Spectroscopy of giants and supergiants

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Spectroscopy of (cool) giants and supergiants

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Outline

- Motivation – why do spectroscopy of giant stars?
- Spectroscopy – state-of-the-art in modeling and observations
- Simulations – predictive power of theory
- Conclusions – forthcoming instruments: what can we expect with ‘giants’ like E-ELT?

RGB, AGB, RSG

- low and high-mass, 0.6 ~ M ~ 30 M_{sun}
- L: 10 - 10^3 $L_\odot$ … 10^2 - 10^3 … 10^4 - 10^6

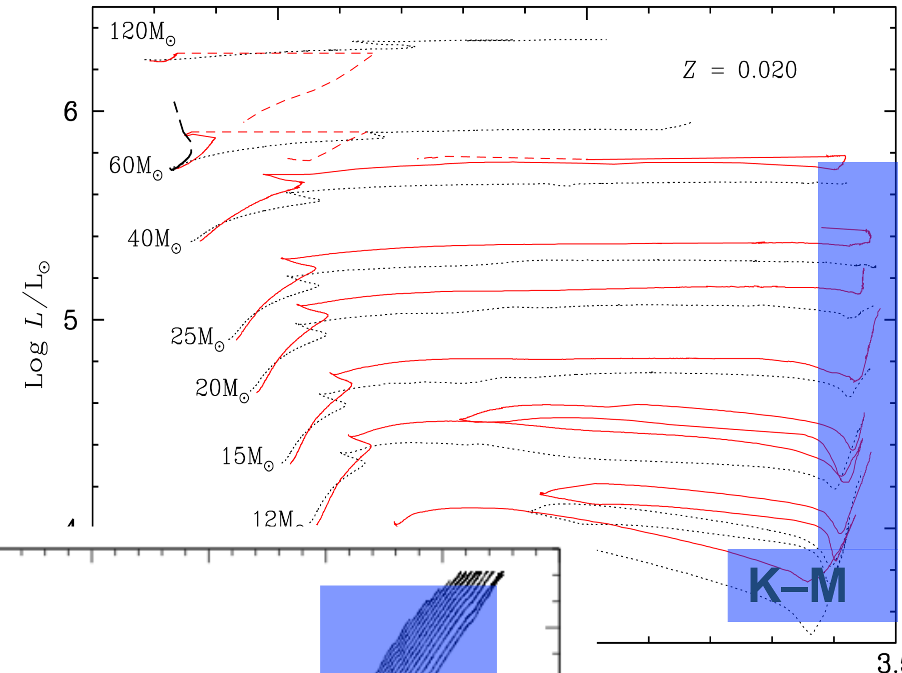
wide range of ages, metallicities, and extremely luminous!

see the talks by C. Evans, B. Davies, R. Kudritzki

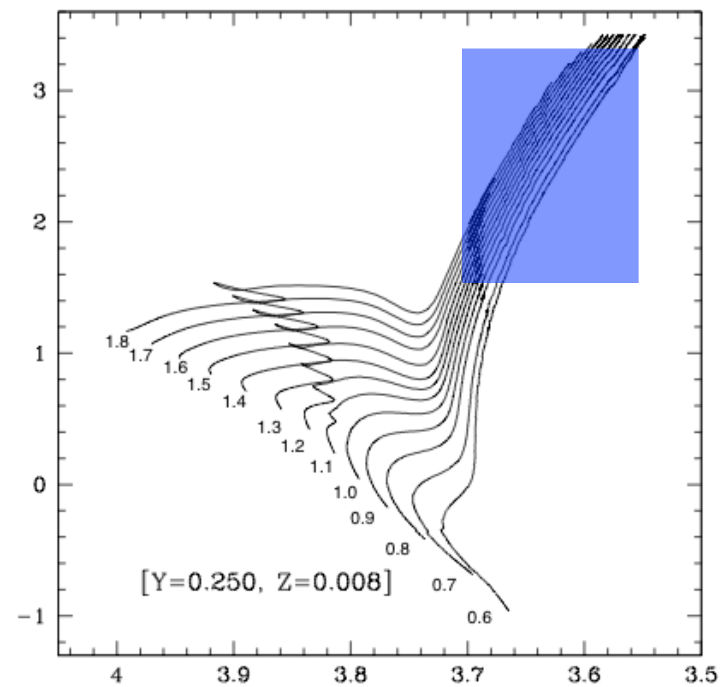
T_{eff} : 3500 ... 5500 K

log g : -0.5 ... 3.5

[Fe/H]: from -5 to +0.5



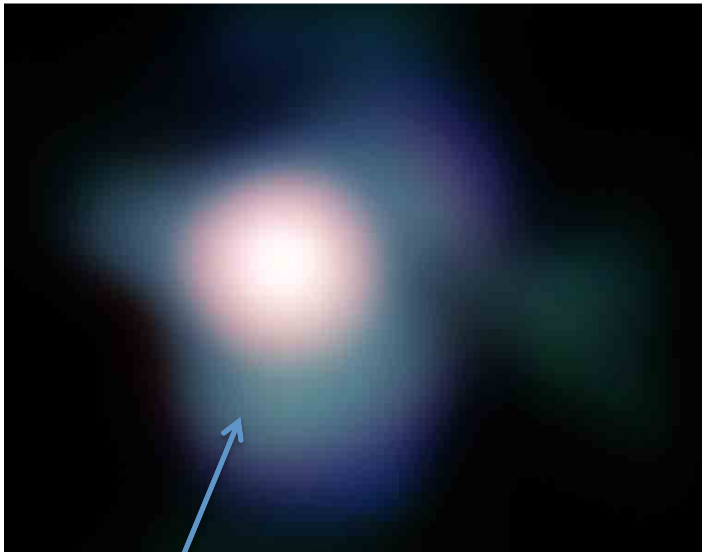
Meynet & Maeder (2000)



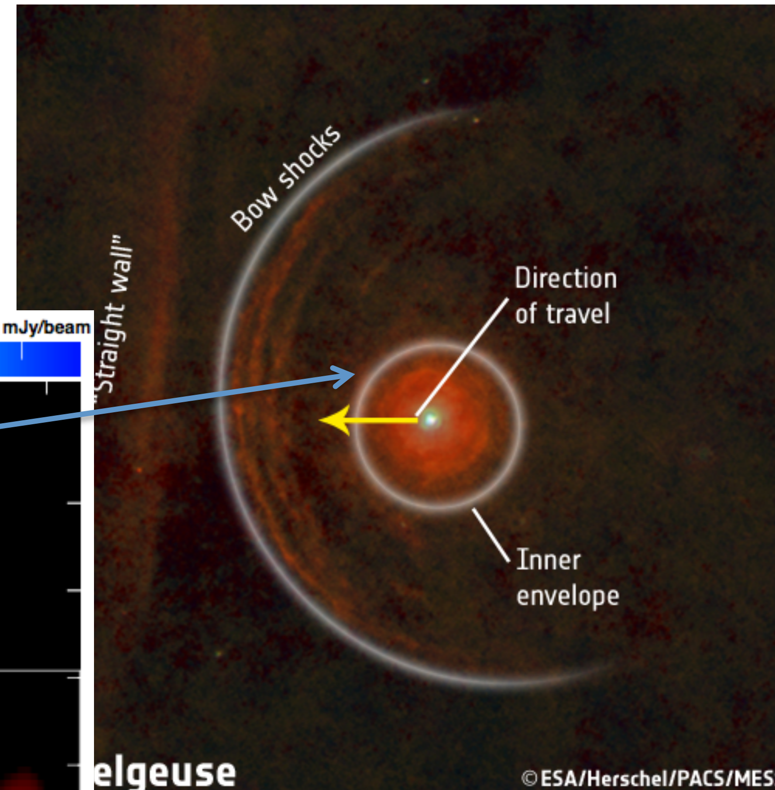
et al. (2000)

Imaging

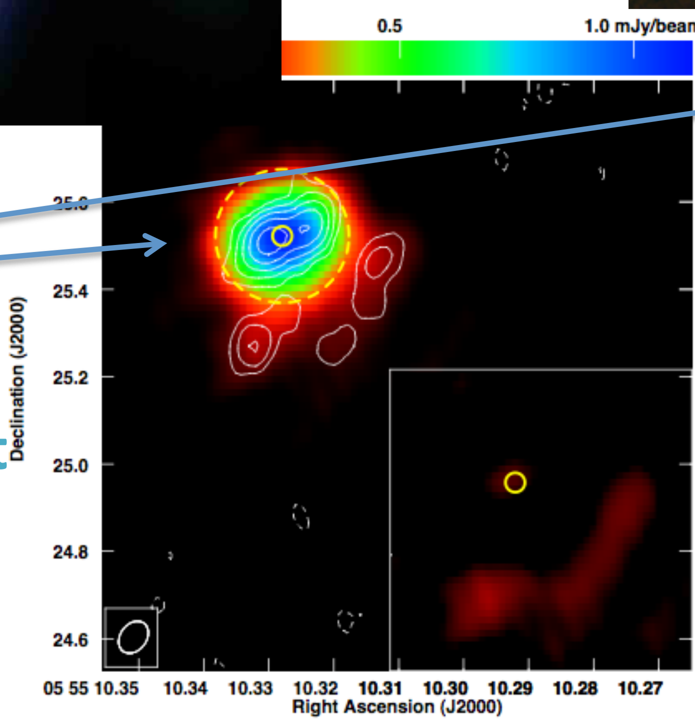
ESO VLT



Herschel Space Observatory
(observations @ 60 – 600 mikron)



Betelgeuse: the nearest Red supergiant



e-MERLIN
radio interferometry (5 cm)

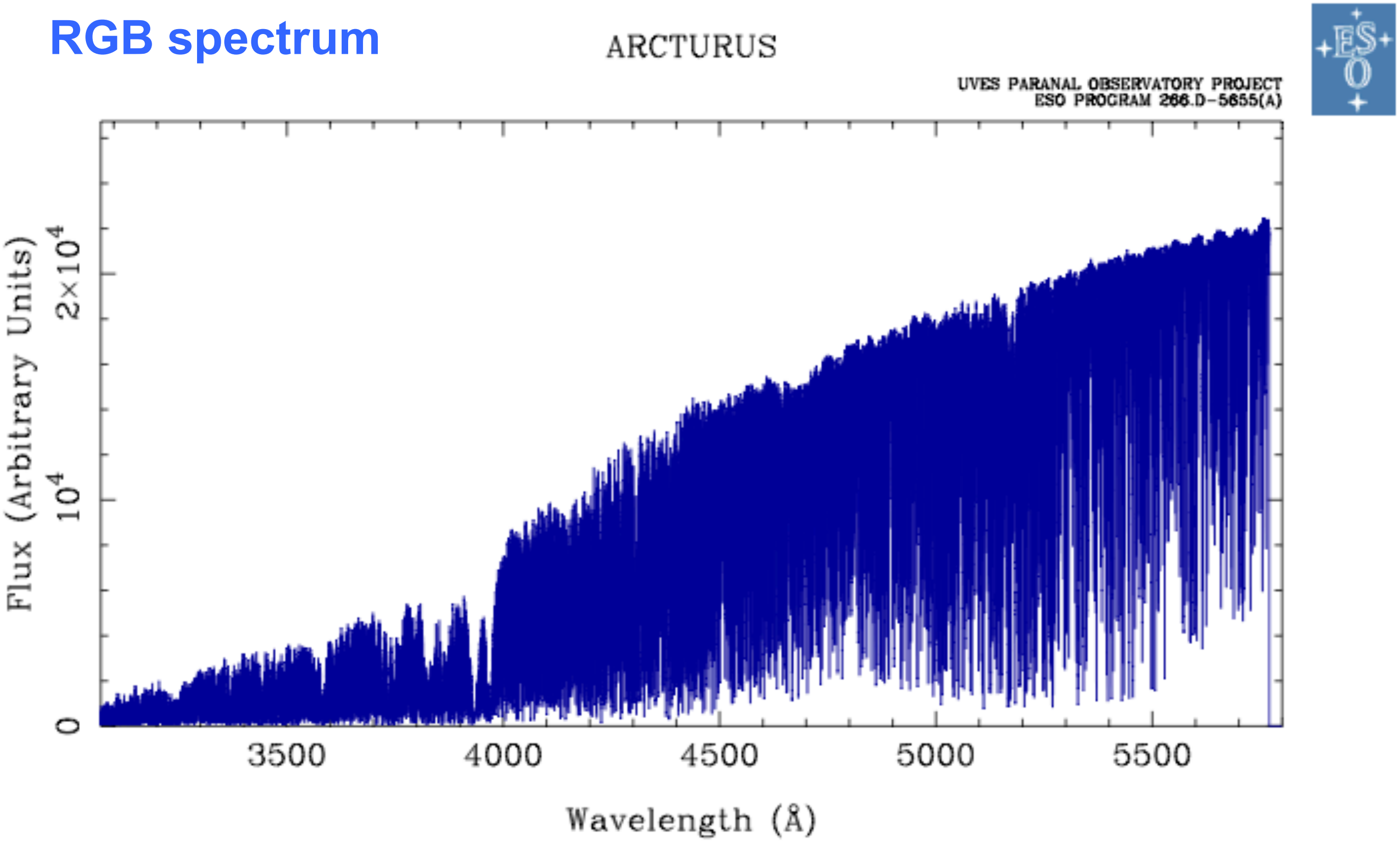
Motivation

- ✓ RSG's, RGB's, AGBs are so bright – best tracers of chemical abundances in galaxies
  bright in the IR – AO advantage
  with E-ELT's we can go as deep as ~ Mpc
- ✓ and we still get a lot of giants in the Milky Way (bulge, outer disk, halo, Ultra-metal-poor stars)
- ✓ probe populations of all ages: from Myr to Gyr
- ✓ astro-seismology
  CoRoT, Kepler2 missions
  very precise log(g) and (finally!) age determinations possible
- ✓ surface chemistry very sensitive to stellar nucleosynthesis
- ✓ they are so good-looking! – resolved (Interferometry) images possible
- ✓ Spectroscopy: the spectra are so rich with chemical elements

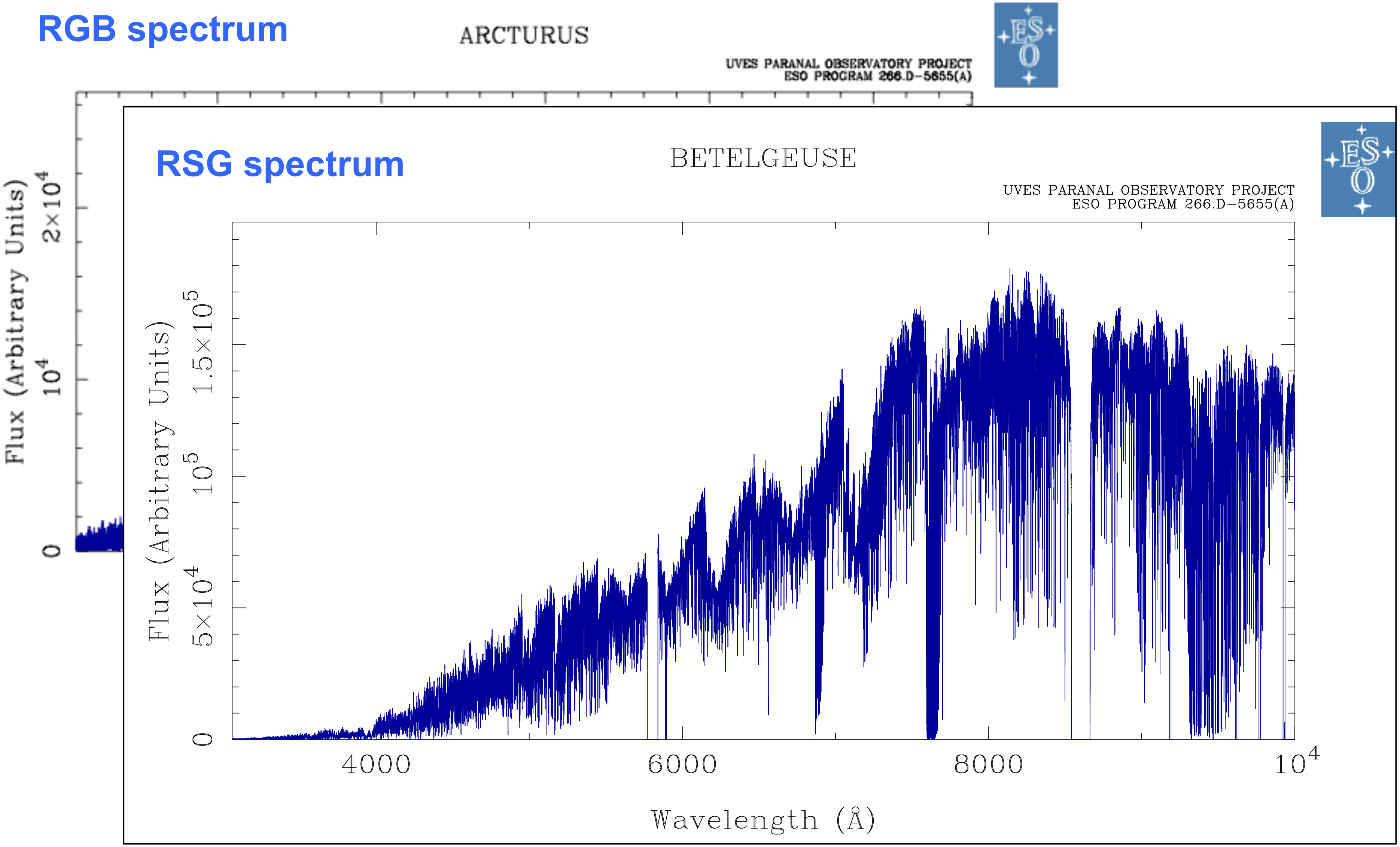
In combination with million datasets from ongoing and future surveys (Gaia-ESO, APOGEE), we get a complete mapping of the Galaxy and extra-galactic populations (Local Group+)

