Radiative transfer

$$I_\lambda(0) = \int_0^{\tau_\lambda} S_\lambda(t_\lambda) e^{-t_\lambda} dt_\lambda$$

Outgoing monochromatic intensity

Stellar atmosphere, boundary condition is set deep (inside a star) —> $I_\lambda(\infty) = B_\lambda(\infty)$

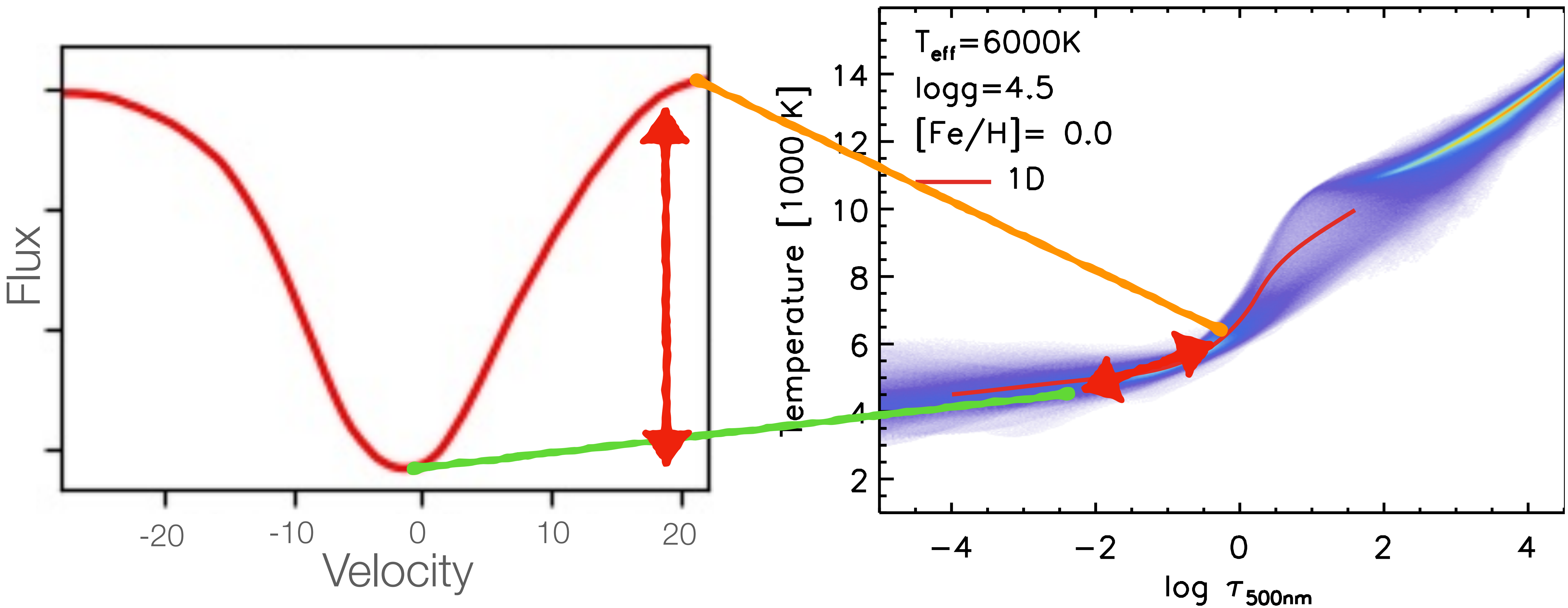
Local Thermodynamic Equilibrium (LTE) -> all microprocesses (radiative, collisional, chemical) are in detailed balance —> $S_\lambda = B_\lambda(T)$

Optical path $d\tau_\lambda = k_\lambda(T, \rho) \cdot \rho(x) \cdot dx$

Critical dependancies

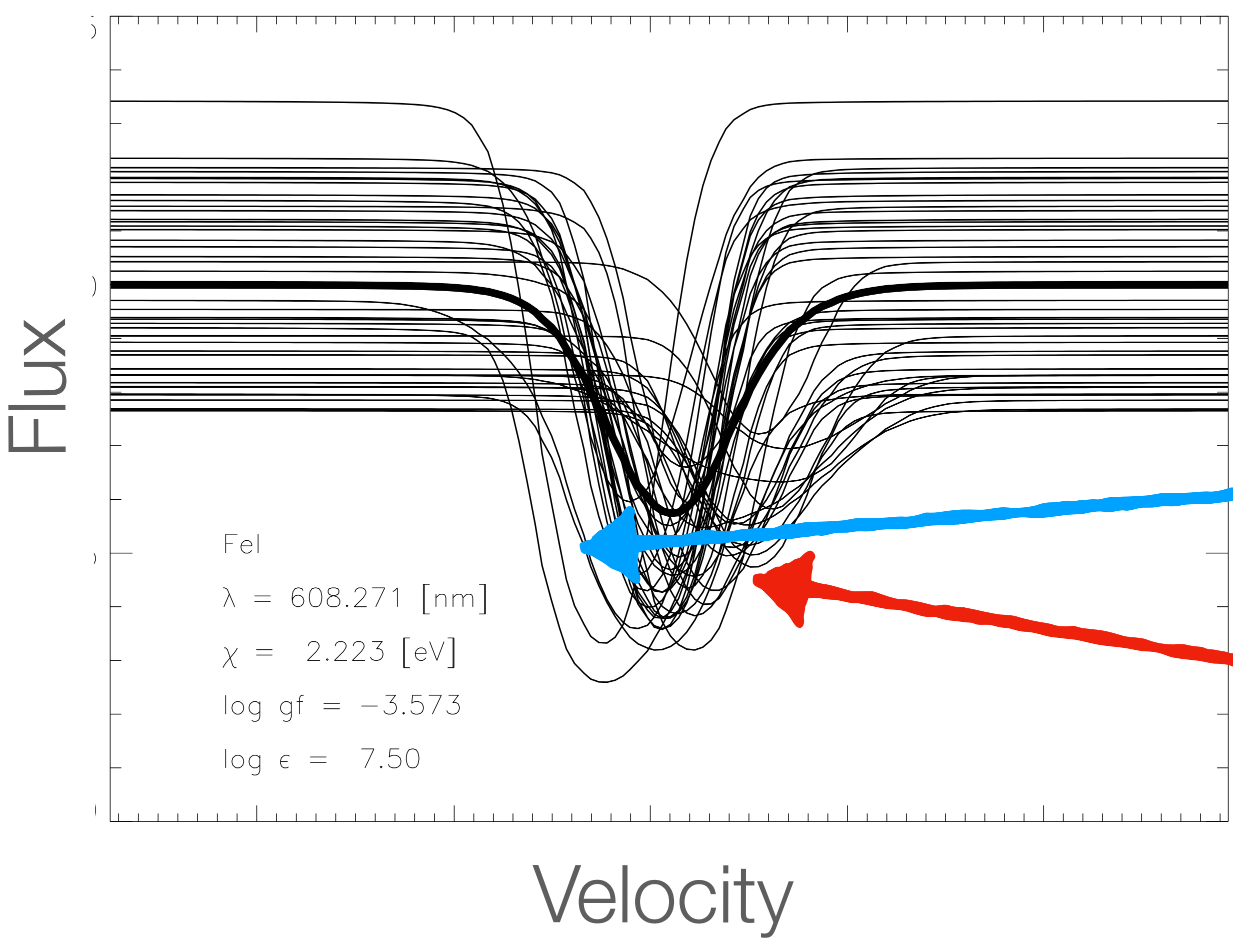
- Geometrical, angular, frequency dependence of opacity k_ν and source function S_ν
- Dependence of the source function S_ν on the radiation field
- Number of absorbers (how many absorbers there is on a given energy level) depend on local physical conditions and radiation field
- Velocity distribution of the absorbers affects the frequency dependence of κ_ν and S_ν

