Kinematic Evolution of the Ionized Shells of Planetary Nebulae

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The present work contains results from collaborations over several years with my colleagues:

-Michael G. Richer

-Margarita Pereyra

-Teresa García Díaz

I am grateful to all of them for their contributions to this project.

The Global Picture:

PNe are Expanding Ionized Shells Evolving from AGB stars

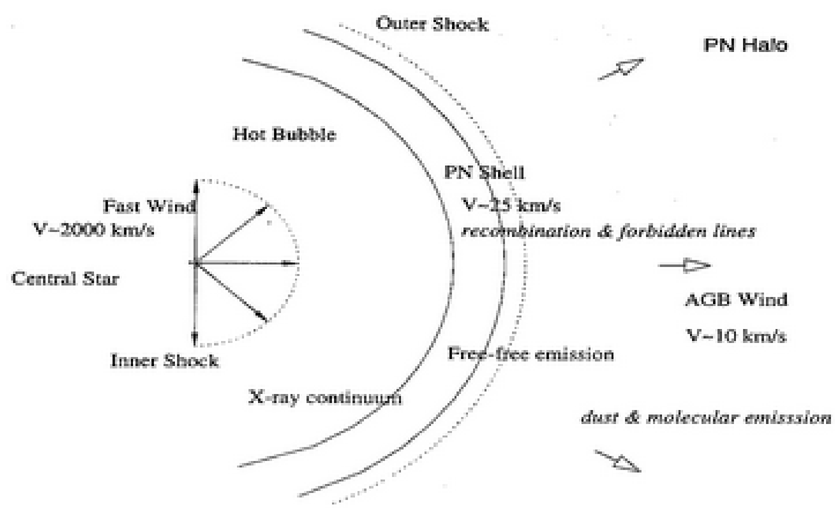
Wilson (1950); Shklovskii (1956) Red Giant → PNe → White Dwarf

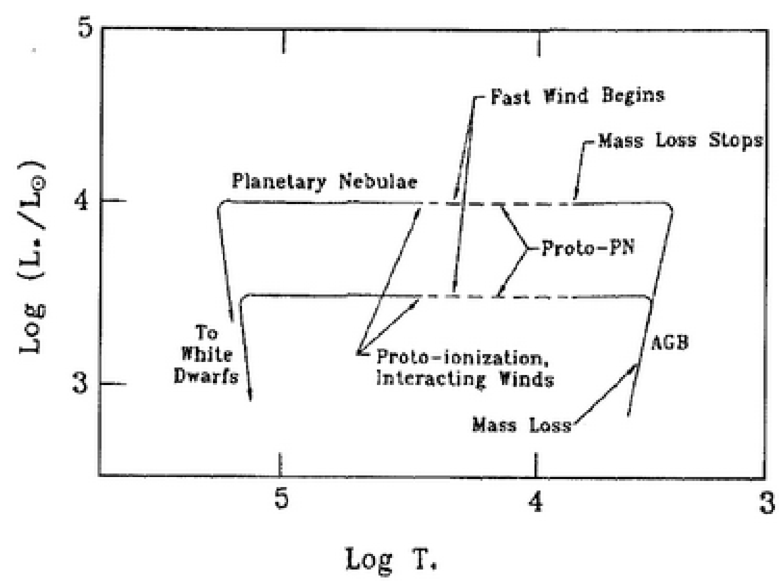
Abell & Goldreich (1966) PNe originate from ejected atmospheres of Red Giants

Paczyński (1970) First consistent stellar evolution model for a PN

The Interacting Winds Model (Kwok et al 1978; Kwok 1982)

Seminal papers ….. fundamental input to evolution models

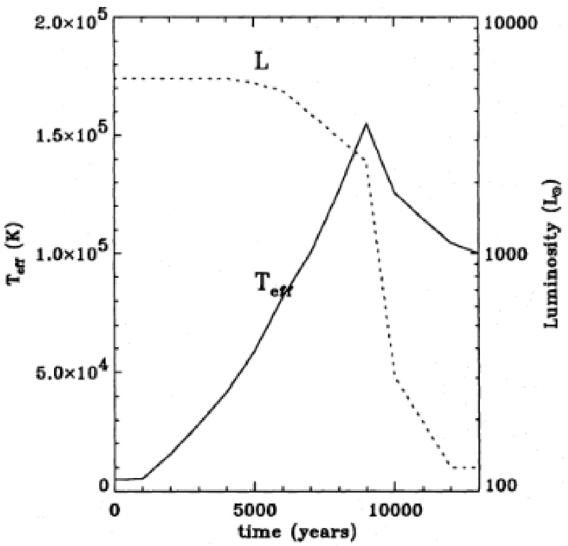




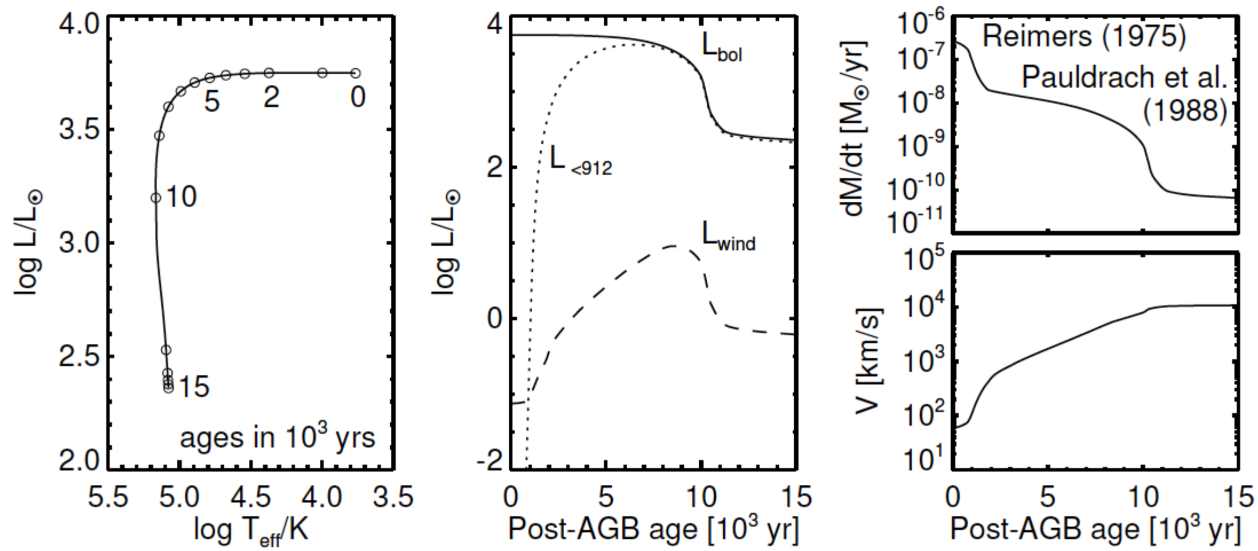
From the book: The Origin and Evolution of Planetary nebulae by Sun Kwok.

The Global Picture:

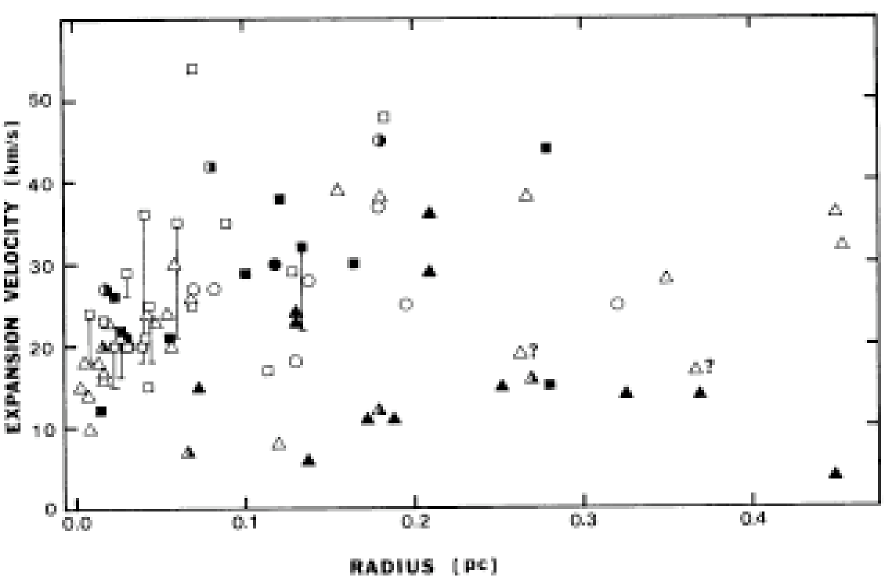
Interacting Winds and Ionizing Luminosity = Kinematic Shell Evolution



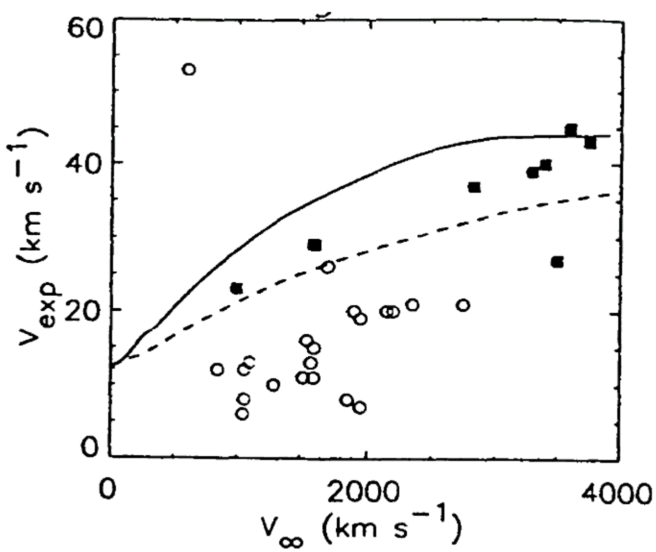
Mellema 1994



Schönberner 2014



In the Galaxy. Heterogeneous, limited samples.

