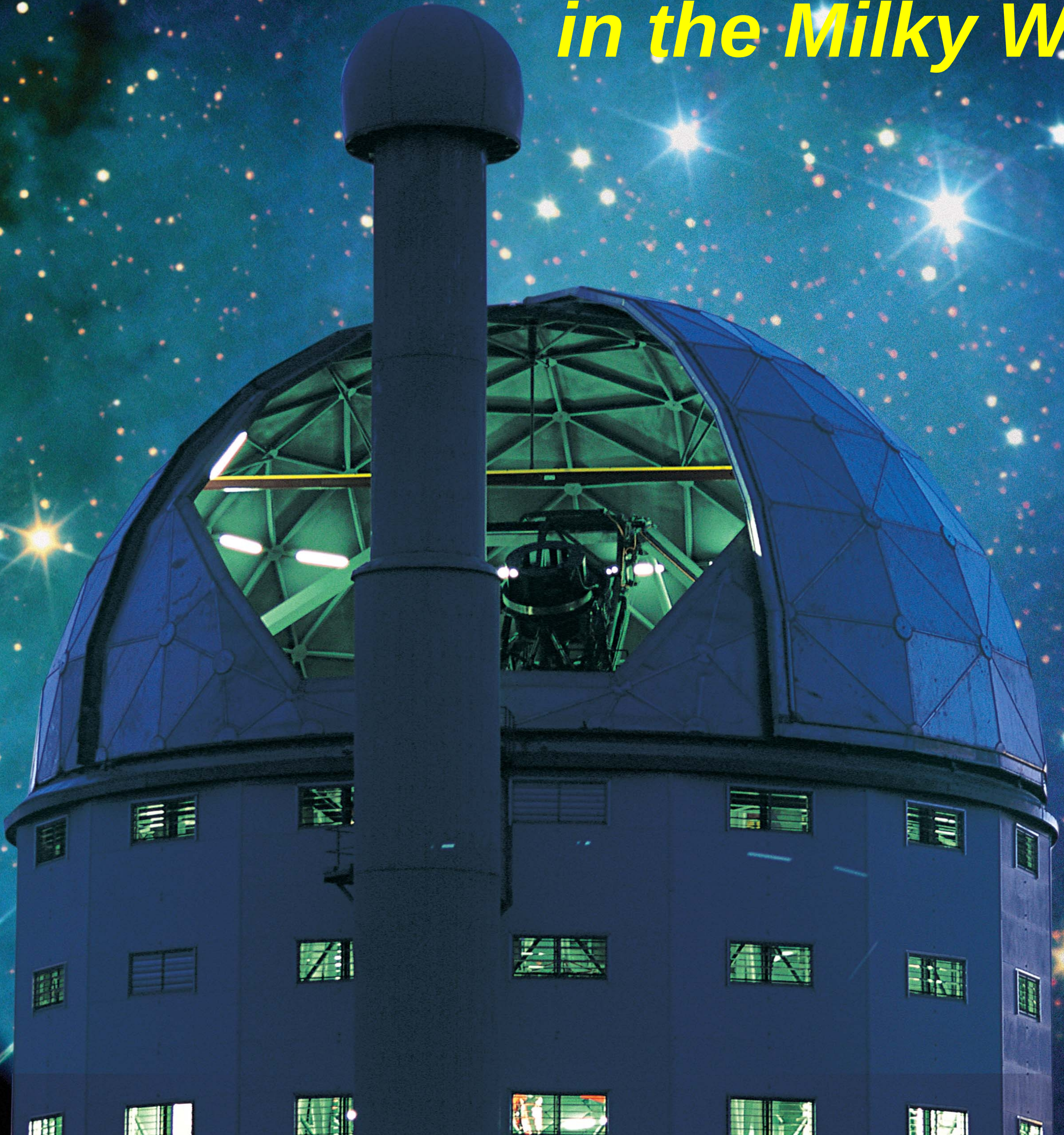
PNe as tracers of stellar streams: PNe in the outskirts of M31 and CMa region in the Milky Way



Alexei Kniazev

In collaboration with:

Eva Grebel

26 Sep 2016

Plan of the talk

Introduction: Reasons to study extragalactic PNe

PNe in the outer regions of M31

- The method of using SDSS data
- Sample of PNe in M31
- Andromeda NE as progenitor of stream

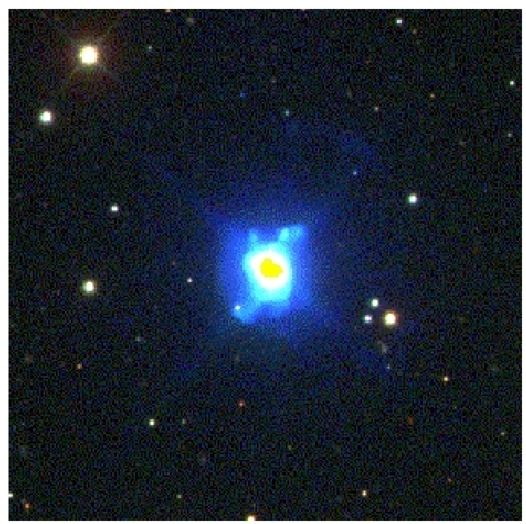
PNe in the region of CMa

Planetary Nebulae (PNe)

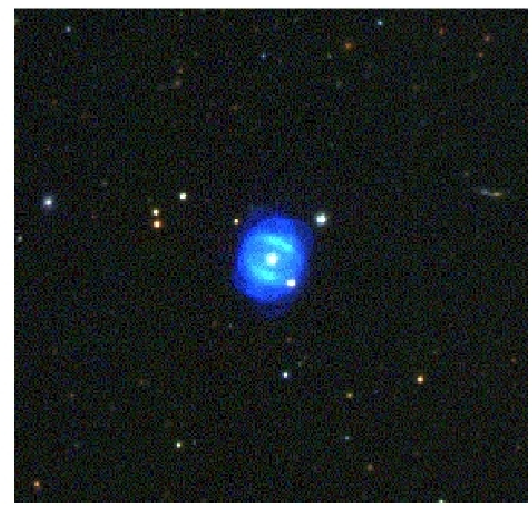
PNe arise in the common low-intermediate mass stars, they provide a representative tracer of the progenitor stars in a galaxy. They have relatively short life time (≤ 20000 yrs).

G164.8+31.1

NGC 6210



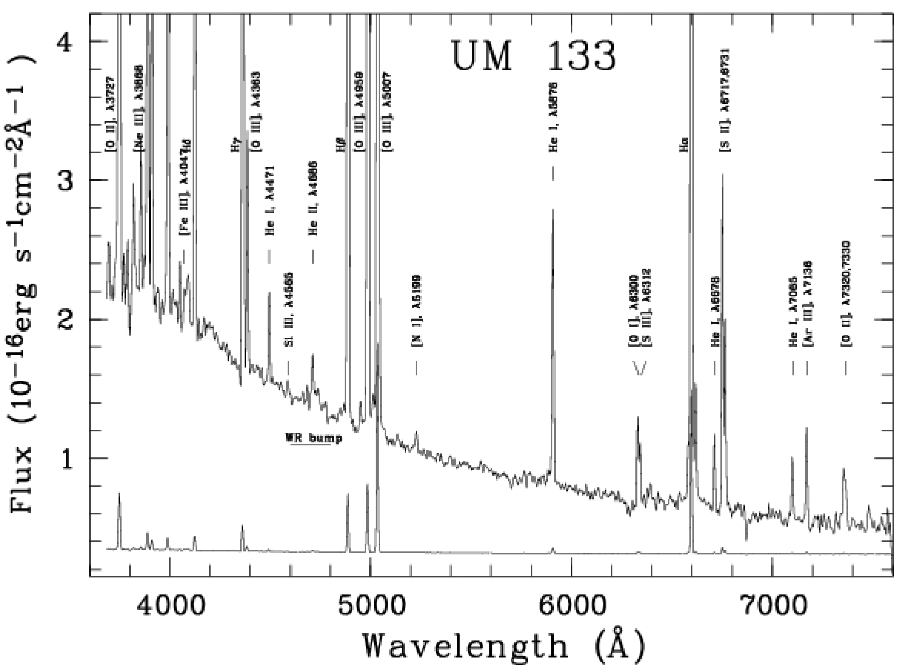
NGC 6058

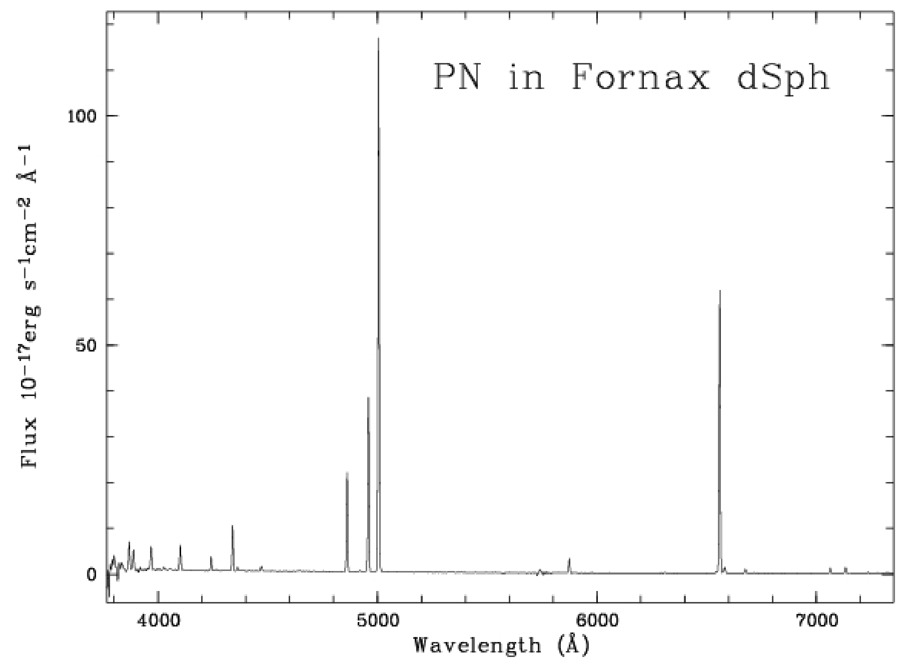


(Pictures are taken from SDSS images)

HII/PNe Spectra

PNe spectra look like spectra of HII regions.





Some reasons to study extra-galactic PNe (1)

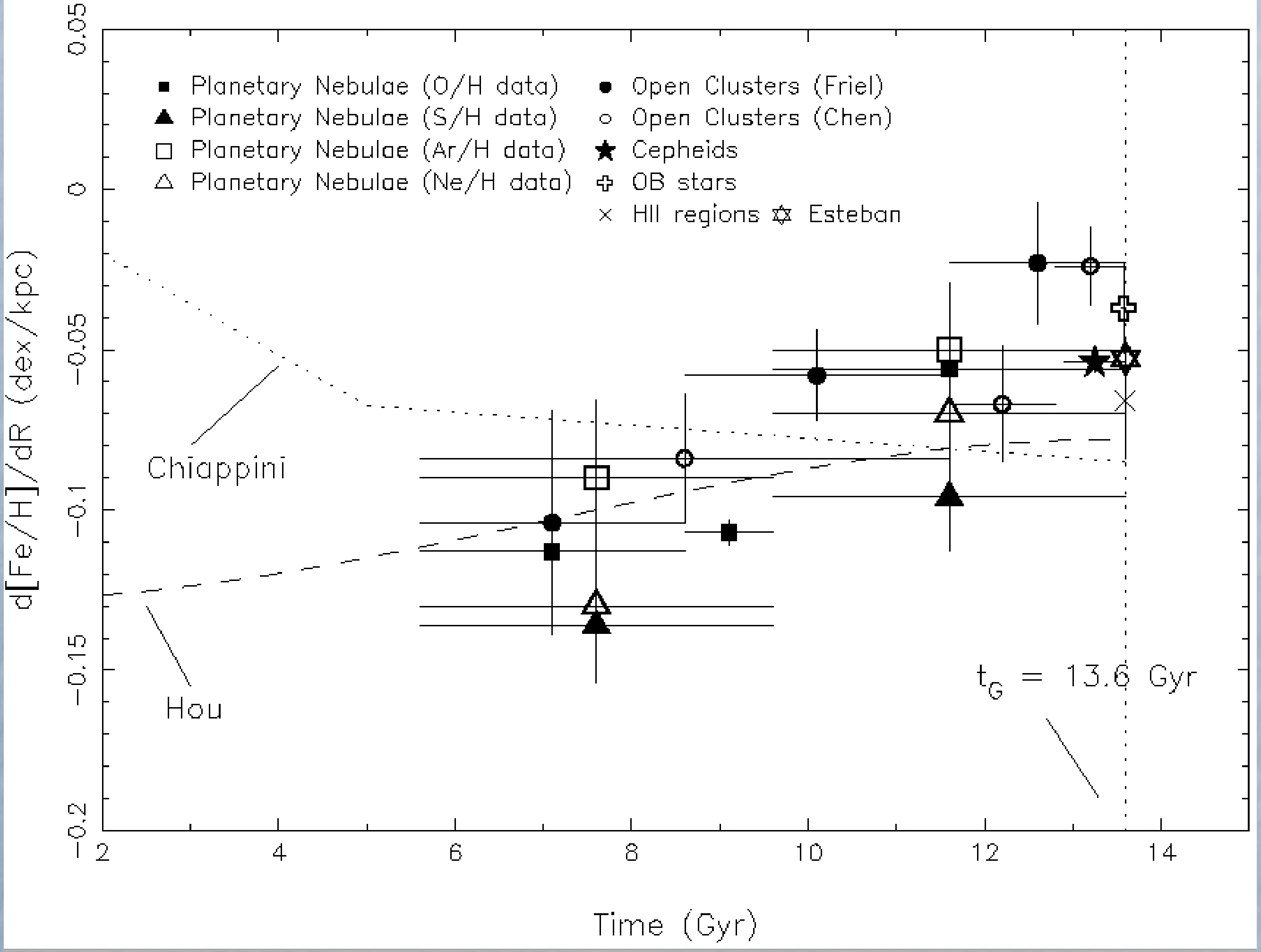
PNe as chemical probes of galaxies –
the emission lines can provide nebular abundances:
for PNe - related to those of the progenitor star

PN in Fornax dSph (Distance = 140 kpc)
V=18.9 mag – 2x30 min with NTT 3.5m telescope:
O, Ar, N, Ne, S, Cl, Fe, He and C with accuracy 0.02 – 0.20 dex

PN in Sextans A (Distance = 1400 kpc)
V=22.4 mag – 3x30 min with NTT:
O, Ar, N, S, He with accuracy 0.05 – 0.25 dex

2 stars (V=17.3 mag) from NGC6822 (Distance = 490 kpc)
3x1 h for each with 10m Keck telescope:
O, Si, Sc, Ti, Cr, Fe, Ni with accuracy 0.1- 0.3 dex

HII/PNe as chemical probes



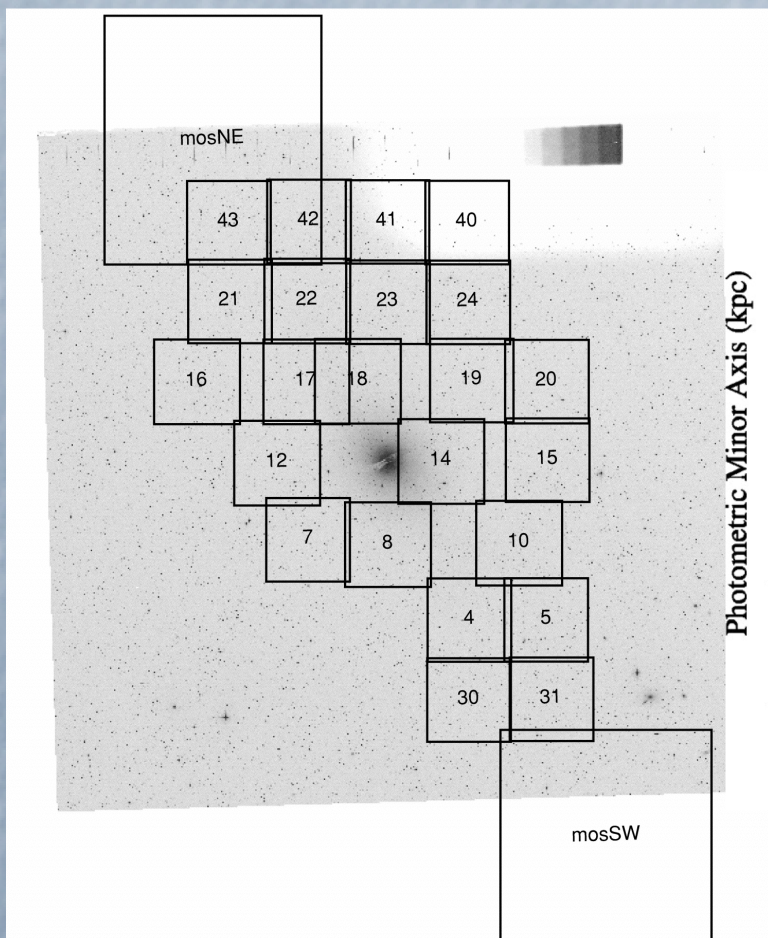
Maciel, Lago & Costa (2006, A&A, 453, 587)

