Physical properties of Wolf-Rayet stars from near- to mid-IR diagnostics

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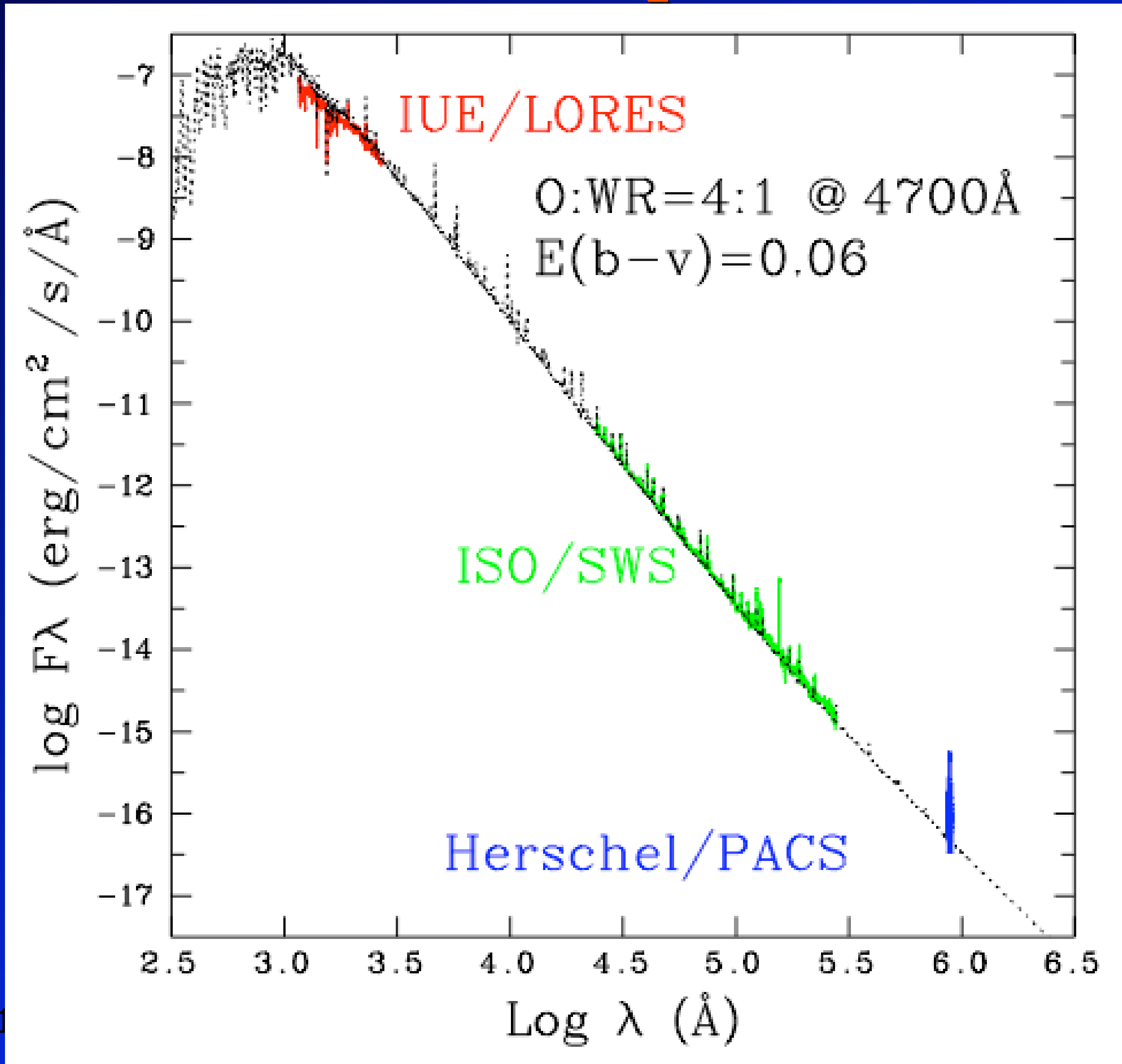
Gamma Vel (WC8+O7)



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- 90% of Galactic Wolf-Rayet stars visually obscured due to interstellar dust, so IR diagnostics needed for spectral analysis (e.g. Crowther & Smith 1996)

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- Mid- to far-IR provides fine-structure lines from which trace elements can be derived (e.g. Barlow+ 1988; Dessart+ 2000)
- Observed near- to far-IR spectral energy distribution helps with (unknown) radial dependence of wind clumping (e.g. Nugis, Crowther & Willis 1998; Schnurr & Crowther 2008)

Wolf-Rayet stars

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- Sequence: O⇒ BSG ⇒ LBV/RSG ⇒ WN ⇒ WC

Phase	^{1}H	^{4}He	^{12}C	^{14}N	^{16}O	^{20}Ne (^{22}Ne)
O	68%	30%	0.5%	0.1%	1%	0.1%
WN	0%	98%	0.1%	1.5%	0.1%	0.1%
WC	0%	70%	25%	0%	3%	0.1% (2%)

Spectroscopic Analysis

Complex radiative transfer in WR stars:

- Intense radiation field (non-LTE);
- Extended atmospheres (spherical geometry);
- Effect of metal lines on atmospheric structure (line blanketing).

