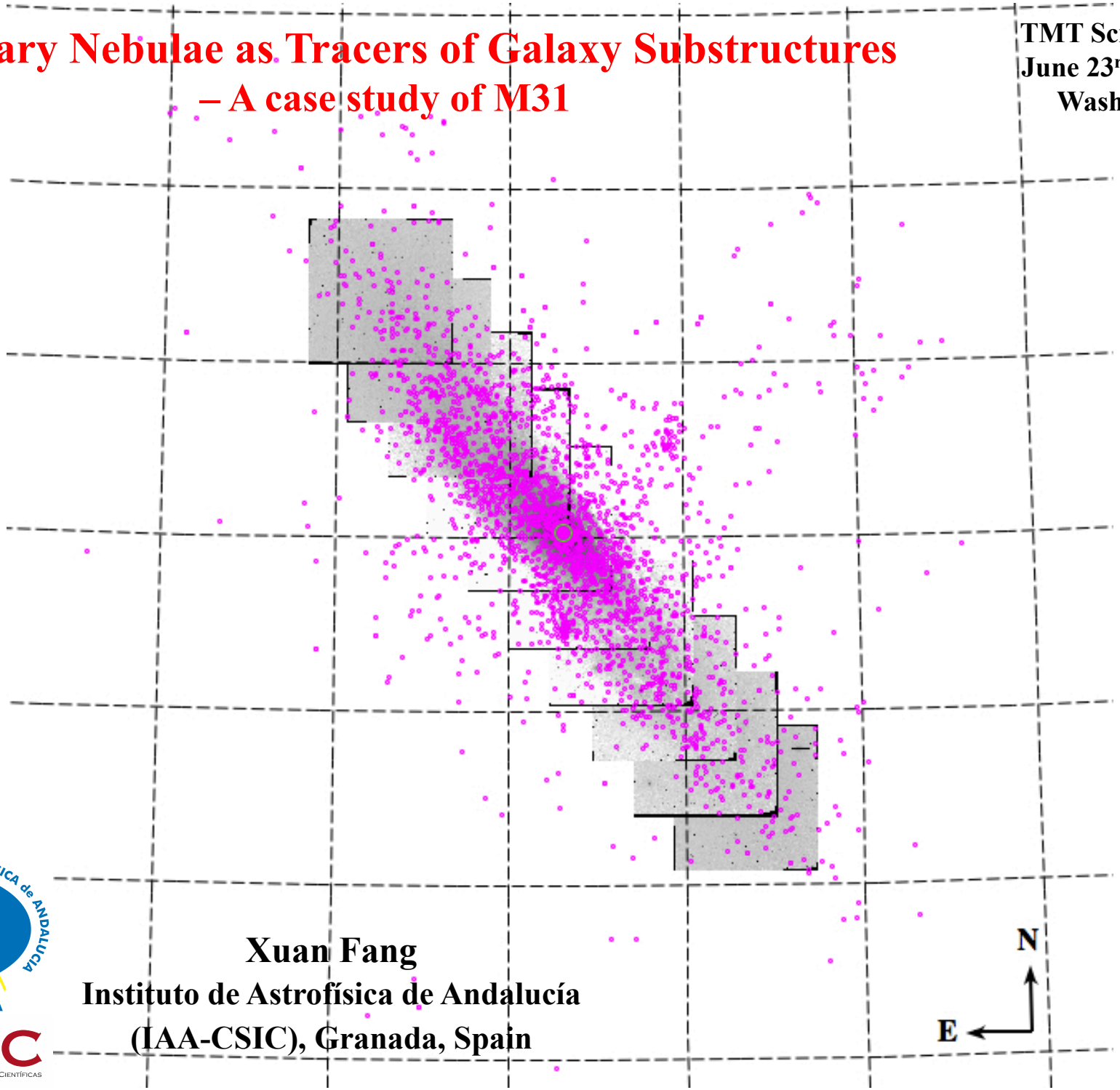
Planetary Nebulae as Tracers of Galaxy Substructures – A case study of M31

TMT Science Forum
June 23rd– 25th, 2015
Washington, D.C.



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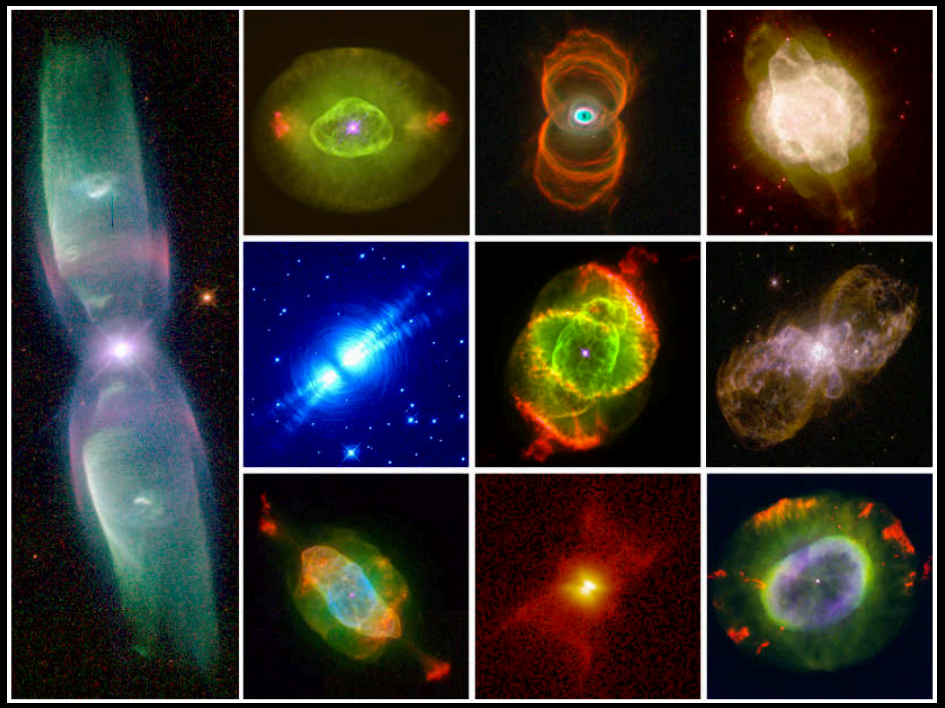
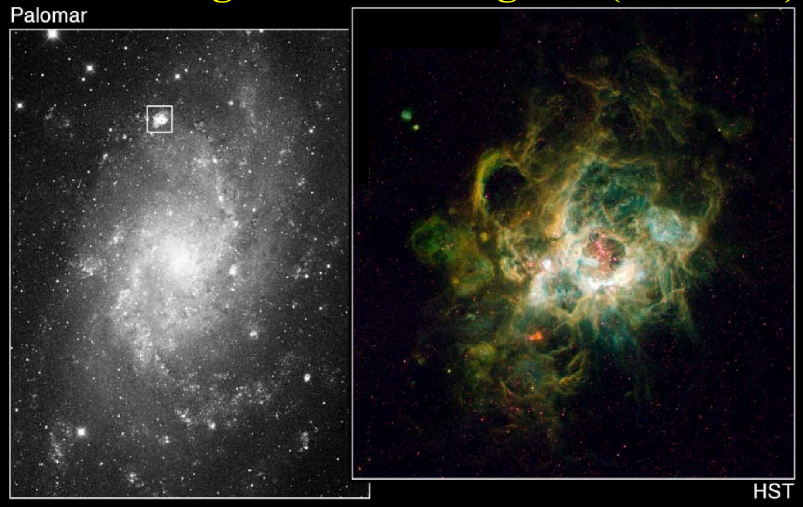
Photoionized gaseous nebulae (emission line nebulae)

Planetary nebulae (PNe)

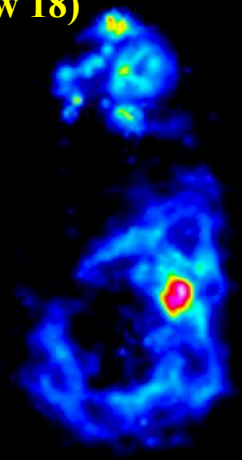


H II regions (Orion / M42)

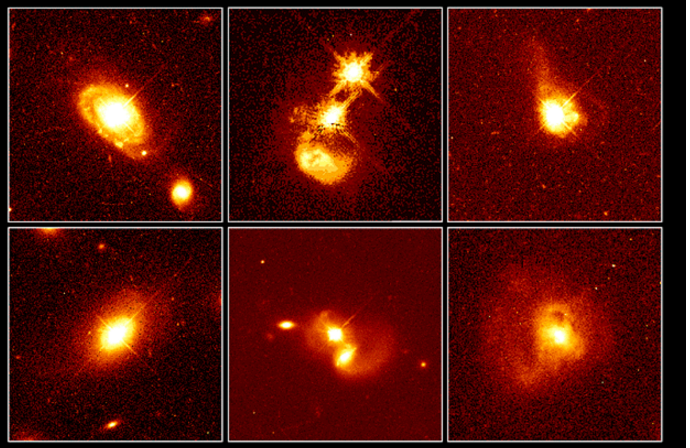
Giant extragalactic H II regions (NGC604)



Starburst galaxies (Izw 18)

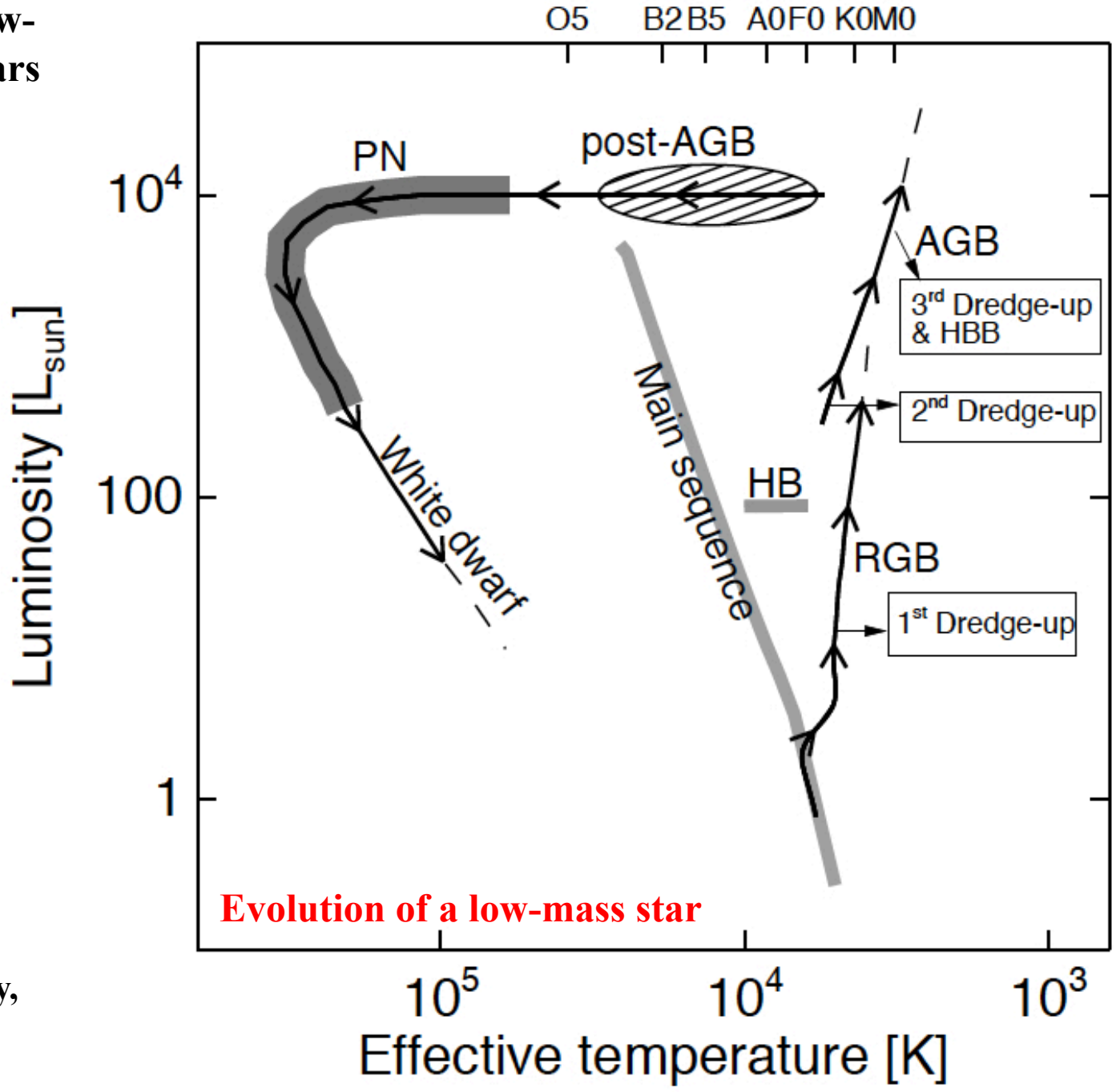


Distant quasars



PNe are descendents of low- and intermediate-mass stars (~0.8–8$M_{\odot}$).

