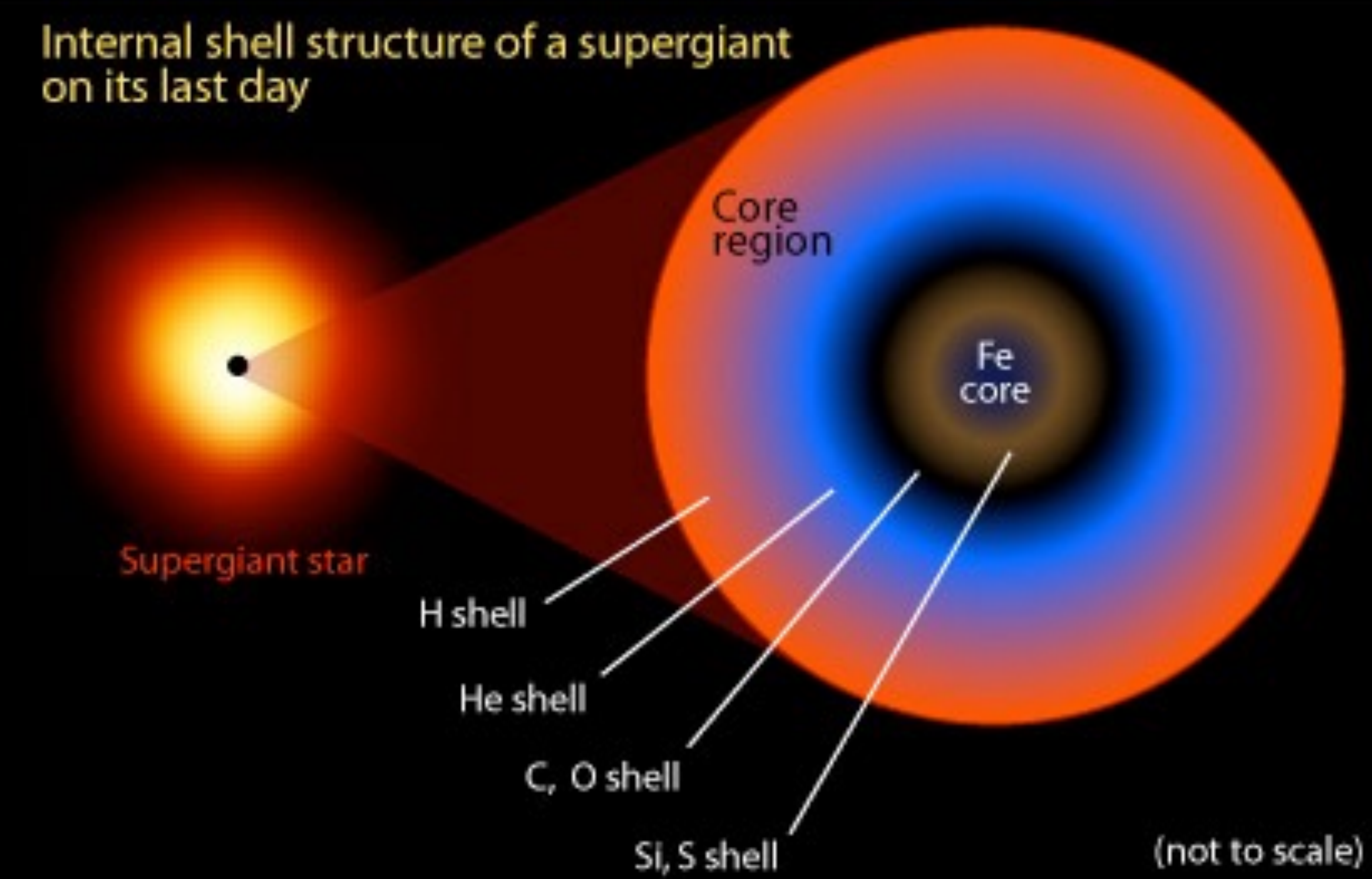
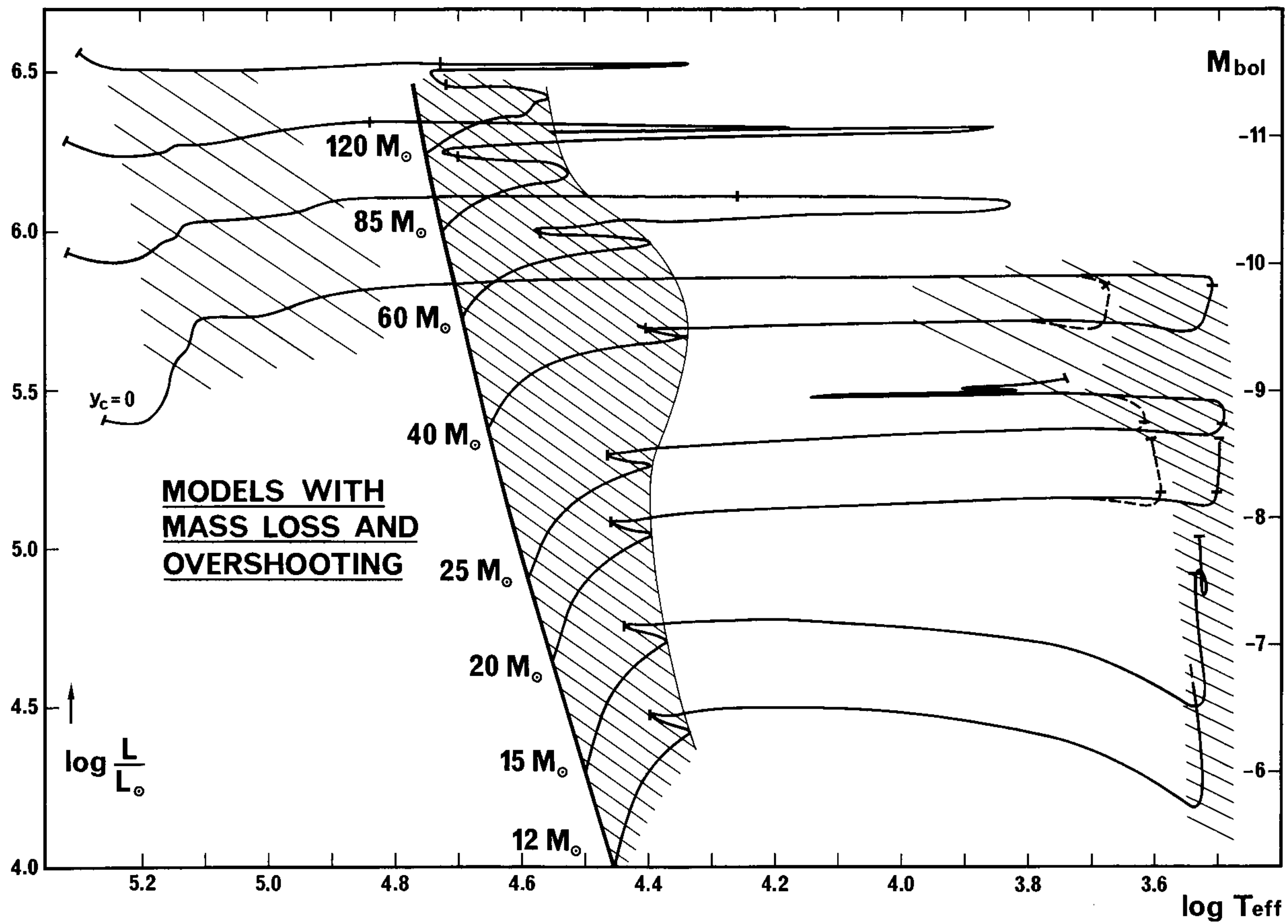
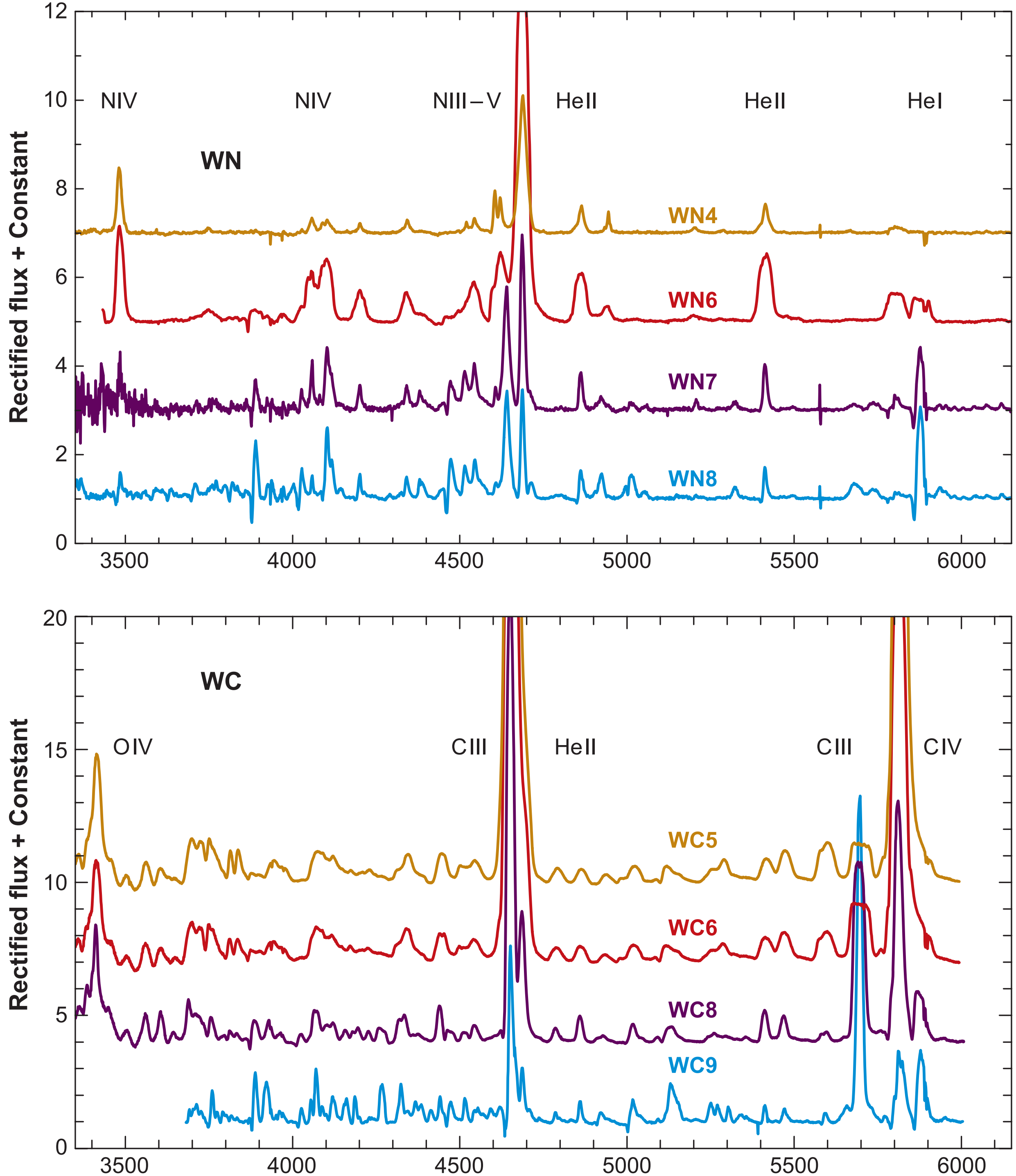
