Consistent Models of the Expanding Atmospheres of Hot Stars

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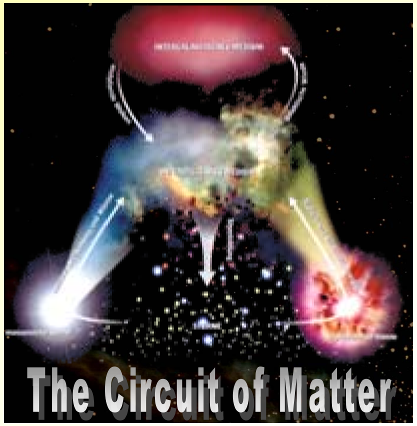
Tool - Models -Theory

Motivation
Observations

development of
consistent atmospheric models



non-equilibrium thermodynamics (NLTE) radiation hydrodynamics

theoretical framework

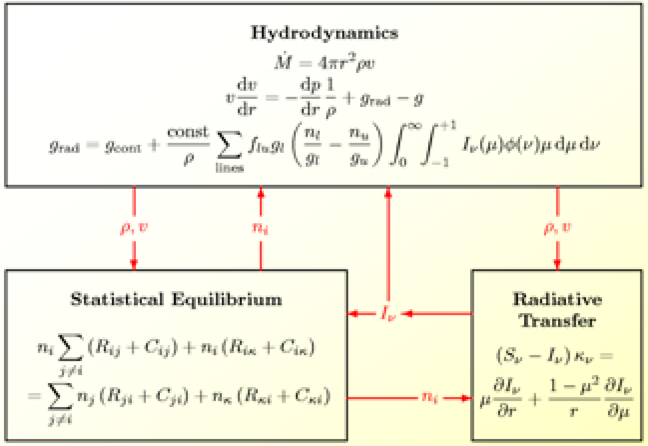
Boltzmann - equation

$$\frac{\partial f}{\partial t} + \underline{\mathbf{v}} \cdot \nabla f + \frac{1}{m} \underline{\mathbf{F}} \cdot \nabla_{\mathbf{v}} f = \left[\frac{\partial f}{\partial t} \right]_{\mathrm{ic}}$$

time development of the distribution functions

Simplifying assumptions for calculating
consistent models of
Expanding Atmospheres of Hot Star:
homogeneity, stationarity, spherical symmetry

Nonetheless, the solution is a
non-trivial problem due to back-reactions
which influence the results of the solution primarily



Hydrodynamics

$$\dot{M} = 4\pi r^2 \rho v$$

$$v \frac{\mathrm{d}v}{\mathrm{d}r} = -\frac{\mathrm{d}p}{\mathrm{d}r}\frac{1}{\rho} + g_{\mathrm{rad}} - g$$

$$g_{\mathrm{rad}} = g_{\mathrm{cont}} + \frac{\mathrm{const}}{\rho} \sum_{\mathrm{lines}} f_{\mathrm{lu}} g_{\mathrm{l}} \left(\frac{n_{\mathrm{l}}}{g_{\mathrm{l}}} - \frac{n_{\mathrm{u}}}{g_{\mathrm{u}}} \right) \int_0^{\infty} \int_{-1}^{+1} I_\nu(\mu) \phi(\nu) \mu \,\mathrm{d}\mu \,\mathrm{d}\nu$$

Statistical Equilibrium

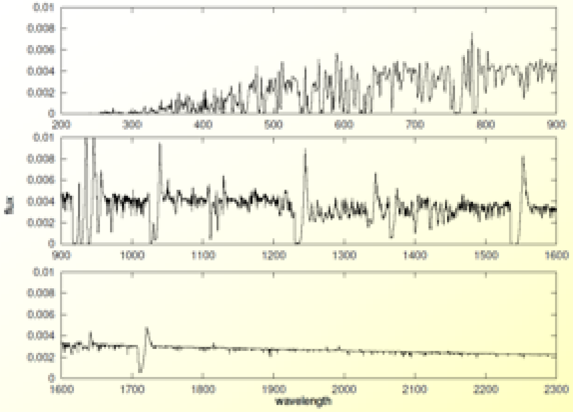
$$n_i \sum_{j \neq i} (R_{ij} + C_{ij}) + n_i (R_{i\kappa} + C_{i\kappa}) = \sum_{j \neq i} n_j (R_{ji} + C_{ji}) + n_\kappa (R_{\kappa i} + C_{\kappa i})$$

Radiative Transfer

$$(S_\nu - I_\nu)\kappa_\nu = \mu \frac{\partial I_\nu}{\partial r} + \frac{1-\mu^2}{r} \frac{\partial I_\nu}{\partial \mu}$$

Application
Spectral Diagnostics

development of
detailed synthetic spectra



Tool - Models -Theory

Motivation
Observations

non-equilibrium thermodynamics (NLTE)
radiation hydrodynamics

Boltzmann - equation

$$\frac{\partial f}{\partial t} + \underline{\mathbf{v}} \cdot \nabla f + \frac{1}{m} \underline{\mathbf{F}} \cdot \nabla_{\mathbf{v}} f = \left[\frac{\partial f}{\partial t} \right]_{\mathrm{ic}}$$

time development of the distribution functions

Application
Spectral Diagnostics

Hot Stars

T_{eff} = 15000 - 100000 K

show wind features

sub-group

Low Mass Stars

0.4 - 1.44 $M_\odot$

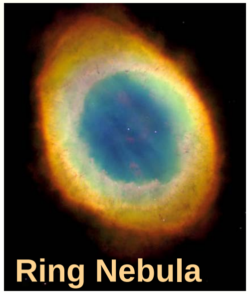
CSPN (SN Ia)

old, 10^{10} yr

luminous, $10^4 L_\odot$

rare, evolution

radiation, UV/EUV



Ring Nebula

sub-group

Massive Stars

20 - 150 $M_\odot$

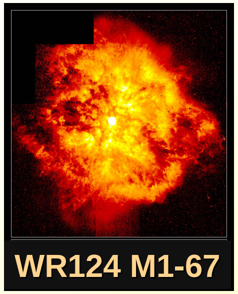
O/B (WR SN II)

young, 10^6 yr

luminous, $10^6 L_\odot$

rare, IMF

radiation, UV/EUV



WR124 M1-67

Expanding Atmospheres

characterized by

high radiation energy density

$10^{-4}\ M_\odot/\mathrm{yr} \geq \dot{M}\, v_\infty$

$\dot{M}\, v_\infty \leq 4000$ km/s

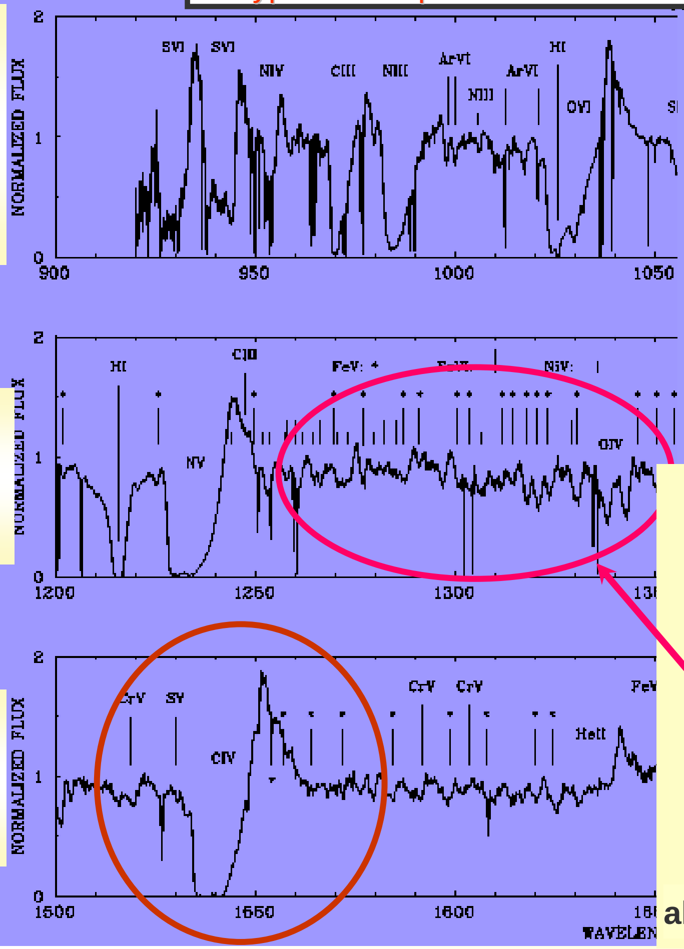
In this talk focus on the status of UV Spectral Diagnostics !

Emergent UV Spectra of O-type Stars are Old Fashioned !

Walborn, Nichols-Bohlin, Panek, 1985, NASA Ref. Publ. 1155; Morton and Underhill, **1977**, Ap. J. Suppl. 33, 83

Typical UV Spectrum of a Massive Star - ζ Pup (O4If)

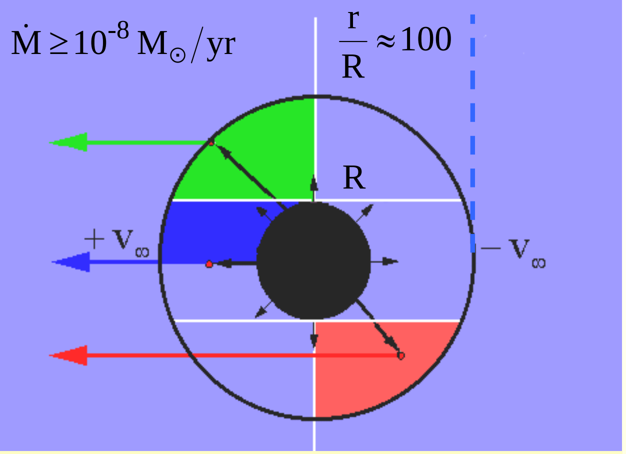
Expanding atmospheres have a pronounced effect on the **emergent spectra** of hot stars!



momentum transfer produces the outflow !

→ consistent models

UV spectral diagnostics should be based on realistic models !


$\dot{M} \geq 10^{-8} M_\odot/yr$

$\frac{r}{R} \approx 100$

Structure of the lines depends on:

log g, T_{eff} and R

⇩

M, L, R, Z

all fundamental parameters can be deduced

Signatures of P-Cygni lines are characterized by the outflow

SVI,CIII,NIII,OVI,PV,NV,OIV,OV,SiIV,CIV,HEII,NIV

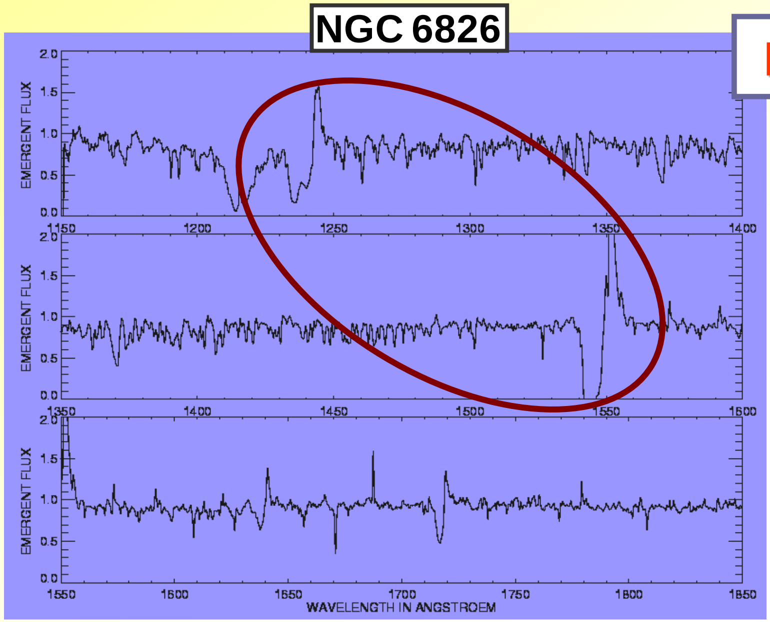
Hundreds of strongly wind contaminated lines are formed throughout the expanding atmosphere

FeV, NiV, FeIV, FeVI, CrV, ArV, ArVI

Synthetic UV Spectra of Hot Stars - Still Relevant ?

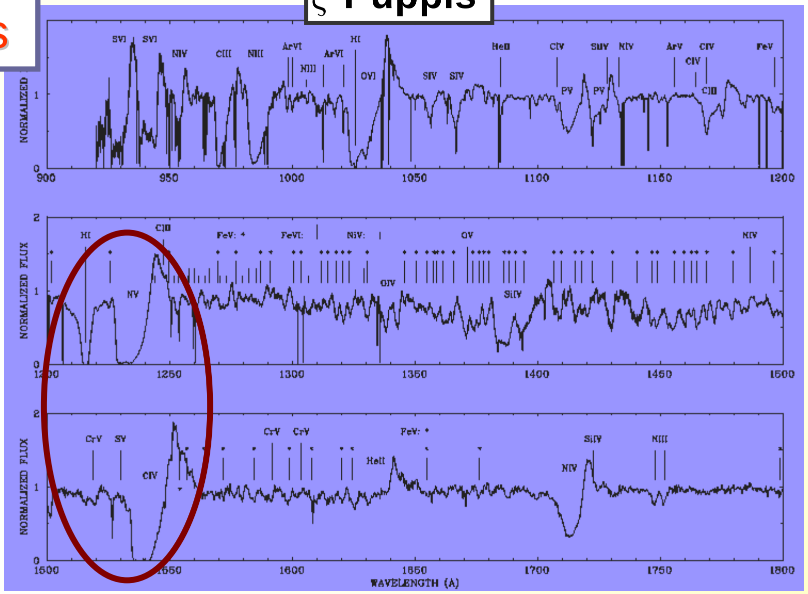
Realistic Synthetic UV Spectra of O-type Stars
a Diagnostic Tool with great Astrophysical Potential ?

NGC 6826



Hot Stars

ζ Puppis



spectra **of O-type CSPN's**

similar to

spectra **of massive O-type stars**

Spectra contain information about stellar and wind parameters and abundances

superb sensitivity and spectral resolution provided for > 25 years
but most work done concentrated on qualitative results and arguments

Powerful Tool for modeling realistic synthetic spectra for diagnostic issues is still in development !

Focus will be on the ionizing radiation of hot stars !