Critical dependancies

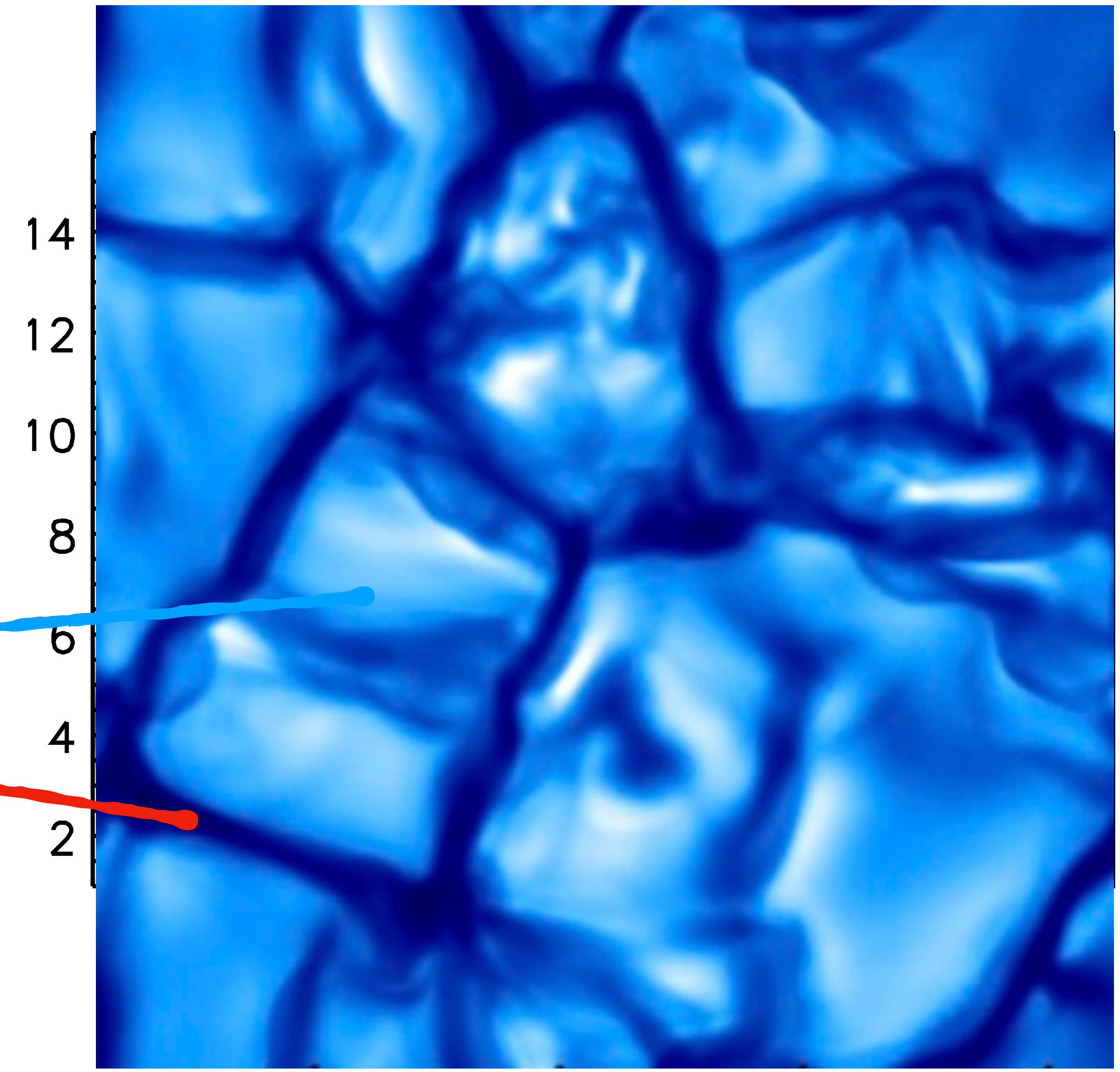


Collet et al., A&A 2007, 469

Critical dependancies



Asplund et al., A&A 2000

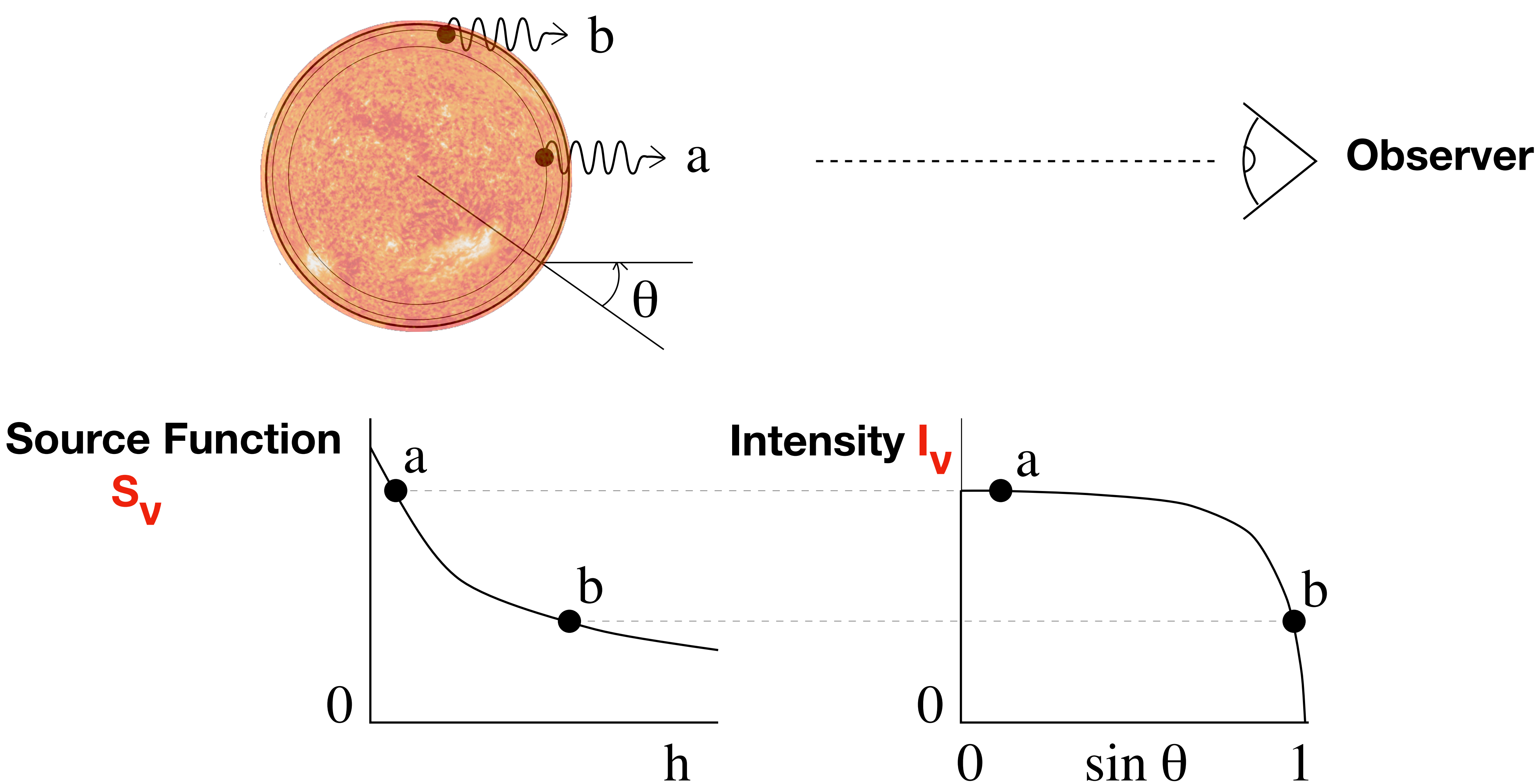


Collet et al., A&A 2007, 469

Critical dependancies

- Geometrical, angular, frequency dependence of opacity k_{ν} and source function S_{ν}
- Dependence of the source function S_{ν} on the radiation field
- Number of absorbers (how many absorbers there is on a given energy level) depend on local physical conditions and radiation field
- Velocity distribution of the absorbers affects the frequency dependence of κ_{ν} and S_{ν}