Spectra

RGB spectrum



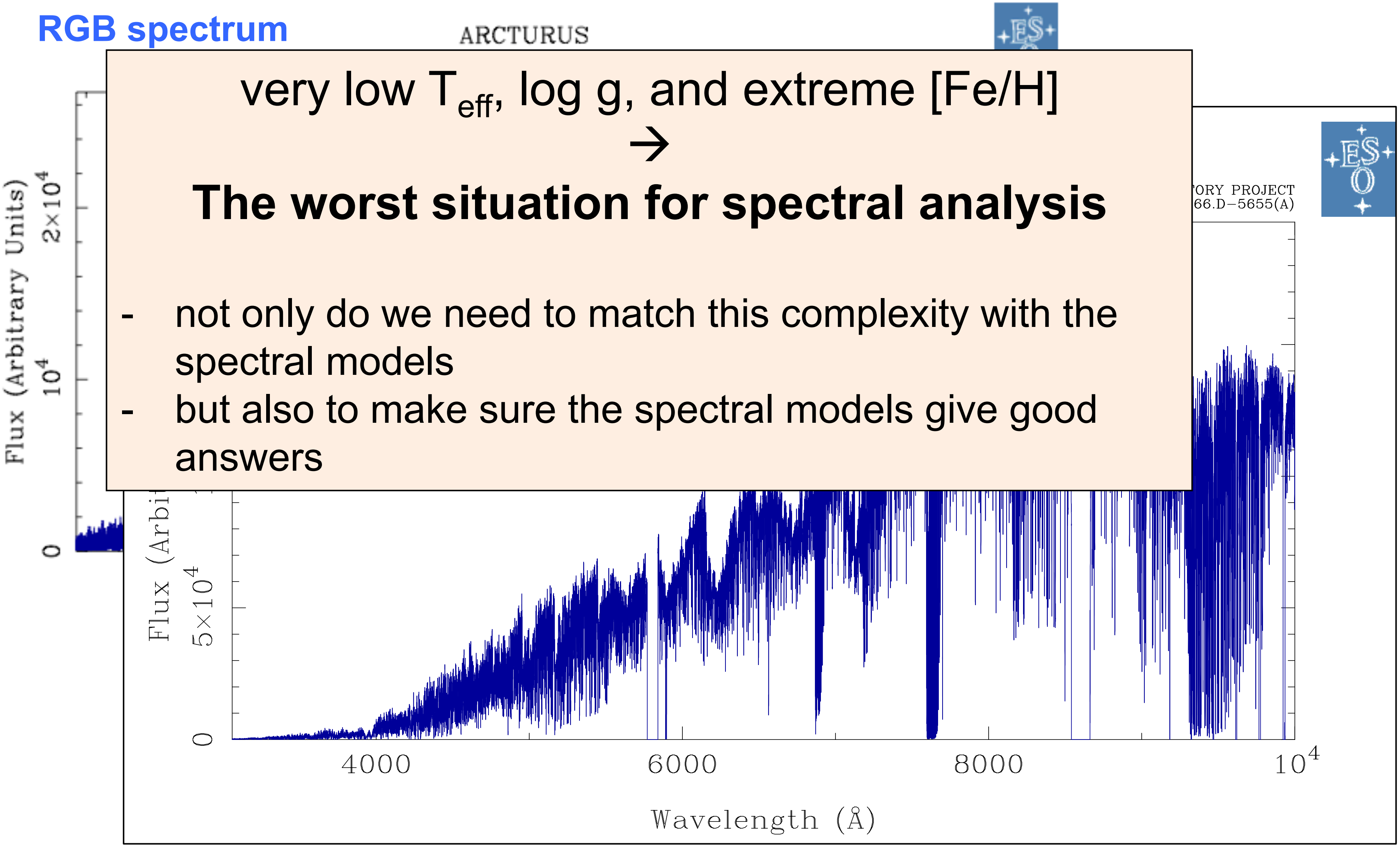
Spectra



RGB spectrum
ARCTURUS
UVES PARANAL OBSERVATORY PROJECT
ESO PROGRAM 266.D-5655(A)
Flux (Arbitrary Units)
2×10^4
10^4
0
RSG spectrum
BETELGEUSE
UVES PARANAL OBSERVATORY PROJECT
ESO PROGRAM 266.D-5655(A)
Flux (Arbitrary Units)
1.5×10^5
10^5
5×10^4
0
4000
6000
8000
10^4
Wavelength (Å)

Spectra

RGB spectrum



very low T_{eff}, log g, and extreme [Fe/H]

→

The worst situation for spectral analysis

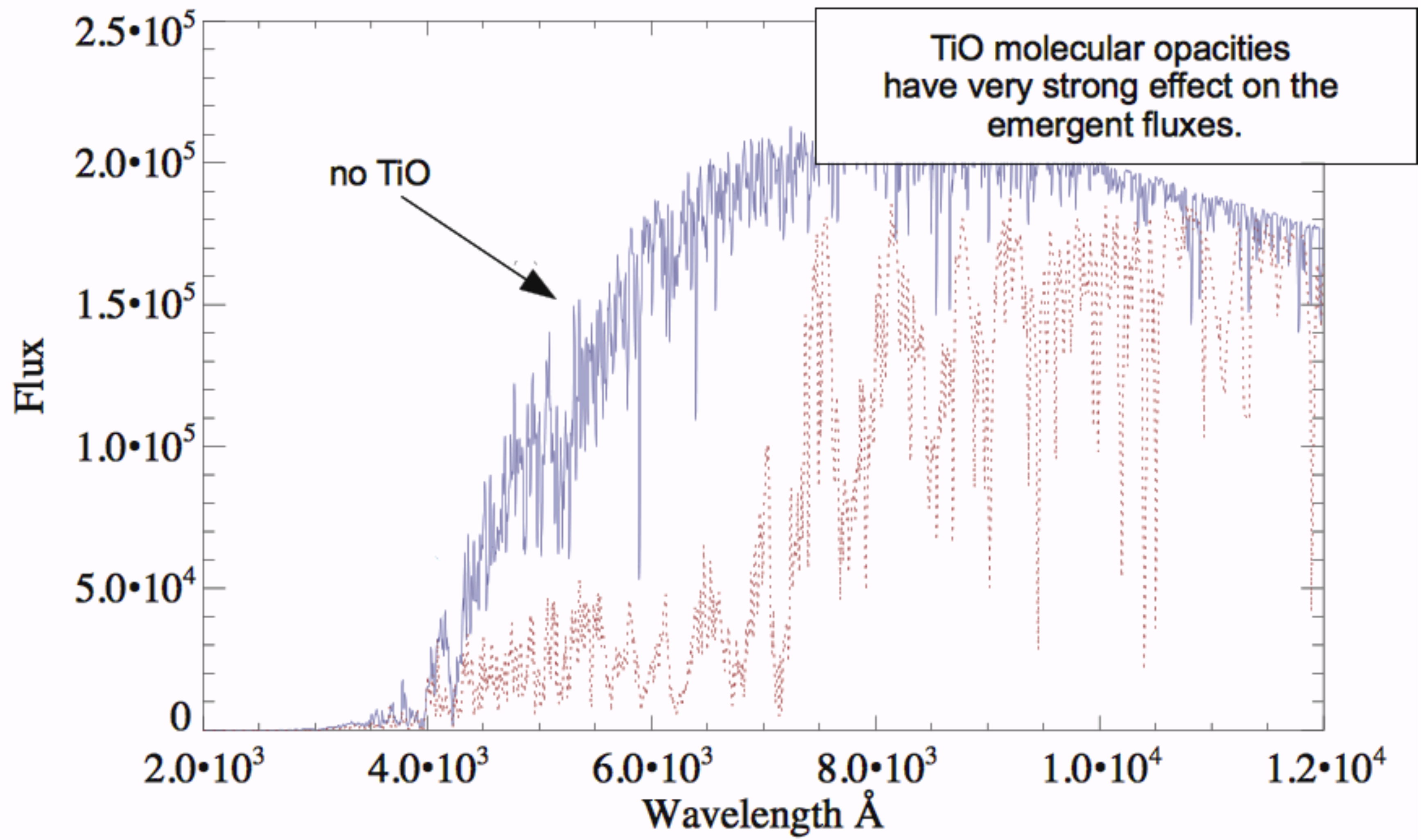
- not only do we need to match this complexity with the spectral models
- but also to make sure the spectral models give good answers

Atmospheres of giants

1. Molecular opacities (+ *a 'forest' of other parasitic spectral features*)
2. Asymmetric shapes with 'hot spots' and mass loss
3. MOLsphere, Dust
   Deviations from hydrostatic equilibrium and giant convective cells
4. Deviations from local thermodynamic equilibrium (NLTE)
5. Chromospheres

Atmospheres of giants

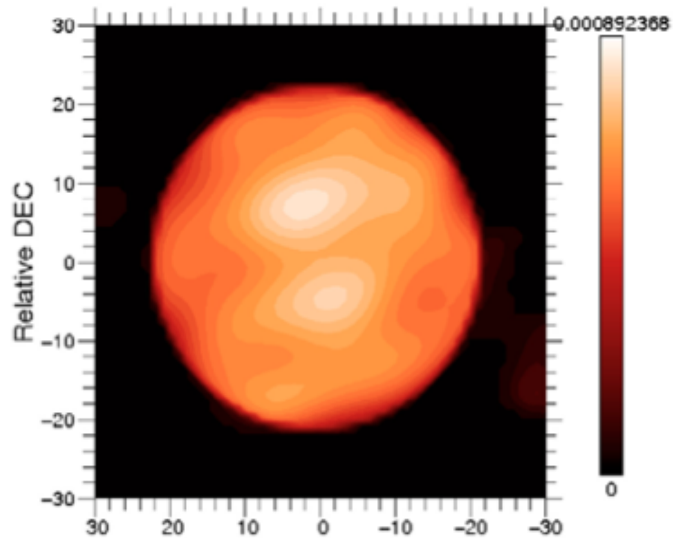
1. Molecular opacities (+ *a 'forest' of other parasitic spectral features*)



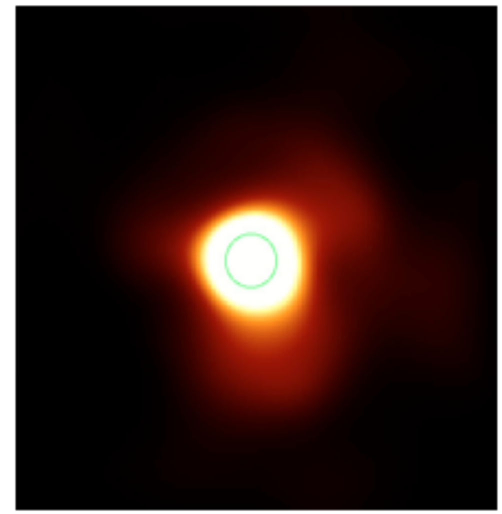
Atmospheres of giants

1. Molecular opacities (+ *a 'forest' of other parasitic spectral features*)
2. Asymmetric shapes with 'hot spots' and mass loss

Interferometric observations resolve structure on Betelgeuse: hot spots, 'plumes' and giant convective cells



Haubois et al. (2009)



Kervella et al. (2009)

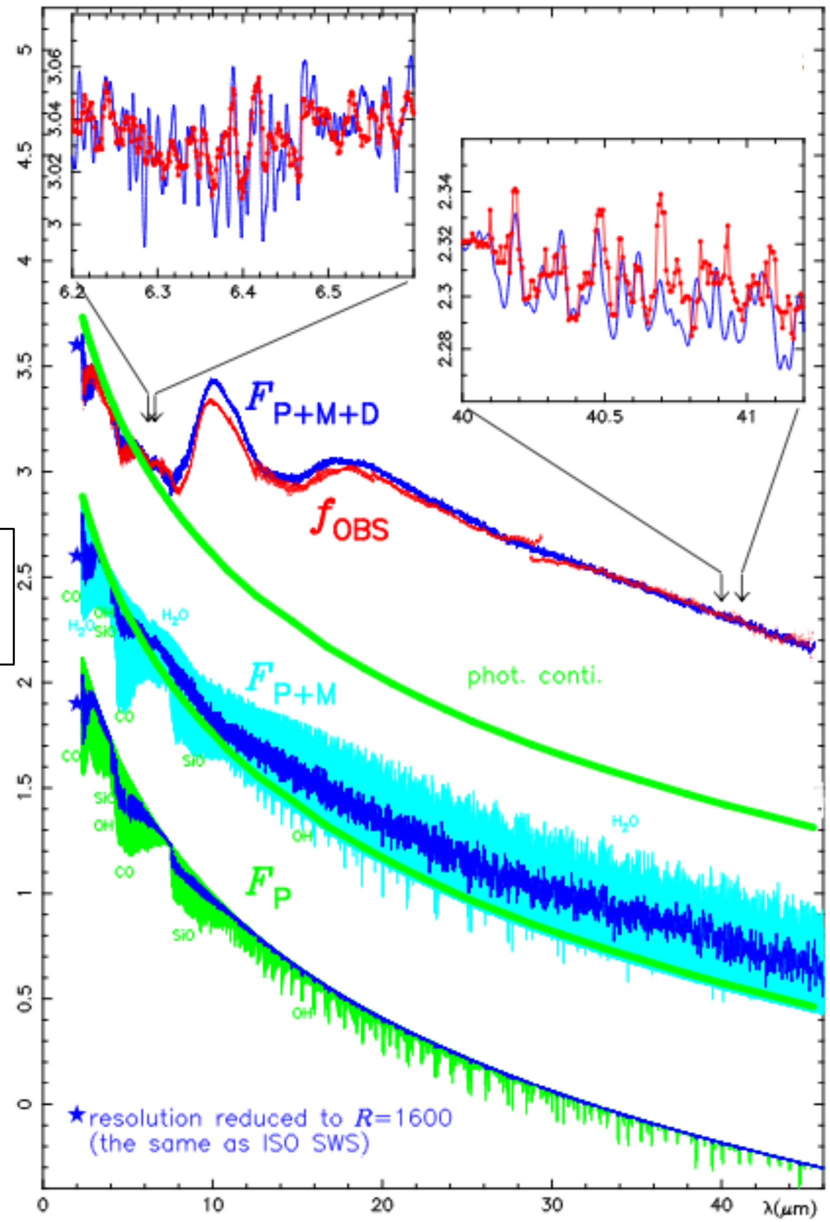
The IOTA Project

Infrared Optical Telescope Array

Atmospheres of giants

1. Molecular opacities (+ *a 'forest' of*
2. Asymmetric shapes with 'hot spots
3. MOLsphere, Dust

Circumstellar dust needed to explain Infra-red radiation excess

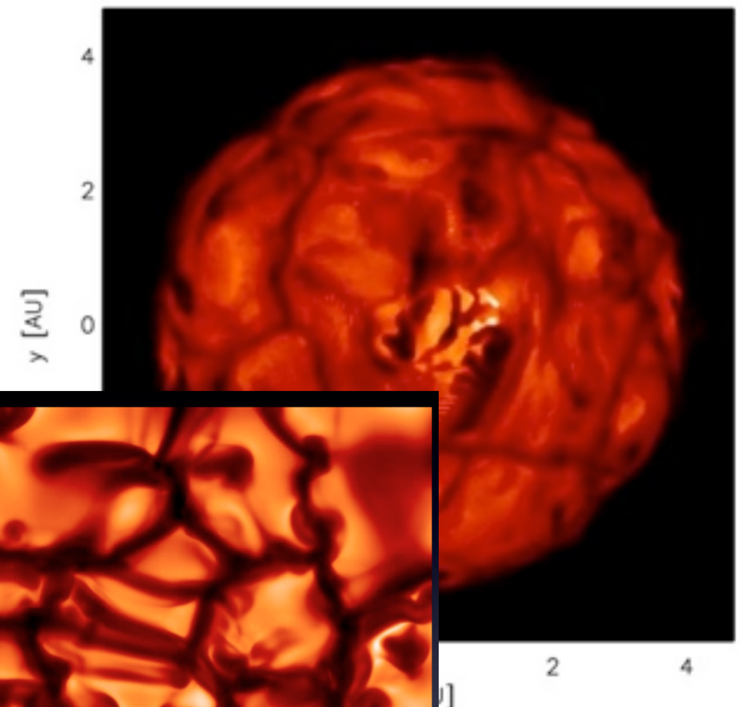


Tsuji (2003)

Atmospheres of giants

1. Molecular opacities (+ *a 'forest' of other parasitic spectral features*)
2. Asymmetric shapes with 'hot spots' and mass loss
3. MOLsphere, Dust
4. Deviations from hydrostatic equilibrium and giant convective cells

Chiavassa et al. (2011)