Some reasons to study extra-galactic PNe (2)

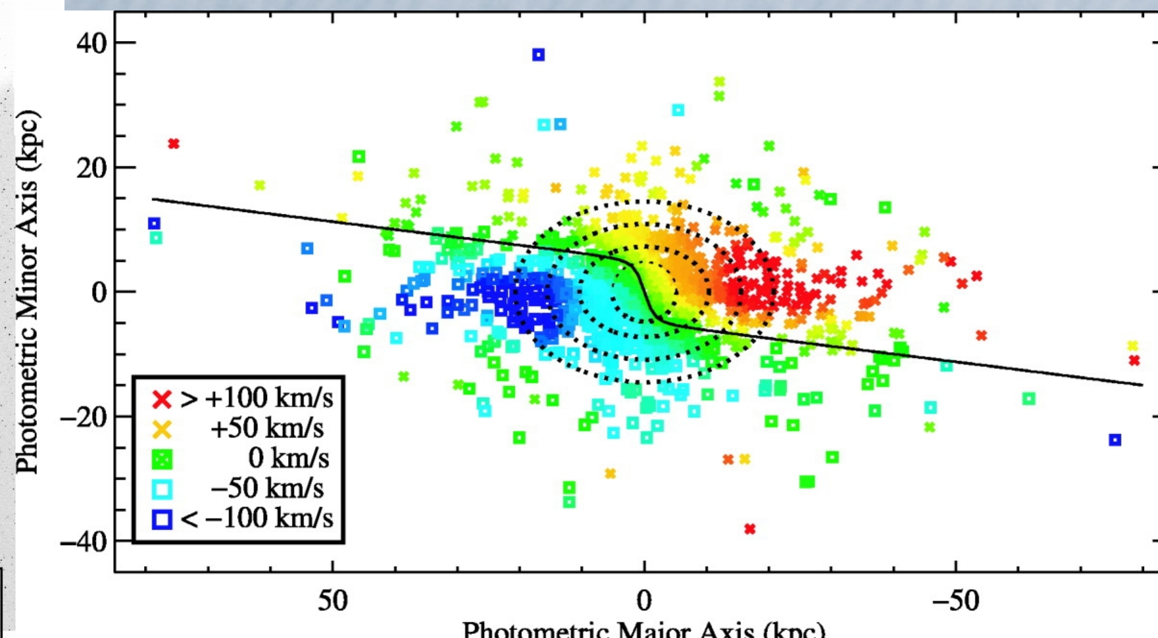
PNe as kinematic probes –

since PNe are just ordinary stars that we happen to catch at the ends of their lives, they are fairly representative of the bulk stellar population of the galaxy;

PNe as kinematic probes



NGC5128 (Centaurus A)

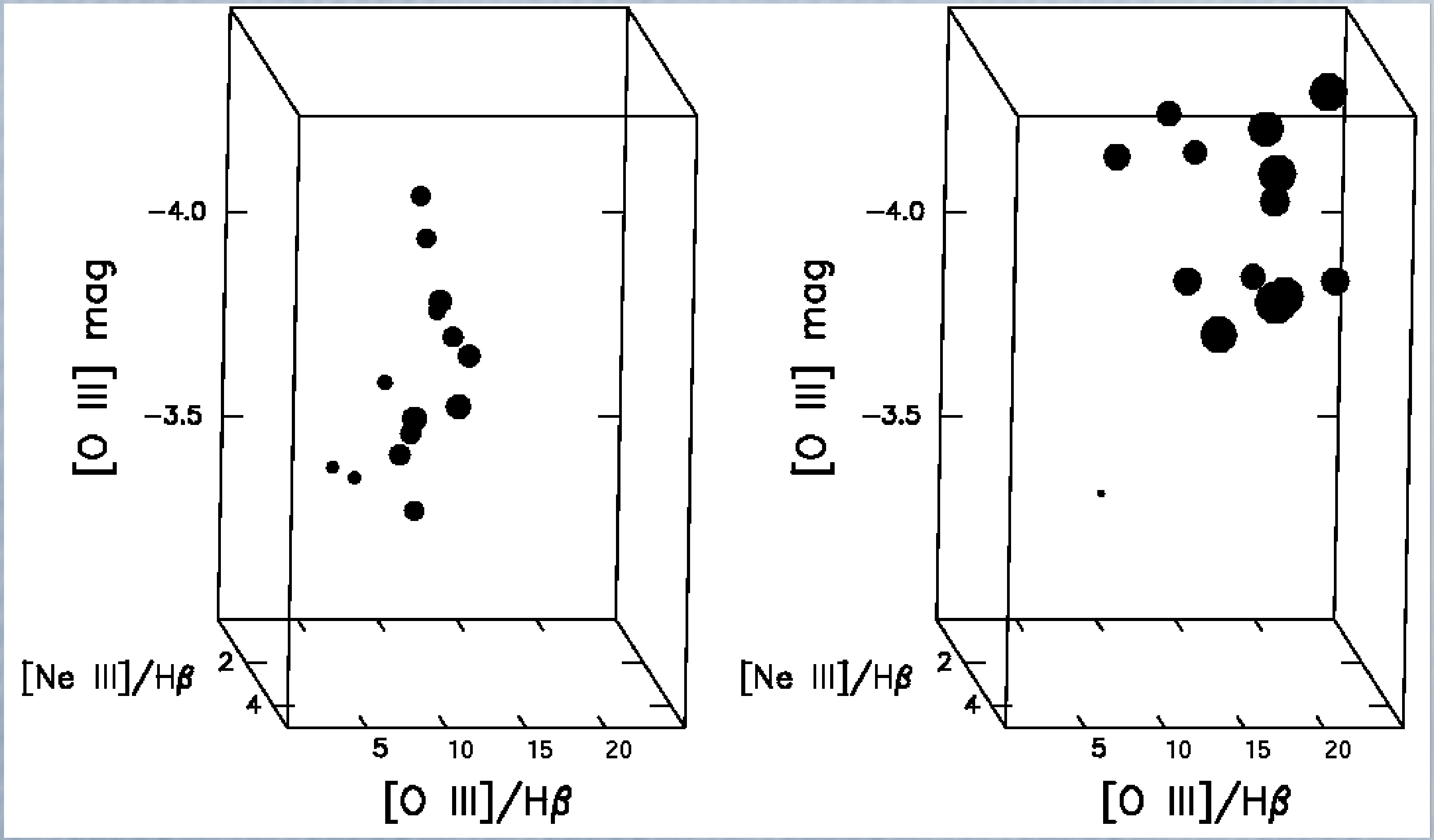


Peng, Ford & Freeman (2004, ApJ,602,685)

Some reasons to study extra-galactic PNe (3)

PNe as probes of stellar populations –
in many systems bright PNe are the only individual objects that are amenable to spectroscopy. Even the knowledge of only strongest emission lines can give us the information about stellar populations.

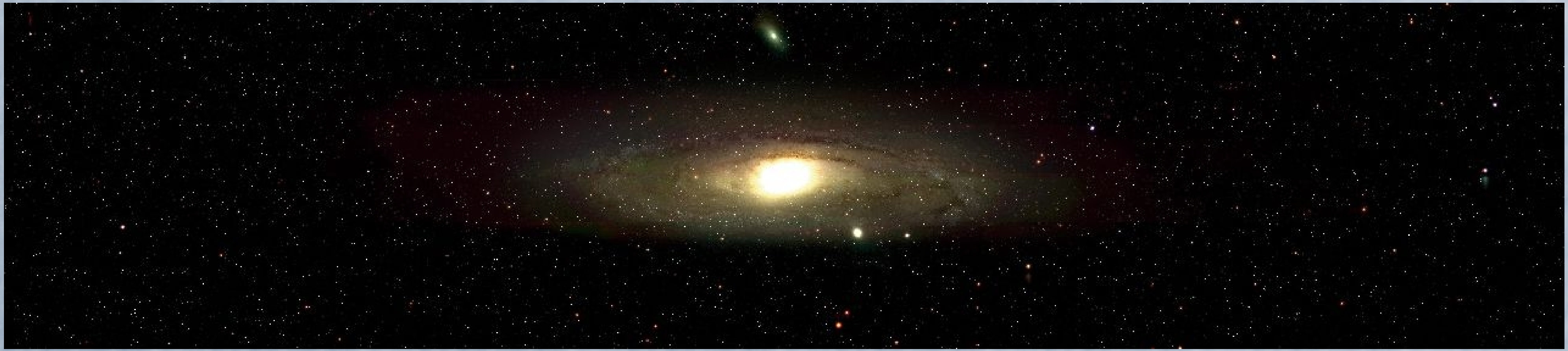
PNe as probes of stellar populations



Comparison of PNe of the LMC (left) and the large elliptical NGC4697

Ciardullo (2006, astro-ph/0605063)

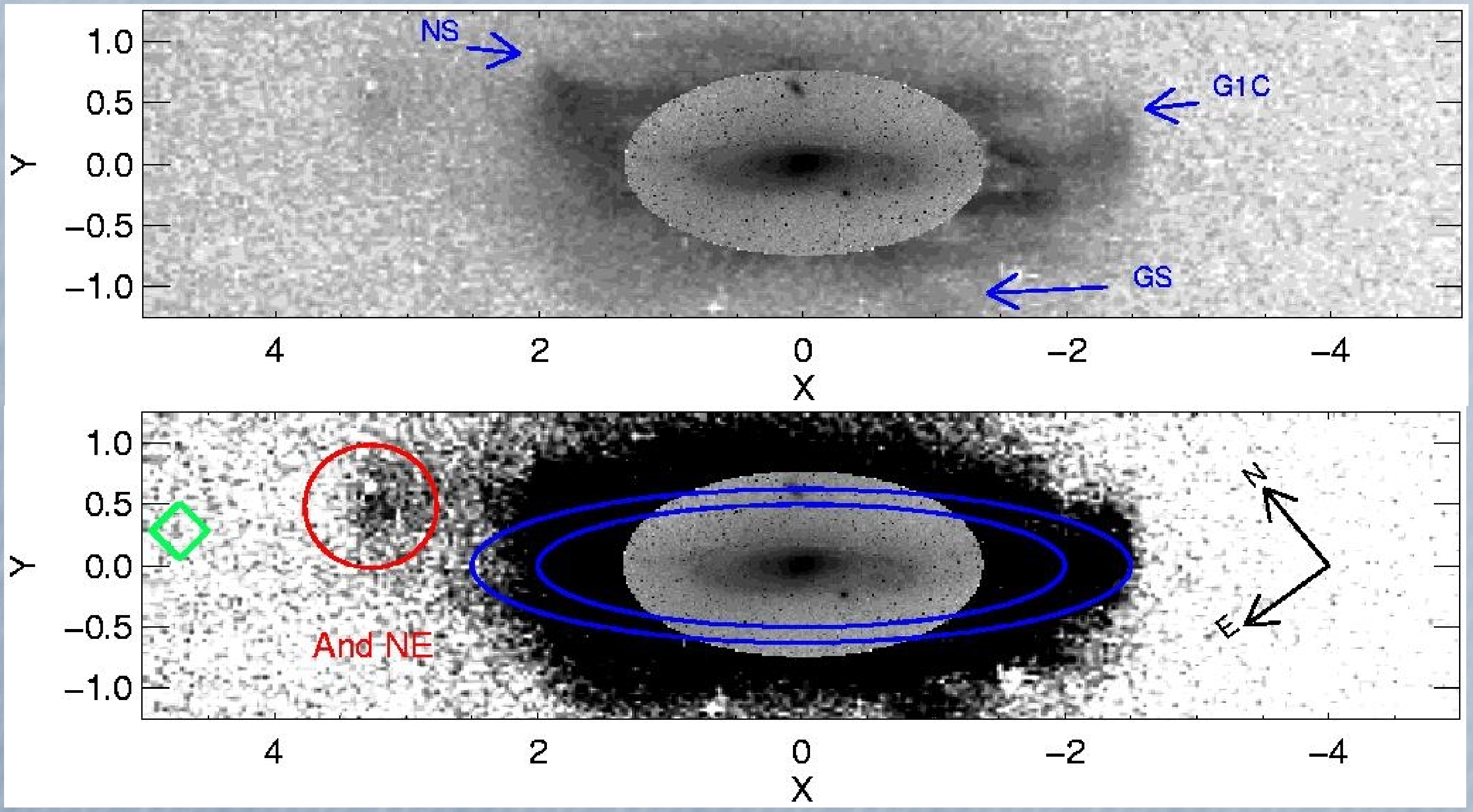
SDSS Observations of M31



Data obtained 5 October 2002 (Runs 3366 and 3367) in 3 hours

Two overlapping strips oriented along the major axis of M31, covering an area of $18^\circ \times 2.5^\circ$

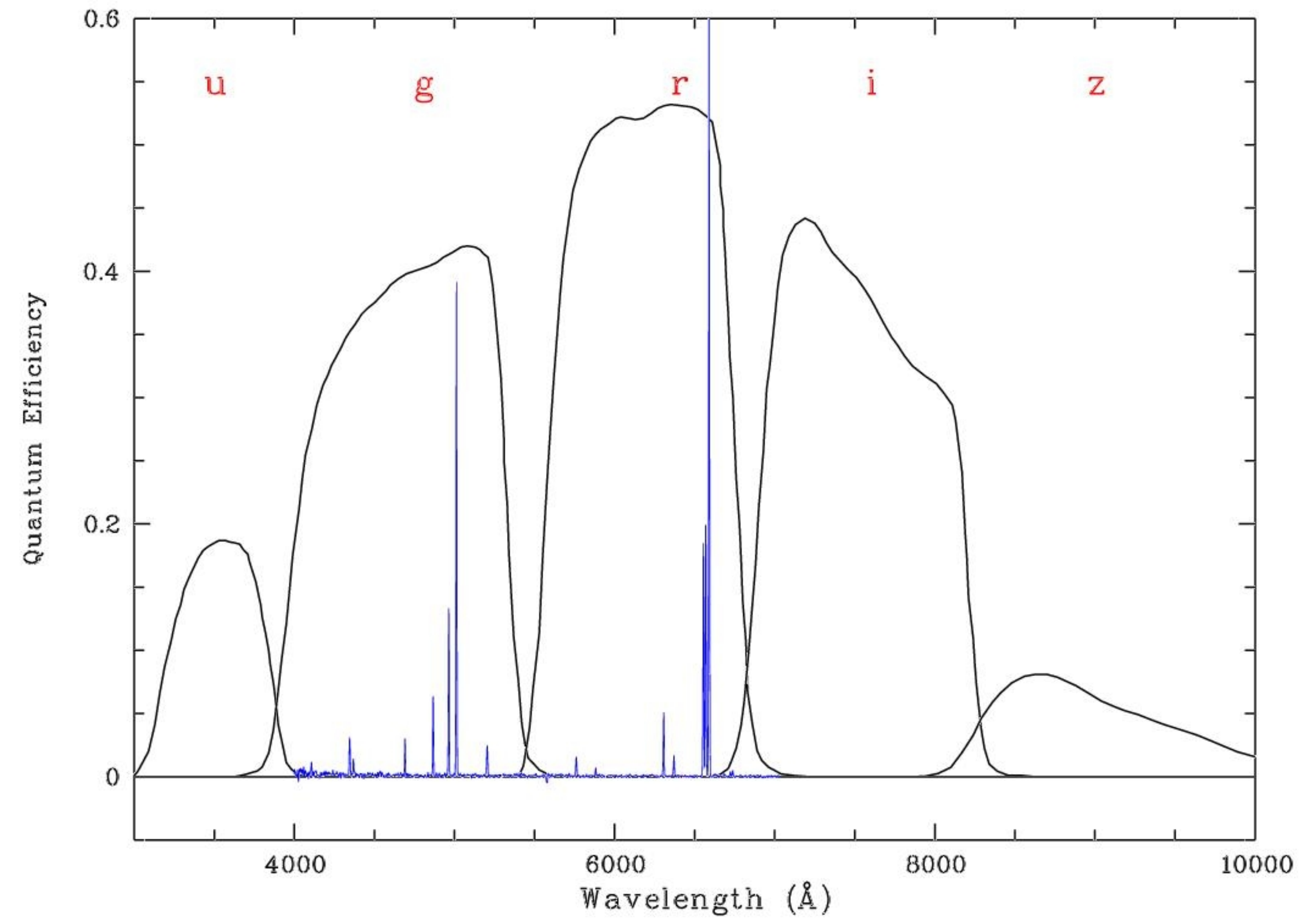
SDSS Stellar Density Distribution



(1) Stellar structure ~3° to NE; (2) At approximately same distance as M31; (3) Radius ~30'; (4) $\mu_{0,V} = 28.6$ and $M_V = -12.4$; (5) Satellite or stream? (6) Can have 0.5 – 2 PNe

From Zucker, Kniazev et al. (2004)

