The Planetary Nebula Luminosity Function (PNLF) explored with BlueMUSE

Martin M. Roth
Leibniz Institute for Astrophysics Potsdam (AIP)
University of Potsdam

Azlizan Soemitro (AIP)
Peter Weilbacher (AIP)

George Jacoby (NOIRlab), Robin Ciardullo (PennState),
Magda Arnaboldi (ESO) & Collaborators,

Outline

(1) The Planetary Nebula Luminosity Function (PNLF)

(2) Early PN observations with IFUs

(3) MUSE-PNLF and the Differential Emission Line Filter (DELF)

(4) PNLF with BlueMUSE

(1) The Planetary Nebula Luminosity Function

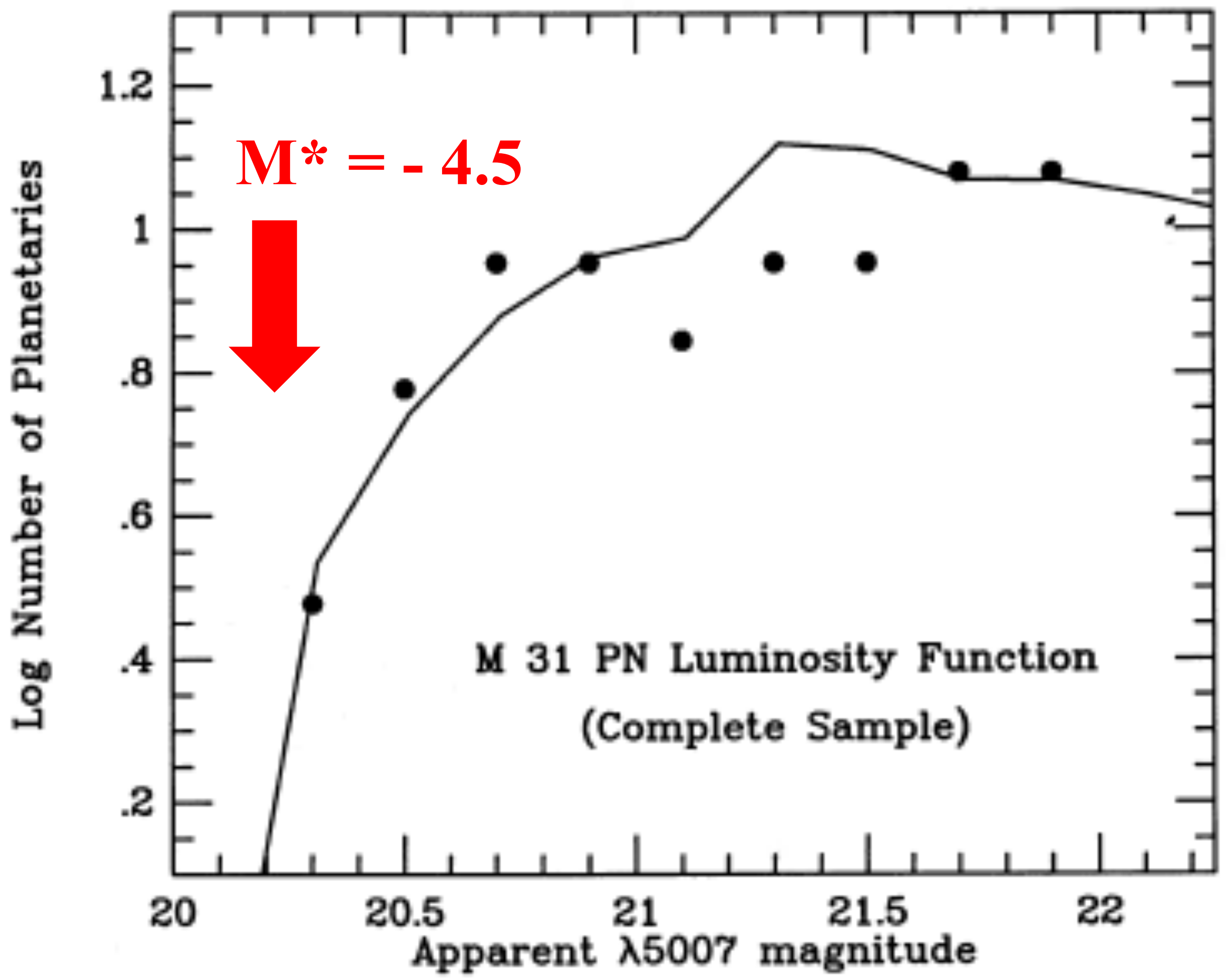
Martin Roth - The Planetary Nebula Luminosity Function~~s~~ explored with BlueMUSE

ay	Day 2 (24.04) - Wednesday	Day 3
	Welcome - ZOOM Link	We
	nd Bacon - MUSE GTO Experience	BlueSi (Martin
	o Castro - Systematic mapping of the ...st massive stars with BlueMUSE	BlueSi
	Break	
isks Seen /LT/MUSE	**Martin Roth** - The Planetary Nebula Luminosity Functions explored with BlueMUSE	**Anne Verh** - On the es galaxies: Lyma
ved ISM in ith MUSE	**Bjarki Björgvinsson** - Resolved stellar populations with KCWI	**Tanya Ur** Fields: scie and les
analysis of perties in	**Cyrielle Opitom** - Observing Comets with BlueMUSE	**Emanuele**
ps with	**Susanna Vergani** - Multi messenger science and synergies with BlueMUSE	**Adélaïde (** gravitat

(1) The Planetary Nebula Luminosity Function

Ciardullo, Jacoby, Ford, Neill 1989, ApJ 339, 53

standard candle



$$m_{5007} = -2.5 \log F_{5007} - 13.74$$

$$N(M) \propto e^{0.307M}\{1 - e^{3(M^* - M)}\}$$

see recent review by

Robin Ciardullo (2022) Frontiers in Astronomy and Space Science, Vol. 9, 896326

(1) The Planetary Nebula Luminosity Function

Harmonizing Cosmic Distance Scales in a Post-Hipparcos Era
ASP Conference Series, Vol. 167, 1999
D. Egret, and A. Heck, eds.

Future Directions for the Planetary Nebula Luminosity Function

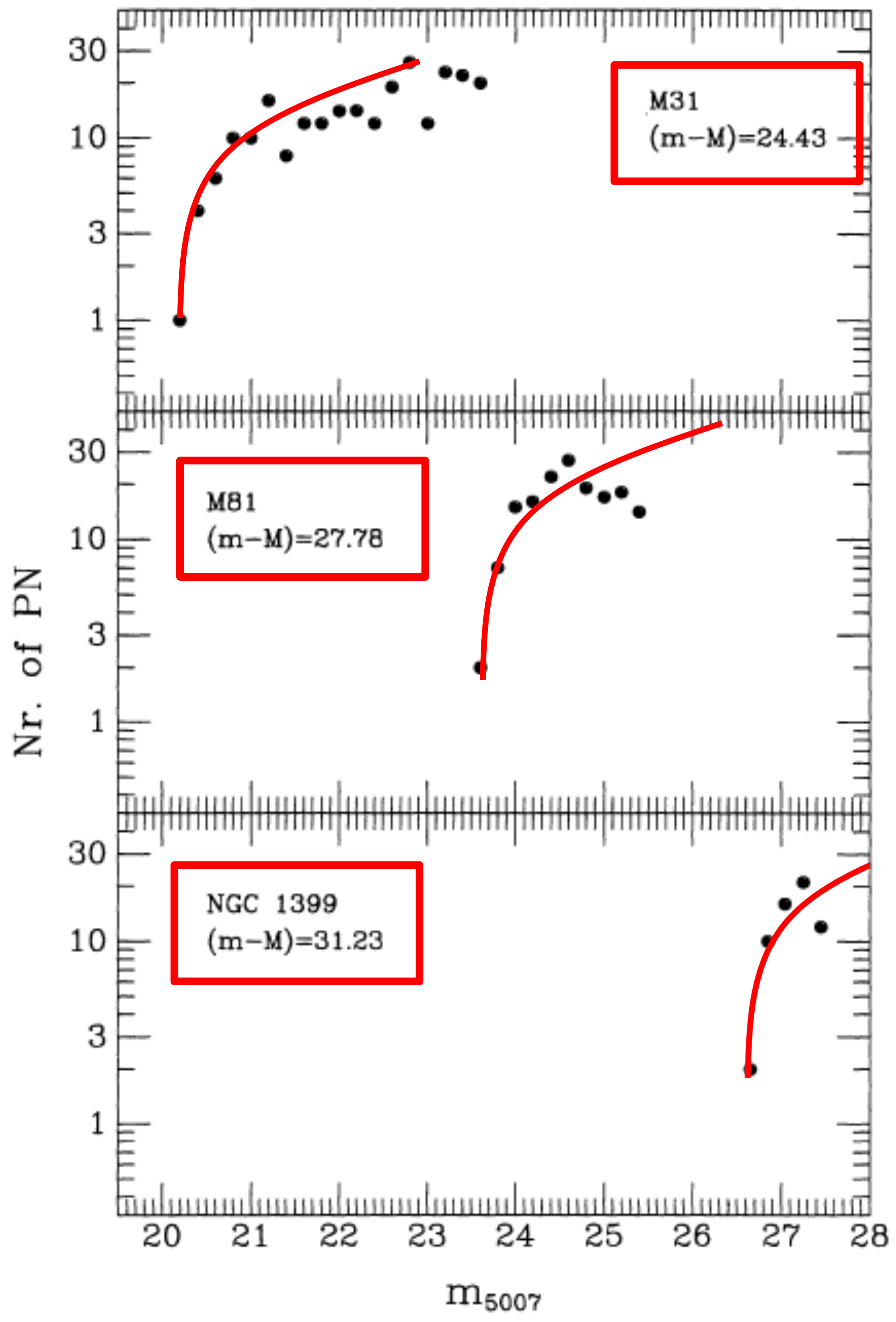
George H. Jacoby

KPNO, NOAO, P. O. Box 26732, Tucson, AZ 85726

Robin Ciardullo and John J. Feldmeier

Department of Astronomy, Penn State University, 525 Davey Lab, University Park, PA 16802

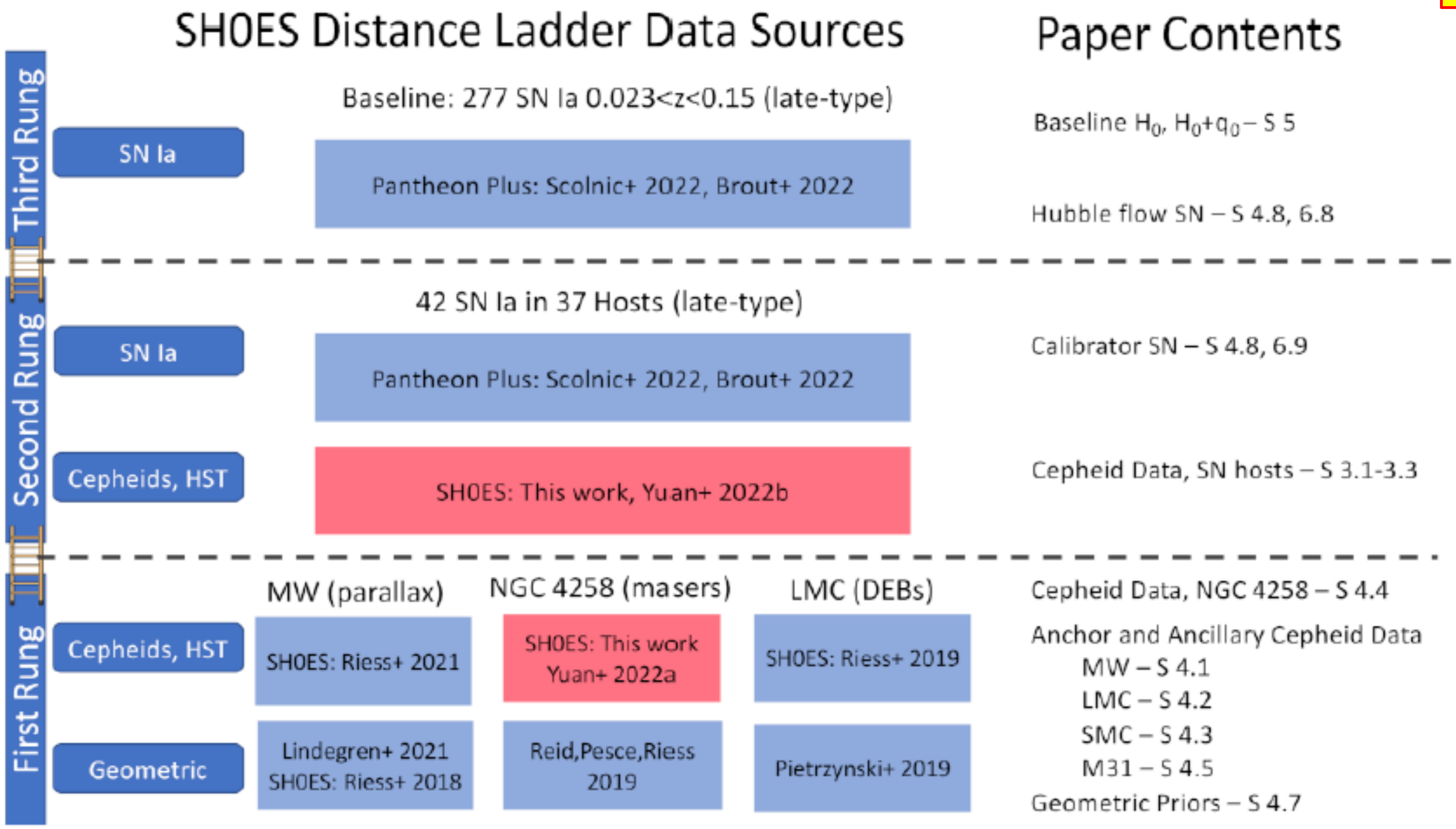
Abstract. For the past 10 years, the planetary nebula luminosity function (PNLF) has been used effectively in galaxies of most Hubble types for distance measurements within ~ 20 Mpc. We review the technique's theoretical foundations, and the reasons why the method is insensitive to age and metallicity differences in galaxies. We also illustrate through comparisons with Cepheid distances that the method is secure against observational bias at the ~ 5% level. We note that, although 8-m class telescopes that promise superior image quality are nearing completion, the useful range of the PNLF can be extended only by a factor of ~ 2. Consequently, the usefulness of the method for resolving questions relating to the large scale Hubble flow is limited. However, the PNLF continues to offer advantages over other distance indicators under special circumstances, and it provides a new probe into the structure and origin of galaxy clusters.



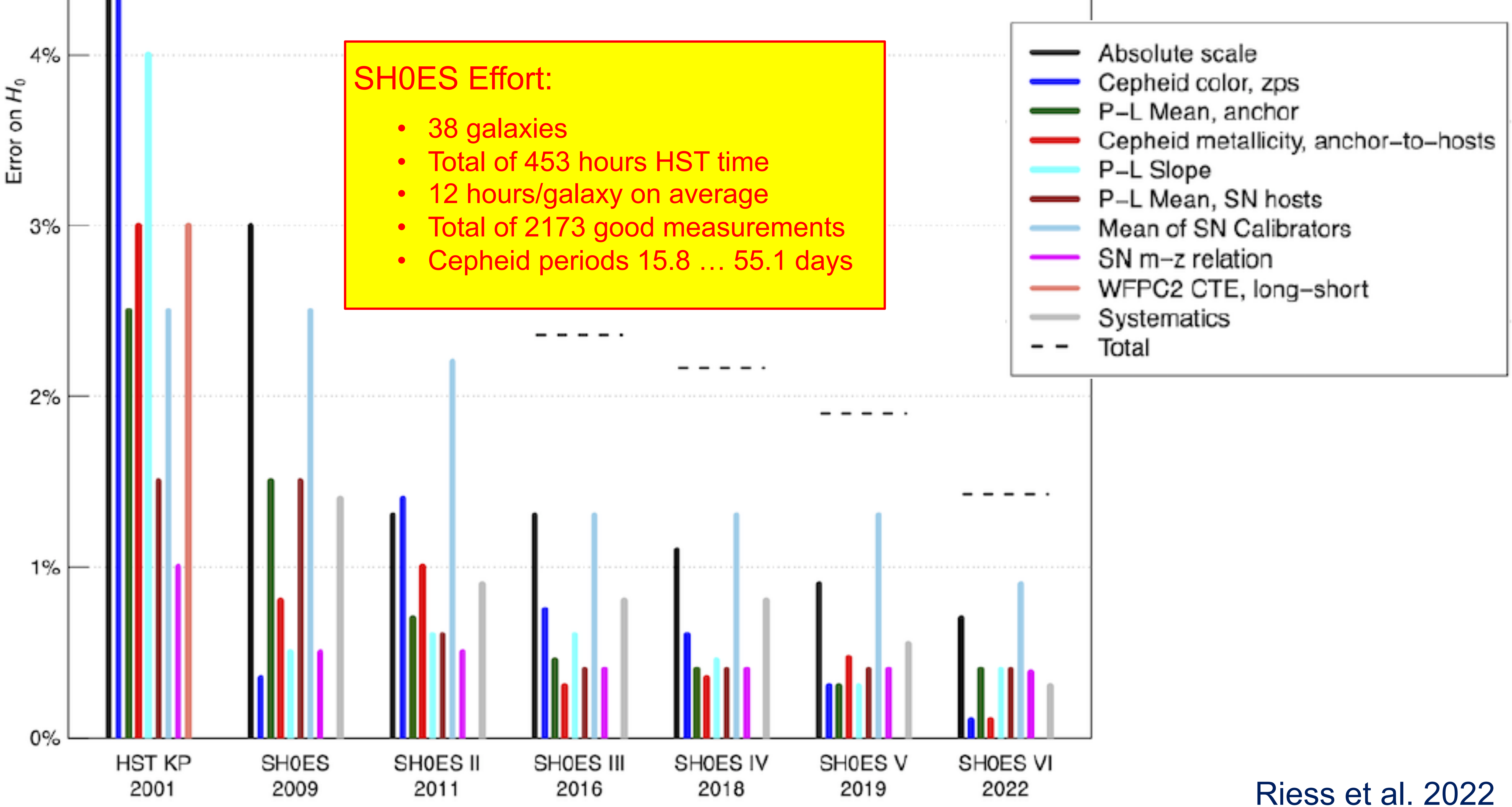
Motivation: MUSE-PNLF to measure H_o

Hubble Tension:

SH0ES: H_0=73.3 ± 1.04 km s^{-1} Mpc^{-1}
Planck: H_0=67.2 ± 1.2 km s^{-1} Mpc^{-1}