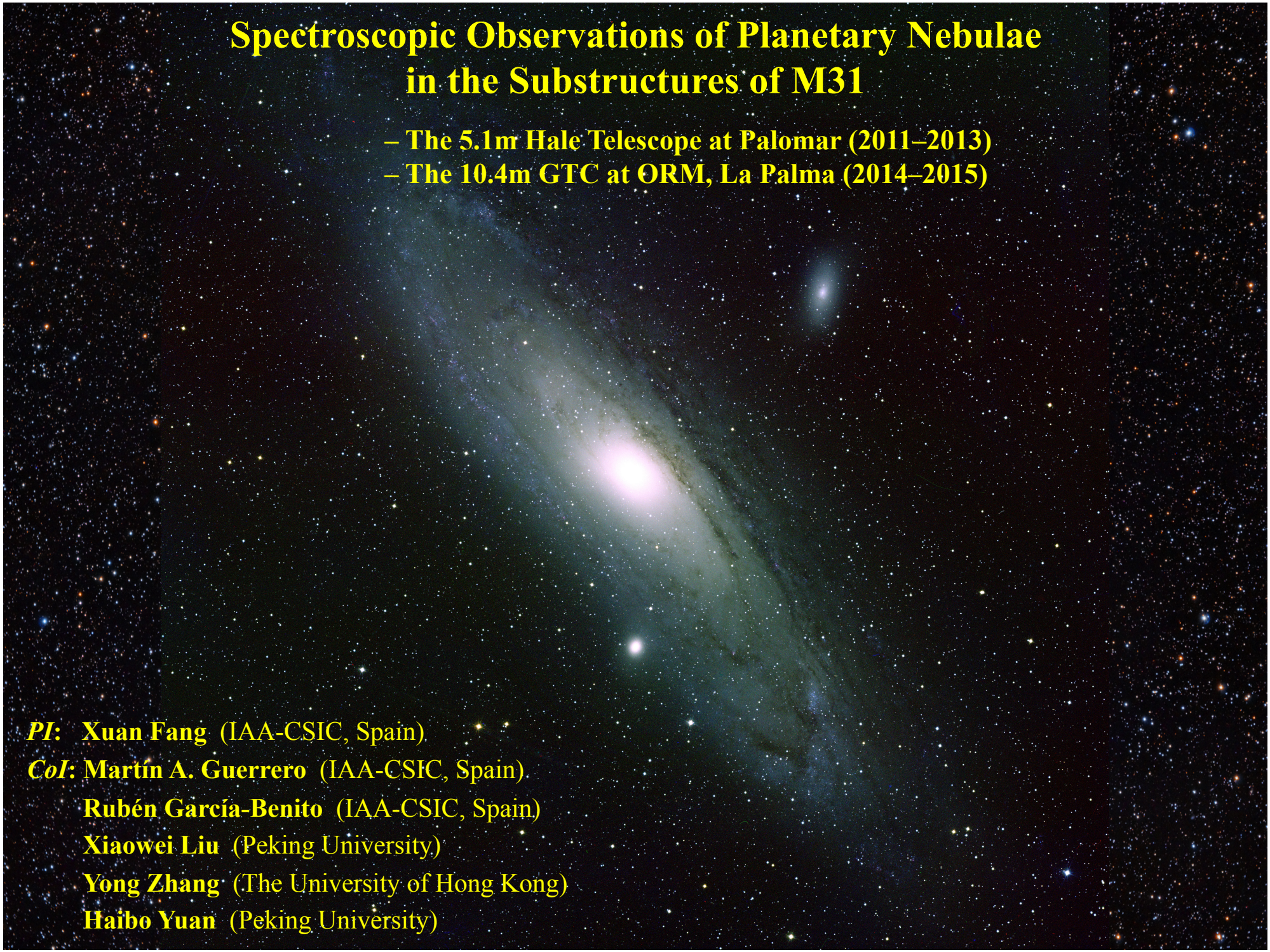
t_{age} ~10^4 yr



PNe are Ubiquitous in the universe;

Narrow and bright emission lines, e.g., [O III], Hα;

Excellent tracers of chemistry, kinematics, and stellar populations of host galaxies;



Spectroscopic Observations of Planetary Nebulae in the Substructures of M31

– The 5.1m Hale Telescope at Palomar (2011–2013)
– The 10.4m GTC at ORM, La Palma (2014–2015)

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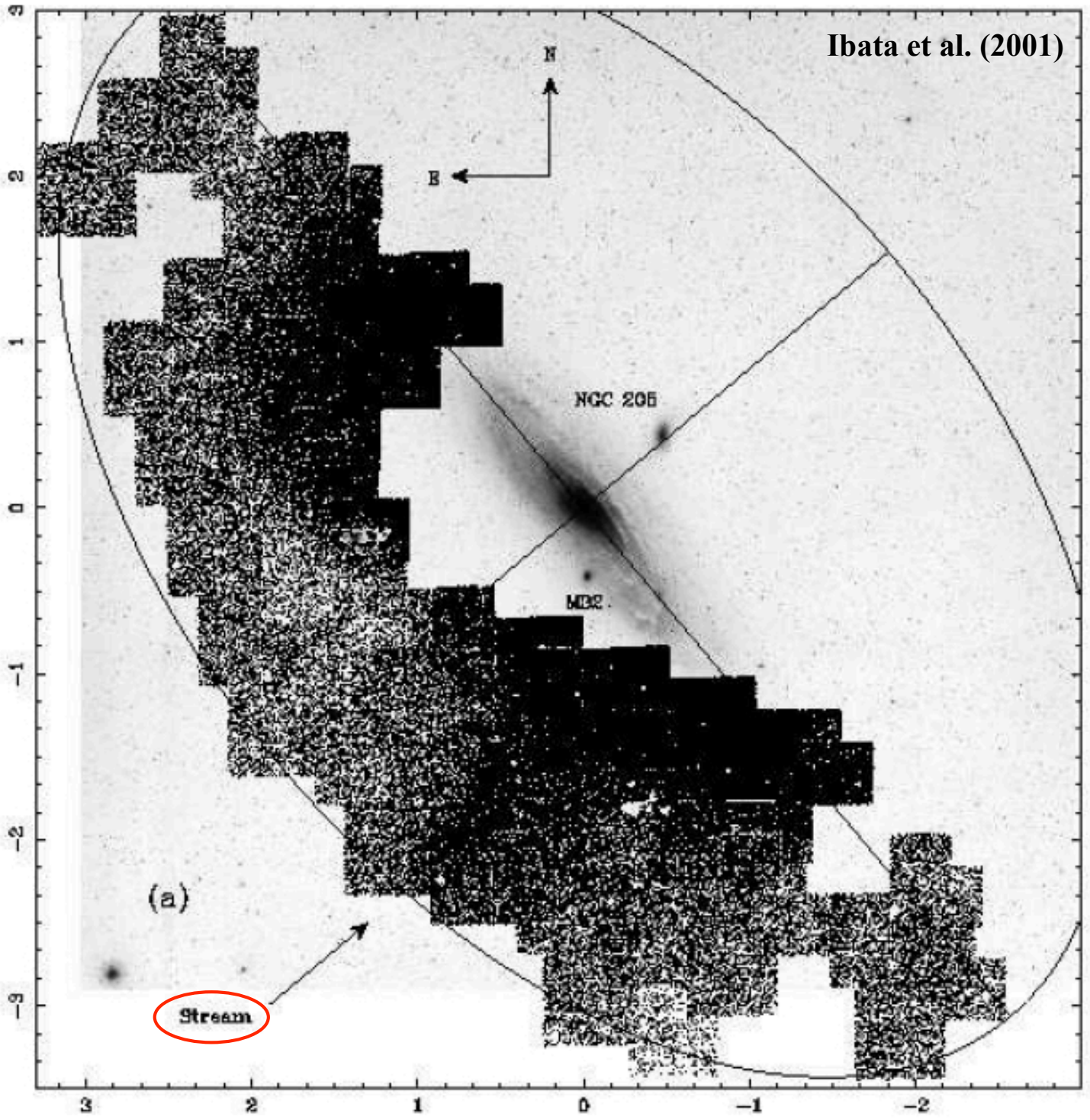
Haibo Yuan (Peking University)

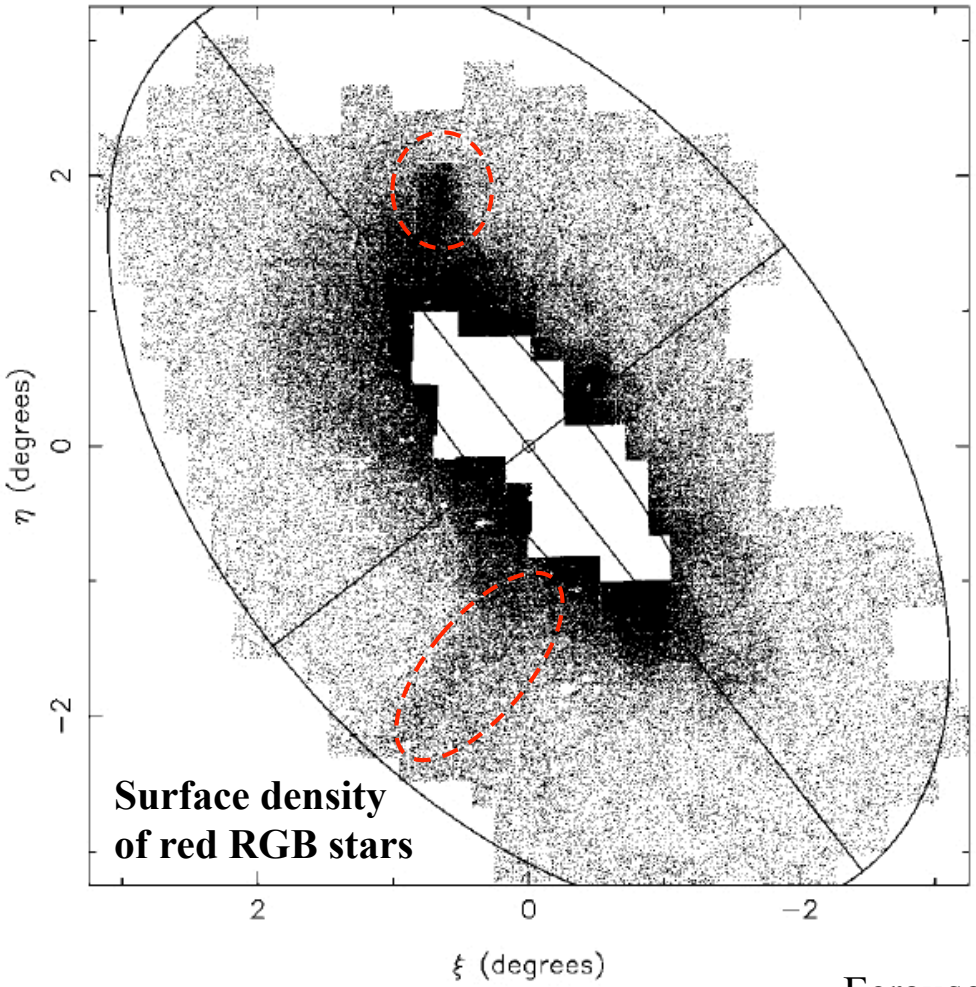
Photometric survey of RGB stars with INT/ WFC

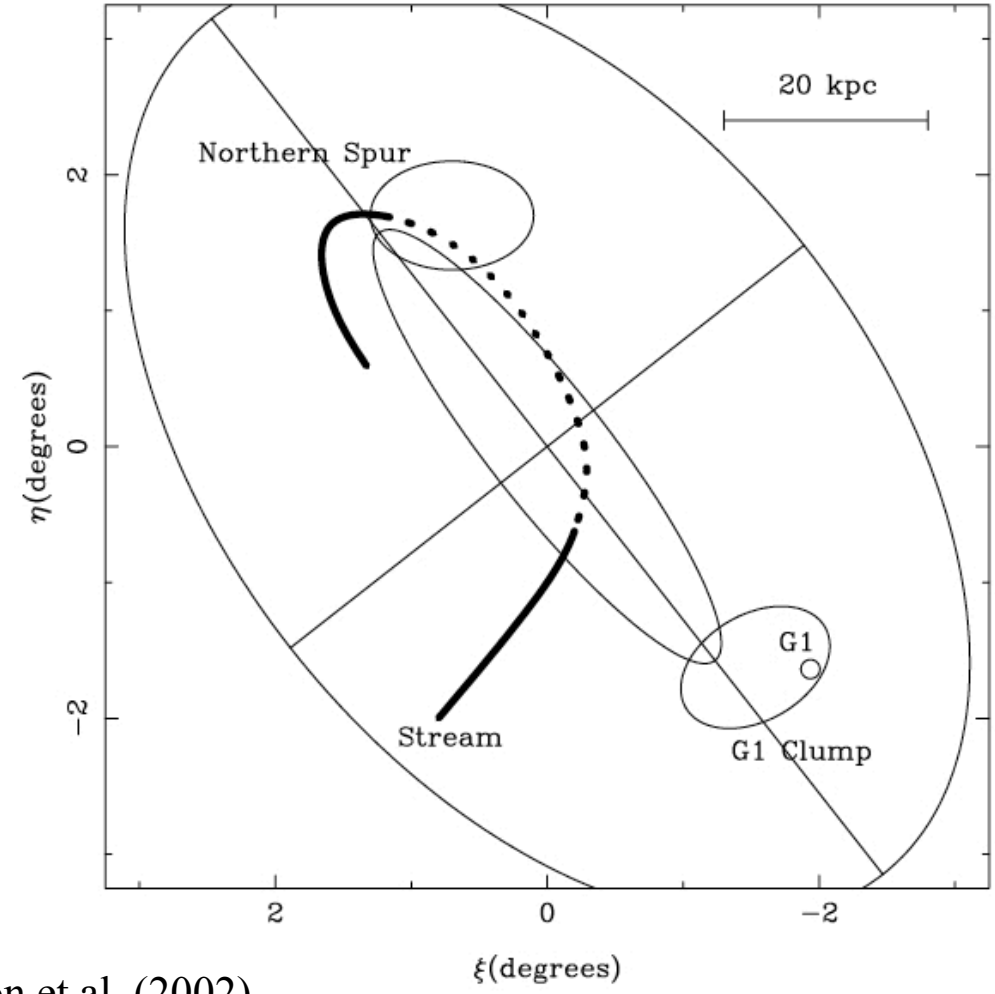
Enhanced metallicity in the stream relative to the halo population