Critical dependancies



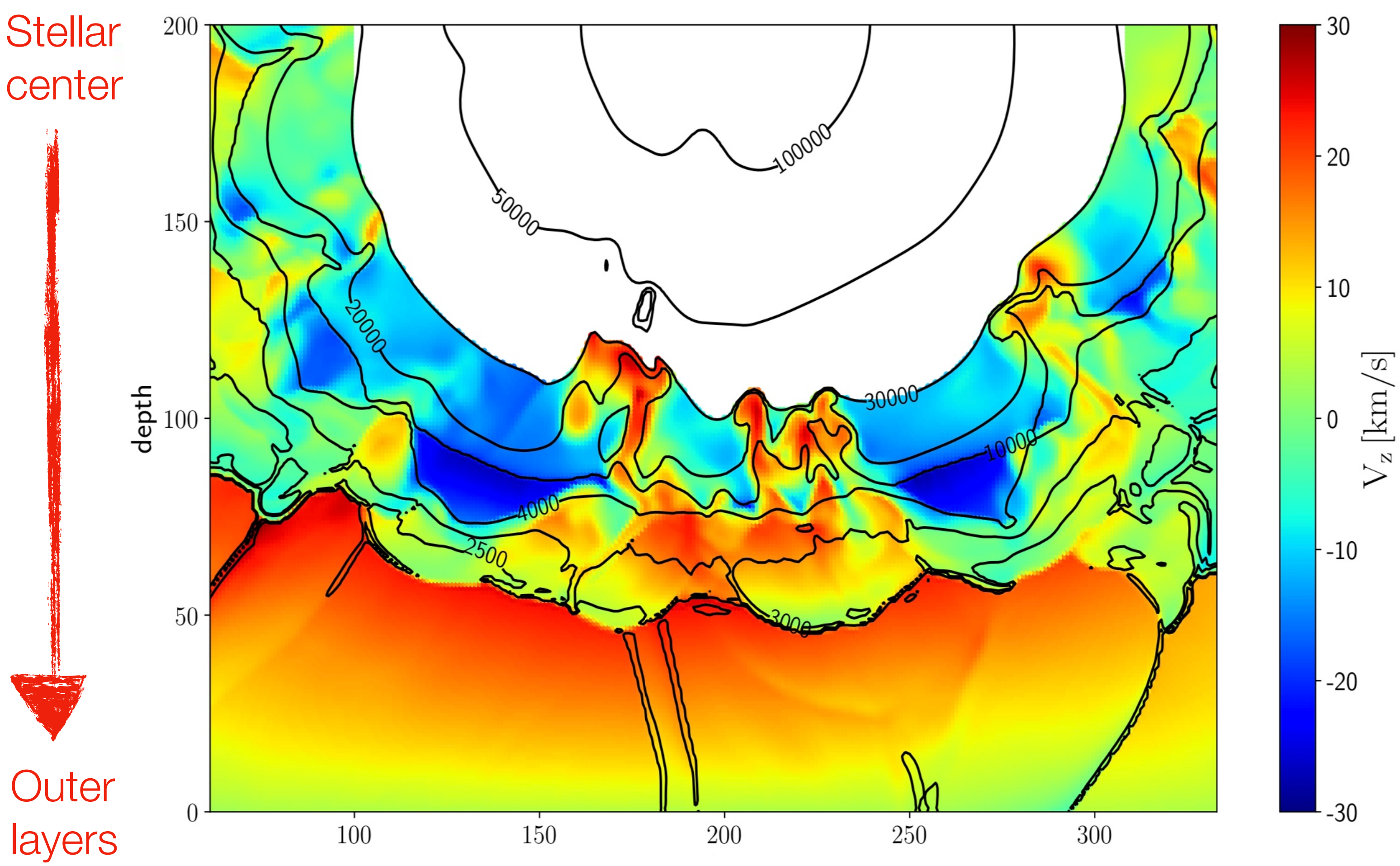
Rutten, online book, 2003

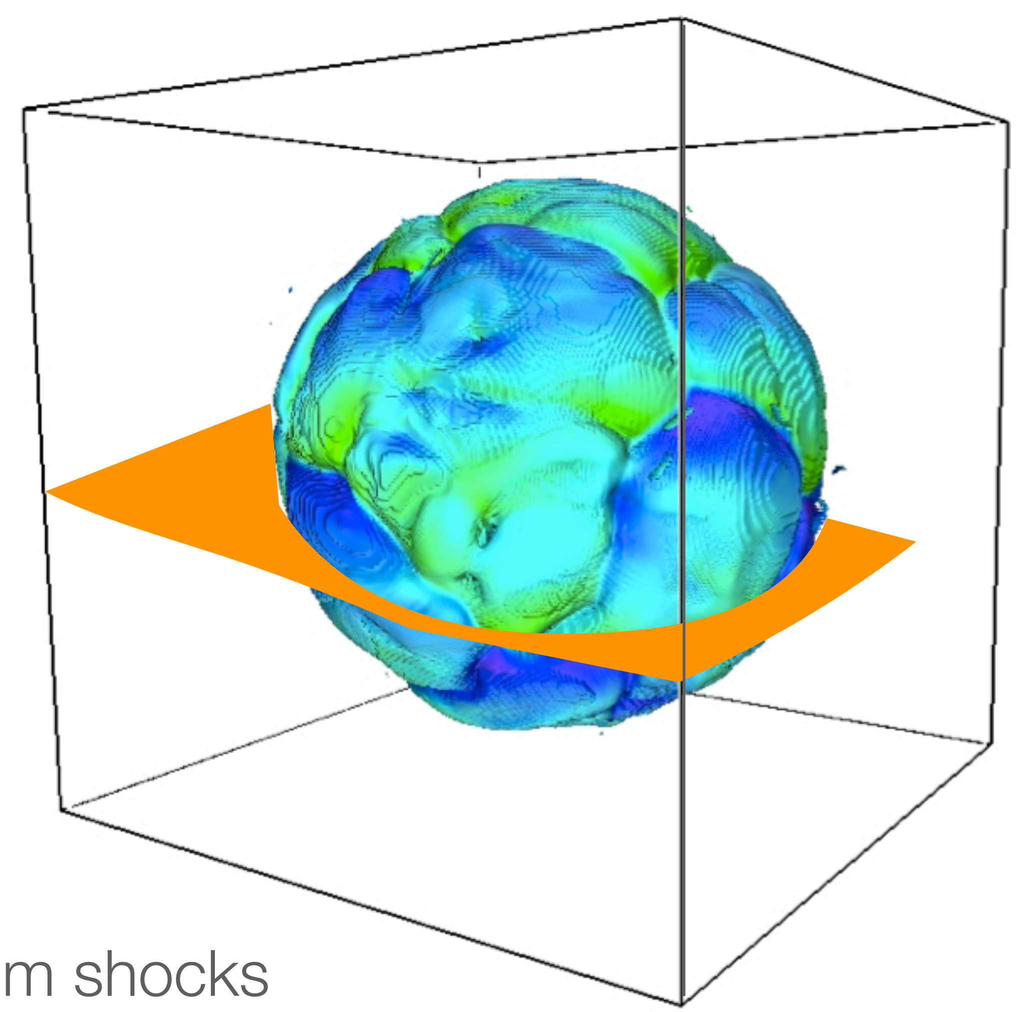
Critical dependancies

- Geometrical, angular, frequency dependence of opacity k_V and source function S_V
- Dependence of the source function S_V on the radiation field
- Number of absorbers (how many absorbers there is on a given energy level) depend on local physical conditions and radiation field
- Velocity distribution of the absorbers affects the frequency dependence of κ_V and S_V

Critical dependancies

Temperature structure
Velocity structure

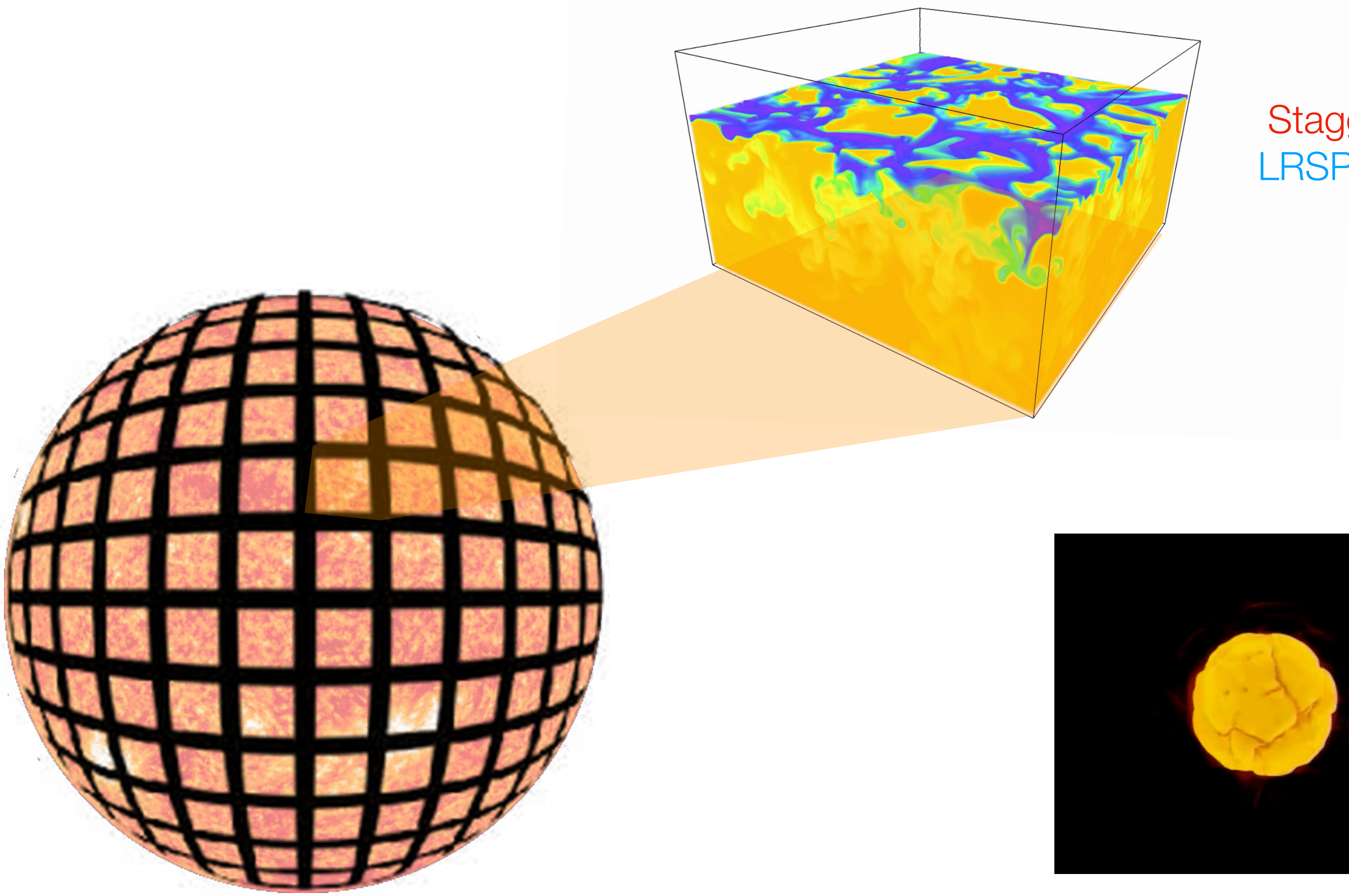




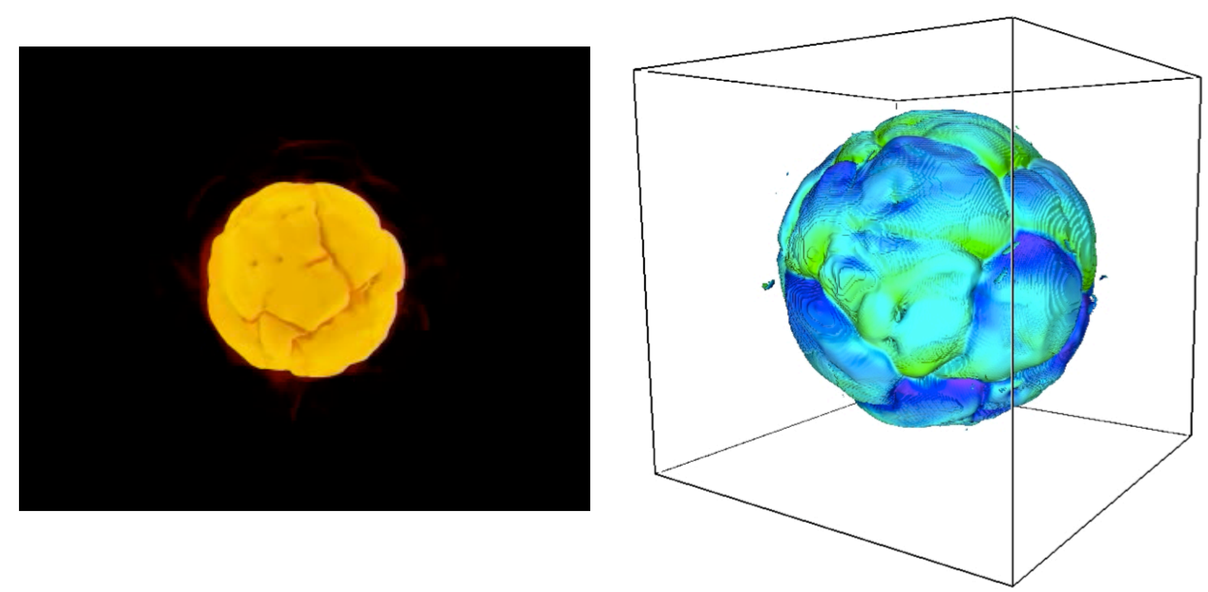
Temperature (and density) structure permeated by random shocks
Velocity field is not-homogeneous. Shocks and variation in the opacity run dominates. Convective flows up to 5 Mach above stellar radius