Riess et al. 2022



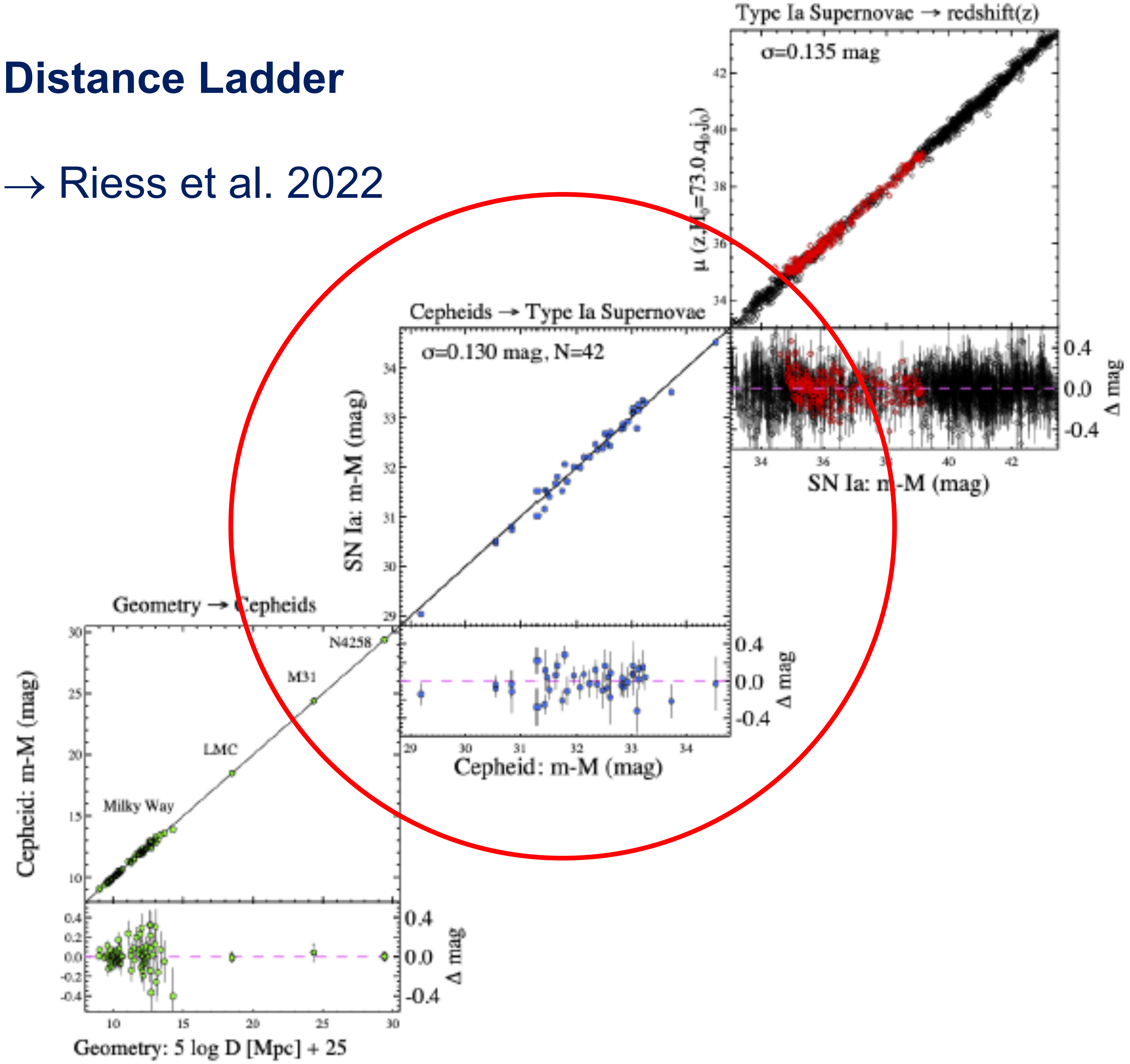
SH0ES Effort:

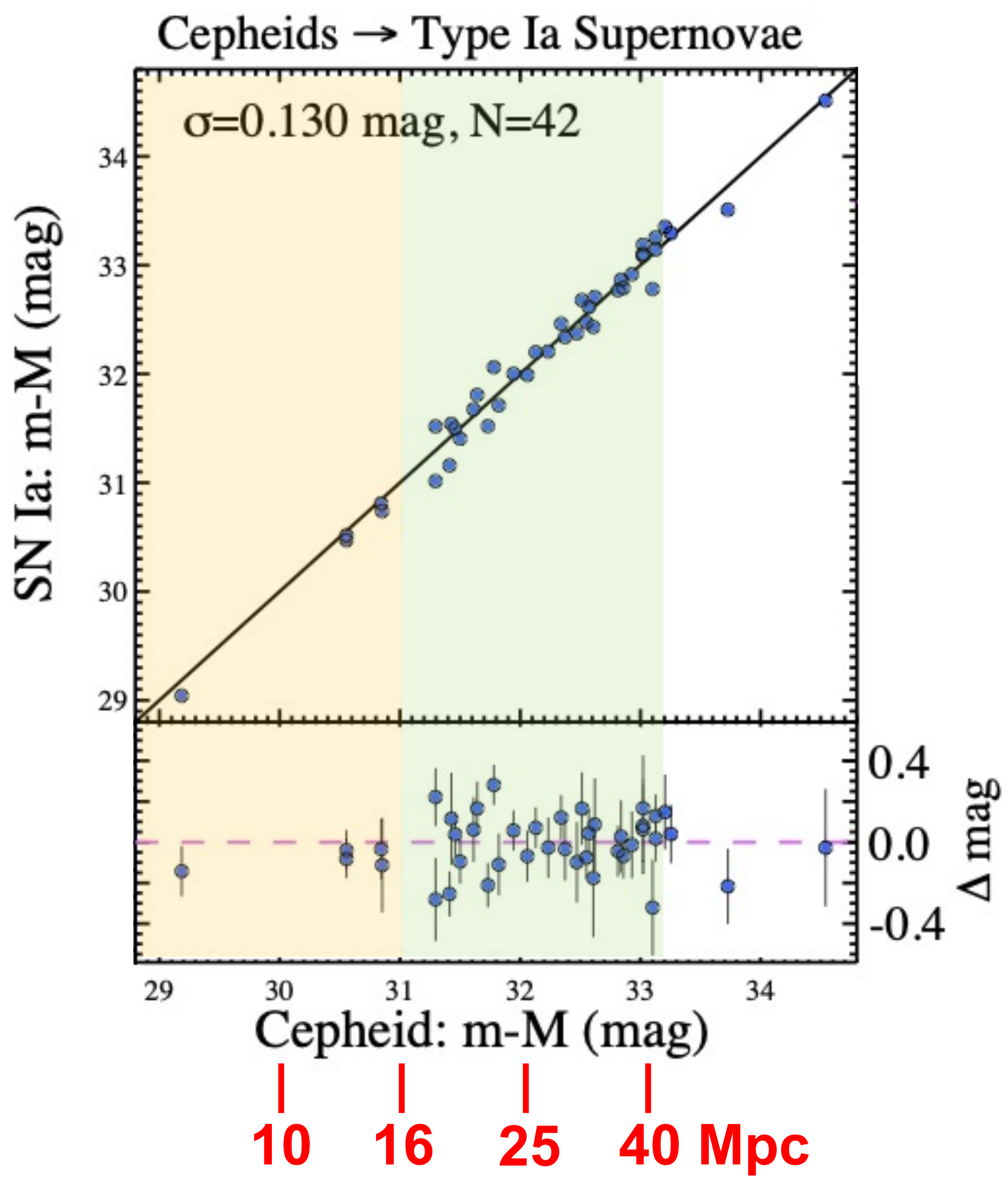
- 38 galaxies
- Total of 453 hours HST time
- 12 hours/galaxy on average
- Total of 2173 good measurements
- Cepheid periods 15.8 … 55.1 days

Riess et al. 2022

Distance Ladder

→ Riess et al. 2022



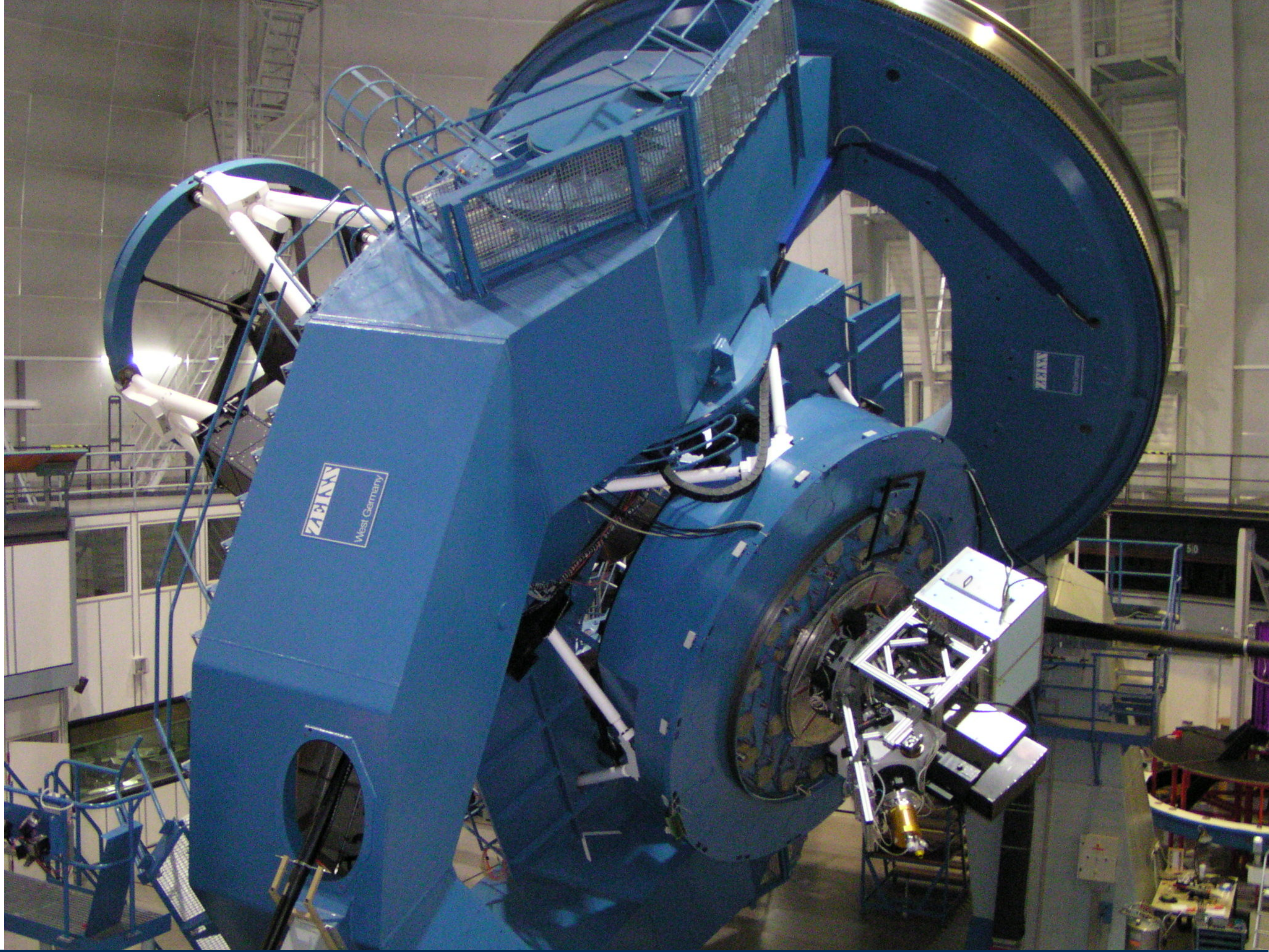


(2) Early PN observations with IFUs

PMAS

Potsdam
Multi
Aperture
Spectrophotometer

Fiber-slit	0.1 x 96 mm
Collimator	f = 450 mm, F/3
Camera	f = 270 mm, F/1.5
Gratings	300/500/600/1200 mm^{-1}
Wavelength range	350 - 900 nm
Dispersion	1.7 – 0.8 – 0.35 A/pix
Coverage	3700 – 1600 – 720 A *)
Resolution ($\lambda/\Delta\lambda$)	730 – 1500 – 3600 (11000 in 2^{nd} order)



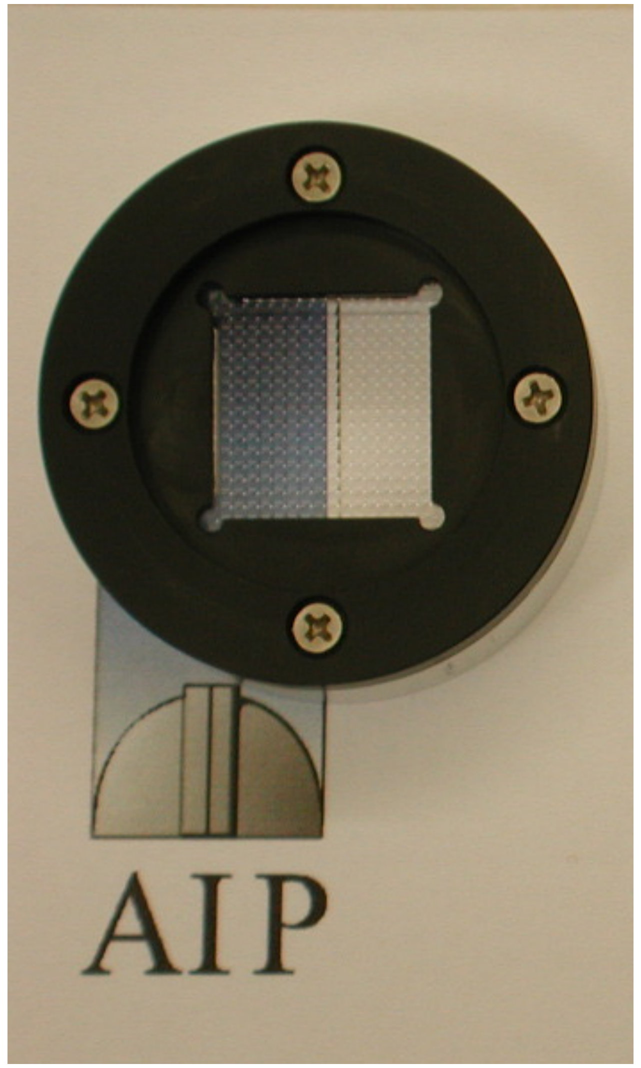
PMAS

Two integral field unit options:

PNLF

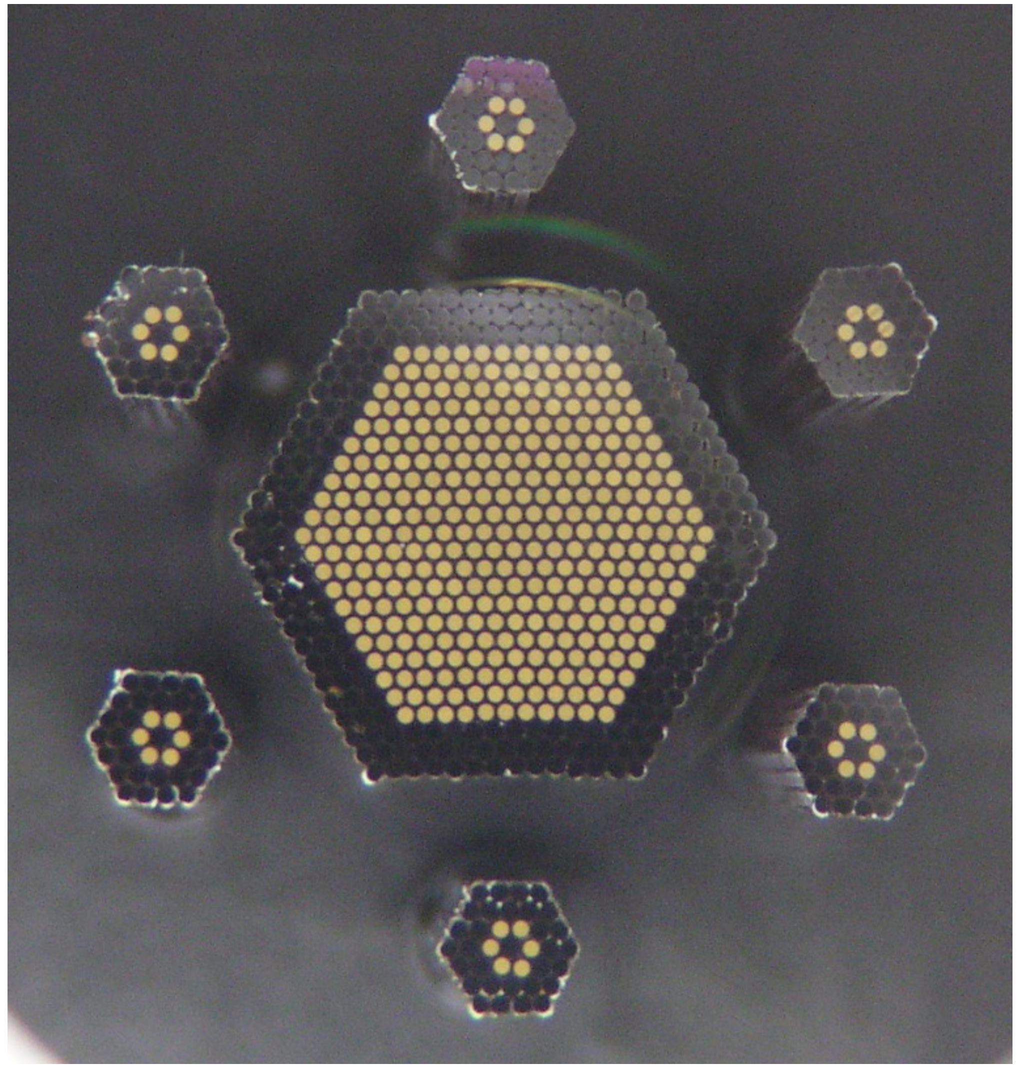
CALIFA Survey

Lensarray IFU



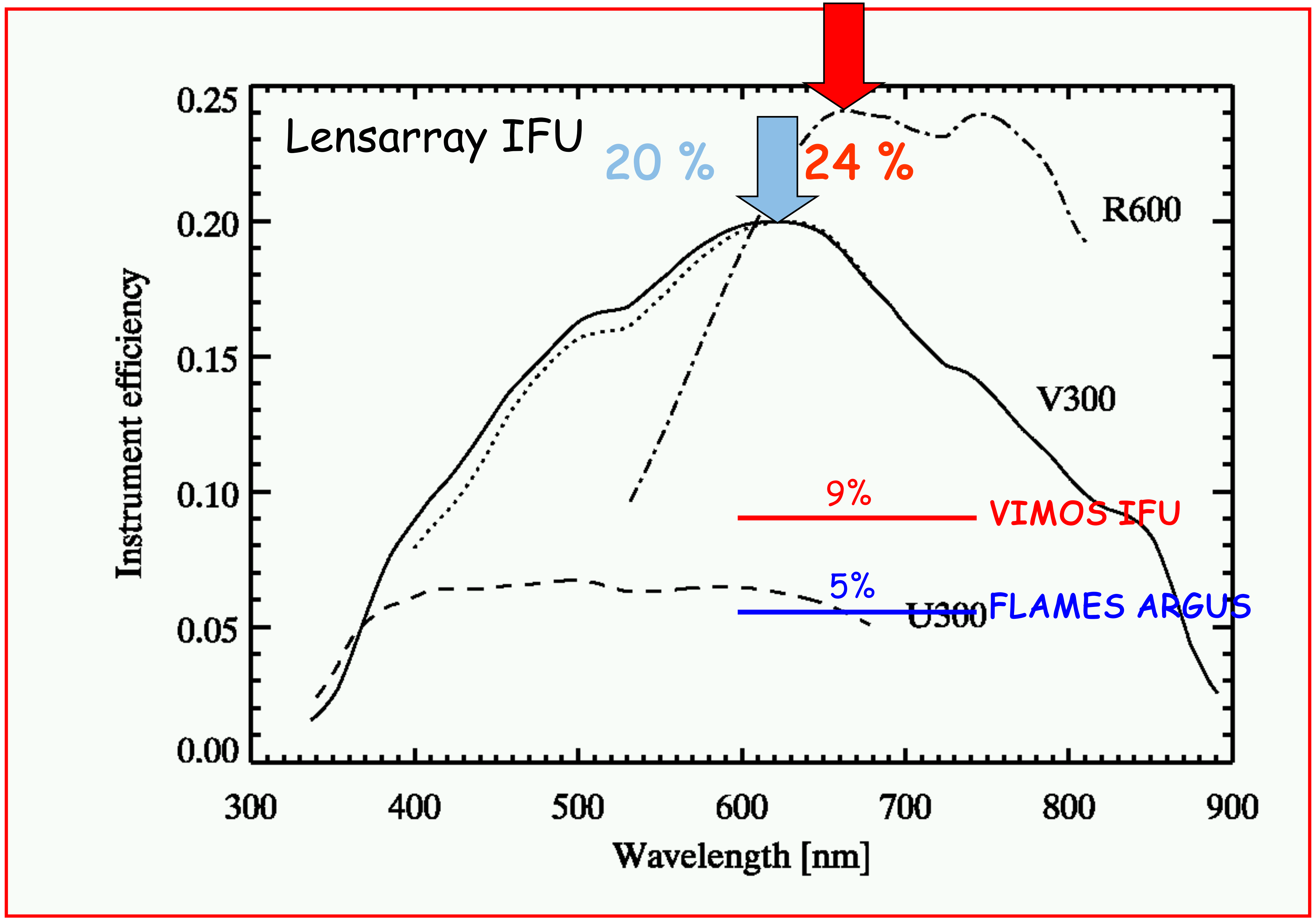
8 x 8 arcsec^2

PPaK IFU



74 x 65 arcsec^2

PMAS



Lensarray IFU
20 %
24 %
R600
V300
9%
VIMOS IFU
5%
U300
FLAMES ARGUS
Instrument efficiency
0.25
0.20
0.15
0.10
0.05
0.00
300
400
500
600
700
800
900
Wavelength [nm]