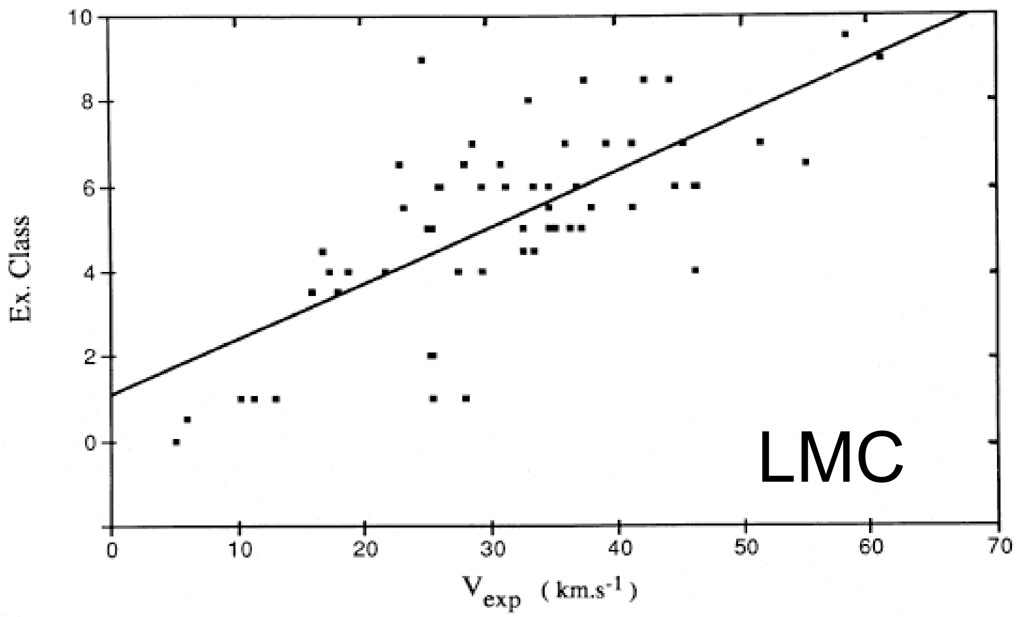


Chu et al. 1984

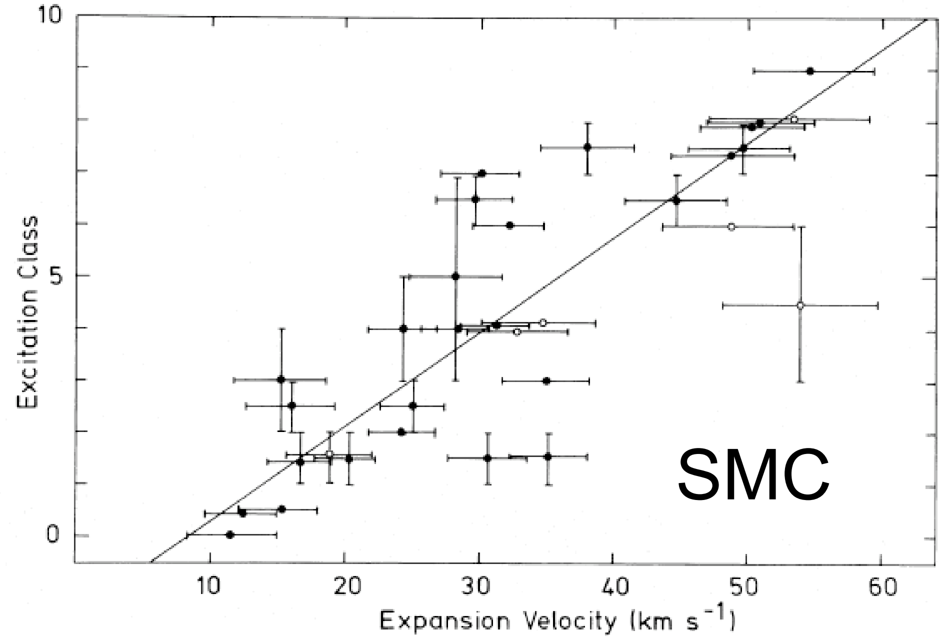
Heap 1993

The Global Picture:

In the LMCs



Dopita et al. 1988



Dopita et al. 1985

The Global Picture:

We know well, from observations and models, the mean expansion velocity of planetary nebulae ~15 - 35 km/s

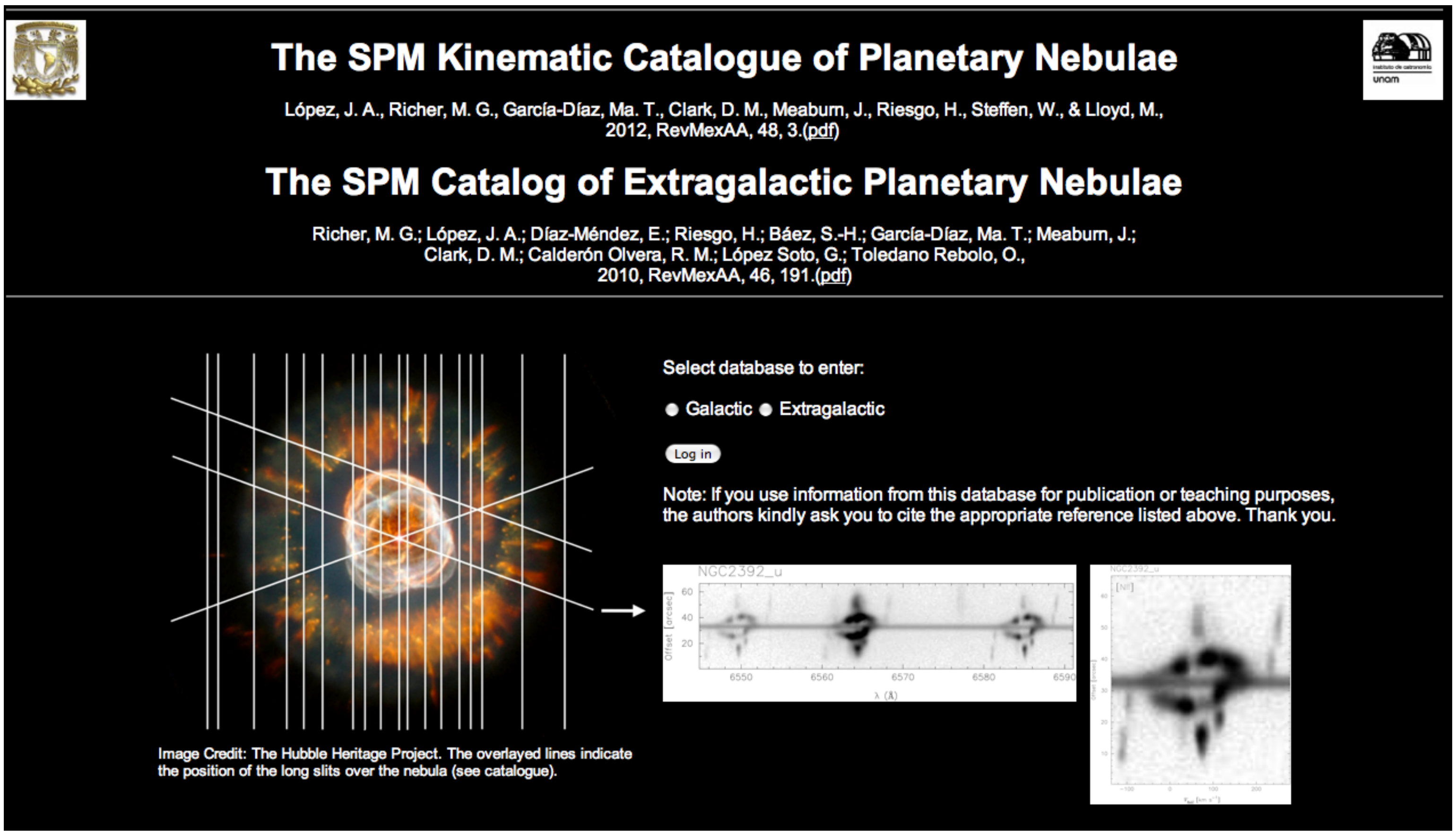
We also know, in general, that the expansion velocity of PNe should evolve throughout their lifetimes as a function of the stellar wind, ionizing radiation and rate of CS evolution

However, the available data has not been sufficient to obtain a clear parametric picture of the kinematic evolution for diverse groups of PNe

…It therefore seems reasonable to pursue R-V relations separately for groups of PNe sharing similar properties: e.g., kinematic structure, evolutionary state of the nebula and/or the central star and distance from the Galactic plane… (Chu, Kwitter, Kaler & Jacoby, 1984)

This task requires measuring expansion velocities for a large number of PNe divided by evolutionary stages, galactic populations, masses and metallicities

For this purpose we are using the SPM Kinematic Catalogue of Galactic PNe. It contains long-slit, echelle, kinematic data for nearly 700 PNe



http://kincatpn.astrosen.unam.mx/

Our studies, in progress, have included up to now 259 PNe, distributed as follows:

86 + 47 = 133 PNe from the galactic bulge

Richer, López ,Pereyra, Riesgo, García-Díaz, 2008, ApJ689, 203 and
Richer, López, García-Díaz, Clark, Pereyra & Díaz-Méndez, 2010, ApJ 716, 857