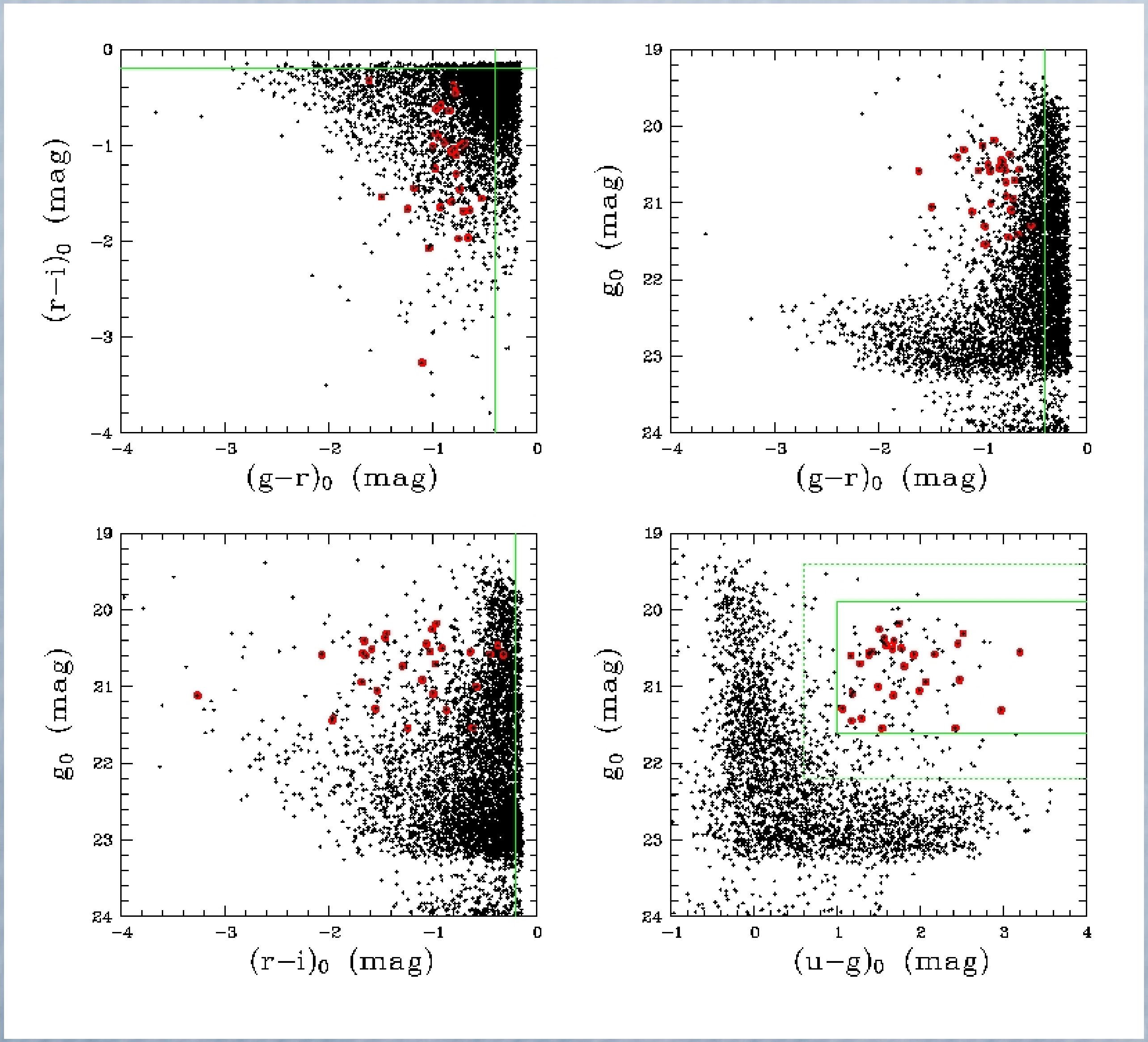
Emission Objects with SDSS



Is it possible to select PNe candidates using SDSS data?

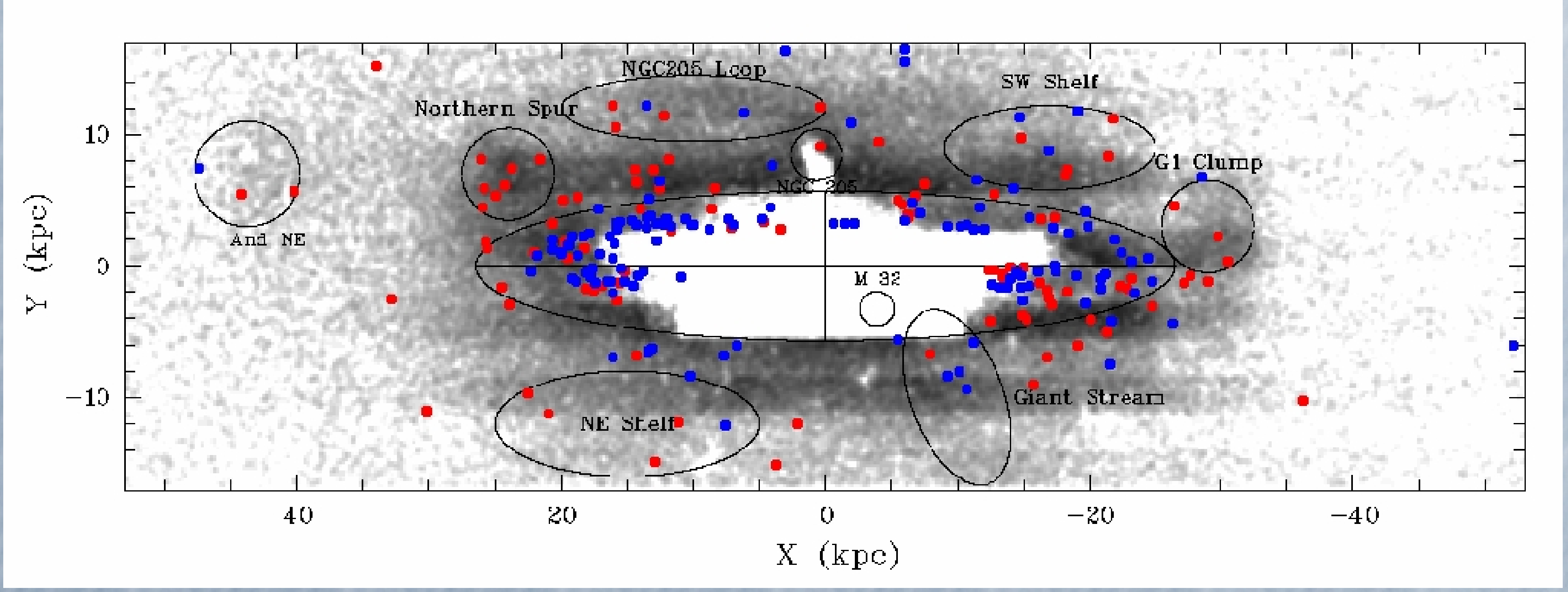
Selection Criteria for PNe candidates

Identification of PNe from Nolthenius & Ford (1987) and from Jacoby & Ford (1986): 30 were identified with position accuracy < 1″



From Kniazev et al. (2014, AJ, 147,16)

PNe canidates in the Outer Part of M31

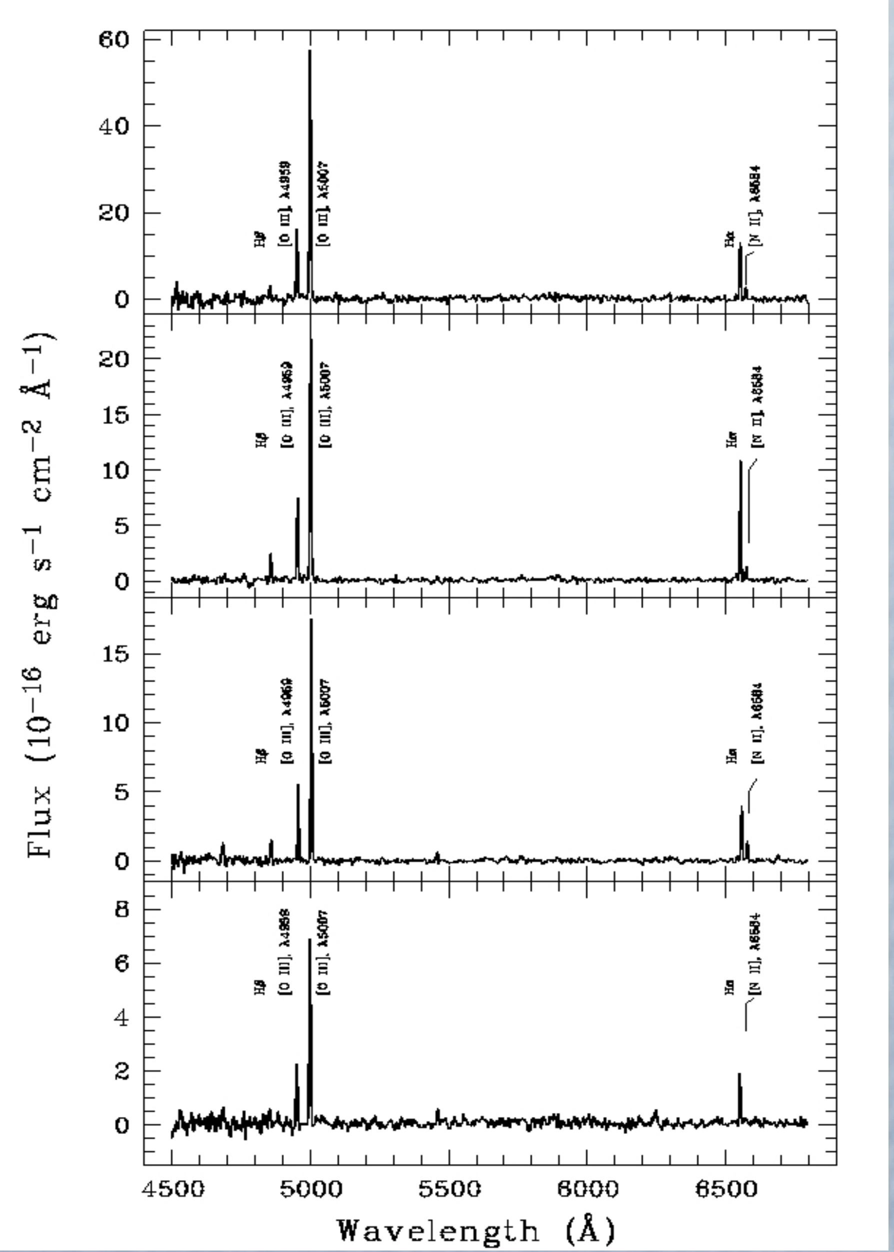


Candidates positions traced different substructures of outer part of M31

3 candidates in the area of Andromeda NE have been found !!!

Spectral follow-up Observations(1)

2.2m telescope at Calar Alto (Spain); CAFOS; 4200–7800 Å, ~1.9 Å/pix; 8 nights in October 2004 under variable weather conditions; 15–30 min exposures; Totally 80 candidates from 167 were observed with efficiency of ~90% for our method



The selection method is very efficient !

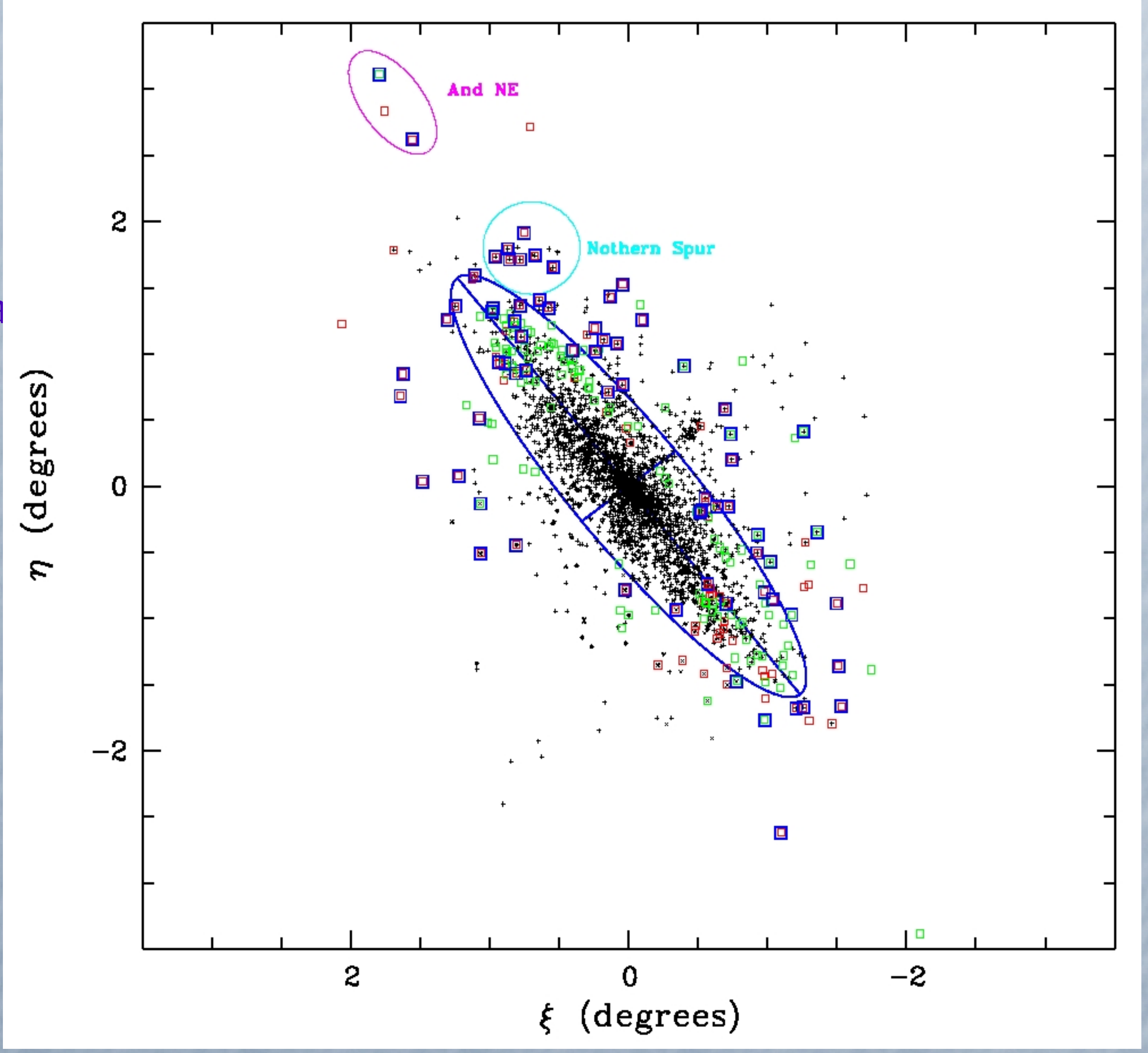
From Kniazev et al. (2014, AJ, 147,16)

Last decade: PNe in M31

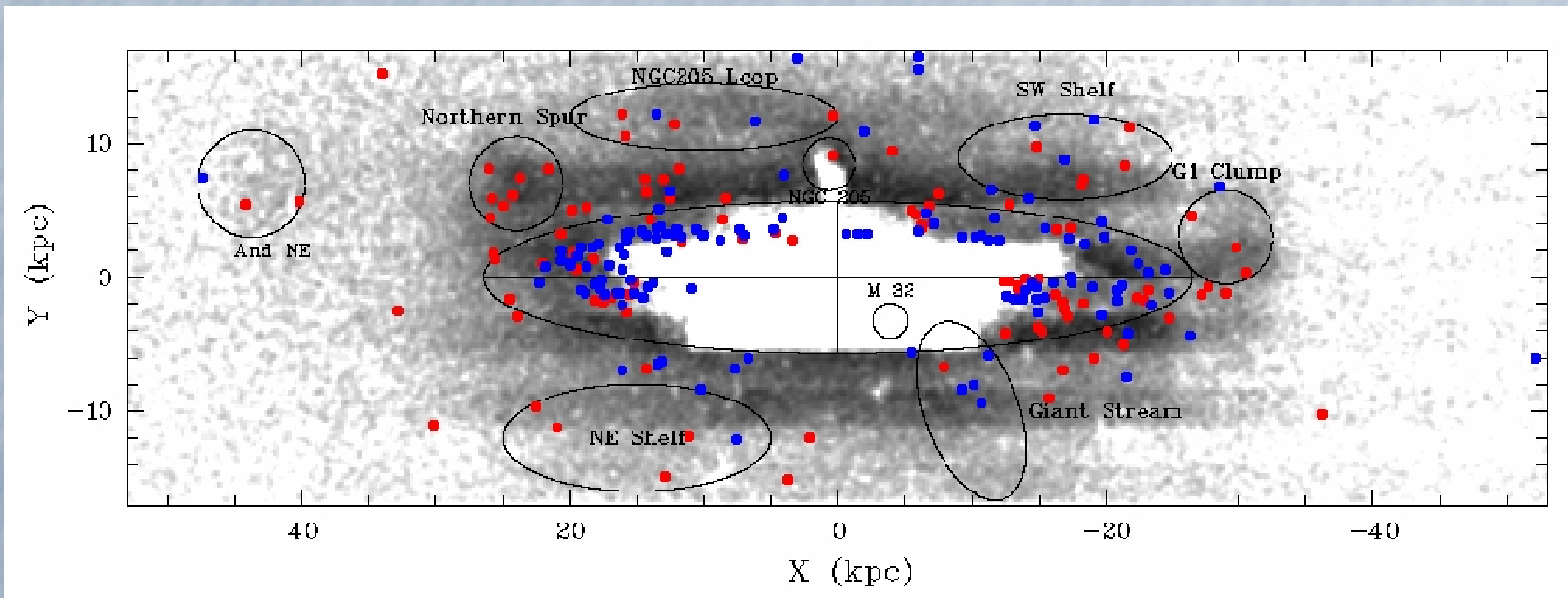
(1) December 2004 - Hurley-Keller et al. (2004): 136 PNe selected with narrow-band imaging and observed with WIYN Hydra fiber spectrograph

(2) Halliday et al. (2006): 723 PNe in the disk and bulge – narrow-band imaging and spectroscopy with fibre-fed spectrograph at WHT (LA Palma)

(3) Merret et al. (2006): 2615 PNe selected with PN.S at WHT



Thick disk in M31?