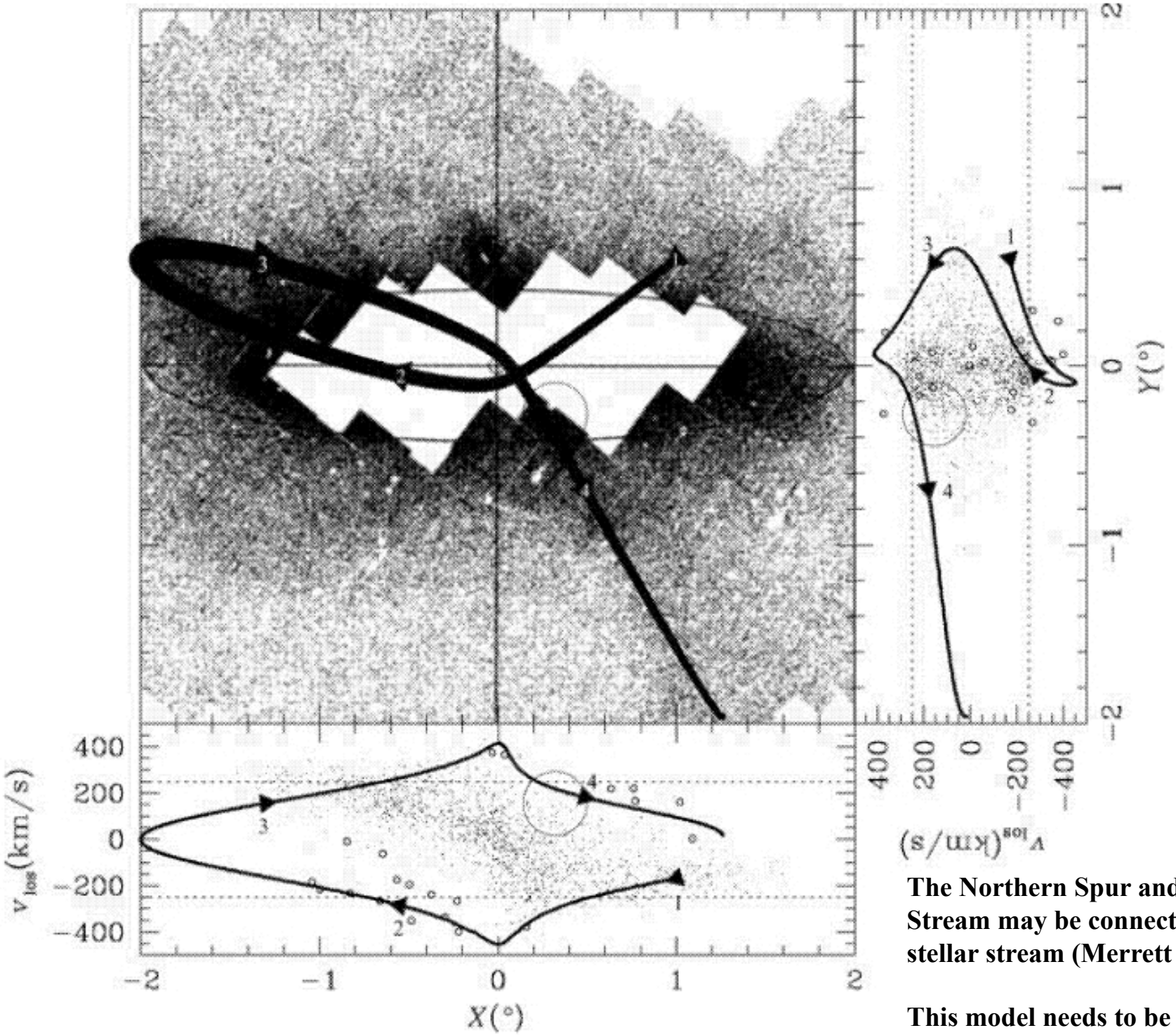
A number of stellar substructures have been detected in the outer disk and halo of M31.

The most prominent are the Northern Spur and the Giant South Stellar Stream (a.k.a., the Giant Stream)





Ferguson et al. (2002)



The Northern Spur and the Giant Stream may be connected by a stellar stream (Merrett et al. 2003).

This model needs to be assessed.

1°

0°.75

N

E

~2800 planetary nebulae have been identified in M31.

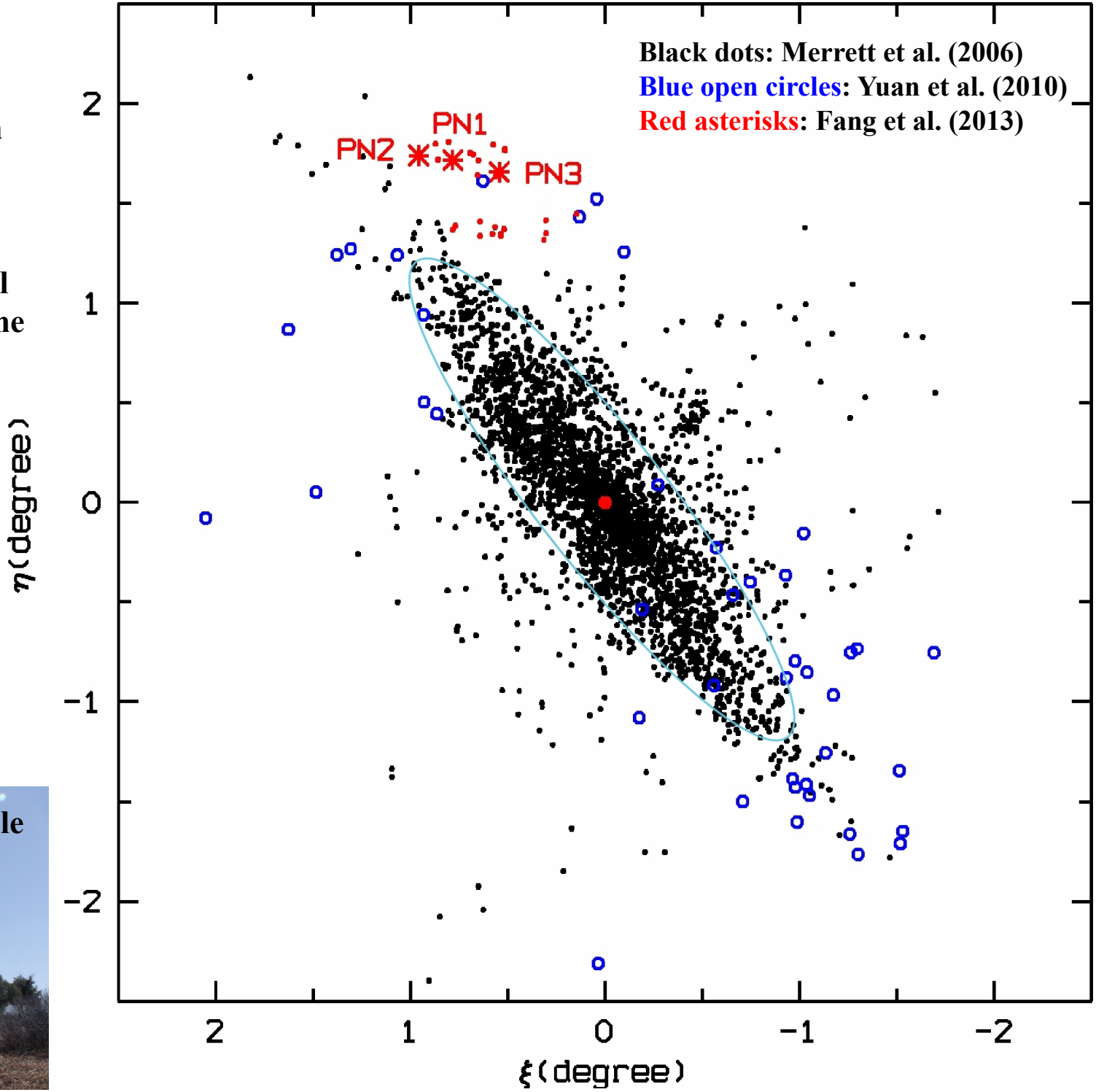
1) Planetary nebulae are excellent tracers of chemistry, kinematics, and stellar population of substructures in the host galaxies.

2) PN spectra for the substructures of M31 are still conspicuously lacking.

Purpose of the program:

To investigate the origin of the Northern Spur substructure of M31.

This is the first chemical study of PNe in one of the substructures of M31.

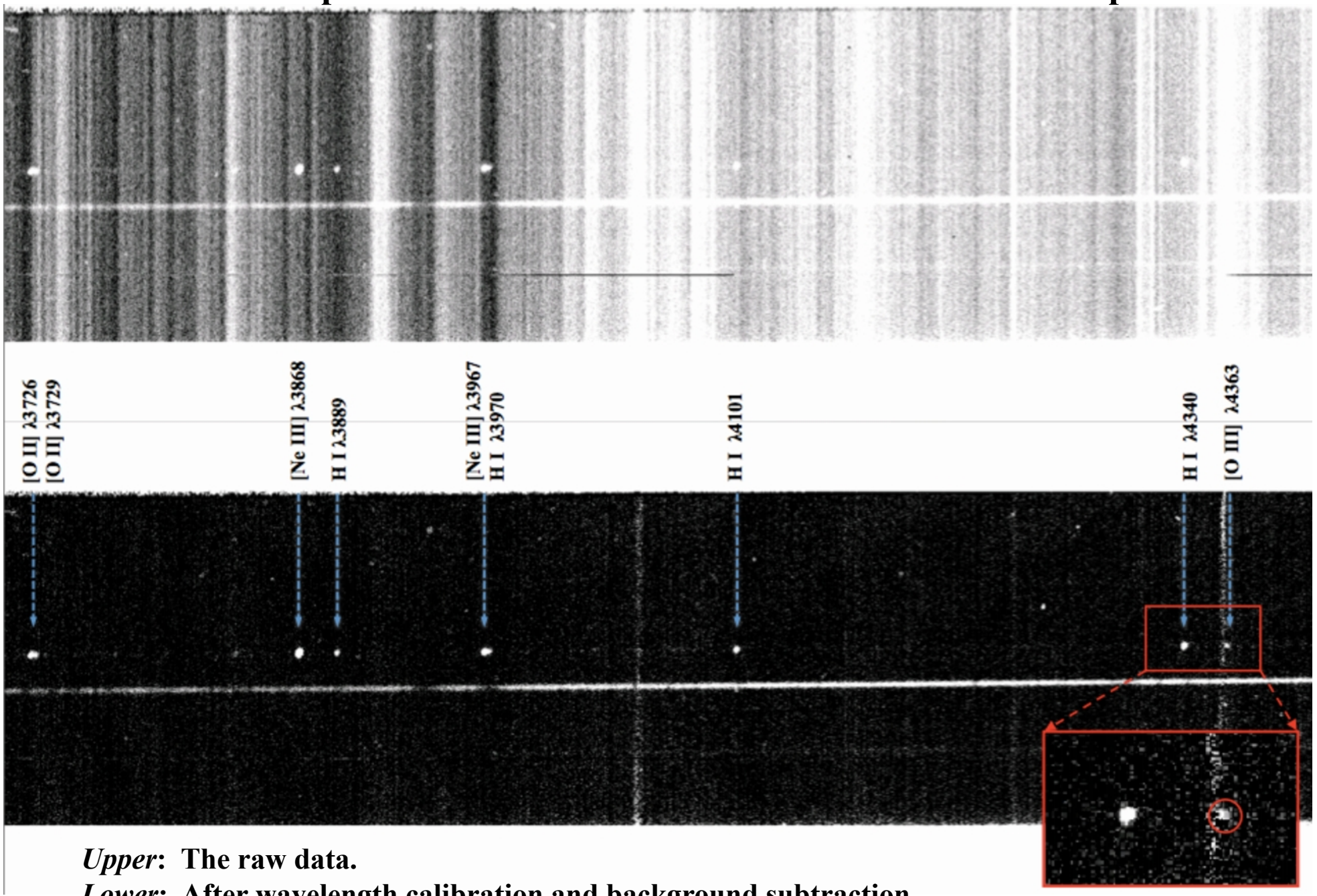


Palomar observations and target properties

- **Palomar 5.1m Hale spectroscopy (visitor mode, 2011 Sept. 22–23)**
- **Double Spectrograph (DBSP)**
- **Blue arm: 1200 lines/mm, Red arm: 316 lines/mm**
- **Dichroic: D48**
- **Wavelength coverage: 3400–4900 Å, 4800–7300 Å**
- **Resolution: 2.4 Å in the blue, 6.9 Å in the red.**

