L'impact de l'activité stellaire sur les observations vue par les simulations de convection stellaire

Andrea Chiavassa

In collaboration with: Matteo Brogi (Warwick University), S. Sulis (LAM, Marseille), M. C. Maimone & L. Bigot (Oca, Nice). J. Leconte & F. Selsis (LAM, Bordeaux)…

LAGRANGE

Observatoire de la CÔTE d'AZUR

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LAGRANGE

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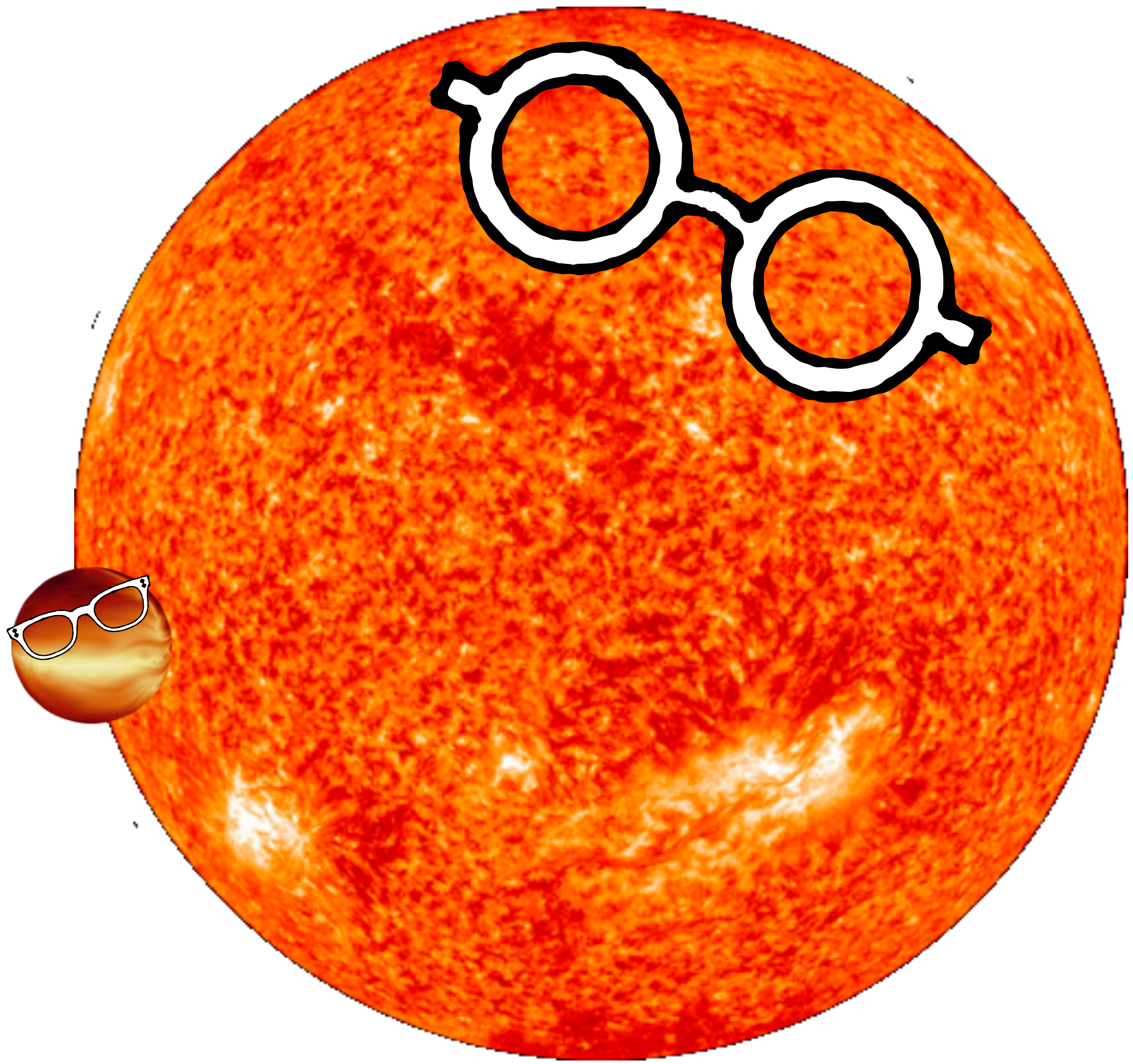
In conclusion …

From the planet point of view:

- the star is the noise, and the stellar spectra need modelling to be processed

From the stellar point of view:

- the “noise” is the signal of stellar dynamics and key point for studying its physical properties
- the planet transits represent and relevant source of information for the star



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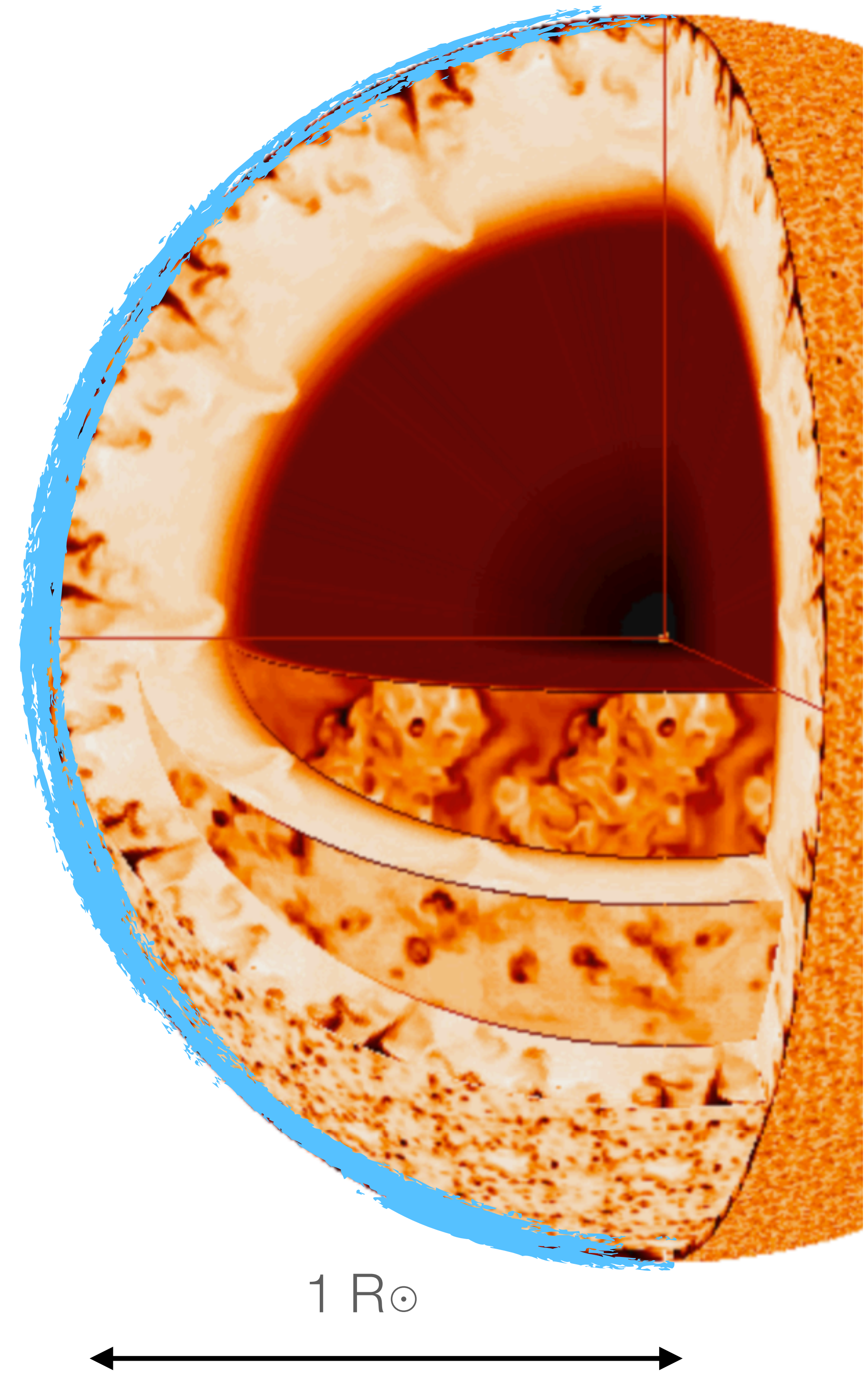
Are the Sun and the stars really smooth?

Is the Sun really smooth?

What is a stellar atmosphere?

The atmosphere is the boundary to the invisible stellar interior: the link between models of stars and stellar evolution and observations. The phenomena of stellar evolution manifest themselves in the stellar surface as changes in chemical composition and in fundamental stellar parameters such as radius, surface gravity, effective temperature, and luminosity.

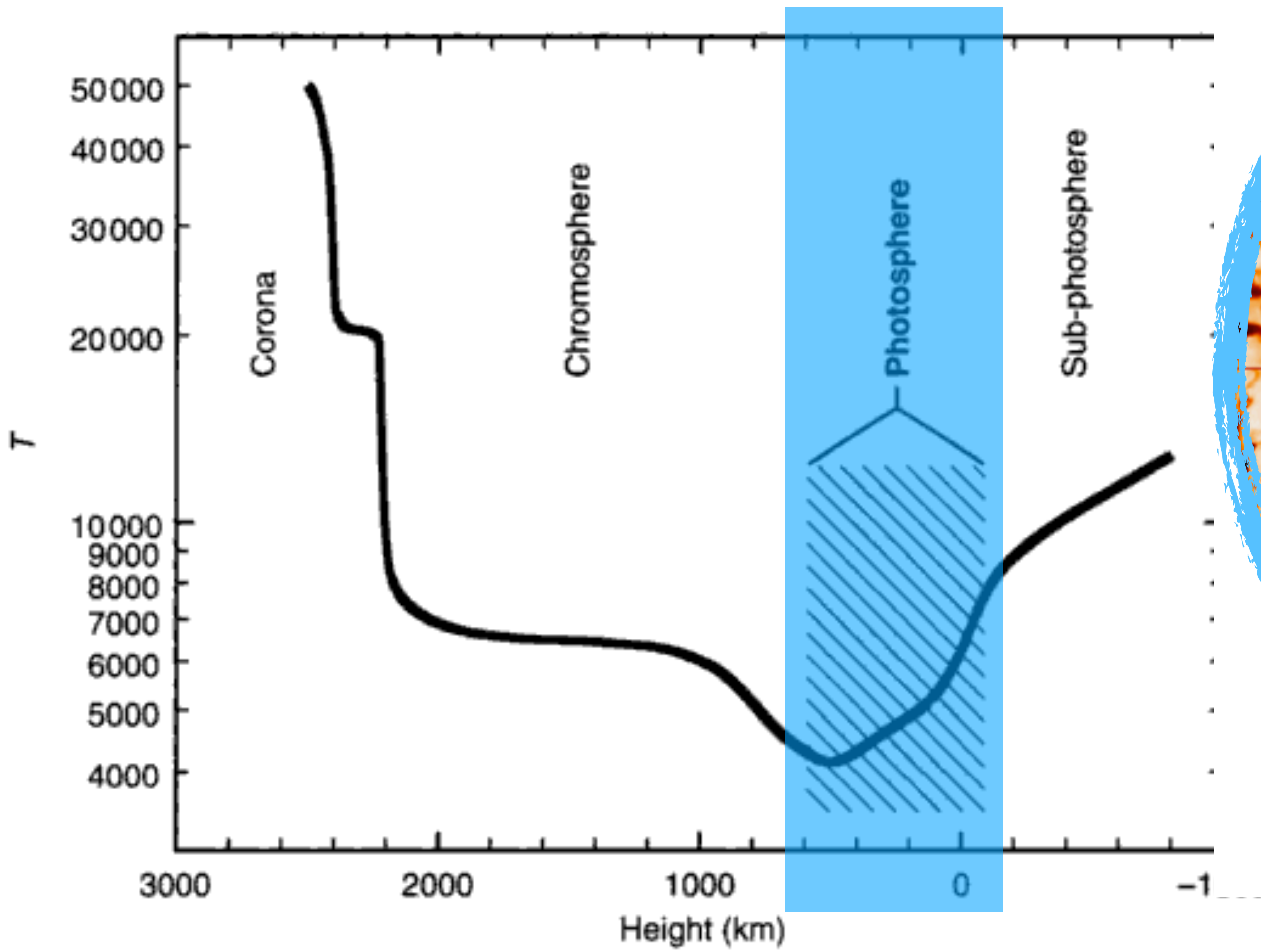
The Sun



Nordlund 2000,
Encyclopedia of Astronomy and Astrophysics

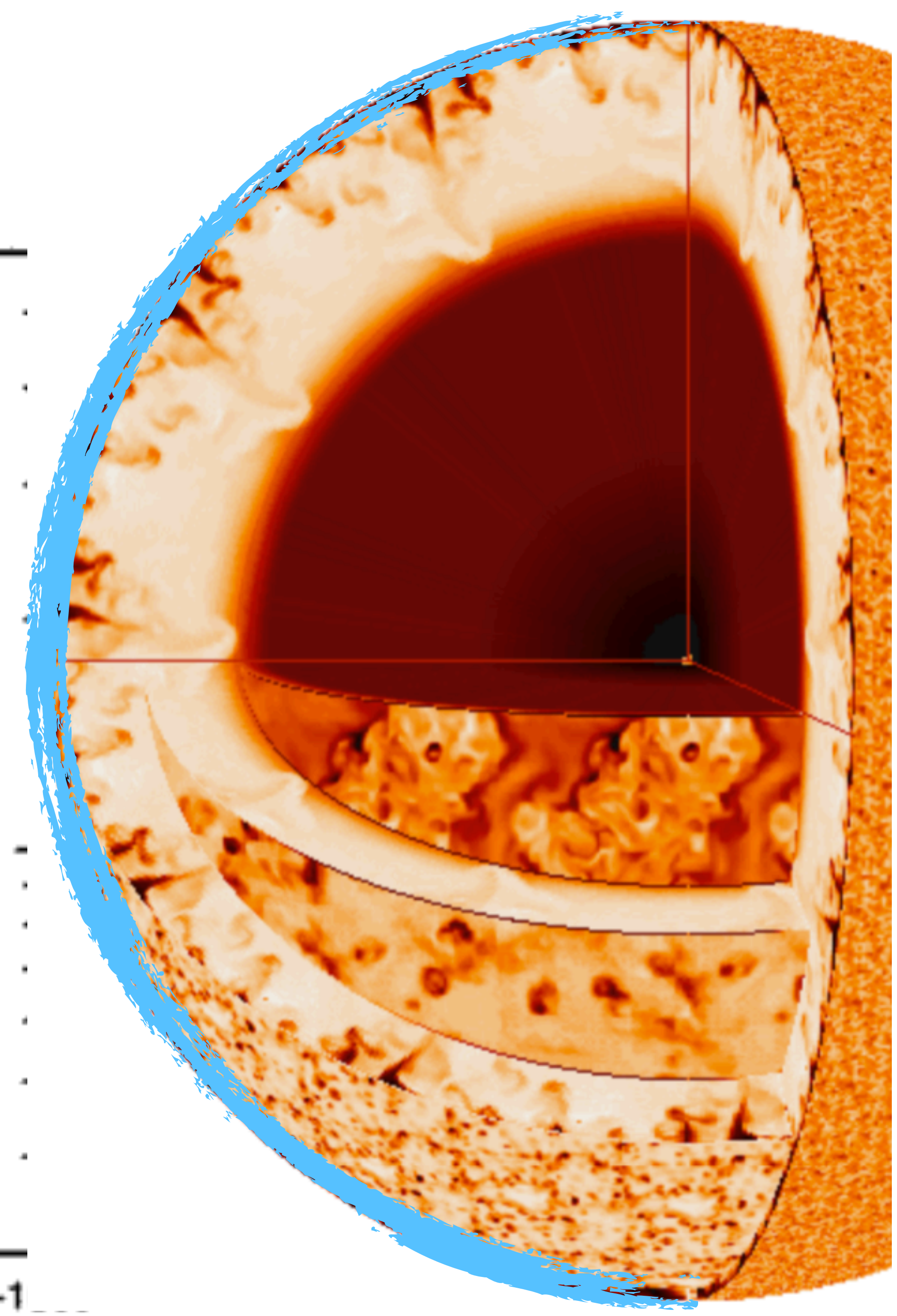
What is a stellar atmosphere?

The information we use to study distant stars (and hosting planets) comes from the flux they have emitted



Vernazza et al. 1975

The Sun

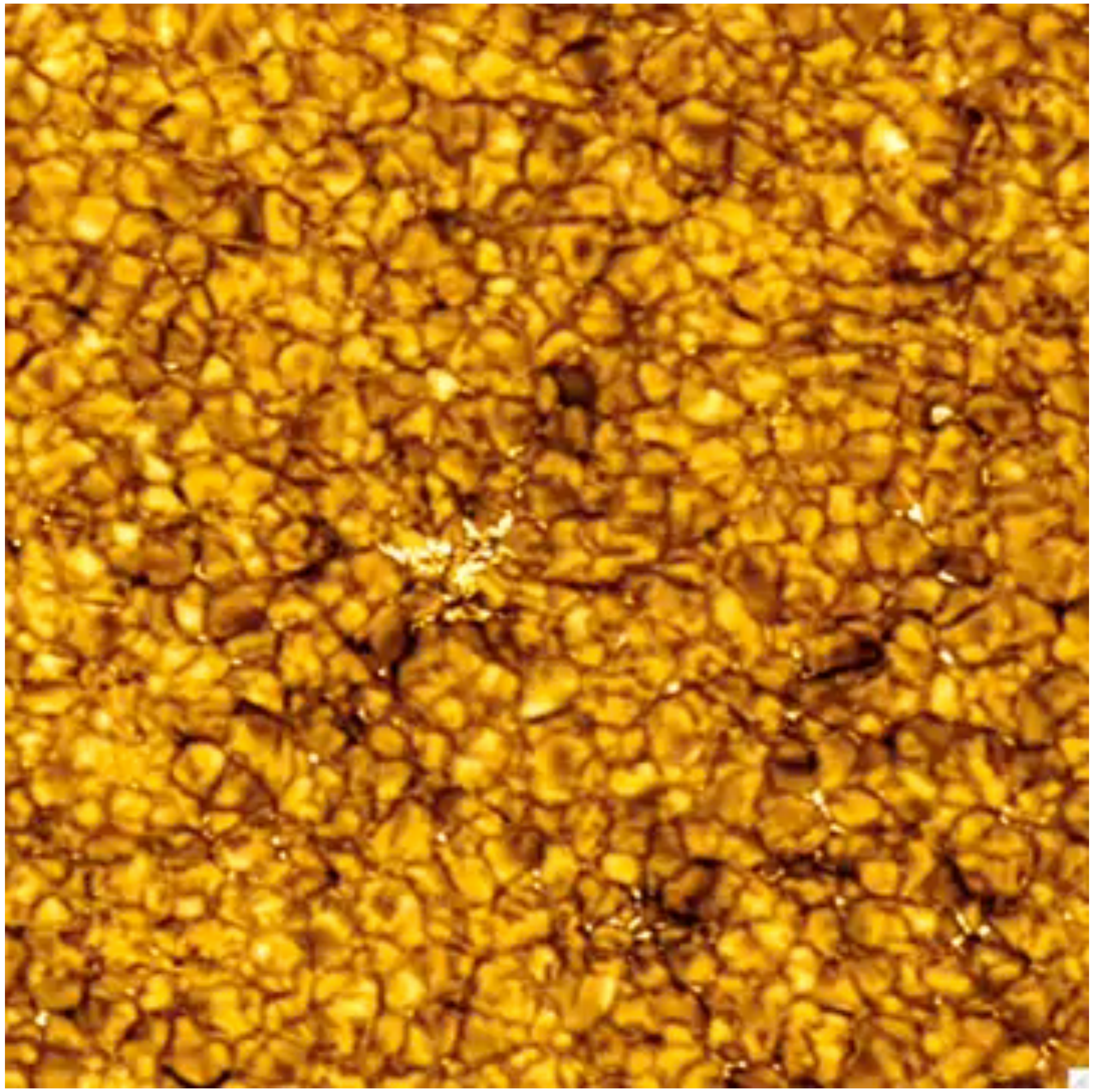


What is a stellar atmosphere?