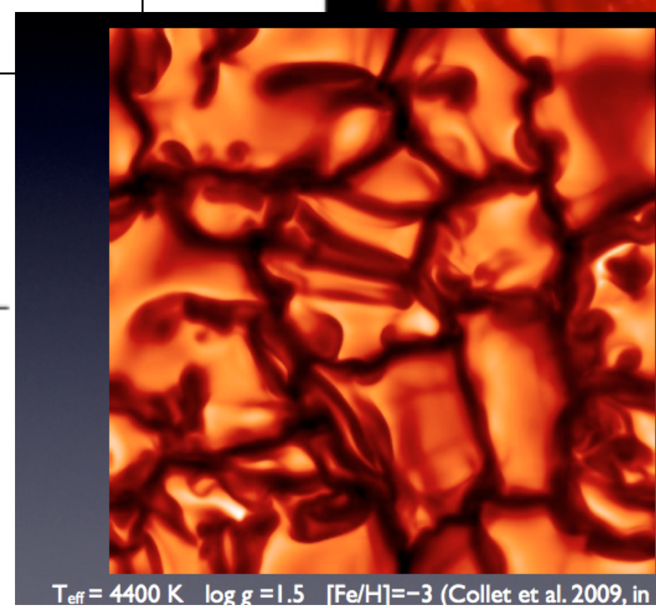
3D radiation hydrodynamics models of surface convection are needed (Freytag et al. 2002)

$$\frac{\partial \ln \rho}{\partial t} = -\mathbf{u} \cdot \nabla \ln \rho - \nabla \cdot \mathbf{u} \,,$$

$$\frac{\partial \mathbf{u}}{\partial t} = -\mathbf{u} \cdot \nabla \mathbf{u} + \mathbf{g} - \frac{P}{\rho} \nabla \ln P +$$

$$\frac{\partial e}{\partial t} = -\mathbf{u} \cdot \nabla e - \frac{P}{\rho} \nabla \cdot \mathbf{u}$$

$$+Q_{rad} + Q_{visc} \,,$$



Atmospheres of giants

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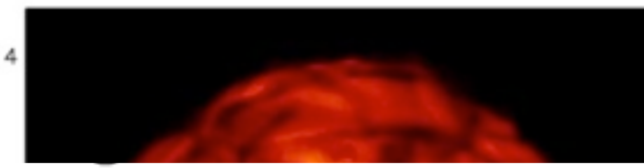
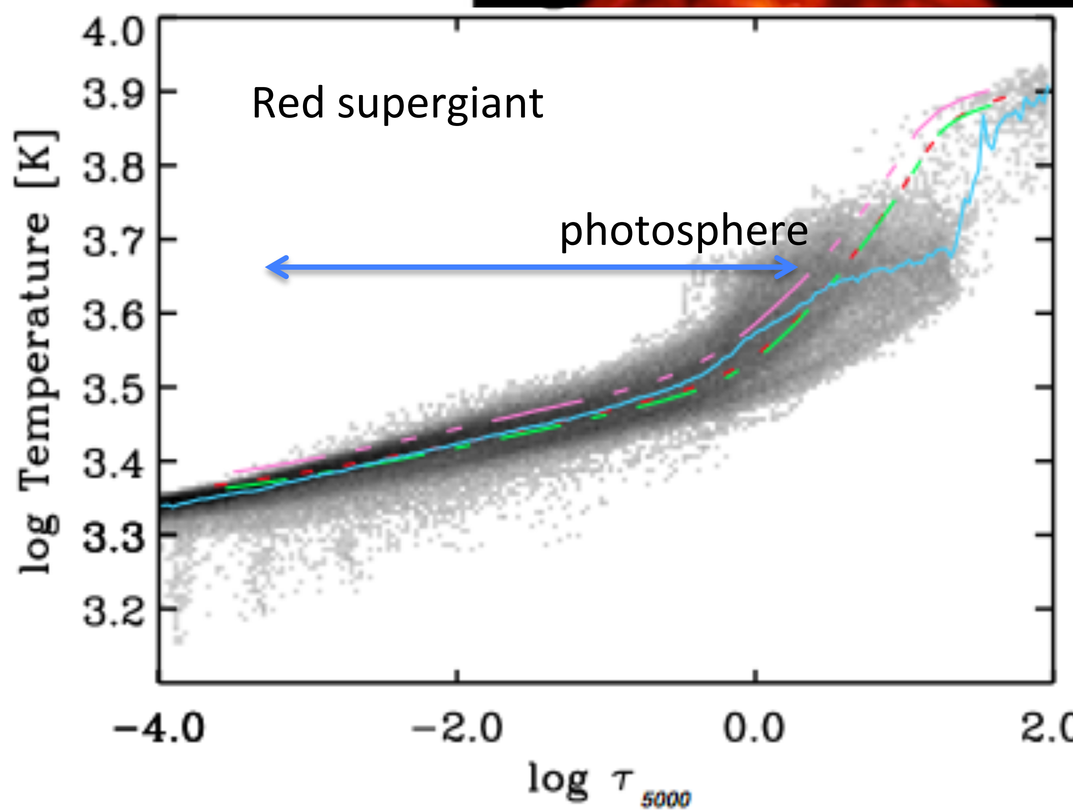


Convective motions over-shoot into the photosphere

→ the concept of a 'mean' 1D hydrostatic structure becomes meaningless



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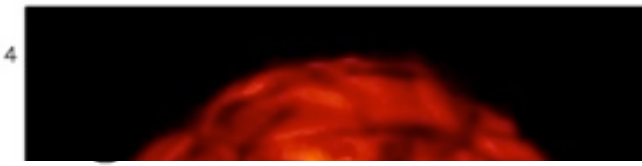

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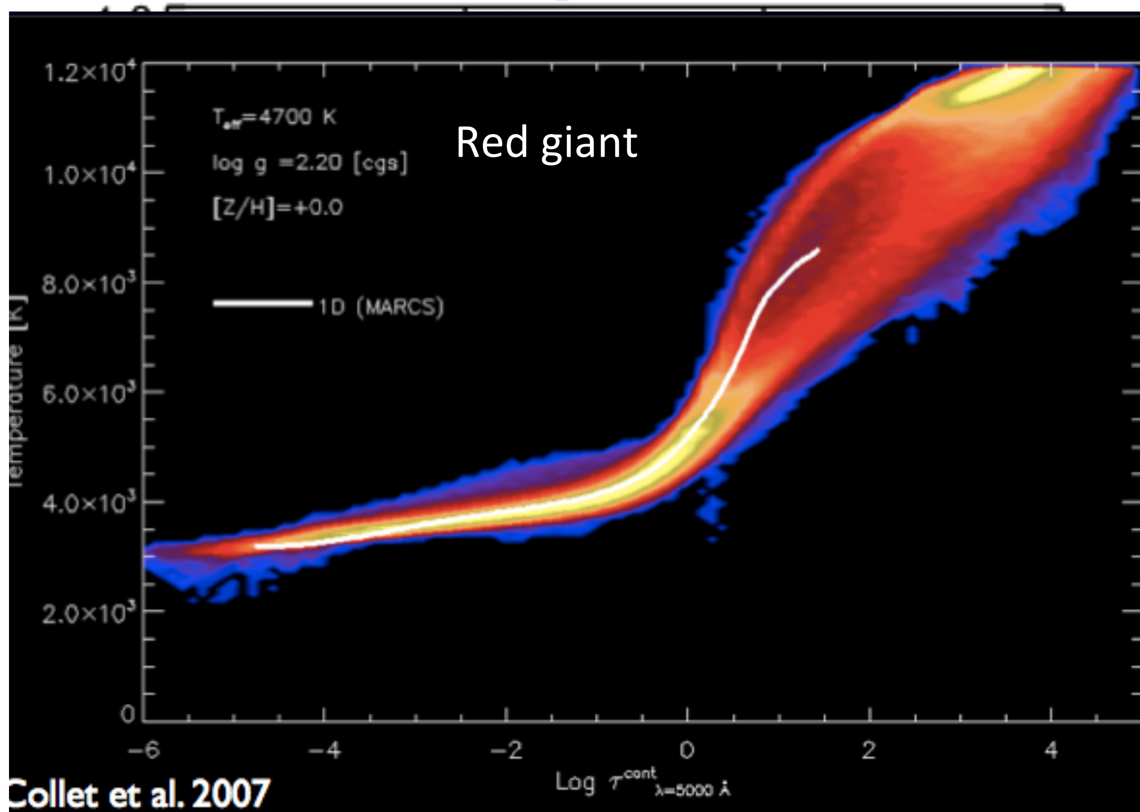

Atmospheres of giants

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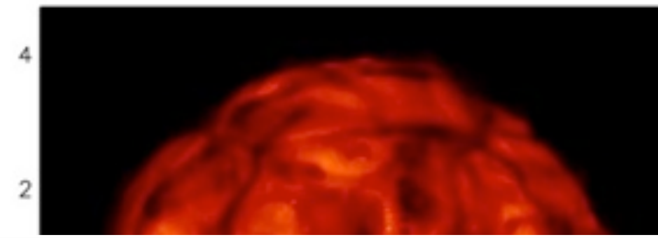
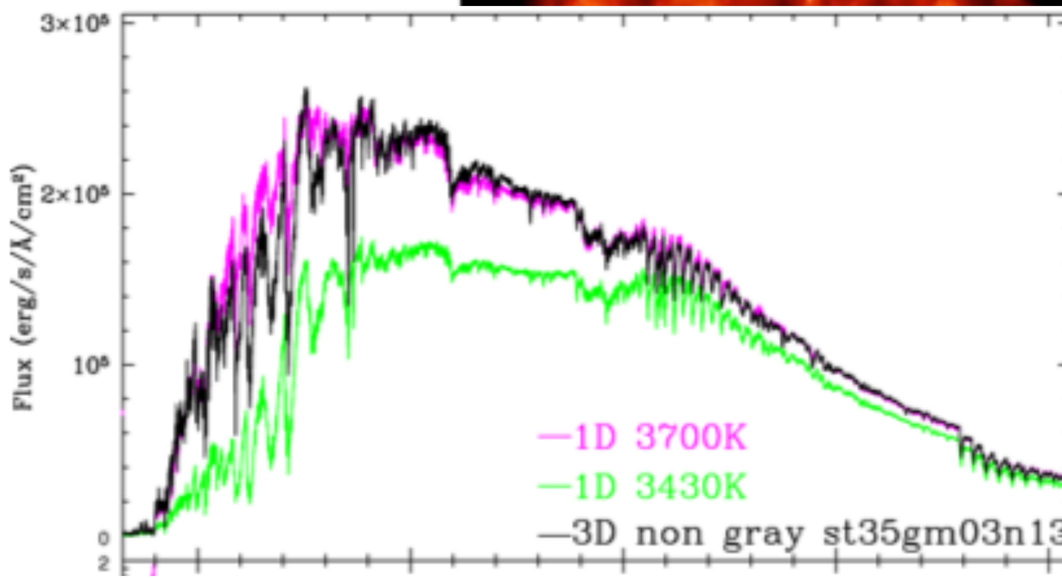


Convective motions over-shoot into the photosphere

→ the concept of a 'mean' 1D hydrostatic structure becomes meaningless

The effect of convection on the radiation field is **strongest** in deep layers of the atmosphere, where the optical and UV continua form.

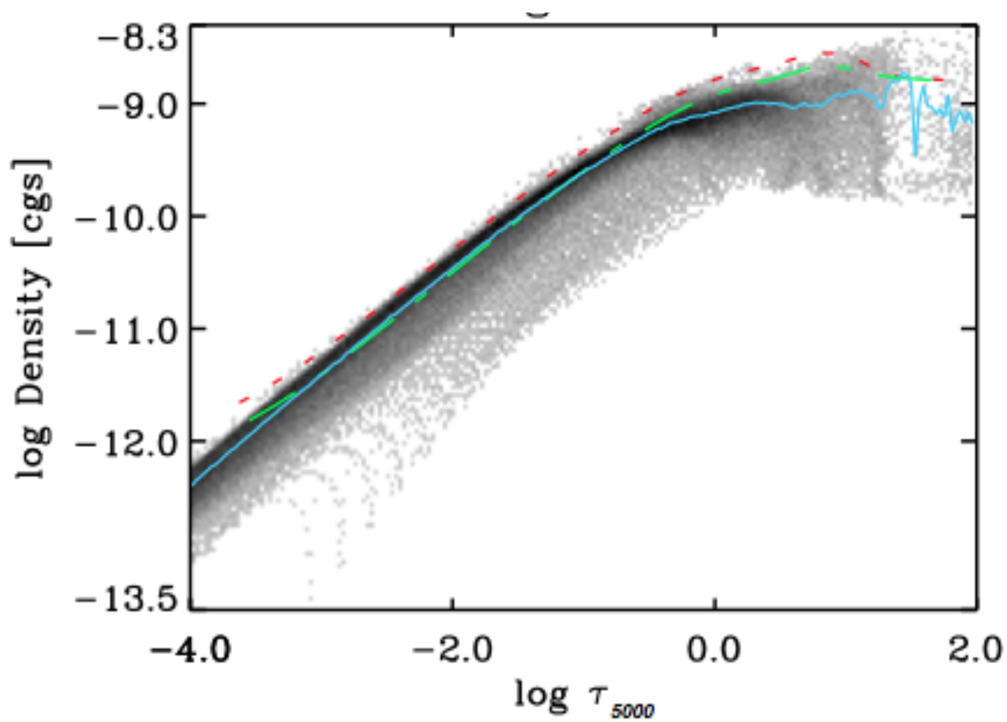


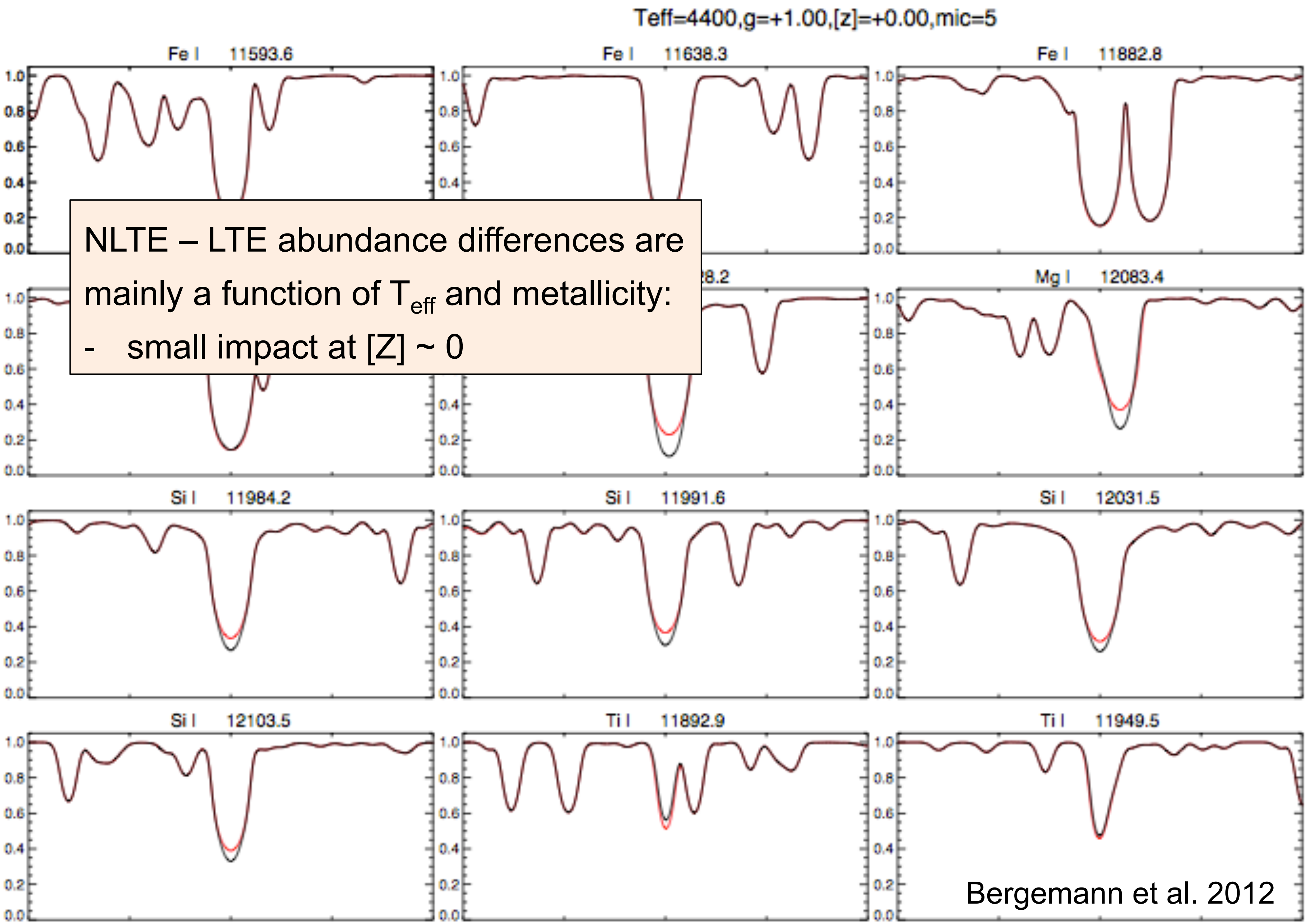
Chiavassa et al. (2011)

Atmospheres of giants

1. Molecular opacities (+ *a 'forest' of other parasitic spectral features*)
2. Asymmetric shapes with 'hot spots' and mass loss
3. MOLsphere, Dust
4. Deviations from hydrostatic equilibrium
   and giant convective cells
5. Deviations from local thermodynamic equilibrium (NLTE)

surface densities in giants and RSGs are 10^{-2} … 10^{-4} that of the Sun
→
collisions are too weak to establish LTE →
We need consistent non-local thermodynamic equilibrium transfer models



