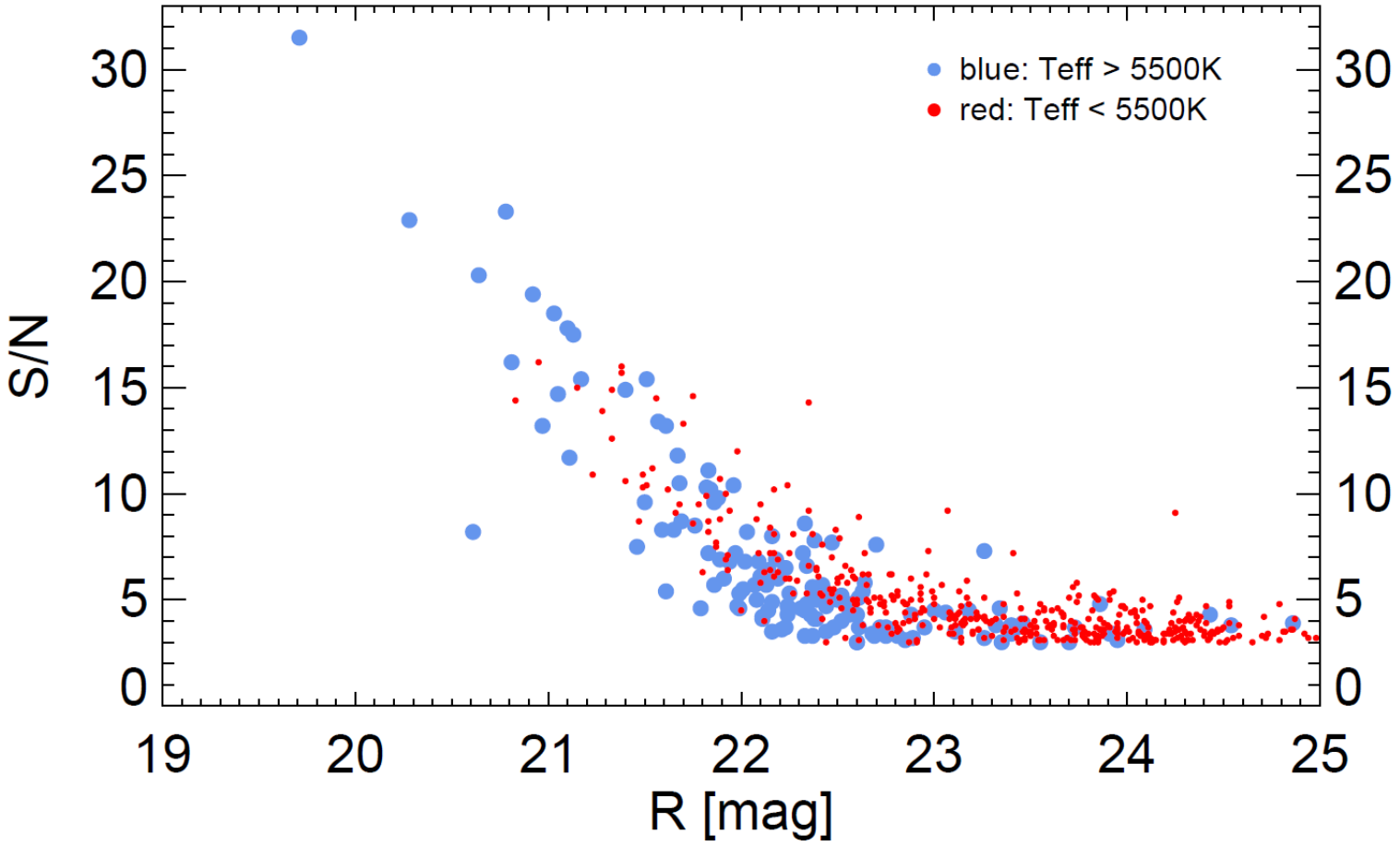


http://p3d.sourceforge.net/

Sandin et al. 2010
Sandin et al. 2011

HII region:
fwhm(Hα)=2.5 Å

Completeness



