SEJONG UNIVERSITY Master's Thesis

Line Formation and Spectroscopic Survey of Raman-scattered He II Features in Young Planetary Nebulae

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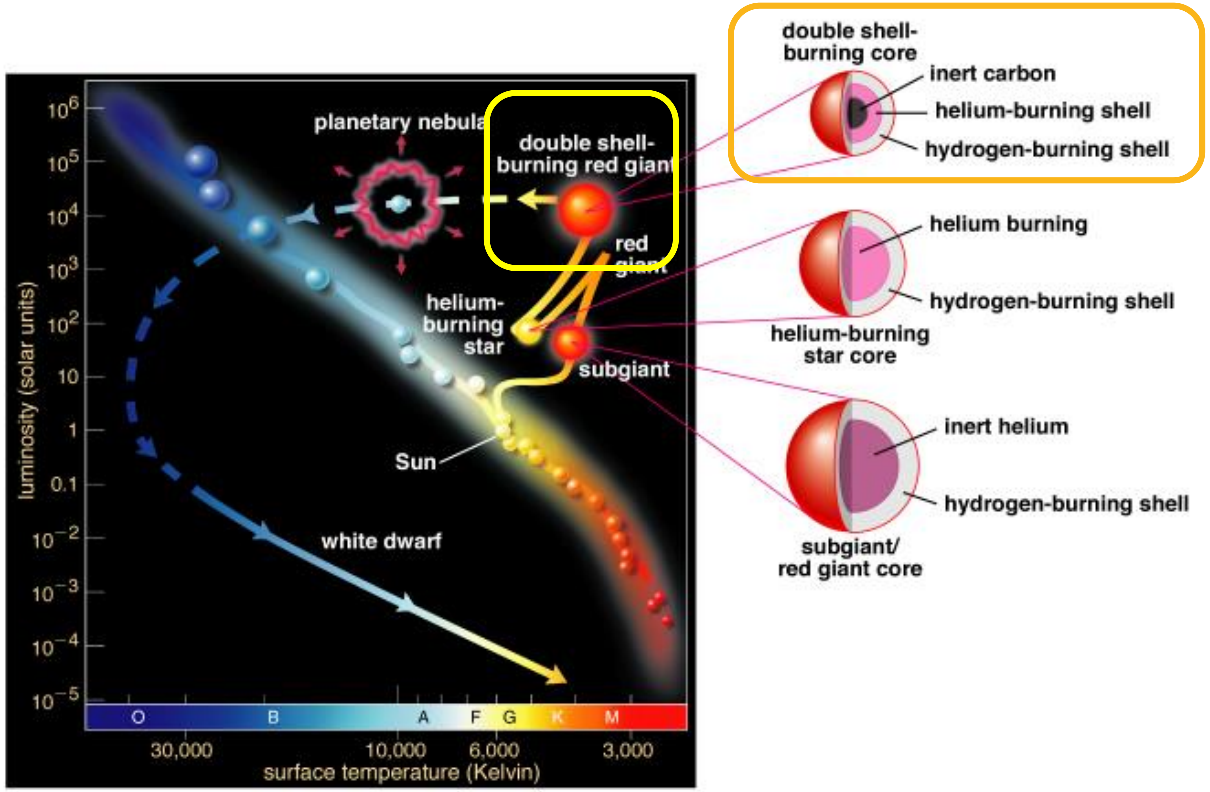
Overview

I. Introduction
  – AGB Mass Loss and the H I region in planetary nebulae
  – Raman Scattering of He II
II. Line Formation Study of Raman-scattered He II λ4851
III. Spectroscopic Survey of Raman-scattered He II
IV. Summary

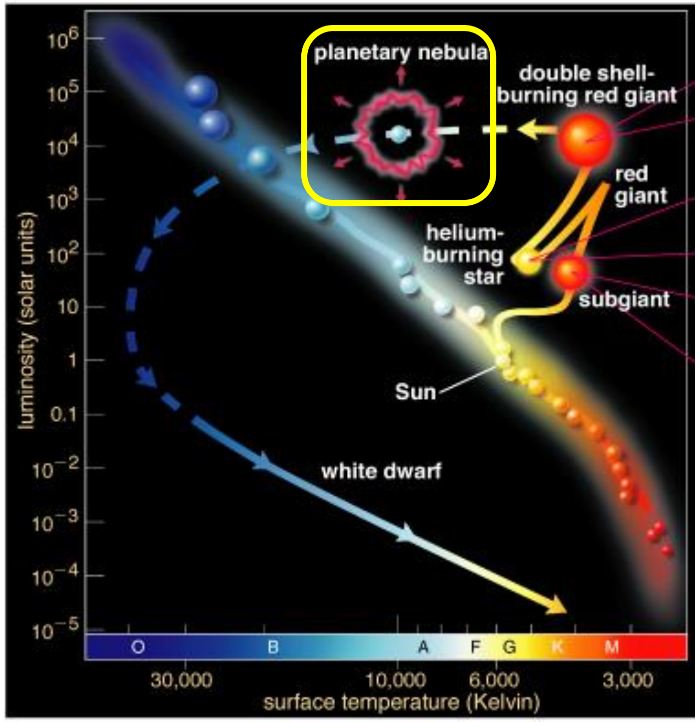
Mass Loss in the Asymptotic Giant Branch (AGB) Stage



▶ AGB stage

- The late evolutionary stage of stars with 0.8 – 8 $M_\odot$
- Chemical enrichment of the ISM and dust formation (Sloan et al. 2008)
- Diverse nucleosynthesis and dredge–up processes (Karakas & Lattanzio 2014)
- Significant mass loss (10^{-8}–10^{-4} $M_\odot\,yr^{-1}$) by slow stellar winds (~ 10 km s^{-1}) or outflows : atomic/ molecular

Planetary Nebulae



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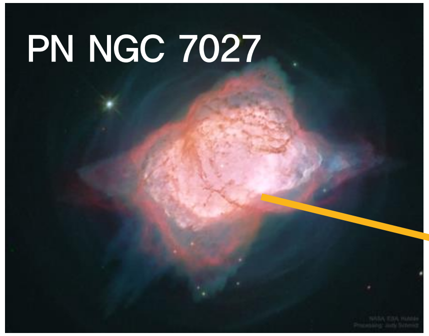
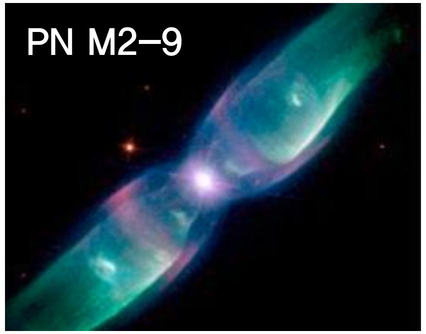
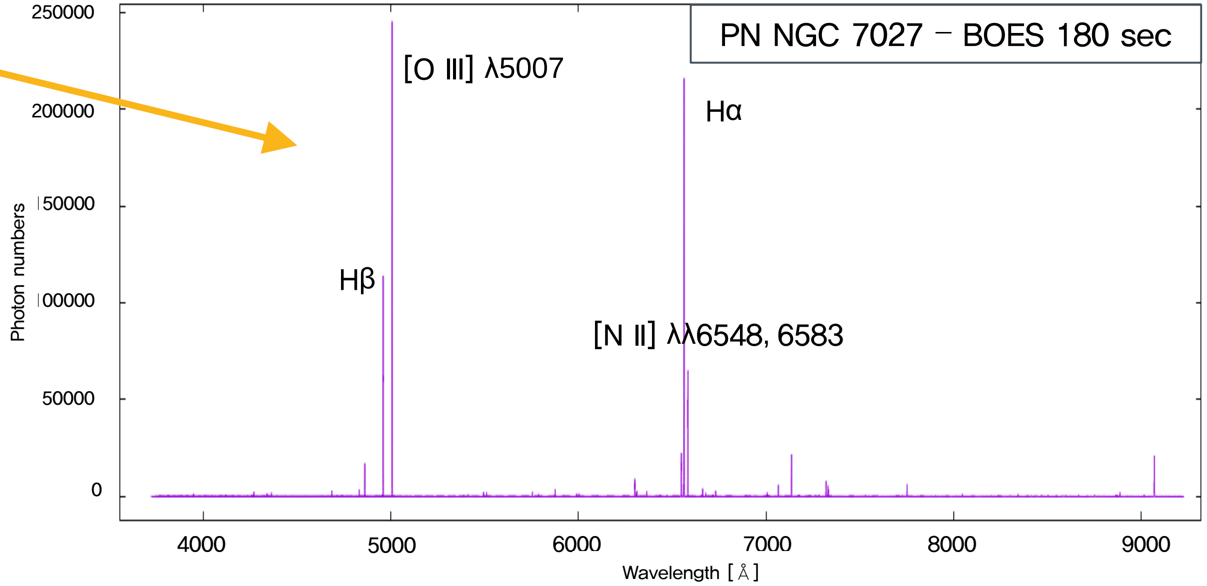


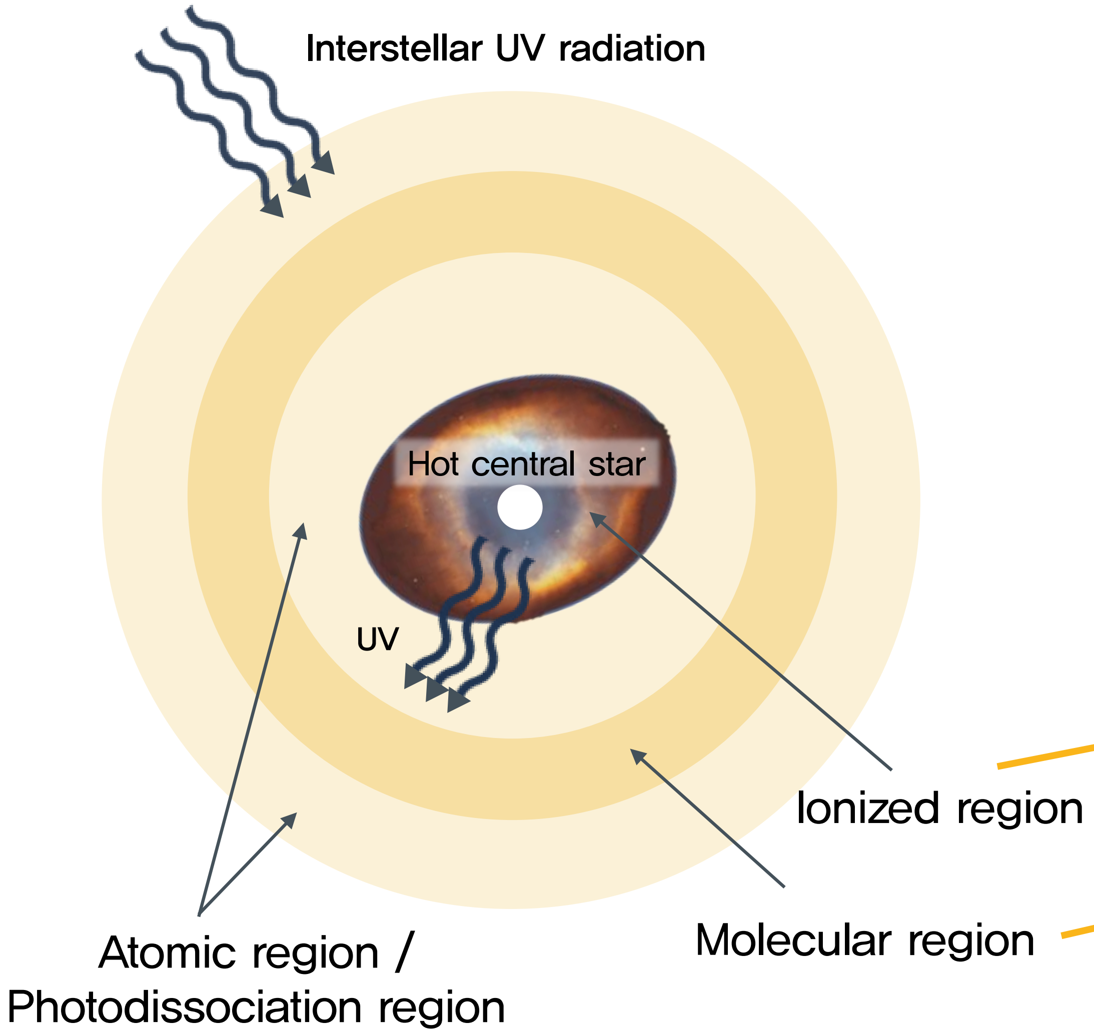


Credit: NASA/ESA

- **Planetary nebula (PN)**
  - Hot central star + ejected material
    Central star → white dwarf (WD)
    (under Chandrasekhar limit 1.4 $M_\odot$)
  - Copious emission lines from the ionized region



Neutral Matter in Young PNe



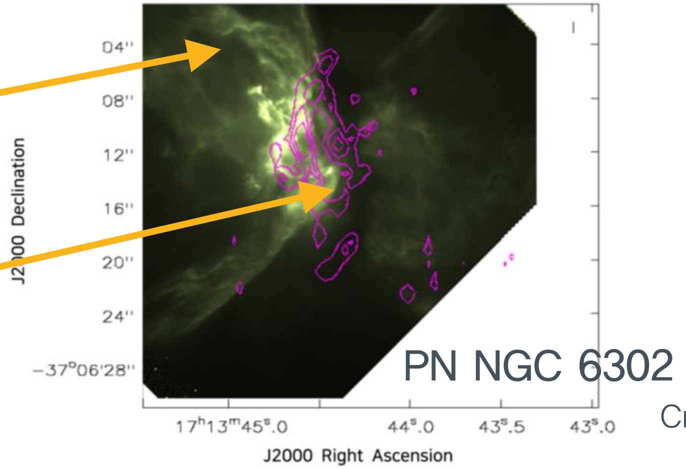
▶ Neutral Matter in PNe

– Molecular region

✓ H_2, CO, HCN molecular lines ~ 100 PNe
(Kastner et al. 1996; Schmidt & Ziurys 2017; Guzman-Ramirez et al. 2018)