PMAS

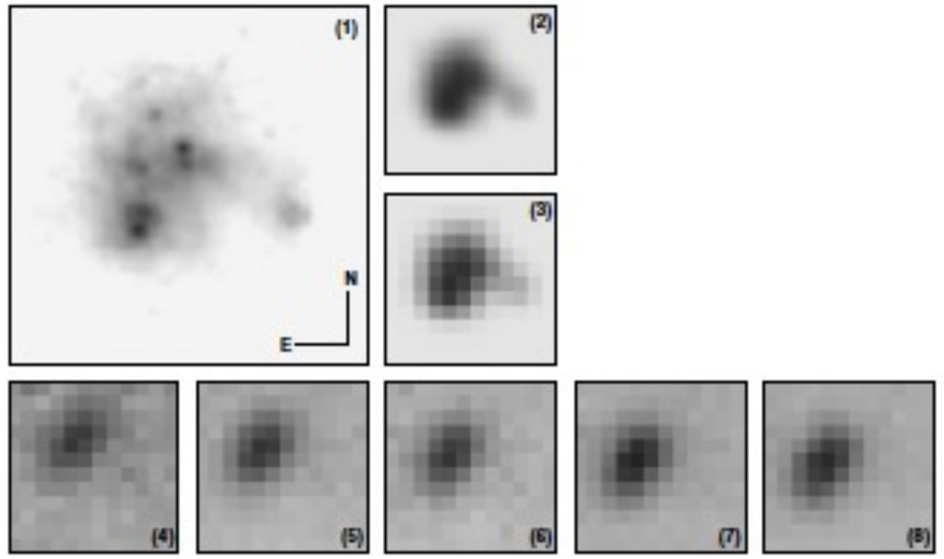
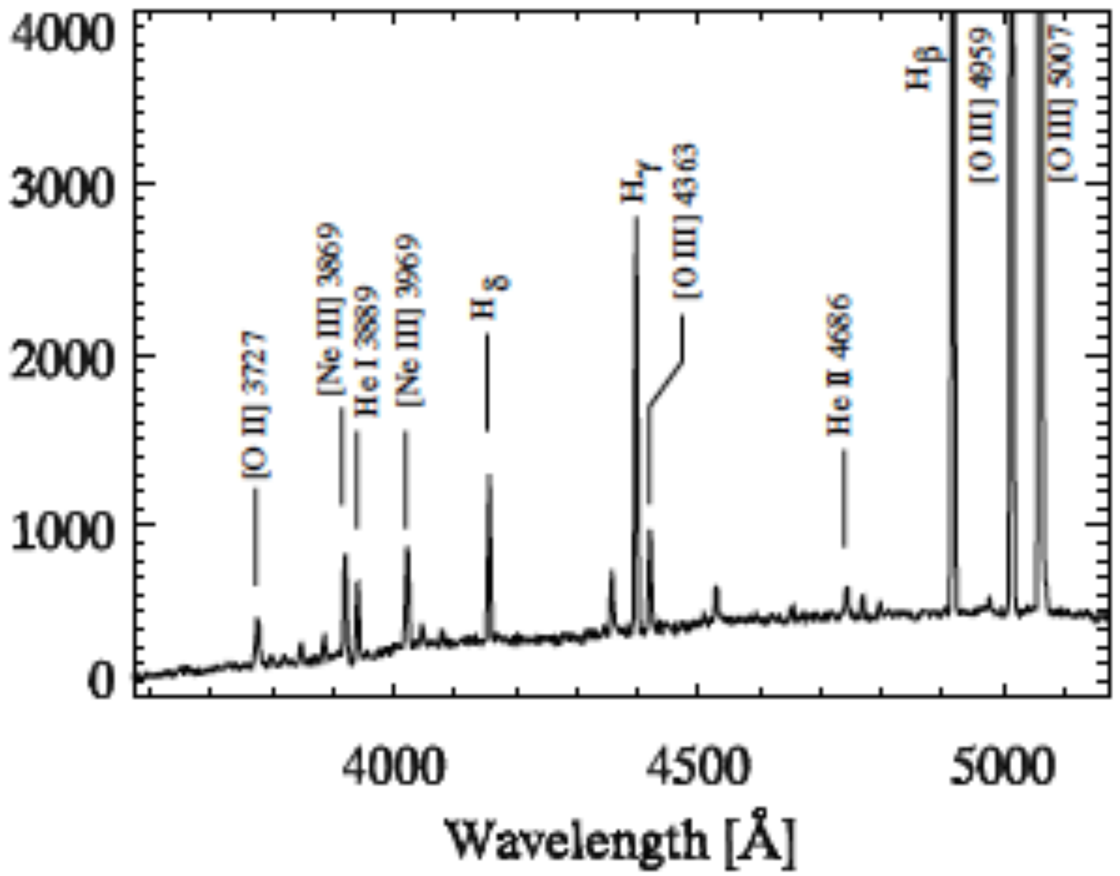
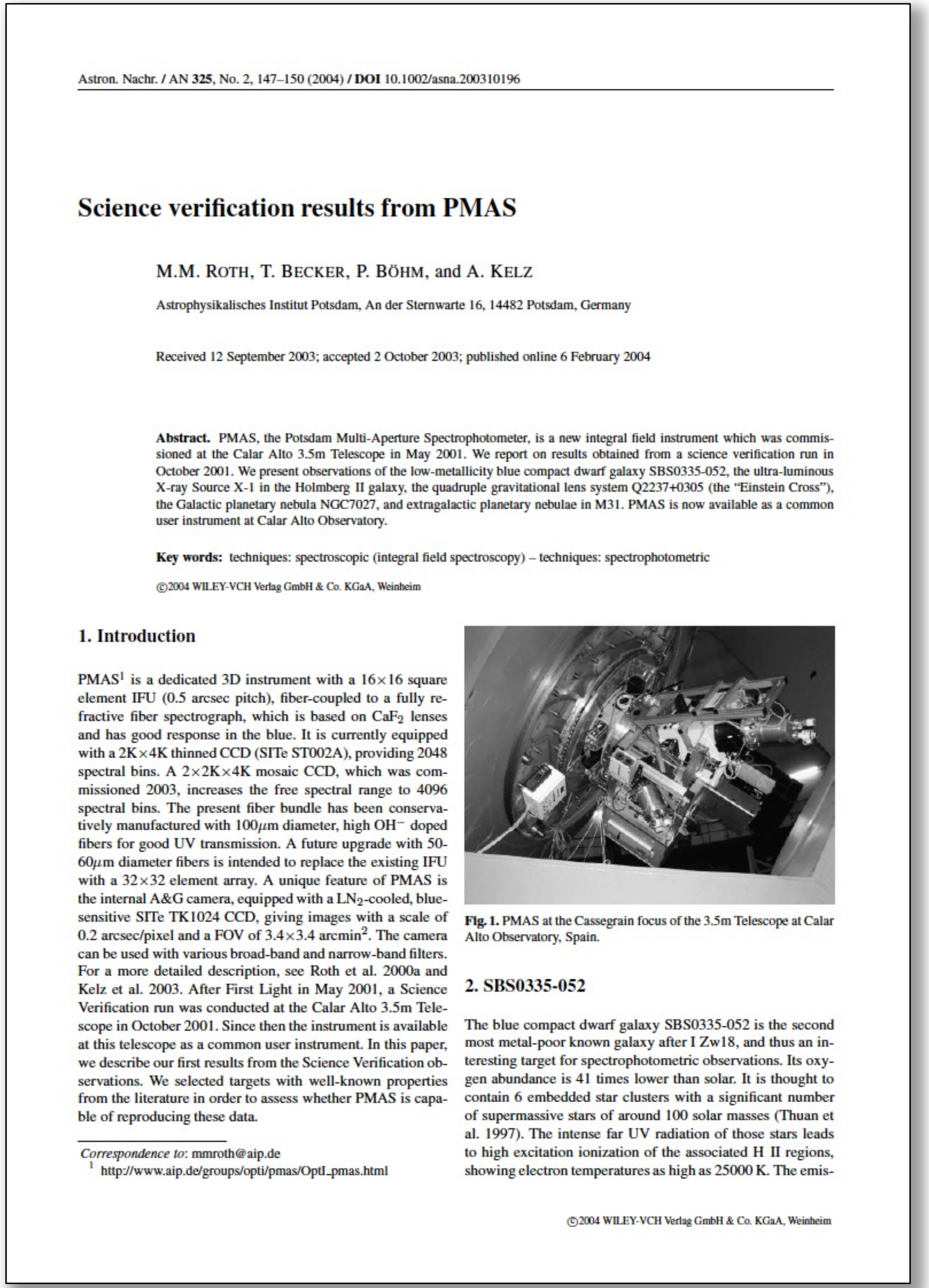


Fig. 2. Direct images and 3D maps of SBS0335-052. Top: Thuan et al. 1997 HST image (1), convolved with 1" seeing (2), and resampled on a 0.5 arcsec grid (3). Bottom: 3D maps in [O II] 3727 Å (4), continuum at 4200 Å (5), H_γ (6), H_β (7), [O III] 4959 Å (8). Note the shifts with wavelength as an effect of atmospheric refraction.





Astron. Nachr. / AN **325**, No. 2, 147–150 (2004) / **DOI** 10.1002/asna.200310196

Science verification results from PMAS

M.M. Roth, T. Becker, P. Böhm, and A. Kelz

Astrophysikalisches Institut Potsdam, An der Sternwarte 16, 14482 Potsdam, Germany

Received 12 September 2003; accepted 2 October 2003; published online 6 February 2004

Abstract. PMAS, the Potsdam Multi-Aperture Spectrophotometer, is a new integral field instrument which was commissioned at the Calar Alto 3.5m Telescope in May 2001. We report on results obtained from a science verification run in October 2001. We present observations of the low-metallicity blue compact dwarf galaxy SBS0335-052, the ultra-luminous X-ray Source X-1 in the Holmberg II galaxy, the quadruple gravitational lens system Q2237+0305 (the "Einstein Cross"), the Galactic planetary nebula NGC7027, and extragalactic planetary nebulae in M31. PMAS is now available as a common user instrument at Calar Alto Observatory.

Key words: techniques: spectroscopic (integral field spectroscopy) – techniques: spectrophotometric

1. Introduction

PMAS[1] is a dedicated 3D instrument with a 16×16 square element IFU (0.5 arcsec pitch), fiber-coupled to a fully refractive fiber spectrograph, which is based on CaF_2 lenses and has good response in the blue. It is currently equipped with a 2K×4K thinned CCD (SITe ST002A), providing 2048 spectral bins. A 2×2K×4K mosaic CCD, which was commissioned 2003, increases the free spectral range to 4096 spectral bins. The present fiber bundle has been conservatively manufactured with 100μm diameter, high OH^- doped fibers for good UV transmission. A future upgrade with 50-60μm diameter fibers is intended to replace the existing IFU with a 32×32 element array. A unique feature of PMAS is the internal A&G camera, equipped with a LN_2-cooled, blue-sensitive SITe TK1024 CCD, giving images with a scale of 0.2 arcsec/pixel and a FOV of 3.4×3.4 arcmin^2. The camera can be used with various broad-band and narrow-band filters. For a more detailed description, see Roth et al. 2000a and Kelz et al. 2003. After First Light in May 2001, a Science Verification run was conducted at the Calar Alto 3.5m Telescope in October 2001. Since then the instrument is available at this telescope as a common user instrument. In this paper, we describe our first results from the Science Verification observations. We selected targets with well-known properties from the literature in order to assess whether PMAS is capable of reproducing these data.

Correspondence to: mmroth@aip.de

[1] http://www.aip.de/groups/opti/pmas/OptI_pmas.html

Fig. 1. PMAS at the Cassegrain focus of the 3.5m Telescope at Calar Alto Observatory, Spain.

2. SBS0335-052

The blue compact dwarf galaxy SBS0335-052 is the second most metal-poor known galaxy after I Zw18, and thus an interesting target for spectrophotometric observations. Its oxygen abundance is 41 times lower than solar. It is thought to contain 6 embedded star clusters with a significant number of supermassive stars of around 100 solar masses (Thuan et al. 1997). The intense far UV radiation of those stars leads to high excitation ionization of the associated H II regions, showing electron temperatures as high as 25000 K. The emis-

PMAS

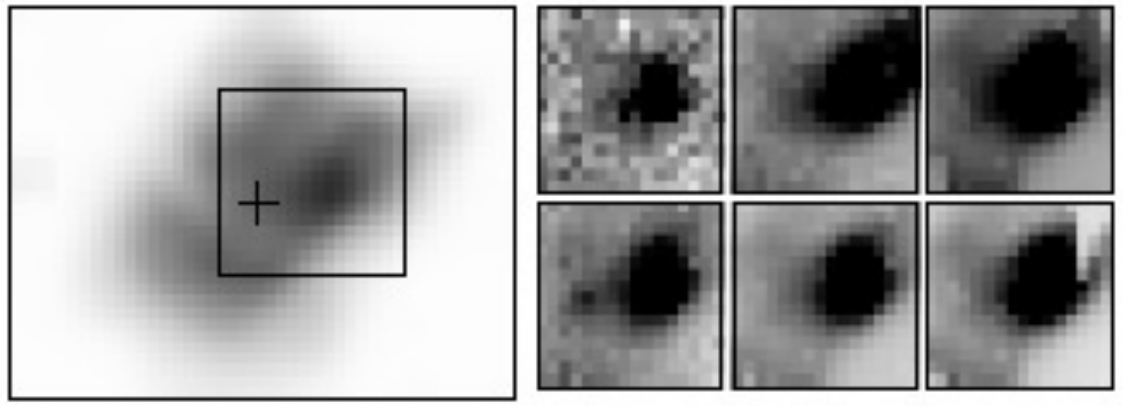
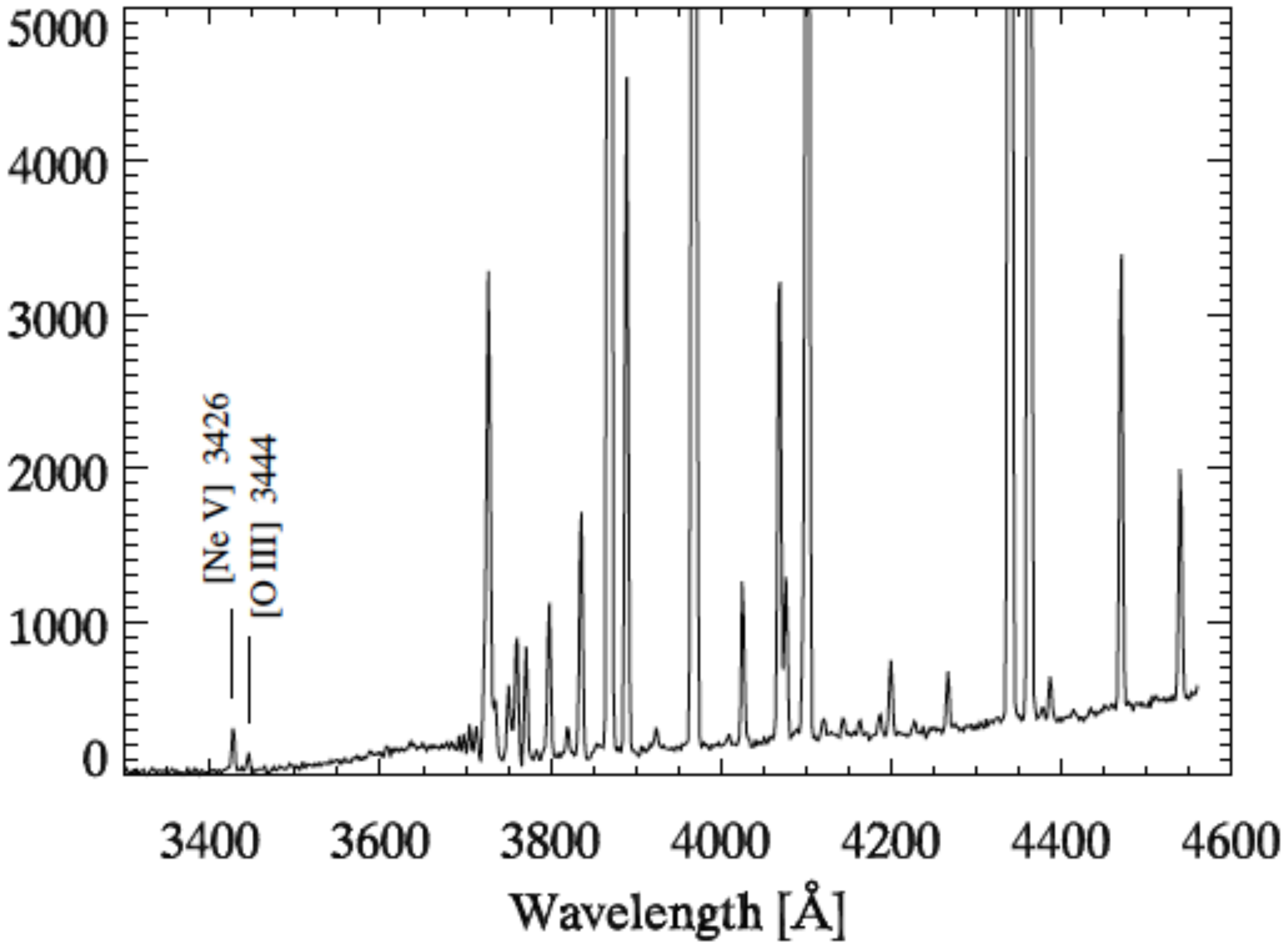


Fig. 8. Direct image and 3D maps of NGC7027 (North up, East left).



