Raman scattering in PDRs

William Henney, IRyA-UNAM, 2019-12-03

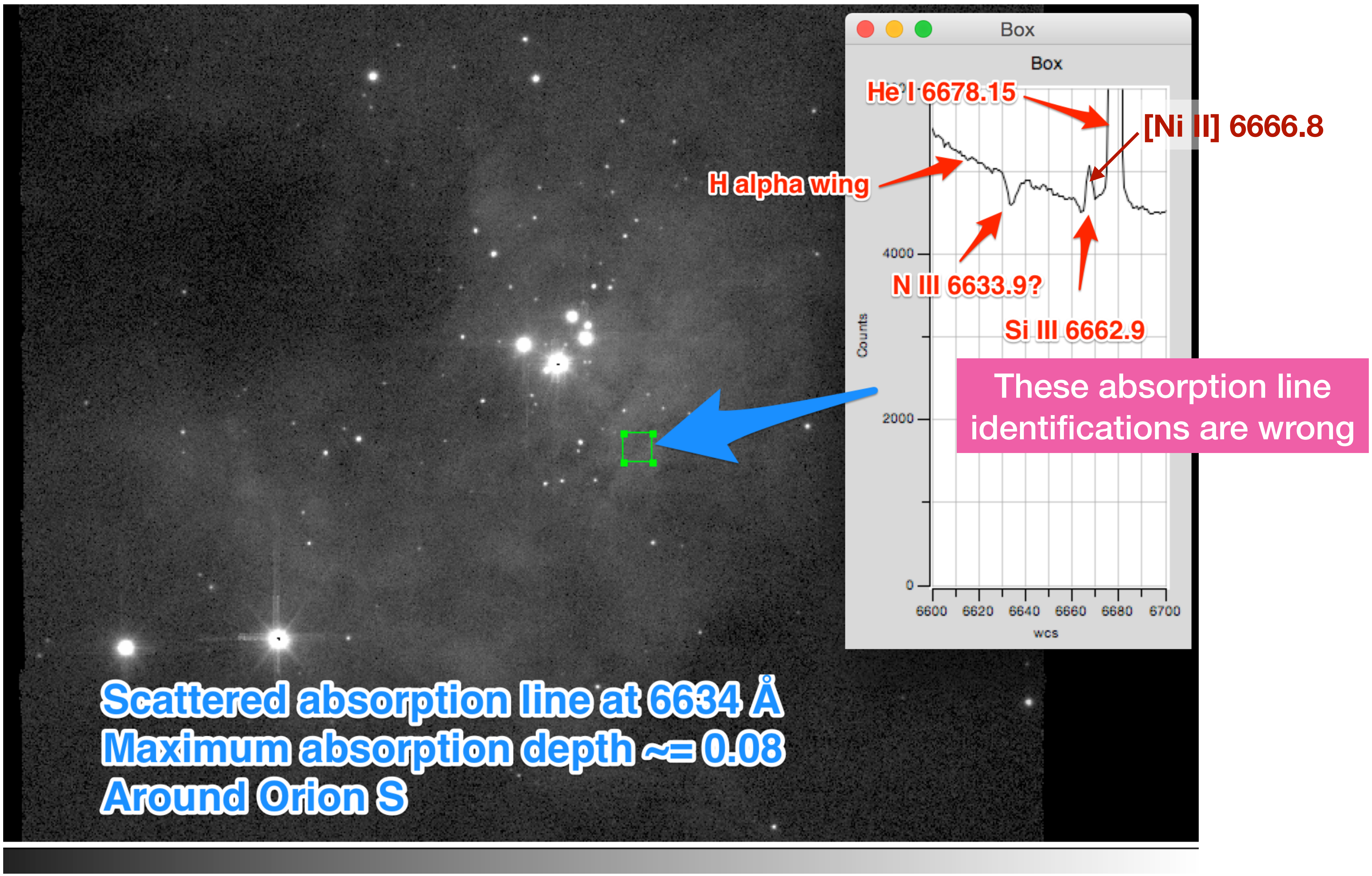
Quick definitions

- **Raman scattering**
  - Non-resonant, inelastic scattering by far wings of atomic/molecular absorption lines
  - Inelastic analog of Rayleigh scattering
- **PDR**
  - Photo-dissociation region *or* photon-dominated region
  - Layer of neutral/molecular gas that surrounds an H II region, illuminated by hot massive stars

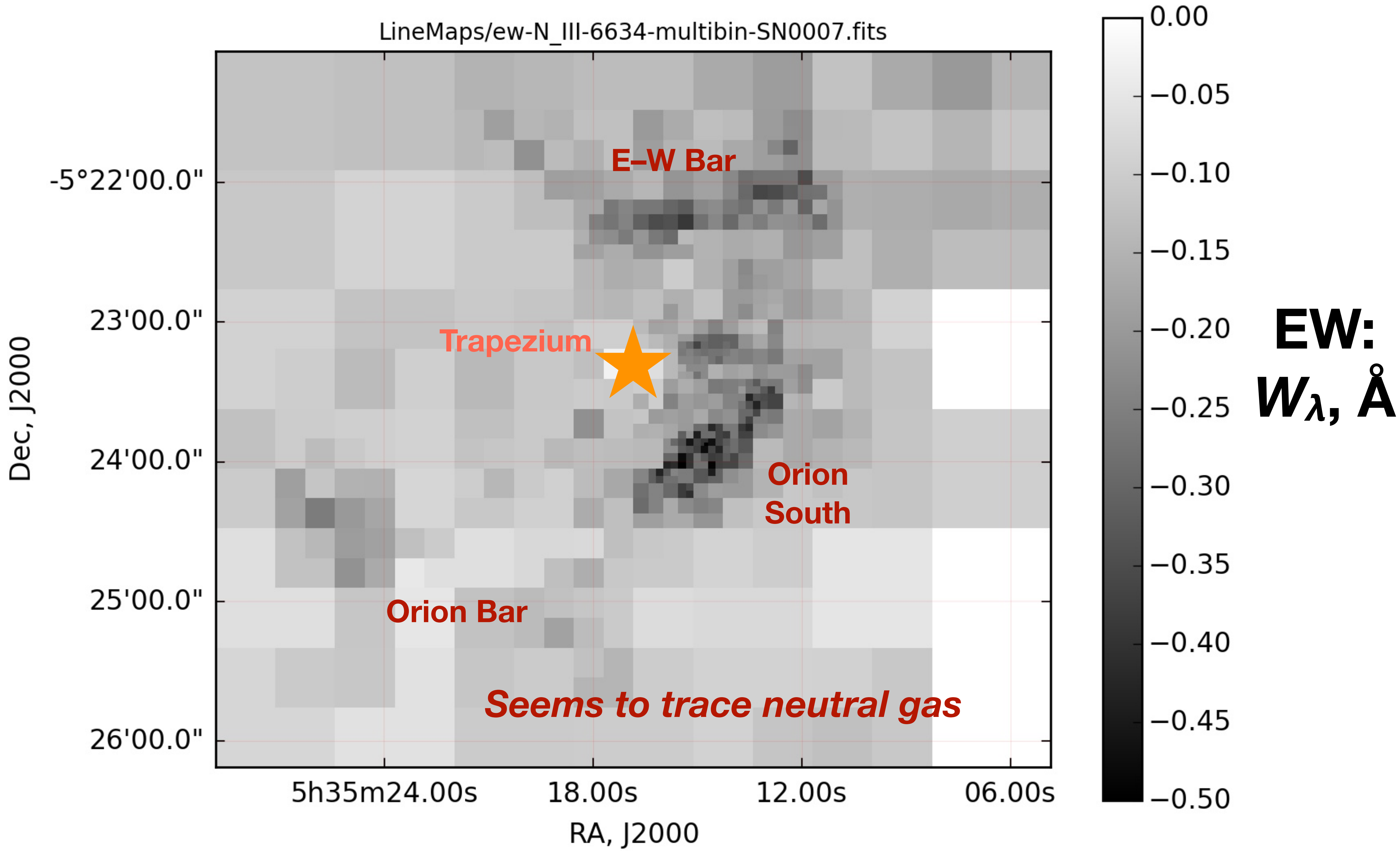
Timeline:2015

The mystery line

A puzzling absorption line in diffuse emission from the Orion Nebula



Equivalent width map of the mystery absorption line



Three explanations for the 6633 Å absorption line that *do not* work

Failed explanation #1

- **Stellar absorption line seen in scattered light?**
  - Not present in the brightest stars
  - N IV λ6634 is present in θ^1E Ori (2 × G2 IV), but with $L = 30\ L_\odot = 0.1\%$ of Trapezium luminosity
  - ***This is too faint to account for any of the diffuse light***

Three explanations for the 6633 Å absorption line that *do not* work

Failed explanation #2

- **Molecular line or atomic line at that wavelength?**
  - The high EW implies large oscillator strength (resonance line) and abundant species. I have searched in all the data bases and asked all the experts ⇒ ***nothing***
  - Also, hard to get absorption imprinted on the nebular light without it also showing up in the stellar spectra
  - ***A contrived geometry is required***

Three explanations for the 6633 Å absorption line that <u>*do not*</u> work

Failed explanation #3

- **Solid state absorption feature?**
  - Diffuse Interstellar Bands have a range of widths, down to ≈ 1 Å, and there is a very weak feature at 6632.85 Å
  - ***But our line is 10 times stronger***
  - Also, only found in highly-reddened stars, and always accompanied by much stronger features at other wavelengths (e.g., 6699 Å)
  - ***We do not see any of them***
  - And our line does not correlate with reddening
  - ***Contrived geometry again***

Timeline:2016

The paper that I ignored (but I shouldn’t have)

Dopita et al. (2016) paper on Raman scattering in H II regions

Astrophysical Journal Letters, 824:L13 (6pp), 2016 June 10
doi:10.3847/2041-8205/824/1/