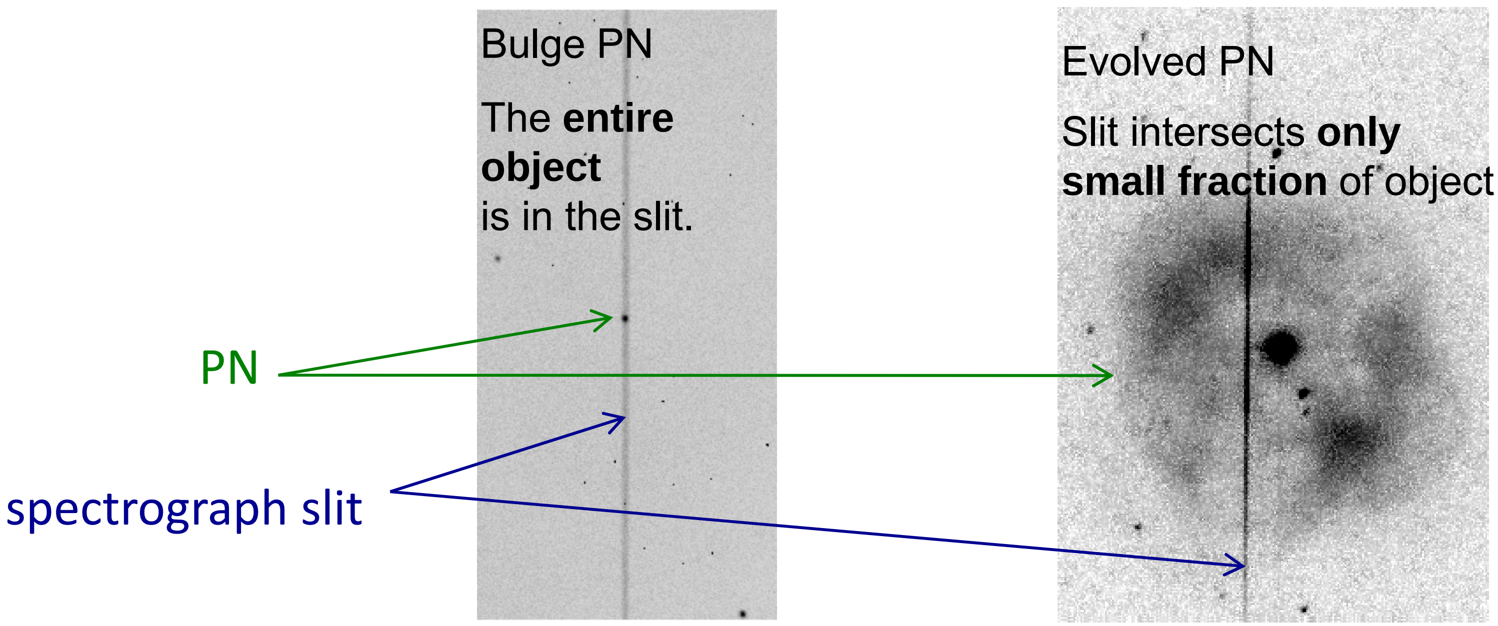
100 PNe from mature and highly advanced stages of evolution

Pereyra, Richer, López, 2013, ApJ 771, 114

11 + 15 = 26 PNe from the Galactic Halo and very low metallicity (i.e. low CS mass)

Pereyra, López, Richer, 2015, AJ, in press

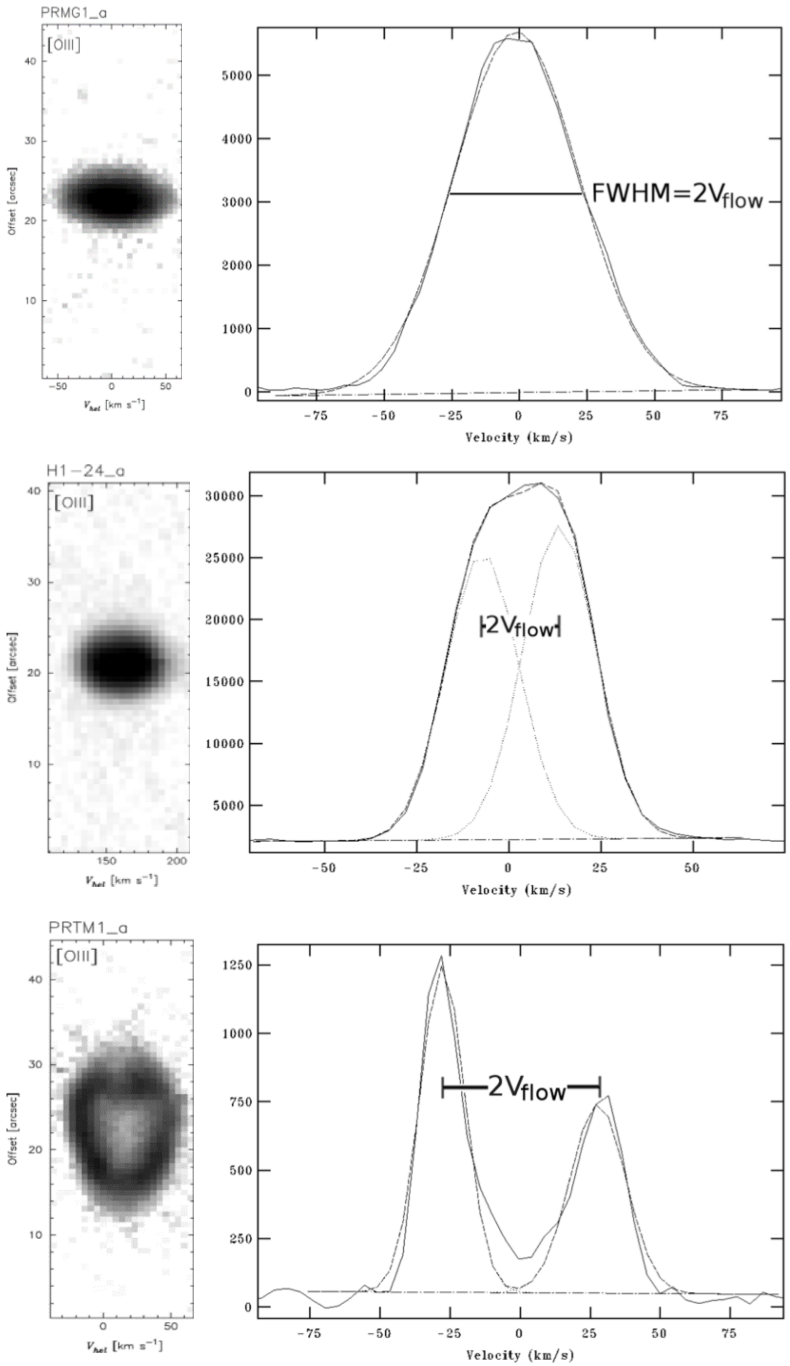
Kinematics & spatial resolution



- PNe from the galactic bulge mostly ≤ 6”,i.e. Many nearly point sources. Spatially unresolved from ground-based observations. All spectral info. is condensed into a gaussian profile (may be symmetric or asymmetric)

- Mature and HE PNe sample, spatially resolved, split or asymmetric line profiles

- Halo and low metal PNe, distant objects, similar to bulge case + weak win



$$\sigma^2 = \sigma^2_{true} + \sigma^2_{inst} + \sigma^2_{fs}$$

$$\Delta V = 2.356\sigma_{true}$$

$$\Delta V_{0.5} = 0.5\Delta V = 1.177\sigma_{true}$$

Spatially Unresolved Cases:

a) - Line profile is a single symmetric profile. We fit a Gaussian profile and assign half of the resulting FWHM after correcting for instrumental, thermal Doppler and fine structure broadening.

b) - Asymmetric profiles and barely resolved profiles. We fit red and blue gaussian components and assign the expansion velocity as half the peak to peak difference

Spatially Resolved Cases: Line splitting. The expansion velocity of the nebular shell is derived from the main receding (redshifted) and approaching (blue-shifted) components of the line profiles as half the peak to peak difference.

The global expansion velocity "V_{exp}" used here is the emission weighted expansion velocity or the bulk outflow velocity for the matter projected within the spectrograh slit. As such "V_{exp}" is an adequate parameter for characterizing the kinematic evolution of the nebular shells.

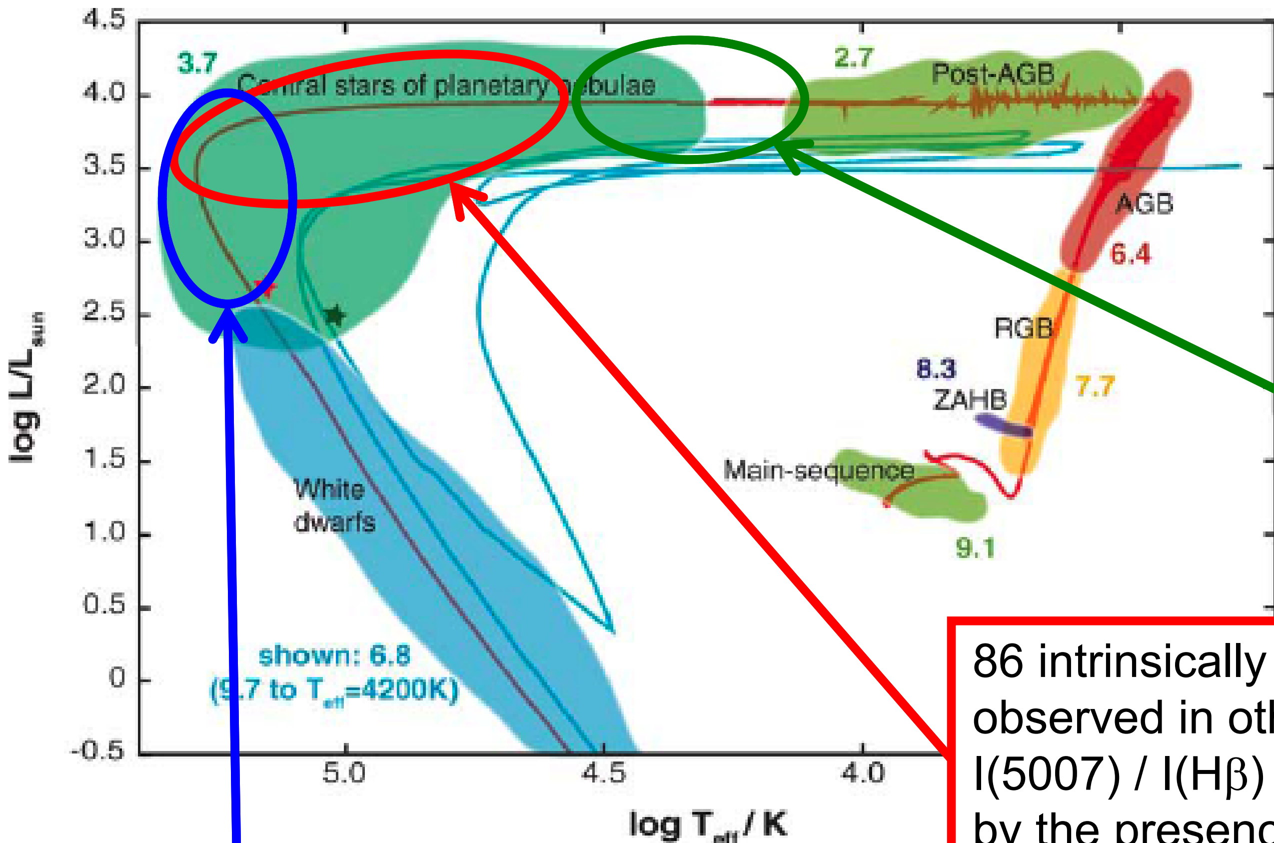
On the other hand "V_{exp}" may be unsuitable for determining kinematic ages or expansion parallaxes distances for which the outer shock velocity or other pattern of velocity may be a better option in some cases (c.f. Jacob 2013)

