GERMAN ASTROPHYSICAL GAVO VIRTUAL OBSERVATORY

AstroGrid-D German Astronomy Community Grid (GACG)

White Dwarf - Atmosphere Models

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and the GAVO and AstroGrid-D Teams

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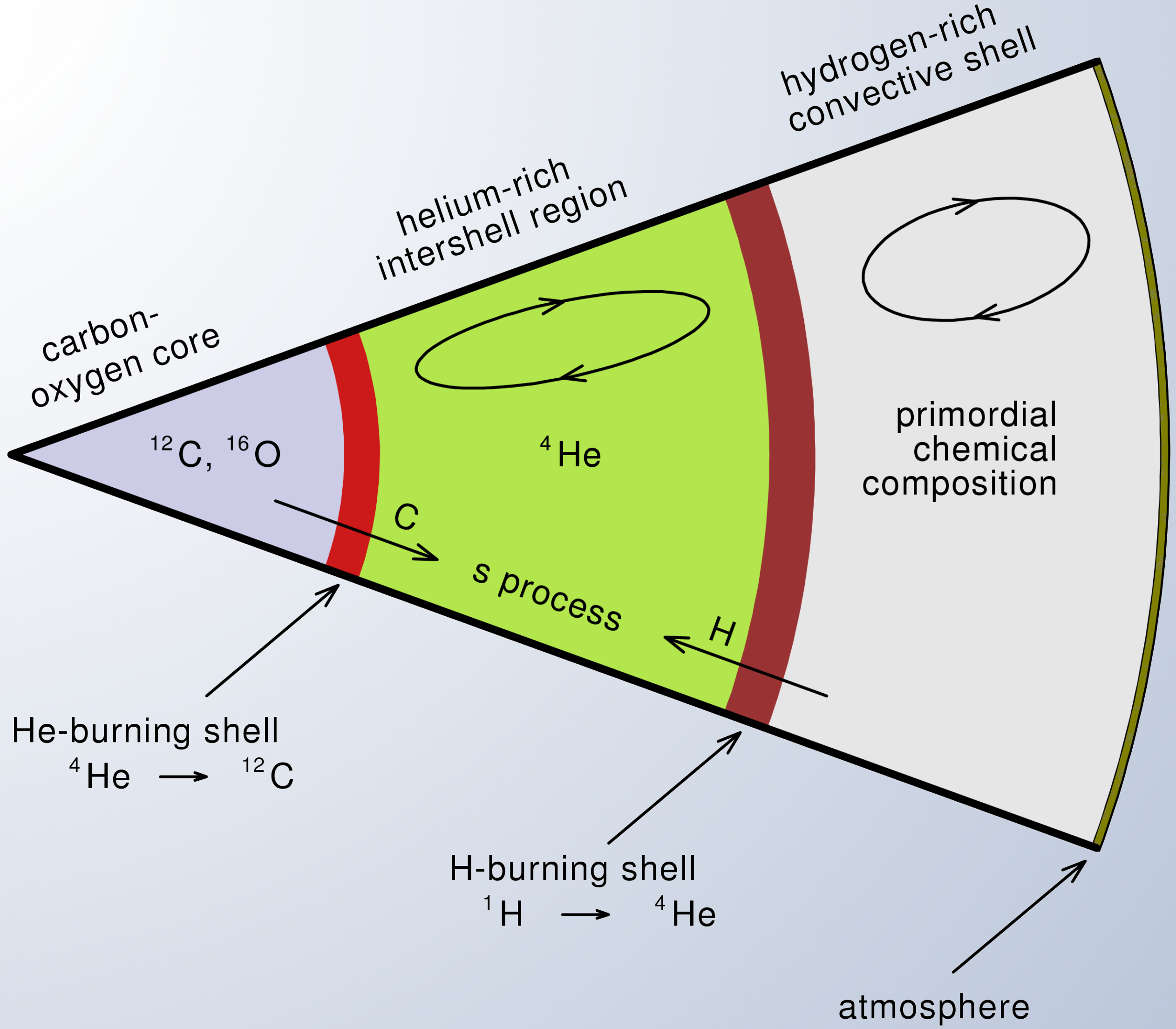
Overview

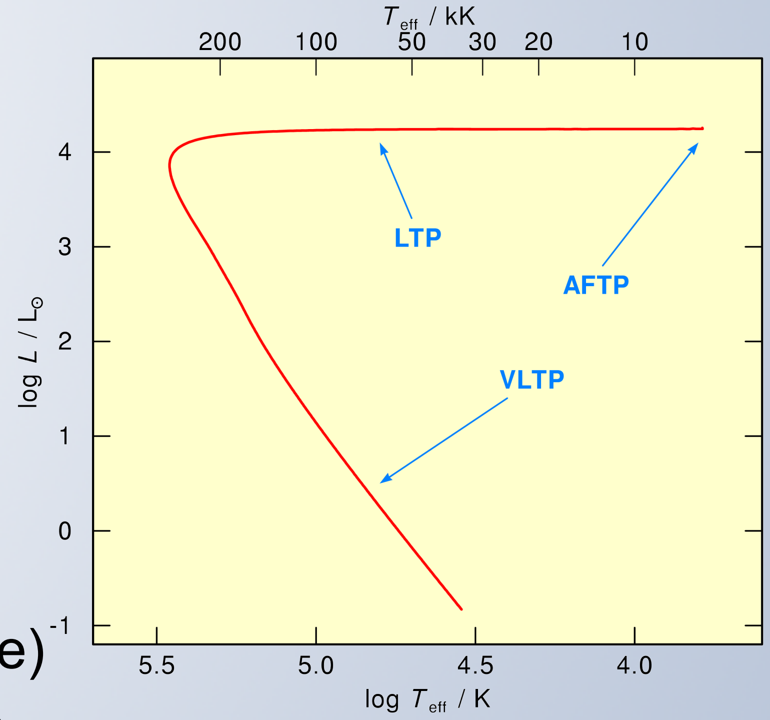
- Hydrogen-Deficient Post-AGB Stars
- Spectral Analysis of Hot, Compact Stars
- Virtual Observatory
  - From the 20th to the 21st Century
- Applications

Interior of AGB Stars

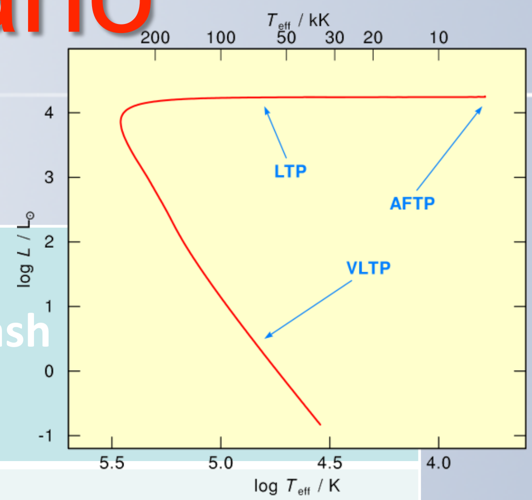


"Born-Again" Post-AGB Stars

- AGB Final Thermal Pulse (AFTP)
  - $M_H \approx 10^{-2}\,M_\odot$, $M_{He} \approx 10^{-2}\,M_\odot$
  - ≈ 20% H left on surface
- Late Thermal Pulse (LTP)
  - $M_H \approx 10^{-4}\,M_\odot$, $M_{He} \approx 10^{-2}\,M_\odot$
  - ≈ 1% H left on surface (not detectable)
- Very Late Thermal Pulse (VLTP)
  - $M_H \approx 10^{-4}\,M_\odot$, $M_{He} \approx 10^{-2}\,M_\odot$
  - no H burning shell, H burned at bottom of He burning shell
  - no H left

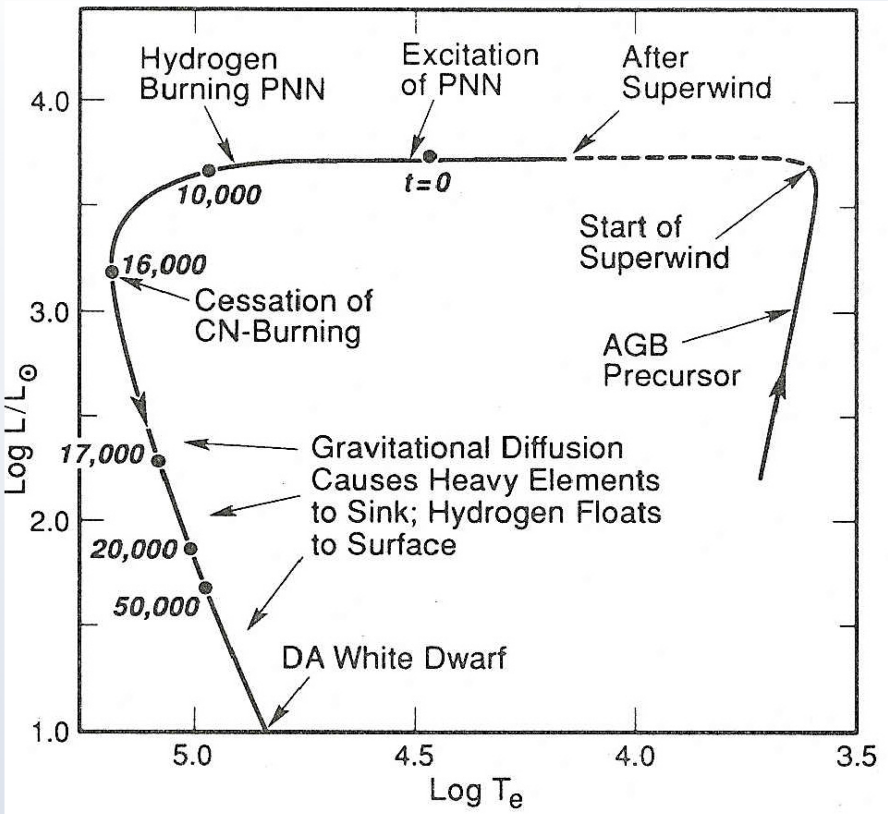


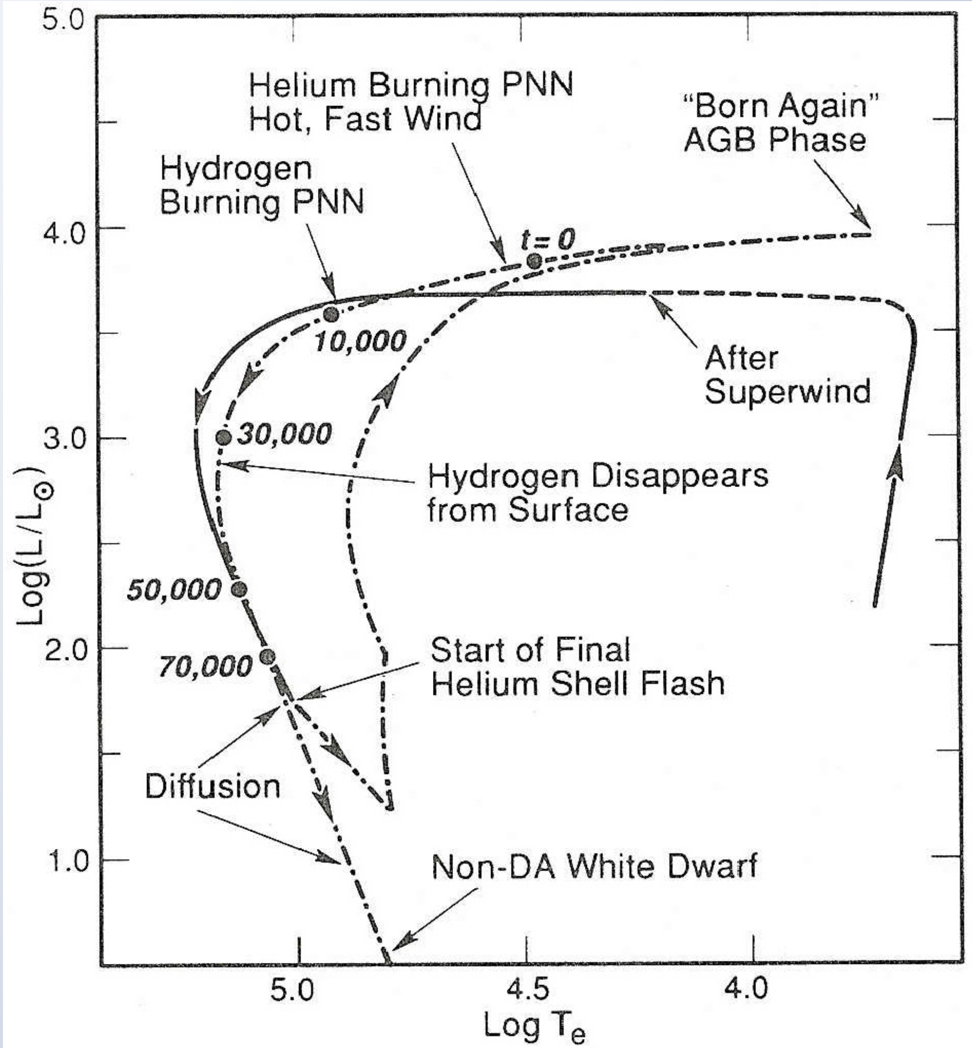
Born-again Scenario



Type of Final Thermal Pulse (He-Shell flash)	before flash	after flash
AFTP AGB Final Thermal Pulse time: still on AGB	envelope: H-rich, $10^{-2}M_{\odot}$ intershell: He-rich, $10^{-2}M_{\odot}$	mixing, remaining H about 20% (by mass)
LTP Late Thermal Pulse time: descended from AGB nuclear burning still on	envelope: H-rich, $10^{-4}M_{\odot}$ intershell: He-rich, $10^{-2}M_{\odot}$	mixing, remaining H about 1% (by mass) – not detectable!
VLTP Very Late Thermal Pulse time: WD cooling track	envelope: H-rich, $10^{-4}M_{\odot}$ intershell: He-rich, $10^{-2}M_{\odot}$	mixing and burning of H, no H left

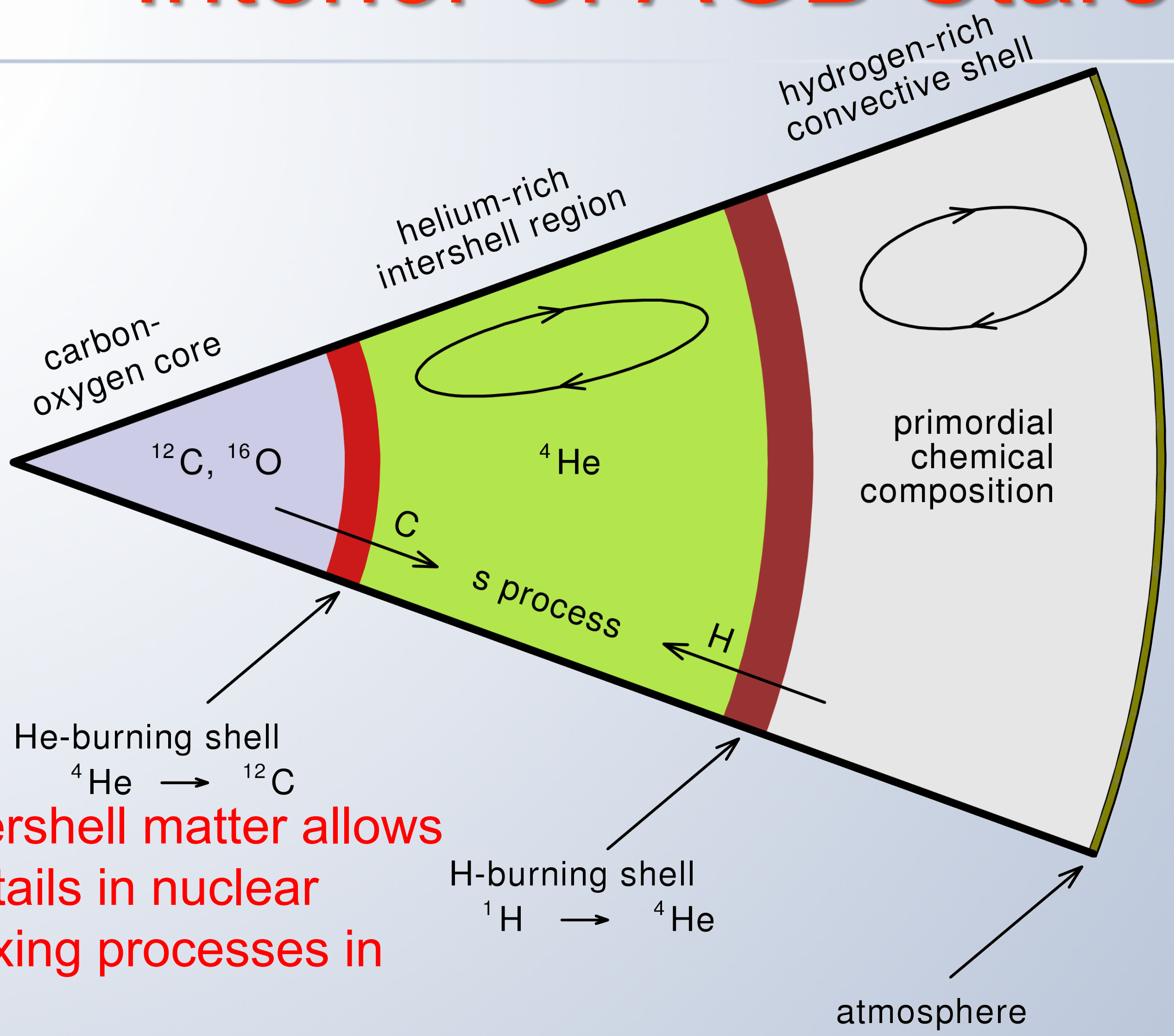
Post-AGB Evolution





Iben 1984, ApJ 277, 333

Interior of AGB Stars



Direct view on intershell matter allows to conclude on details in nuclear processes and mixing processes in AGB stars
→ Test for stellar-evolution models

Model Atmospheres

- **LTE** (Local Thermodynamical Equilibrium)
  - dimension of region in LTE > mean free path of photons
  - occupation numbers from Boltzmann distribution + Saha equation
  - $S \equiv B$
- **NLTE**
  - occupation numbers n_i in stationary equilibrium $\frac{dn_i}{dt} = 0$

Equation System

$$\cos\Theta \frac{dI_\nu(\tau_\nu,\Theta)}{d\tau_\nu} = I_\nu(\tau_\nu,\Theta) - S_\nu(\tau_\nu)$$

$$S_\nu = \frac{\eta_\nu}{\kappa_\nu}$$

mean intensity → 0 equations + frequency points NF equations = NF

statistical equations

$$\dot{n}_i = 0$$

NLTE levels (NL levels) = NL

hydrostatic equilibrium 1
particle conservation 1
radiative equilibrium 1

NF + NL + 3 equations

Classical Models

- before 1986!

ion	NLTE (levels)	LTE (levels)	RBB (line transitions)
H I	5	11	6
H II		1	
He I	5	11	0
He II	6	16	0
He III	1		
	18	48	6

NF = 65
NL = 18

→ 86 equations

numerical accuracy!
(32 bit computers …)

Λ Iteration

$$J_\nu(\tau_\nu) = \Lambda_\nu S_\nu(\tau_\nu)$$

$$= \frac{1}{2}\int_0^\infty S_\nu(t_0) E_1(|t_\nu - \tau_\nu|) dt_\nu$$

$$\approx \frac{e^{-x}}{x}$$ → good for $\Delta\tau \leq 1$

Approximate Λ^* Operator

iteration

step i: $$J_\nu^i = \Lambda_\nu^* S_\nu^i + \underbrace{\left(\Lambda_\nu - \Lambda_\nu^*\right) S_\nu^{i-1}}_{:=\Delta J_\nu^{i-1}}$$

convergence: $$S_\nu^i = S_\nu^{i-1}$$

advantage: Λ_ν^* local operator!

$$J_\nu^i = J_\nu^i\left(n_i, n_e, n_t, T, \Delta J_\nu^{i-1}\right)$$

→ reduction of equation system!

- transfer equations
- rate equations

$$\Lambda_\nu^* S_\nu(\tau_\nu) = S_\nu(\tau_\nu), \tau_\nu > \gamma$$
$$= 0, \tau_\nu < \gamma$$

Accelerated Lambda Iteration

- *"Classical"* models
  - 1969 H models, complete linearization
    - Auer & Mihalas 1969, ApJ 156, 157
  - 1972 H+He models (Auer & Mihalas, Kudritzki 1976)
  - 1972 H+He + average light element (Mihalas)

- *"Beyond classical"* models
  - 1986 H+He+C, ALI method (Werner)
  - 1990 H - Fe, multi-frequency/multi gray (Anderson)
  - 1991 H+He+C+N+O+Si (Werner, Dreizler, Rauch)
  - 1993 impact of iron-group elements (Hubeny & Lanz)

Model Atoms

– levels treated in NLTE energies ?

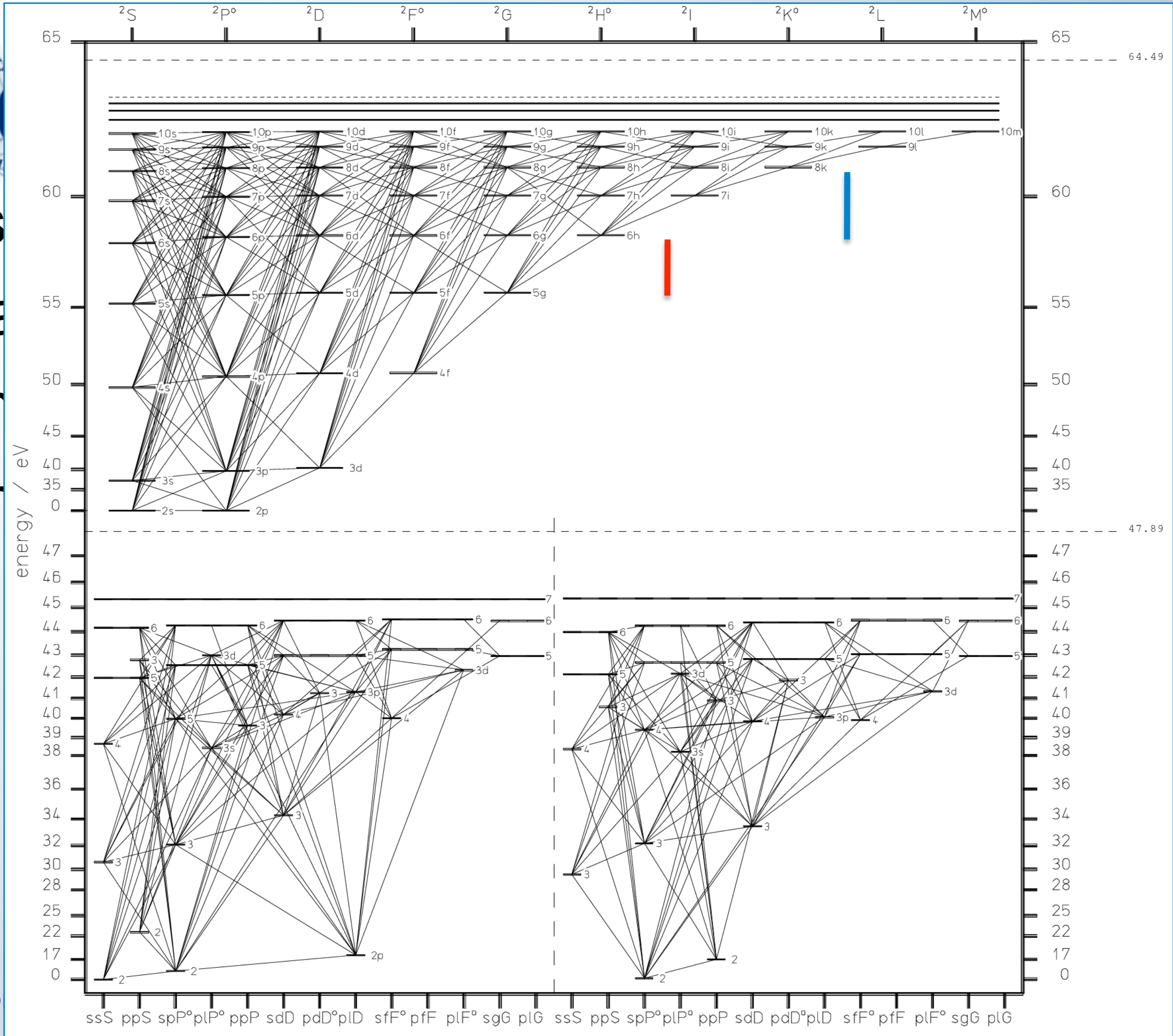
– levels treated in LTE energies ?