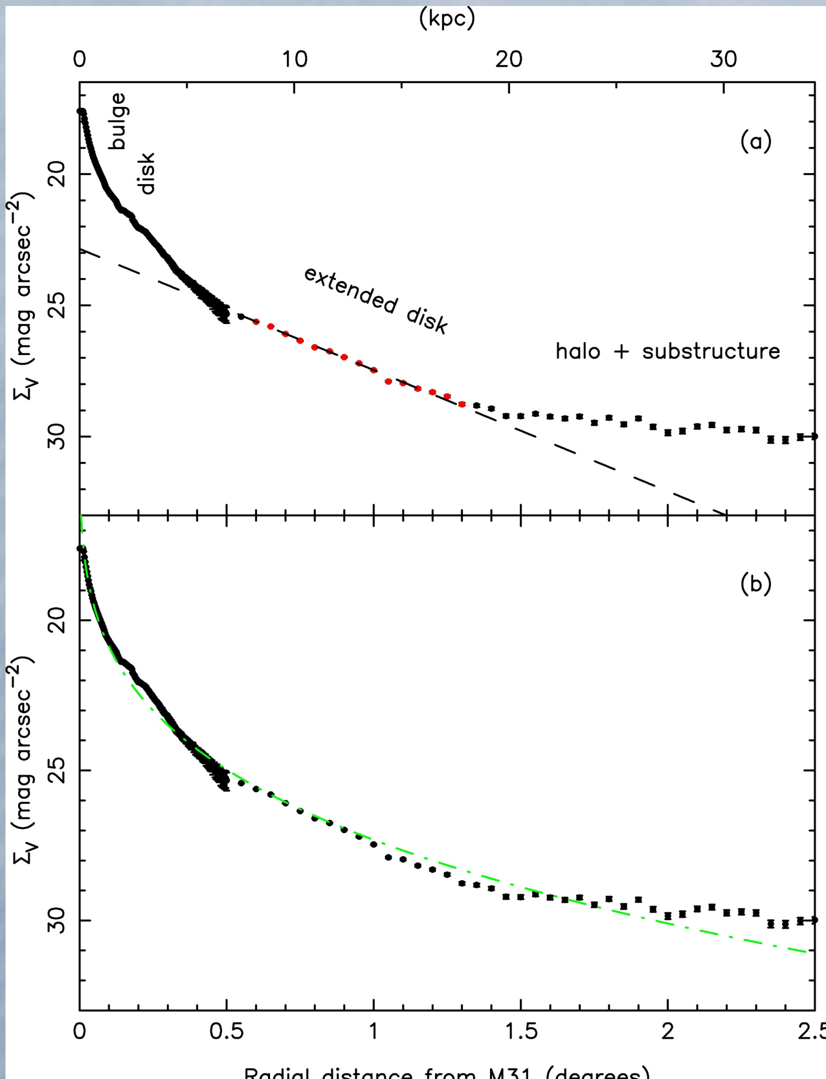


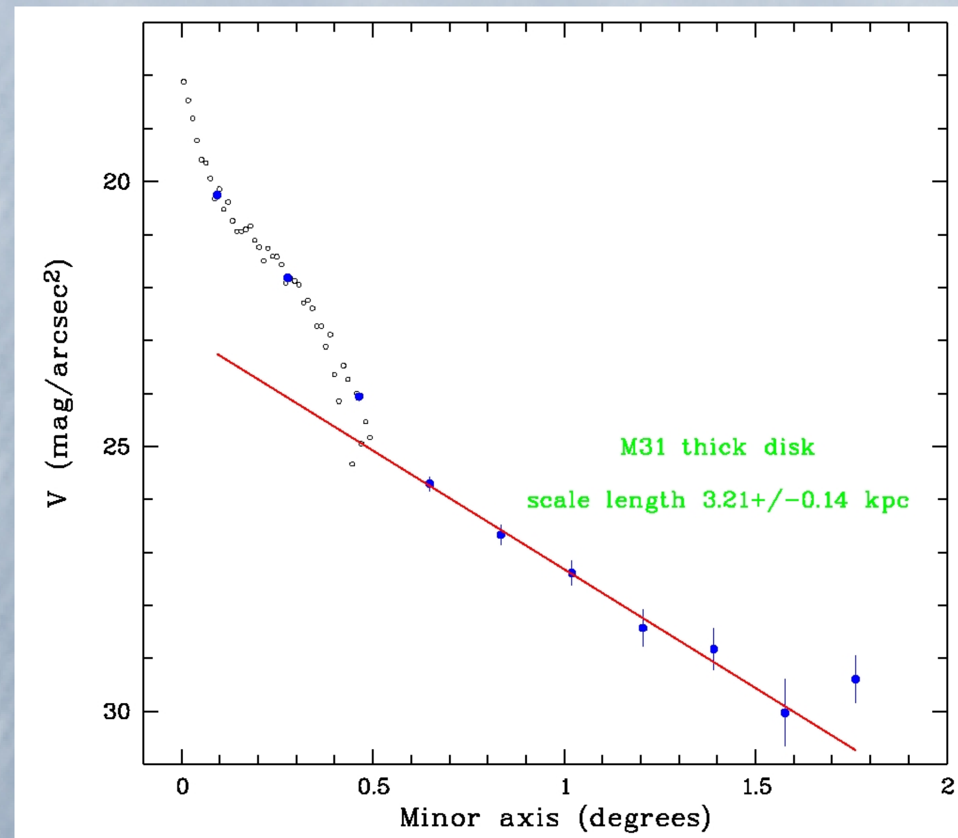
Several edge-on galaxies probably indicating the presence of thick disk (Dalcanton & Bernstein 2002)

Tikhonov et al. (2004, 2005) with HST data showed that all disk galaxies have thick disk

<u>Can we trace it with PNe?</u>

Thick disk in M31: stars and PNe



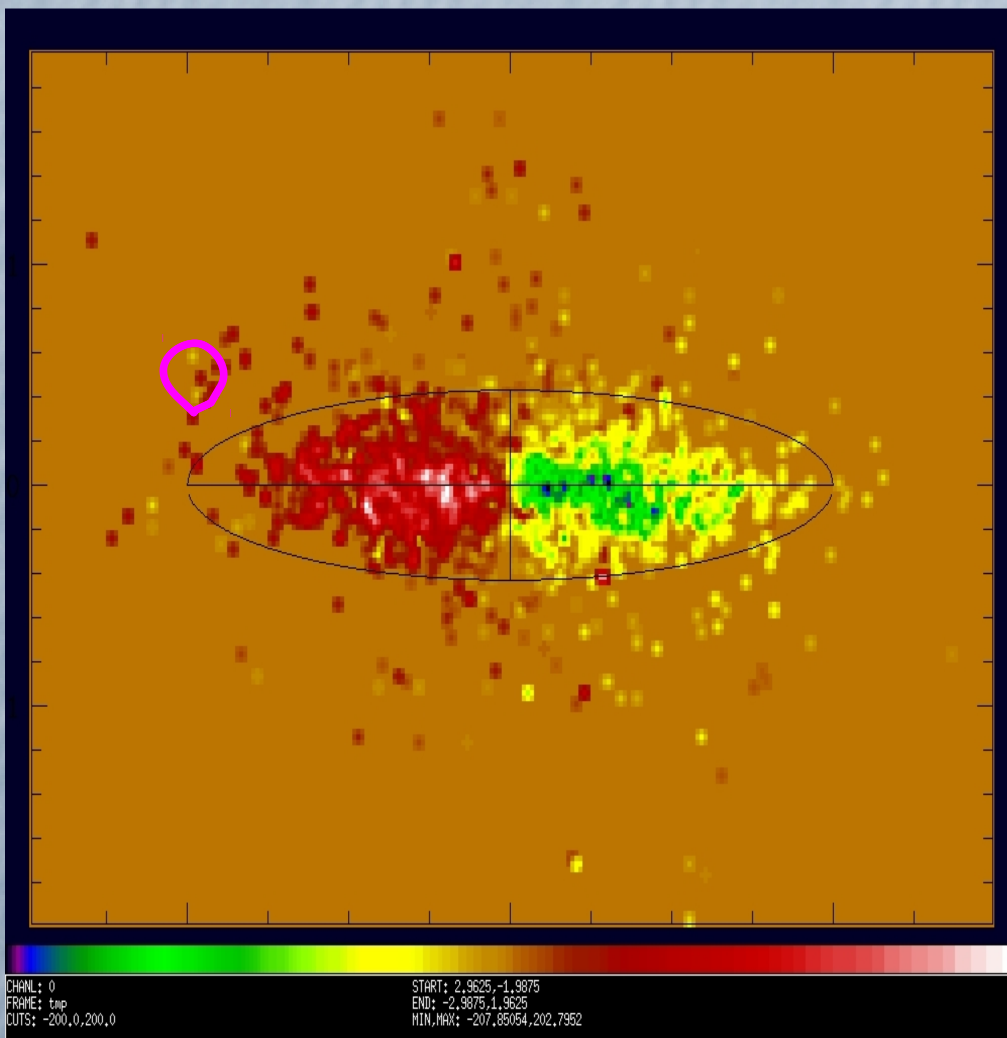


Irwin et al. (2005) and Ibata et al. (2007) with INT survey data of M31 have found exponential scale length 3.22+/- 0.02 kpc along the minor axis profile.

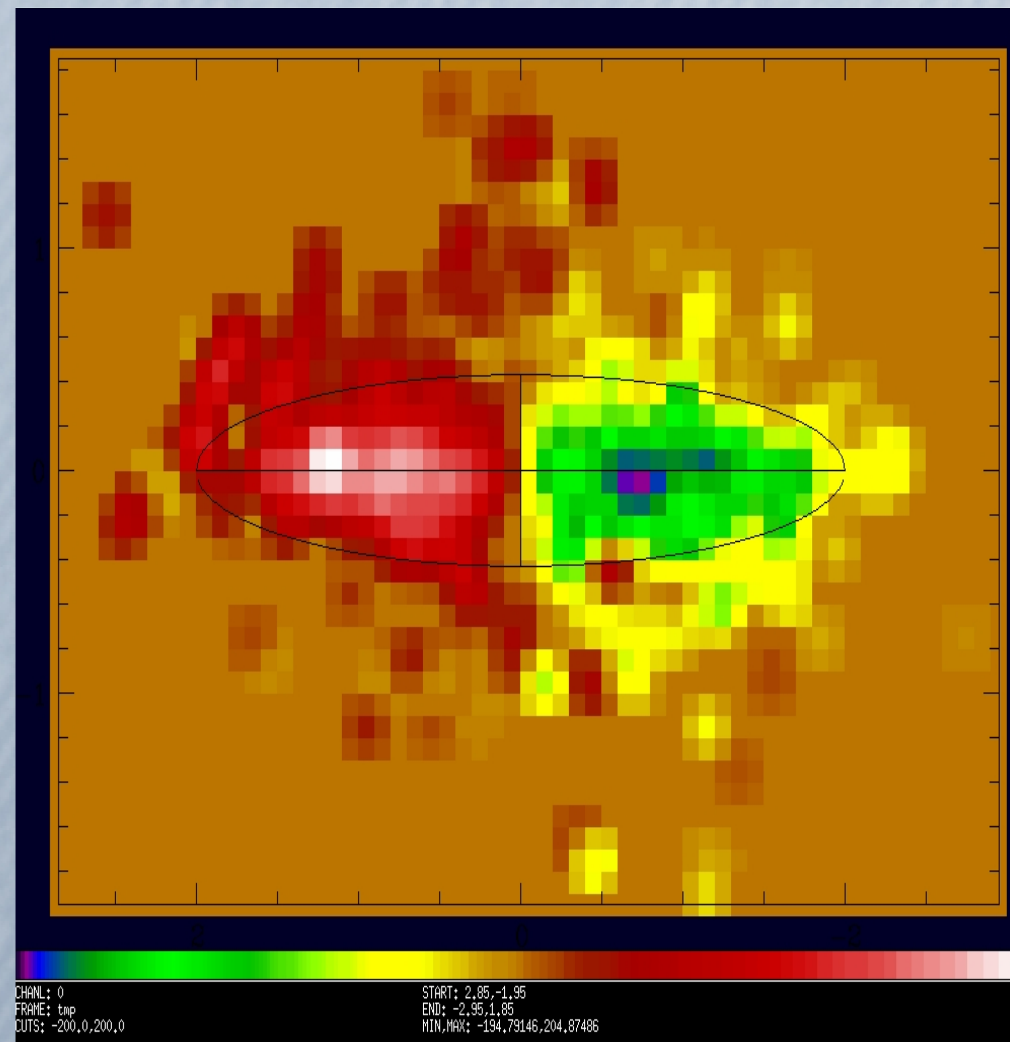
Can we see this disk in velocities distribution?

