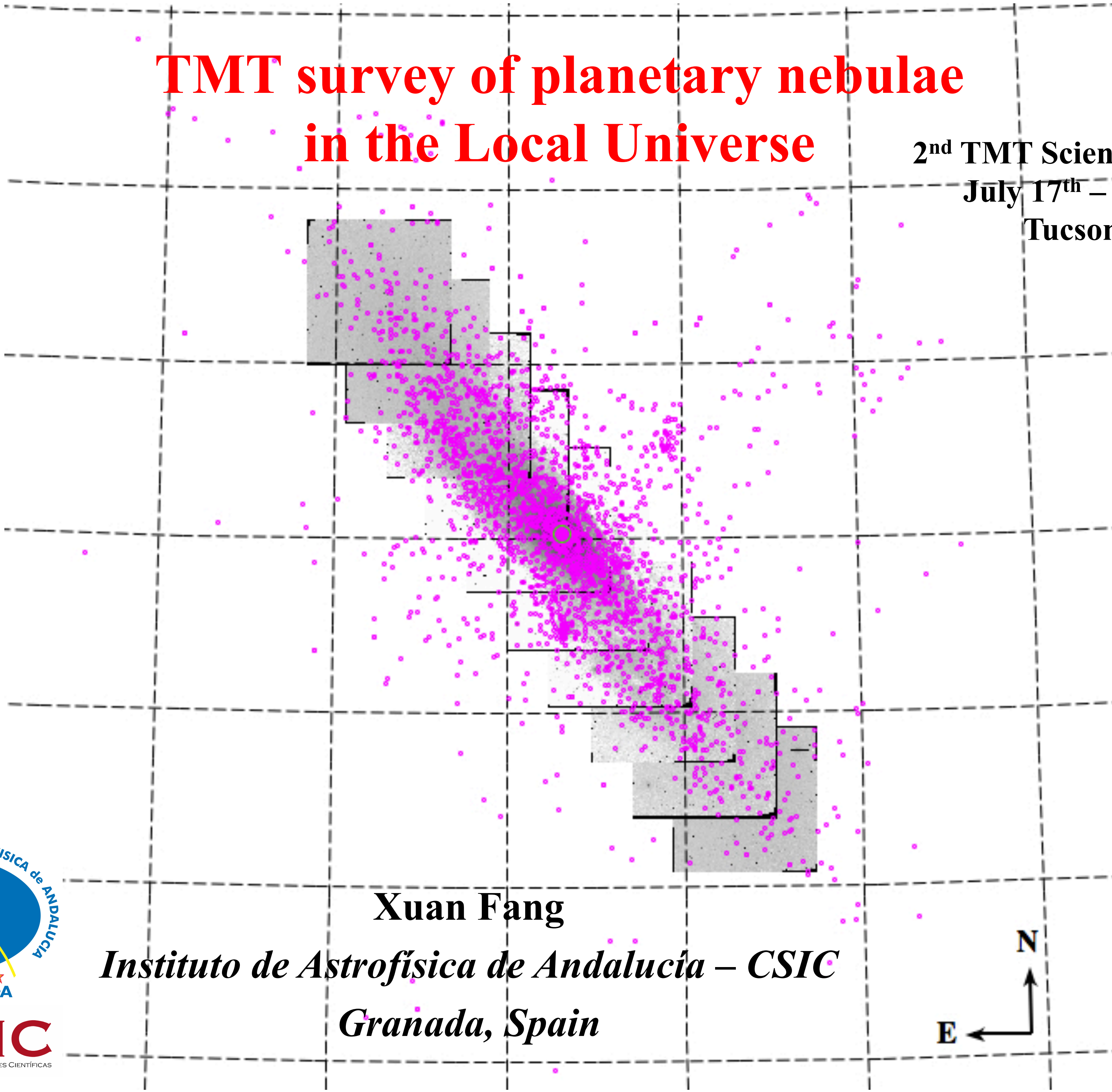
TMT survey of planetary nebulae in the Local Universe

2nd TMT Science Forum
July 17th – 19th, 2014
Tucson, Arizona



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Planetary Nebulae

- **Descendents of low- and intermediate-mass stars (≤8–10 $M_{\odot}$)**
- **Ubiquitous in the universe; exist in all types of galaxies**
- **Narrow and bright emission lines, e.g., [O III] λ5007, Hα**
- **Excellent tracers of properties of the host galaxies**
  - **Chemistry**
  - **Kinematics**
  - **stellar populations**
- **Indicator of properties of the pristine universe**

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				

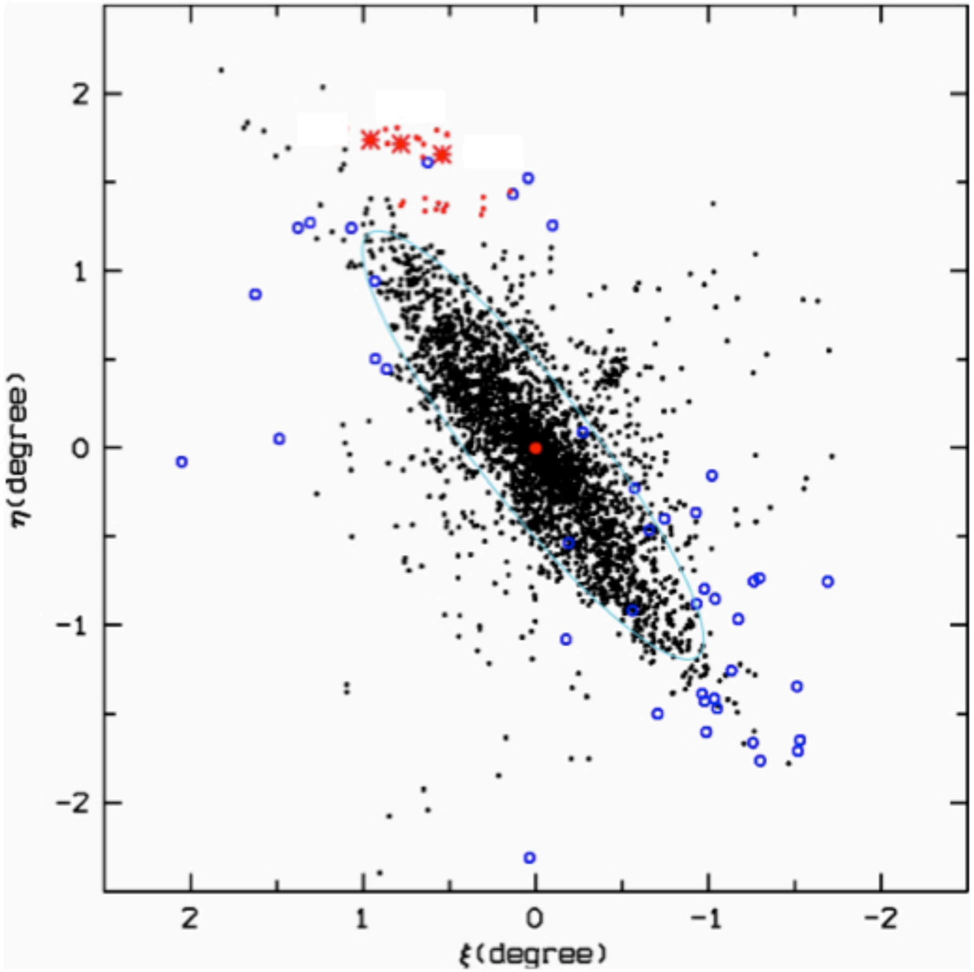
Planetary Nebulae discovered in the Local Group (2006–2011)

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				

What can we learn from Local Group PNe in TMT era? – A few science cases

- Discovery of more (faint) PNe out to ~30 Mpc
- Abundance gradients (O/H) of galaxies
- Star formation histories in different types of galaxies (in combination with H II region abundances)
- **Investigation of substructures in spiral galaxies**
- Two basic problems in nebular astrophysics

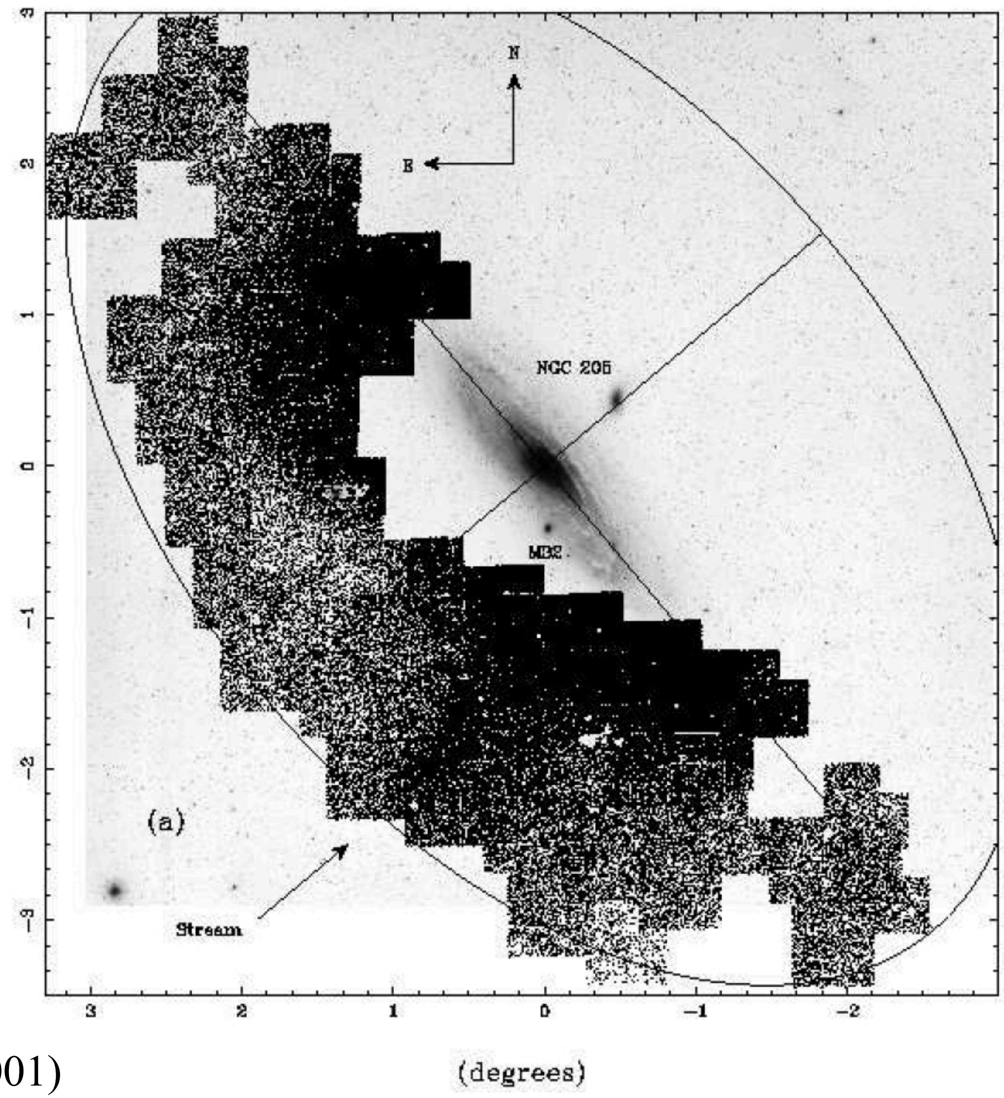
Substructures in spiral galaxies
– e.g., M31



Substructures in the halo and outer disk of M31

– Discovery of the Southern Giant Stream

- Giant stream of metal-rich stars
  - Photometric survey with INT/WFC by Ibata et al. (2001);
  - Spatial (surface density) distribution of the RGB stars;
  - Enhanced metallicity in the stream relative to the 'normal' M31 halo population;
  - The stream might be the debris stripped from M32 and/or NGC205.