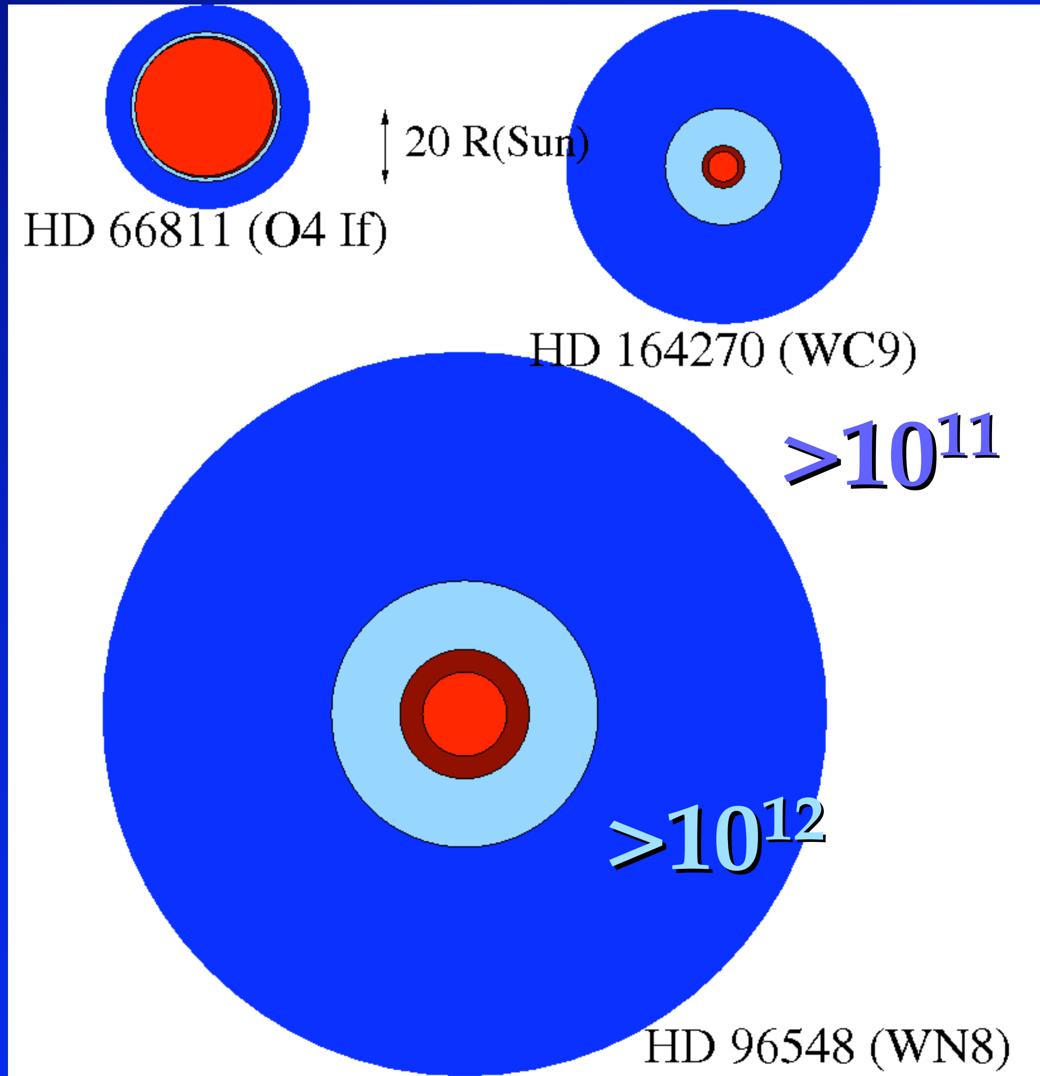
Tools from John Hillier (CMFGEN) & Wolf-Rainer Hamann (PoWR) account for these effects, providing physical & chemical parameters

- Issues remain with driving the wind & clumping…

Inner Wolf-Rayet winds

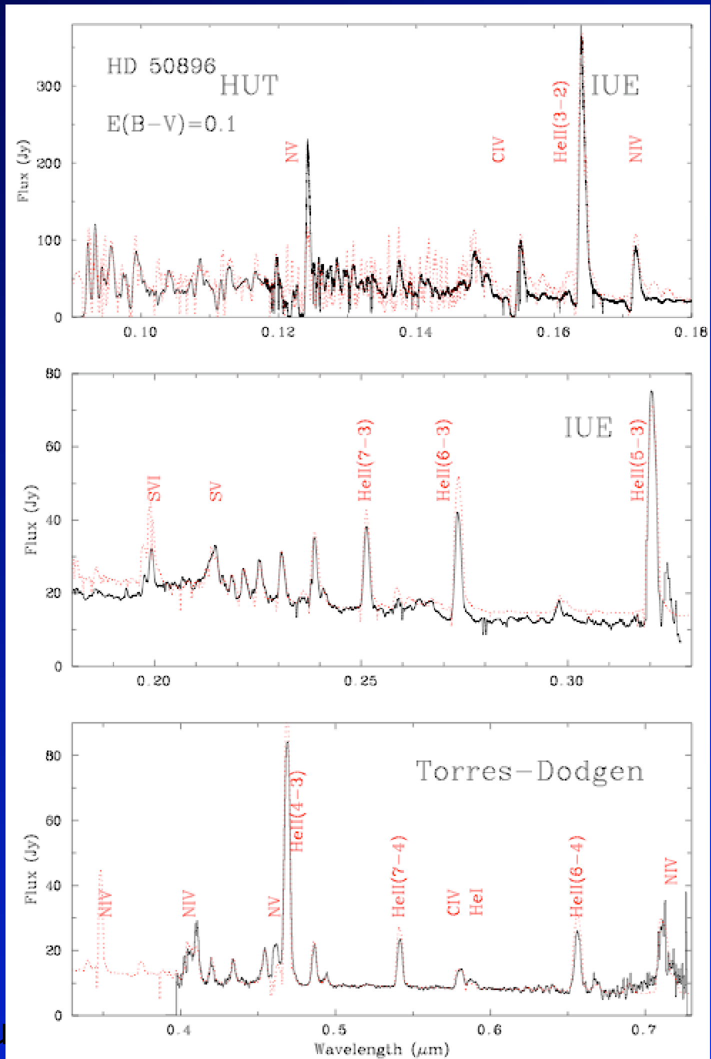
Optical, near-IR & mid-IR permitted (recombination) lines formed at high densities within accelerating part of outflows:

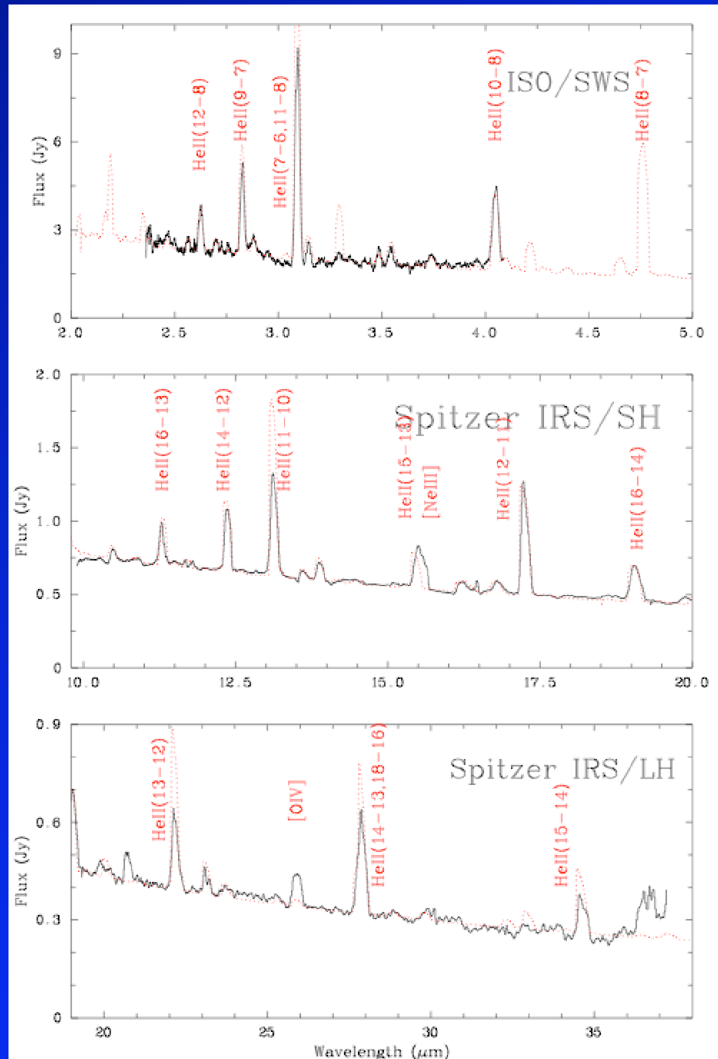
log (N_e/cm^3) ~ 11-12



Inner Wolf-Rayet winds

HD 50896 (WN4b): Morris, Crowther & Houck (2004)