2D Velocity distribution of M31

90 arcsec x 90 arcsec



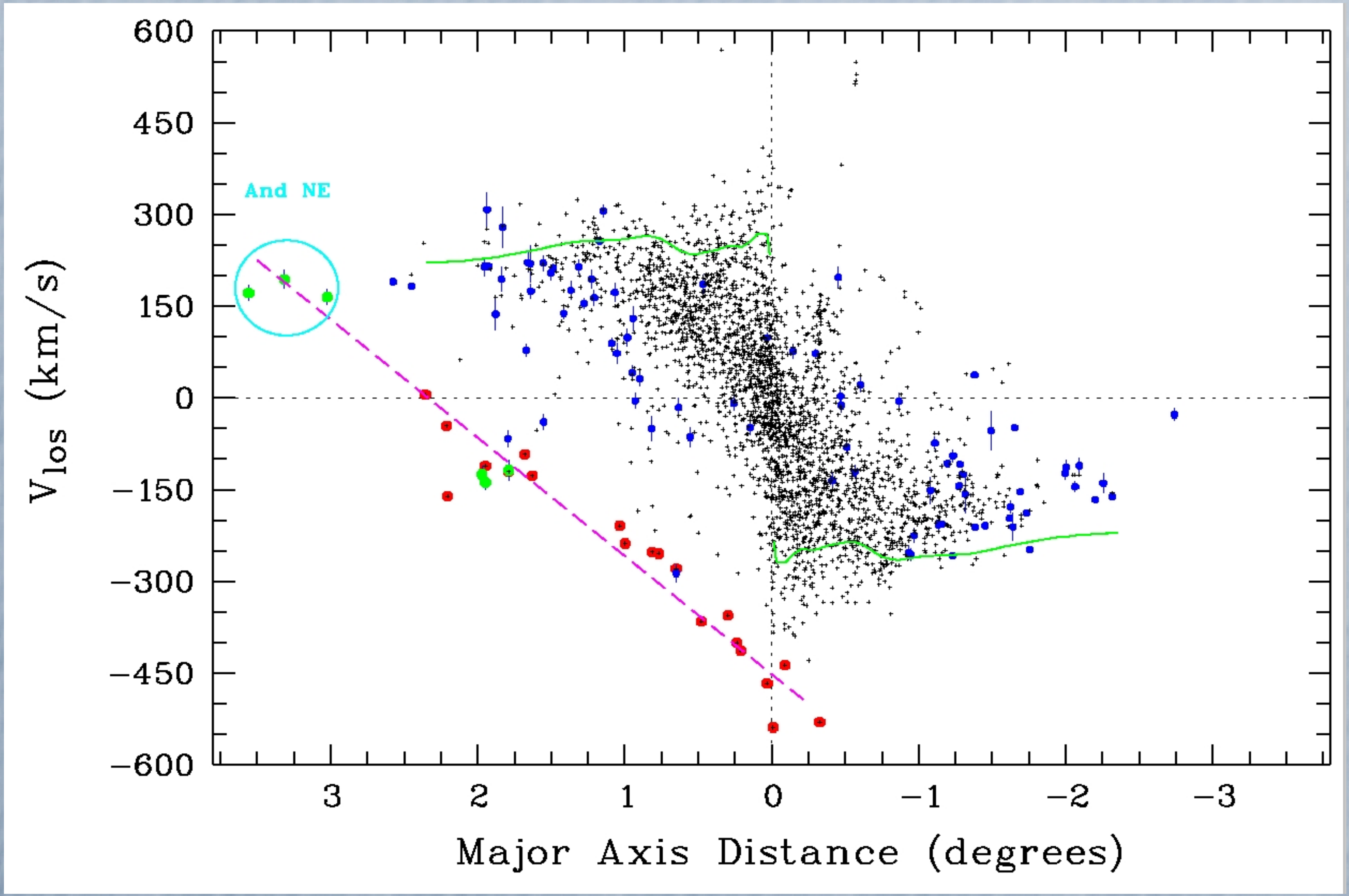
6 arcmin x 6 arcmin



Velocity distribution with PNe

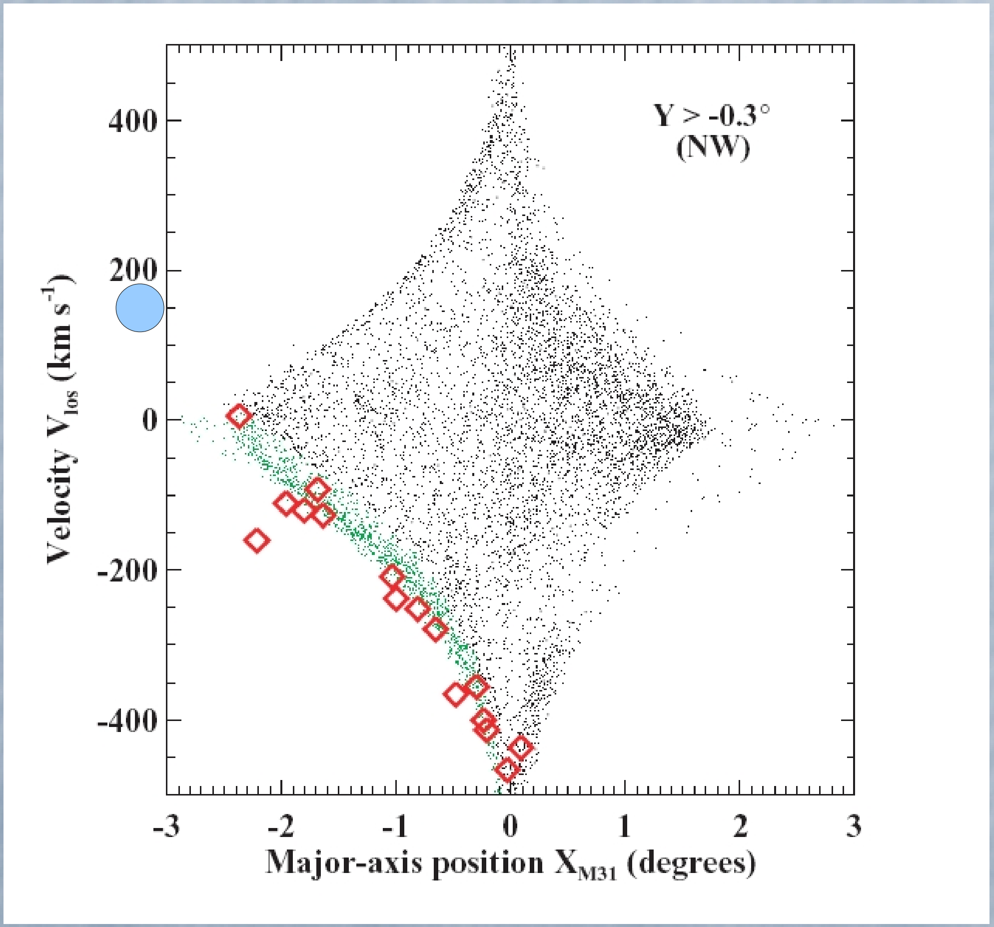
Some PNe were identified by Merrett et al. (2003, 2006) as a possible continuation of the merging Southern Stream of stars (Ibata et. 2001,2004)

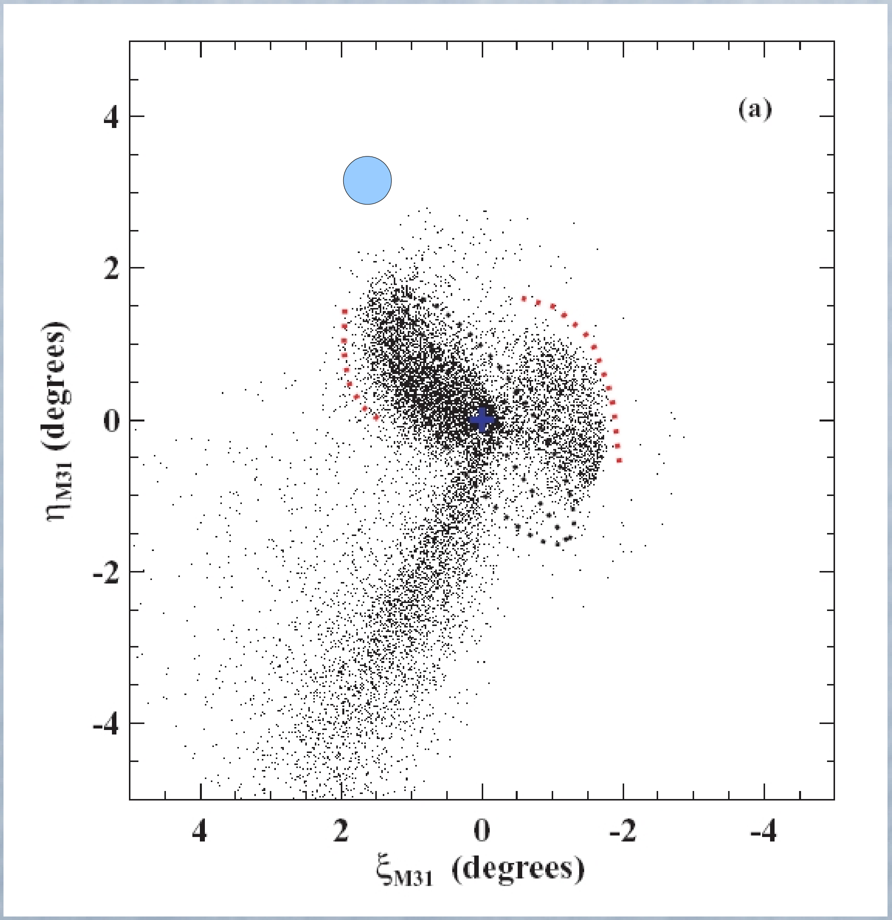
No HI
in the region
of And NE



From Kniazev et al. (2014, AJ, 147,16)

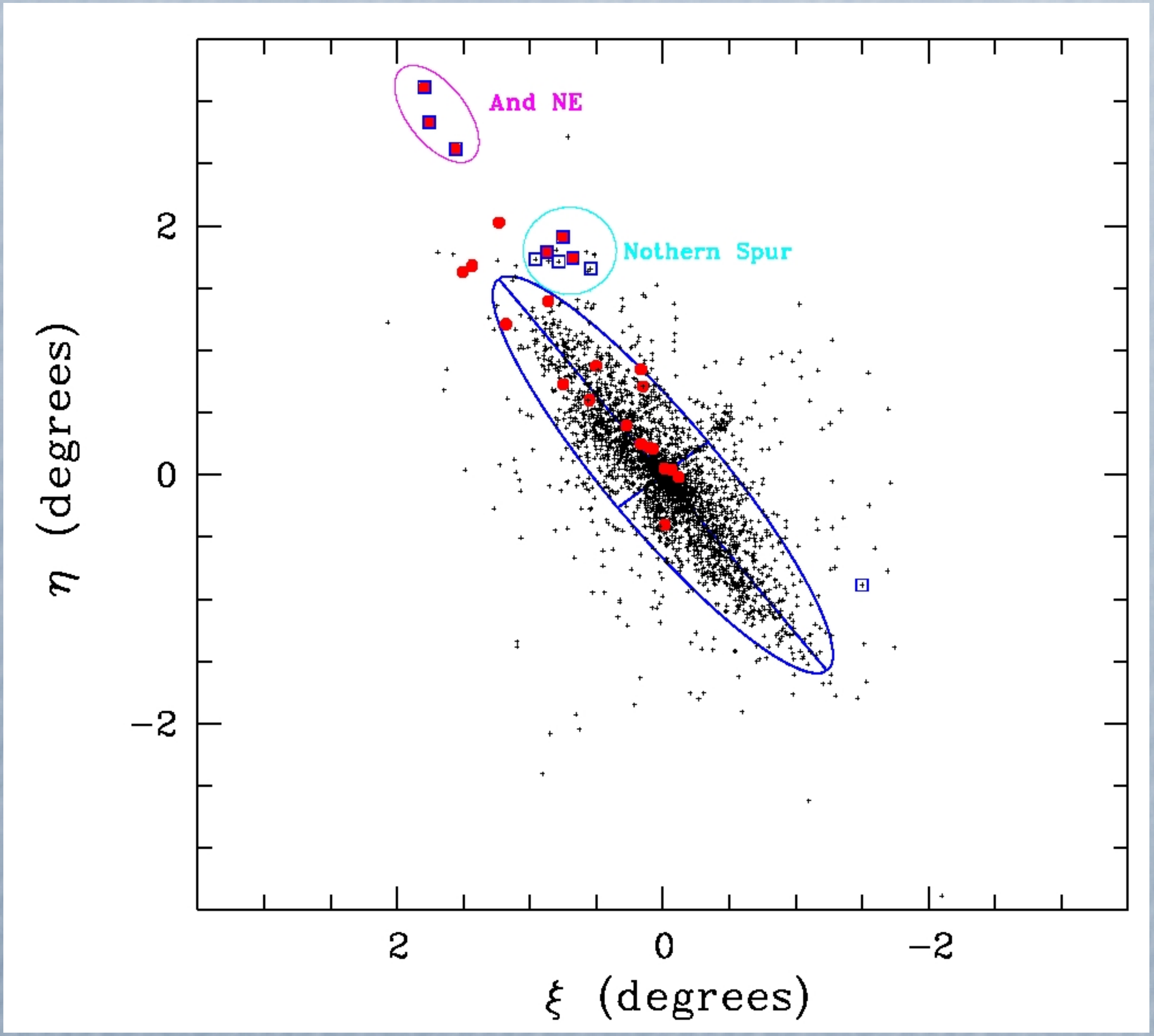
Is And NE the core or remnant of the progenitor of this stream ?





The model from Fardal et al. (2007, MNRAS, 380, 15)

Is And NE the core or remnant of the progenitor of this stream ?



Spectral Observations of selected PNe

3.5m telescope at Calar Alto (Spain);

TWIN; 3500–7500 Å, ~1 Å/pix

(FWHM ~ 5Å);

4 (3) nights in August 2005 under variable weather conditions;

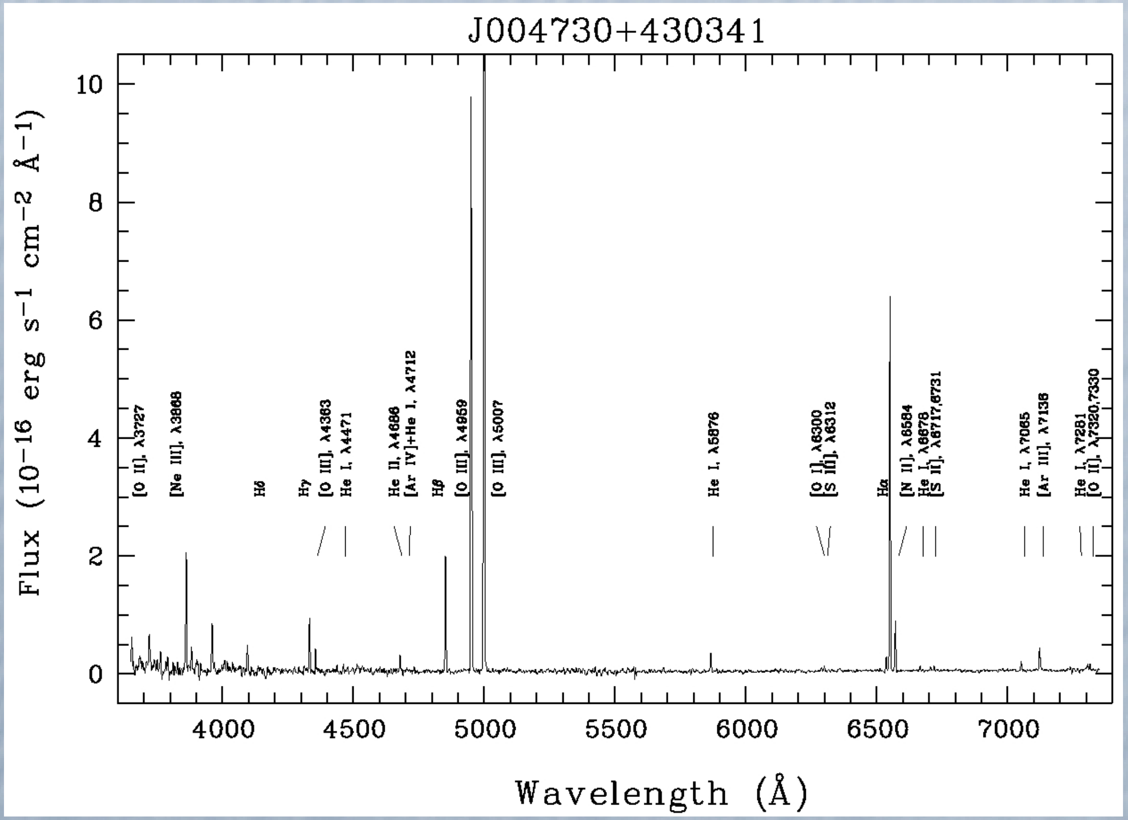
Total exposures 45–60 min;

Totally 9 PNe were observed

6m telescope (SAO; Russia);