Cross

THE DISCOVERY OF RAMAN SCATTERING IN H II REGIONS

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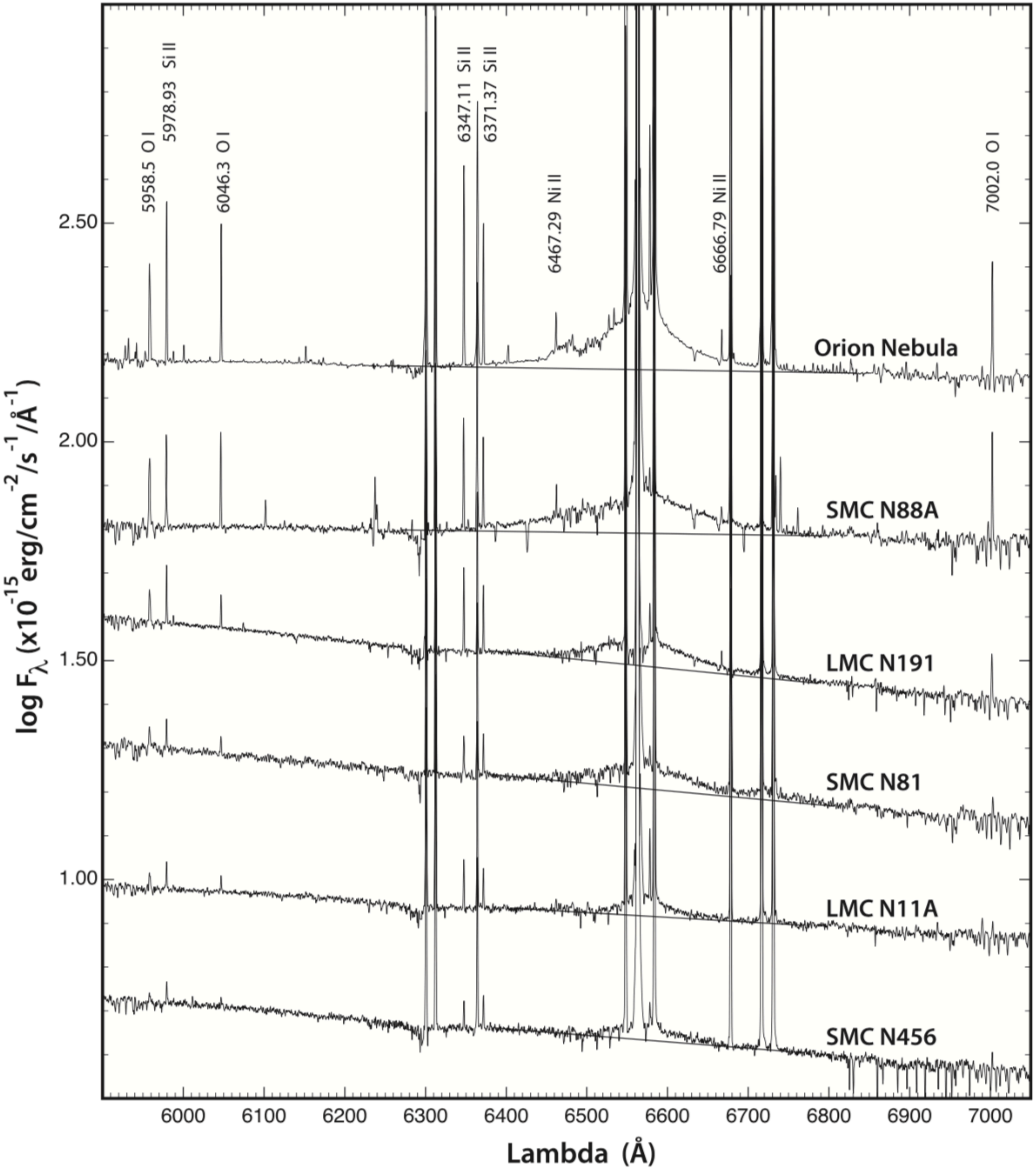
ABSTRACT

We report here on the discovery of faint extended wings of Hα observed out to an apparent velocity of $\sim$7600 km s^{-1} in the Orion Nebula (M42) and in five H II regions in the Large and the Small Magellanic Clouds. We show that these wings are caused by Raman scattering of both the O I and Si II resonance lines and stellar continuum UV photons with H I followed by radiative decay to the H I $n = 2$ level. The broad wings also seen in Hβ and in Hγ result from Raman scattering of the UV continuum in the H I $n = 4$ and $n = 5$ levels, respectively. The Raman scattering fluorescence is correlated with the intensity of the narrow permitted lines of O I and Si II. In the case of Si II, this is explained by radiative pumping of the same 1023.7 Å resonance line involved in the Raman scattering by the Lyβ radiation field. The subsequent radiative cascade produces enhanced Si II $\lambda\lambda$5978.9, 6347.1, and 6371.4 Å permitted transitions. Finally, we show that in O I, radiative pumping of the 1025.76 Å resonance line by the Lyman series radiation field is also the cause of the enhancement in the permitted lines of this species lying near Hα in wavelength, but here the process is a little more complex. We argue that all these processes are active in the zone of the H II region near the ionization front.

Key words: atomic processes – H II regions – line: formation – Magellanic Clouds – radiation mechanisms: thermal – ultraviolet: ISM


5958.5 O I
5978.93 Si II
6046.3 O I
6347.11 Si II
6371.37 Si II
6467.29 Ni II
6666.79 Ni II
7002.0 O I
Orion Nebula
SMC N88A
LMC N191
SMC N81
LMC N11A
SMC N456
log F_λ ($\times 10^{-15}$ erg/cm^{-2}/s^{-1}/Å^{-1})
2.50
2.00
1.50
1.00
6000
6100
6200
6300
6400
6500
6600
6700
6800
6900
7000
Lambda (Å)