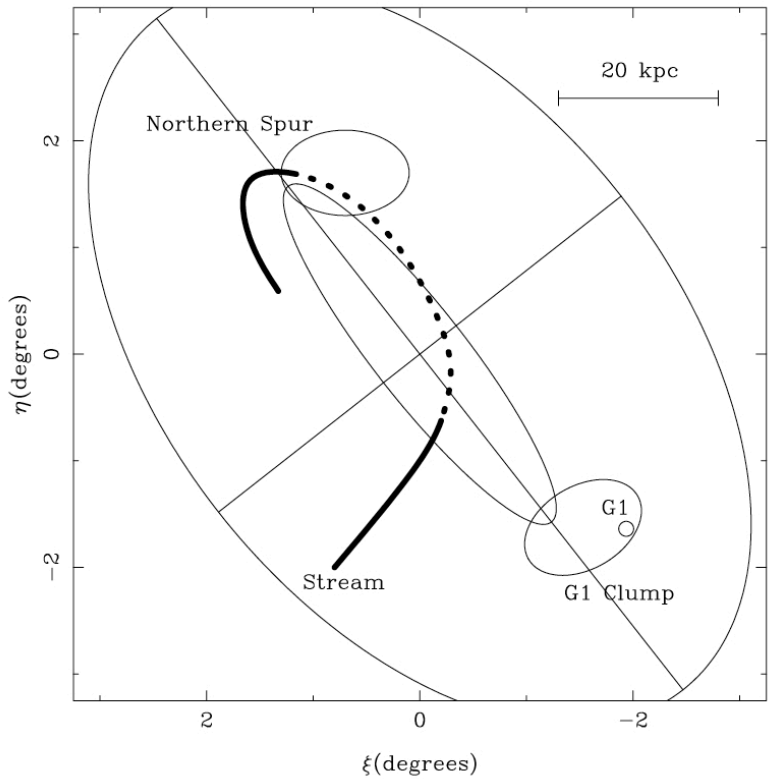
Ibata et al. (2001)

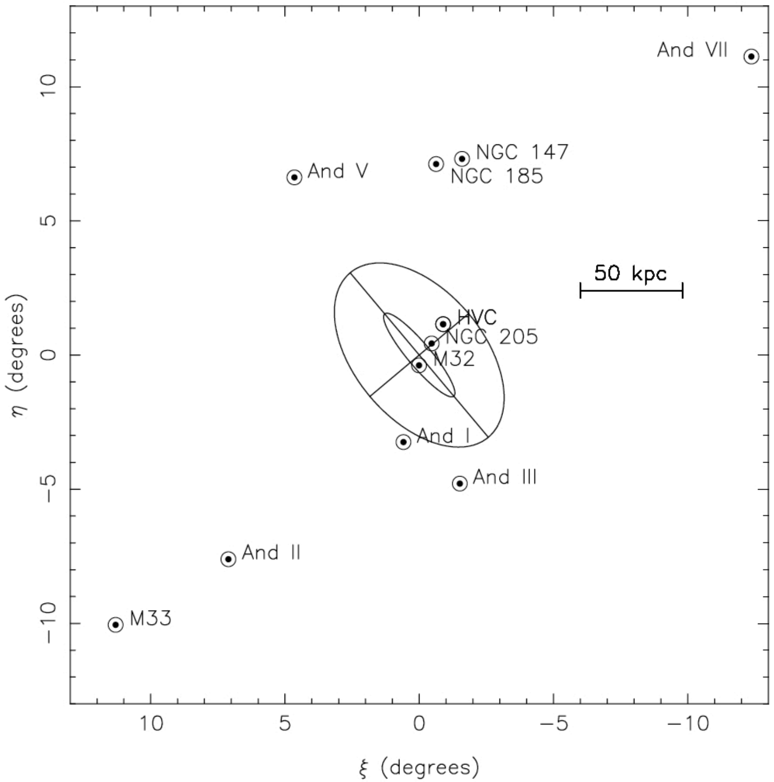
Origin of the Northern Spur and Giant Stream

– Connected with each other?

- Observations (photometry)
  - Deep panoramic survey (25 deg^2) by Ferguson et al. (2002);
  - density and color distribution of RGB stars;
  - origin of the Southern Stream could be M32;
  - the Northern Spur: distortion (i.e. stellar warps) and disruption of the outer disk due to close passage of a satellite;
  - identity of the perturber was unknown.

Ferguson et al. (2002)

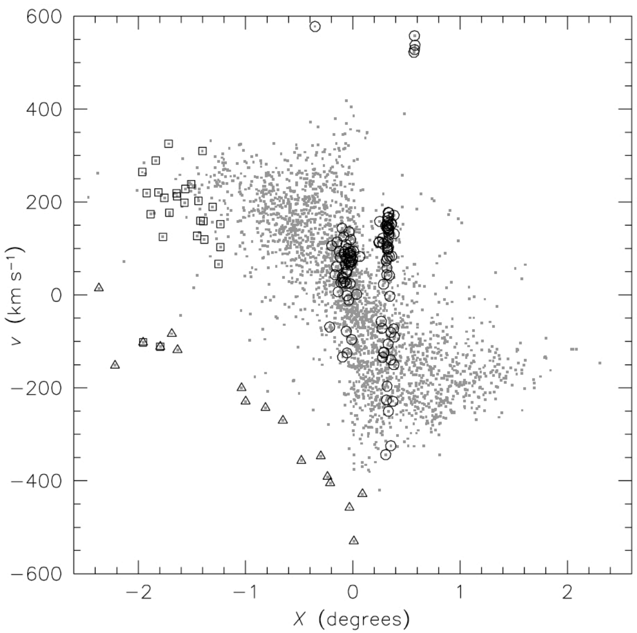




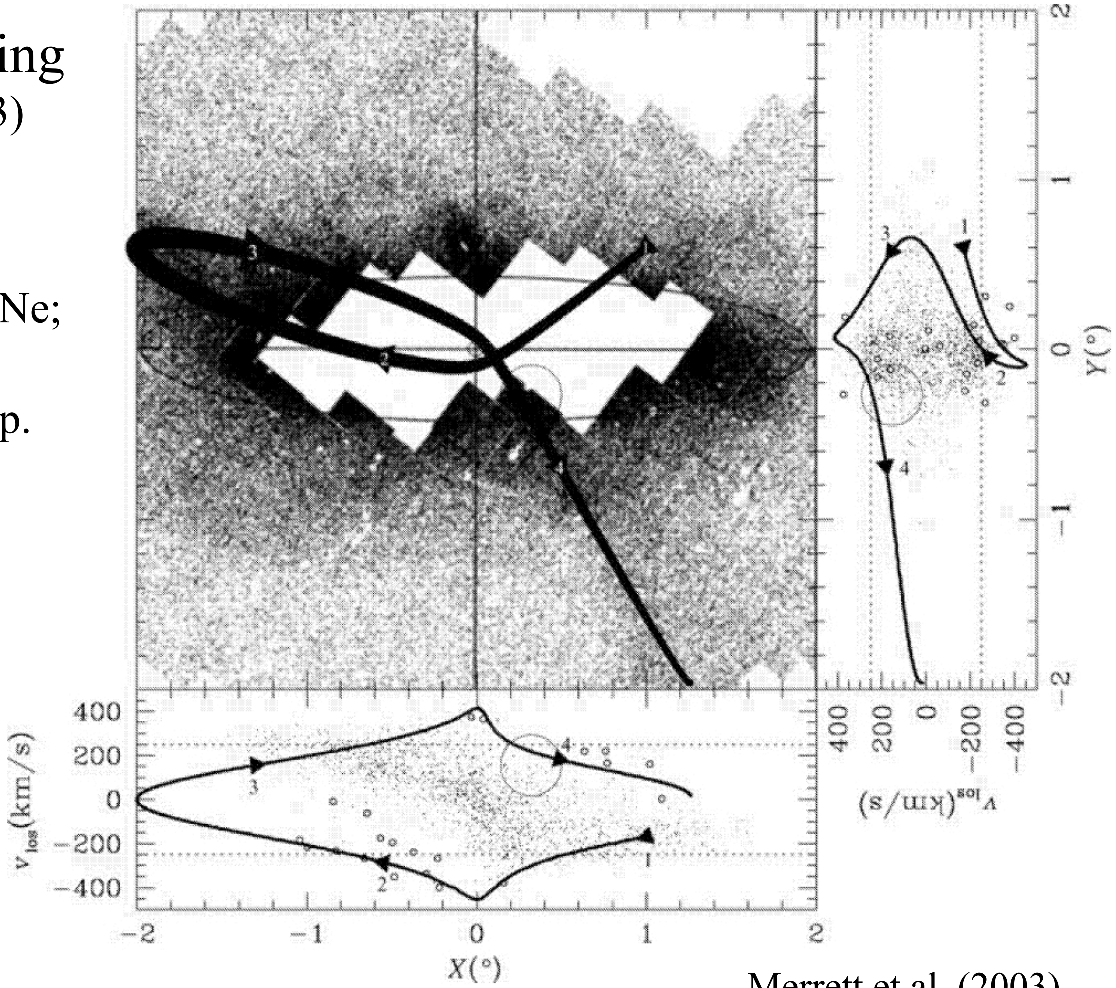
Origin of the Northern Spur and Giant Stream

– Connected with each other?

- Observations (photometry and slitless spectroscopy) and modeling
  - A stellar orbit (Merrett et al. 2003) connects the Southern Stream to Northern Spur;
  - based on the kinematics of ~20 PNe;
  - No need to invoke the stellar warp.



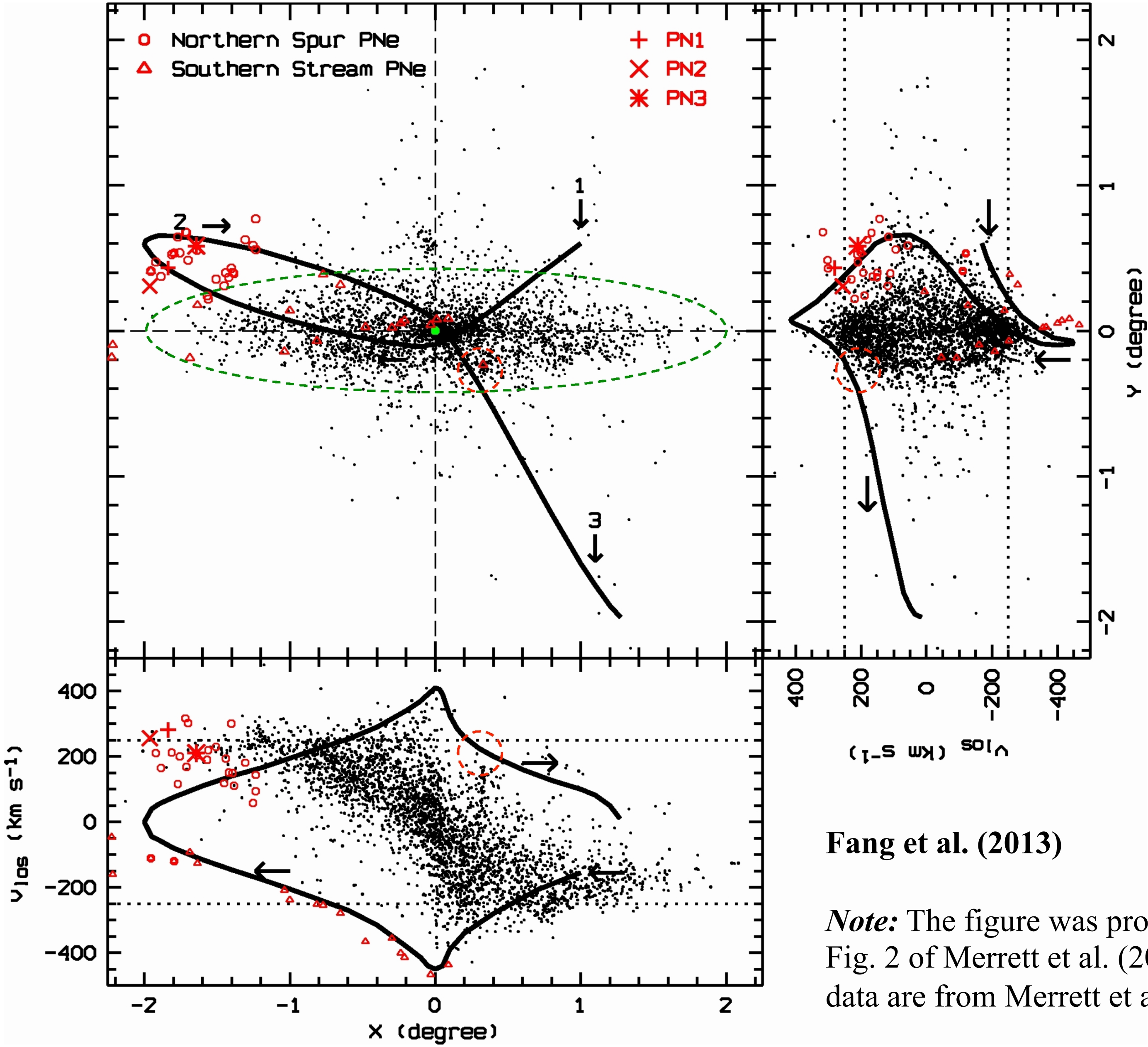
Merrett et al. (2006)