Clumping I

Plenty of evidence points to *clumped* WR winds:

- Electron scattering wings (Hillier 1991);
- Linear polarization (St Louis+ 1993; Kurosawa+ 2002)
- Blobs (Moffat+ 1988; Lepine+ 2000)

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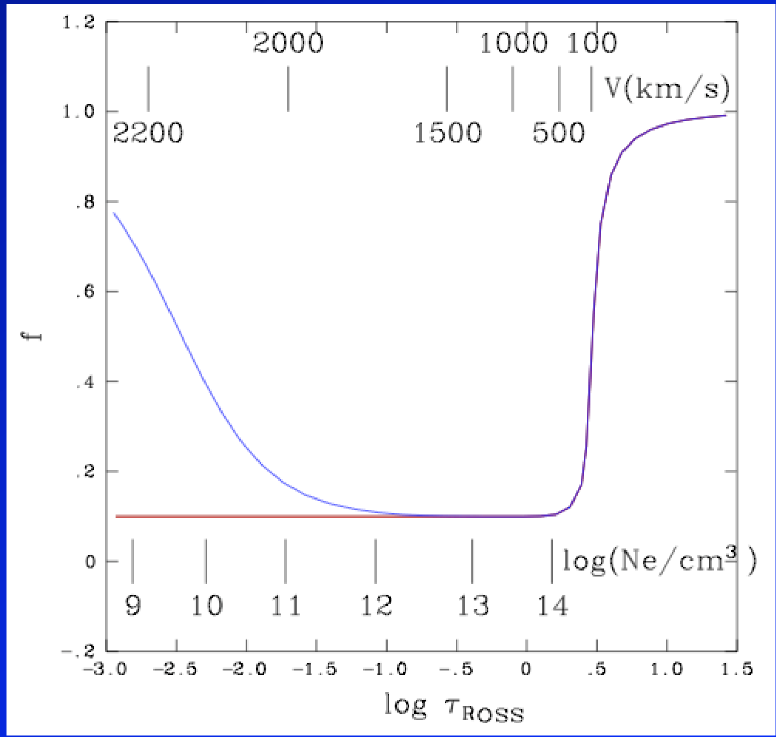
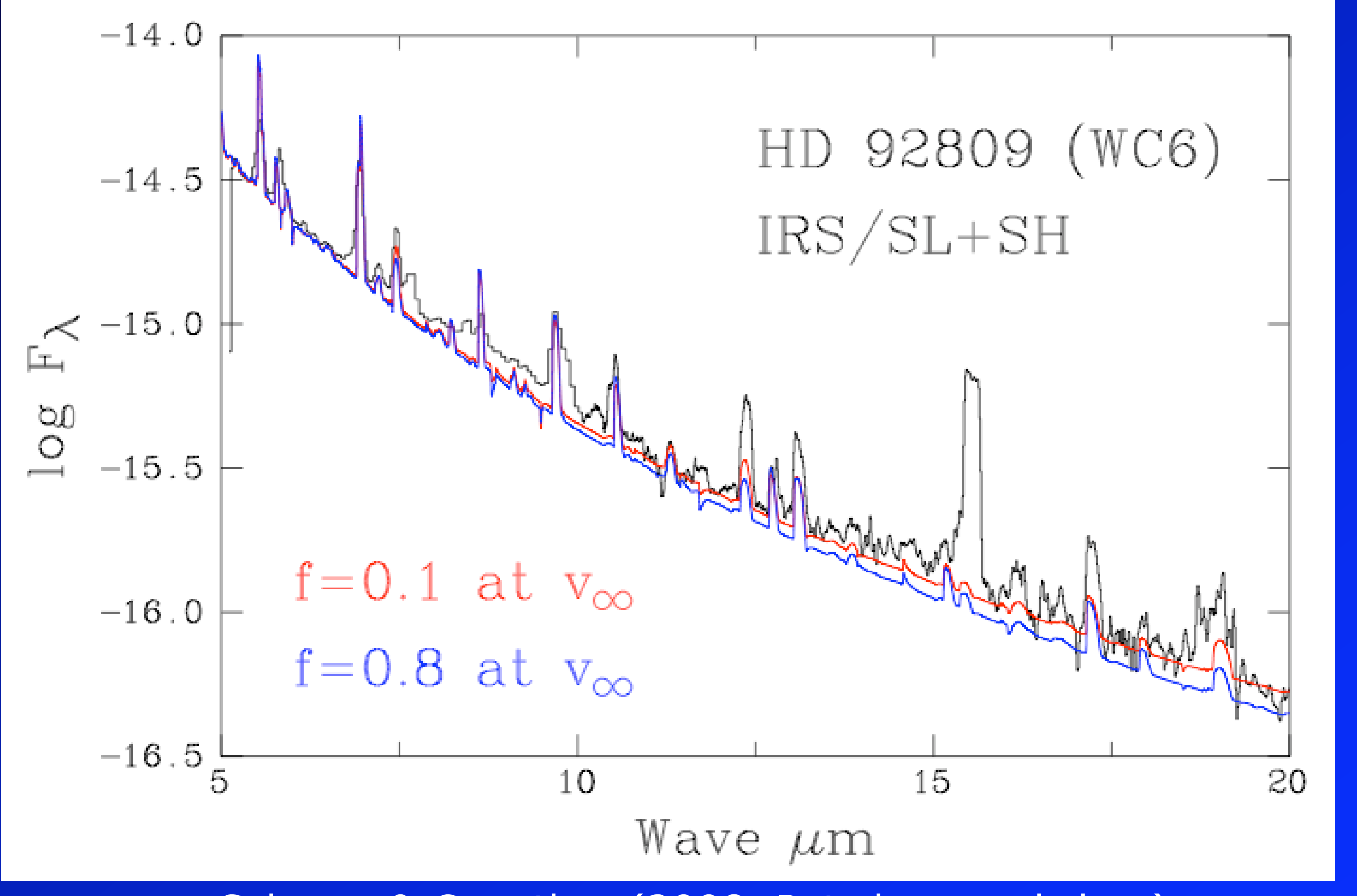
For optically thin clumps, a volume filling factor $f \sim 0.1$ reduces dM/dt by $f^{0.5}$ albeit subject to complications due to porosity (optical depth effects: Oskinova+ 2007) & the radial clumping dependence (Runacres & Owocki 2002)



Schnurr & Crowther (2008, Potsdam workshop)