Timeline:2019

Epiphany

The absorption lines and the broad wings are connected

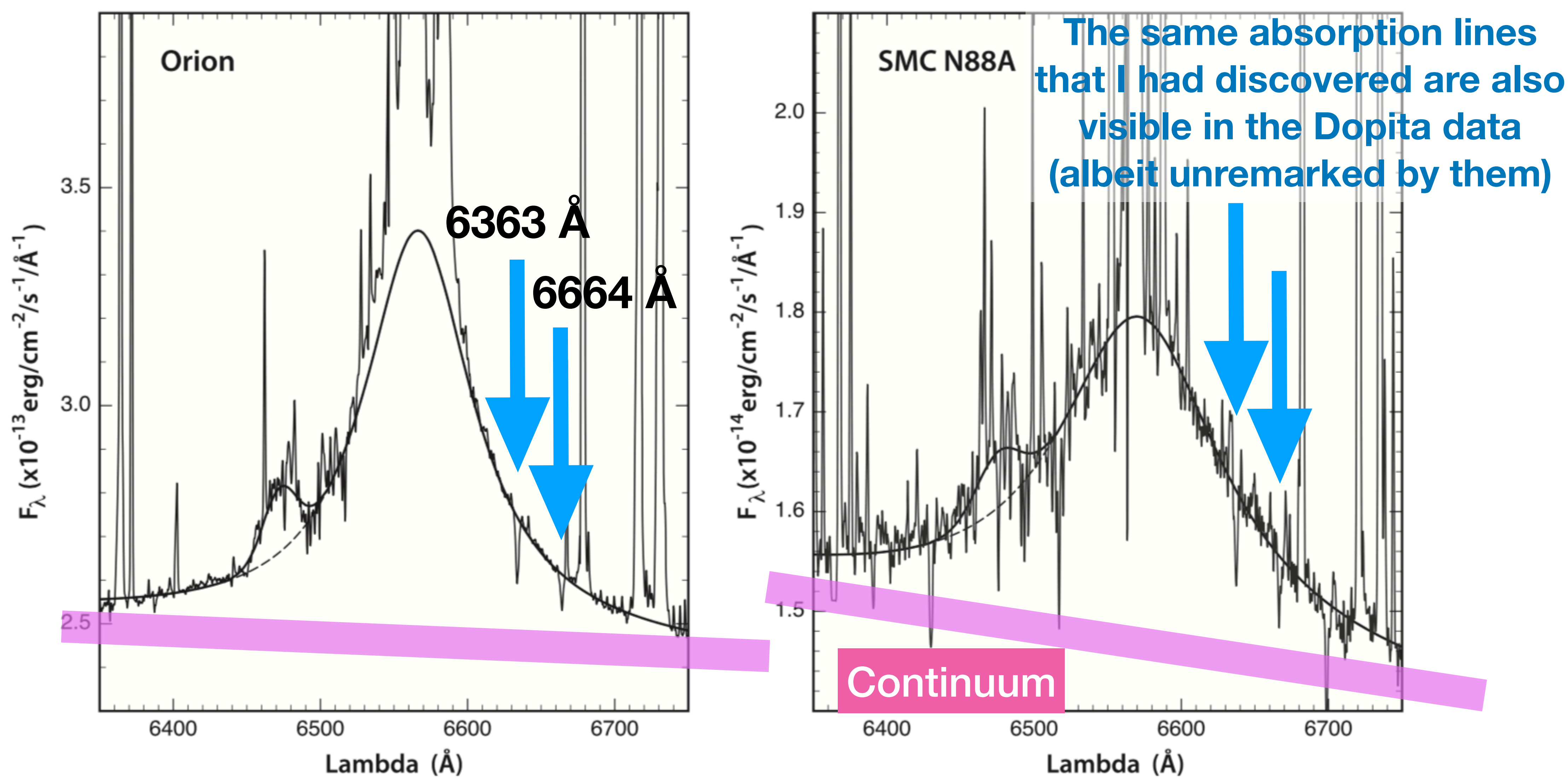


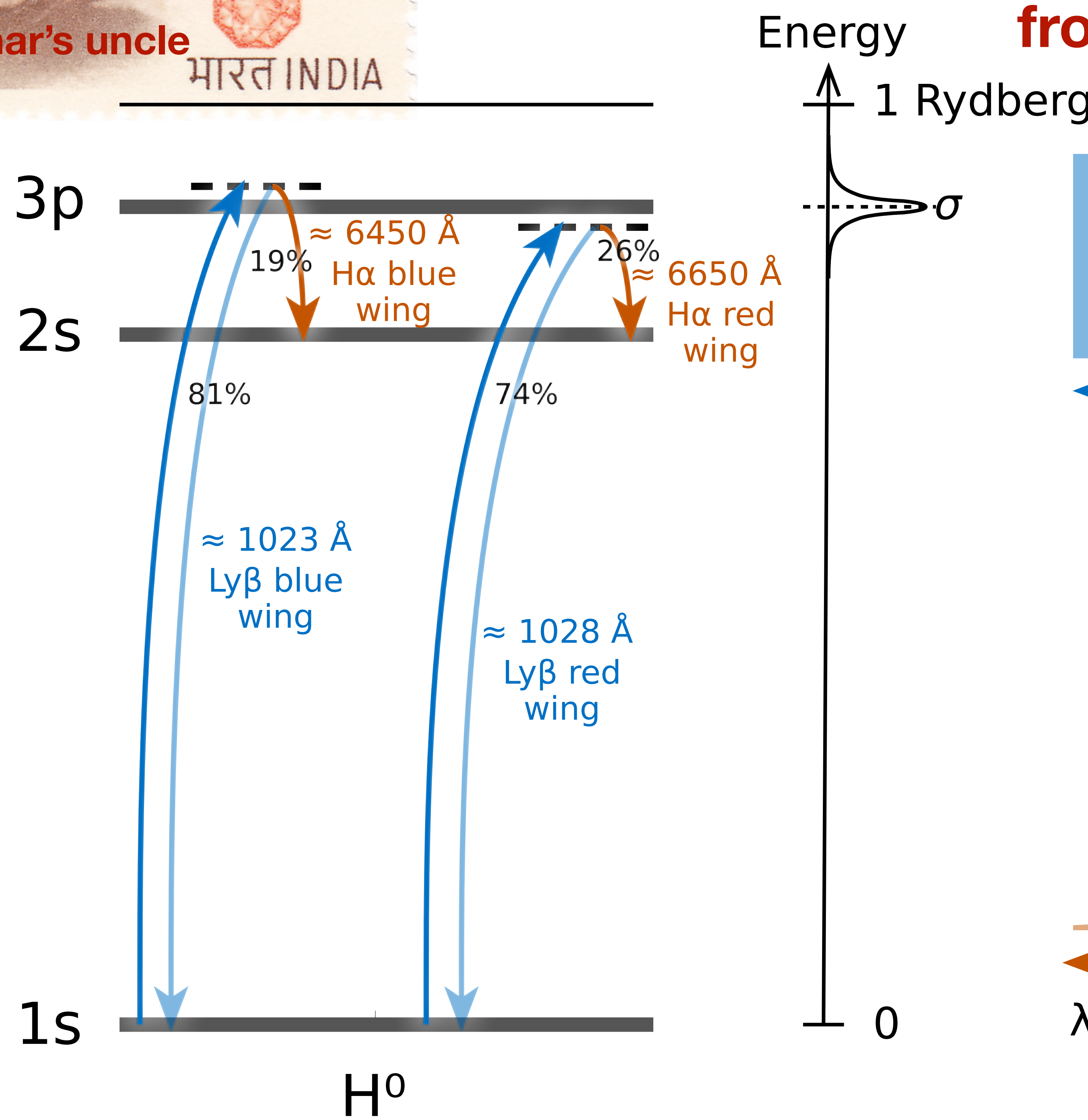
Figure 3. Fit to the Raman scattering profiles of O I and Si II in the Orion Nebula (M42) and in SMC N88A. The O I Raman profile is best fit with a Lorentzian, the broad wings of which result from Raman scattering of the stellar UV continuum (see the text), while the Si II bump is better fit with a simple Gaussian.

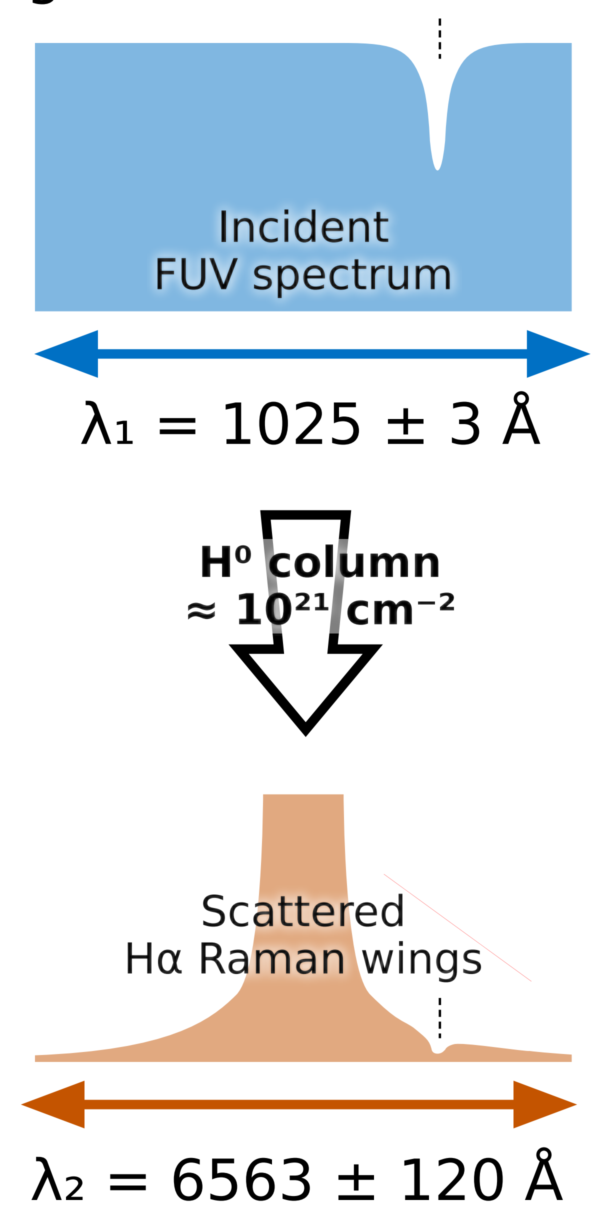
The two lines never dip below the continuum level – maybe it is the *wings* that are being absorbed and not the continuum

Raman scattering

Chandrasekhar's uncle

Spectral features are mapped from ultraviolet to optical





Raman scattering of emission lines in symbiotic stars

Astron. Astrophys. 211, L31–L34 (1989)

Schmid (1989) O VI 1032,38 Å → 6830, 7088 Å

Previous examples of Raman scattering in nebulae have mainly been of emission lines

Letter to the Editor

Identification of the emission bands at λλ6830, 7088

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Received November 22, accepted December 20, 1988

Summary. Broad emission bands at 6830 Å and 7088 Å are observed in more than 50 per cent of symbiotic stars. Up to now these features have not been identified. They have only been observed in spectra of symbiotic binaries, which show high excitation emission and M–type absorption. I suggest that the emission features are due to Raman scattering of the OVI resonance doublet λλ 1032, 1038 by neutral hydrogen. In this process the OVI photons are absorbed by hydrogen in its ground state $1s\,^2S$. The absorption leads to an intermediate state from where a photon is emitted, and the hydrogen atom is left in the excited state $2s\,^2S$. According to energy conservation the emitted photons have wavelengths of approximately 6830 Å and 7088 Å. Raman scattering can well explain the observed properties of the emission bands. Physical conditions required for efficient Raman scattering of OVI photons in symbiotic stars will be briefly discussed.

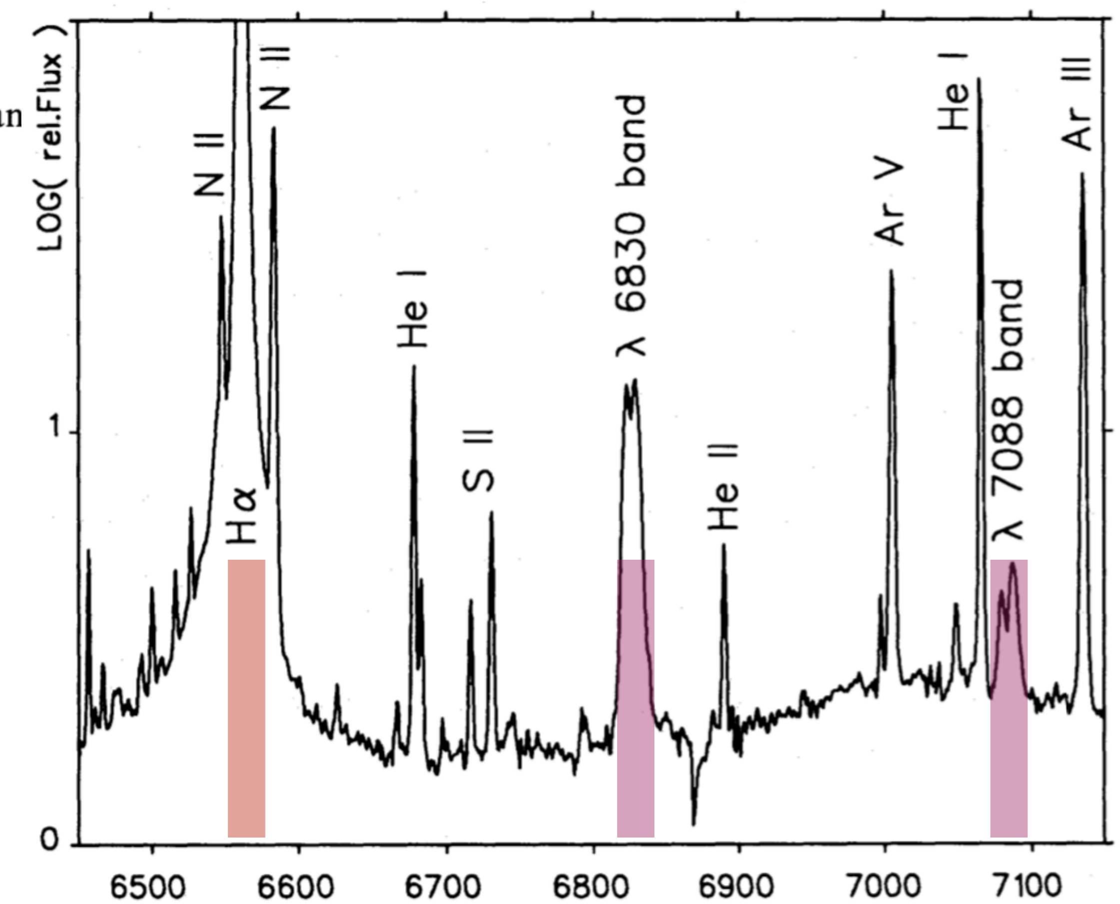


Fig.1. Raman scattered emission bands in the symbiotic star V1016 Cyg. The spectrum was obtained on the 1.93m telescope at the Observatoire de Haute Provence.