RT in 3D RHD simulations of stellar atmosphere

3D radiative hydrodynamical simulations of stellar convection. They solve the equations for the compressible hydrodynamics (conservation of mass, energy and momentum) coupled with non-local transport of radiation with detailed opacities



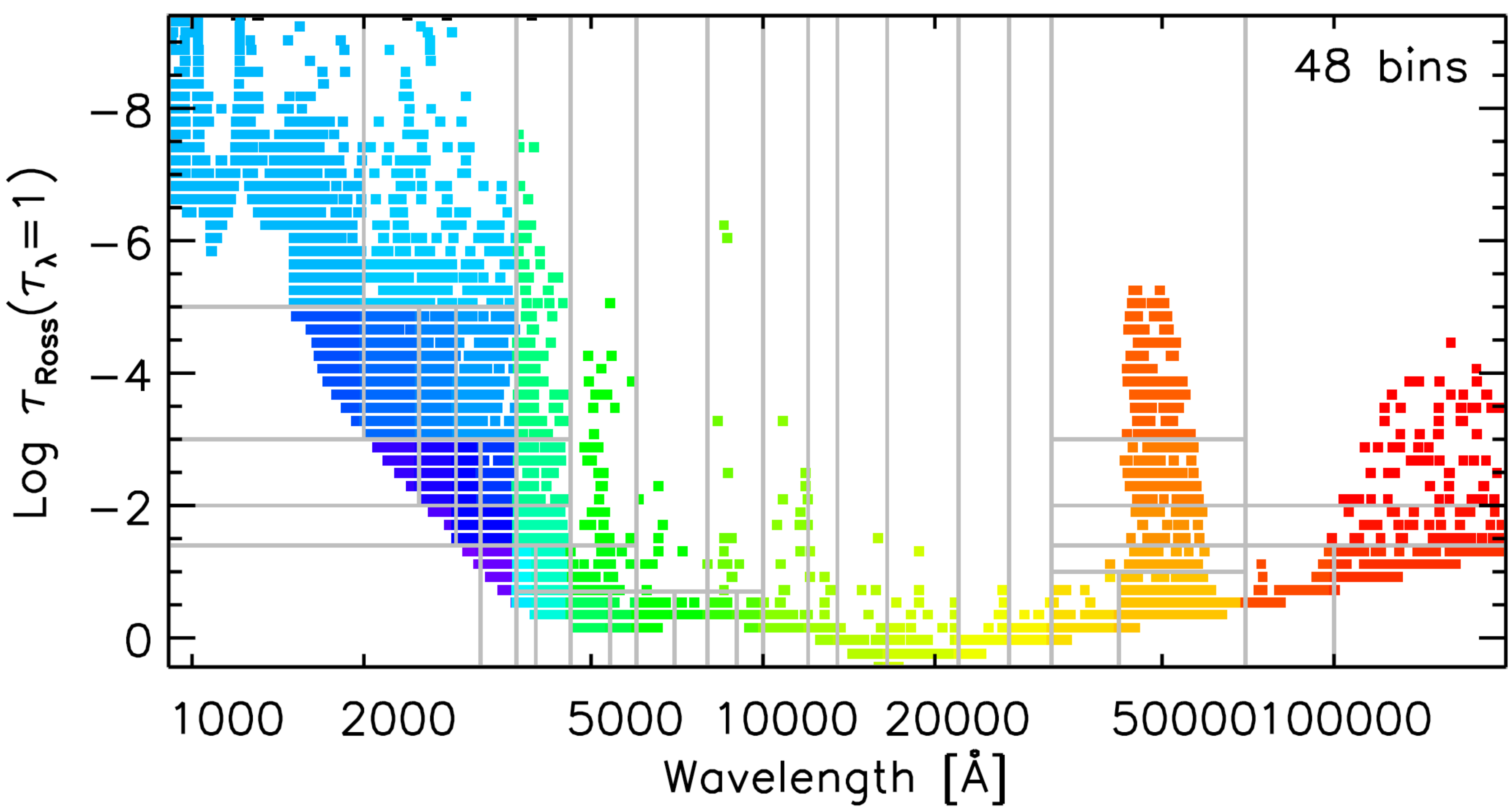
Stagger-Code (Nordlund et al. 2009, LRSP, 6; Collet et al. 2011, A&A, 528)



CO5BOLD (Freytag et al. 2012, JCP, 919)

RT in 3D RHD simulations of stellar atmosphere

- Sort monochromatic wavelengths into groups (opacity bins)
- Solve radiative transfer for average opacities and integrated source functions in bins



Collet et al., A&A 2018, 475

RT in 3D RHD simulations of stellar atmosphere

Typical values for a simulation with Co5BOLD (Hybrid OpenMP and MPI) - short characteristic RT, 5 bins

Computation time: 1 month depending on the complexity increasing linearly with the number of opacity bins

Virtual memory: 2Gb (255^3 grid points) and 4Gb for (401^3)

Hard disk space: 100 Gb (255^3) and 400 Gb (401^3)

Typical values for a simulation with Stagger-code (MPI) - long characteristic RT, 12 to 48 bins

Computation time: few days to few weeks depending on the simulated star

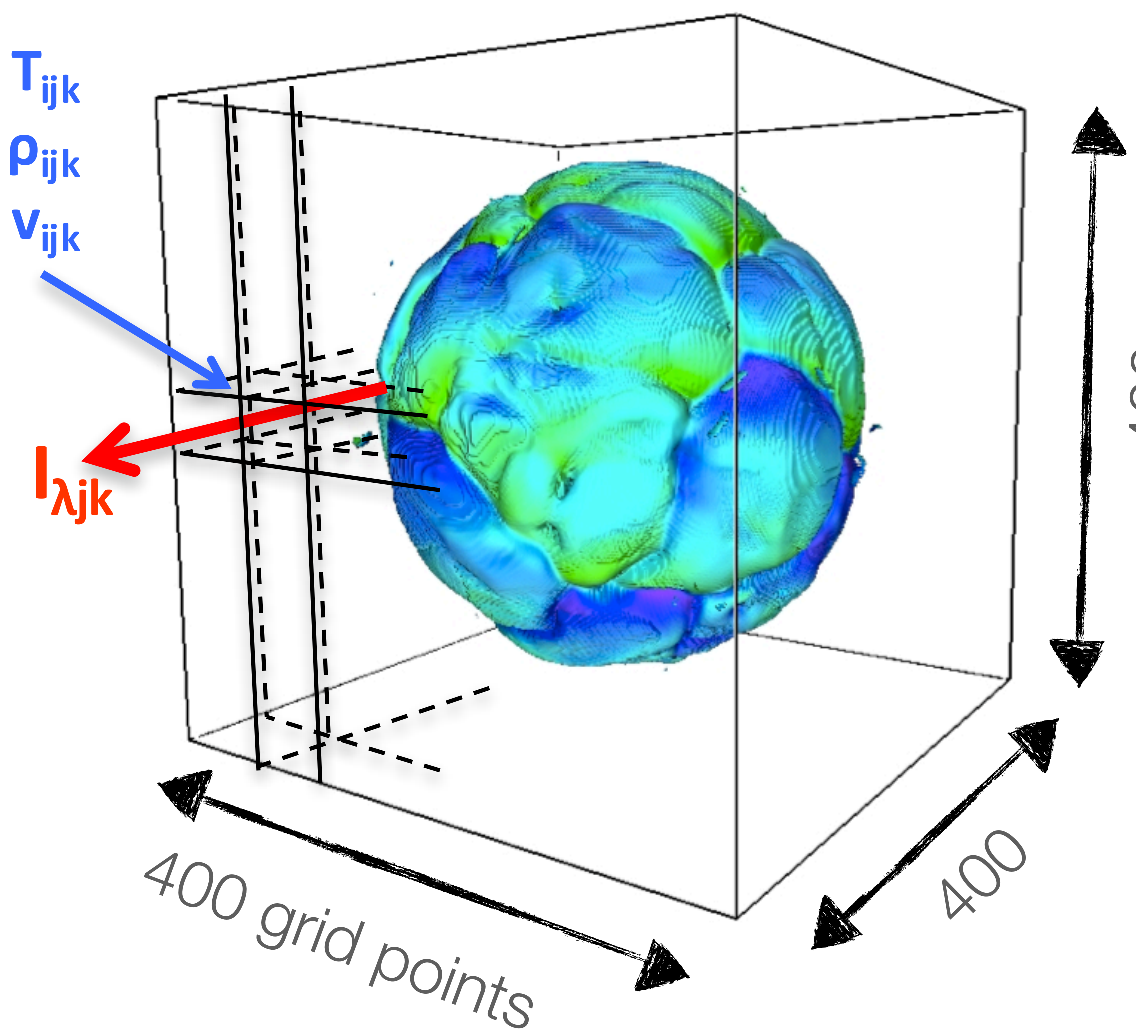
Virtual memory: 1Gb, but increasing with numerical box size

Hard disk space: 50 Gb

Post-processing LTE RT

Detailed (billions of atomic and spectral lines, from MARCS and VALD) and fast (computational time slightly larger than 1D computation) post processing of 3D simulations. No micro- or macro- turbulence

Gauss-Laguerre quadrature integration of order n = 10, linear and double linear interpolations in pre-computed opacity tables