However, the atmospheric layers where this flux forms is the transition region between convective and radiative regime.

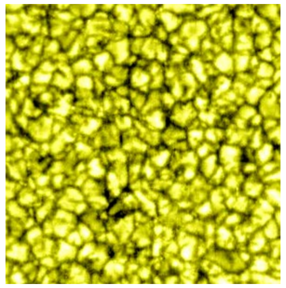
The surface structures and dynamics of cool stars are characterised by the presence of convective motions and turbulent flows which shape the emergent spectrum.

Convection manifests in the surface layers as a particular pattern of downflowing cooler plasma and bright areas where hot plasma rises (Nordlund et al. 2009).

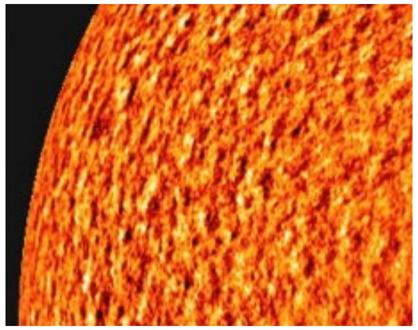


Is the Sun really smooth?

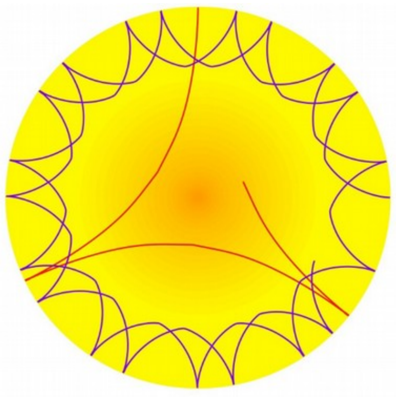
Granulation



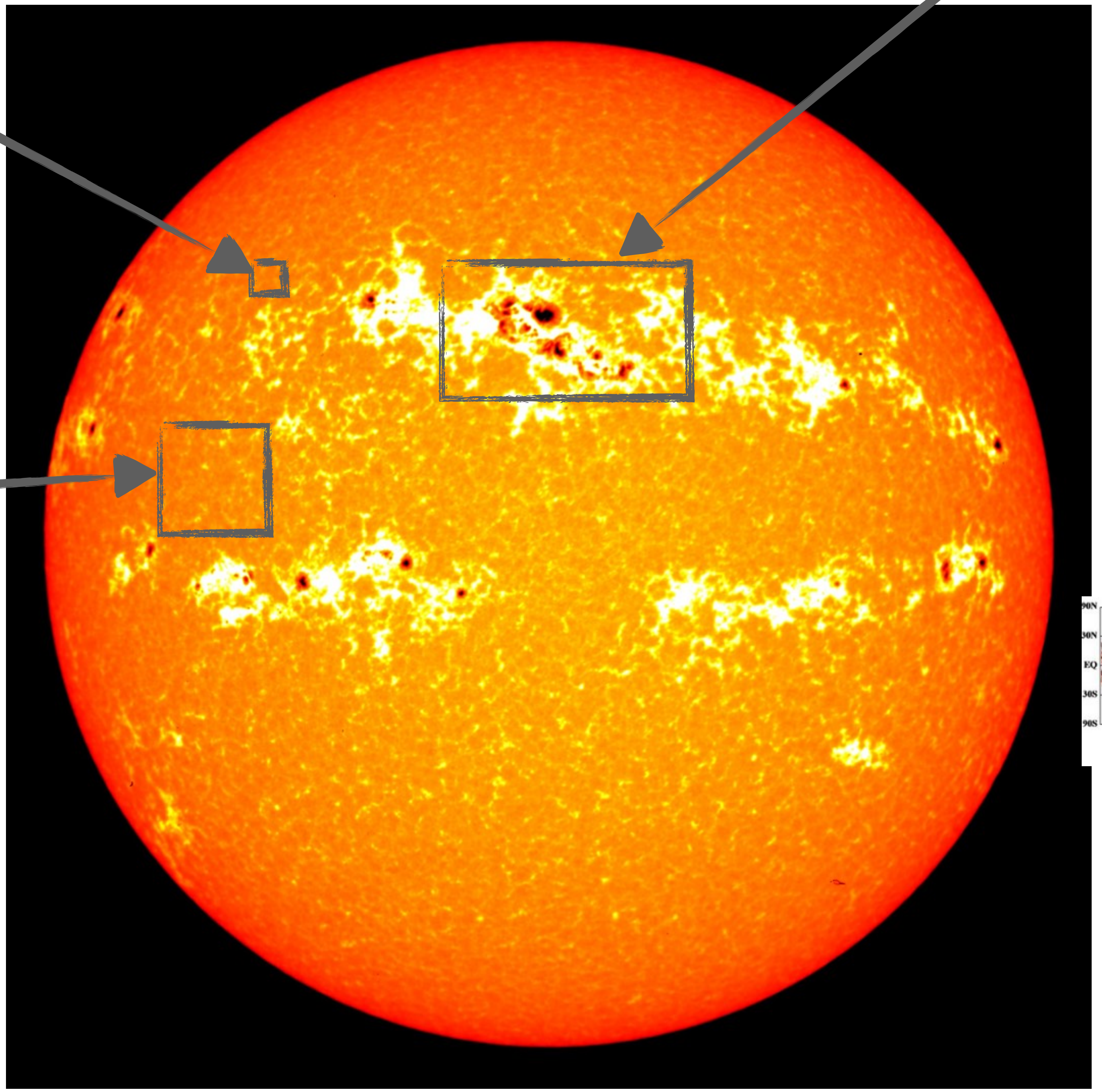
Super granulation



Oscillations

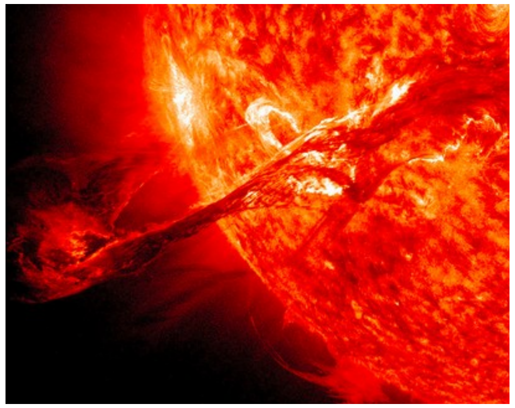


Starspots and faculae

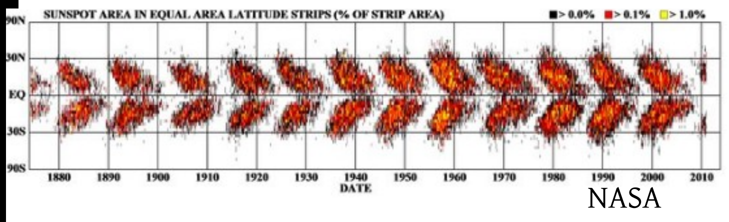


High solar activity: 28 marche 2001, NASA

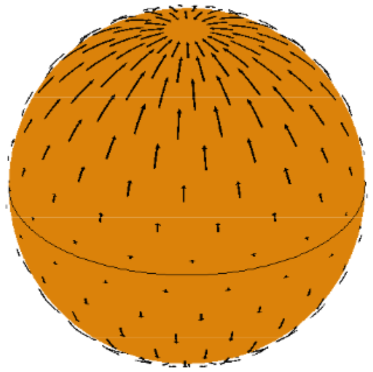
Flares



Cycles

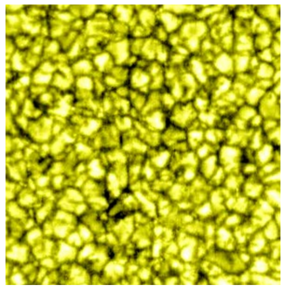


Meridional circulation

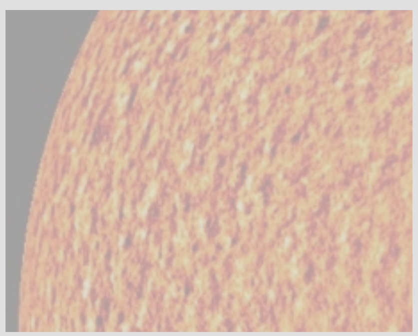


Is the Sun really smooth?

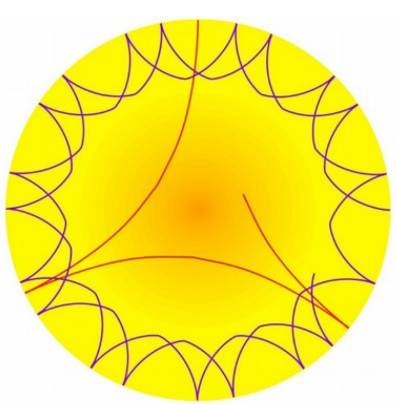
Granulation

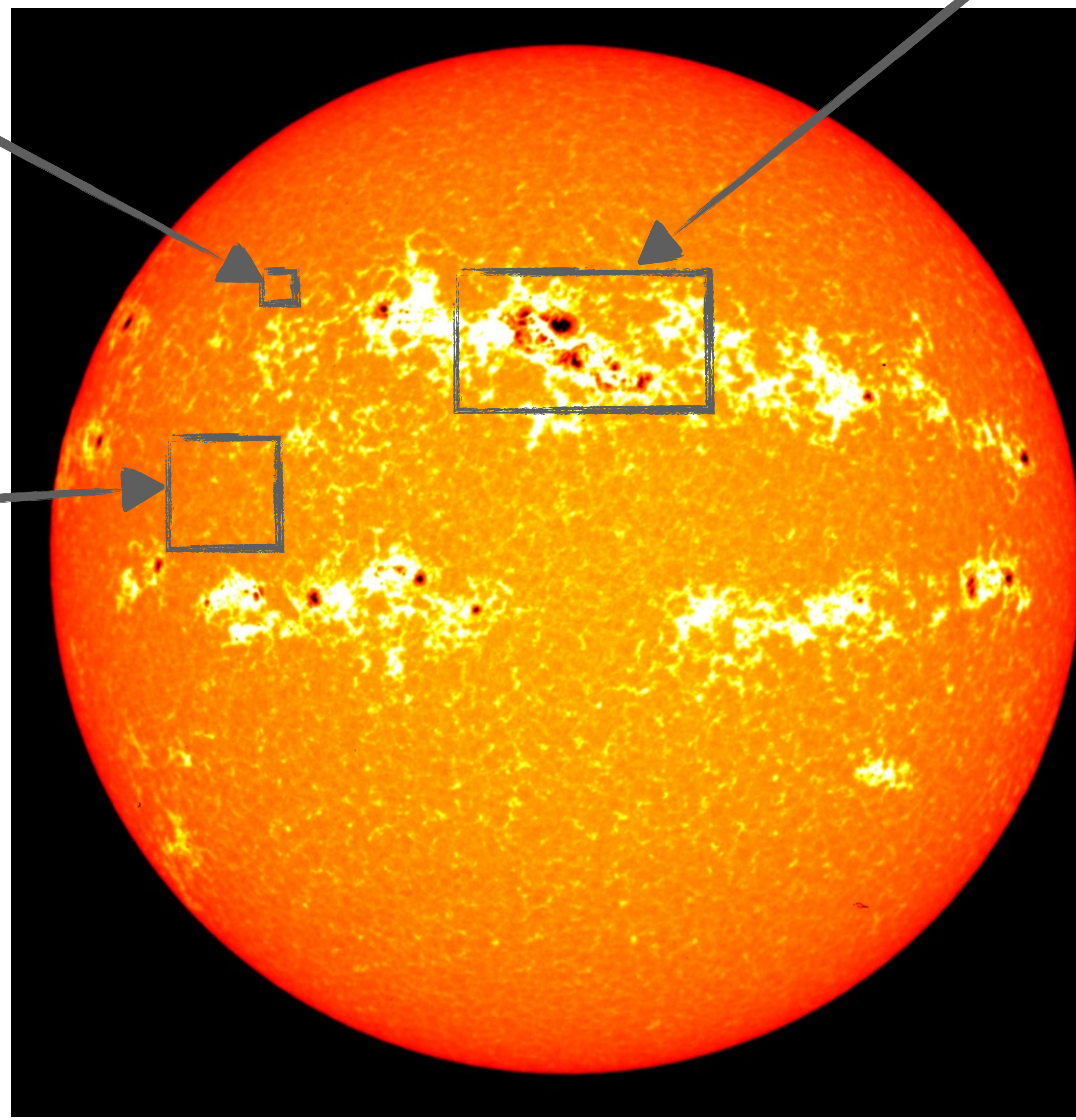


Super granulation



Oscillations

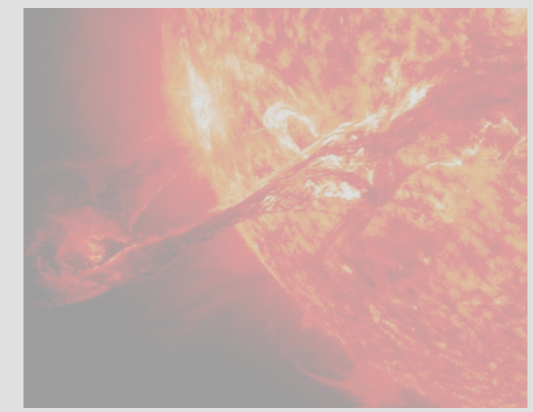




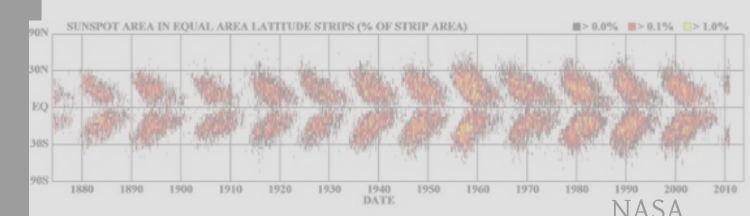
High solar activity: 28 marche 2001, NASA

Starspots and faculae

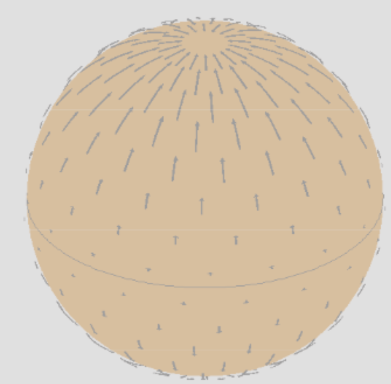
Flares



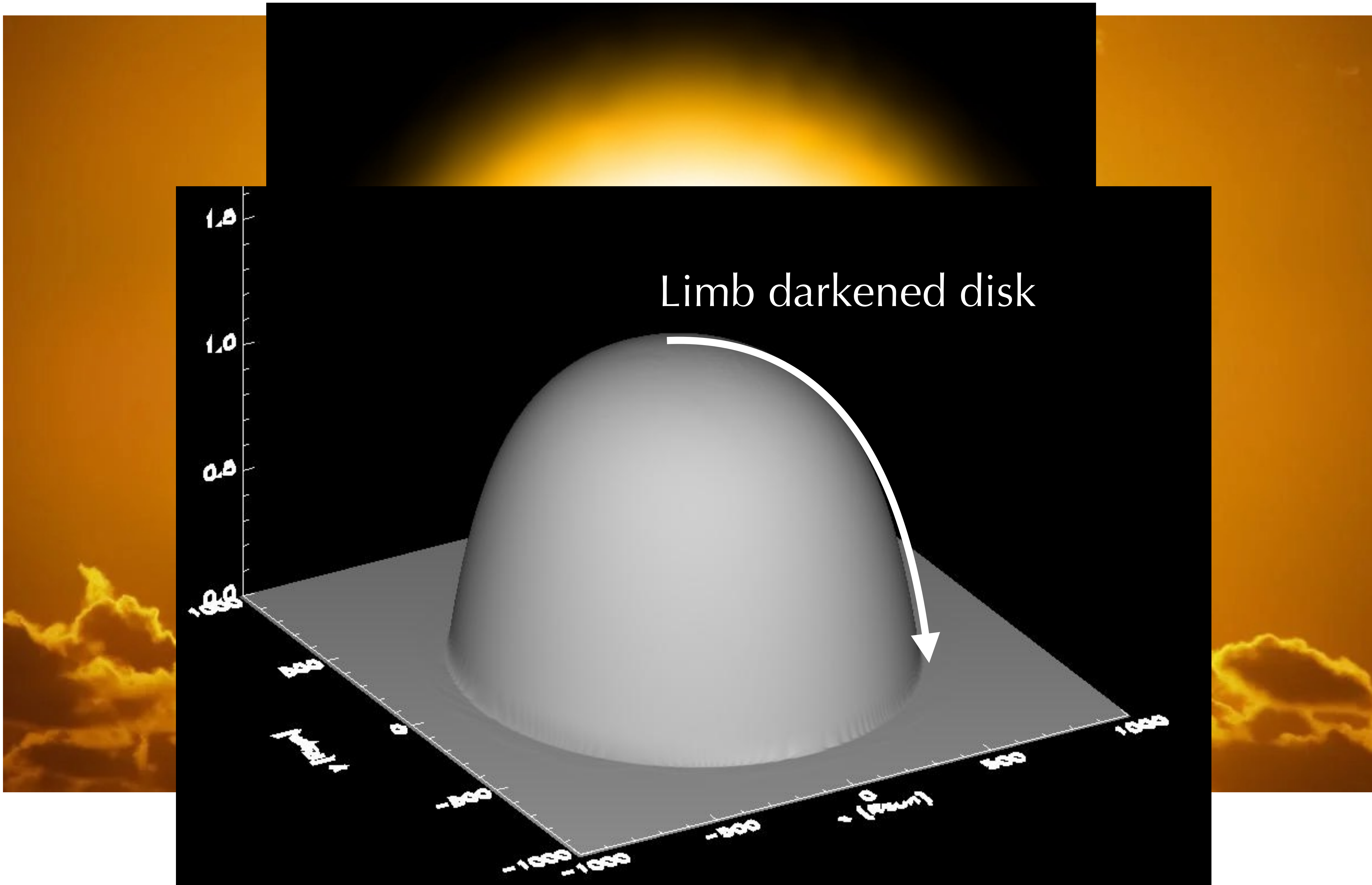
Cycles



Meridional circulation



Is the Sun really smooth?



