Institute of
Astronomy
and Astrophysics
at the
Ludwig-Maximilian
University
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Theory - Models

non-equilibrium thermodynamics (NLTE)
radiation hydrodynamics

Observations Motivation

Application Spectral Diagnostics

Boltzmann - equation

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

time development of the distribution functions

Hot Stars

T_{eff} = 15000 - 100000 K

show wind features

sub-group

Low Mass Stars

0.4 - 1.44 $M_\odot$

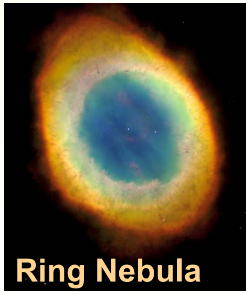
CSPN (SN Ia)

old, 10^{10} yr

luminous, $10^4 L_\odot$

rare, evolution

radiation, UV/EUV



sub-group

Massive Stars

20 - 150 $M_\odot$

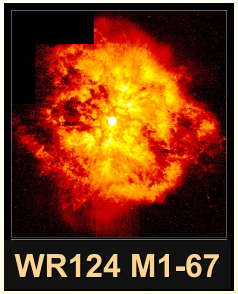
O/B (WR SN II)

young, 10^6 yr

luminous, $10^6 L_\odot$

rare, IMF

radiation, UV/EUV



Expanding Atmospheres

characterized by

high radiation energy density

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

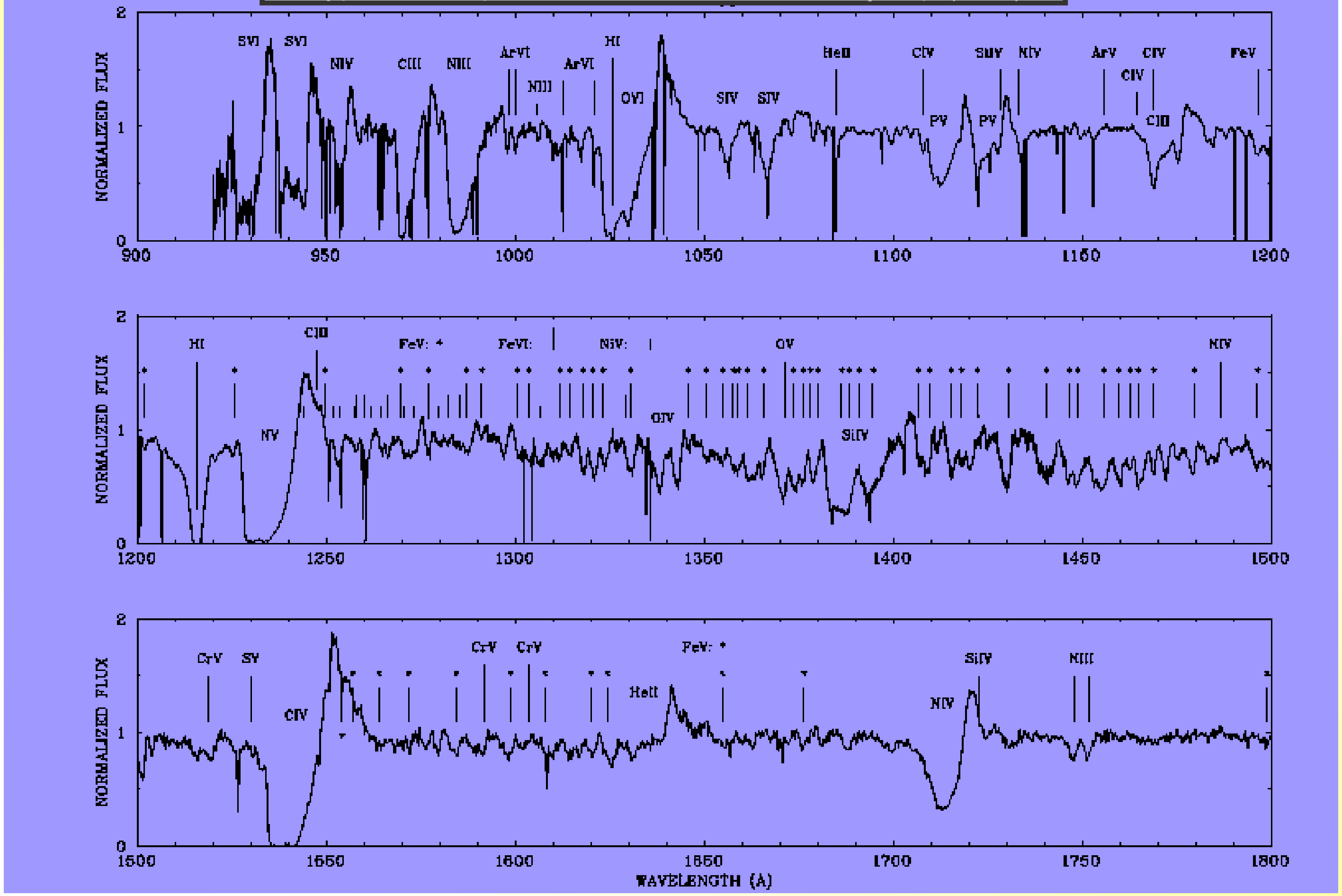
$\dot{M}\ v_\infty \leq 4000$ km/s

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)



Signatures of P-Cygni lines

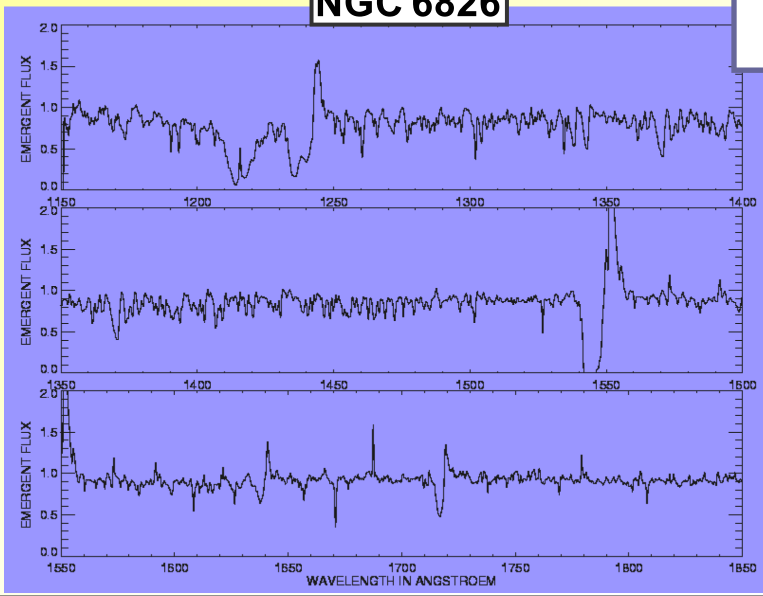
SVI,CIII,NIII,OVI,PV,NV,OIV,OV,SiIV,CIV,HEII,NIV

Hundreds of strongly wind contaminated lines

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

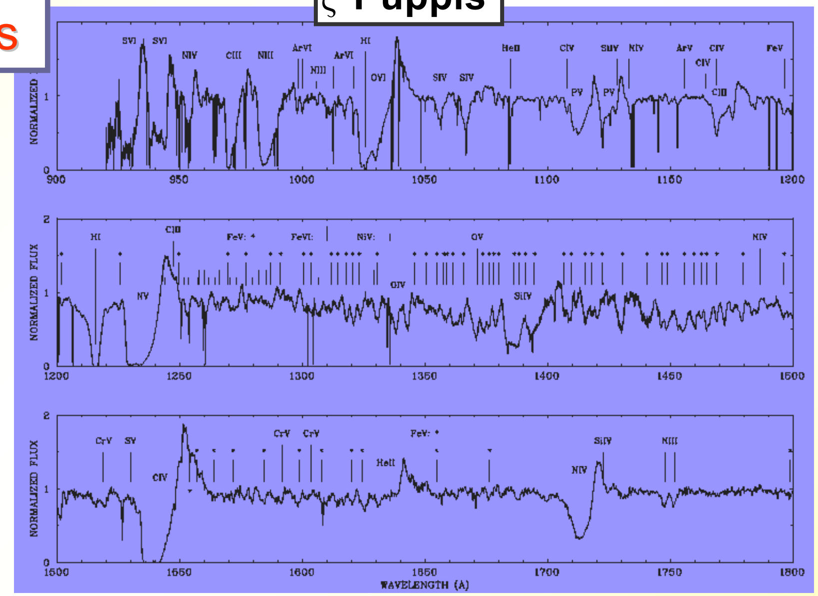
Realistic Synthetic UV Spectra of O-type Stars
A Diagnostic Tool with great Astrophysical Potential !?

NGC 6826



Hot Stars

ζ Puppis



spectra of O-type CSPN's

similar to

spectra of massive O-type stars

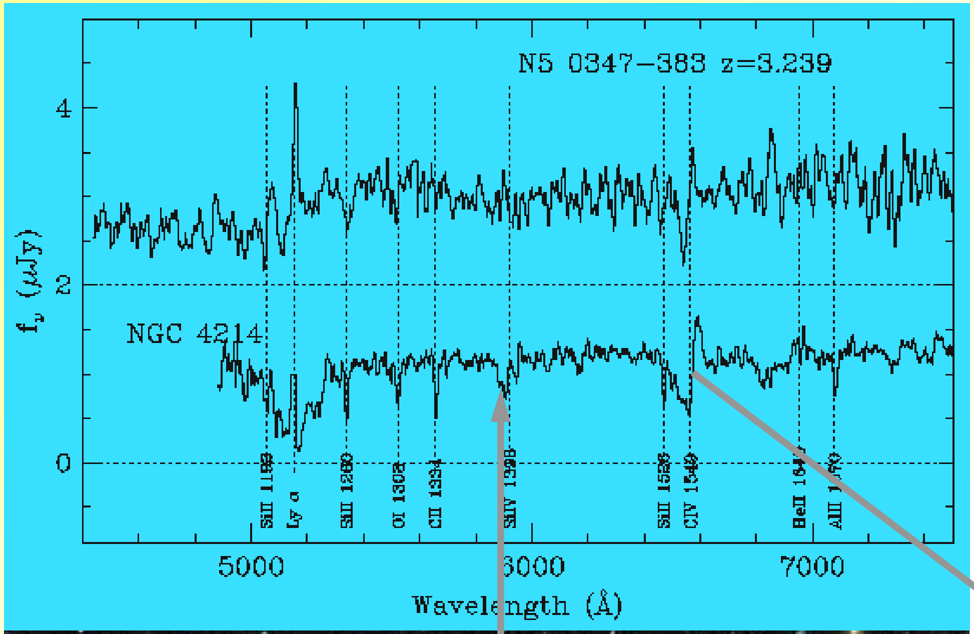
Spectra contain information about stellar and wind parameters and abundances

Spectra available 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 !

Motivation: Galaxies and Galaxy Clusters are Trendy !



Needful Things
for diagnostic issues
Synthetic UV Spectra of O-type Stars

Corresponding Spectrum of a Starburst Galaxy at z=3

Keck spectrum of a $z > 3$ galaxy, chosen to illustrate the variety of features encountered.

For comparison a recent HST spectrum of the central starburst region in the Wolf-Rayet galaxy NGC4214 is also shown.

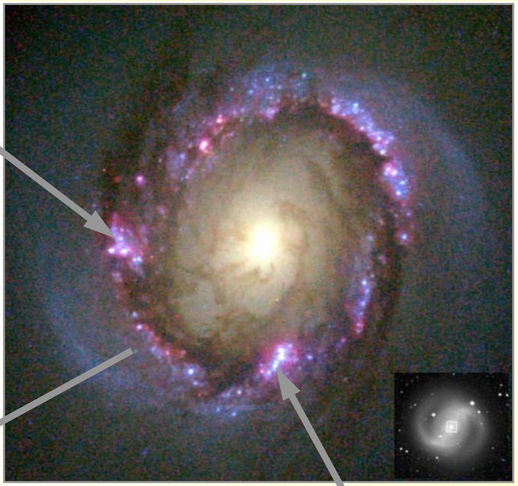
Note the characteristic P-Cygni lines – CIV, SiIV

Steidel et al., 1996, Ap.J.L. 462, L17

Distance:~12 Mpc

located in the constellation of Coma Berenices.

© Hubble Space Telescope



Starburst Ring

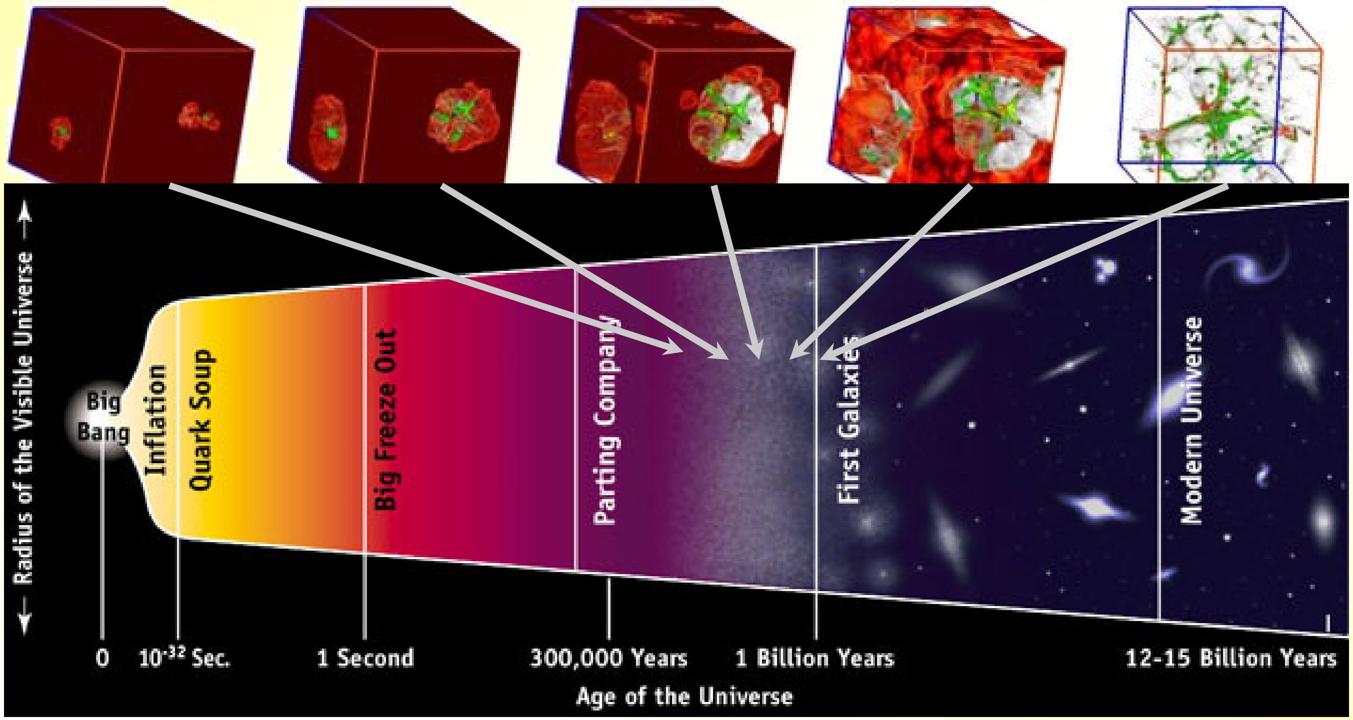
Dominated by Massive Stars

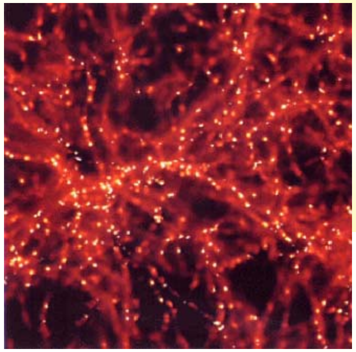
End of Cosmic Dark Ages

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





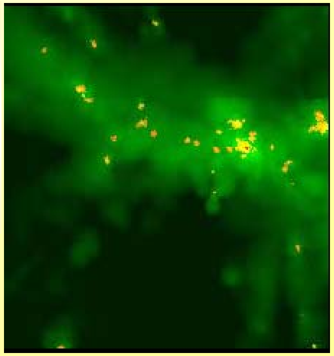
Population III stars ($Z<10^{-3}$)
are important for the reionization