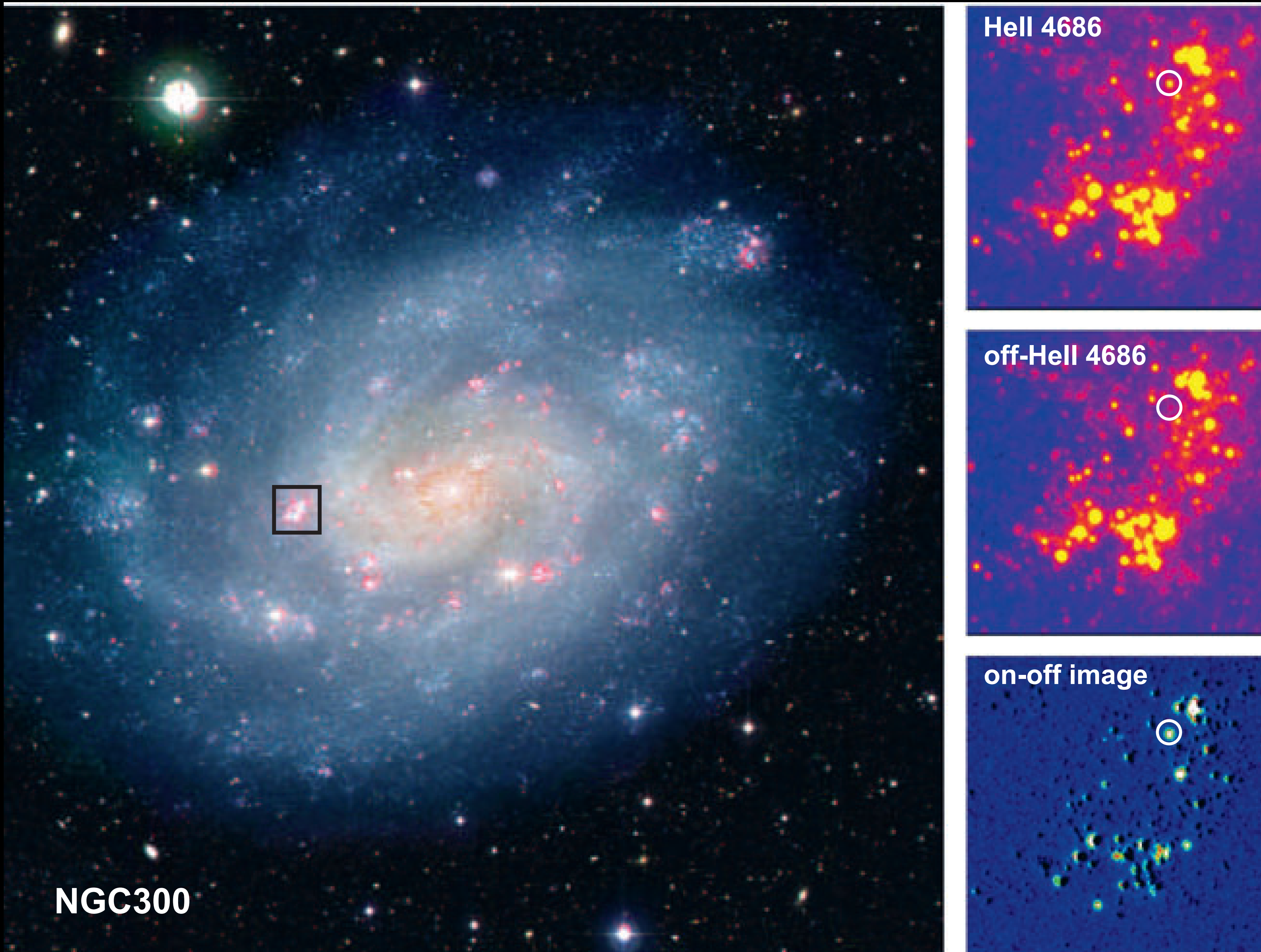
Structure and Evolution of Stars
Lecture 15