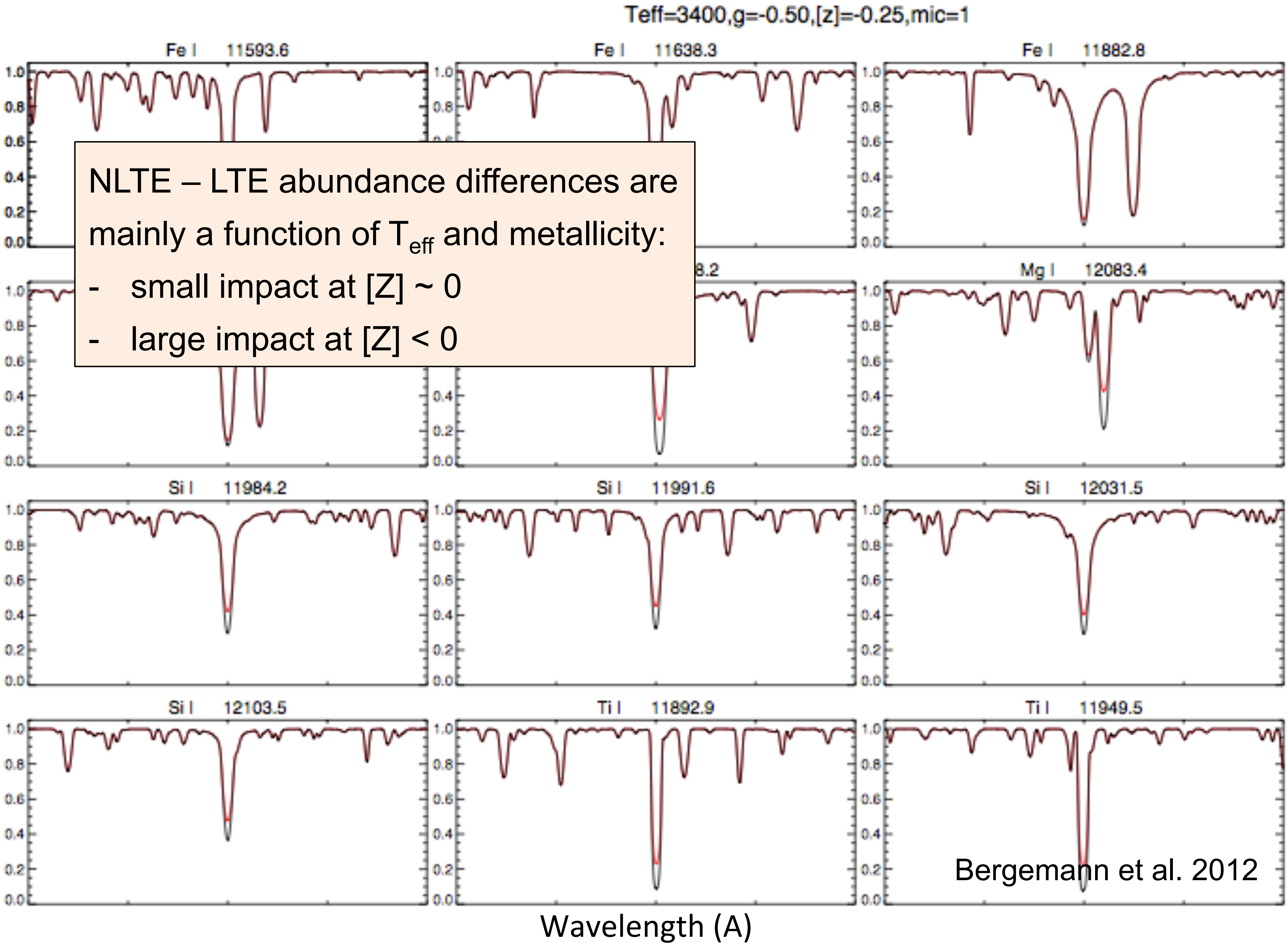


NLTE – LTE abundance differences are mainly a function of T_{eff} and metallicity:

- small impact at [Z] ~ 0

Bergemann et al. 2012

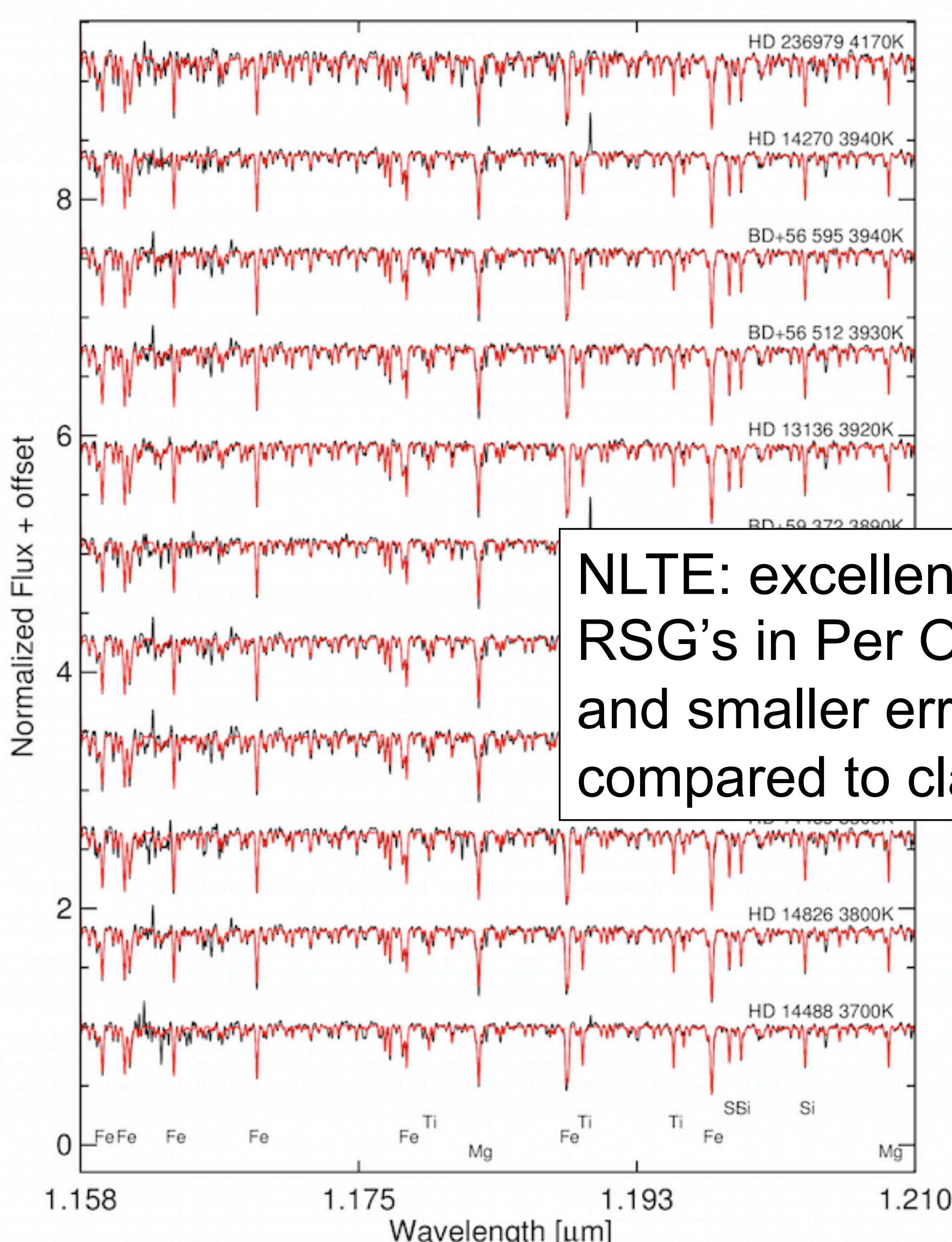
Wavelength (A)



NLTE – LTE abundance differences are mainly a function of T_{eff} and metallicity:

- small impact at [Z] ~ 0
- large impact at [Z] < 0

Bergemann et al. 2012



NLTE: excellent fits to spectra of RSG's in Per OB1 cluster and smaller errors in [Fe/H] compared to classical models

Models and their predictive power

Models and their predictive power

- Simulations for modern and future instruments

ISAAC (VLT), KMOS (Keck), NIRspec, XSHOOTER – R from 1000 to 20000

CRIRES

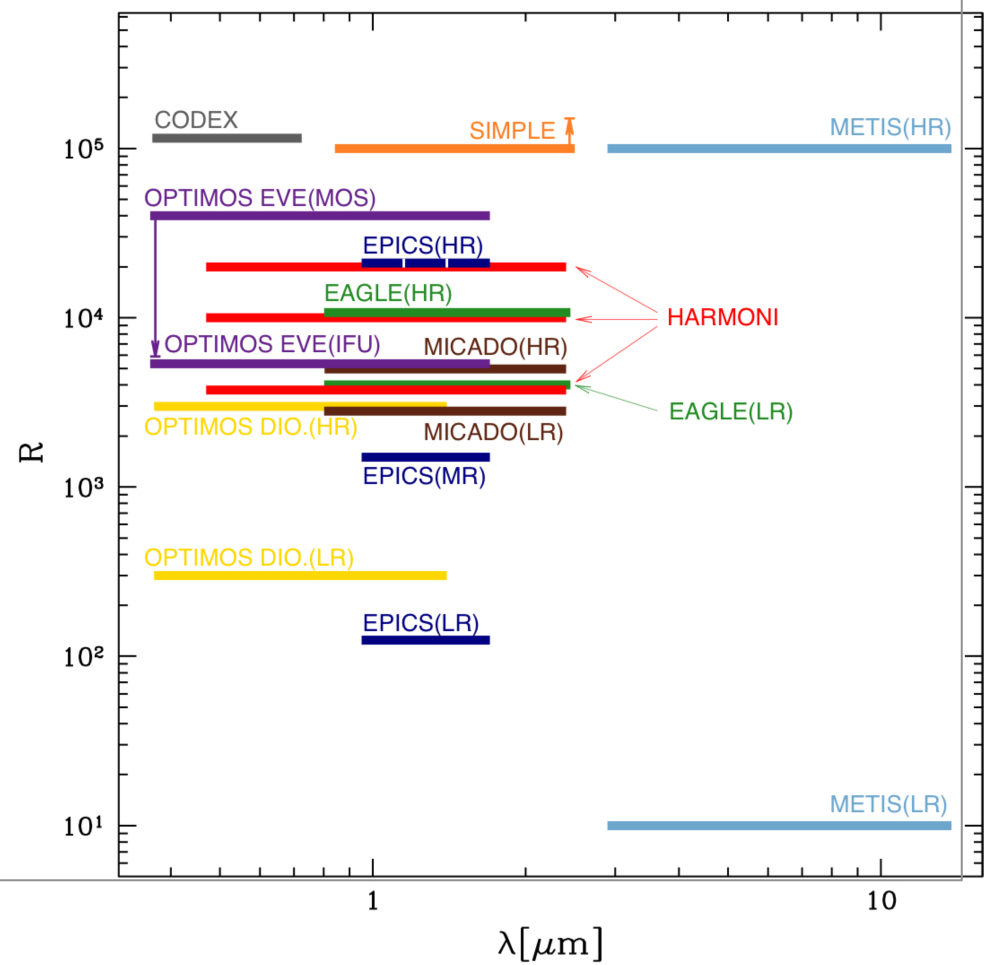
R ~ 100000

OPTIMOS-EVE,

HARMONI (E-ELT)

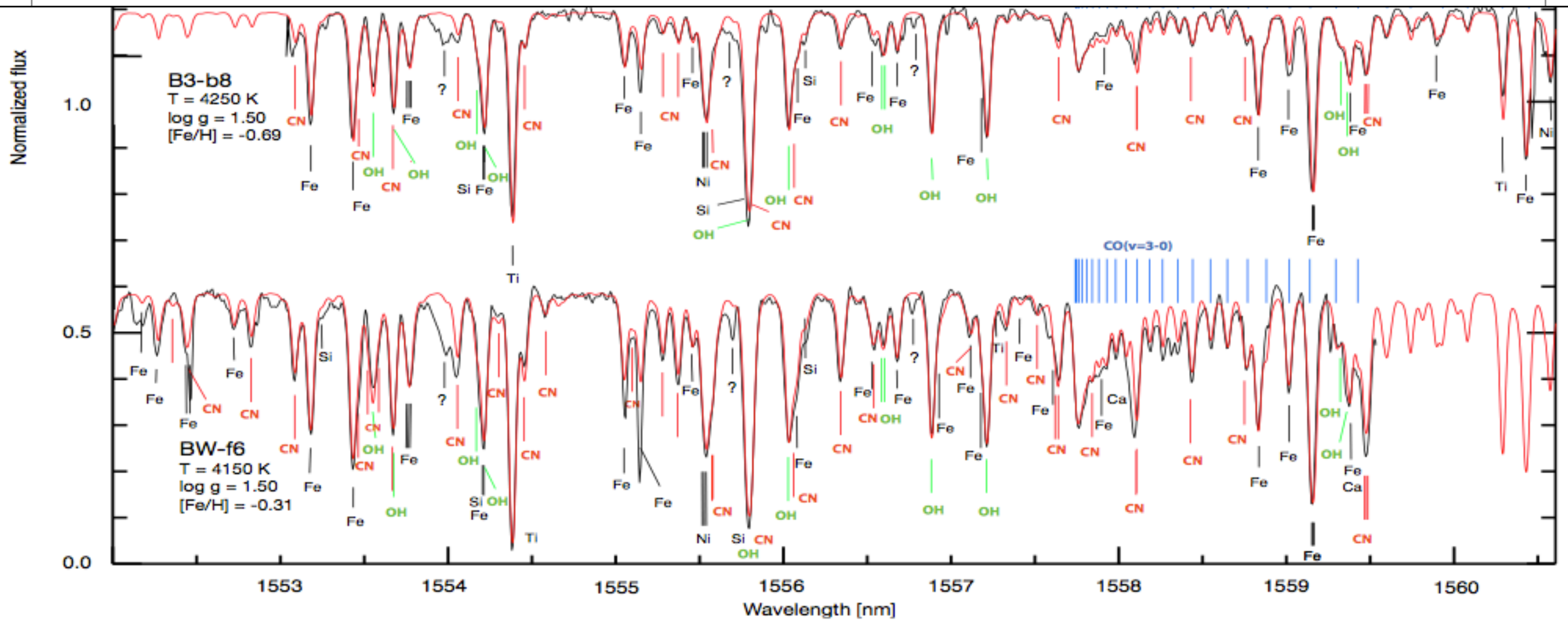
R ~ 500 to 20000

YJHK bands



High-resolution

Exquisite resolution is very useful: 15 chemical elements, isotopes
red giants in the H-band – CRIRES, R up to 100000