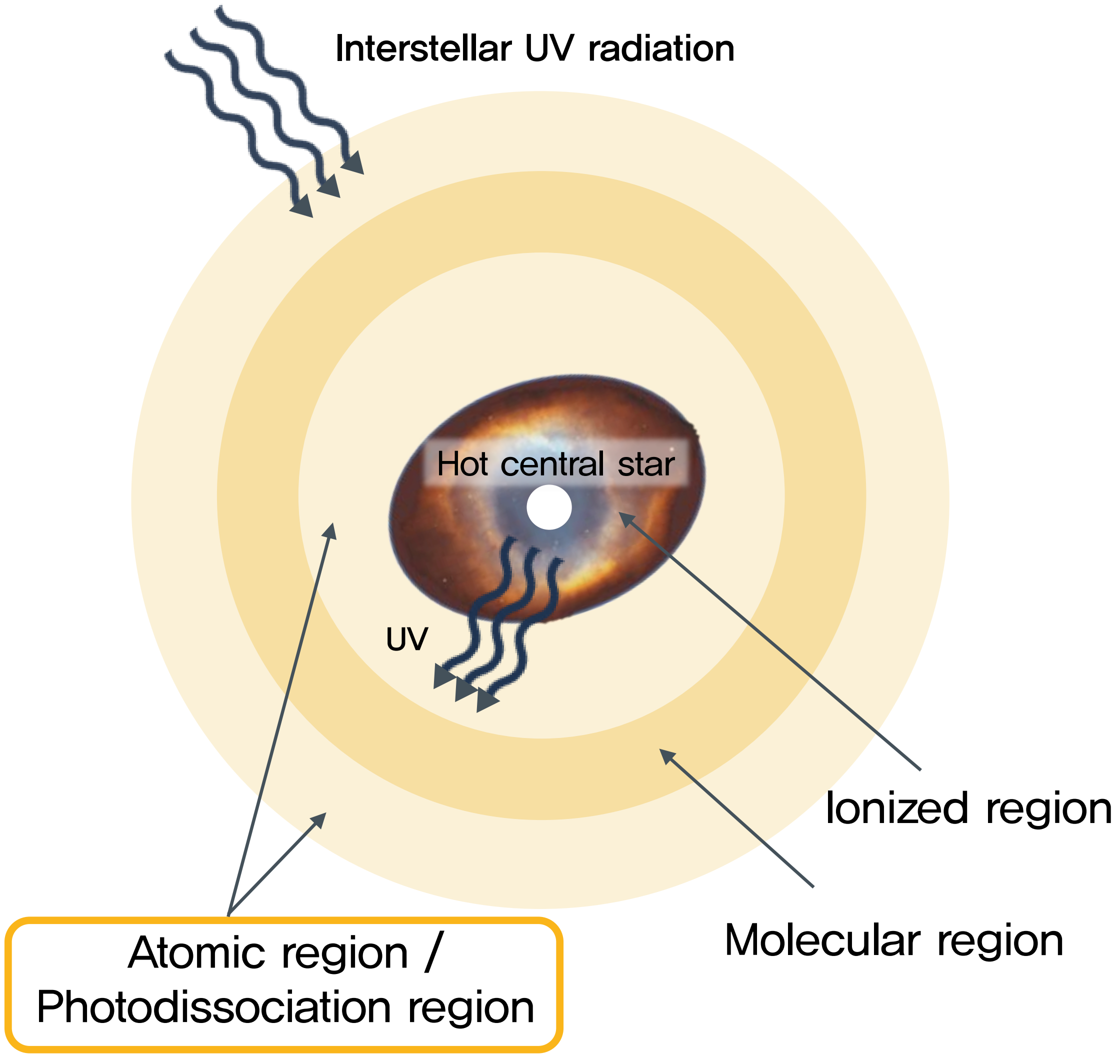
✓ Additional mass

* **Missing mass problem in PNe**
: The lower value of the estimated mass for ionized region
~ 0.01 – 0.1 $M_\odot$ (Buckley & Schneider 1995)



Credit: B.-E. Choi/ HST/ ALMA

H I Region in PNe

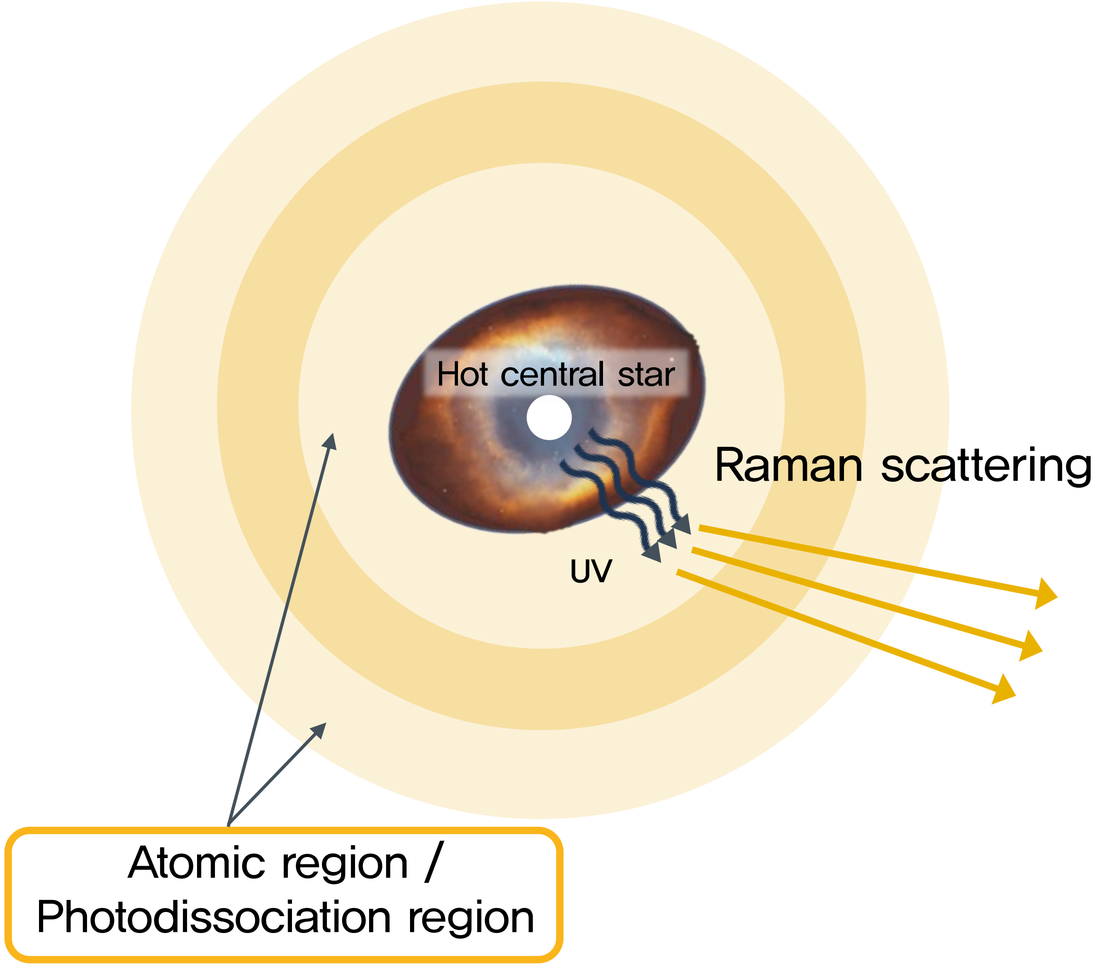


▶ **Possible origins of H I component**

- Atomic stellar winds (Glassgold & Huggins 1983)
- Photodissociation region (PDR)
  - ✓ expected to extend ~ 2–4 × 10^{21} cm^{-2} (Hollenbach & Tielens 1997)
  - ✓ The central star/ Interstellar UV radiation (Taylor et al. 1990)

- One of the possible solution of the missing mass problem
- Mass loss in the late AGB stage
- The evolution of PNe

H I Region in PNe

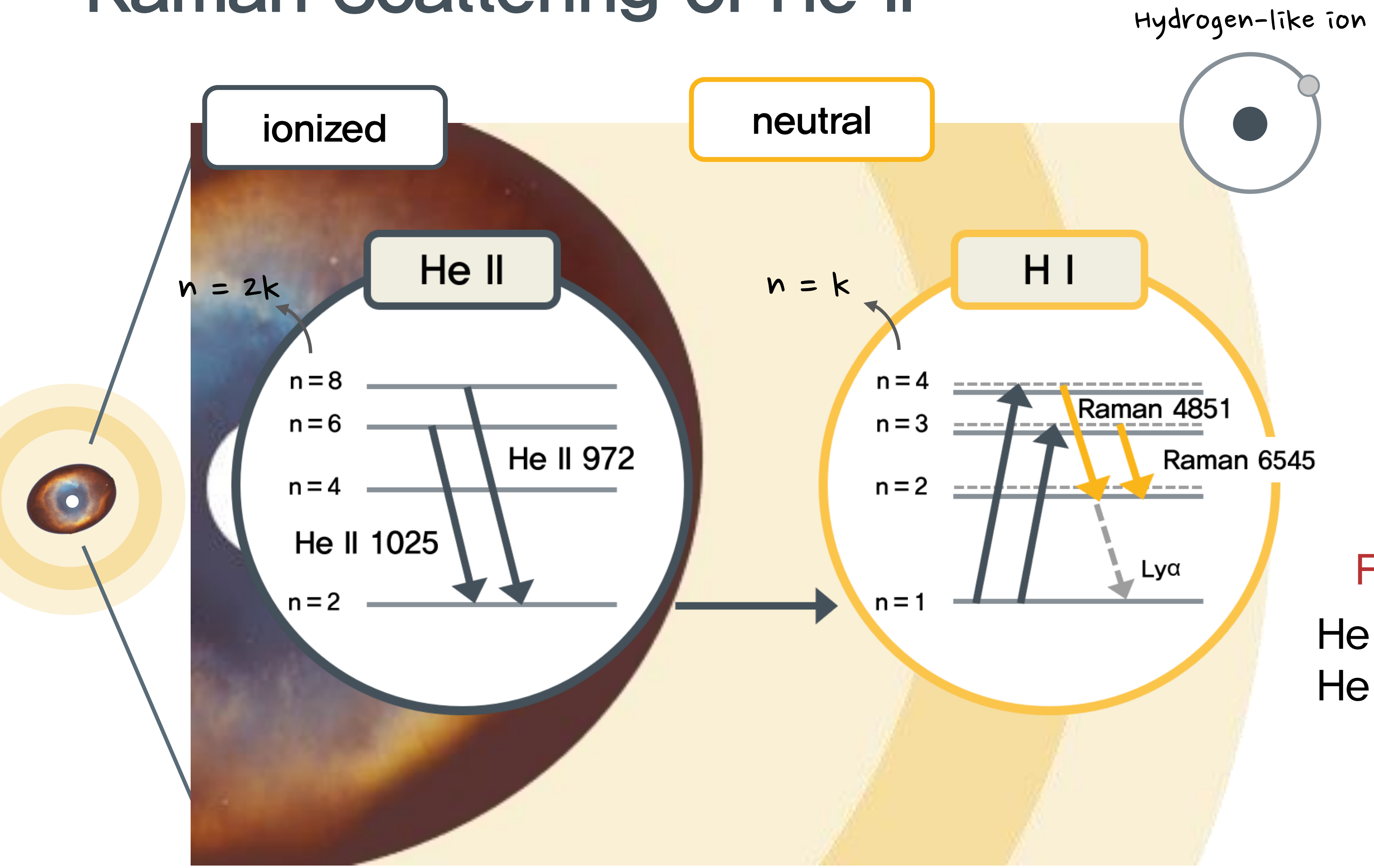


▶ **H I observation**

- Severe confusion from the Galactic emission (Gérard & Le Bertre 2006)
- H I 21cm observation for ~ 15 PNe (Taylor et al. 1990, Gussie & Taylor 1995)

- Raman-scattered He II features
  - ✓ Optical wavelength, optically thin to H I
  - ✓ The first detection of H I in NGC 6881 via Raman He II features (Choi & Lee 2020)
  - ✓ Expected to be found in young PNe (remains of atomic stellar winds or PDR formed by the central star)