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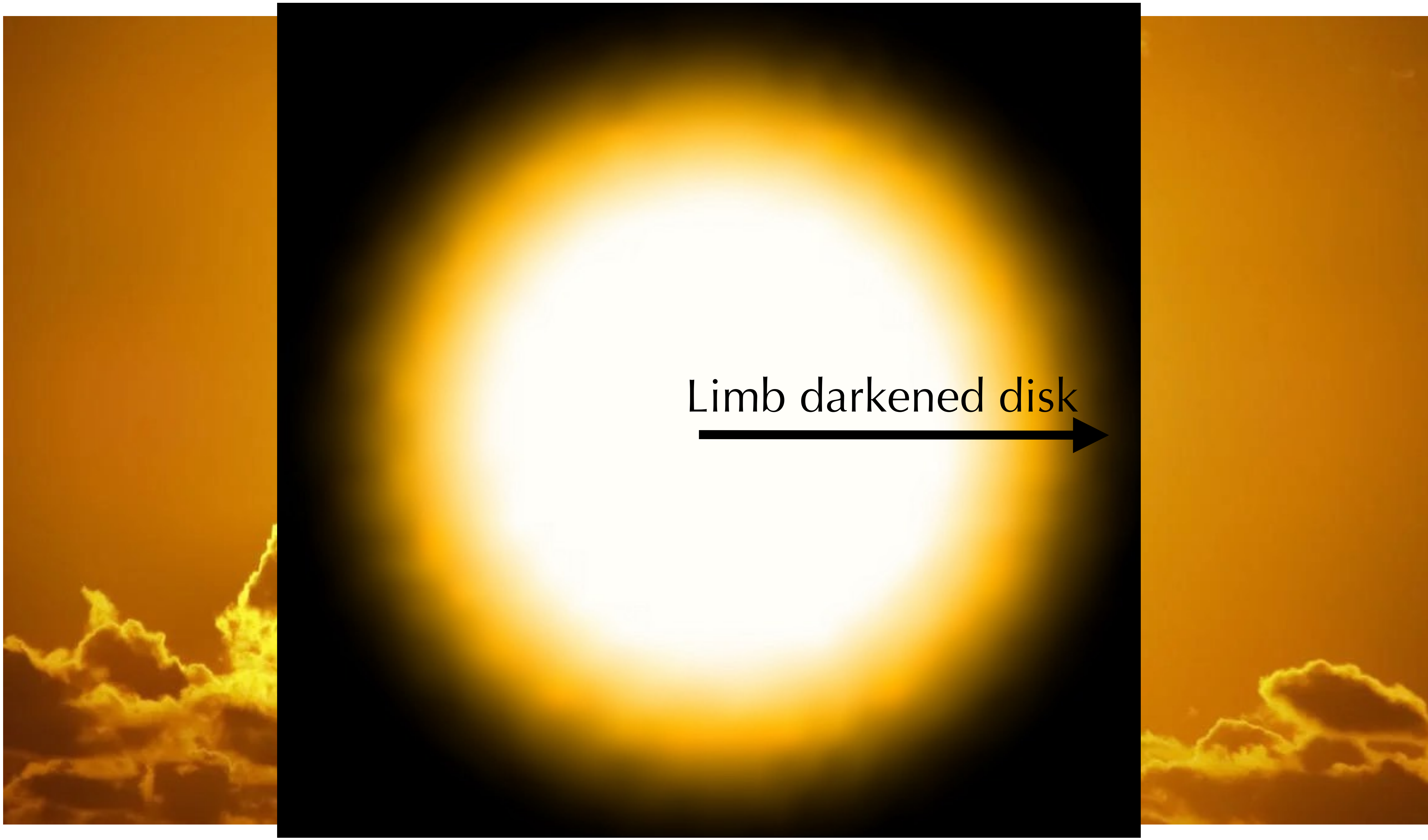

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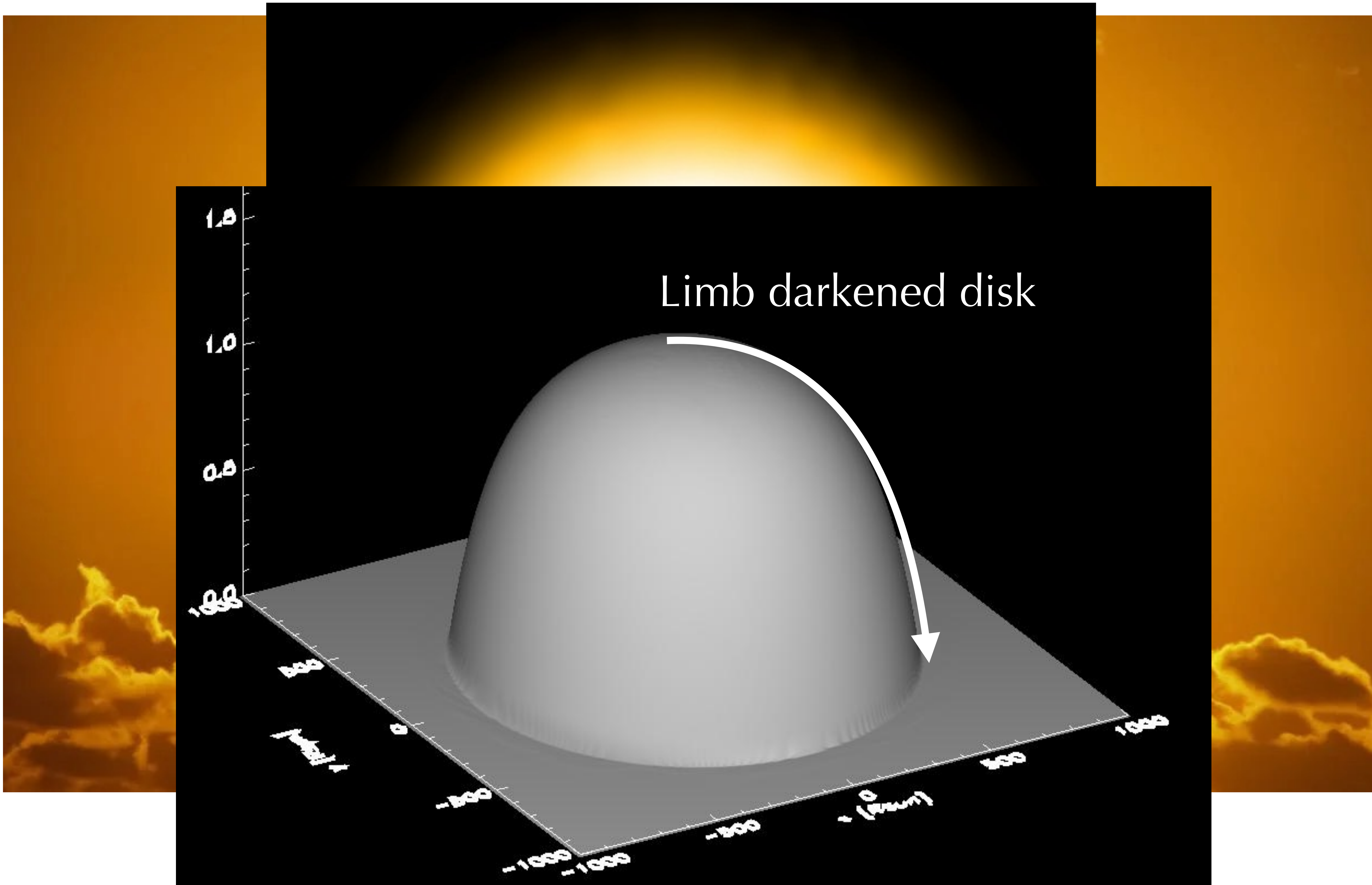

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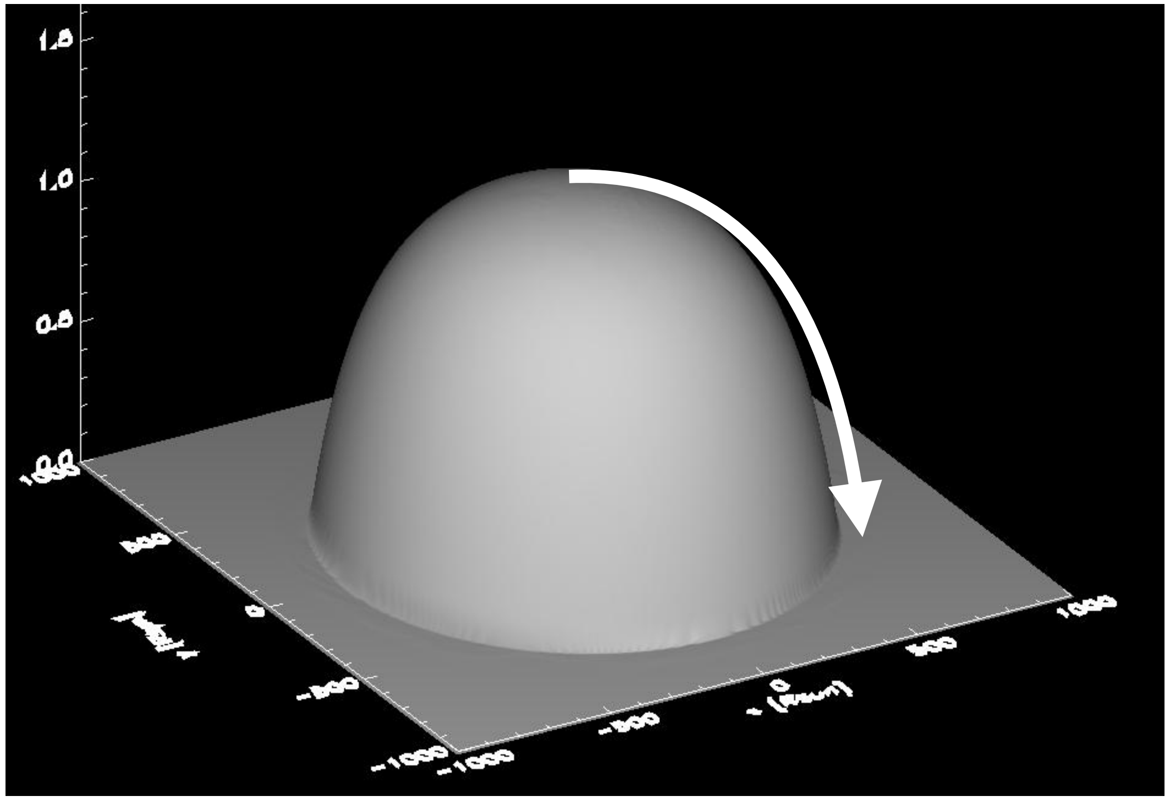

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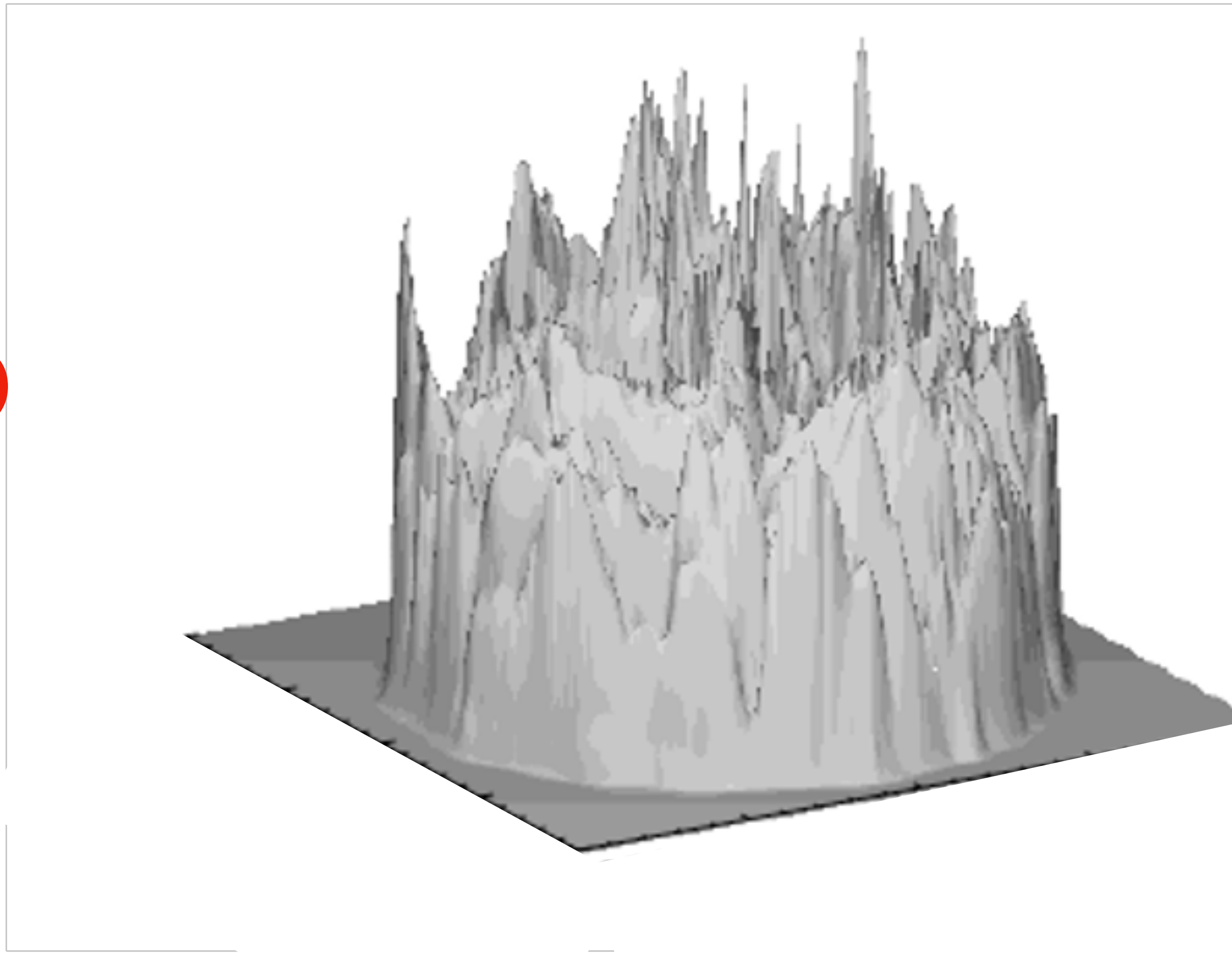