Our sample does not contain spatially resolved double shell or rim/shell PNe (Shönberner, previous talk), though some may be present in the bulge sample (spatially unresolved). Their possible inclusion may only underestimate their relative weight in the region of high "V_{exp}" since they all are high excitation PNe, but would not alter the general statistical conclusions of this work.

The Bulge sample

Aim: Systematic observations of single Galactic population of PNe, spanning from the earliest evolutionary stages until the cessation of nuclear burning in the central star (the knee)

The bulge sample
Grouped by evolutionary stages vía excitation classes



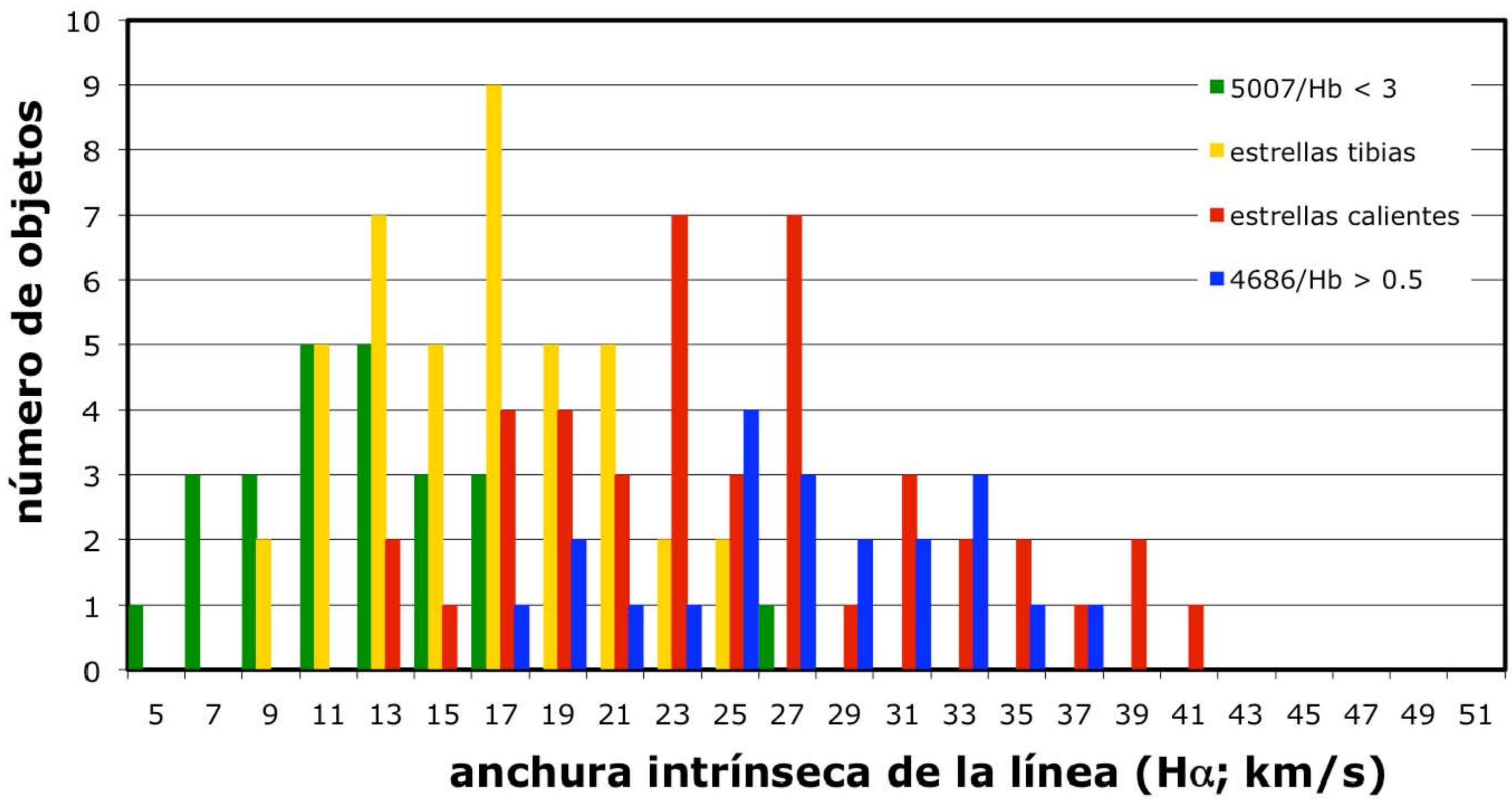
Herwig (2005, ARA&A, 43, 435)

24 young PNe :
I(5007) / I(Hβ) <3 and
high L(Hβ)

86 intrinsically bright PNe, similar to those observed in other galaxies:
I(5007) / I(Hβ) >6 and high L(Hβ). Sub-divided by the presence or absence of He II 6560

23 evolved PNe: I(4686)>0.5I(Hβ)

The samples from the Galactic bulge



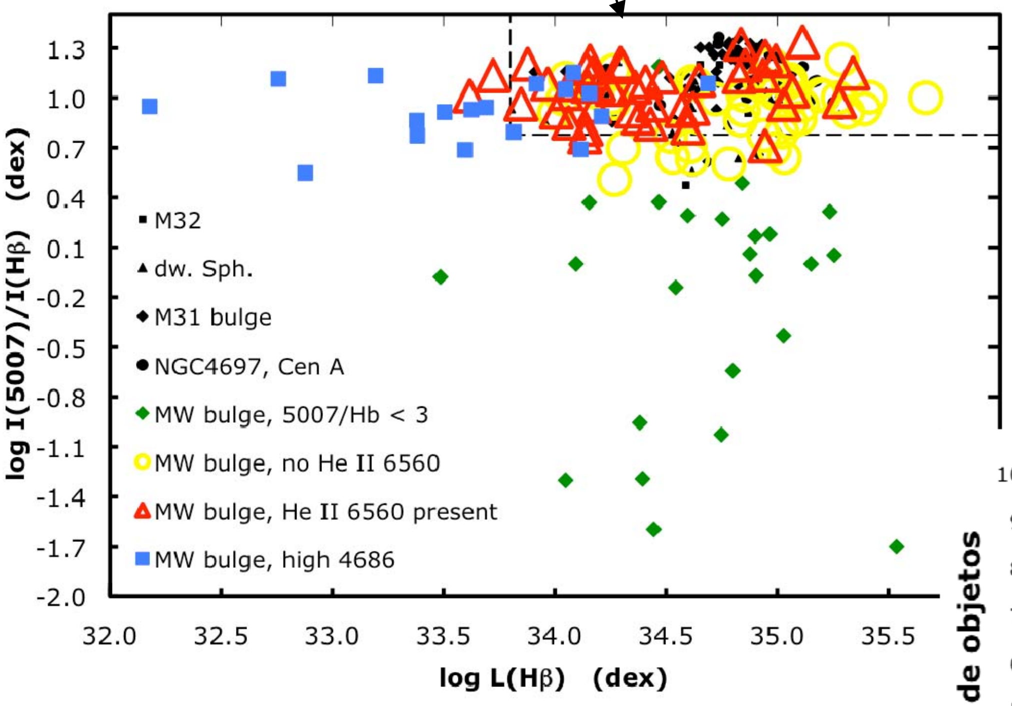
No He II 6560

He II 6560 present

Line width correlates with CS evolutionary stage. As the PN evolves its V_{exp} increases

Kinematics and CS evolution

Area within box corresponds to bright extragalactic PNe



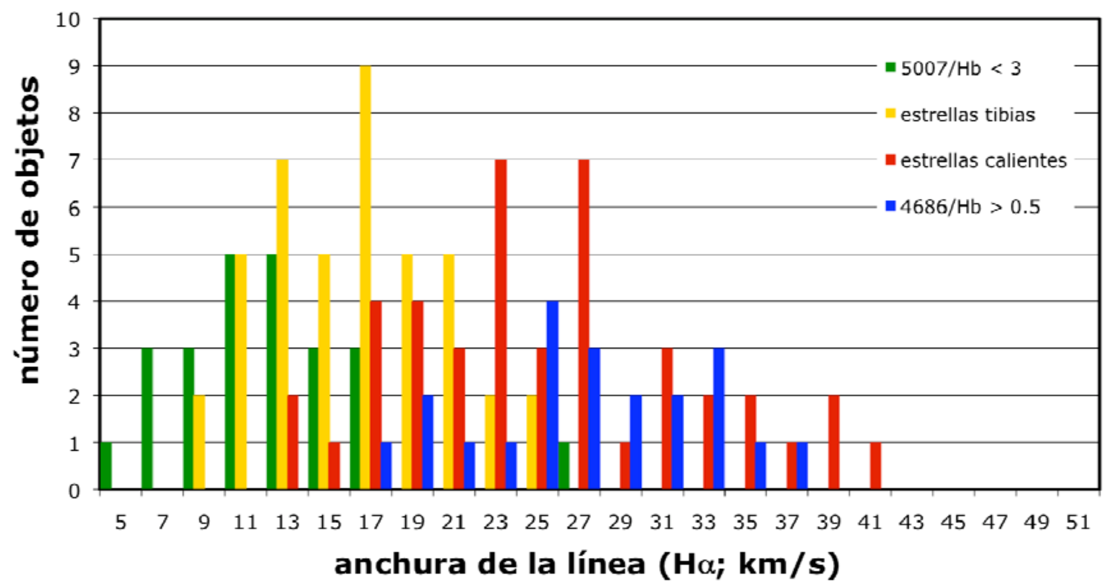
$\Delta V_{0.5}(H\alpha)$ medians:

Young PNe: 10.7 km/s

He II 6560 absent: 15.7 km/s

He II 6560 present: 23.6 km/s

Evolved PNe: 26.5 Km/s

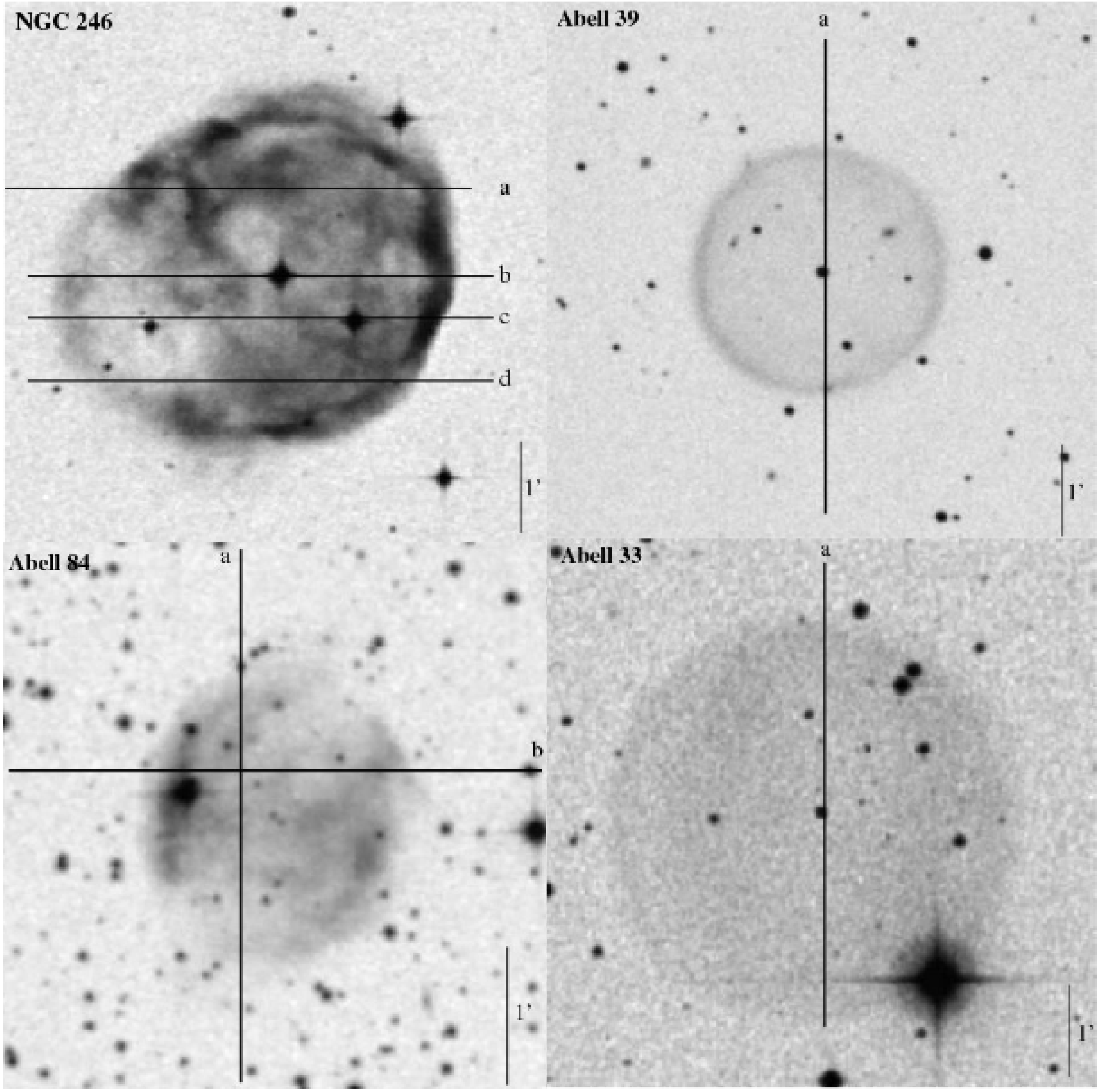


The agreement between evolutionary stage and kinematics is excellent

The mature and highly evolved PNe sample

Aim: to test the global expansion velocities of PNe at very late evolutionary stages.
PNe selected with no rims or filamentary structures, i.e. old nebulae composed of a single, closely spherical, smooth shell where the overall expansion velocities can be adequately determined from the matter with highest emission measure within the spectrograph slit

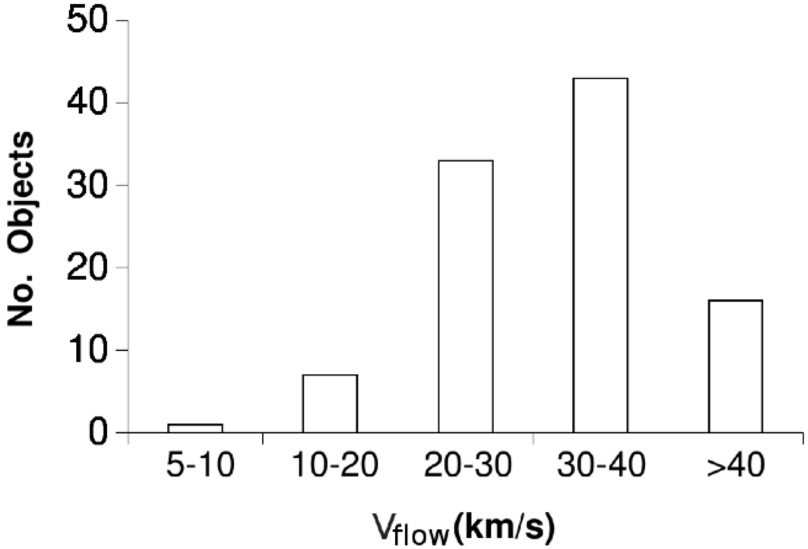
This sample is divided into two groups:
Moderately evolved or mature (M)
-show some structure and bright outer edges-
Highly evolved (HE)
--very low surface brightness, no inner structure, no rim-