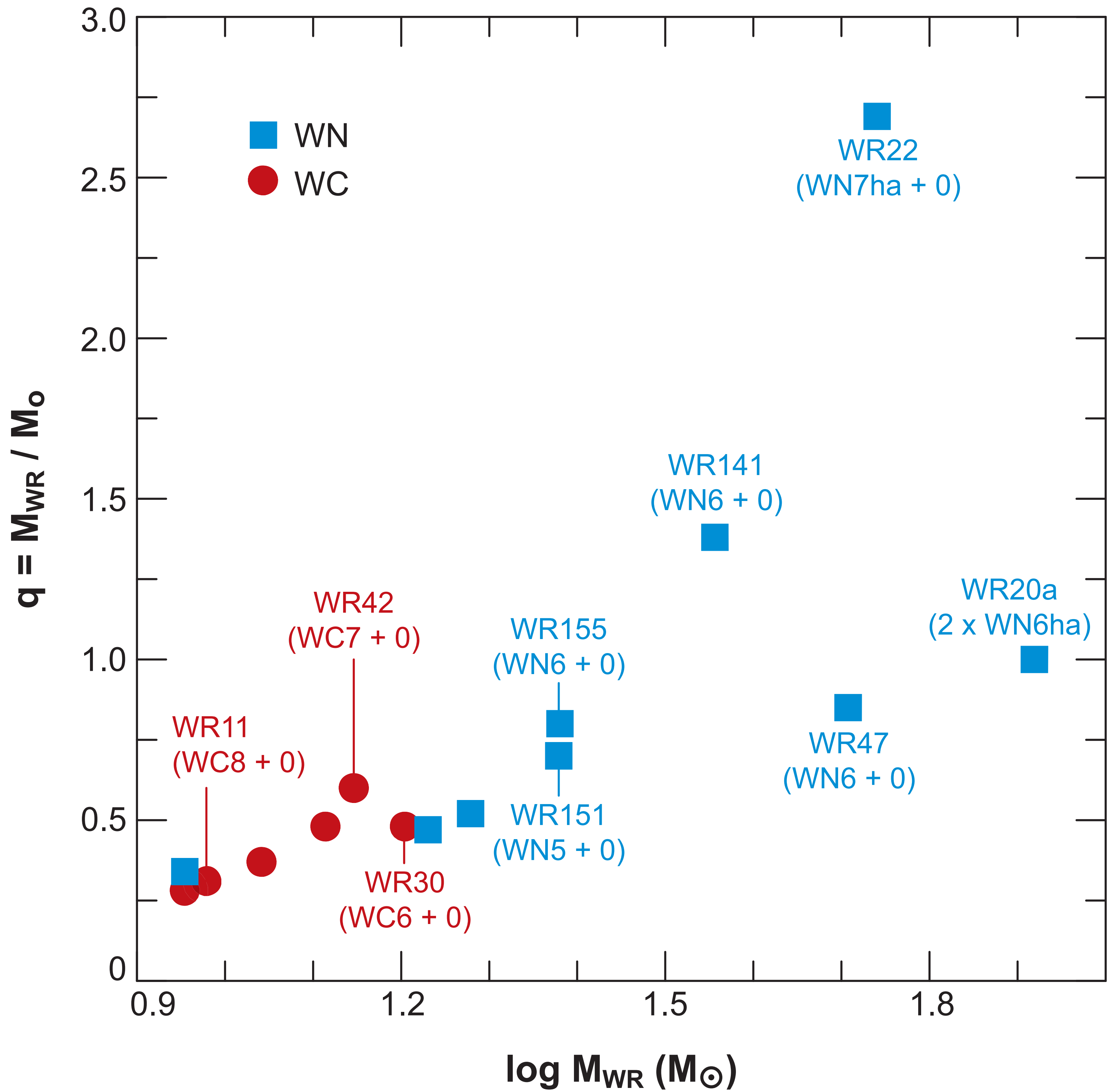

Internal shell structure of a supergiant
on its last day
Core
region
Fe
core
Supergiant star
H shell
He shell
C, O shell
Si, S shell
(not to scale)