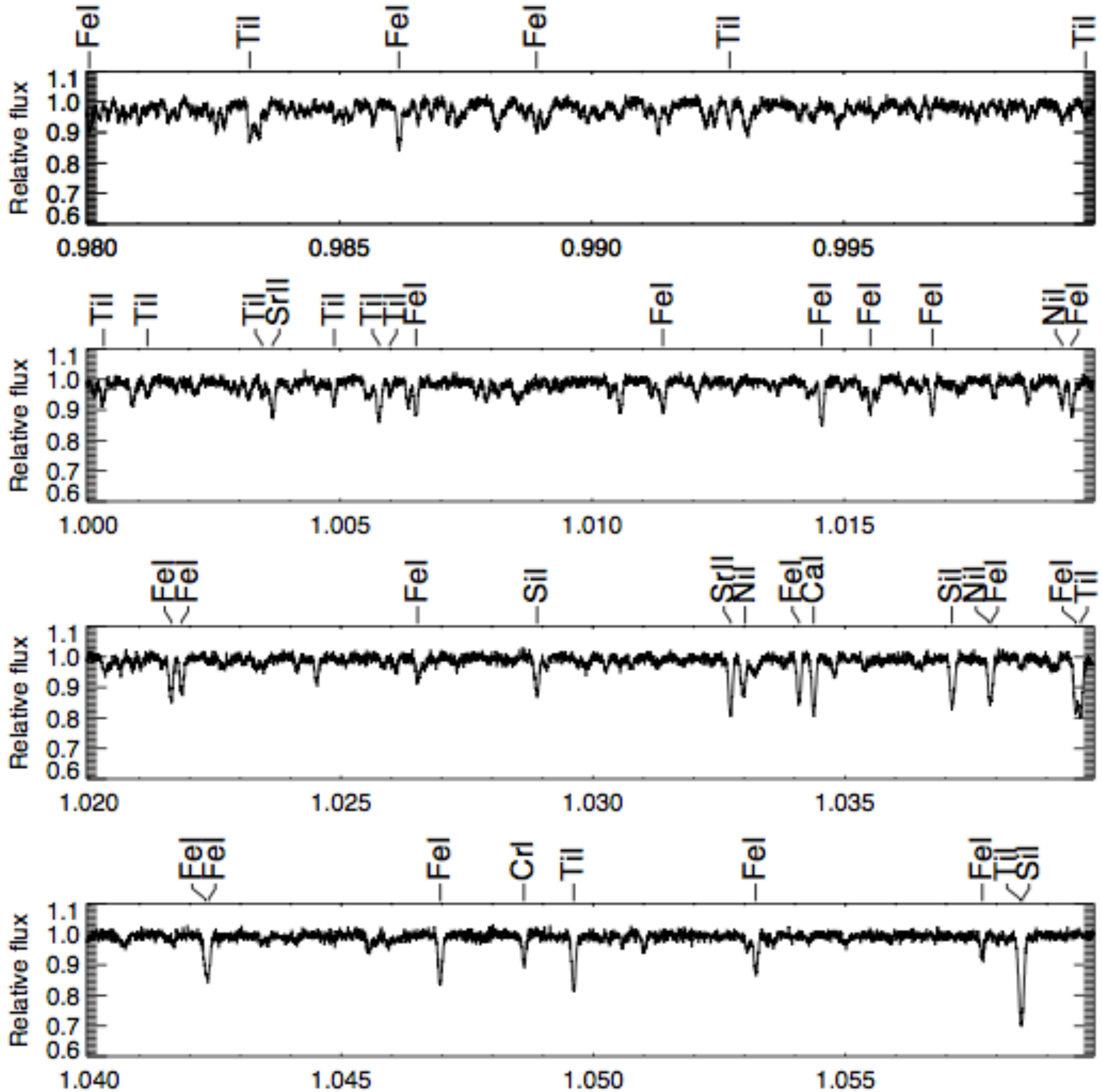


Simulations

1. S/N 100, Res = 20000
2. S/N 30, Res = 6000
3. S/N 10, Res = 3000

Y-band: S/N 100, R - 20000

T_{eff}= 4300, log(g) = 1.5, [Fe/H] = -0.5

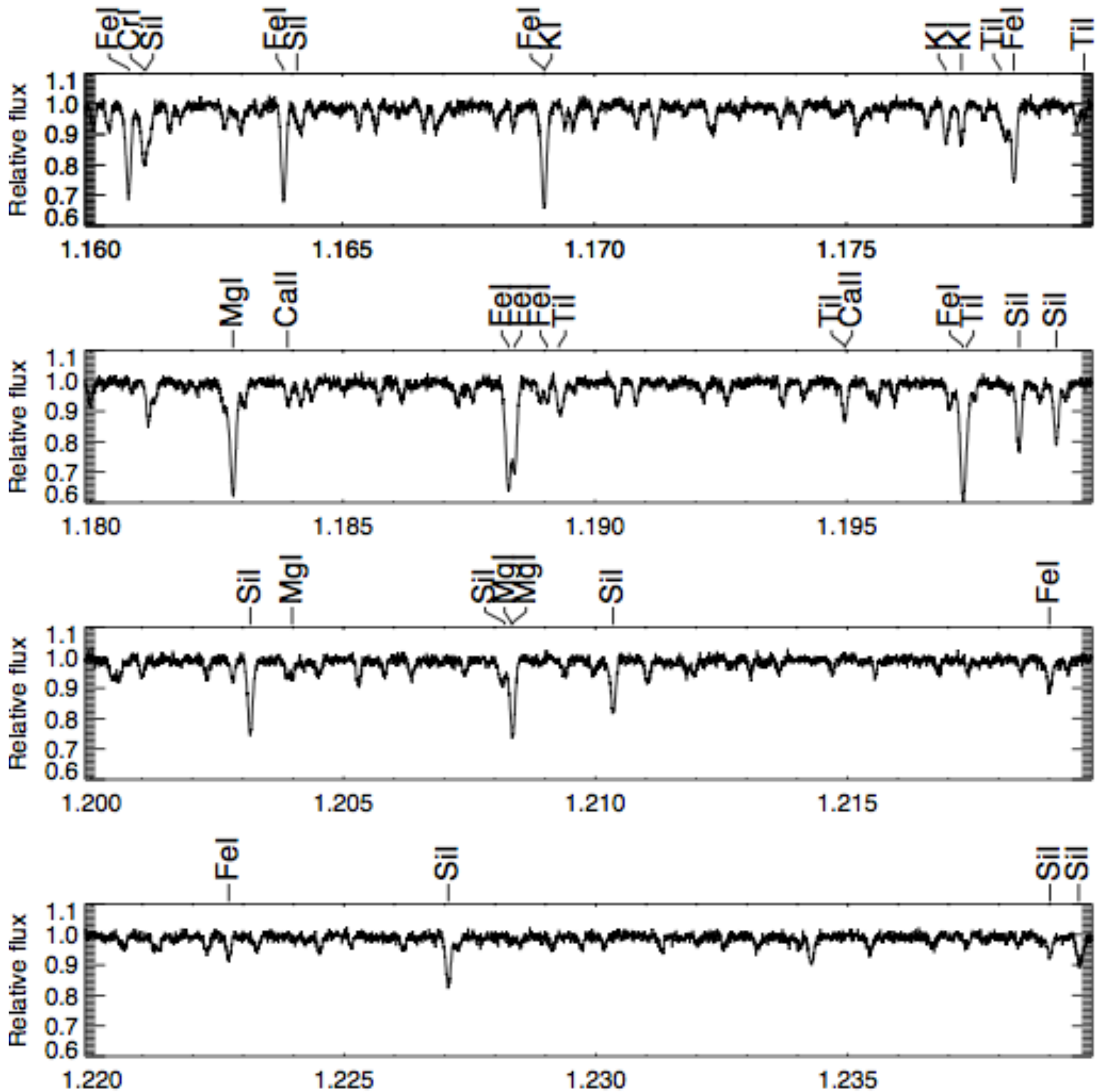


Y-band

- Fe I
- Cr I
- Ti I
- Ca I
- Si I
- Sr II
- S I
- Ni I

J-band: S/N 100, R - 20000

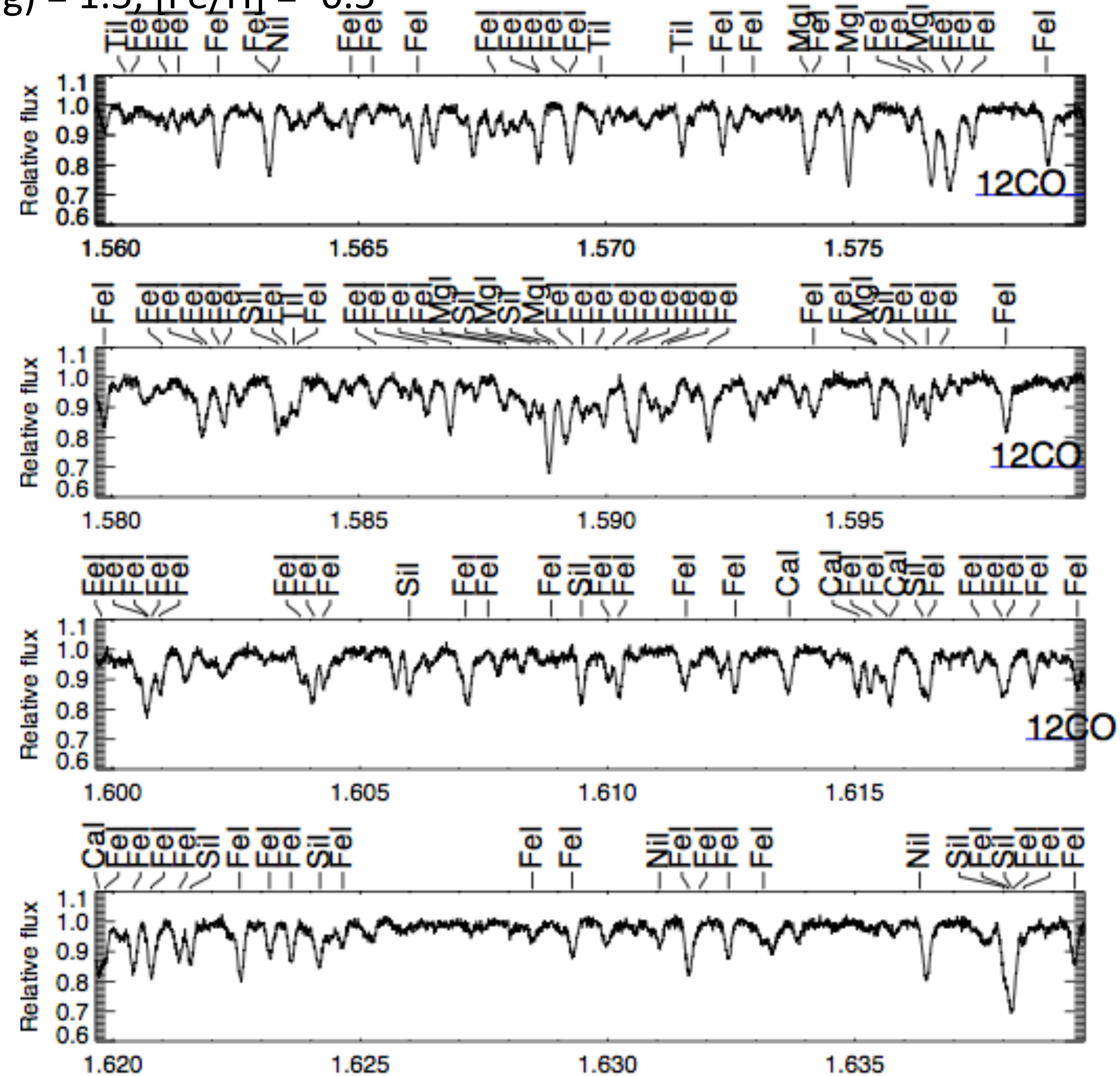
T_{eff}= 4300, log(g) = 1.5, [Fe/H] = -0.5



J-band
- K I
- Si I
- Mg I
- Cr I
- Fe I
- Ti I
- Ca I

H-band: S/N 100, R - 20000

T_{eff}= 4300, log(g) = 1.5, [Fe/H] = -0.5

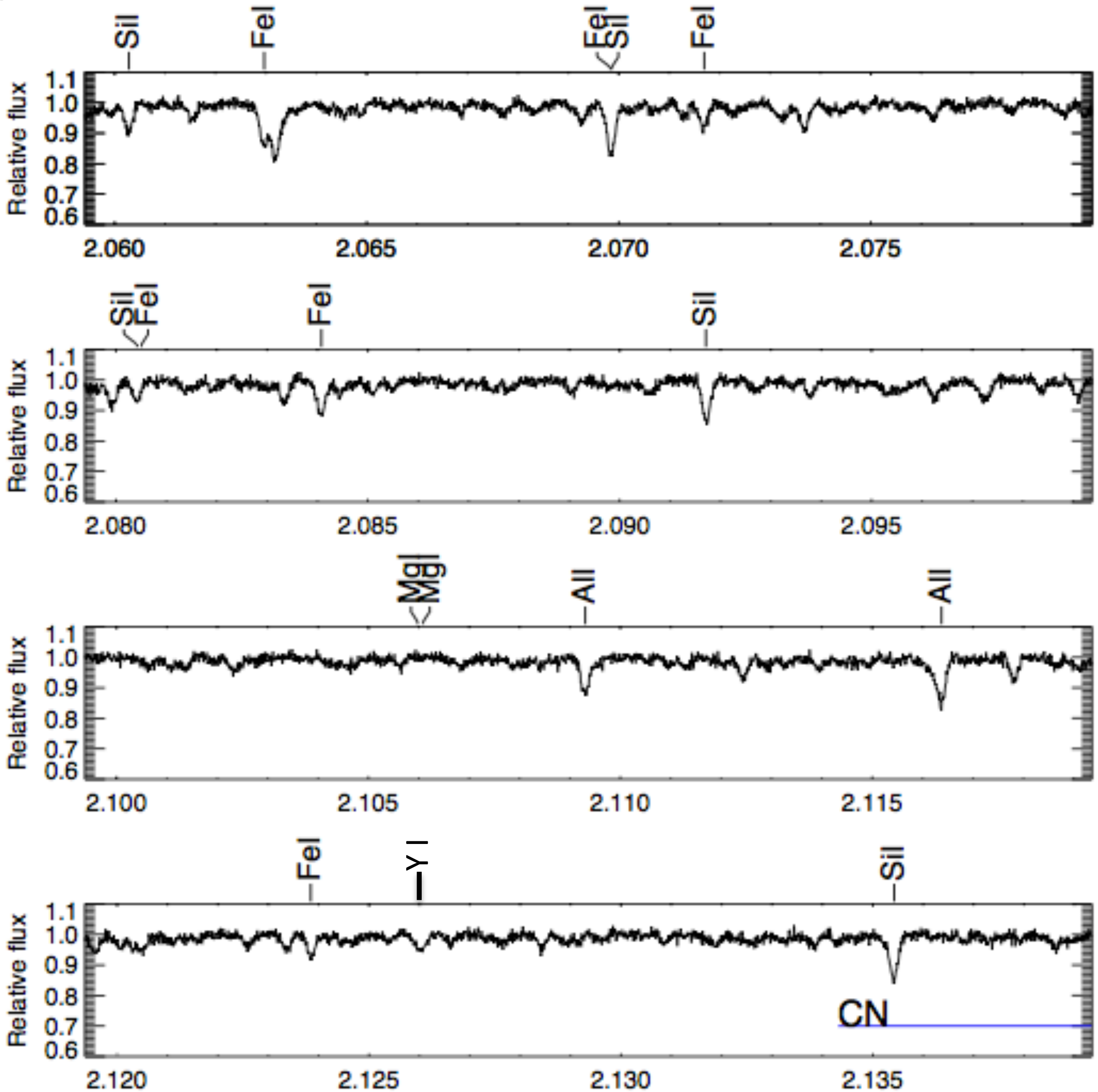


H-band

- K I
- Si I
- Mg I, Al I
- Cr I
- Fe I
- Ti I
- Ni I
- CO
- CN
- OH
- V I (1.67)

K-band: S/N 100, R - 20000

T_{eff}= 4300, log(g) = 1.5, [Fe/H] = -0.5



K-band

- Mg I
- Si I
- Fe I
- Sc I
- Al I
- Na I (2.2)
- C12/C13
- HF (2.3)