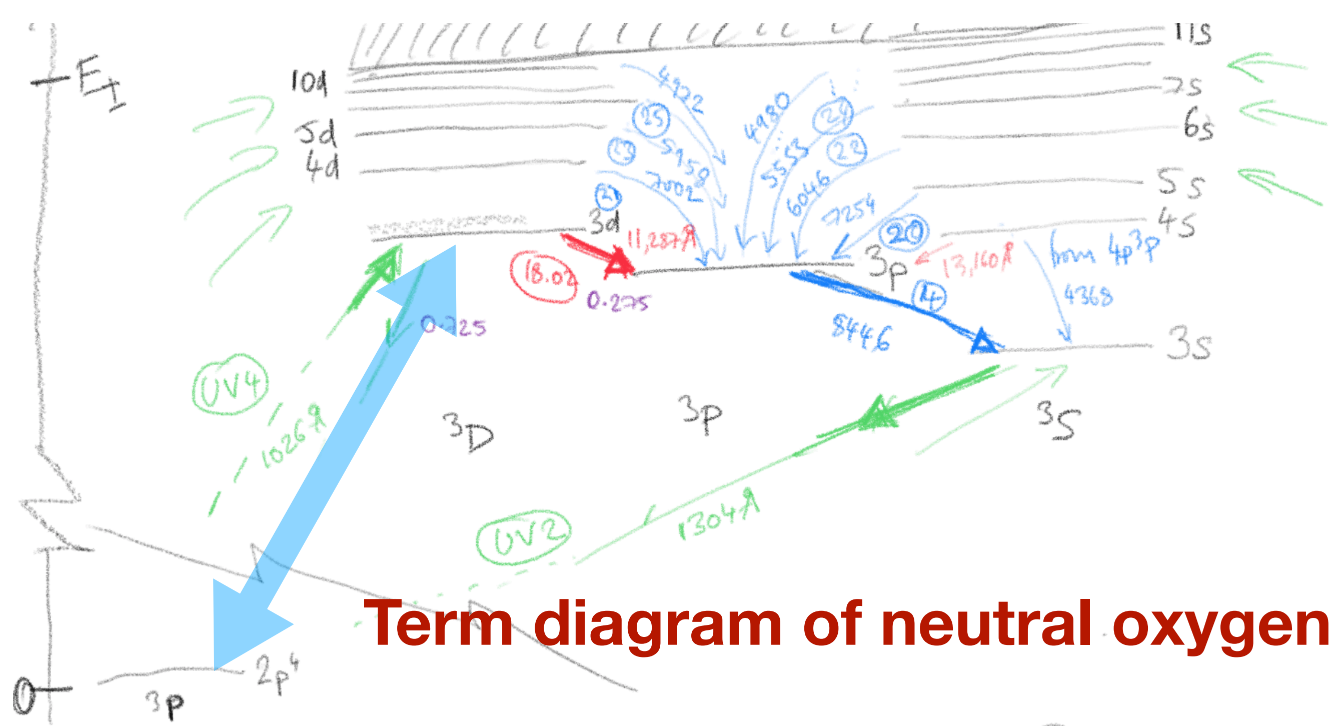
FUV nebular O^0 absorption lines, Raman-scattered to the optical band

Table A1. FUV/optical wavelength equivalencies for Raman scattering

Ion	Transition	$J_i \rightarrow J_k$	λ_1, Å	$\tilde{\nu}_1$, cm^{-1}	$\Delta\tilde{\nu}$, cm^{-1}	$\tilde{\nu}_2$, cm^{-1}	λ_2, Å	λ_{air}, Å
			.... Lyβ, $n = 1$			....	Hα, $n = 2$	....
H I	$ns\ ^2\mathrm{S} \rightarrow 3p\ ^2\mathrm{P}$	1/2 → 1/2, 3/2	1025.72220	97492.283	0.000	15233.329	6564.553	6562.740
O I	$2s^22p^4\ ^3\mathrm{P} \rightarrow 2s^22p^3(^4\mathrm{S})3d\ ^3\mathrm{D}^o$	0 → 1	1028.15729	97261.383	−230.900	15002.429	6665.587	6663.747
		1 → 1	1027.43139	97330.100	−162.183	15071.146	6635.196	6633.364
		1 → 2	1027.43077	97330.159	−162.124	15071.205	6635.170	6633.338
		2 → 1	1025.76339	97488.369	−3.914	15229.415	6566.240	6564.427
		2 → 2	1025.76276	97488.429	−3.854	15229.475	6566.215	6564.401
		2 → 3	1025.76170	97488.530	−3.753	15229.576	6566.171	6564.358
Si II	$3s^23p\ ^2\mathrm{P}^o \rightarrow 3s^25s\ ^2\mathrm{S}$	1/2 → 1/2	1020.6989	97972.086	+479.803	15713.132	6364.104	6362.345
		1/2 → 3/2	1023.7001	97684.859	192.576	15425.905	6482.602	6480.811

$$\lambda_2 = \left(\frac{1}{\lambda(\mathrm{H}\alpha)} + \frac{1}{\lambda_1} - \frac{1}{\lambda(\mathrm{Ly}\beta)} \right)^{-1} .$$

$$\Rightarrow \lambda_2 \approx 6.4\,\lambda_1$$



Term diagram of neutral oxygen

Lyβ wing cross section

THE ASTROPHYSICAL JOURNAL, 814:98 (8pp), 2015 December 1
doi:10.1088/0004-637X/814/2/98

FORMATION OF RAMAN SCATTERING WINGS AROUND Hα, Hβ, AND PAα
IN ACTIVE GALACTIC NUCLEI

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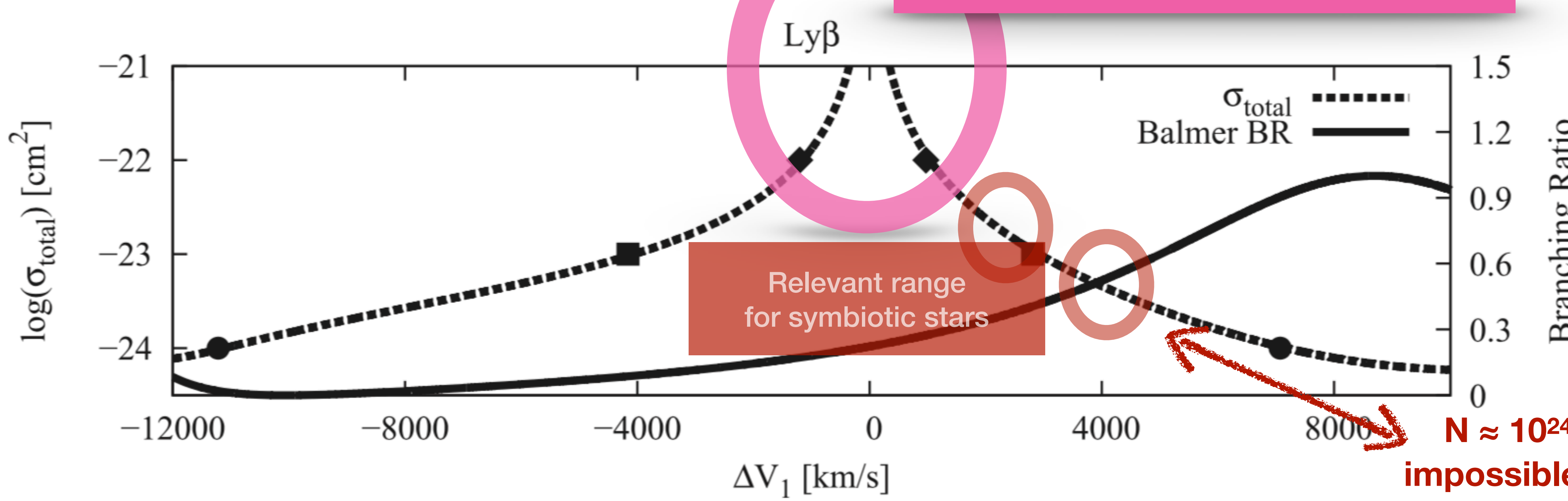
Received 2015 August 27; accepted 2015 Septemb