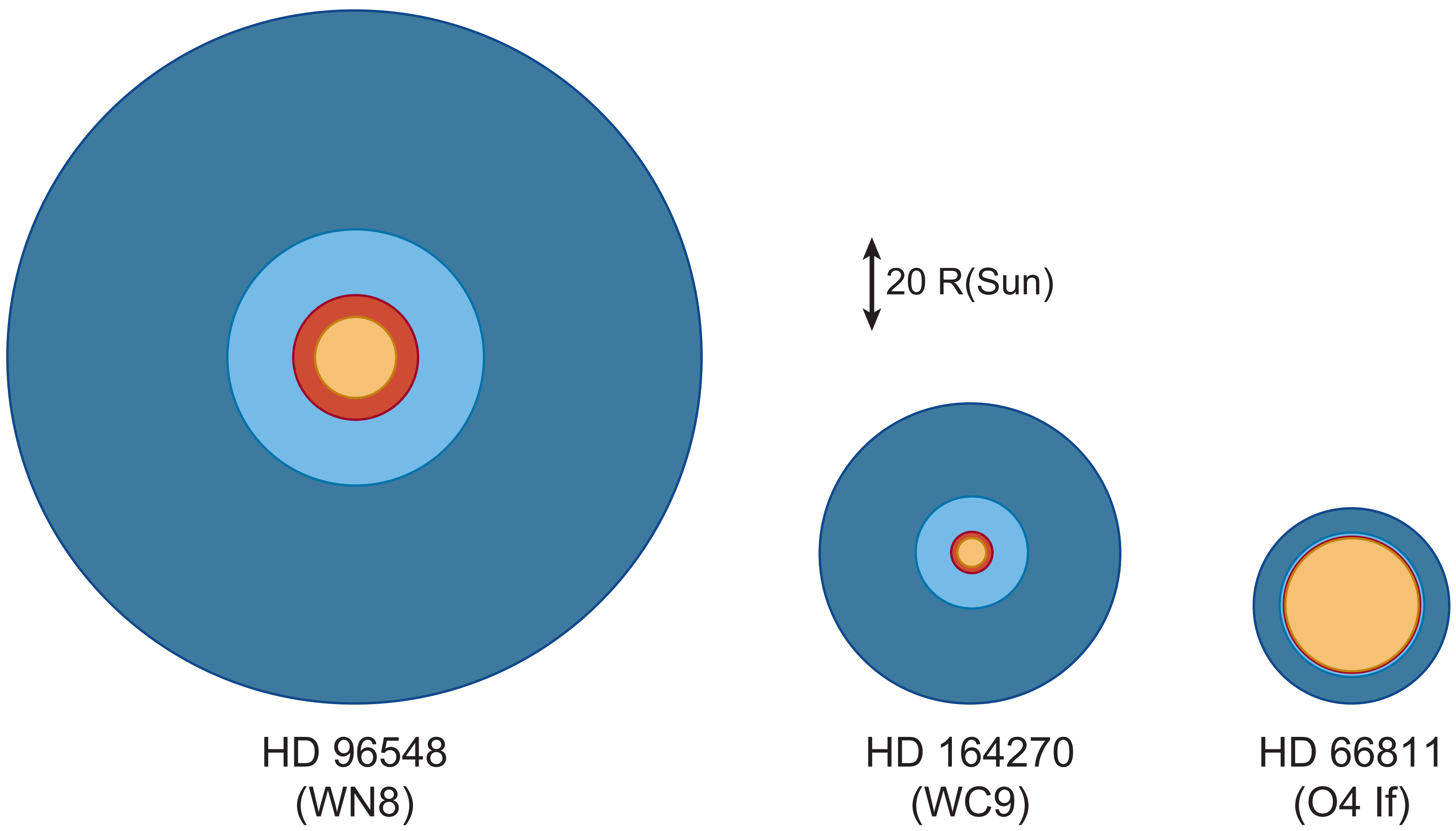
MODELS WITH
MASS LOSS AND
OVERSHOOTING
120 M⊙
85 M⊙
60 M⊙
40 M⊙
25 M⊙
20 M⊙
15 M⊙
12 M⊙
$y_c = 0$
$\log \frac{L}{L_\odot}$
M_{bol}
$\log T_{eff}$
6.5
6.0
5.5
5.0
4.5
4.0
5.2
5.0
4.8
4.6
4.4
4.2
4.0
3.8
3.6
-11
-10
-9
-8
-7
-6


Rectified flux + Constant
WN
NIV
NIV
NIII–V
HeII
HeII
HeI
WN4
WN6
WN7
WN8
0
2
4
6
8
10
12
3500
4000
4500
5000
5500
6000
WC
OIV
CIII
HeII
CIII
CIV
WC5
WC6
WC8
WC9
0
5
10
15
20


NGC300
HeII 4686
off-HeII 4686
on-off image



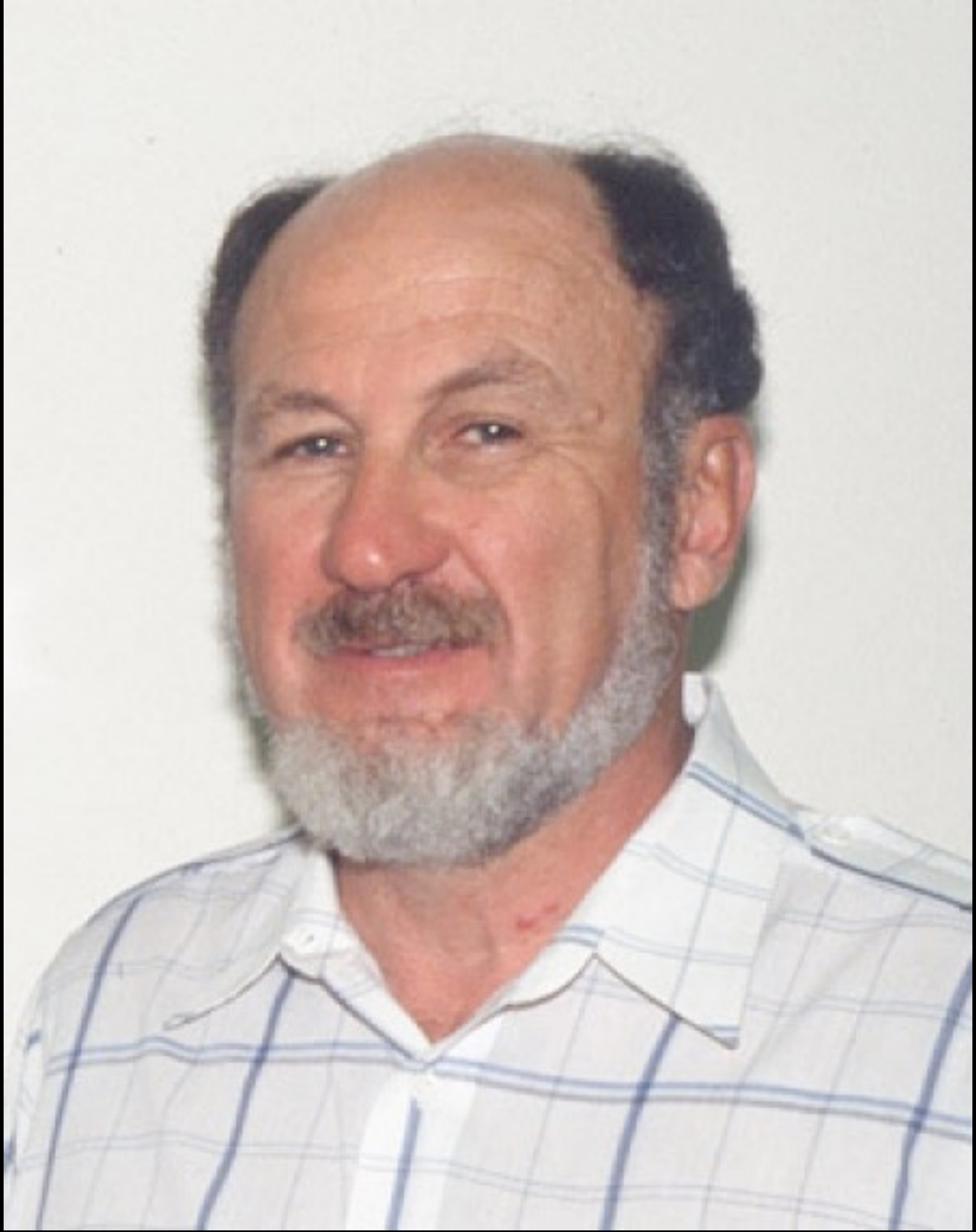
WN
WC
WR22
(WN7ha + 0)
WR141
(WN6 + 0)
WR20a
(2 x WN6ha)
WR42
(WC7 + 0)
WR155
(WN6 + 0)
WR11
(WC8 + 0)
WR47
(WN6 + 0)
WR151
(WN5 + 0)
WR30
(WC6 + 0)
3.0
2.5
2.0
1.5
1.0
0.5
0
0.9
1.2
1.5
1.8
$q = M_{WR} / M_O$
log M_{WR} ($M_\odot$)