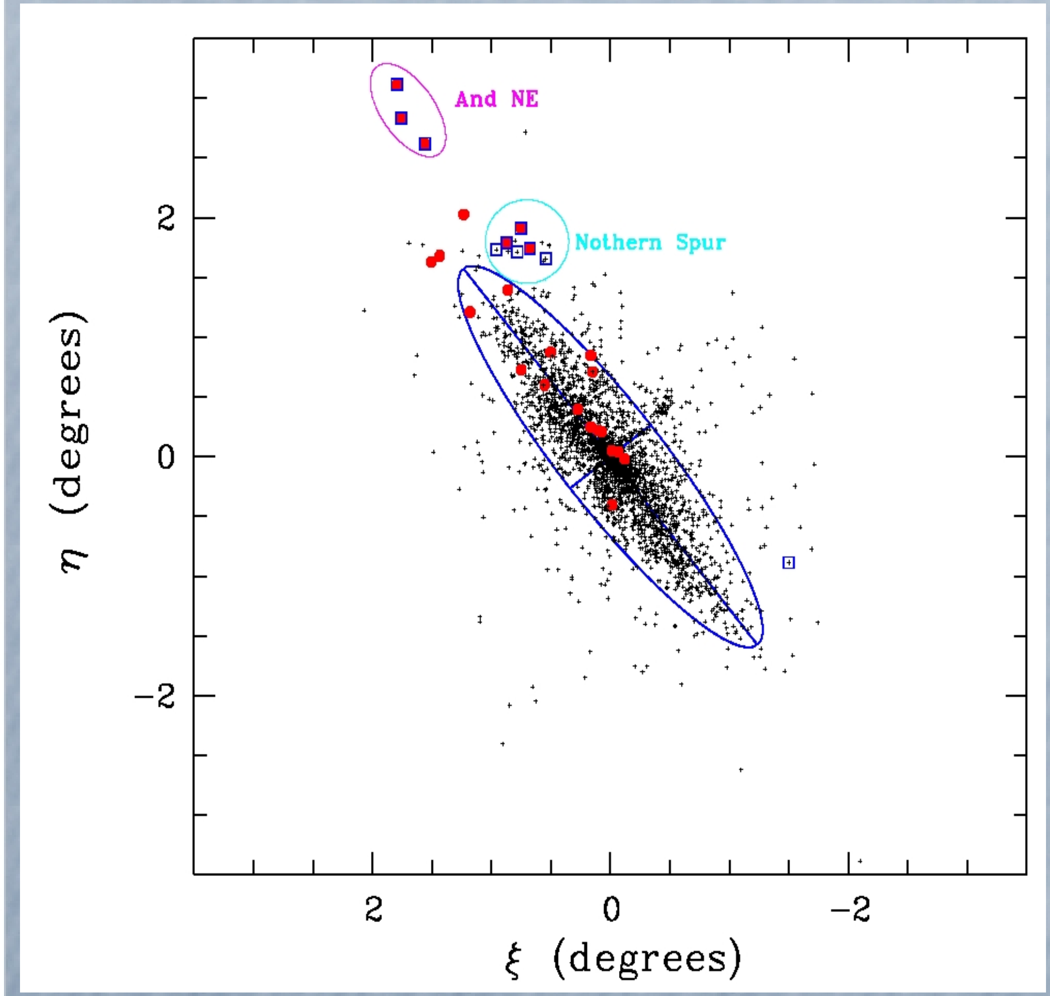
SCORPIO; 3700-7200 Å, ~2.5 Å/pix

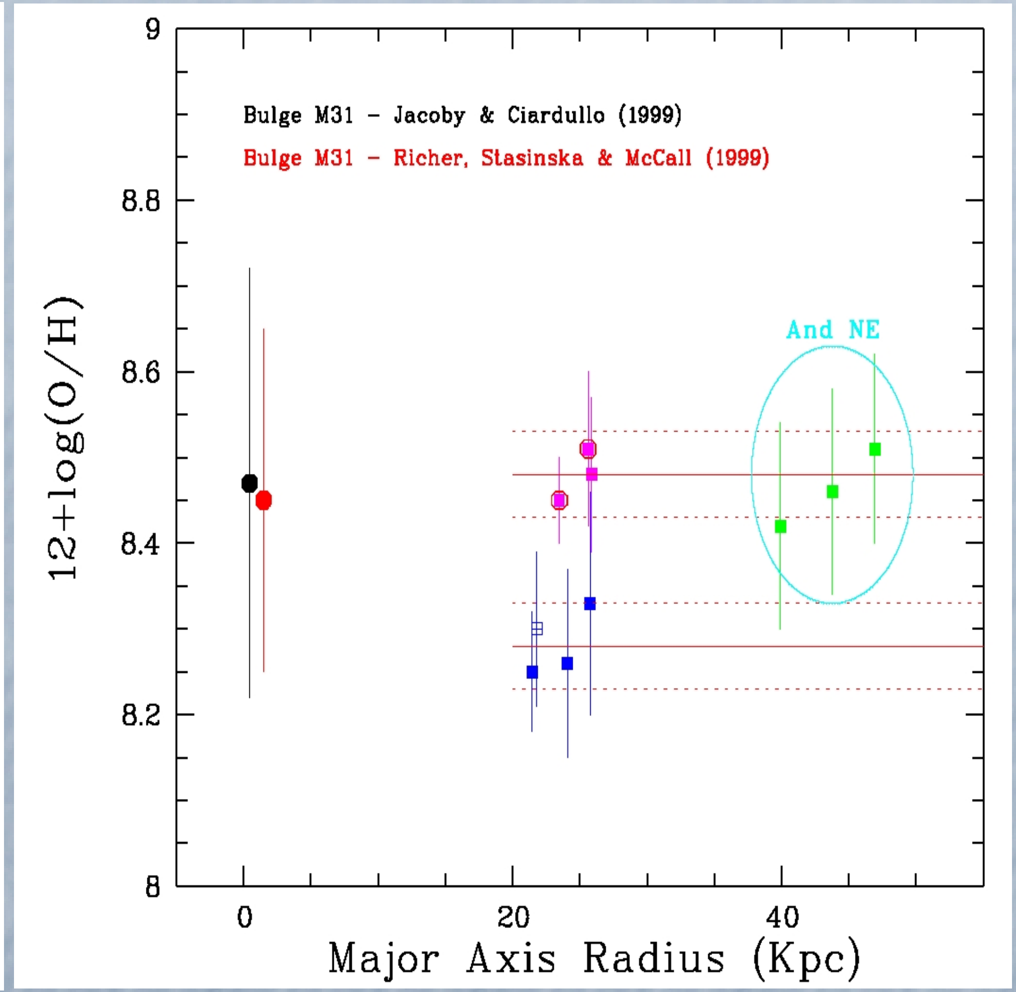
1 additional PN in Andromeda NE



From Kniazev et al. (2016, in preparation)

And NE as the core or remnant of the progenitor of the stream (1)



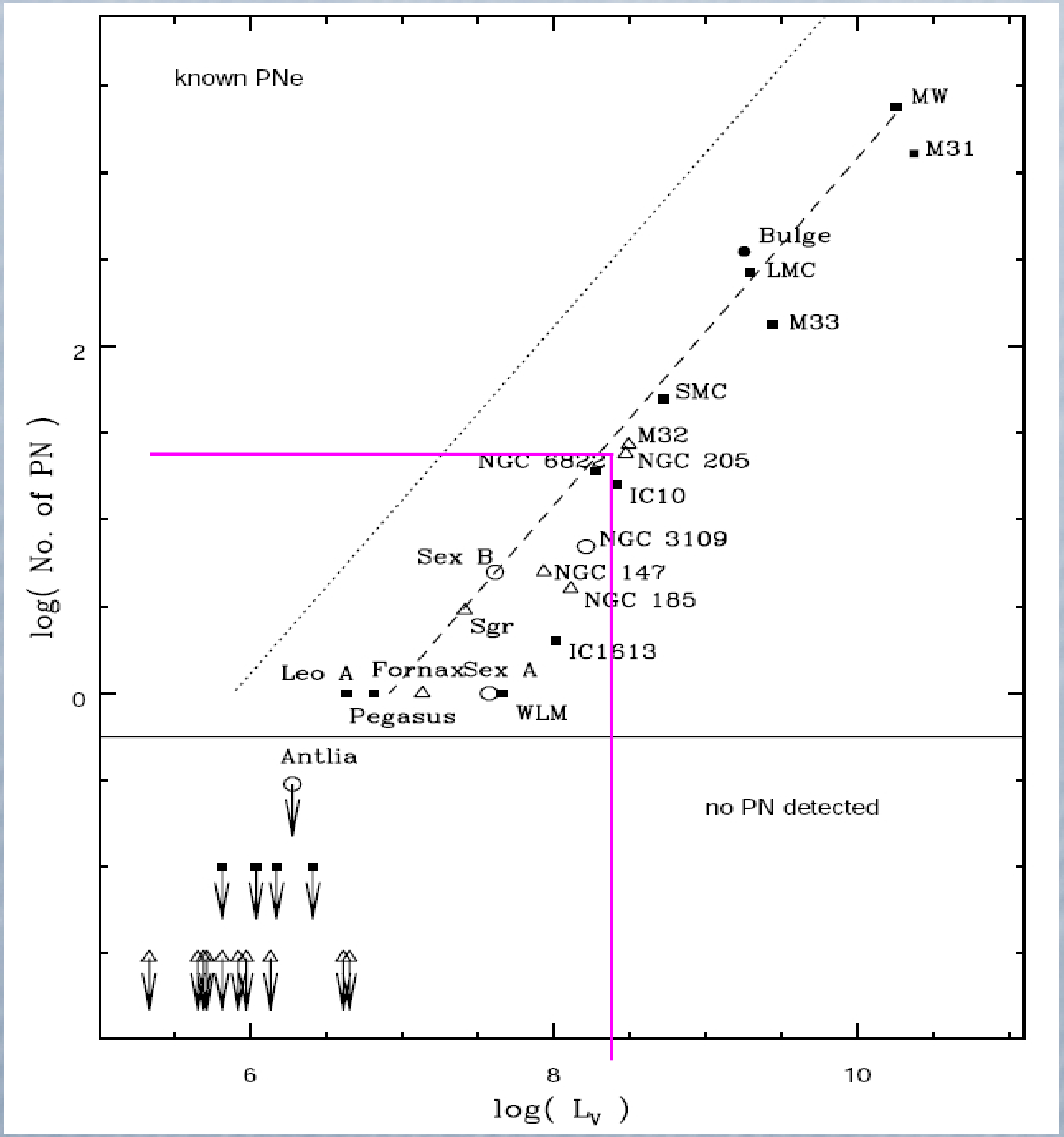


How bright was And NE before? (1)

In total 22 PNe are selected as members of this stream

M(V) ~ -15.9

Was comparable to NGC205!



From Magrini et al. (2003)

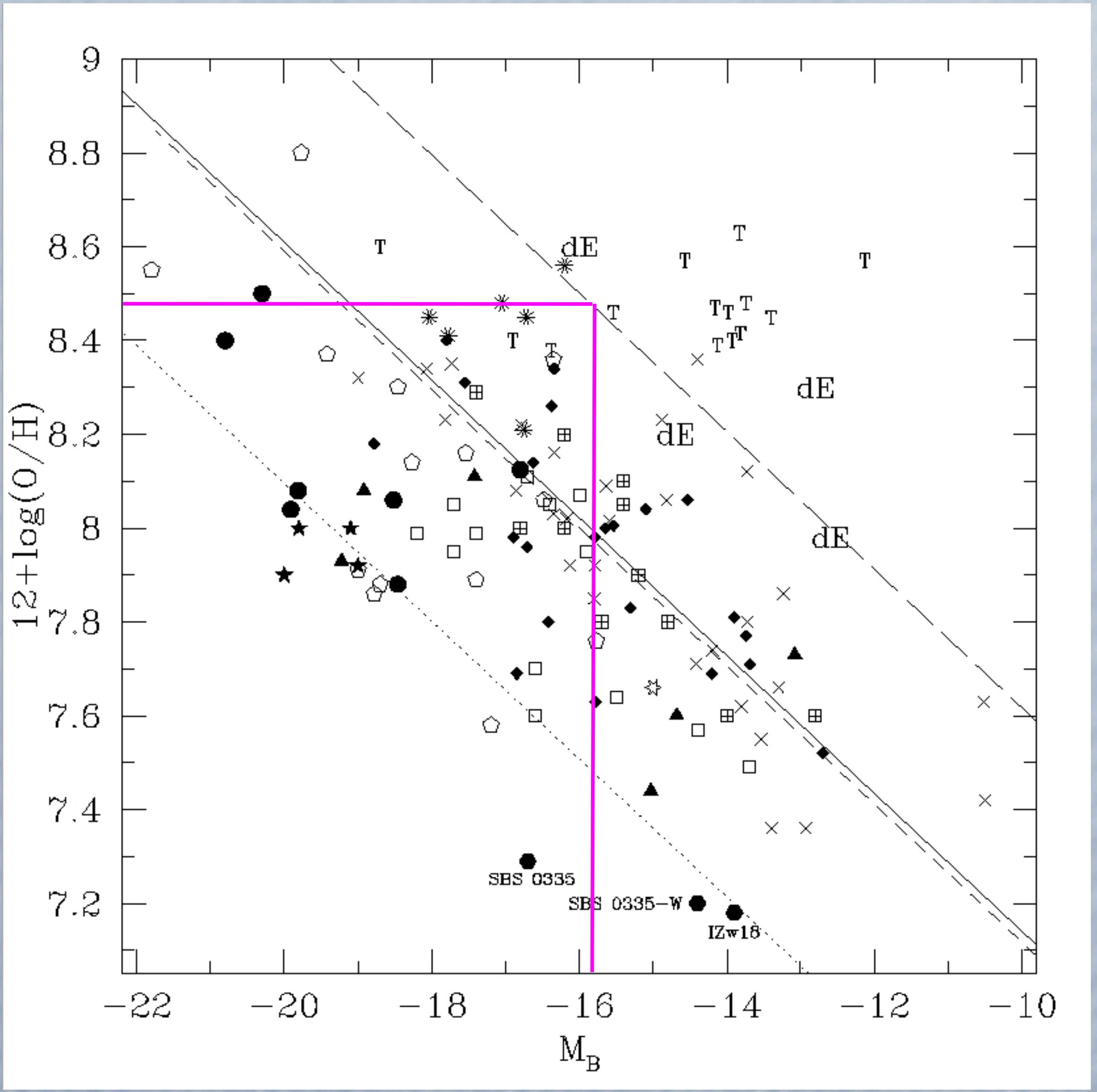
How bright was And NE before? (2)

From LZ ratio for dEs

M(B) = -15.8

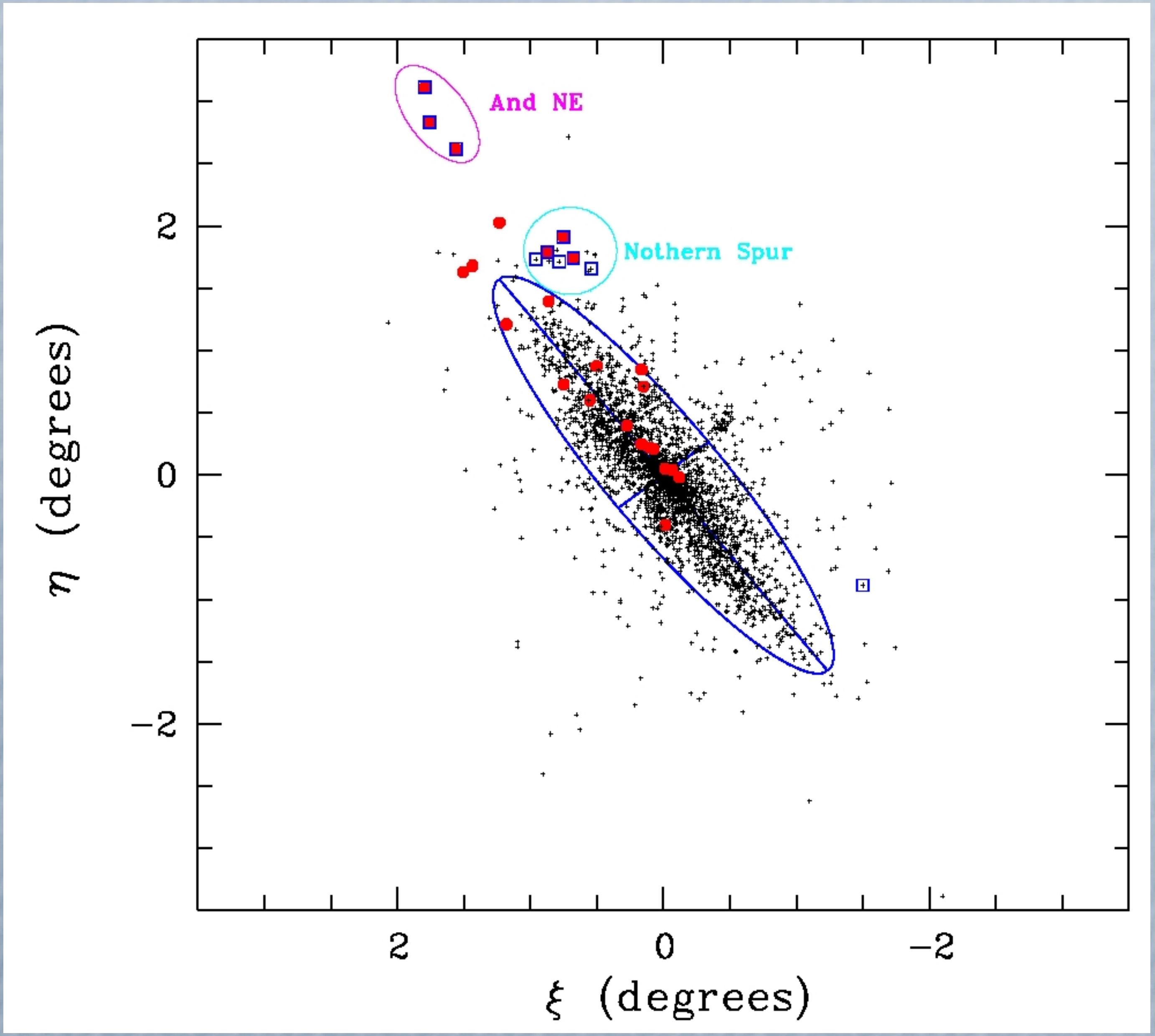
Was comparable to NGC205!

> 90% of stars was lost?



From Kunth & Ostlin et al. (1999)

How it is hard to find such a stream?