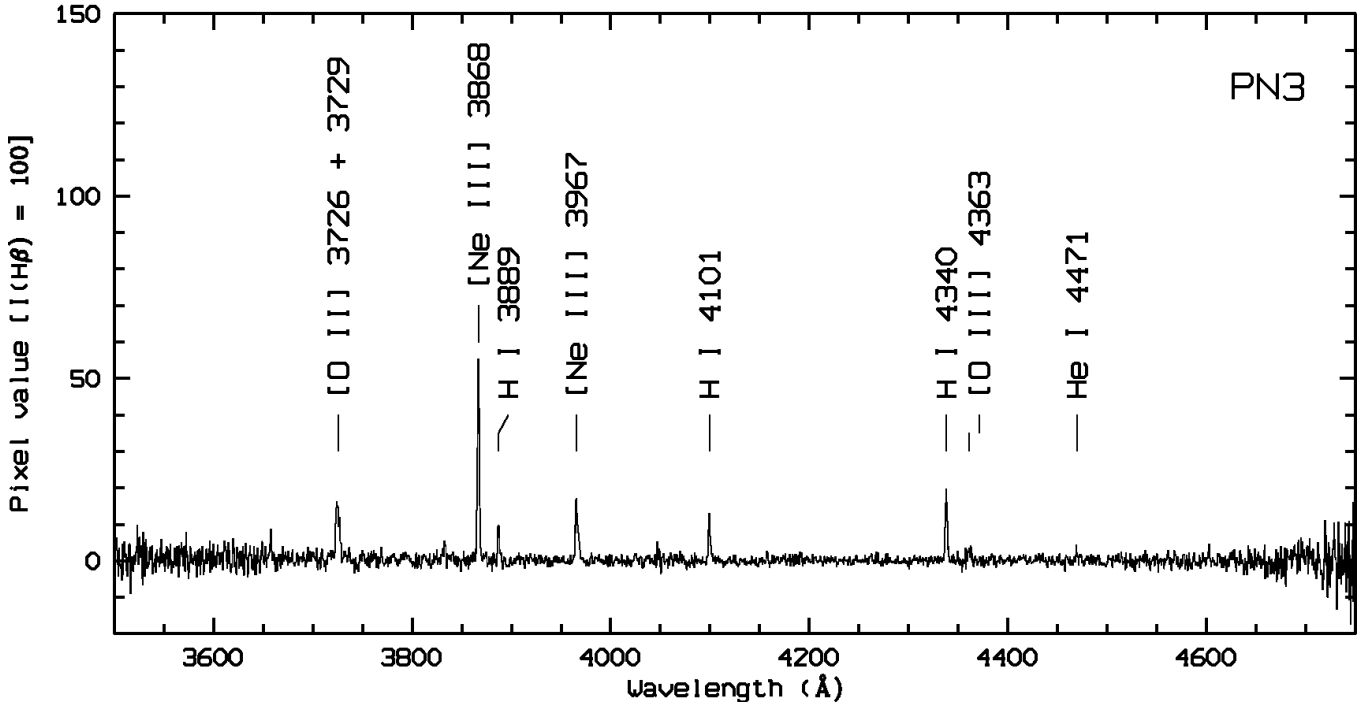
PN ID	R.A. (J2000)	Decl. (J2000)	m(5007)	V_{helio} (km/s)	R_{gal} (kpc)	DBSP Exp. (s)	
						Blue Arm	Red Arm
PN1 (2426)	00:47:00.69	42:58:55.20	20.61	-19.6	25.9	8 × 1800	8 × 1800
PN2 (2431)	00:47:58.60	43:00:06.48	20.83	-44.4	27.2	8 × 1800	8 × 1800
PN3 (2421)	00:45:42.60	42:55:26.30	20.84	-90.3	23.9	6 × 1800	6 × 1800

2D blue spectrum of PN3 obtained at the 5.1m Hale Telescope

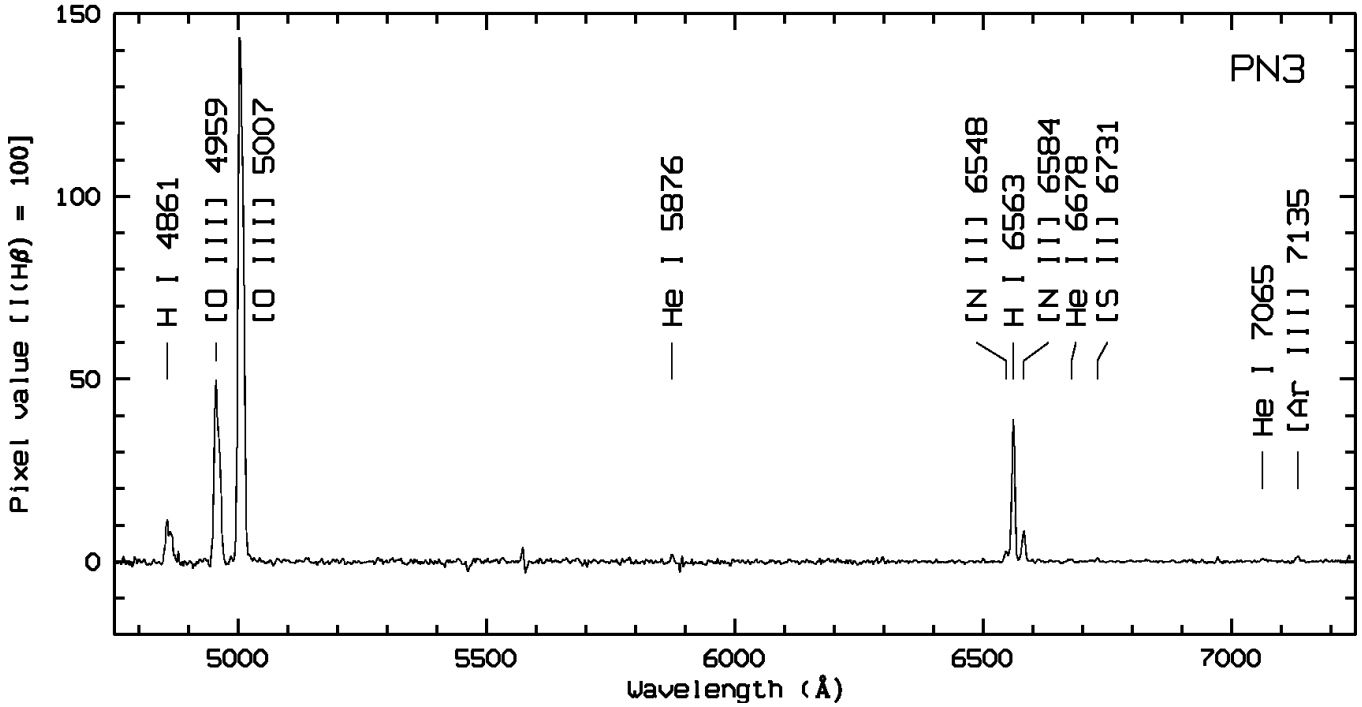


Upper: **The raw data.**
Lower: **After wavelength calibration and background subtraction.**

Blue spectrum of PN3:



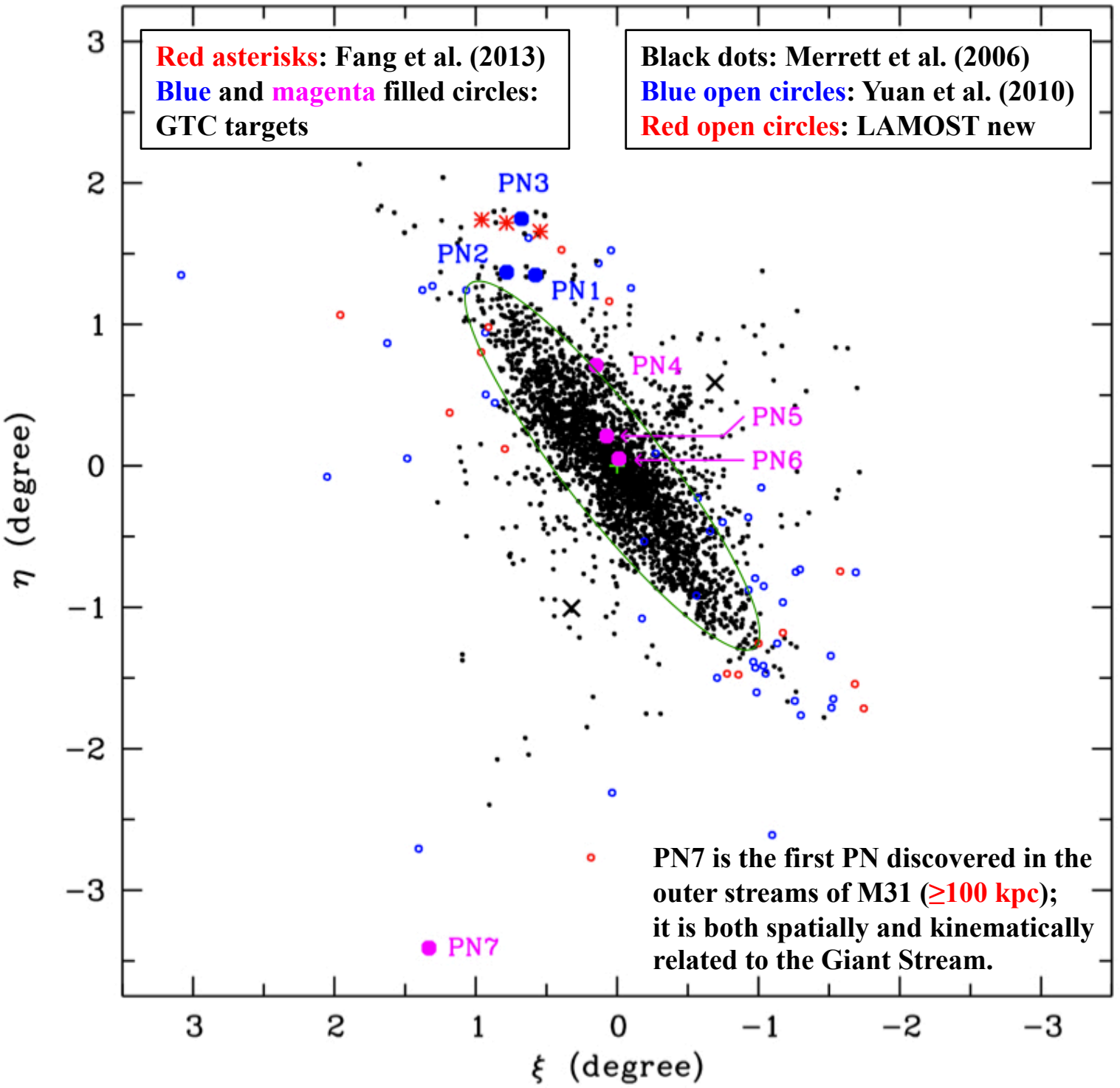
Red spectrum of PN3:

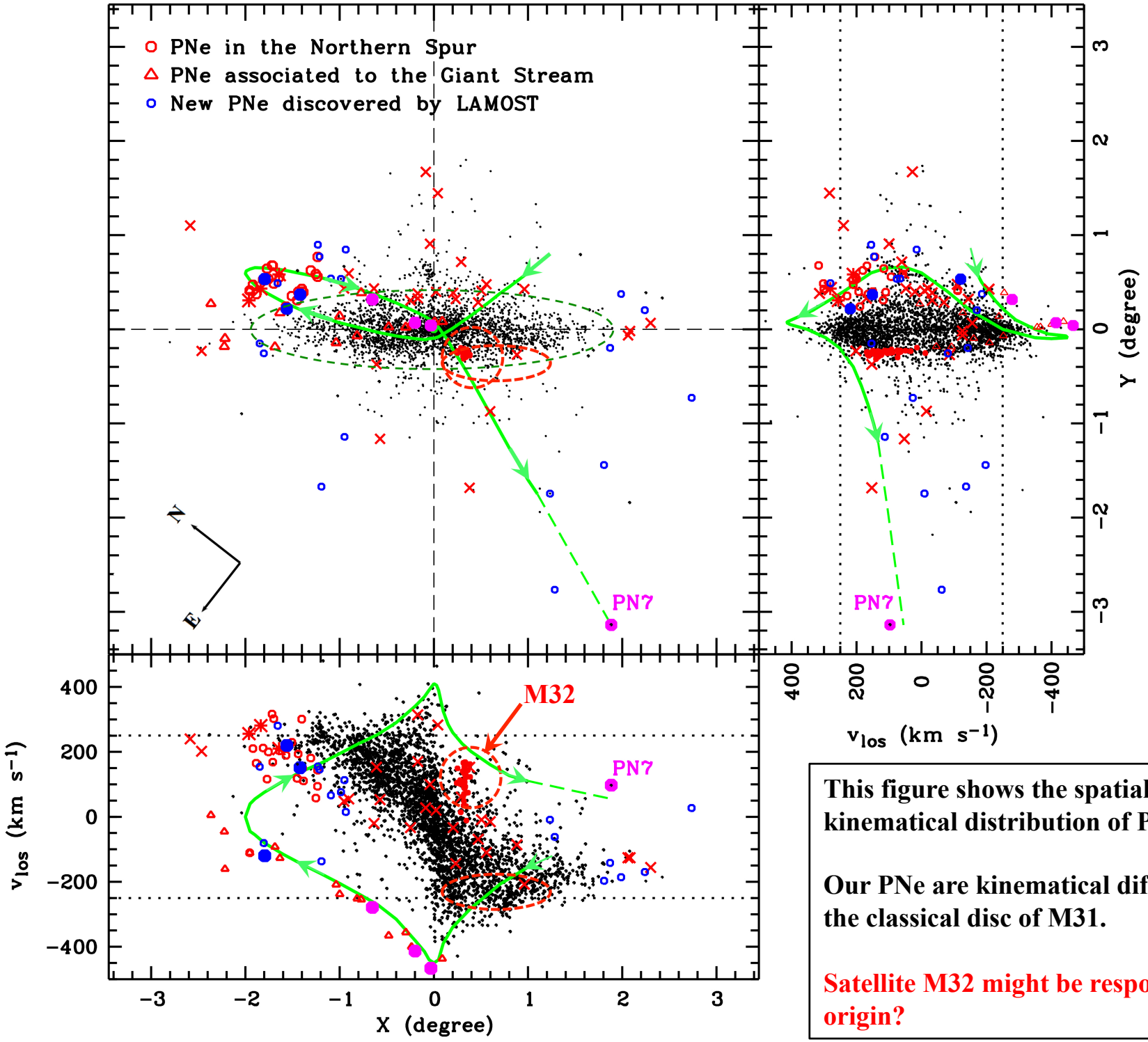


Follow-up work:
GTC spectroscopy of PNe in the Northern Spur and the Giant Stream of M31.