Carr et al.,1984,ApJ 277, 445

but

ionization history of the IGM depends crucially on the **IMF of the First Stars**

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

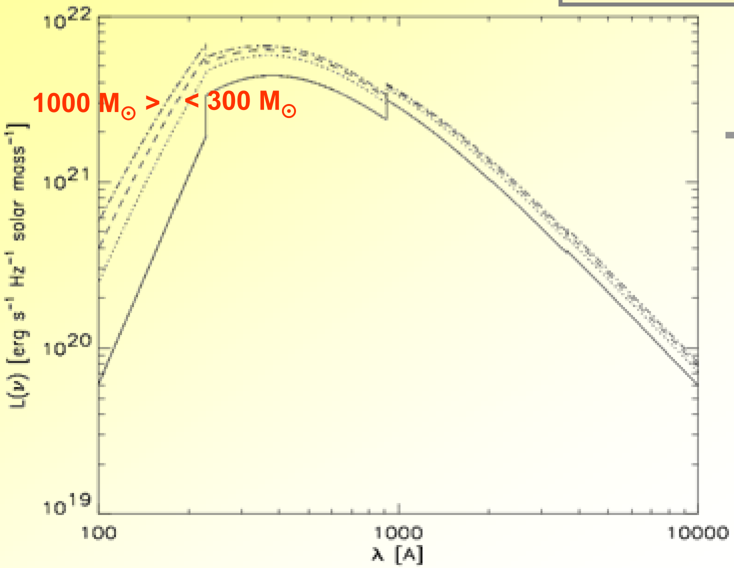


Numerical simulation of the first stars in the universe

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

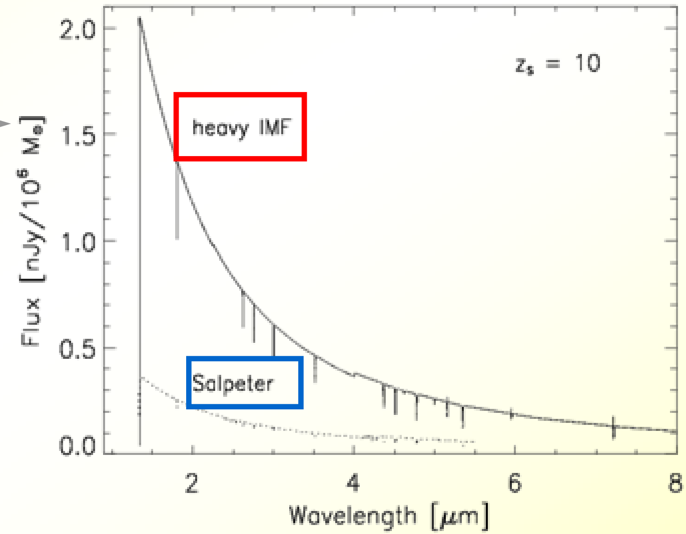
In the **Early Universe Population III stars** favoured the formation of very **Massive Stars**

$M > 100\ M_\odot$



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, 687

IMF becomes top-heavy



Predicted flux from a Population III star cluster at z=10
A flat universe with $\Omega_\Lambda = 0.7$ is assumed.
The cutoff is due to complete Gunn-Peterson absorption (1965, ApJ, 142, 1633).
Observable 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

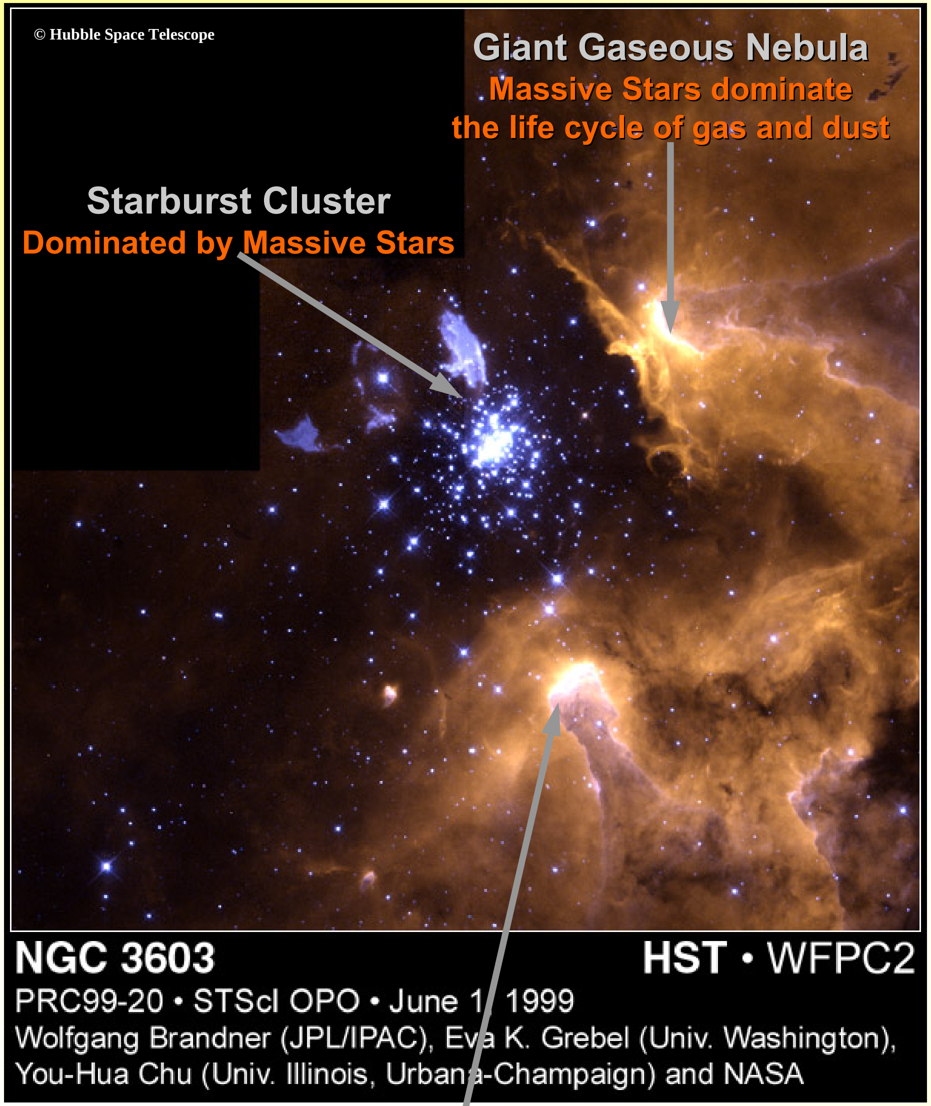
Two points are missing:

observations for starbursting galaxies at high redshift

and

Synthetic UV Spectra of O-type Stars for metallicities Z >0

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



Realistic Spectral Energy Distributions
of massive stars and stellar clusters are required
to analyze the excited HII regions

Giant Galactic Nebula NGC 3603

various stages of the life cycle of stars are.captured

© Hubble Space Telescope

Near the center of the view is a Starburst Cluster dominated by young, early O-type stars

The Interaction of ionizing radiation with cold molecular-hydrogen cloud material results in the giant gaseous nebula structures to the right of the cluster.

In the Carina spiral arm of the Galaxy at a distance of about 6 kpc
field 2.5 x 2.5 $arcmin^2$ (~ 6 x 6 pc^2)

Massive stars dominate the life cycle of gas and dust in several types of galaxies

Interaction leads to

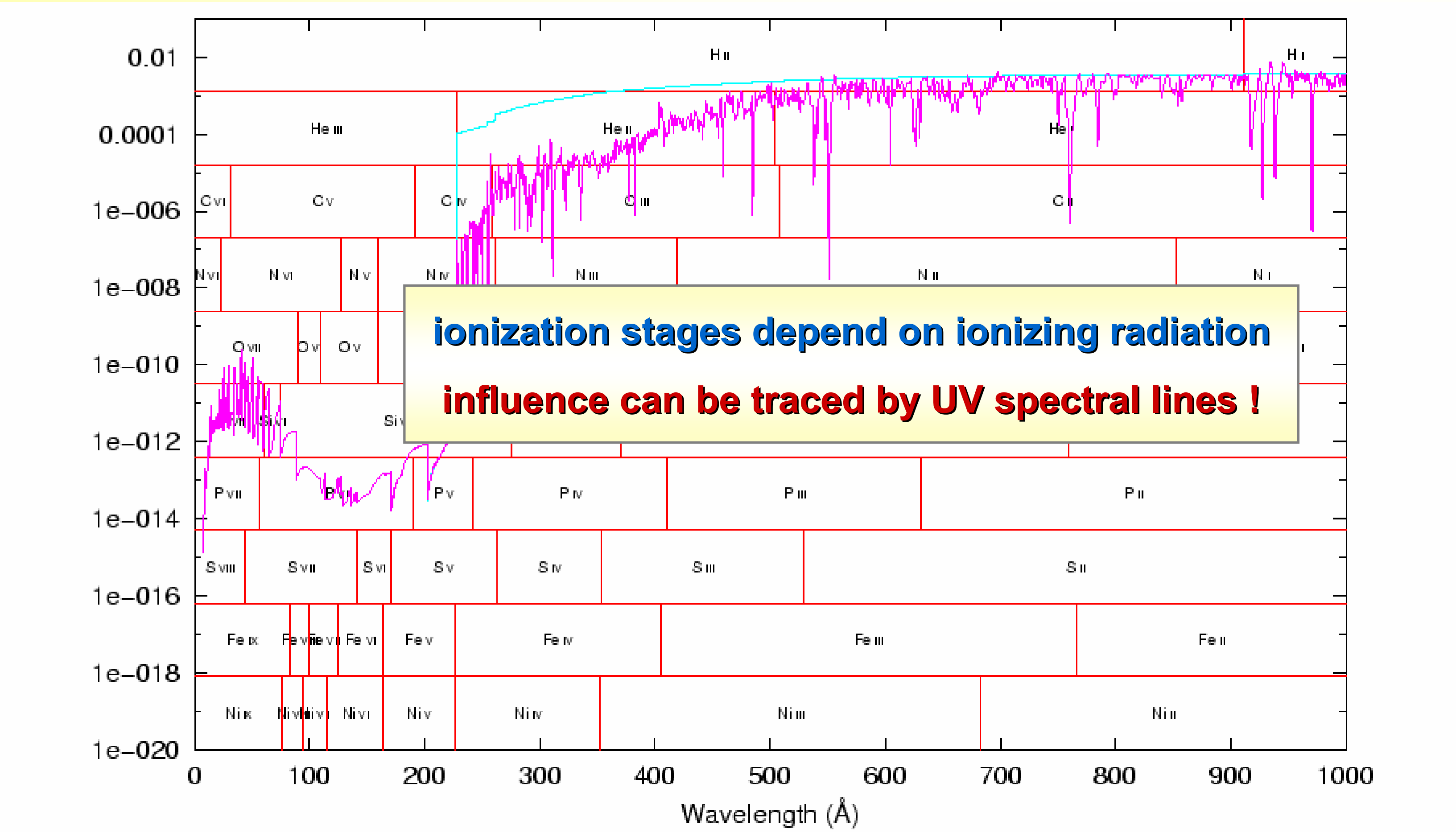
chemical enrichment of the ISM large amount of momentum and energy input into the ISM basis for star formation

Ionizing flux of ζ Puppis (O4If)

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

UV Spectra of O Stars:

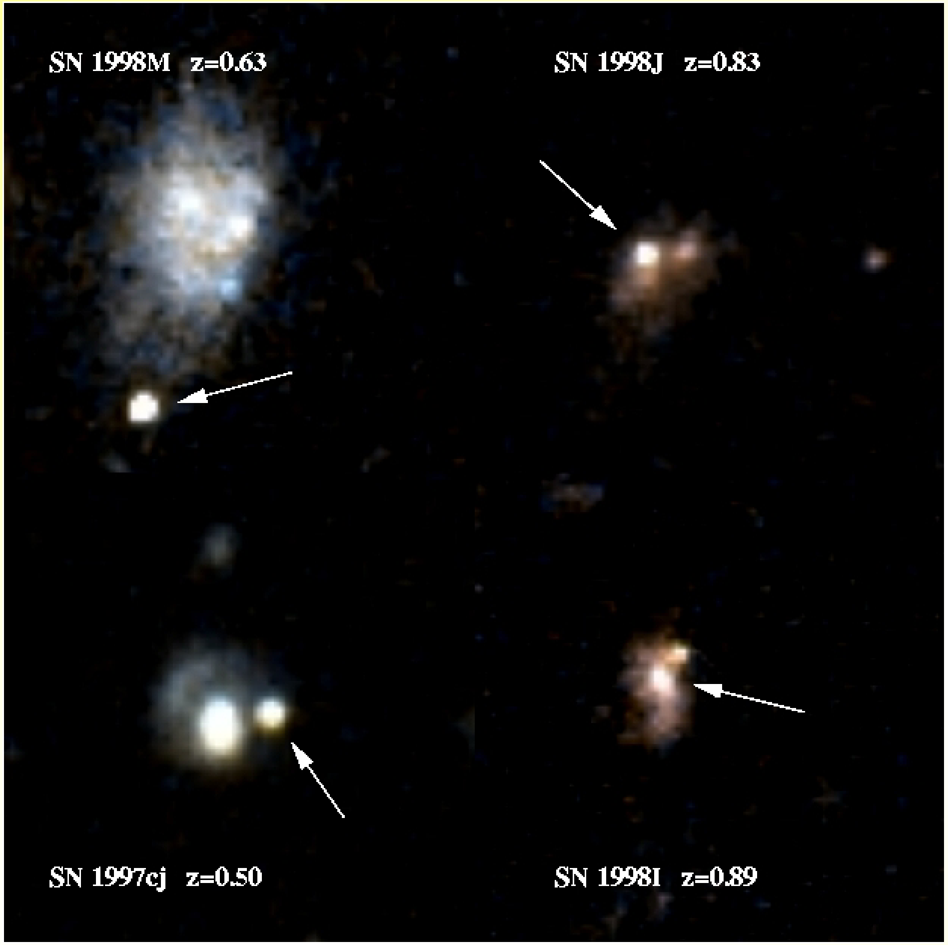
test involves hundreds of spectral signatures of different ionization stages



ionization stages depend on ionizing radiation

influence can be traced by UV spectral lines !