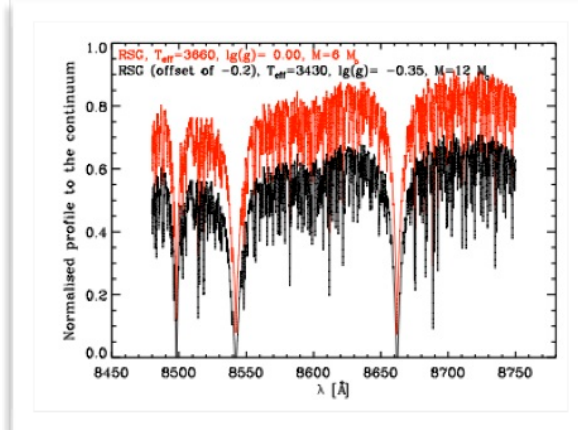
3D → 400 x 400 x 10

about 10^6 times more than the 1D calculation

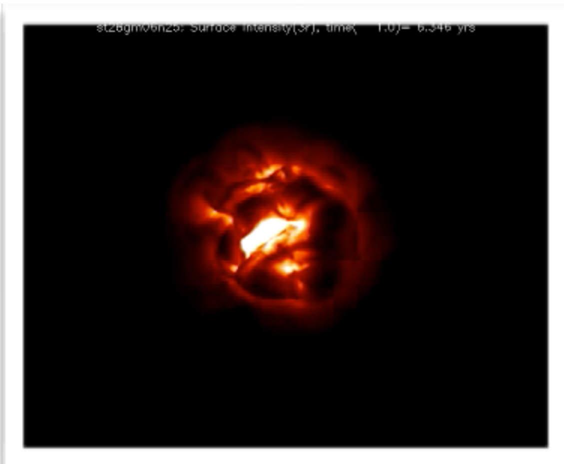
Extraction of interferometric, spectroscopic, photometric, astrometric observables

Chiavassa, Plez, Josselin, Freytag 2009, A&A, 506, 1351

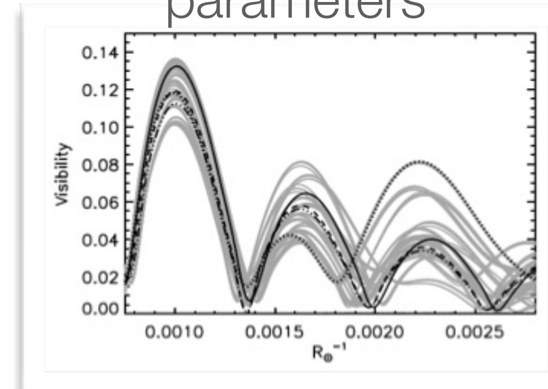
Abundances, radial velocities: cinematic of the Galactic stellar populations



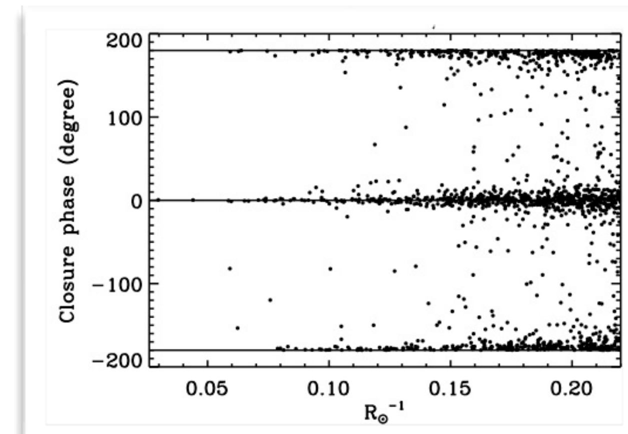
Stellar dynamics, mass loss



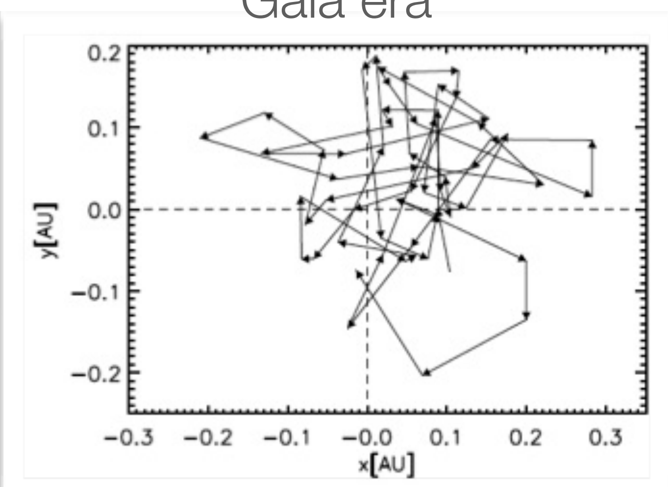
Visibilities: stellar fundamental parameters

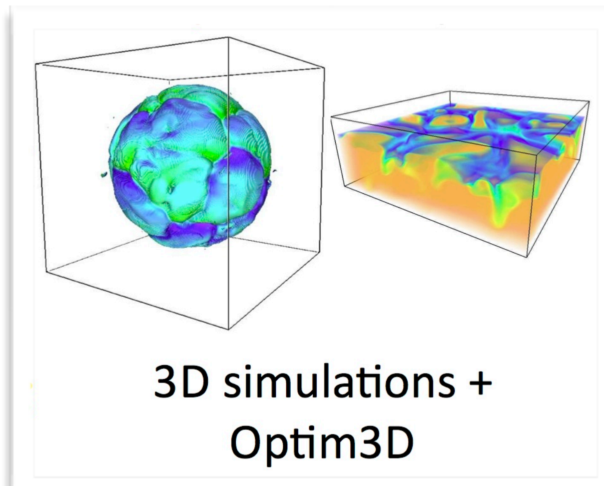


Closure phases: stellar granulation

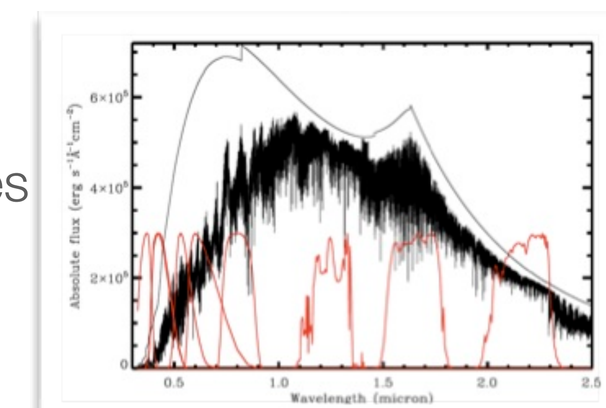


Photocenter displacement in Gaia era

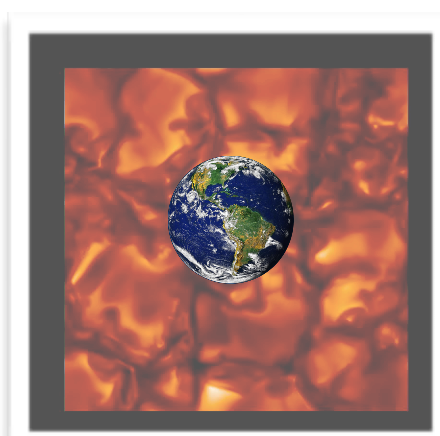


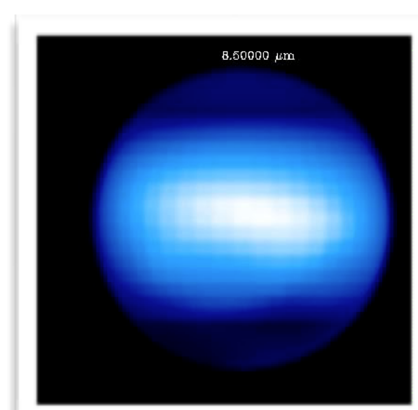


SED: stellar fundamental parameters, etc.