Purpose of the program:
To further study the origin of substructures using high-quality PNe spectra.

The 10.4m Gran Telescopio Canarias



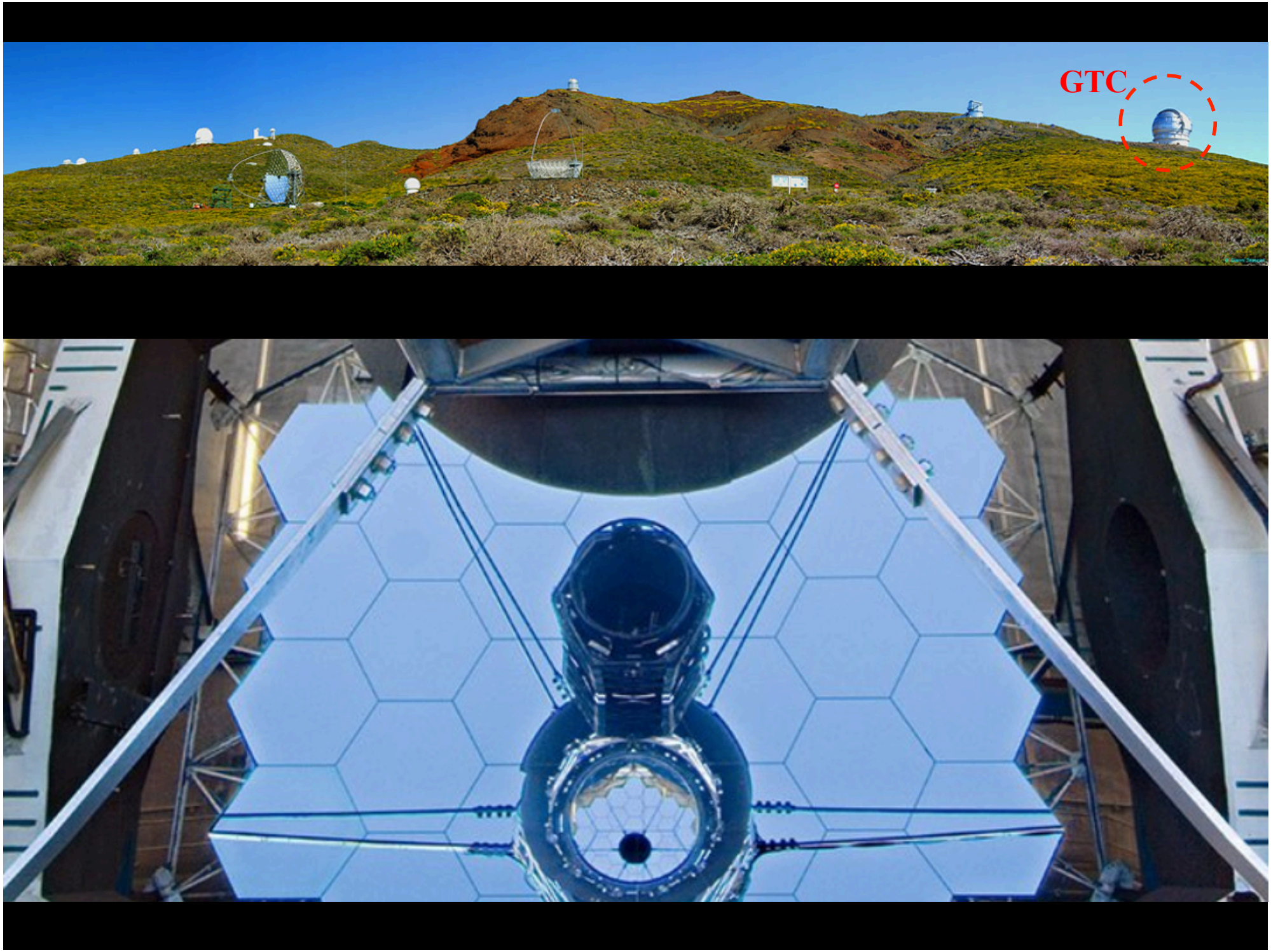


Fang et al.,
in preparation

This figure shows the spatial and kinematical distribution of PNe in M31.

Our PNe are kinematical different from the classical disc of M31.

Satellite M32 might be responsible for the origin?


GTC

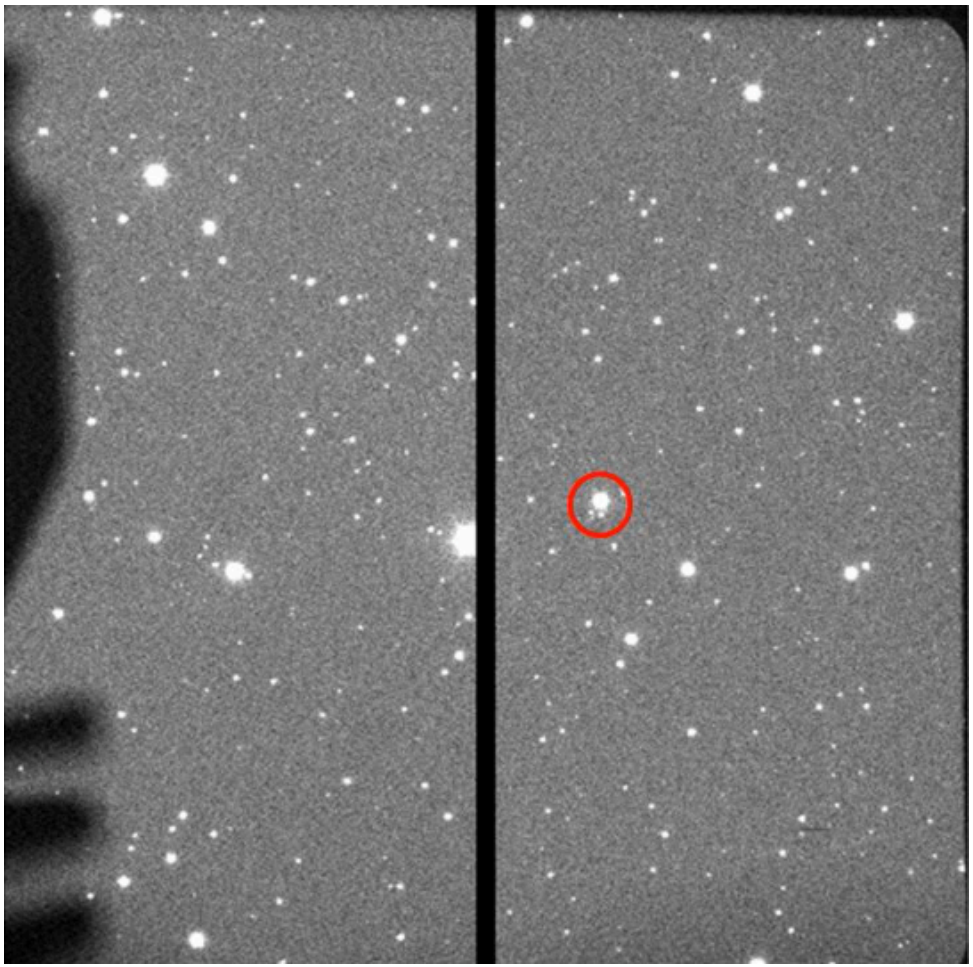
GTC observations and target properties

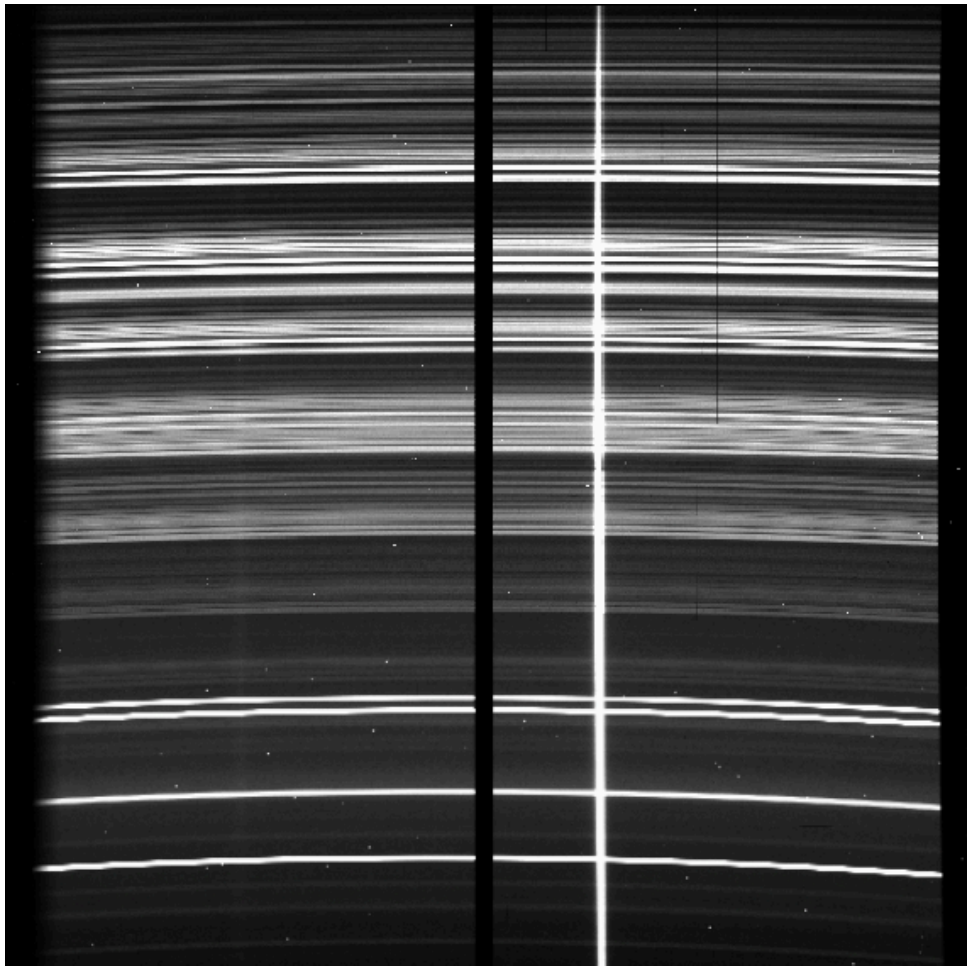
- GTC OSIRIS spectroscopy (in service mode, 2014 Aug. 23–29)
- Total time allocated: 15 hours
- Clear nights, seeing 0.5”–0.8”; 1” wide long slit
- Two CCDs (CCD1 + CCD2), 2k×4k each, 0.127”/pixel
- Grism R1000B, 1000 lines/mm, λ_c = 5455 Å
- Wavelegnth coverage: 3630–7760 Å
- FWHM ~ 6 Å (2.06 Å/pixel)