– radiative + collisional transistions

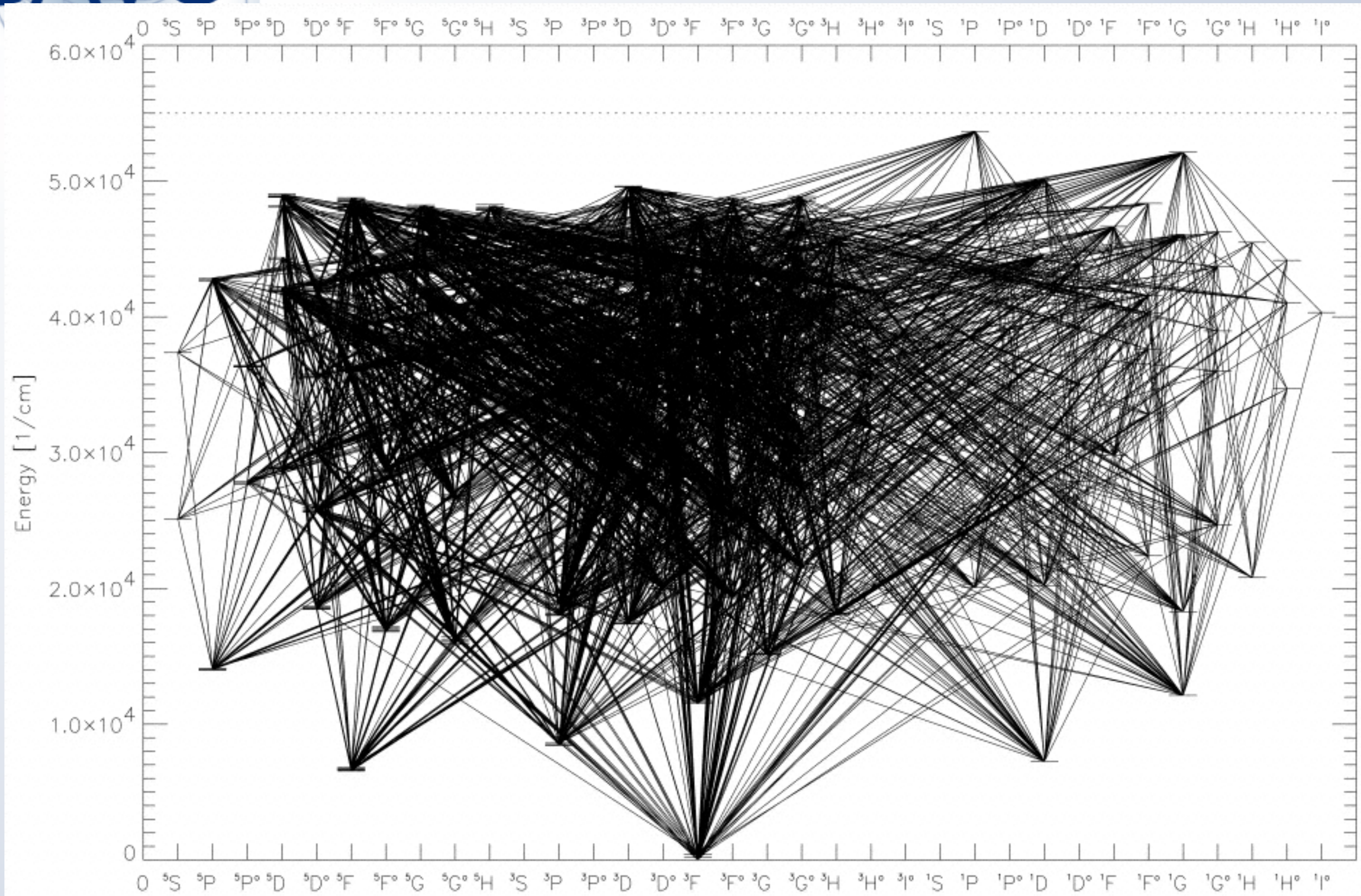
- RBB/CBB oscillator strengths ?
- RBF/CBF ionization cross sections ?
- RFF cross sections ?

– line broadening ?

- all s
- rega
- high
- ator

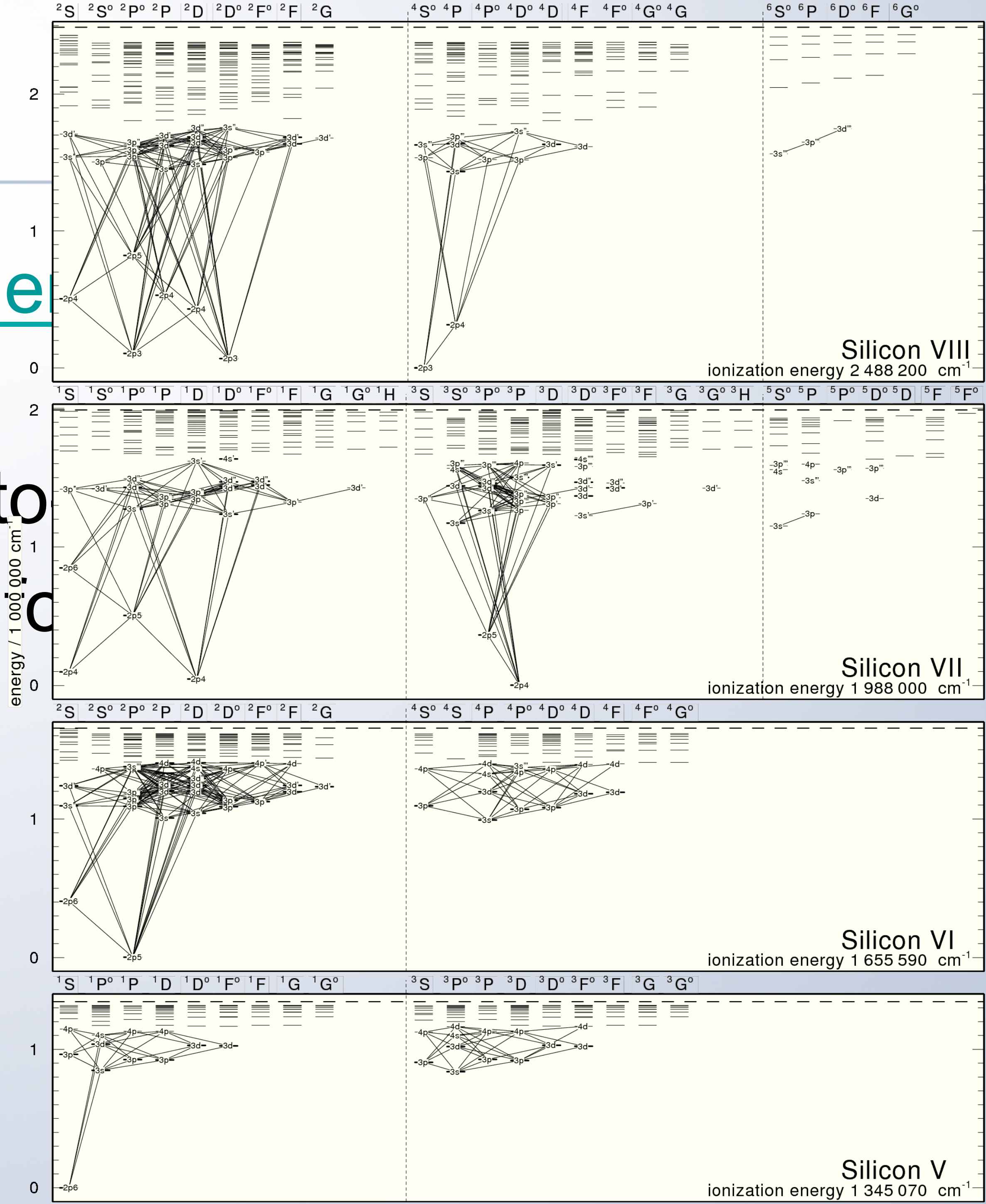


More Model Atoms … Fe VII



GERMAN ASTROPHYSICAL GAVO VIRTUAL OBSERVATORY

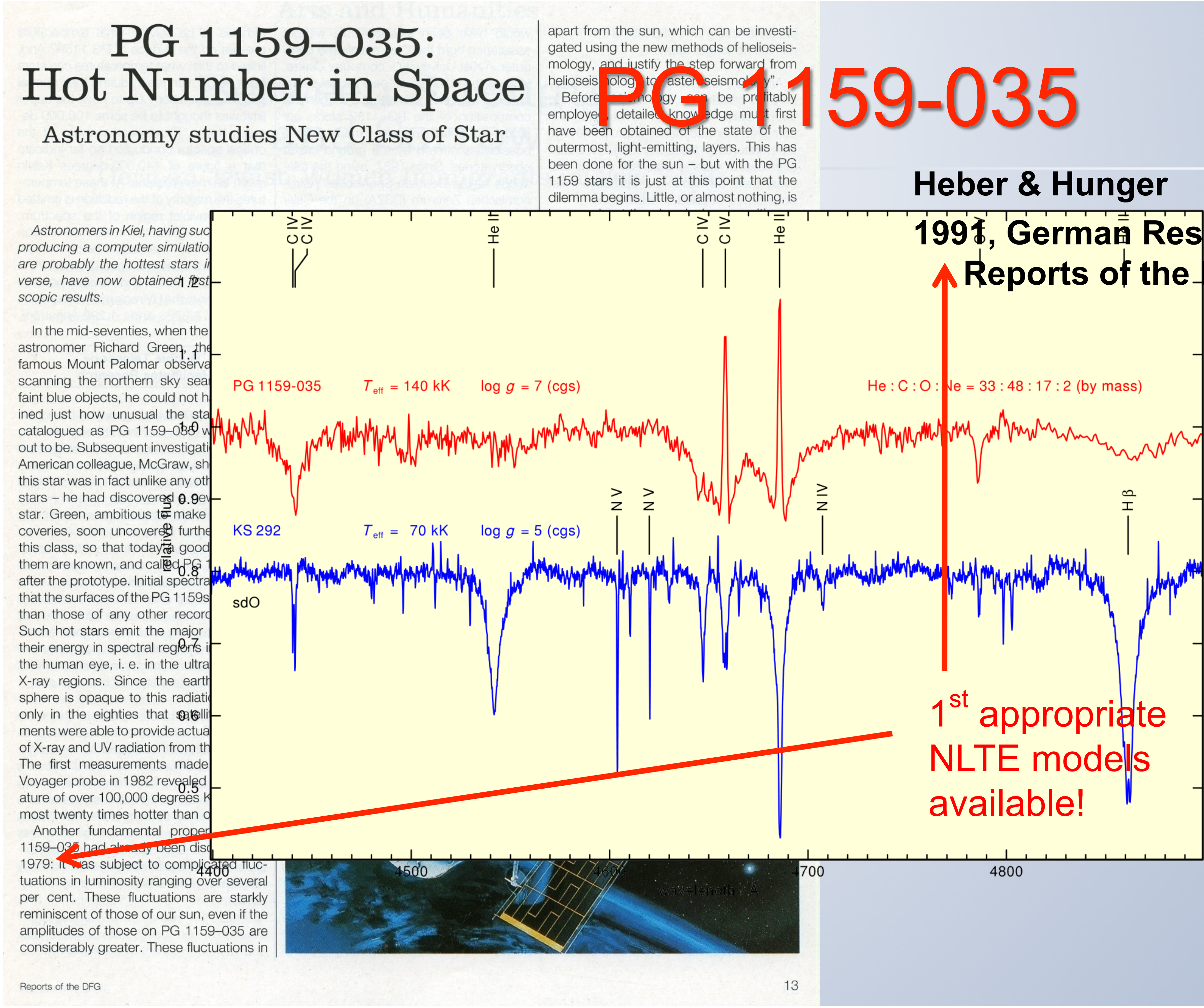
- Tübinge
- ready-to
- *TMAP* 'c



PG 1159-035

Heber & Hunger

1991, German Research, Reports of the DFG



1[st] appropriate NLTE models available!

Beyond Classical Models

- 1986 H+He+C, ALI method (Werner)
- 1990 H - Fe, multi-frequency/multi gray (Anderson)
- 1991 H+He+C+N+O+Si (Werner, Dreizler, Rauch)
- 1993 impact of iron-group elements (Hubeny & Lanz)
- 1993 iron-group elements (Dreizler & Werner)
- 1997 “light-metal” (H-Ca) models (Rauch)
- 2003 H-Ni models (Rauch)
    - “fully metal-line blanketed”

TMAP

- Tübingen Model-Atmosphere Package
  - http://astro.uni-tuebingen.de/~rauch/TMAP/TMAP.html
    - Werner et al. 2003, ASPC, 288, 31
    - Rauch & Deetjen, 2003, ASPC, 288, 103
  - NLTE
  - plane-parallel or spherical
  - homogeneous or diffusion
  - hydrostatic equilibrium
  - radiative equilibrium

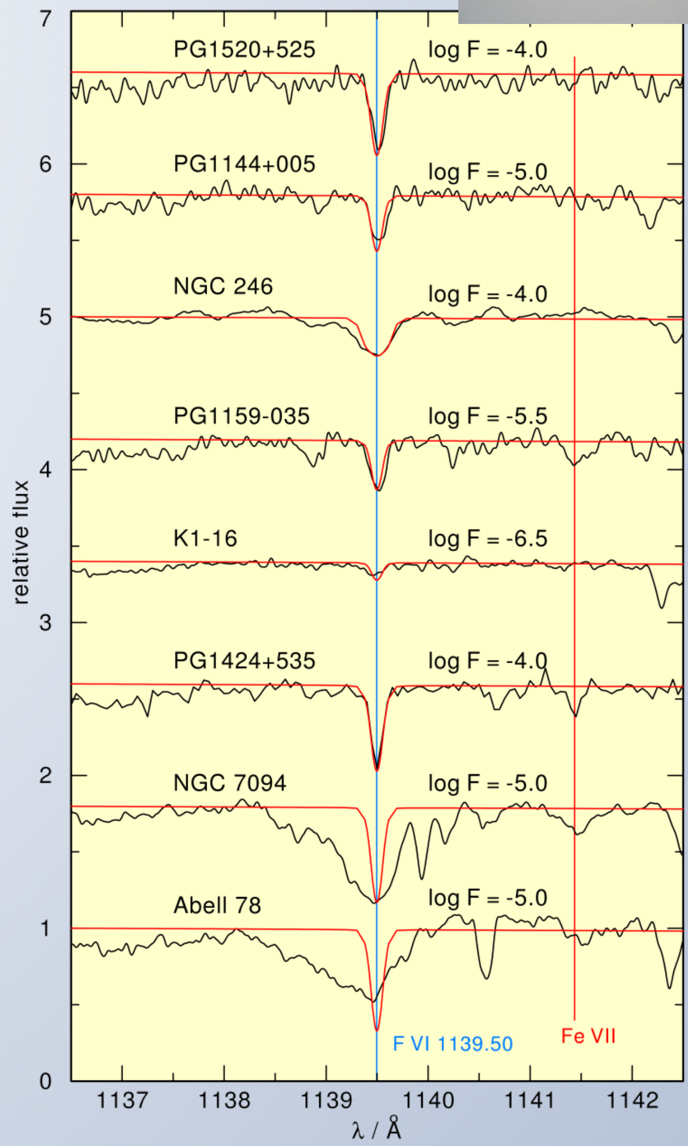
- Spectral Analysis of Hot Stars – Old-Fashioned or Trendy?

- On the Reliability of White Dwarf - Model Atmospheres

- Towards high Energies

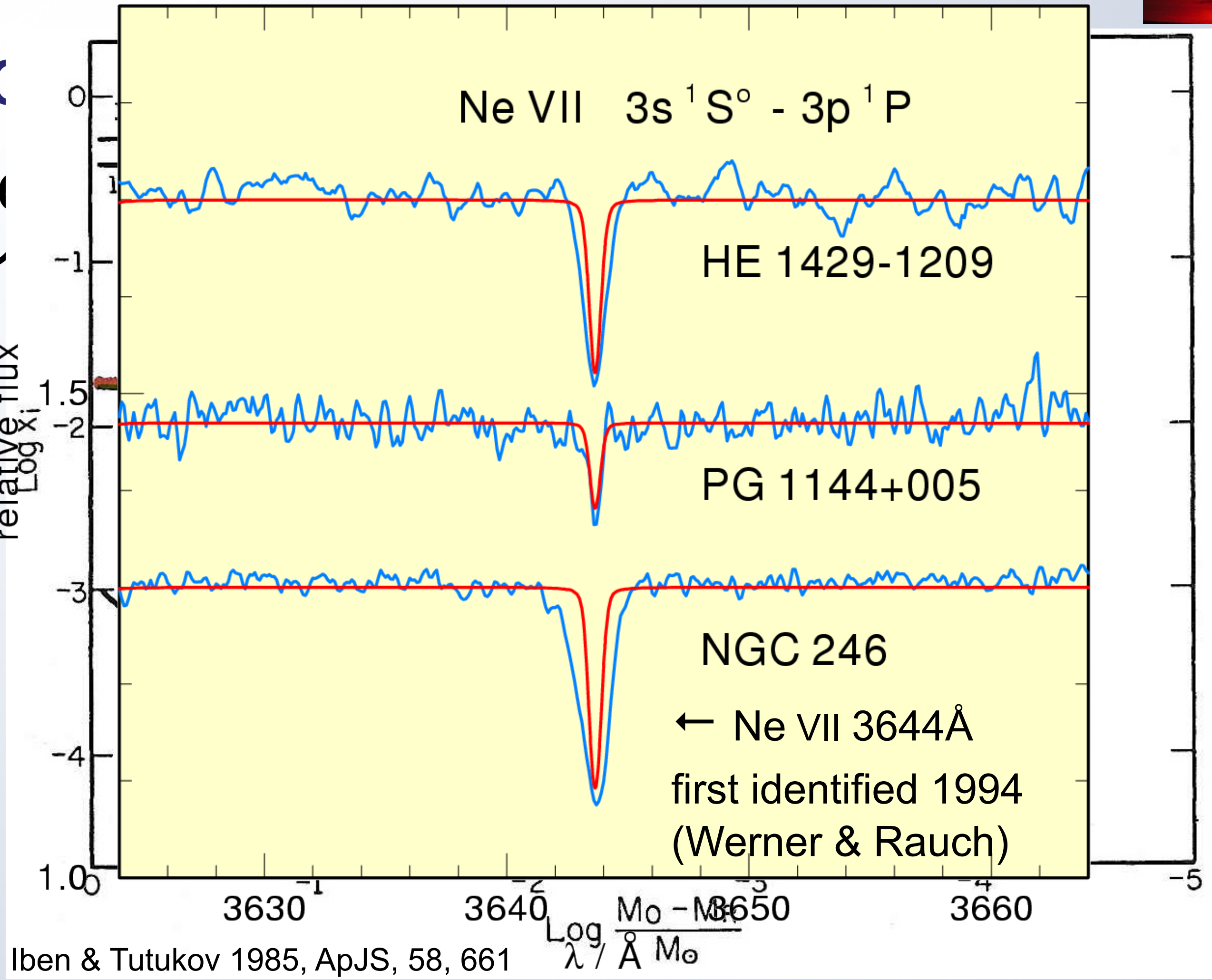
Fluorine

- First discovery of fluorine in hot post-AGB stars:
  - **F VI λ1139.50 Å**
    - $^{14}N(\alpha,\gamma)^{18}F(\beta^+)^{18}O(p,\alpha)^{15}N(\alpha,\gamma)^{19}F$
  - F abundance in PG 1159 stars up to 200 × solar
    - Werner, Rauch & Kruk 2005
  - F intershell abundance in evolutionary models is right
    - Lugaro et al. 2004

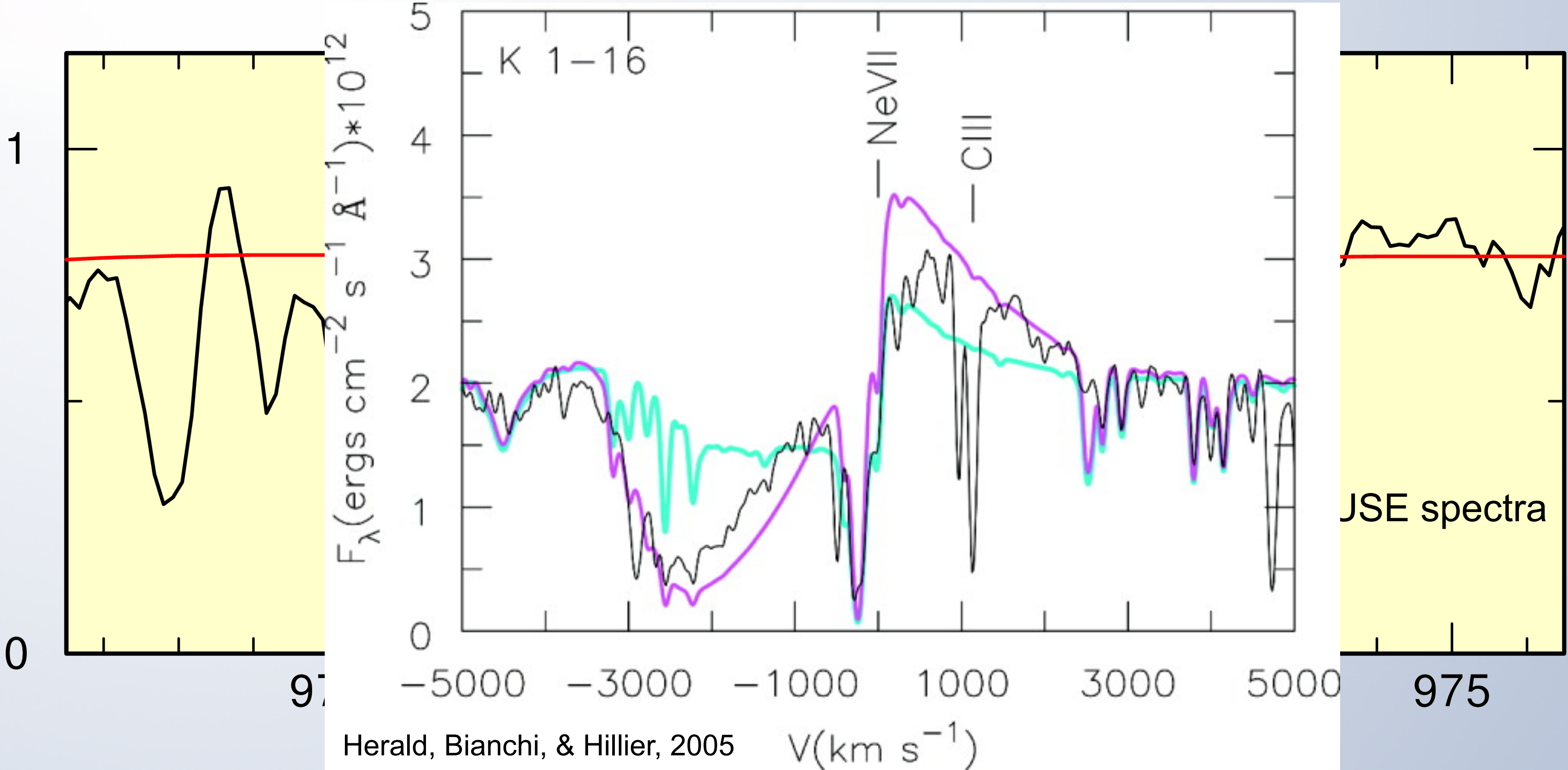


Neon

- ^{14}N(
  - int
    (1



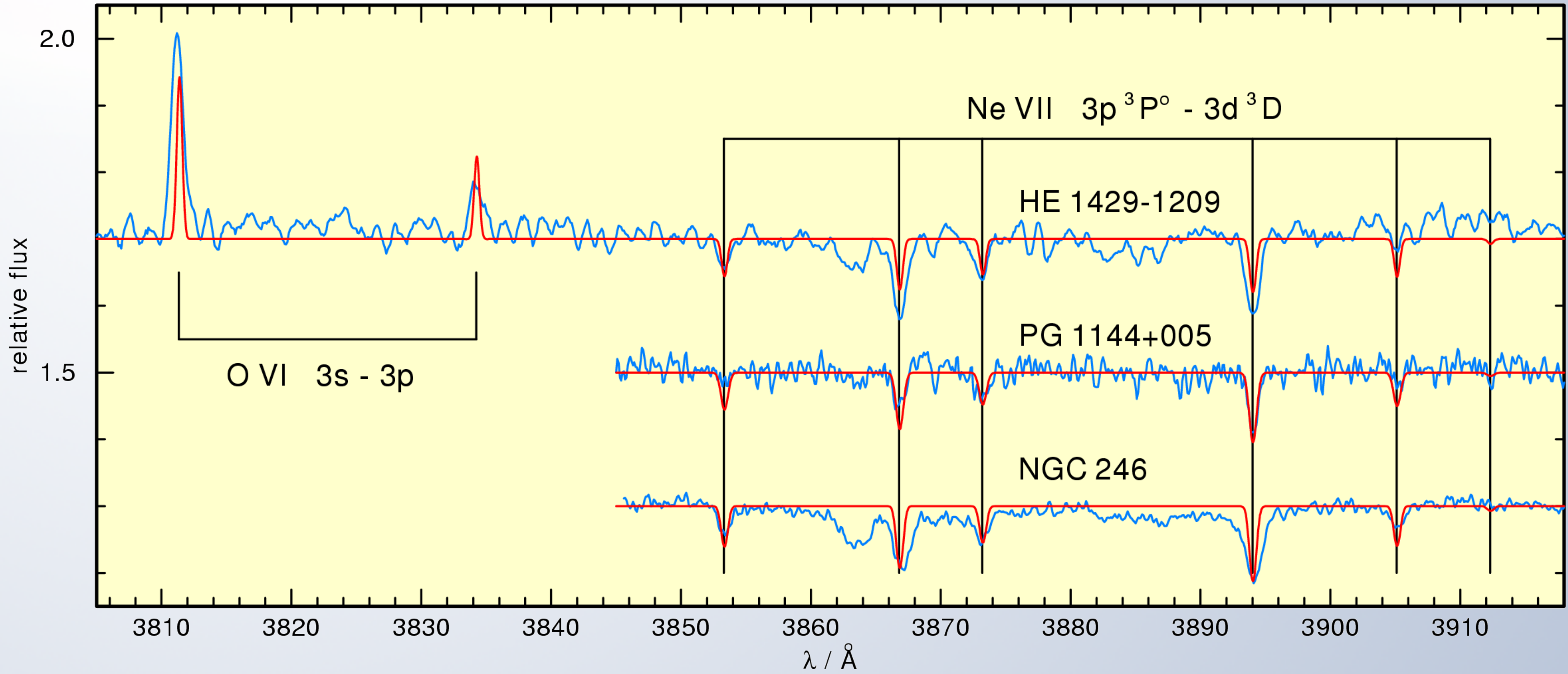
FUSE: Ne VII



Herald, Bianchi, & Hillier, 2005

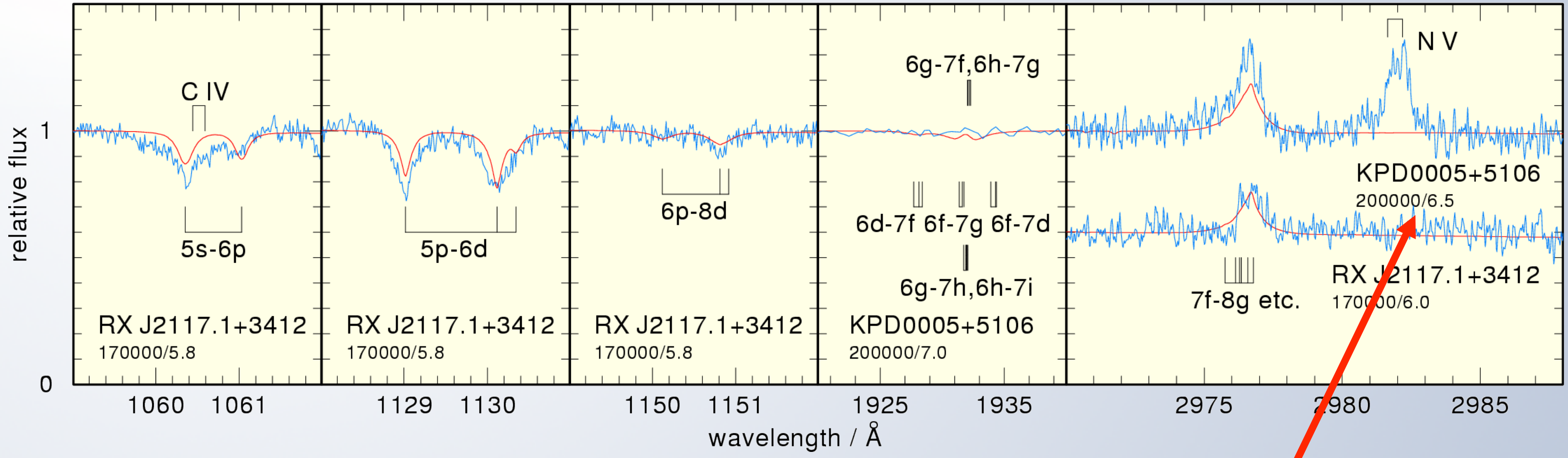
Ne VII λ973Å –
the assumed C III λ977Å P Cygni feature