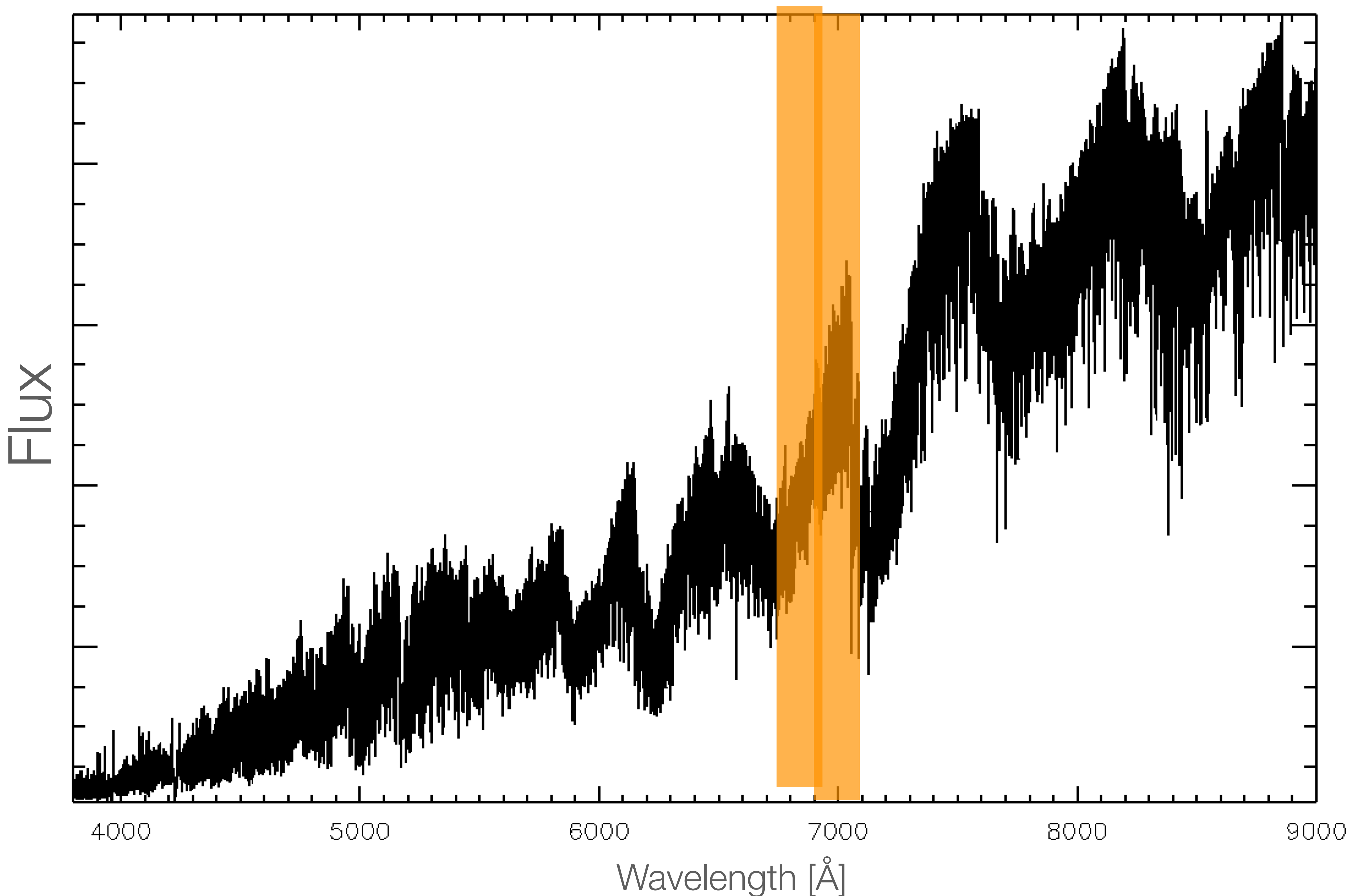


Stellar and planetary atmospheres:
detection & characterisation of planetary atmospheres