SNIa are **Standard Candles !**



Observations: 4 High-z Supernovae imaged with HST
http://cfa-www.harvard.edu/cfa/oir/Research/supernova/highz/figures/index.html.

Are SNIa **Standard Candles ?**

surprising result:
Distant SNe Ia appear **fainter** than a **standard candle** in an empty Friedmann model of the universe !

↓

SNIa-luminosity distances indicate **accelerated expansion!**

↑

Are **SNIa Standard Candles** independently of age**?**
Or is there some evolution of **SNIa-luminosity** with age**?**

↓

Spectroscopy
is a powerful tool to search for **differences**!

SN 1992A

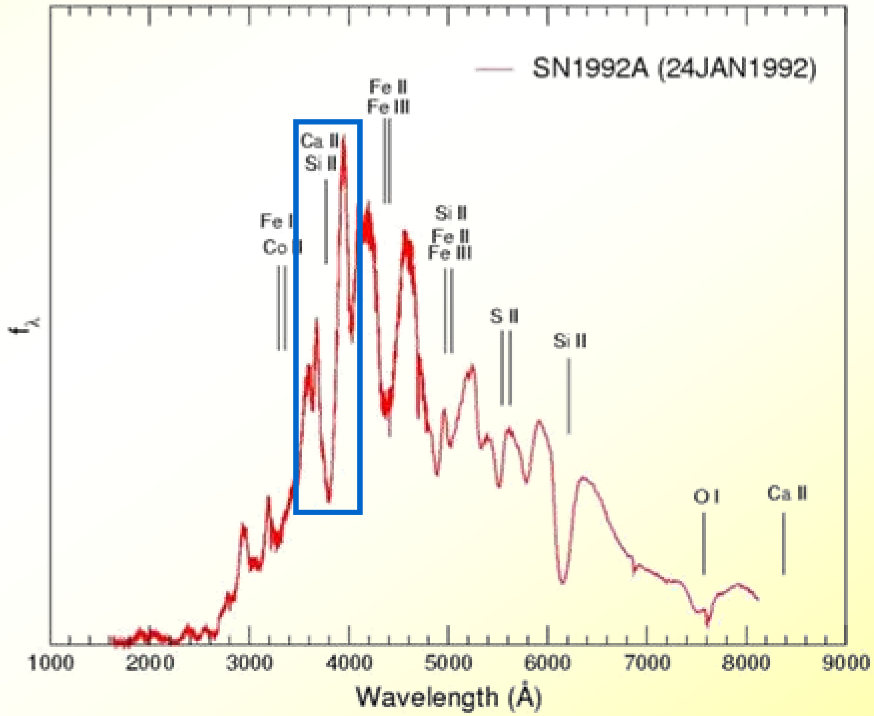
at early phases ~ 5 days after B maximum

Early epochs (< 2 weeks after maximum):

No hints for H and He lines

Prominent absorption features of mainly intermediate mass elements embedded in a non-thermal pseudo continuum (SiII, OI, SII, CaII, MgII...)
→ "**photospheric epoch**"

Characteristic P-Cygni line profiles
blue-shifted absorption
red-shifted emission
broad lines → **high ejecta velocities**



HST spectrum of 24. Jan. 1992 from Kirshner et al., 1993, ApJ 415, 589

Are SNe Ia standard candles in a cosmological sense ?

Required:
Realistic Models and Synthetic Spectra of Type Ia Supernovae

Hot Stars play an important role in Astrophysics

they dominate the physical conditions of galaxies and the life cycle of gas and dust

chemical enrichment of the ISM - significant impact on chemical evolution

large amount of momentum and energy input into the ISM - major dynamical role

relevance to cosmological issues

Realistic Synthetic UV Spectra of Hot Stars

are still relevant for current astronomical research

!

Concept for consistent models of hot star atmospheres

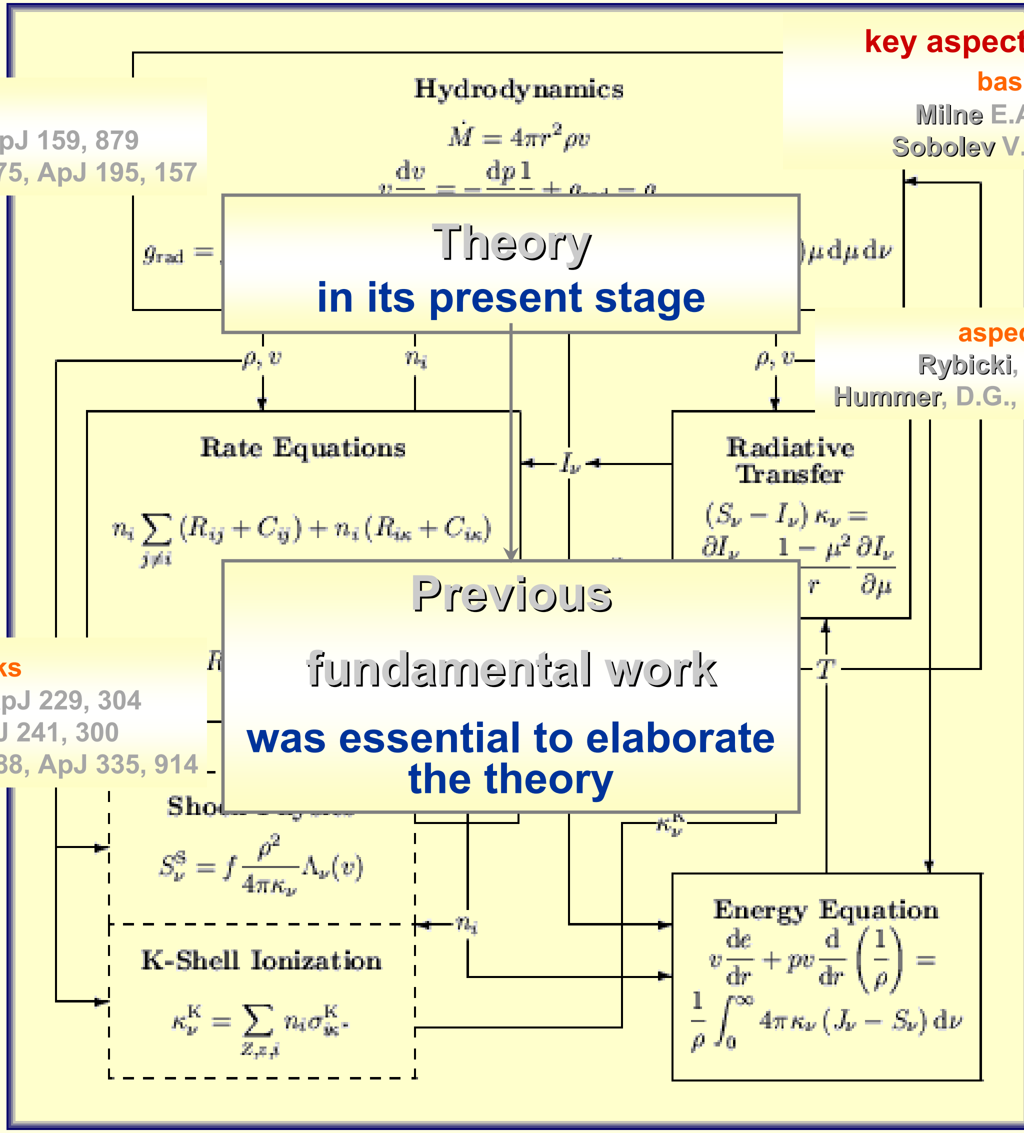
key aspects of theoretical activity

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



Theory
in its present stage

aspects of radiative transfer

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

Previous
fundamental work
was essential to elaborate the theory

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

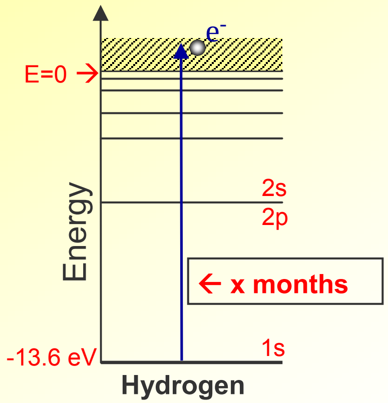
basis of our theoretical framework

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

in GNs radiative processes are not balanced in detail !

→ thermodynamic equilibrium can not be established !

main processes:



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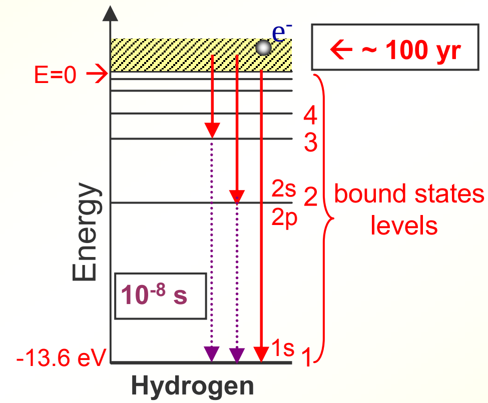


↓

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

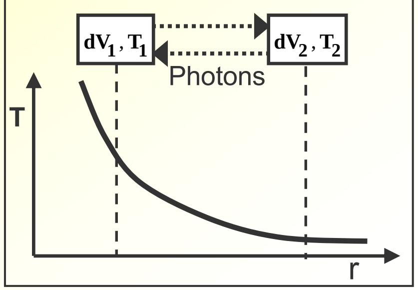
Transport Theory

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**

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

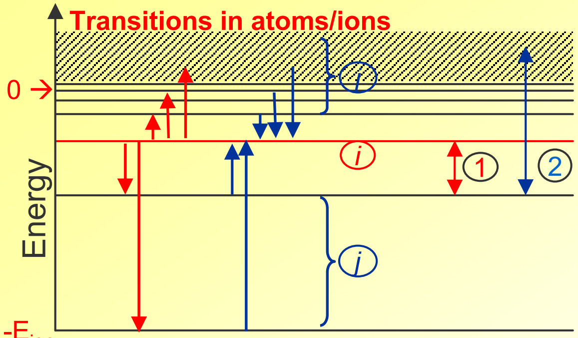
ionization equation

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

the equation of transfer in spherical symmetry

Integro-Differential Equation

Theory: Motivation

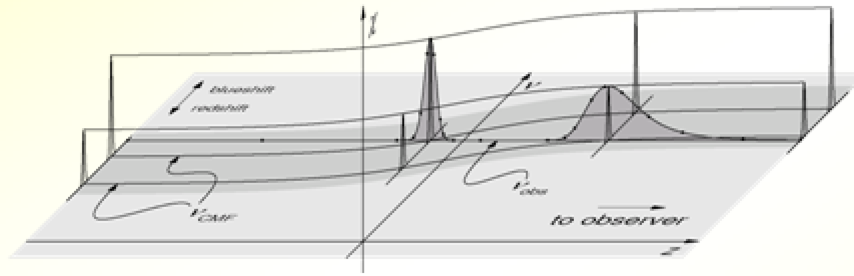


de-population | population | of level i

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

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}



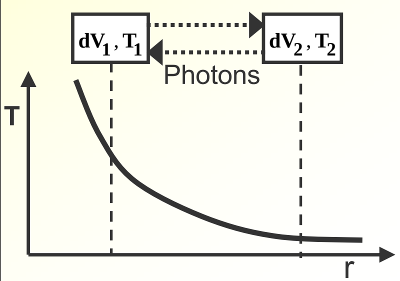
0-th moment of distribution function f_{Ki} for each element K, level i :

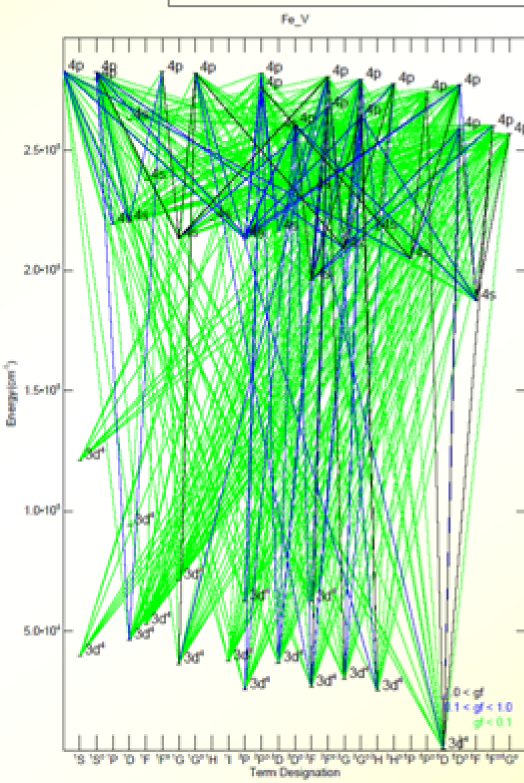
$$\nabla\cdot(n_{Ki}\underline{\mathbf{u}}) = \int_{-\infty}^{+\infty}\left[\frac{\partial f_{Ki}}{\partial t}\right]_{\rm ic} d^3{\rm v} = \sum_{j\neq i} n_{Kj}P_{ji} - \sum_{j\neq i} n_{Ki}P_{ij}$$

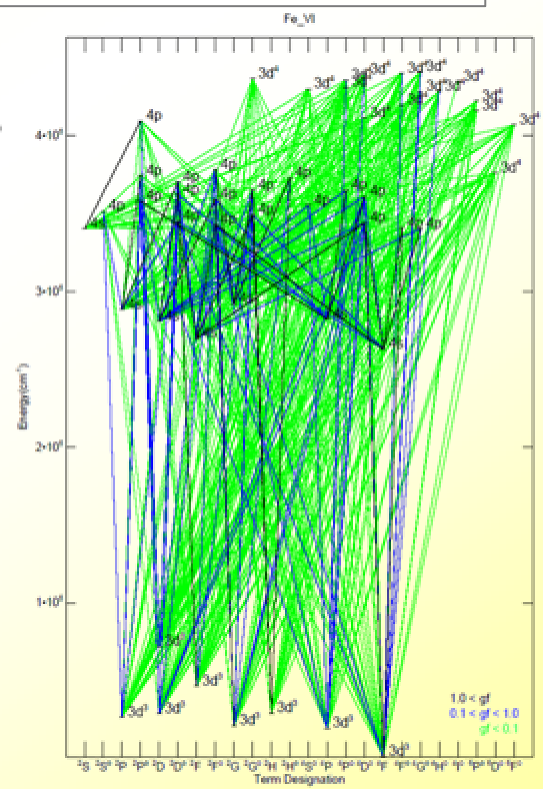
yields net rate of changes for each K, i

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

Disadvantage of NLTE:
non local problem!