Clumping II



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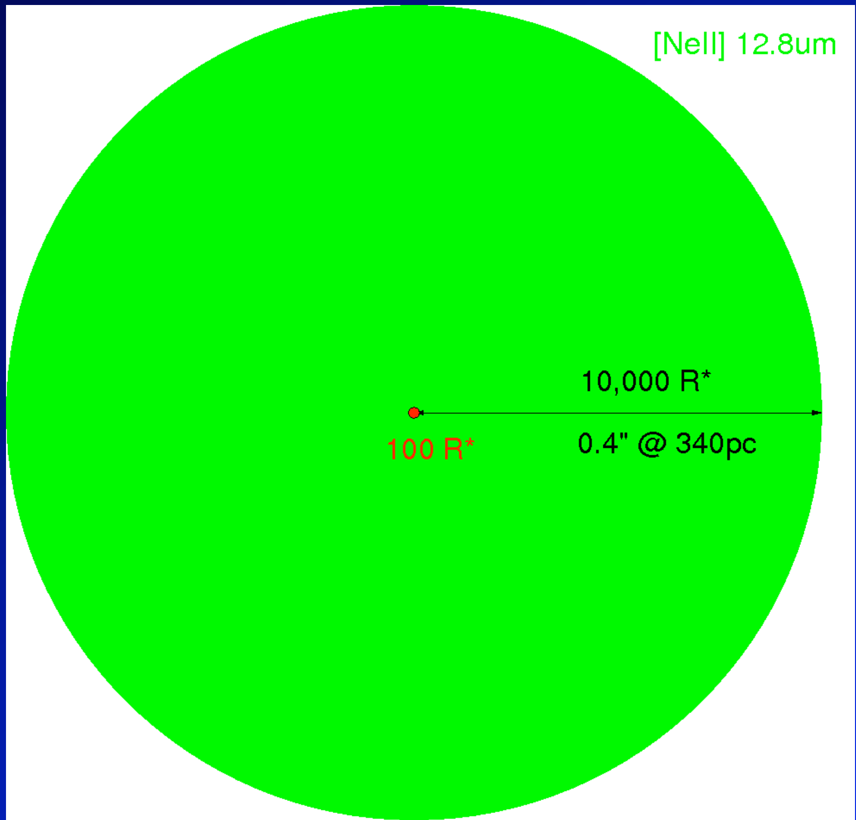
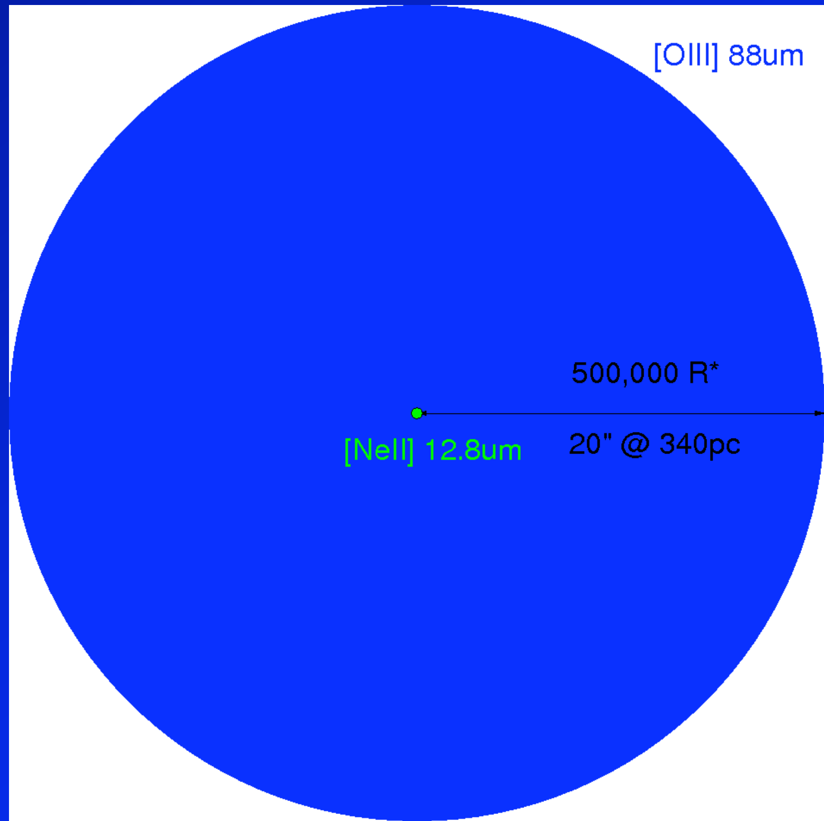
Outer Wolf-Rayet winds

Forbidden fine-structure lines are formed in the extreme outer wind, close to their critical densities N_C