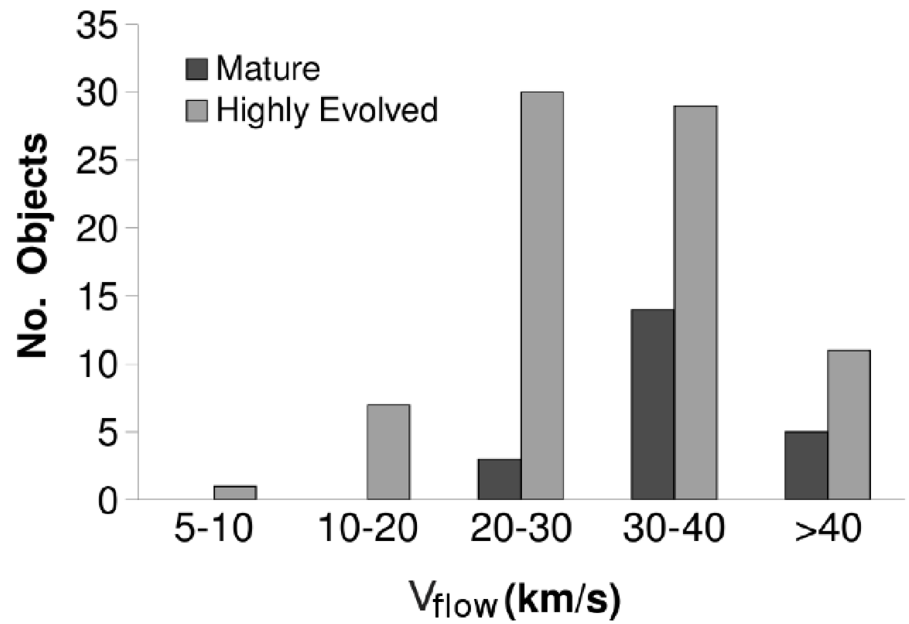


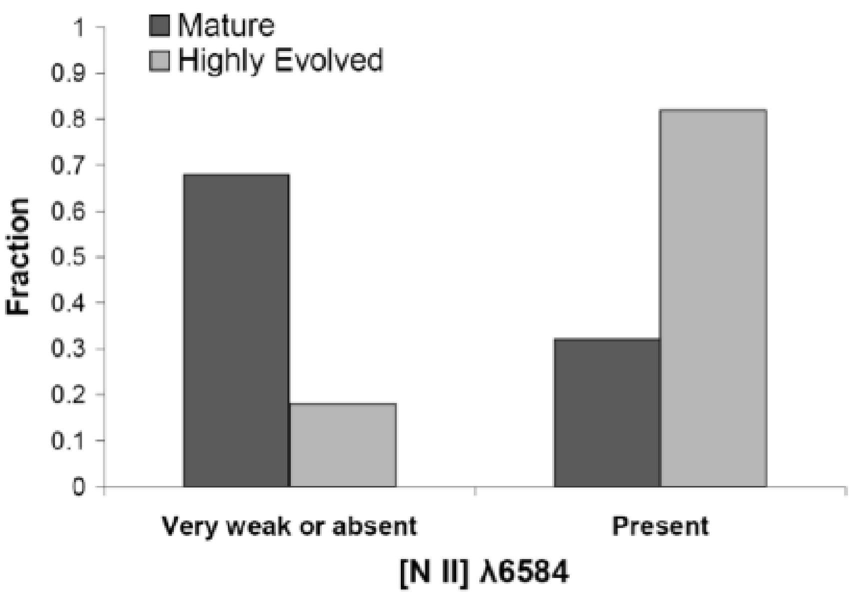
Mature

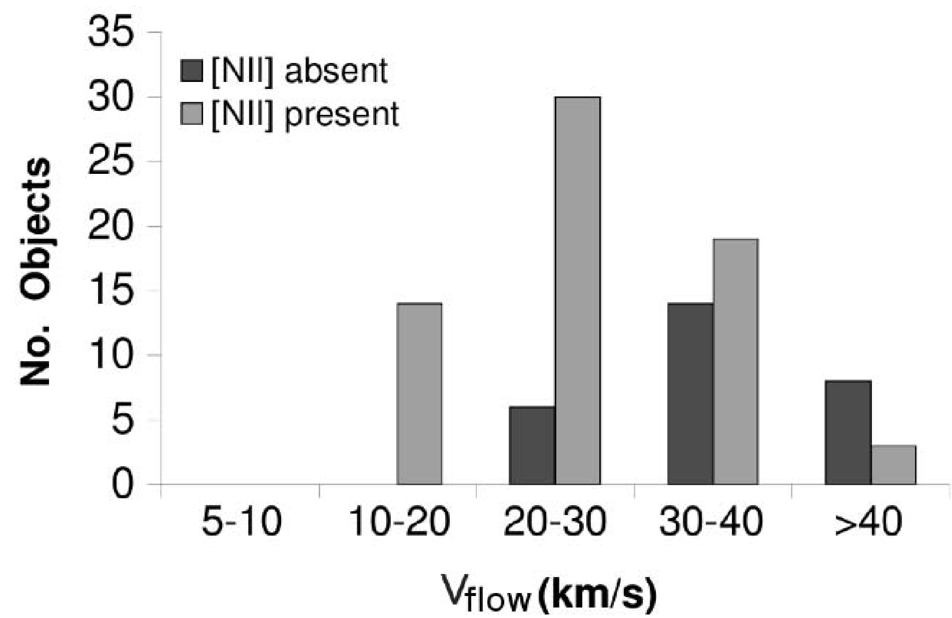
Highly Evolved

Median Vexp (= V_{flow})
22 Mature PNe 37 ± 8km/s
78 Highly Evolved PNe 30 ± 9 km/s

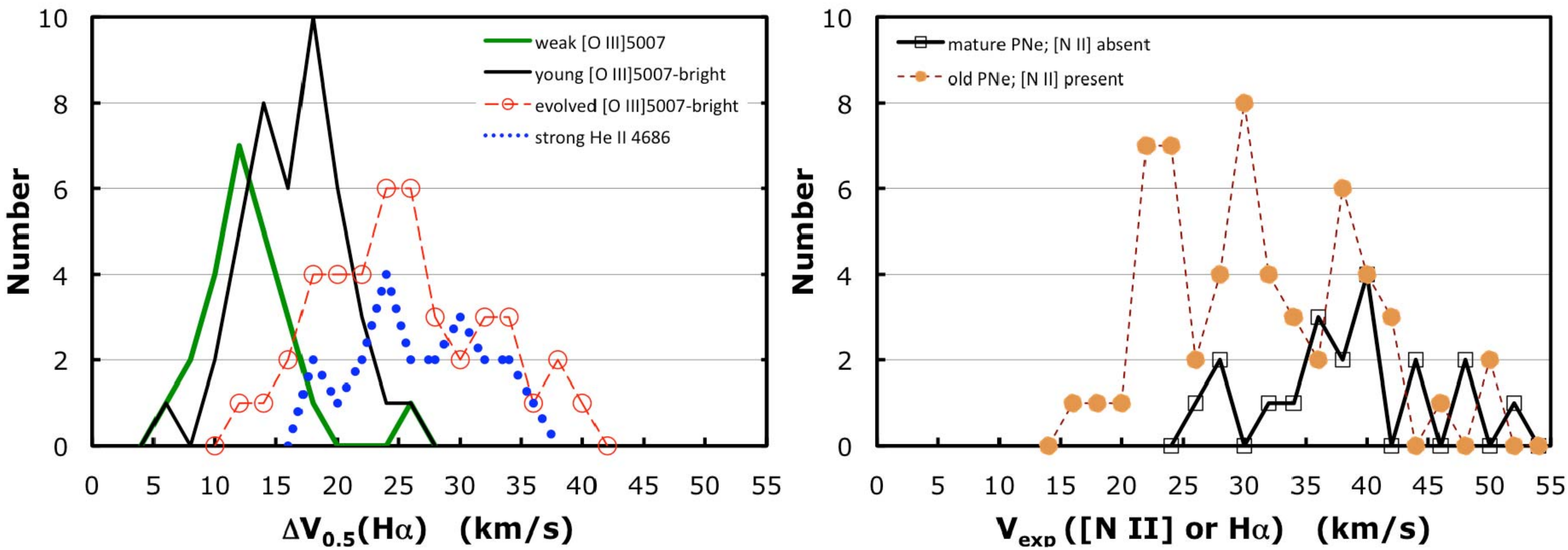








PNe Kinematics changes with time.
In this context the CS acts as a natural clock



Mature PNe near max T_{eff} in evolutionary tracks, have high luminosity CS and the highest $V_{exp,,}$ lack the presence of [N II], have the strongest He II 4686.

Degree of excitation controlled by luminosity of CS.

Highly Evolved PNe have lower luminosity CS and lower V_{exp}.

CS luminosity, nebular morphology and nebular excitation are all related to evolutionary stage
This is reflected in the PNe expansion rate

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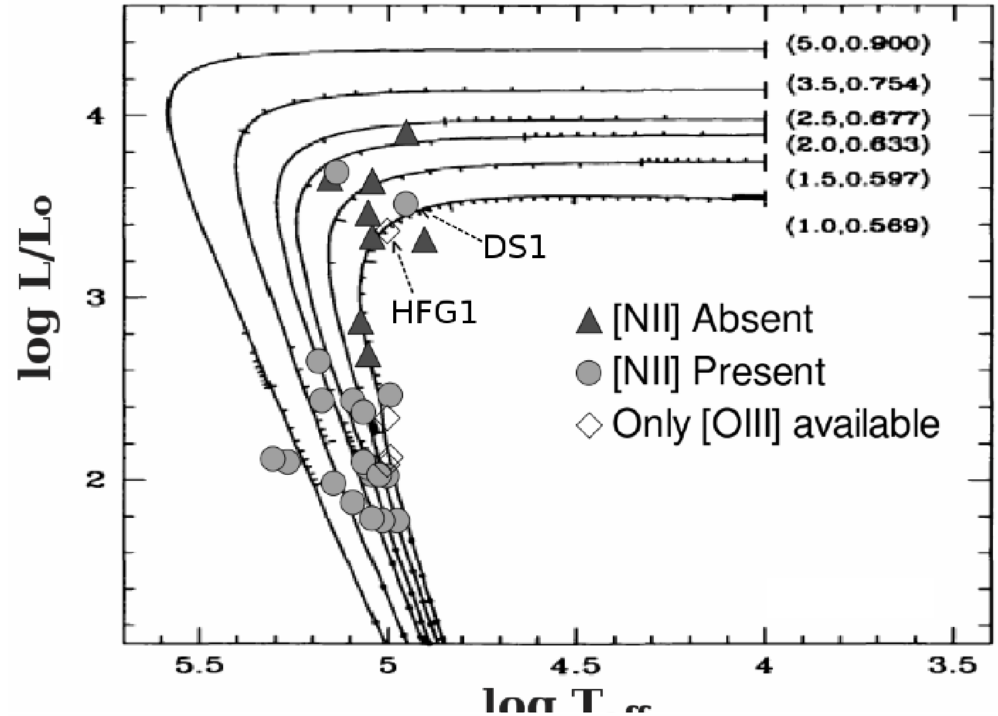
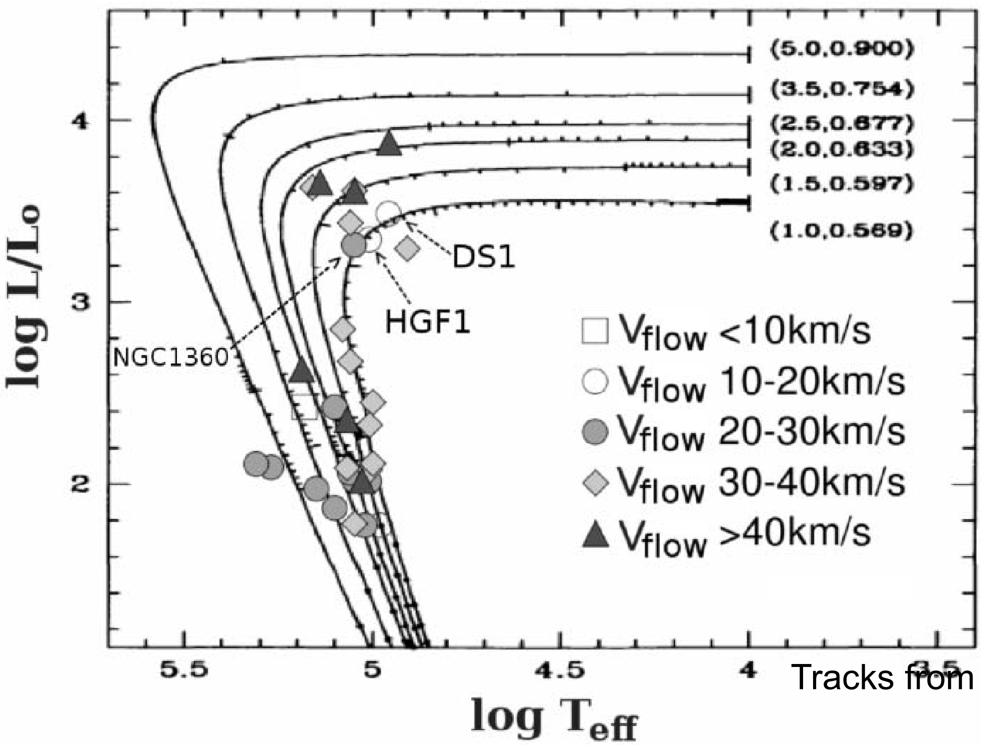
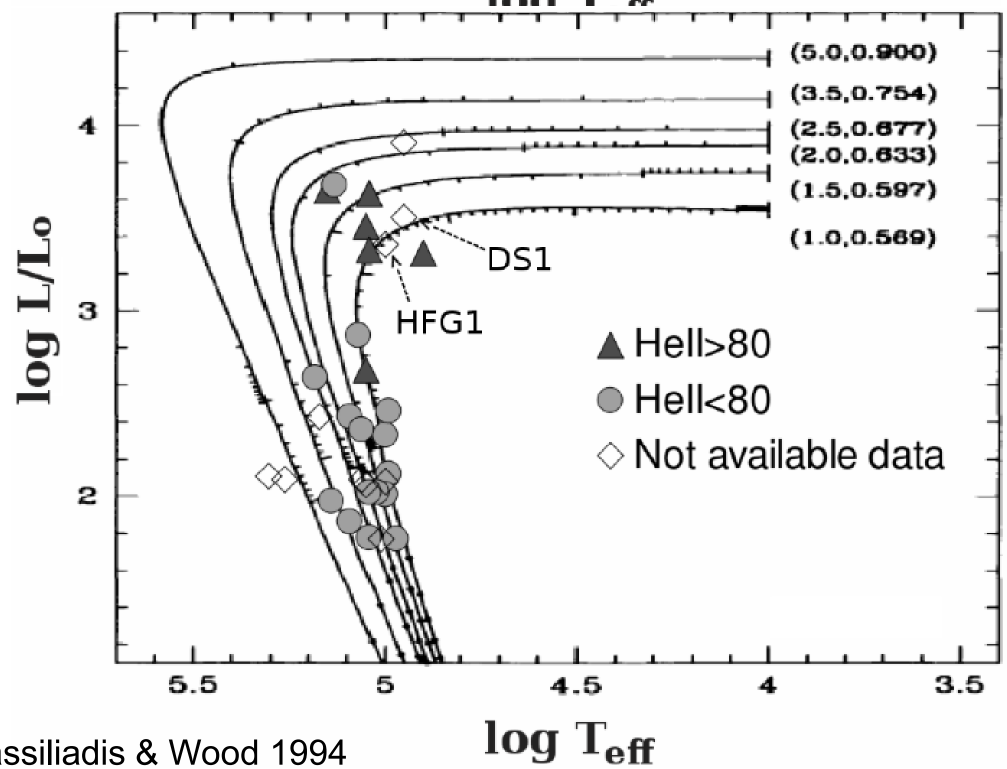
8 Mature PNe, Mean $V_{exp} = 37 \pm 4$ km/s
24 HE PNe, Mean $V_{exp} = 28 \pm 10$ km/s