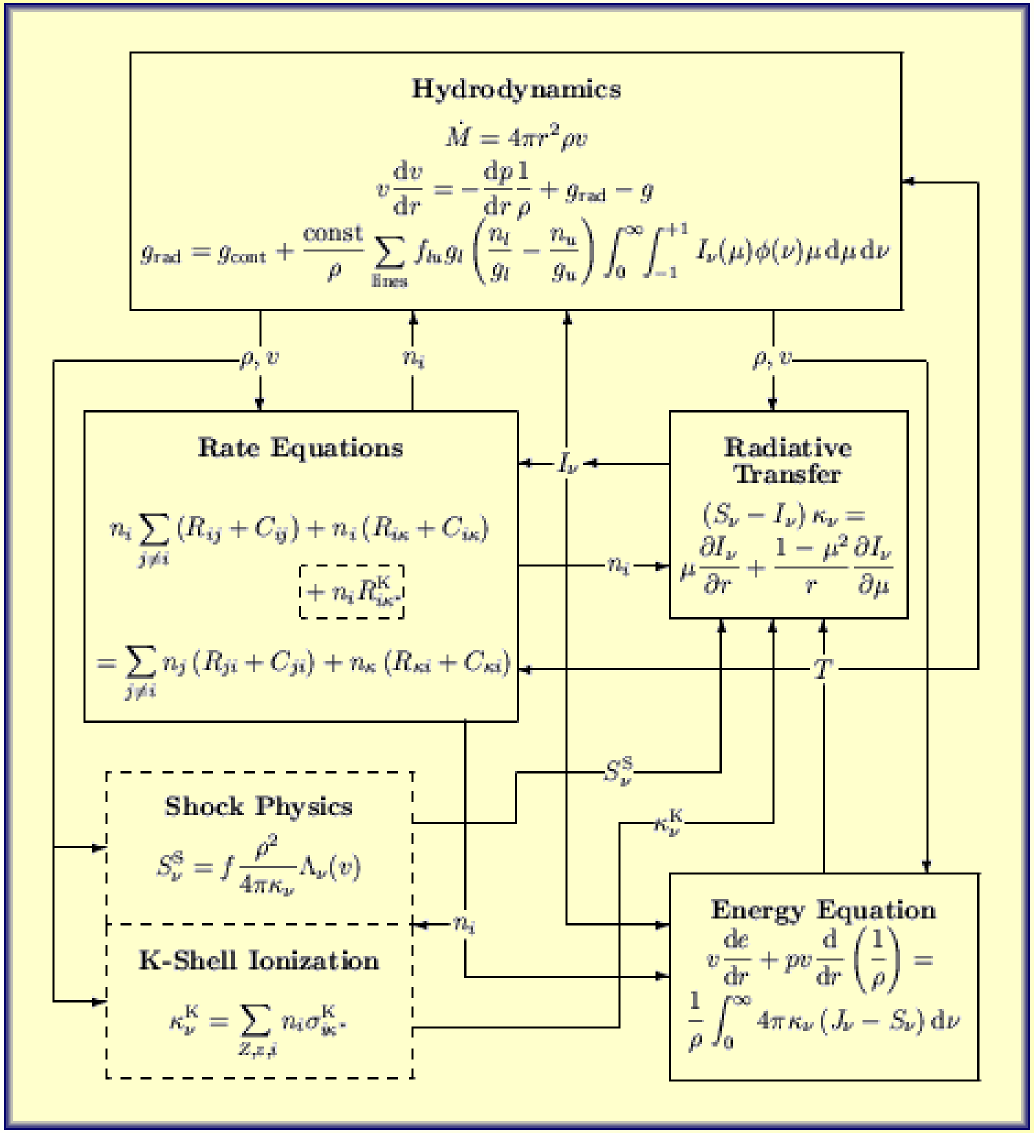




Non-Local Thermodynamic Equilibrium (NLTE)
described by a well defined mixture of macroscopic and microscopic physics
Transport Theory
Thermodynamics
Quantum Mechanics

$T_{\rm eff}$ log g
R Z

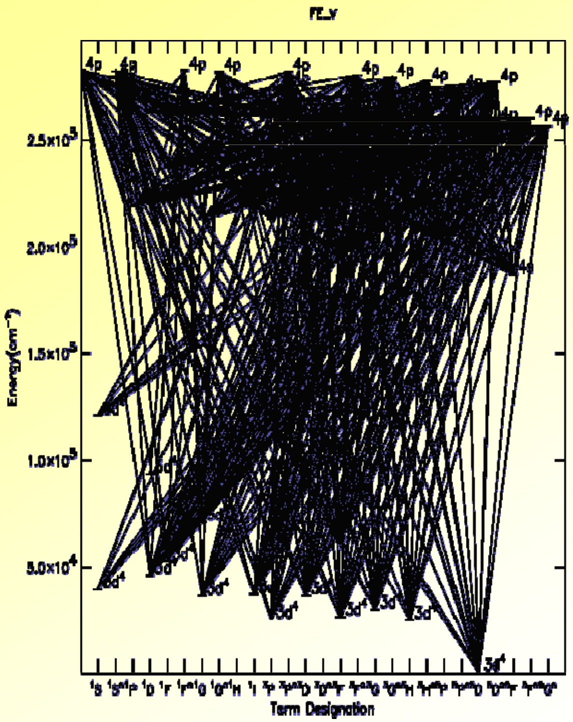
→



→

$\dot{M}$ v(r)
synthetic spectra

Concept for consistent models of hot star atmospheres



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

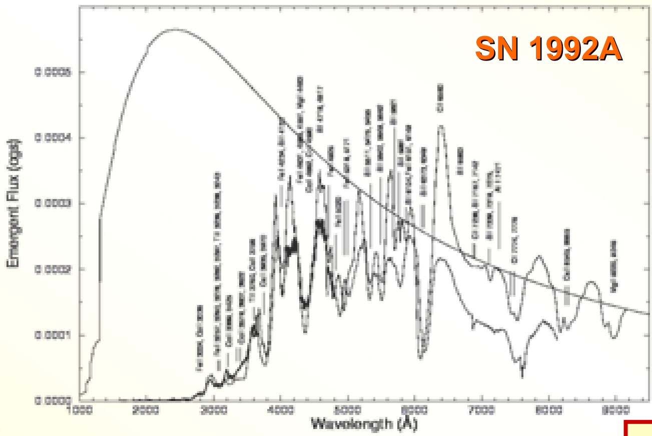
Accurate atomic models have been included

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

Concept for consistent models of hot star atmospheres

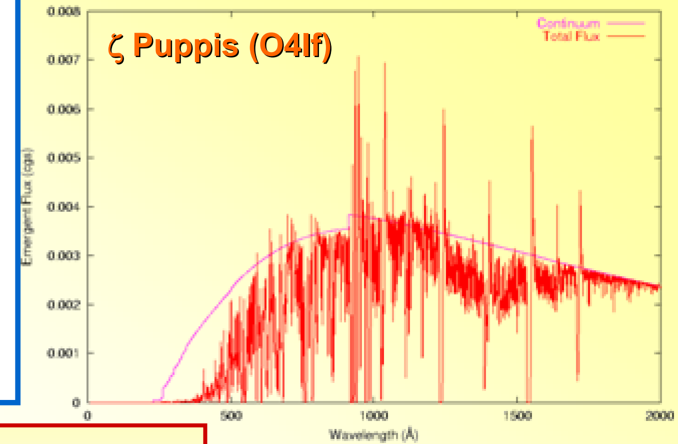


EUV line blocking and blanketing:

drastic effects on ionization excitation and emergent flux

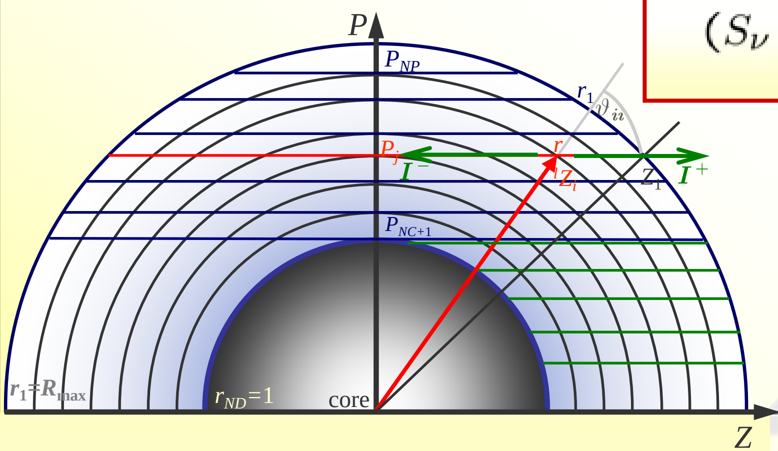
reason:

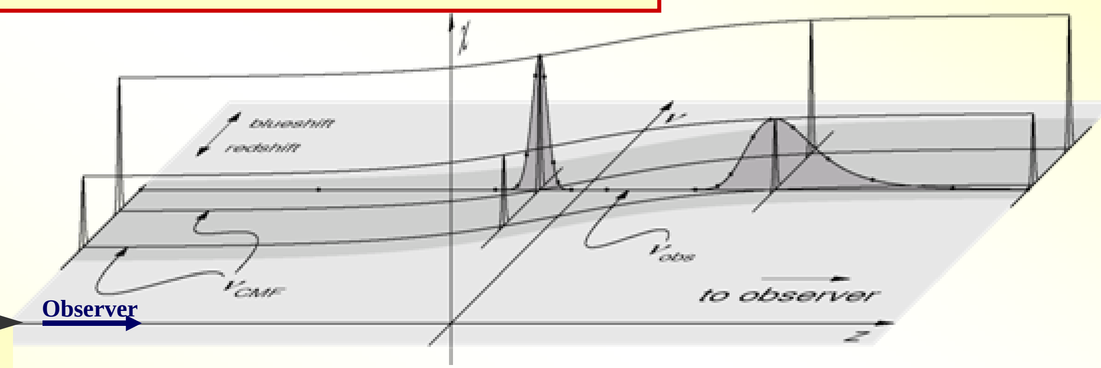
the velocity field shifts at different radii up to 1000 spectral lines into the line of sight at the observer's frequency

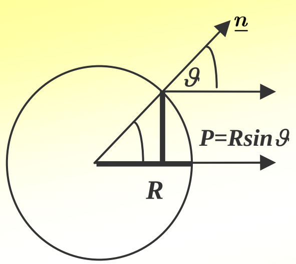


Radiative Transfer

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







$$P = R\sin\vartheta$$
$$P^2 = R^2(1-\mu^2)$$
$$PdP = -R^2\mu d\mu$$

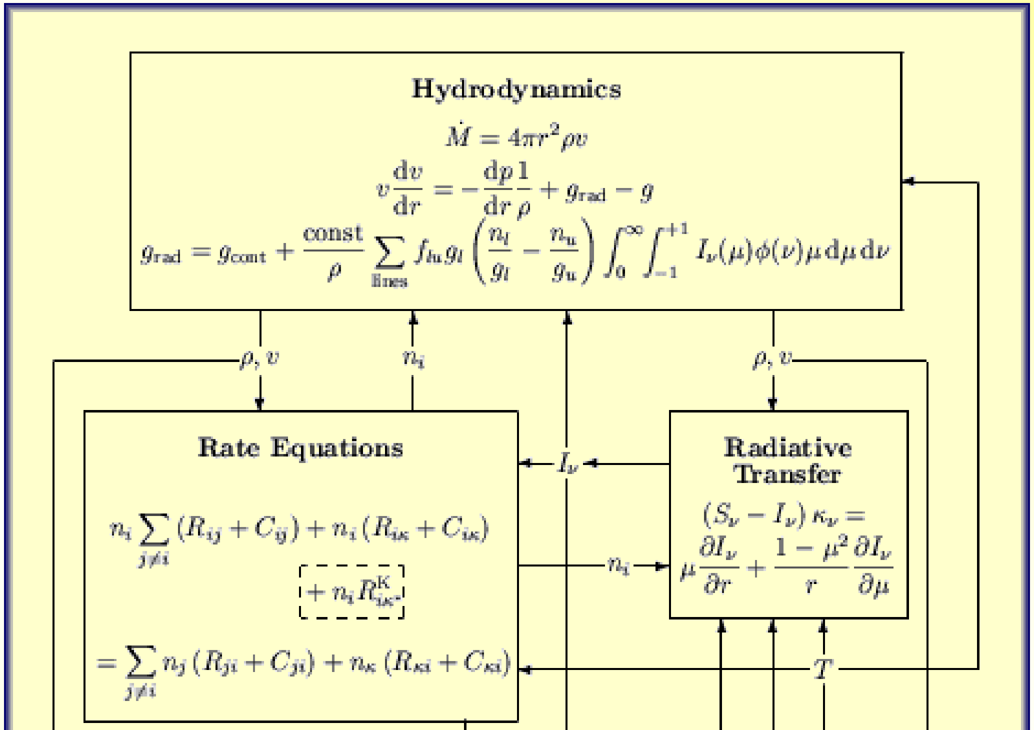
Numerical integration on this grid:

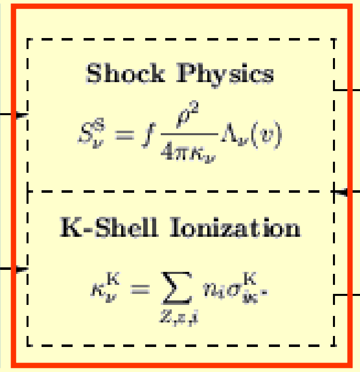
Optical depth $\tau_i = \int_{Z_1}^{Z_i} \kappa\left(r = \sqrt{Z_i^2 + P_j^2}\right) dZ$

Emergent intensity $I_j^+ = \int_{\tau'=0}^{\tau_{\max}} S(\tau')e^{-\tau'}d\tau' = \sum_{i=1}^{i_{\max}} S_l w_i$

Emergent flux $H^+R_{\max}^2 = \frac{1}{2}\int_{P=0}^{R_{\max}} I^+(P)PdP = \frac{1}{2}\sum_{j=1}^{NP} I_j^+ w_j$

Concept for consistent models of hot star atmospheres

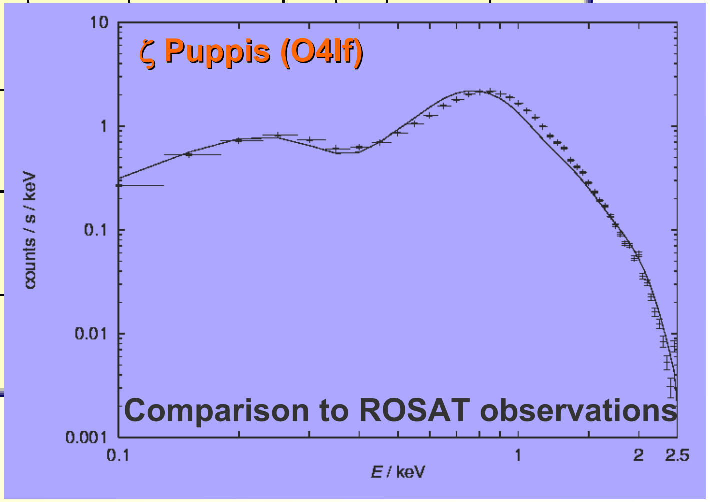




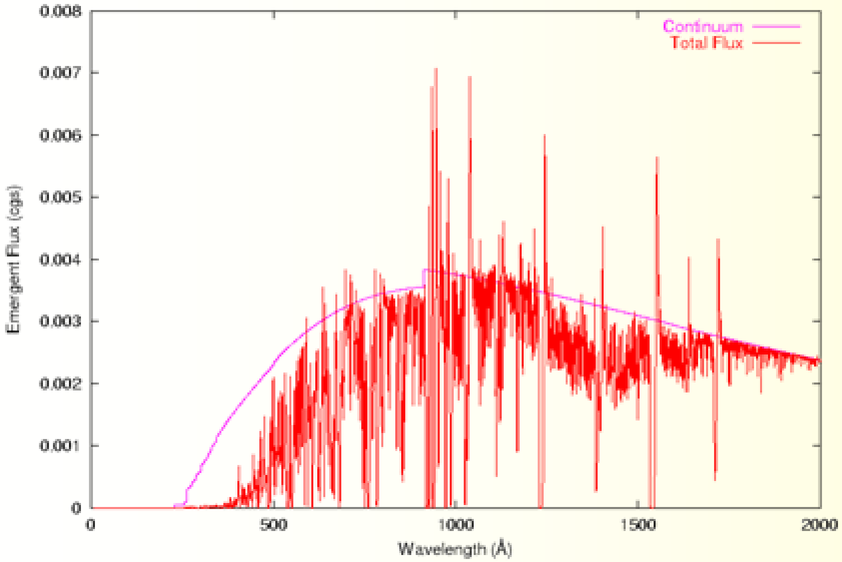
radiative emission of shock-cooling zones:

influence on rate equations and radiative transfer with respect to high ionization stages – OVI