20 R(Sun)
HD 96548
(WN8)
HD 164270
(WC9)
HD 66811
(O4 If)

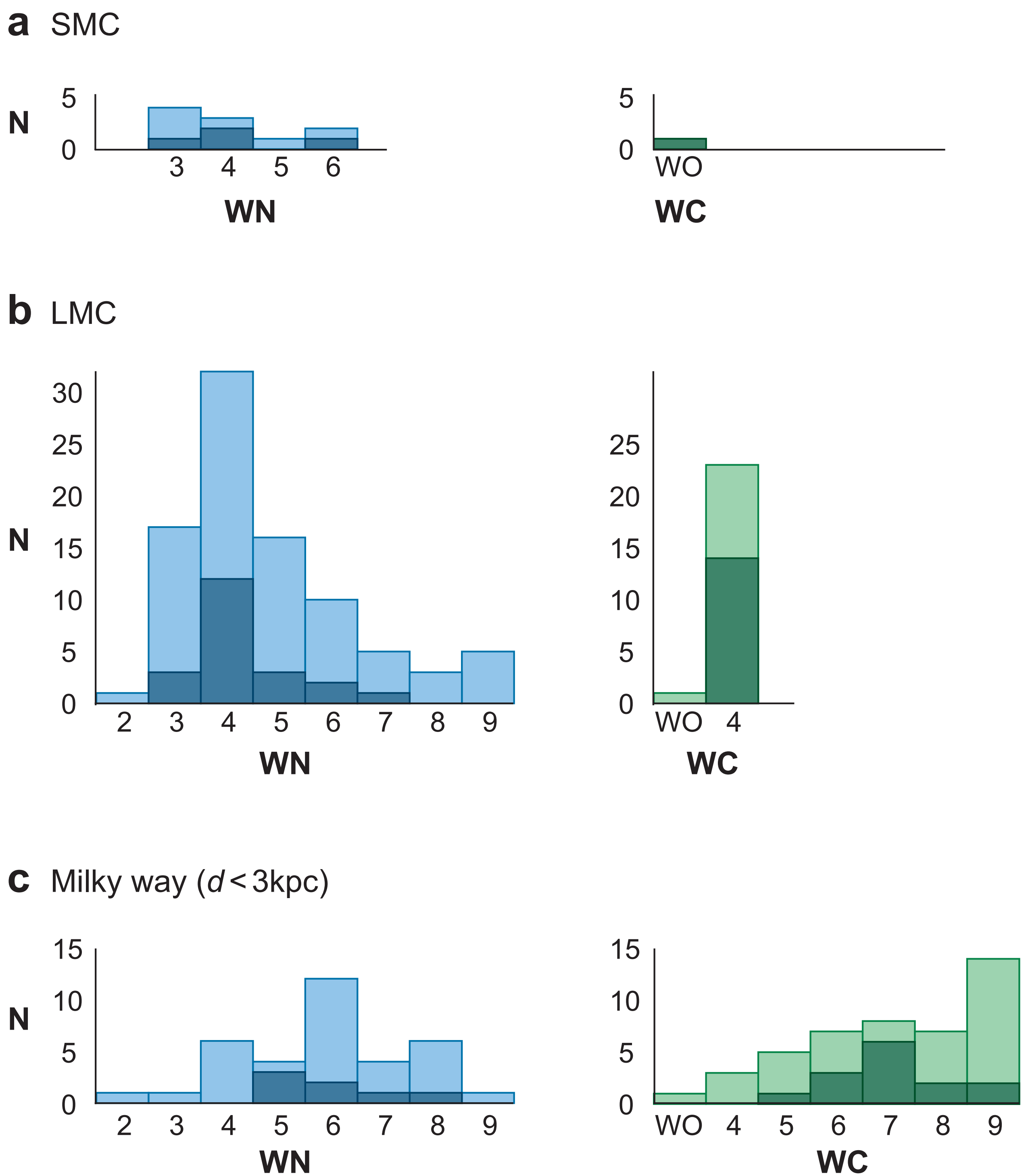

© Selby Hanson


2009 Daniel Lopez IAC (Isaac Newton Telescope, ING)


Telescope Live / Nik Szymanek



$M \lesssim 15\,M_\odot$	MS (OB) $\rightarrow$ RSG ($\rightarrow$ BSG in blue loop? $\rightarrow$ RSG) $\rightarrow$ SN II mass loss is relatively unimportant, $\lesssim$ few $M_\odot$ is lost during entire evolution
$15\,M_\odot \lesssim M \lesssim 25\,M_\odot$	MS (O) $\rightarrow$ BSG $\rightarrow$ RSG $\rightarrow$ SN II mass loss is strong during the RSG phase, but not strong enough to remove the whole H-rich envelope
$25\,M_\odot \lesssim M \lesssim 40\,M_\odot$	MS (O) $\rightarrow$ BSG $\rightarrow$ RSG $\rightarrow$ WNL $\rightarrow$ WNE $\rightarrow$ WC $\rightarrow$ SN Ib the H-rich envelope is removed during the RSG stage, turning the star into a WR star
$M \gtrsim 40\,M_\odot$	MS (O) $\rightarrow$ BSG $\rightarrow$ LBV $\rightarrow$ WNL $\rightarrow$ WNE $\rightarrow$ WC $\rightarrow$ SN Ib/c an LBV phase blows off the envelope before the RSG can be reached



a SMC
N
5
0
3
4
5
6
WN
5
0
WO
WC
b LMC
N
30
25
20
15
10
5
0
2
3
4
5
6
7
8
9
WN
25
20
15
10
5
0
WO
4
WC
c Milky way (d < 3kpc)
N
15
10
5
0
2
3
4
5
6
7
8
9
WN
15
10
5
0
WO
4
5
6
7
8
9
WC

Table 3. WC/WN ratio vs. metallicity for the Local Group Galaxies.

Region	log(O/H) + 12	# WCs and WOs	# WNs	WC/WN
SMC	8.13	1	11	0.09 ± 0.09
M33 outer	8.29	12	54	0.22 ± 0.06
LMC	8.37	28	124	0.23 ± 0.01
M33 middle	8.41	15	54	0.28 ± 0.07
Milky Way	8.70	46	53	0.83 ± 0.10
M33 inner	8.72	26	45	0.58 ± 0.09
M31	8.93	62	92	0.67 ± 0.11

Neugent & Massey 2019

Table 15.1. Properties of nuclear burning stages in a 15 $M_\odot$ star (from Woosley et al. 2002).

burning stage	T (10^9 K)	ρ (g/cm^3)	fuel	main products	timescale
hydrogen	0.035	5.8	H	He	1.1×10^7 yr
helium	0.18	1.4×10^3	He	C, O	2.0×10^6 yr
carbon	0.83	2.4×10^5	C	O, Ne	2.0×10^3 yr
neon	1.6	7.2×10^6	Ne	O, Mg	0.7 yr
oxygen	1.9	6.7×10^6	O, Mg	Si, S	2.6 yr
silicon	3.3	4.3×10^7	Si, S	Fe, Ni	18 d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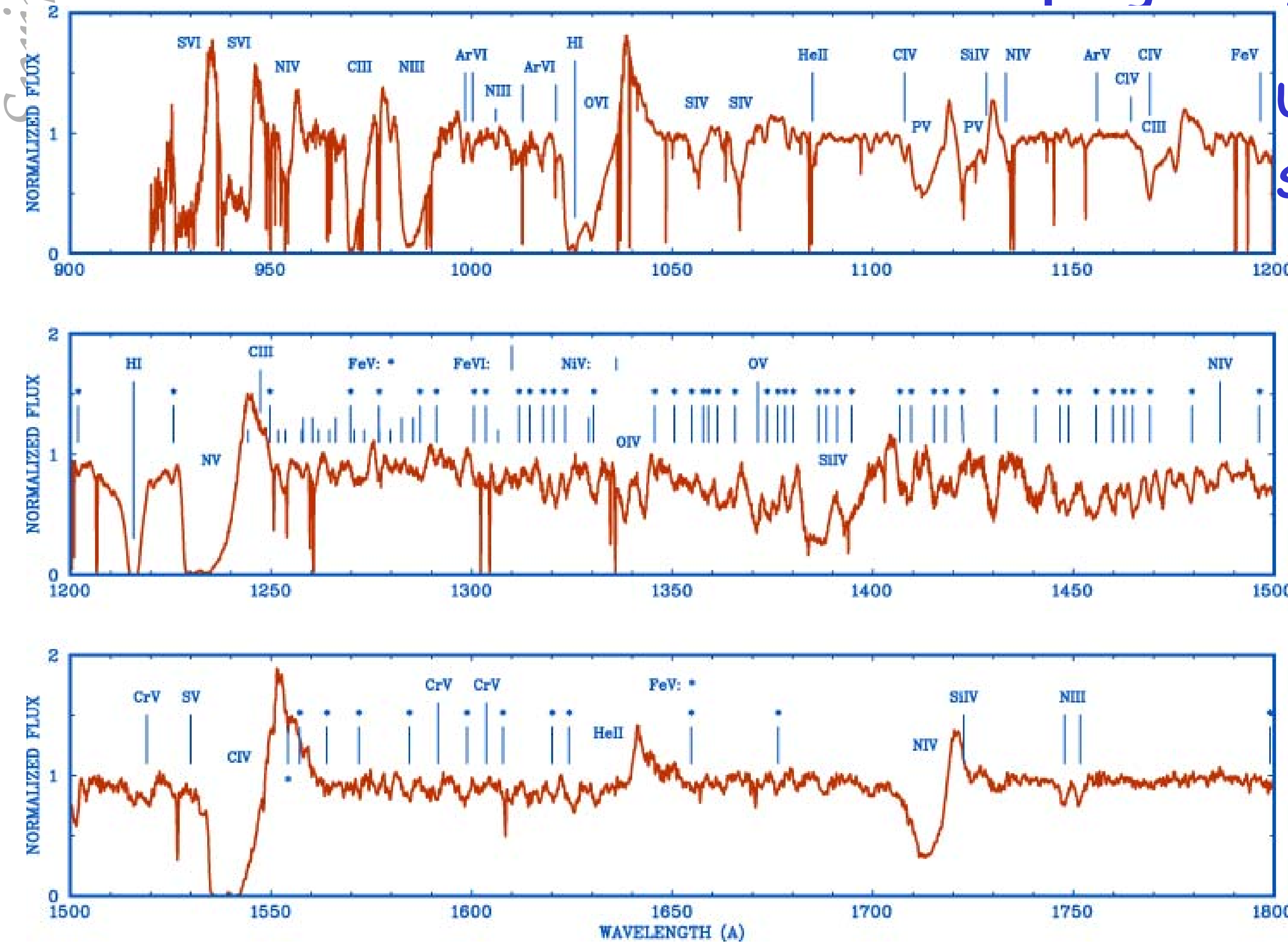
Example of spectral analysis: hot stars