H^0 Column density,
$N \approx 1/\sigma \approx 10^{22}$ cm^{-2}

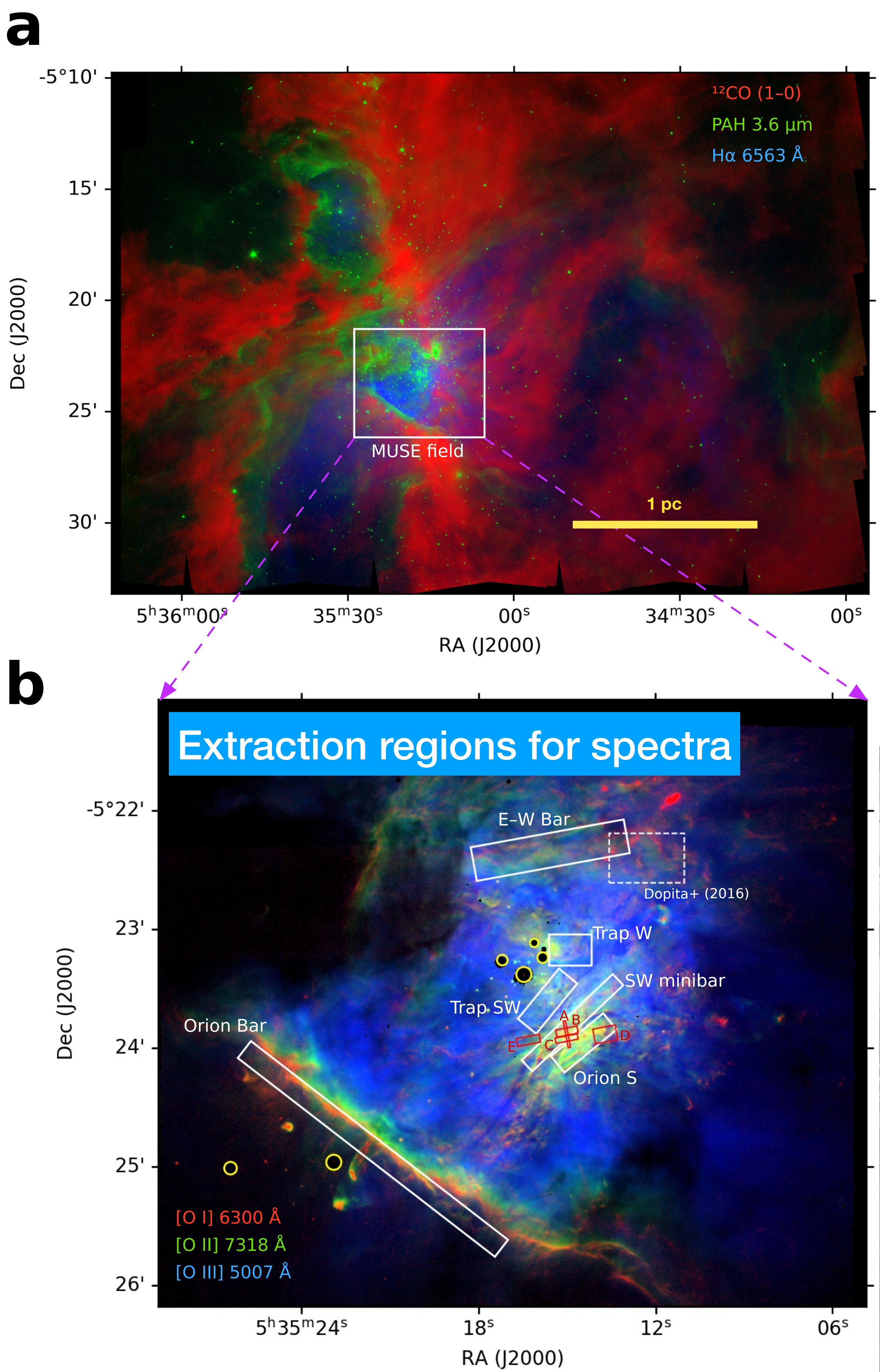
Relevant range for H II regions

Chang et al. (2015)