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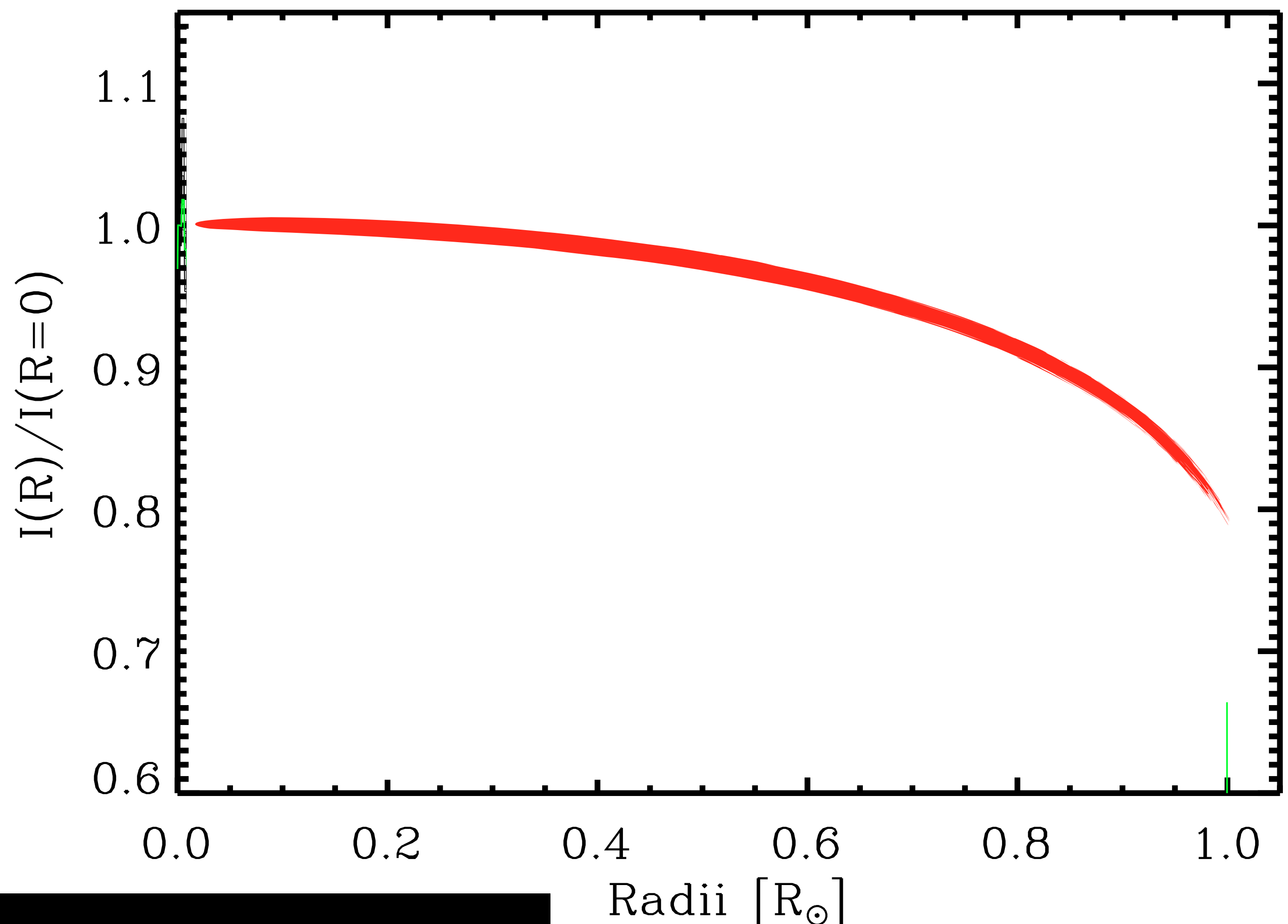
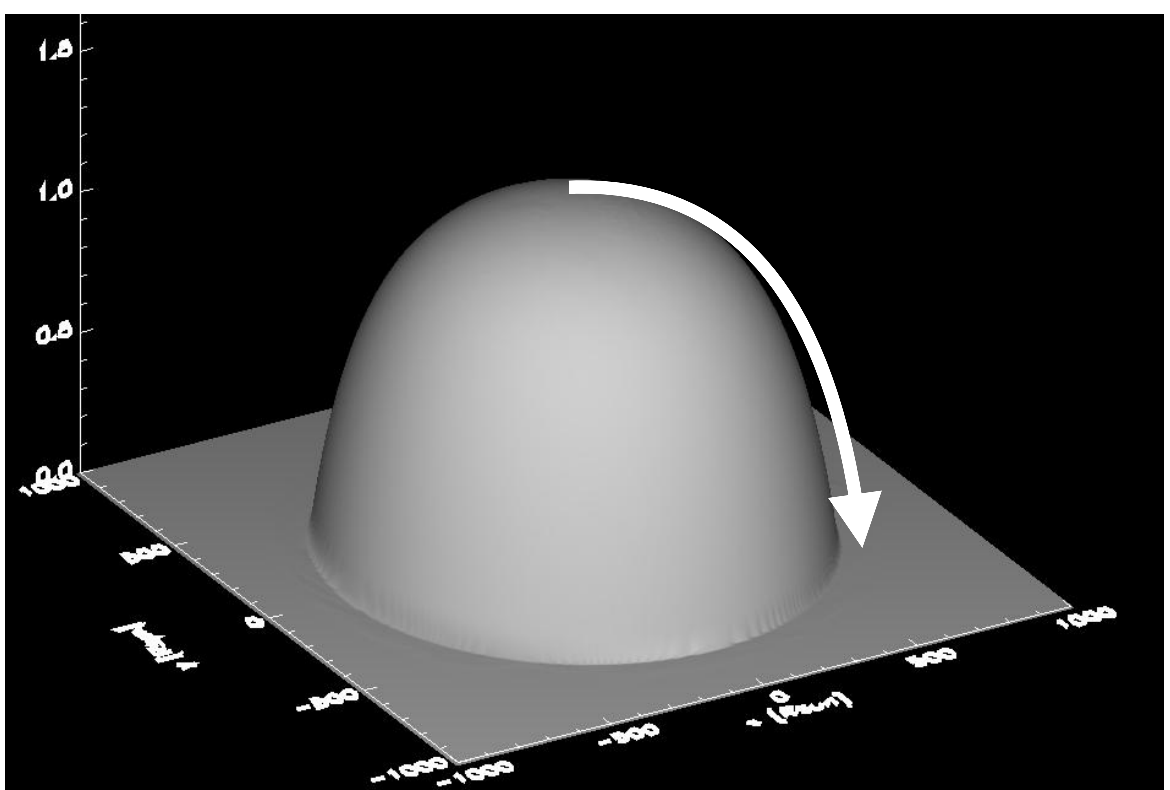
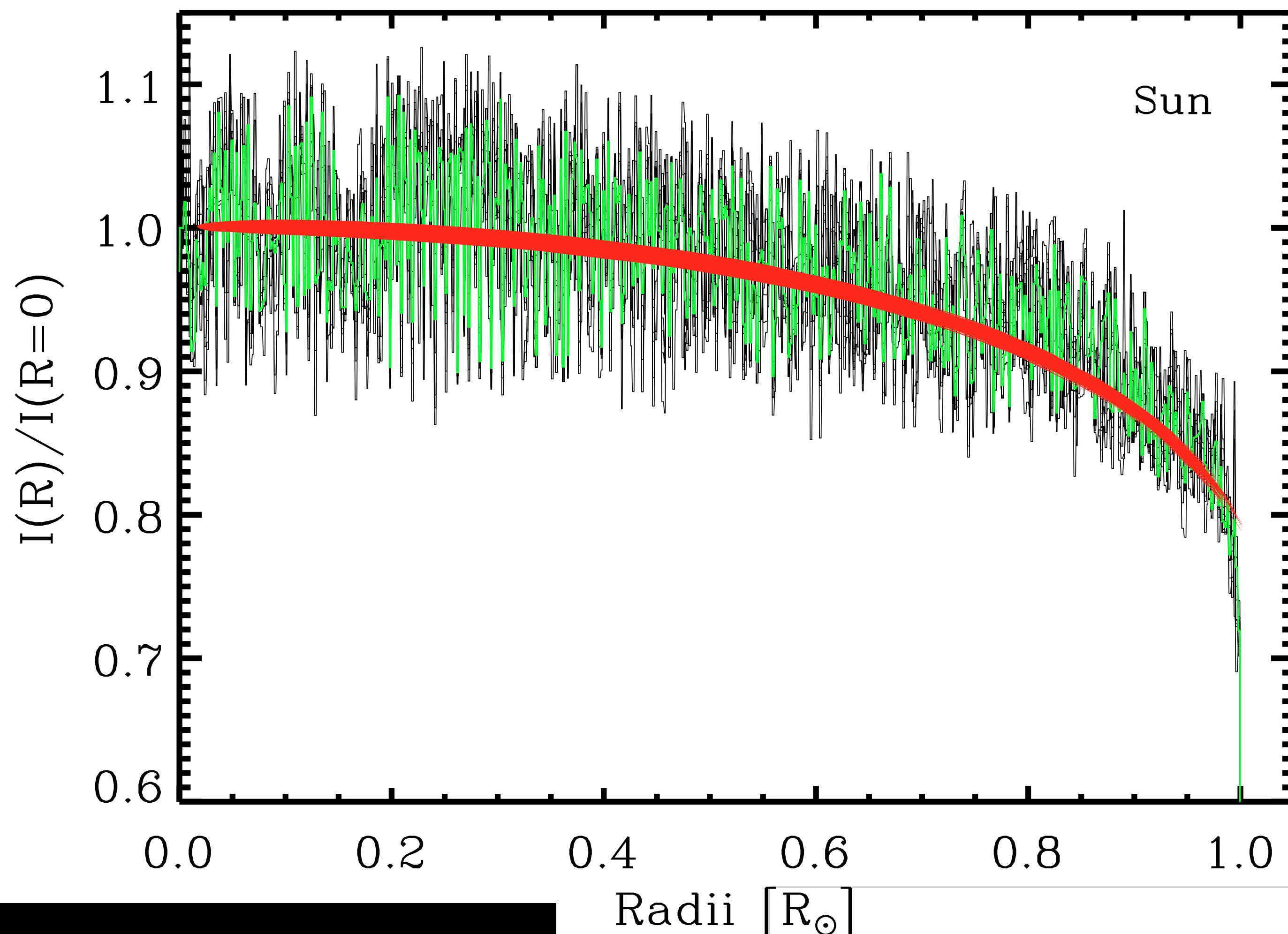
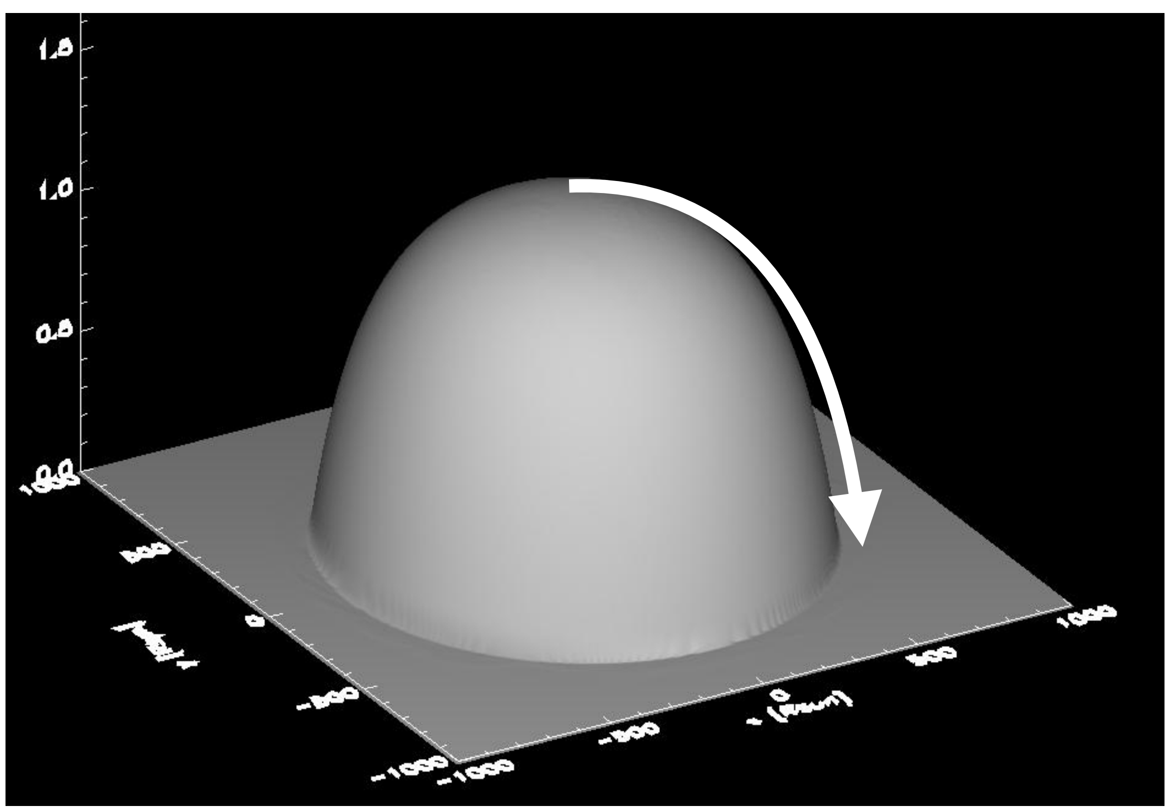
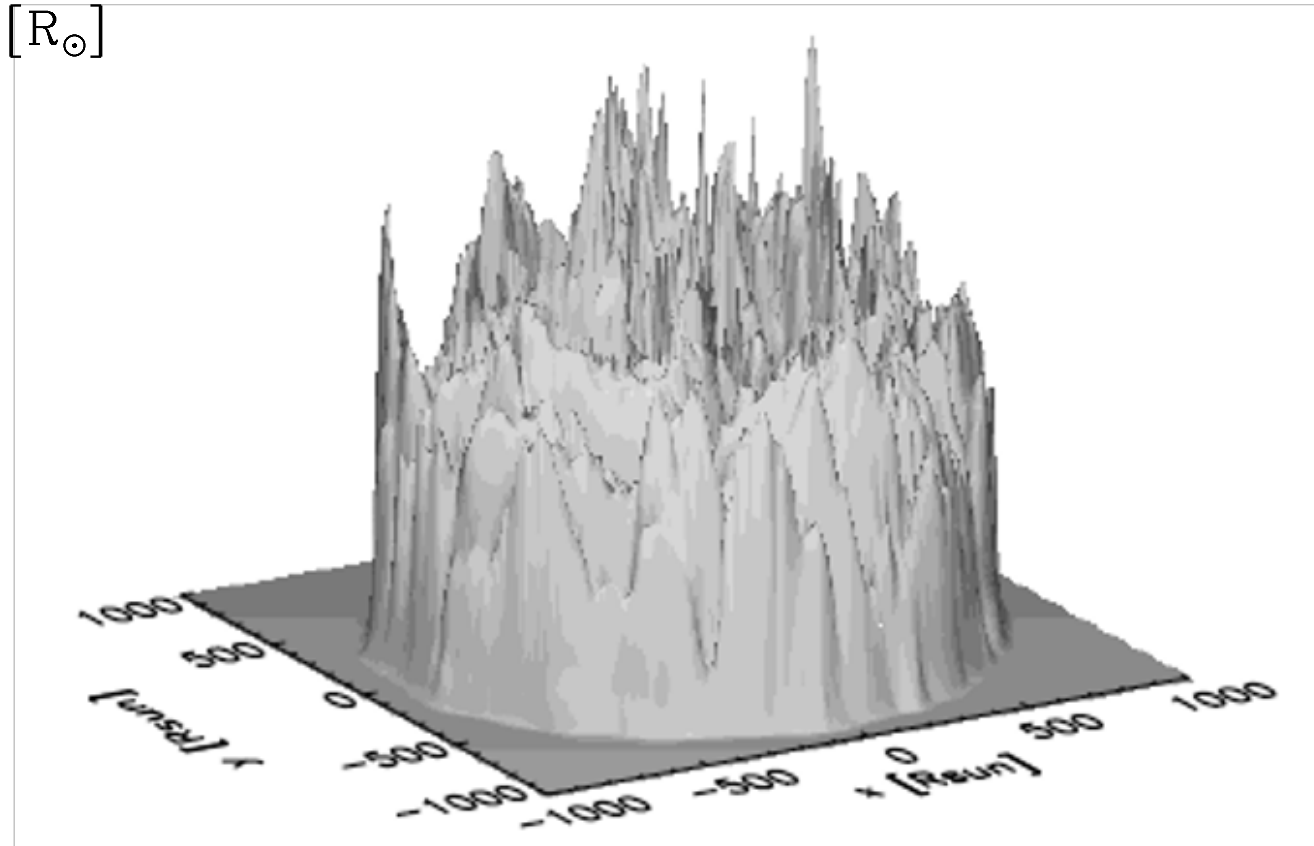




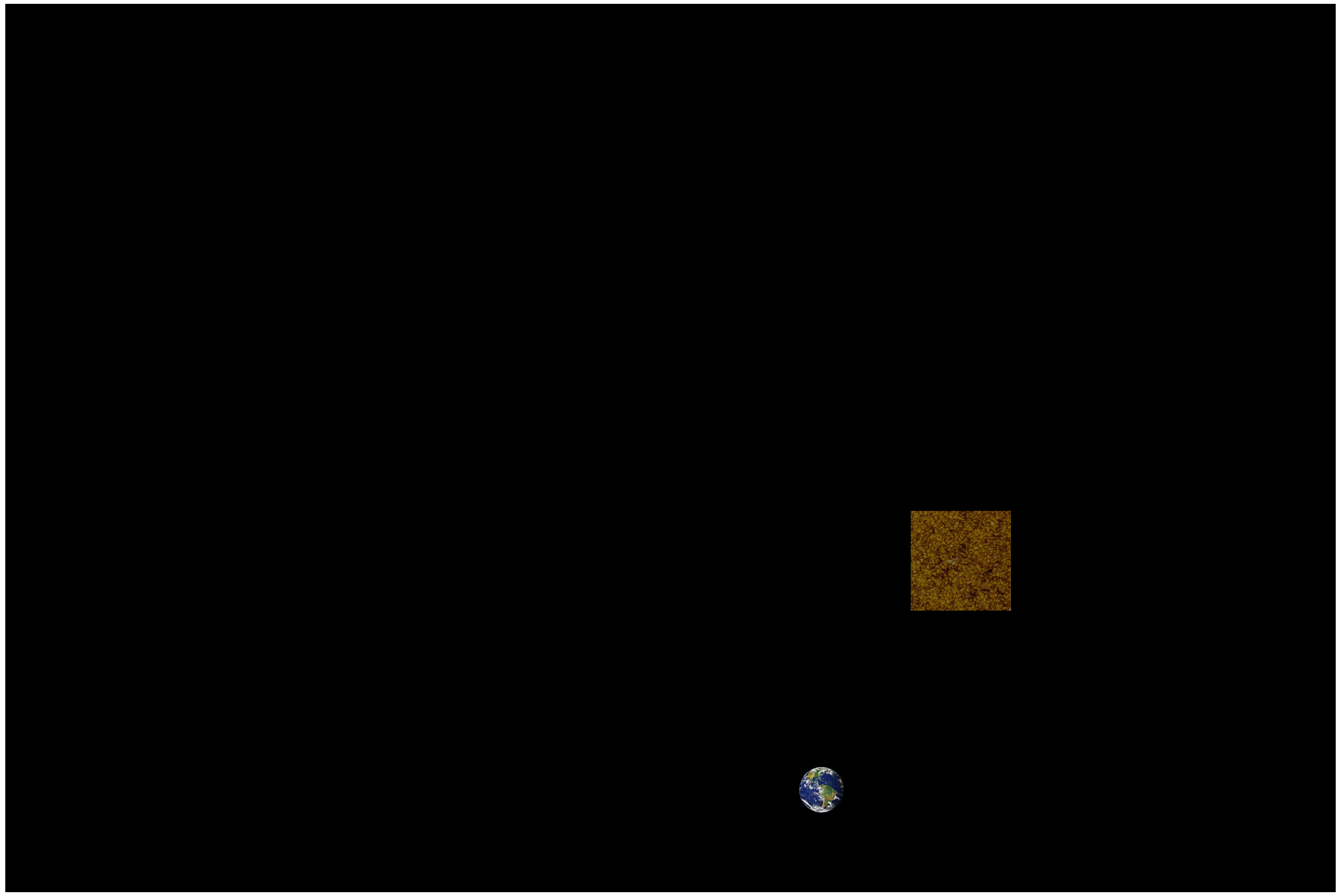
Is the Sun really smooth?