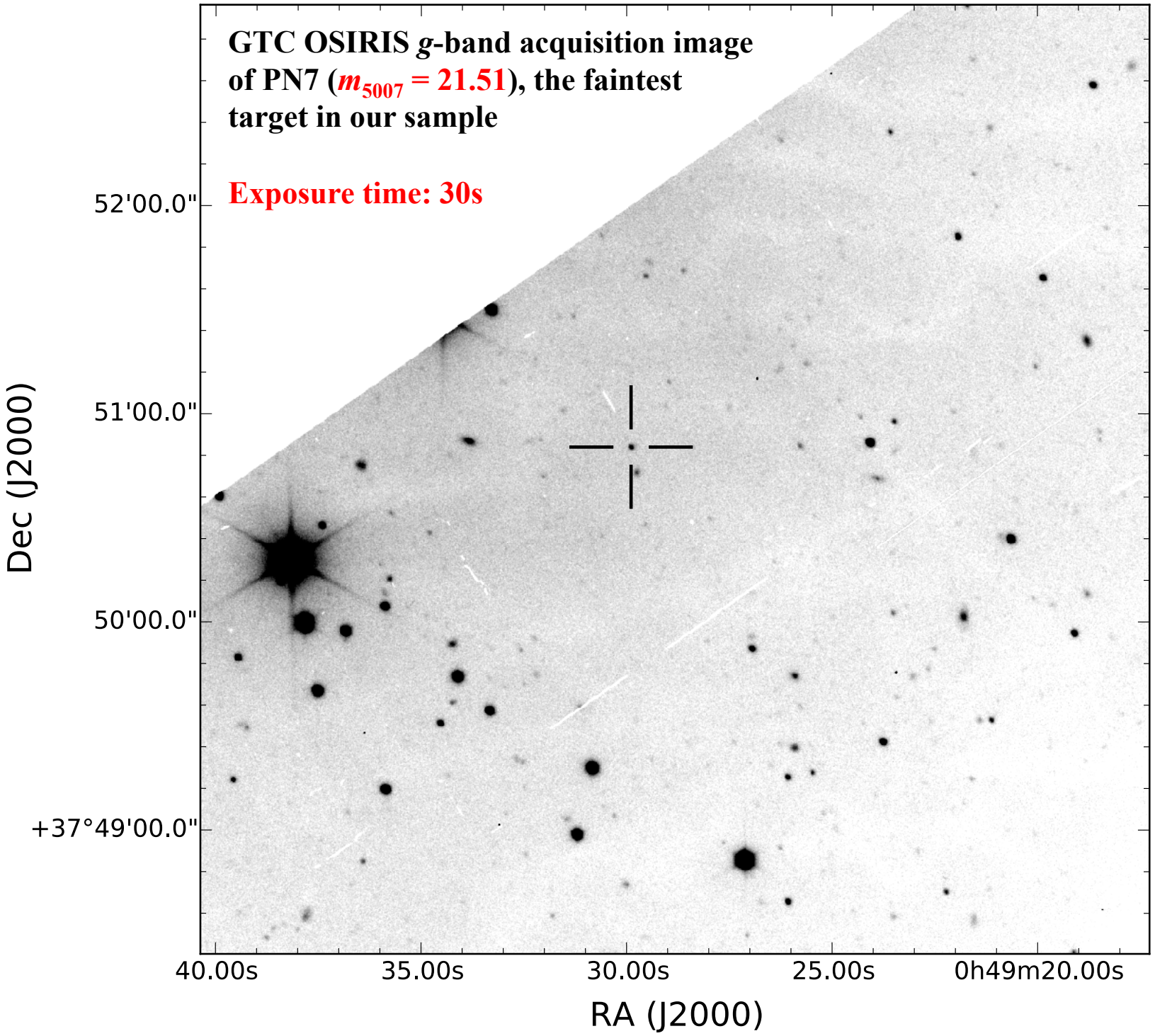
PN ID	R.A. (J2000)	Decl. (J2000)	m_{5007}	V_{helio} (km/s)	R_{gal} (kpc)	GTC exposure (s)
PN1 (2445)	00:45:52.8	42:36:52.9	20.65	-149	20.1	4 × 1250
PN2 (2451)	00:46:59.3	42:37:58.2	20.81	-81	21.6	4 × 1250
PN3 (2427)	00:46:26.5	43:00:43.0	20.48	-420	25.7	4 × 1250
PN4 (77)	00:43:32.3	41:58:42.5	20.99	-579	9.93	4 × 1200
PN5 (586)	00:43:07.9	41:28:45.5	20.82	-713	3.05	4 × 1200
PN6 (2750)	00:42:40.3	41:19:07.4	21.23	-766	0.70	4 × 1200
PN7 (LAMOST)	00:49:29.0	37:50:45.4	21.51	-203	50.2	4 × 2400 1 × 1200

OSIRIS: **Optical System for Imaging and low-intermediate-Resolution Integrated Spectroscopy**

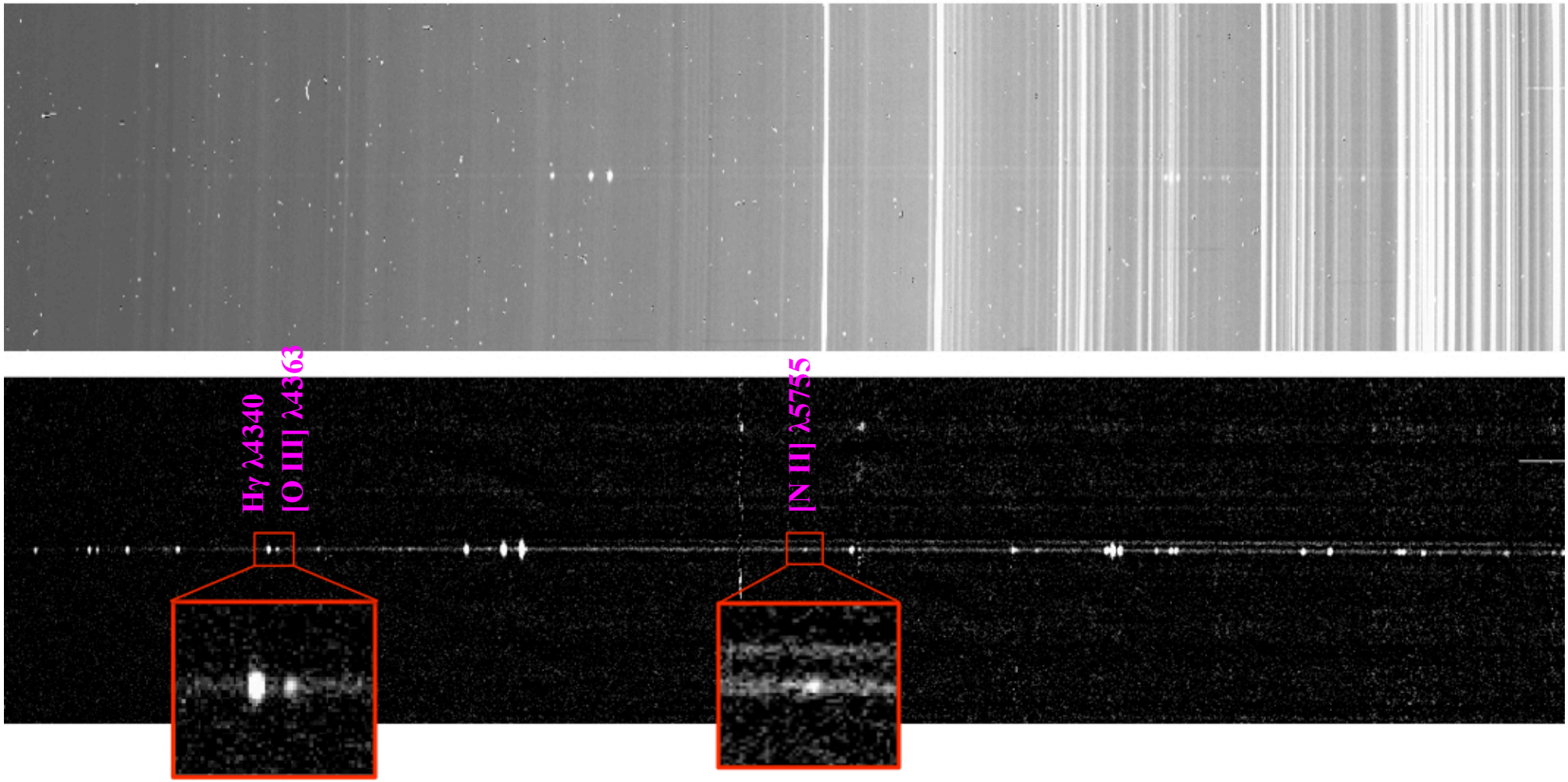
CCD1 + CCD2: 2048×4096 pixels each, 0.127” per pixel;
Standard observing modes: 1k×1k binned; 0.254” per pixel.






GTC OSIRIS g-band acquisition image of PN7 (m_{5007} = 21.51), the faintest target in our sample
Exposure time: 30s
52'00.0"
51'00.0"
50'00.0"
+37°49'00.0"
Dec (J2000)
40.00s
35.00s
30.00s
25.00s
0h49m20.00s
RA (J2000)