$\sigma = 10^{-22}$ to 2×10^{-21} cm^2

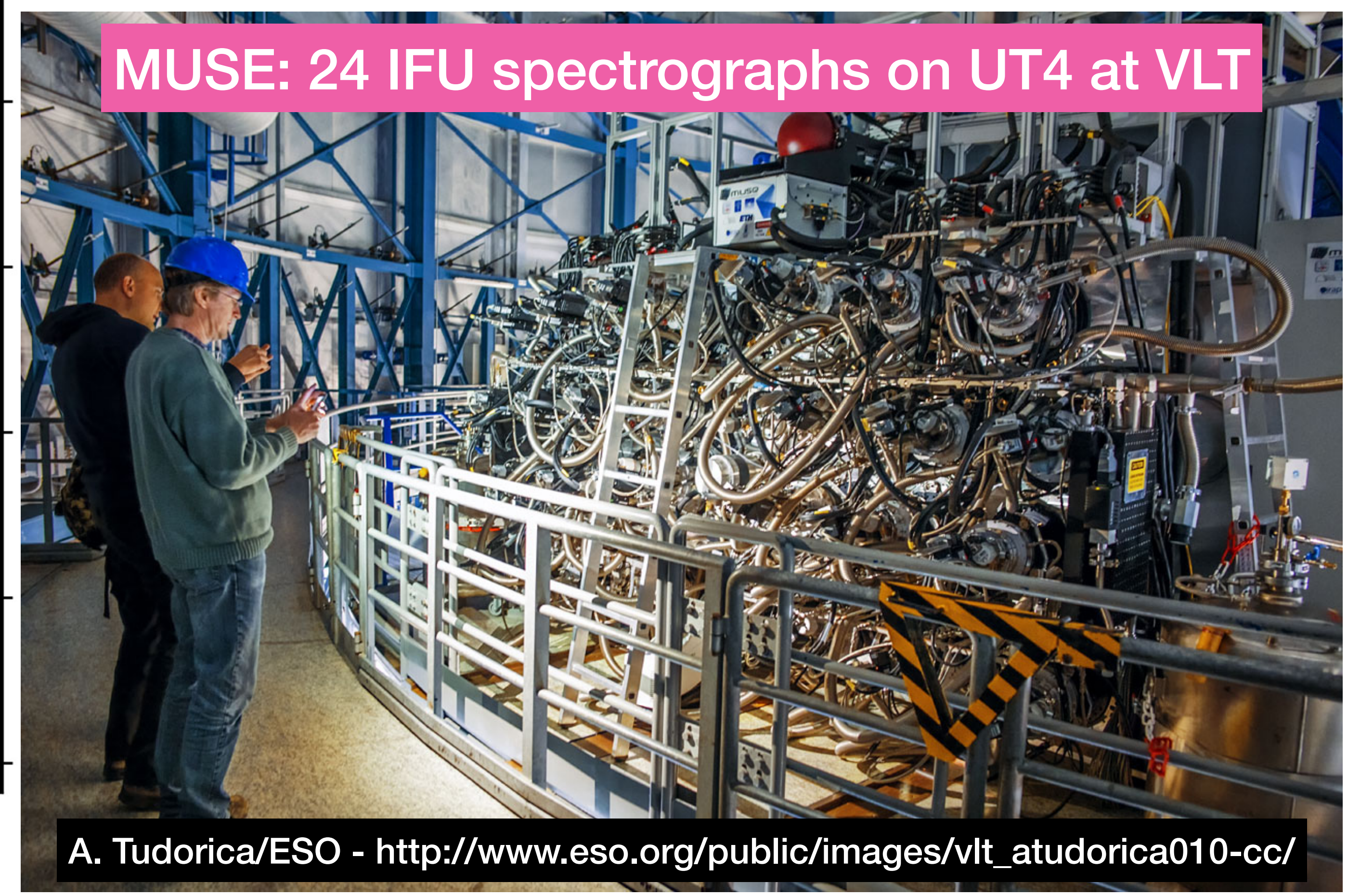


$N \approx 10^{24}$ cm^{-2}
impossible if dust present

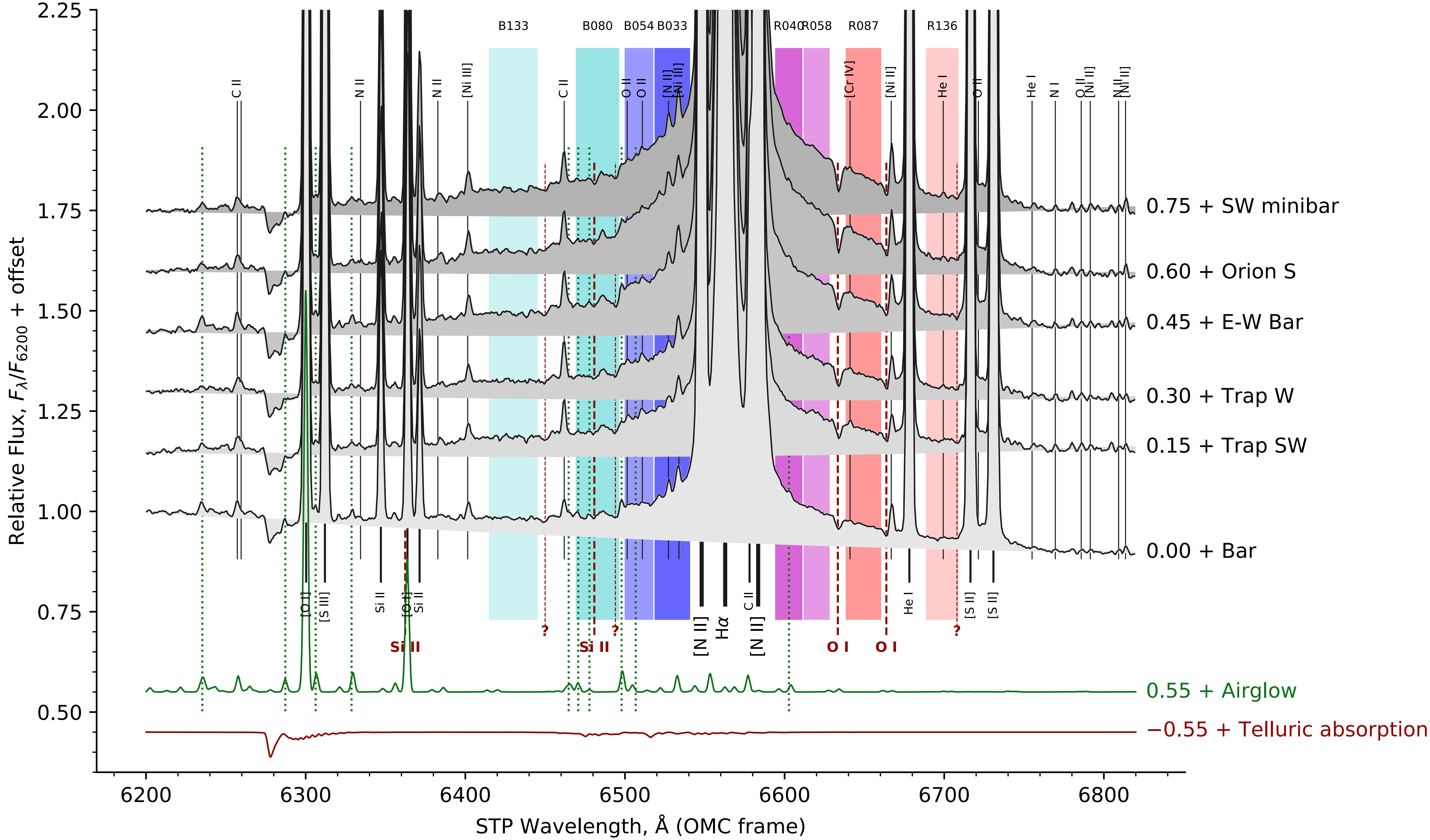


MUSE observations of Raman scattering in the inner Orion Nebula

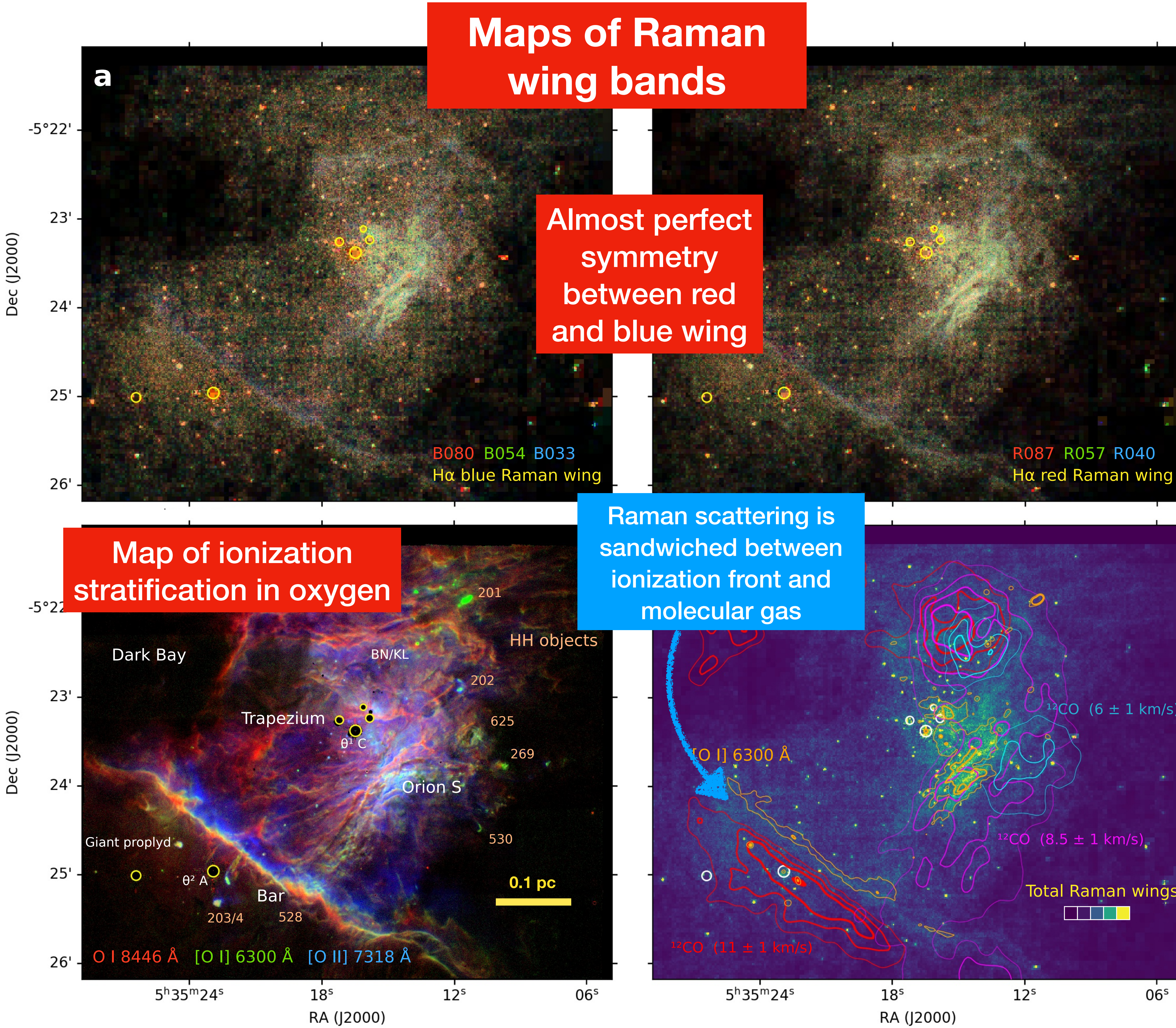
Δλ = 2.5 Å, R = 2500 @ Hα



Define four bands in each of the red and blue Raman wings

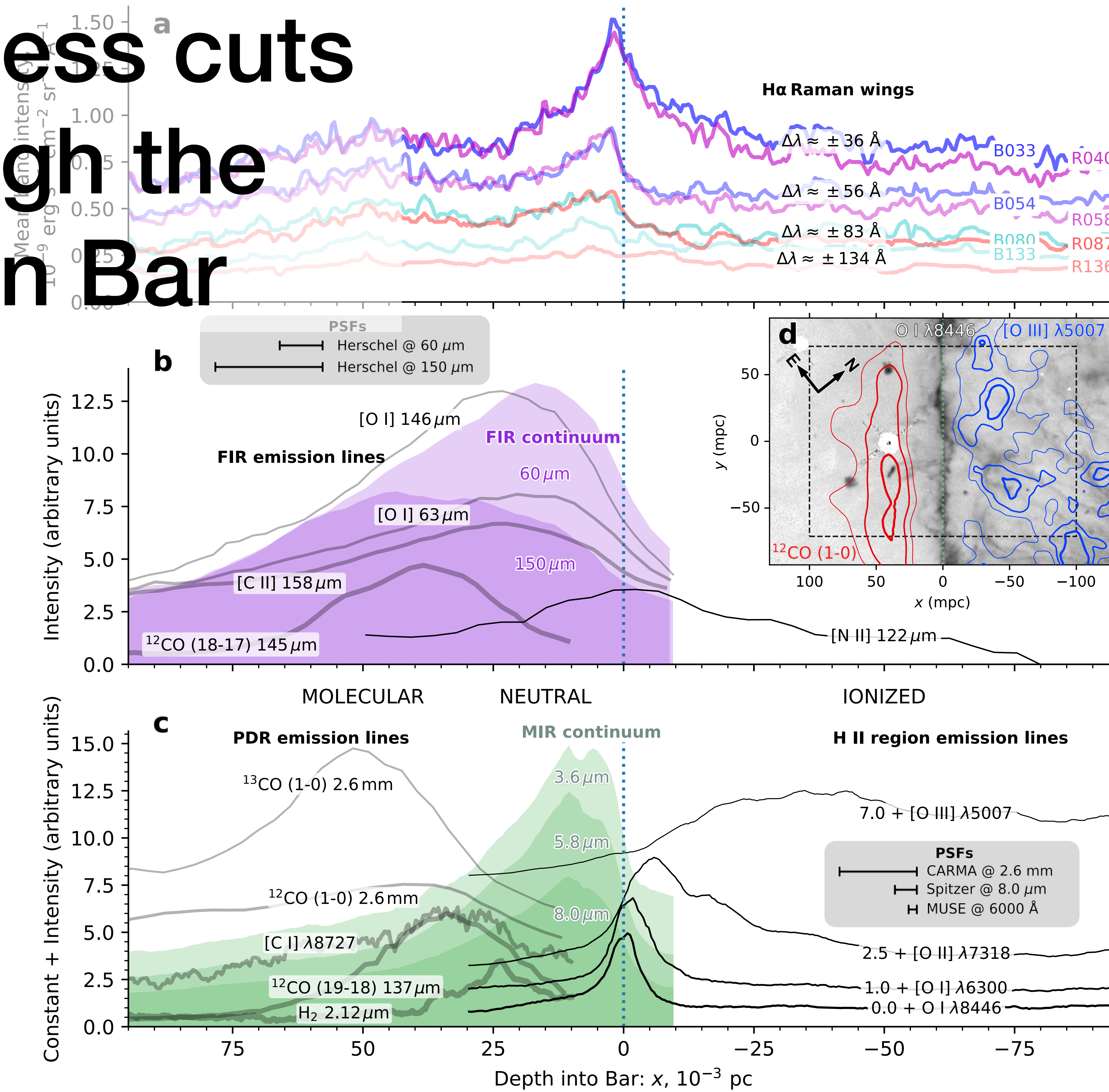


Avoid nebular and telluric lines as far as possible

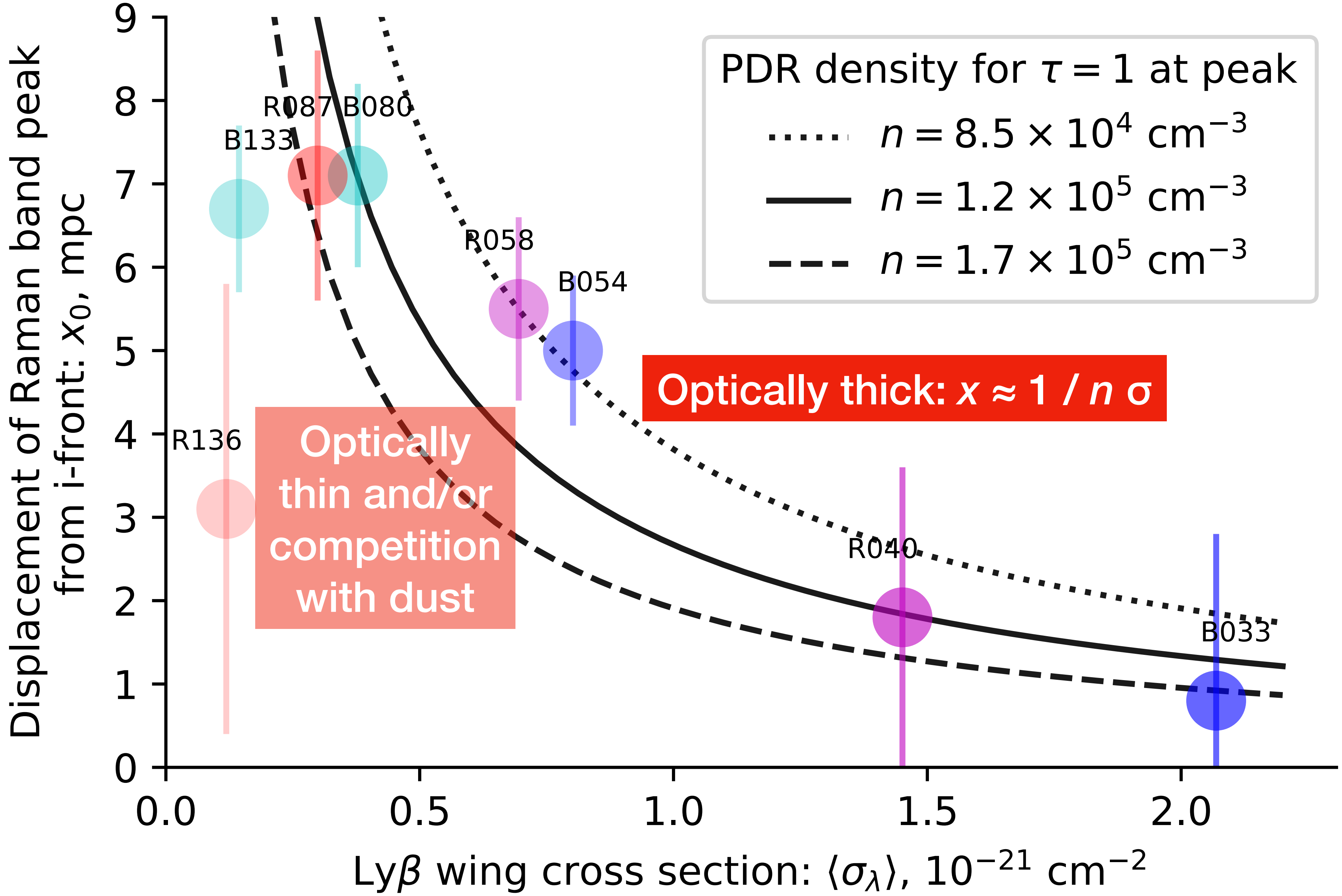

Maps of Raman wing bands
a
Almost perfect symmetry between red and blue wing
B080 B054 B033
Hα blue Raman wing