Merrett et al. (2003)

Origin of the *Northern Spur*

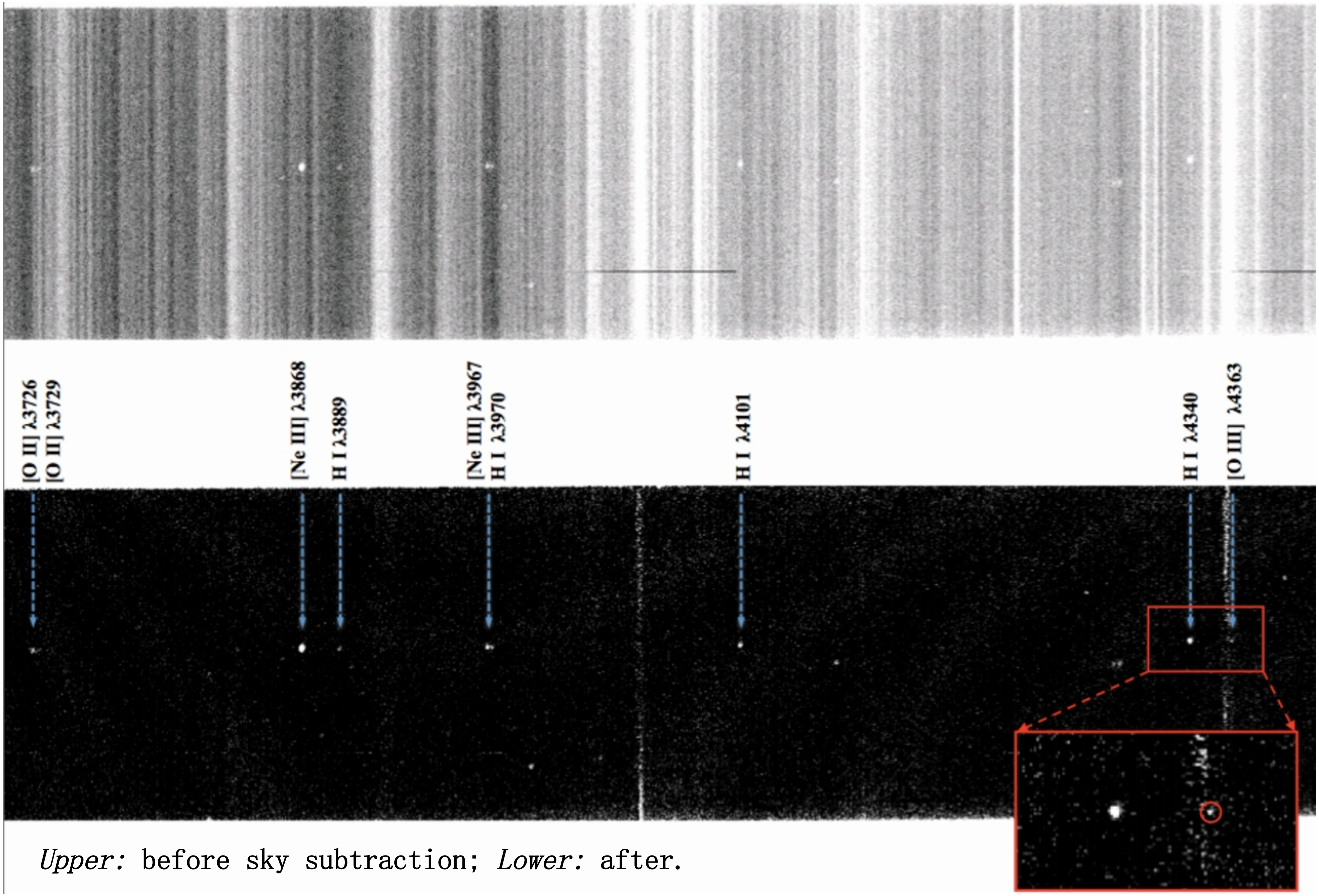
– The spatial and kinematic distribution of M31 PNe



Fang et al. (2013)

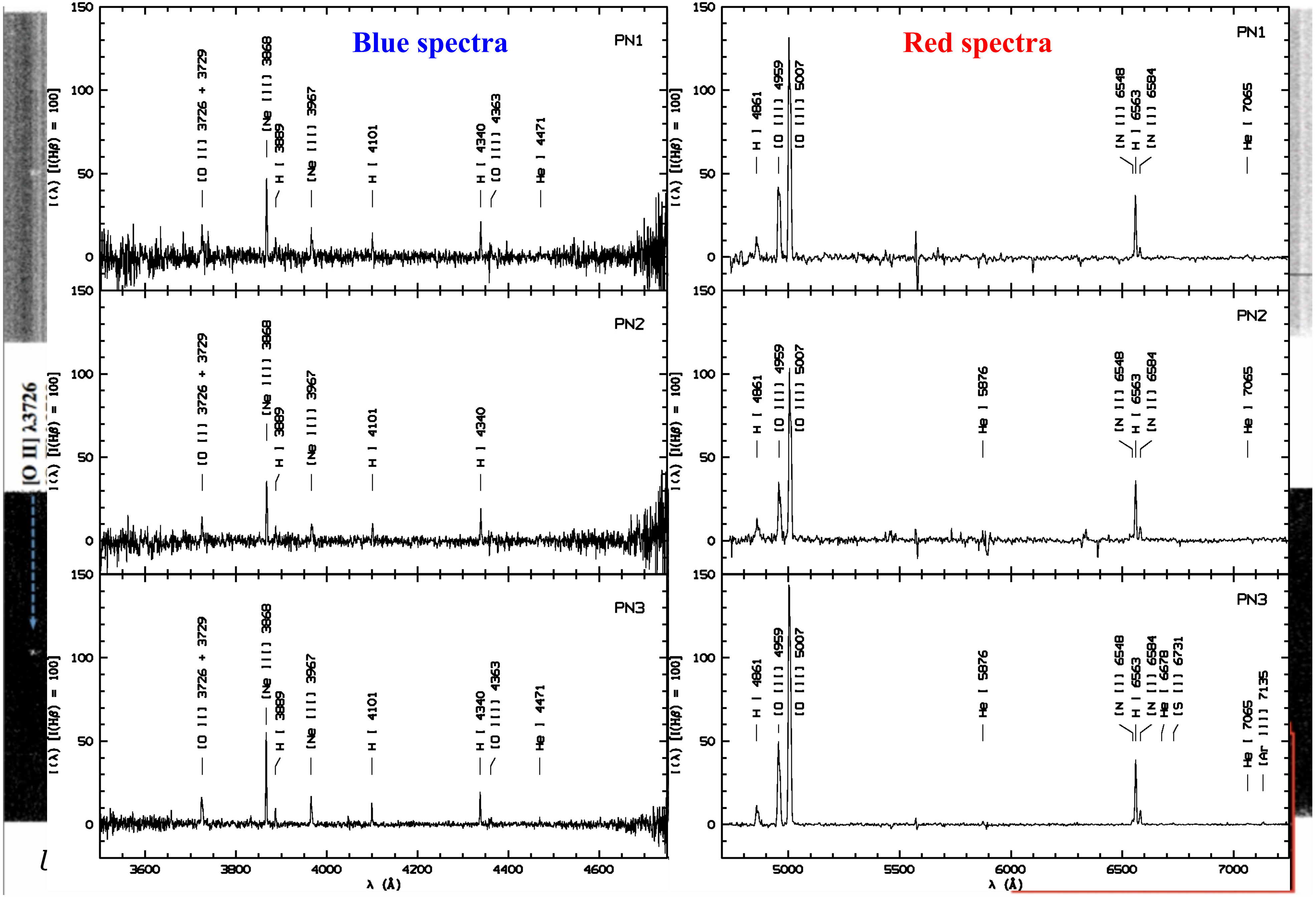
Note: The figure was produced based on Fig. 2 of Merrett et al. (2003); PNe (~3000) data are from Merrett et al. (2006).

Spectrum obtained at Palomar 5m



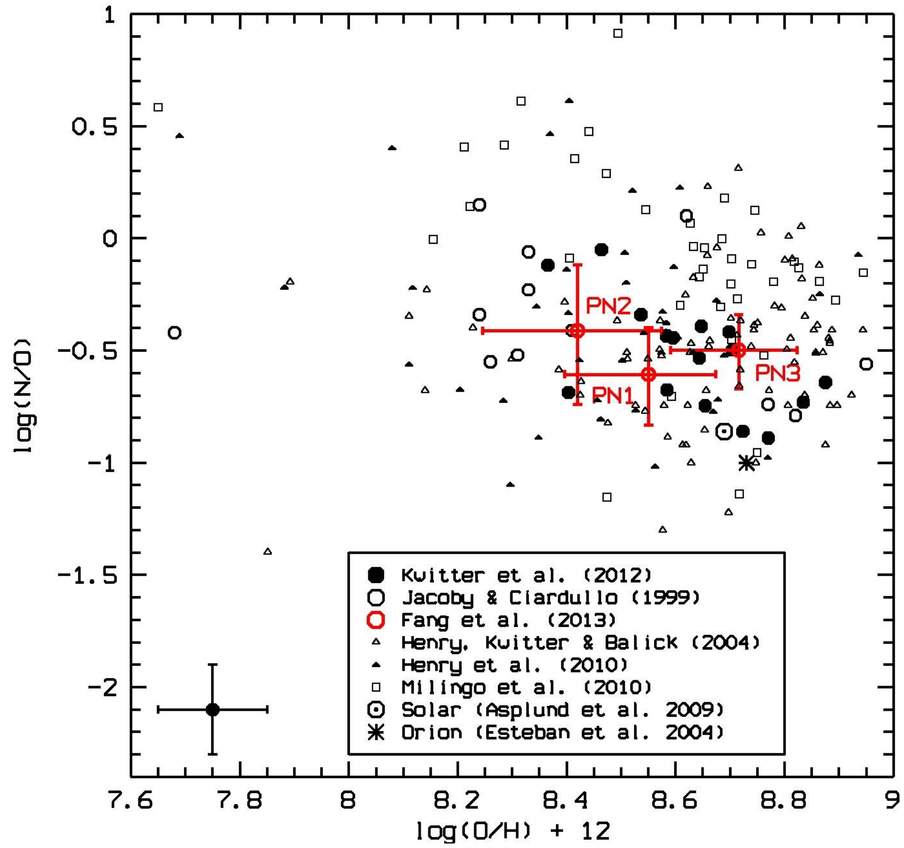
Upper: before sky subtraction; *Lower:* after.