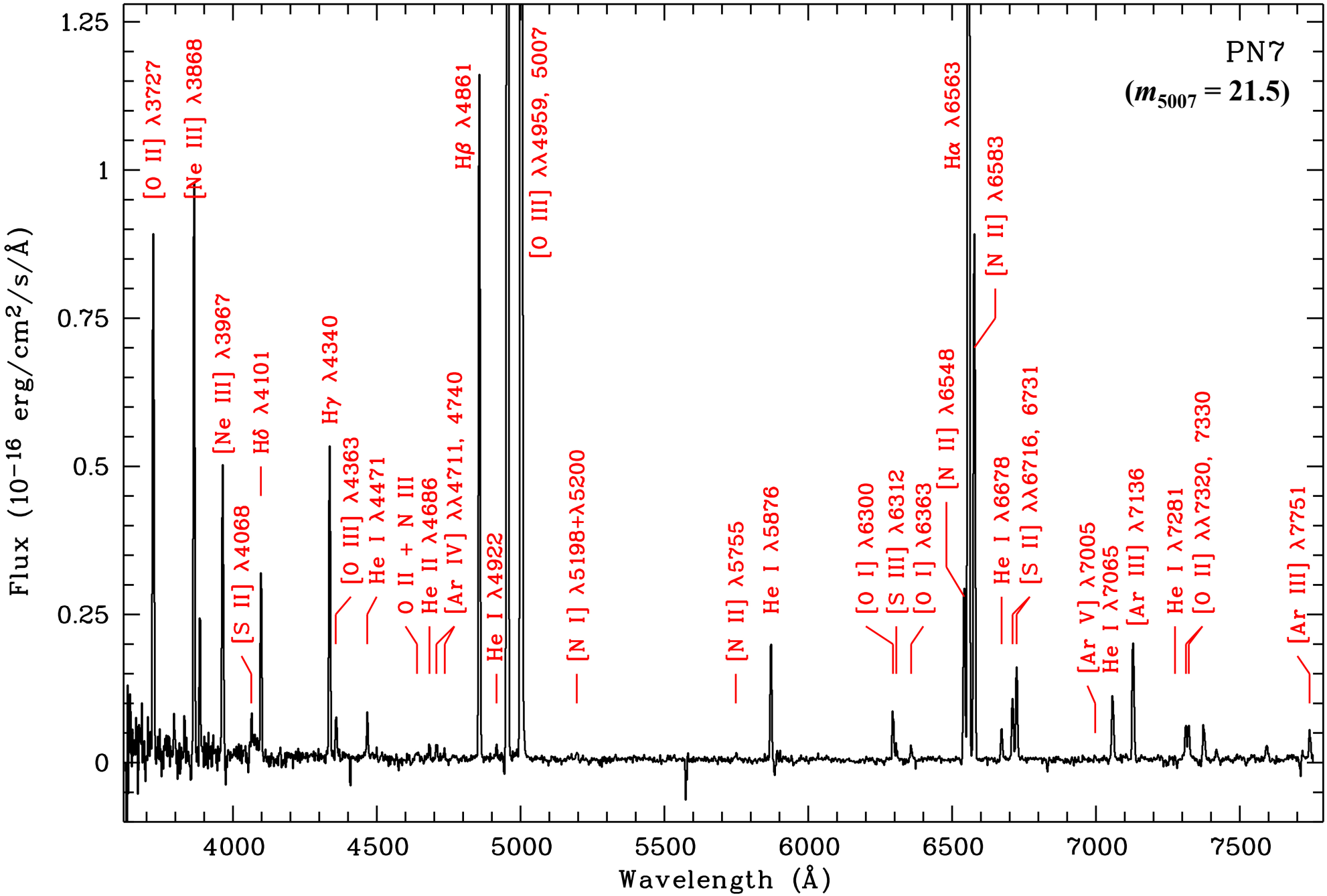
GTC OSIRIS 2D spectrum of PN7



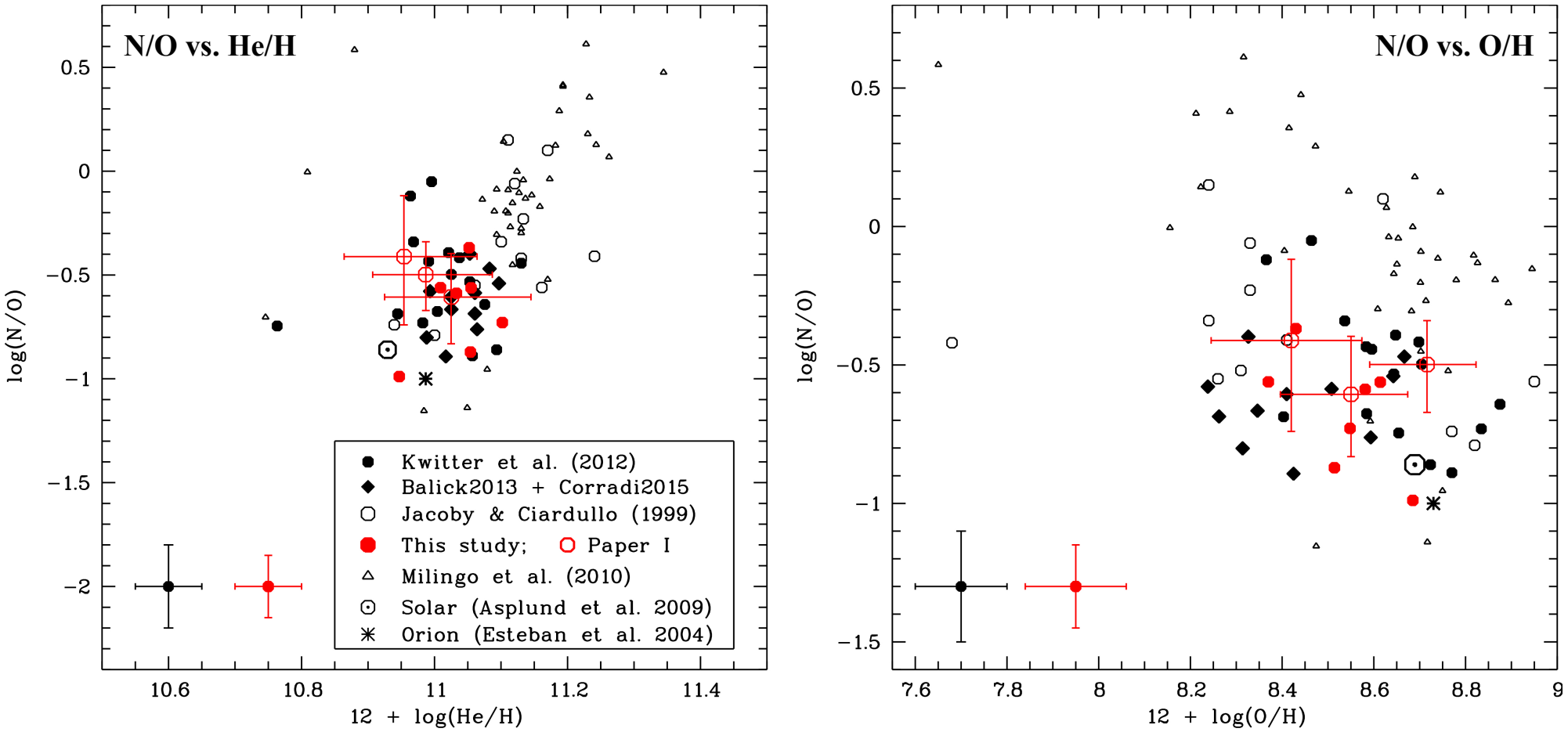
Upper: **The raw data**

Lower: **The 2D spectrum after image combine (4×40min), cosmic-ray removal, wavelength calibration, geometry rectification, and background subtraction; the inset shows the Hγ, [O III] λ4363, and [N II] λ5755 lines.**

GTC OSIRIS 1D spectrum of PN7

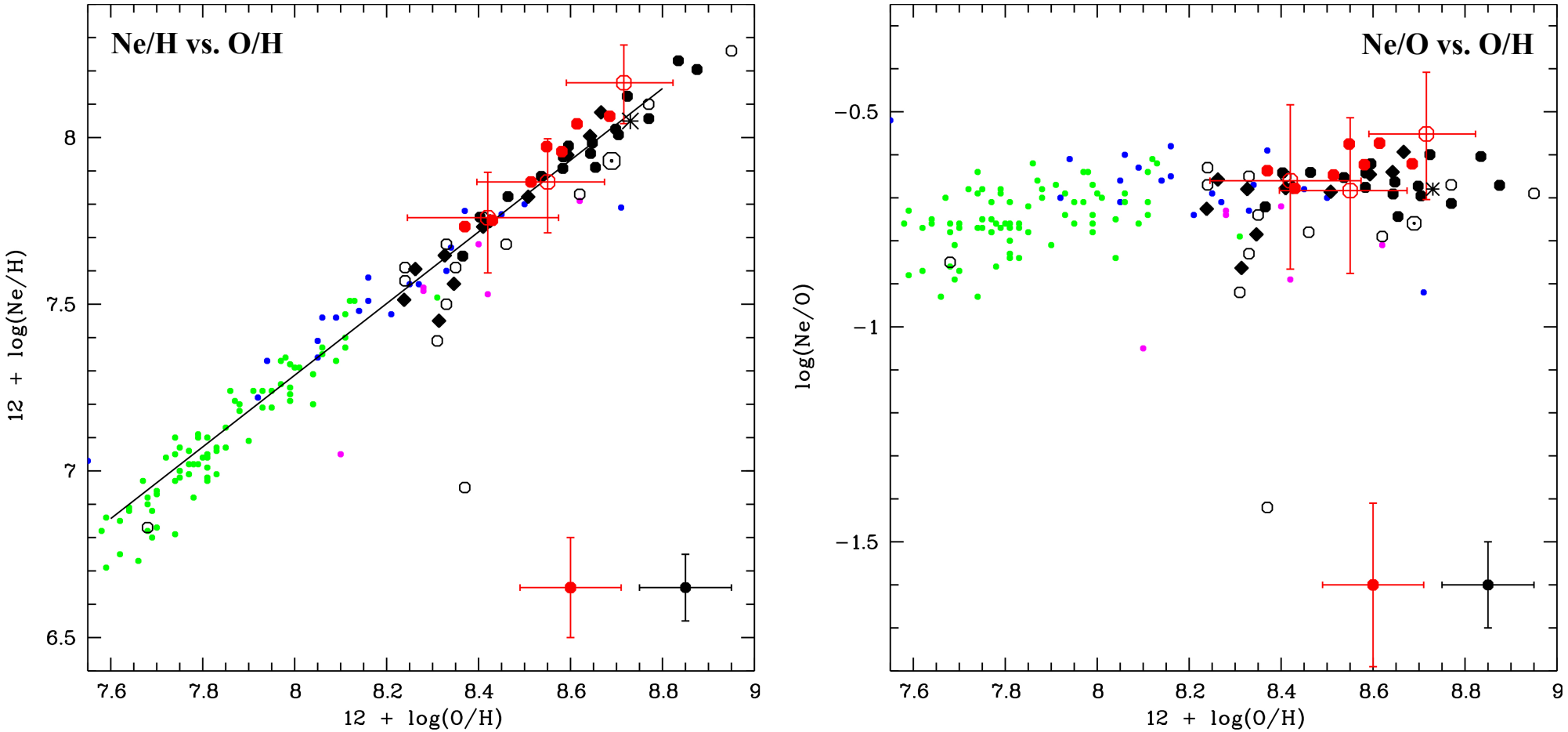


Abundance correlations: N/O vs. He and O



Red filled circles – PNe sample of this study
Red open circles – PNe sample observed by Fang et al. (2013) using 5. Hale
Black filled circles – PNe sample of Kwitter et al. (2012) and Balick et al. (2013)
Black open circles – PNe sample of Jacoby & Ciardullo (1999)
Black open triangles: the Galactic Type I PNe of Milingo et al. (2010)
Green dots – H II regions and metal-poor galaxies from Izotov & Thuan (1999) and Izotov et al. (2012)
Blue dots – M101 H II regions of Kennicutt et al. (2003)
Magenta dots – M31 H II regions of Zurita & Bresolin (2012)

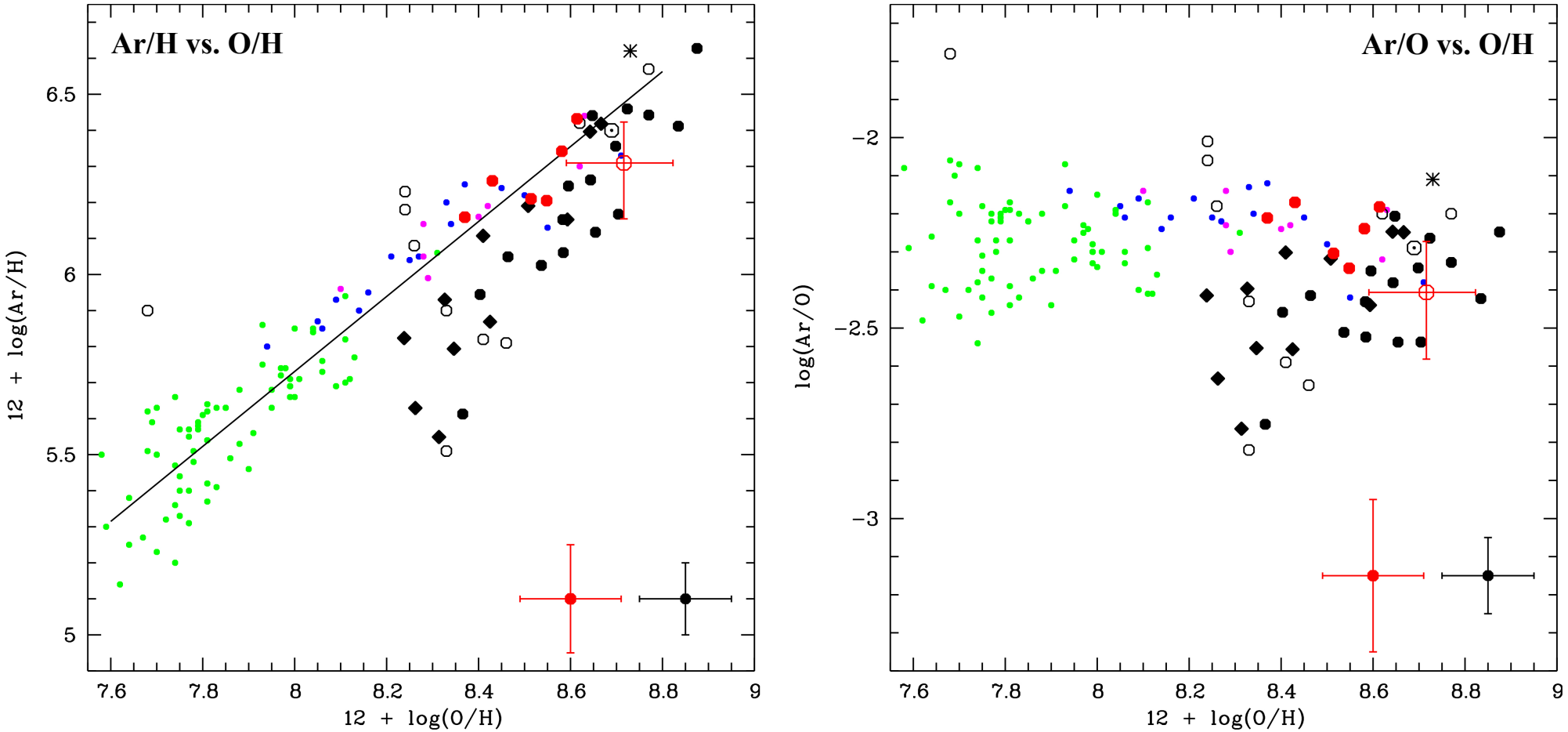
Abundance correlations: Ne vs. O



The black straight line is a linear fit to the H II region/metal-poor galaxies data of Kennicutt et al. (2003), Izotov & Thuan (1999) and Izotov et al. (2012).

The neon of M31 PNe is well correlated with oxygen.

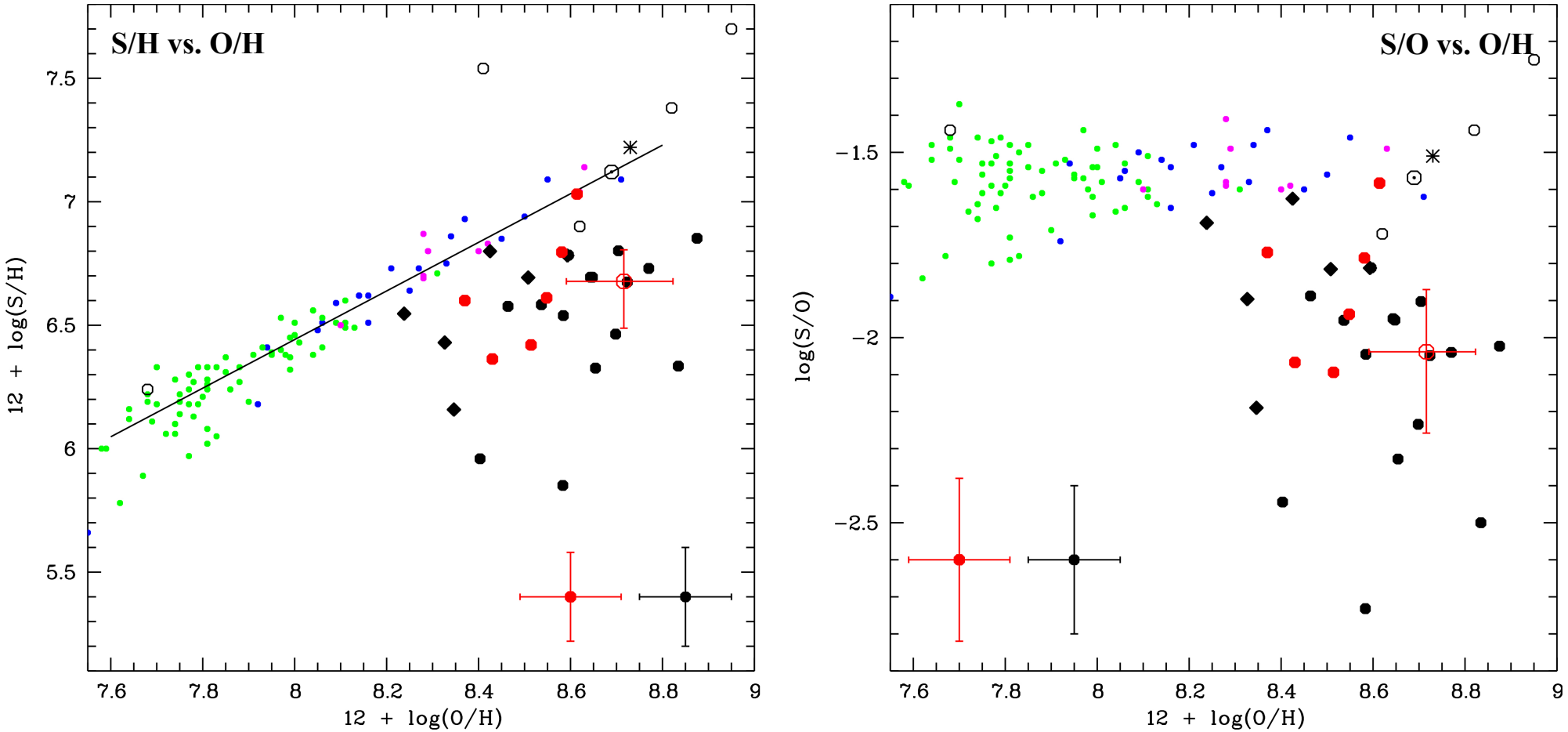
Abundance correlations: Ar vs. O



The black straight line is a linear fit to the H II region/metal-poor galaxies data of Kennicutt et al. (2003), Izotov & Thuan (1999) and Izotov et al. (2012).