Raman Scattering of He II



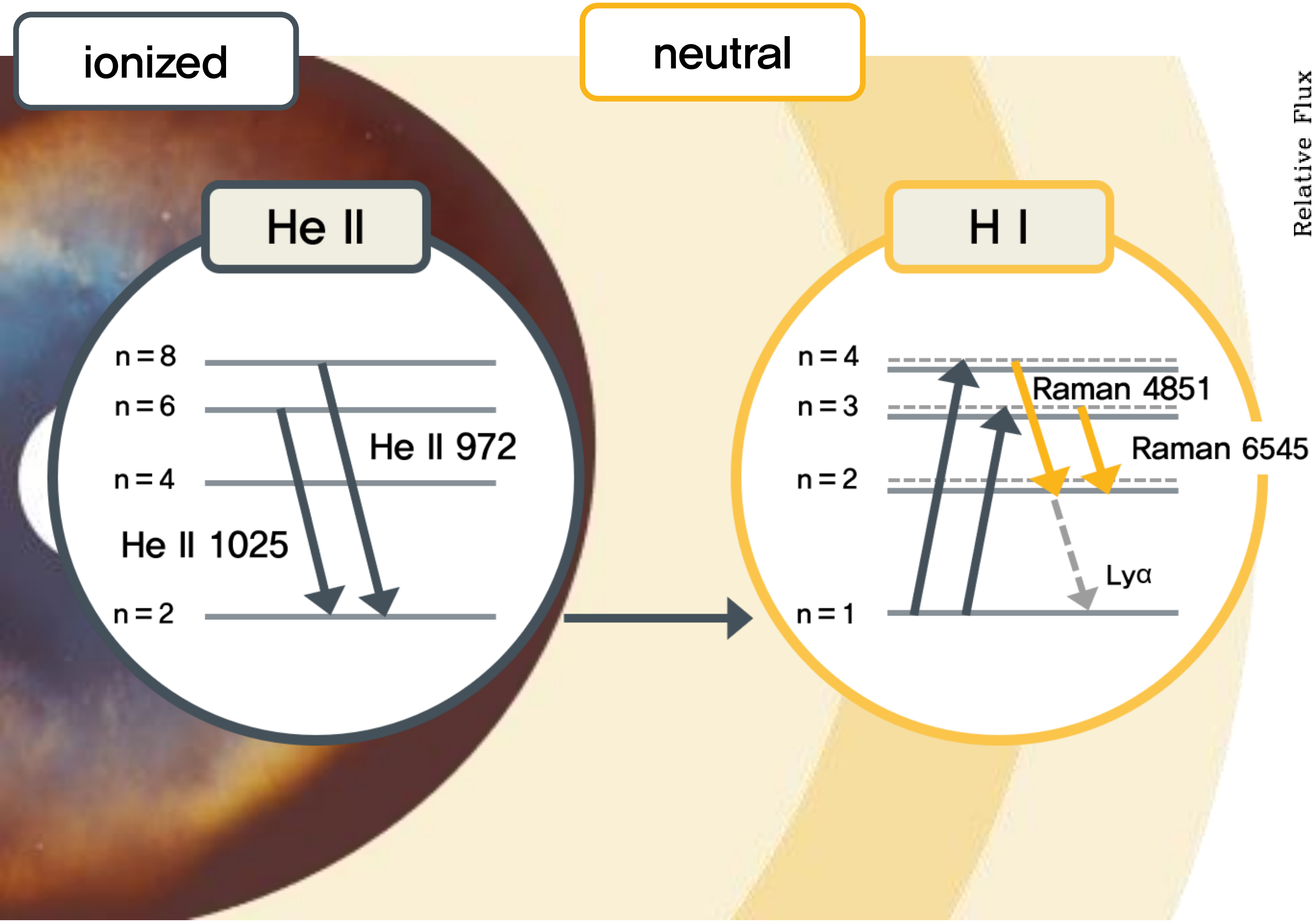
– Energy conservation

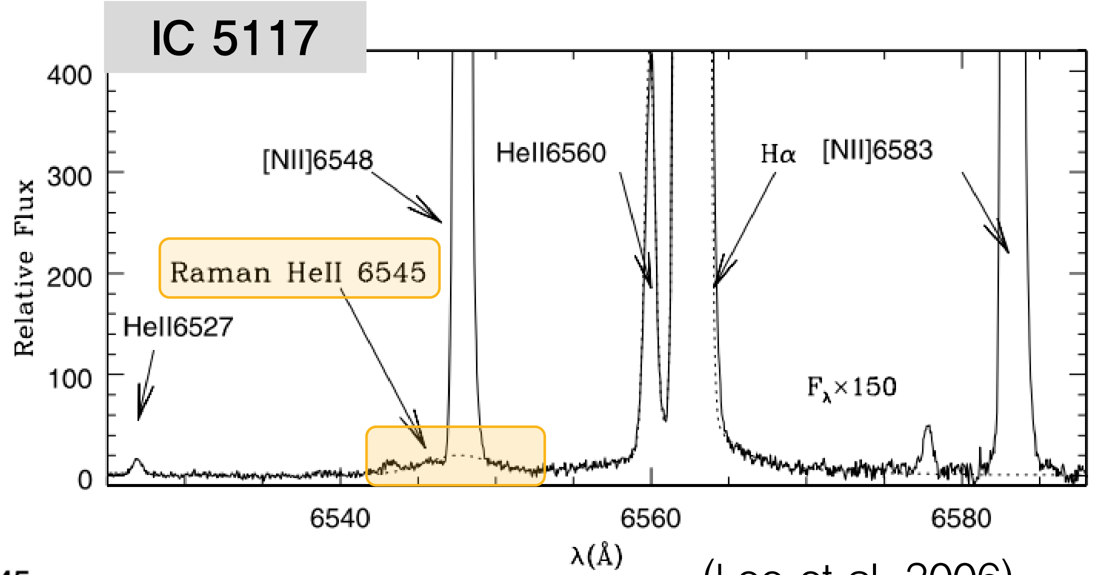
$$E_i = E_o + E_{Ly\alpha}$$

ex) Deexcited to n = 2

Far UV		Optical		
He II λ1025	→	λ6545	<	Hα λ6563
He II λ972	→	λ4851	<	Hβ λ4861

Raman Scattering of He II





(Lee et al. 2006)

– Energy conservation

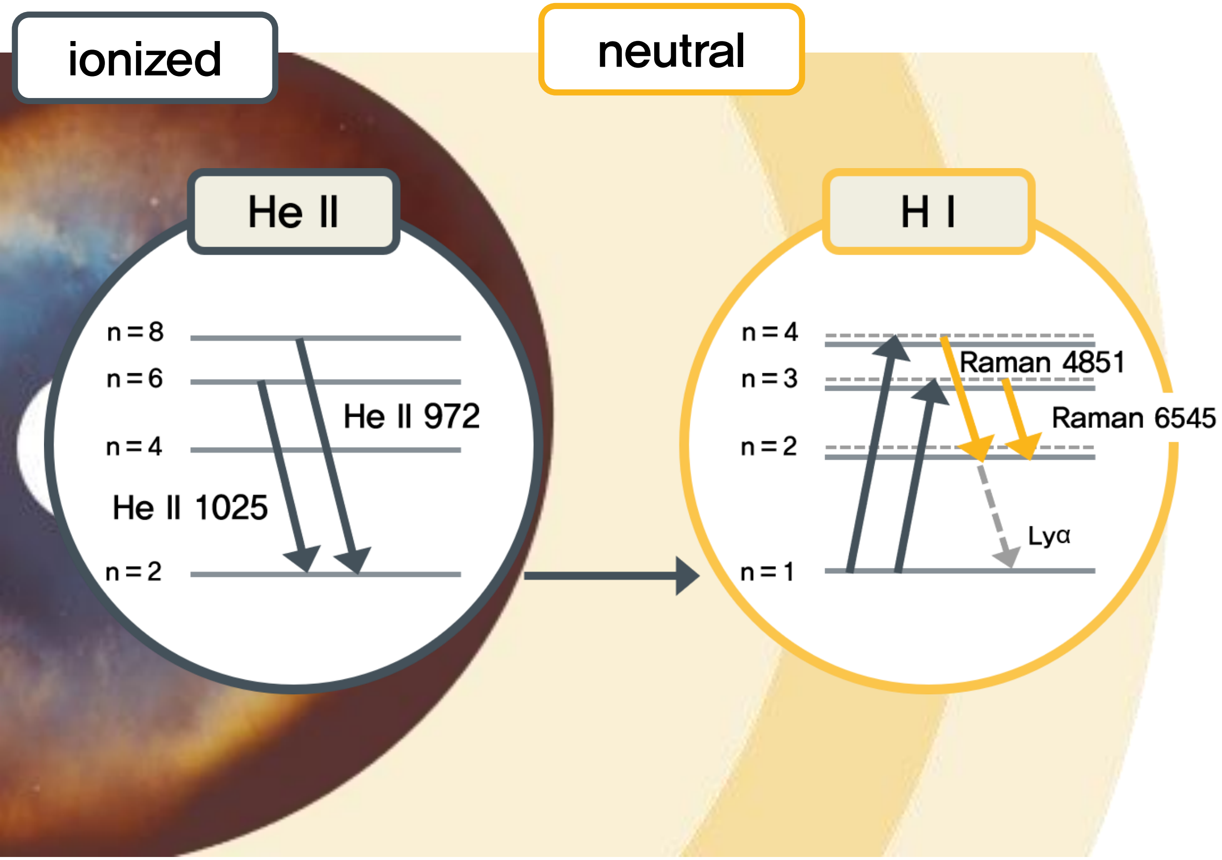
Line broadening

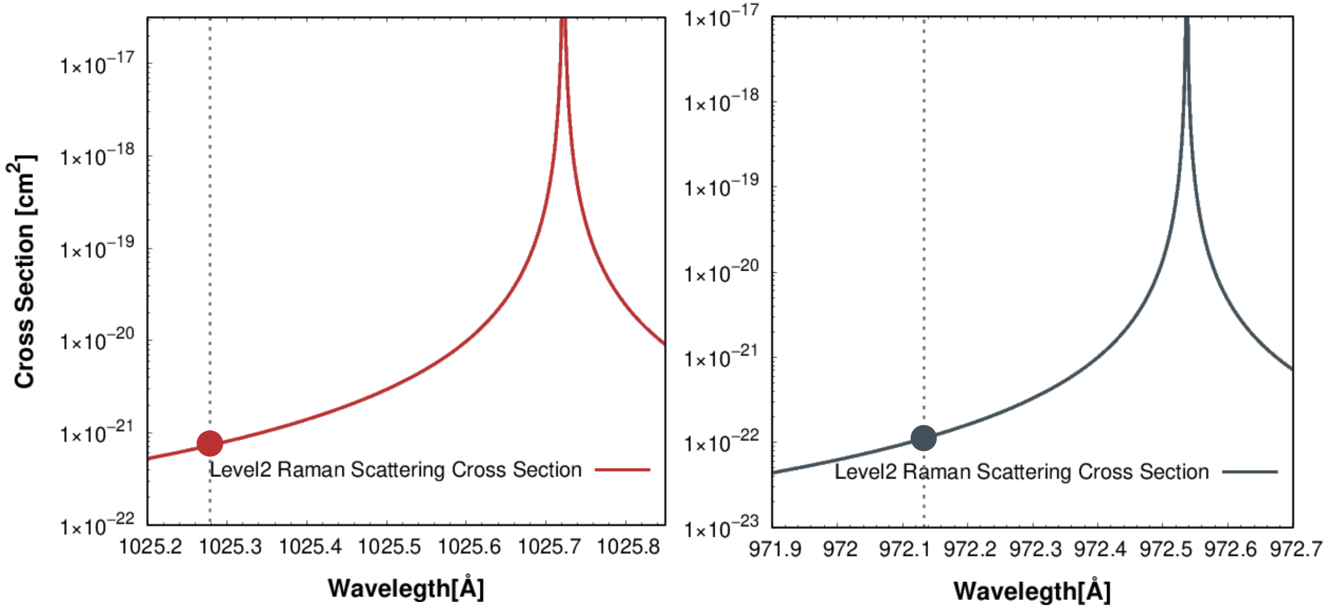
$$\frac{\Delta\lambda_o}{\lambda_o} = \left(\frac{\lambda_o}{\lambda_i}\right)\frac{\Delta\lambda_i}{\lambda_i}$$

ex) He II λ1025 → λ6545 : $\frac{\lambda_o}{\lambda_i} \sim 6.4$

He II λ972 → λ4851 : $\frac{\lambda_o}{\lambda_i} \sim 5.0$

Raman Scattering of He II

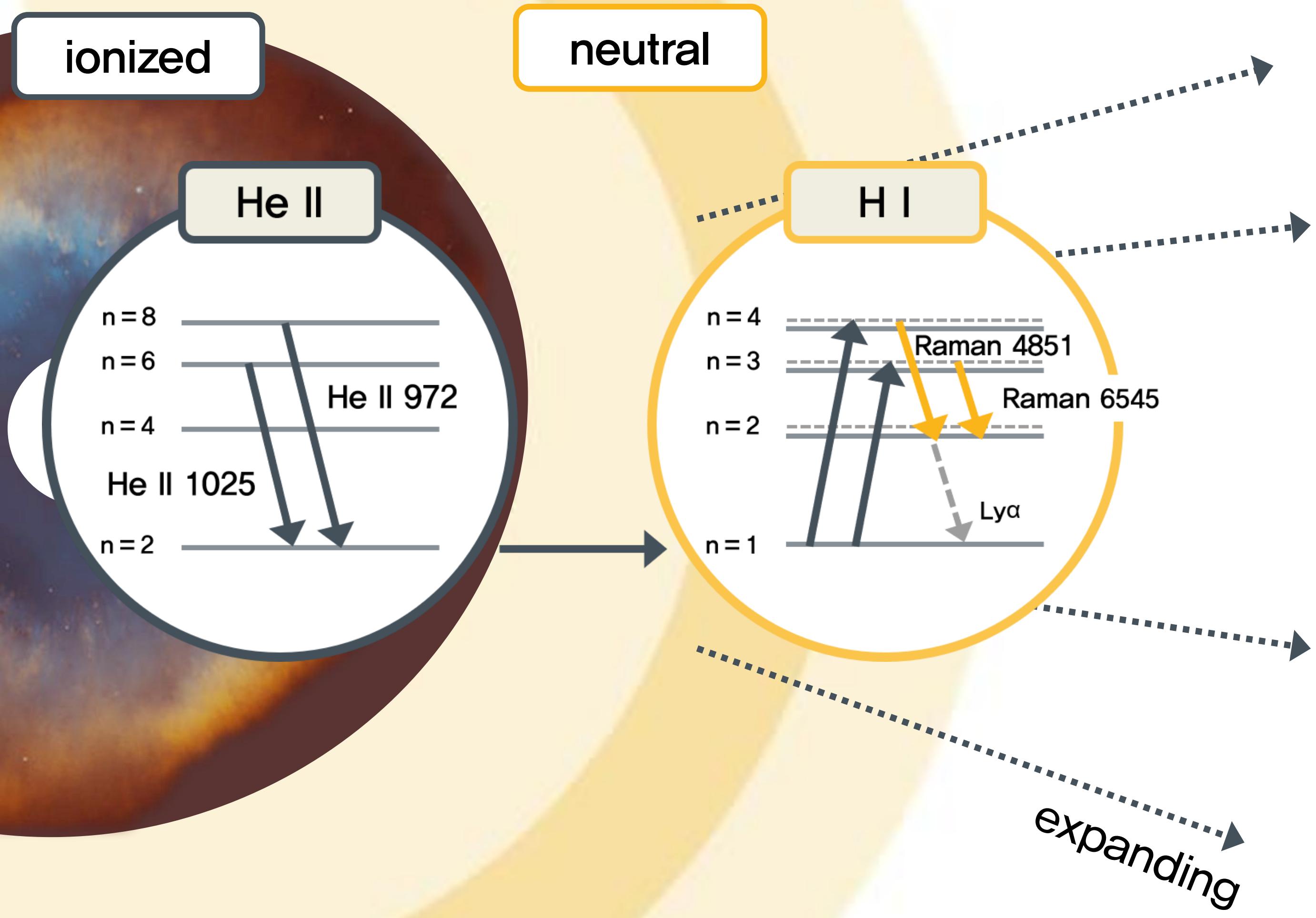


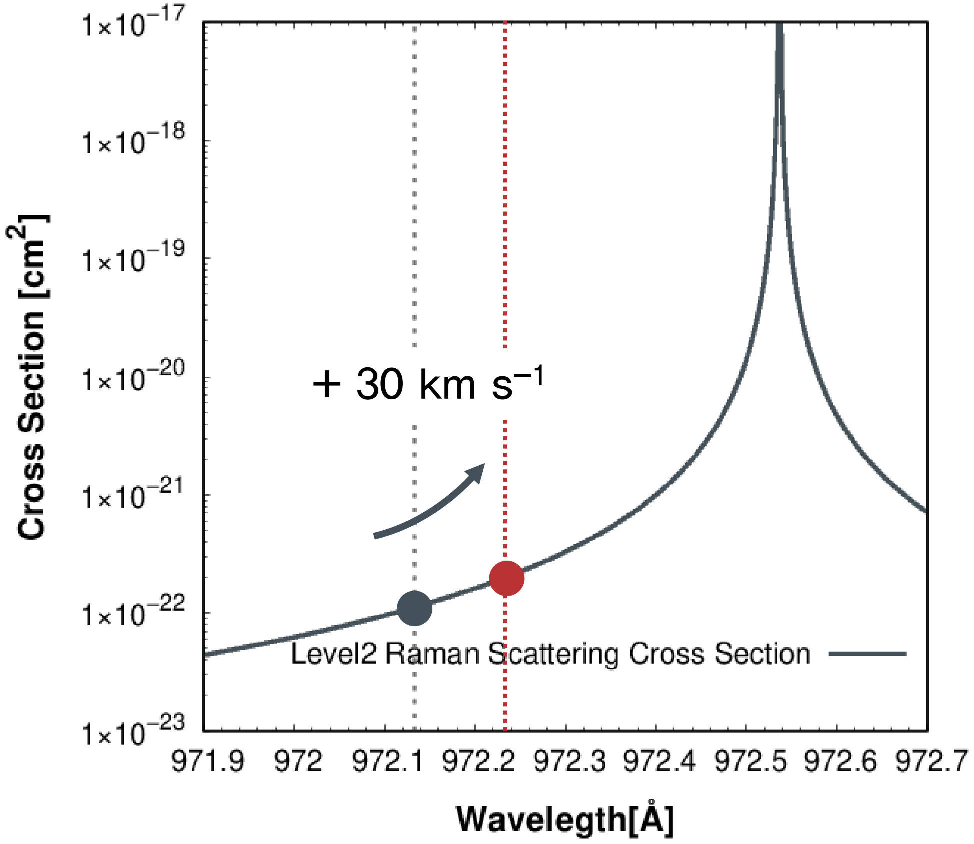


$$\sigma_{1025,\mathrm{Ram}} = 7.4 \times 10^{-22}\ \mathrm{cm}^2$$
$$\sigma_{972,\mathrm{Ram}} = 1.0 \times 10^{-22}\ \mathrm{cm}^2$$