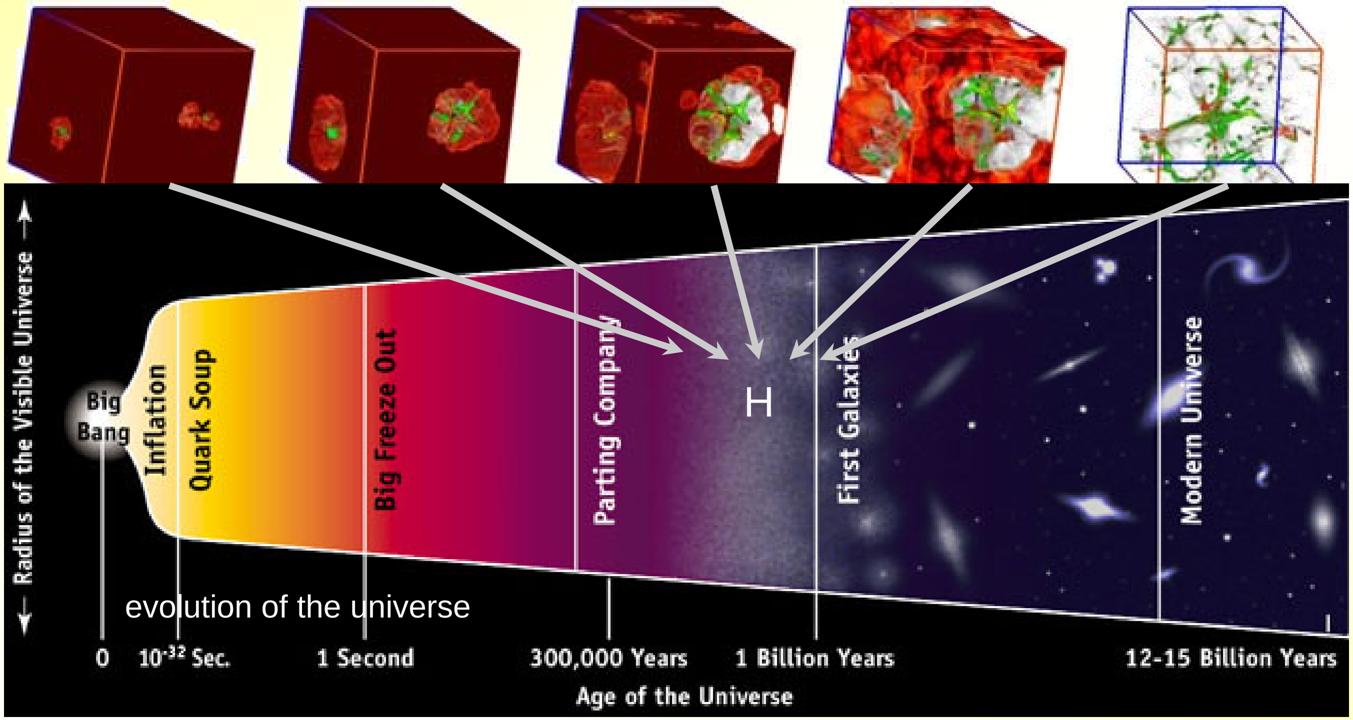
Motivation: Reionization of the universe

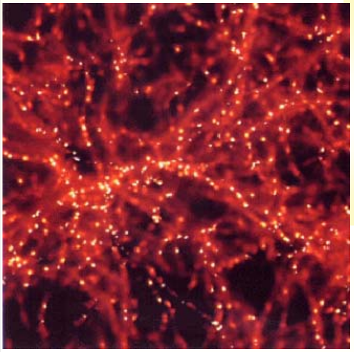
End of Cosmic Dark Ages

absence of Gunn-Peterson trough in the spectra of high-redshift quasars implies that **the universe** was **reionized** at a **redshift of z ~ 6**

Fan et al., 2000, AJ, 120, 1167

Gnedin, 2000, ApJ, 535, 530





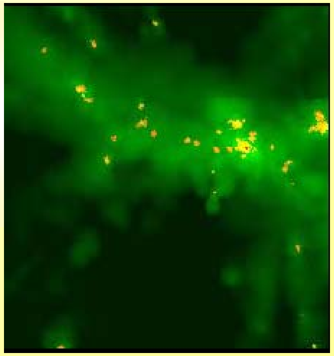
What caused the reionization of the universe ?

Are population III stars ($Z<10^{-3}$) the source for the reionization ?

Carr et al.,1984,ApJ 277, 445

this is just the case if the IMF of the **First Stars** is different from what we know

Bromm et al., 1999, ApJ, 527, L5



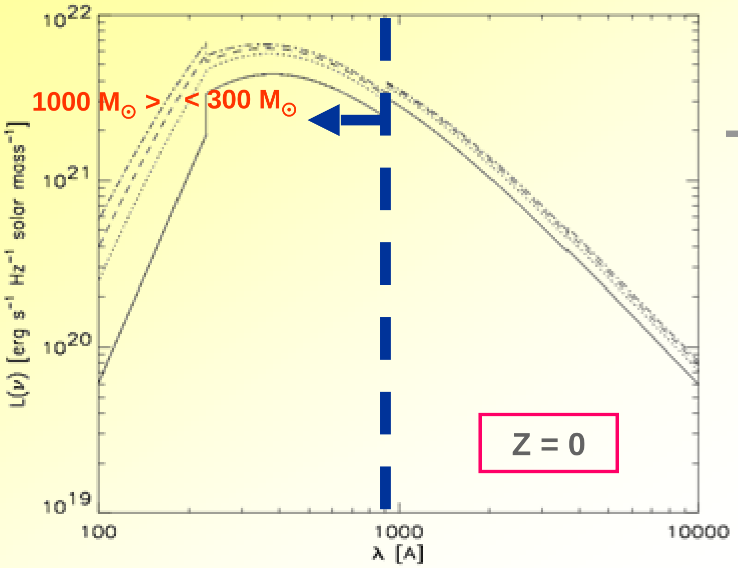
Numerical simulation of the first stars in the universe

Davé, Katz, Weinberg, 2002, ApJ, 579, 23

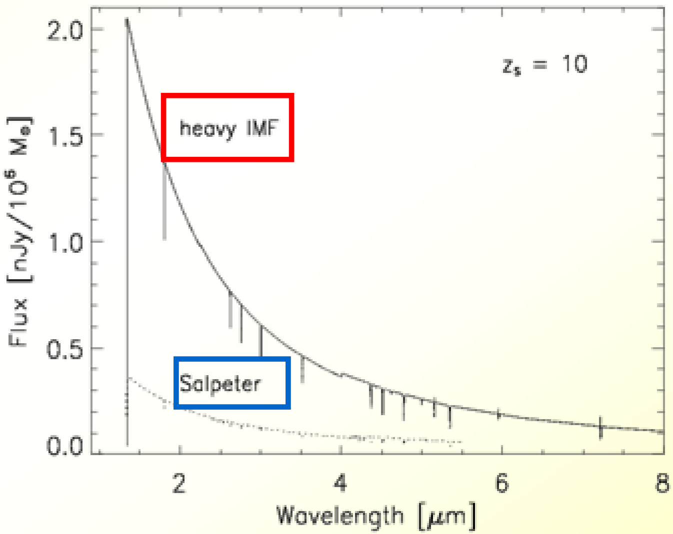
Reionization : Ionization Efficiency of the First generations of Stars

In the **Early Universe Population III stars** favoured the formation of very **Massive Stars**

M > 100 M$_\odot$



IMF becomes top-heavy



Normalized **spectral energy distribution** in the continuum
100 – 1000 M$_\odot$ Z=0
Per unit mass the spectra attain
an universal form for M>300 M$_\odot$
Bromm, Kudritzki et al., 2001, ApJ, 540, 68

Predicted flux from a Population III star cluster at z=10
A flat universe with Ω_Λ= 0.7 is assumed.
The cutoff is due to complete Gunn-Peterson absorption
(1965, ApJ, 142, 1633).
able flux is larger by an order of magnitude for the
case of the **heavy IMF**
Bromm, Kudritzki et al., 2001, ApJ, 540, 687

The enormous amount **of UV and EUV radiation** of these stars can change the status of the **universe** to **become reionized** again

Realistic Spectral Energy Distributions

of O-type Stars are also required

to analyze excited HII regions and Planetary Nebulae

the flux of **very massive stars** can contribute the decisive part to the unexplained **deficit of ionizing photons**

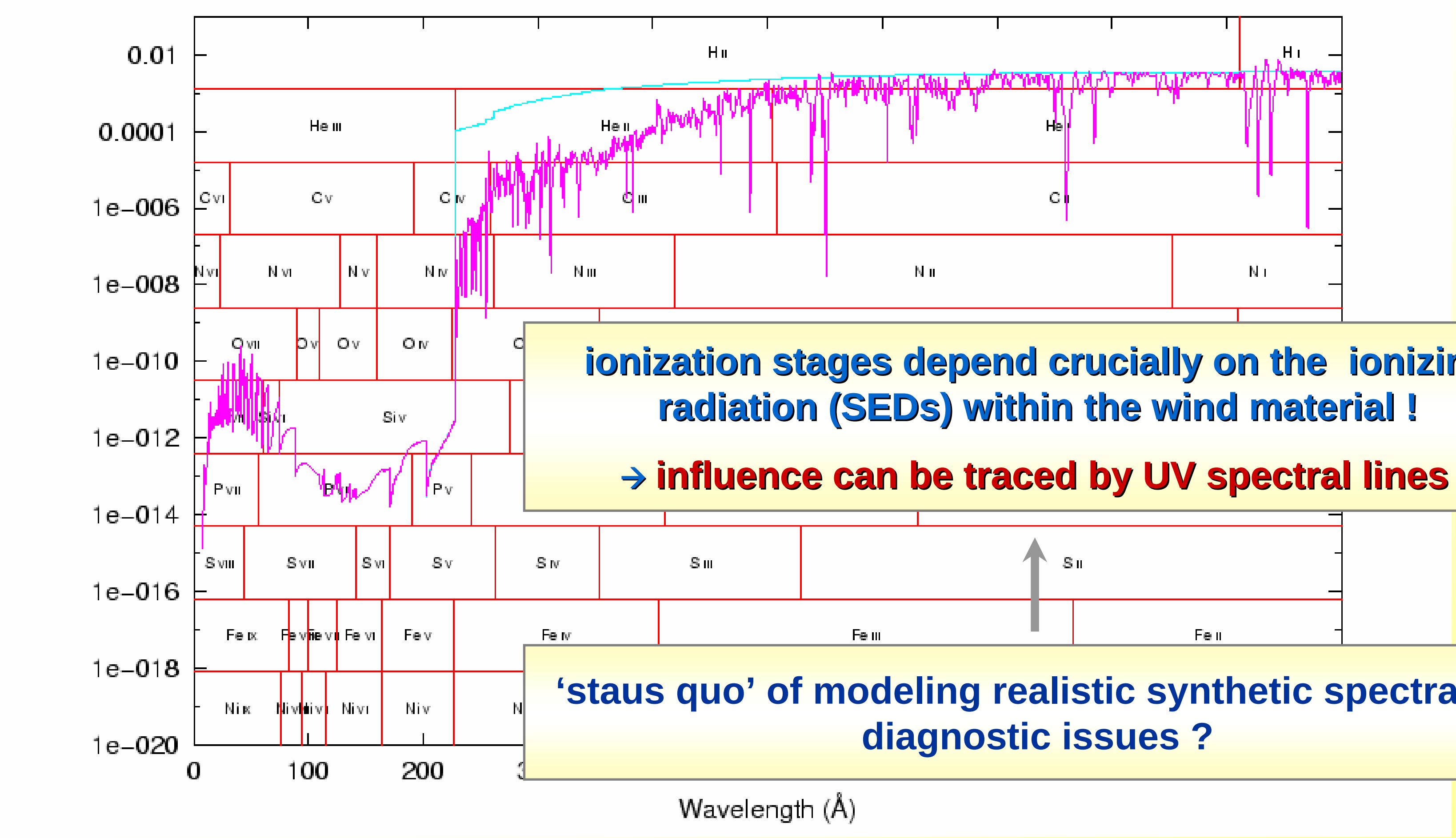
***Ultimate test:* comparison of observed and synthetic UV spectra of hot stars**

Ionizing flux of ζ Puppis (O4If)

small vertical lines indicate the
ionization edges for all important ions !

UV Spectra of O Stars:

test involves hundreds of spectral signatures of different ionization stages



ionization stages depend crucially on the ionizing radiation (SEDs) within the wind material !

→ influence can be traced by UV spectral lines !

‘staus quo’ of modeling realistic synthetic spectra for diagnostic issues ?

Concept for consistent atmospherical models of hot stars

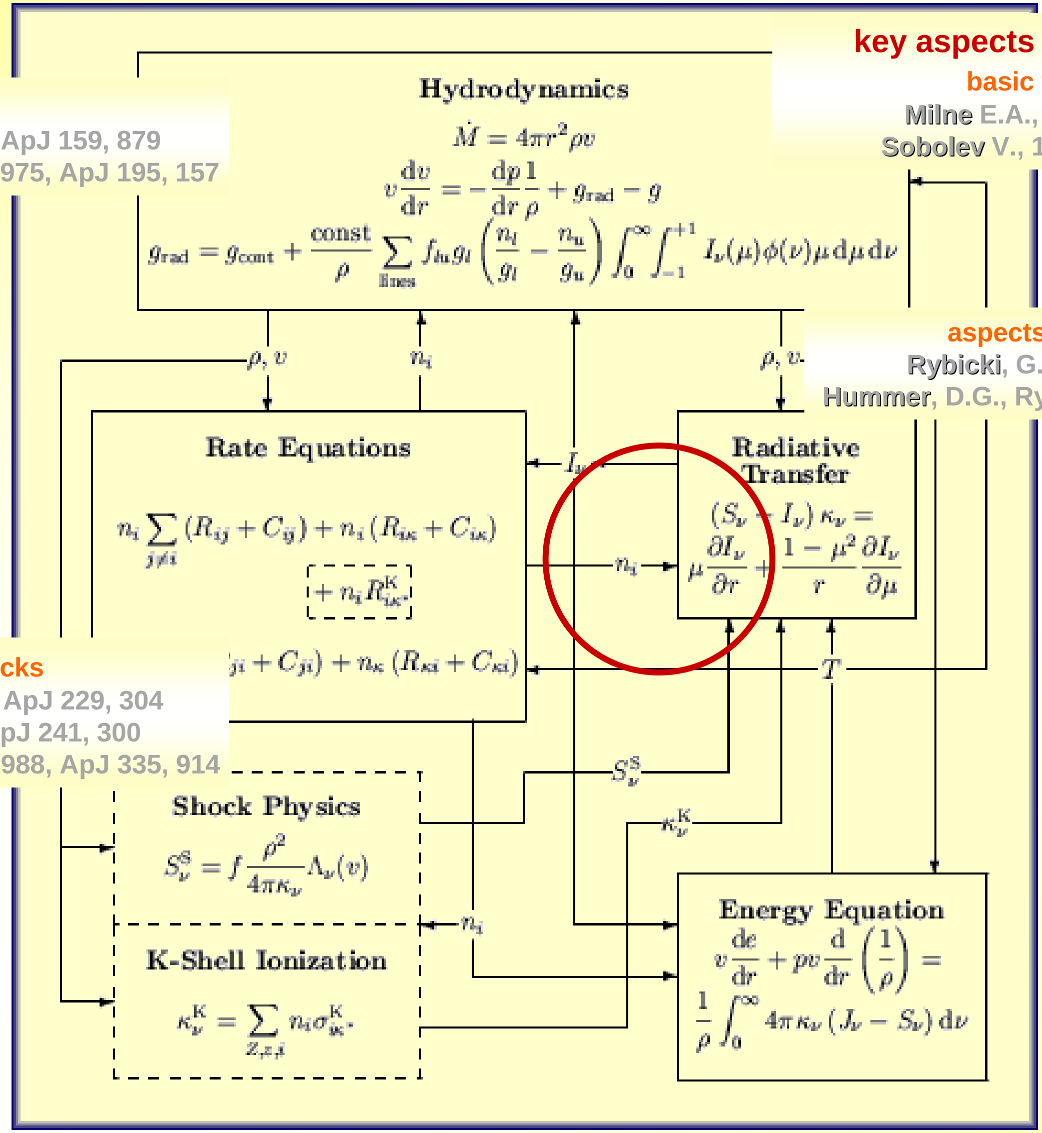
key aspects of theoretical activity

basic theoretical ideas

Milne E.A., 1926, MNRAS 86, 459
Sobolev V., 1957, Sov. A&A J. 1, 678

theoretical basis

Lucy L. B., Solomon P., 1970, ApJ 159, 879
Castor J.I., **Abbott** D.C., **Klein** R.: 1975, ApJ 195, 157