Spectrum obtained at Palomar 5m (3 hr exposure)

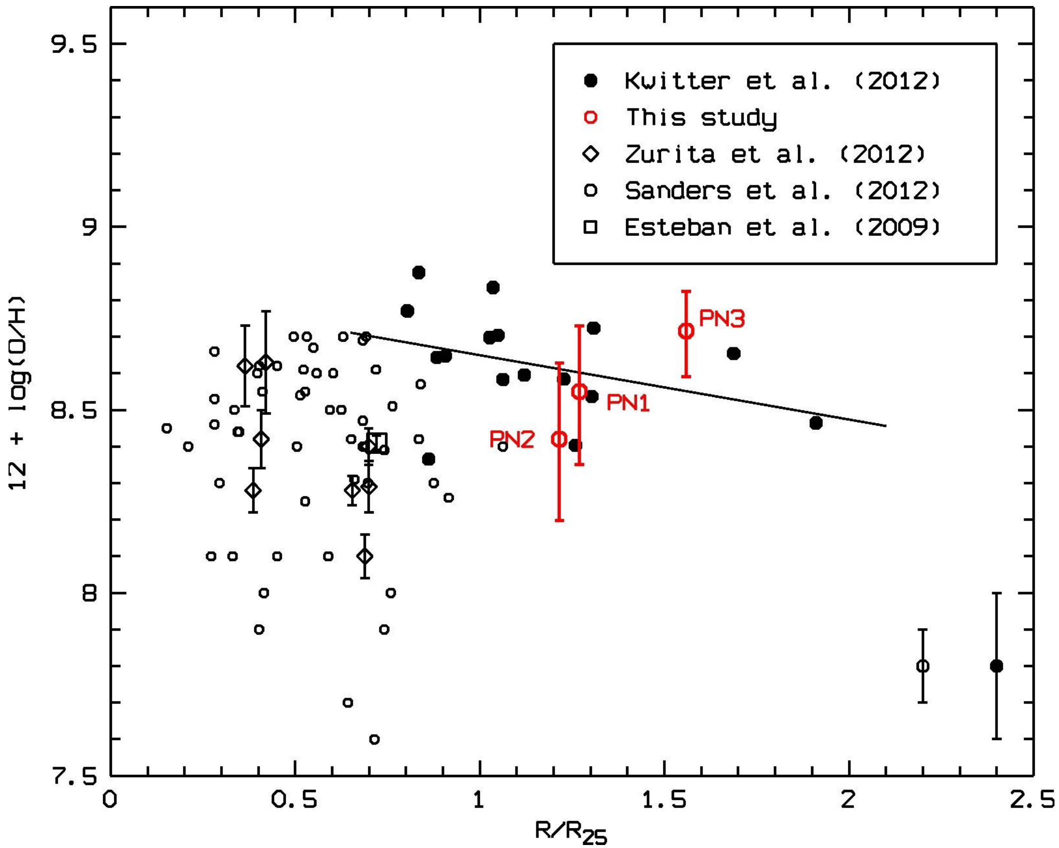


Abundances

N/O versus O/H



Oxygen gradient



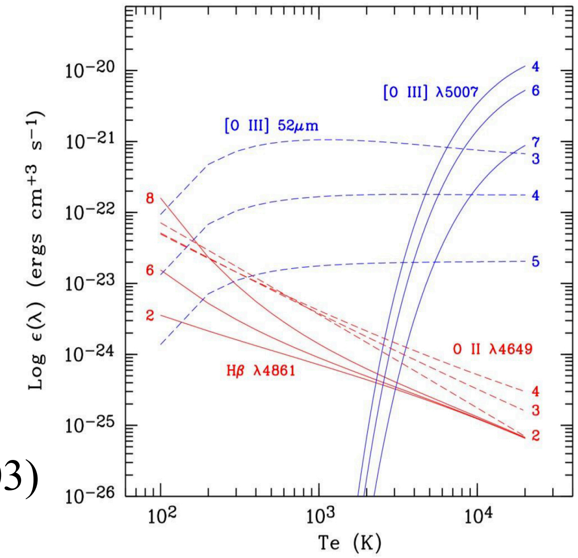
Fang et al. (2013)

What can we learn from Local Group PNe in TMT era? – A few science cases

- Discovery of more (faint) PNe out to ~30 Mpc
- Abundance gradients (O/H) of galaxies
- Star formation histories in different types of galaxies (in combination with abundances of H II regions and giant stars if available)
- Investigation of substructures in spiral galaxies
- **Two basic problems in nebular astrophysics**

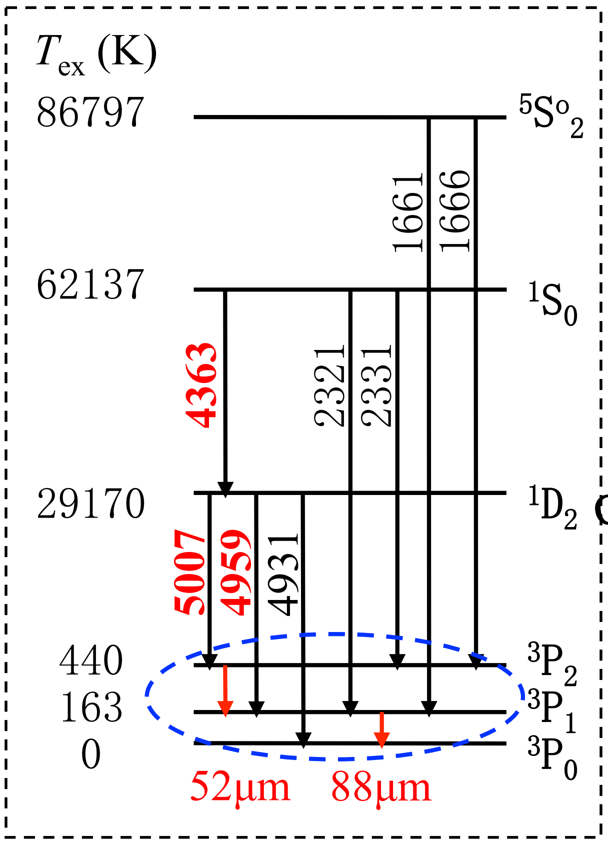
Emission lines used for nebular analysis; CELs & ORLs/continua

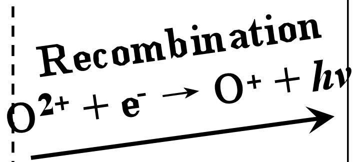
- **Collisionally excited lines (CELs; also forbidden lines)**
  Strong, very sensitive to T_e: $j_\nu = T_e^{-1/2}\exp(-E_{ex}/kT_e)$
- **Optical recombination lines (ORLs)**
  Weak ($\lesssim 10^{-3}$–10^{-4} Hβ); $j_\nu = T_e^{-\alpha}, (\alpha \sim 1)$



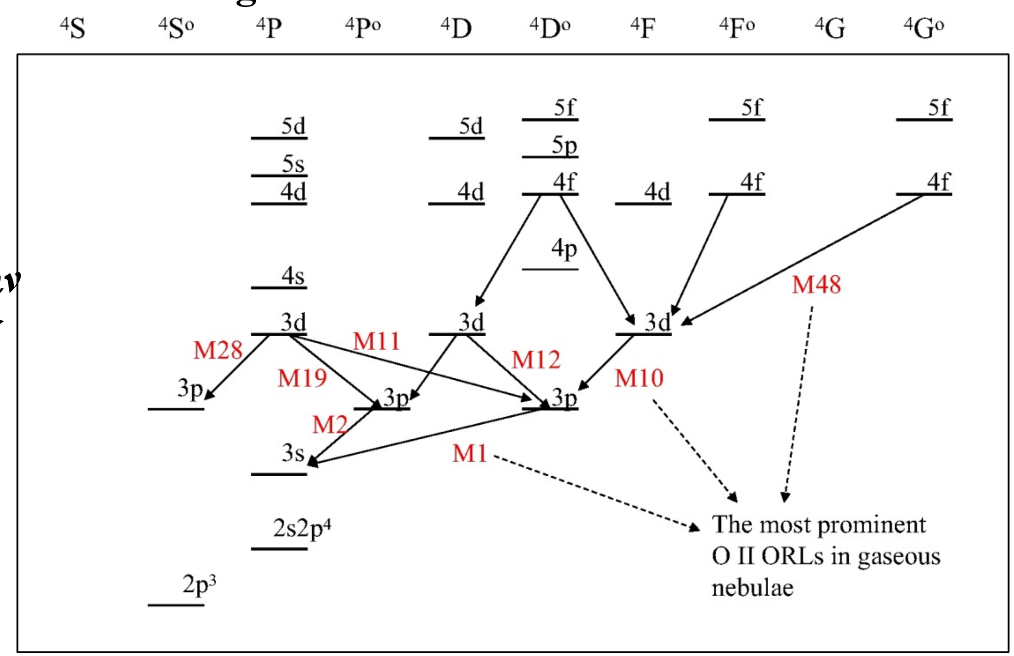
(Liu et al. 2003)