An excellent probe of H I regions with H I column density $N_{HI} \geq 10^{20}\ \mathrm{cm}^{-2}$

Raman Scattering of He II



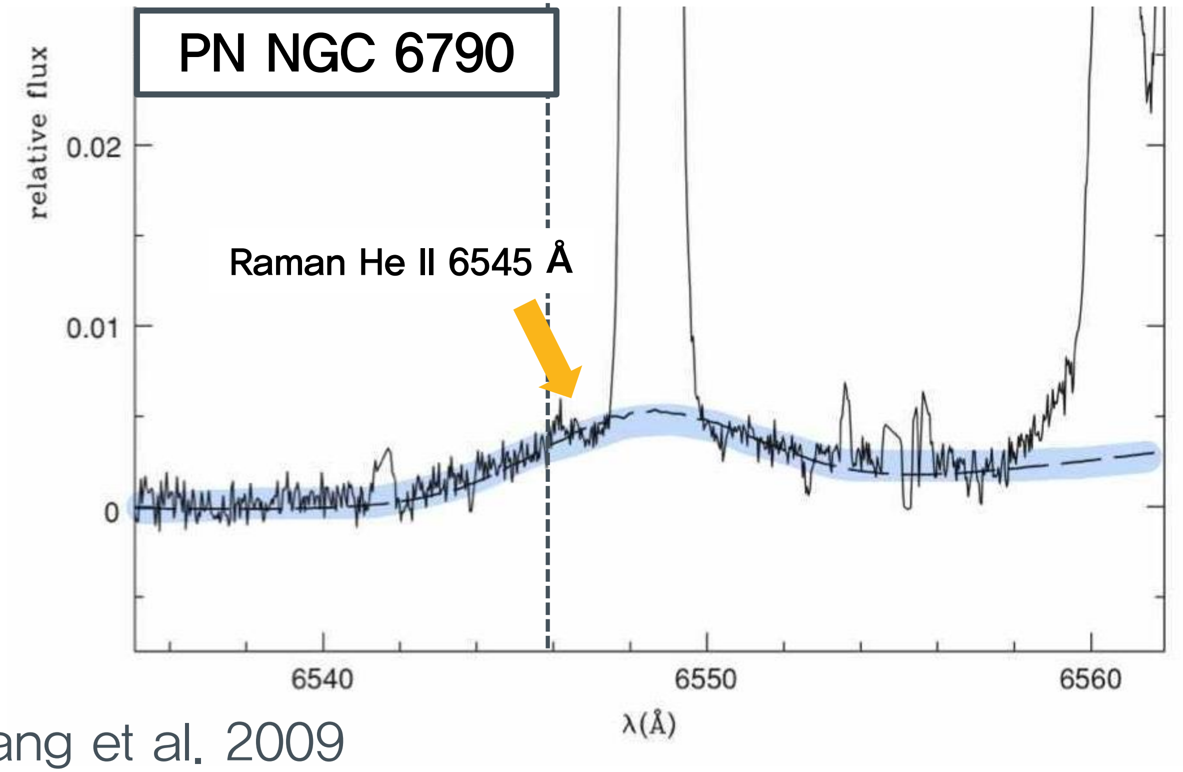


$$\sigma_{972,\mathrm{Ram}} = 1.0 \times 10^{-22}\ \mathrm{cm}^2$$

↓

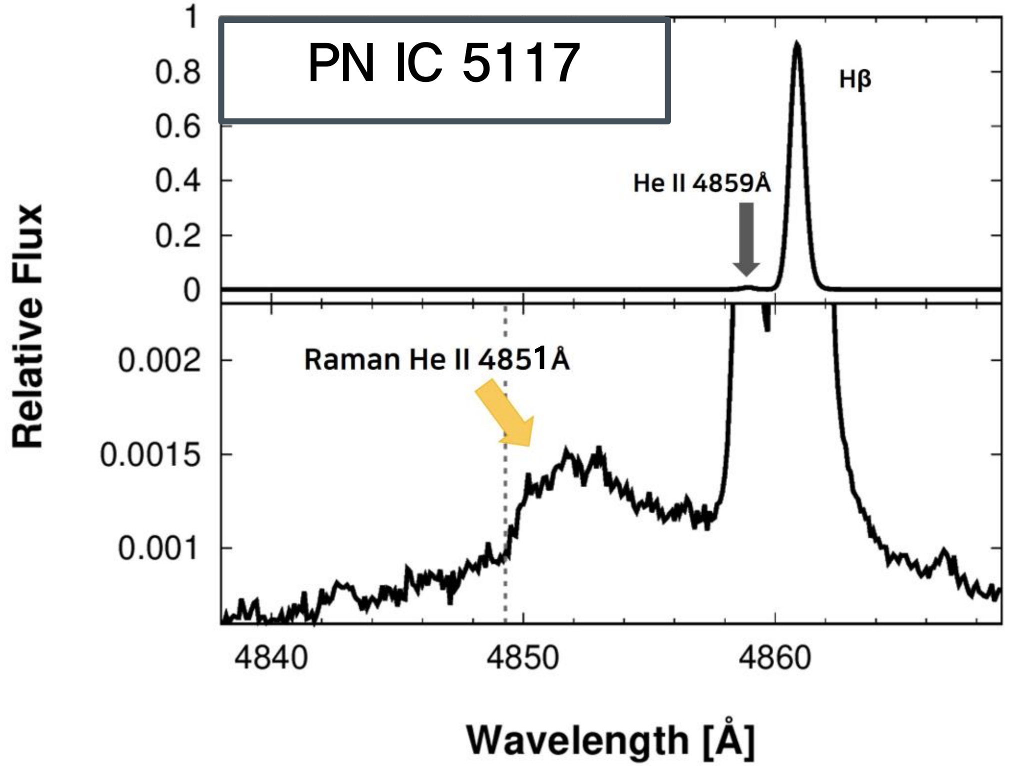
$$\sigma_{972,+30,\mathrm{Ram}} = 1.9 \times 10^{-22}\ \mathrm{cm}^2$$