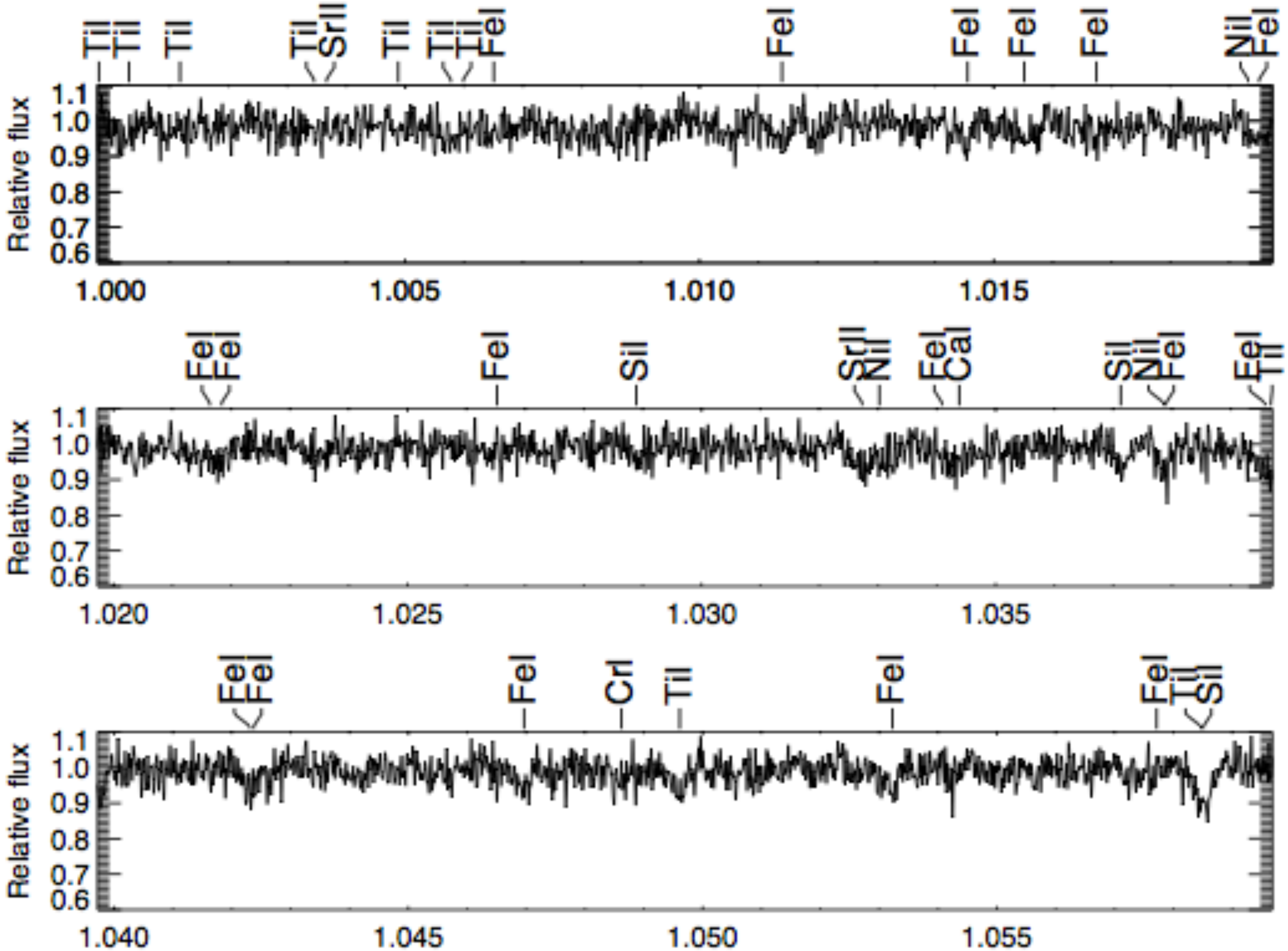
Simulations

MAX-PLANCK-GESELLSCHAFT

1. S/N 100, Res = 20000
2. S/N 30, Res = 6000
3. S/N 10, Res = 3000

Y-band: S/N 30, R - 6000

T_{eff}= 4300, log(g) = 1.5, [Fe/H] = -0.5

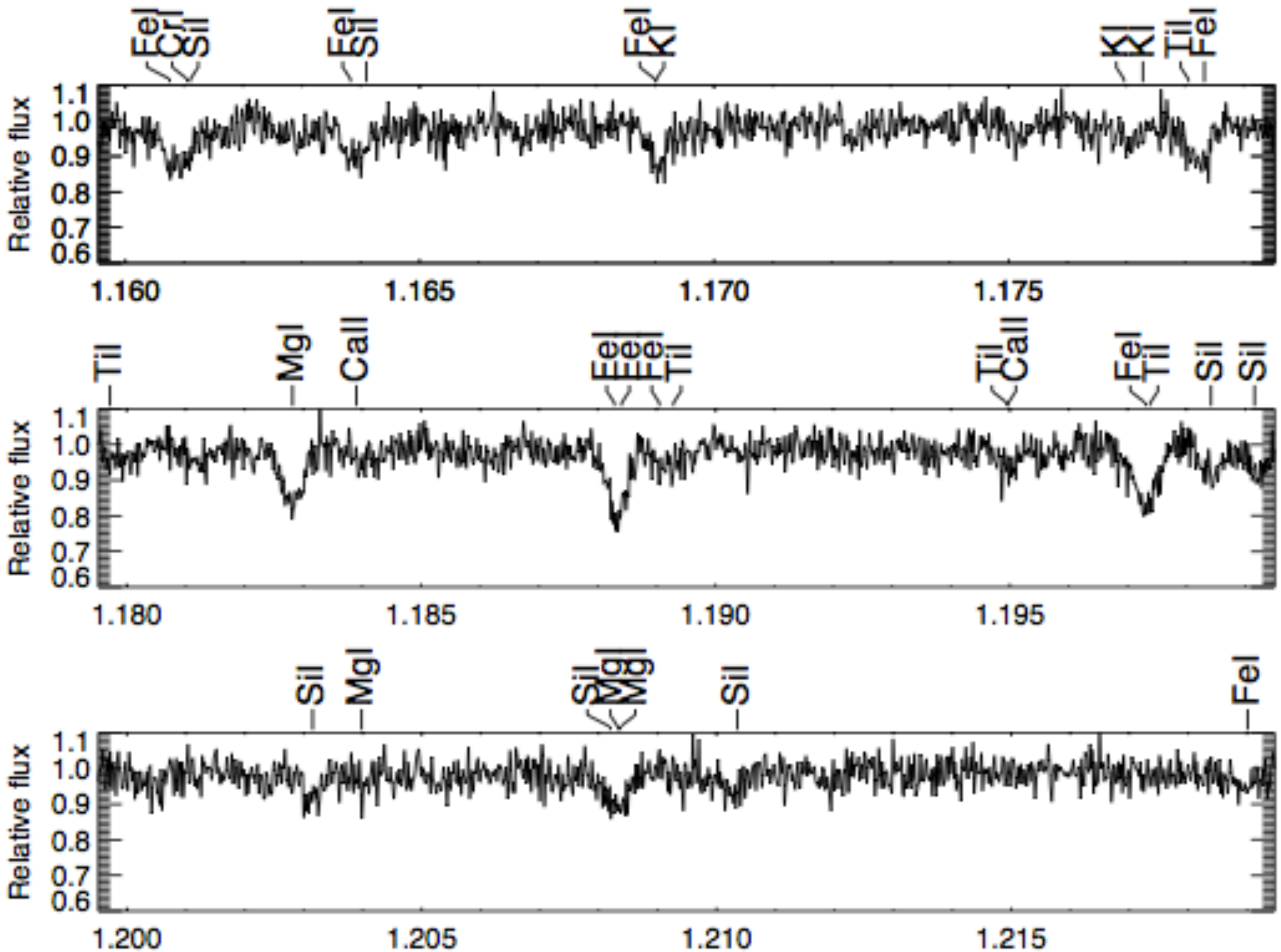


Y-band

- Fe I
- Cr I
- Ti I
- Ca I
- Si I
- Sr II
- S I
- Ni I

J-band: S/N 30, R - 6000

T_{eff}= 4300, log(g) = 1.5, [Fe/H] = -0.5



J-band

- K I
- Si I
- Mg I
- Cr I
- Fe I
- Ti I
- Ca I

H-band: S/N 30, R - 6000

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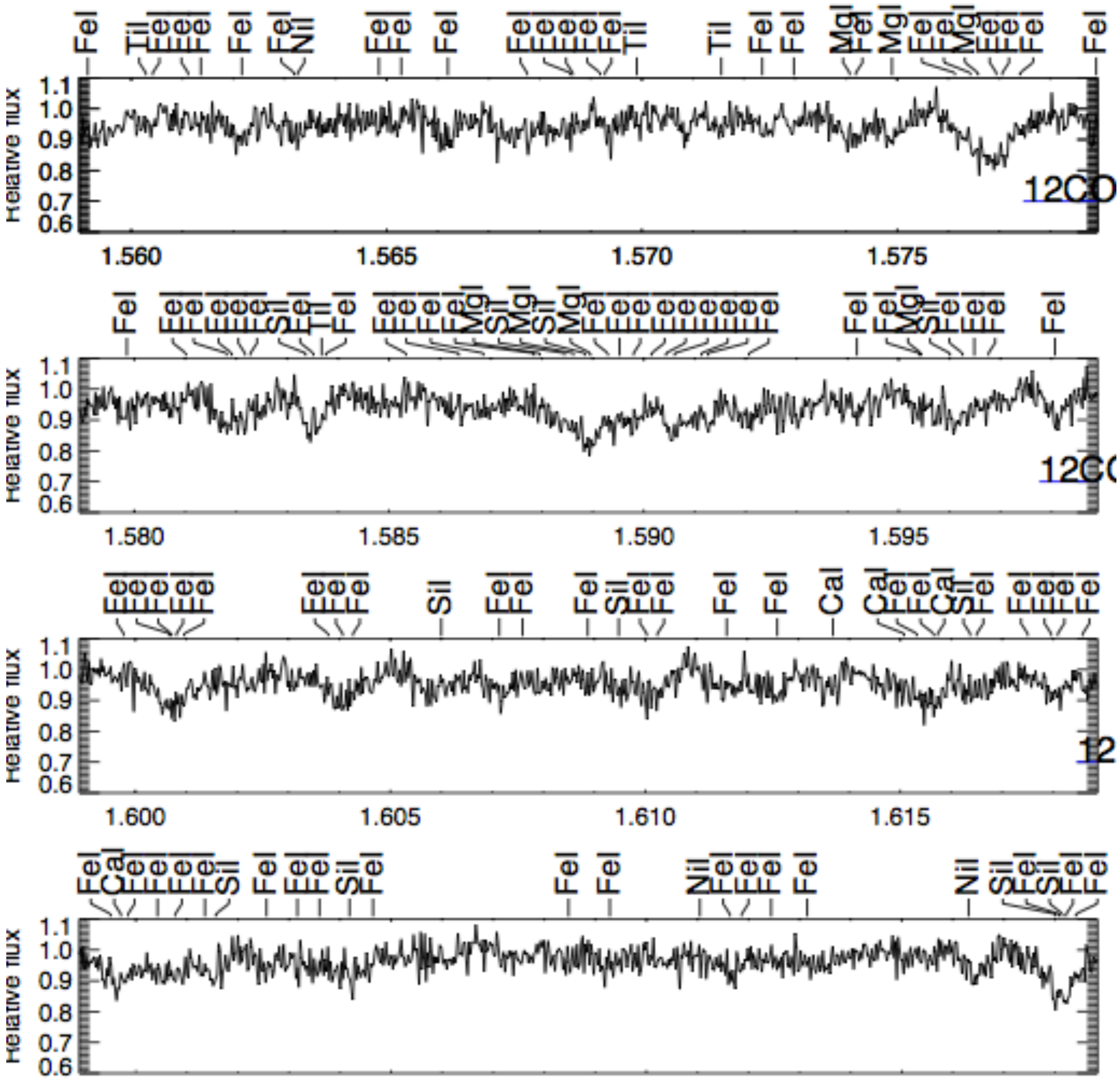
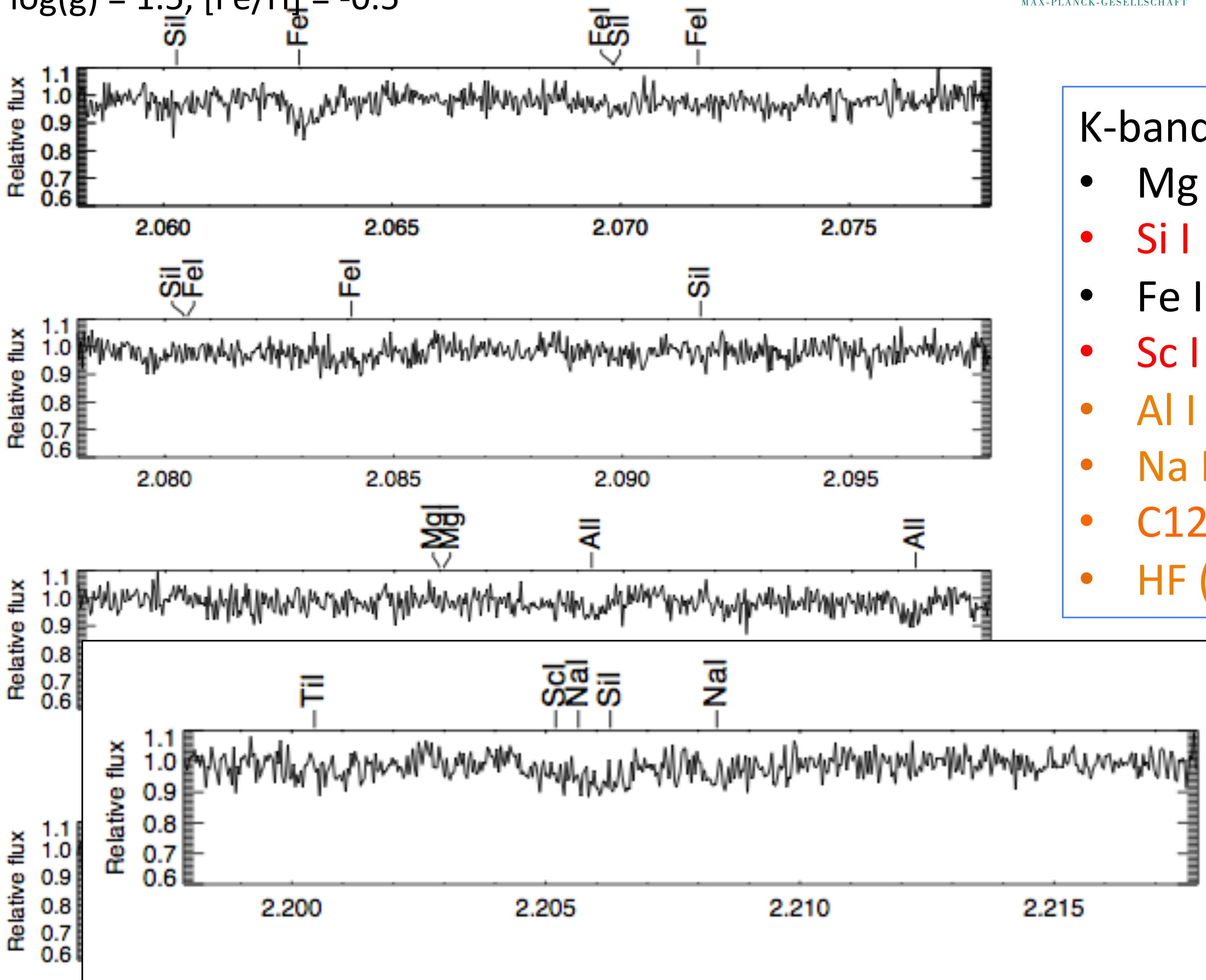


H-band

- K I
- Si I
- Mg I, Al
- Cr I
- Fe I
- Ti I
- Ni I
- CO
- CN
- OH
- V I (1.67)

K-band: S/N 30, R - 6000

T_{eff}= 4300, log(g) = 1.5, [Fe/H] = -0.5



K-band

- Mg I
- Si I
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- Na I (2.2)
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- HF (2.3)

Simulations

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Y-band: S/N 30, R - 3000

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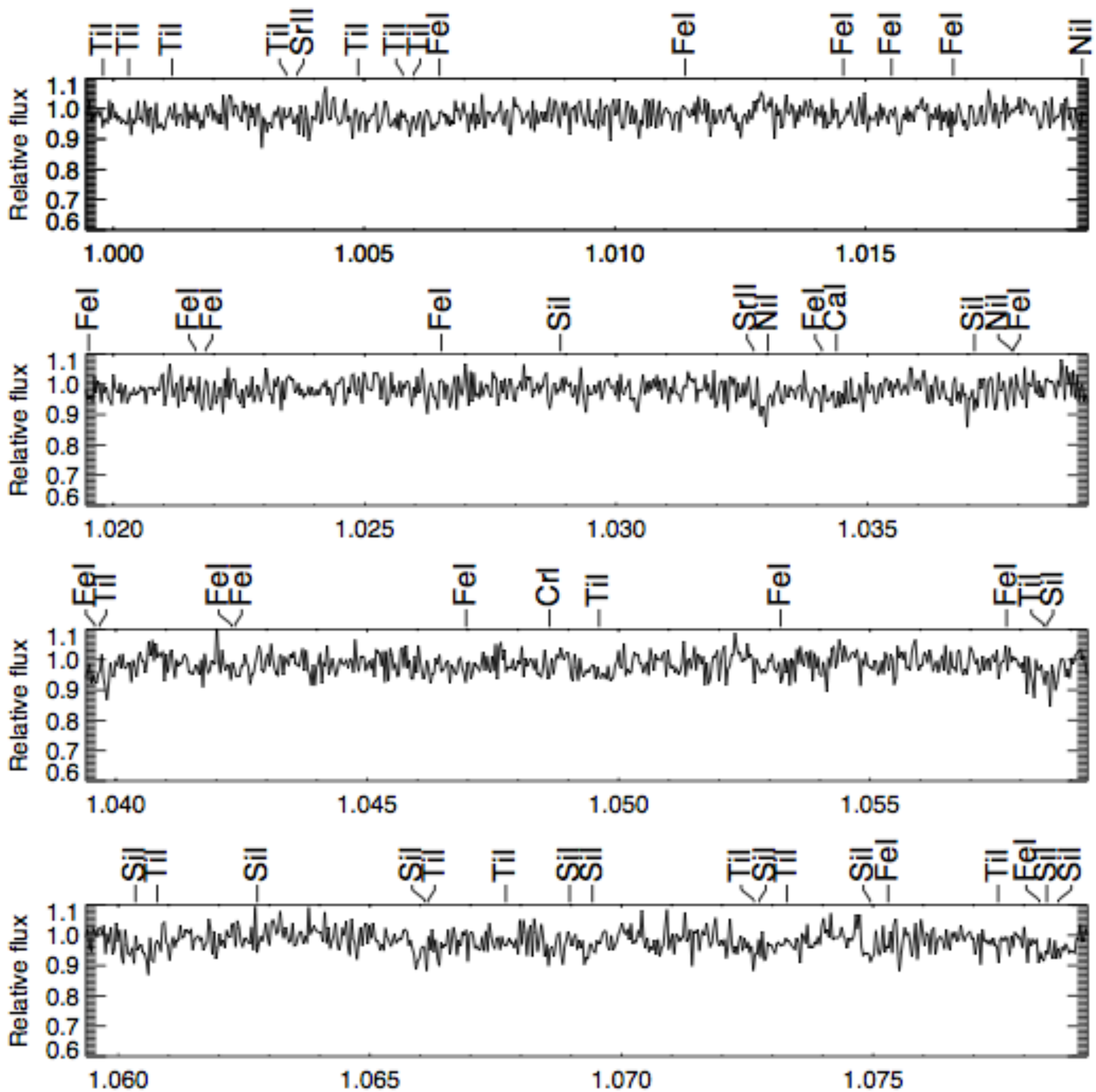

Y-band

- Fe I
- Cr I
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J-band: S/N 30, R - 3000

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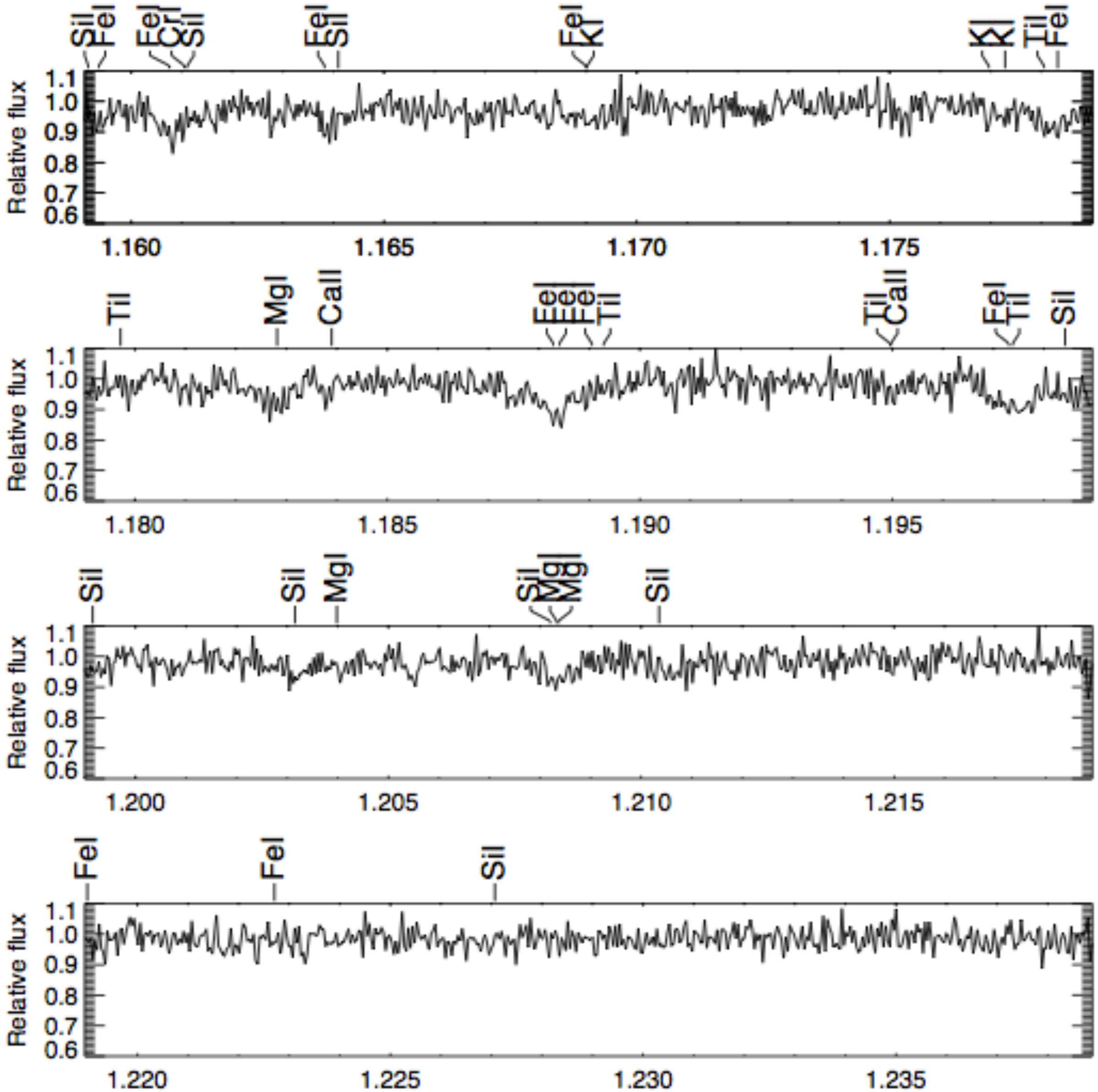