Hydrodynamics

$$\dot{M} = 4\pi r^2 \rho v$$

$$v\frac{\mathrm{d}v}{\mathrm{d}r} = -\frac{\mathrm{d}p}{\mathrm{d}r}\frac{1}{\rho} + g_{\mathrm{rad}} - g$$

$$g_{\mathrm{rad}} = g_{\mathrm{cont}} + \frac{\mathrm{const}}{\rho}\sum_{\mathrm{lines}} f_{lu} g_l \left(\frac{n_l}{g_l} - \frac{n_u}{g_u}\right) \int_0^\infty \int_{-1}^{+1} I_\nu(\mu)\phi(\nu)\mu\,\mathrm{d}\mu\,\mathrm{d}\nu$$

Rate Equations

$$n_i \sum_{j \neq i} (R_{ij} + C_{ij}) + n_i (R_{i\kappa} + C_{i\kappa})$$

$$\boxed{+\, n_i R^{\mathrm{K}}_{i\kappa^*}}$$

$$\ldots_{ji} + C_{ji}) + n_\kappa (R_{\kappa i} + C_{\kappa i})$$

Radiative Transfer

$$(S_\nu - I_\nu)\,\kappa_\nu = \mu\frac{\partial I_\nu}{\partial r} + \frac{1-\mu^2}{r}\frac{\partial I_\nu}{\partial \mu}$$

Shock Physics

$$S^{\mathrm{S}}_\nu = f\frac{\rho^2}{4\pi\kappa_\nu}\Lambda_\nu(v)$$

K-Shell Ionization

$$\kappa^{\mathrm{K}}_\nu = \sum_{Z,z,i} n_i \sigma^{\mathrm{K}}_{i\kappa^*}$$

Energy Equation

$$v\frac{\mathrm{d}e}{\mathrm{d}r} + pv\frac{\mathrm{d}}{\mathrm{d}r}\left(\frac{1}{\rho}\right) = \frac{1}{\rho}\int_0^\infty 4\pi\kappa_\nu (J_\nu - S_\nu)\,\mathrm{d}\nu$$

aspects of radiative transfer

Rybicki, G.B., 1971, JQSRT 11, 589
Hummer, D.G., Rybicki, G.B., 1985, ApJ 293, 258

X-rays and wind shocks

Cassinelli, J., Olson, G., 1979, ApJ 229, 304
Lucy L. B., White,R., 1980, ApJ 241, 300
Owocki S., Castor, J., Rybicki, G. 1988, ApJ 335, 914

basis of our theoretical framework

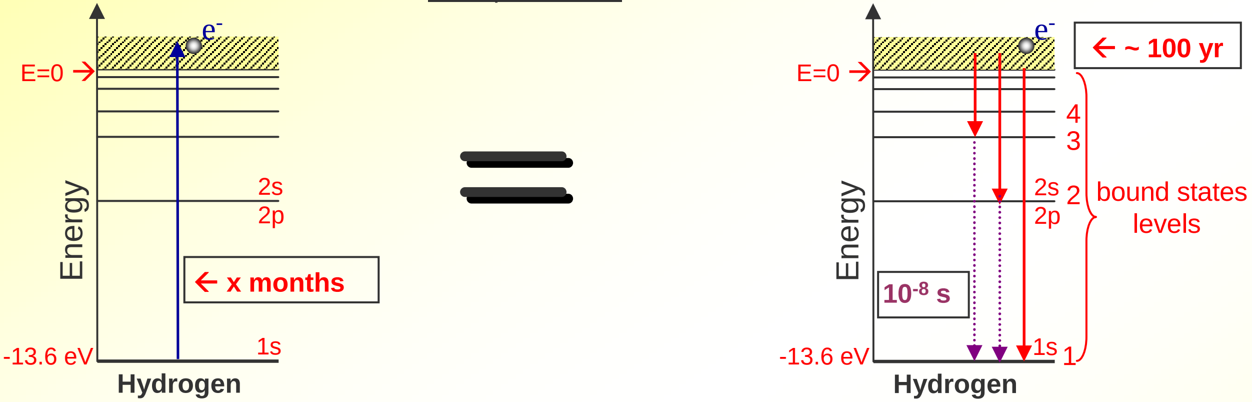
Pauldrach, A.W.A., Puls, J., Kudritzki, R.P.,1986, A&A,164,86; Pauldrach, A.W.A., 1987, A&A, 183, 295
Puls, J., Pauldrach, A.W.A., 1990, PASPC 7, 203; Pauldrach, A.W.A. et al., 1994, A&A, 283, 525
Feldmeier, A. et al., 1997, A&A 320, 899; Pauldrach, A.W.A. et al., 1998, ASPCS 131, 258
Pauldrach, A.W.A., Hoffmann, T.L., Lennon, M., 2001, A&A, 375, 161

Theory: Motivation

in GNs radiative processes are not balanced in detail !

→ thermodynamic equilibrium can not be established !

main processes:



just ground states are occupied

→no thermodynamic equilibrium (TE)

instead

Non-Equilibrium Thermodynamics (NLTE)

described by a well defined mixture of macroscopic and microscopic physics

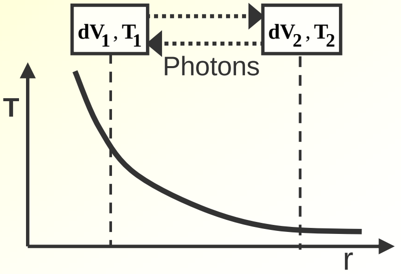
Transport Theory

Thermodynamics

Quantum Mechanics

Disadvantage of NLTE:

non local problem!



Advantage of TE:

In **TE** state of the gas completely described by

2 macroscopic variables

→ **local problem**!

$$n_i^* = n_i(\rho, T)$$

n_i^* = occupation numbers of bound levels (number of particles per cm^3)

n_i follows from **Boltzmann statistics**

$$n_1 4\pi \int_{\nu_{1k}}^{\infty} \frac{\alpha_{1k}(\nu)}{h\nu} J_\nu \, d\nu = n_P n_e \alpha_R$$

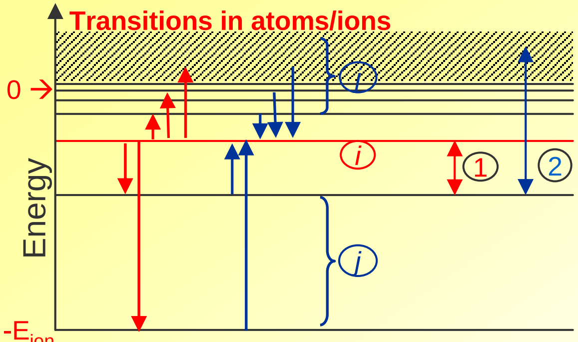
ionization equation

$$\left[\frac{1}{r^2}\frac{\partial}{\partial r}\right] r^2 J_\nu = -n_1 \alpha_{1k} J_\nu \, (+\eta_\nu)$$

the equation of transfer in spherical symmetry

Integro-Differential Equation

all existing microscopic processes have to be considered for all atomic levels

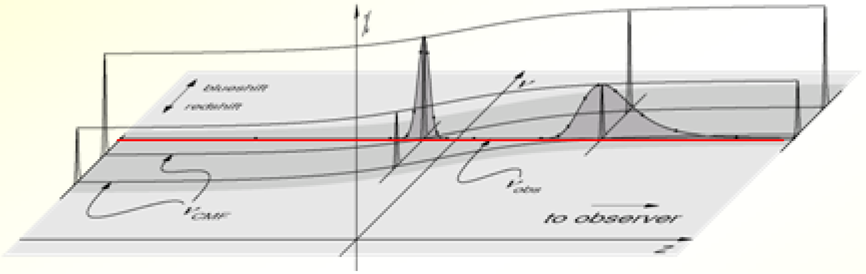


de-population population of level i

$n_{Ki}P_{ij}$ $n_{Kj}P_{ji}$ $\left[{}^{1}\!/_{cm^3 s}\right]$

① **bound-bound transitions**
excitation and de-excitation
radiative/collisional rates
R_{ij} , C_{ij}

② **bound-free transitions**
ionization and recombination processes
R_{ik} , C_{ik}



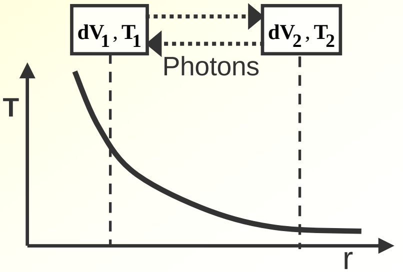
0-th moment of distribution function f_{Ki} for each element $K,$ level i :

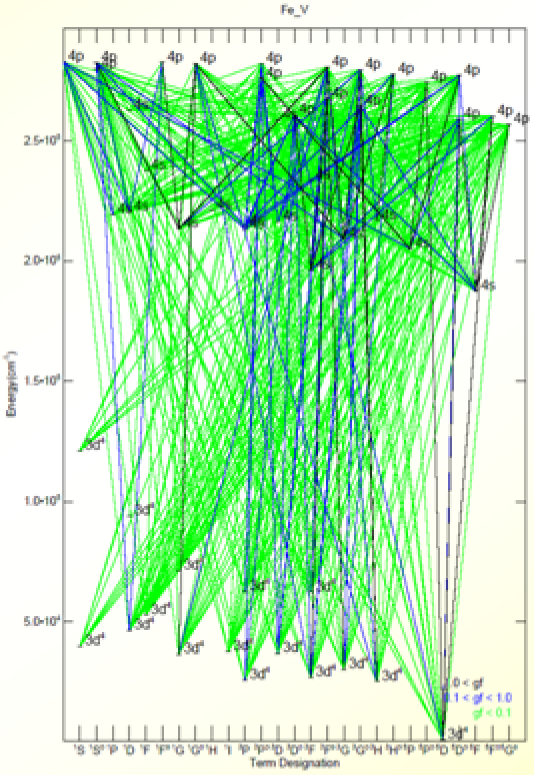
$$\underline{\nabla}\cdot(n_{Ki}\underline{\mathbf{u}}) = \int_{-\infty}^{+\infty}\left[\frac{\partial f_{Ki}}{\partial t}\right]_{\mathrm{ic}} d^3\mathrm{v} = \sum_{j\neq i} n_{Kj}P_{ji} - \sum_{j\neq i} n_{Ki}P_{ij}$$

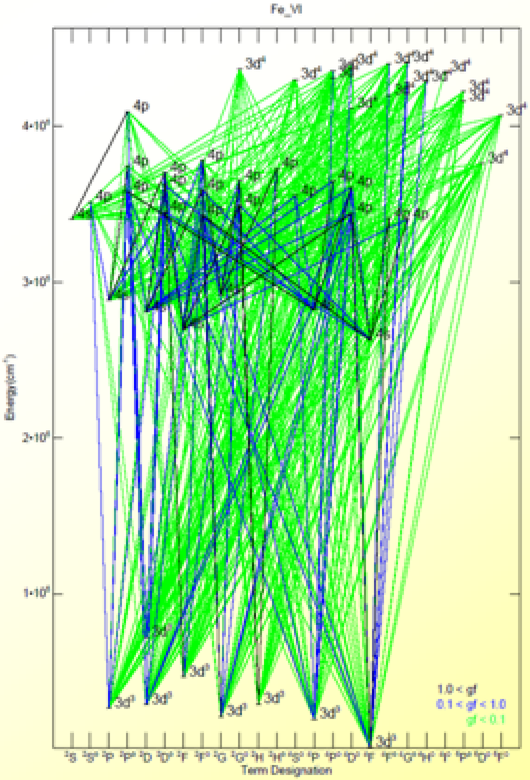
yields net rate of changes for each K, i

Nonequilibrium thermodynamics
is a rather esoteric field of physics
that we would do well to avoid!
...

Disadvantage of NLTE:
non local problem!





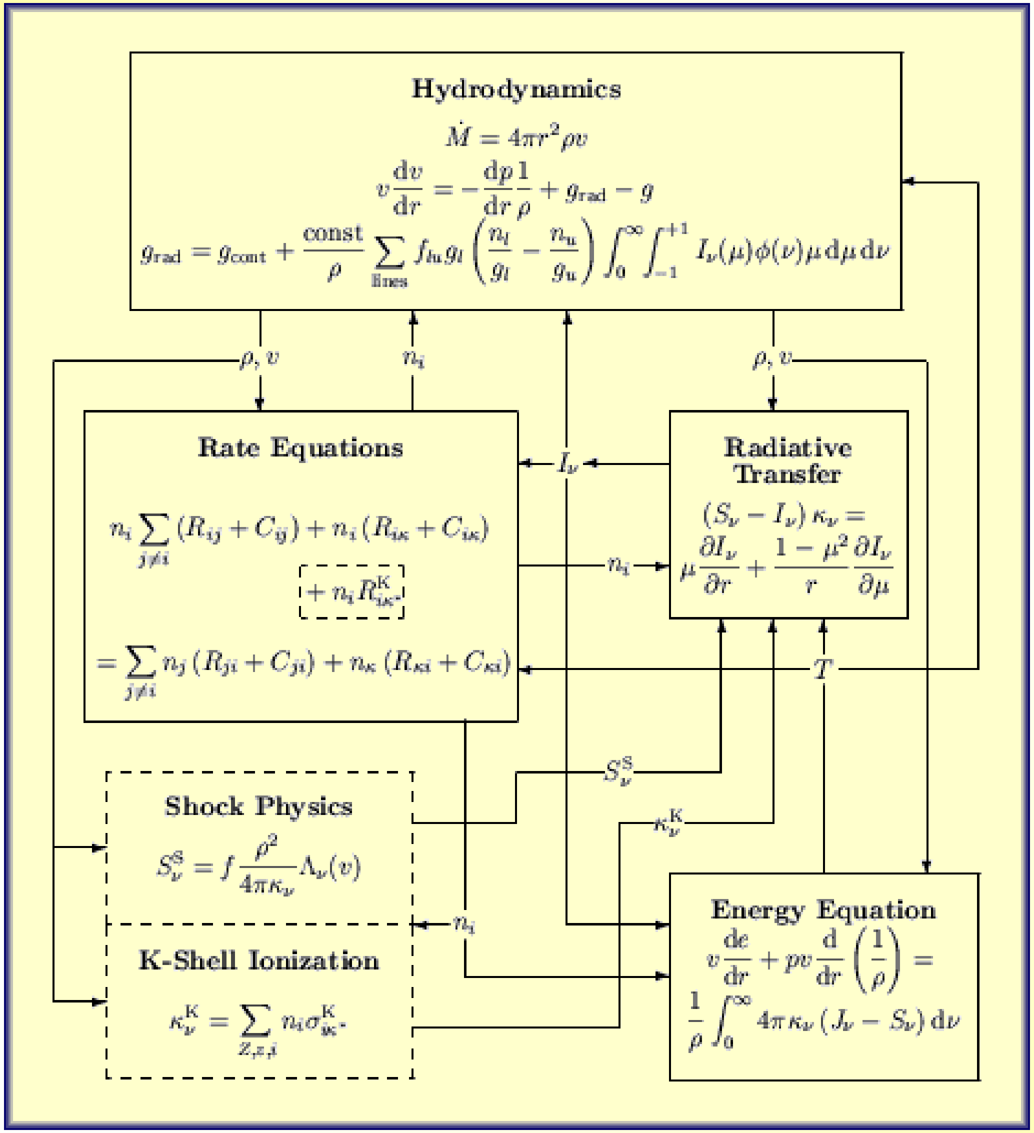


Correct treatment of the influence of the velocity field

The velocity field shifts
at different radii
up to 1000 spectral lines
into the line of sight
at the observer's frequency
→ back-reaction