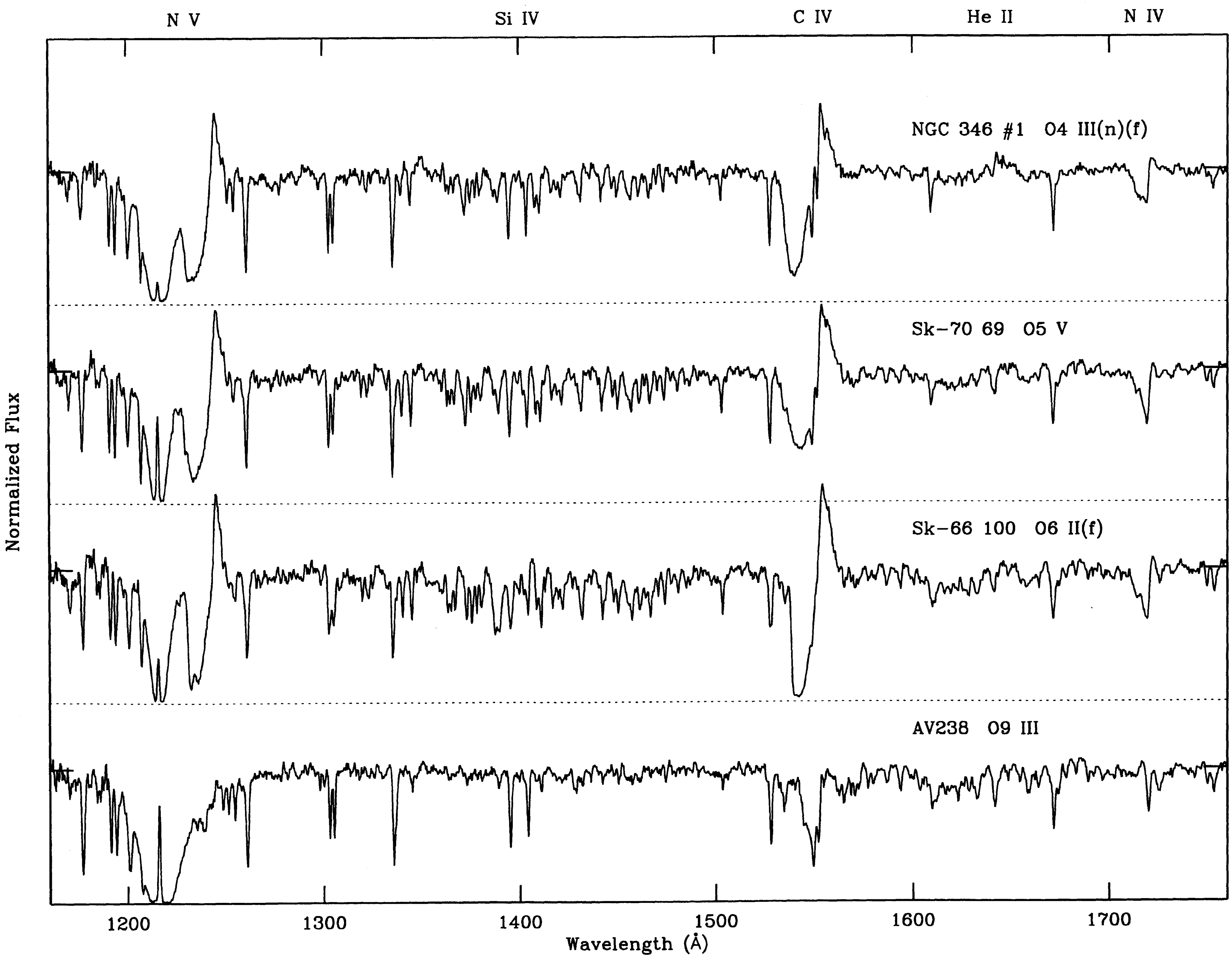
O4 supergiant ζ Puppis

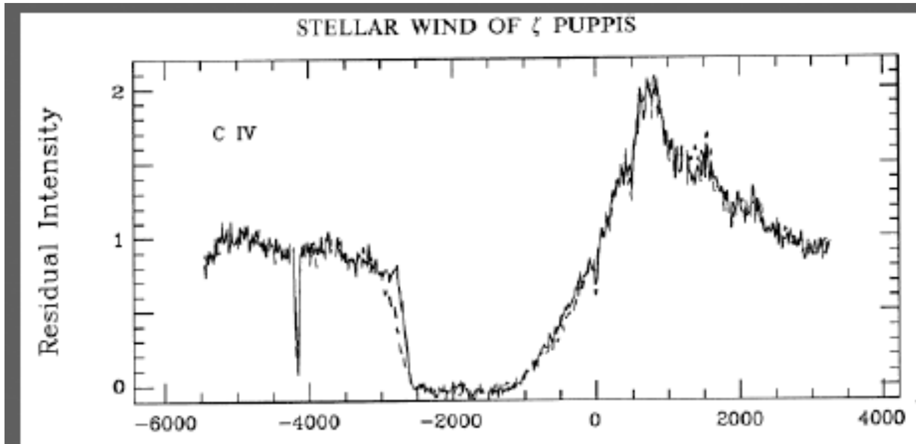


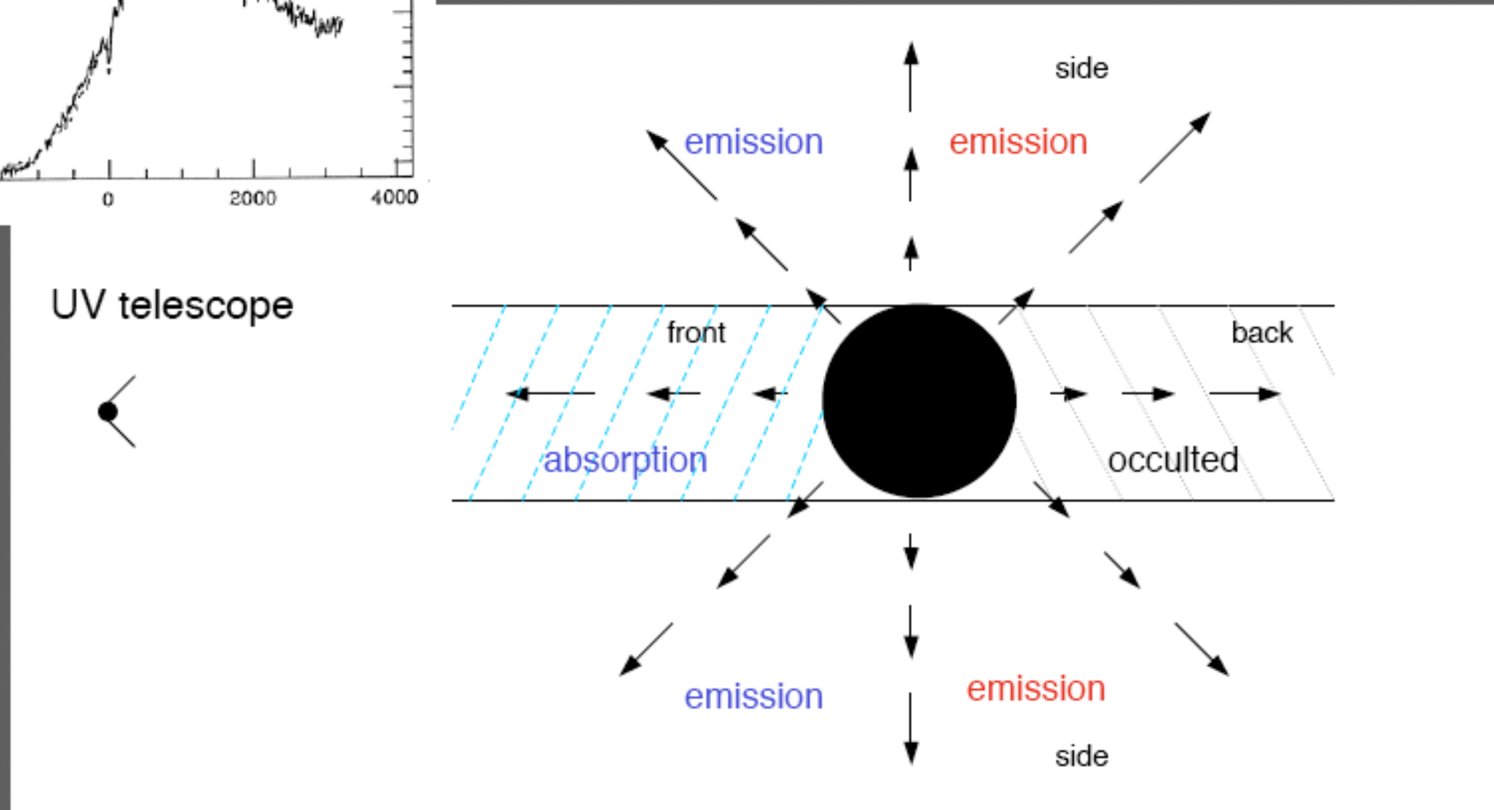
UV spectrum

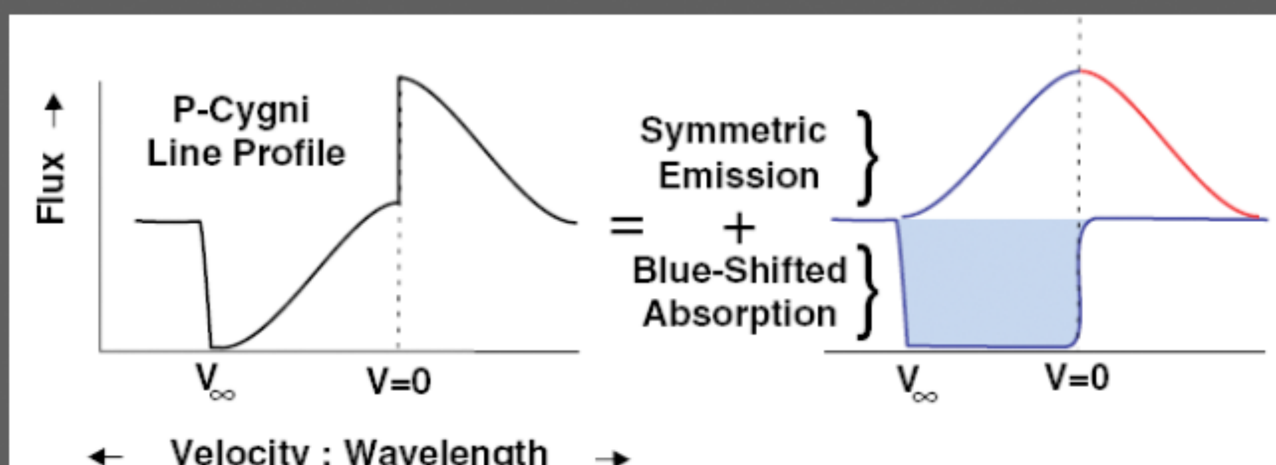
Stellar winds

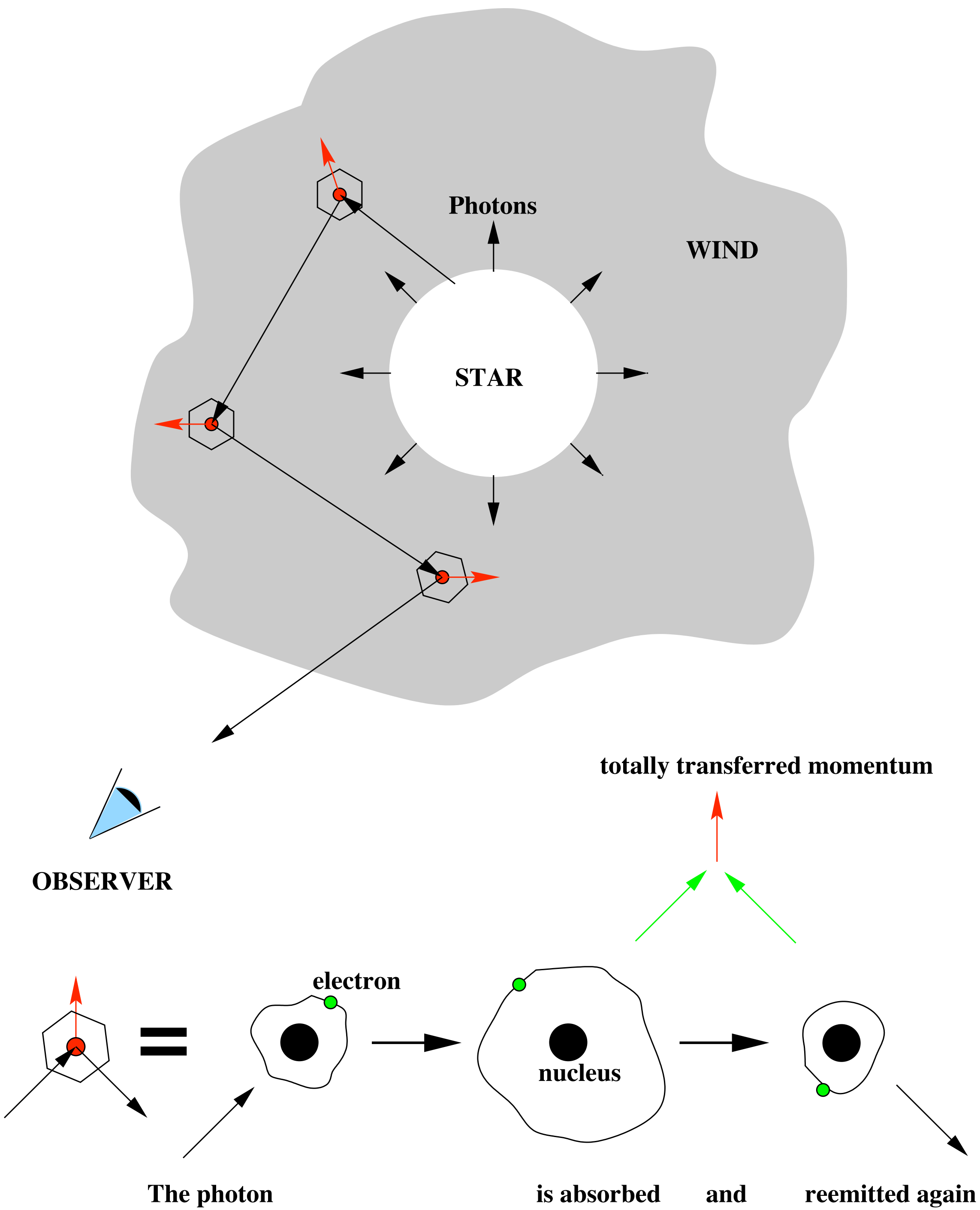
Pauldrach, Puls, Kudritzki et al. 1994, SSRev, 66, 105