A semi-empirical approximation for the emission coefficient is used



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

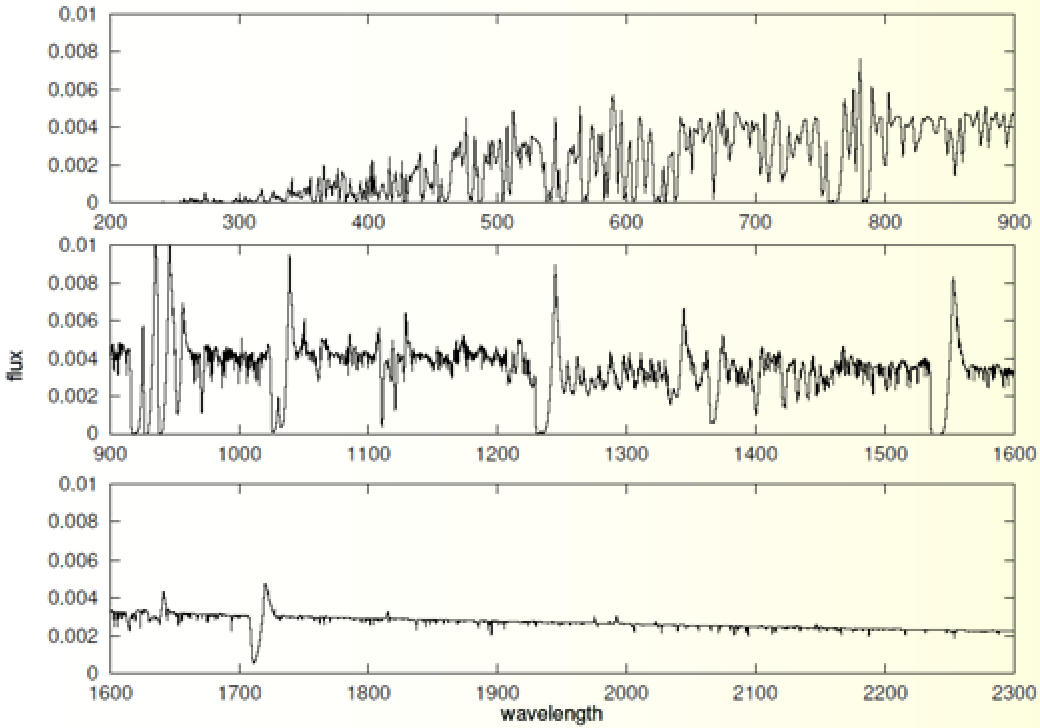


O supergiant model

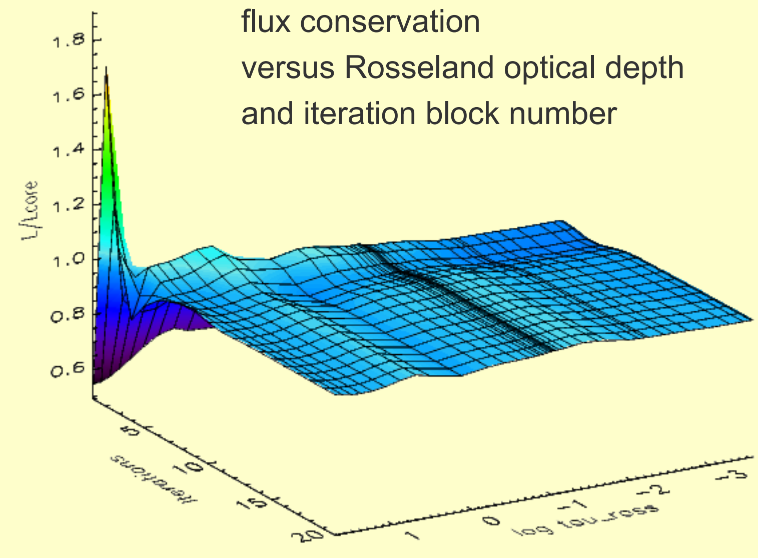
$$\mathbf{T_{eff}} = 45000\ \mathbf{K}$$
$$\mathbf{log\ g} = 3.6$$
$$\mathbf{R} = 18\ \mathbf{R_\odot}$$

Are the models realistic ?

Strategy for quantitative spectral UV analysis



flux conservation
versus Rosseland optical depth
and iteration block number



flux conservation is on the 1% level

Results: Synthetic and observed spectra of Supernovae of Type Ia

Comparison to observations
→ verification of explosion models

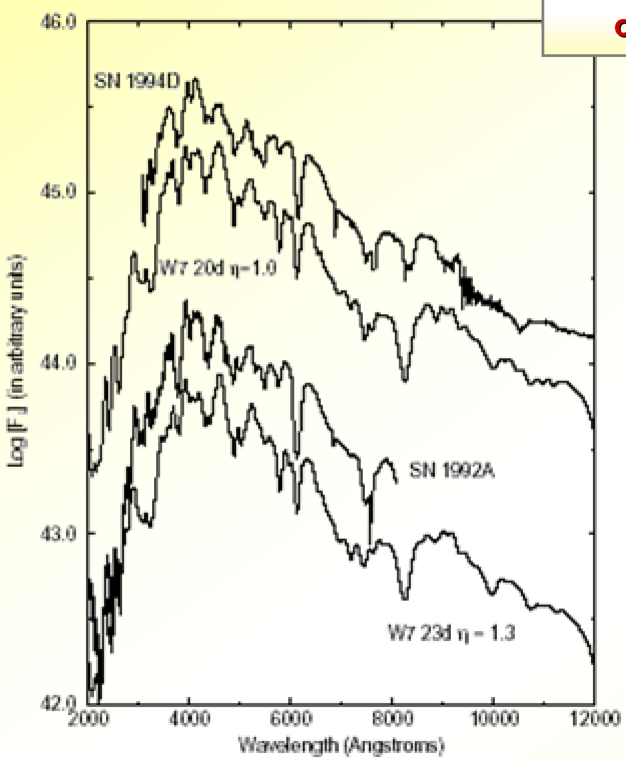
Constraints for
- Abundances
- Velocity-structure
- Density-structure

$T_{eff} = 14000$ K
$R = 9900\ R_\odot$
$Z = Z_{W7}$
$v_\infty = 22000$ km/s
$L = 3.4 \cdot 10^9\ L_\odot$

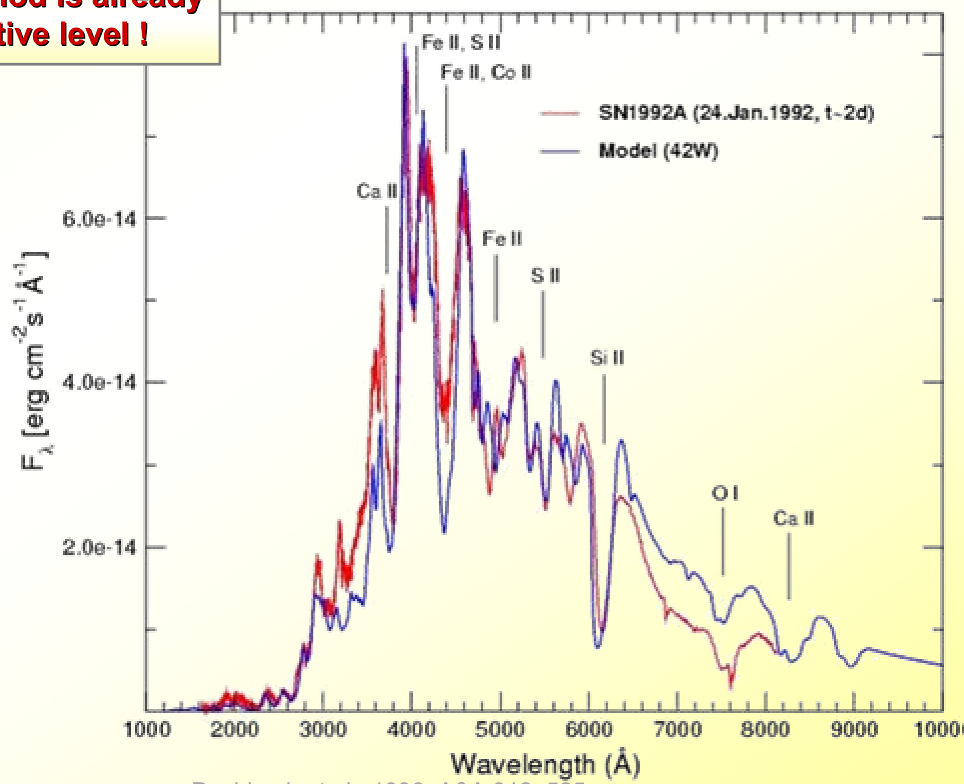
SN 1992A
at early phases ~ 5 days after B maximum

Models based on W7 explosion model
averaged chemical composition above the photosphere
Nomoto et al, 1984, ApJ. 286, 644

The present method is already on a quantitative level !



Nugent et al., 1997, ApJ. 485, 812



Pauldrach et al., 1996, A&A 312, 525
Sauer and Pauldrach, 2002, Nuclear Astrophysics, MPA/P13

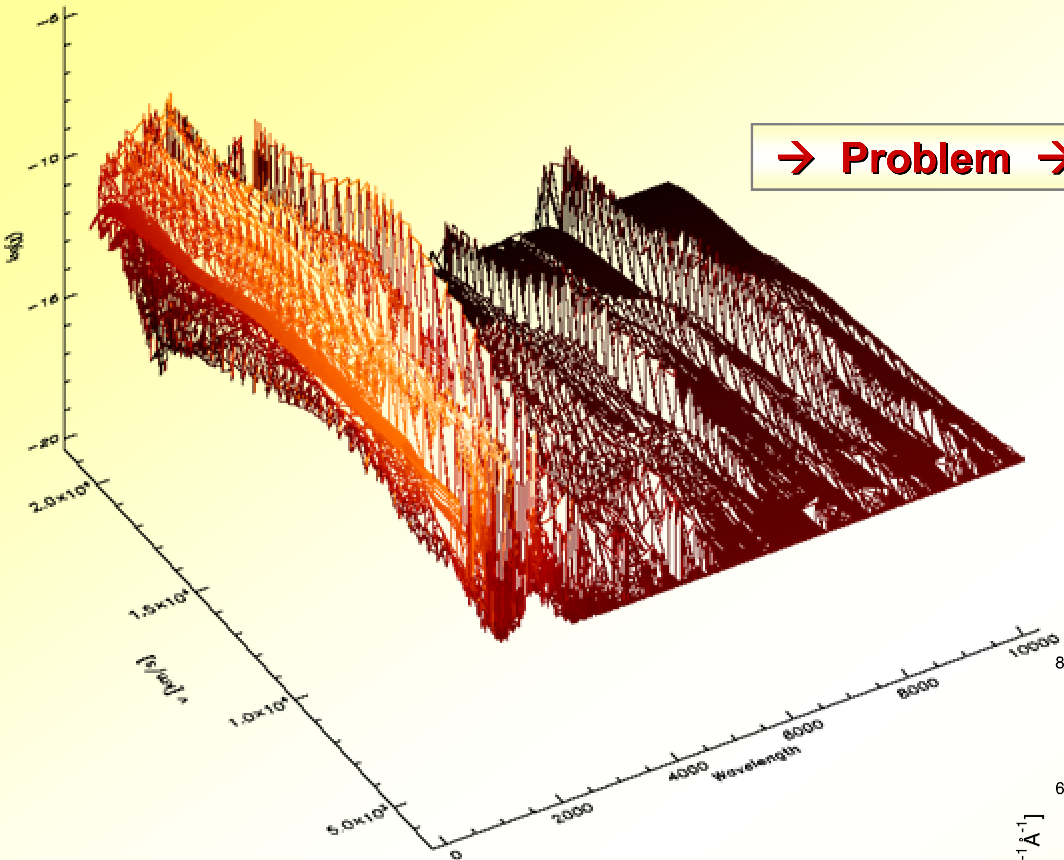
Results: Synthetic and observed spectra of Supernovae of Type Ia

Diffusion approximation - standard for inner boundary :

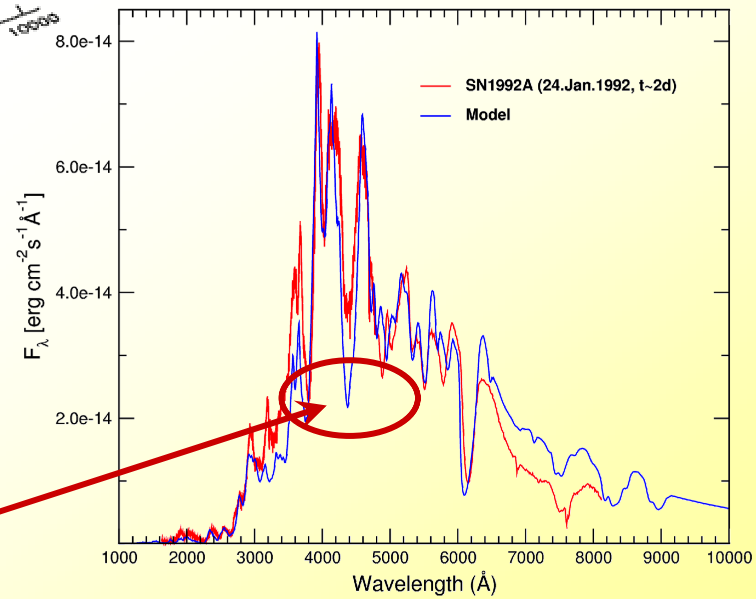
$$I^{+}_{\tau_{\max}} = \left(B_\nu + 3\mu H^0_\nu\right)(\tau_{\max})$$

$$H^0_\nu(R) = -\frac{1}{3}\frac{dB_\nu}{\kappa_\nu dr}$$

→ Problem →



Logarithm of the total opacity versus velocity and wavelength
of a SN Ia model
Sauer and Pauldrach, 2005, A&A



HST spectrum of 24. Jan. 1992 from Kirshner et al., 1993, ApJ 415, 589
Model Sauer and Pauldrach, 2002, Nuclear Astrophysics, MPA/P13

Main features of the spectrum
are fairly well reproduced
especially in the blue and UV range
However,
Some features are "too deep"