Astron. Nachr. / AN **325**, No. 2, 147–150 (2004) / **DOI** 10.1002/asna.200310196

Science verification results from PMAS

M.M. ROTH, T. BECKER, P. BÖHM, and A. KELZ

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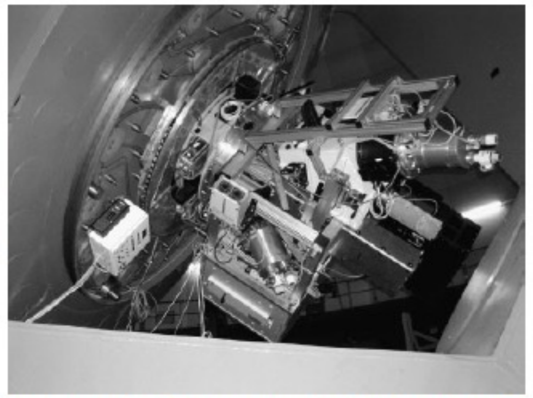

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PMAS

Roth+2004

THE ASTROPHYSICAL JOURNAL, 603:531–547, 2004 March 10

SPECTROPHOTOMETRY OF PLANETARY NEBULAE IN THE BULGE OF M31

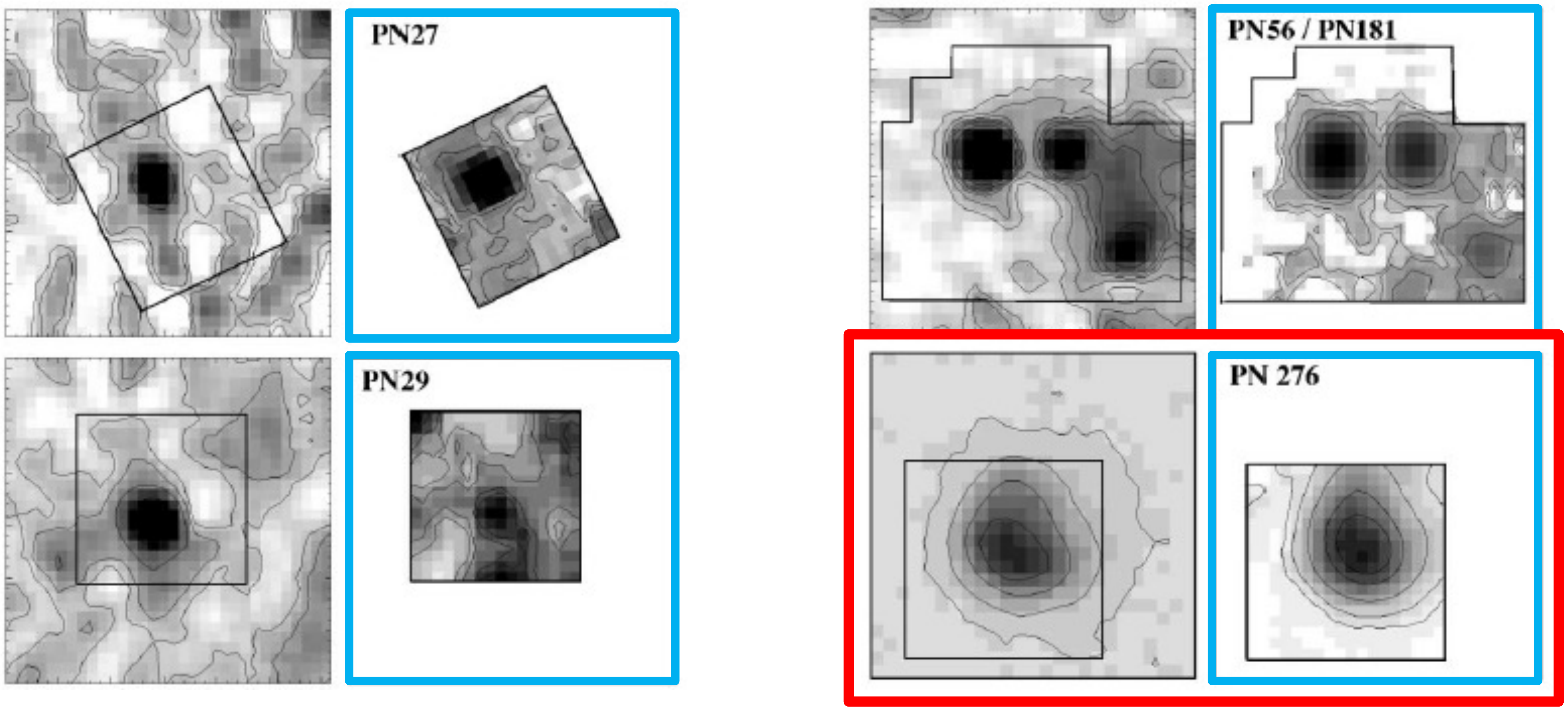
MARTIN M. ROTH,[1,2] THOMAS BECKER,[1,2] AND ANDREAS KELZ[1]
Astrophysikalisches Institut Potsdam, An der Sternwarte 16, D-14482 Potsdam, Germany; mmroth@aip.de

AND

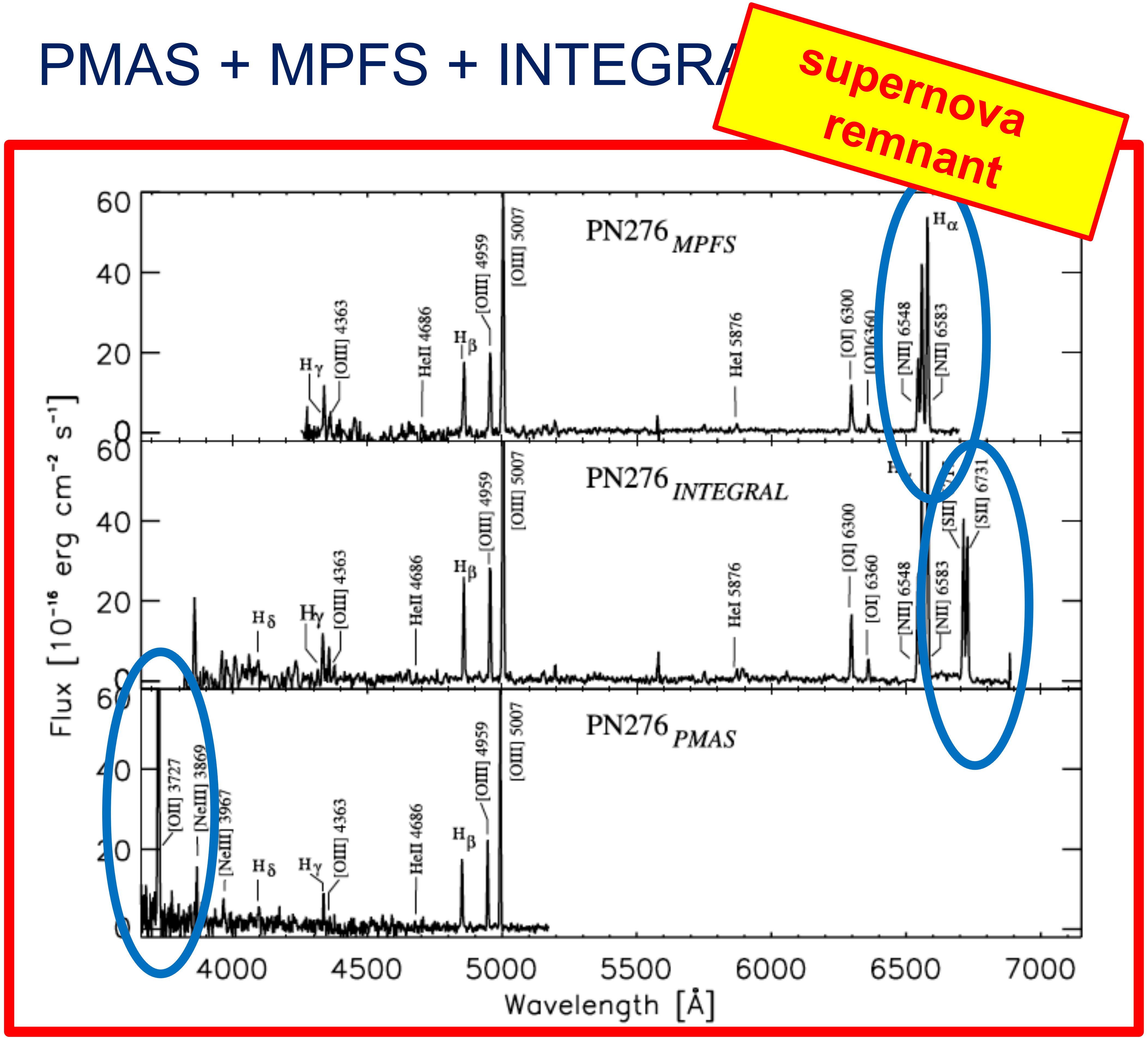
JÜRGEN SCHMOLL[1,2,3]
Astronomical Instrument Group, Department of Physics, University of Durham, Rochester Building, South Road, Durham DH1 3LE, UK;
Jurgen.Schmoll@durham.ac.uk
Received 2003 September 7; accepted 2003 November 19

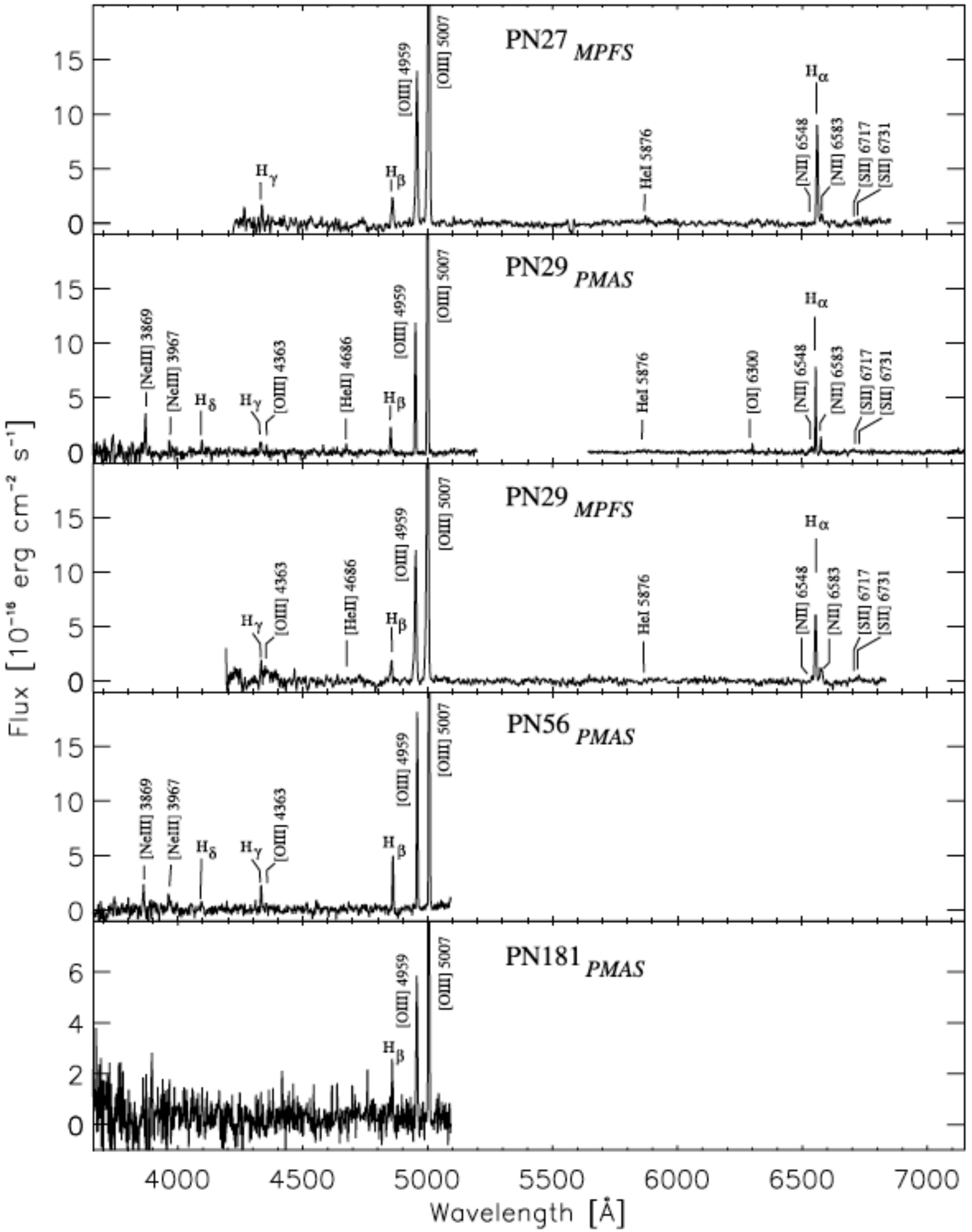
M31 planetary nebula candidates

CCD image | **PMAS reconstructed** | CCD image | **PMAS reconstructed**



PMAS + MPFS + INTEGRAL





(3) MUSE-PNLF and the Differential Emission Line Filter (DELF)

(3) MUSE-PNLF

muse
multi unit spectroscopic explorer

GTO

Pilot Study in NGC 300

- Use MUSE GTO to measure PNLF in nearby NGC 300 to unprecedented depth
- study partially resolved stellar population

(3) MUSE-PNLF

Coordin…
Institute…
Written…

Referen…
Issue :
Date :
File :
Distribut…

History:
- 0.1
- 0.2
- 0.25
- 0.3
- 1.0
- 1.1
- 1.2
- 1.3

Approve…
- R.

Cambridge Du…

Title:	Science Case
Reference:	MUSE-MEM-SCI-052
Issue:	1.3
Date:	04/02/2004
Page:	84/100

instruments at 8m class telescopes are most efficiently used to measure the halo PNe, this technique fails completely in the high surface brightness regions near the nucleus (Walsh et al. 1999). Crowded Field 3D Spectroscopy is the *only* method to provide the required accuracy for background subtraction in this galaxy. The combination of high spatial resolution, 1' FOV, large wavelength coverage, a suitable spectral resolution (R~1500) and high efficiency will make MUSE an unchallenged instrument for these observations.

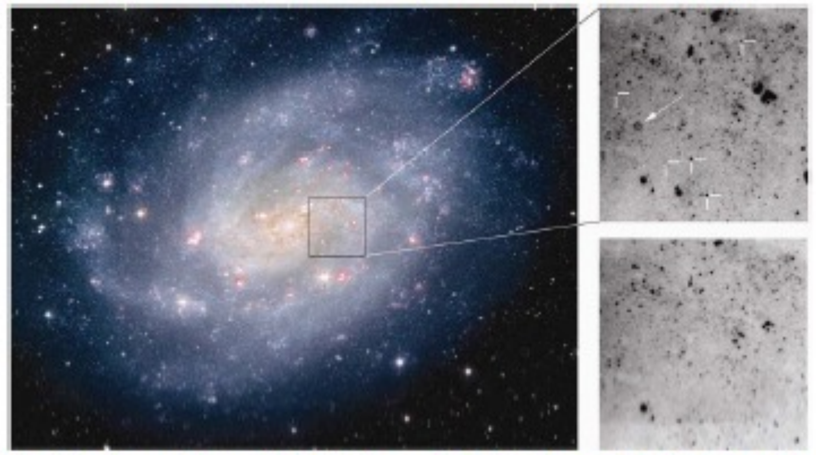


Fig. 4-11: Planetary Nebulae in NGC300, discovered with [O III] onband/offband imaging technique, using SUSI at the NTT. The frame in the color composite picture of the galaxy indicates the 2.2x2.2 arcmin² FOV of the CCD camera. [O III] onband (top) and offband (bottom) frames are shown to the right. Several examples of XPN are indicated in the onband image (left to right): objects #27 (26.07), #23 (25.69), #2 (23.00), #7 (23.25), #13 (24.38). From Soffner et al. 1996, m_{5007} magnitudes in paranthesis. The total exposure time of the onband frame is 1800 sec

XPN are ideal tracers of intermediate age and old extragalactic stellar populations, because their hot central stars are among the most luminous stars in the HRD, emitting their radiation predominantly in the UV. A substantial fraction (of order 10%) of the total luminosity is re-emitted by the surrounding nebula in a prominent emission line spectrum, which gives enough contrast (for the bright lines) to detect the object as a point source against the bright background of unresolved stars of the parent galaxy. A practical application of this property has consisted in narrow-band imaging spectrophotometry, centered on the bright emission line of [O III] λ5007, and the construction of PN luminosity functions (PNLF) for the purpose of distance determinations (see review by Ciardullo 2003). Approximately 5000 XPN in more than 40 galaxies have been identified to date (Ford et al. 2002).

Currently the only way to measure individual abundances from old or intermediate age stars in galaxies more distant than the Magellanic Clouds is through the emission line spectra of extragalactic planetary nebulae (Walsh et al. 2000). This approach has some similarities with the standard method of measuring abundance gradients from individual H II regions in the disk of spiral galaxies (Shaver et al. 1983, Zaritsky et al. 1994). As opposed to H II regions, XPN metallicities can be derived in a homogeneous way for galaxies of *any* Hubble type, and

muse
multi unit spectroscopic explorer

GTO

European Organisation for Astronomical Research in the Southern Hemisphere

OBSERVING PROGRAMMES OFFICE • Karl-Schwarzschild-Straße 2 • D-85748 Garching bei München • e-mail: opo@eso.org • Tel.: +49 89 320 06473

APPLICATION FOR OBSERVING TIME — PERIOD: **94A**

Important Notice: **MUSE-consortium GTO**

By submitting this proposal, the PI takes full responsibility for the content of the proposal, in particular with regard to the names of CoIs and the agreement to act according to the ESO policy and regulations, should observing time be granted.

1. Title — Category: **B–2**

A study of the faint end of the planetary nebulæ luminosity function of NGC 300

2. Abstract / Total Time Requested

Total Amount of Time:

We propose to make new and unique observations of six $1' \times 1'$ fields in the Scd galaxy NGC 300 with the MUSE instrument. By making use of good seeing and 1.5h integrated exposure time in each field, our observations will reach an unprecendented depth. Specifically, we aim at discovering planetary nebulæ, through measurements in Hα and [OIII] λλ4959, 5007. Hereby, we will be able to measure a cumulative planetary nebulæ luminosity function six maxnitudes below its bright cutoff in this galaxy. Earlier studies, in comparison, reach 3.5 magnitudes below the cutoff, and appear to be incomplete at higher magnitudes.