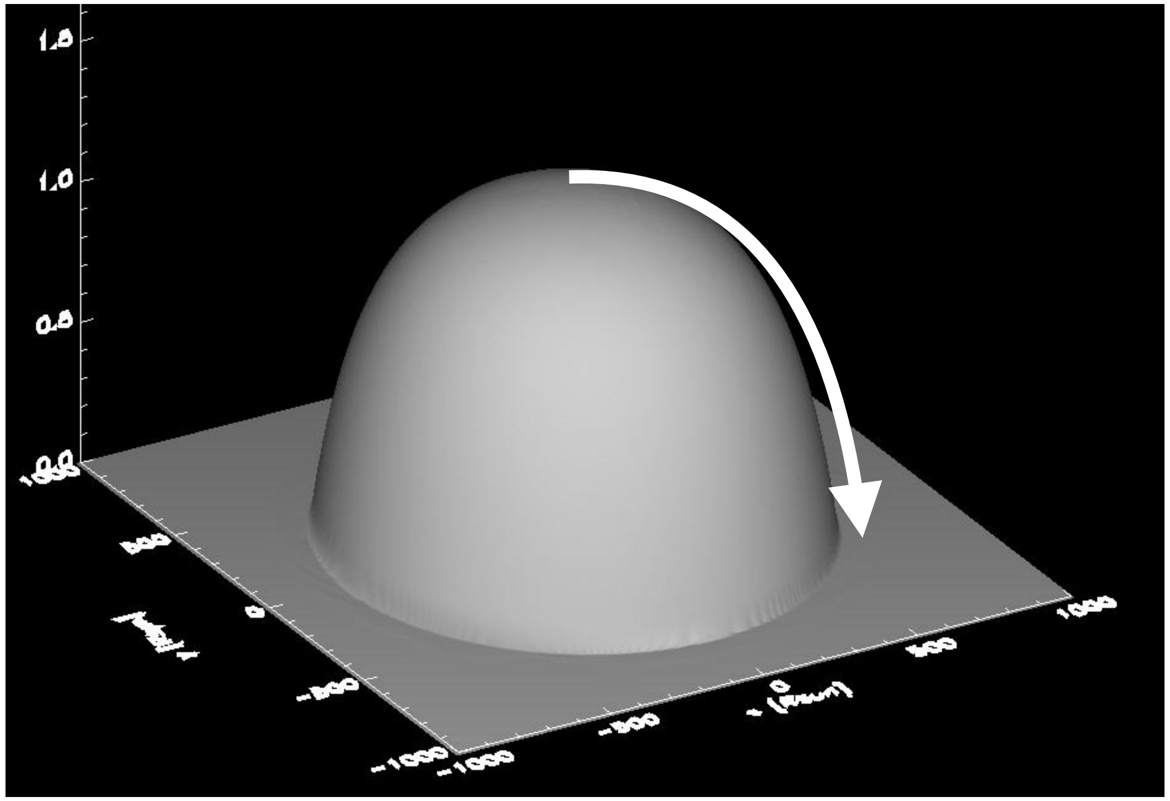


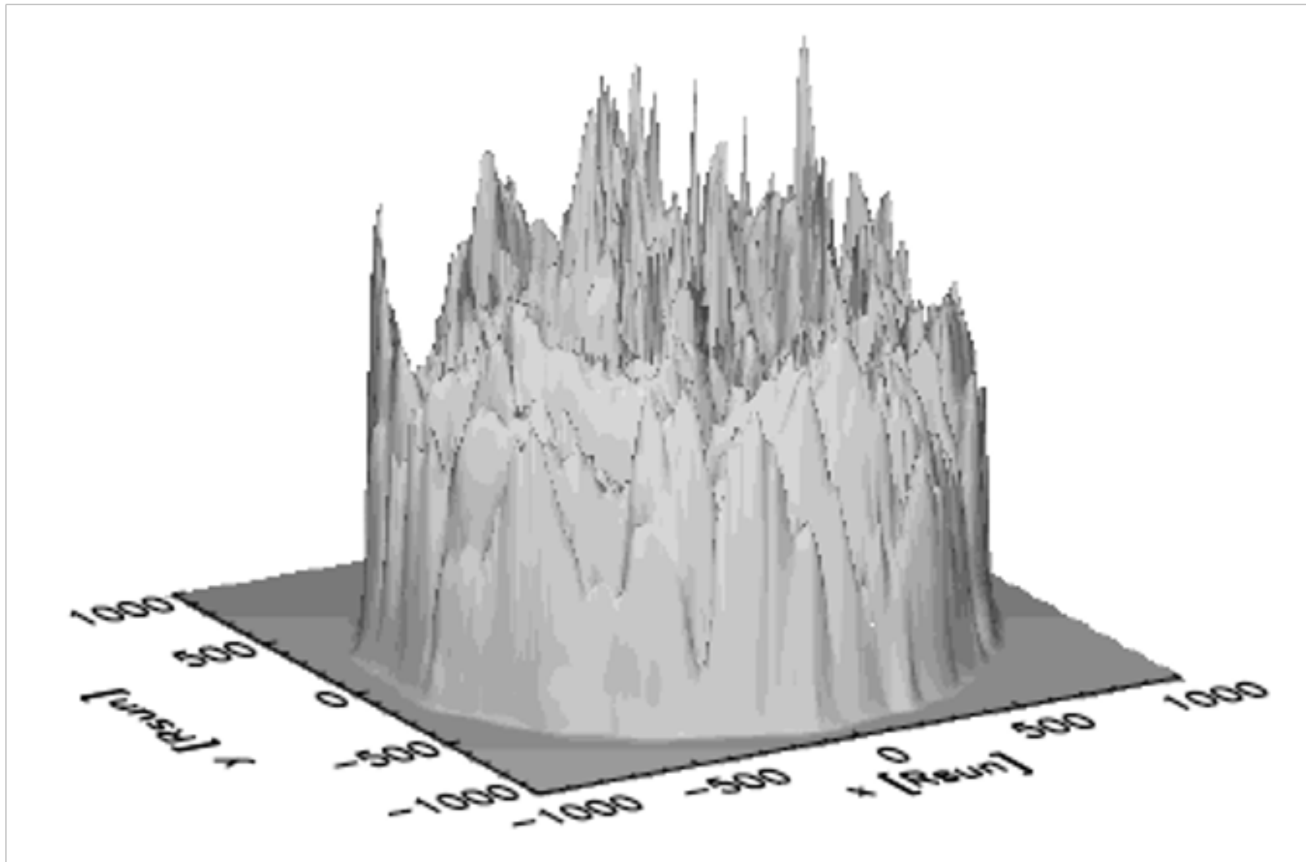


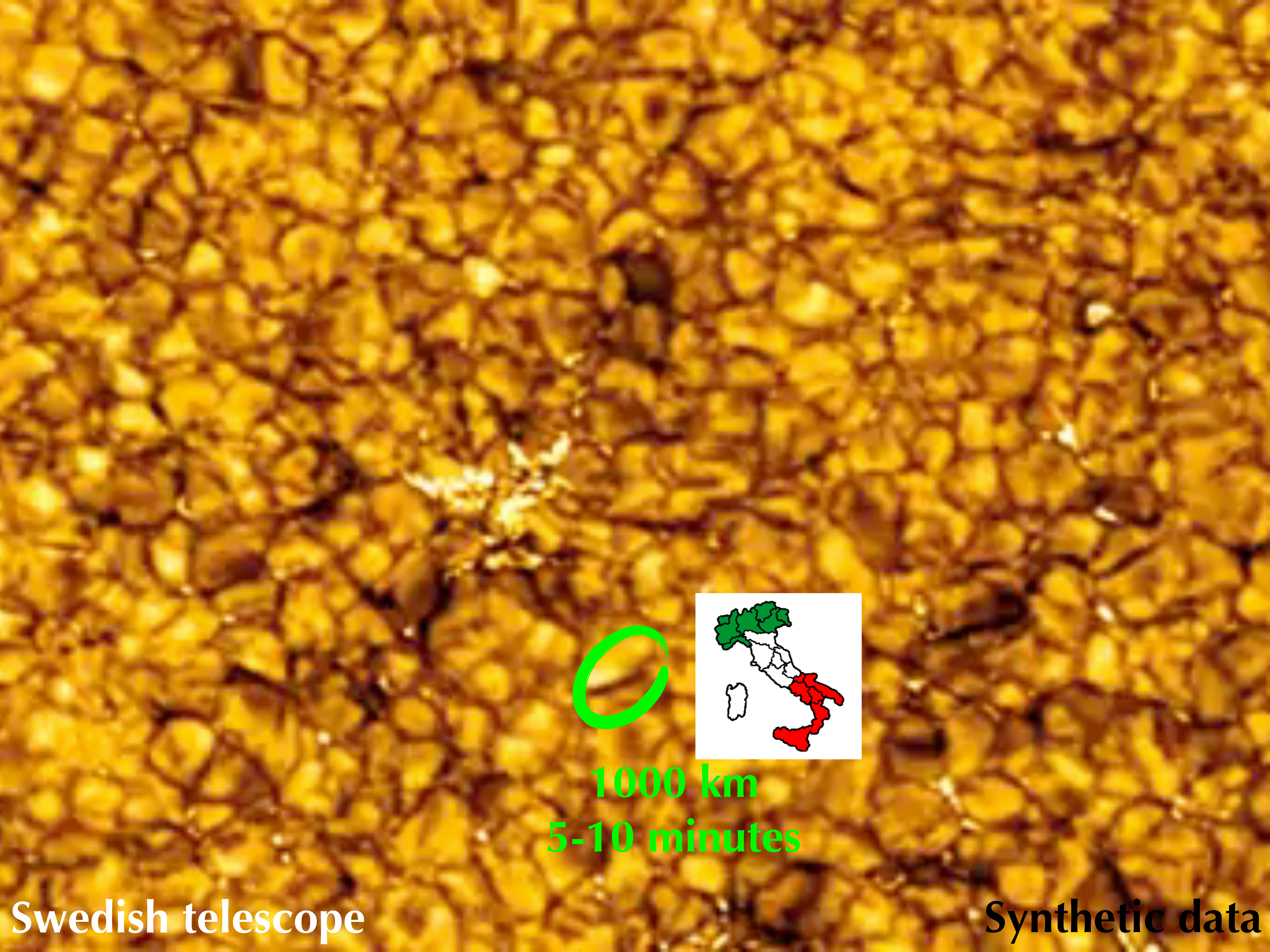


Is the Sun really smooth?





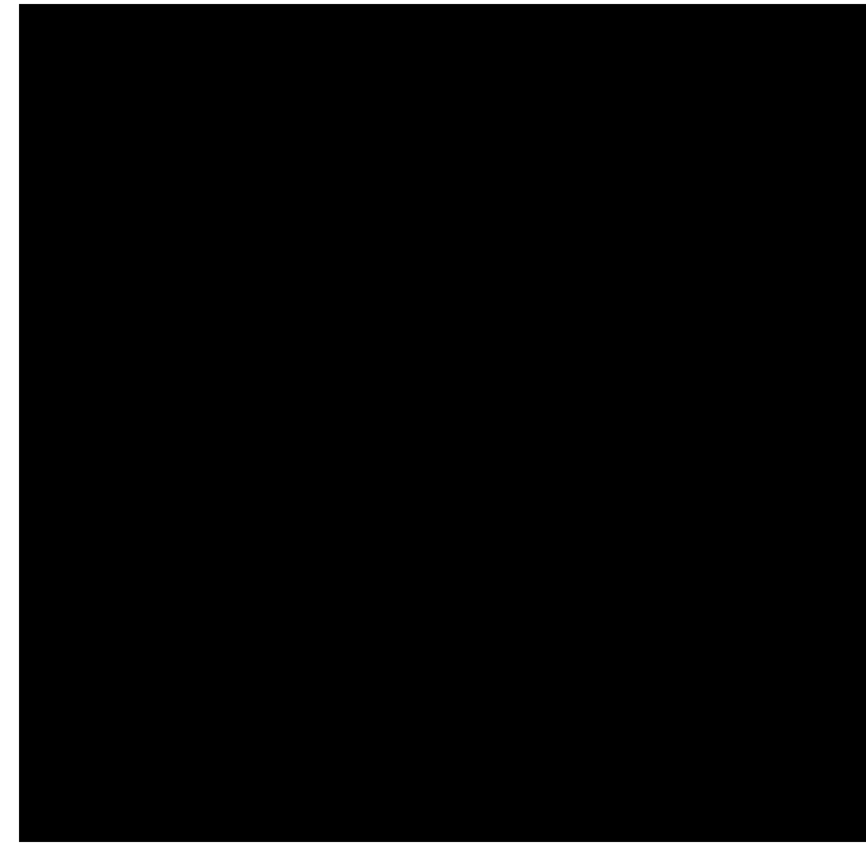


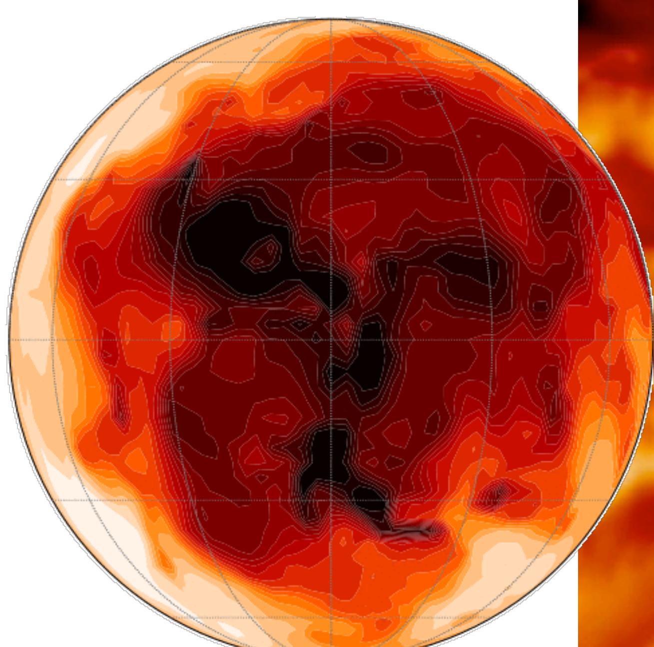

1000 km
5-10 minutes
Swedish telescope
Synthetic data

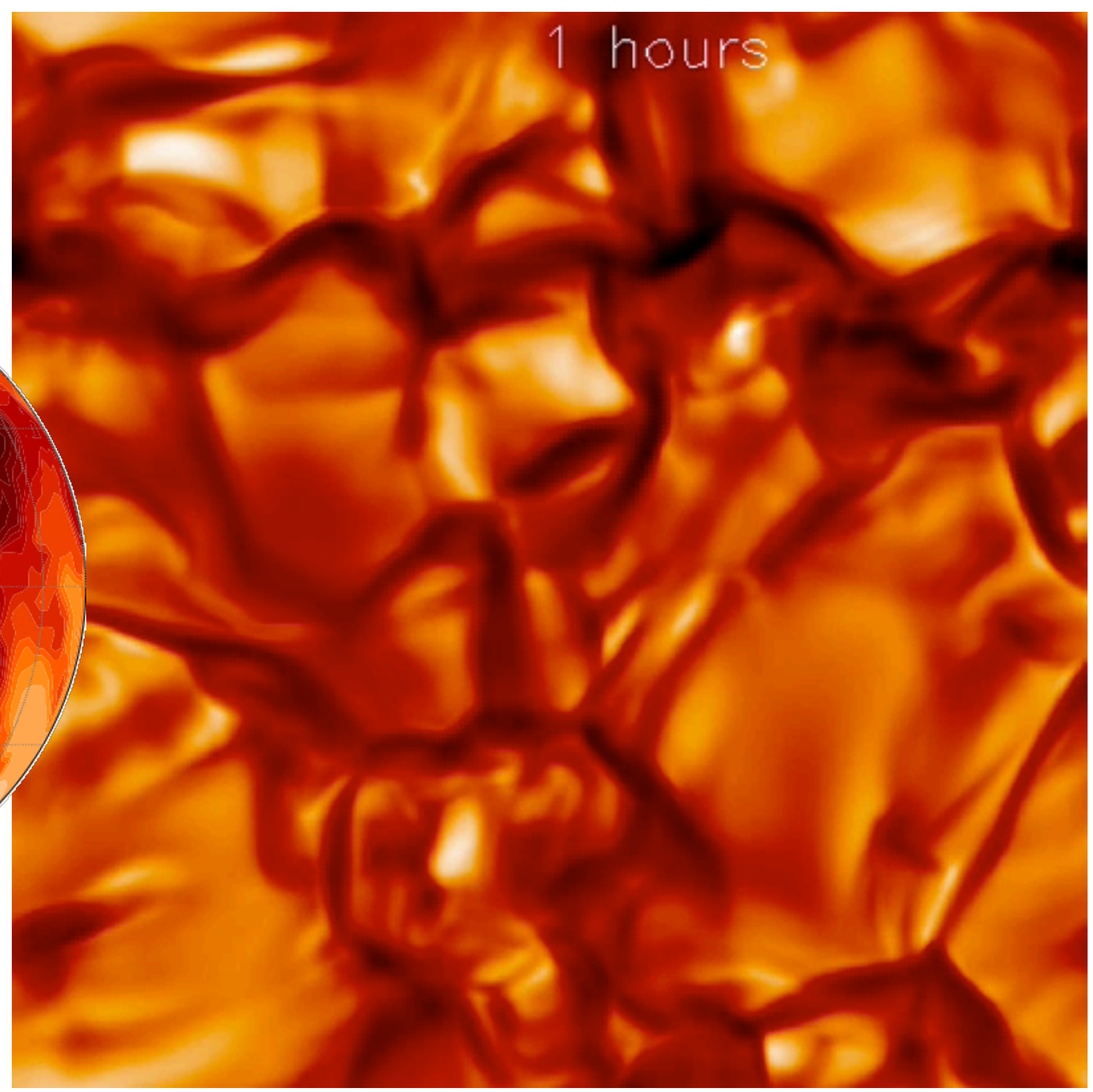
Is the Sun really smooth?

What is the impact of stellar granulation on the observed planetary signal?

- Photometric transits
- Brightness and velocity variability
- High spectral resolution



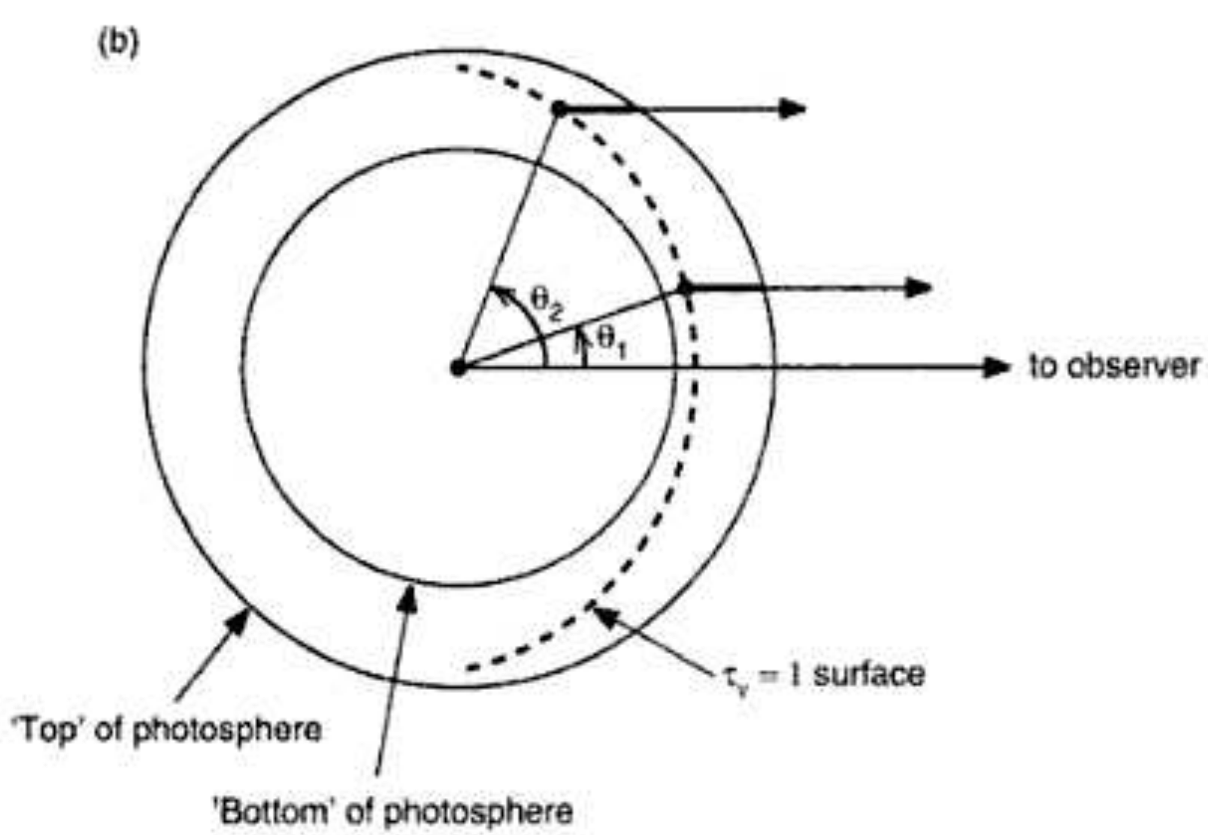




Modelling stellar atmospheres

What is a model atmosphere?

The model atmosphere consists of a table of numbers giving the source function and the pressure as a function of the optical depth and for a particular chemical composition.



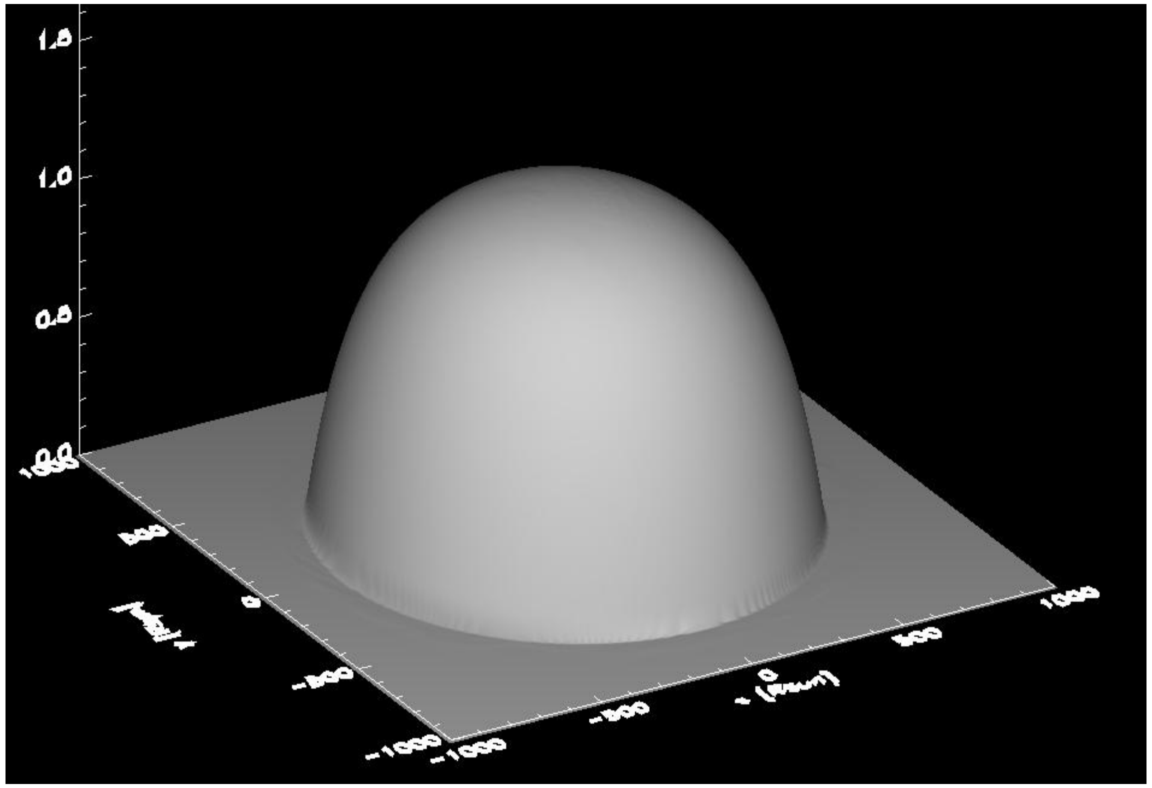
Gray, D.; Stellar Photosphere (book)

One dimensional hydrostatic (since the 70ies)