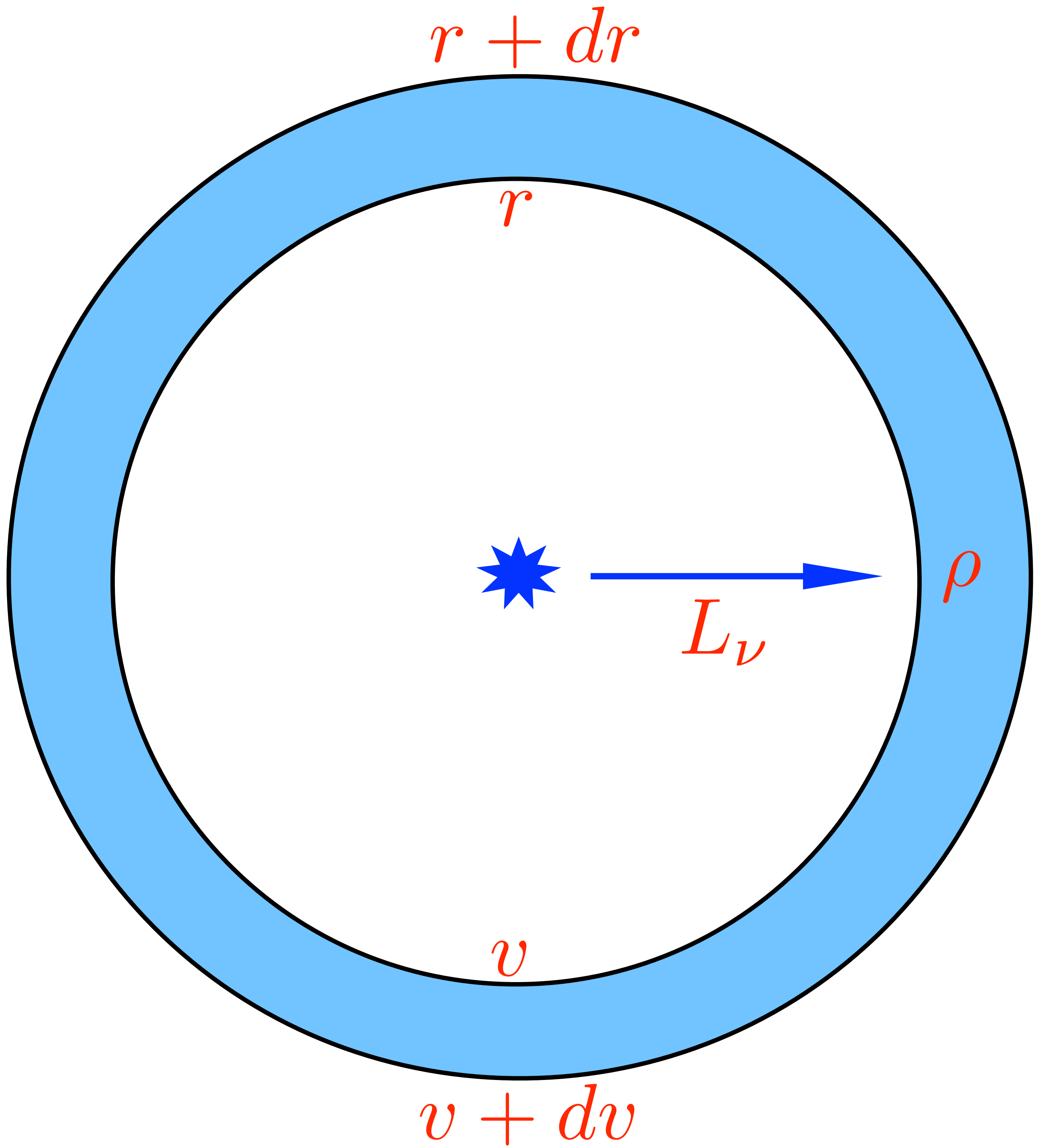

N V
Si IV
C IV
He II
N IV
NGC 346 #1 O4 III(n)(f)
Sk-70 69 O5 V
Sk-66 100 O6 II(f)
AV238 O9 III
Normalized Flux
1200
1300
1400
1500
1600
1700
Wavelength (Å)


STELLAR WIND OF ζ PUPPIS
C IV
Residual Intensity
0
1
2
−6000
−4000
−2000
0
2000
4000


UV telescope
side
emission
emission
front
back
absorption
occulted
emission
emission
side

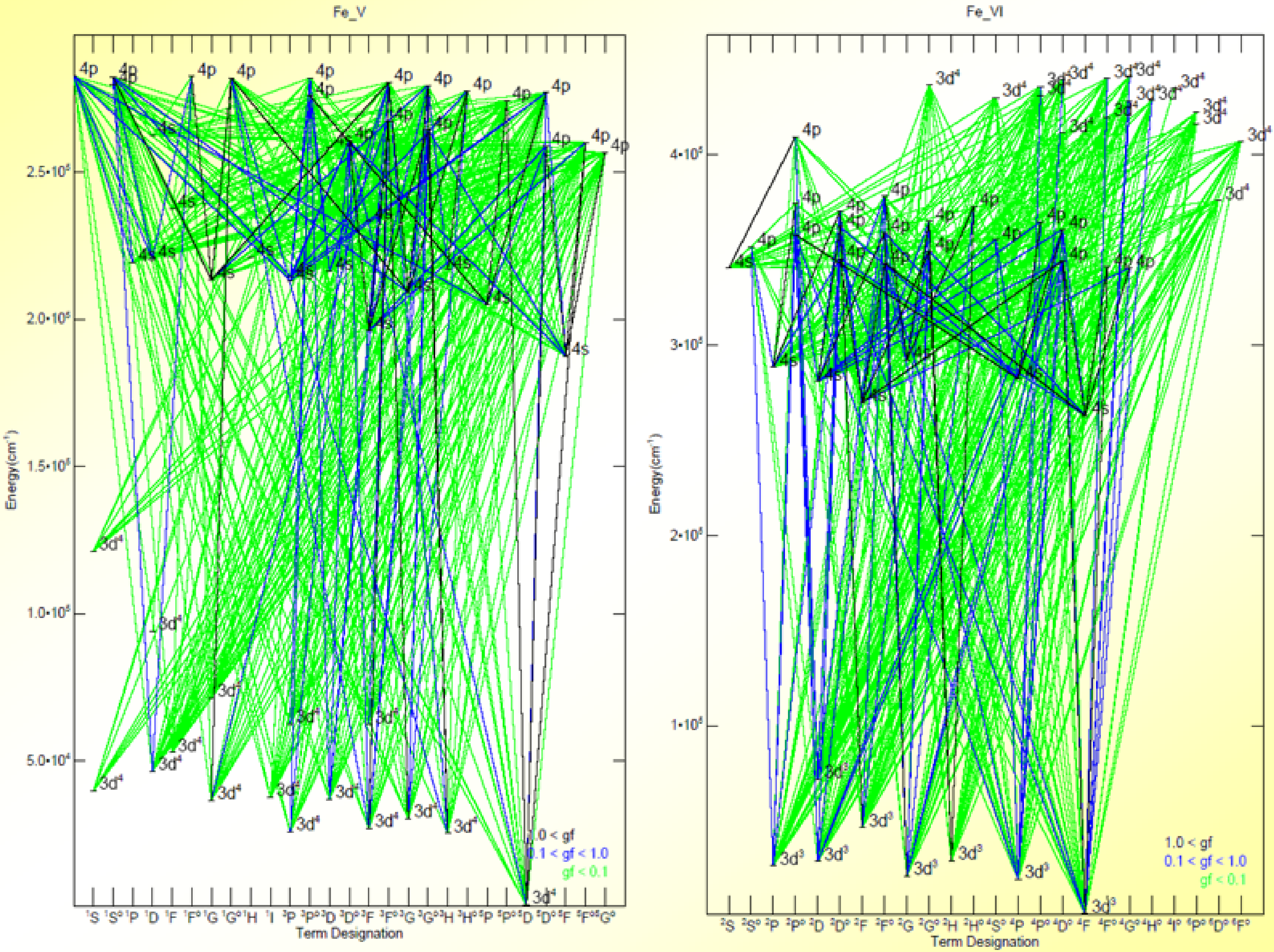

P-Cygni
Line Profile
Flux
=
Symmetric
Emission
+
Blue-Shifted
Absorption
V_∞
V=0
V_∞
V=0
Velocity ; Wavelength


Photons
WIND
STAR
OBSERVER
totally transferred momentum
electron
nucleus
The photon
is absorbed
and
reemitted again