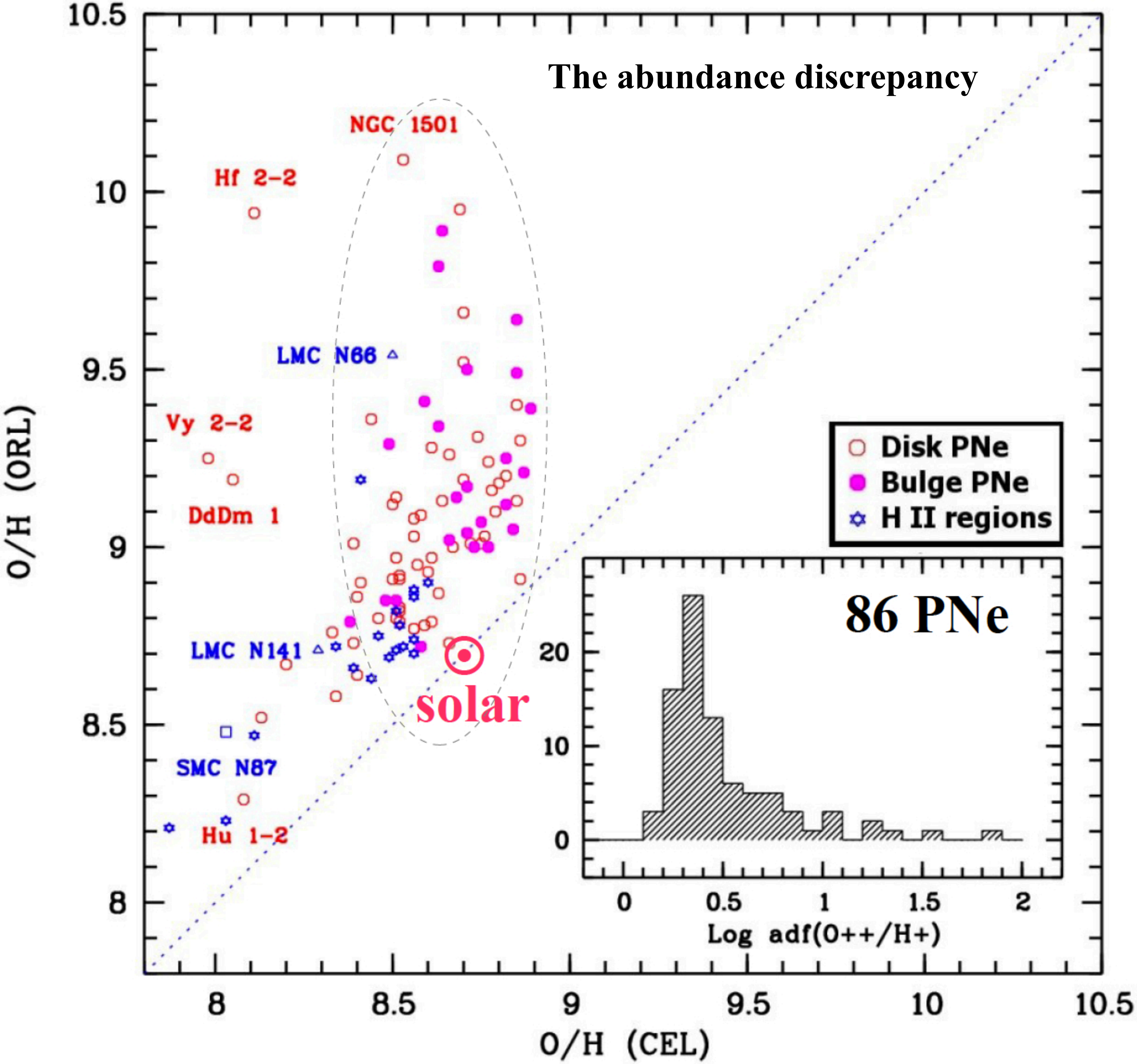
[O III] $2p^2$ $2s2p^3$



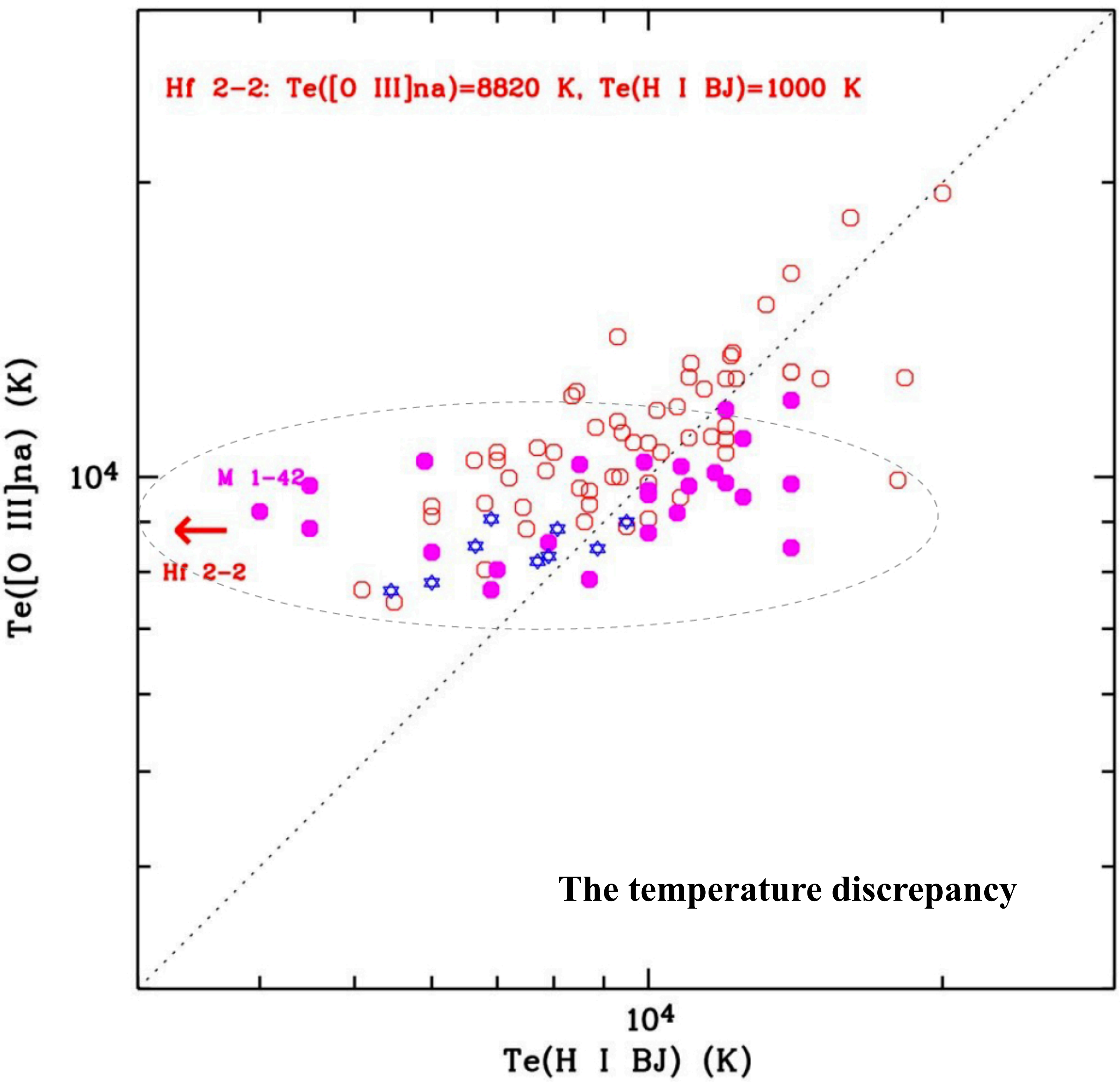


Grotrian diagram for O II





The abundance discrepancy
NGC 1501
Hf 2-2
LMC N66
Vy 2-2
DdDm 1
LMC N141
SMC N87
Hu 1-2
solar
Disk PNe
Bulge PNe
H II regions
86 PNe
Log adf(O++/H+)
O/H (ORL)
O/H (CEL)



Hf 2-2: Te([O III]na)=8820 K, Te(H I BJ)=1000 K
M 1-42
Hf 2-2
The temperature discrepancy
10^4
10^4
Te(H I BJ) (K)
Te([O III]na) (K)

CELs versus ORLs/continua

Two basic problems in nebular astrophysics: the two discrepancies

- **X^{i+}/H^{+}(ORLs) > X^{i+}/H^{+}(CELs)**

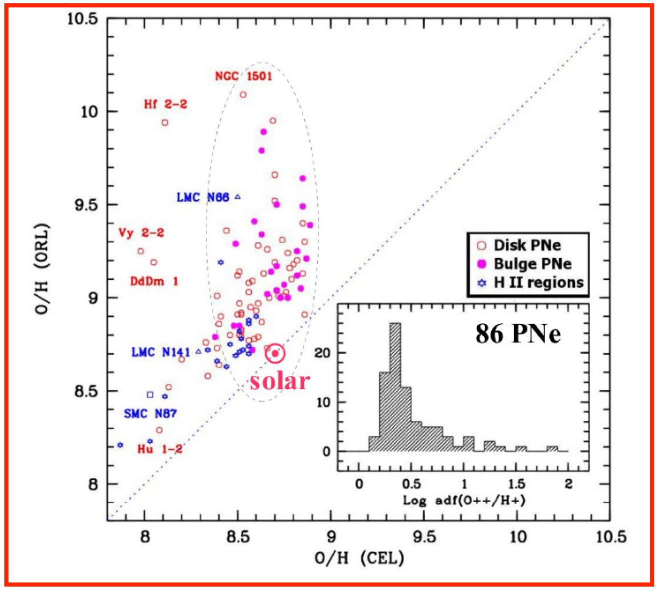
where X is C, N, O, and Ne;
Discovered in 1980s in C III] v.s. C II.
Abundance discrepancy factor
ADF ≡ X^{i+}(ORLs)/X^{i+}(CELs);

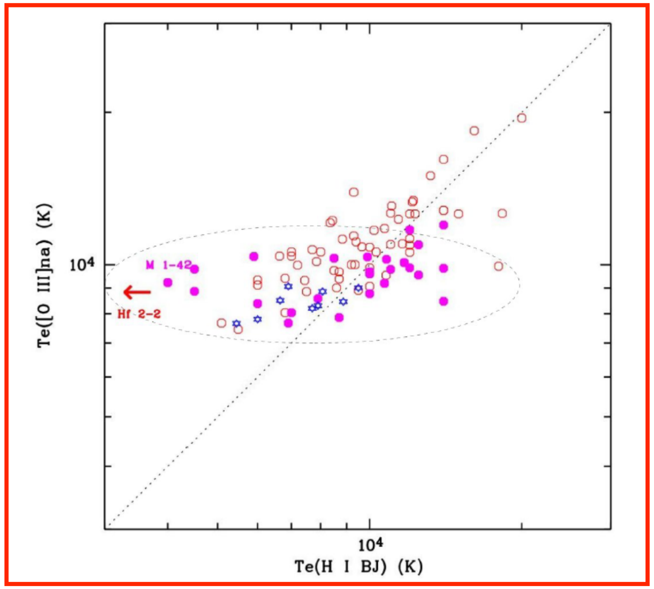
The abundance discrepancy

- **T_e(CELs) > T_e(H I Balmer jump)**

First observed by Peimbert (1967).

The temperature discrepancy

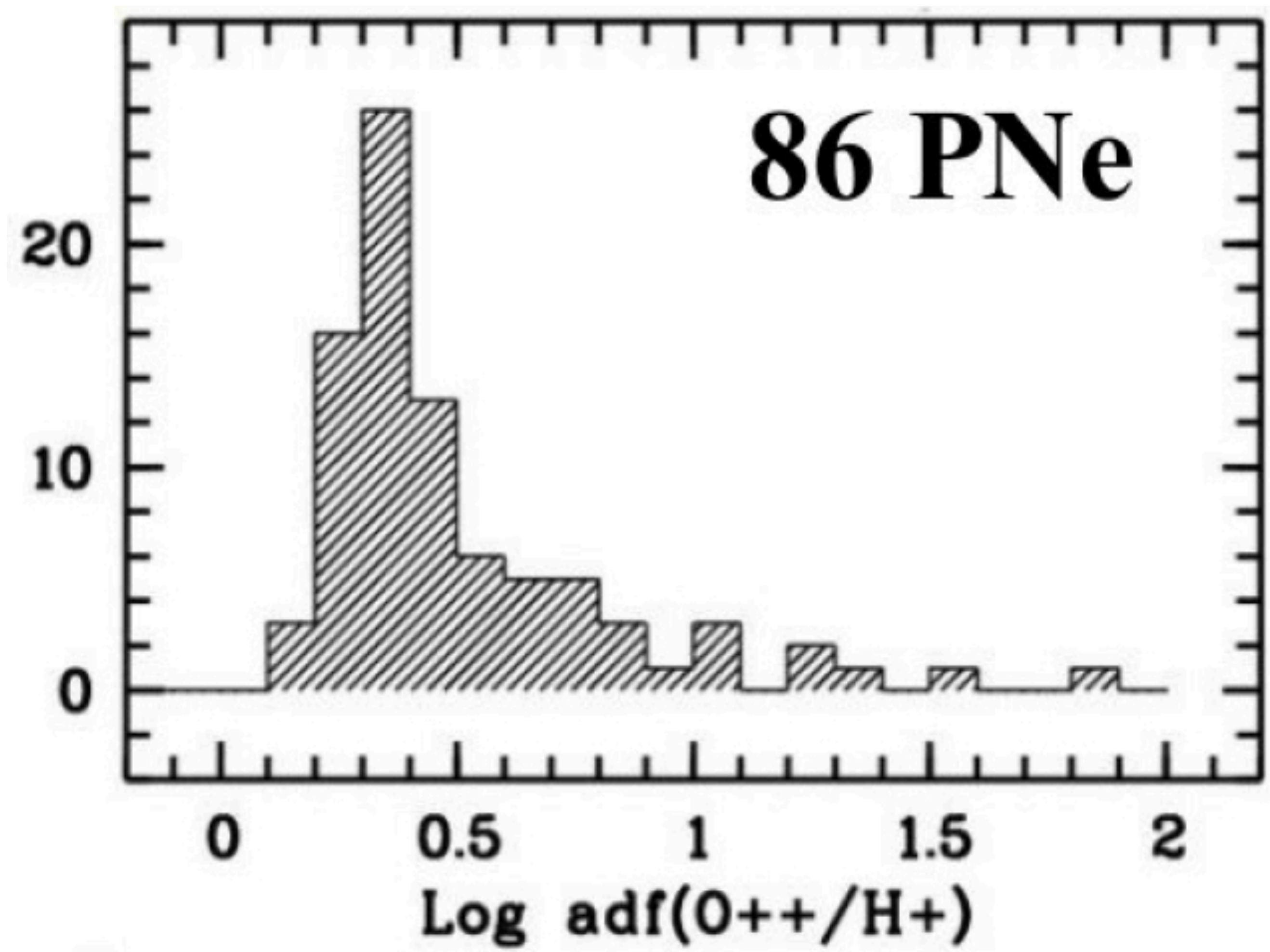




- The discrepancies are **real** and probably **physical**, not due to
  - **Measurement errors**
  - **Uncertainties in dereddening**
  - **Line blending**
  - **Contamination of ORLs by other excitation mechanisms (e.g., fluorescence, charge-transfer)**
  - **Inaccuracy in the atomic data**