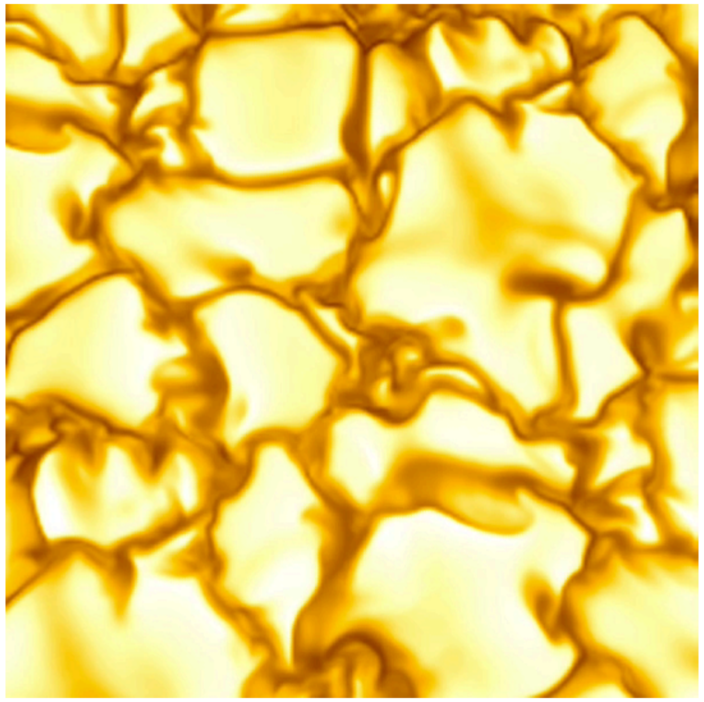
Multi-dimensional hydrostatic (since the 90ies)

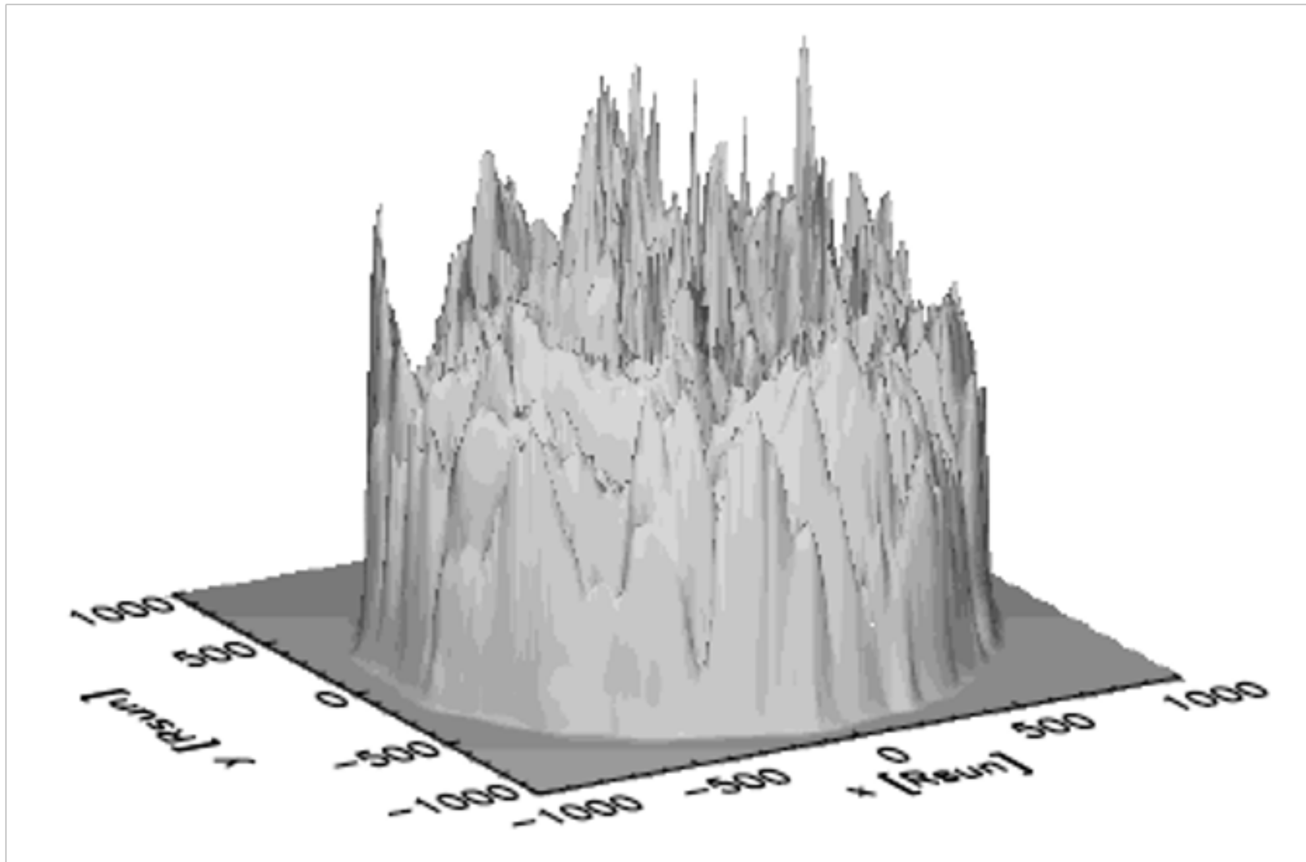
What is a model atmosphere?

1D, since 1970…



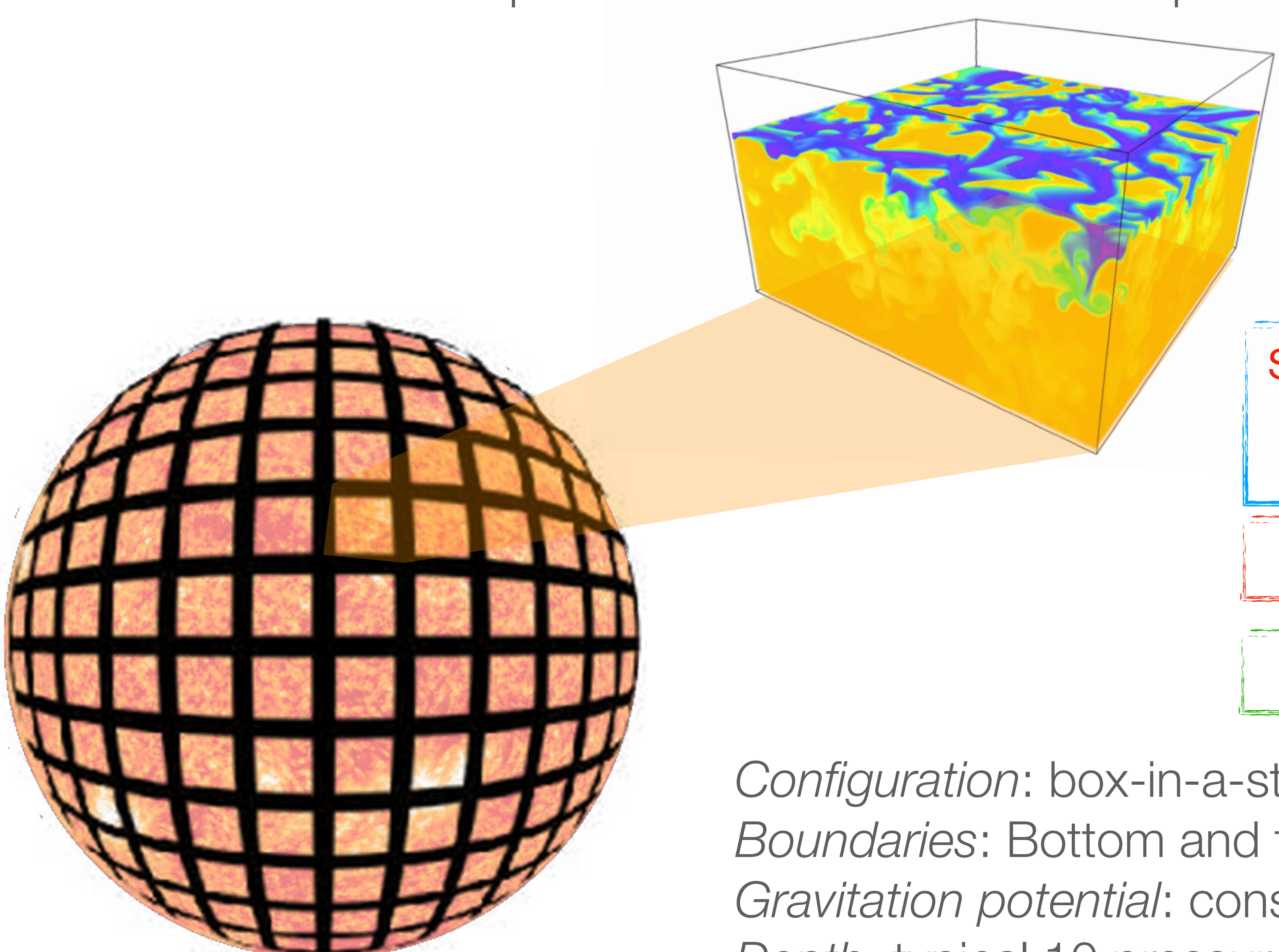
Multi-D, since 1990…





3D (M-)RHD simulations of stellar convection

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



Three main codes:

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

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

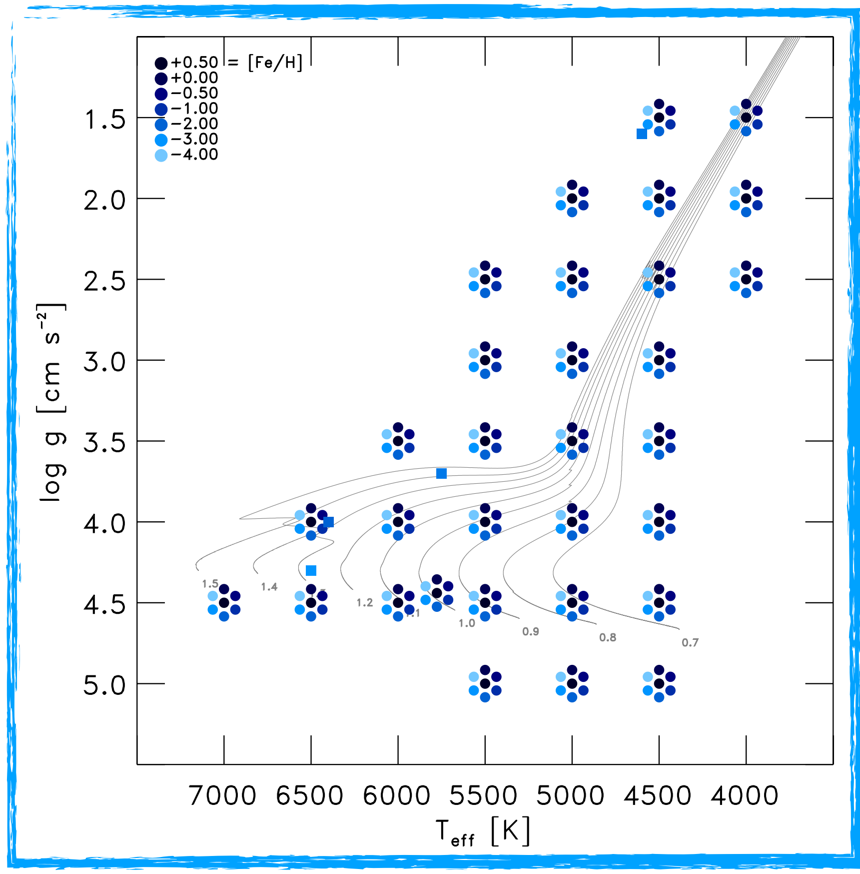
MURaM (Vögler et al. 2005, A&A, 429)

Configuration: box-in-a-star, including about 10 granules
Boundaries: Bottom and top open, periodic on the side
Gravitation potential: constant over the box
Depth: typical 10 pressure scale height
Radiation Scheme: long characteristic, up to 48 bins
Stellar type: Main sequence to Red Giant Branch
Computational time (12 bins): few days to few weeks (MPI)

Available grids of stellar convection simulations

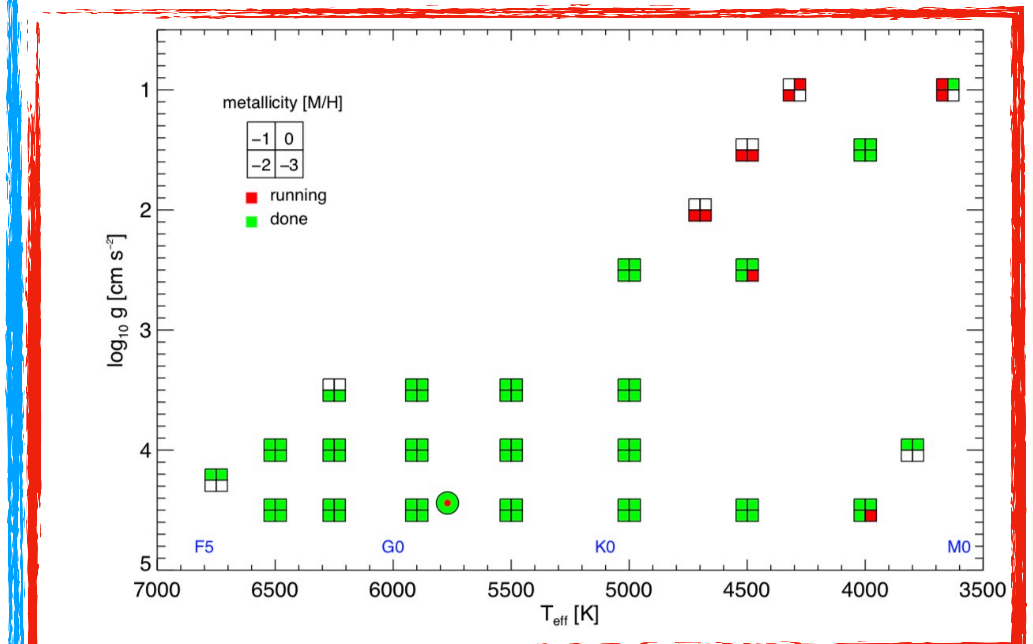
Stagger-Code

Magic et al. 2013, A&A, 557



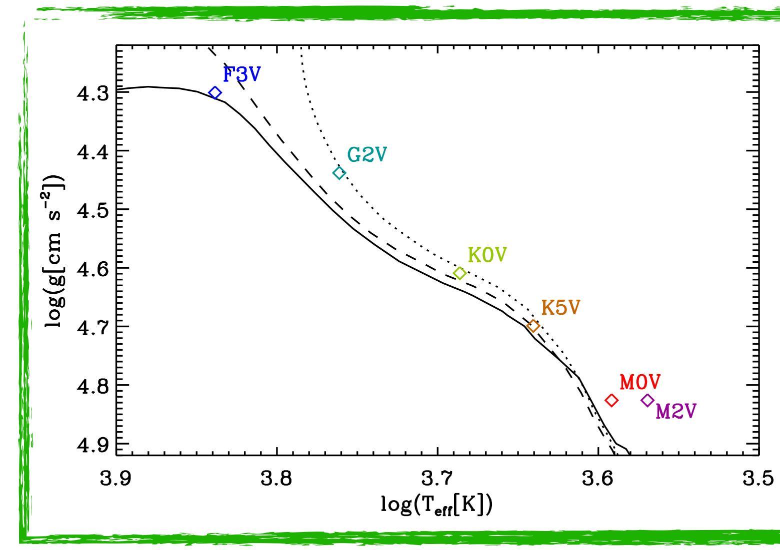
CO5BOLD

Ludwig et al. 2009, Memorie, 80



MURaM

Beeck et al. 2013, A&A, 558



Mostly FGK stellar type stars

Principal planet-related publications:

Magic et al. 2015, A&A
Meunier et al. 2015, A&A
Chiavassa et al. 2014, 2017, 2019 A&A
Flowers et al. 2018, ApJ
Brogi & Line 2019, ApJ
Sulis et al. 2020, 2022, A&A
Maimone et al. 2022, A&A
Debras et al. in prep.

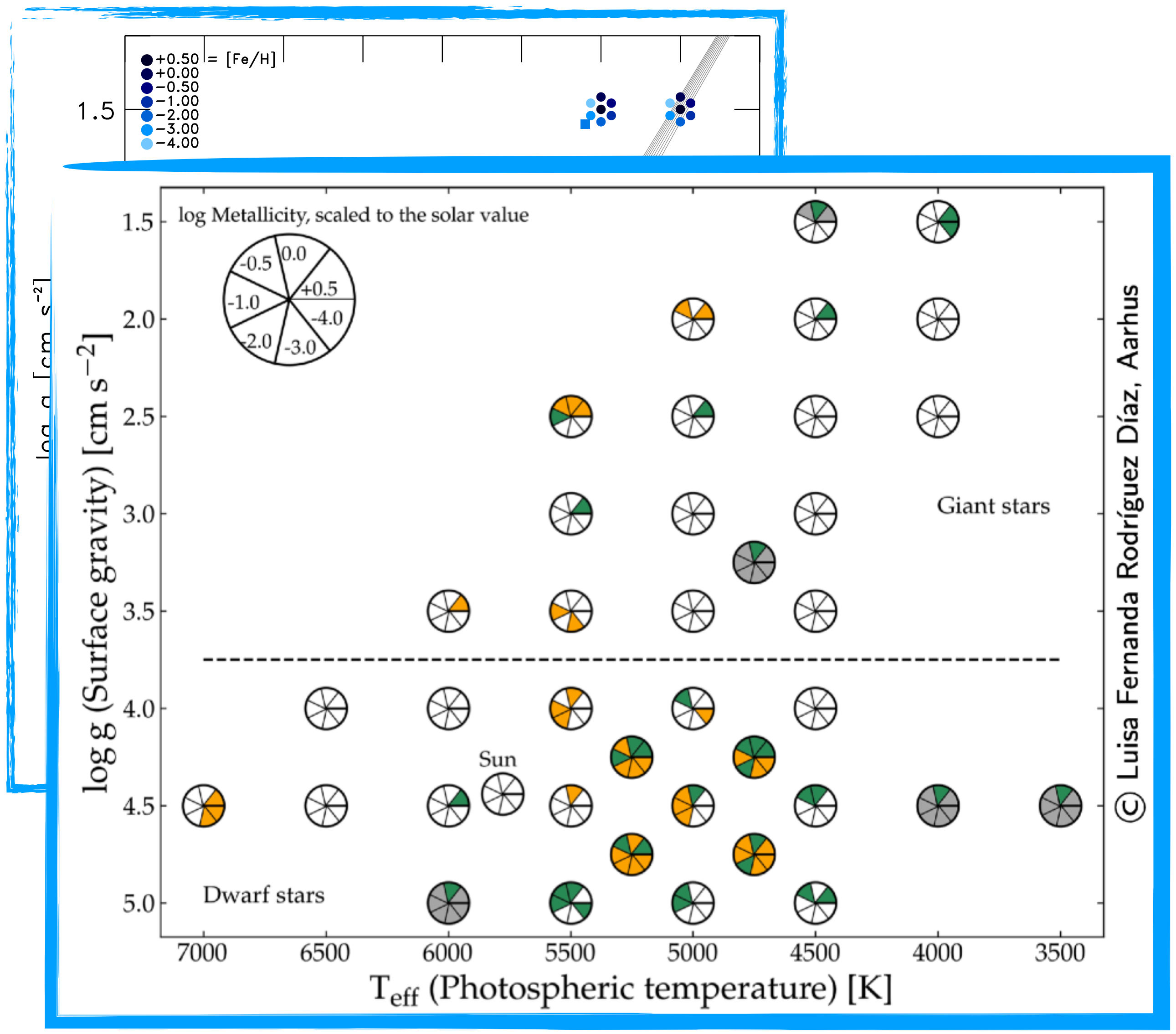
Dravins et al. 2015, A&A
Dravins et al. 2017, A&A
Dravins et al. 2021, A&A