J-band
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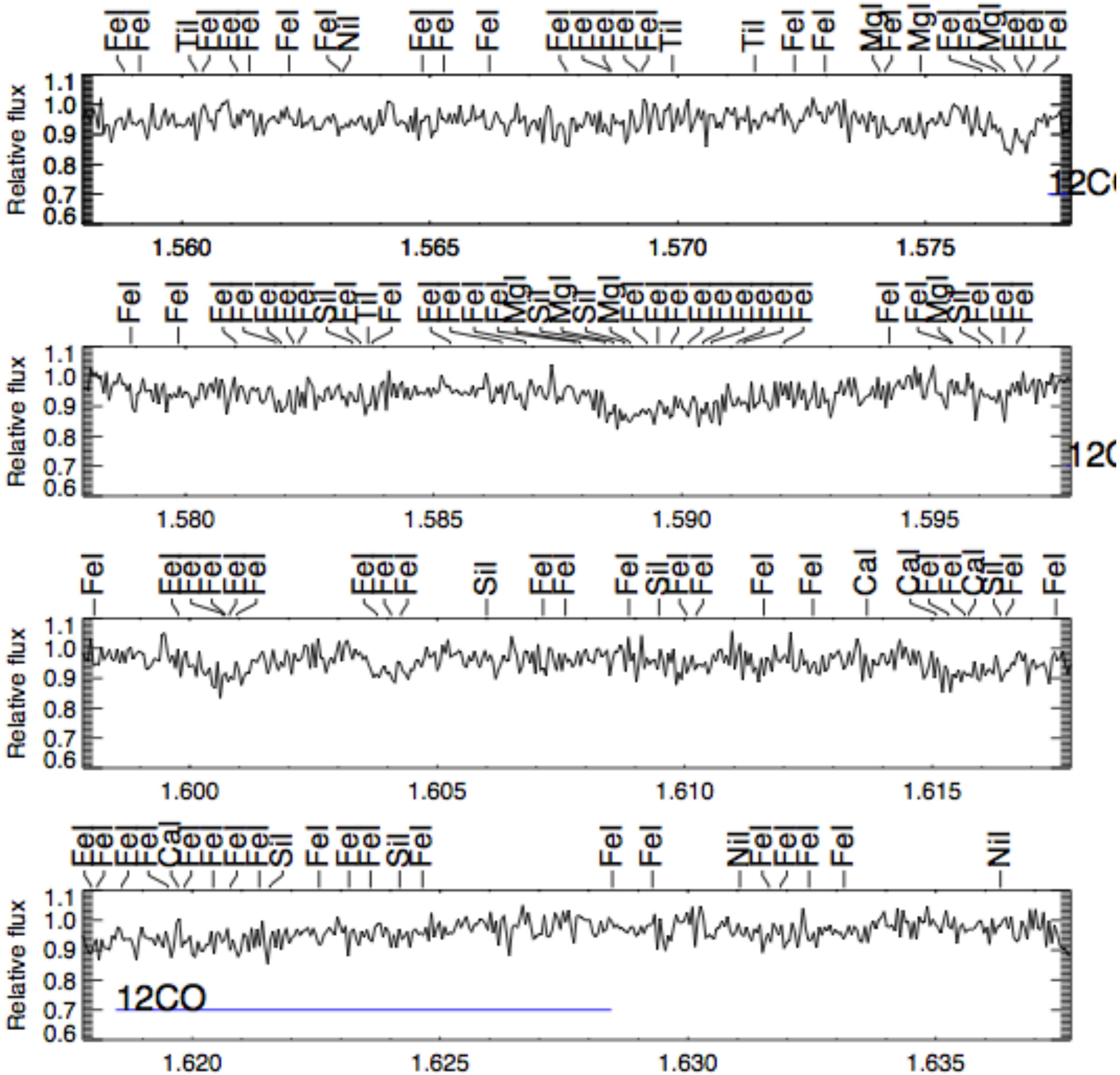
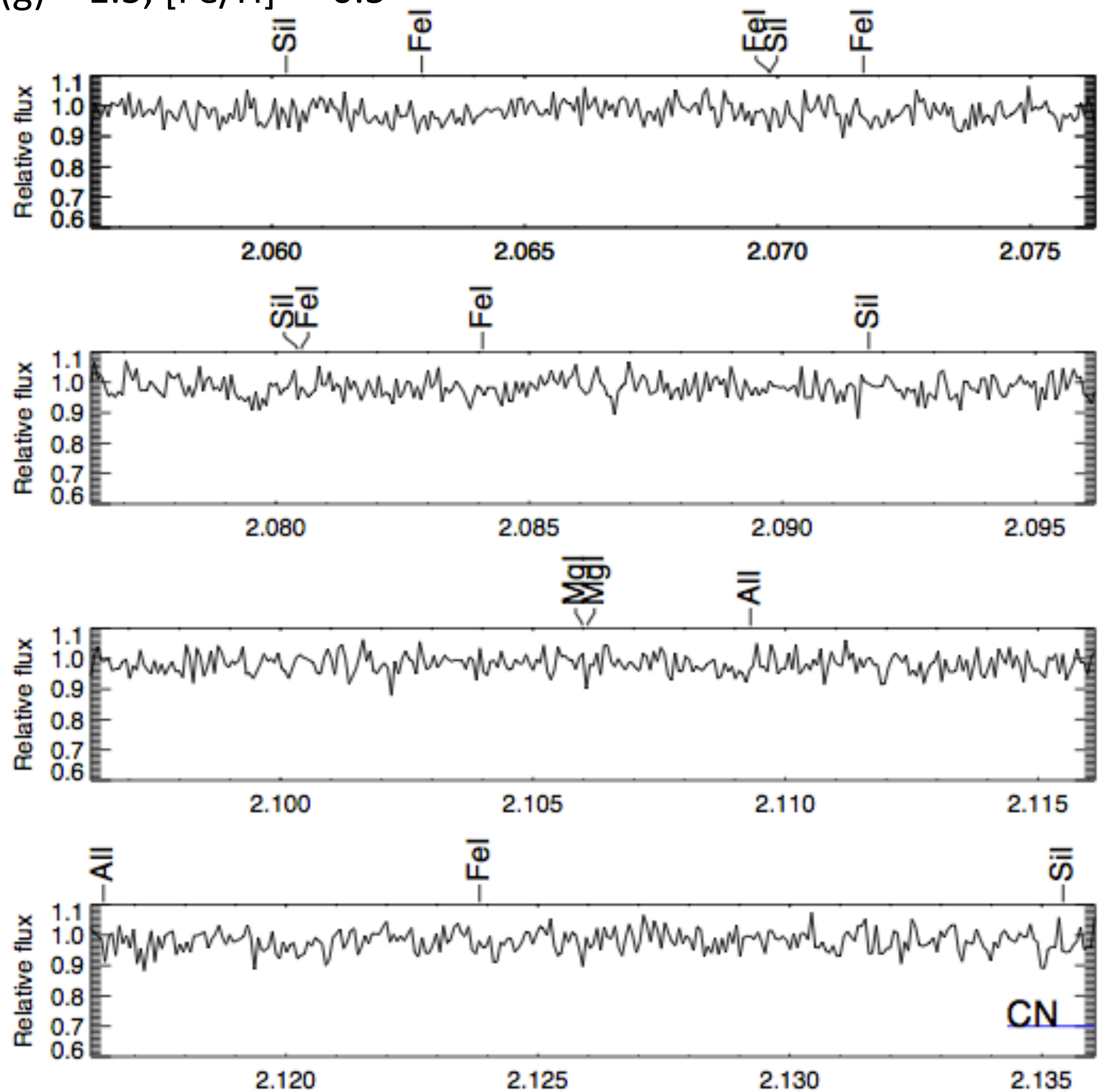


H-band

- K I
- Si I
- Mg I, Al
- Cr I
- Fe I
- Ti I
- Ni I
- CO
- CN
- OH
- V I (1.67)

K-band: S/N 30, R - 3000

T_{eff}= 4300, log(g) = 1.5, [Fe/H] = -0.5

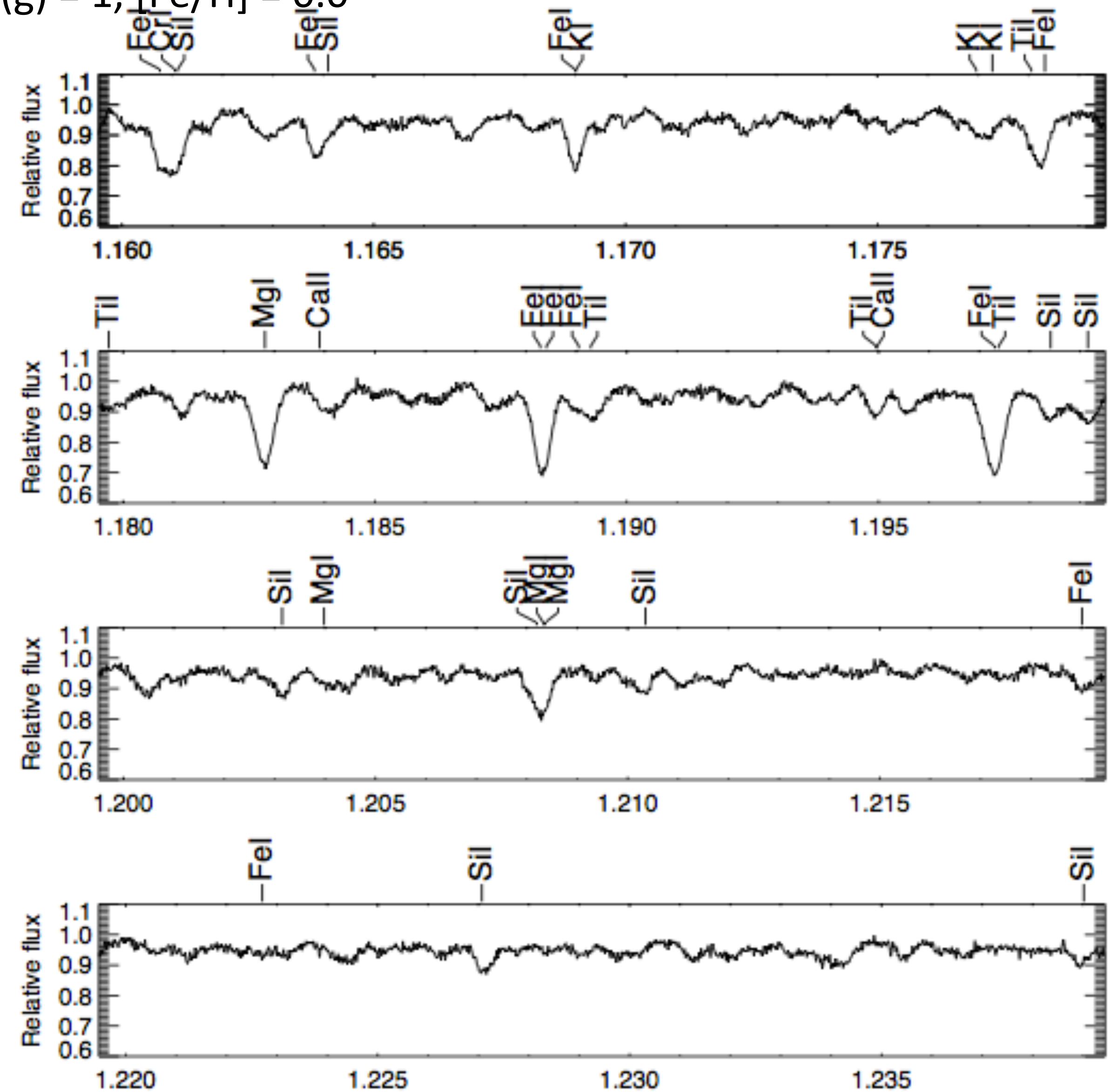


K-band

- Mg I
- Si I
- Fe I
- Sc I
- Al I
- Na I (2.2)
- C12/C13
- HF (2.3)

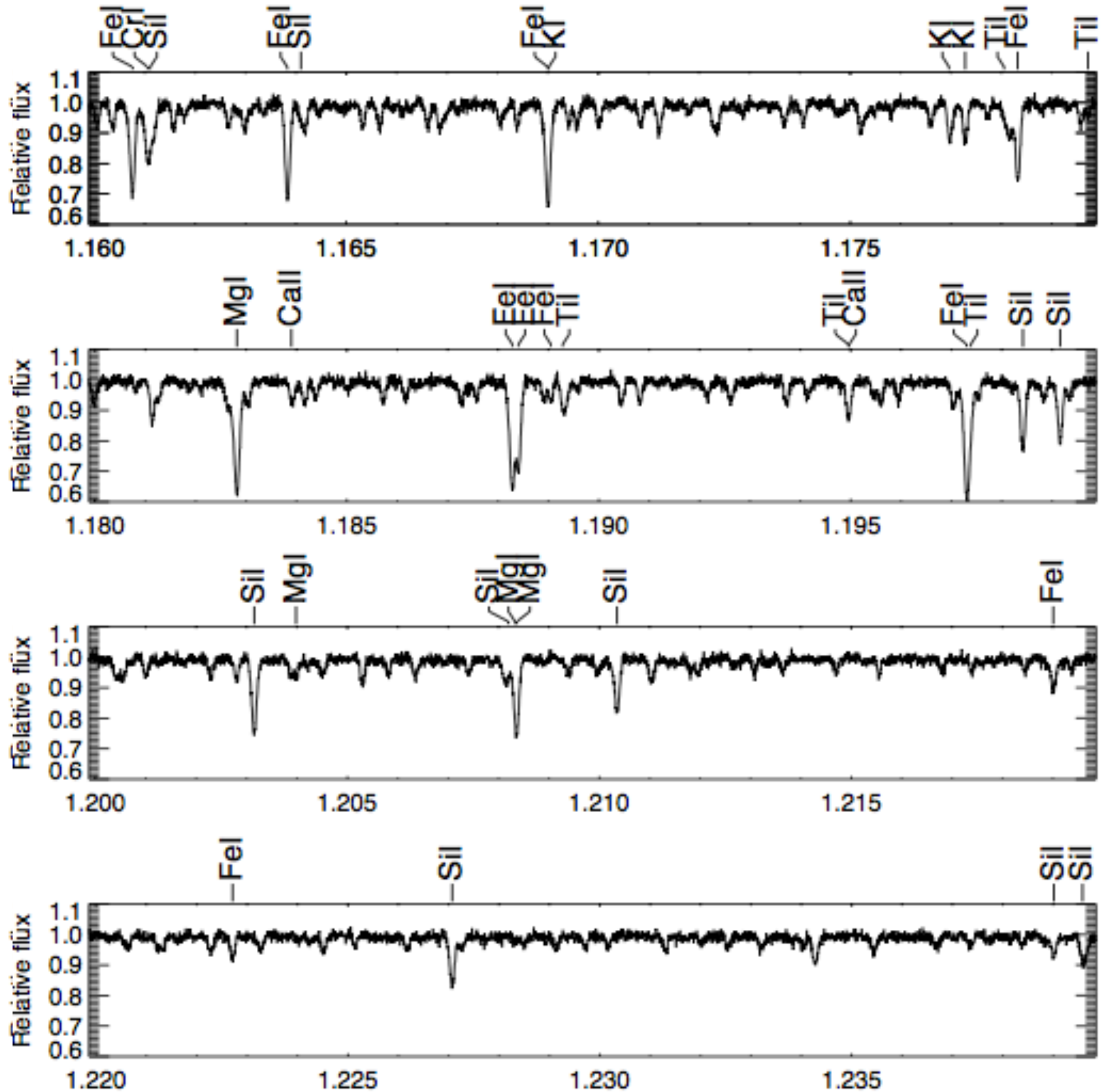
Red supergiant: S/N 100, R - 5000

T_{eff}= 4400, log(g) = 1, [Fe/H] = 0.0

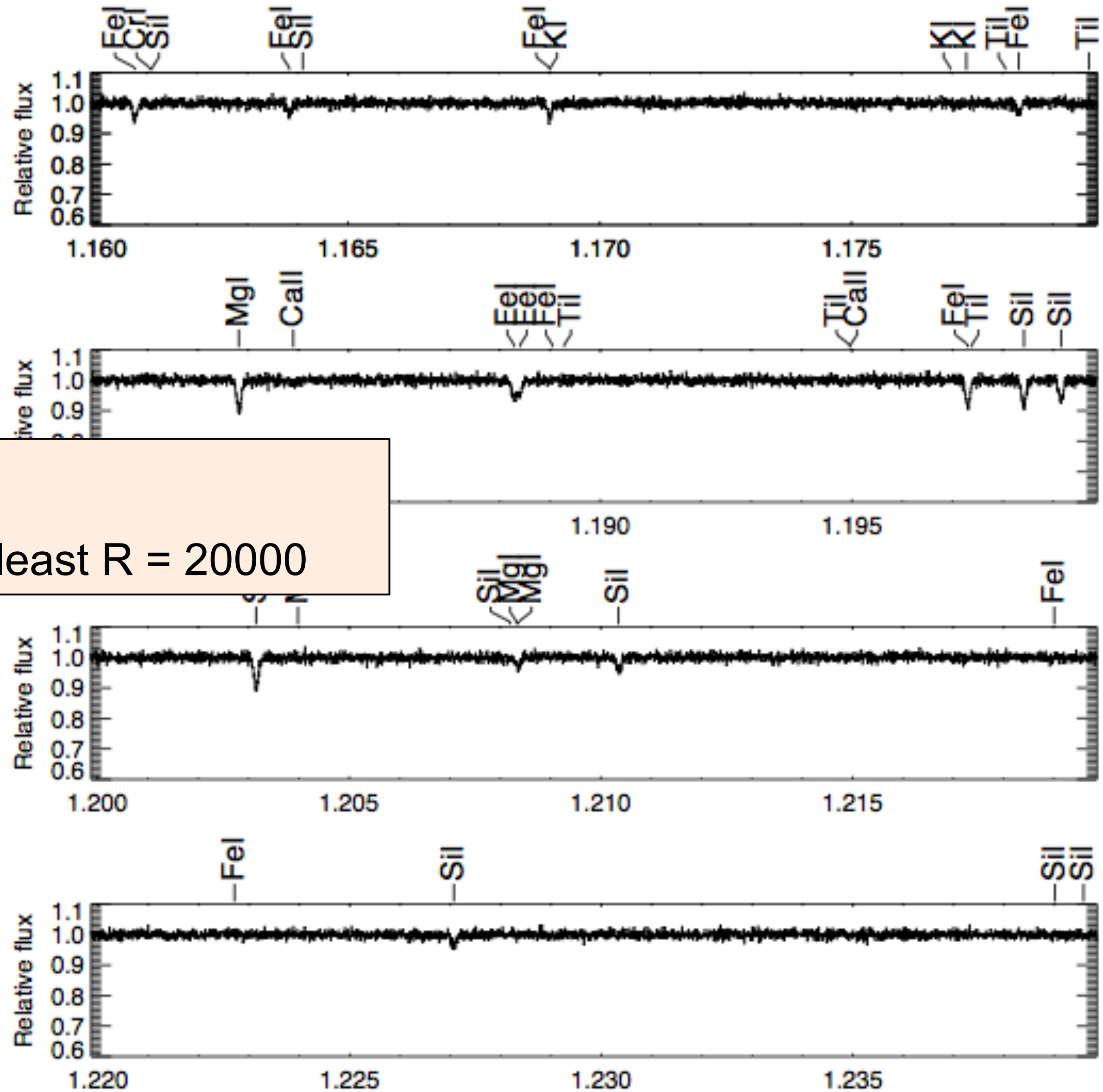


J-band
- K I
- Si I
- Mg I
- Cr I
- Fe I
- Ti I
- Ca II

Metal-rich giant [Fe/H] = 0, S/N 100, R - 20000



Metal-poor giant [Fe/H] = -3, S/N 100, R - 20000



Metal-poor stars:

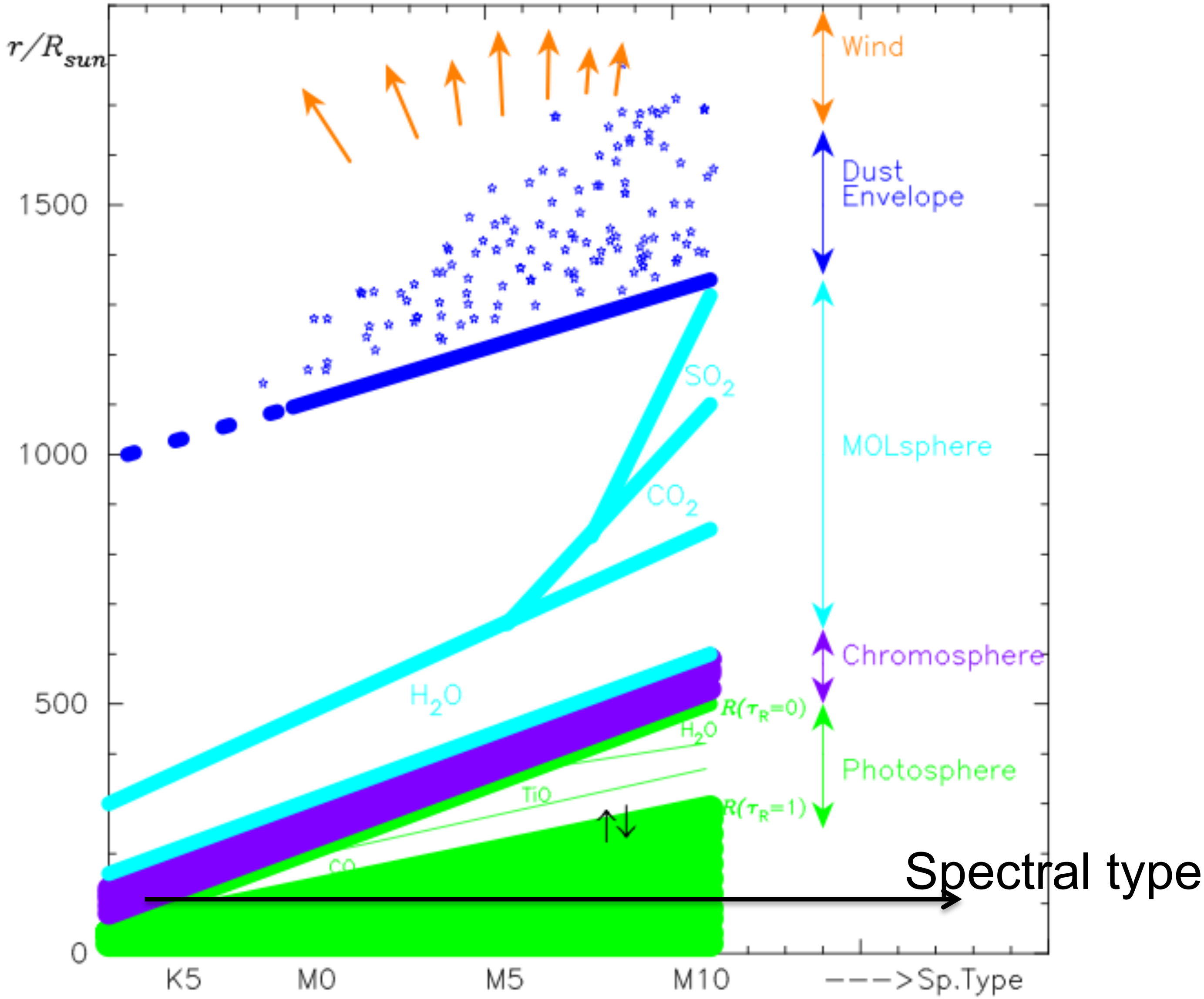
Spectroscopy at least R = 20000

Conclusions

- great progress with instrumentation and spectroscopic surveys in the Milky Way
  medium/high-resolution, e.g. Gaia-ESO – optical, APOGEE - IR
- State-of-the-art models: atmospheres and radiative transport
  - attained the necessary level of complexity
  - need improvements to describe features forming in the chromospheres, outflows & dynamics
- IR is tricky
  - R > 20000 is needed for metal-poor stars
  - Red Supergiants – J-band O'K for R down to 3000

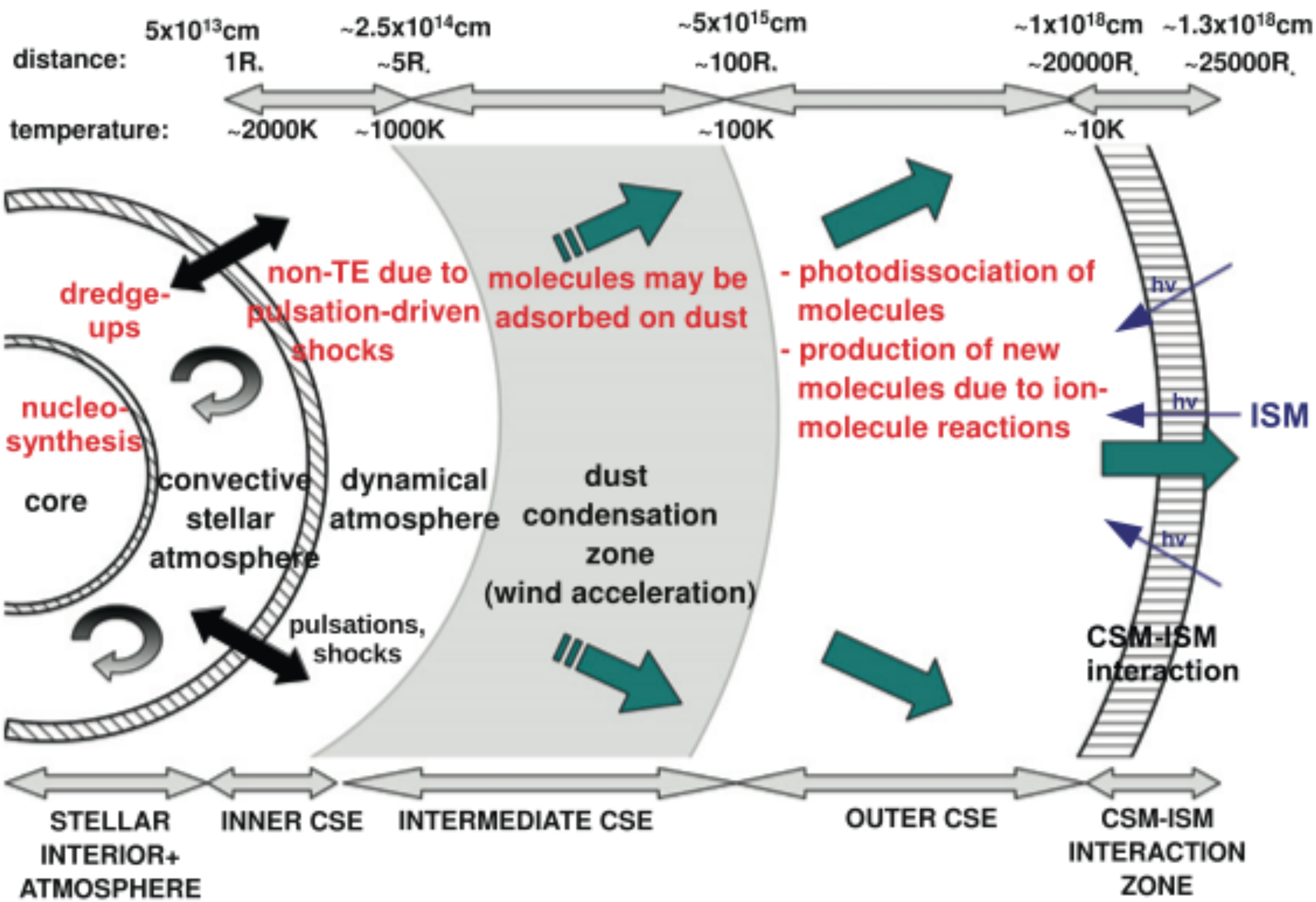
For the future generation instruments, well-defined programs based on simulations and careful target selection are needed.

One of possible scenarios: RGB surface



Tsuji (2002)

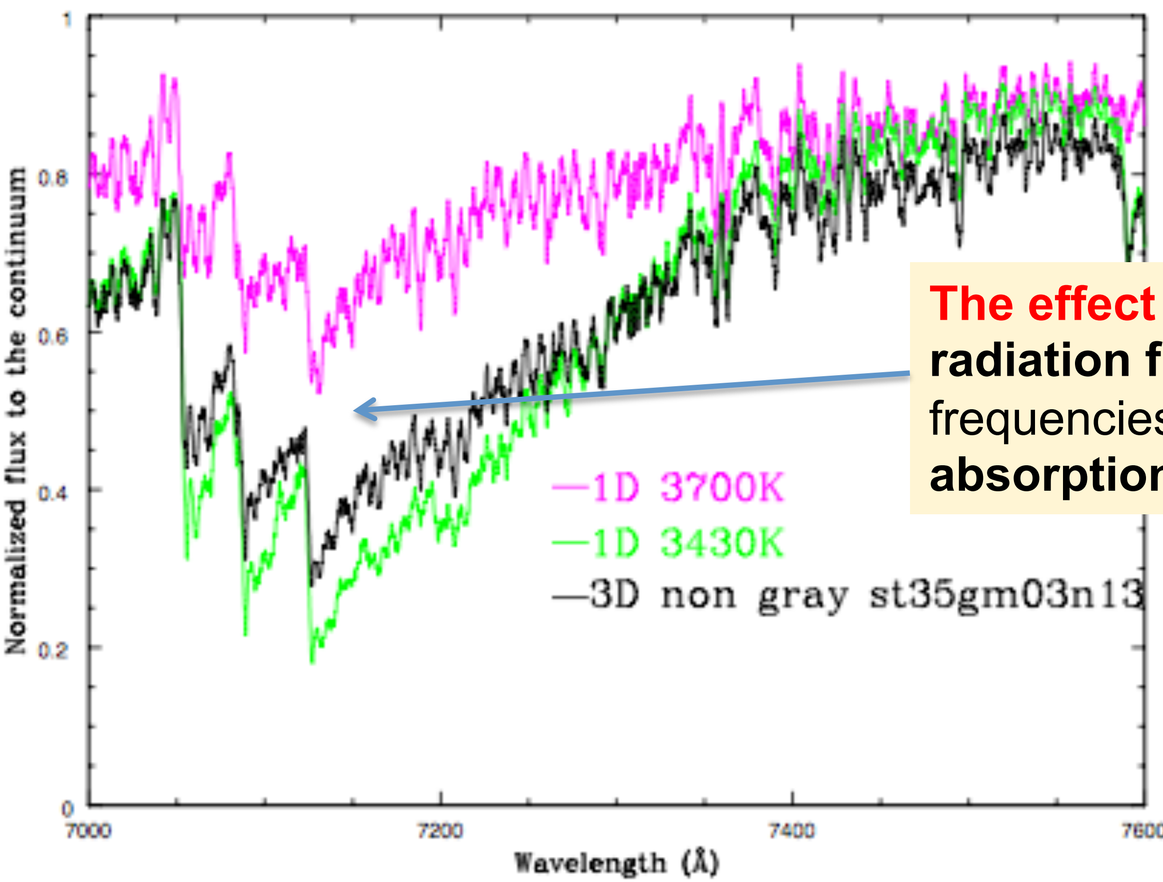
AGB stars: atmospheres



Decin (2013)

Modeling complexities

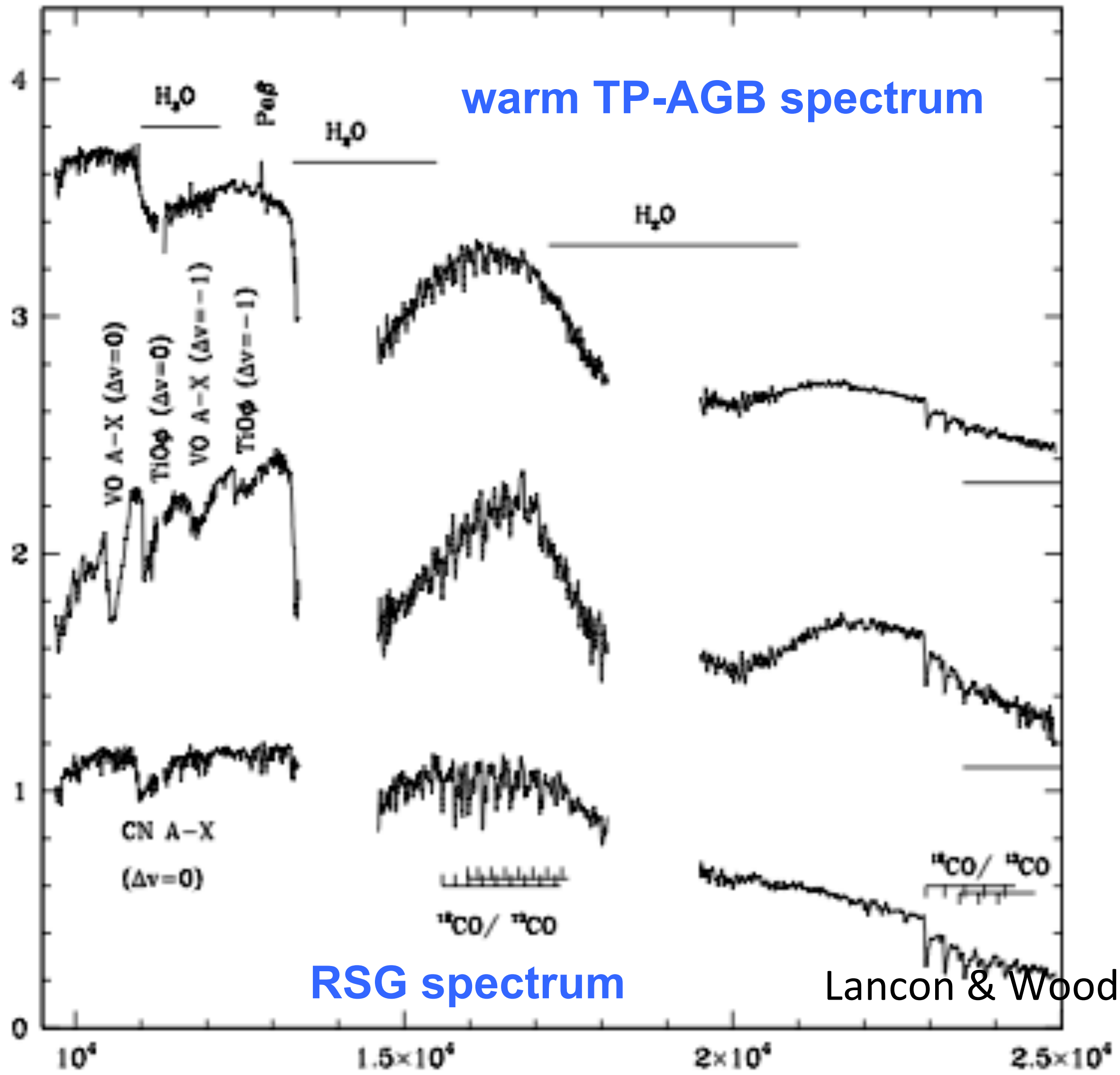
1. Molecular opacities
2. Asymmetric shapes with ‘hot spots’
3. MOLsphere (H_2O, SiO)
4. Deviations from hydrostatic equilibrium and giant convective cells



The effect of convection on the radiation field is huge in the frequencies of **strong molecular absorption** (e.g TiO)

Chiavassa et al. (2011)

Spectra



Lancon & Wood (2000)