Liu et al. (2012)

So far only studied in the Milky Way

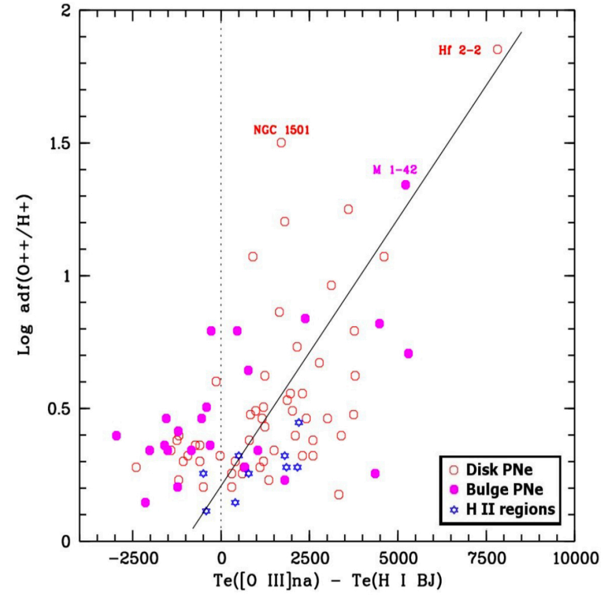


CELs versus ORLs/continua

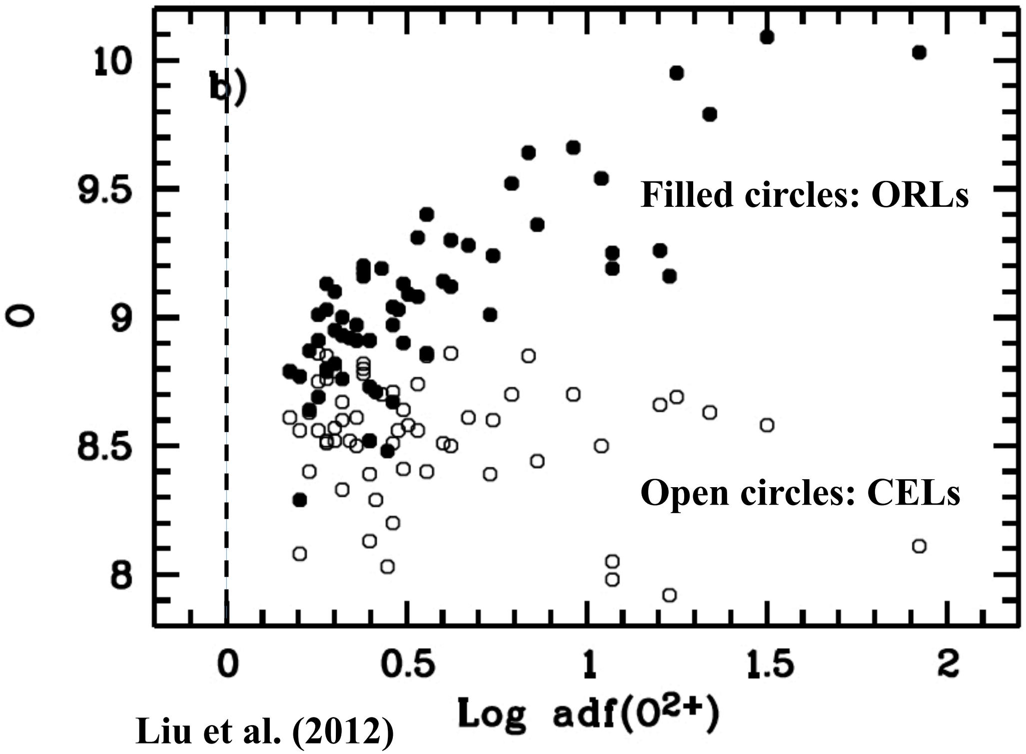
Intriguing phenomena related to the two discrepancies

- **ADF is correlated with ΔT_e**
  [$\Delta T_e = T_e$([O III]) – T_e(H I BJ)]

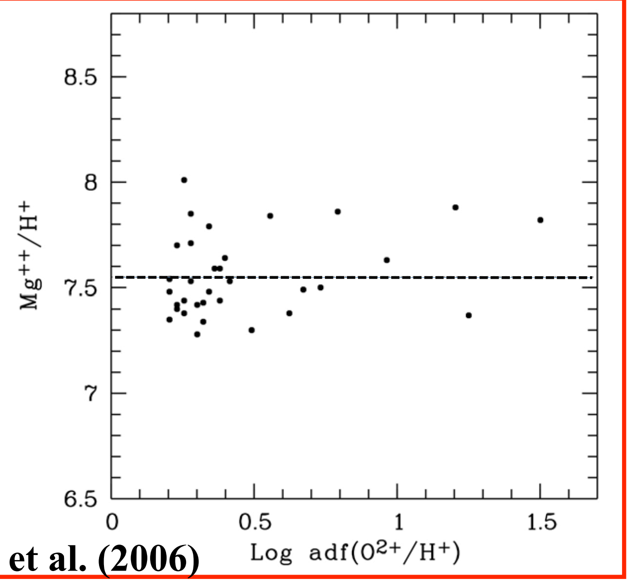
- **For a given PN, similar ADF values are found for all abundant 2nd-row elements C, O, N and Ne, but not for the 3rd-row Mg.**



Oxygen versus ADF:



Liu et al. (2012)

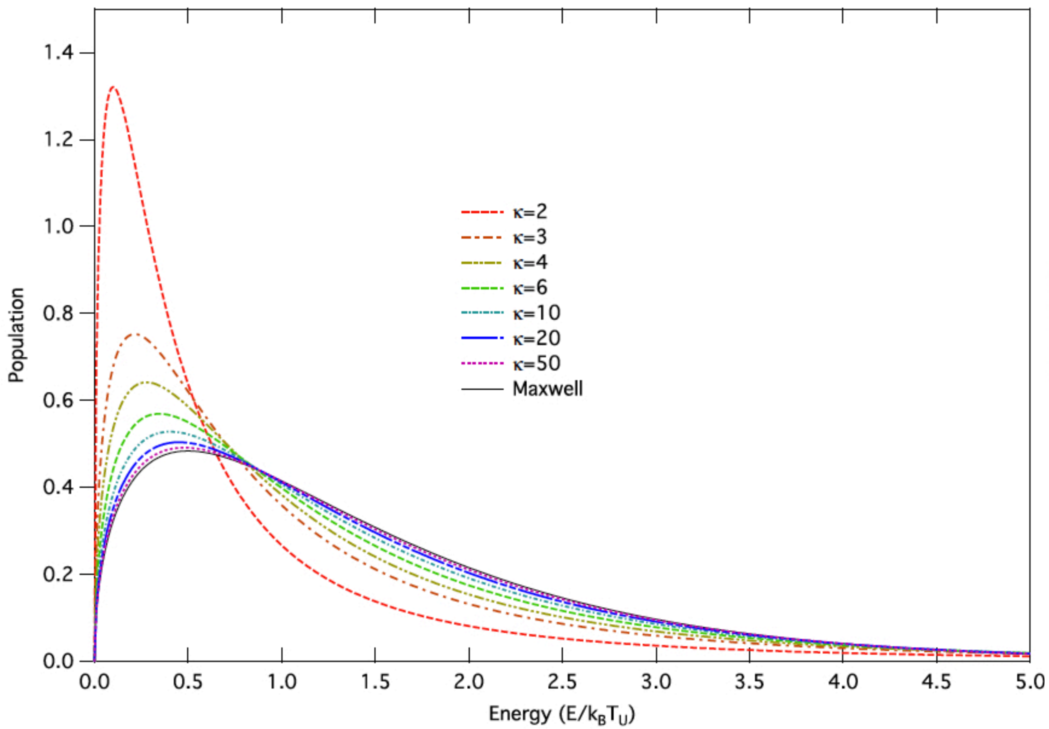


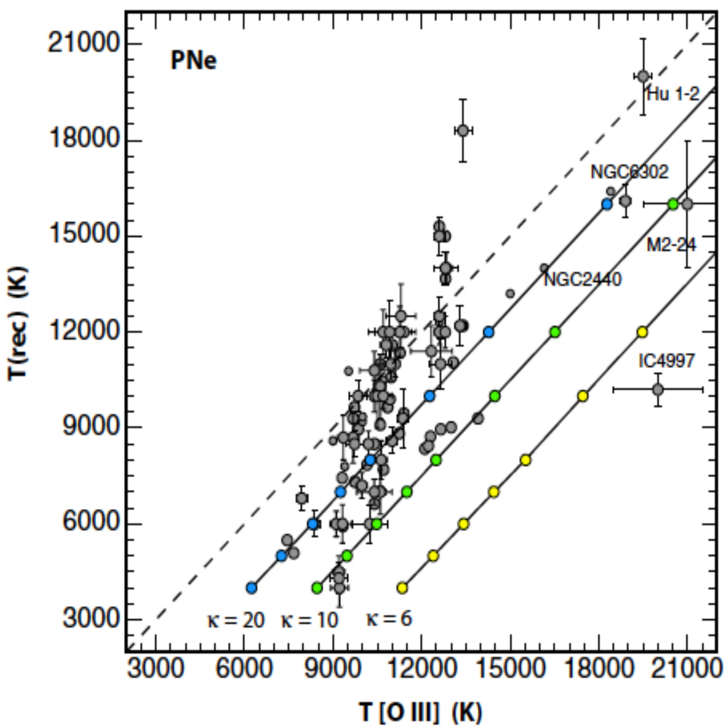
Barlow et al. (2006)

Interpretations

- Explanations of the discrepancies
  - T_e fluctuations and/or N_e inhomogeneities; chemical imhomogeneities **(Peimbert 1967, 1971; Rubin 1989; Viegas & Clegg 1994; Stasińska et al. 1994)**.

  - Most recently: κ-distributed electrons **(Nicholls et al. 2012)**.