Cegla et al. 2016, A&A
Cegla et al. 2018, A&A
Cegla et al. 2019, A&A
…

… Ongoing extensions

Stagger-Code

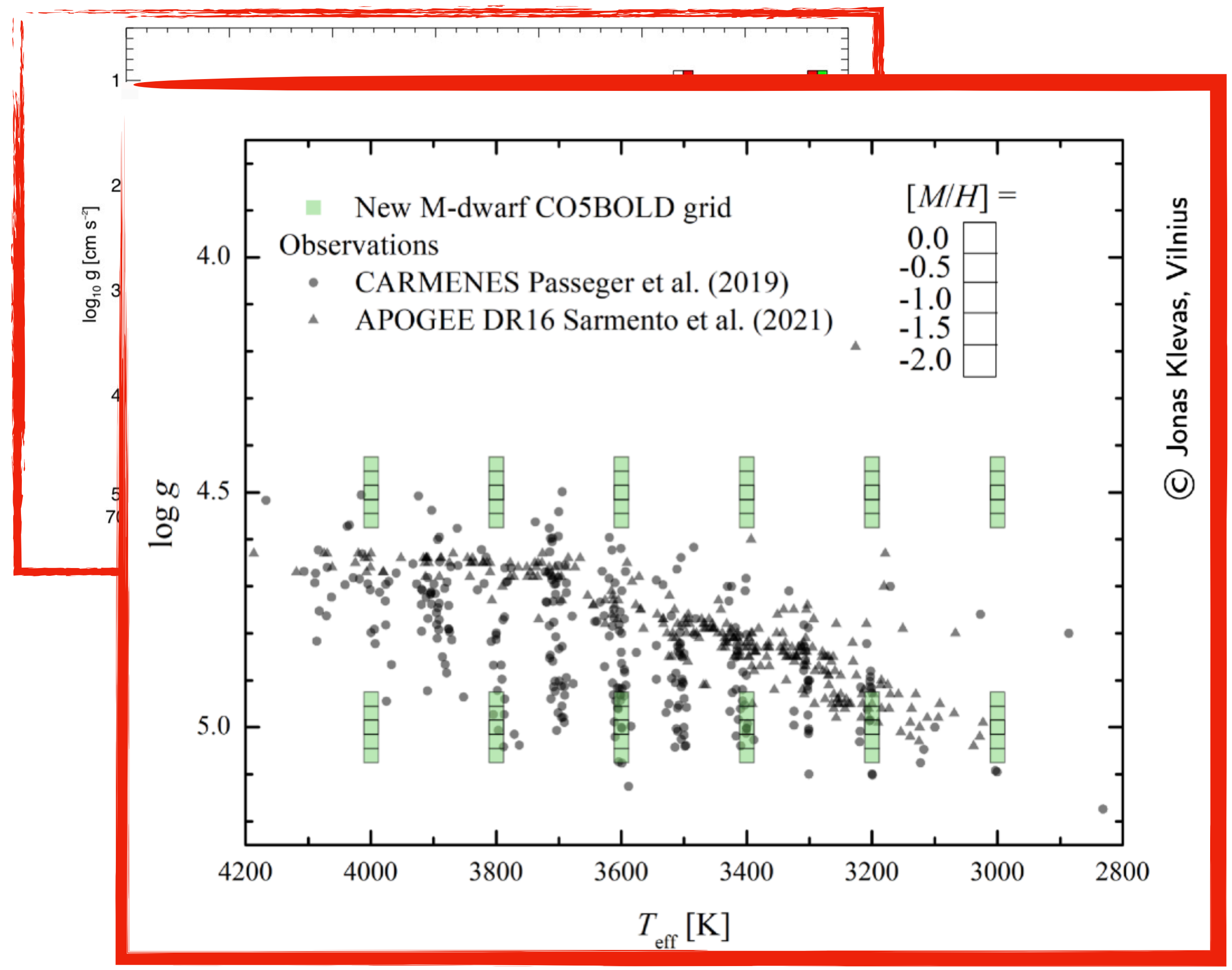
Magic et al. 2013, A&A, 557



Rodriguez Díaz et al. 2022

CO5BOLD

Ludwig et al. 2009, Memorie, 80

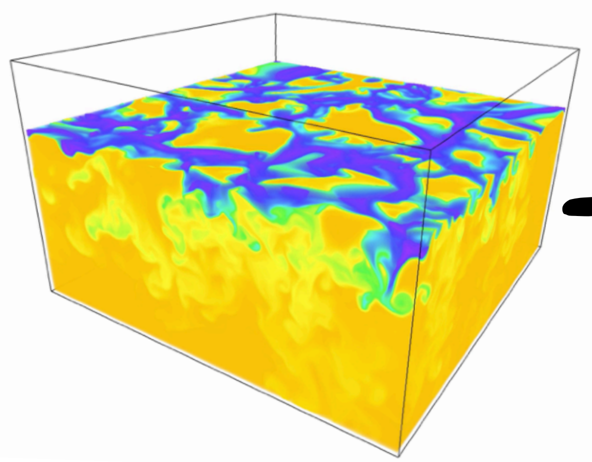


Klevas et al., in prep.

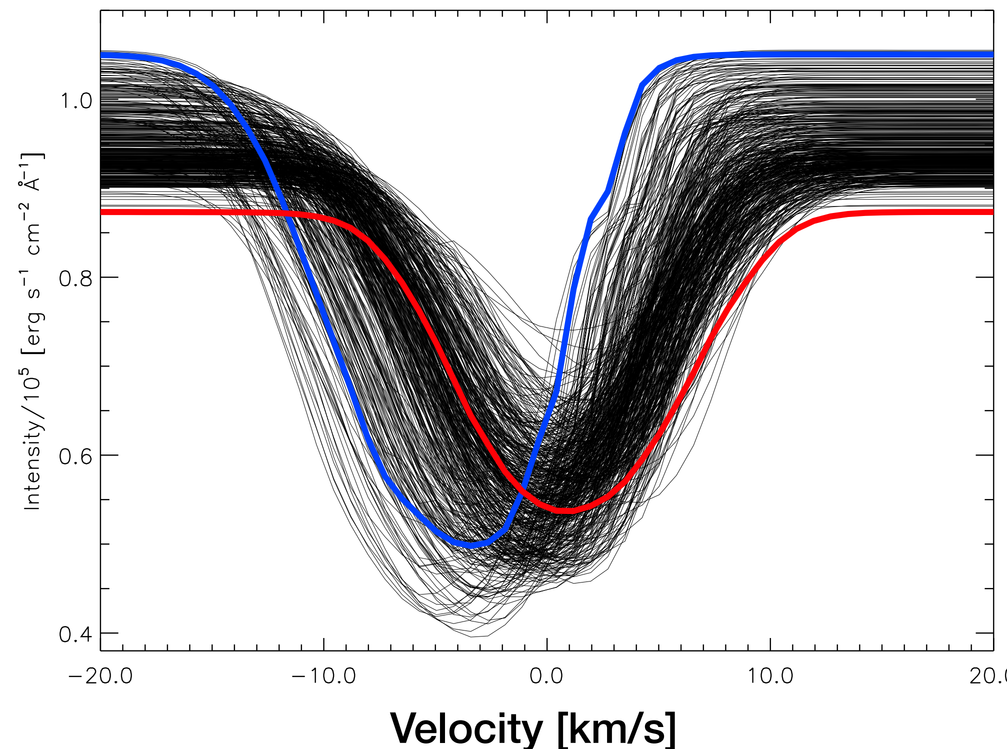
M dwarfs regime

(T_{eff} < 4000 K)

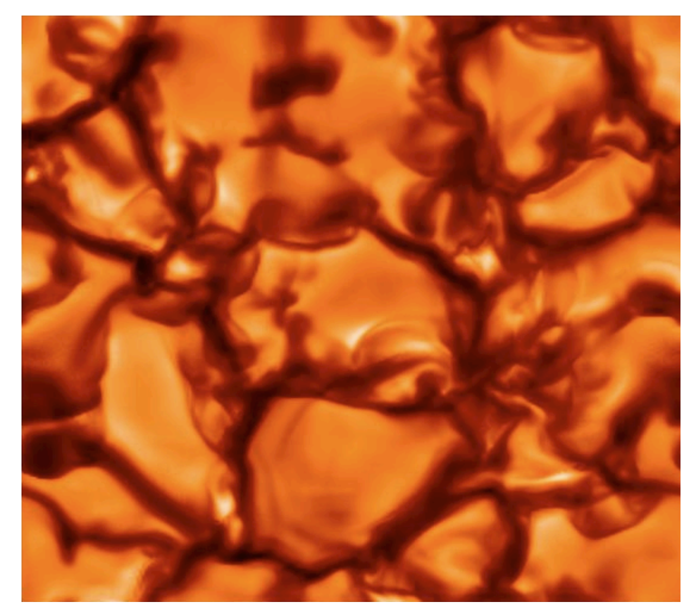
What kind of observables do they produce?



Post-processing
3D radiative transfert



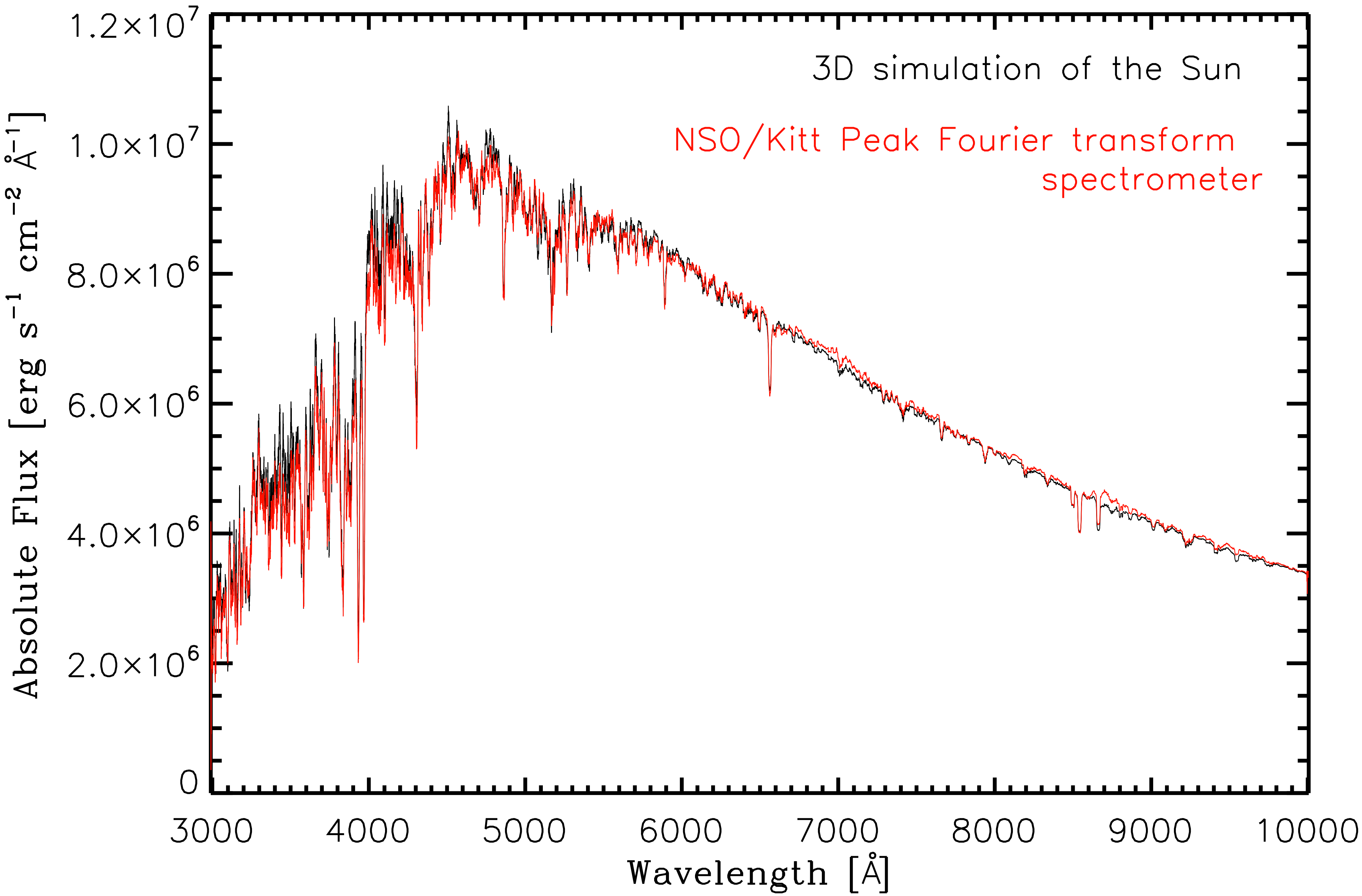
Low (R<20000) and high resolution (R>20000) spectra (photometry for stellar parameters or chemical compositions)



Images to produce semi-global models

Detailed (billions of atomic and spectral lines) and fast (computational time slightly larger than 1D computation) post processing of 3D simulations.

What kind of observables do they produce?



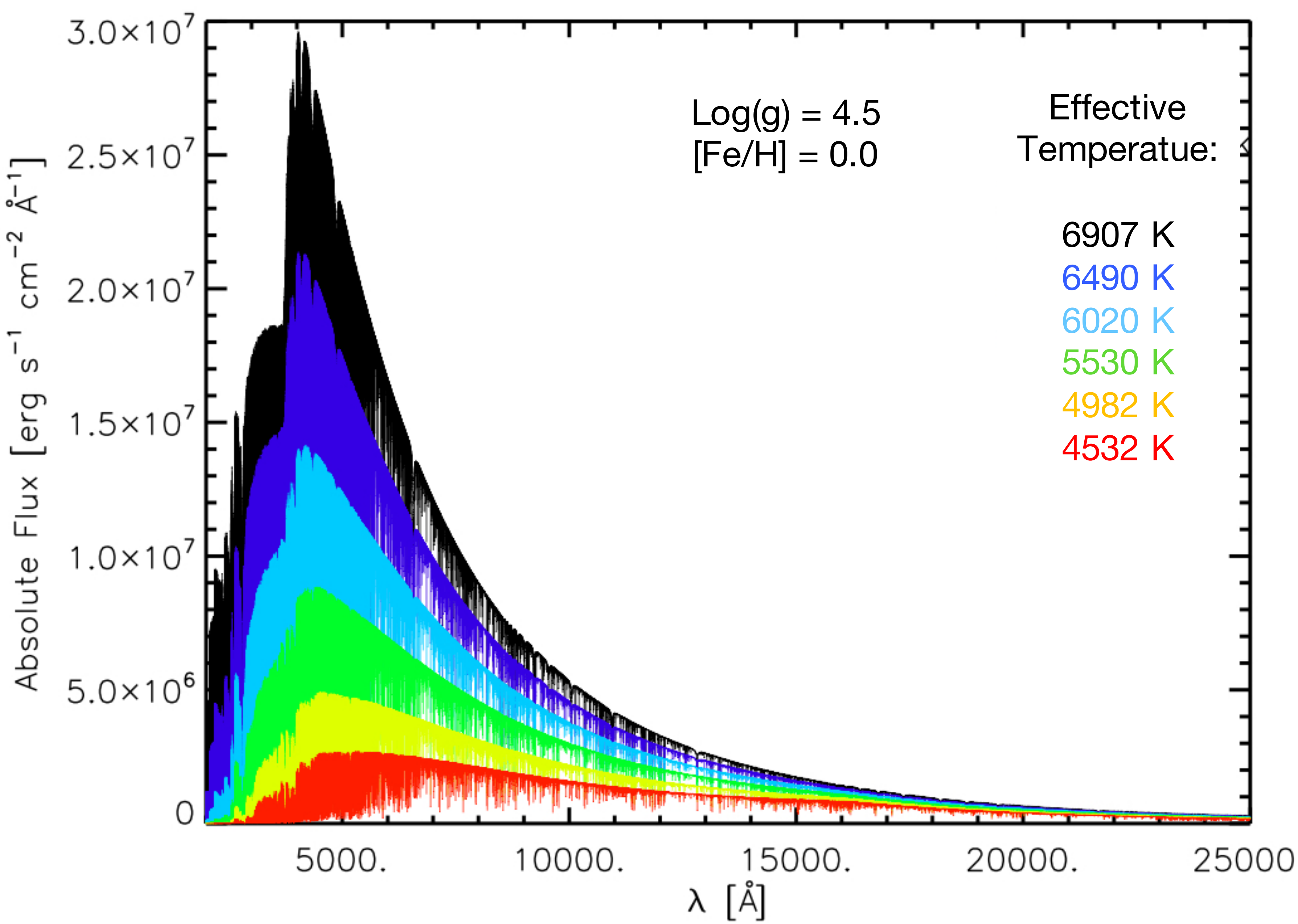
For the Sun, at low resolution, it works very well!

Chiavassa et al., 2018

What kind of observables do they produce?

3D synthetic spectra 2000 and 200000 Å at constant resolution (λ/Δλ) of 20 000.

Study of stellar parameters (see Orlagh's talk) with 3D Bolomentric corrections for all most used photometric systems are available.



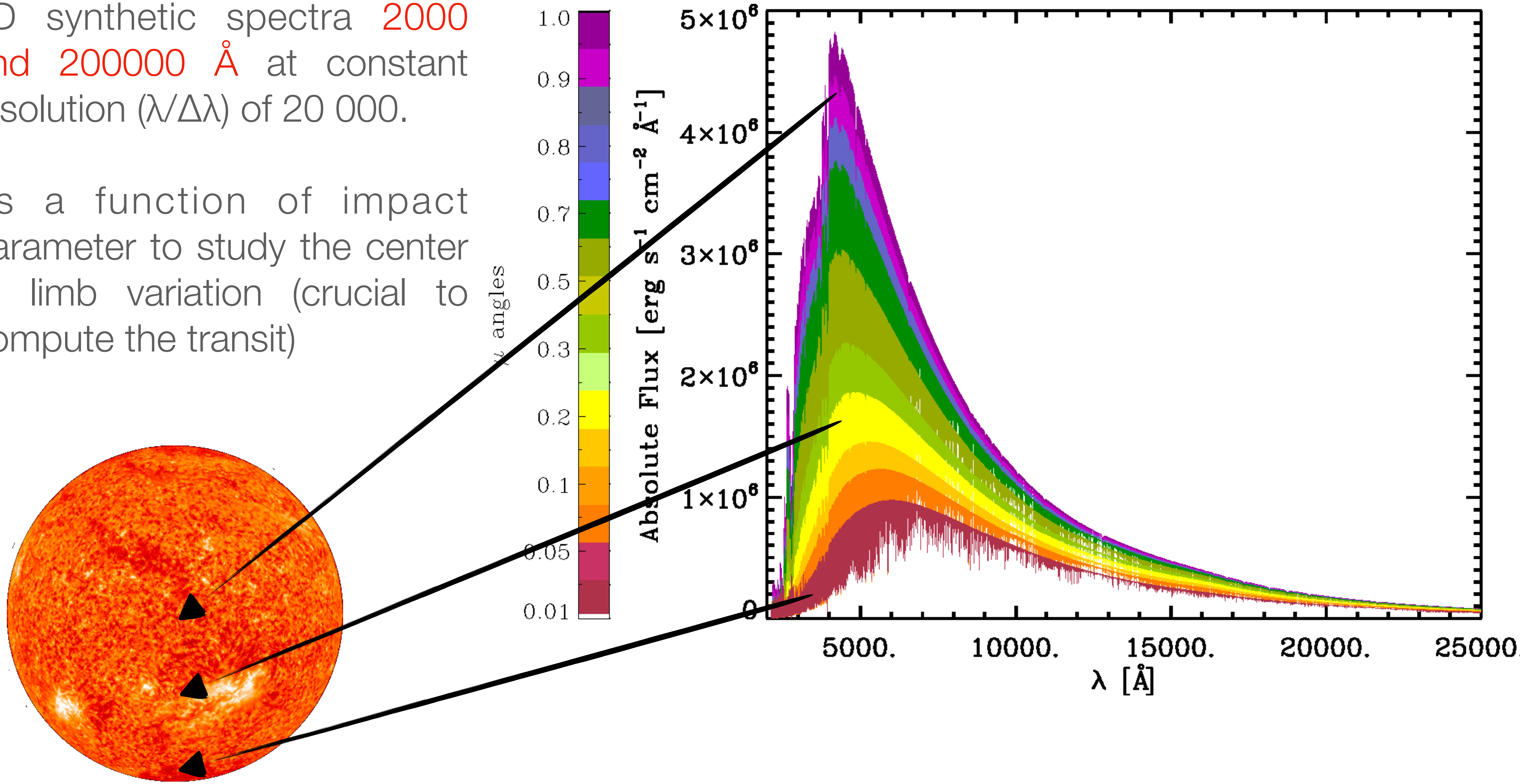
Spectra publicly available on POLLUX database (http://pollux.graal.univ-montp2.fr)

Chiavassa et al., 2018

What kind of observables do they produce?