VLT: Ne VII



Newly discovered Ne VII multiplet in VLT spectra (Werner et al. 2004)
Improvement of atomic data of highly excited Ne VII lines → NIST (Kramida et al. 2006)

Ne VIII



precise determination of T_{eff} in hottest stars, here DO KPD 0005+5106

before: T_{eff} = 120 000 K

now: T_{eff} = 200 000 K

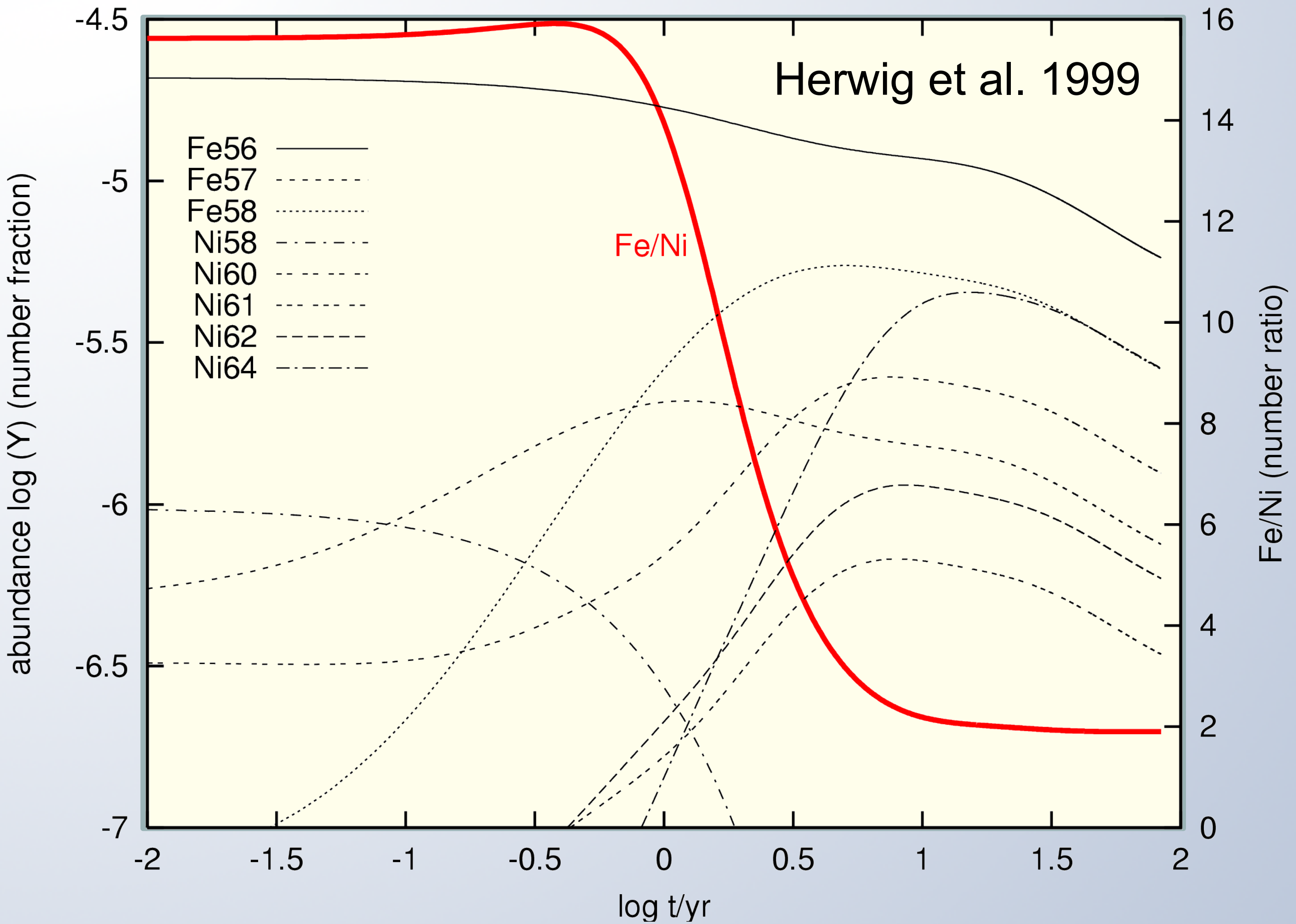
Iron

- FUSE spectral range covers strongest Fe VII lines.

- Up to now, FUSE spectra from four PG1159 stars (K 1-16, PG 1159-035, NGC 7094, A 78) with sufficiently high S/N analyzed.

- What is expected?
- reduced (sub-solar) intershell Fe abundance, by n-captures - Reduced to what extent?

S-Process: Fe-Depletion

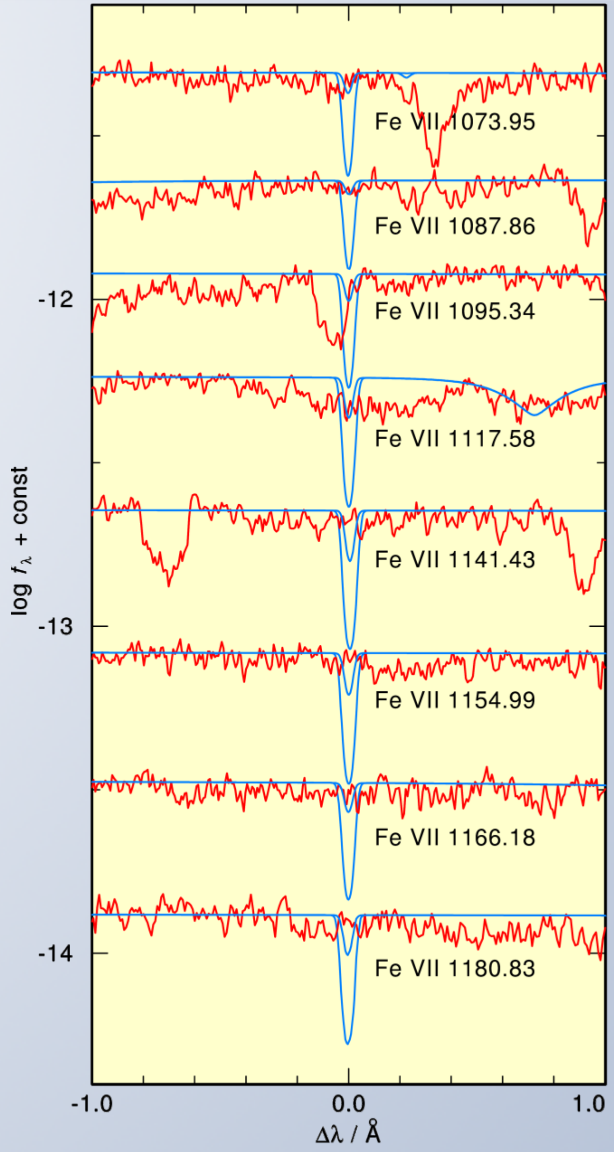


Iron-Deficiency in LTP Stars

- CSPN Abell 78
  - T_{eff} = 110 000 K
  - log g = 5.5 (cm/sec^2)
  - Fe abundance variation
    - 1/10 and 1/100 solar

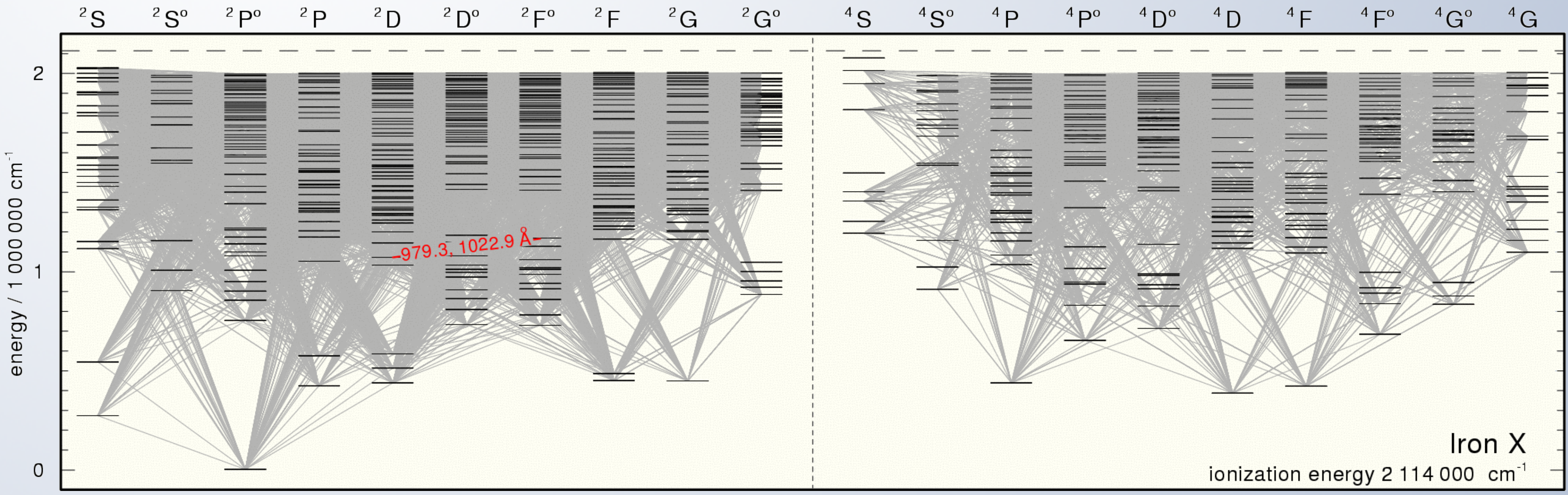
- no iron lines detectable in FUSE spectra of all four examined PG1159 stars:
  - Fe deficiency of 1-2 dex
- **very strong Fe depletion in intershell**

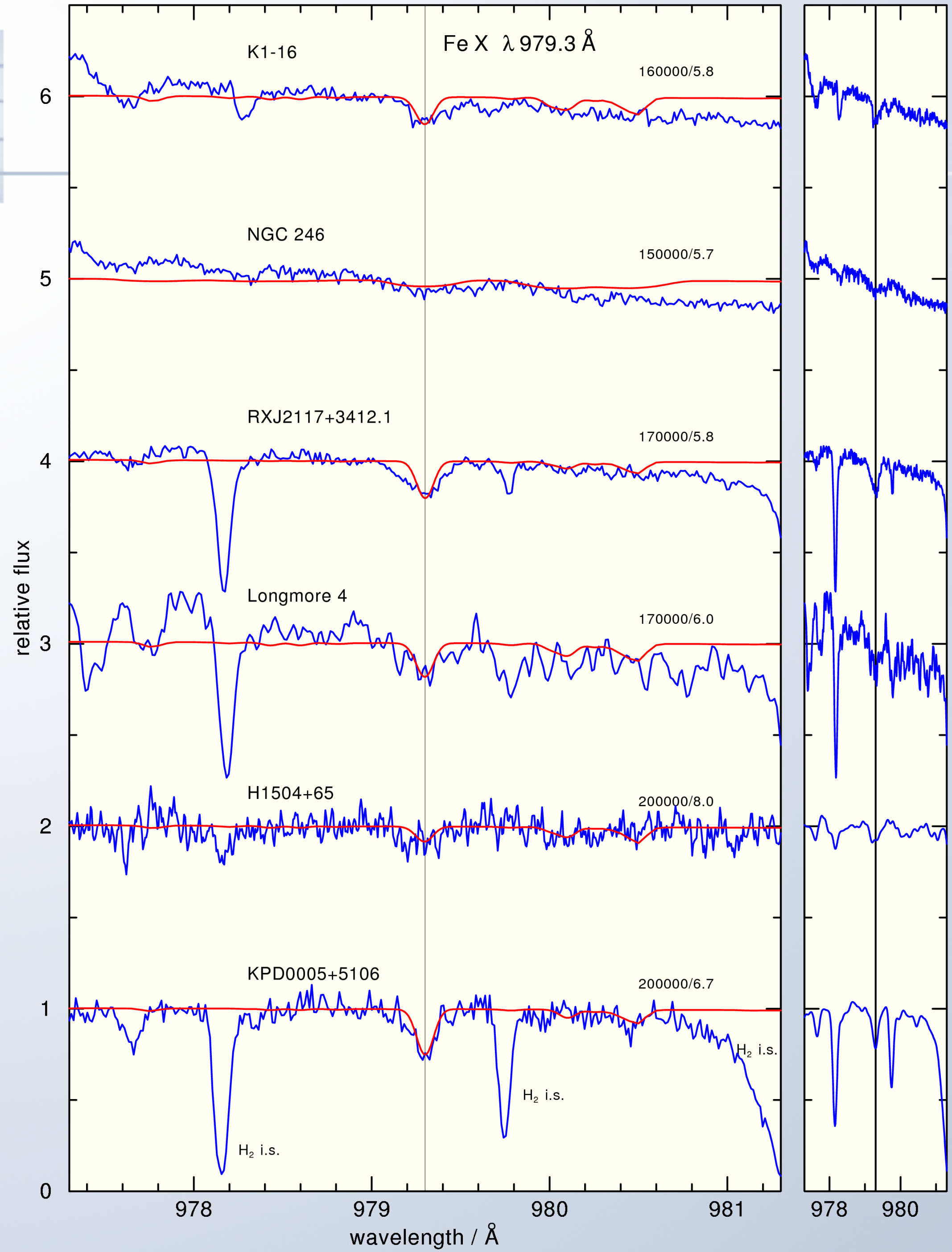
- Miksa et al. 2002, Jahn et al. 2007



Iron in PG 1159 Stars

- Werner, Rauch, & Kruk 2010, ApJL 719, 32

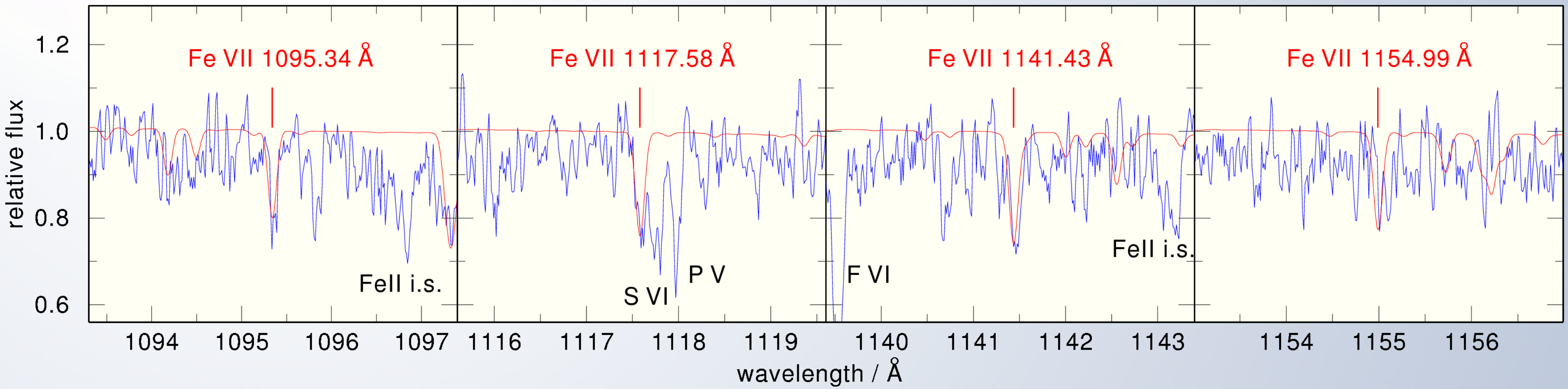


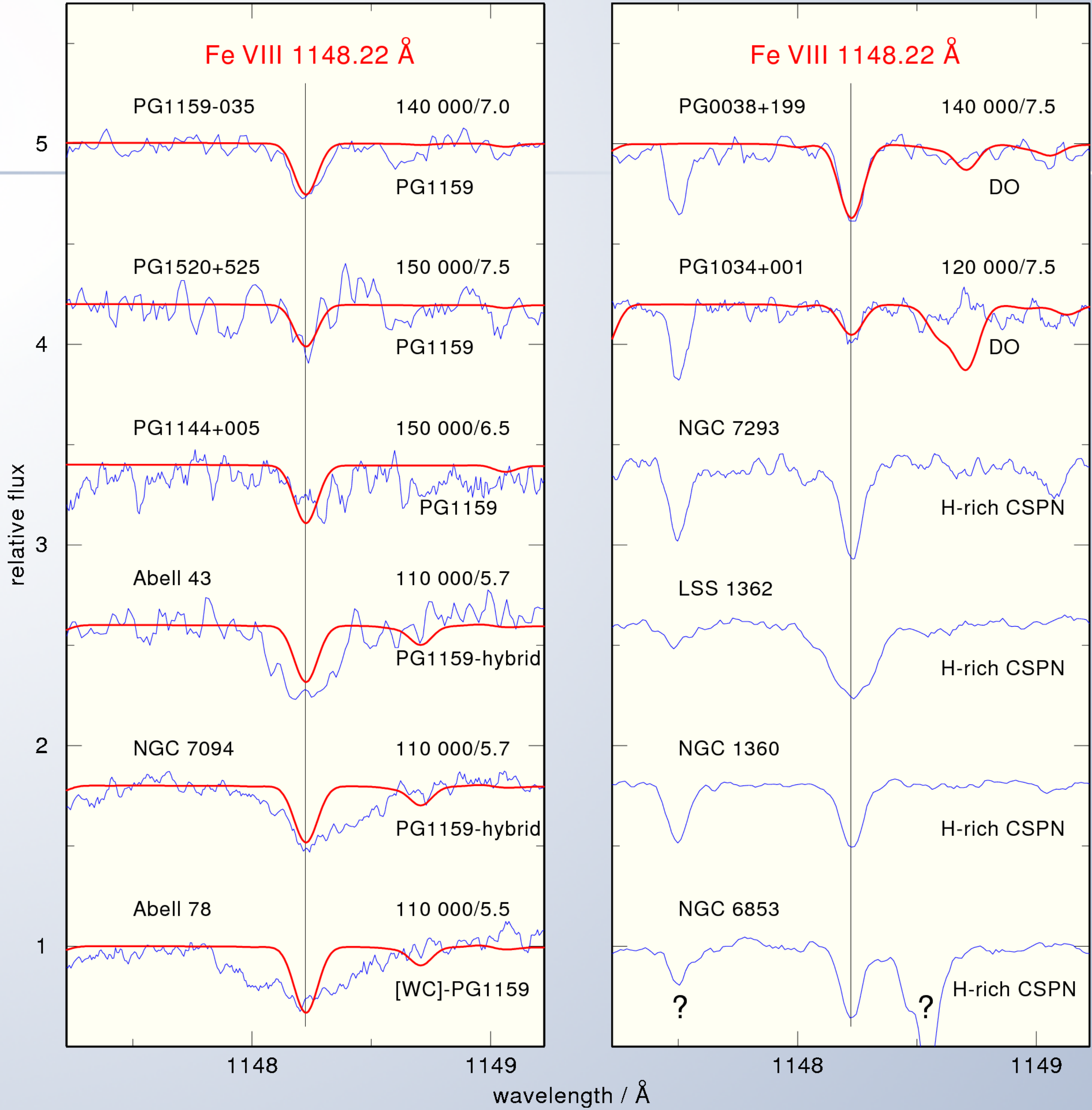

Fe X λ 979.3 Å
K1-16
160000/5.8
NGC 246
150000/5.7
RXJ2117+3412.1
170000/5.8
Longmore 4
170000/6.0
H1504+65
200000/8.0
KPD0005+5106
200000/6.7
H_2 i.s.
H_2 i.s.
H_2 i.s.
relative flux
0
1
2
3
4
5
6
978
979
980
981
wavelength / Å
978
980

www.g-vo.org

- FUSE: Ne VII λ973.3Å, 2% by mass
  - Werner, Rauch, …, & Kruk 2004
- FUSE: F VI λ1139.5Å, 200 times solar
  - Werner, Rauch & Kruk 2005
- FUSE: Ar VII λ1063.55Å, solar
  - Werner, Rauch & Kruk 2007
- FUSE: Ne VIII lines, 2% by mass
  - Werner, Rauch & Kruk 2007
- HST/STIS: Ca X λλ1462, 1504Å, solar
  - Werner, Rauch & Kruk 2008
- FUSE: Fe X λλ979.3, 1022.9Å, solar
  - Werner, Rauch & Kruk 2010

Iron in PG1159-035




Fe VIII 1148.22 Å
PG1159-035
140 000/7.0
PG1159
PG1520+525
150 000/7.5
PG1159
PG1144+005
150 000/6.5
PG1159
Abell 43
110 000/5.7
PG1159-hybrid
NGC 7094
110 000/5.7
PG1159-hybrid
Abell 78
110 000/5.5
[WC]-PG1159
Fe VIII 1148.22 Å
PG0038+199
140 000/7.5
DO
PG1034+001
120 000/7.5
DO
NGC 7293
H-rich CSPN
LSS 1362
H-rich CSPN
NGC 1360
H-rich CSPN
NGC 6853
H-rich CSPN
?
?
relative flux
1
2
3
4
5
1148
1149
1148
1149
wavelength / Å

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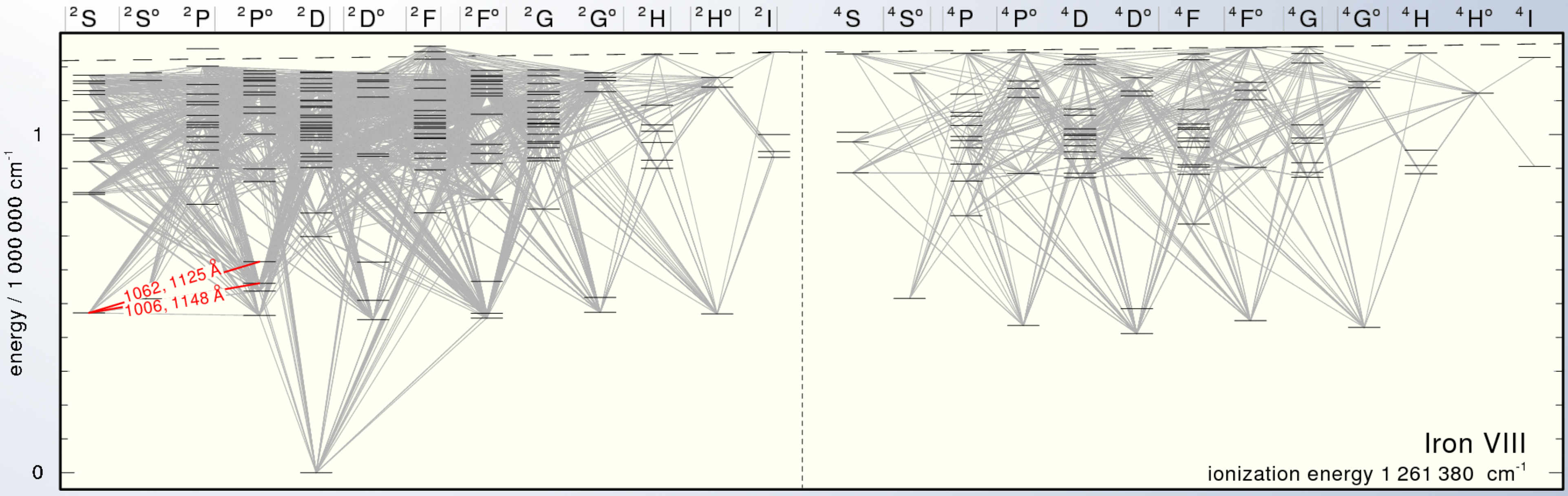
Grotrian diagram of Fe VIII



Spectral Energy Distributions for Hot Stars

A&A (2008)

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Astronomy & Astrophysics

The nebular information indicates that the spectrum of the star deviates considerably from a blackbody.