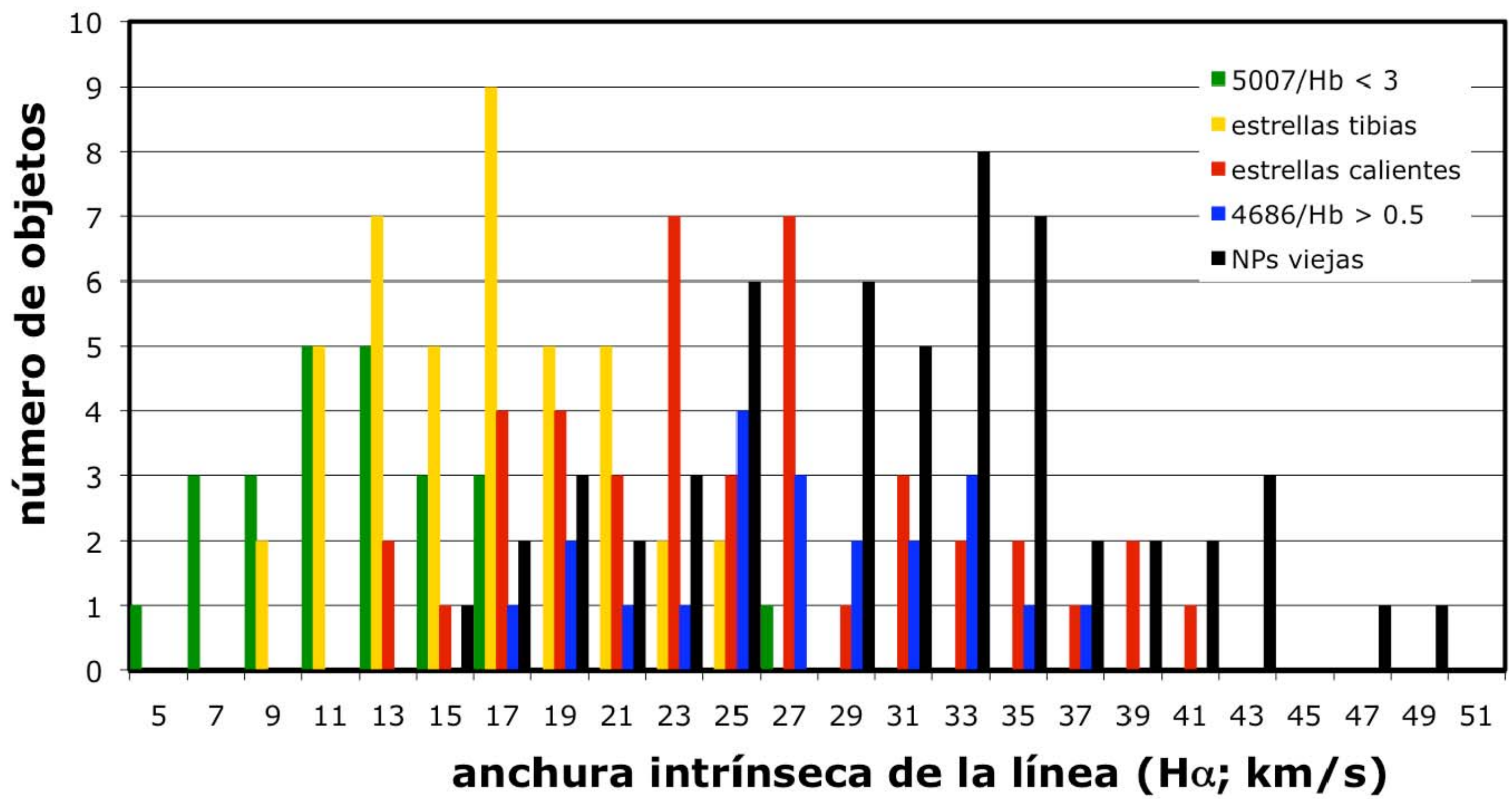






Tracks from Vassiliadis & Wood 1994

Including the sample of evolved PNe with the samples from the galactic bulge



The tendency is consistent: the more evolved and hotter the CS the faster the PN expansion.

When the CS luminosity and stellar wind decline also does V_{exp},

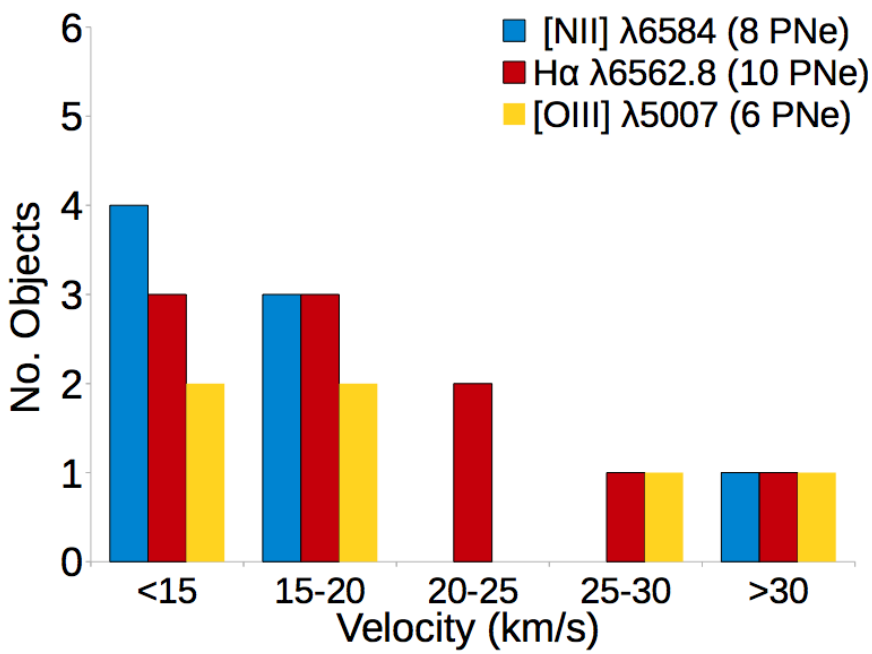
This deceleration effect may have various explanations