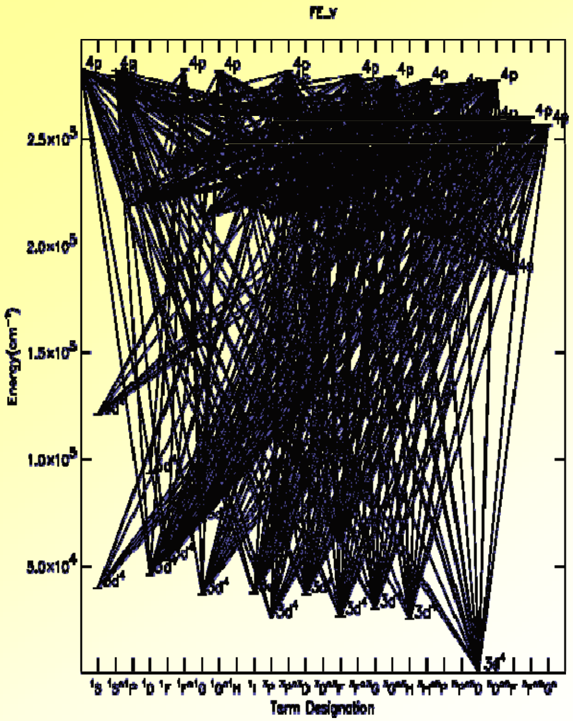
Constraints for the parameters and the abundances are obtained

T_{eff} Z
L M
$\dot{M}$ v_∞



observed spectra

Points which are of special importance for the complete procedure



well-elaborated

atomic models

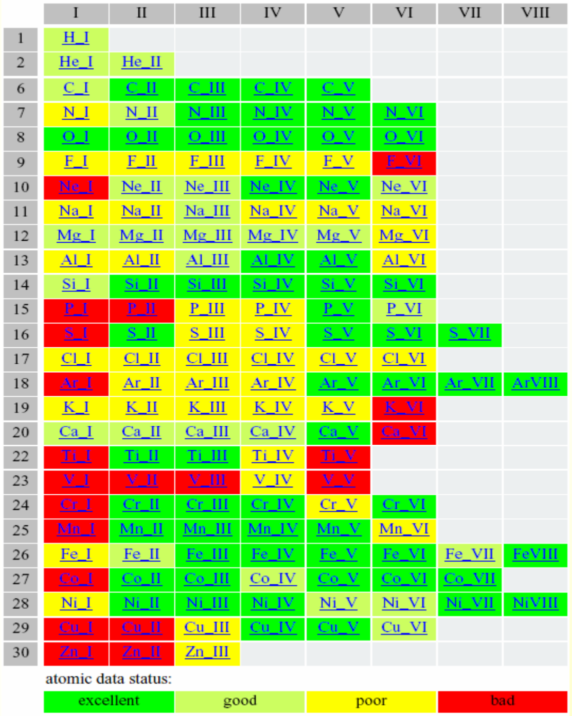
are required

in order to avoid

GIGO

Rate Equations

$$n_i \sum_{i \neq j} (R_{ij} + C_{ij}) + n_i (R_{ik} + C_{ik})$$
$$= \sum_{i \neq j} n_j (R_{ji} + C_{ji}) + n_k (R_{ki} - C_{ki})$$



	I	II	III	IV	V	VI	VII	VIII
1	🟢 H_I							
2	🟢 He_I	🟢 He_II						
6	🟢 C_I	🟩 C_II	🟩 C_III	🟩 C_IV	🟩 C_V			
7	🟨 N_I	🟢 N_II	🟩 N_III	🟩 N_IV	🟩 N_V	🟩 N_VI		
8	🟩 O_I	🟩 O_II	🟩 O_III	🟩 O_IV	🟩 O_V	🟩 O_VI		
9	🟨 F_I	🟨 F_II	🟨 F_III	🟨 F_IV	🟨 F_V	🟥 F_VI		
10	🟥 Ne_I	🟢 Ne_II	🟢 Ne_III	🟩 Ne_IV	🟩 Ne_V	🟢 Ne_VI		
11	🟨 Na_I	🟨 Na_II	🟢 Na_III	🟨 Na_IV	🟨 Na_V	🟨 Na_VI		
12	🟢 Mg_I	🟢 Mg_II	🟢 Mg_III	🟢 Mg_IV	🟢 Mg_V	🟨 Mg_VI		
13	🟨 Al_I	🟨 Al_II	🟢 Al_III	🟩 Al_IV	🟩 Al_V	🟨 Al_VI		
14	🟢 Si_I	🟩 Si_II	🟩 Si_III	🟩 Si_IV	🟩 Si_V	🟩 Si_VI		
15	🟥 P_I	🟥 P_II	🟨 P_III	🟨 P_IV	🟩 P_V	🟢 P_VI		
16	🟥 S_I	🟩 S_II	🟨 S_III	🟨 S_IV	🟩 S_V	🟩 S_VI	🟩 S_VII	
17	🟨 Cl_I	🟨 Cl_II	🟨 Cl_III	🟨 Cl_IV	🟨 Cl_V	🟨 Cl_VI		
18	🟥 Ar_I	🟨 Ar_II	🟨 Ar_III	🟨 Ar_IV	🟩 Ar_V	🟩 Ar_VI	🟩 Ar_VII	🟩 ArVIII
19	🟨 K_I	🟨 K_II	🟨 K_III	🟨 K_IV	🟨 K_V	🟥 K_VI		
20	🟢 Ca_I	🟢 Ca_II	🟢 Ca_III	🟢 Ca_IV	🟩 Ca_V	🟥 Ca_VI		
22	🟥 Ti_I	🟩 Ti_II	🟩 Ti_III	🟨 Ti_IV	🟥 Ti_V			
23	🟥 V_I	🟥 V_II	🟥 V_III	🟨 V_IV	🟥 V_V			
24	🟥 Cr_I	🟩 Cr_II	🟩 Cr_III	🟩 Cr_IV	🟨 Cr_V	🟩 Cr_VI		
25	🟥 Mn_I	🟩 Mn_II	🟩 Mn_III	🟩 Mn_IV	🟩 Mn_V	🟨 Mn_VI		
26	🟨 Fe_I	🟢 Fe_II	🟩 Fe_III	🟩 Fe_IV	🟩 Fe_V	🟩 Fe_VI	🟢 Fe_VII	🟩 FeVIII
27	🟥 Co_I	🟩 Co_II	🟩 Co_III	🟢 Co_IV	🟩 Co_V	🟩 Co_VI	🟩 Co_VII	
28	🟨 Ni_I	🟩 Ni_II	🟩 Ni_III	🟩 Ni_IV	🟢 Ni_V	🟢 Ni_VI	🟩 Ni_VII	🟩 NiVIII
29	🟥 Cu_I	🟥 Cu_II	🟨 Cu_III	🟩 Cu_IV	🟩 Cu_V	🟢 Cu_VI		
30	🟥 Zn_I	🟥 Zn_II	🟨 Zn_III					

atomic data status:

🟩 excellent	🟢 good	🟨 poor	🟥 bad

NLTE Models require atomic data for

lines, collisions, ionization, recombination

Essential for occupation numbers, line blocking, line force

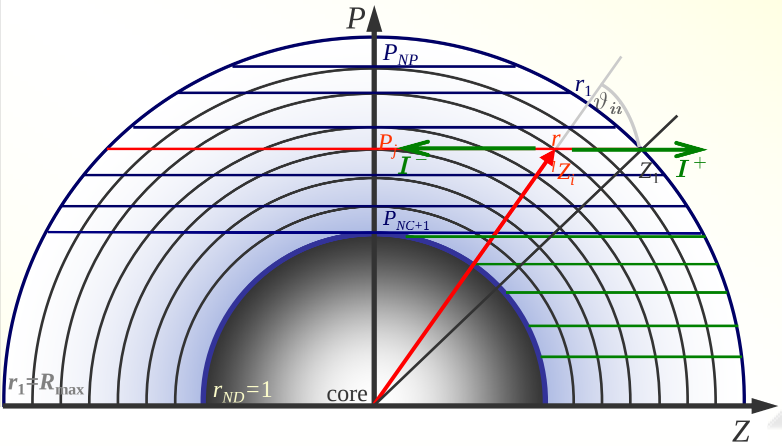
Accurate atomic models have been included

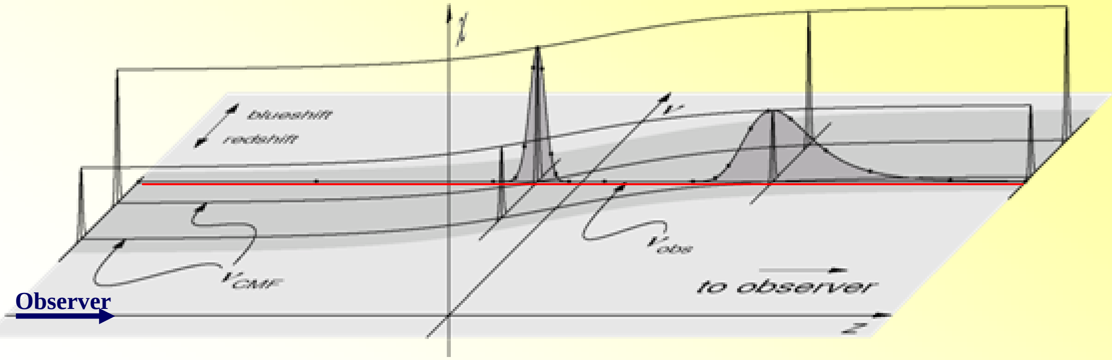
26	elements
149	ionization stages
5,000	levels (+ **100,000**)
20,000	diel. rec. transitions
4 10^6	b-b line transitions
	Auger-ionization

recently improved models are based on Superstructure

Eisner et al., 1974, CPC 8,270

General principle of using adaptive grids also for proplems involving radiative transfer

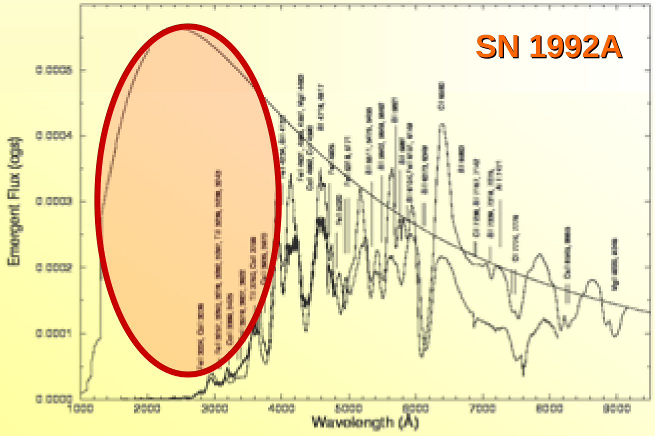




Radiative Transfer

$$(S_\nu - I_\nu)\chi_\nu = \mu\frac{\partial I_\nu}{\partial r} + \frac{1-\mu^2}{r}\frac{\partial I_\nu}{\partial \mu}$$

a very close spatial resolution is required in order to resolve the spectral lines shifted into the line of sight!

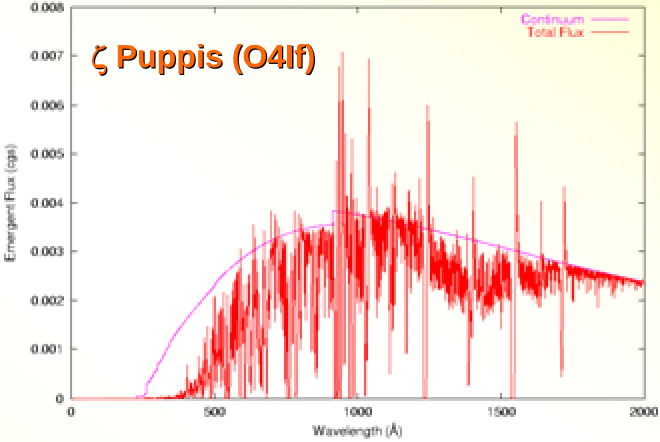


EUV line blocking and blanketing:

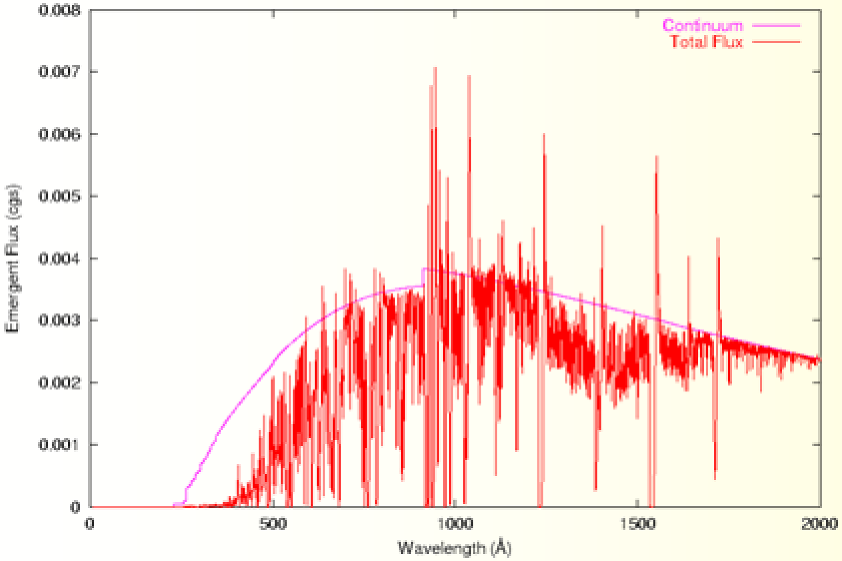
drastic effects on ionization excitation and emergent flux

reason:

the velocity field shifts
at different radii
up to 1000 spectral lines
into the line of sight
at the observer's frequency



Solution of this system presents the required Tool for calculating synthetic spectra