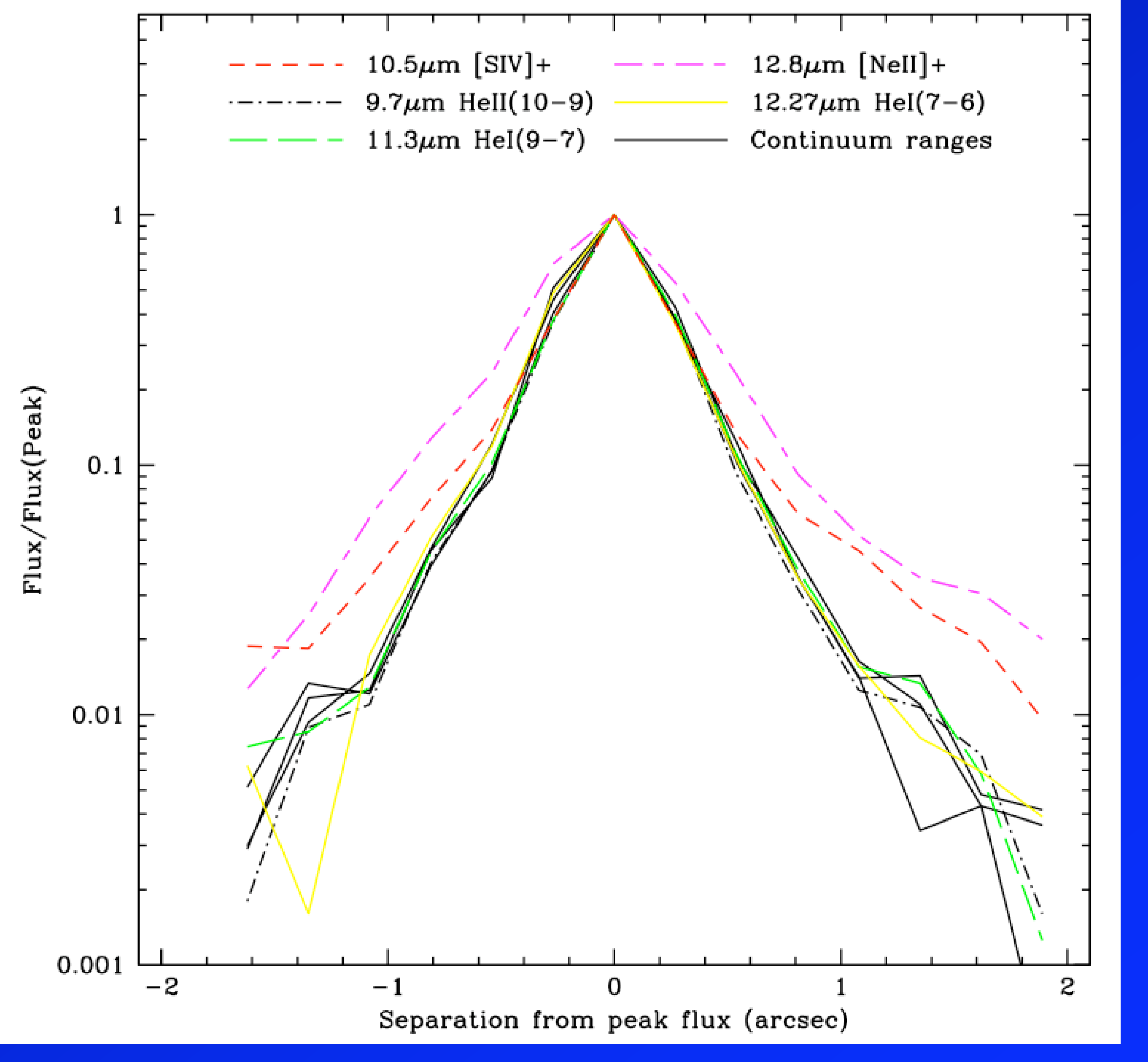
N_C[NeII]/cm^3~5x10^5



N_C[OIII]/cm^3~500

γ Vel: Gemini T-ReCS

High resolution (FWHM 0".45) long slit mid-IR spectroscopy of γ Vel, confirms spatial extension# of [NeII] & [SIV] lines.



If $R_* = 3R_\odot$ then R_c[NeII]~7×10^{-3} pc, (0.4" @ d=340 pc)

Roche, Colling & Barlow (2012)

Ionic abundances

Barlow et al. (1988) provided a method of deriving ionic abundances, γ_I, from mid-IR fine structure lines in WR winds via

$$\gamma_I \propto I\, d^2\, v_\infty^{1.5} (dM/dt)^{-1.5}$$

I=line intensity; d=distance; v_∞=terminal velocity; dM/dt=mass-loss rate

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Most f.s. lines require spectroscopy from orbit

- ISO/SWS: [NeII-III] 12.8μm, 15.5μm (e.g. Dessart, Crowther+ 2000)
- Spitzer/IRS: [NeII-III] 12.8μm, 15.5μm; [SIII-IV] 18.7μm, 10.5μm, [OIV] 25.9μm (e.g. Morris+ 2004; Crowther+ 2006)
- Herschel/PACS: [OIII] 88μm (Crowther+ in prep);

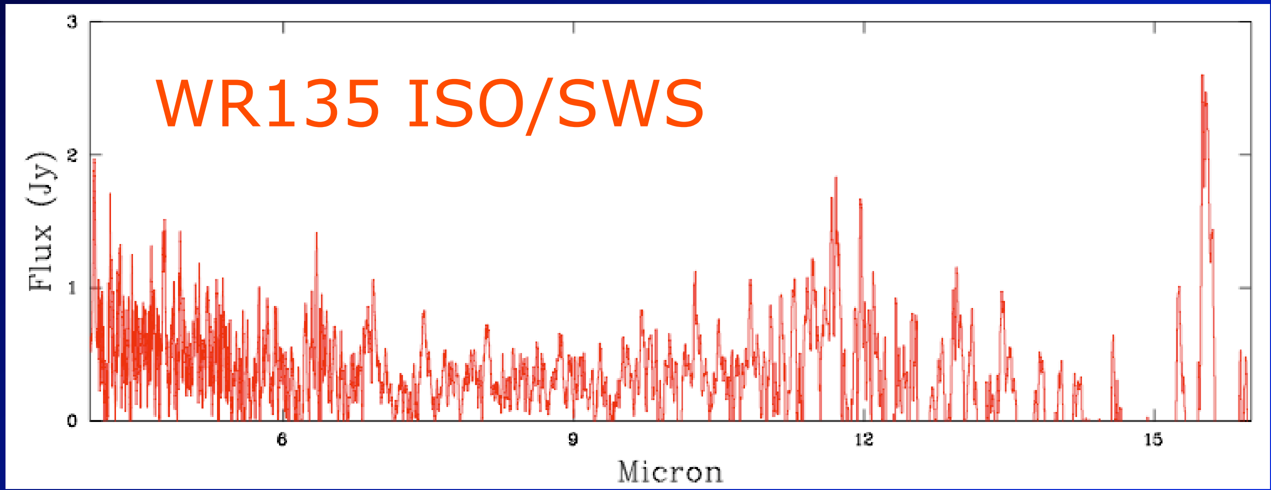
Neon problem?

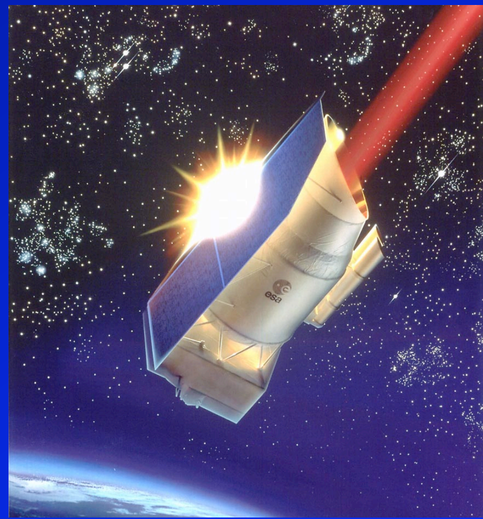
- ^{20}Ne comprises 0.1% of atmosphere and remains constant until late evolutionary stages.
- ^{14}N (produced via CNO cycle) transformed into ^{22}Ne at beginning of He-burning:

$$^{14}N(\alpha,\gamma)^{18}F(e^-,\nu_e)^{18}O(\alpha,\gamma)^{22}Ne$$

- From established reaction rates we expect >2% of ^{22}Ne in WC stars (for $Z=Z_\odot=2\%$ by mass).
- Aitken et al. (1982), van der Hucht & Olnon (1985) & Barlow et al. (1988) quantified Ne in γ Vel (WC8+O) using mid-IR observations of [NeII] & [NeIII].
- Surprisingly Ne didn’t appear to be enhanced..