Modified diffusion approximation for Supernovae of Type Ia

Modified diffusion approximation for inner boundary :

$$I^+_{\tau_{\max}} = \left(J_\nu + 3\mu H^0_\nu\right)(\tau_{\max})$$

after some calculation

$$\Rightarrow H^0_\nu(R) = -\frac{1}{3}\left(\frac{dB_\nu}{\kappa_\nu dr} + C^*_\nu(\tau_\nu)\right) - \frac{df_\nu}{\kappa_\nu dr}\left[J_\nu\left(\frac{3\tau_\nu}{\kappa_\nu R} + 1\right) + \tau_\nu\left(\frac{dB_\nu}{\kappa_\nu dr} + C^*_\nu(\tau_\nu)\right)\right]$$

and

$$J_\nu(\tau_\nu) = B_\nu(\tau_\nu) + \frac{C_\nu}{qf(\nu,\tau)r^2} e^{-\sqrt{\beta_\nu/q^2 f_\nu} s_\nu}$$

with

$$C^*_\nu(\tau_\nu) = \frac{B_\nu - J_\nu}{f_\nu}\left(\frac{3f_\nu - 1}{r\kappa_\nu} + \frac{df_\nu}{\kappa_\nu dr}\right) + \sqrt{\beta_\nu/q^2 f_\nu}\,\frac{C_\nu}{f_\nu r^2} e^{-\sqrt{\beta_\nu/q^2 f_\nu}\, s_\nu}$$

and

$$C_\nu = \frac{-\tilde{B}_\nu(\tau_{0\nu}) + j_\nu(\tau_{0\nu}) \left.\dfrac{d\left[qf_\nu(\tau)\tilde{B}_\nu(\tau)\right]}{ds_\nu}\right|_{\tau_{0\nu}}}{(1/qf_\nu)_{\tau_{0\nu}} + j_\nu(\tau_{0\nu})\sqrt{\beta_\nu/q^2 f_\nu}} e^{\sqrt{\beta_\nu/q^2 f_\nu} s_{0\nu}}$$

where $j_\nu(\tau_{0\nu}) = \dfrac{J_\nu(\tau_{0\nu})}{H_\nu(\tau_{0\nu})} \sim 2$

with the Eddington factor $f_\nu = K_\nu / J_\nu$ and the sphericality factor $r^2 q(r) = \exp\left(\int_1^r \frac{3f(r') - 1}{r' f(r')} dr'\right)$

with the Thomson opacity: $\kappa_e = n_e \sigma_e,\ \eta_e = \kappa_e J$ and $\beta_\nu(\tau_\nu) = \dfrac{\kappa_\nu}{\kappa_\nu + \kappa_e}$

and $S = \dfrac{\eta}{\kappa + \kappa_e} + \dfrac{\kappa_e}{\kappa + \kappa_e}\dfrac{\eta_e}{\kappa_e} = S^t + \kappa_{Th} J$

and $ds_\nu = -q\kappa_\nu dr,\ s_\nu = \int_r^{r_{\max}} q\kappa_\nu dr$ and $d\tau_\nu = -\kappa_\nu dZ,\ \tau_\nu = \int_Z^{Z_{\max}} \kappa_\nu dZ$

moments of the radiation field

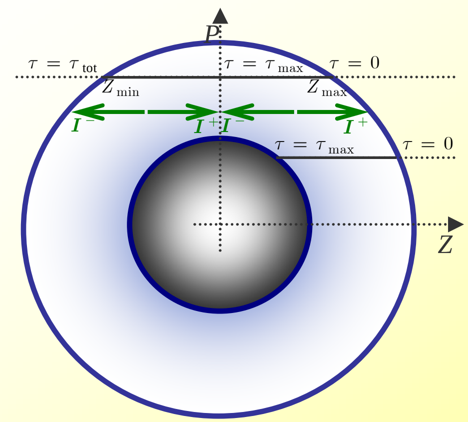
0th: $J = \frac{1}{2}\int_{\mu=-1}^{+1} I(\mu) d\mu,\ \tilde{J} = r^2 J$ 1st: $H = \frac{1}{2}\int_{\mu=-1}^{+1} I(\mu)\mu d\mu,\ \tilde{H} = r^2 H$ 2nd: $K = \frac{1}{2}\int_{\mu=-1}^{+1} I(\mu)\mu^2 d\mu,\ \tilde{K} = r^2 K$

Diffusion approximation - standard for inner boundary :

$$I^+_{\tau_{\max}} = \left(B_\nu + 3\mu H^0_\nu\right)(\tau_{\max})$$

$$H^0_\nu(R) = -\frac{1}{3}\frac{dB_\nu}{\kappa_\nu dr}$$

Modifications to the inner boundary that allow **deviations of the radiation field from thermal equilibrium conditions** is considered.
The **dominating contribution from Thomson scattering** is explicitly taken into account



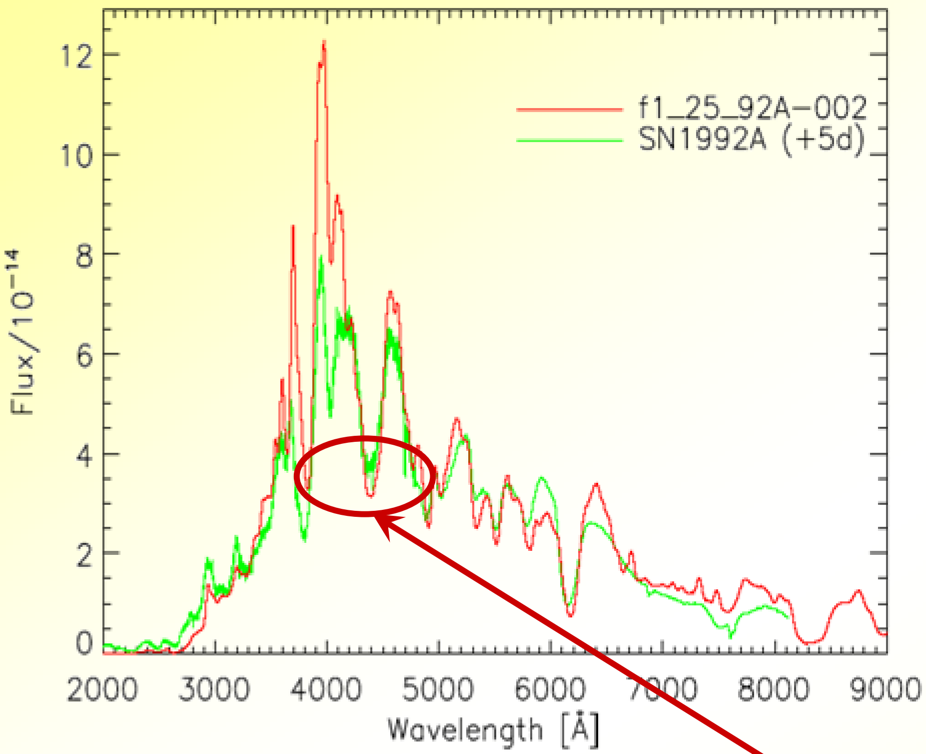
Equation of radiative transfer

$$\frac{d^2(I^+ + I^-)(\tau)}{d\tau^2} = (I^+ + I^-)(\tau) - S_\nu(\tau)$$

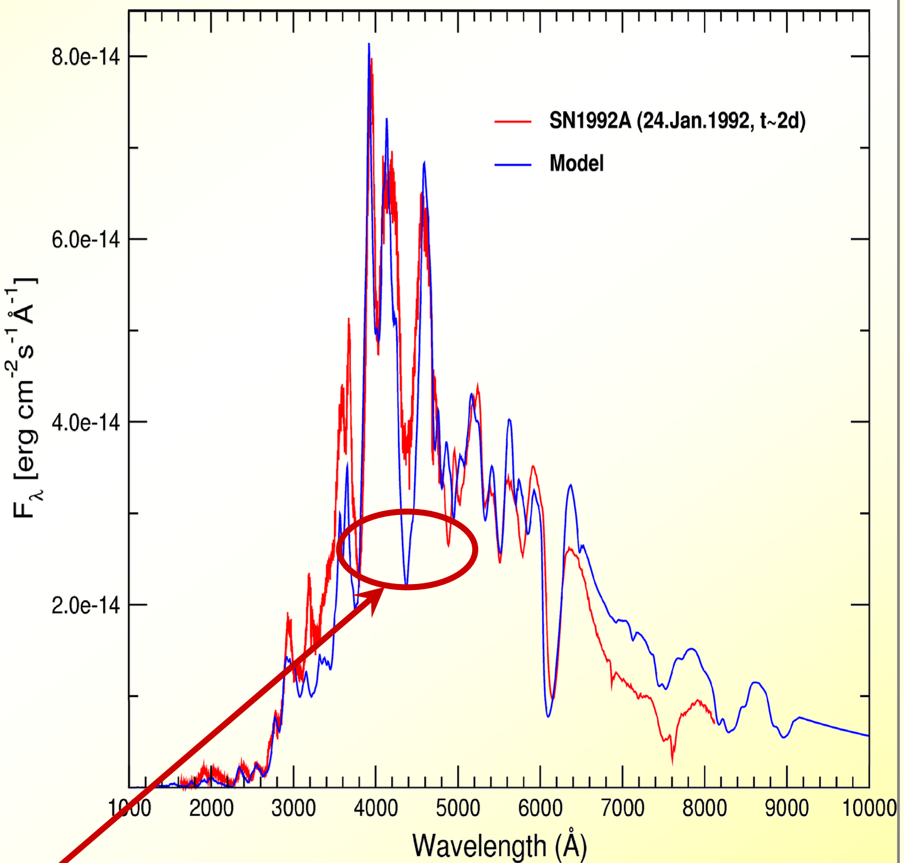
iterated with moment equation of radiative transfer

$$\frac{d^2(qf\tilde{J})}{ds^2} = \frac{1}{q}(\tilde{J} - \tilde{S})$$

Improvement ?



Sauer and Pauldrach, 2005, A&A



Sauer and Pauldrach, 2002, Nuclear Astrophysics, MPA/P13

Improvement is striking !

Primary objective:

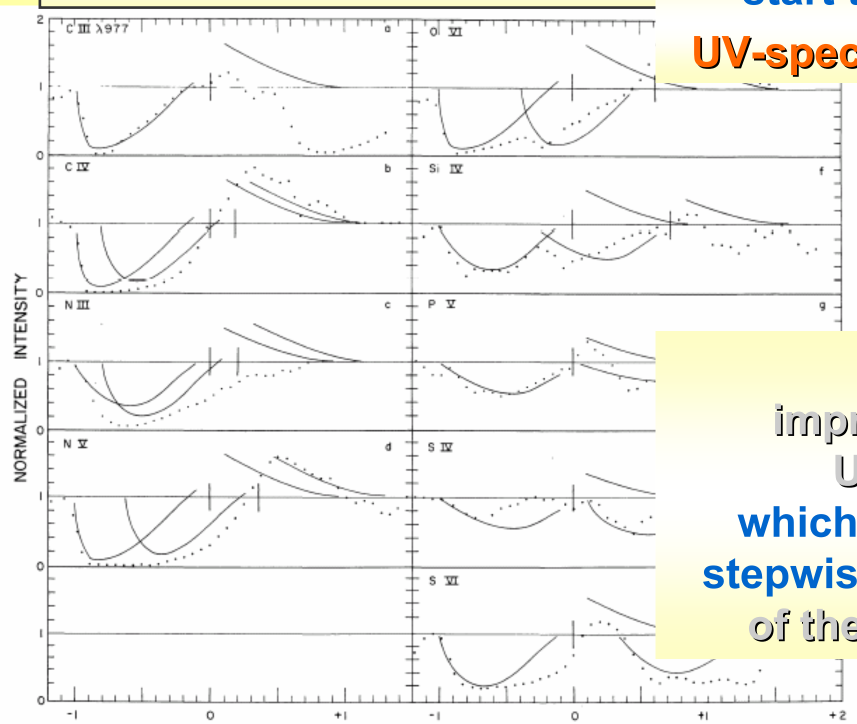
search for spectral differences between local and distant SNe Ia !

Are SNe Ia standard candles in a cosmological sense ?

dynamical structure, occupation numbers, and temperature structure are assumed

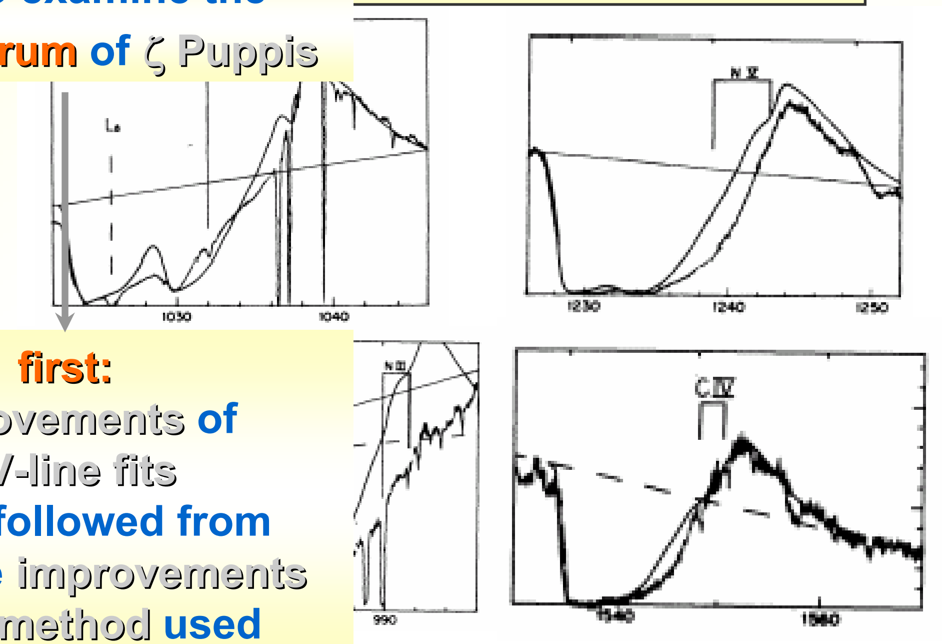
approximate treatment of line radiative

tment of line radiative transfer



Lamers and Morton, 1976, Ap.J.S. 32, 715

start to examine the **UV-spectrum** of ζ Puppis



Hamann, 1980, A&A 84,342

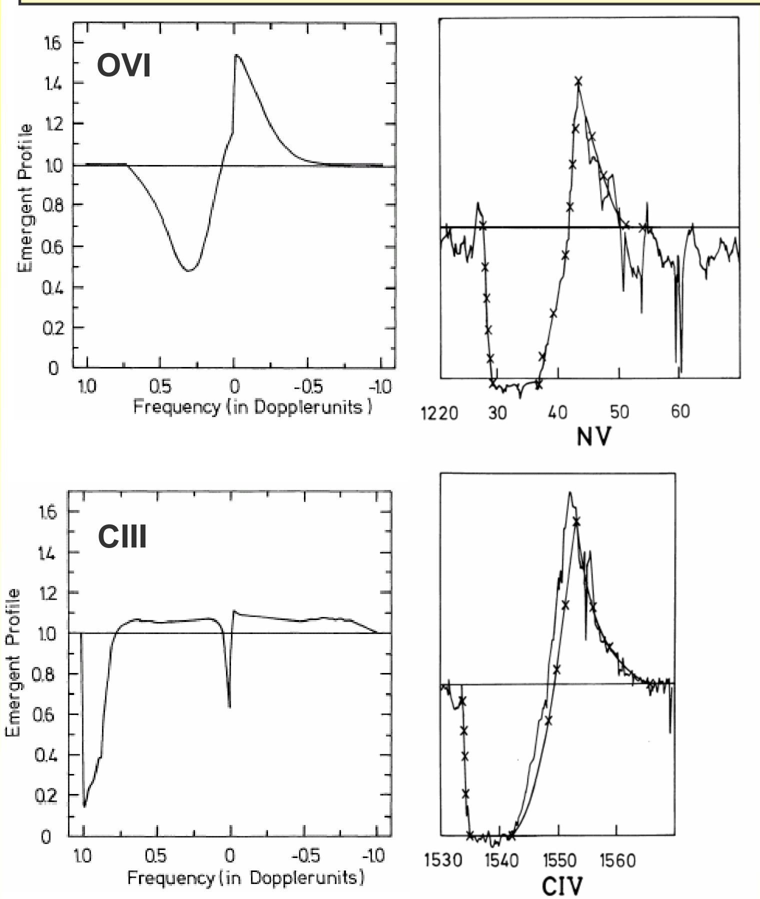
first:
improvements of UV-line fits which followed from stepwise improvements of the method used