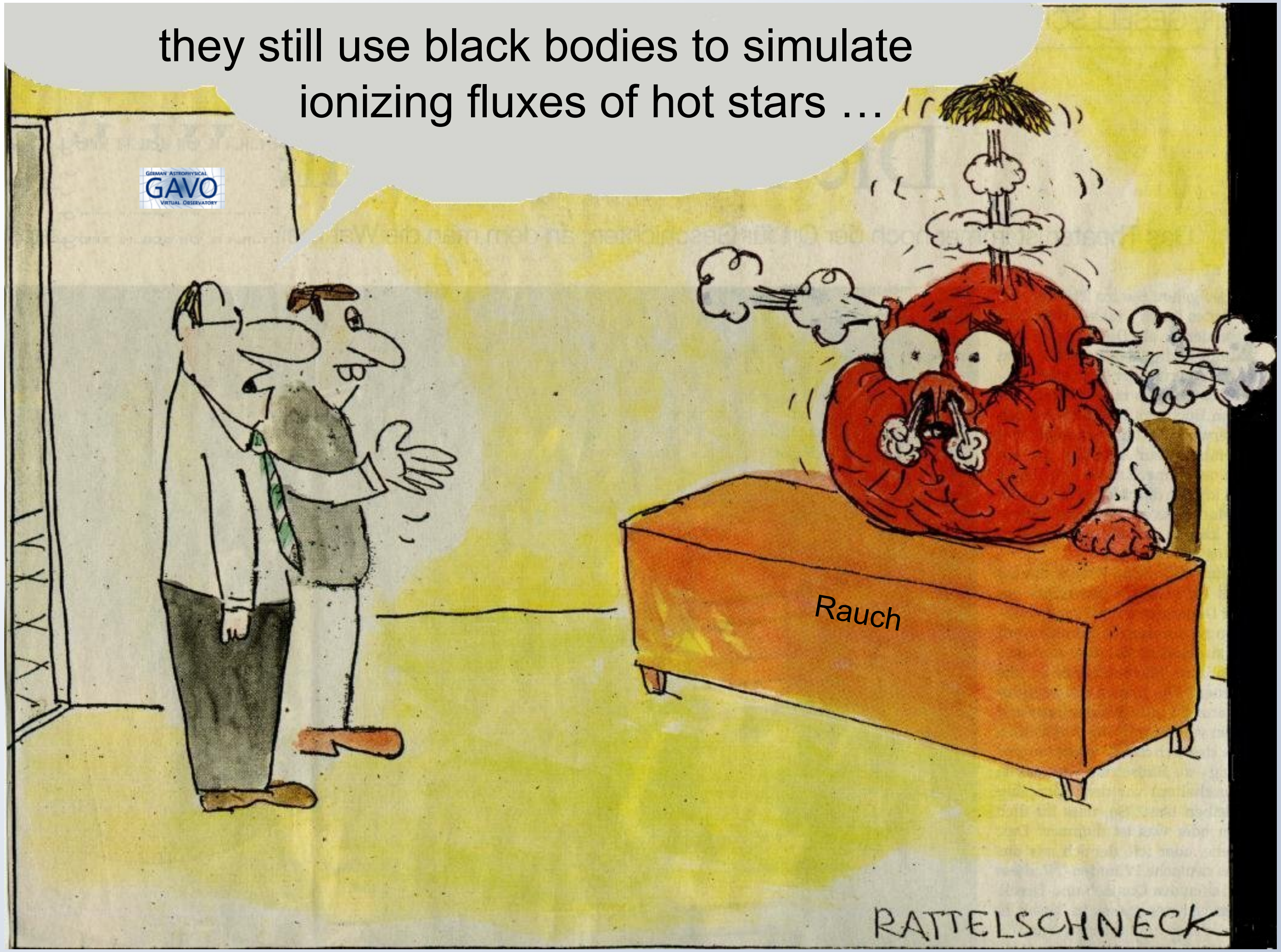
Author in 2008!

Received 2007 /Accepted 2008

ABSTRACT

The spectra of the planetary nebula is reanalysed

The temperature of the central star is discussed in the light of the observed high stages of ionization. The nebular information indicates that the spectrum of the star deviates considerably from a blackbody.


they still use black bodies to simulate
ionizing fluxes of hot stars …
GAVO
Rauch
RATTELSCHNECK

NLTE Model Atmospheres

- regarded as a domain of specialists
- high computational times
- atomic data

GAVO Project

- provide access to SEDs at three levels:
  - fast and easy
    - unexperienced user, no detailed knowledge about the model-atmosphere code necessary
  - individual
    - interested user, detailed analysis of special objects
  - experienced
    - define own model atoms, comparison of codes, etc.

VO Service *TheoSSA*

- based on the Tübingen NLTE Model Atmosphere Package *TMAP*, the *GAVO* Service *TheoSSA* provides
  - Spectral Energy Distributions (SEDs)
    - ***TheoSSA*** ***(http://vo.ari.uni-heidelberg.de/ssatr-0.01/TrSpectra.jsp?)***
  - Simulation Software
    - ***TMAW*** ***(http://astro.uni-tuebingen.de/~TMAW/TMAW.shtml)***
  - Atomic Data
    - ***TMAD*** ***(http://astro.uni-tuebingen.de/~rauch/TMAD/TMAD.html)***

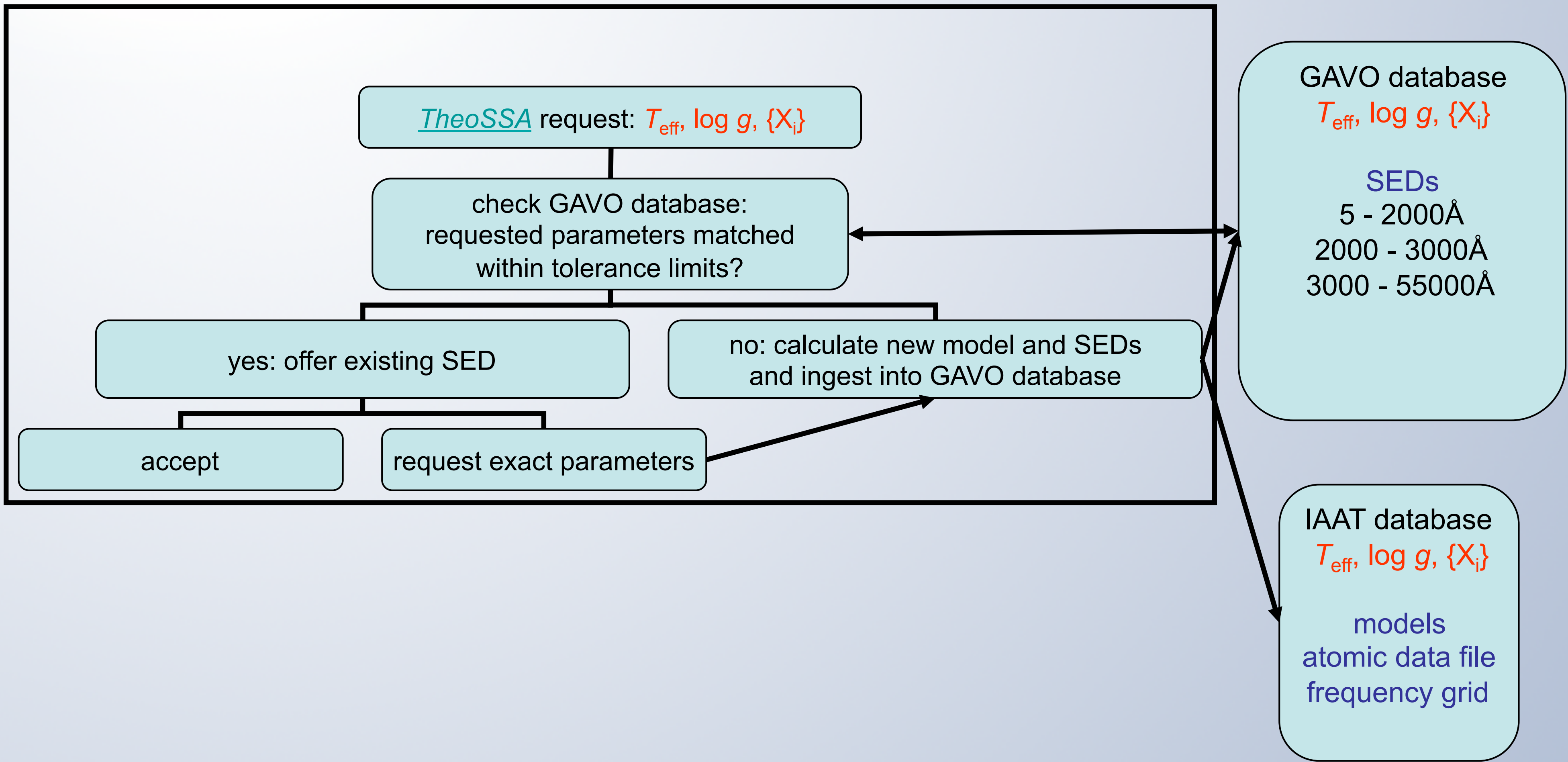
Way to Reality in the 21st Century

– use SED grids
  - ready to use, interpolation

– calculate individual model atmospheres
  - T_{eff}, log g, mass fraction $\{X_i\}$, $i \in$ (H, He, C, N, O)
    – standard model atoms

– create own atomic-data files, $i \in$ (H - Ni), and calculate model atmospheres and SEDs

TheoSSA



TheoSSA request: Teff, log g, {Xi}
check GAVO database: requested parameters matched within tolerance limits?
yes: offer existing SED
no: calculate new model and SEDs and ingest into GAVO database
accept
request exact parameters
GAVO database
Teff, log g, {Xi}
SEDs
5 - 2000Å
2000 - 3000Å
3000 - 55000Å
IAAT database
Teff, log g, {Xi}
models
atomic data file
frequency grid

TheoSSA Data Base

- growing in time
  - newly calculated SEDs are automatically ingested
  - meta data at ARI (Heidelberg)
  - SEDs etc. at IAAT (Tübingen)

Calculation of SEDs

- cpu time increases with number of considered elements
  - 1 H+He+C+N+O model ≈ 1 day on a fast PC
  - IAAT cluster: 16/48 models parallel
- calculation of SED grids
  - compute resources of

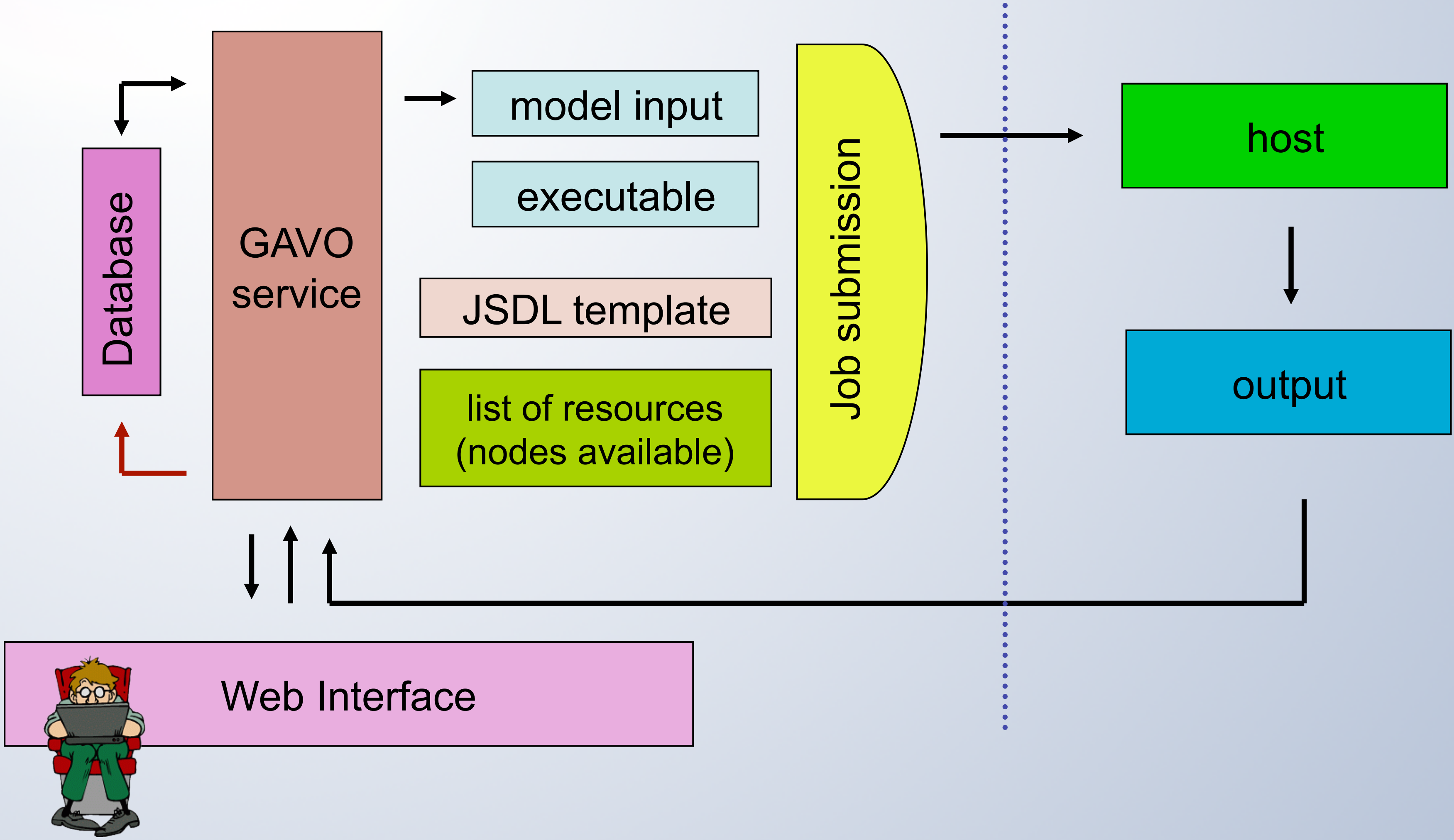
Why use a Grid?

- scales according to demand
  - 1, 10, or 100 cores available at any time
- higher reliability
- middleware offers additional options
  - job monitoring, statistics, error handling
- *TMAP* is easy to compute
  - no inter-process communication
  - no complex compilation, all libraries present

Technical Details

- AstroGrid-D uses the Globus Toolkit middleware (GT4)
- compute resources are retrieved from the MDS (monitoring and discovery service)
- the Job is submitted using a JSDL template (Job Submission Description Language)
- data transfer uses gsiftp, the job staging process is based on GT4 web services (globusrun-ws)
- all written in a two-page shell script

Task farming with Globus



Spectroscopy of LS V +46°21

Hα + [O III]
Dean Salman
www.deansalman.com

- exciting star of Sh 2-216
  - closest PN known, d = 130pc
  - apparent diameter 1.6°
  - LS V +46°21 about 0.2 radii off centre
    - mild interaction with ISM
    - thin disk orbit of low inclination and eccentricity
      - Kerber et al. 2004
- FUSE: 67.6 ksec in 2003/2004, $R \approx 0.05$ Å
- STIS: 5.5 ksec in 2000, $R \approx 0.06$ Å

Spectroscopy of LS V +46°21

- HHeCNOFMgSiPSAr + CaScTiVCrMnFeCoNi
  - IrOnIc
    - Rauch & Deetjen 2003
  - 686 NLTE levels
  - 2417 individual lines
  - 9 million iron-group lines
    - Kurucz 1996

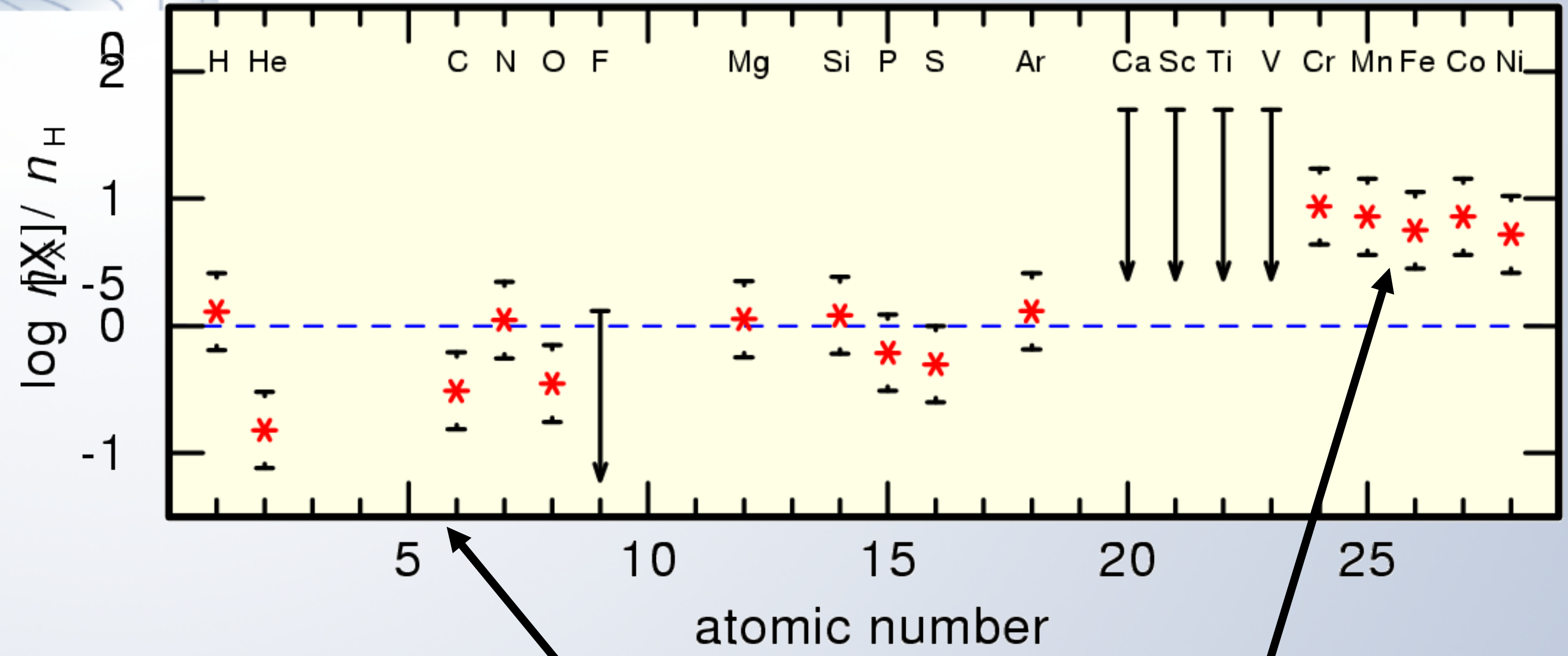
T_{eff} = 95 000 K
log g = 6.9

(200 million)

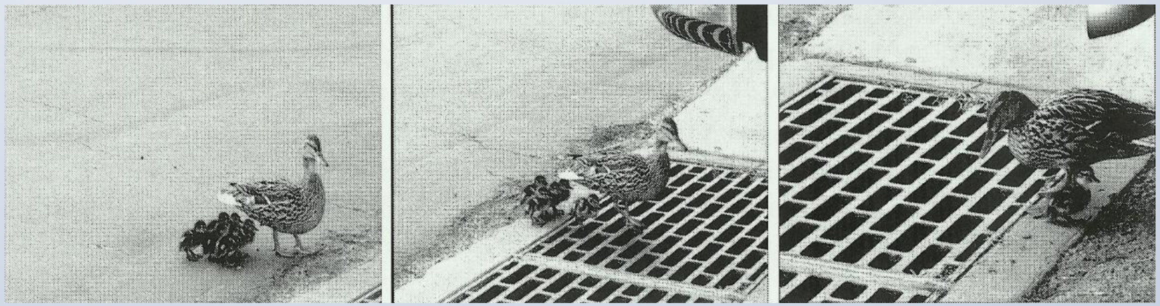
(2009, …)

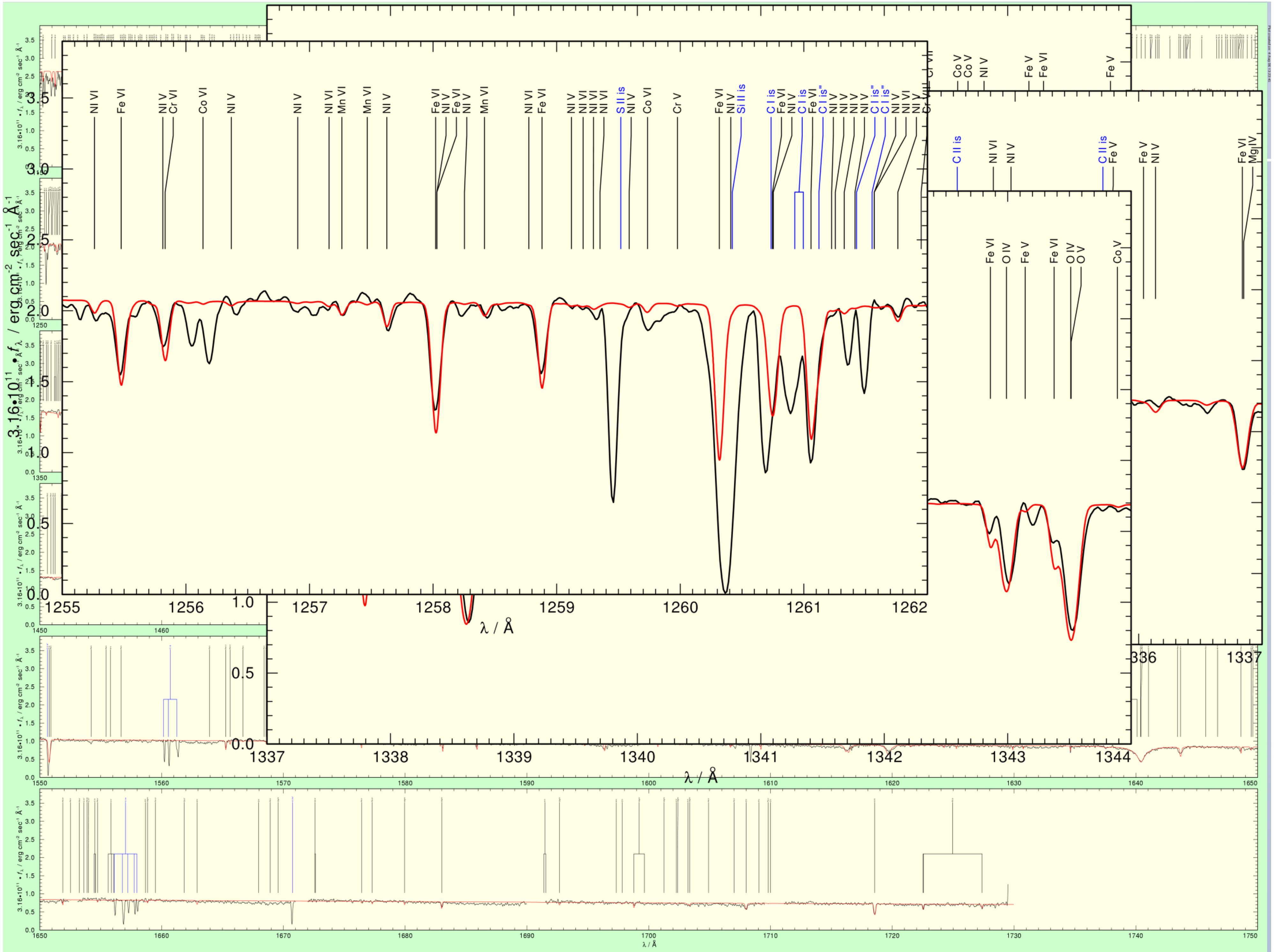
- Rauch et al. 2007, A&A, 470, 317

LS V +46°21



Photospheric abundances
exhibit interplay of gravitational settling and radiative levitation
in agreement with diffusion predictions (Chayer et al. 1995)