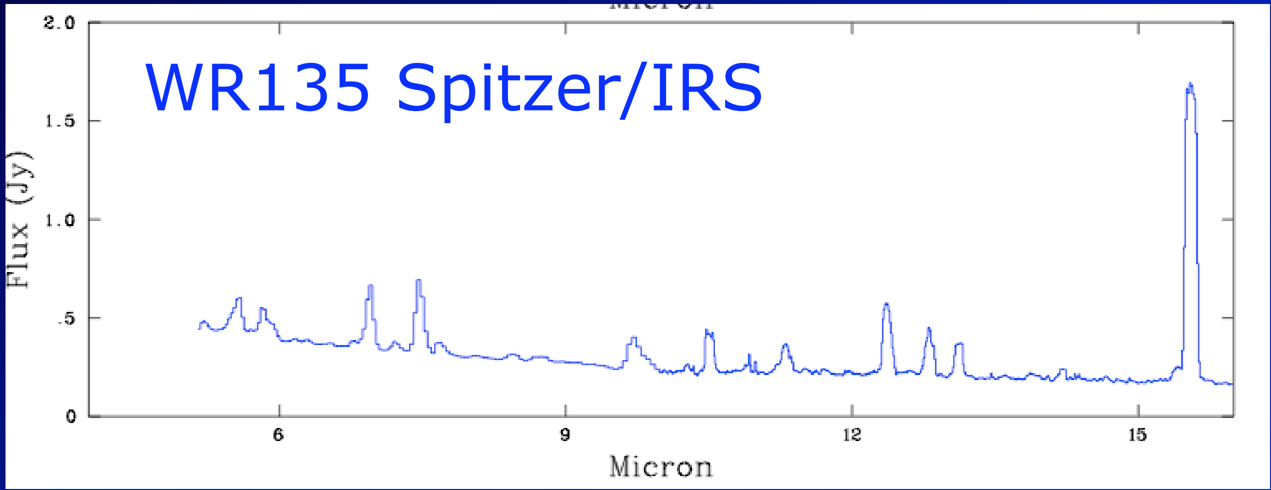
Neon in WC stars: ISO





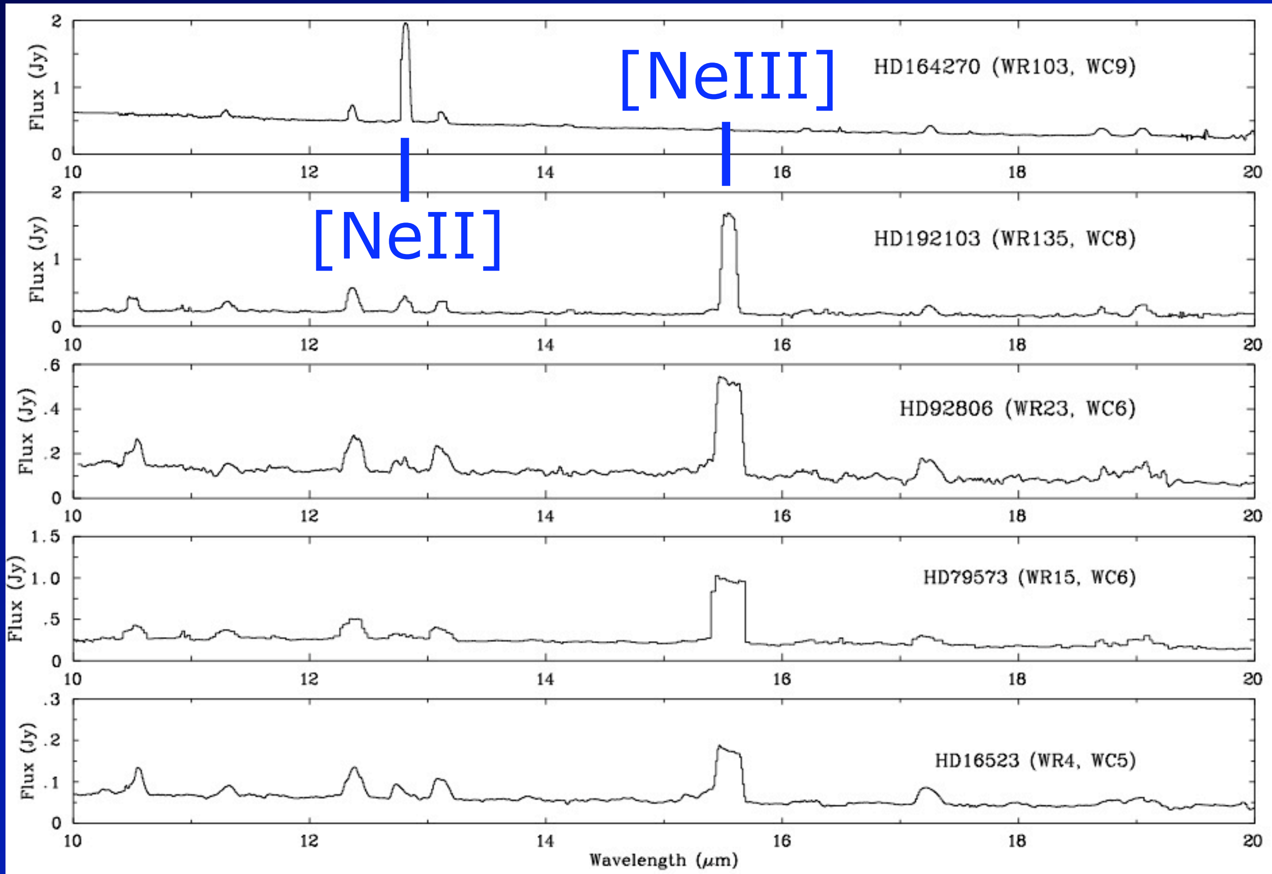
GTO (PI. van der Hucht) & GI (PI. Willis) SWS spectroscopy of 1 WN (Morris+ 2001) 4 WC stars (Dessart+ 2000), revealing X(Ne)~1% once dM/dt corrected for wind clumping.

Neon in WC stars: Spitzer



GTO (PI. Houck) & GI (PI. Crowther) IRS spectroscopy of 1 WN (Morris+ 2004), 2 WN/C, 6 WC (Crowther+ 2006) & 2 WO stars..

IRS spectroscopy



V_∞ from fine-structure lines, dM/dt, X(C), X(O), ionization, from atmospheric models. Distances from cluster membership (or sp type-calibration)

Spitzer/IRS WC results

Star	Subtype	Ion	v_∞	X(C)	X(O)	X(Ne)
WR4	WC5	Ne^{2+}	2250	53%	8%	0.5%
WR15	WC6	Ne^{2+}	2800	40%	8%	1.1%
WR23	WC6	Ne^{2+}	2200	49%	8%	1.1%
WR135	WC8	Ne^{2+}	1300	25%	8%	1.0%
WR103	WC9	Ne^{+}	900	36%	2%	0.6%
Z=2% ($Z_\odot$=1.3%)	Meynet Maeder			40%	10%	2.3% (1.4%)

WO stars

Rare subtype showing OVI emission lines (Barlow & Hummer 1982) thought to be final, brief WR stage (Kingsburgh et al. 1995). Two included in IRS program: WR102 (Sand 4), WR93b (Drew+ 2004)