The PNe in the area of CMa dwarf galaxy (1)

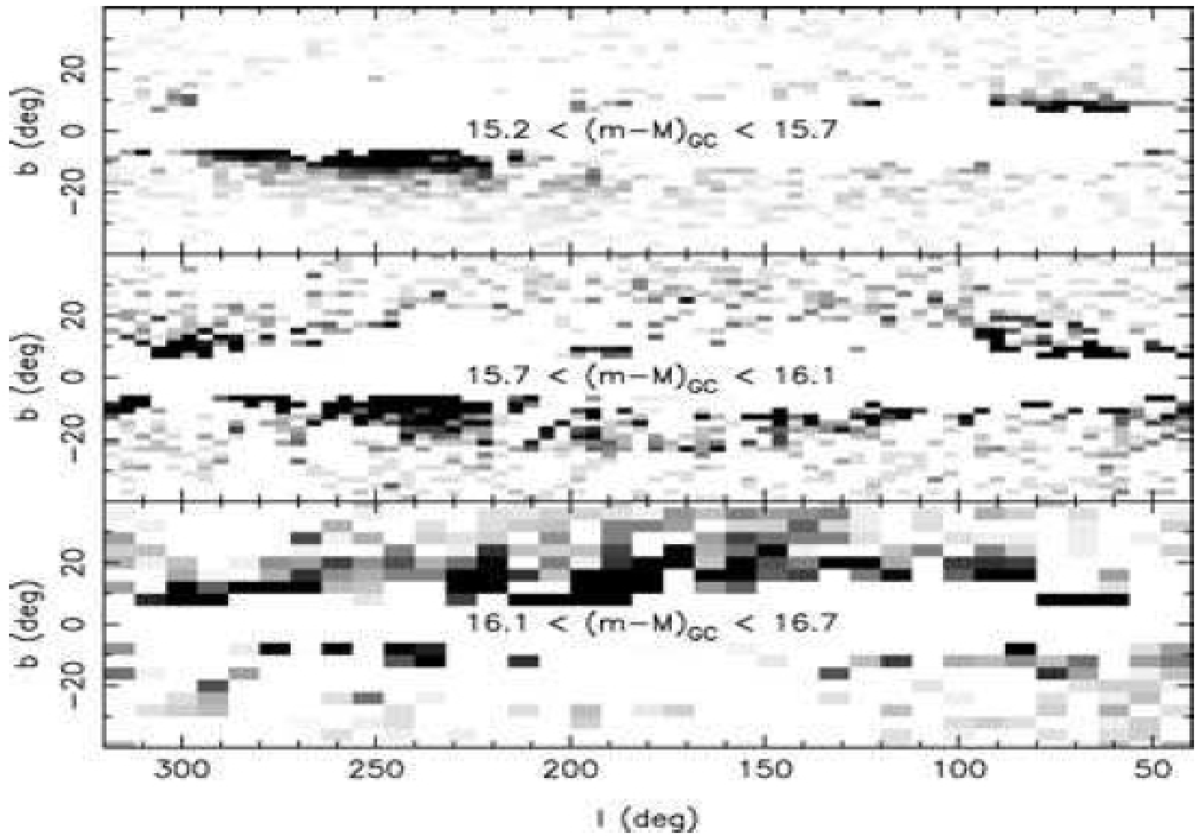


Figure 4. As Fig. 3, but showing the difference in M-giant starcounts between the two hemispheres. The Canis Major overdensity at ($\ell \sim 240°$, $b \sim -10°$) is clearly visible on the upper two panels. The middle panel also shows a fainter population arcing over the sky between $110° \lesssim \ell \lesssim 210°$ in the southern hemisphere. Another huge arc-like structure is present in the northern hemisphere in the bottom panel ranging from $\ell \sim 140°$ to $\ell \sim 220°$. In the top, middle and bottom panels, a black pixel corresponds to 40, 8 and 8 counts, respectively.

From Martin et al. (2004, MNRAS, 348,12) – the total area ~100 sq.deg

The PNe in the area of CMa dwarf galaxy (1)

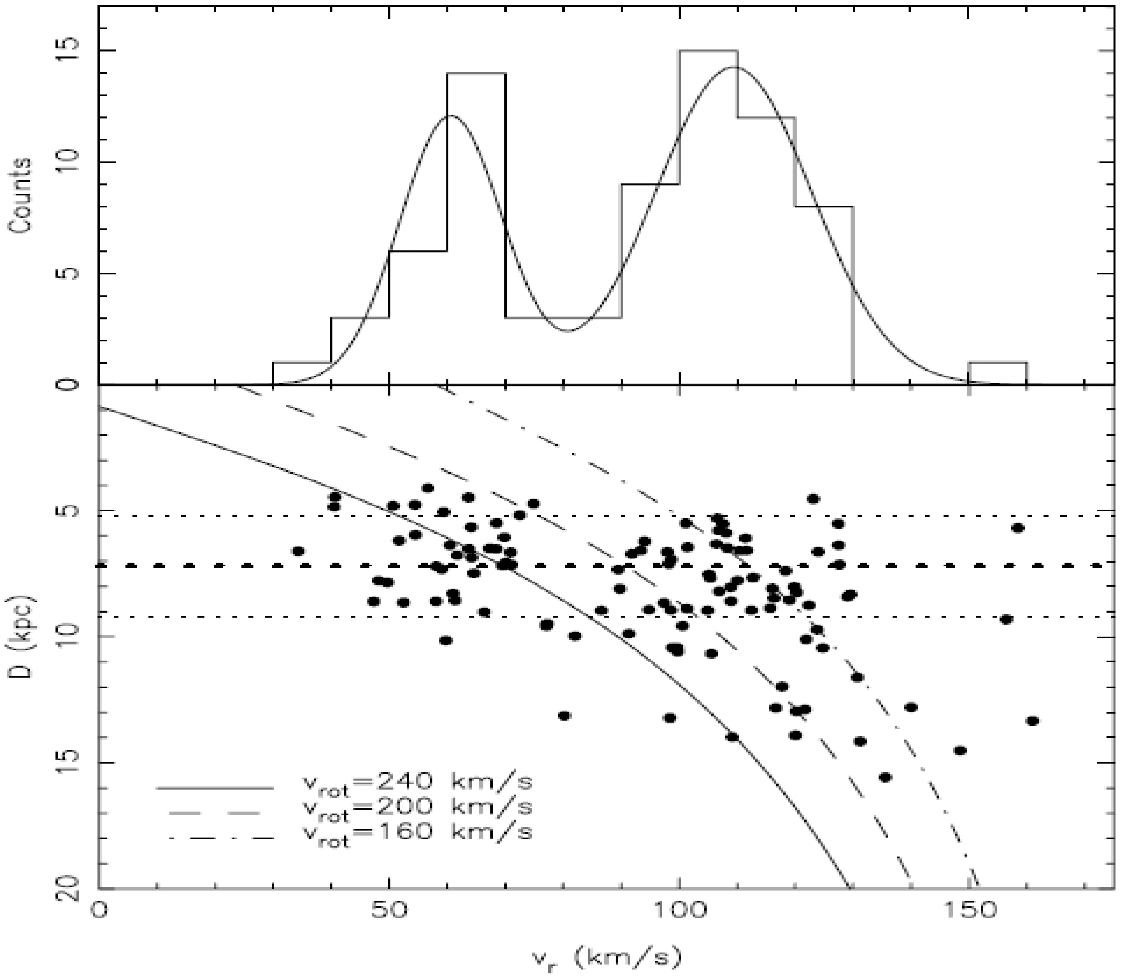


Figure 3. The top panel shows the distribution of radial velocities of the M giant targeted in our two 2dF fields (see text for details). A clear bimodality is present that we fit by a double Gaussian model (thin line) using a maximum-likelihood algorithm. We identify the second, more numerous population centred on $v_r = 109\ \mathrm{km\,s^{-1}}$, as the CMa overdensity. The bottom panel

Martin et al. (2004, MNRAS, 355,L33)

The PNe in the area of CMa dwarf galaxy (1)

IF the over-density of stars in the direction of Canis Major IS the remnant of a disrupted dwarf spheroidal galaxy (dSph):

(1) it is located at a distance of $\sim$7.2 kpc from the Sun or $\sim$15 kpc from the center of the Milky Way

(2) its stars can have metallicities [Fe/H] ~ -1 or even lower

(3) have radial velocities of the order of Vr = 109 km/s

The PNe in the area of CMa dwarf galaxy (1)

The dSph galaxy? Or warped thin Galactic disk? Or warped thick Galactic disk?
Or structural peculiarities of the outer part of the Norma–Cygnus spiral arm?

Table 1
Summary of Previous Stellar Population Studies Conducted in CMa

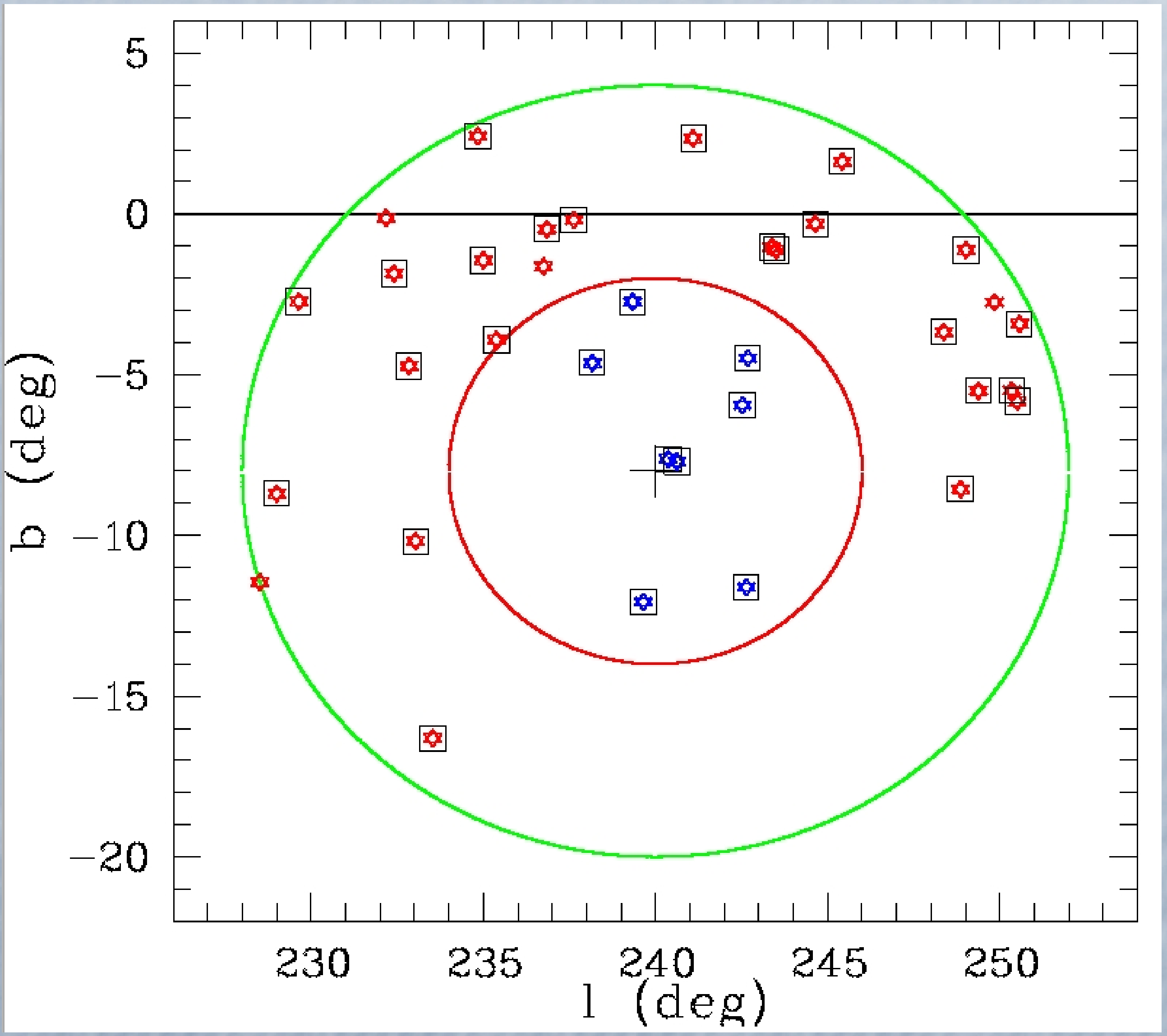
Tracer	Age (Gyr)	[Fe/H]	$D_\odot$ (kpc)	Technique	Filters	Interpretation	Reference
Blue plume	1–2	...	...	MS-fitting	*BV*	dSph galaxy	B04
Blue plume	~0.7–2	−0.3 or ~−1.0	~7.5 or 9.3	HD modelling	*BR*	dSph galaxy	dJ07
Blue plume	$\lesssim$0.1	...	10.8	TCDs, MS fitting	*UBVRI*	Spiral arm	C05, Moi06
Blue plume	...	−0.37 to −0.5	6.0 ± 2.7	TCDs, spectroscopy	*UBV*	Spiral arm	P08
B5-A0 stars	$\lesssim$0.1	...	$9.8^{+1.5}_{-1.0}$	TCDs	*UBVRI*	Spiral arm	C08
MS	3–6	~−1.0 ± 0.1	~7.5	HD modelling	*BR*	dSph galaxy	dJ07, B07
RGB, MS	4–10	−0.66 to −0.35	~8.1 ± 1.2	Isocrone fitting	*BV*	dSph galaxy	B04
M giants	4–10	−1.0 < [M/H]	7.1 ± 0.1	CMD fitting	*JHK*	dSph galaxy	M04
RGB, RC	...	...	5.5 to 8.5	Spectroscopy	...	dSph galaxy	M05
F–G–K stars	6 ± 2	~−0.3 ± 0.3	6	TCDs	*UBVRI*	Warped thick disk	C08

References. B04=Bellazzini et al. (2004); M04=Martin et al. (2004a); M05=Martin et al. (2005); C05=Carraro et al. (2005); Moi06=Moitinho et al. (2006); B07=Butler et al. (2007); dJ07=de Jong et al. (2007); C08=Carraro et al. (2008); P08=Powell et al. (2008).

From Mateu et al. (2009, AJ, 137,44)

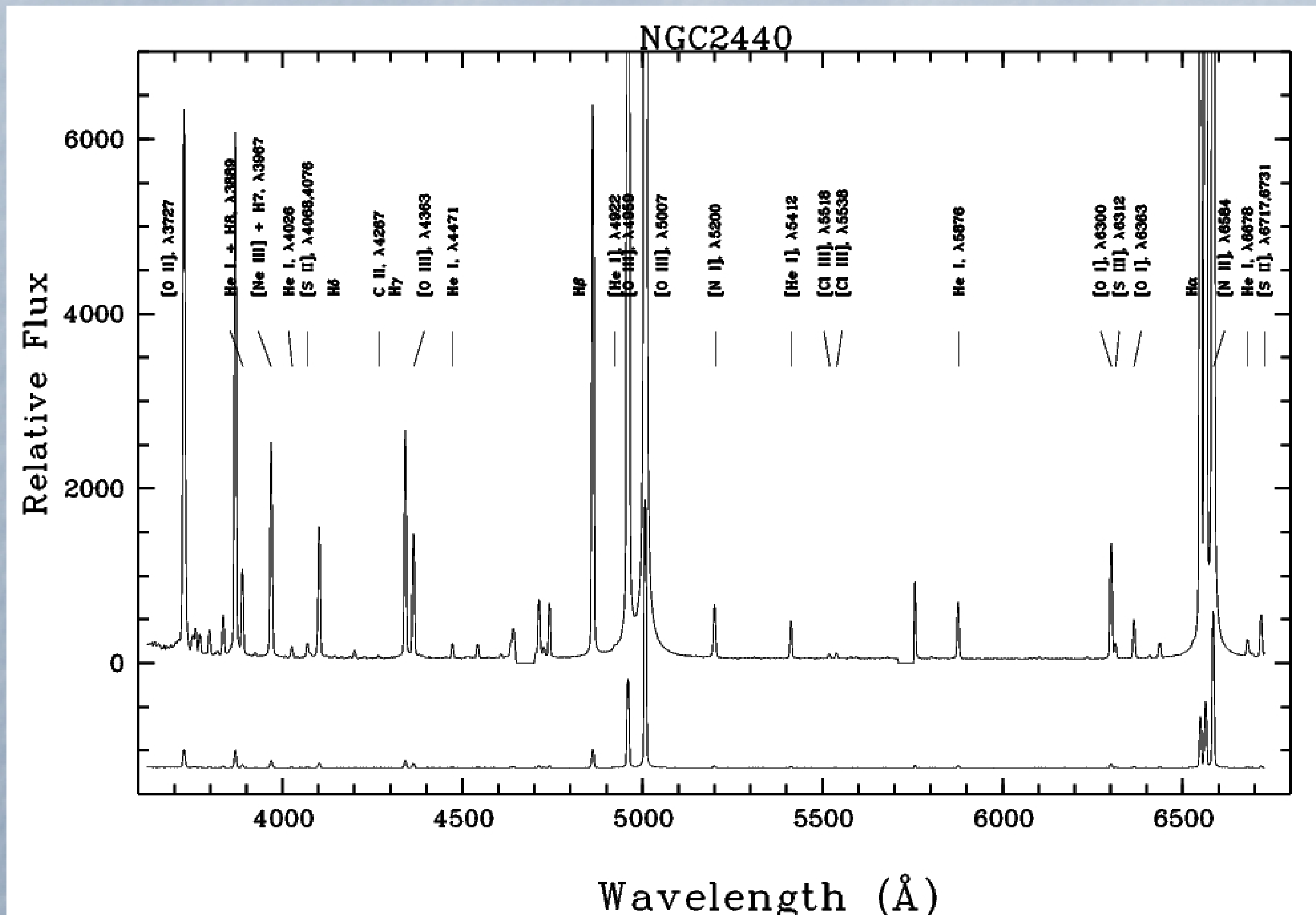
The PNe in the area of CMa dwarf galaxy (2)

Sky distribution of the sample of PNe and PN candidates from the region of CMa in the Galactic coordinate system. The center of the region with coordinates (l, b) =(240◦,−8◦) is indicated by the cross at the center. The first- (11) and second-priority (27) objects are indicated by the blue and red symbols, respectively.