3. Run	Period	Instrument	Time	Month	Moon	Seeing	Sky	Mode	Type
A	94	MUSE	9h	sep	g	0.6	CLR	v	

(3) MUSE-PNLF

Roth+2018

A&A 618, A3 (2018)
https://doi.org/10.1051/0004-6361/201833007

MUSE crowded field 3D spectr

I. First results from centr

Martin M. Roth[1], Christer Sandin[1], Sebastian Kamann[2,3], Ti
Ana Monreal-Ibero[4,5], Roland Bacon[7], Mark den Brok
Raffaella Anna Marino[6], and Matt

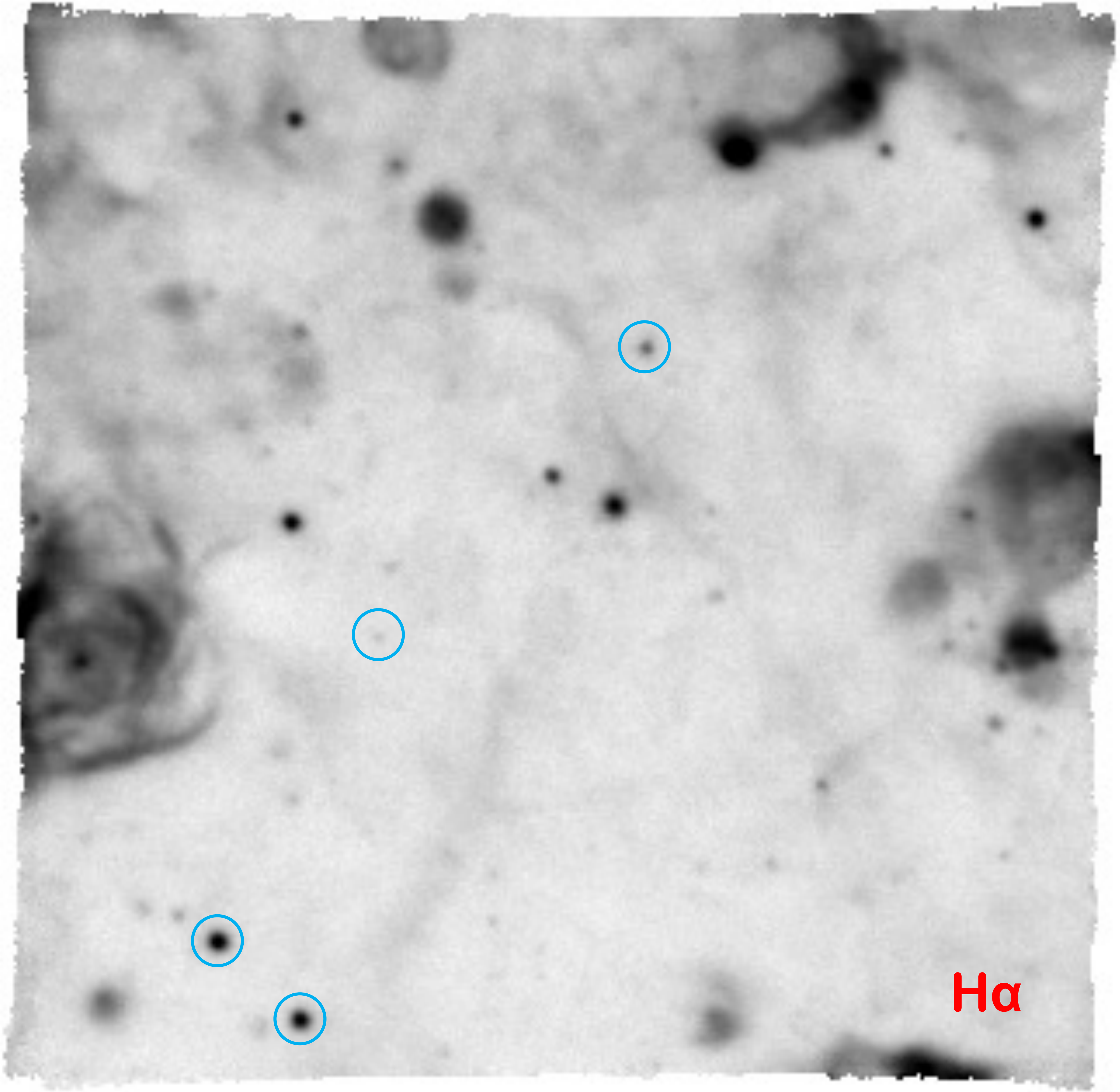
Table 3. Synthetic filter definitions.

Filter	λ'_c	$\Delta\lambda$	λ_0–λ_1	λ-bins
He II	4687.16	5.00	4687.35–4691.10	70–73
He II_{c_1}		70.00	4612.35–4681.10	10–65
He II_{c_2}		62.50	4763.60–4824.85	131–180
Hβ	4862.69	6.25	4862.35–4866.10	210–213
Hβ_{c_1}		62.50	4788.60–4849.85	151–200
Hβ_{c_2}		62.50	4888.60–4949.85	231–280
[O III]	5008.24	6.25	5007.35–5012.35	326–330
[O III]$_c$		126.25	5028.60–5153.60	343–443
Hα	6564.61	6.25	6564.85–6569.85	1572–1576
Hα_{c_1}		92.50	6371.10–6462.35	1417–1490
Hα_{c_2}		103.75	6609.85–6712.35	1608–1690
[N II]$_1$	6549.86	5.00	6549.85–6553.60	1560–1563
[N II]$_2$	6585.27	5.00	6586.10–6589.85	1589–1592
[N II]$_{c_1}$		92.25	6371.10–6462.35	1417–1490
[N II]$_{c_2}$		103.75	6609.85–6712.35	1608–1690
[S II]$_1$	6720.29	5.00	6718.41–6722.16	1695–1698
[S II]$_2$	6734.66	3.75	6733.41–6735.91	1707–1709
[S II]$_{c_1}$		75.0	6626.10–6699.85	1621–1680
[S II]$_{c_2}$		62.5	6763.60–6824.85	1731–1780
[S III]	9071.1	5.00	9073.25–9076.10	3578–3581
[S III]$_c$		46.25	9016.10–9061.10	3533–3569
V	5149.66	1101.25	4599.66–5699.66	0–880
R	6475.29	1550.00	5700.91–7249.66	881–2120
I	8299.66	2098.75	7250.91–9348.41	2121–3799

Notes. [N II]$_{c_1}$ identical to Hα_{c_1}, [N II]$_{c_2}$ identical to Hα_{c_2}.

(3) MUSE-PNLF

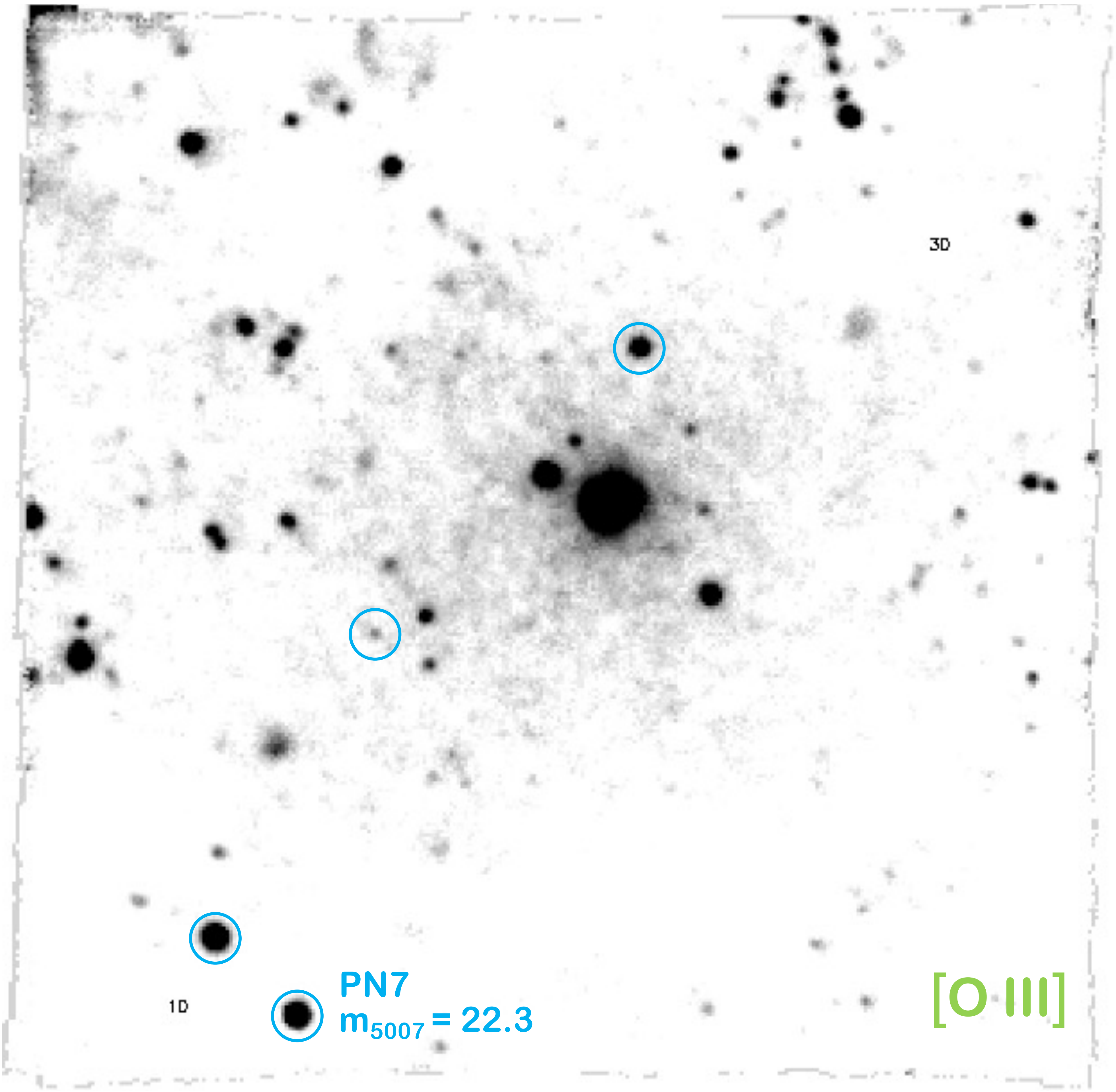
VLT-MUSE 2016



Roth+2018

(3) MUSE-PNLF

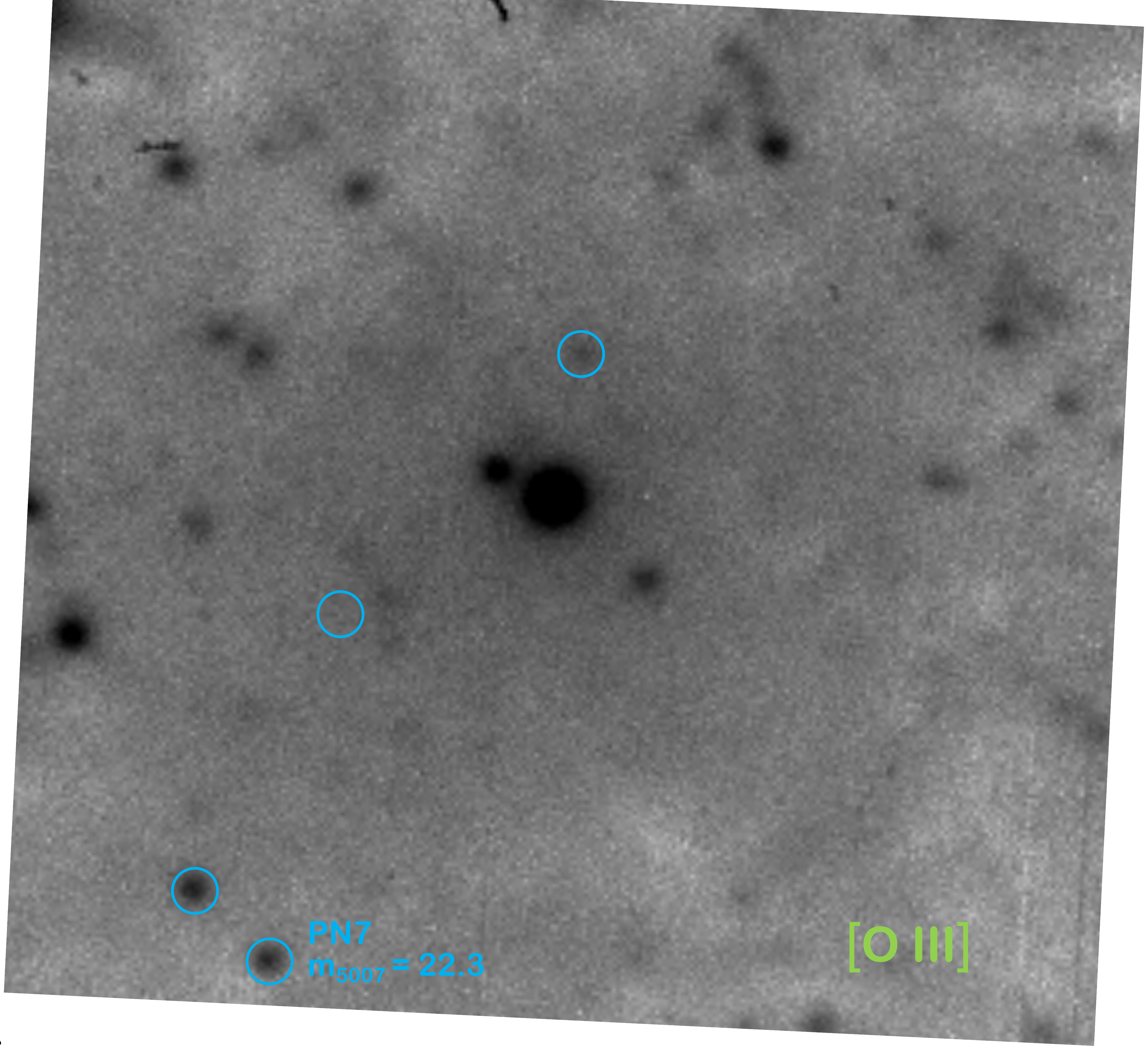
VLT-MUSE 2016



Roth+2018

(3) MUSE-PNLF

ESO-NTT
1993



Soffner+1996

(3) MUSE-PNLF

Roth+2021

The Astrophysical Journal, 916:21 (44pp), 2021 July 20
https://doi.org/10.3847/1538-4357/ac02ca

CrossMark

Toward Precision Cosmology with Improved PNLF Distances Using VLT-MUSE I. Methodology and Tests

Martin M. Roth[1], George H. Jacoby[2], Robin Ciardullo[3,4], Brian D. Davis[3], Owen Chase[3], and Peter M. Weilbacher[1]
[1] Leibniz Institute for Astrophysics Potsdam (AIP), An der Sternwarte 16, D-14482 Potsdam, Germany; mmroth@aip.de
[2] NSF's NOIRLab, 950 N. Cherry Avenue, Tucson, AZ 85719, USA
[3] Department of Astronomy & Astrophysics, The Pennsylvania State University, University Park, PA 16802, USA
[4] Institute for Gravitation and the Cosmos, The Pennsylvania State University, University Park, PA 16802, USA
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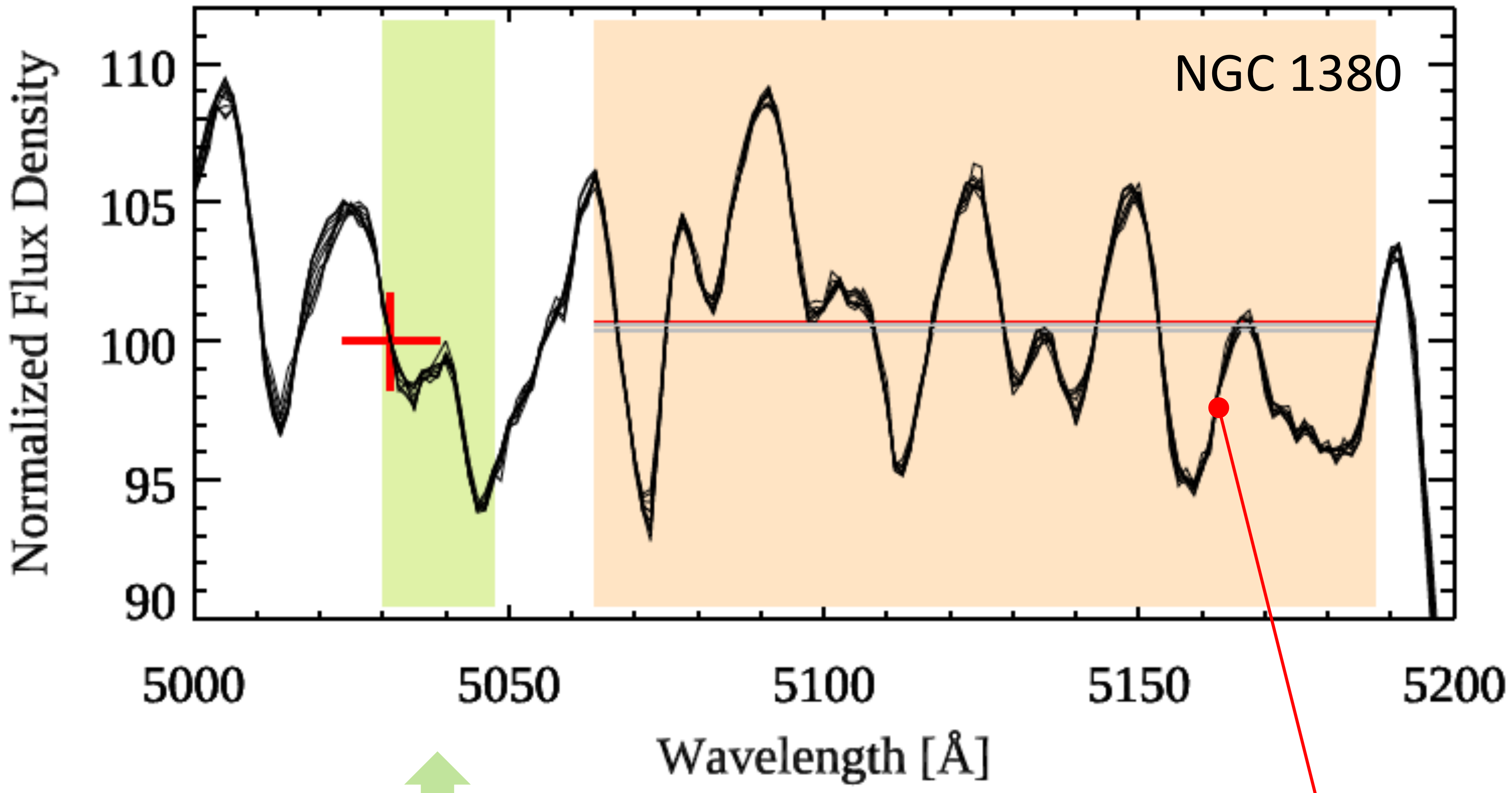
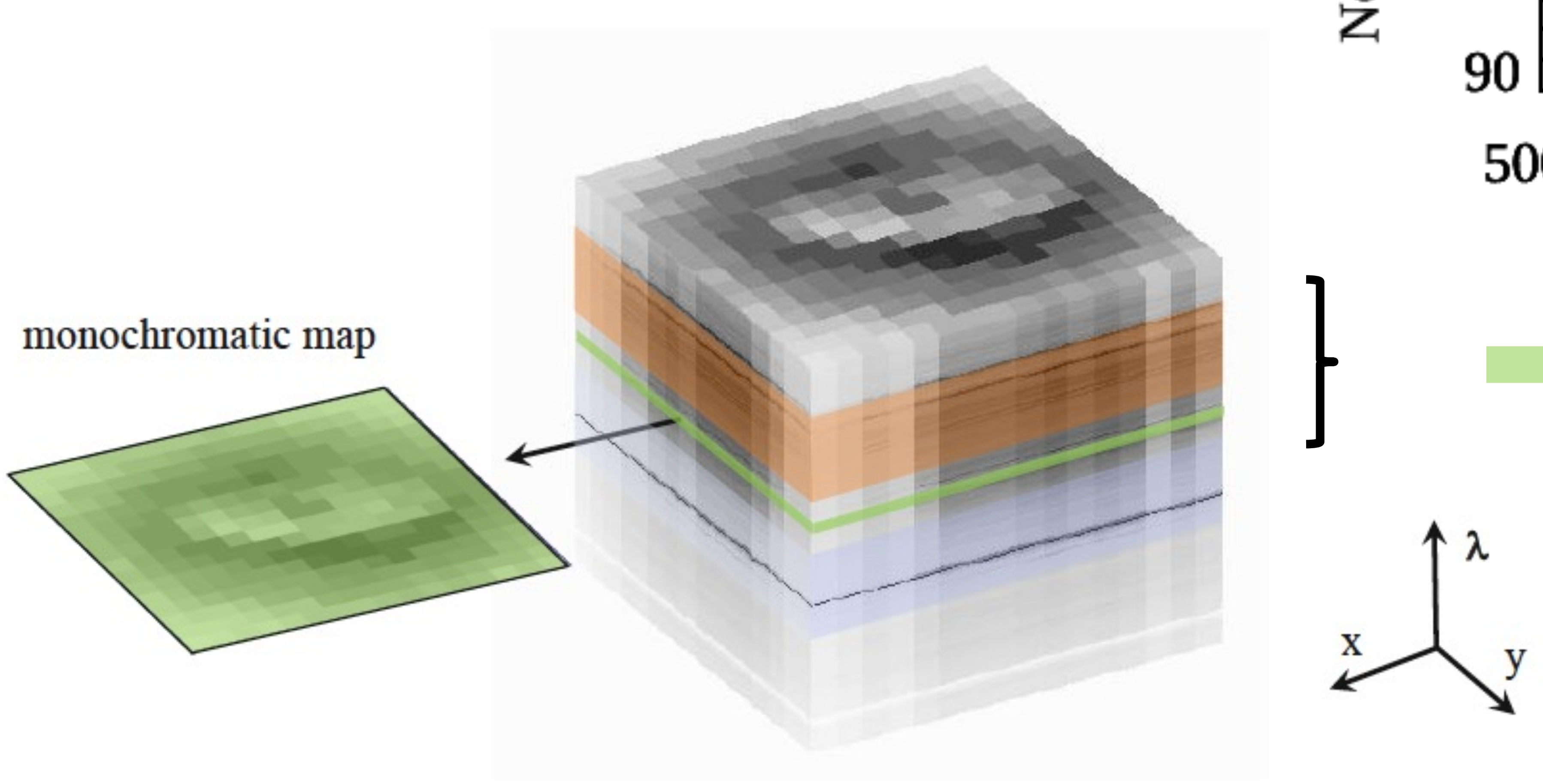
(3) MUSE-PNLF