Clearly Redshifted Raman He II Features in Young PNe



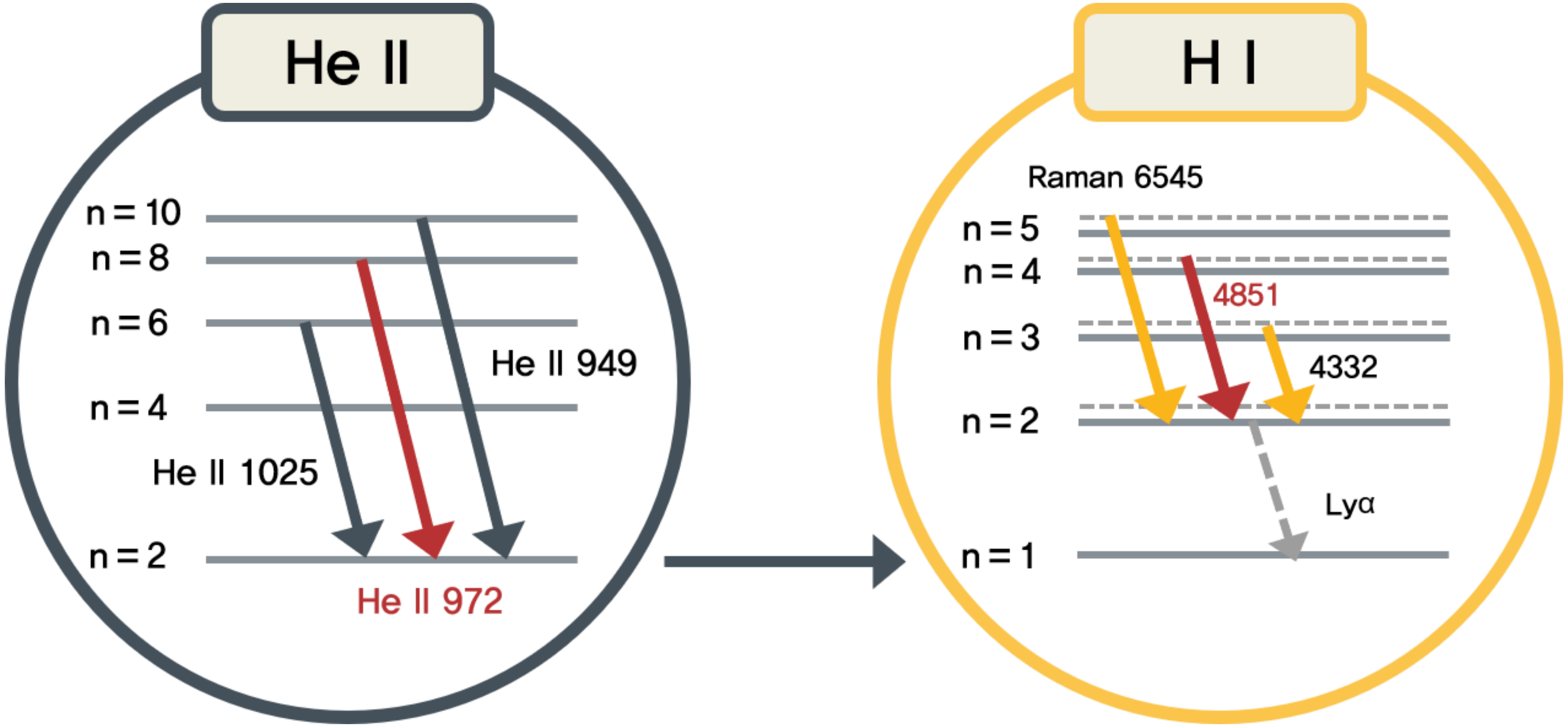
Kang et al. 2009

$v_{shift} \sim 15$ km s^{-1}

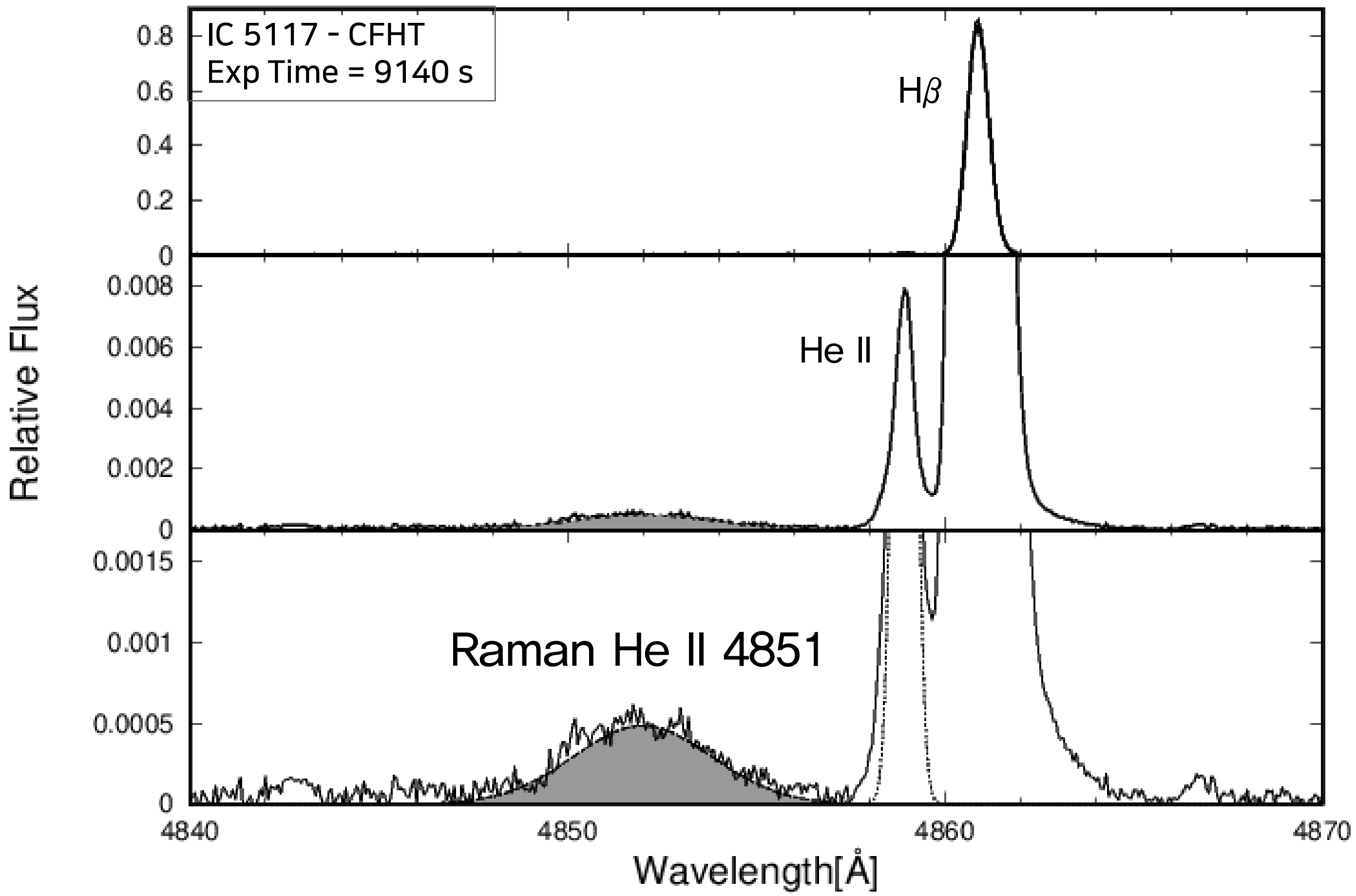


$v_{shift} \sim 29$ km s^{-1}

Line Formation Study of Raman He II λ4851



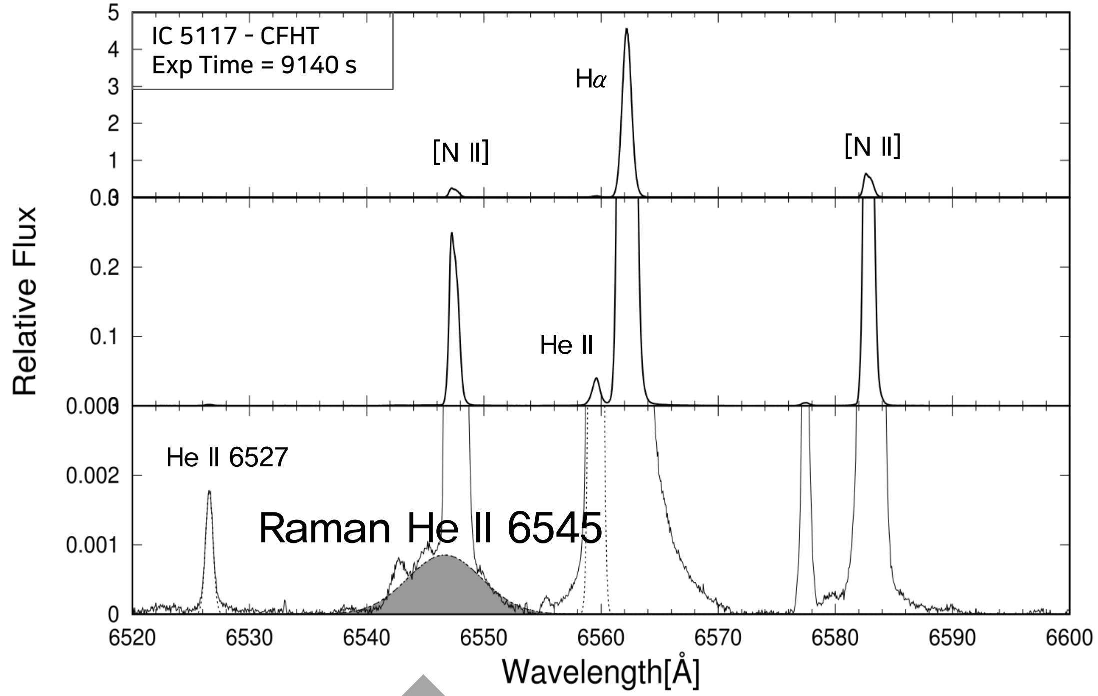
Why Raman He II λ4851?

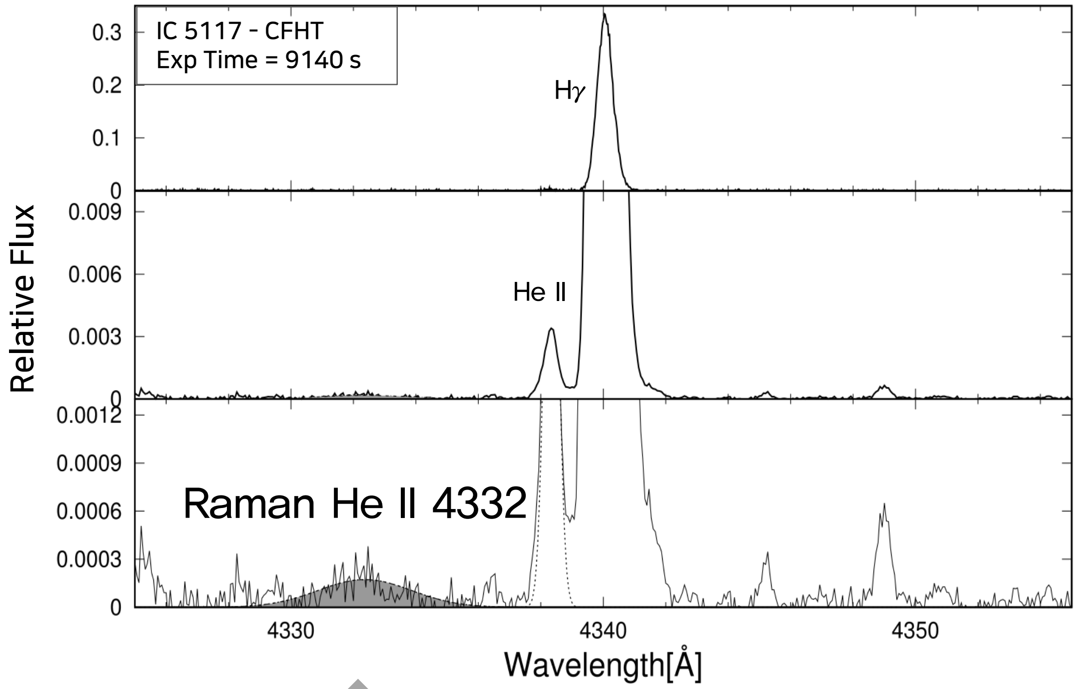


Comparison with observational data

- Isolated from other spectral lines
- Expected to obtain sufficient intensity using large telescopes to perform line profile analysis

Why Raman He II λ4851?





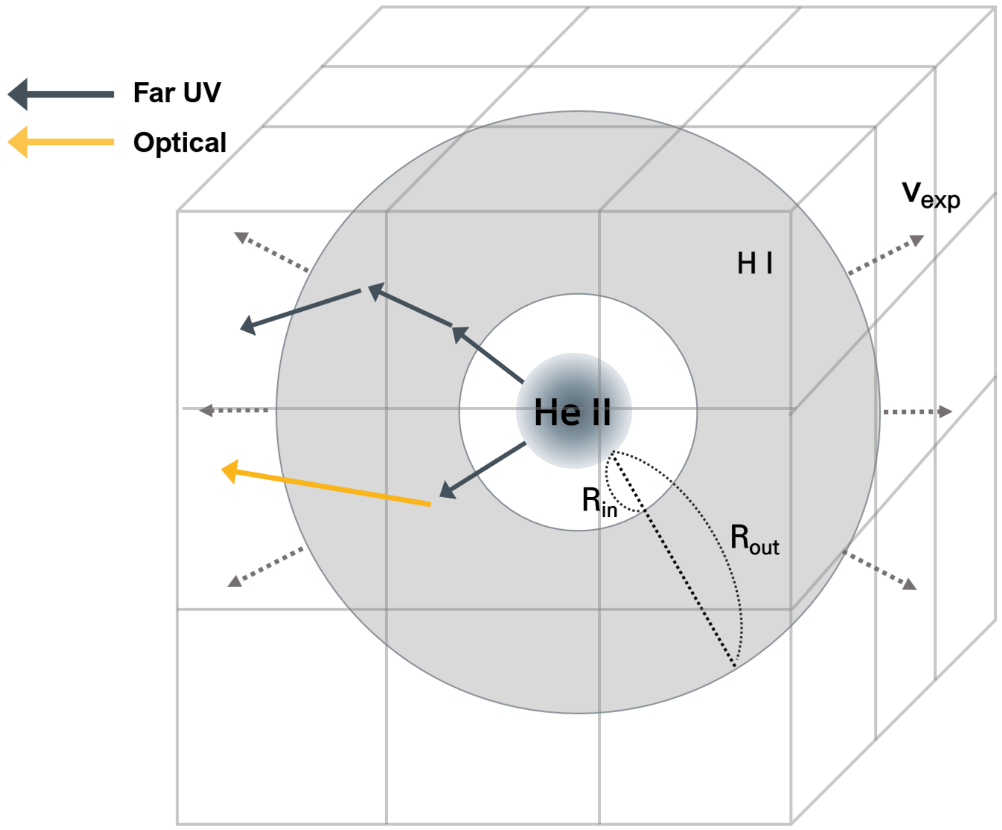
Strongest intensity
But frequently blended with [N II] λ6548

very weak feature
compared with noise

STaRS : A Grid–based Monte Carlo Radiative Transfer Code

▶ STaRS (Sejong Radiative Transfer through Raman and Rayleigh Scattering)

(Chang & Lee 2020, arXiv:2012.03424, accepted for publication to JKAS)



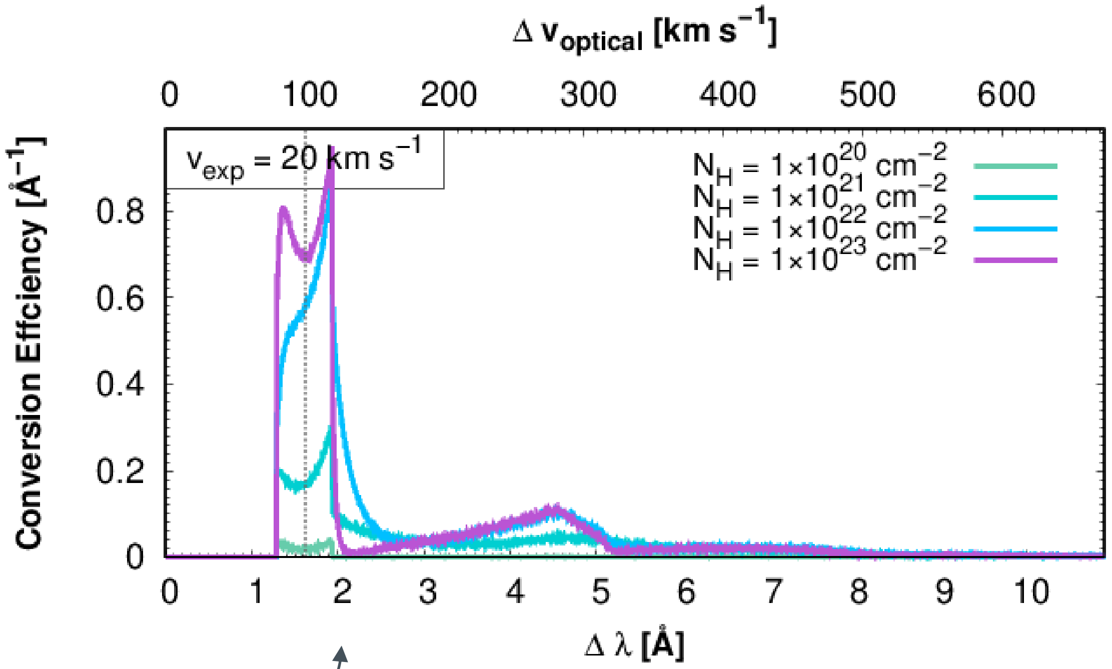
– Flexibility in the scattering geometry and kinematics

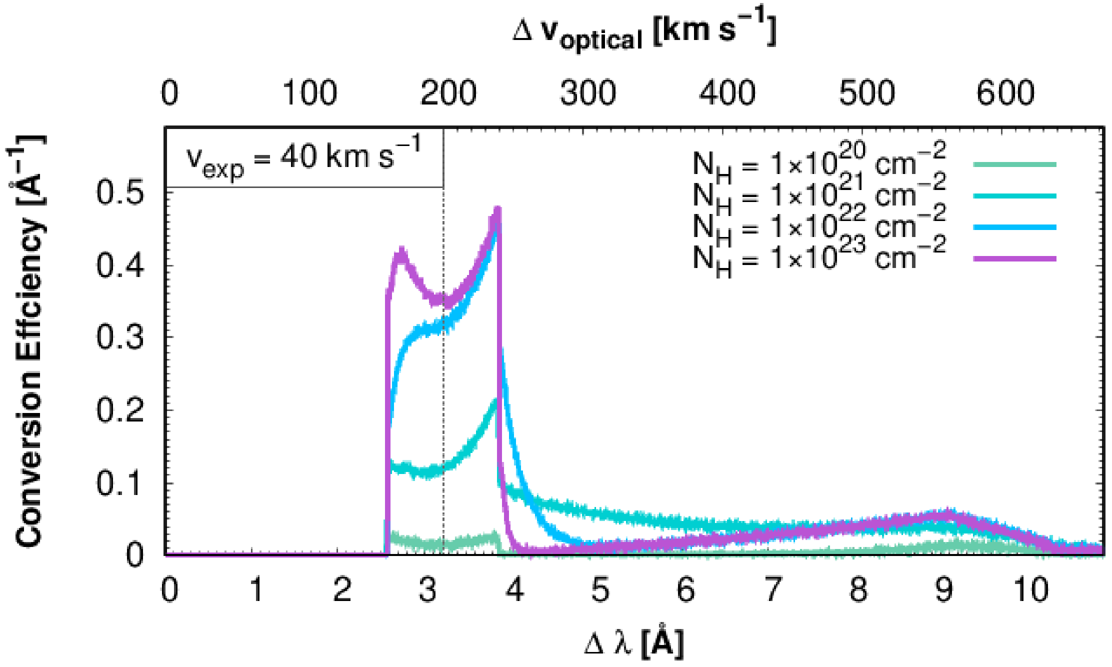
– A uniform spherical shell–like scattering geometry expanding with a constant speed (Standard circumstellar envelope model)

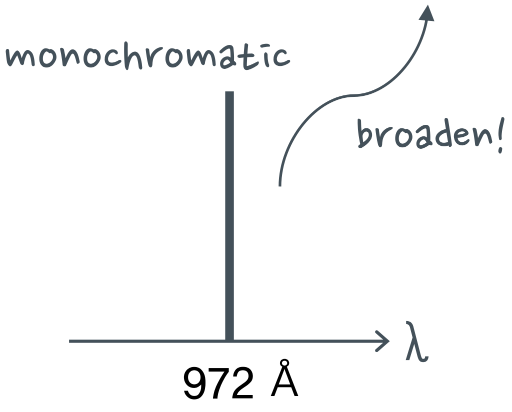
– Parameters
  - ✓ N_{HI} : H I column density
  - ✓ v_{exp} : expanding speed