Ni VI
Fe VI
Ni V
Cr VI
Co VI
Ni V
Ni V
Ni VI
Mn VI
Mn VI
Ni V
Fe VI
Ni V
Fe VI
Ni V
Mn VI
Ni VI
Fe VI
Ni V
Ni VI
Ni VI
Ni VI
S II is
Ni V
Co VI
Cr V
Fe VI
Ni V
Si II is
C I is
Fe VI
Ni V
C I is
Fe VI
C I is"
Ni V
Ni V
Ni V
Ni V
C I is"
C I is"
Ni V
Ni VI
Ni V
Cr VII
Co V
Co V
Ni V
Fe V
Fe VI
Fe V
C II is
Ni VI
Ni V
C II is
Fe V
Fe V
Ni V
Fe VI
Mg IV
Fe VI
O IV
Fe V
Fe VI
O IV
O V
Co V
3.16•10^11 • f_λ / erg cm^-2 sec^-1 Å^-1
λ / Å
1255
1256
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1262
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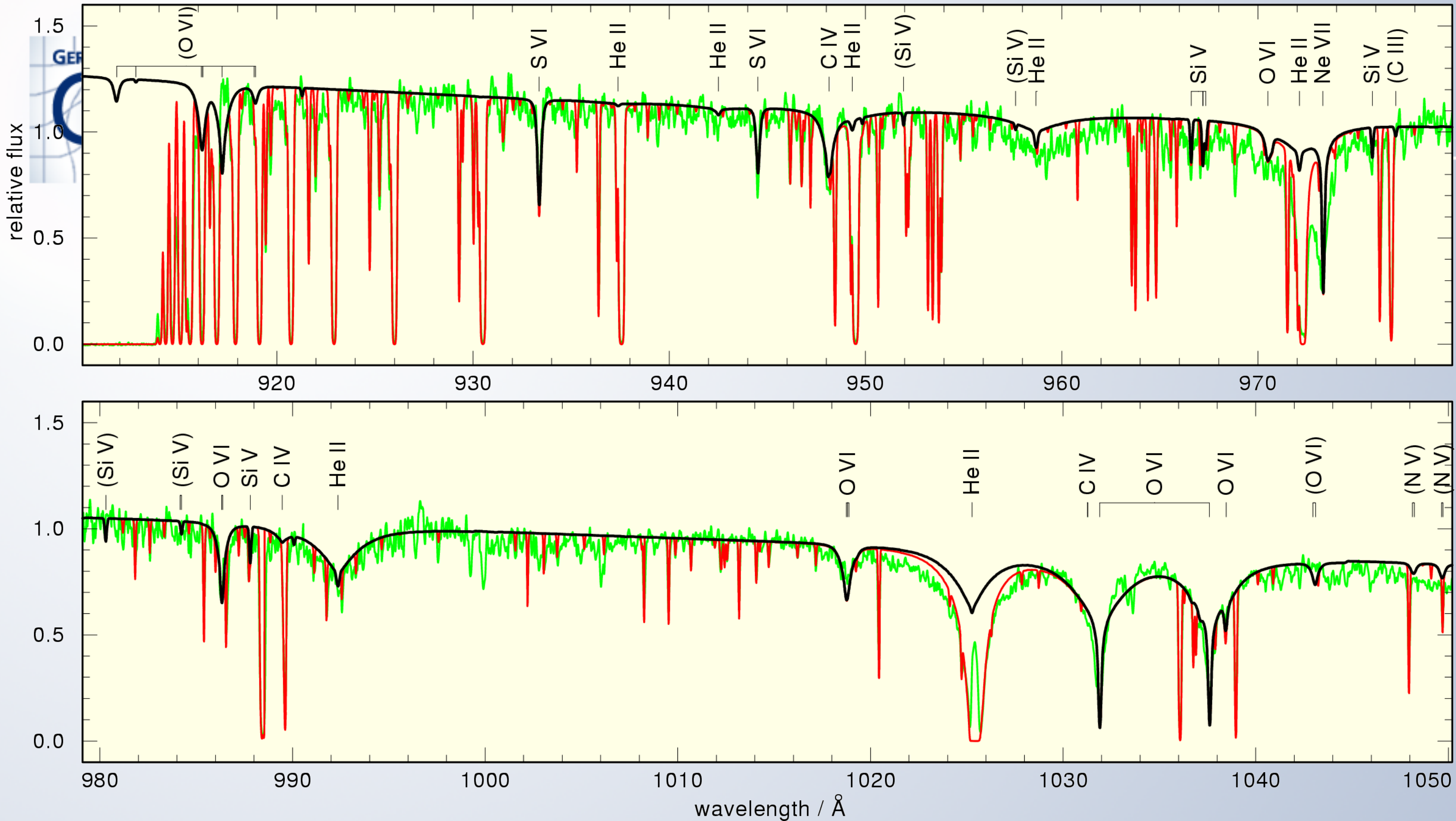


FUSE spectrum of PG1159-035

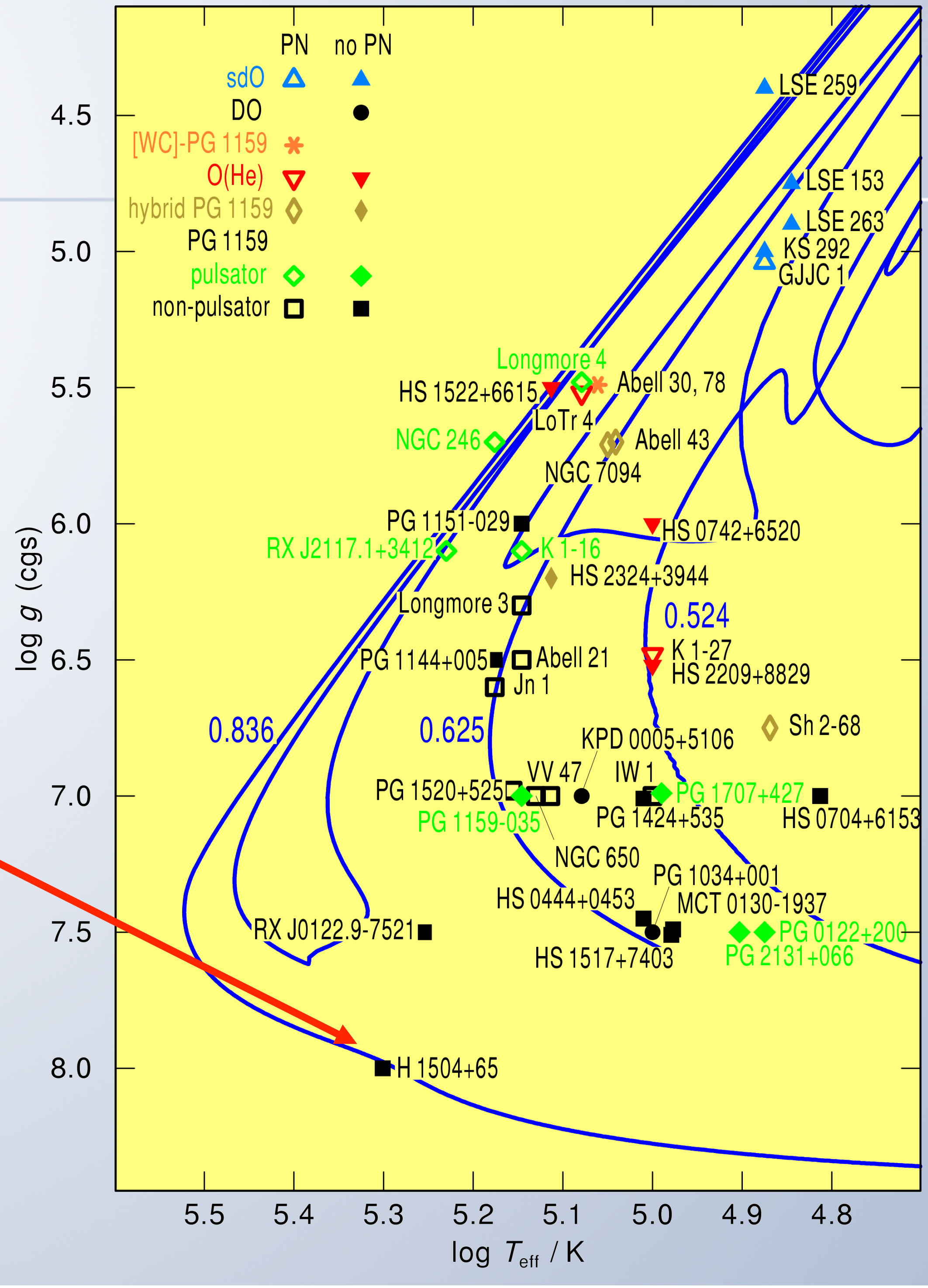
and model fit incl. ISM model

Jahn et al. 2007, A&A, 462, 281

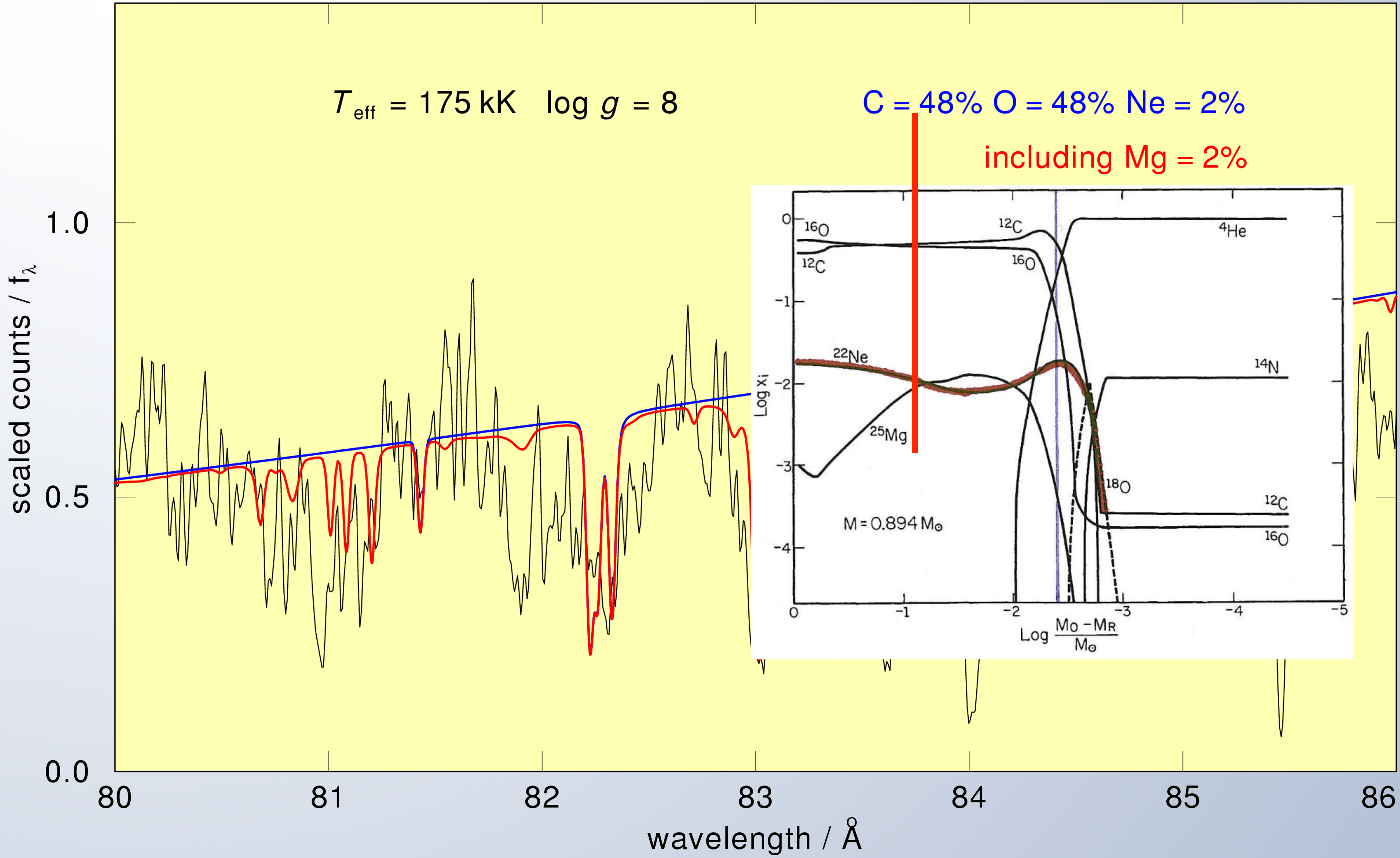
GERMAN ASTROPHYSICAL GAVO VIRTUAL OBSERVATORY

H1504+65

T_{eff} = 200 000 K
log g = 8



Magnesium in H 1504+65



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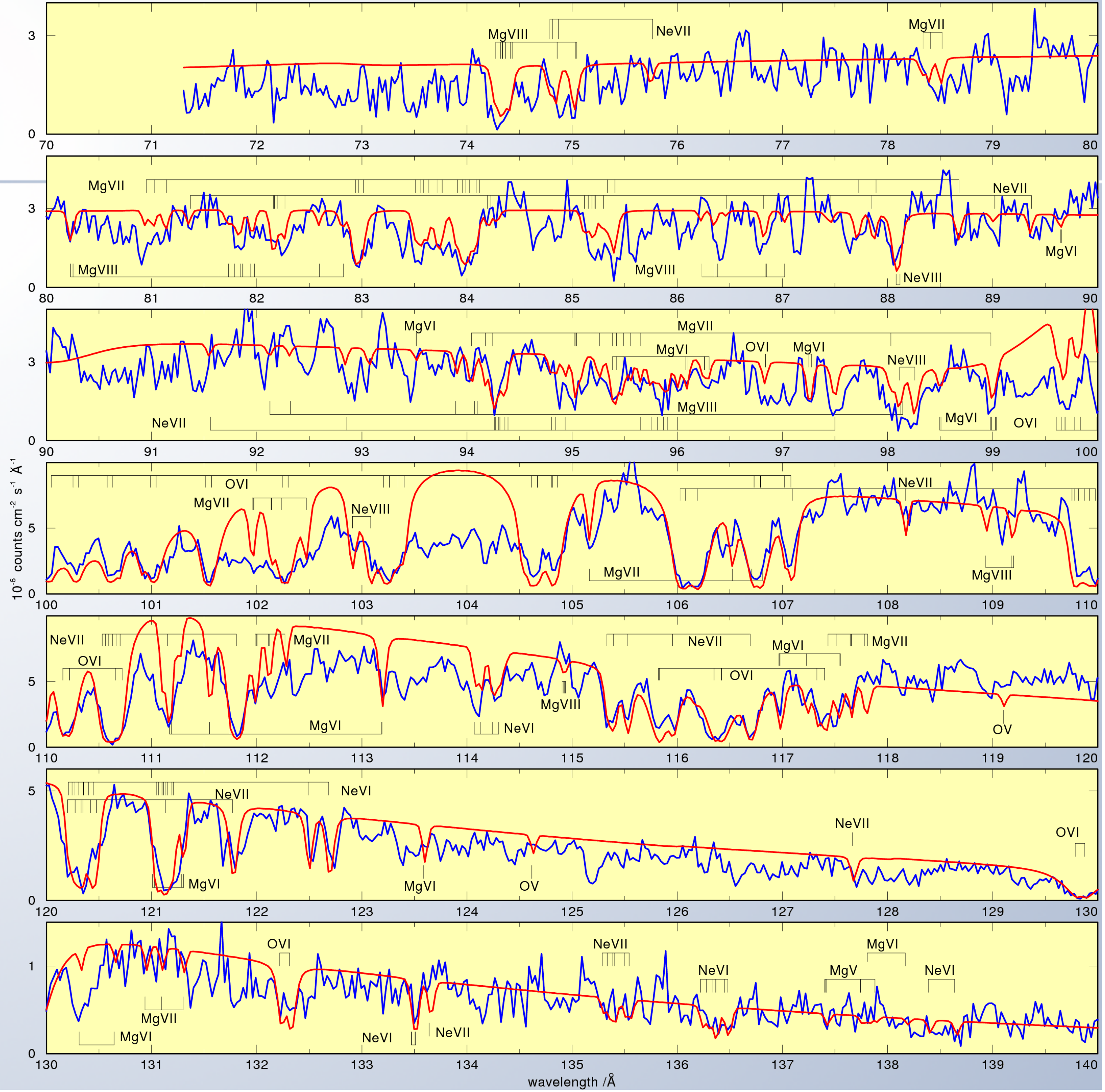
H 1504+65: CHANDRA Spectrum



Werner et al. 2004

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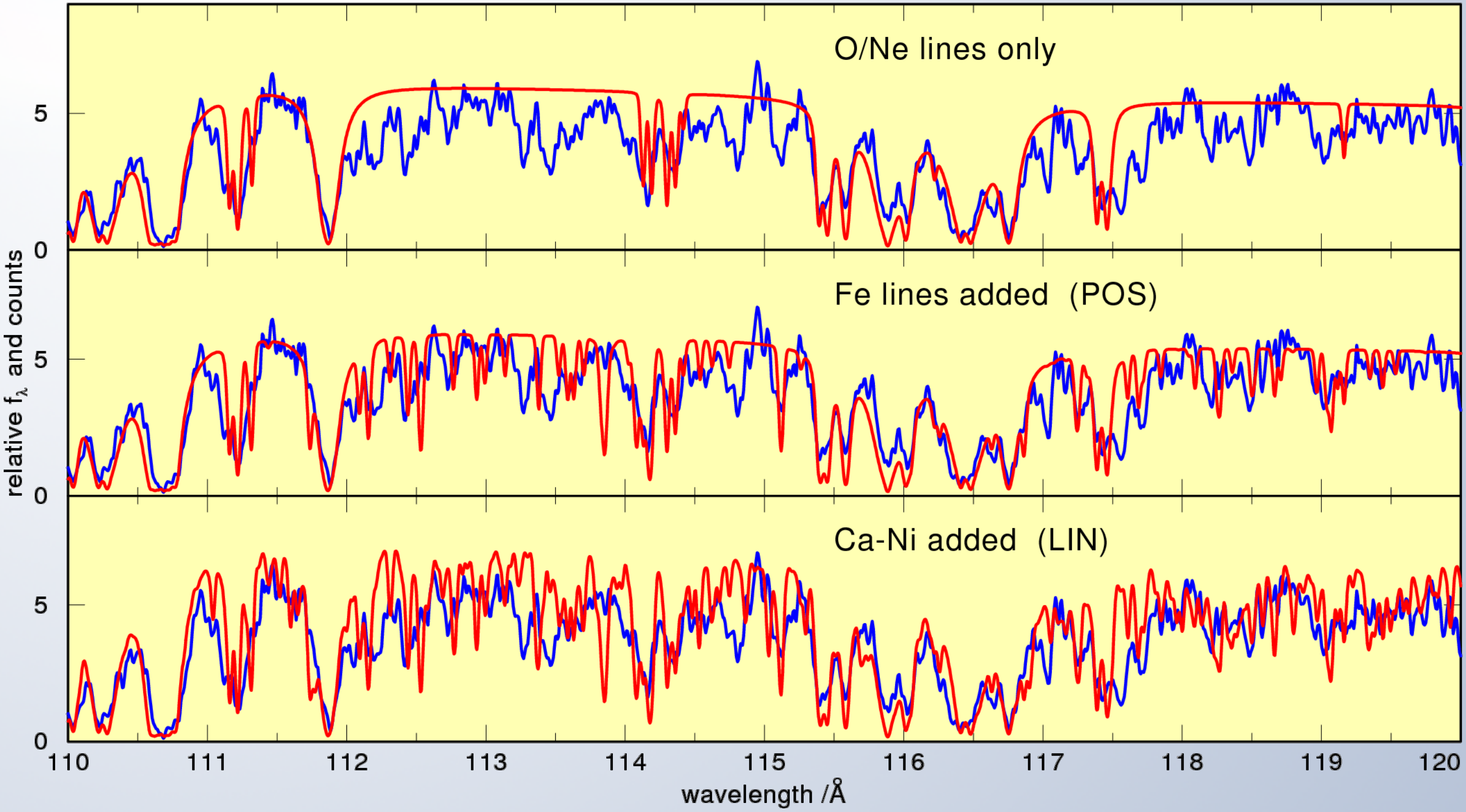
H 1504+65: Iron group



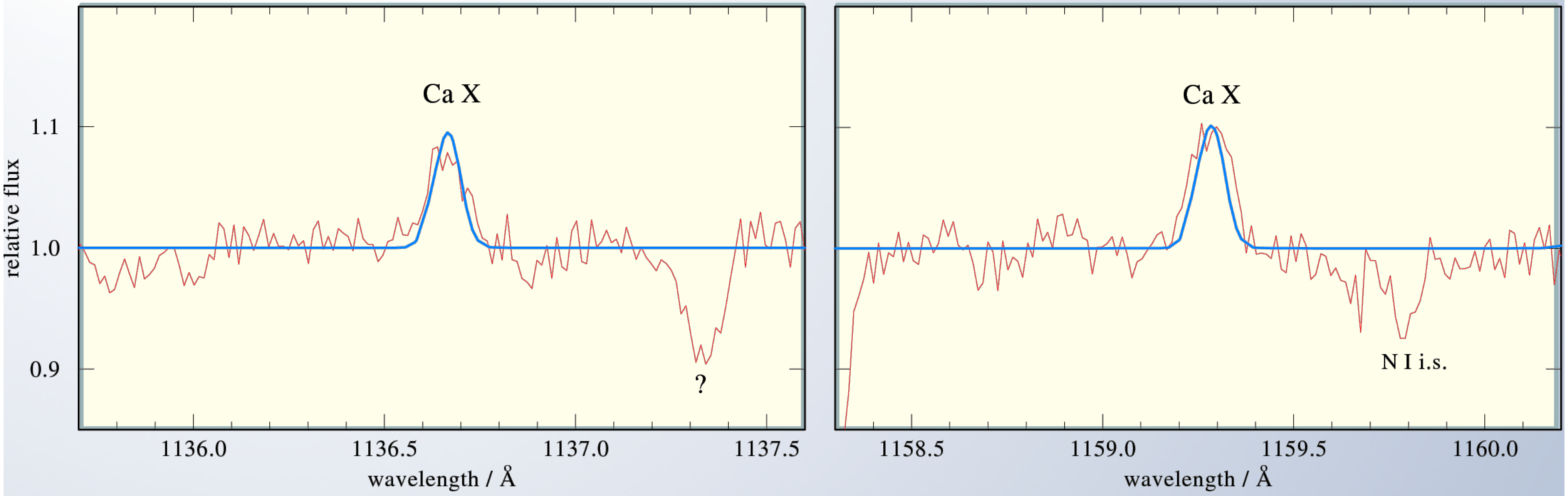
GUINNESS WORLD RECORDS™

CERTIFICATE

A study led by
Professor Klaus Werner (Germany)
of the Universität Tübingen
measured the highest surface
temperature on a white dwarf star
of around 200,000 C (360,000 F)
on H1504+65
announceing the results
in May 2004

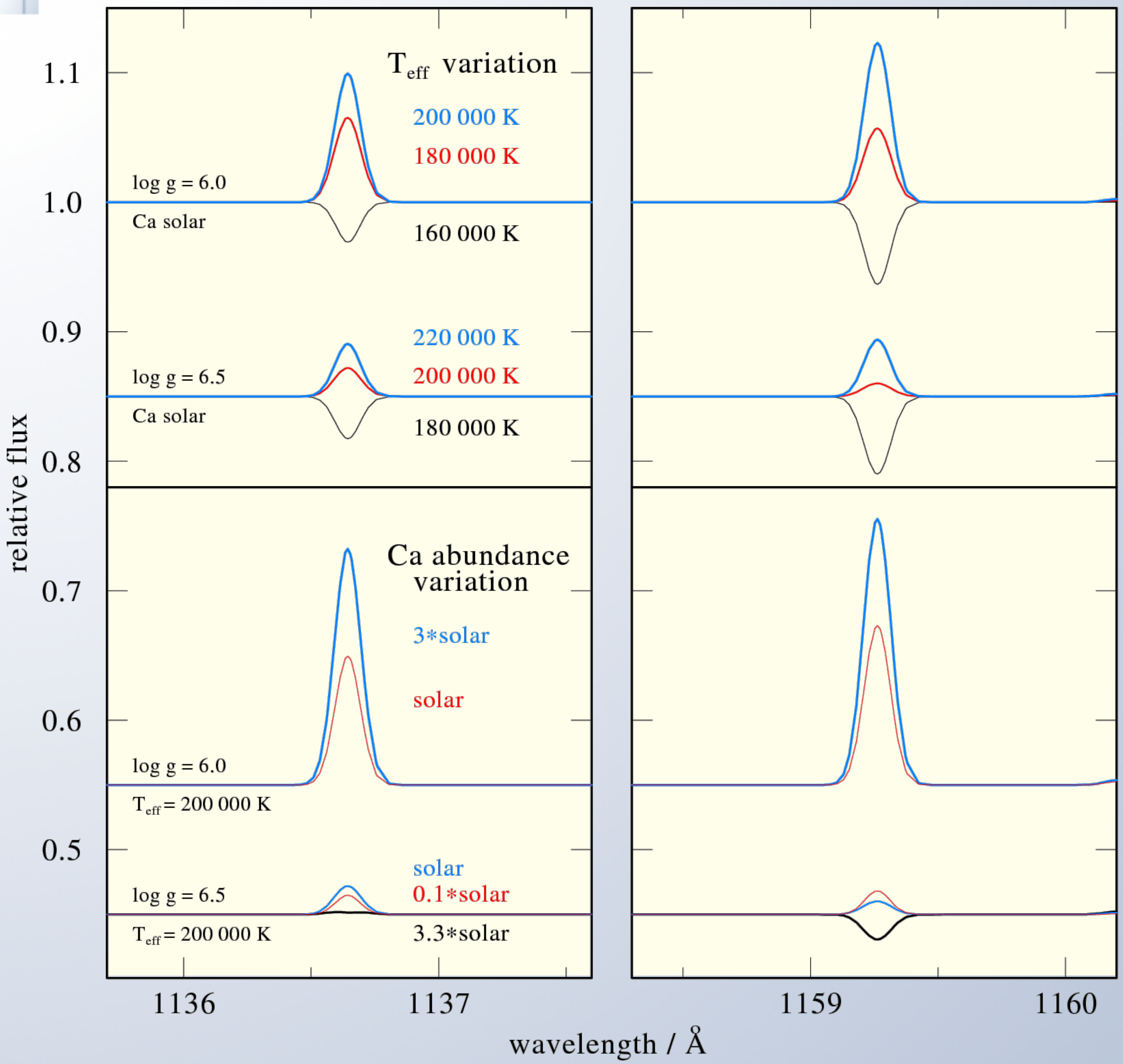
Keeper of the Records
GUINNESS WORLD RECORDS LTD