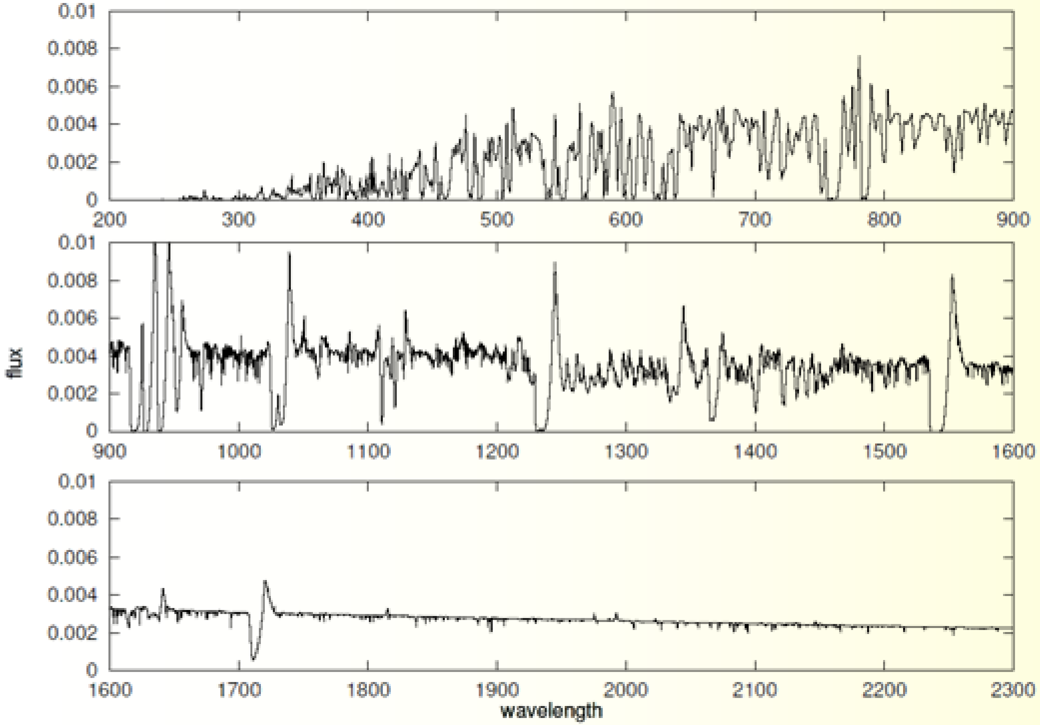


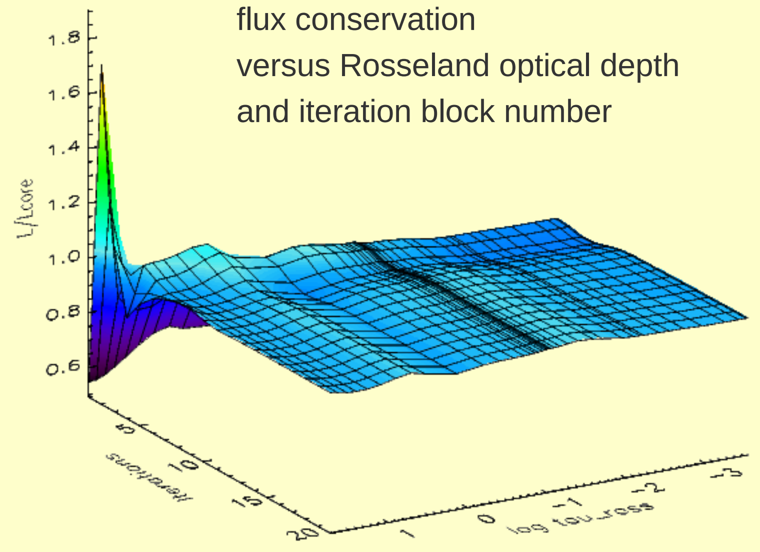
O supergiant exemplary model

$$\mathbf{T_{eff}} = 45000\ \mathbf{K}$$
$$\mathbf{log\ g} = 3.6$$
$$\mathbf{R} = 18\ \mathbf{R_\odot}$$

models lead to realistic results ?

Strategy for quantitative spectral UV analysis



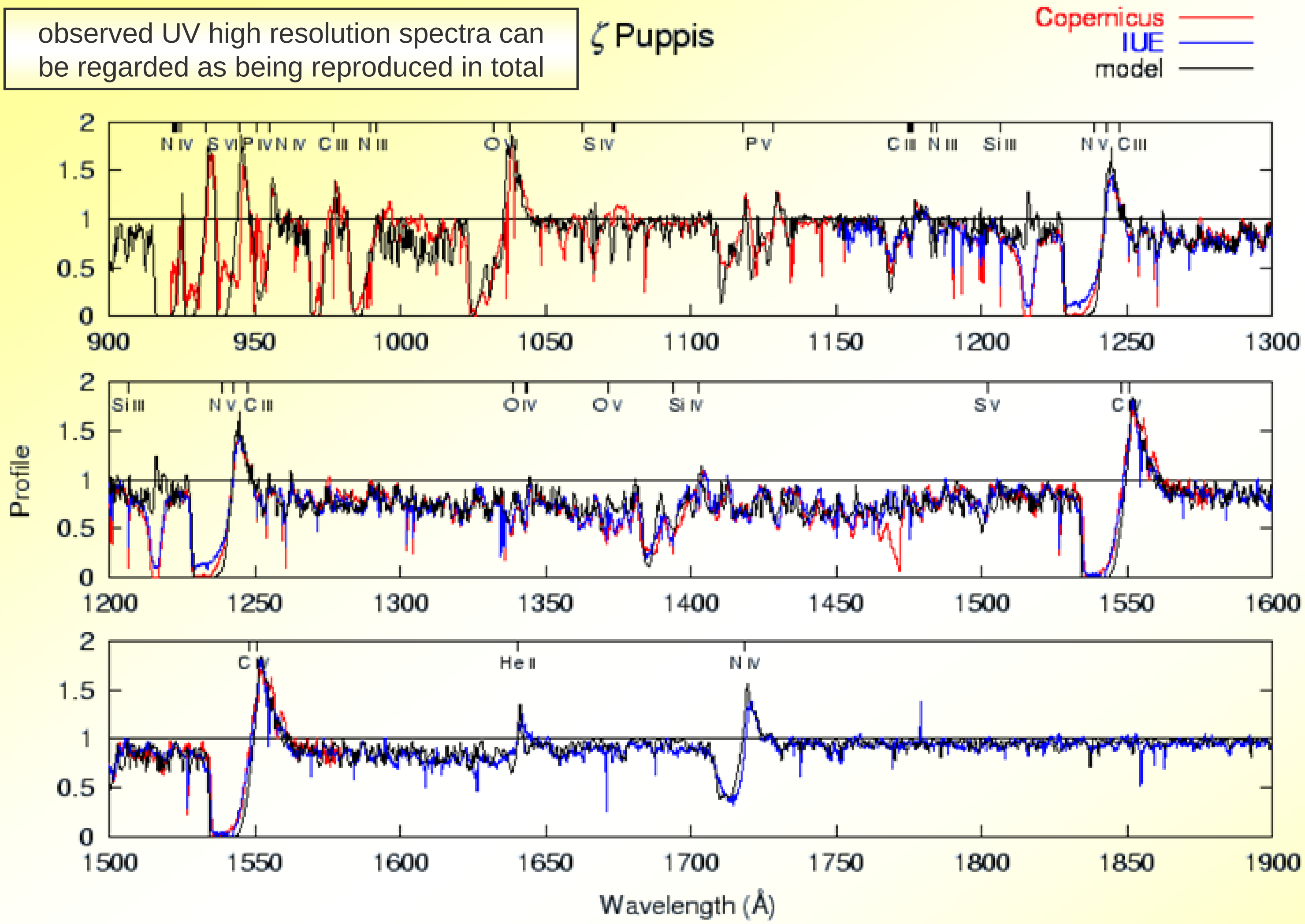


flux conservation
versus Rosseland optical depth
and iteration block number

flux conservation is on the 1% level

Detailed analysis of the hot O-supergiant ζ Puppis – final step

observed UV high resolution spectra can be regarded as being reproduced in total



Values Determined:

stellar parameters

$T_{\mathrm{eff}} = 40$ kK

$\log g = 3.40$

$R/R_{\odot} = 28.$

$v_{\mathrm{rot}}/(\mathrm{km/s}) = 220.$

wind parameters

$\frac{\dot{M}}{10^{-6} M_{\odot}/\mathrm{yr}} = \mathbf{13.7}$

$v_{\infty}/(\mathrm{km/s}) = \mathbf{2120.}$

abundances

$C/C_{\odot} = 1.50$

$N/N_{\odot} = 5.00$

$O/O_{\odot} = 0.10$

$Si/Si_{\odot} = 7.00$

$S/S_{\odot} = 0.50$

$Fe/Fe_{\odot} = 2.00$

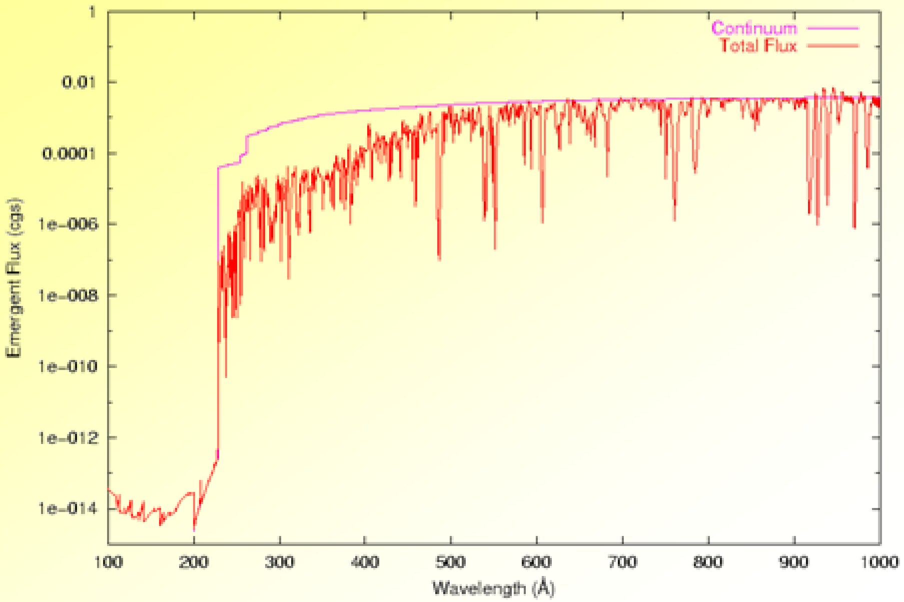
$Ni/Ni_{\odot} = 2.00$

consistent treatment of expanding atmospheres along with **spectrum synthesis techniques** allow the determination of **stellar parameters, wind parameters, and abundances**

present method of quantitative spectral UV analyses of hot stars leads to realistic models !

Pauldrach, 2003, Reviews in Modern Astronomy, Vol. 16

Realistic Spectral Energy Distribution of ζ Puppis

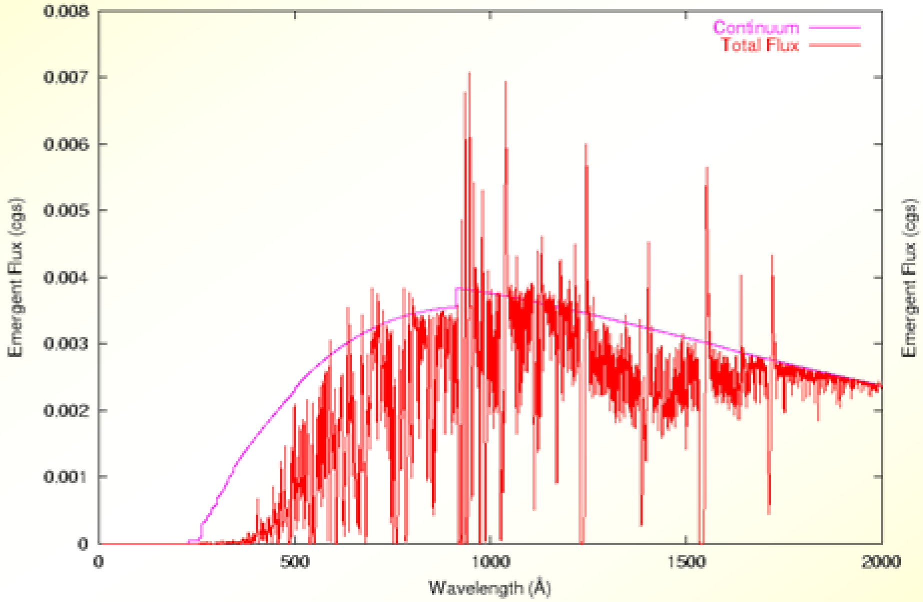


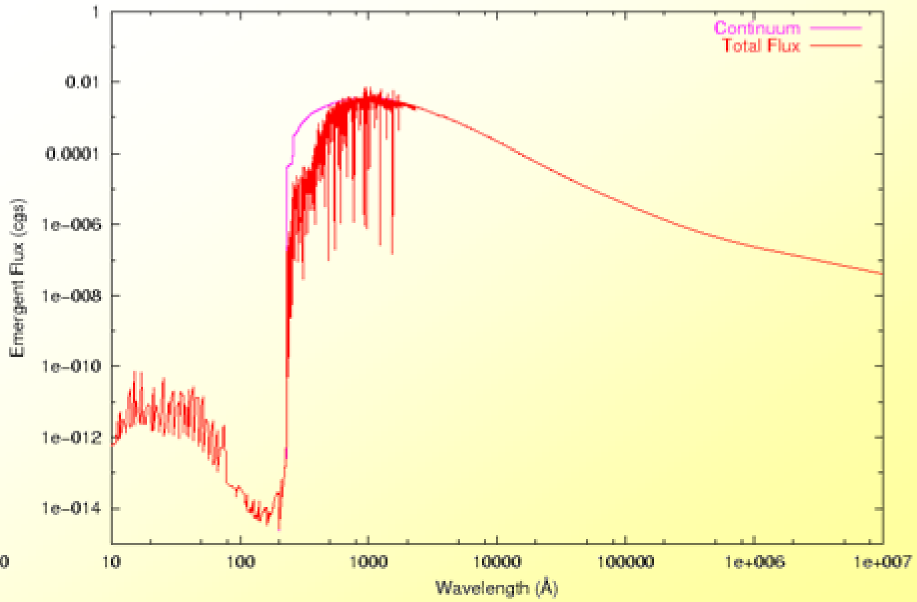
quantitative spectral UV analyses:

ultimate test for the accuracy of theoretical ionizing fluxes

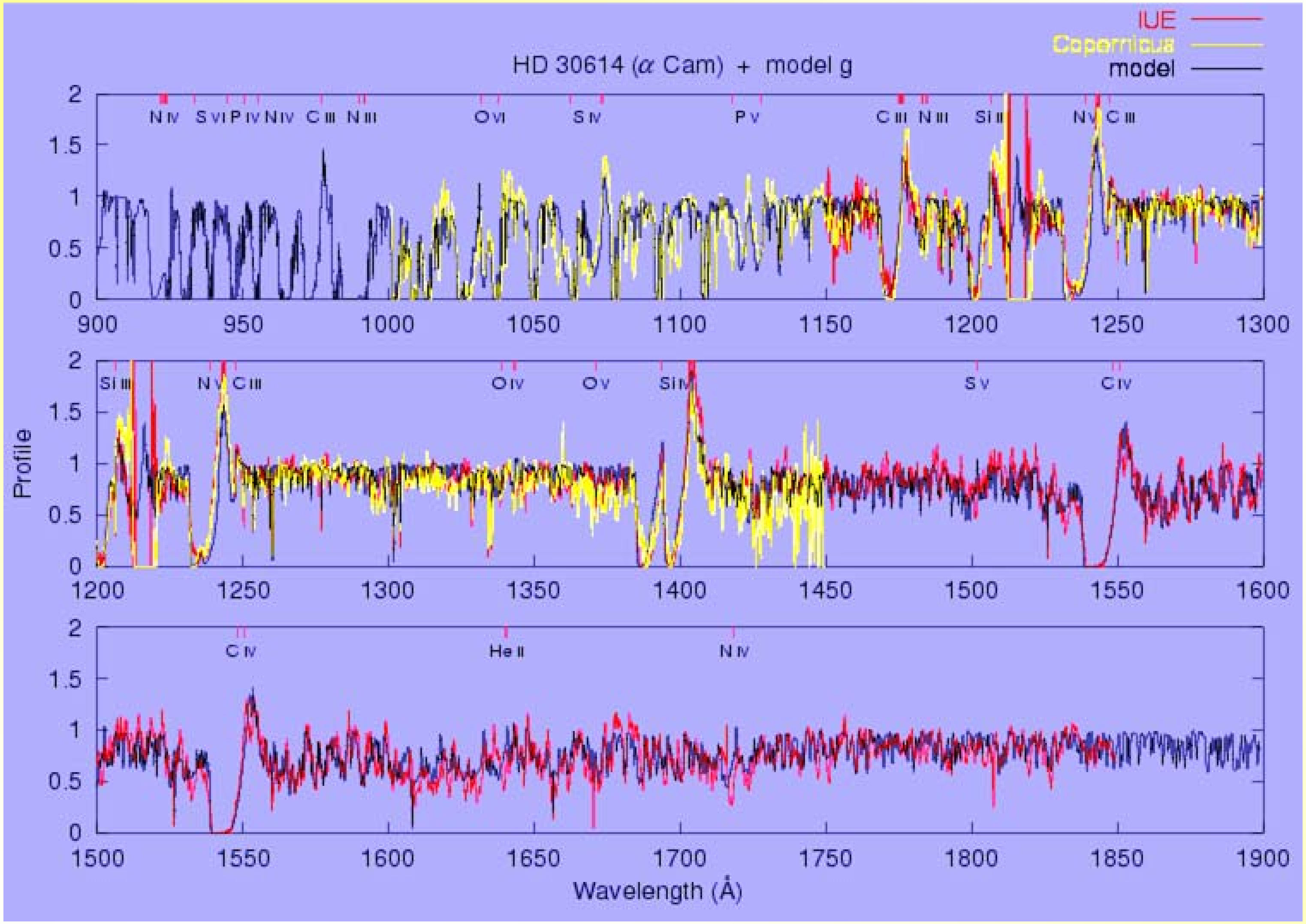
↓

Realistic Spectral Energy Distributions





The method also works for cool O-supergiants - α Cam



$T_{\text{eff}} = 29\ \text{kK}$

$\log g = 3.00$

$R/R_{\odot} = 30$

$\dfrac{\dot{M}}{10^{-6} M_{\odot}/\text{yr}} = 5.0$

$V_{\infty}/(\text{km/s}) = 1500.$

$C/C_{\odot} = 0.05$

$N/N_{\odot} = 1.00$

$O/O_{\odot} = 0.30$

$P/P_{\odot} = 0.05$

$S/S_{\odot} = 1.00$

$Fe/Fe_{\odot} = 1.50$

$Ni/Ni_{\odot} = 1.50$

Spectrum synthesis technique allows the determination of all required parameters
T_{eff} (within 1000 K), log g (within 0.05), R (within 1.0),
and the abundances (within a range of 20%)

Pauldrach, Hoffmann, Lennon, 2001, A&A, 375, 161

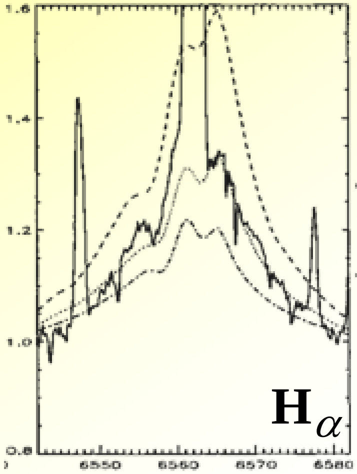
Wind momentum luminosity relation - significance of the dynamical parameters

winds driven by radiation → **mechanical momentum** of wind flow
mostly a function of **photon momentum**

$$\dot{M} v_\infty R^{1/2} \propto L^{3/2}$$

$\dot{M}^{obs}(R/R_\odot)^{0.5}$

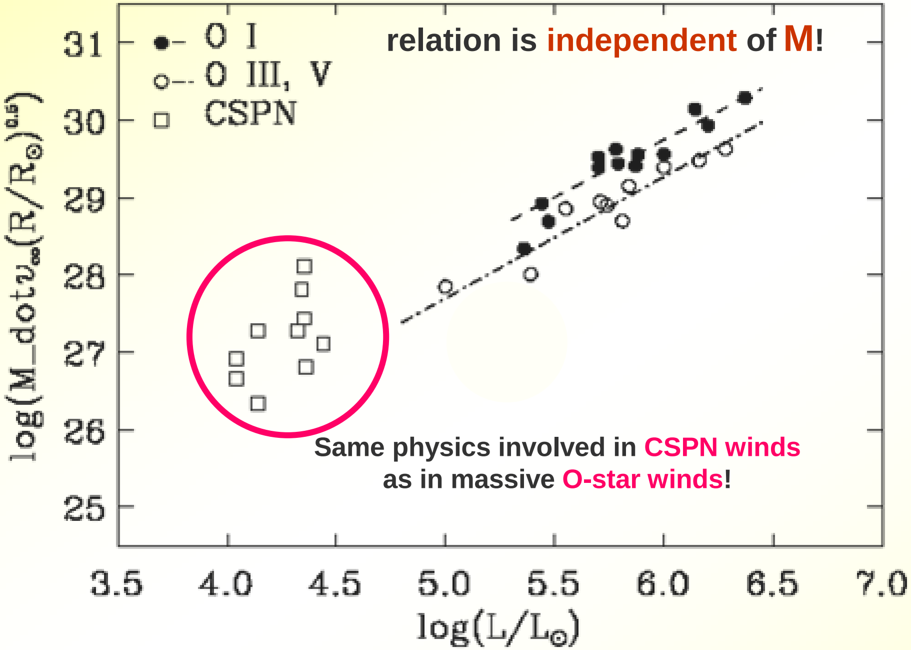
NGC 6826



$$\dot{M} = 3.5 * 10^{-7}\ M_\odot/yr$$

$$\dot{M} = 2.5 * 10^{-7}\ M_\odot/yr$$

$$\dot{M} = 1.9 * 10^{-7}\ M_\odot/yr$$



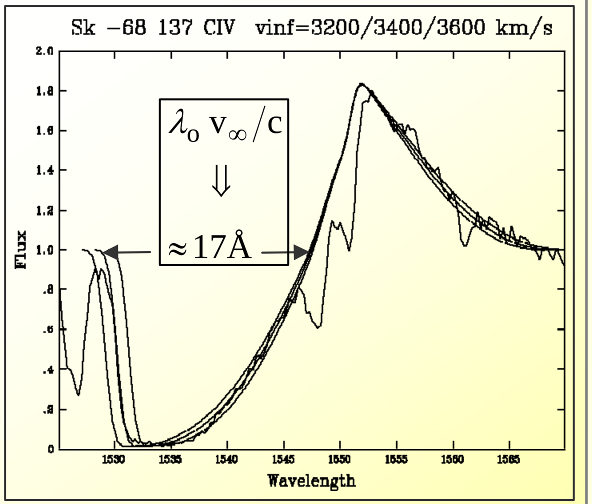
relation is independent of $\dot{M}$!

Same physics involved in CSPN winds
as in massive O-star winds!

Puls et al., 1996, A&A 305; Kudritzki et al.,1997, IAU Symp. 180

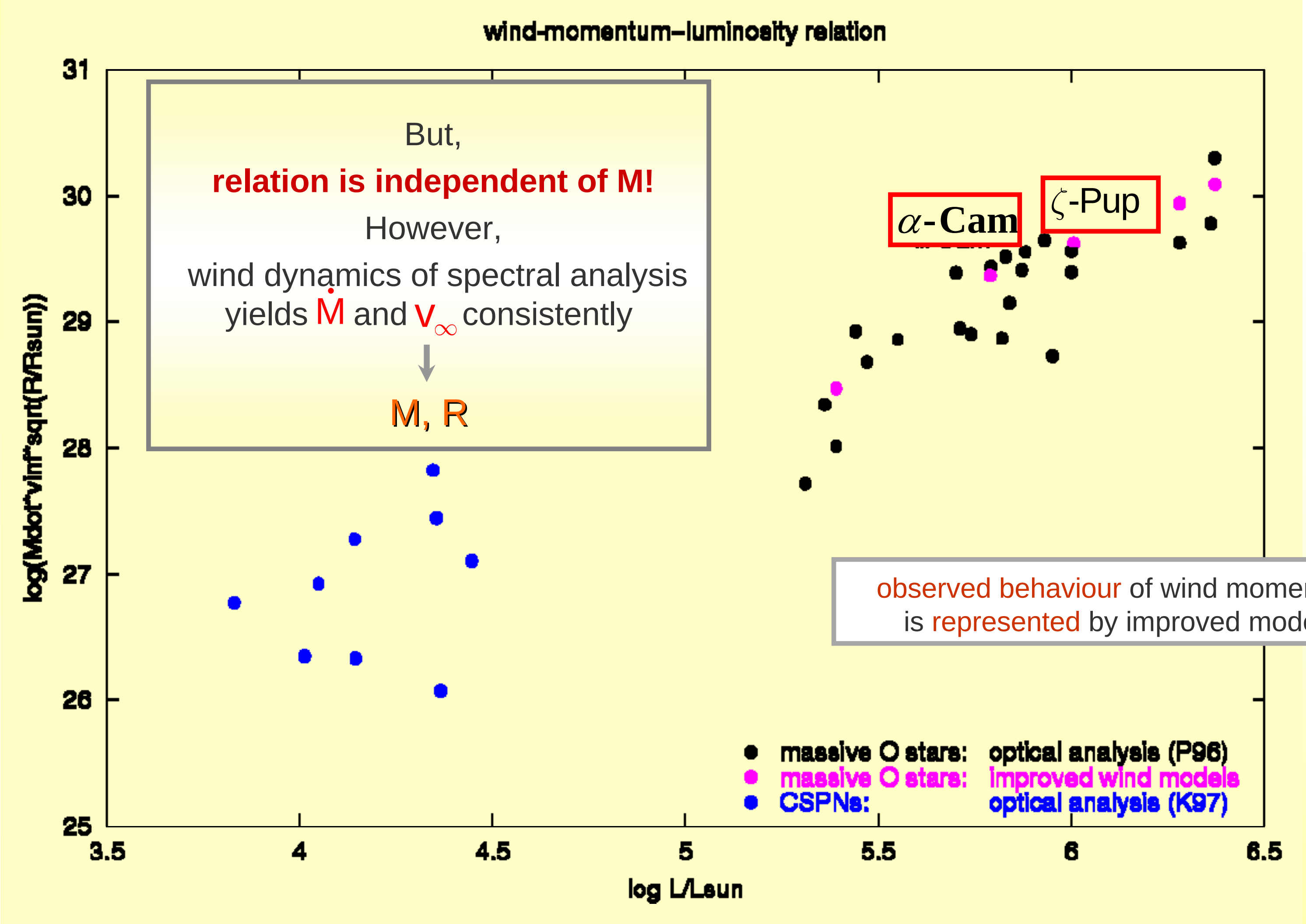
v_∞^{obs}

C IV (λλ1548,1551Å)



v_∞ can be measured directly

Wind momentum luminosity relation of massive O-stars



But,

relation is independent of M!

However,

wind dynamics of spectral analysis yields $\dot{M}$ and v_∞ consistently

↓

M, R

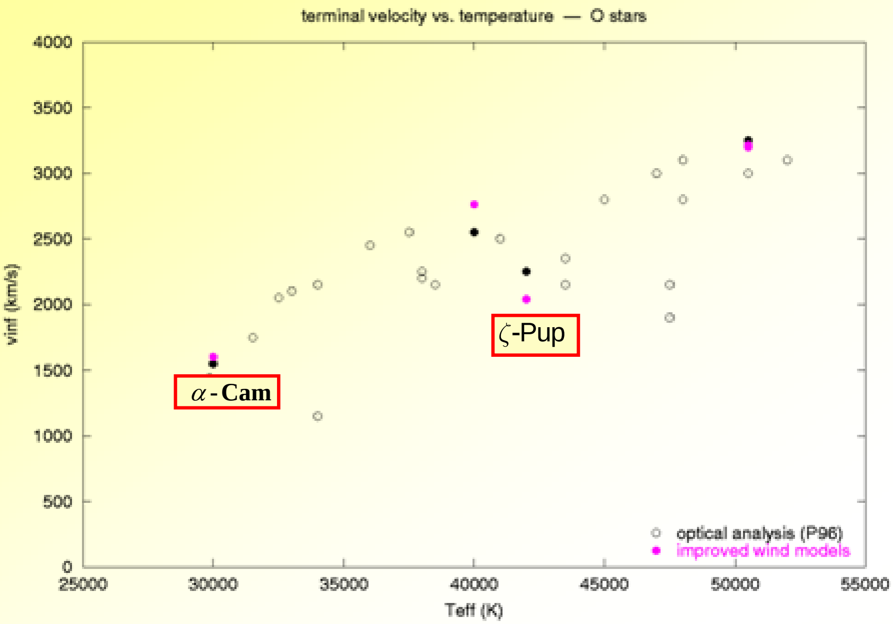
observed behaviour of wind momentum is represented by improved models

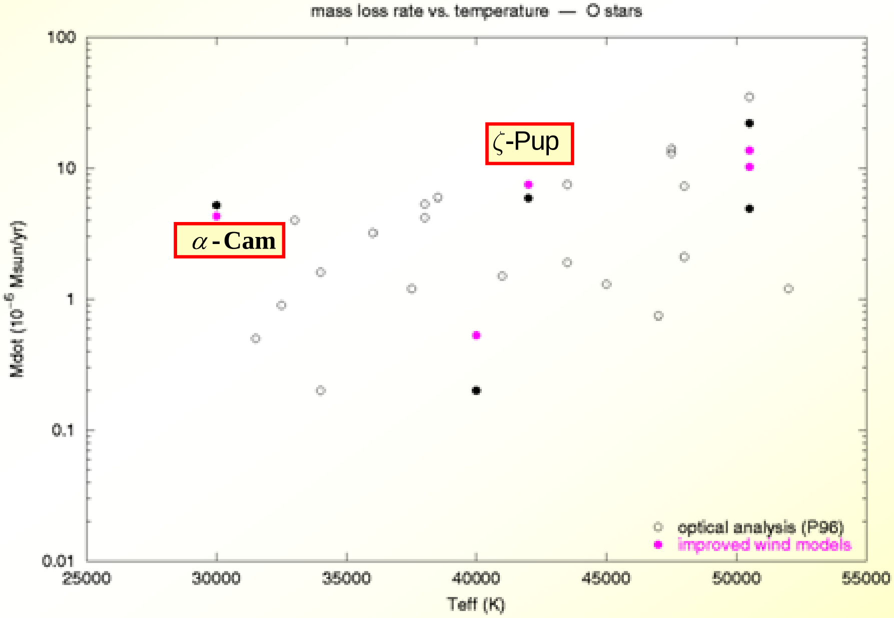
$$\dot{M} v_\infty R^{1/2} \propto L^{3/2}$$

observed values from Puls et al., 1996, A&A 305; Kudritzki et al.,1997, IAU Symp. 180