– Monochromatic/ Gaussian He II λ972 source

Results ① Monochromatic Source

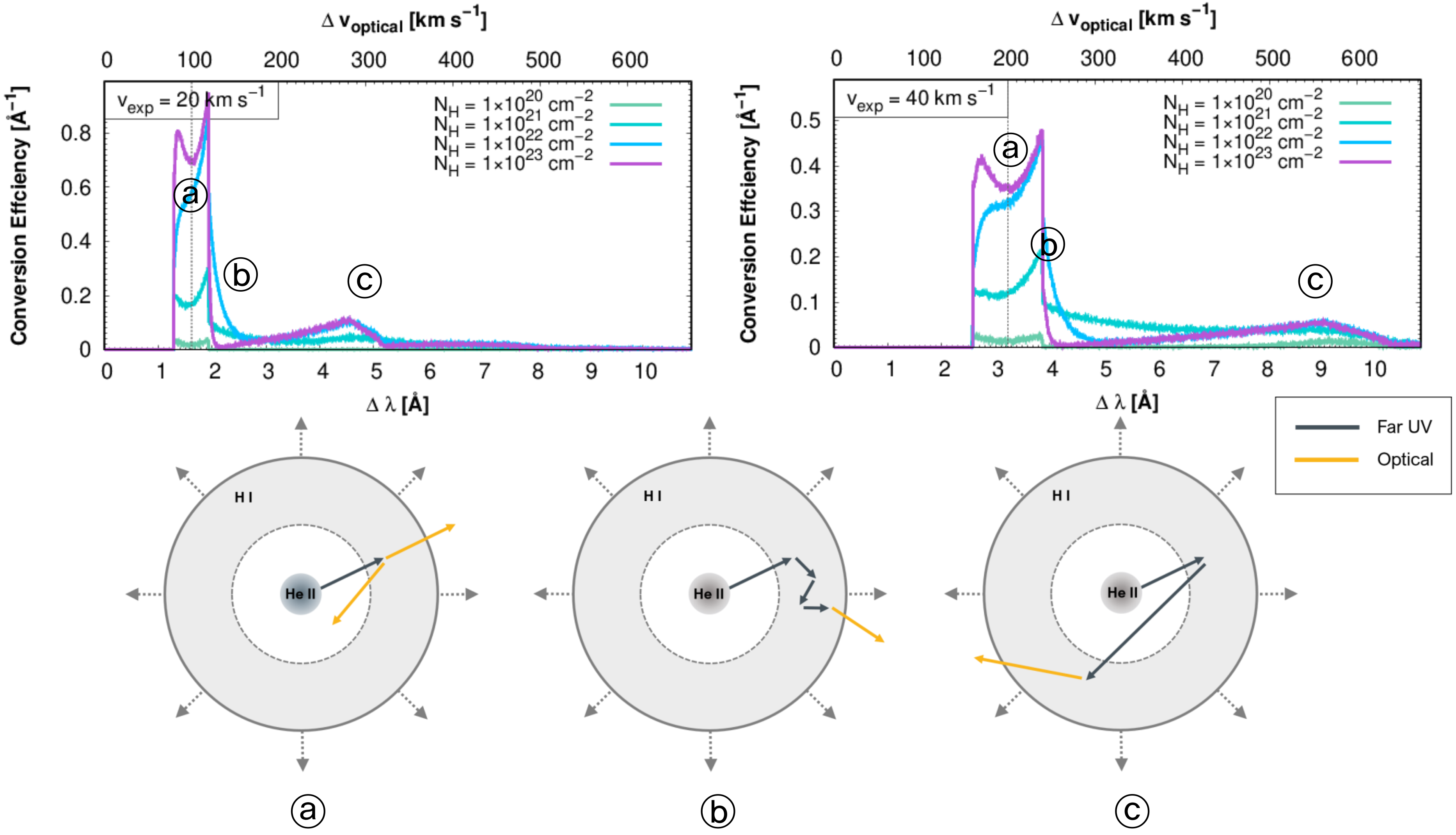






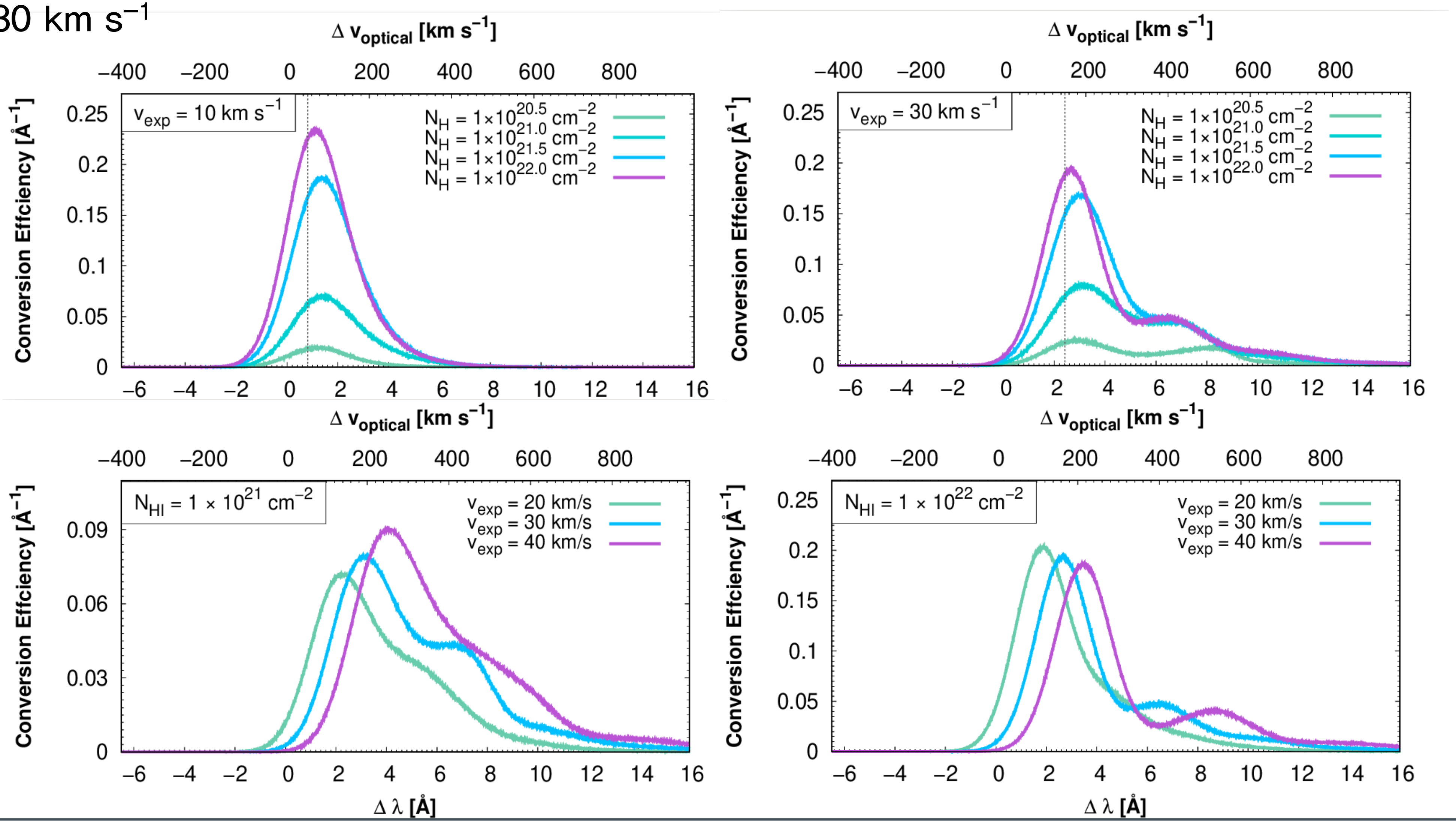
① The width of primary peak ≈ 2 v_{exp}
② Double peak structure varying with column densities
③ Appearance of a tertiary peak

Results ① Monochromatic Source



Results ② Gaussian Source

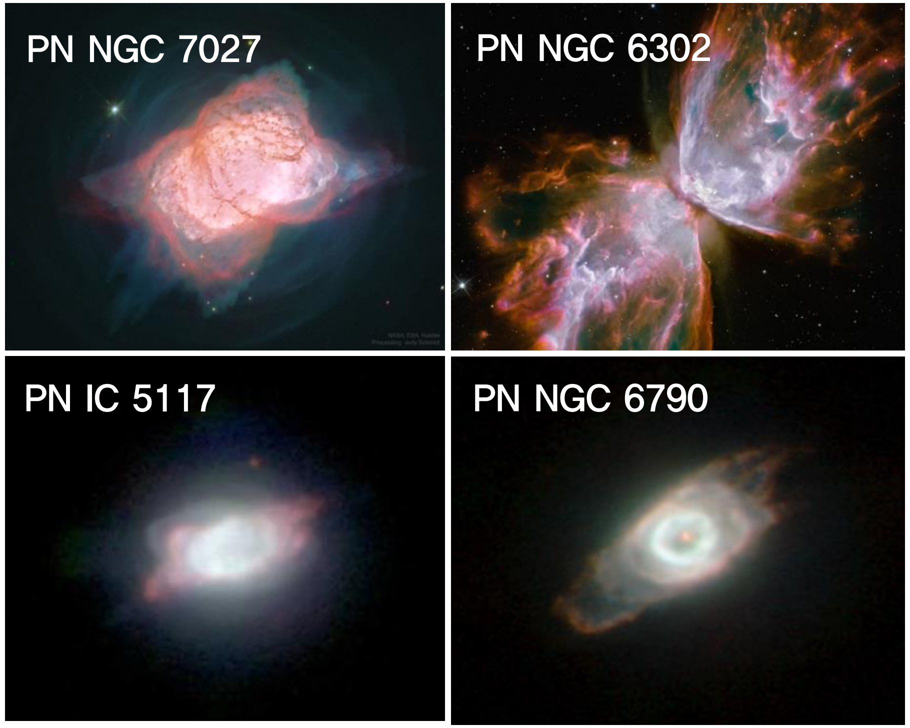
FWHM = 30 km s^{-1}



Discussion

- It is necessary to consider the kinematics of the scattering medium.
- With observational data, Raman He II features can be used a great tool to investigate the H I kinematics and distribution (∵ sensitive to N_{HI} and v_{exp})
- Precise line profile analysis will provide the information of the hidden H I region of PNe.
- High-quality of observational data is required.

Raman He II Survey



Credit: NASA/ESA, Hsia et al. 2014 (IC 5117)

▶ Young PNe exhibiting Raman He II features

– Only reported in 5 PNe

(NGC 7027, NGC 6302, NGC 6886, IC 5117, and NGC 6790)

– Young and non–spherical PNe

▶ Morphology of PNe – AGB mass loss

– Relation between H_2 – bipolarity

→ massive progenitor? (Kastner et al. 1996)

✓ Common progenitor properties? → similar mass loss processes? → Raman He II features?

✓ Other common properties?

Raman He II Survey

▶ Candidate selection criteria

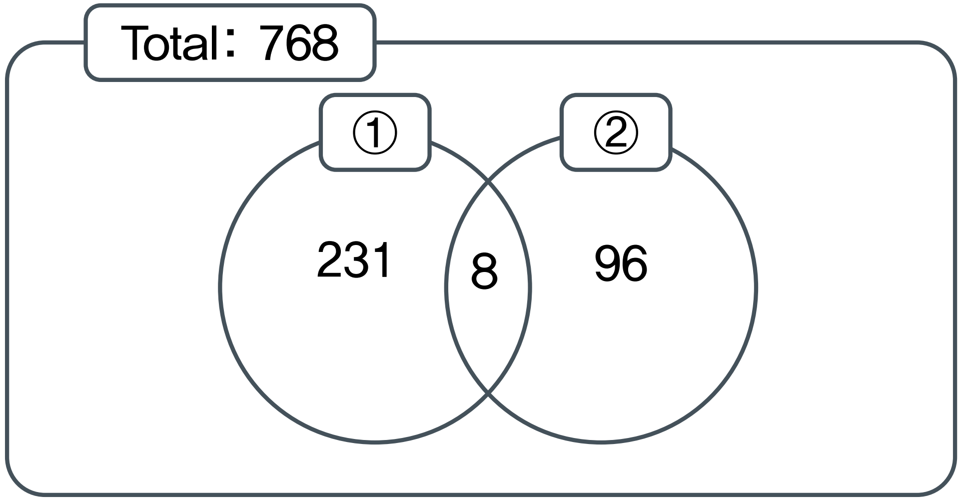
① Copious He II emission

✓ He II λ4686 line intensity catalog (Tylenda et al. 1994) (~ 770 Galactic PNe)

✓ High values for He II λ4686 / Hα (≥ 0.05) ~ 240 PNe

② Abundant neutral matter → Smaller size, Young PNe, H_2 components ~ 100 PNe

(Kastners et al. 1996; Sahai et al. 2011, Hsia et al. 2014)



Raman He II Survey

▶ BOES Spectroscopy

– Bohyunsan Optical Echelle Spectrograph

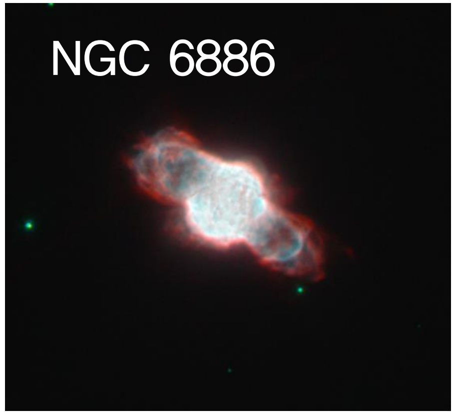
– Installed on the 1.8 m telescope of BOAO

– The fiber having spectral resolution R ~ 30,000 / field of view = 4.2″

– 2×2 binning to improve signal to noise

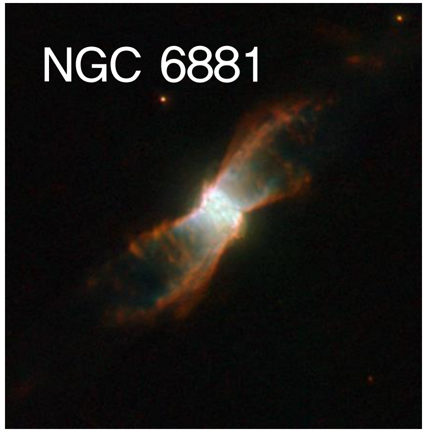
– Obtained spectra of 12 PNe during April 2019 – March 2020