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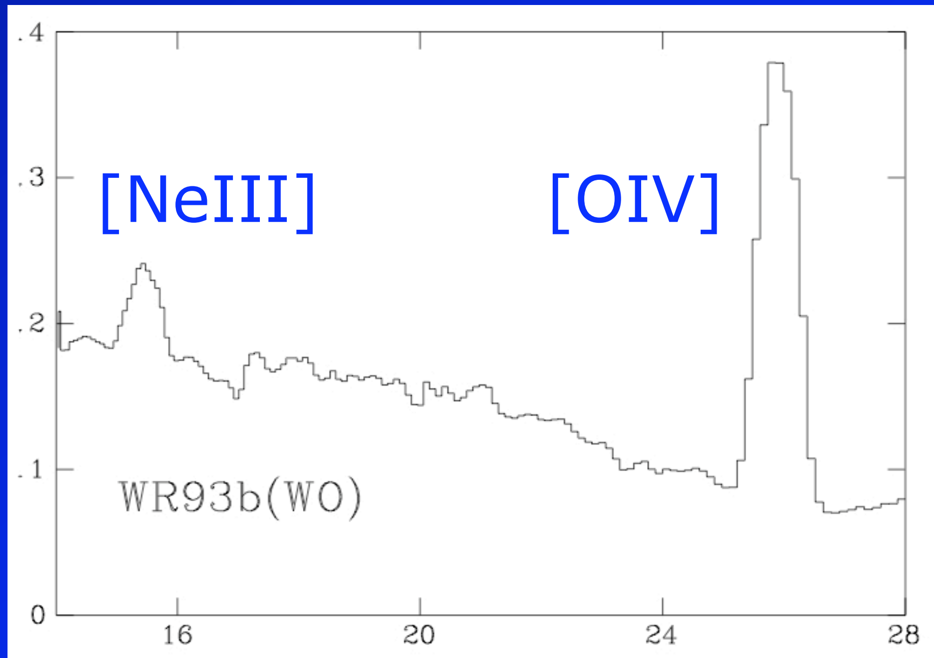
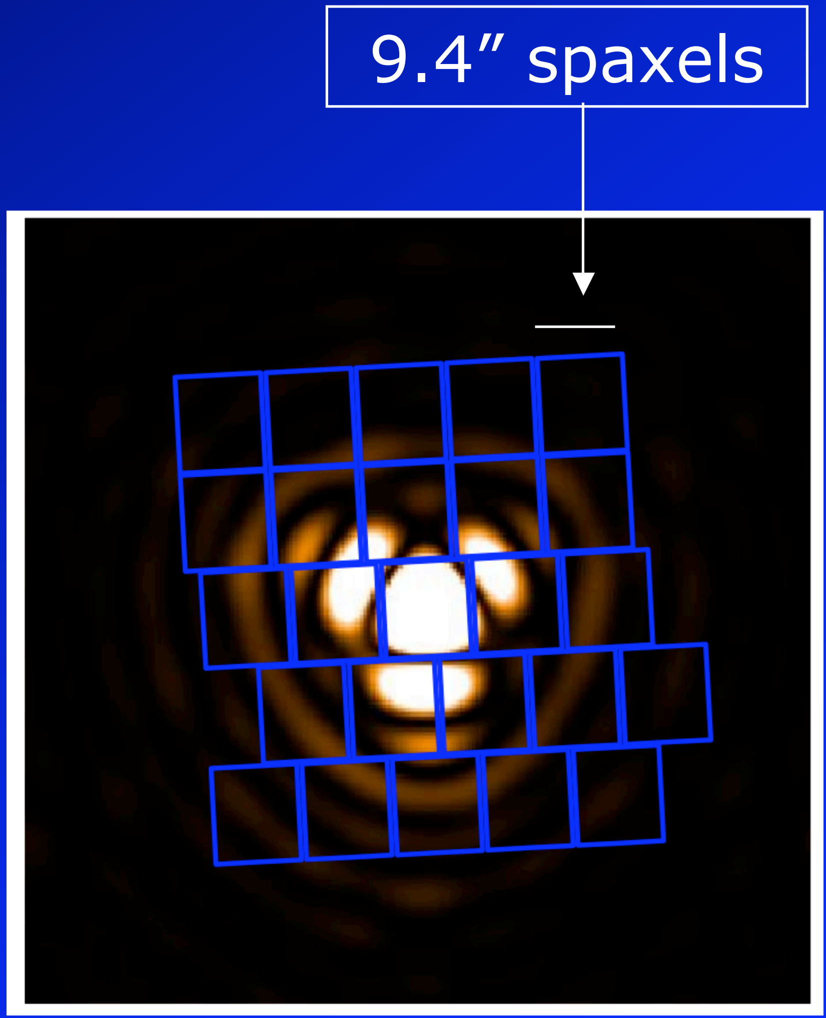


- Do they show evidence for highly processed reactions, i.e $^{16}O(\alpha,\gamma)^{20}Ne$?
- Analysis of WR93b indicates this is not so: X(Ne)~2%, X(O)~7%, the latter a factor of two lower than recombination line studies.

Herschel/PACS

Optical/near-IR carbon diagnostics in WC stars are plentiful, whereas oxygen abundances are more challenging:

- A Herschel/PACS programme to observe a sample of WC stars at 88.3μm ([OIII], 2nd order) & 177μm (continuum, 1st order) for (OT2, PI. Crowther) is underway;
- .Our first observations, of γ Vel (WC8+O) were obtained in July 2012…



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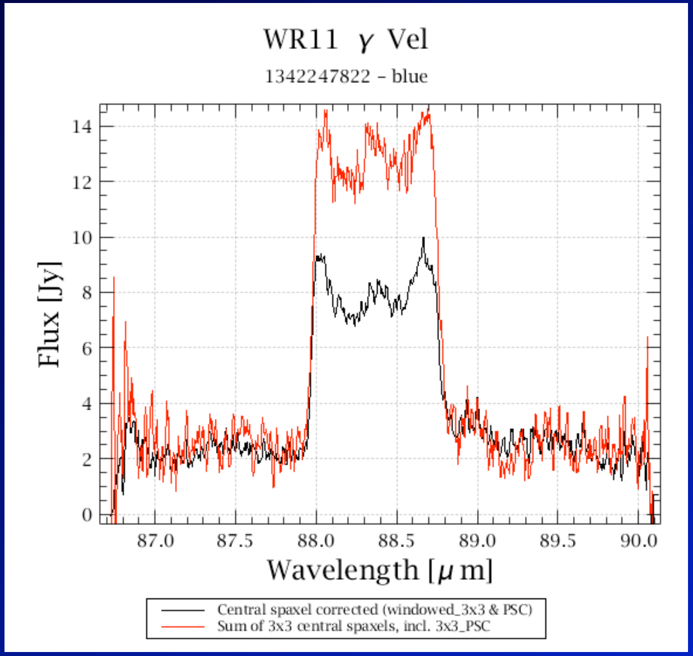

PACS spectroscopy of γ Vel indicates [OIII] 88.3μm is spatially extended# (recall low critical density of ~500 cm^{-3}).