R087 R057 R040
Hα red Raman wing
Map of ionization stratification in oxygen
Raman scattering is sandwiched between ionization front and molecular gas
Dark Bay
BN/KL
HH objects
201
202
625
269
530
Trapezium
θ¹ C
Orion S
Giant proplyd
θ² A
Bar
203/4
528
0.1 pc
O I 8446 Å [O I] 6300 Å [O II] 7318 Å
[O I] 6300 Å
¹²CO (6 ± 1 km/s)
¹²CO (8.5 ± 1 km/s)
¹²CO (11 ± 1 km/s)
Total Raman wings
Dec (J2000)
RA (J2000)
-5°22'
23'
24'
25'
26'
5ʰ35ᵐ24ˢ
18ˢ
12ˢ
06ˢ

Brightness cuts through the Orion Bar

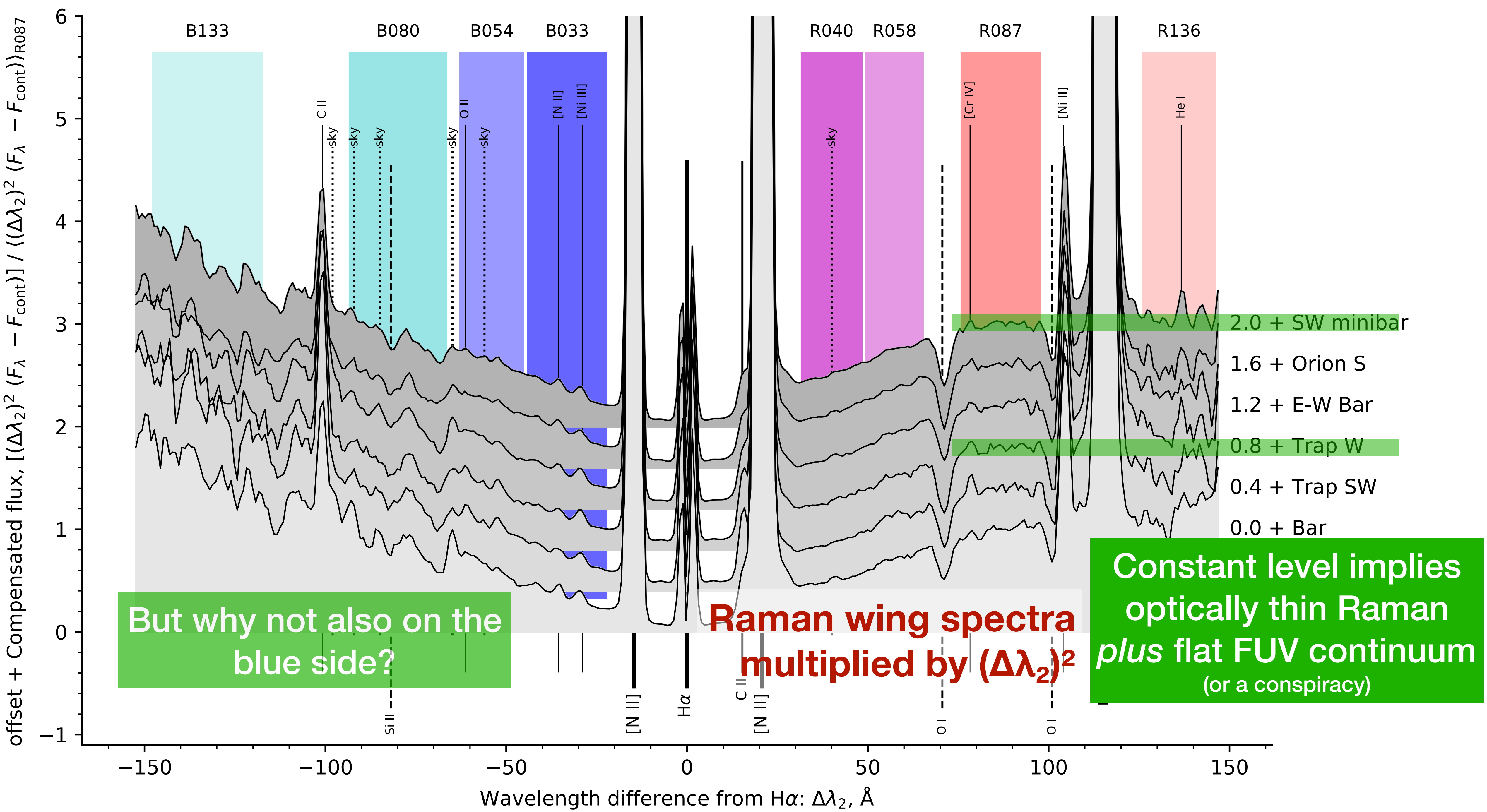
Spatial distribution of Raman wings is most similar to mid-infrared PAH emission and 21 cm H I