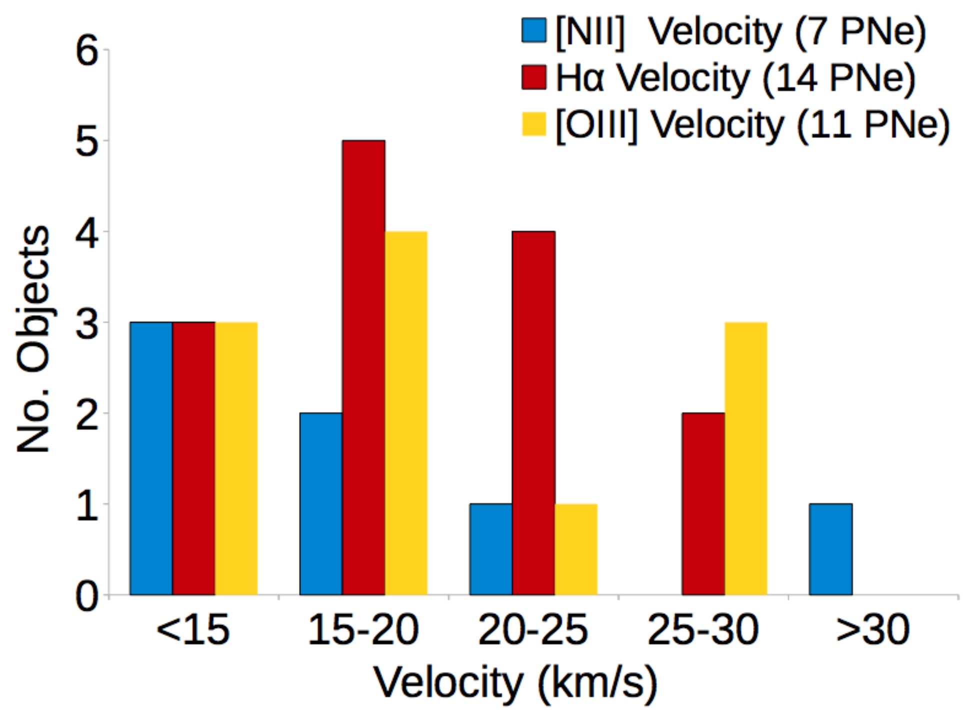
PNe from the Halo and very low mass progenitors

Aim: Characterize the role played by the CS in driving the expansion velocity of the nebular shells for the progenitors stars of the lowest masses and slow evolution

Selection of sample: PNe classified as belonging to the Halo (11 objects) and PNe with log(O/H) + 12 ≤ 8.0 dex (15 objects)

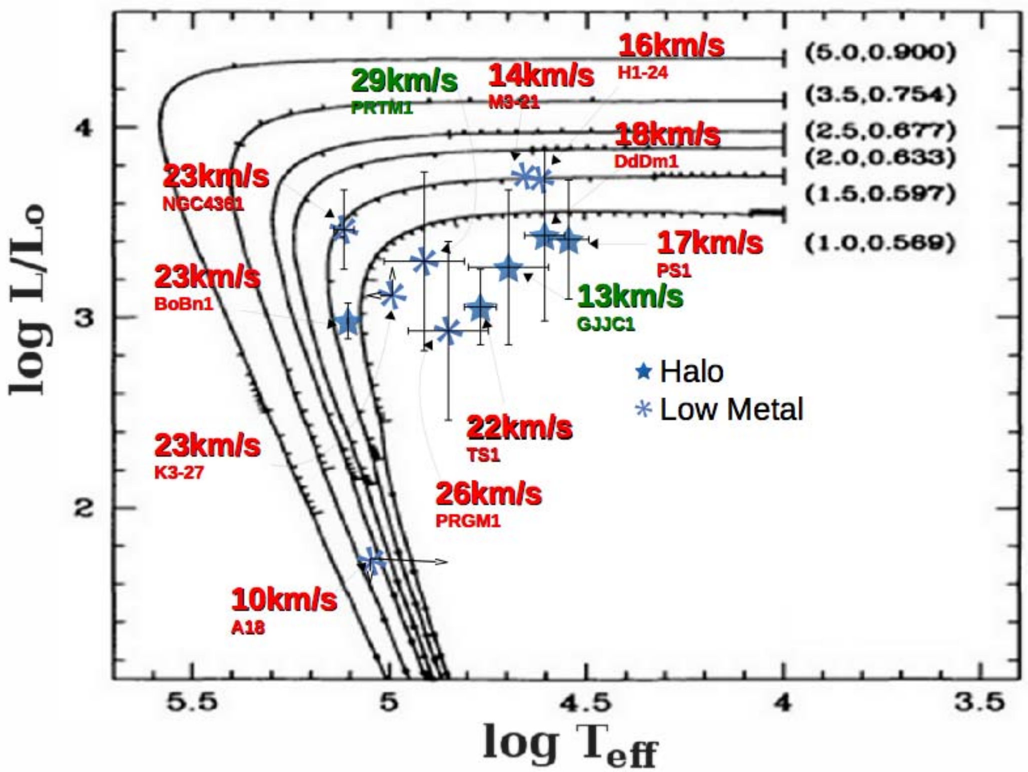
Distribution of expansion velocities



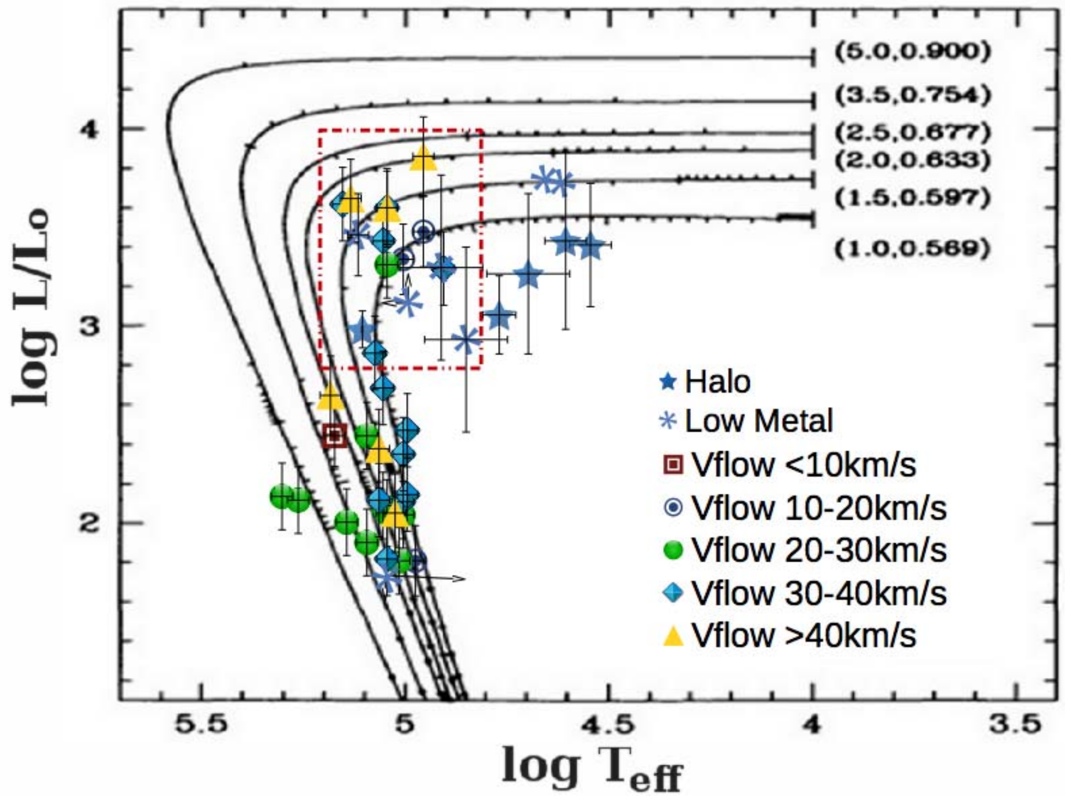


Halo PNe

Low metal PNe



16km/s
H1-24
29km/s
PRTM1
14km/s
M3-21
18km/s
DdDm1
23km/s
NGC4361
17km/s
PS1
23km/s
BoBn1
13km/s
GJJC1
22km/s
TS1
23km/s
K3-27
26km/s
PRGM1
10km/s
A18
Halo
Low Metal
(5.0,0.900)
(3.5,0.754)
(2.5,0.677)
(2.0,0.633)
(1.5,0.597)
(1.0,0.569)
log L/Lo
log Teff
5.5
5
4.5
4
3.5
4
3
2



(5.0,0.900)
(3.5,0.754)
(2.5,0.677)
(2.0,0.633)
(1.5,0.597)
(1.0,0.569)
Halo
Low Metal
Vflow <10km/s
Vflow 10-20km/s
Vflow 20-30km/s
Vflow 30-40km/s
Vflow >40km/s
log L/Lo
log Teff
5.5
5
4.5
4
3.5
4
3
2

Table 2: Average expansion velocities for Halo and Low Metal PNe.

Group	$\overline{V}_{\text{[NII]}}$ †	No. Objects considered	$\overline{V}_{\text{H}\alpha}$ †	No. Objects considered	$\overline{V}_{\text{[OIII]}}$ †	No. Objects considered
Halo PNe	17	8	19	10	20	6
Low Metal PNe	17	7	19	14	18	11

† The uncertainty in the measurements in $\pm 2\ \mathrm{km\,s^{-1}}$.

Table 3: Comparison of recent kinematic observations of halo PNe.

Object	Present work			Schönberner et al. (2014)	Otsuka et al.		
	Hα ($\mathrm{km\,s^{-1}}$)	[NII] ($\mathrm{km\,s^{-1}}$)	[OIII] ($\mathrm{km\,s^{-1}}$)	[OIII] (rim/post-shock; $\mathrm{km\,s^{-1}}$)	HI ($\mathrm{km\,s^{-1}}$)	[NII] ($\mathrm{km\,s^{-1}}$)	[OIII] ($\mathrm{km\,s^{-1}}$)
BoBn 1	23	19		12/52	23[a]	19	21
DdDm 1	18	18	11		18[b]	19	11
H 4-1	13	13			15[c]		18
K 648/Ps 1	17	12	17	8/35	15[d]	14	16
PRMG 1	26		26	12/49			

[a] Otsuka et al. (2010) measure Hβ.

[b] Otsuka et al. (2009) measure Hα.

[c] Otsuka et al. (2003) measure Hα. The data are for a position angle of 90°, as for our observations.

[d] Otsuka et al. (2015) measure 26 HI Balmer lines.

Evolutionary sequence for the global kinematics of the nebular shell over the lifetime of the PNe as a function of Central Star evolution