Observing Targets



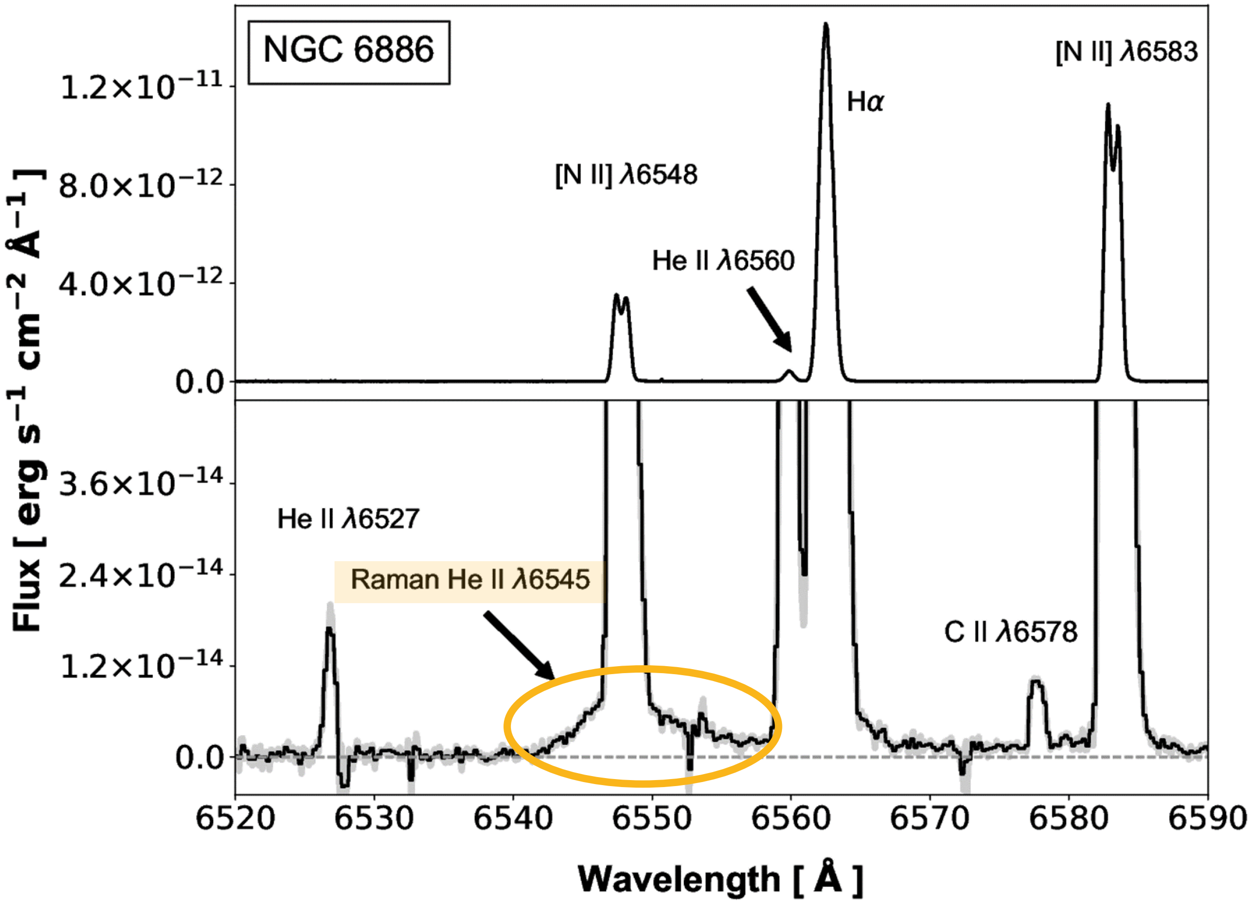
Credit: NASA/ESA

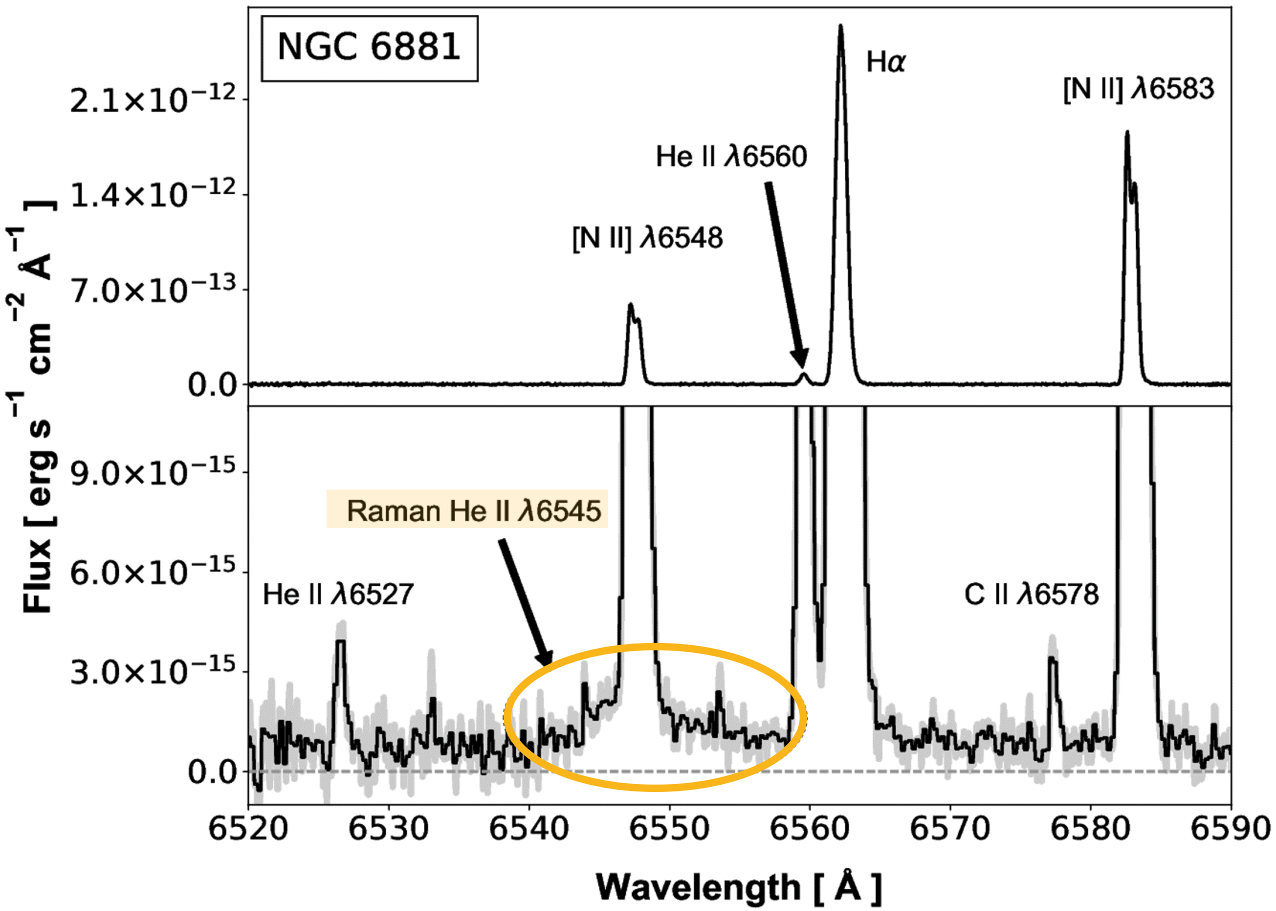
Name	PN G	Date	Exp. Time (sec)	I(HeII4686)/I(Hα) (%)
NGC 6741	033.8-02.6	2020-03-28	1200	6.67
H 4-1	049.3+88.1	2019-04-06	1800	3.10
Hu 2-1	051.4+09.6	2020-03-30	2400	0.24
Hen 2-447	057.9-01.5	2019-06-05	1500	-
NGC 6886	060.1-07.7	2020-10-30	2400	6.13
NGC 6881	074.5+02.1	2020-03-30	3300	2.58
NGC 6884	082.1+07.0	2020-03-28	3600	2.50
J 900	194.2+02.5	2019-04-06	1800	7.74
NGC 2392	197.8+17.3	2020-03-30	1200	13.93
M 1-8	210.3+01.9	2020-03-30	3600	6.46
NGC 2346	215.6+03.6	2019-04-05	1800	6.00
NGC 3242	261.0+32.0	2020-03-30	3600	8.52