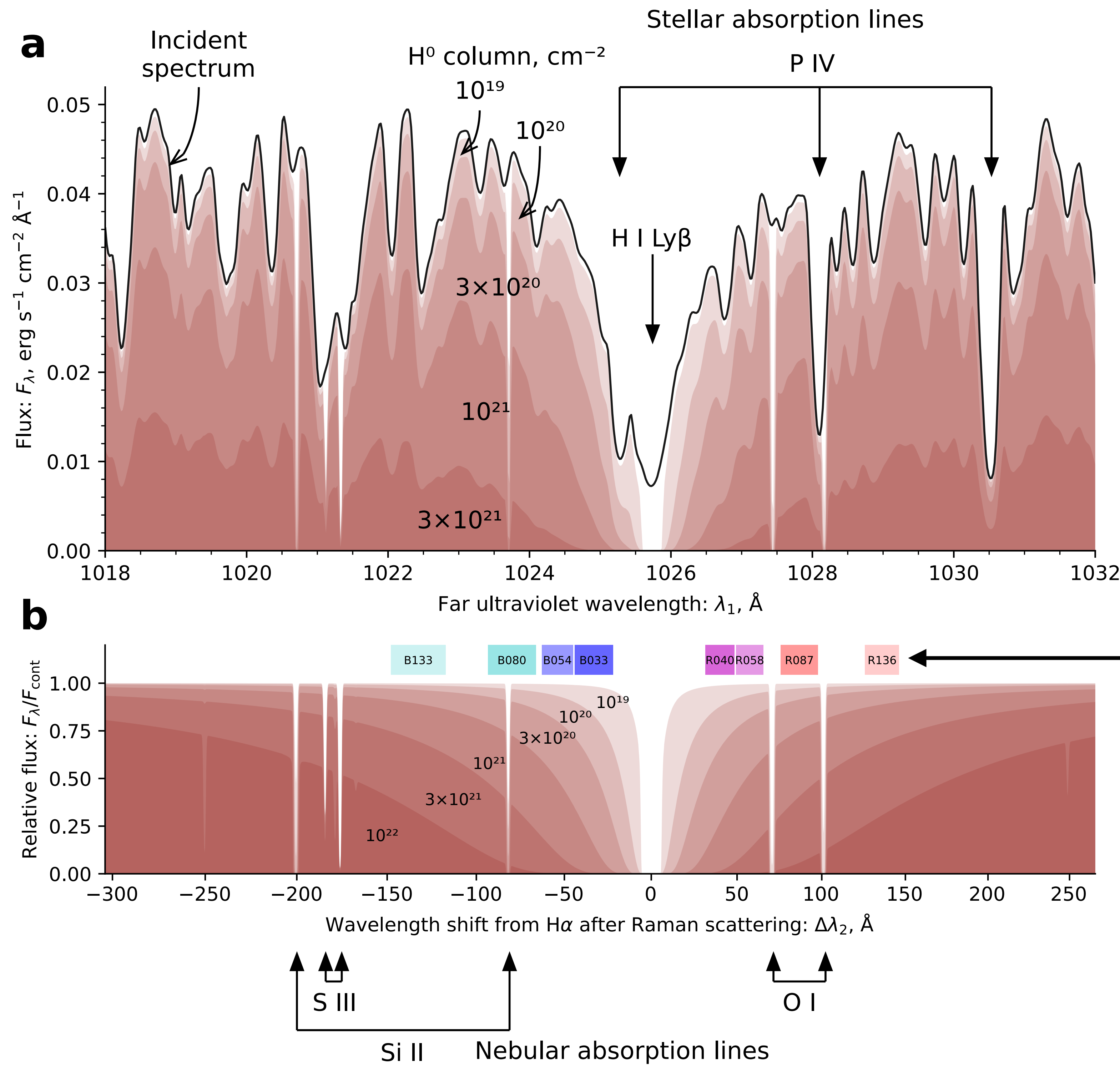
PDR density diagnostic from Raman bands



Further evidence for optically thick/thin transition



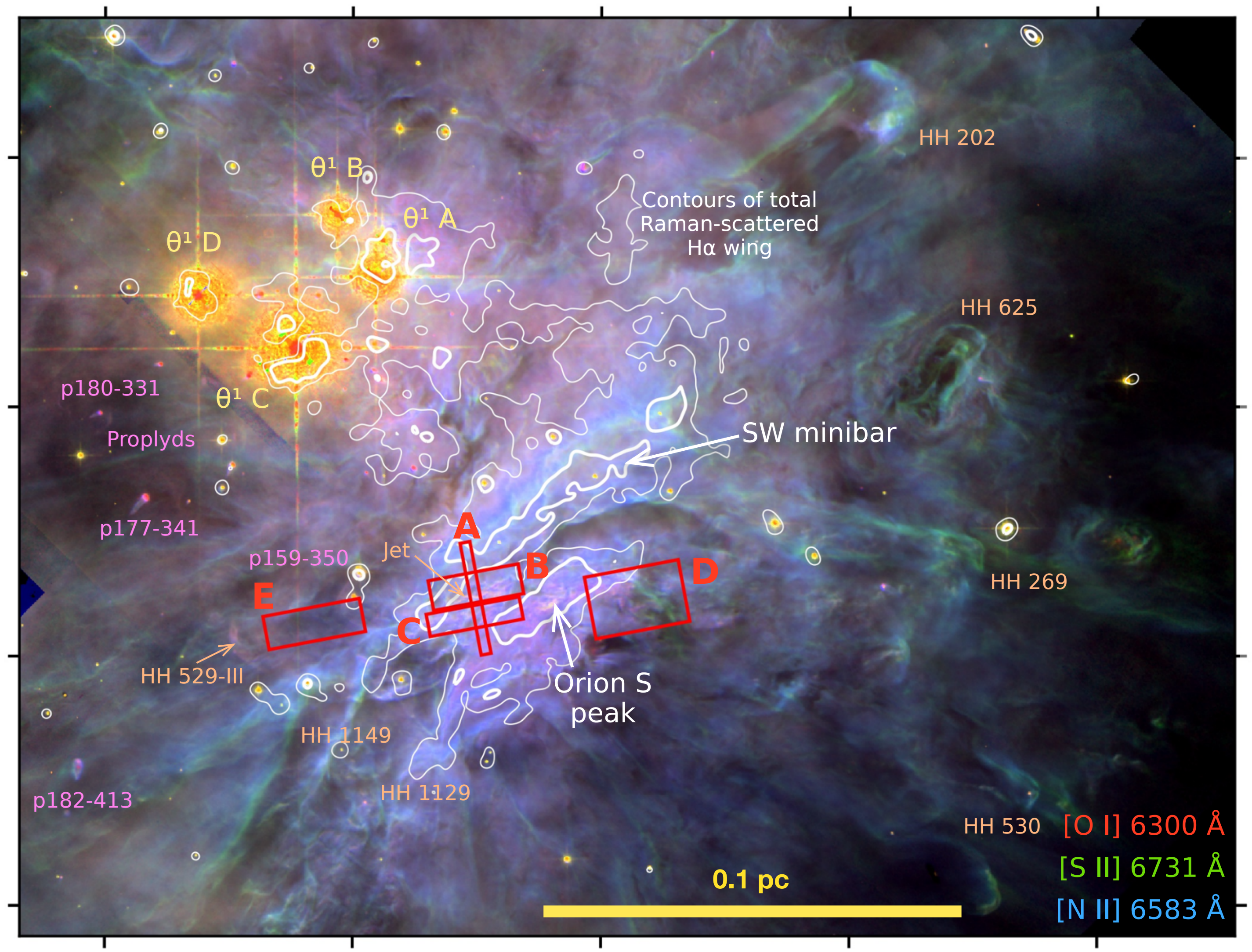
Stellar atmosphere models passing through a Cloudy model



No evidence for the P IV stellar lines predicted by the Potsdam models

Raman bands

Ultra-high resolution spectroscopy with Keck HIRES

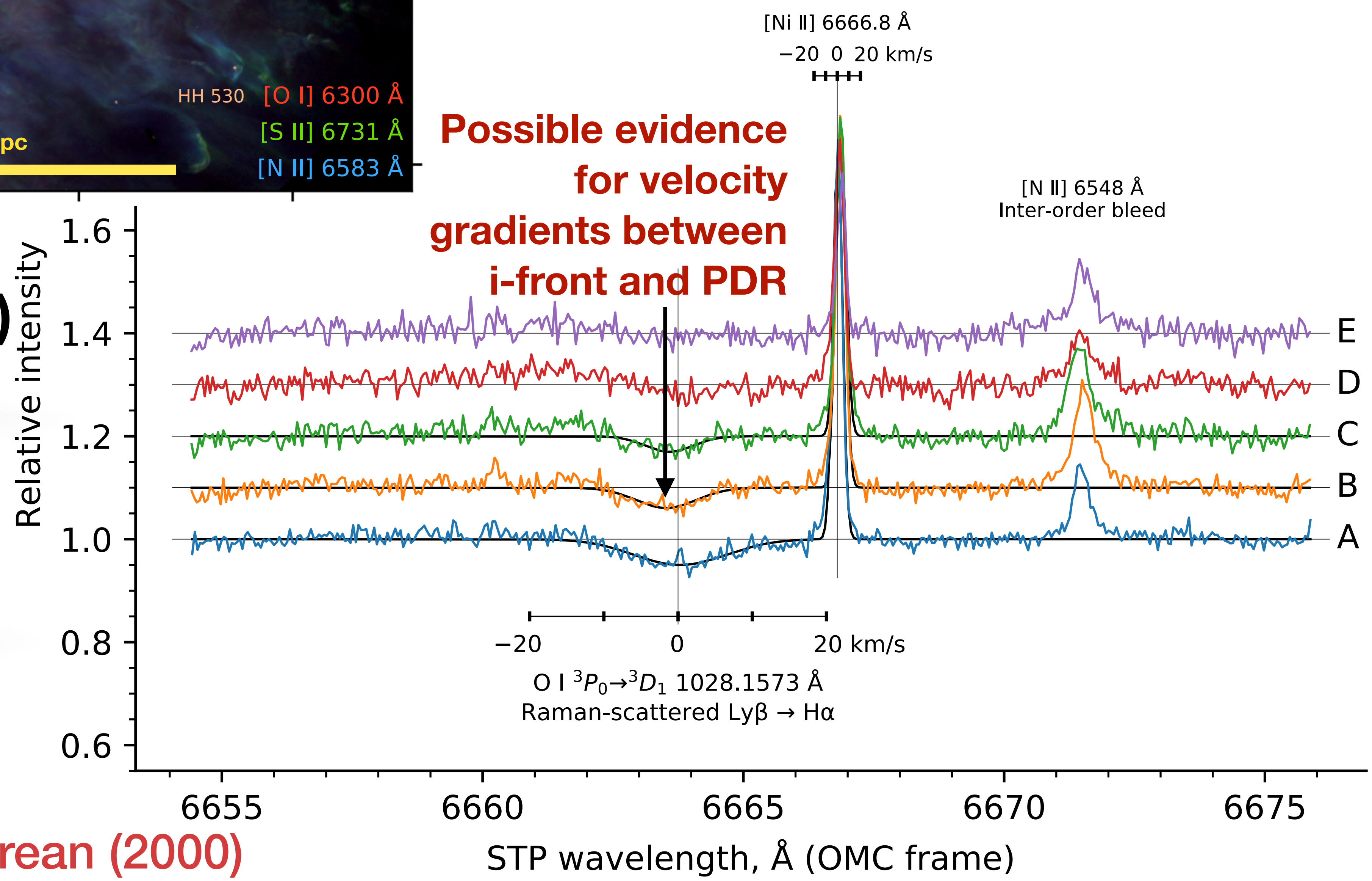


R = 50,000 (ΔV= 6 km/s) at red wavelengths

Effective R = 325,000 (ΔV < 1 km/s) in UV !!!

Old data from 1998:

- Henney & O’Dell (1999)
- Bally, O’Dell. & McCaughrean (2000)



Conclusions

- I identify the 6633 Å and 6664 Å absorption features with FUV O I 1027 Å and 1028 Å lines that have been Raman-scattered from the Lyβ to Hα wings
- The Raman-scattered Hα wings can be spatially mapped in star-forming regions, giving a new diagnostic window into the outer layers of the PDR
- Extremely high velocity resolution (1 km/s) is easily achievable by measuring Raman-scattered FUV lines

Future plans

- **Orion** –
  - Structure of Orion S – brighter than Bar but more confused
- **Modeling** –
  - Do radiative transfer properly
  - Implement Raman scattering in Cloudy
- **More observations** –
  - Tarantula in LMC with MUSE
  - More objects (should be very common)