The argon of our sample is generally correlated with oxygen; but the sample of Kwitter et al. (2012) have systematically lower argon abundances.

Abundance correlations: S vs. O

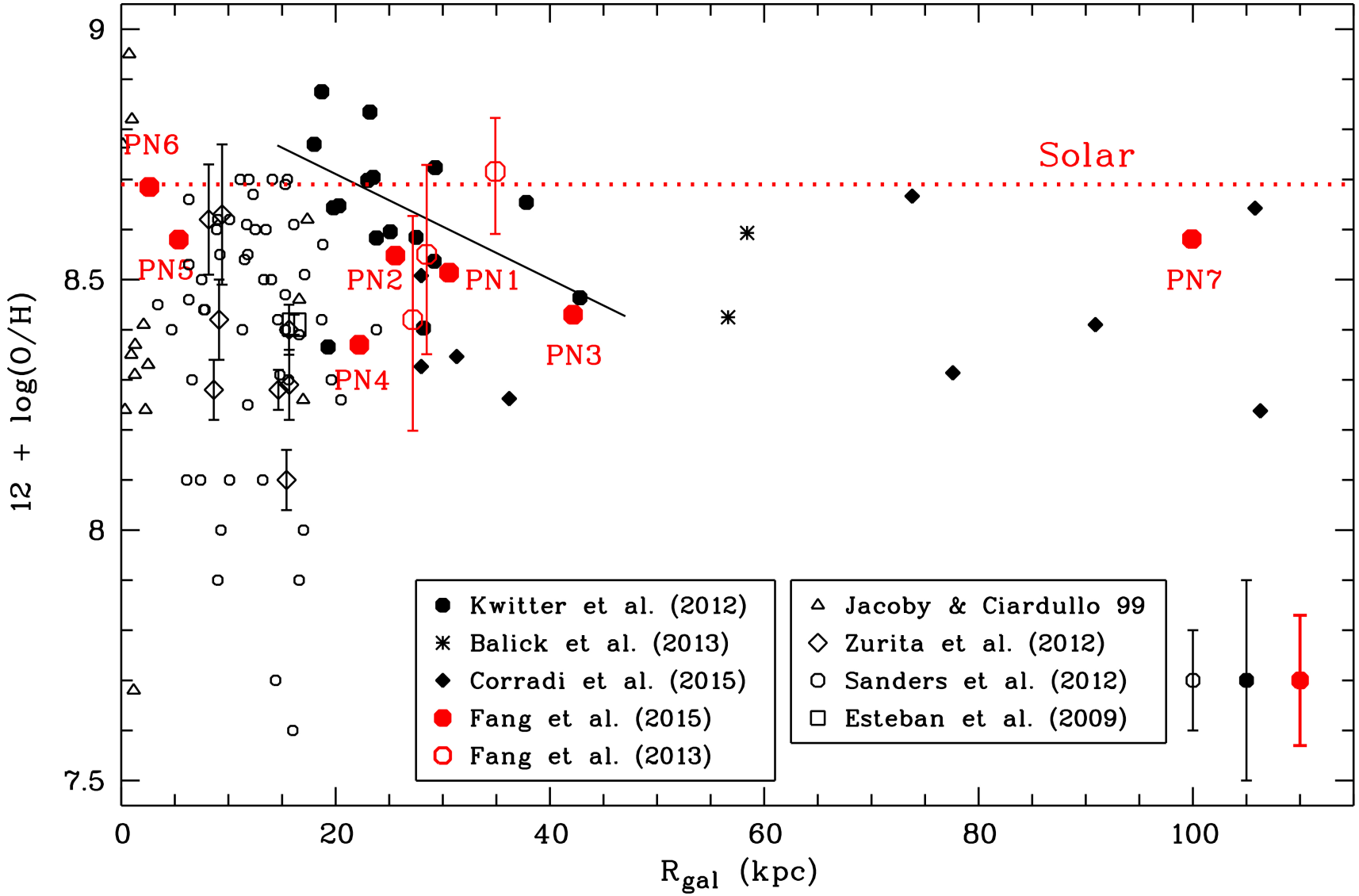


The black straight line is a linear fit to the H II region/metal-poor galaxies data of Kennicutt et al. (2003), Izotov & Thuan (1999) and Izotov et al. (2012).

The "sulfur anomaly" (first recognized by Henry et al. 2004 in the Galactic PNe) is also present in M31 PNe: Sulfur in PNe are lower than H II regions at a given oxygen value.

M31 Oxygen gradient exhibited by PNe

Fang et al.,
in preparation



The samples of Zurita et al. (2012) and Esteban et al. (2009) are H II regions; the others are PNe.

PN7 is >100 kpc from the center of M31 center.

Our PNe have homogeneous oxygen abundances! $\langle \log(O/H) + 12 \rangle = 8.54 \pm 0.11$

Summary

- **We obtained long-slit spectra of 10 PNe in the substructure of M31**

- **Our GTC spectra are the deepest ever obtained for extragalactic PNe.**

- **Abundance analysis of our sample**
  - **N/O and He/H ratios indicate that PNe are Type II.**
  - **"Sulfur anomaly" also exists in M31 PNe.**

- **Our targets have *homogeneous* oxygen abundances**

- **Possible origin of the Northern Spur and the Giant Stream**
  - **Our targets are well located on the stellar orbit proposed by Merrett et al. (2003).**
  - **The spatial and kinematical information, combined with the homogeneity in abundances, indicates they probably have the same origin.**
  - **Satellites M32 might be responsible for the substructures?**

Summary

- **Some comments**

  1) So far, deep spectra of M31 PNe are still scarce.

  2) Deep spectroscopy can be well obtained on 8–10m class telescopes (e.g., GTC).

  3) This effort can be efficiently extended to other Local Group galaxies using the next-generation Thirty Meter Telescope (TMT).

TMT observations of PNe in nearby galaxies

- TMT Wide-Field Optical Spectrometer (WFOS)
  - **Large field of view (40.5 arcmin^2)**
  - **Broad wavelength coverage (0.31–1.0 μm)**
  - **Medium resolution ($R \approx 1000$–5000)**
  - **MOS mode: ~100 targets at $R = 1000$, with complete wavelength coverage**

- Deep imaging of Local Group galaxies

- Follow-up optical spectroscopy of PNe

Planetary Nebulae discovered in the Local Group
(before 2006)

Magrini (2006)

Name	T	$\log L_V$	D [kpc]	N. PNe	Reference	N. S.	Reference
M31	Sb	10.43	760	2615	Merrett et al. 2006	30	Jacoby & Ciardullo 1999
M33	Sc	9.51	795	152	Ciardullo et al. 2004	26	Magrini et al. 2003A
LMC	Ir	9.35	50	1000	Reid & Parker 2005	141	Leisy & Dennefeld 2006A
SMC	Ir	8.79	59	132	Jacoby 2005	42	Leisy & Dennefeld 2006A
M32	E2	8.55	760	46	Merrett et al. 2006	14	Richer & McCall 2002
NGC205	Sph	8.51	760	35	Corradi et al. 2005	13	Richer & McCall 2002
IC10	Ir	8.47	660	16	Magrini et al. 2003B	-	Magrini et al. 2006
NGC6822	dIr	8.35	500	17	Leisy et al. 2005	17	Leisy et al. 2006B, Hernandez & Peña 2006
NGC185	Sph	8.19	660	5	Corradi et al. 2005	5	Richer & McCall 2002
IC1613	dIr	8.07	725	2	Magrini et al. 2005B	-	Corradi et al. 2006
NGC147	Sph	7.99	660	9	Corradi et al. 2005	8	Gonçalves et al. 2006
WLM	dIr	7.61	925	1	Magrini et al. 2005B	-	
Sagitt.	dSp	7.47	24	4	Zijlstra et al. 2006	4	Zijlstra et al. 2006
Fornax	dSp	7.19	138	1	Danziger et al. 1978	1	Danziger et al. 1978
Pegasus	dIr	6.87	760	1	Jacoby & Lesser 1981	-	
LeoA	dIr	6.55	690	1	Magrini et al. 2003B	1	van Zee et al. 2006
NGC3109	dIr	8.27	1330	13	Leisy et al. 2006B, Peña et al. 2006	12	Leisy et al. 2006B, Peña et al. 2006
SextansB	dIr	7.63	1600	5	Magrini et al. 2002	5	Magrini et al. 2005A
SextansA	dIr	7.67	1320	1	Magrini et al. 2003B	1	Magrini et al. 2005A

Planetary Nebulae discovered in the Local Group (2006–2011)

Name	Type	Mv	Dist. [kpc]	PNe 2006	PNe 2011	Ref (old) 2006	Ref (new) 2011
M31	Sb	-21.2	785	2766	2766	Merrett 2006	
Milky Way	Sbc	-20.9		2400	3000	Acker *et al.* 1996	Parker *et al.* 2006; Miszalski *et al.* 2008
M33	Sc	-18.9	795	152	152	Ciardullo *et al.* 2004	
LMC	Ir	-18.5	50	277	740	Jacoby 2006	Reid 2006a,b, 2011[1]
SMC	Ir	-17.1	59	105	139	Jacoby *et al.* 2002	Jacoby 2006
M32 (NGC221)	E2	-16.5	760	30	45	Ciardullo *et al.* 1989	Sarzi *et al.* 2011
NGC205	Sph	-16.4	760	35	35	Corradi *et al.* 2005	
IC10	Ir	-16.3	660	16	27	Magrini *et al.* 2003	Kniazev, *et al.* 2008
NGC6822	dIr	-16.0	500	17	26	Leisy *et al.* 2005	HM[2] *et al.* 2009
NGC185	Sph	-15.6	660	5	5	Corradi *et al.* 2005	
IC1613	dIr	-15.3	725	3	3	Magrini *et al.* 2005	
NGC147	Sph	-15.1	660	9	9	Corradi *et al.* 2005	
WLM	dIr	-14.4	925	1	1	Magrini *et al.* 2005	
Sagittarius	dSph/E7	-13.8	24	3	4	Zijlstra 1999	Zijlstra *et al.* 2006
Fornax (E351-G30)	dSph	-13.1	138	1	2	Danziger *et al.* 1978	Larsen 2008
Pegasus (DDO 216)	dIr	-12.3	760	1	1	Jacoby *et al.* 1981	
Leo I (DDO 74)	dSph	-11.9	250				
Andromeda I	IDsPH	-11.8	810				
Andromeda II	dSph	-11.8	700				
Leo A	dIr	-11.5	690	1	1	Magrini *et al.* 2003	
DD 210	dIr	-11.3	1025				
Sag DIGD	dIr	-10.7	1300				
Pegasus II	dSph	-10.6	830				
Pisces (LGS3)	dIr	-10.4	810				
Andromeda V	dSph	-10.2	810				
Andromeda III	dSph	-10.2	760				
Leo II (Leo B)	dSph	-10.1	210				

Planetary Nebulae discovered in the Local Group (2006–2011)

Name	Type	Mv	Dist. [kpc]	PNe 2006	PNe 2011	Ref (old) 2006	Ref (new) 2011
Cetus*	dSph	-9.9	755				
Phoenix	dSph	-9.8	395		1		Saviane *et al.* 2009
Sculptor (E351-G30)	dSph	-9.8	87				
Cassiopeia (An VII)	dSph	-9.5	690				
Tucana	dSph	-9.6	870				
Sextans	dSph	-9.5	86				
Carina (E206-G220)	dSph	-9.4	100				
Draco (DDO 208)	dSph	-8.6	79				
Ursa Minor	dSph	-8.5	63				
Canes Venatici I*	dSph	-7.8	220				
Leo T*	dSph	-7.1	420				
Ursa Major*	dSph	-6.7	100				
Canis Major Dwarf*	Irr		7.6				
Canes Venatici II*	dSph	-5.8	150				
Bootes*	dSph	-5.8	60				
Ursa Major II*	dSph	-3.8	30				
LG outskirts							
GR8	dSph	-11.8	2200	0		Magrini *et al.* 2005	
Antlia	dSph	-15.8	1330				
NGC3109	dIr	-15.8	1330	18	20	Corradi *et al.* 2006	Peña *et al.* 2007
Sextans B	dIr	-14.3	1600	5	5	Magrini *et al.* 2000	
Sextans A	dIr	-14.2	1320	1	1	Magrini *et al.* 2003	
EGB0427+63	sIr	-10.9	2200				

Thank you !