A more consistent treatment of expanding atmospheres is required for a detailed analysis

Consistent wind models of the O-supergiant ζ Puppis

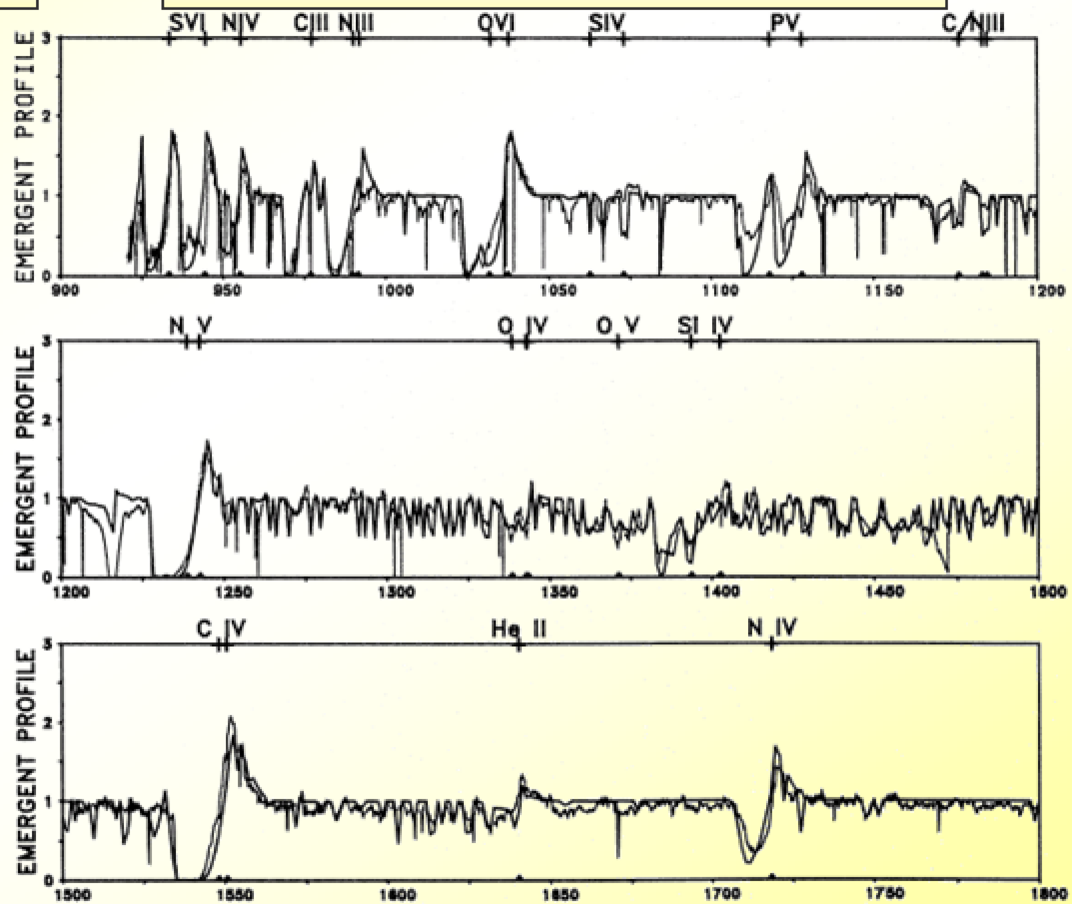
line blanketing neglected - approximated temperature structure
approximate treatment of line blocking
simple treatment of shocks

approximate treatment of line blocking – no shocks



Pauldrach, 1987, A&A, 183, 295; Puls, 1987, A&A, 184, 227

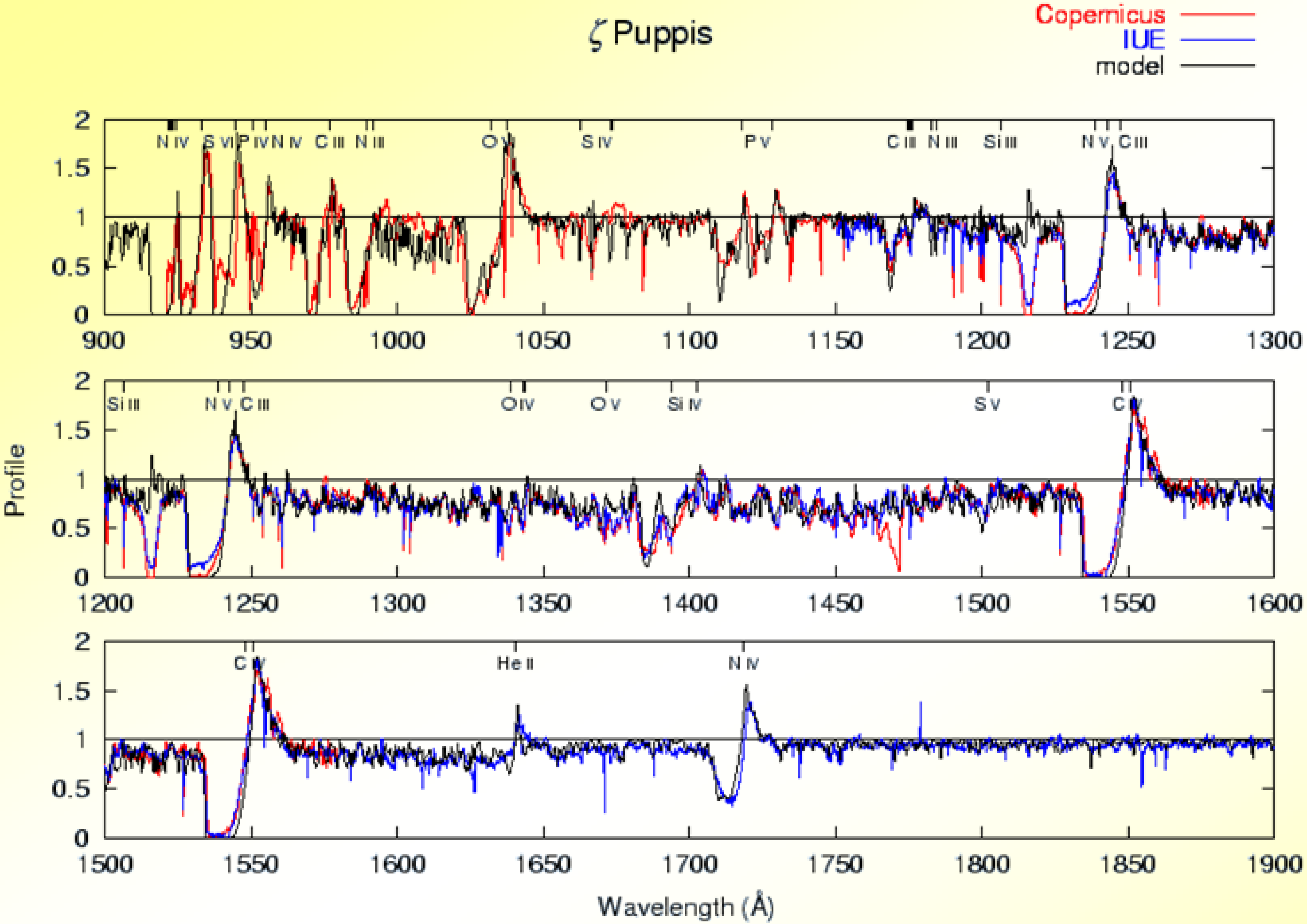
improved treatment of line blocking and shocks



Pauldrach et al., 1994, A&A, 283, 525

A more realistic treatment of expanding atmospheres is required for a detailed analysis

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



Values Determined:

stellar parameters

$T_{eff} = 40$ kK

$\log g = 3.40$

$R/R_\odot = 28.$

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

wind parameters

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

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

abundances

$C/C_\odot = 1.50$

$N/N_\odot = 5.00$

$O/O_\odot = 0.10$

$Si/Si_\odot = 7.00$

$S/S_\odot = 0.50$

$Fe/Fe_\odot = 2.00$

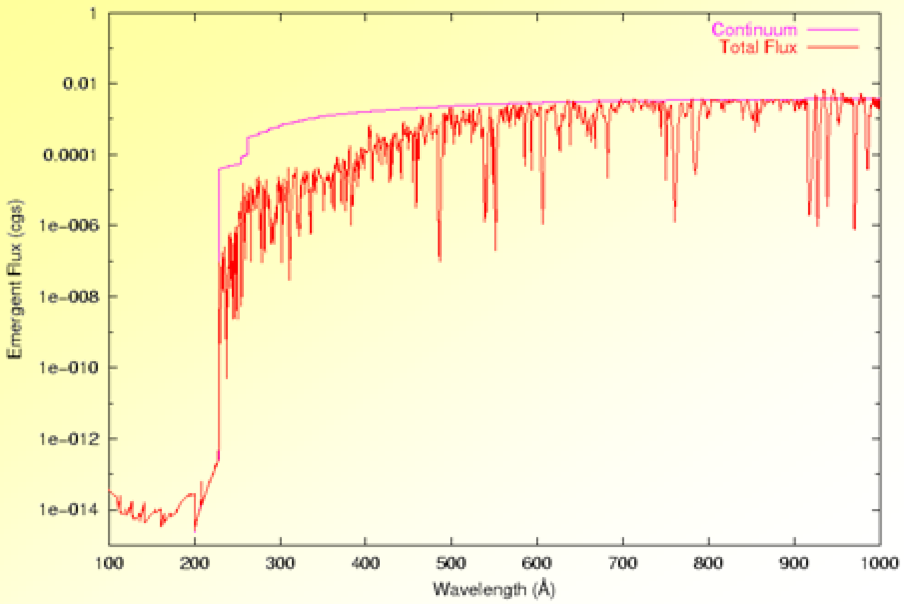
$Ni/Ni_\odot = 2.00$

state of the art models for 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

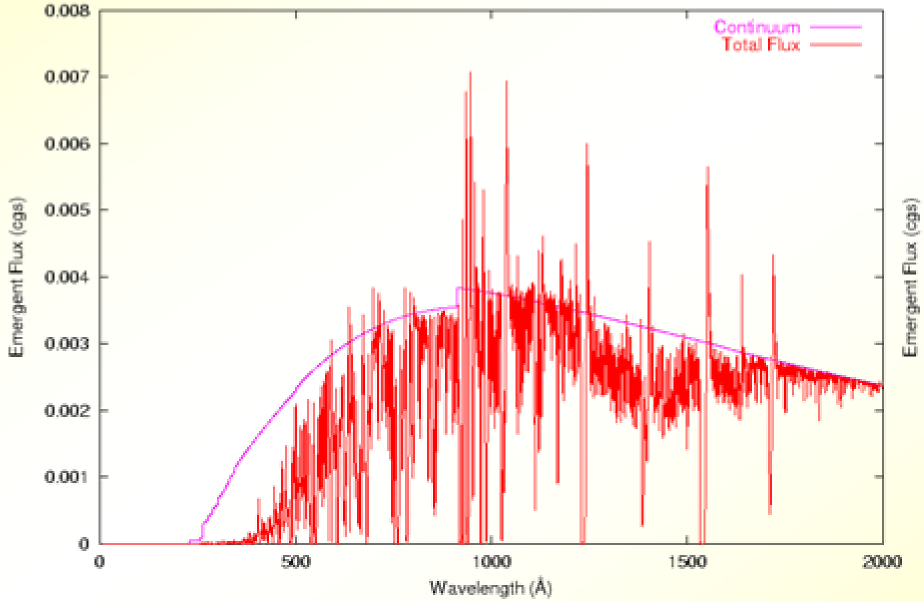
Realistic Spectral Energy Distribution of ζ Puppis

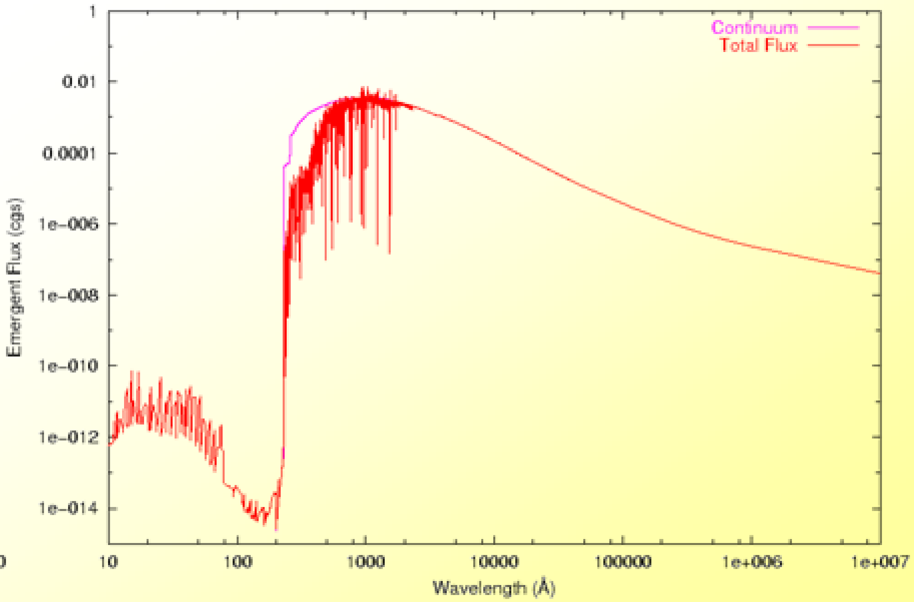


quantitative spectral UV analyses:
ultimate test for the accuracy of theoretical ionizing fluxes