Pauldrach , Hoffmann, Mendez, 2004, A&A, 419, 1111

Wind properties of massive O-stars





Pauldrach , Hoffmann, Mendez, 2004, A&A, 419, 1111

$$v_\infty \propto v_{esc} = \left(\frac{2GM}{R}(1-\Gamma)\right)^{1/2}$$

predicted terminal velocities
of improved models
agree within 10% with observed values

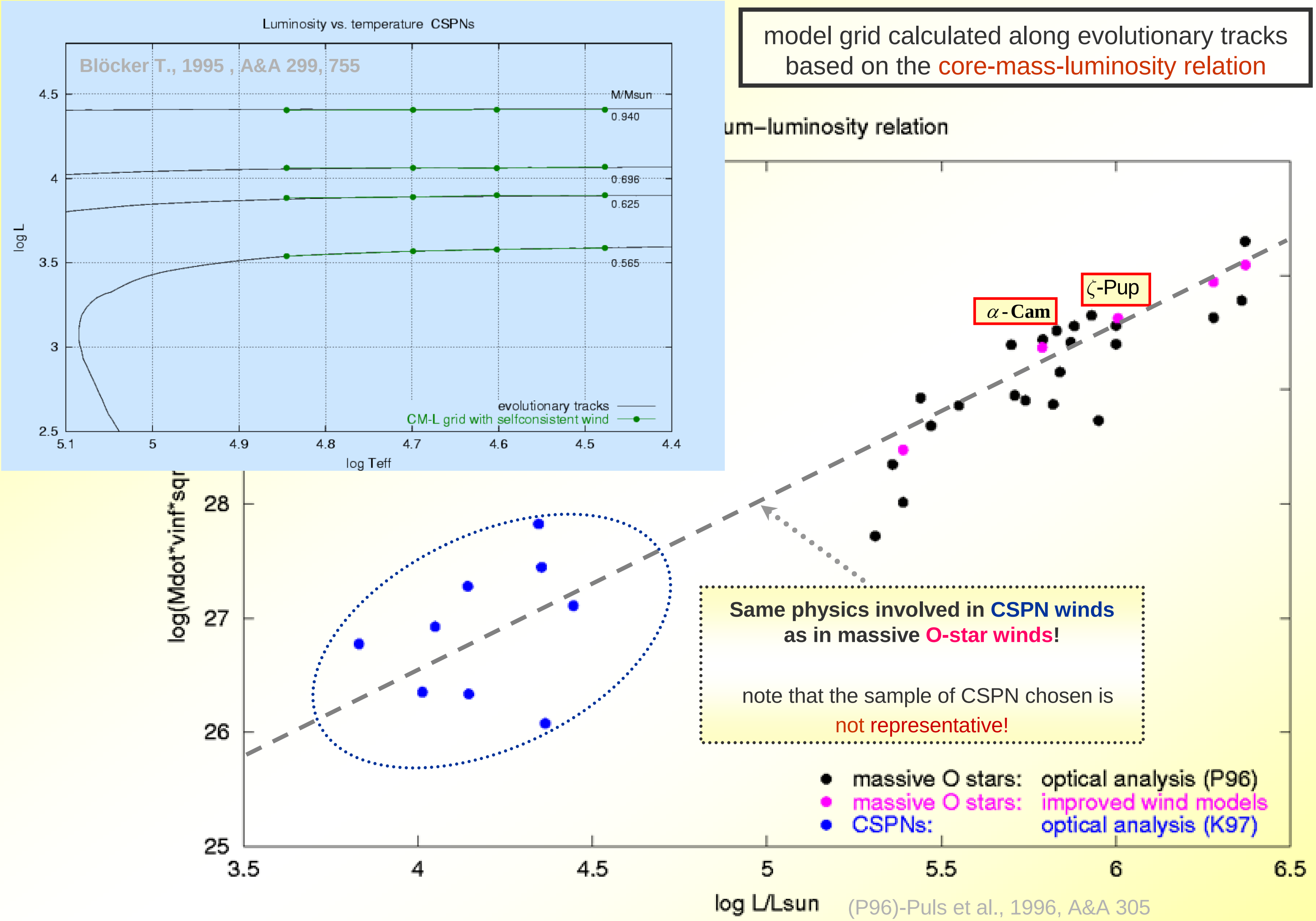
predicted mass-loss-rates
of improved models
agree within a factor smaller than 2 with
observed optical values

$$\dot{M} \propto L$$

M , R

Wind properties of CSPN's

model grid calculated along evolutionary tracks
based on the core-mass-luminosity relation



Same physics involved in CSPN winds as in massive O-star winds!

note that the sample of CSPN chosen is
not representative!

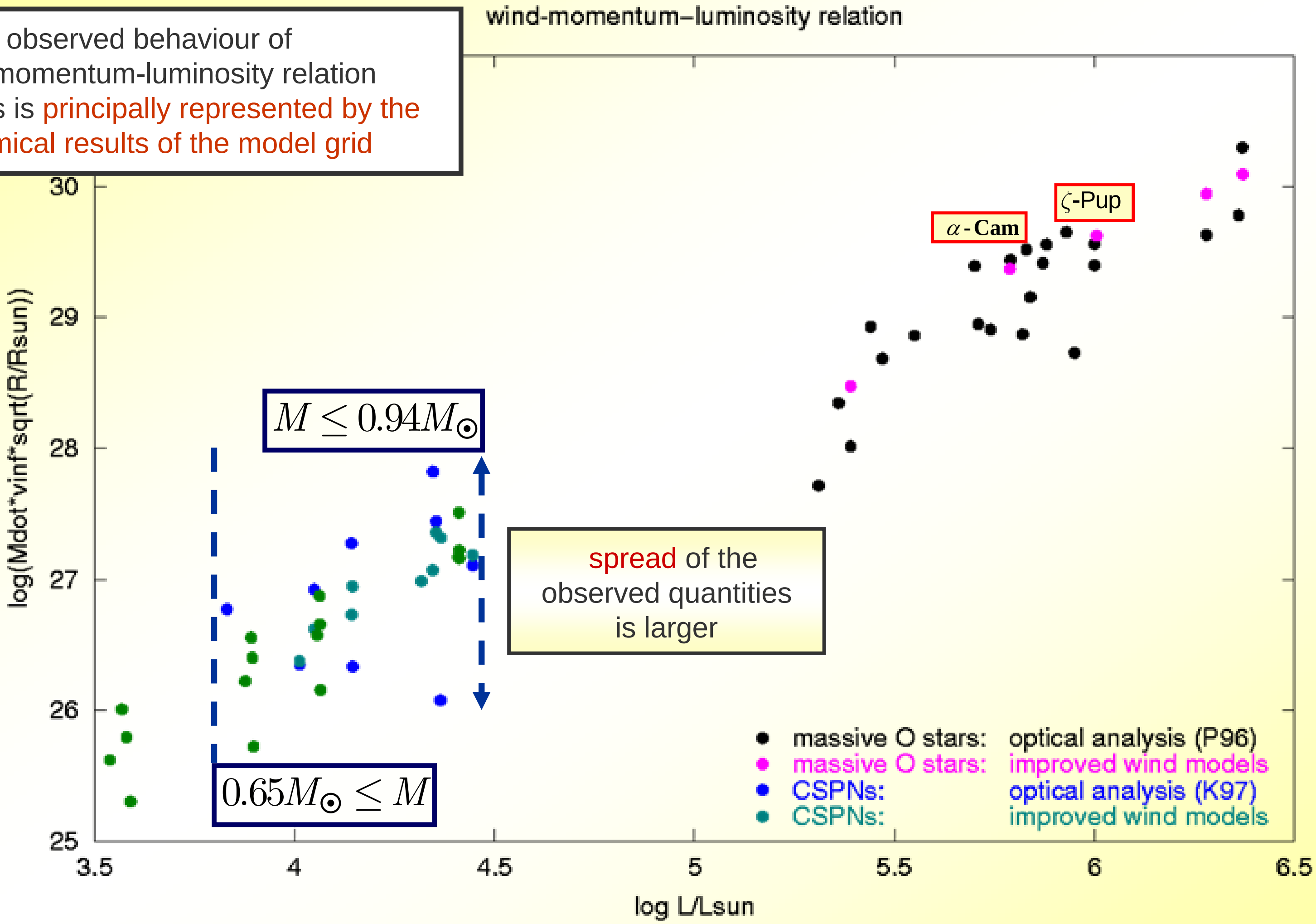
(P96)-Puls et al., 1996, A&A 305
(K97)-Kudritzki et al., 1997, IAU Symp. 180

$$\boxed{\dot{M} v_\infty R^{1/2} \propto L^{3/2}}$$

Wind properties of CSPN's

model grid calculated along evolutionary tracks based on the core-mass-luminosity relation

observed behaviour of wind-momentum-luminosity relation of CSPNs is principally represented by the dynamical results of the model grid



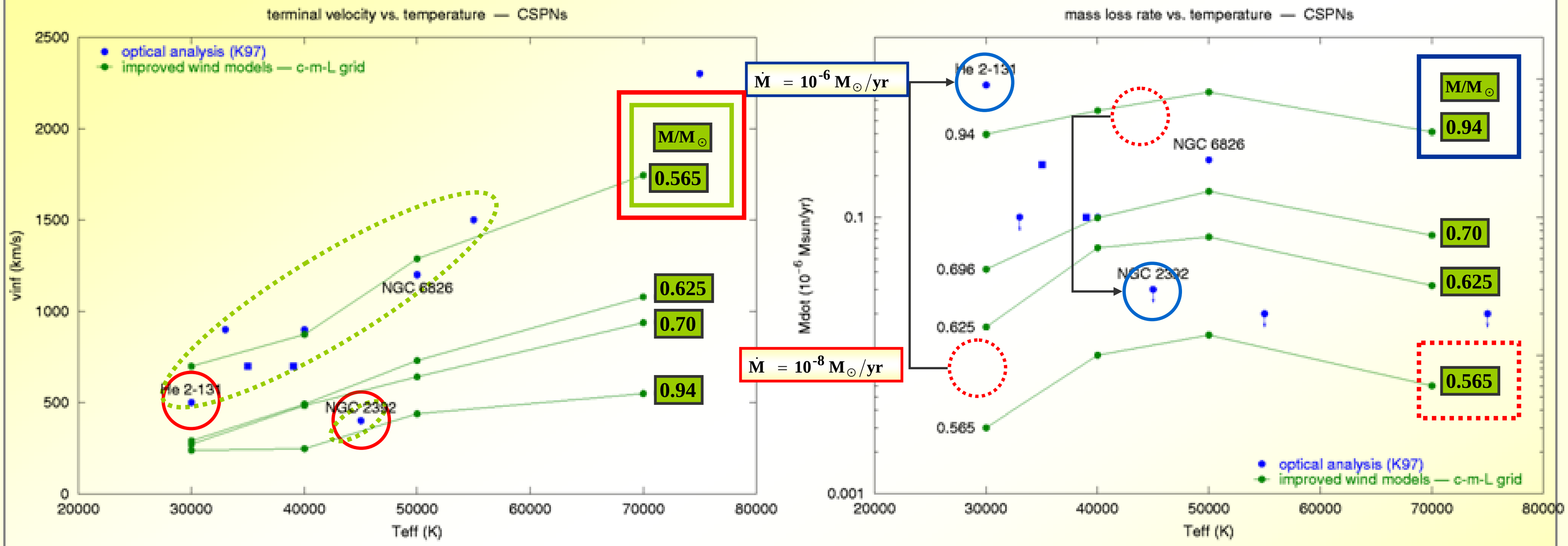
spread of the observed quantities is larger

$$\dot{M} v_\infty R^{1/2} \propto L^{3/2}$$

Pauldrach, Hoffmann, Mendez, 2004, A&A 419, 1111

Wind properties of CSPN's

wind models calculated along evolutionary tracks based on the
core-mass-luminosity relation



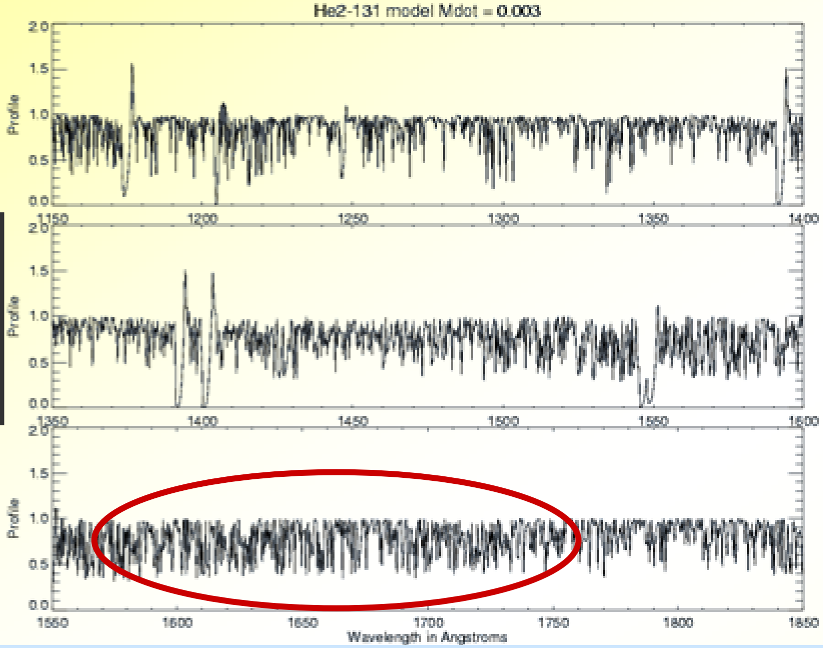
terminal velocities
indicate mostly small masses **< 0.6 Msun**
apart from NGC 2392
for which a high mass of **~ 0.9 Msun**
is indicated

mass loss rates
indicate for 6 objects high masses **> 0.7 Msun**
but for NGC 2392
a small mass of **< 0.6 Msun**
is indicated

next step:
UV-diagnostics with models based on **stellar parameters**
consistent with the terminal velocities

Analysis of the UV-spectrum of He2 131

wind model based on stellar parameters consistent with the evolutionary tracks and the terminal velocity