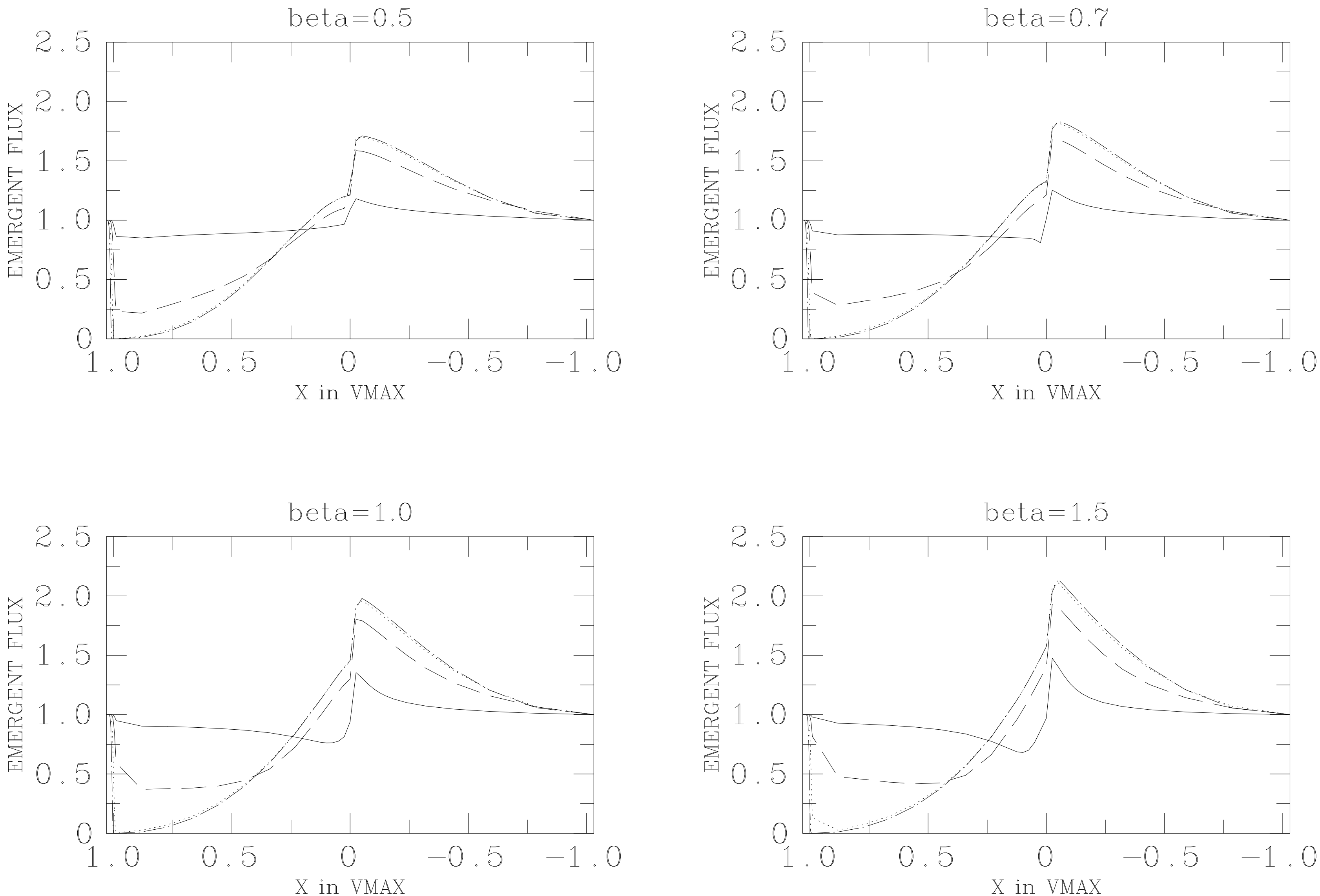


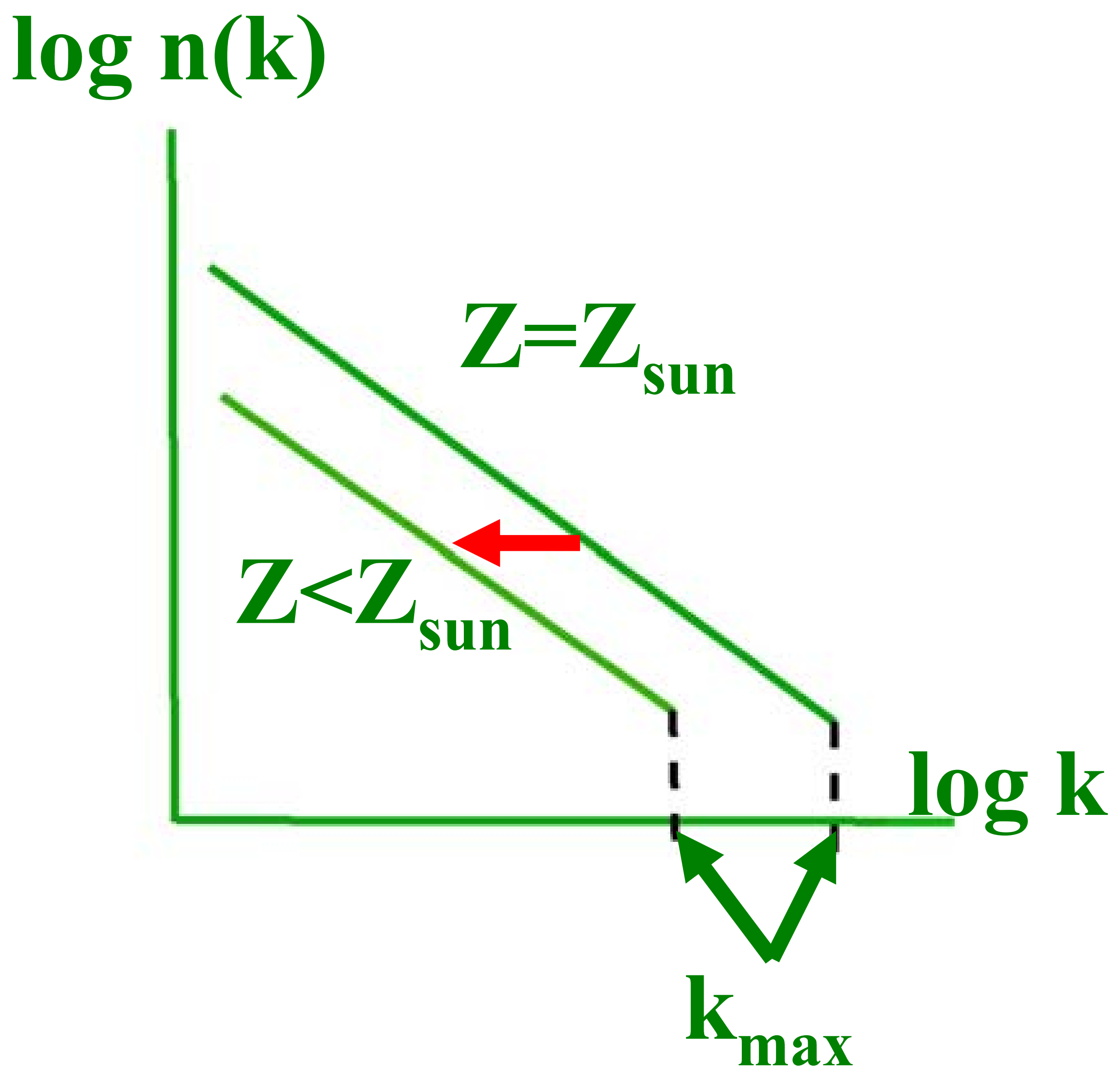
$r + dr$
r
L_ν
ρ
v
$v + dv$

complex atomic models for O-stars (Pauldrach et al., 2001)

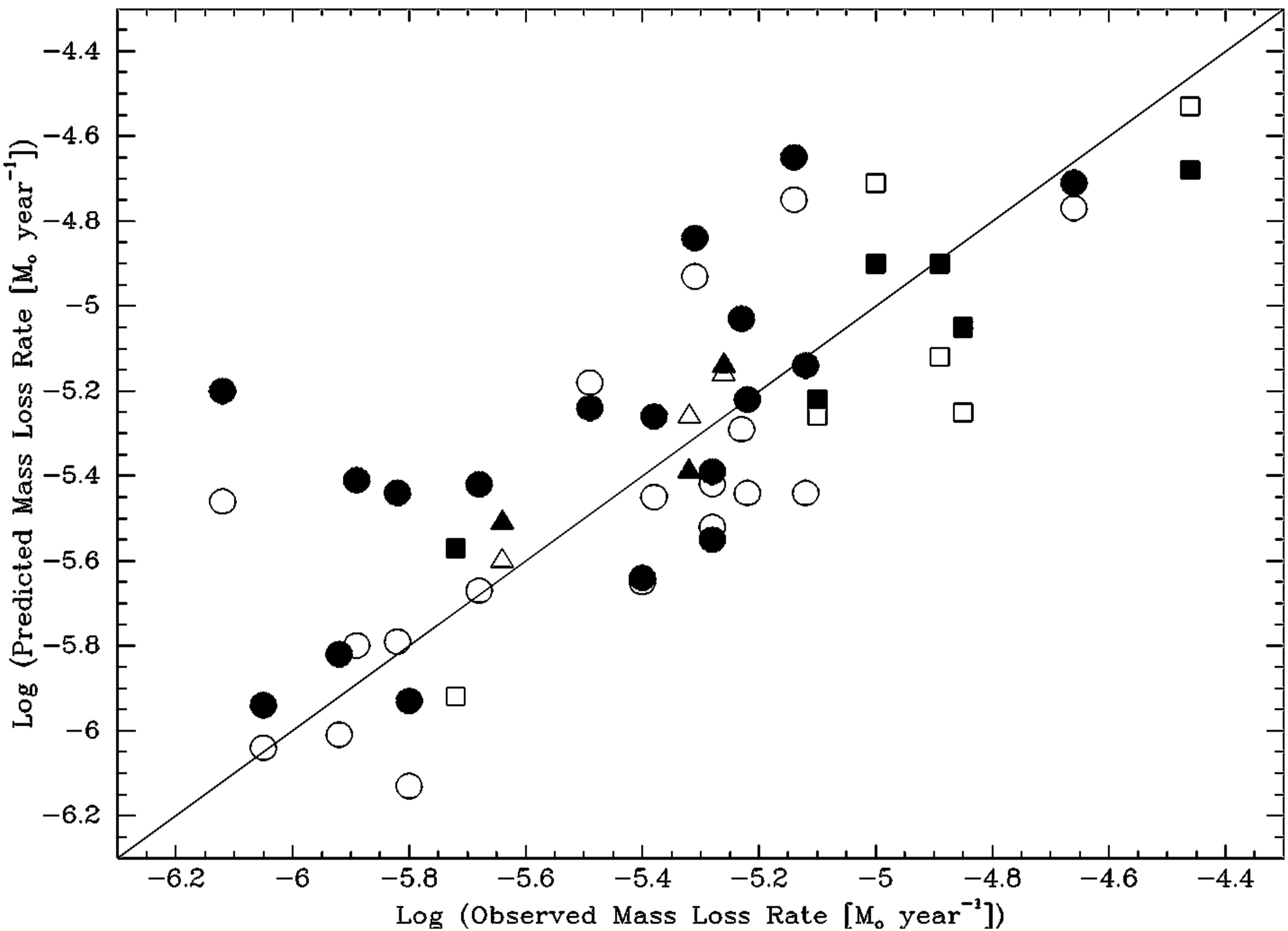


Munich solar eclipse, 1999


beta=0.5
beta=0.7
beta=1.0
beta=1.5
EMERGENT FLUX
X in VMAX
2.5
2.0
1.5
1.0
0.5
0
1.0
0.5
0
−0.5
−1.0



log n(k)
Z=Z$_{sun}$
Z<Z$_{sun}$
log k
k$_{max}$


Log (Predicted Mass Loss Rate [M☉ year⁻¹])
Log (Observed Mass Loss Rate [M☉ year⁻¹])
-4.4
-4.6
-4.8
-5
-5.2
-5.4
-5.6
-5.8
-6
-6.2

Massey 2003


C1
C6
C8
C9
C12
C14
C16
B5
B8
A6
B10
A8
B12
B11
A9
A10
B11
A11
D8
D7
B15
A13
D10
B19
D12
D13
A18
D17
D18