KPD 0005+5106



T_{eff} = 200 000 K instead of T_{eff} = 120 000 K

KPD 0005+5106



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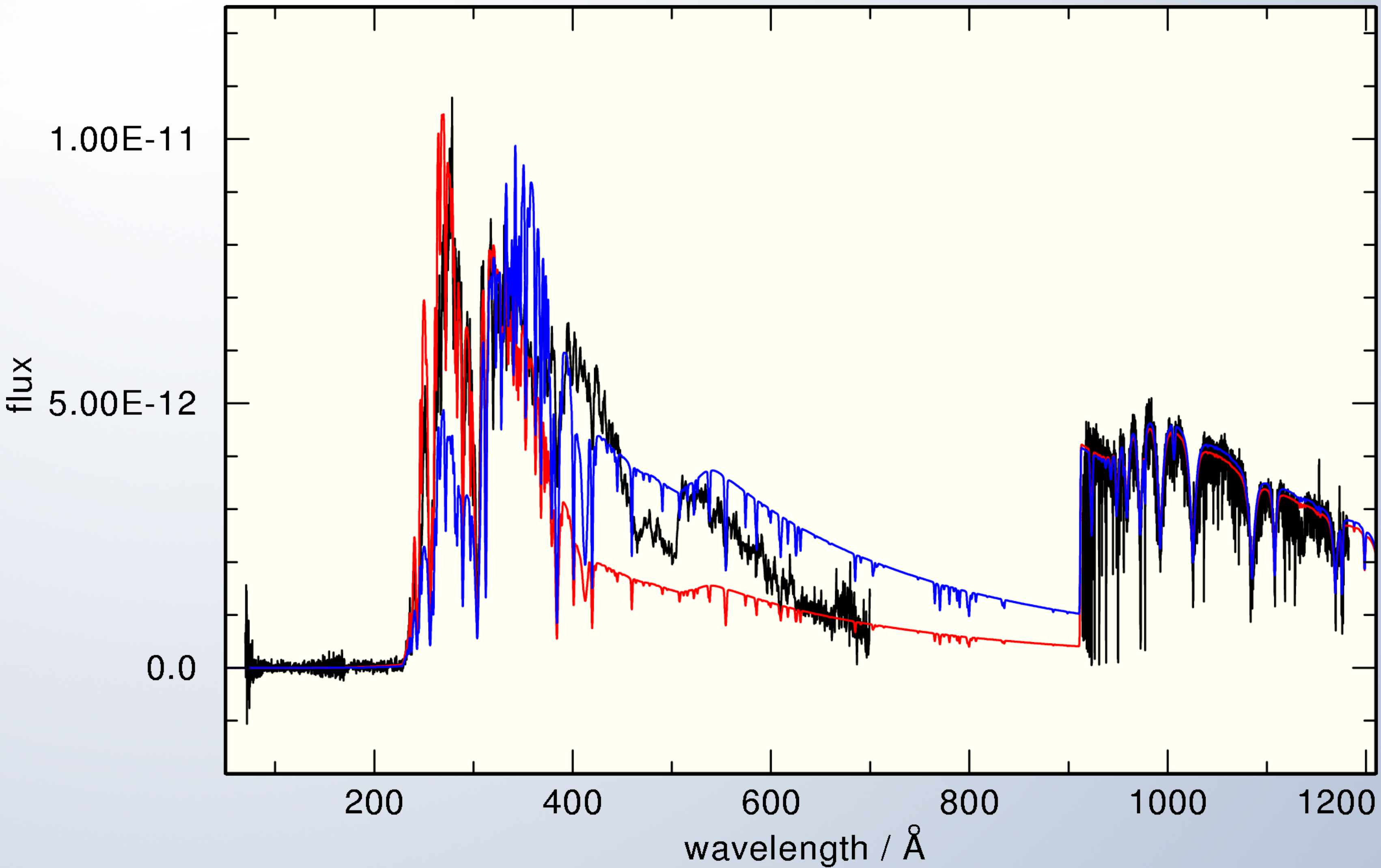
RE0503-289



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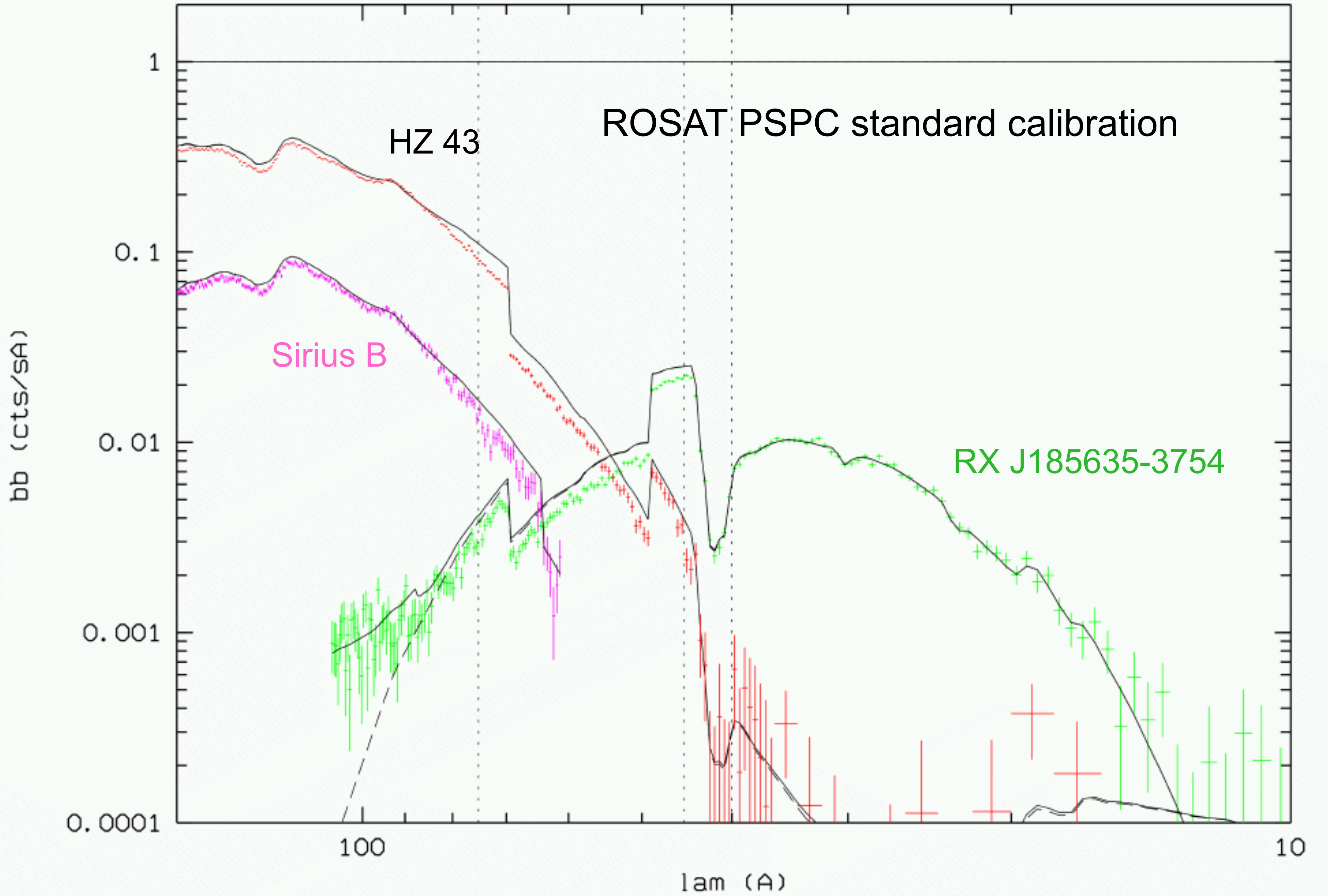
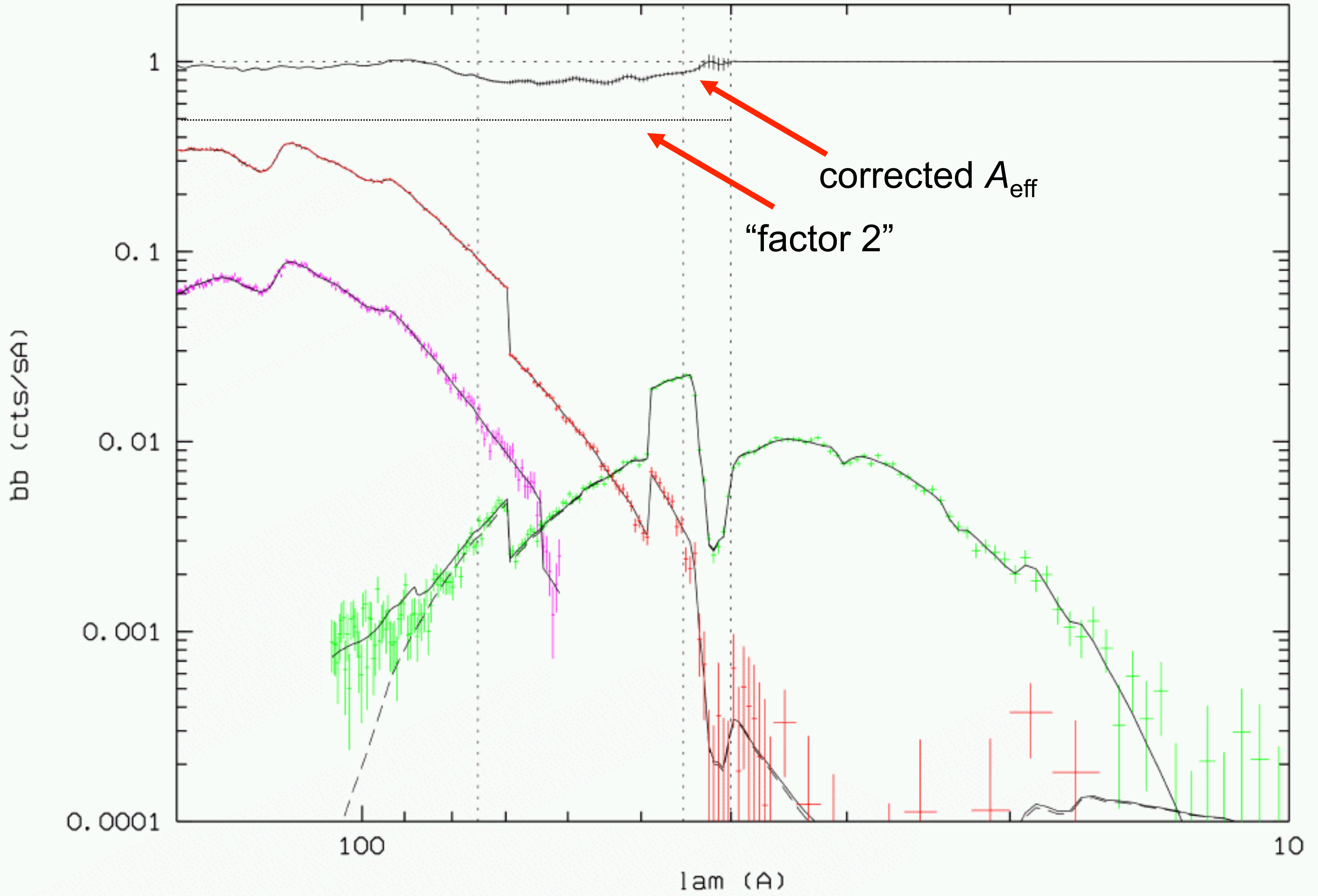
Calibration of Soft X-ray Spectra

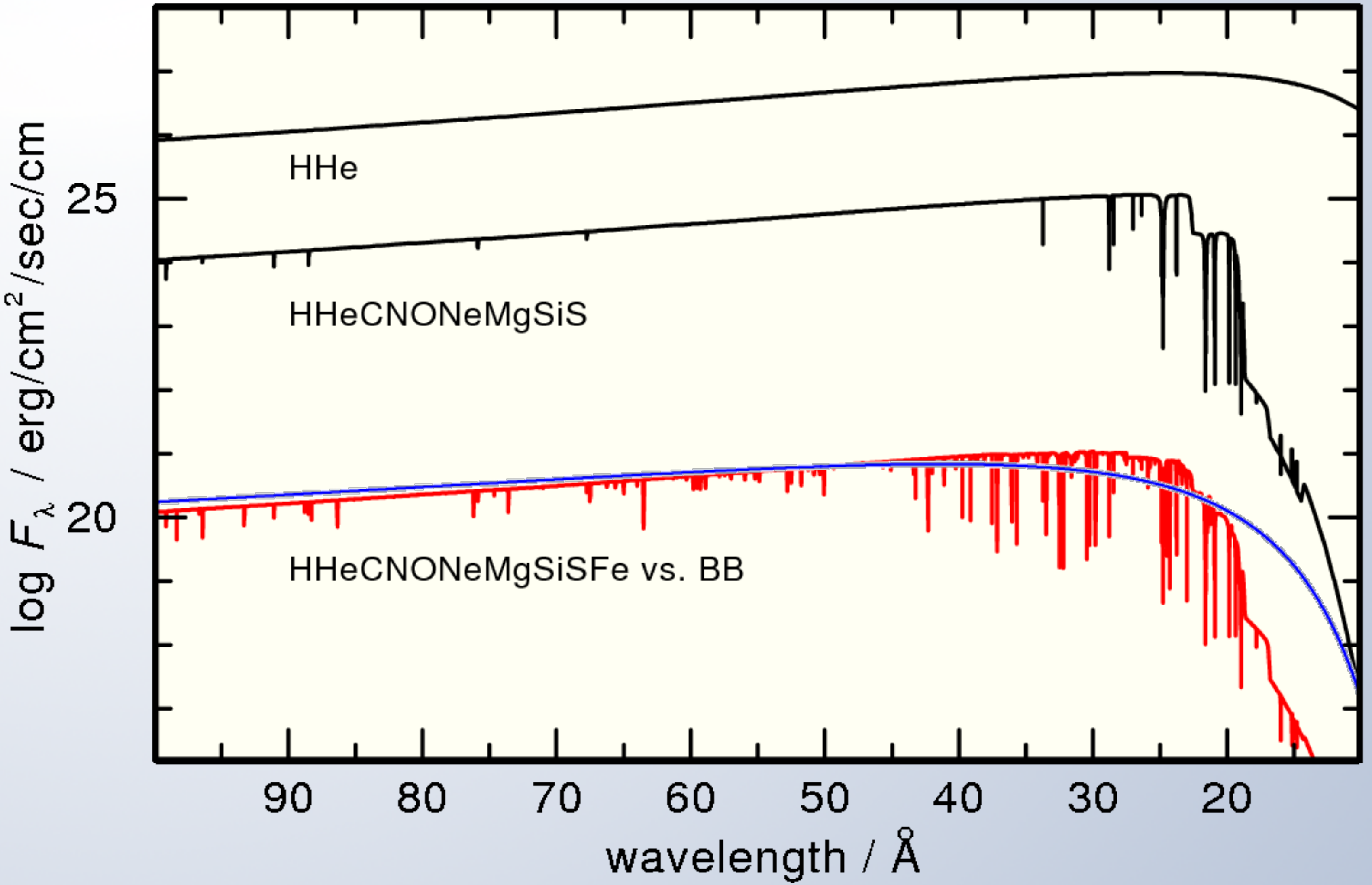
- old problem: ROSAT PSPC detector is a factor 2.0±0.3 more sensitive to the very soft X-ray photons compared to the standard calibration
  - Jordan et al. 1994, A&A 290, 834
  - A_{eff} wrong?

- new investigation by Beuermann et al. 2006
  - Sirius B, HZ 43 (NLTE model-atmosphere fluxes)
  - RX J185635-3754 (black body)

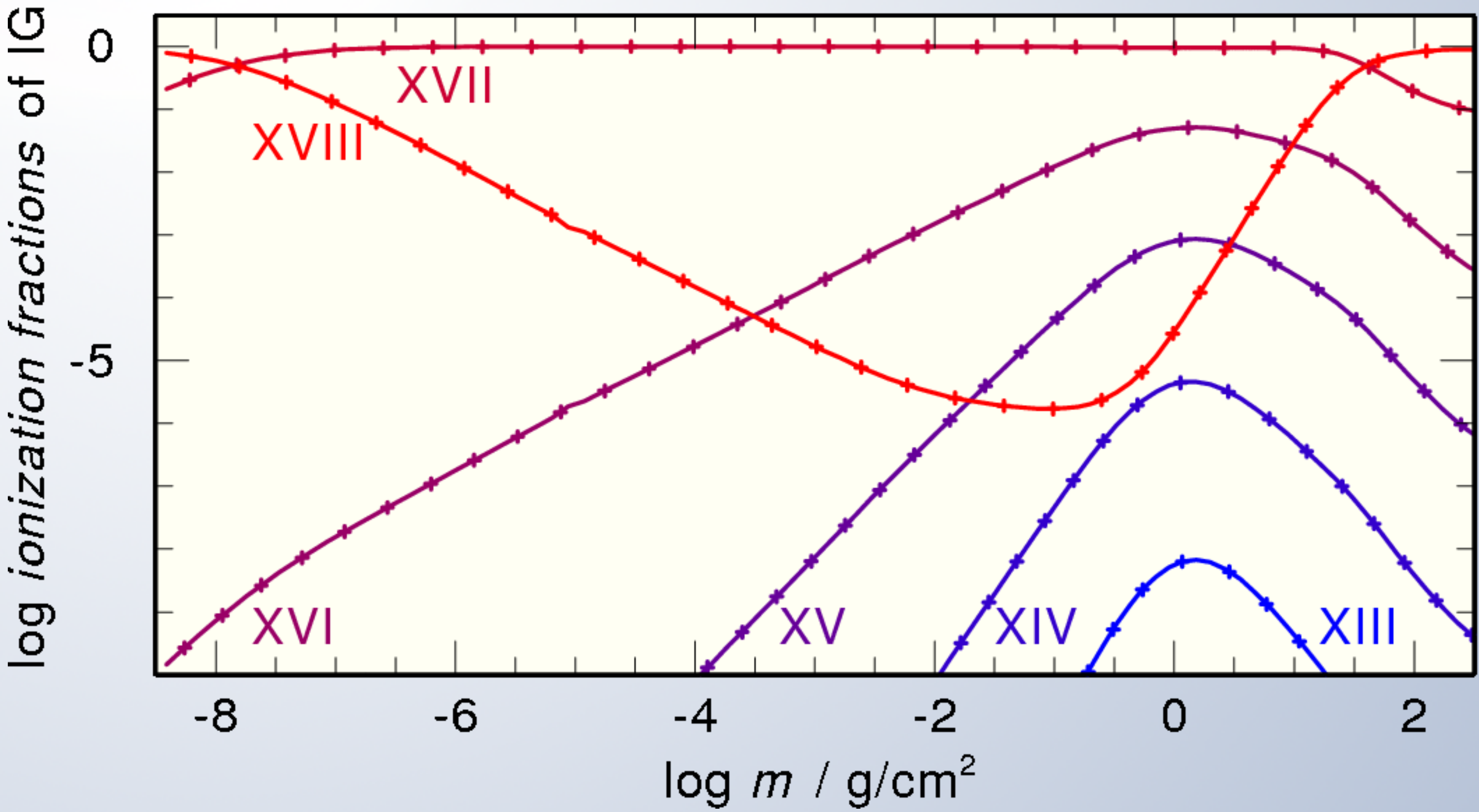

ROSAT PSPC standard calibration
HZ 43
Sirius B
RX J185635-3754
bb (cts/sA)
lam (A)
1
0.1
0.01
0.001
0.0001
100
10

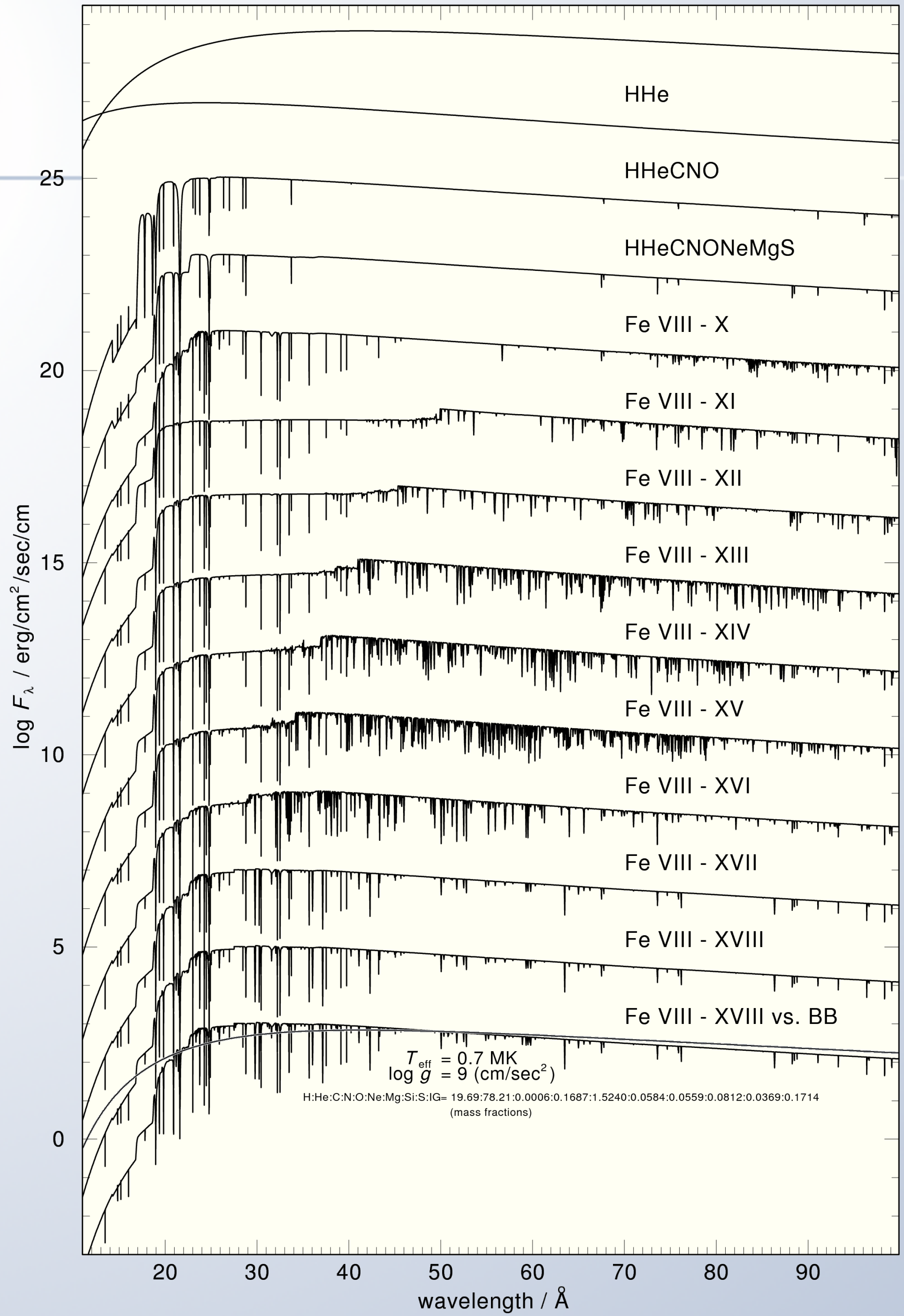


1
0.1
0.01
0.001
0.0001
bb (cts/sA)
100
10
lam (A)
corrected A_{eff}
"factor 2"



HHe
HHeCNONeMgSiS
HHeCNONeMgSiSFe vs. BB
log F_λ / erg/cm^2/sec/cm
25
20
90 80 70 60 50 40 30 20
wavelength / Å


log ionization fractions of IG
0
-5
XVII
XVIII
XVI
XV
XIV
XIII
-8
-6
-4
-2
0
2
log m / g/cm2


HHe
HHeCNO
HHeCNONeMgS
Fe VIII - X
Fe VIII - XI
Fe VIII - XII
Fe VIII - XIII
Fe VIII - XIV
Fe VIII - XV
Fe VIII - XVI
Fe VIII - XVII
Fe VIII - XVIII
Fe VIII - XVIII vs. BB
T_{eff} = 0.7 MK
log g = 9 (cm/sec^2)
H:He:C:N:O:Ne:Mg:Si:S:IG= 19.69:78.21:0.0006:0.1687:1.5240:0.0584:0.0559:0.0812:0.0369:0.1714
(mass fractions)
log F_λ / erg/cm^2/sec/cm
25
20
15
10
5
0
20
30
40
50
60
70
80
90
wavelength / Å