DELF

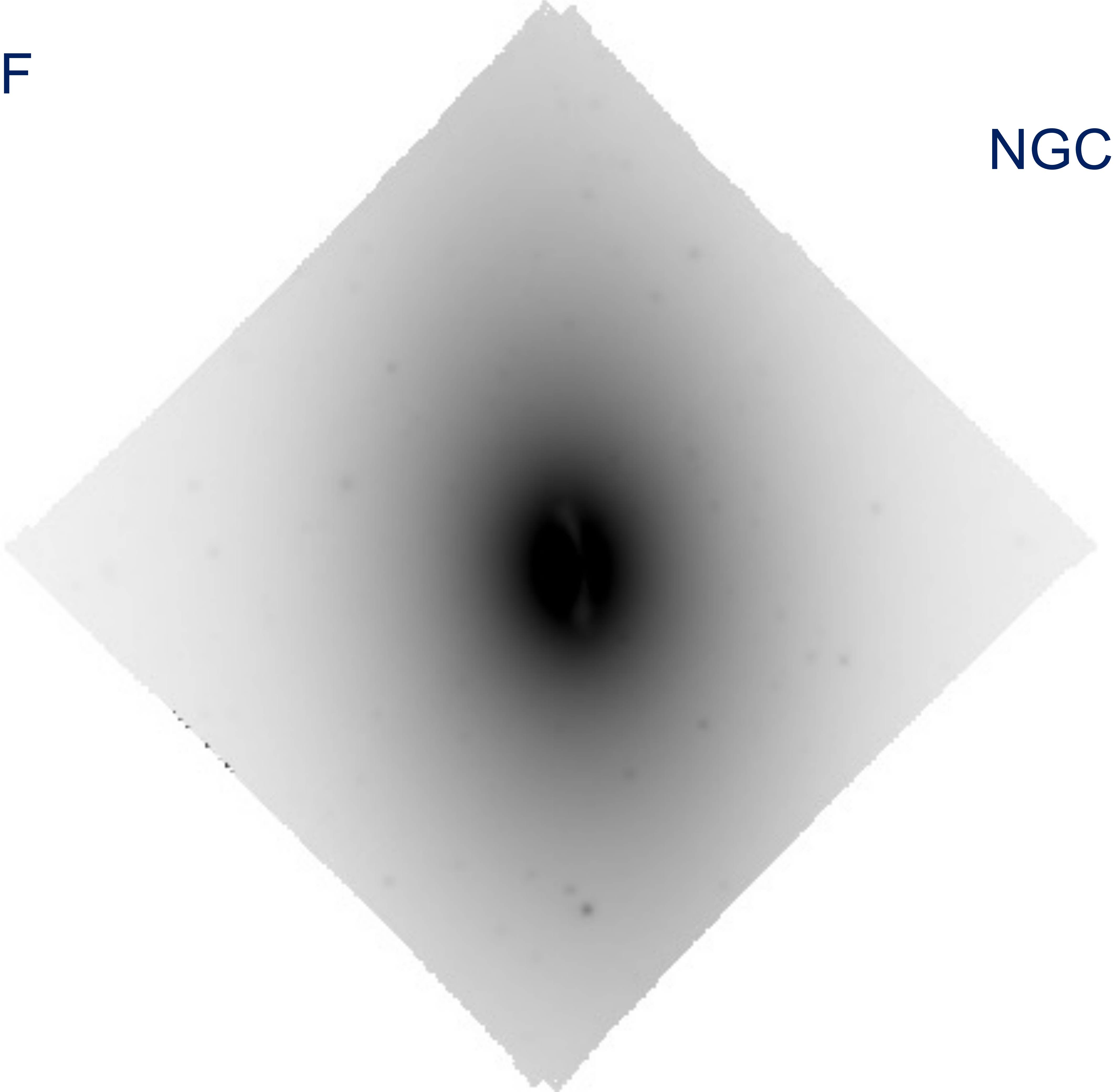




10 samples of galaxy background

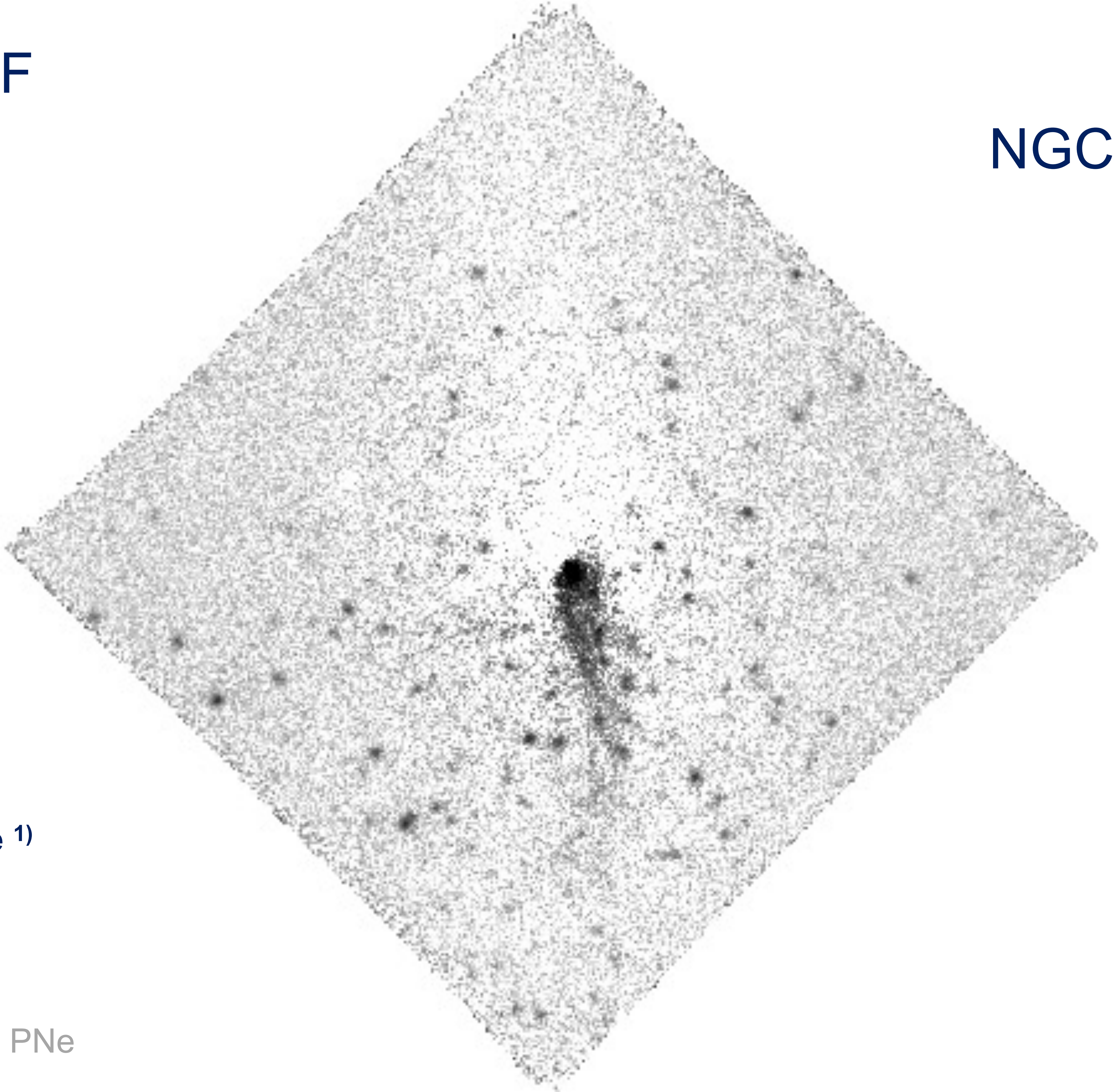
(3) MUSE-PNLF

NGC 1380



(3) MUSE-PNLF

NGC 1380

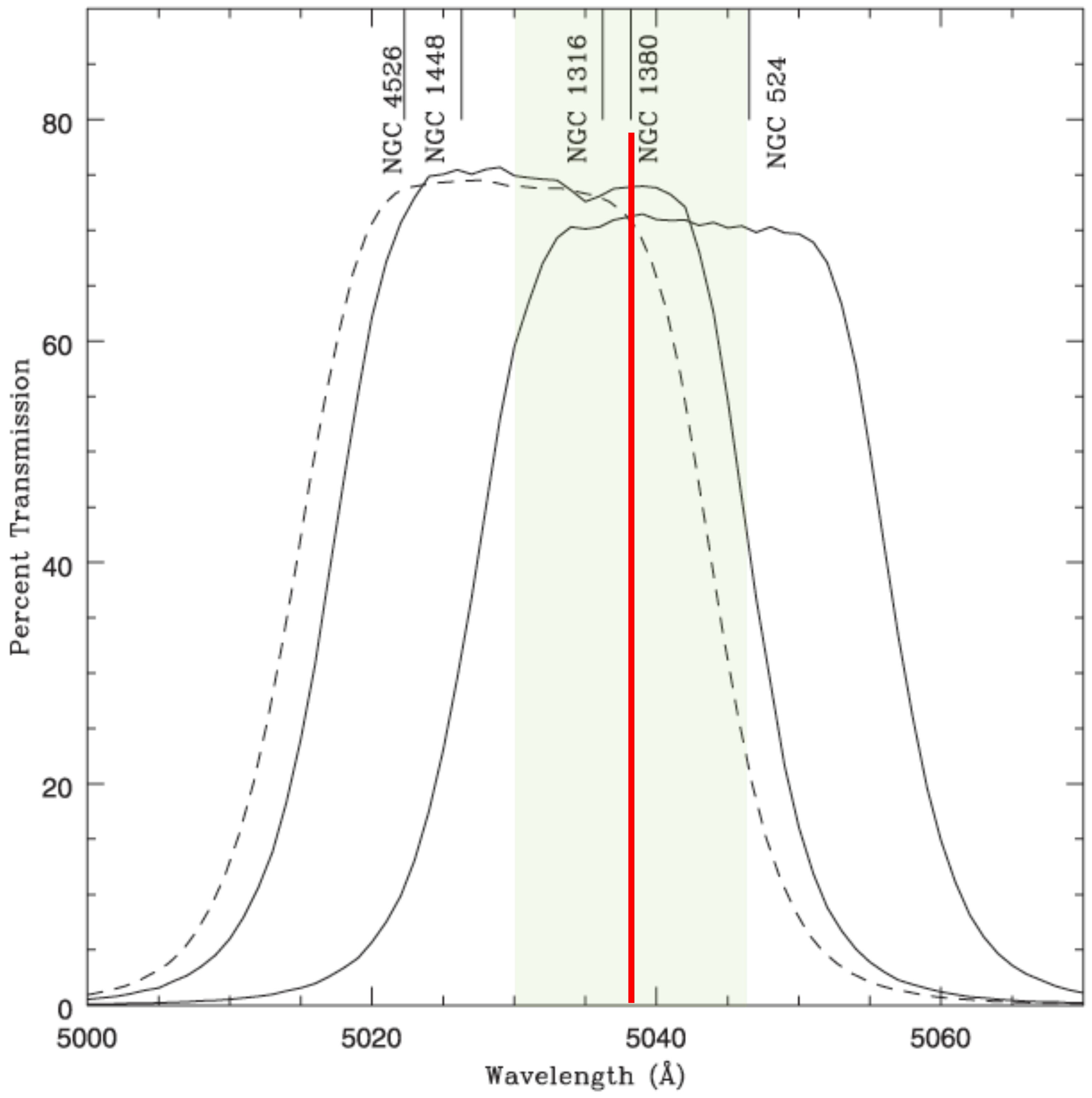


118 confirmed PNe [1)]

+ 40 in 2nd pointing
+ 8 in halo pointing

1) Spriggs+2020: 91 PNe

(3) MUSE-PNLF

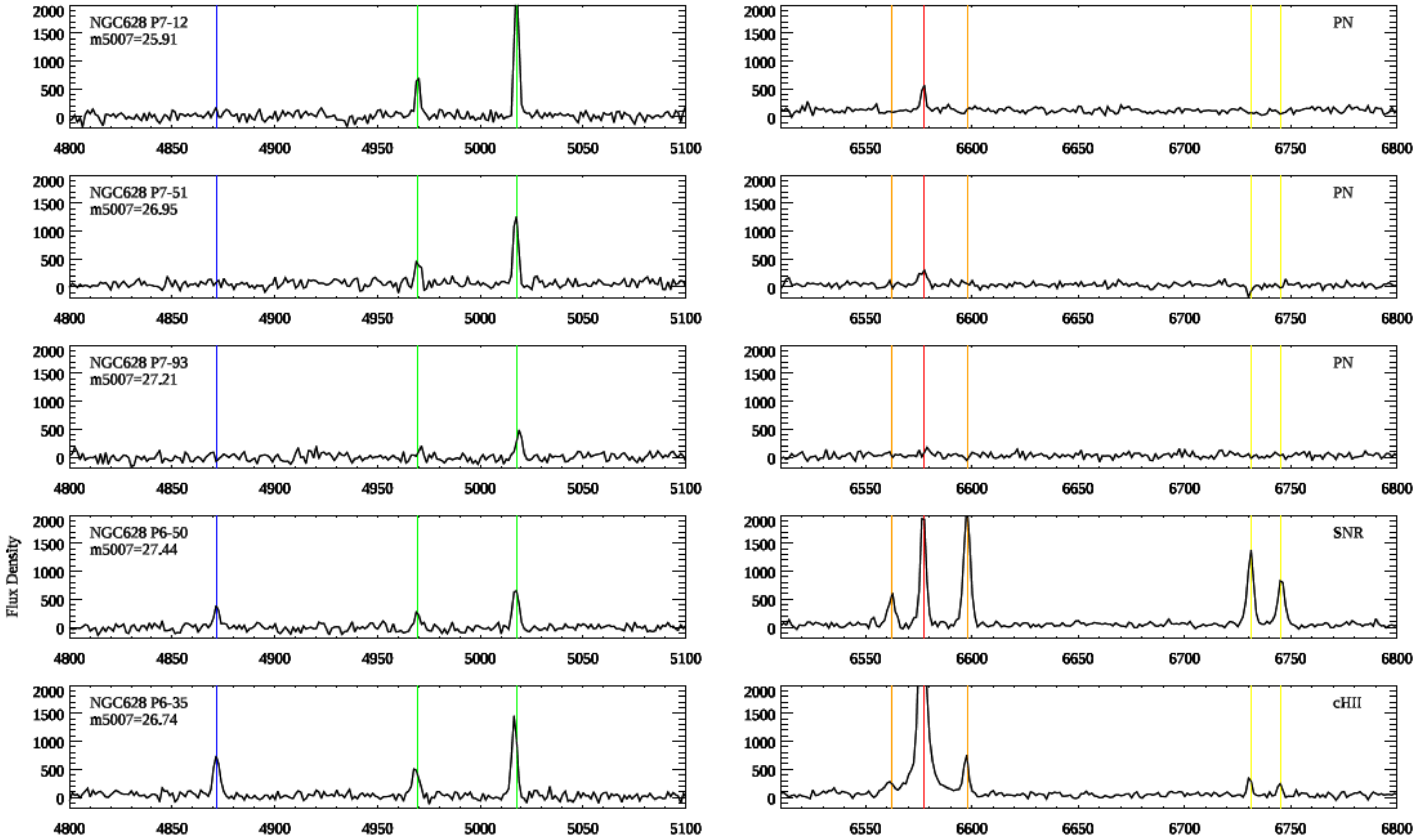


Feldmeier et al. 2007

MUSE:

- insensitive to LOSV
- 8m-class telescope
- image quality / AO
- DELF

(3) MUSE-PNLF



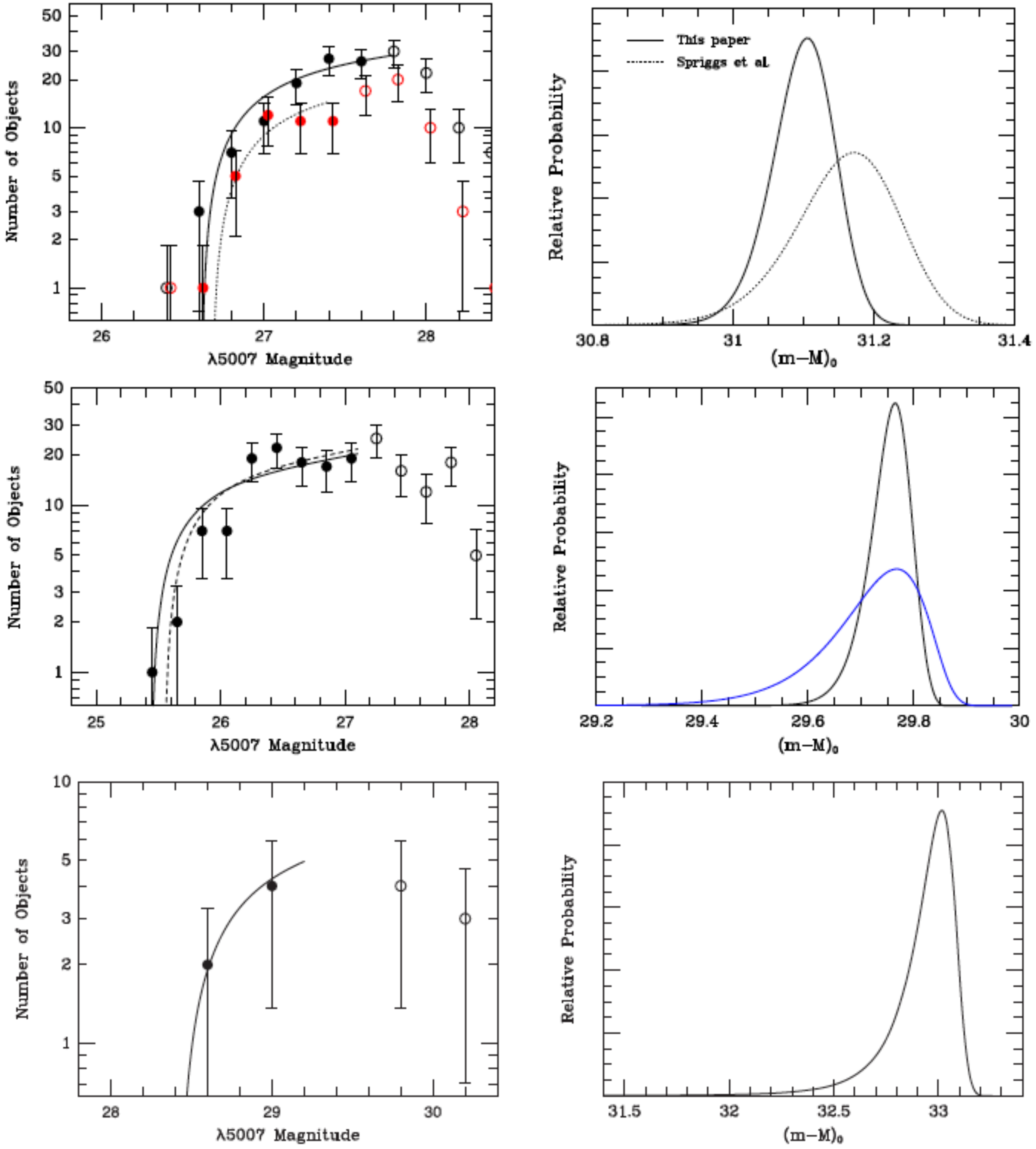
NGC628 P7-12
m5007=25.91
PN
NGC628 P7-51
m5007=26.95
PN
NGC628 P7-93
m5007=27.21
PN
NGC628 P6-50
m5007=27.44
SNR
NGC628 P6-35
m5007=26.74
cHII
Flux Density
2000
1500
1000
500
0
4800
4850
4900
4950
5000
5050
5100
6550
6600
6650
6700
6750
6800