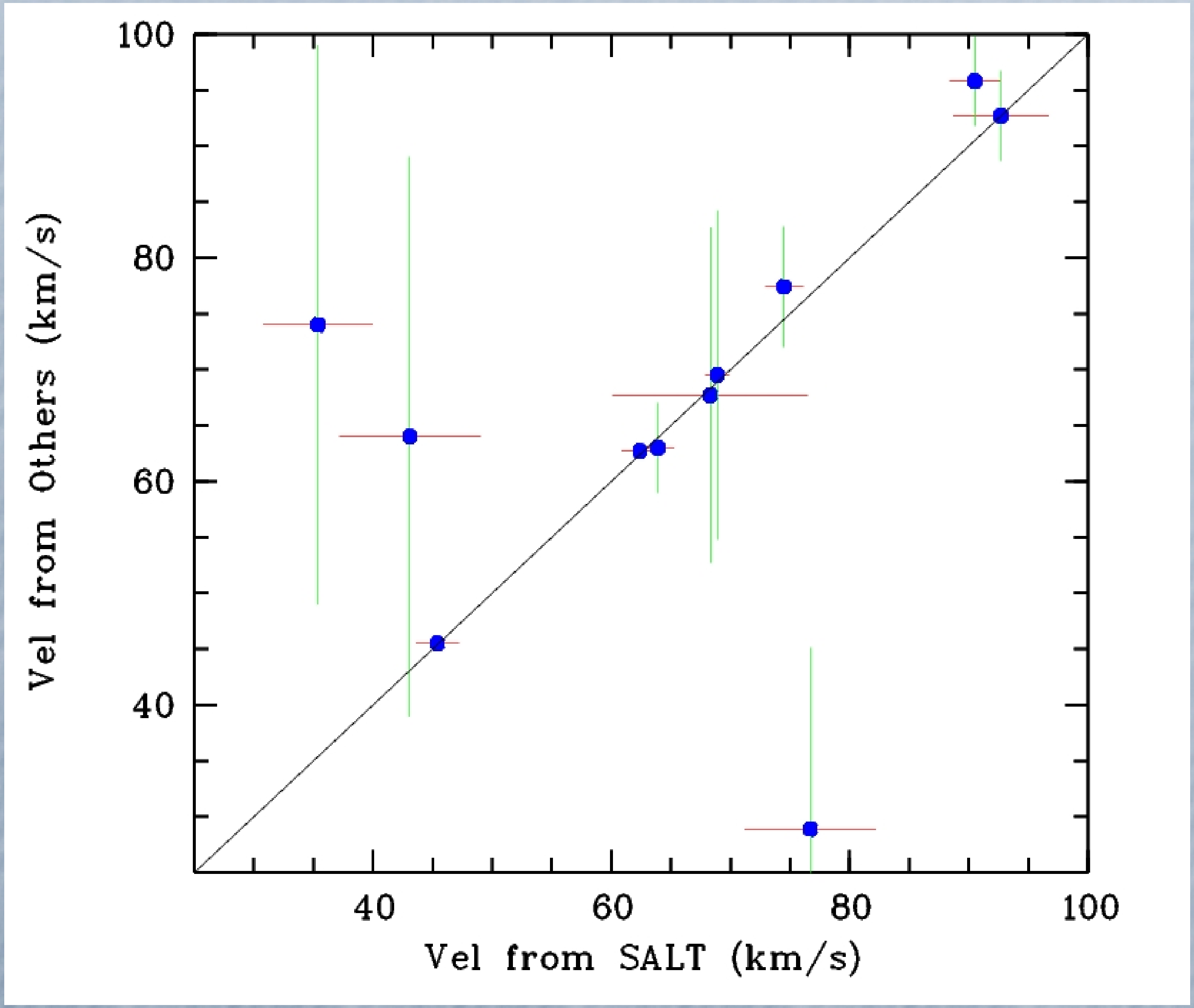
Pilot results on observations of first 7 PNe were published in **Kniazev (2012).**
From the total sample of 38 PNe and PNe candidates with size <100",
31 were observed with SALT during 2006 and 2012-2013.

The PNe in the area of CMa dwarf galaxy (3)



From the total sample of 38 PNe and PNe candidates, 31 were observed with SALT during 2006 and 2012-2013.

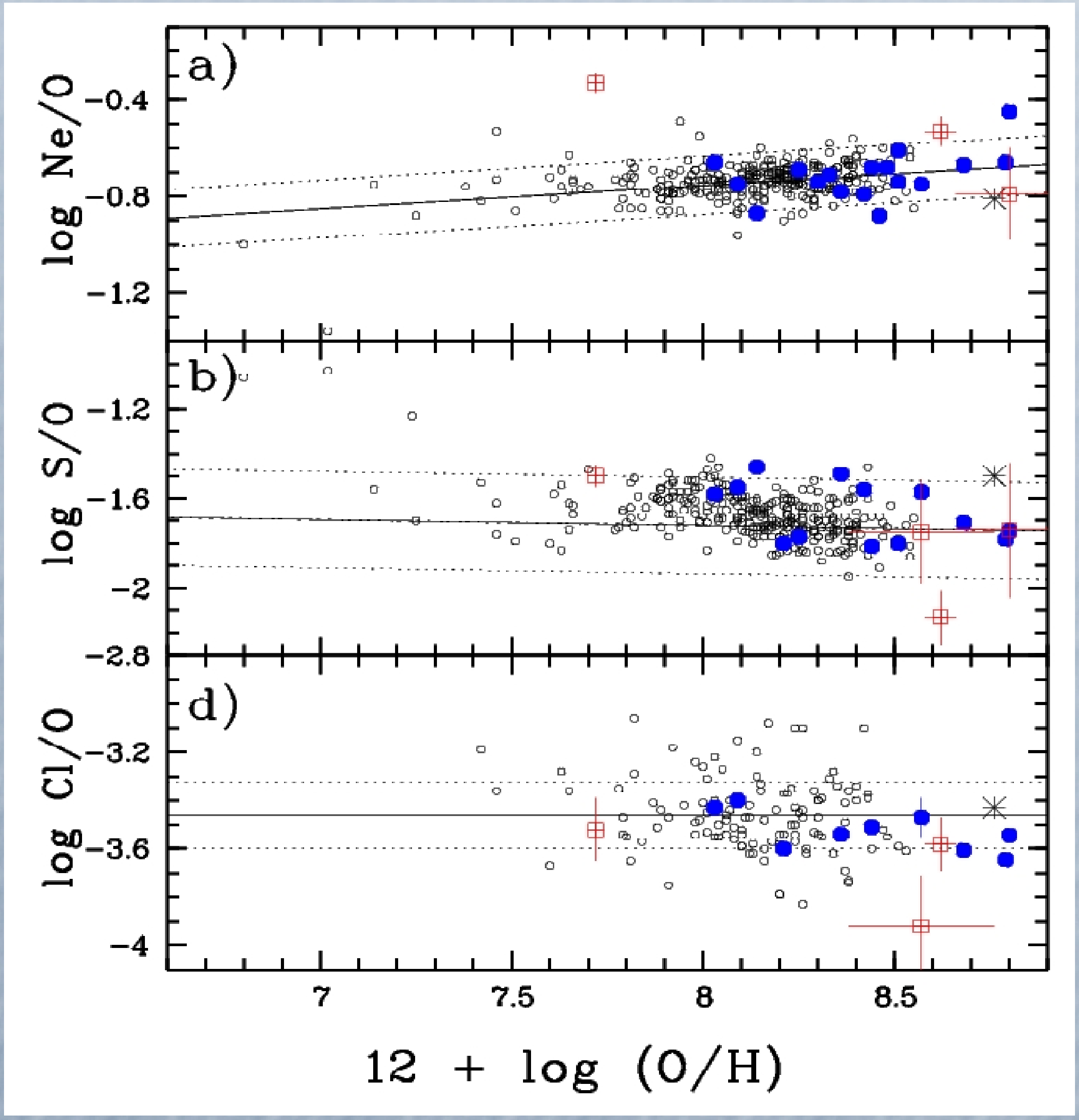
The PNe in the area of CMa dwarf galaxy (4)



The comparison of velocities taken from SALT data (grating GR900) and from other sources. SALT data show very nice accuracy.

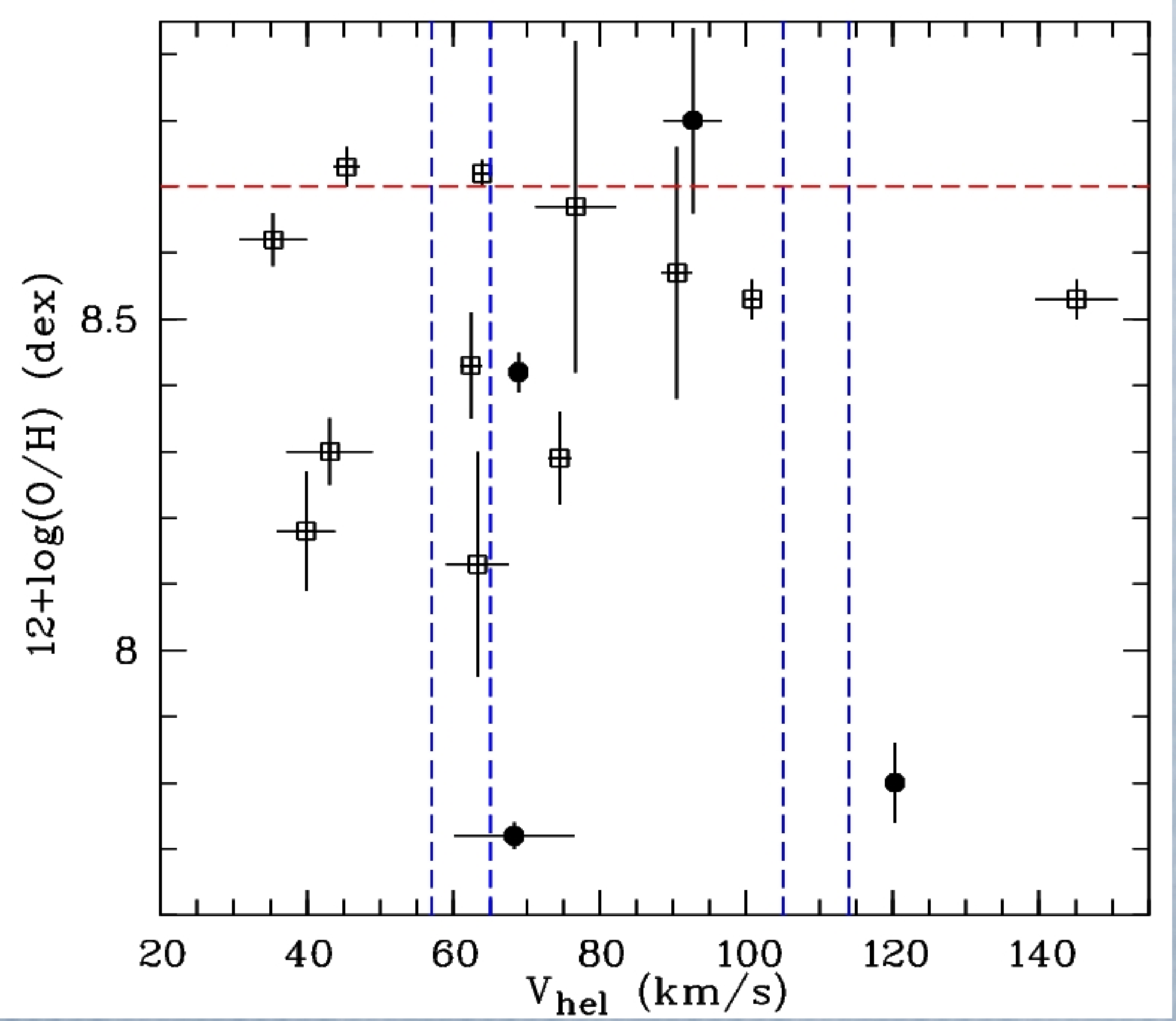
The PNe in the area of CMa dwarf galaxy (5)

α-element/oxygen abundance ratios log(Ne/O), log(S/O), and log(Cl/O) for HII regions versus oxygen abundance. The large filled circles and open red squares represent the calculated abundance ratios for observed PNe with SALT .



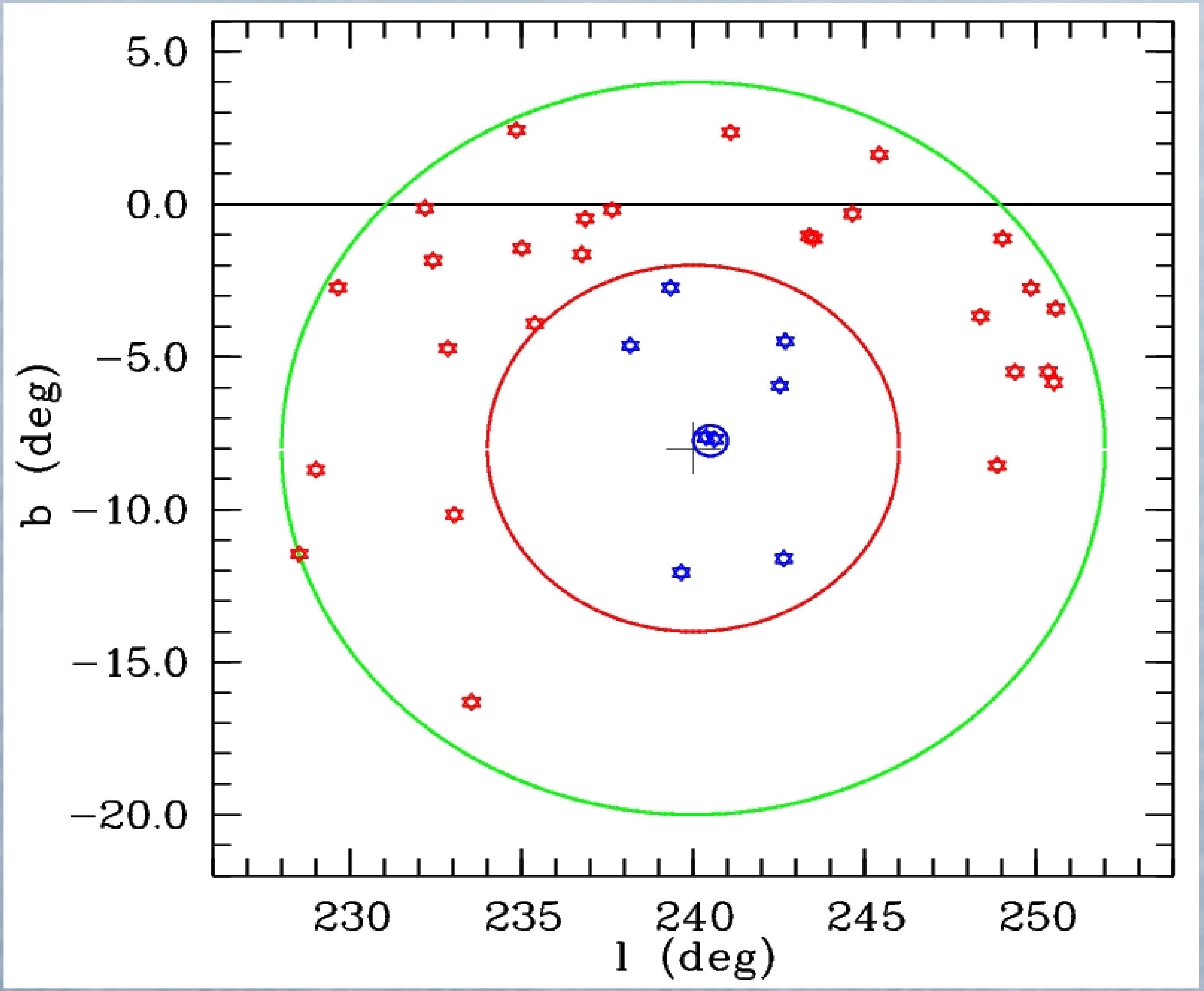
The PNe in the area of CMa dwarf galaxy (6)

Distribution of measured velocities for all of the nebulae studied relative to their calculated oxygen abundances. The filled circles and open squares indicate the first- and second-priority objects, respectively.



New results are from Kniazev et al. (in preparation)

The PNe in the area of CMa dwarf galaxy (7)



New results are from Kniazev et al. (in preparation)

The PNe in the area of CMa dwarf galaxy (8)

Found two PNe:

(1) are located almost at the center of the CMa region

(2) as minimum one of them is located at a distance of ~7.2 kpc from the Sun or ~15 kpc from the center of the Milky Way

(3) their measured metallicity 12+log (O/H) =7.72 dex and 7.8 dex differ from the metallicities for all of the remaining PNe and it is close to [Fe/H] ~−1

(4) one has radial velocity of the order of Vr = 109 km/s and another one has of the order of Vr = 60 km/s

Conclusions:

(*) PNe in the outer regions of M31:

(a) New method of selection of PNe candidates was developed

(b) Our follow-up spectroscopy confirms that we have found three new PNe in the area of Andromeda NE

(c) Our spectroscopy shows a kinematic and metallicity connection between the Giant Stream and PNe in Andromeda NE confirming that Andromeda NE is the core or remnant of the Giant Stream

(*) PNe in the region of CMa:

Among the studied PNe, two have properties (metallicity, velocity, position) which make them most likely candidates for belonging to the remnants of a possible dwarf galaxy disrupted by the tidal interaction with the MilkyWay