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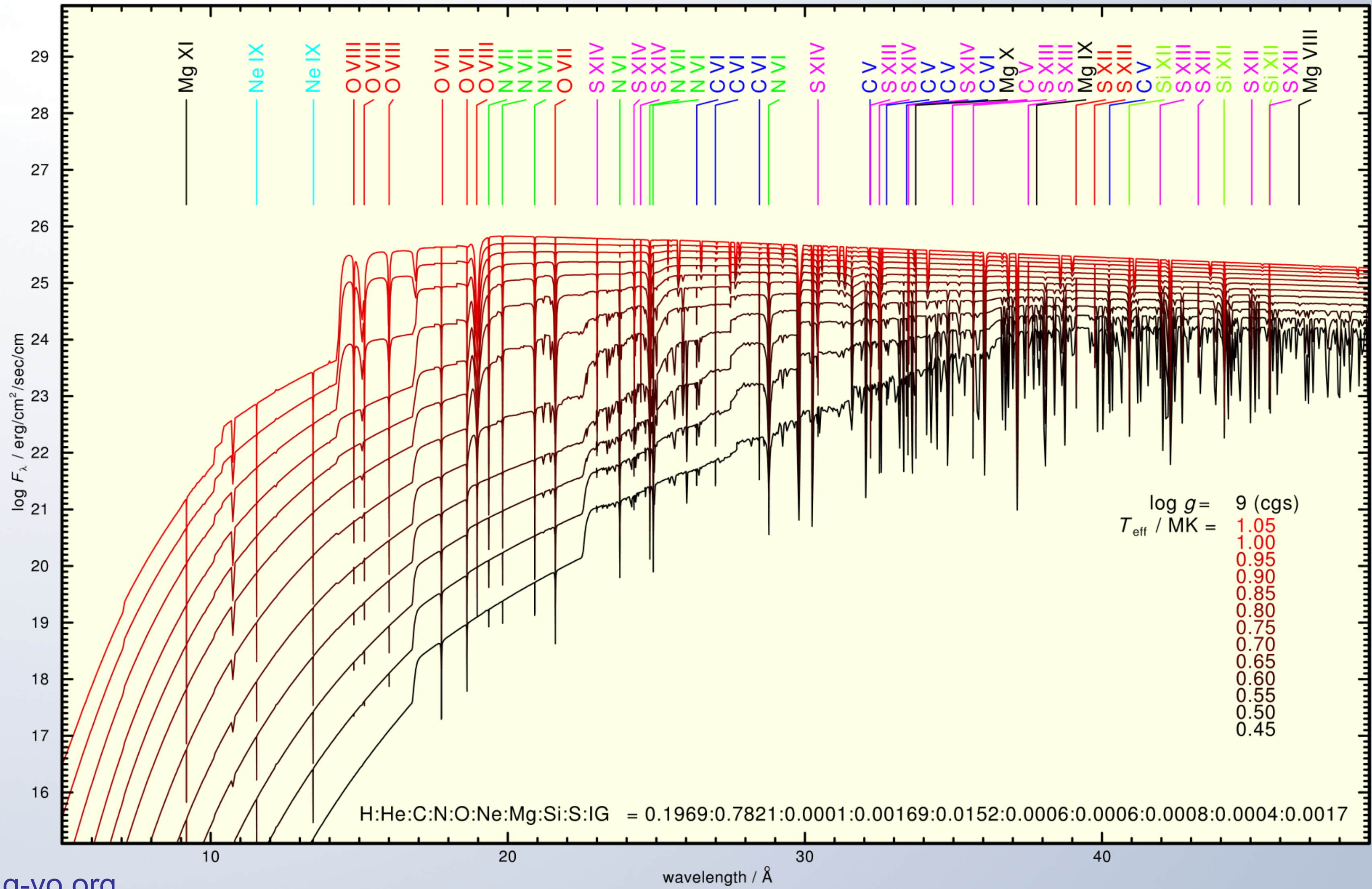
SEDs for Extremely Hot Stars



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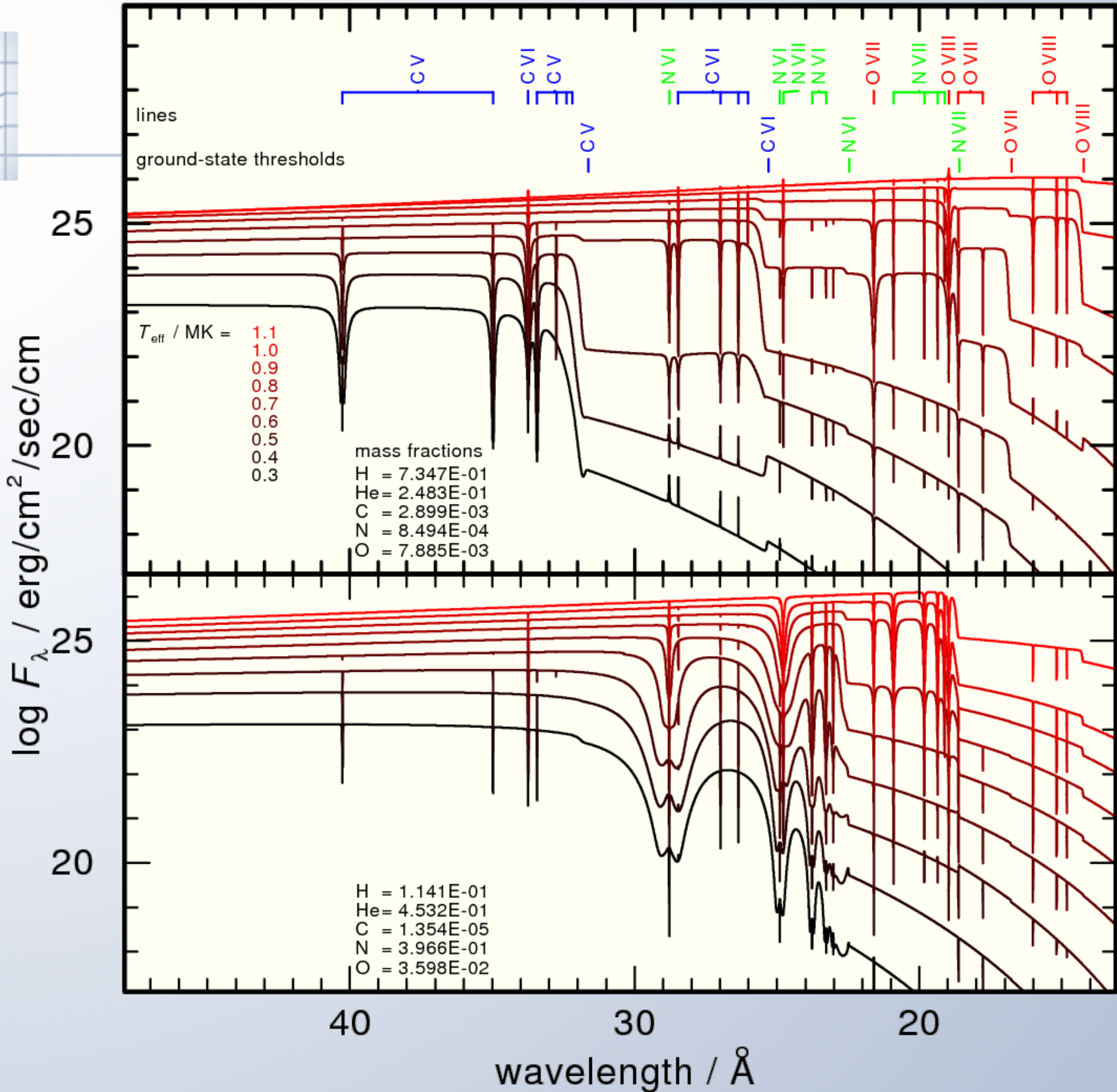
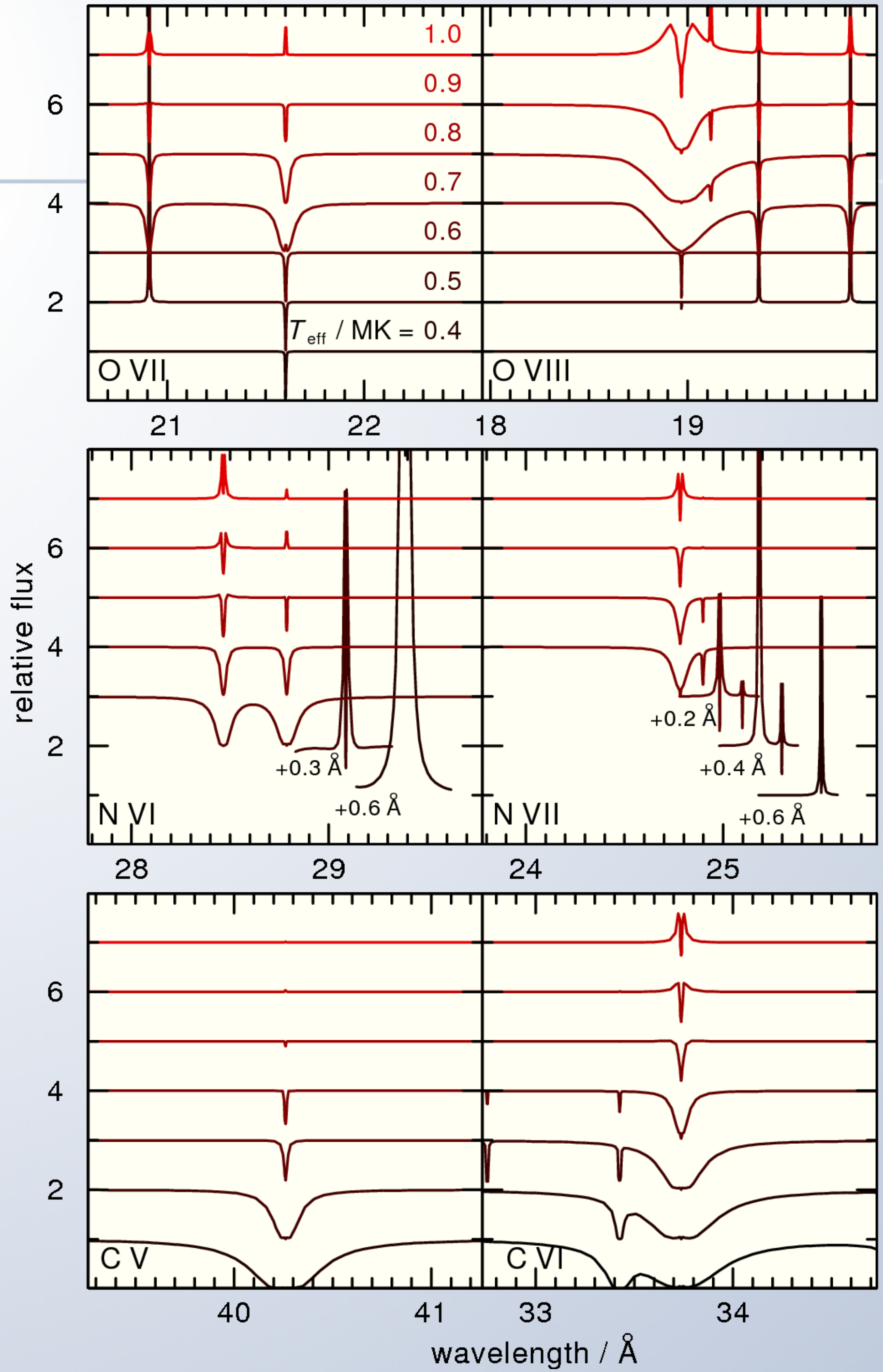
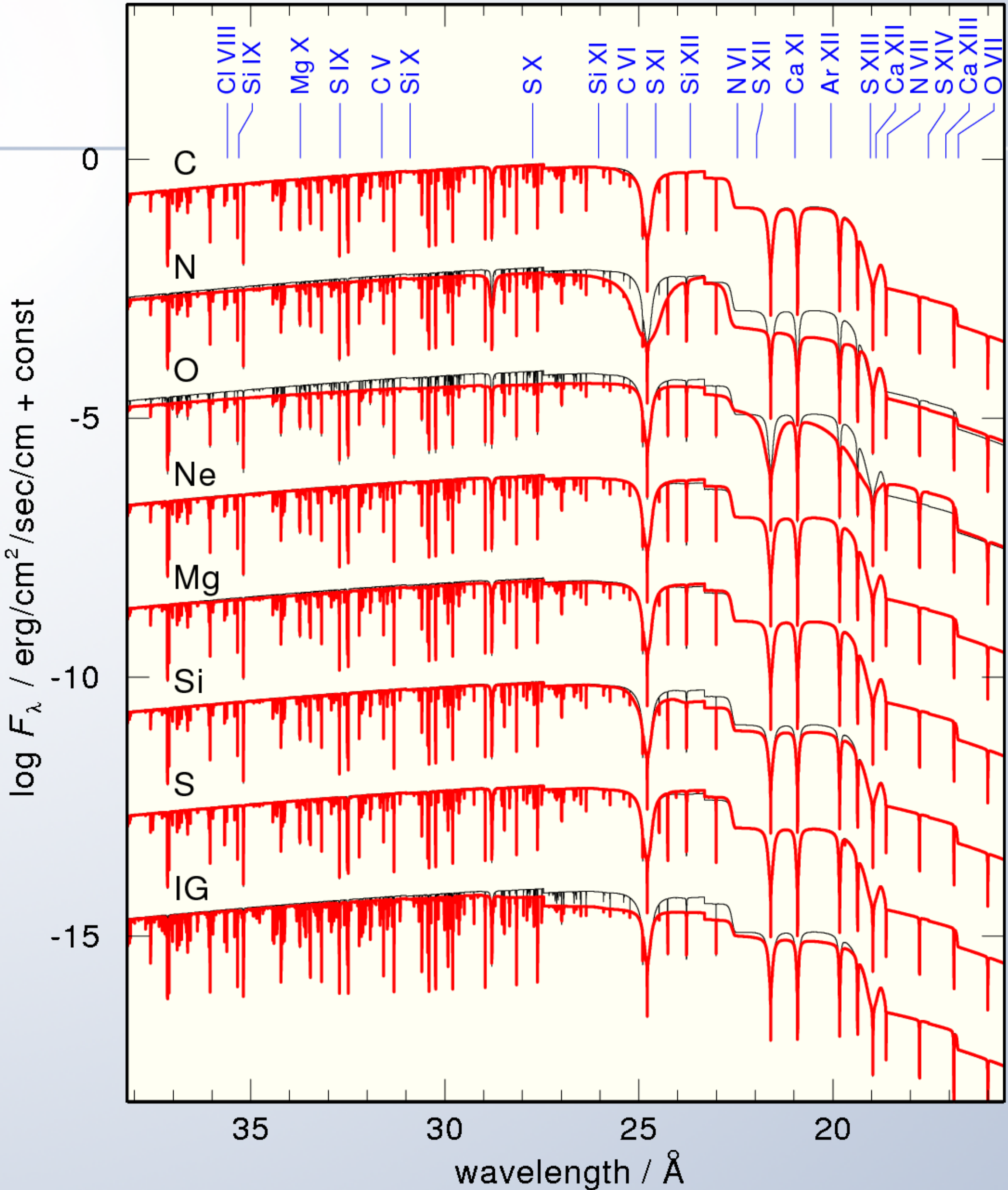




1.0
0.9
0.8
0.7
0.6
0.5
Teff / MK = 0.4
O VII
O VIII
N VI
N VII
C V
C VI
+0.3 Å
+0.6 Å
+0.2 Å
+0.4 Å
+0.6 Å
relative flux
wavelength / Å



T_{eff} = 0.7 MK

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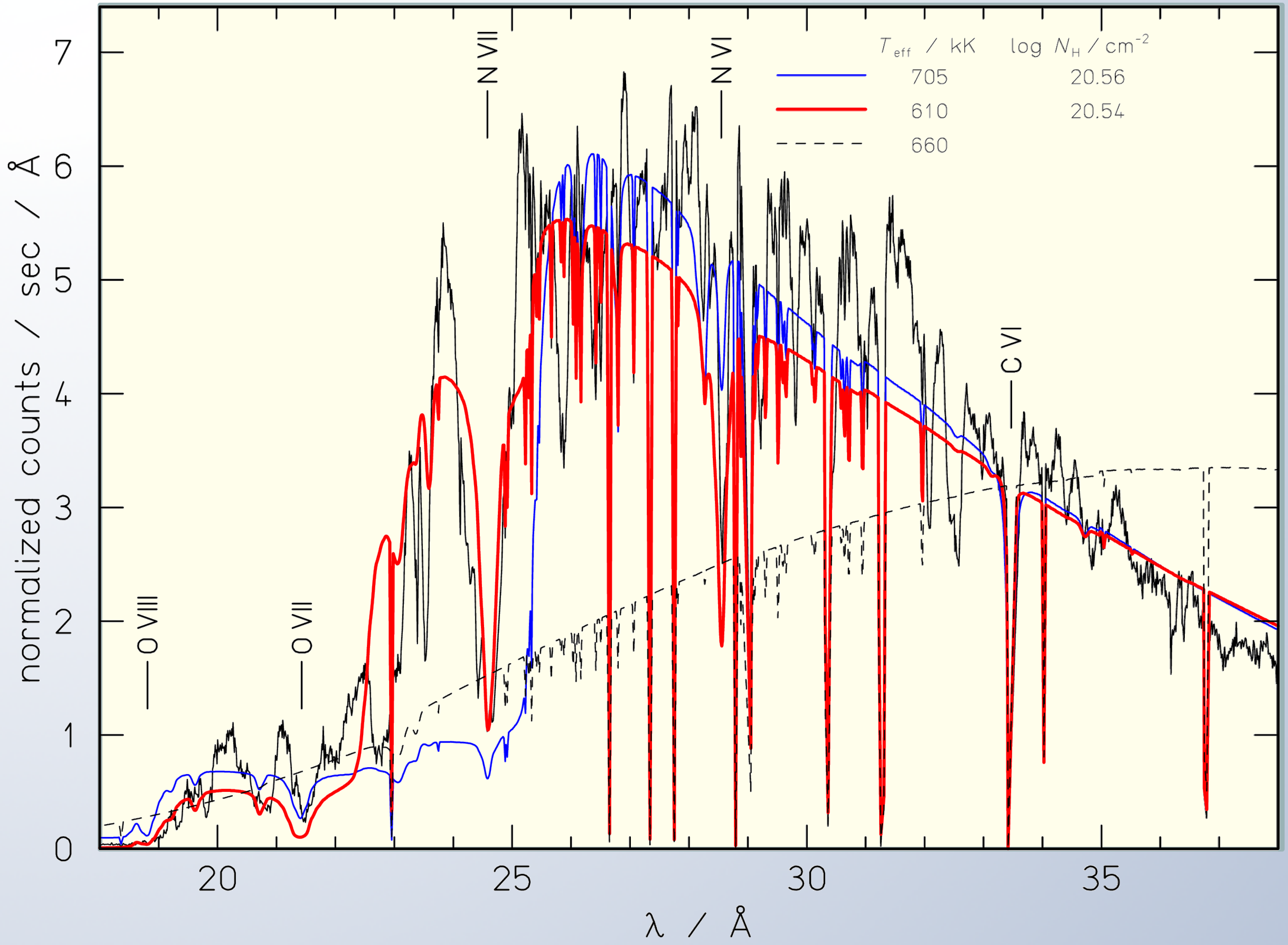
Nova V 4743 Sgr

- outburst Sep 20, 2002, $m_V = 5$
- Mar 2003: brightest super-soft source in the sky

- CHANDRA spectrum
  - C V, C VI, N VI, N VII, O VII absorptions
  - $T_{eff} \approx 1 - 2$ MK (Ness et al. 2003)

- XMM-RGS spectrum (Apr 4, 2003)
  - $T_{eff} \approx 610$ kK (Rauch, Werner & Orio 2005)

V 4743 Sgr



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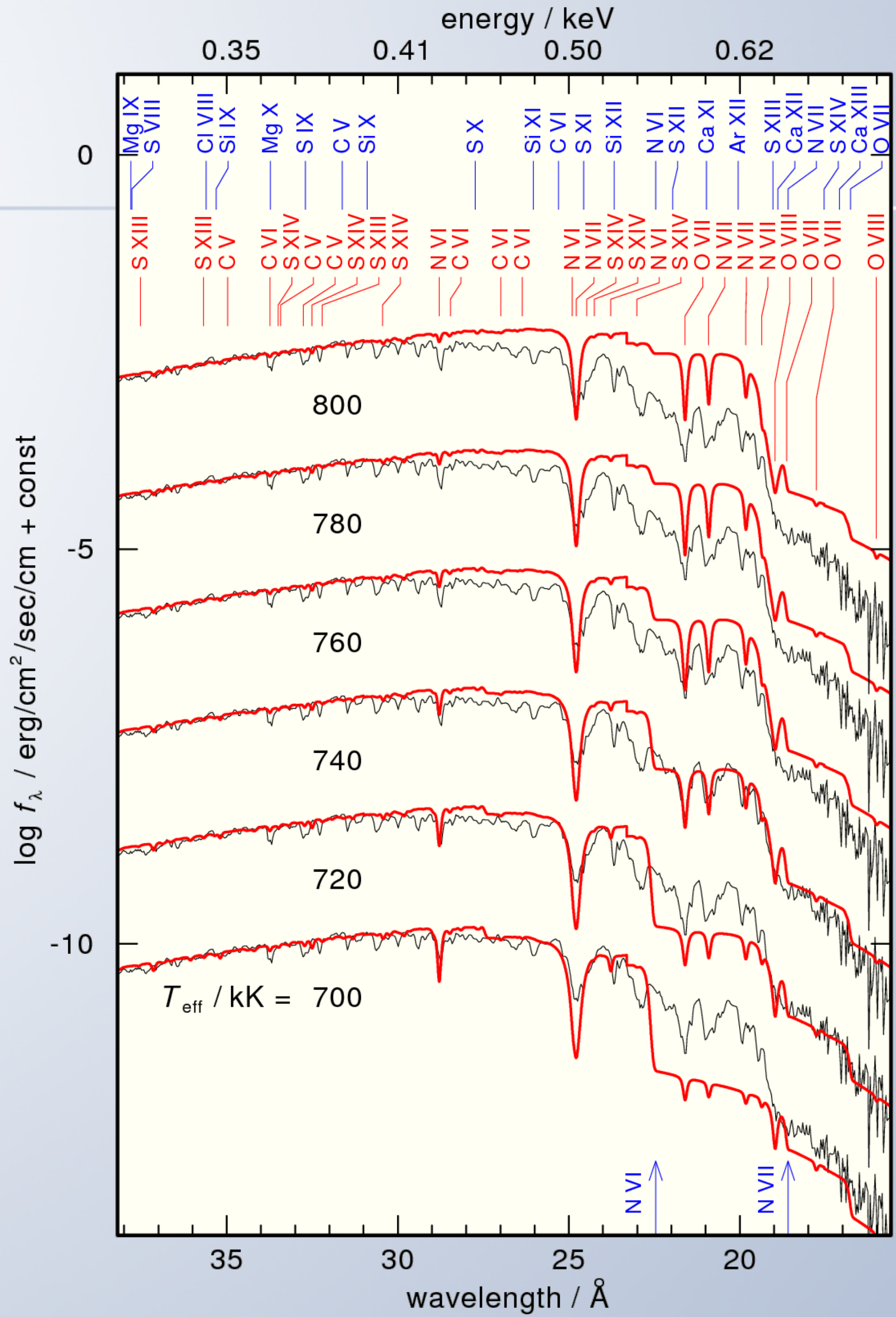
T_{eff} Determination:

N VI / N VII Ionization Equilibrium



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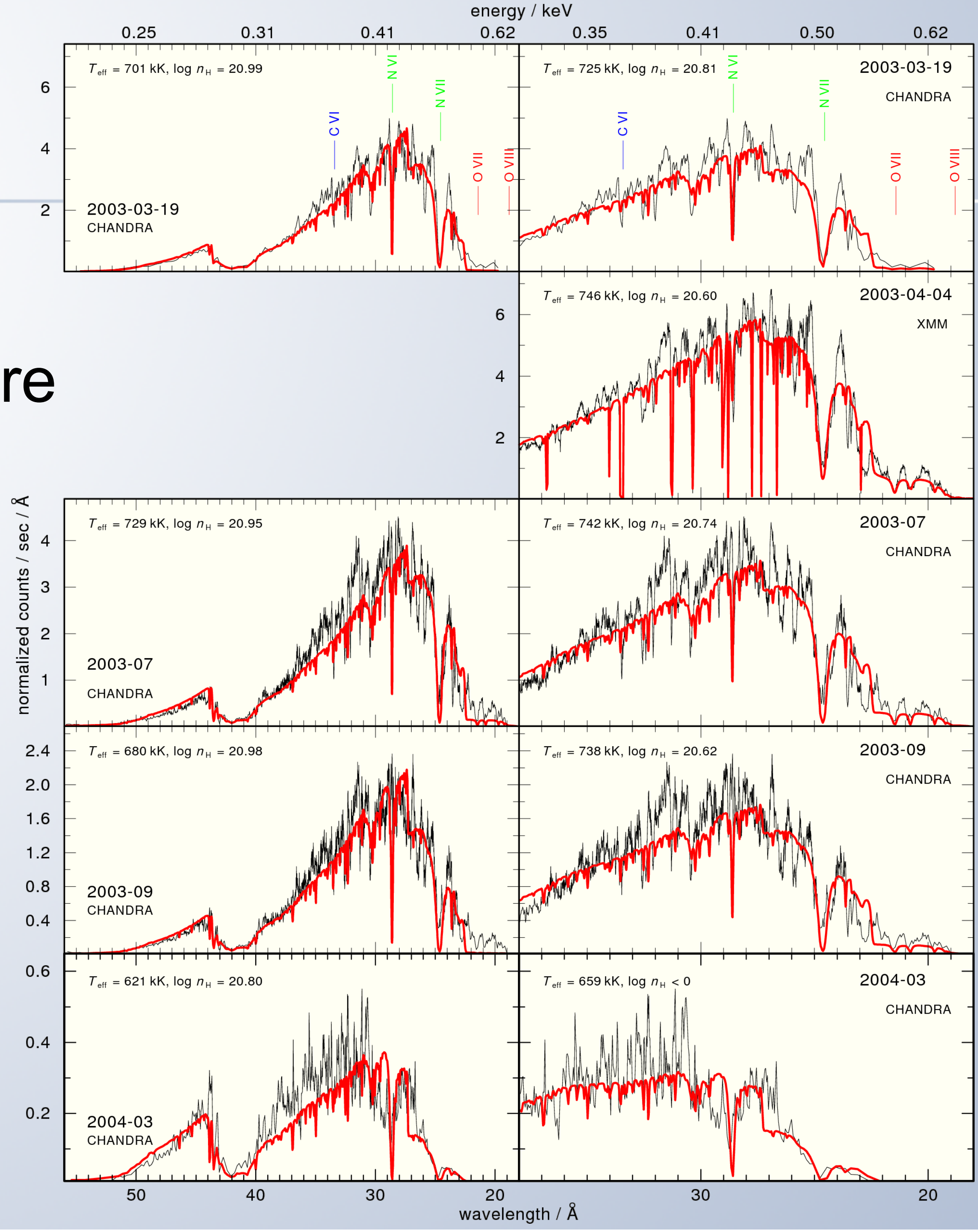
Effective Temperature of Nova V 4743 Sgr after Burst



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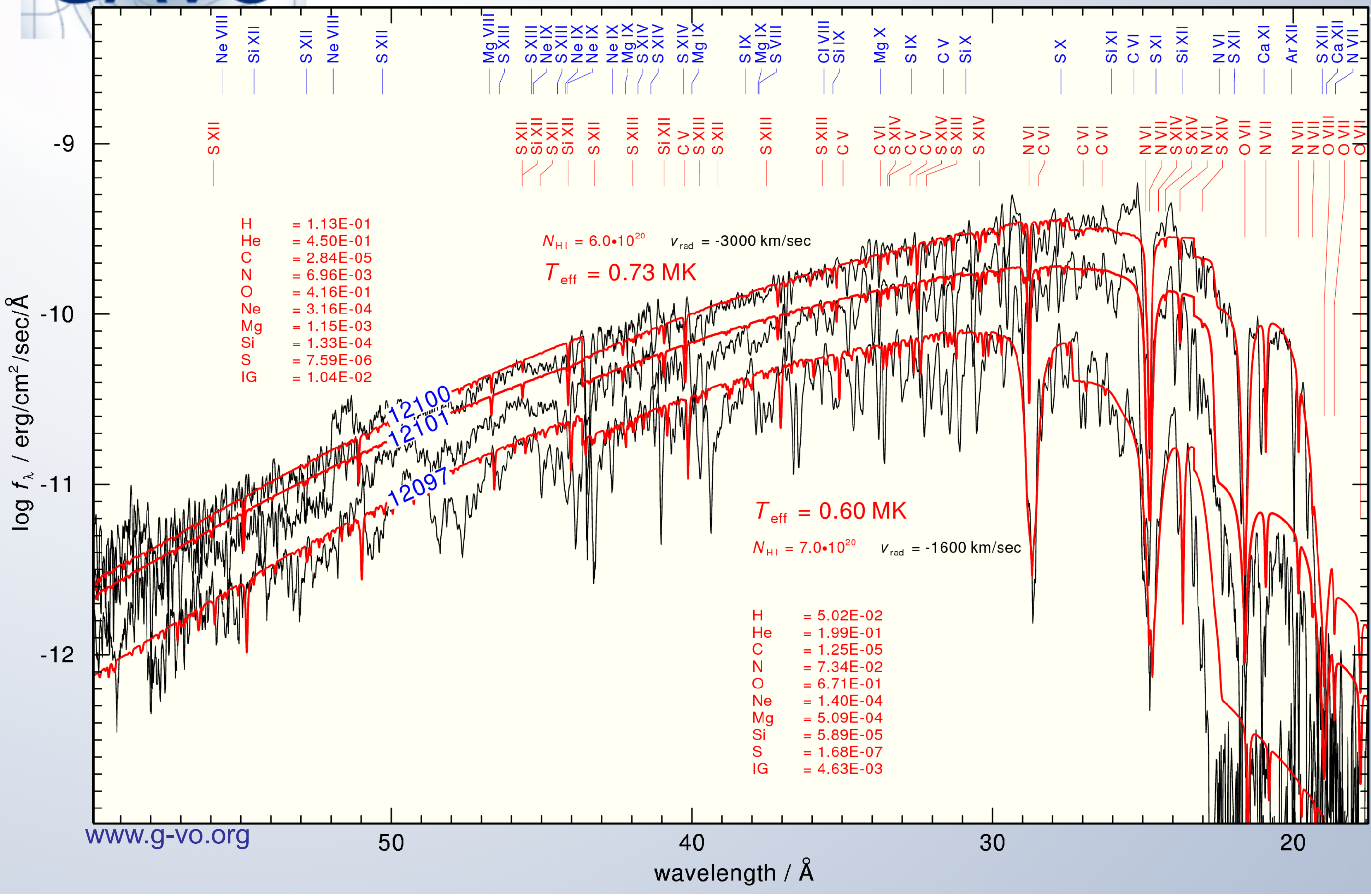
SSS SEDs

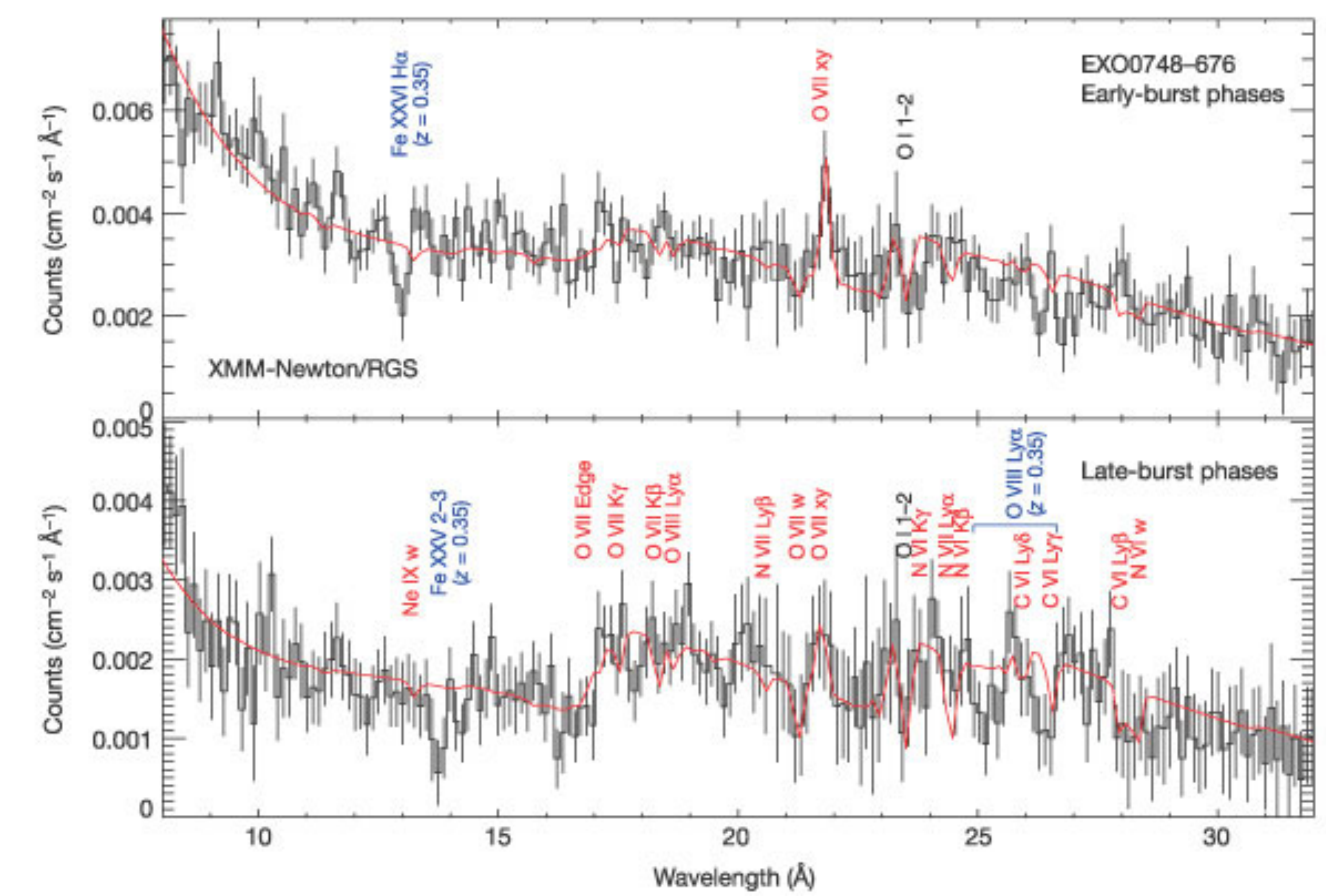
- $T_{\rm eff}$ = 550 – 1050 kK
- log g = 9
- "V 4743 Sgr" abundance pattern
  - C/N abundance ratio from
    [C] = -1.5, [N] = 1.8 to [C] = -0.4, [N] = 0.2
- http://astro.uni-tuebingen.de/~rauch/
  - atables (in FITS format) for XSPEC

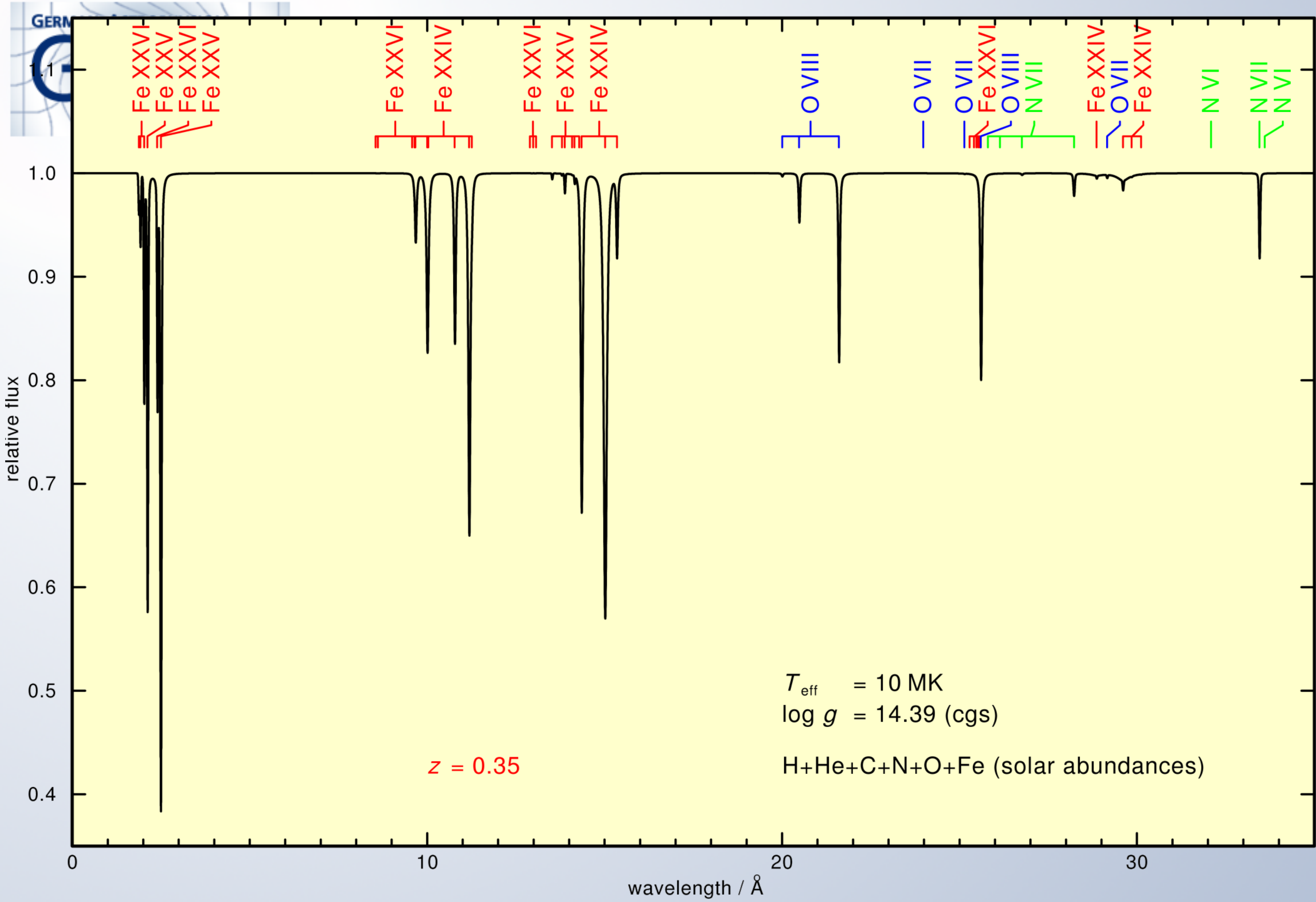
KT Eri



H = 1.13E-01
He = 4.50E-01
C = 2.84E-05
N = 6.96E-03
O = 4.16E-01
Ne = 3.16E-04
Mg = 1.15E-03
Si = 1.33E-04
S = 7.59E-06
IG = 1.04E-02
$N_{\rm H\,I}$ = 6.0•10^20 $v_{\rm rad}$ = -3000 km/sec
$T_{\rm eff}$ = 0.73 MK
12100
12101
12097
$T_{\rm eff}$ = 0.60 MK
$N_{\rm H\,I}$ = 7.0•10^20 $v_{\rm rad}$ = -1600 km/sec
H = 5.02E-02
He = 1.99E-01
C = 1.25E-05
N = 7.34E-02
O = 6.71E-01
Ne = 1.40E-04
Mg = 5.09E-04
Si = 5.89E-05
S = 1.68E-07
IG = 4.63E-03
log f_λ / erg/cm²/sec/Å
-9
-10
-11
-12
50
40
30
20
wavelength / Å

EXO 0748-676 (LMXB)




Fe XXVI
Fe XXV
Fe XXVI
Fe XXV
Fe XXVI
Fe XXIV
Fe XXVI
Fe XXV
Fe XXIV
O VIII
O VII
O VII
Fe XXVI
O VIII
N VII
Fe XXIV
O VII
Fe XXIV
N VI
N VII
N VI
relative flux
wavelength / Å
$T_{\rm eff}$ = 10 MK
log g = 14.39 (cgs)
H+He+C+N+O+Fe (solar abundances)
z = 0.35

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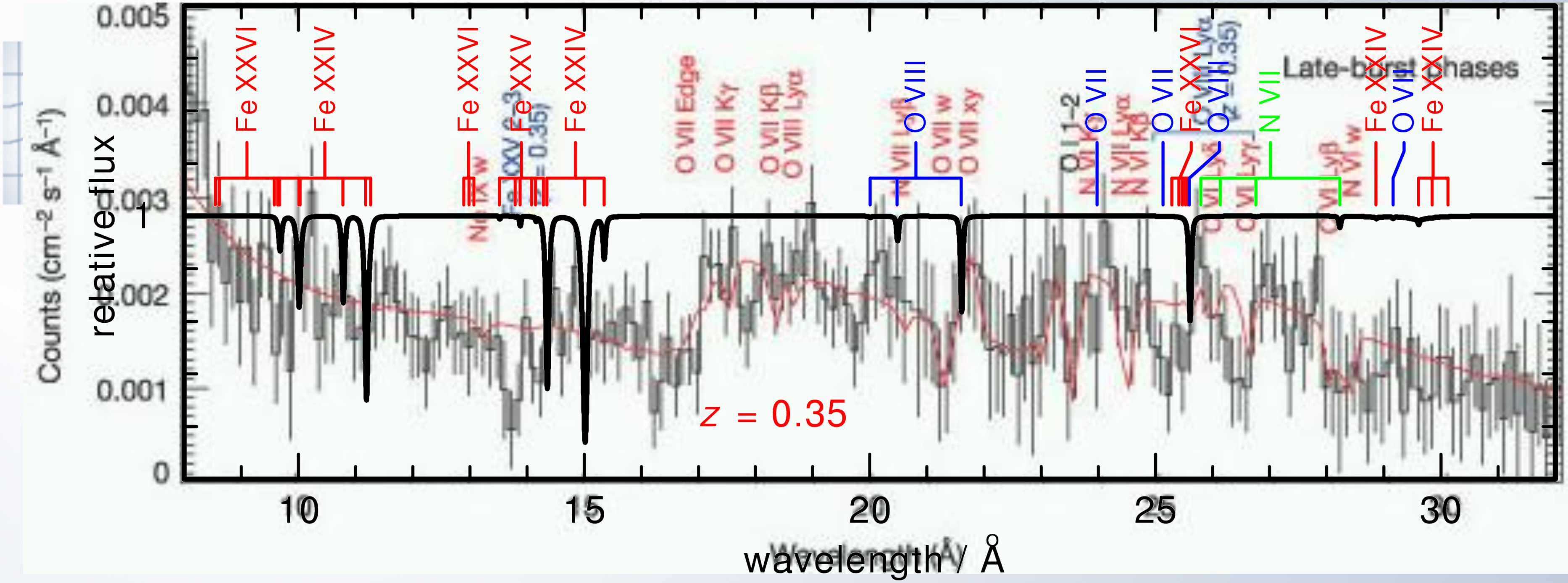
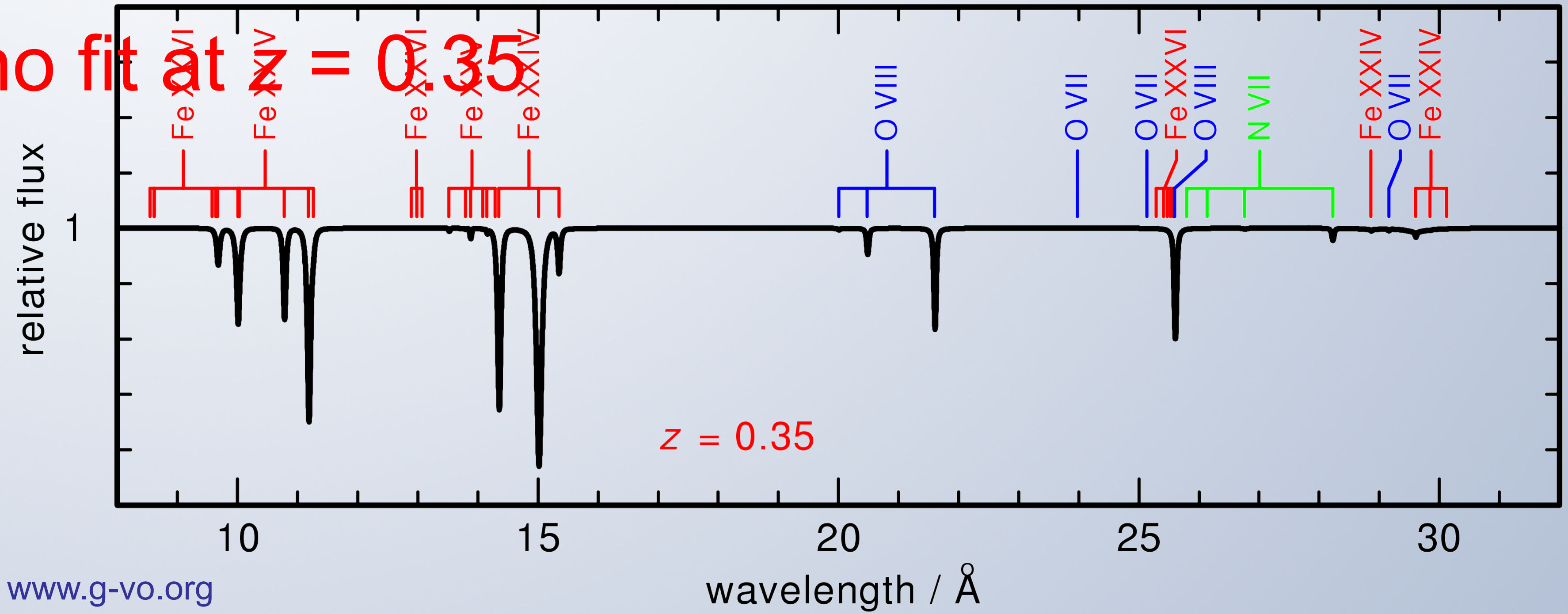
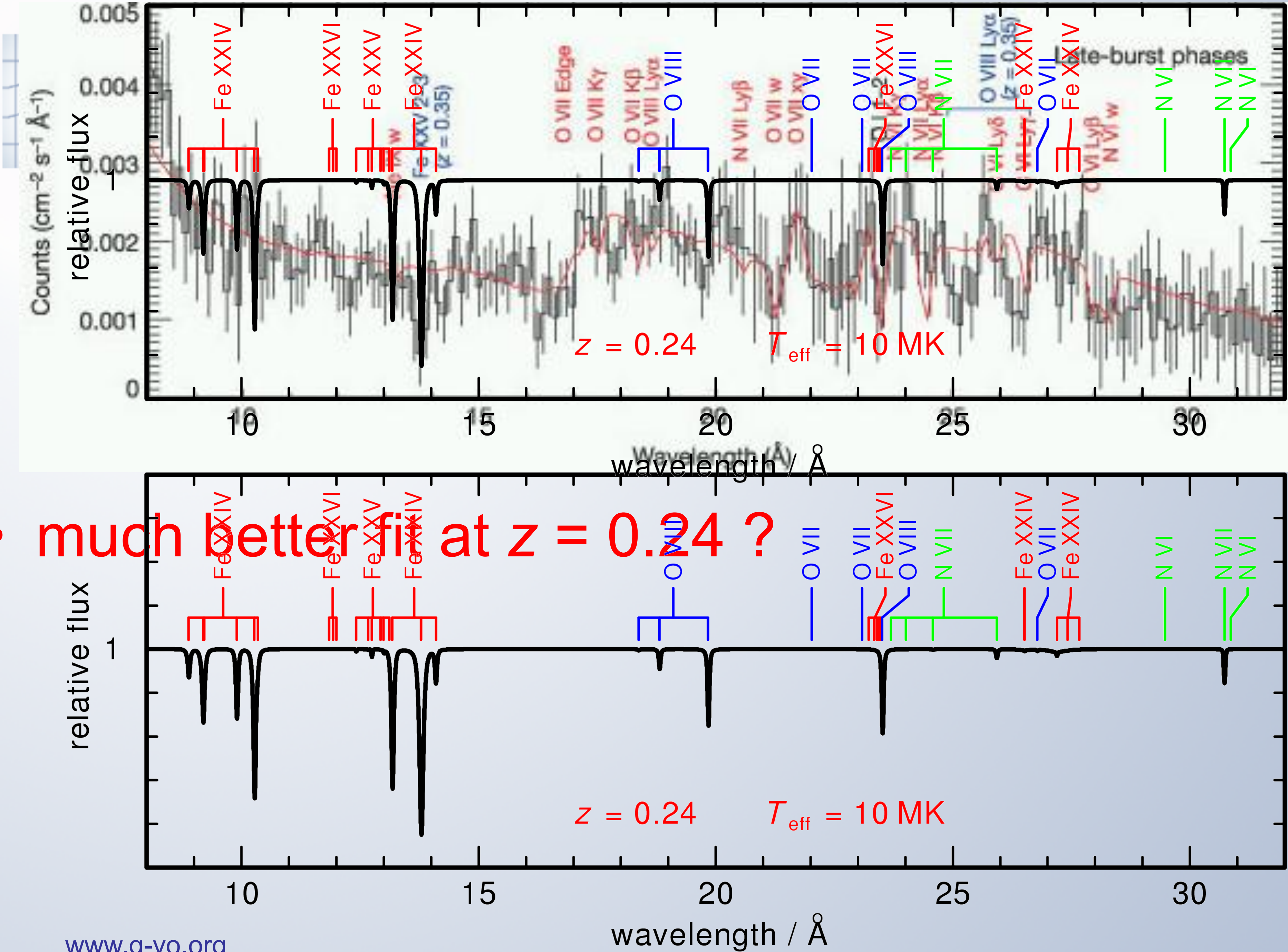


- no fit at z = 0.35





- much better fit at $z = 0.24$?

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  - ***TheoSSA*** ***(http://vo.ari.uni-heidelberg.de/ssatr-0.01/TrSpectra.jsp?)***
- Simulation Software
  - ***TMAW*** ***(http://astro.uni-tuebingen.de/~TMAW/TMAW.shtml)***
- Atomic Data
  - ***TMAD*** ***(http://astro.uni-tuebingen.de/~TMAD/TMAD.html)***