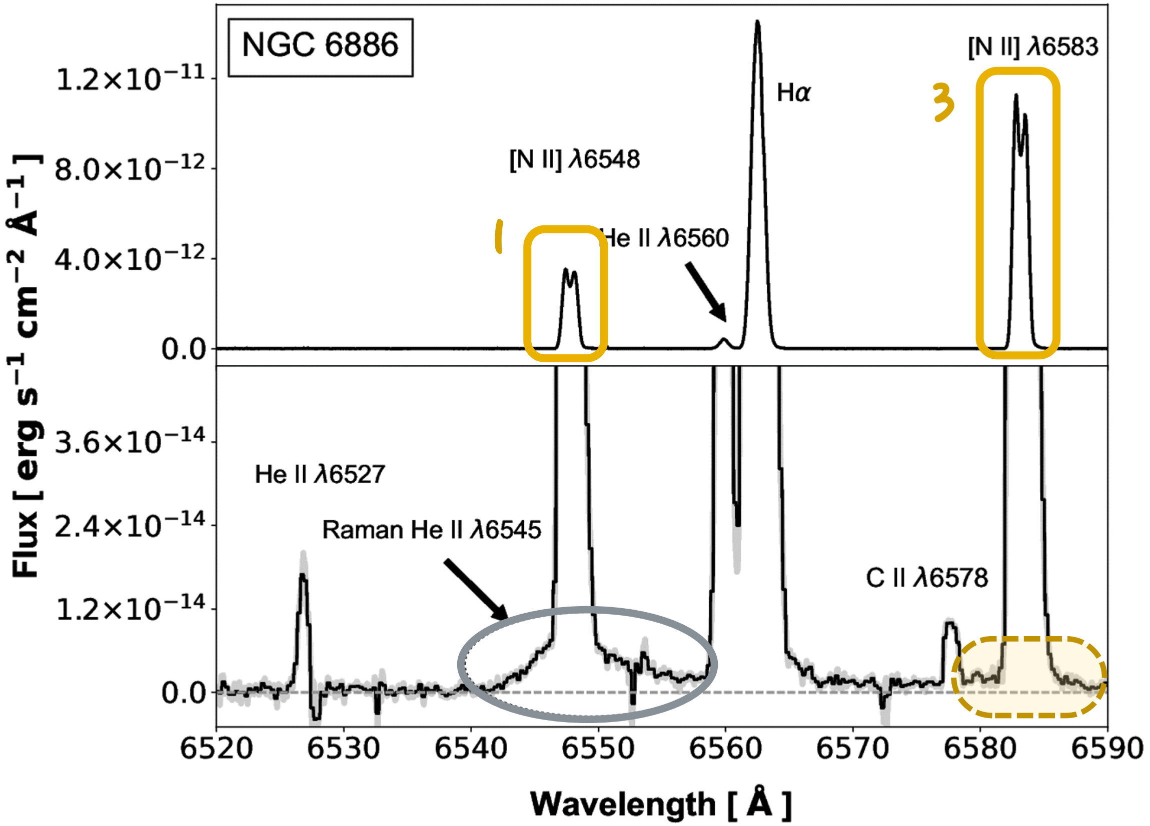
Credit: NASA/ESA

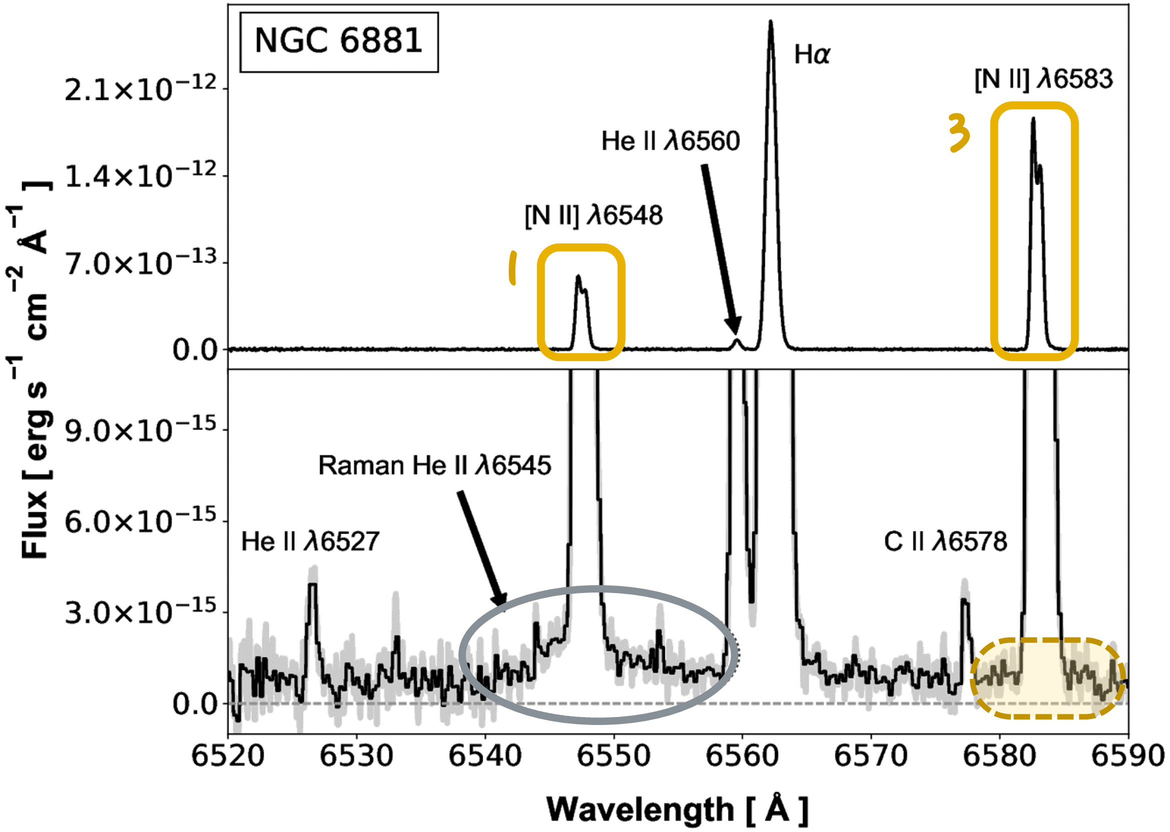
Raman He II in NGC 6886 & NGC 6881





Raman He II in NGC 6886 & NGC 6881

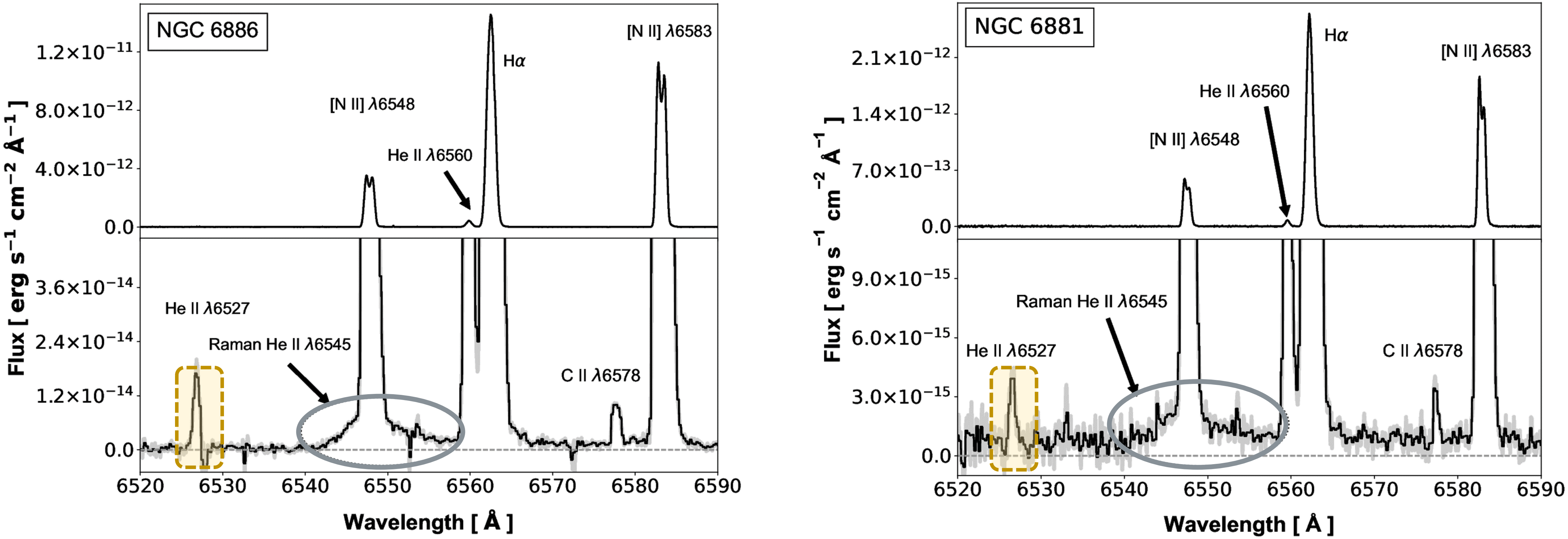




✓ The absence of broad feature around the [N II] λ6583 line

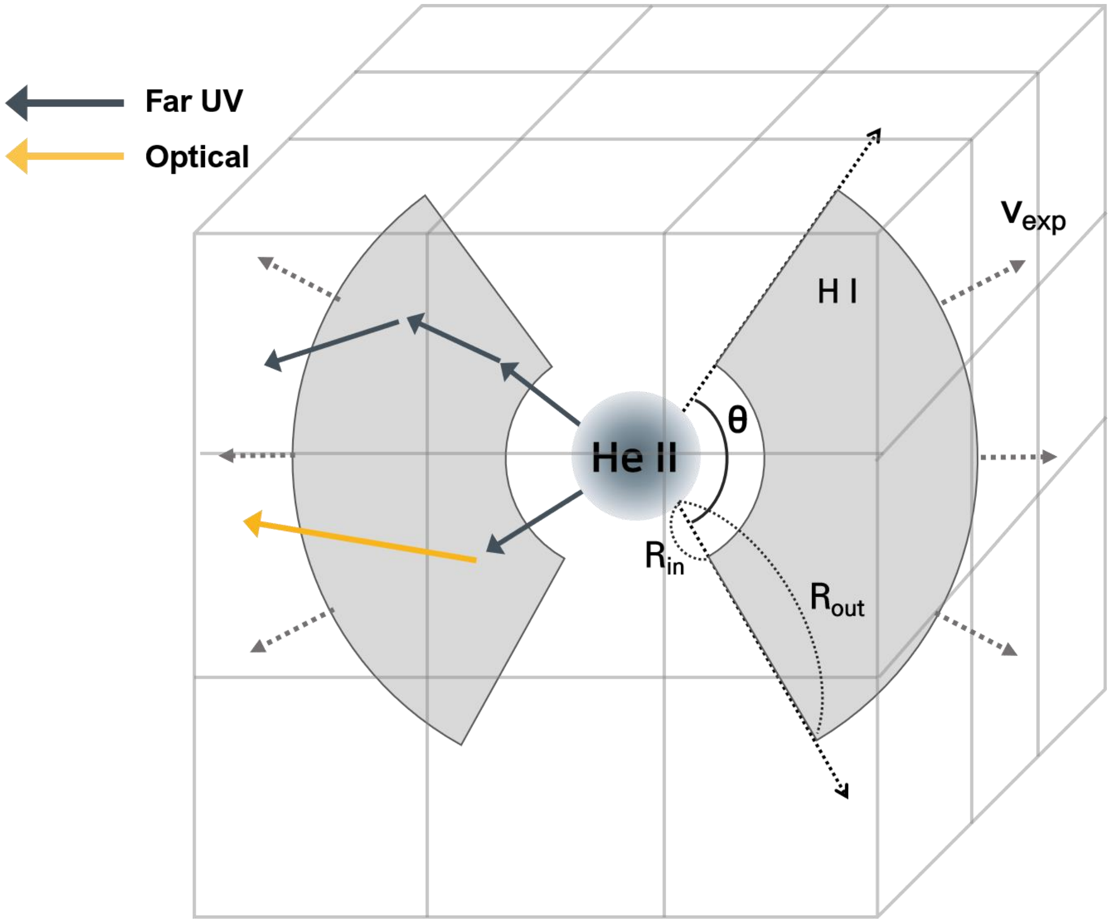
- [N II] λλ6548, 6583 doublet → expected to have an identical line profile
- [N II] λ6583 line is theoretically 3 times stronger than [N II] λ6548

Raman He II in NGC 6886 & NGC 6881



✓ Detected very weak He II 6527 emission → sufficient He II emission

Radiative Transfer Simulation



- **STaRS** (Chang & Lee 2020)
  - A uniform spherical shell–like scattering geometry expanding with a constant speed
  - Parameter
    - ✓ N_{HI} : H I column density
    - ✓ v_{exp} : expanding speed
    - ✓ CF: θ / π, covering factor of scattering region
  - Input He II emission
    - ✓ Gaussian profile
    - ✓ Flux is estimated from He II λ6560 flux based on case B theory

(Kaler et al. 1987; Hyung et al. 1995; Pottash & Surendiranath 2005)

Best–fit Results

Severely blended with [N II] λ6548

▶ NGC 6886

– Best–fit (CF = 0.3)

$N_{HI} = 5 \times 10^{20}\ cm^{-2}$

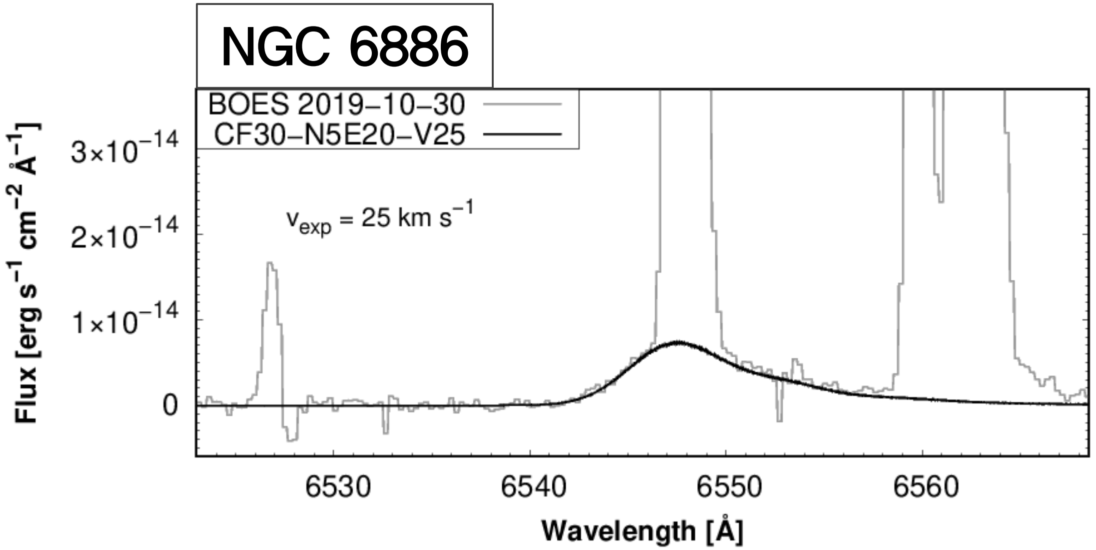
$v_{exp} = 25\ km\ s^{-1}\ (\pm 5\ km\ s^{-1})$

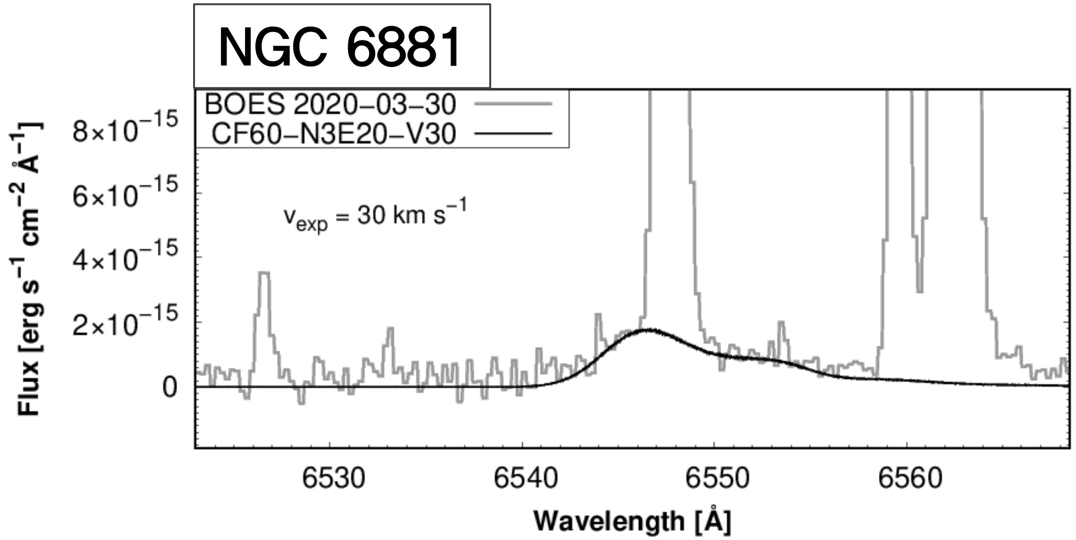
▶ NGC 6881

– Best–fit (CF = 0.6)

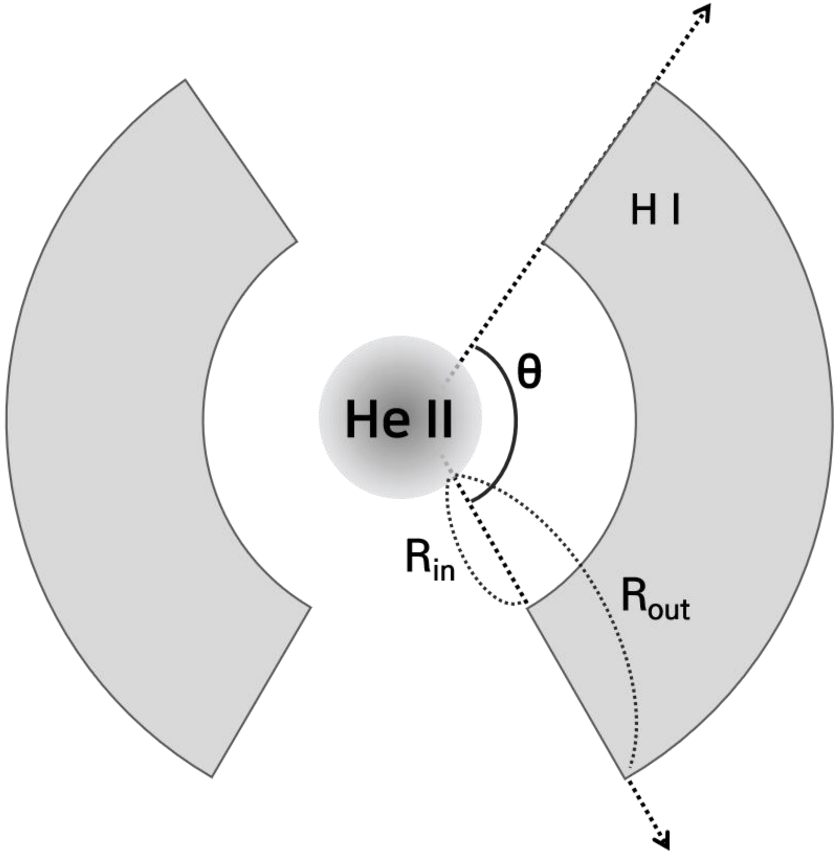
$N_{HI} = 3 \times 10^{20}\ cm^{-2}$

$v_{exp} = 30\ km\ s^{-1}\ (\pm 10\ km\ s^{-1})$





H I Mass Estimation



(Assume that R_{out} = 2 R_{in})

$$M_{HI} \simeq 1.4 \times 10^{-4} \left(\frac{N_{HI}}{10^{20}\ cm^{-2}}\right)\left(\frac{R_{out}}{10^{3}\ au}\right)^{2} CF\ M_{\odot}$$

▶ **NGC 6886**

– Distance ~2.6 kpc / angular size ~ 5″
(Pottasch & Surendiranath 2005)

– M_{HI} ~ 0.03 $M_{\odot}$

: Comparable with the study of Taylor et al. 1990

▶ **NGC 6881** * The first detection of H I !

– Distance ~2.5 kpc / angular size ~ 5″
(Cahn et al. 1992; Kwok & Su 2005)

– M_{HI} ~ 0.04 $M_{\odot}$

Discussion

▶ Relation with chemical abundance

✓ Weak C II λ6578, Polycyclic aromatic hydrocarbon (PAH) emitters, relatively high C/O
: carbon–enhancement? ← third dredge–up?

✓ C/O, He/H, N/H abundance

✓ Progenitor properties : Dredge–up process, Nucleosynthesis (Karakas & Lattanzio 2014)

	C II λ6578	PAH[1,2]	C/O[1,3]	$M_{progenitor}$
NGC 7027	O	O	2.15	3–4 $M_\odot$ [4], C–rich
NGC 6302	–	–	0.88	–
IC 5117	O	O	1.92	–
NGC 6790	O	O	0.82	–
NGC 6886	O	O	1.3	4 $M_\odot$ [5]
NGC 6881	O	O	–	3 $M_\odot$ [6]

[1] Smith & McLean 2008
[2] Ohsawa et al. 2016
[3] Casassus et al. 2000
[4] Salas et al. 2001
[5] Pottasch & Surendiranath 2005
[6] Kaler et al. 1987

Summary

- Raman He II features are a useful tool to study the hidden H I region in PNe.
- Using the grid-based radiative transfer code 'STaRS', we examined the line formation of Raman He II in an expanding medium.
- We confirmed that the line profile varies with the expansion speed of the medium as well as the column density.
- We discovered Raman He II λ6545 in young PNe NGC 6886 and NGC 6881.
- Estimated their H I mass is about few percent of solar mass.
- Carbon-enhancement → the active third dredge-up processes?