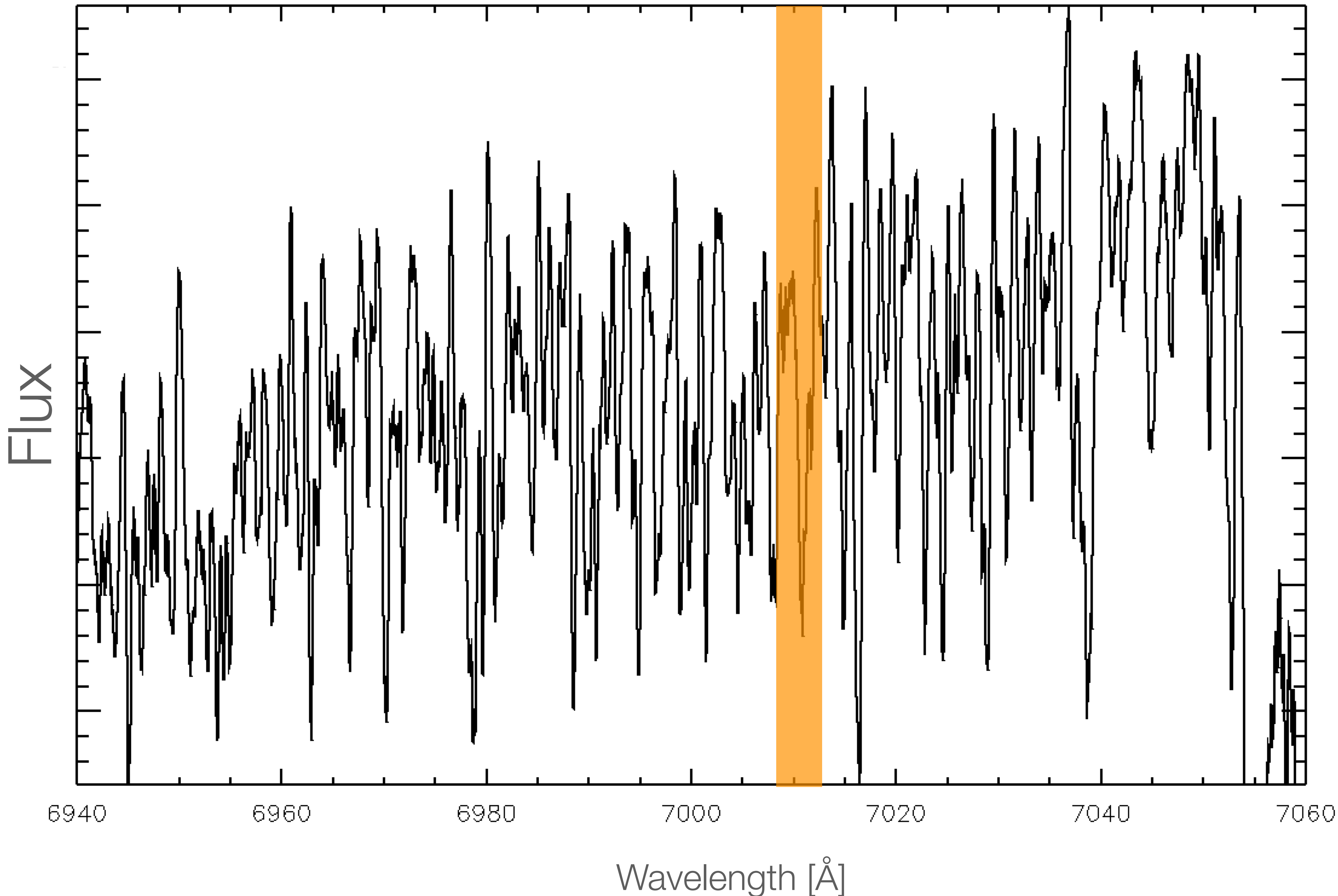




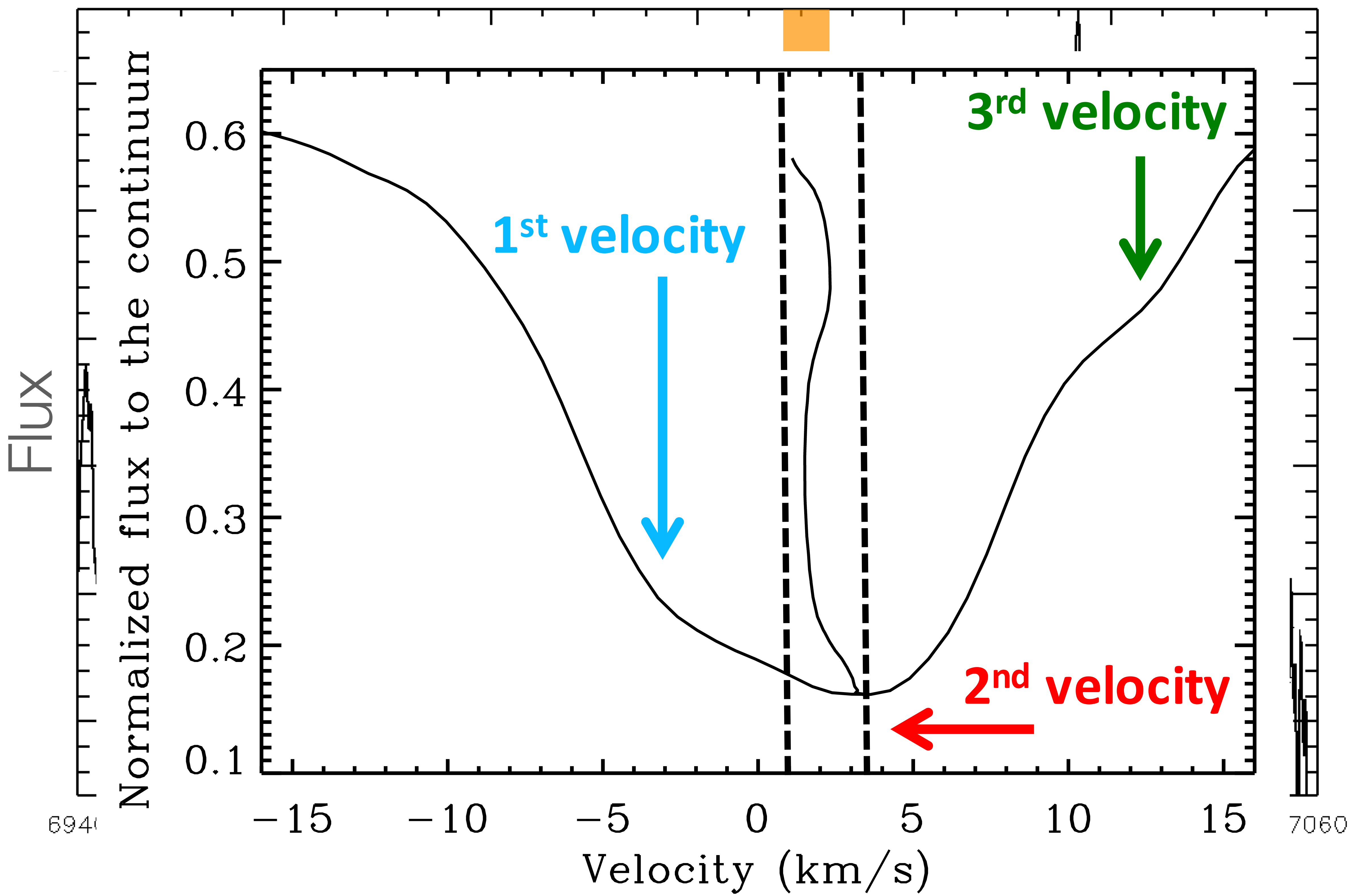
Post-processing LTE RT - examples



Post-processing LTE RT - examples

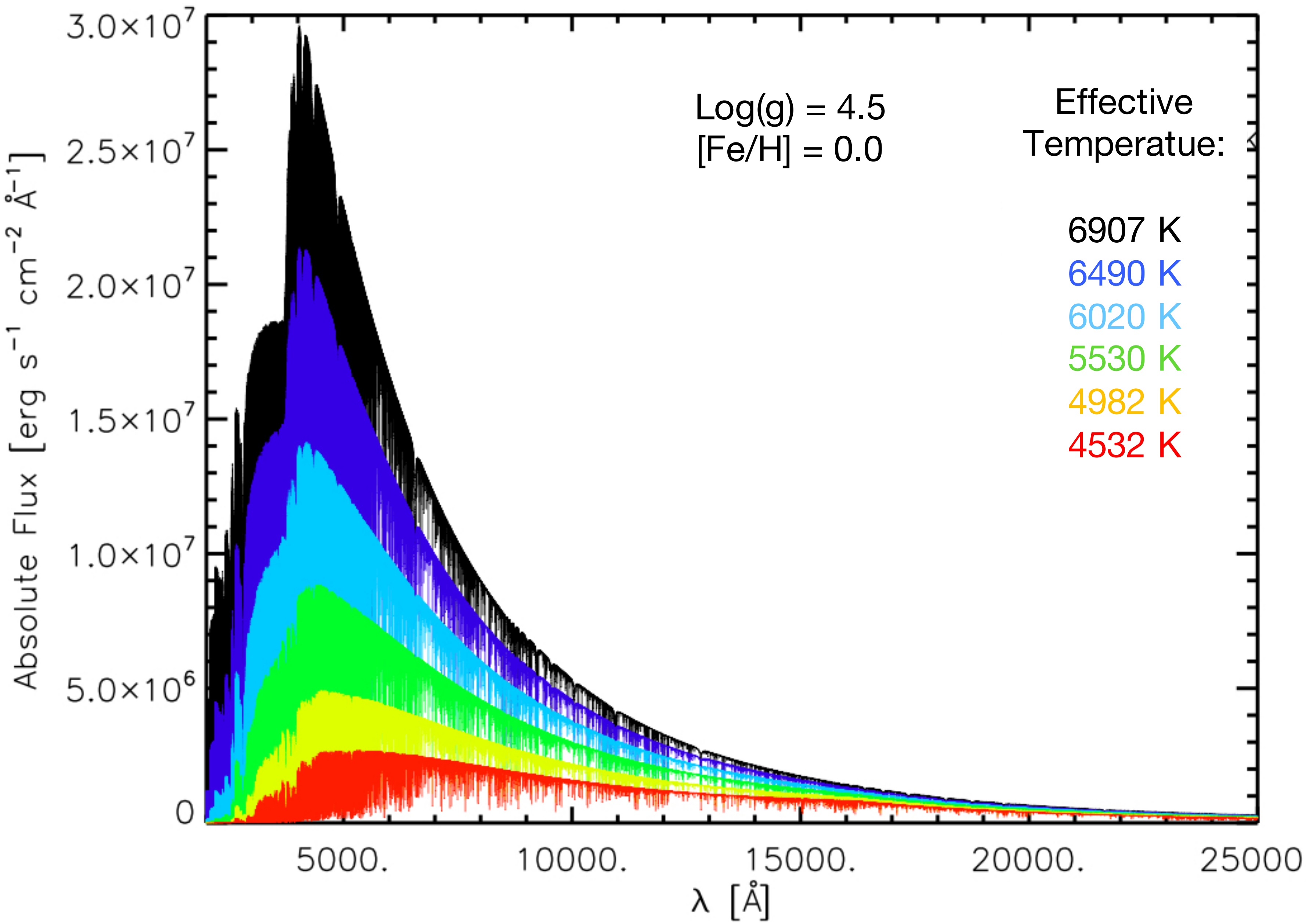


Post-processing LTE RT - examples



Post-processing LTE RT - examples

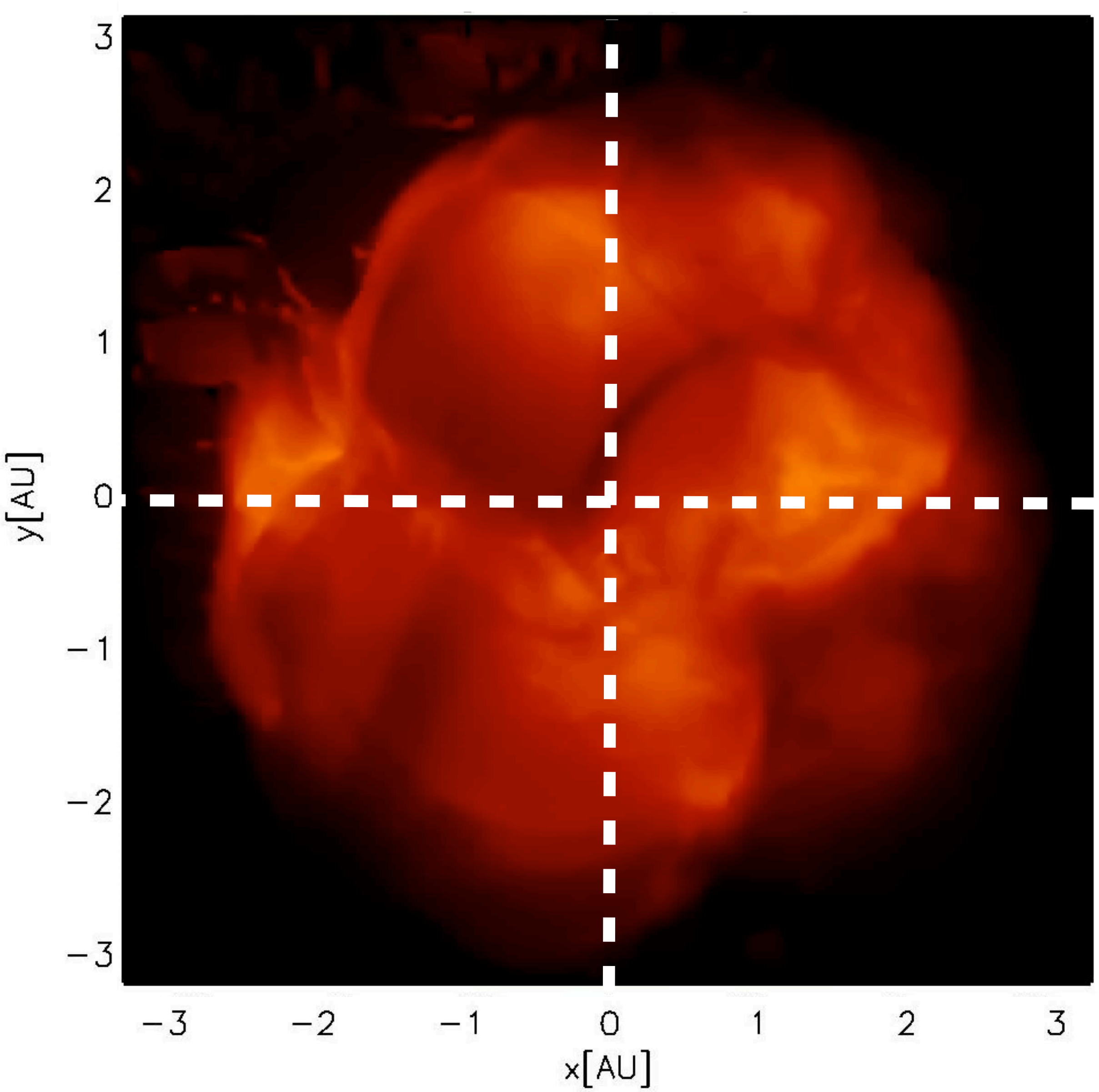
Full 3D grid spectra between **2000 and 200000 Å** at constant resolution (λ/Δλ) of 20 000 and 8400 and 8900 Å (Gaia RVS) at constant resolution of 300 000



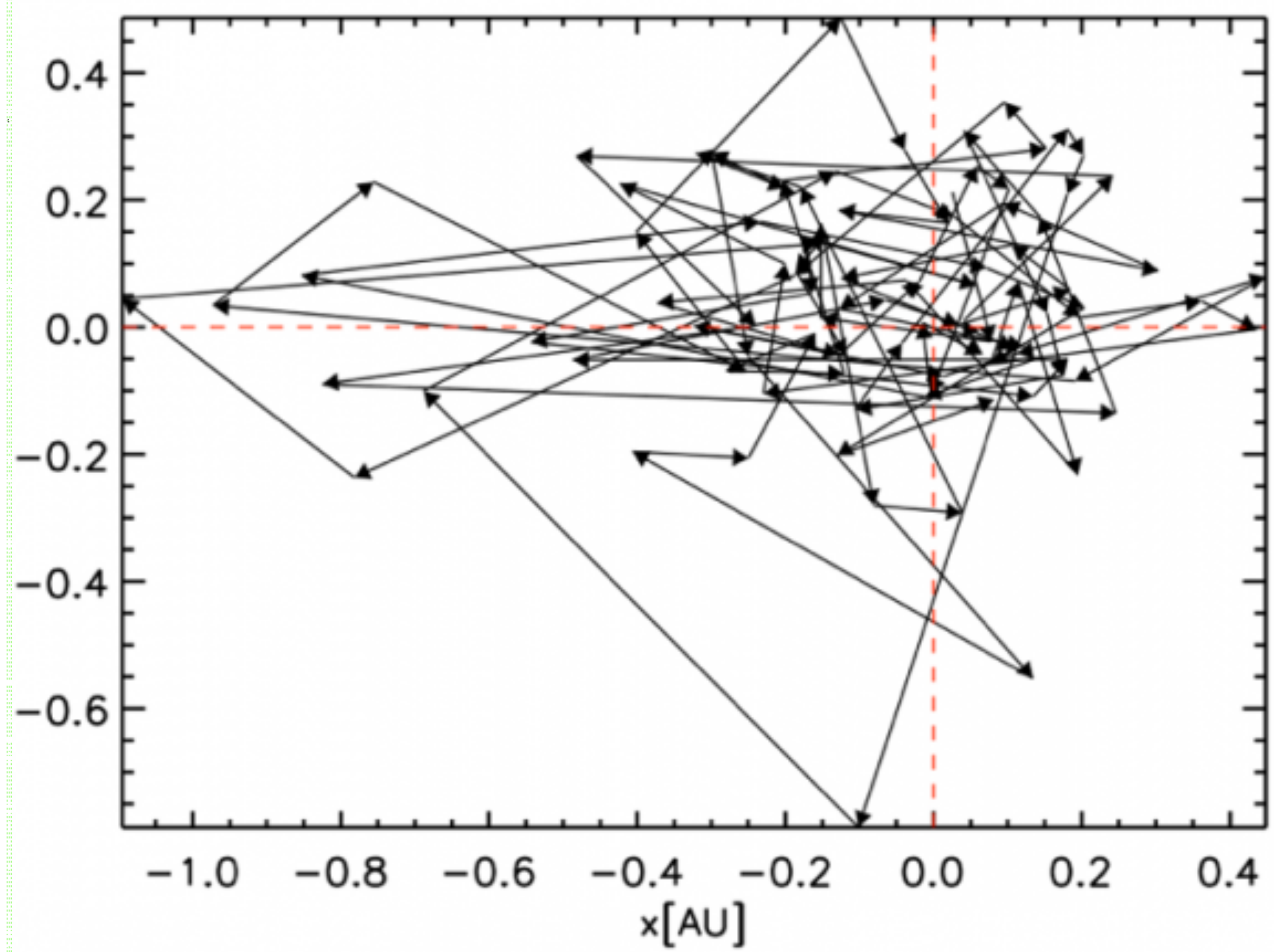
Chiavassa, Casagrande, Collet, Magic, Bigot, Thèvenin, Asplund, A&A 2018, 611, A11