$T_{eff} = 30$ kK

$\log L/L_\odot = 3.59$

$\log g = 3.47$

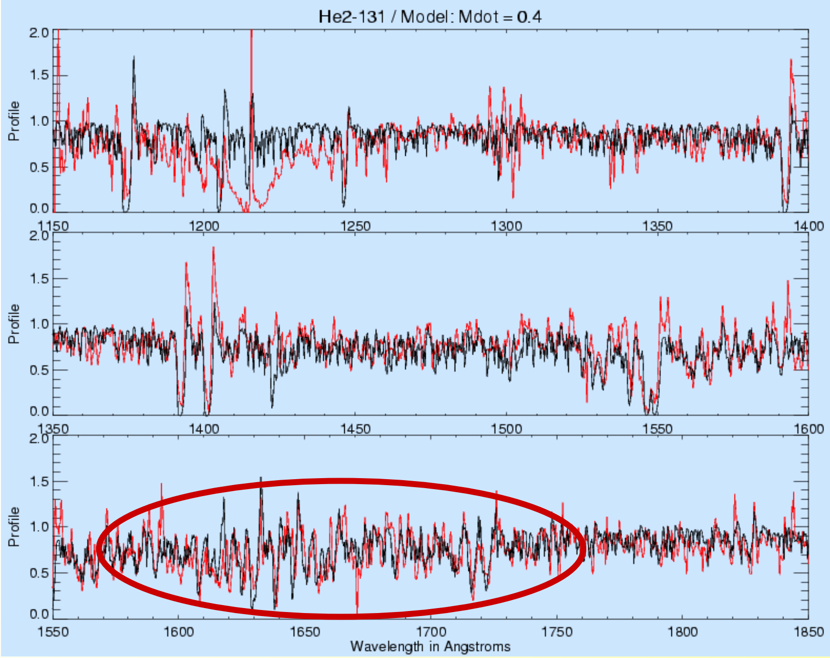
$R/R_\odot = 2.3$

$$\frac{\dot{M}}{10^{-6} M_\odot/yr} = 0.003$$

$v_\infty/(km/s) = 470.$

UV-diagnostics:

stellar parameters deduced from a comparison of observed and synthetic spectra



$T_{eff} = 33$ kK

$\log L/L_\odot = 4.51$

$\log g = 3.1$

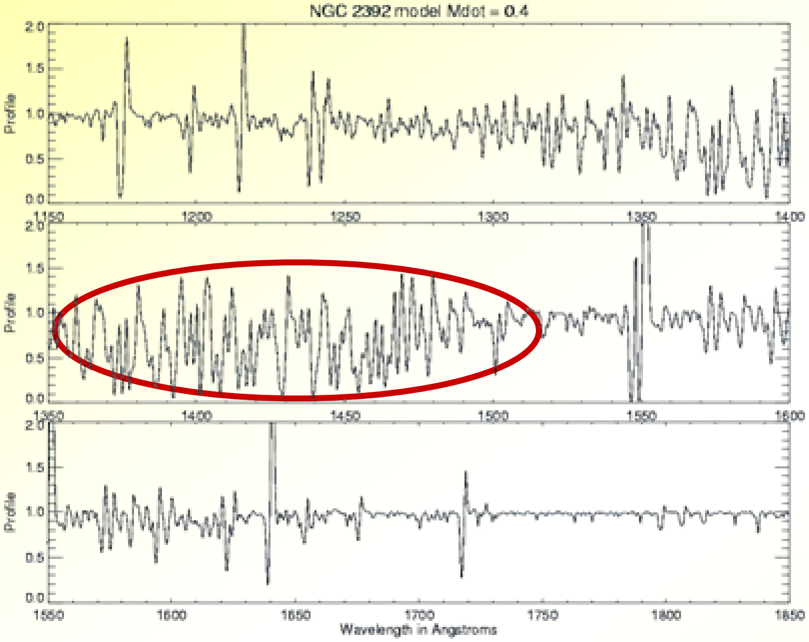
$R/R_\odot = 5.5$

$$\frac{\dot{M}}{10^{-6} M_\odot/yr} = 0.35$$

$v_\infty/(km/s) = 450.$

Analysis of the UV-spectrum of NGC 2392

wind model based on stellar parameters consistent with the evolutionary tracks and the terminal velocity



$T_{\rm eff} = 45$ kK

$\log L/L_\odot = 4.365$

$\log g = 3.6$

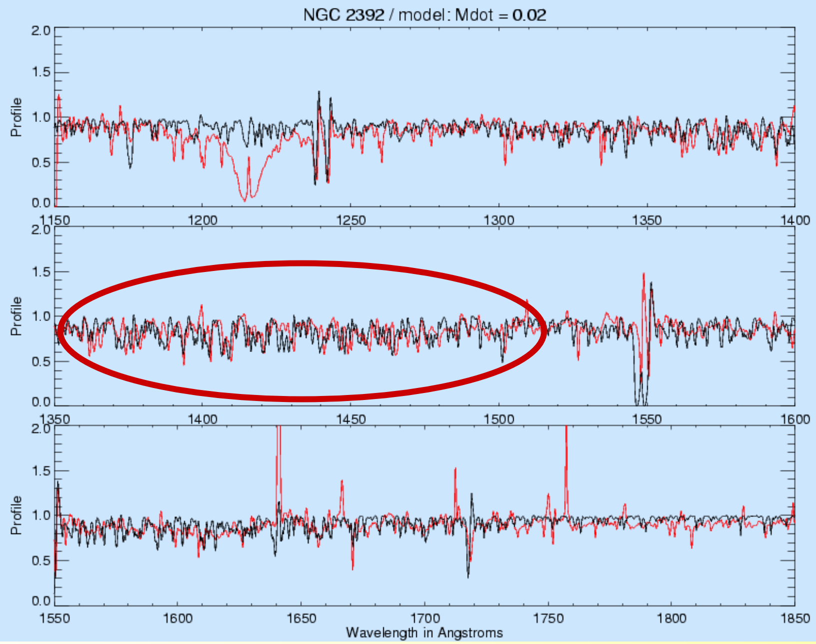
$R/R_\odot = 2.5$

$\frac{\dot{M}}{10^{-6} M_\odot/{\rm yr}} = 0.38$

$v_\infty/({\rm km/s}) = 400.$

UV-diagnostics:

stellar parameters deduced from a comparison of observed and synthetic spectra



$T_{\rm eff} = 40$ kK

$\log L/L_\odot = 3.72$

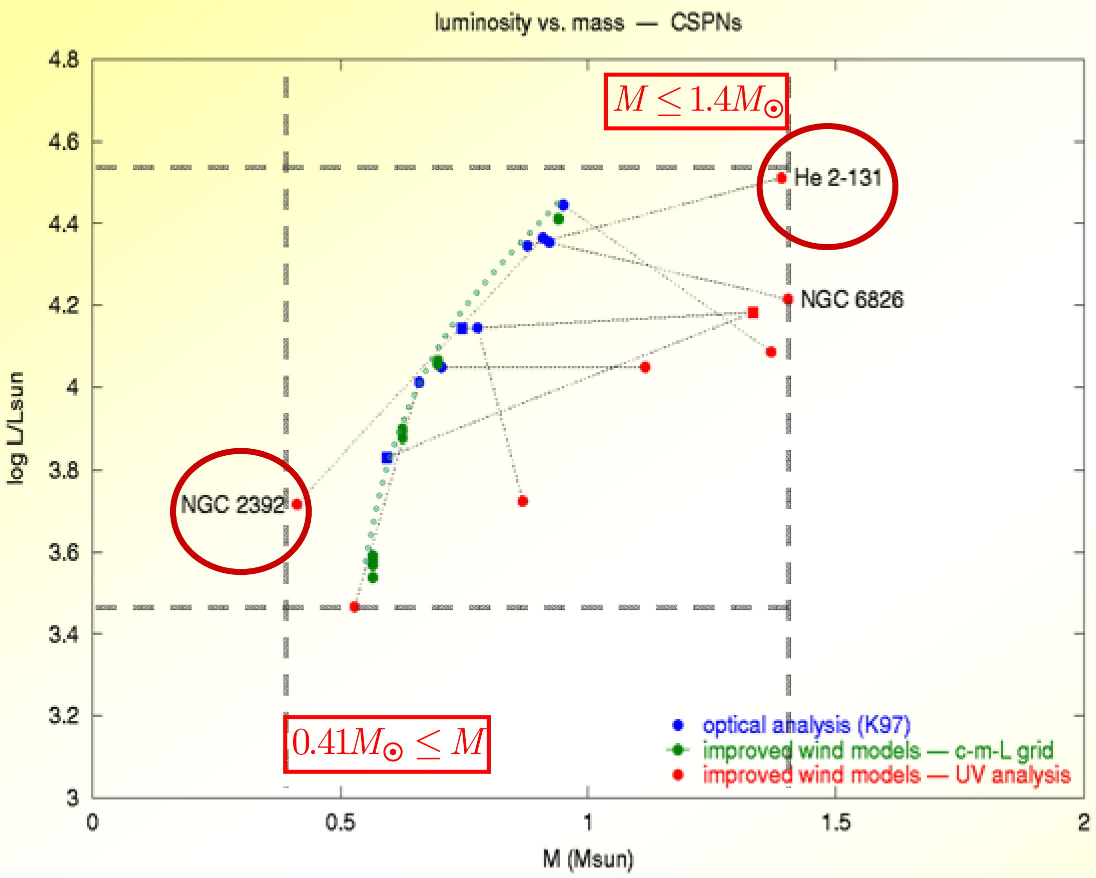
$\log g = 3.7$

$R/R_\odot = 1.5$

$\frac{\dot{M}}{10^{-6} M_\odot/{\rm yr}} = 0.018$

$v_\infty/({\rm km/s}) = 420.$

Luminosities and masses of the CSPN sample



luminosities are in the expected range

Object	$T_{\rm eff}$ (K)	R ($R_\odot$)	$\log \frac{L}{L_\odot}$	M ($M_\odot$)	$\dot{M}$ ($10^{-6} M_\odot$/yr)	v_∞ (km/s)
NGC 2392	40000	1.5	3.7	0.41	0.018	420
NGC 3242	75000	0.3	3.5	0.53	0.004	2400
IC 4637	55000	0.8	3.7	0.87	0.019	1500
IC 4593	40000	2.2	4.0	1.11	0.062	850
He 2-108	39000	2.7	4.2	1.33	0.072	800
Tc 1	35000	3.0	4.1	1.37	0.021	900
He 2-131	33000	5.5	4.5	1.39	0.35	450
NGC 6826	44000	2.2	4.2	1.40	0.18	1200

Object	$T_{\rm eff}$ (K)	R ($R_\odot$)	$\log \frac{L}{L_\odot}$	M ($M_\odot$)	$\dot{M}$ ($10^{-6} M_\odot$/yr)	v_∞ (km/s)
NGC 2392	45000	2.5	4.4	0.91	$\le$ 0.03	400
NGC 3242	75000	0.6	4.0	0.66	$\le$ 0.02	2300
IC 4637	55000	1.3	4.1	0.78	$\le$ 0.02	1500
IC 4593	40000	2.2	4.0	0.70	0.1	900
He 2-108	35000	3.2	4.1	0.75	0.24	700
Tc 1	33000	5.1	4.4	0.95	$\le$ 0.1	900
He 2-131	30000	5.5	4.3	0.88	0.9	500
NGC 6826	50000	2.0	4.3	0.92	0.26	1200

very large spread in the masses
(0.4–1.4 Msun)

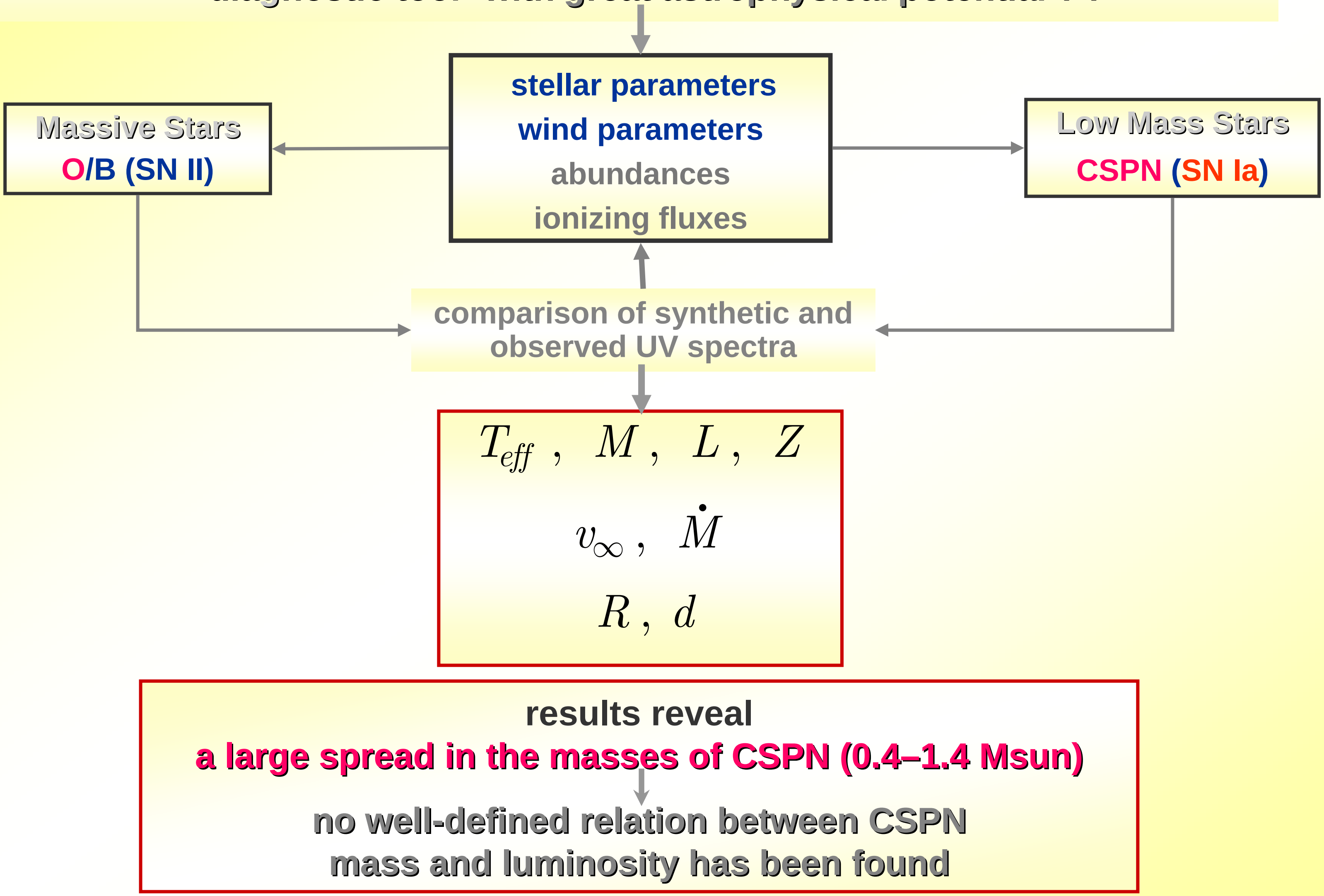
for the sample of CSPN chosen there is no well-defined relation between mass and luminosity !

Pauldrach, Hoffmann, Mendez, 2004, A&A 419, 1111

Conclusions

Consistent state of the art models for expanding atmospheres of hot stars

a diagnostic tool* with great astrophysical potential ? !



stellar parameters
wind parameters
abundances
ionizing fluxes

Massive Stars
O/B (SN II)

Low Mass Stars
CSPN (SN Ia)

comparison of synthetic and observed UV spectra

$$T_{eff}\ ,\quad M\ ,\quad L\ ,\quad Z$$

$$v_\infty\ ,\quad \dot{M}$$

$$R\ ,\quad d$$

results reveal
a large spread in the masses of CSPN (0.4–1.4 Msun)

no well-defined relation between CSPN mass and luminosity has been found

* download of the program package -including an easy to use interface- is possible from
http://www.usm.uni-muenchen.de/people/adi/adi.html