Interpretations

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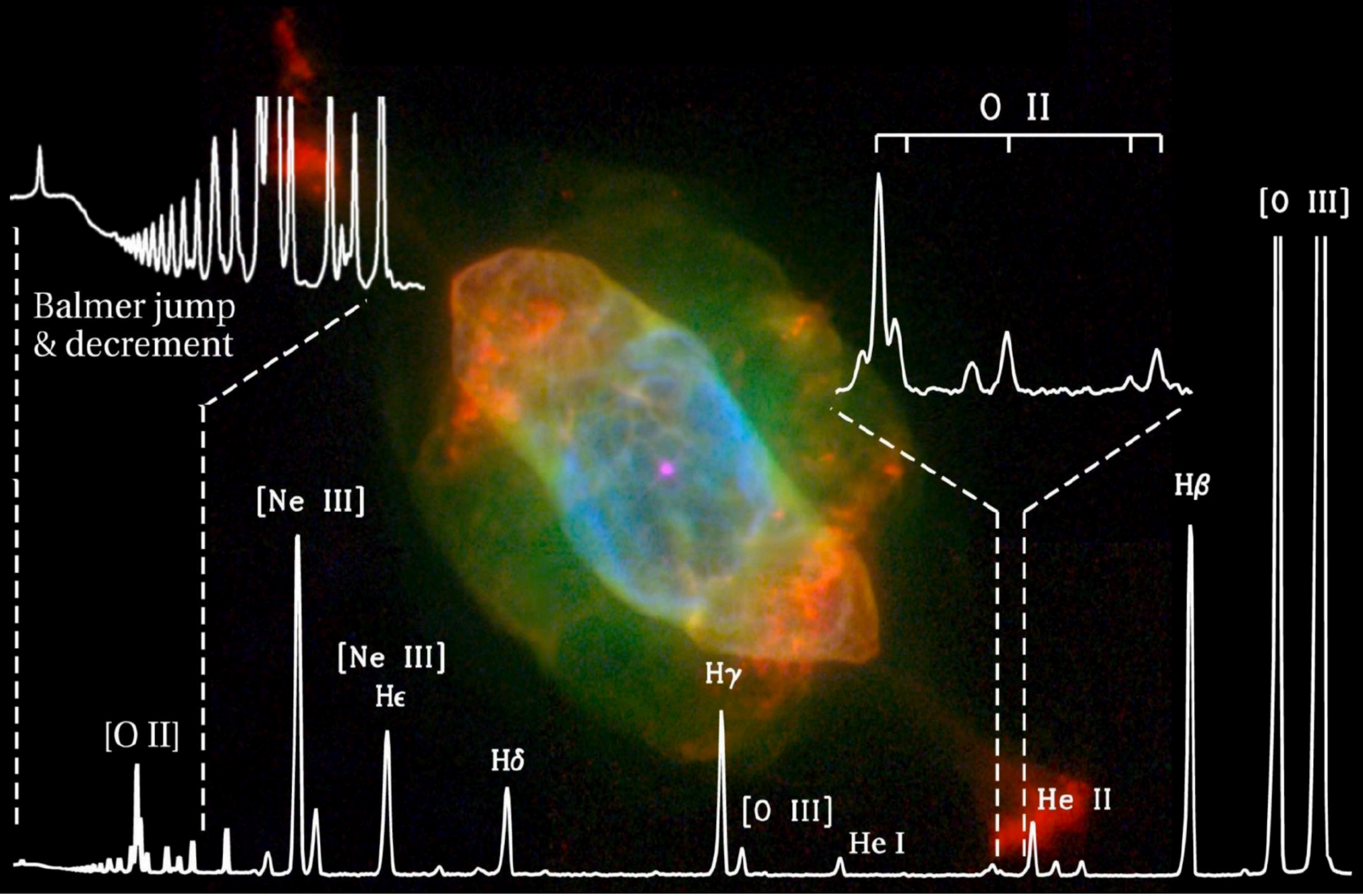
  - Most recently: κ-distributed electrons **(Nicholls et al. 2012)**.
  - The bi-abundance nebular model **(Liu et al. 2000)**: A cold (< 1000 K), metal-rich (probably **H-deficient**) plasma component in PNe (probably also H II regions).
- **The bi-abundance (two-component) nebular model**
  - CELs from the **hot** ambient gas; ORLs from the **cold**, metal-rich component.
  - So far, explains the wide ranges of observations (IR-UV).
  - However, its origin is unclear; its lifetime is a problem.
  - First need to know T_e, N_e, X/H, mass, etc.

Accurate measurements of heavy-element ORLs are demanding.

E.g., the blue-region spectrum of the planetary nebula NGC 7009:

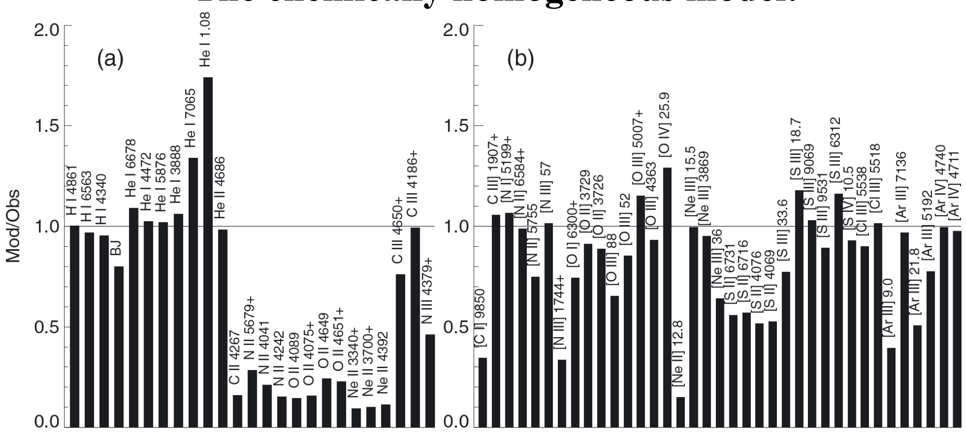


Modeling

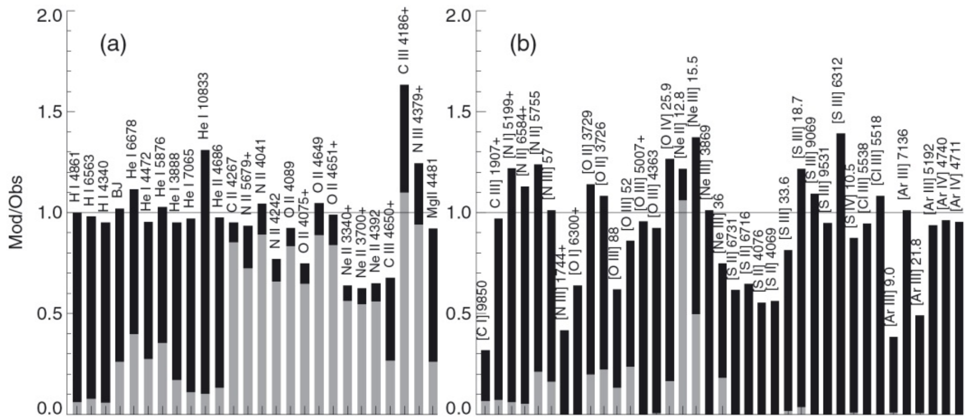
– A two-component nebular model

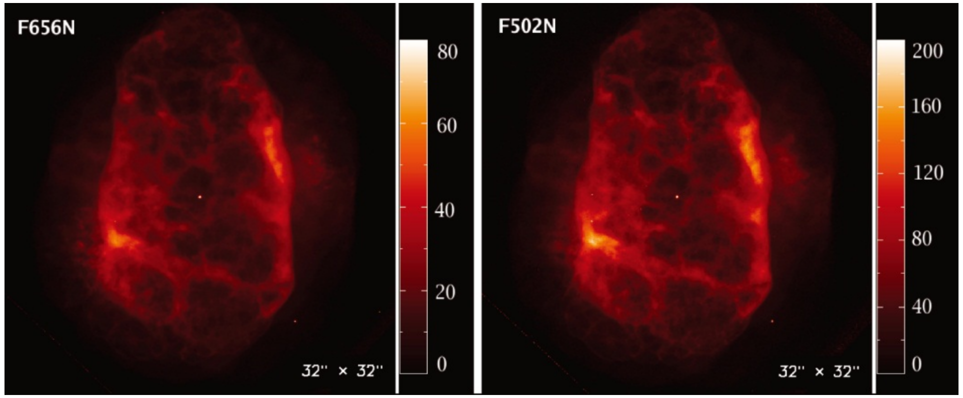
- 3D photoionization modeling of NGC6153 **(Yuan et al. 2011)**
  - ADF(O^{2+}/H^{+}) ≈ 10

The chemically homogeneous model:

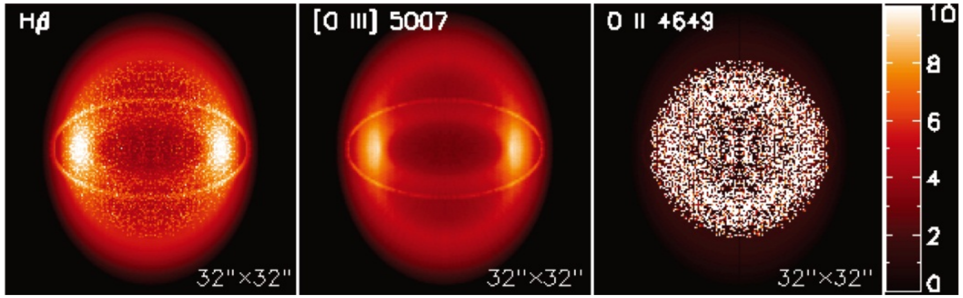


The bi-abundance model:

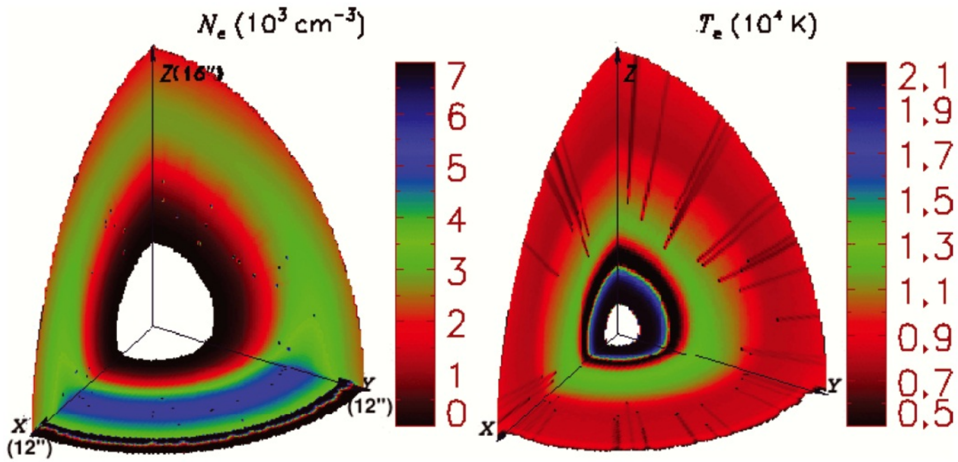


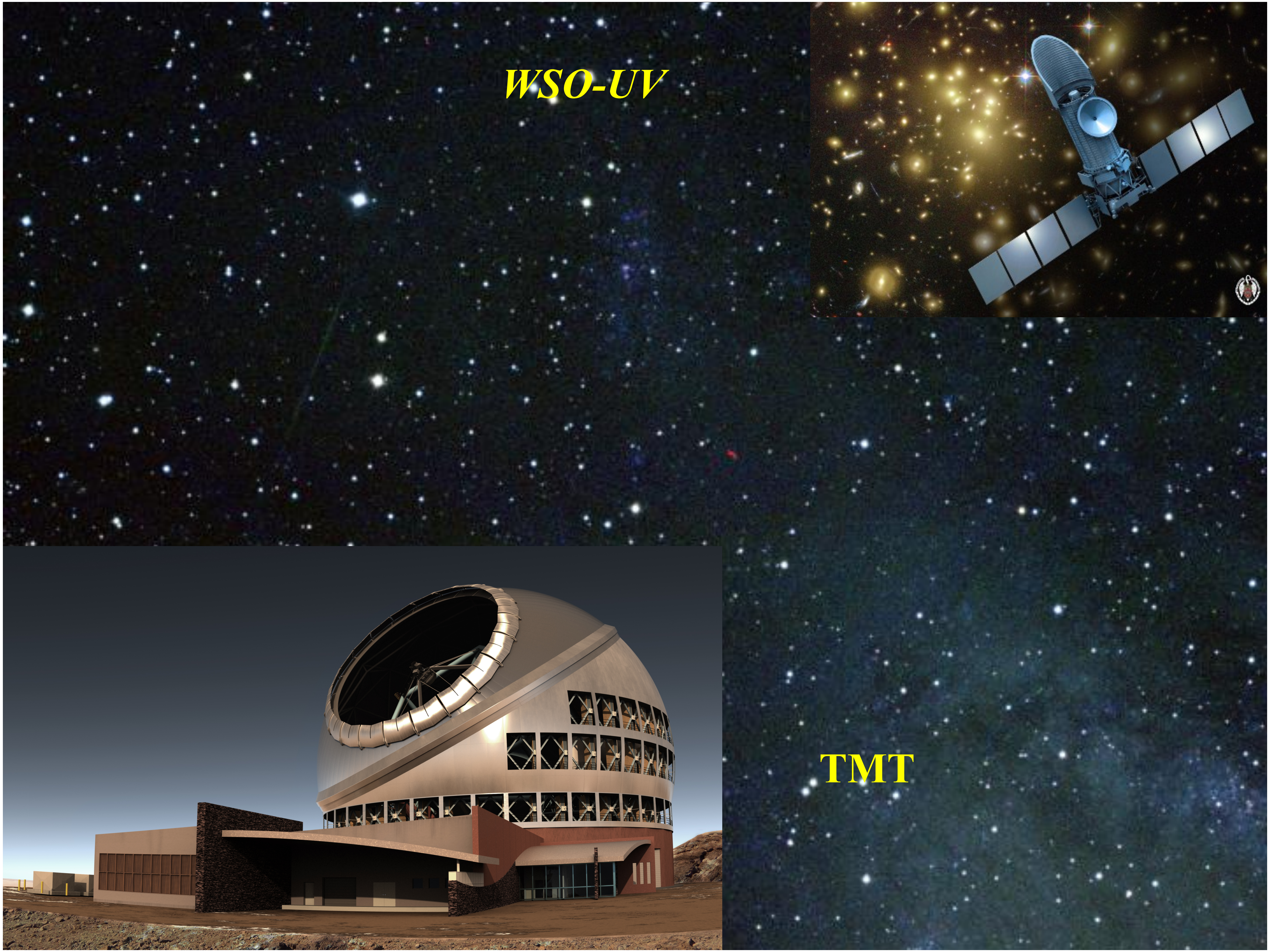


HST/WFPC2 images of NGC6153 (*Upper*)



Projected monochromatic images of the 3D model (*Mid*)




WSO-UV
TMT

- An international (Russia + Spain + Germany) space telescope to be launched in 2017
- To guarantee observational access in UV to astronomers after the *HST*
- A 1.7m aperture telescope
- High and intermediate resolution spectroscopy, slitless low-resolution spectroscopy, and deep UV imaging
- A five-year mission and an extension of five years

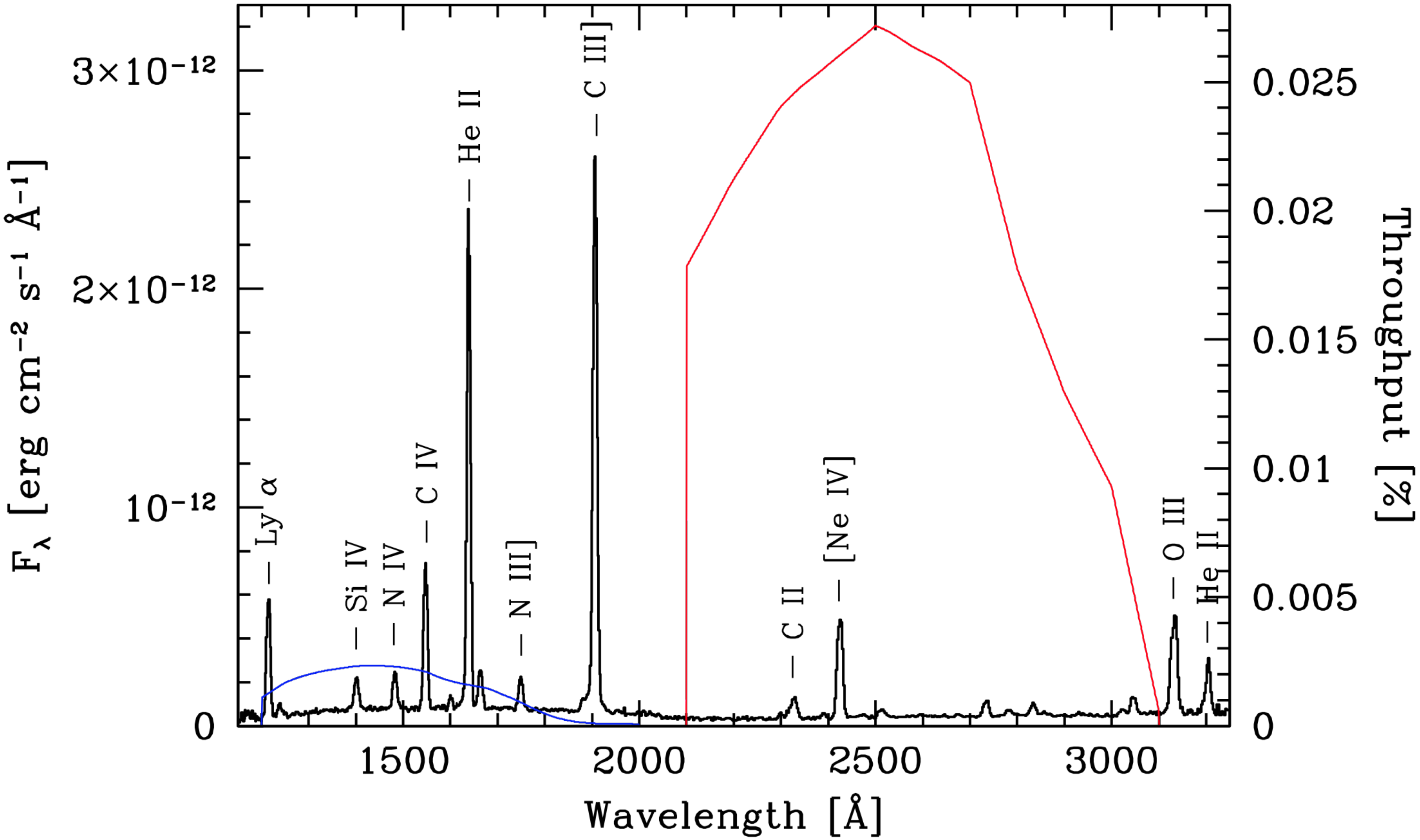
World Space Observatory – UltraViolet (*WSO-UV*)

- Instruments
  - Imaging and Slitless Spectrograph Instrument for Surveys, **ISSIS**: 1150-1750Å (FUV), 1850-3200Å (NUV, *R* ~500)
  - Far-UV echelle spectrograph, **VUVES**: 1020-1720Å (*R* ~55000)
  - Near-UV echelle spectrograph, **UVES**: 1740-3100Å (*R* ~50000)
  - Long slit spectrograph, **LSS**: 1020-3200Å (*R*~ 1500–2500)

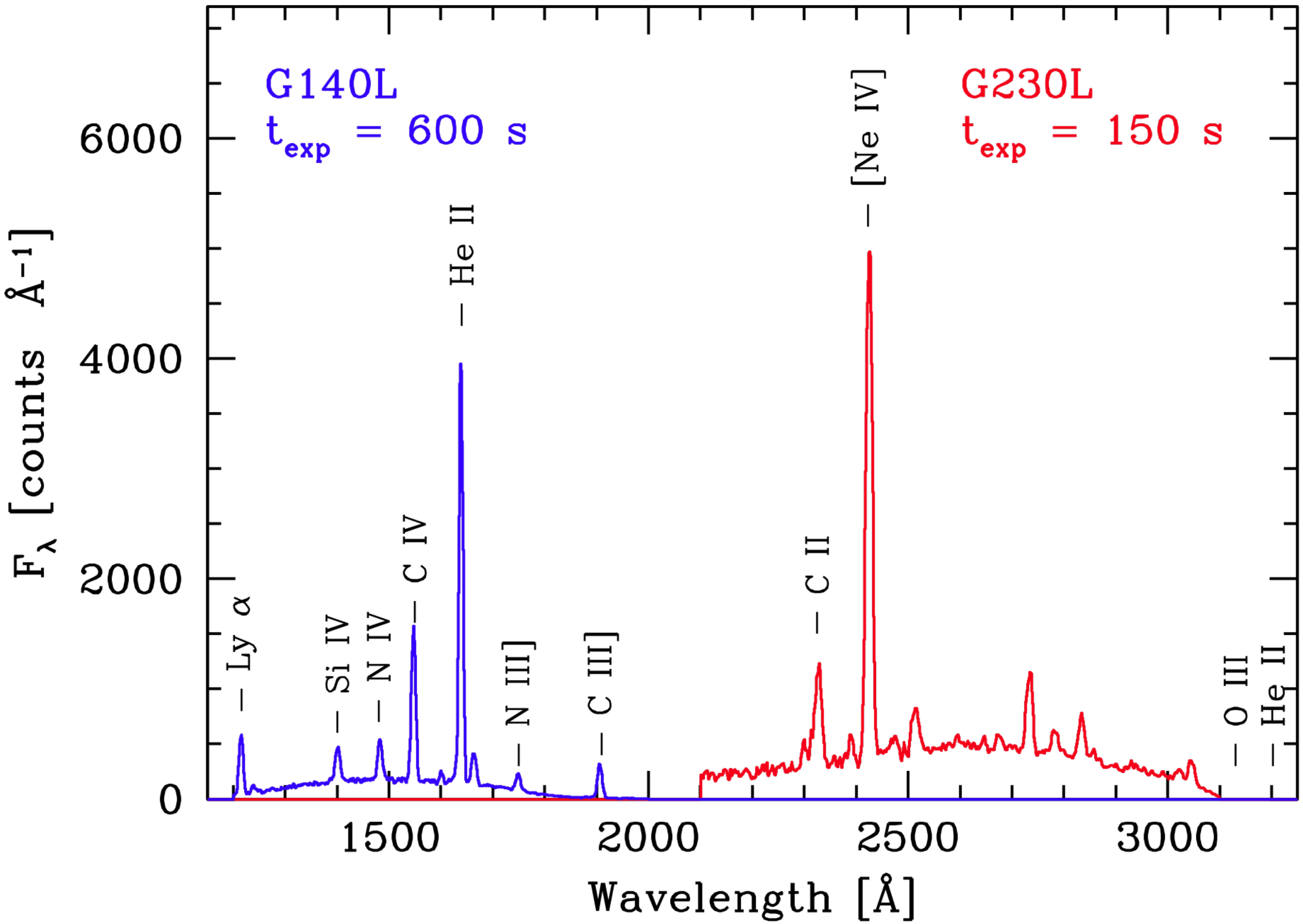
- *WSO-UV*/ISSIS versus *HST*/ACS/SBC:

	FUV Channel	NUV Channel
Spectral range	1150-1750 Å	1850-3200 Å
Peak throughput (imaging)	1400 Å	2300 Å
Field of View: imaging	70 arcsec x 75 arcsec	70 arcsec x 75 arcsec
Field of View: spectroscopy	36 arcsec x 65 arcsec	36 arcsec x 65 arcsec
Detector type	CsI MCP	CsTe MCP
Detector diameter	40 mm	40 mm
Detector format (equivalent)	> 2048 x 2048 pix	> 2048 x 2048 pix
Pixel scale	0.036 arcsec	0.036 arcsec
Scale ratio	< 7 %	< 7 %
Number of reflections	4	4
Temporal resolution	40 ms	40 ms
Slitless spectroscopy resolution	R=500	R=500

Throughput of ISSIS



***WSO-UV* ISSIS synthetic spectrum of a compact PN**



Summary

- **TMT spectroscopic surveys of extragalactic PNe**
- **Tackle with the basic problems in nebular astrophysics using TMT**
- **A synergy between TMT and *WSO-UV***


Thank you
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