Post-processing LTE RT - examples

Gaia G band filter (time lapse during Gaia mission)



Predicted photocenter variability during Gaia mission: up to 5-10% of stellar radius

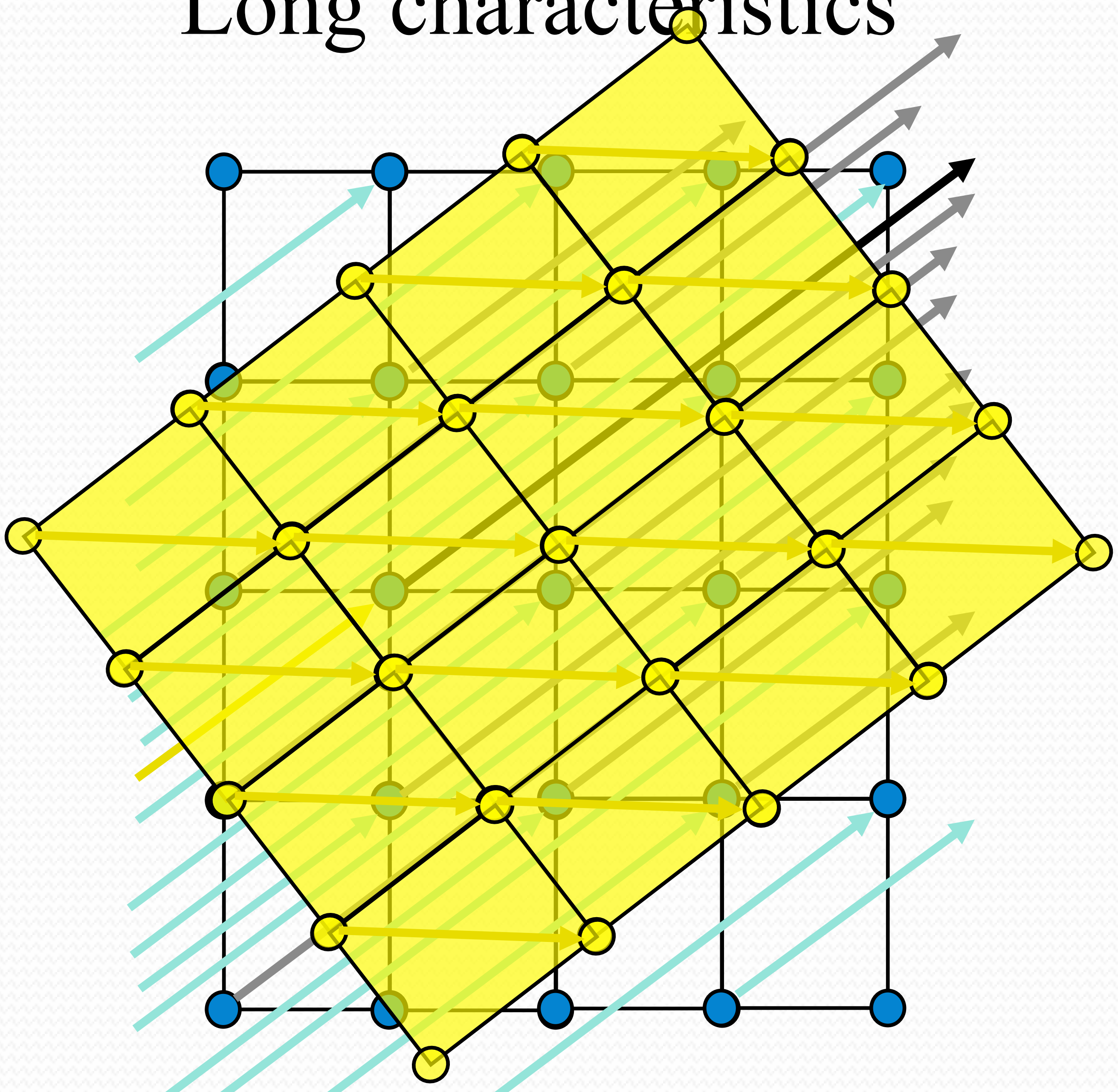


RSG → Chiavassa et al. 2011, A&A, 528, A120

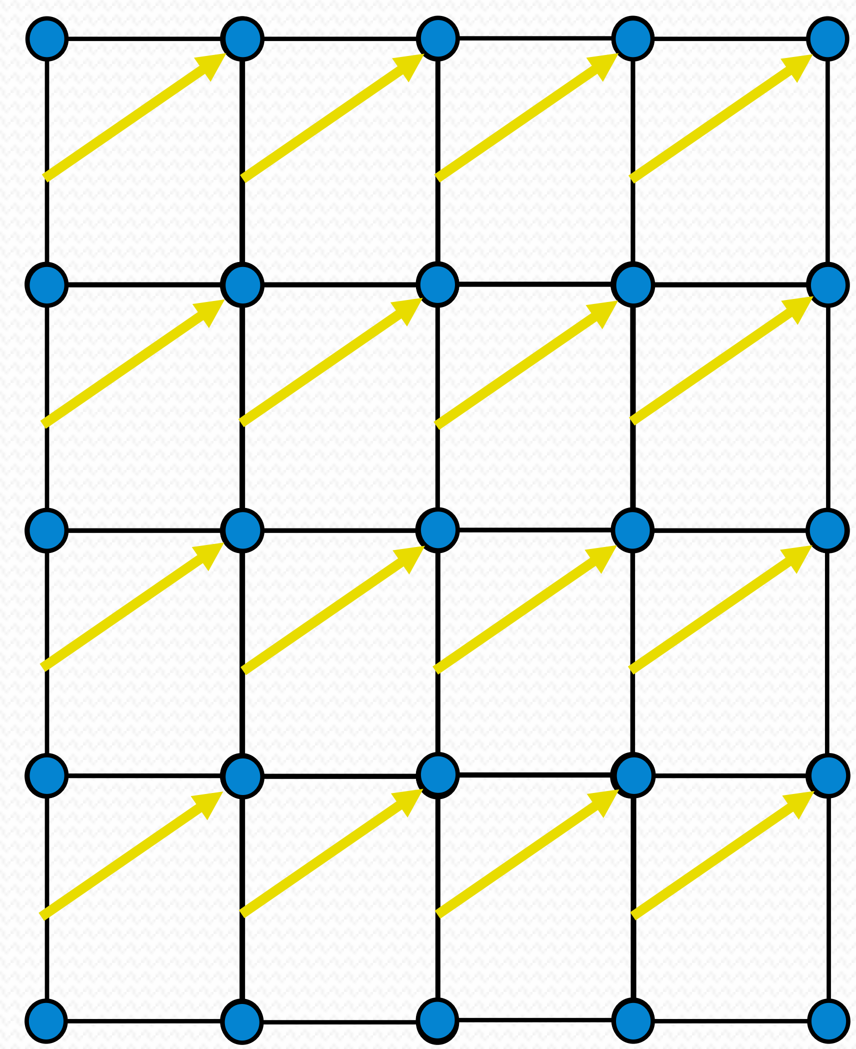
AGB → Chiavassa, Freytag & Schultheis 2018, A&A, 617, L1

Short versus long characteristics

Long characteristics



Short characteristics



Gauss-Laguerre quadrature

$$I_\lambda(0) = \int_0^{\tau_\lambda} S_\lambda(t_\lambda)\,\mathrm{e}^{-t_\lambda}\mathrm{d}t_\lambda$$

Gauss-Laguerre quadrature of order *n* for $\tau \to \infty$

Fast and reliable for well behaving source function, because it uses only the value of the source function at *n* depth points weighted with *n* predetermined weights.

Abscissa	Weight
0.137793470540	3.08441115765E-01
0.729454549503	4.01119929155E-01
1.808342901740	2.18068287612E-01
3.401433697855	6.20874560987E-02
5.552496140064	9.50151697518E-03
8.330152746764	7.53008388588E-04
11.843785837900	2.82592334960E-05
16.279257831378	4.24931398496E-07
21.996585811981	1.83956482398E-09
29.920697012274	9.91182721961E-13

Abramowitz & Stegun 1972, Handbook of mathematical functions