(3) MUSE-PNLF

3 benchmark galaxies:

- NGC 1380
- NGC 628
- NGC 474

→ comparison with literature



NGC 1380

$(m-M)_0 = 31.10^{+0.04}_{-0.05}$

→ 16.6 Mpc

NGC 628

$(m-M)_0 = 29.76^{+0.03}_{-0.05}$

$29.87^{+0.03}_{-0.05}$

→ 8.95 Mpc

NGC 474

$(m-M)_0 = 32.86^{+0.08}_{-0.25}$

→ 37.4 Mpc

(3) MUSE-PNLF, Paper II

Jacoby+2024

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Toward Precision Cosmology with Improved Planetary Nebula Luminosity Function Distances Using VLT-MUSE. II. A Test Sample from Archival Data

George H. Jacoby[1], Robin Ciardullo[2,3], Martin M. Roth[4], Magda Arnaboldi[5], and Peter M. Weilbacher[4]
[1] NSF's NOIRLab, 950 N. Cherry Ave., Tucson, AZ 85719, USA; george.jacoby@noirlab.edu
[2] Department of Astronomy & Astrophysics, The Pennsylvania State University, University Park, PA 16802, USA
[3] Institute for Gravitation and the Cosmos, The Pennsylvania State University, University Park, PA 16802, USA
[4] Leibniz Institute for Astrophysics Potsdam (AIP), An der Sternwarte 16, 14482 Potsdam, Germany
[5] European Southern Observatory, Karl-Schwarzschild-Straße 2, 85748, Garching, Germany
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(3) MUSE-PNLF, Paper II

Table 8. PNLF Galaxy Distances

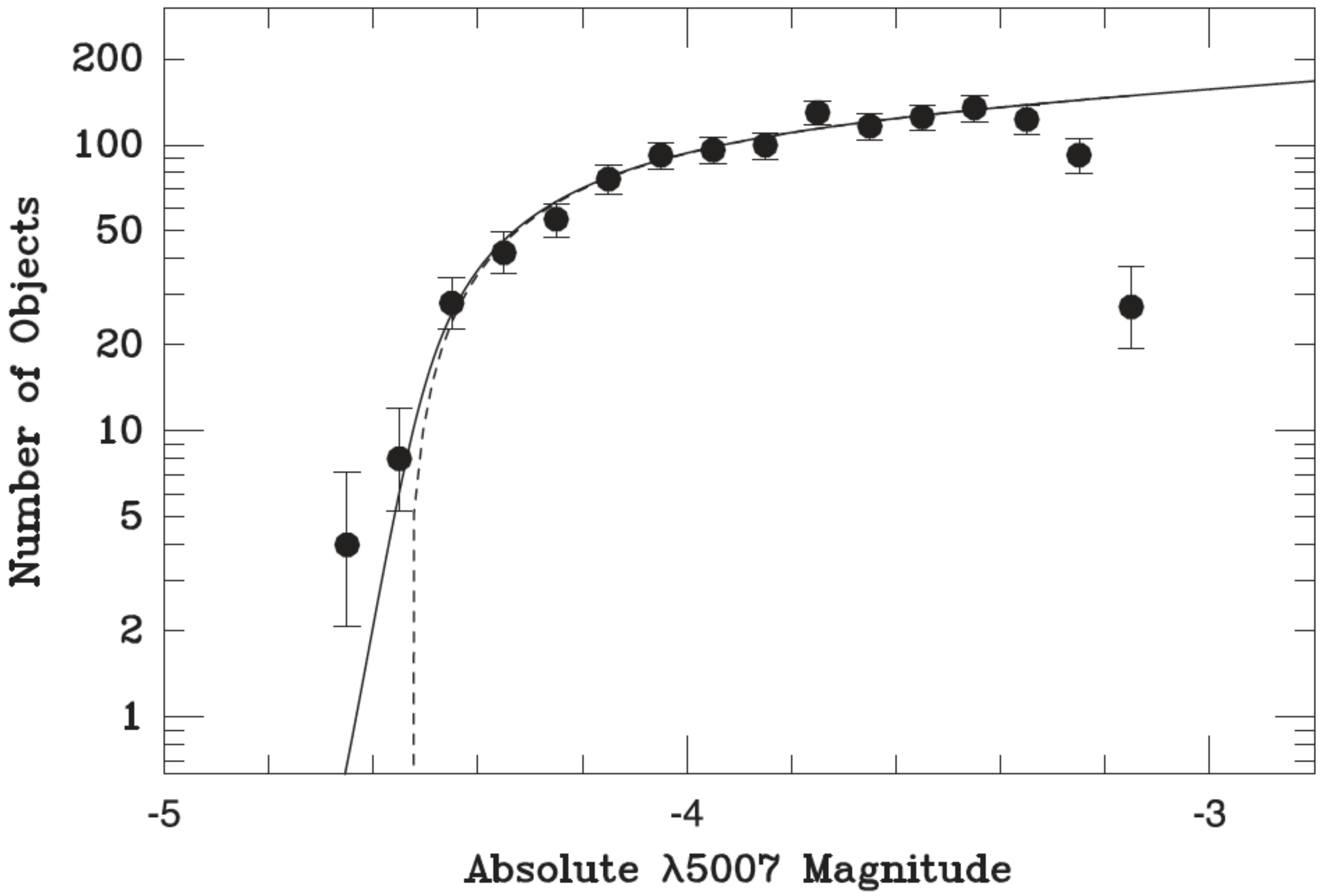
	Galaxy	Number[a] of PNe	$(m-M)_0$	PN Distance Mpc	Other Distance Mpc	Notes
	NGC 253	34/10	$28.66^{+0.12}_{-0.28}$	$05.4^{+0.3}_{-0.6}$		
	NGC 1052	86/50	$31.26^{+0.04}_{-0.07}$	$17.9^{+0.3}_{-0.6}$	18.0 ± 2.4 (SBF)	
	NGC 1326	55/20	$30.99^{+0.06}_{-0.11}$	$15.8^{+0.5}_{-0.8}$		overluminous PN rejected
	NGC 1351	102/45	$31.39^{+0.04}_{-0.08}$	$19.0^{+0.4}_{-0.7}$	19.2 ± 0.6 (SBF)	overluminous PN rejected
	NGC 1366	22/13	$31.39^{+0.10}_{-0.22}$	$19.0^{+0.9}_{-1.8}$	20.3 ± 4.1 (SBF)	
	NGC 1385	78/54	$31.99^{+0.06}_{-0.08}$	$25.0^{+0.7}_{-0.9}$		
	NGC 1399	232/164	$31.23^{+0.04}_{-0.05}$	$17.6^{+0.3}_{-0.4}$	21.1 ± 0.7 (SBF)	
*	NGC 1404	124/64	$31.37^{+0.04}_{-0.07}$	$18.8^{+0.3}_{-0.6}$	18.7 ± 0.6 (TRGB), 20.4 ± 0.6, 20.2 ± 0.6 (SBF)	
	NGC 1419	21/12	$31.39^{+0.10}_{-0.26}$	$18.9^{+0.9}_{-2.1}$	22.9 ± 0.9 (SBF)	
	NGC 1433	258/160	$31.33^{-0.06}_{+0.04}$	$18.5^{+0.3}_{-0.4}$	9.0 (TRGB)	2 overluminous PNe included
	NGC 1512	210/144	$31.30^{+0.04}_{-0.04}$	$18.2^{+0.3}_{-0.3}$	11.7 ± 1.1 (TRGB)	
*	NGC 2207	3/0		< 40		
	NGC 3501	6/0		< 38		
*	NGC 4038/9	228/154	$31.77^{+0.03}_{-0.04}$	$22.6^{+0.3}_{-0.4}$	21.7 ± 0.5 (TRGB)	"Antennae Galaxies"
					18.1 ± 0.9, 20.4 ± 0.6, 21.4 ± 0.8 (CEPH)	
	NGC 4365	64/30	$31.55^{+0.05}_{-0.08}$	$20.4^{+0.5}_{-0.8}$	23.1 ± 0.8 (SBF)	
	NGC 4418	47/24	$32.59^{+0.07}_{-0.10}$	$33.0^{+1.1}_{-1.5}$		overluminous PN included
	NGC 4472	67/43	$30.85^{+0.05}_{-0.07}$	$14.8^{+0.3}_{-0.4}$	15.9 ± 1.0 (SBF)	SBF is average of 22 values in NED
	NGC 5248	29/15	$31.80^{+0.07}_{-0.10}$	$22.9^{+0.8}_{-1.1}$		overluminous PN rejected
	NGC 6958	28/15	$32.80^{+0.24}_{-0.21}$	$36.2^{+4.3}_{-3.3}$		
	ESO 338-IG04	0				
	MCG-06-08-024	7/0				

[a] Given as Total number of PNe / Approximate number of PNe contributing to distance

(3) MUSE-PNLF, Paper II

Combined PNLF

Galaxy	M_{lim}	Total PNe	PN with $M < M_{lim}$
NGC 628	−3.19	202	90
NGC 1052	−3.74	87	39
NGC 1326	−3.26	55	39
NGC 1351	−3.43	102	45
NGC 1380	−3.22	112	78
NGC 1385	−3.65	78	40
NGC 1399	−3.27	232	163
NGC 1404	−3.70	126	38
NGC 1433[a]	−3.25	258	95
NGC 1512	−3.16	210	144
NGC 4038/9	−3.40	228	152
NGC 4365	−3.71	64	30
NGC 4418	−3.86	47	24
NGC 4472	−3.91	81	39

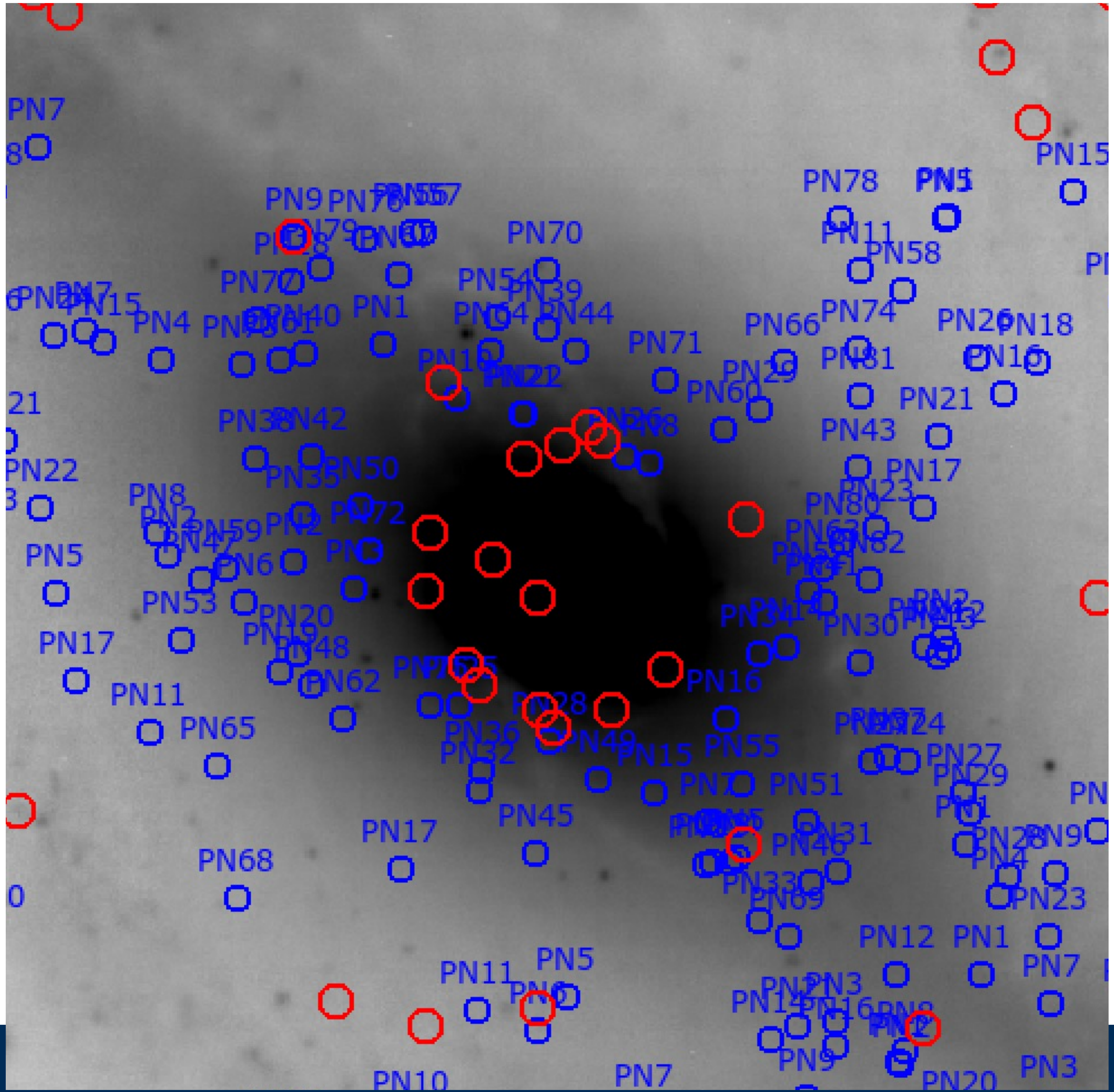


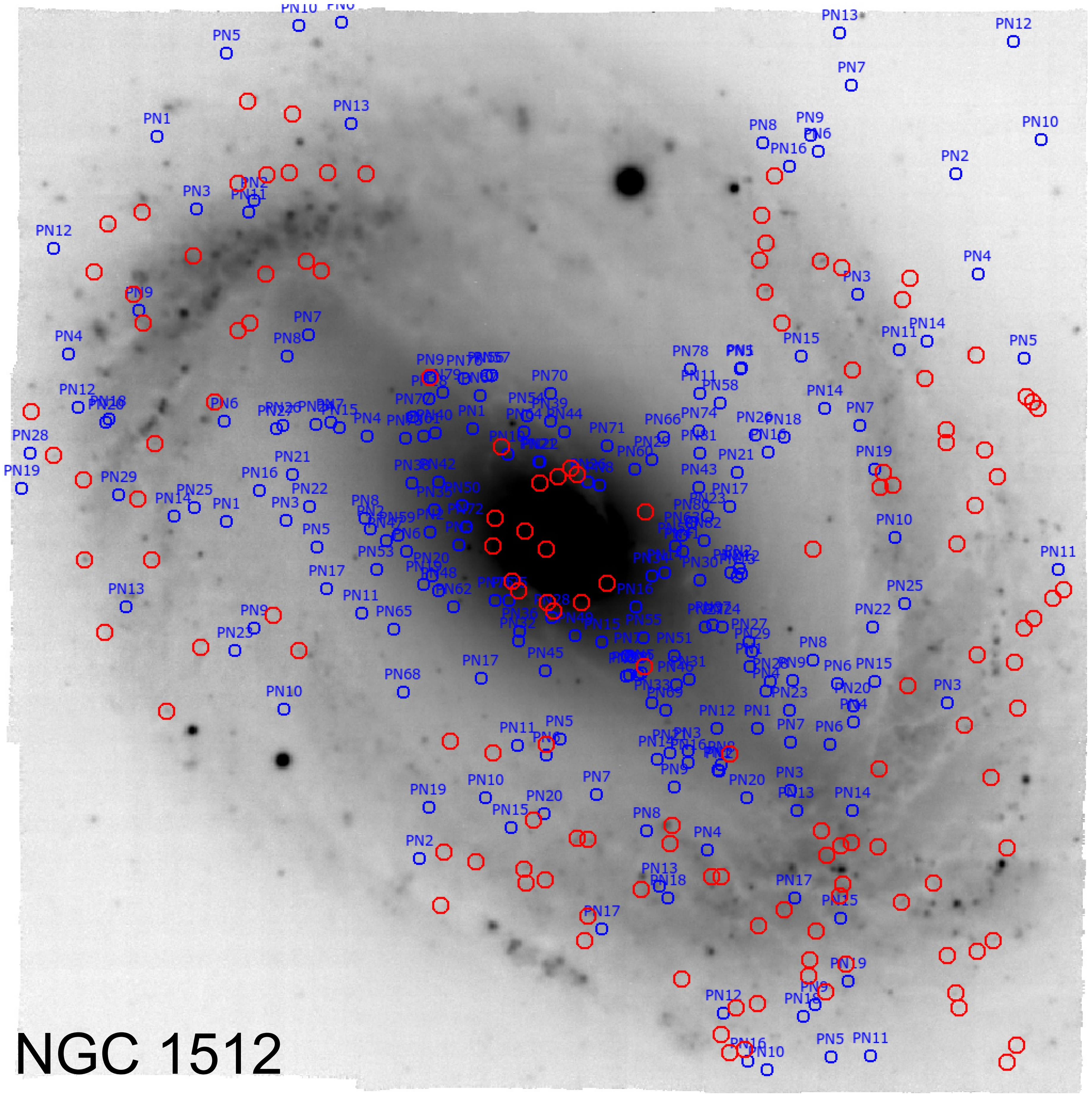
(4) PNLF with BlueMUSE

- Factor 2x higher throughput than MUSE
- Factor 2x higher spectral resolution:
  suppression of continuum background
  → most efficient in nuclear regions