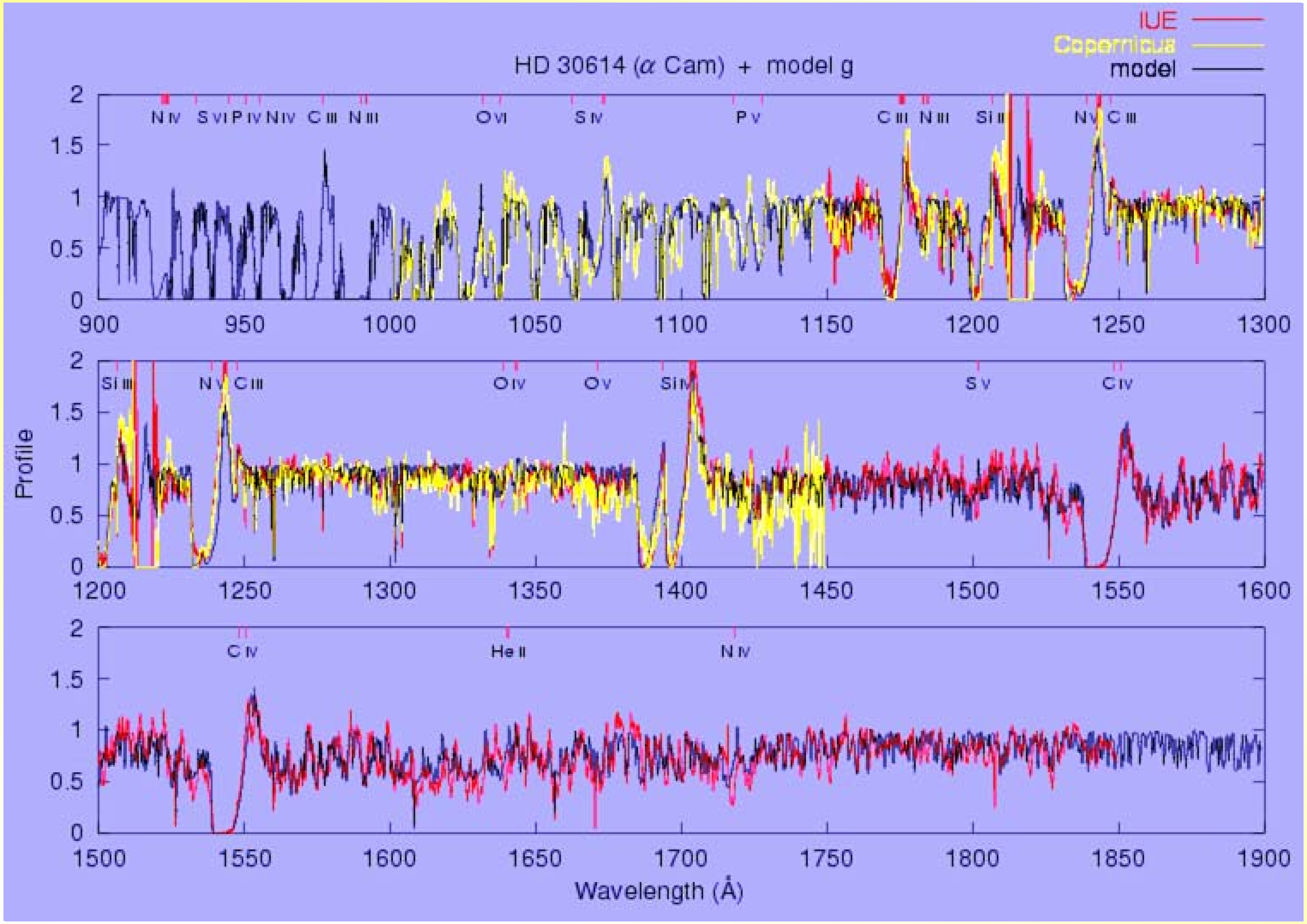
↓

Realistic Spectral Energy Distributions





Detailed analysis of the cool O-supergiant α Cam



$T_{eff} = 29$ kK

$\log g = 3.00$

$R/R_\odot = 30$

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

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

$C/C_\odot = 0.05$

$N/N_\odot = 1.00$

$O/O_\odot = 0.30$

$P/P_\odot = 0.05$

$S/S_\odot = 1.00$

$Fe/Fe_\odot = 1.50$

$Ni/Ni_\odot = 1.50$

Spectrum synthesis technique allows the determination of 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

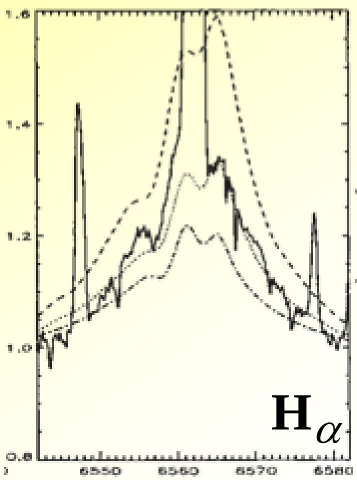
Wind momentum luminosity relation

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

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

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

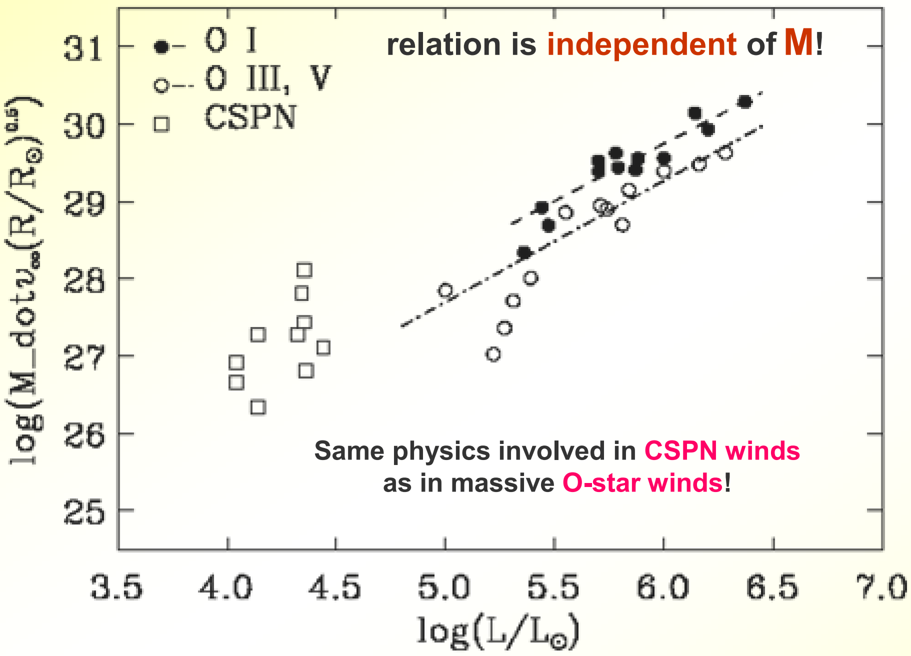
NGC 6826



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

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

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



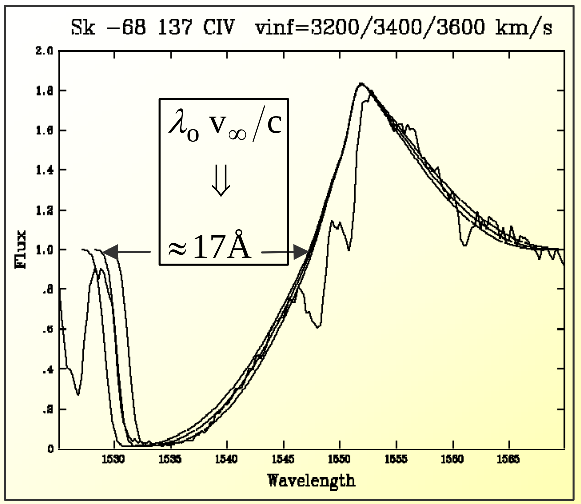
Puls et al., 1996, A&A 305; Kudritzki et al.,1997, IAU Symp. 180

↓

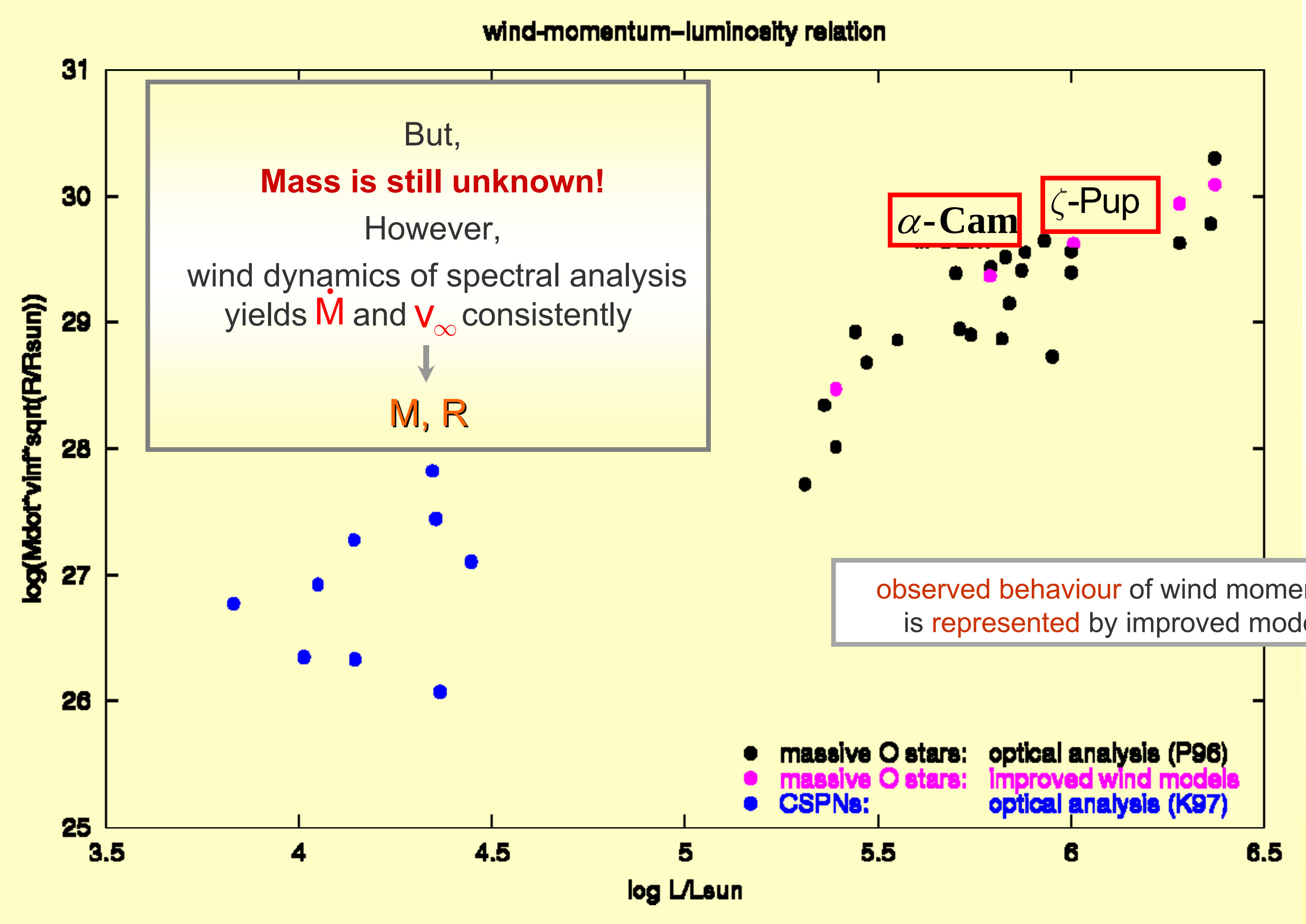
independent tool for measuring extragalactic distances up to Virgo and Fornax

v_∞^{obs}

C IV ($\lambda\lambda$1548,1551Å)



v_∞ can be measured directly



But,

Mass is still unknown!

However,

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

↓

M, R

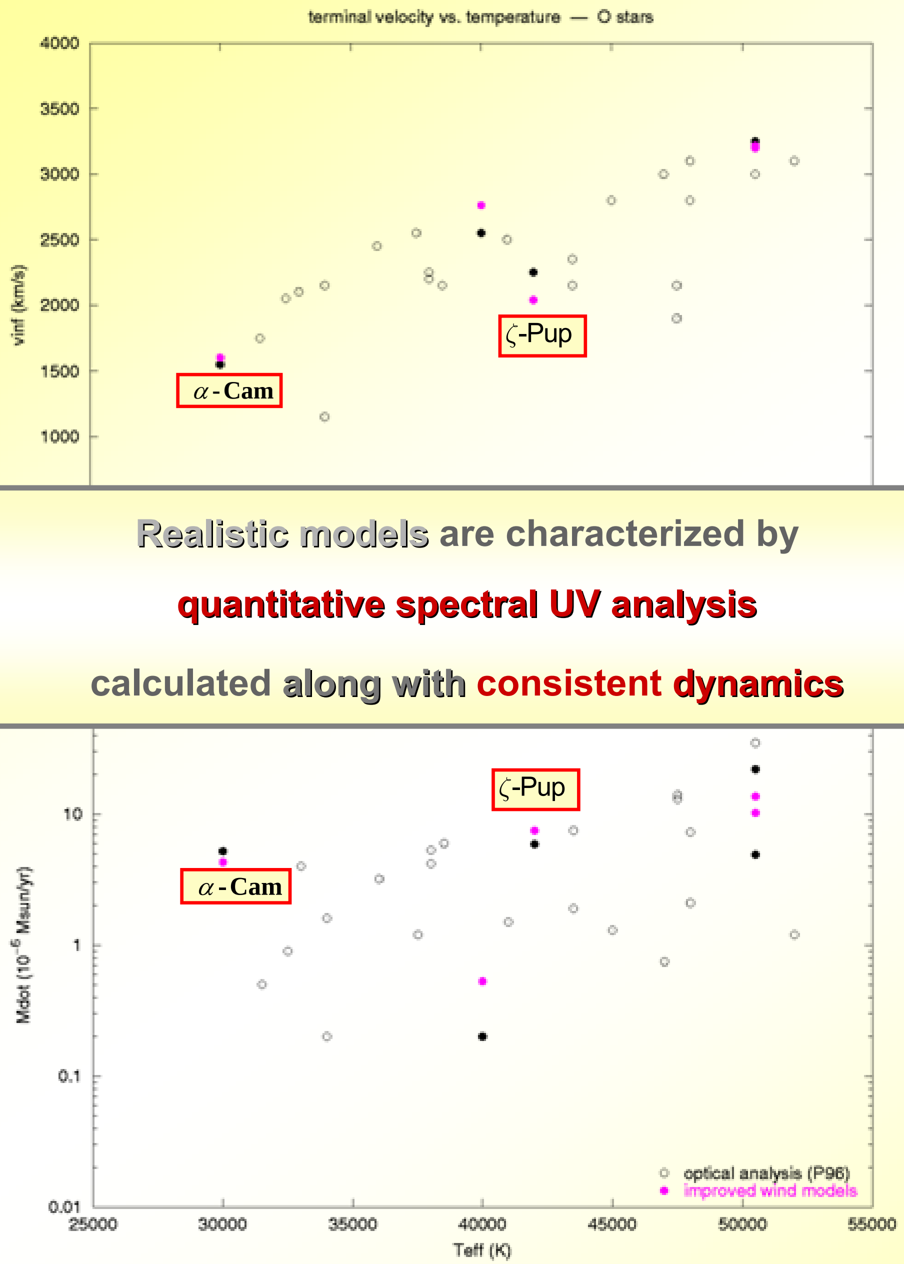
observed behaviour of wind momentum is represented by improved models

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

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

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

Wind properties of massive O-stars



Realistic models are characterized by

quantitative spectral UV analysis

calculated along with consistent dynamics

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 of 2 with observed optical values

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

↓

M , R

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

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

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

$$R\ ,\quad d$$

Analysis of integrated synthetic spectra of galaxies
based on population synthesis is feasible

stellar content, IMF, SFR, Z, burst age

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