#If $R_*=3R_\odot$ then R_c[OIII]~0.03pc (~20″ @ d=340 pc)

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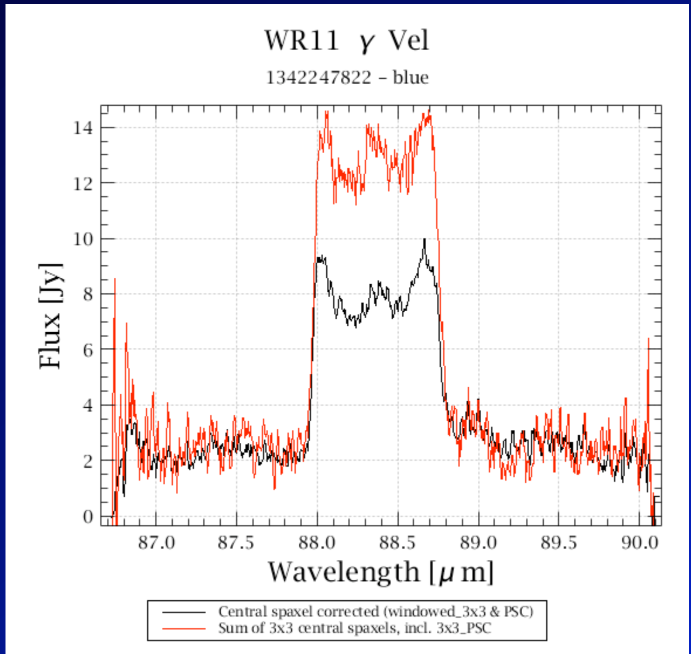

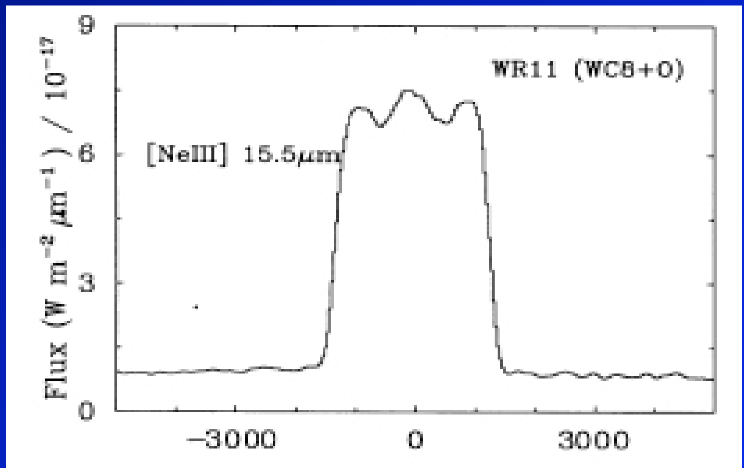

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Structure within line resembles [NeIII] in ISO/SWS spectroscopy.

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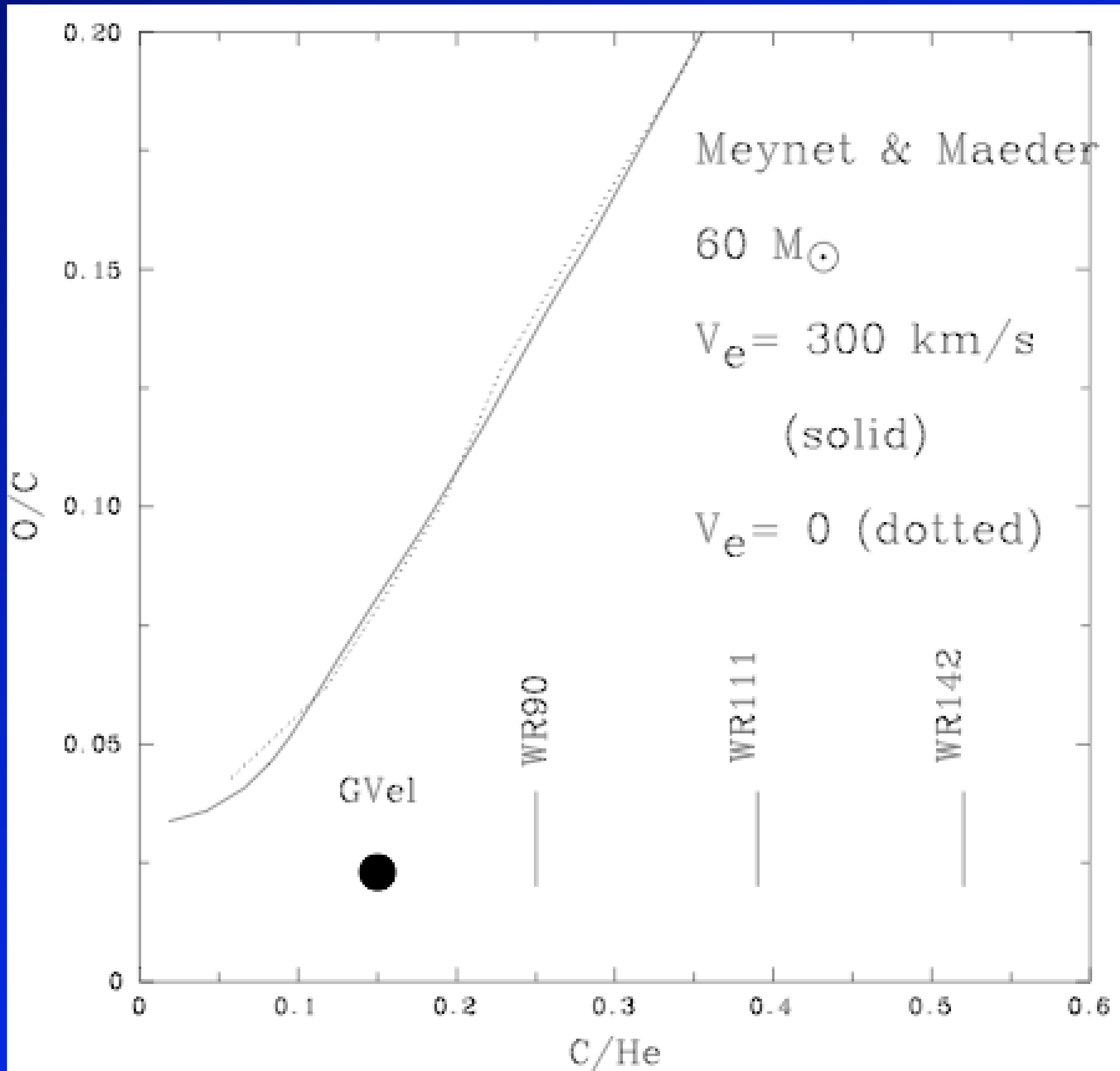
Oxygen in WC stars

O^{2+} is predicted to dominate the oxygen ionization balance in the extreme outer wind of γ Vel, so we find a low value of O~1% (by mass) i.e. O/C ~ 0.02 (by number, for C/He~0.15, De Marco+ 2000)



Summary

- Permitted optical/near-IR/mid-IR wind lines produced in dense, inner WR wind (n_e~10^{11} cm^{-3}). Radial dependence of wind clumping from near to mid-infrared SED.
- Forbidden mid-IR/far-IR wind produced in outer (n_C~10^5 cm^{-3} for [NeII] 12.8μm) or extreme outer (n_C~10^2 cm^{-3} for [OIII] 88μm), confirmed by Gemini/T-ReCS & Herschel/PACS

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- WC stars studied with Spitzer/IRS indicate X(Ne)~1% (Neon is close to expectations once clumped winds accounted for) while no evidence is found for ^{20}Ne in WO star.
- Herschel/PACS study in progress. So far: low oxygen abundance for γ Vel using [OIII] 88.3μm

Herschel/PACS @ 180μm