(4) PNLF with BlueMUSE

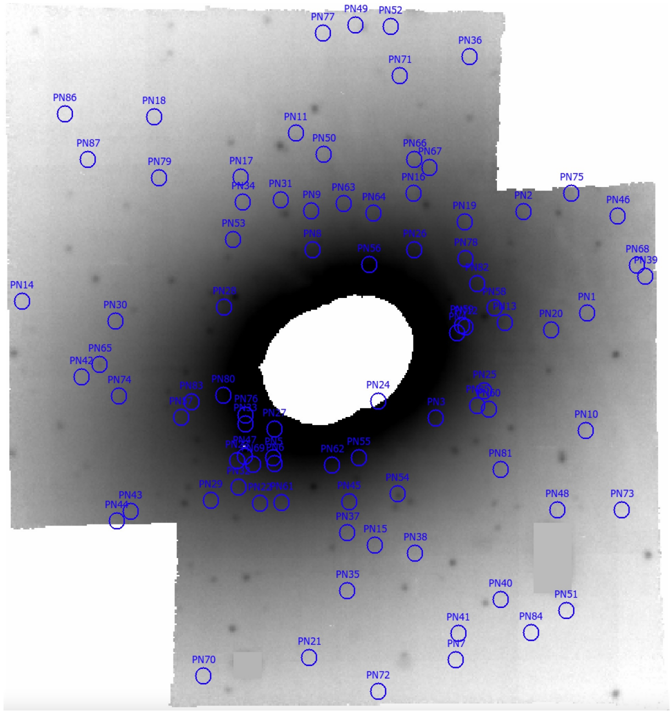
- high surface brightness limit



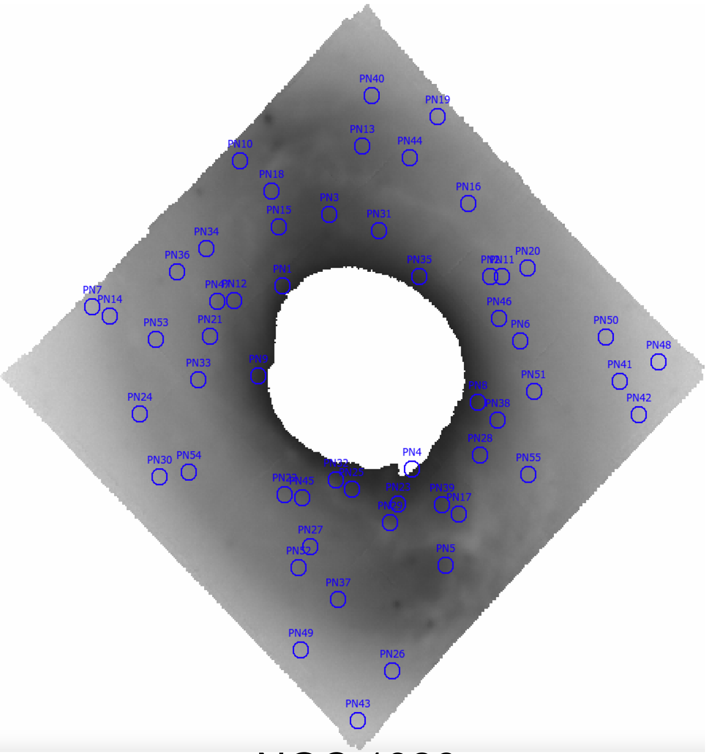


(4) PNLF with BlueMUSE

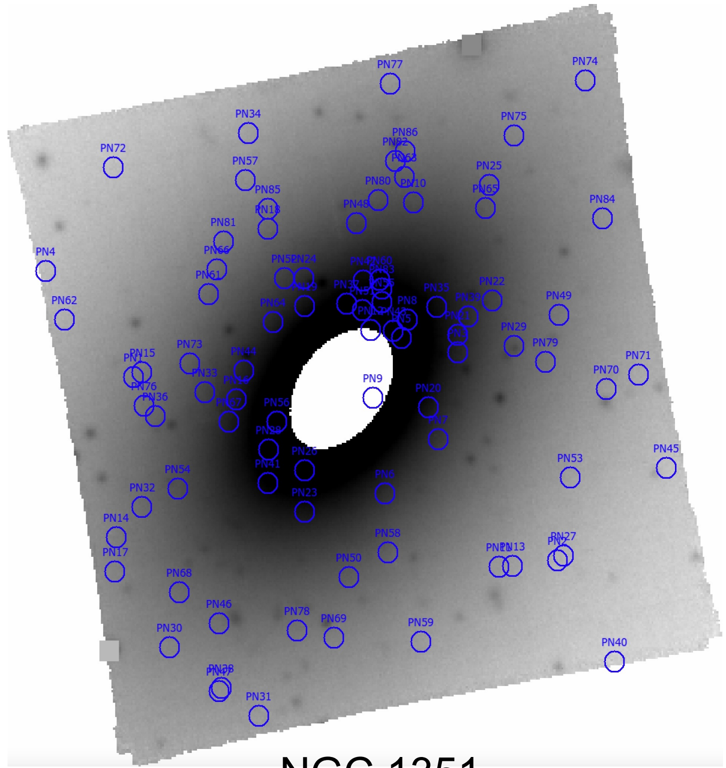
high surface brightness limit



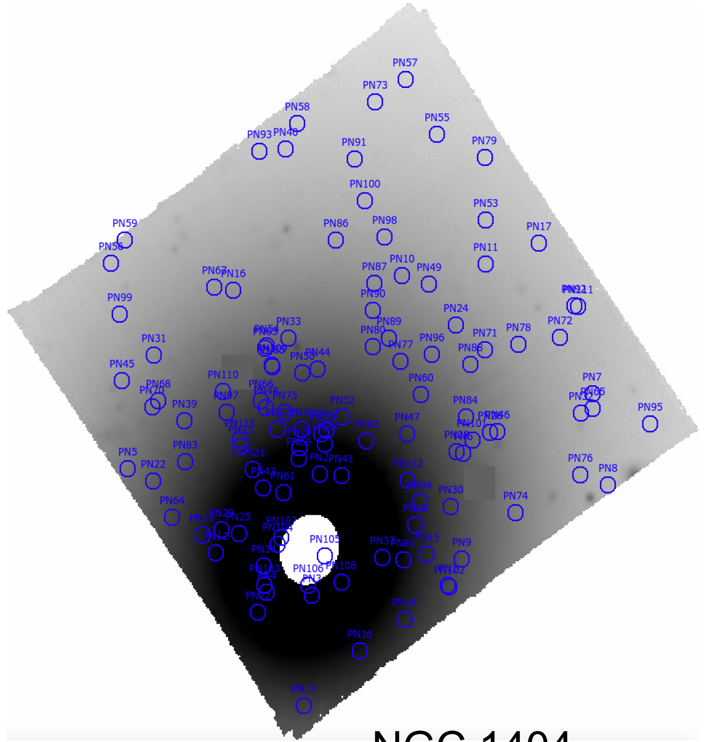
NGC 1052



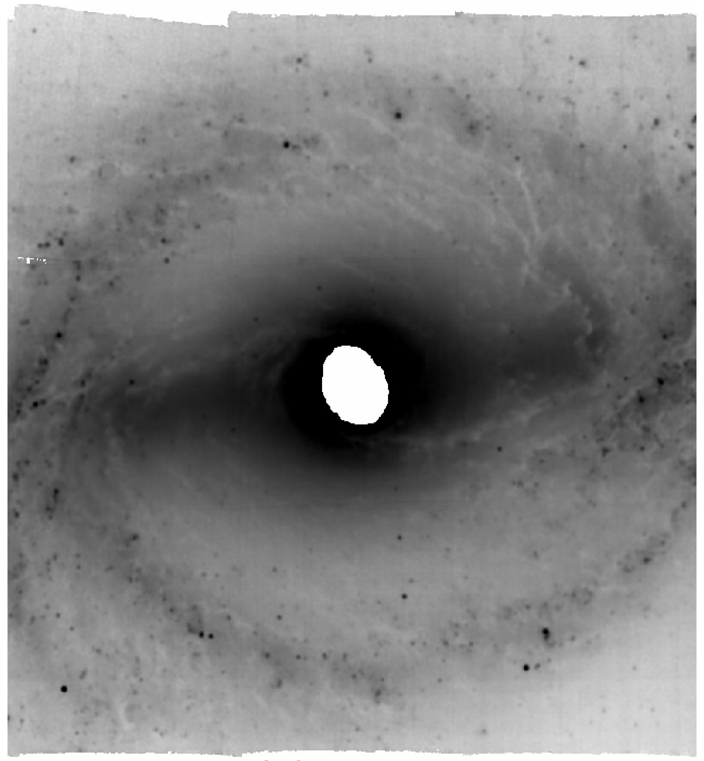
NGC 1326



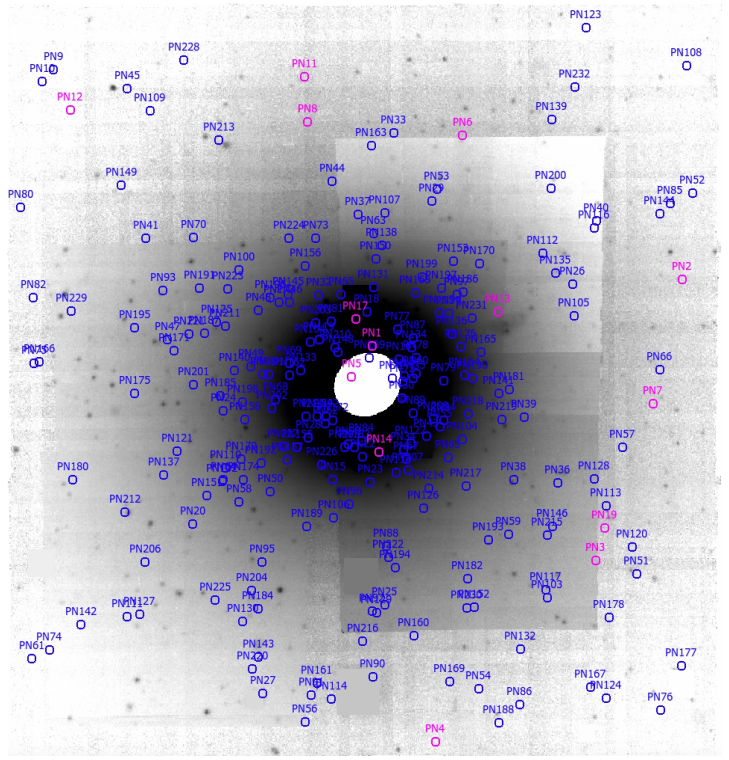
NGC 1351



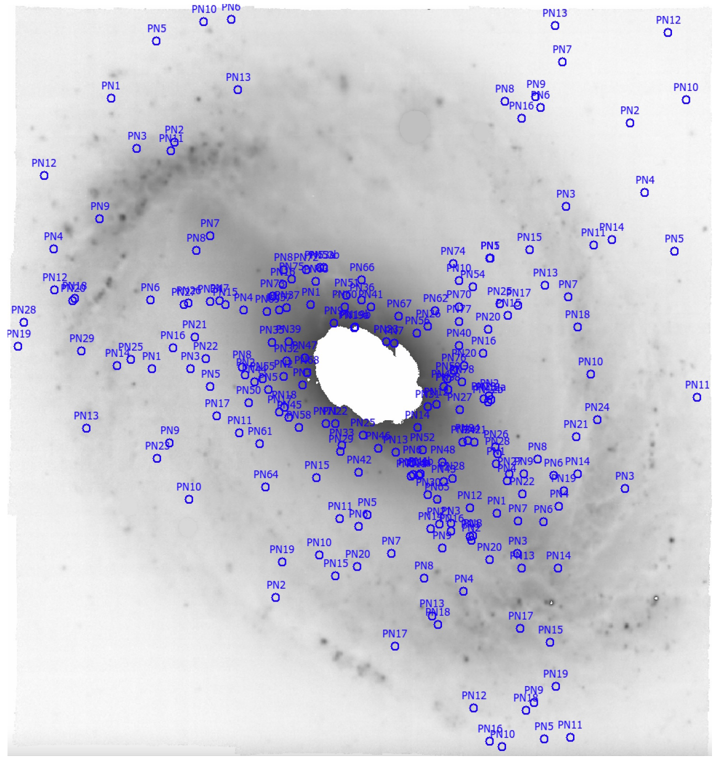
NGC 1404



NGC 1433

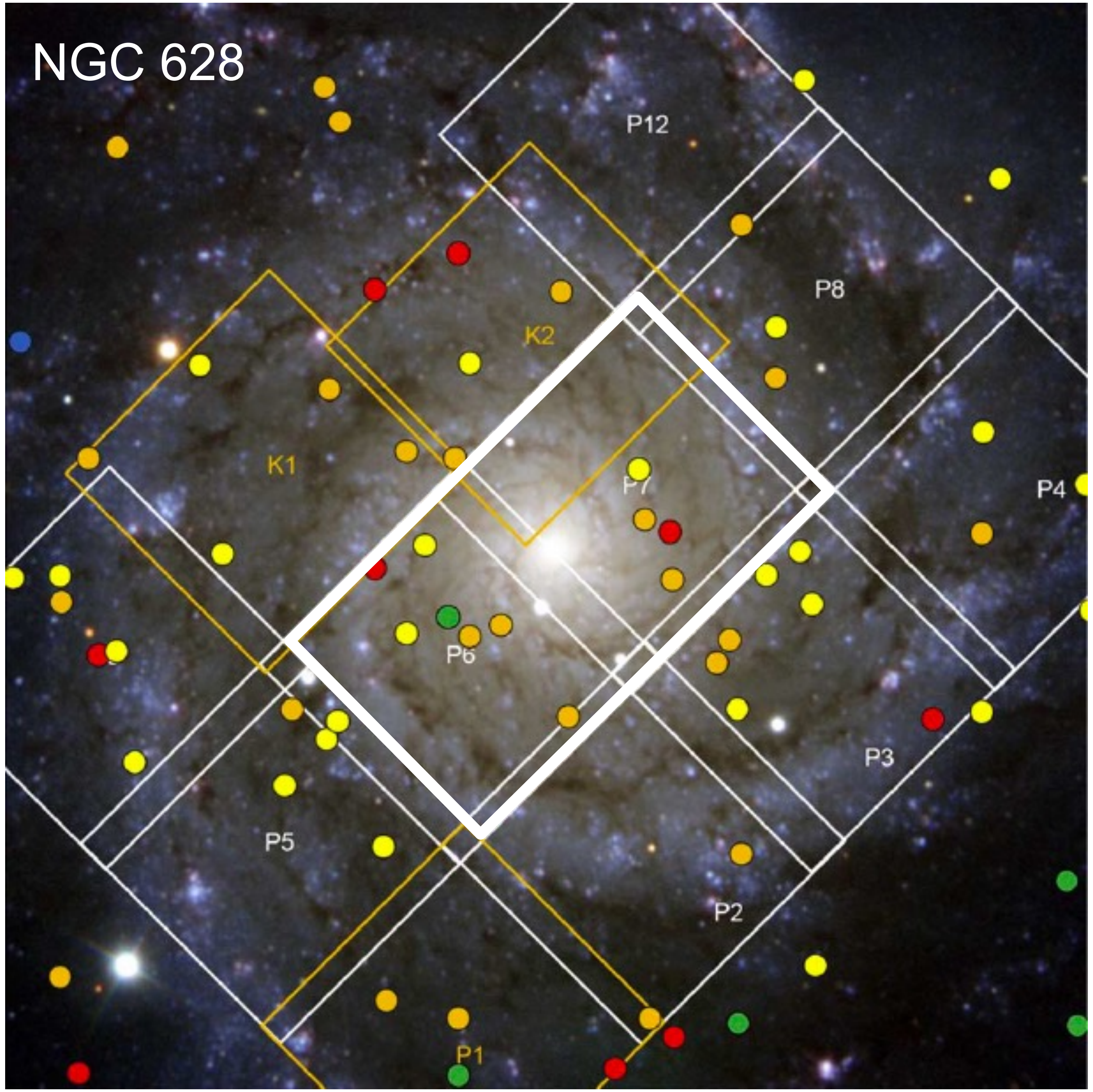


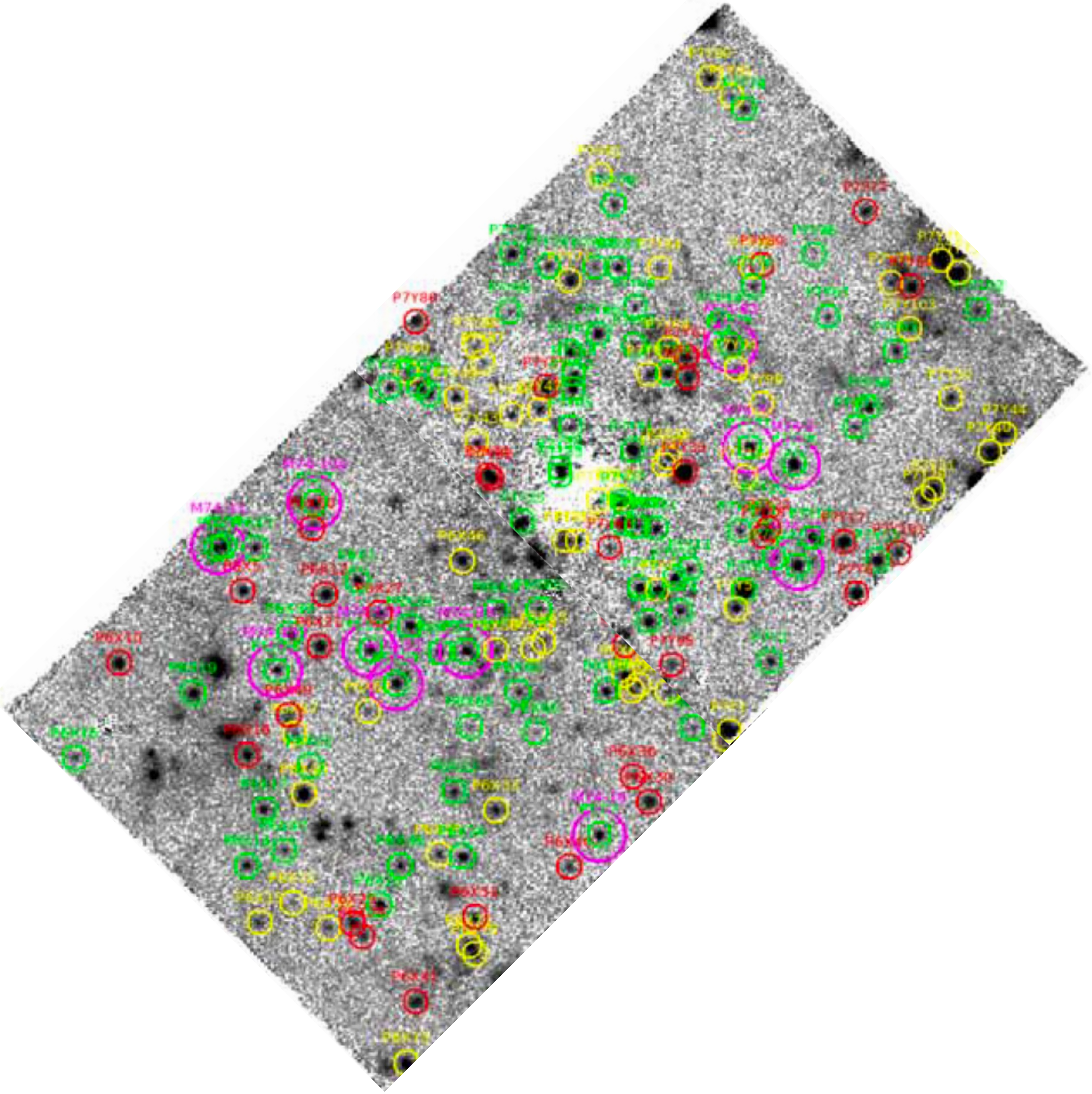
NGC 1399



NGC 1512

(4) PNLF with BlueMUSE





Herrmann+2008, Kreckel+2017

(5) Summary

- MUSE datacubes offer extremely small bandwidth narrow-band imaging
- Small bandwidth ⇒ low continuum background
  ⇒ low continuum background shot noise
  ⇒ low continuum background systematic errors
- Differential Emission Line Filter works on a spaxel-by-spaxel basis and efficiently removes systematic „flatfield“ errors
- Differential Emission Line Filter introduces minimal shot noise in the process of continuum background subtraction
- BlueMUSE‘s higher efficiency @ 500.7nm boosts sensitivity
- BlueMUSE‘s higher spectral resolution reduces continuum background