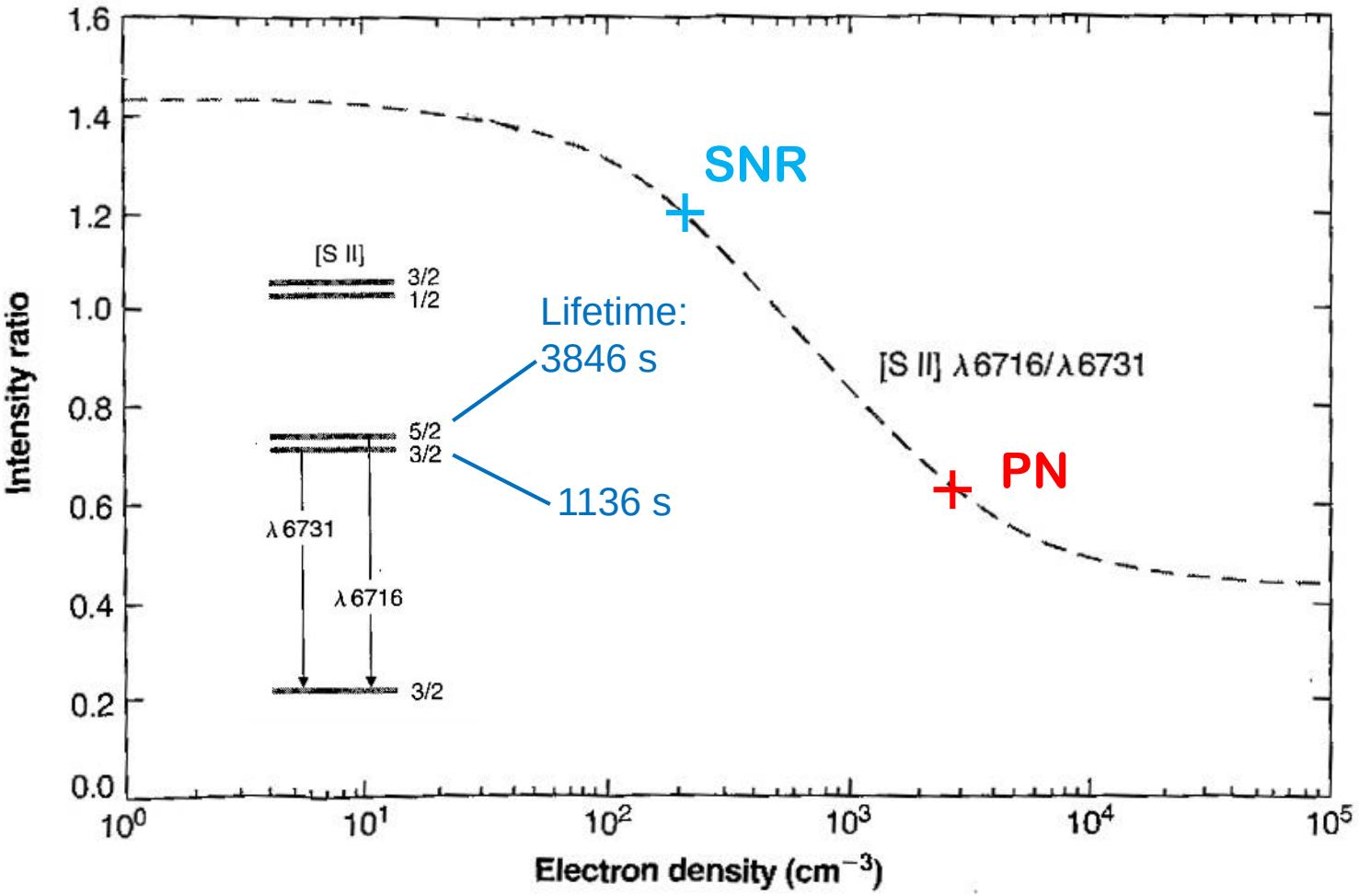


Fig. 5.8 from *Astrophysics of Gaseous Nebulae and Active Galactic Nuclei*,2nd ed., Osterbrock & Ferland, 2005