3D synthetic spectra 2000 and 200000 Å at constant resolution (λ/Δλ) of 20 000.

As a function of impact parameter to study the center to limb variation (crucial to compute the transit)



Spectra publicly available on POLLUX database (http://pollux.graal.univ-montp2.fr)

Chiavassa et al., 2018

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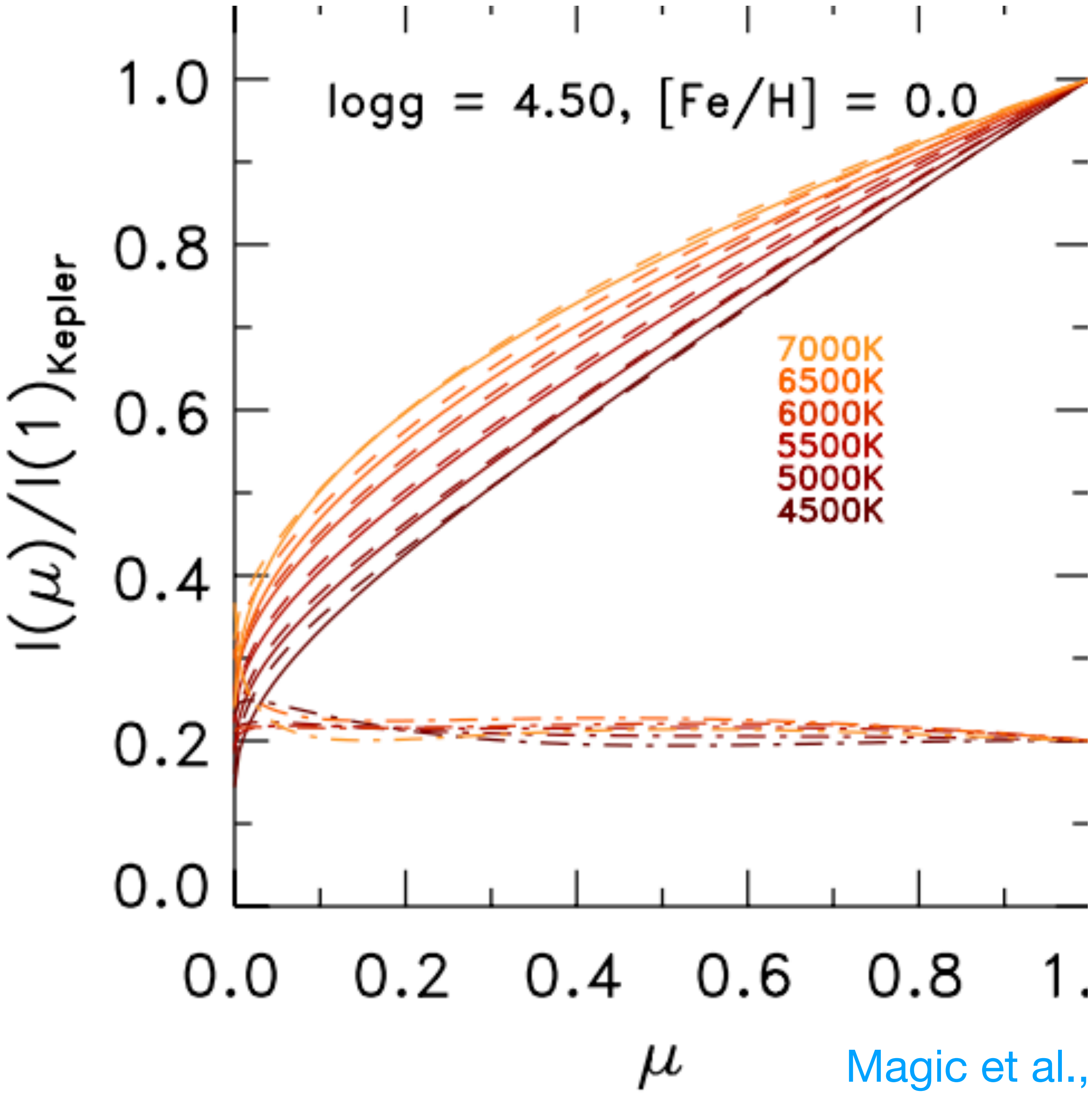


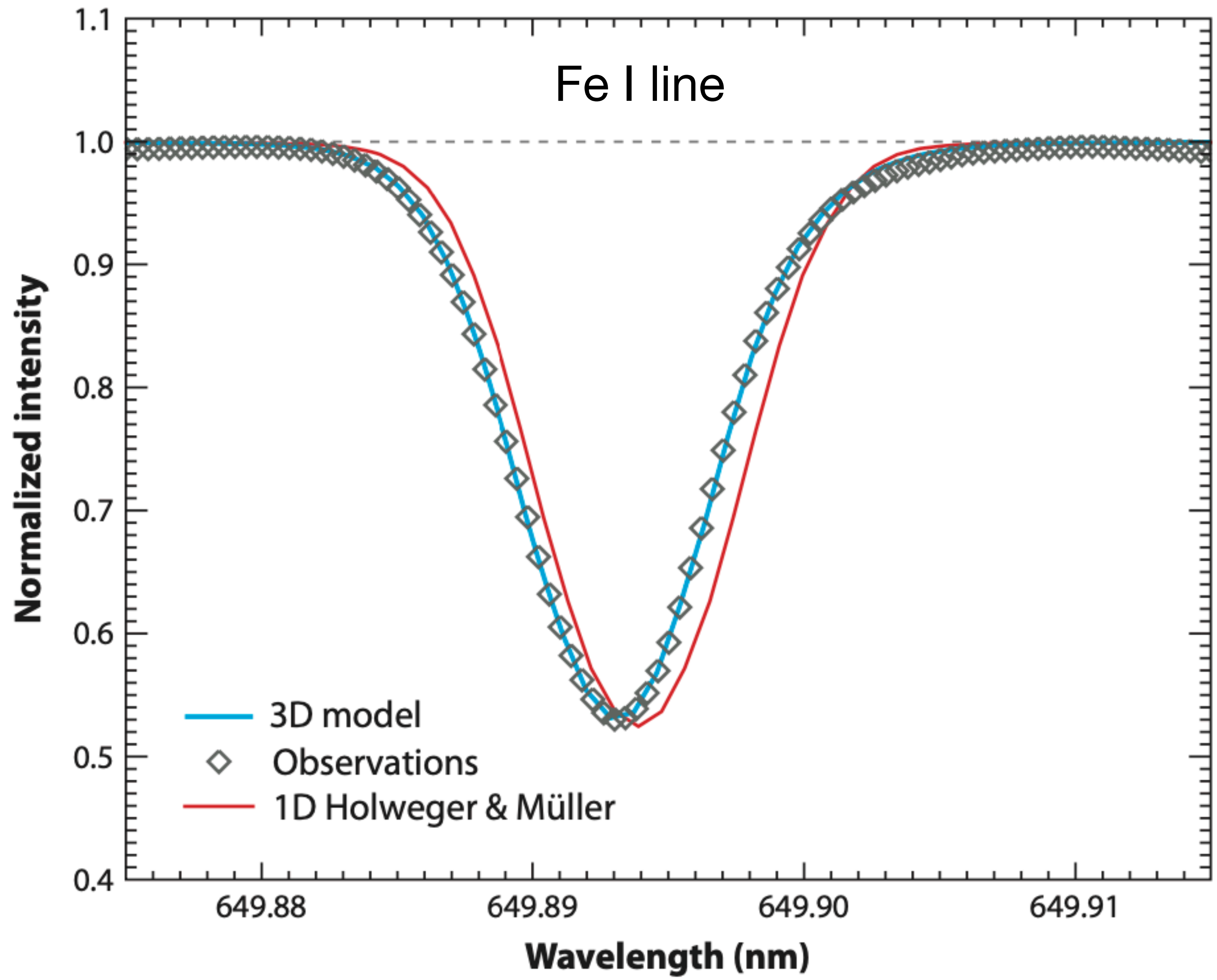
Magic et al., 2015

Spectra publicly available on POLLUX database (http://pollux.graal.univ-montp2.fr)

Chiavassa et al., 2018

What kind of observables do they produce?

Measurements of solar (stellar) abundances that you likely use in your codes or plotting reference for the Sun



There is not a complete agreement on the abundances.
Which one has to be taken?
The differences are not negligible (up to 20% for some elements)

Asplund et al., 2009, 2020
Stagger-code LTE

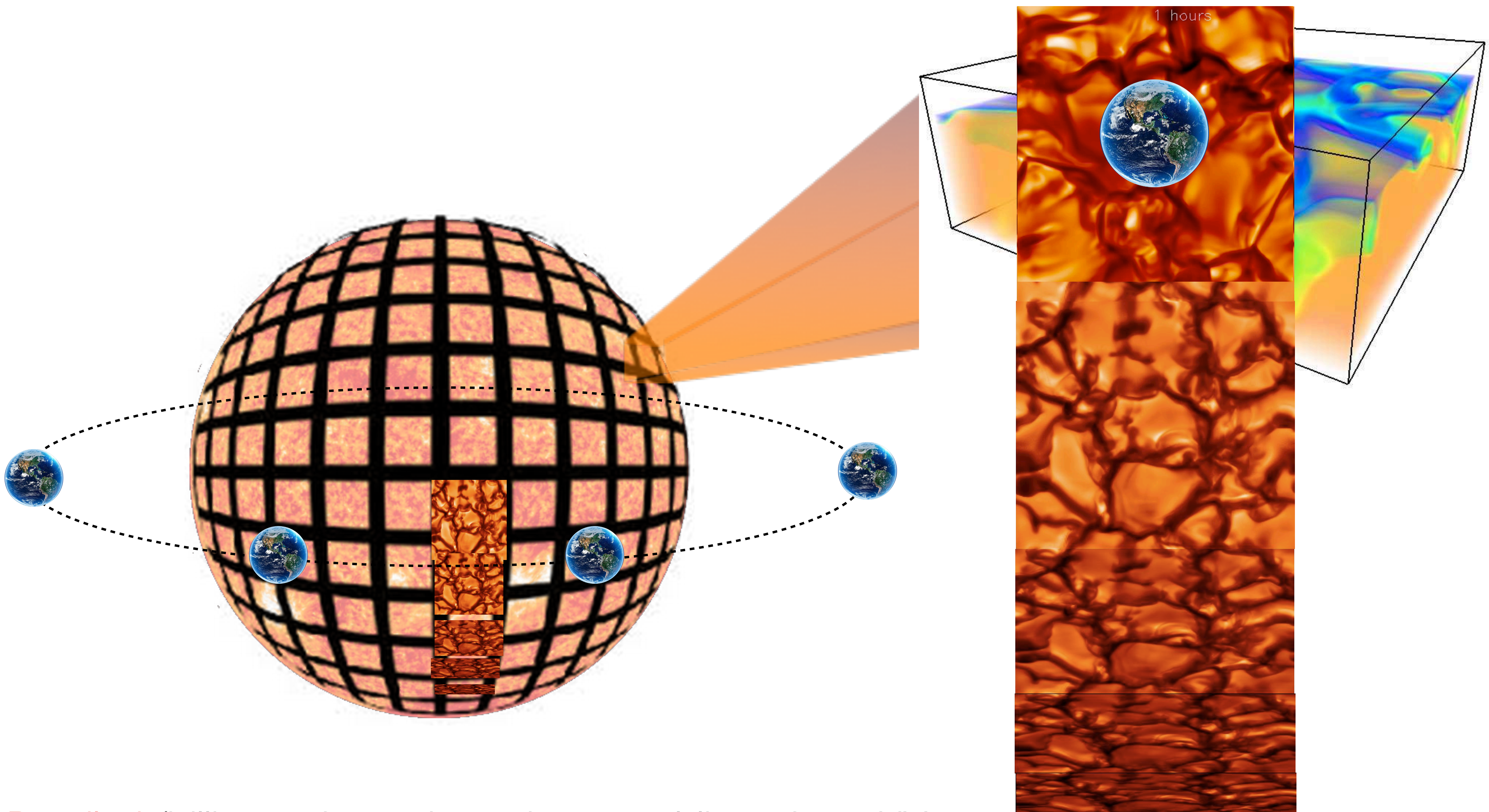
Caffau et al., 2011
Co5bold LTE

Amarsi et al., 2021
Stagger-code LTE (new analysis on molecules)

Magg et al., 2022
1D NLTE analysis

Photometric transits

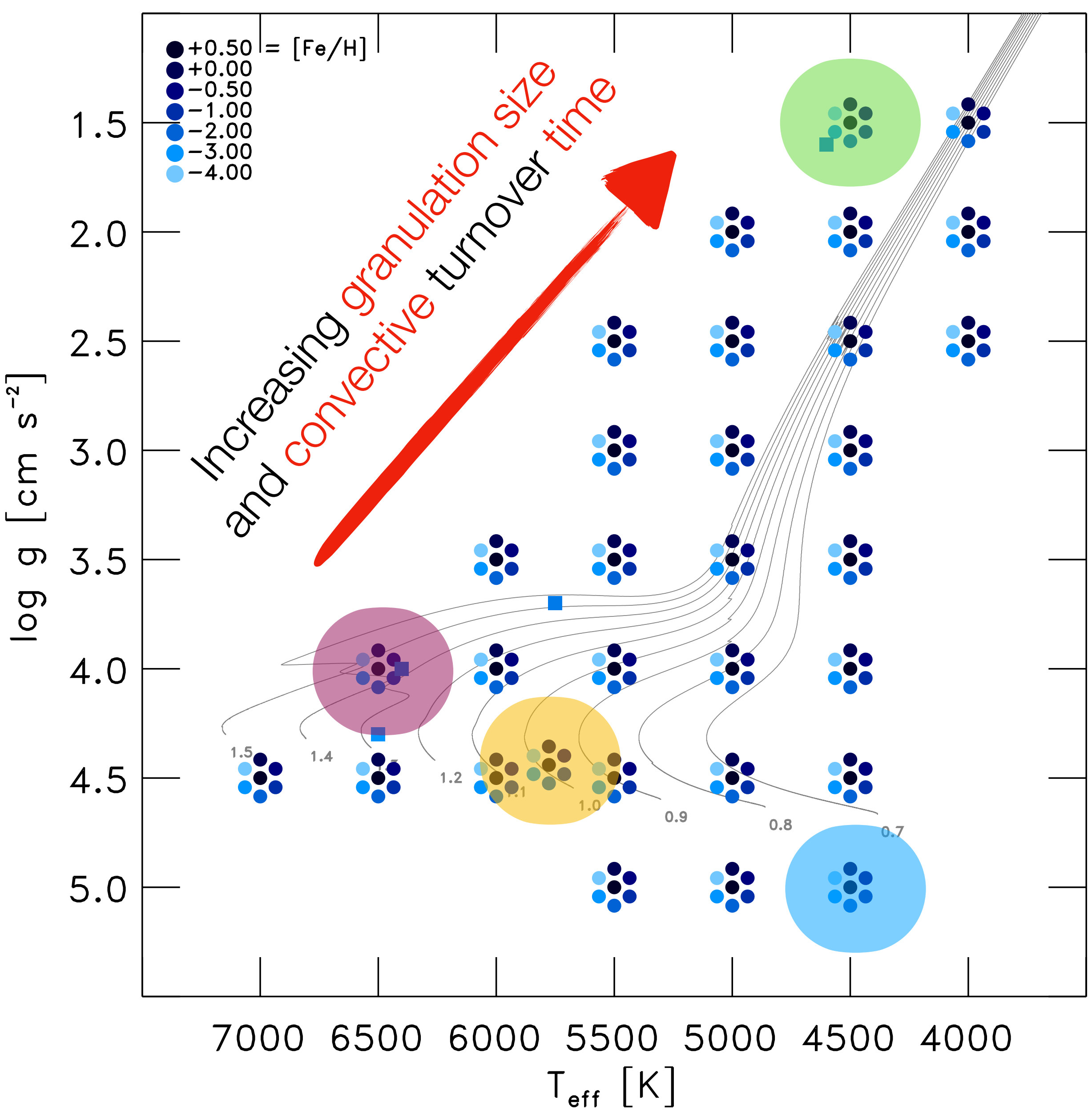
Semi-global models of stellar surfaces

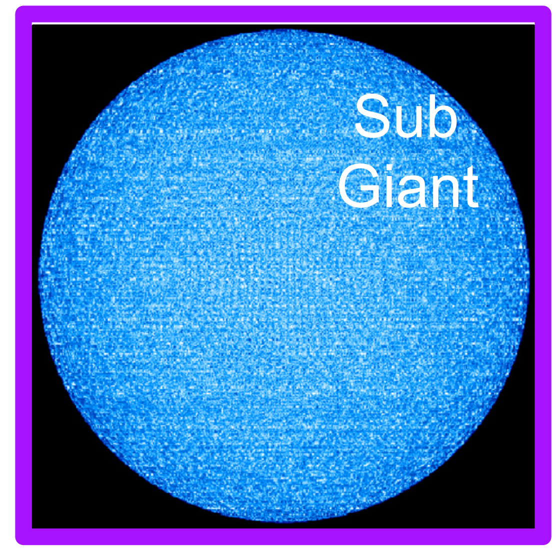


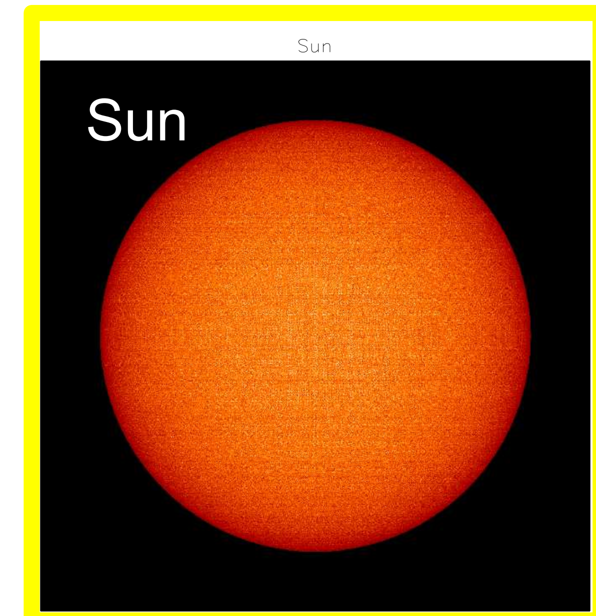
Detailed (billions of atomic and spectral lines from UV to far IR) and fast post processing of 3D simulations with *Optim3D* (Chiavassa et al. 2009, A&A, 506, 1351)

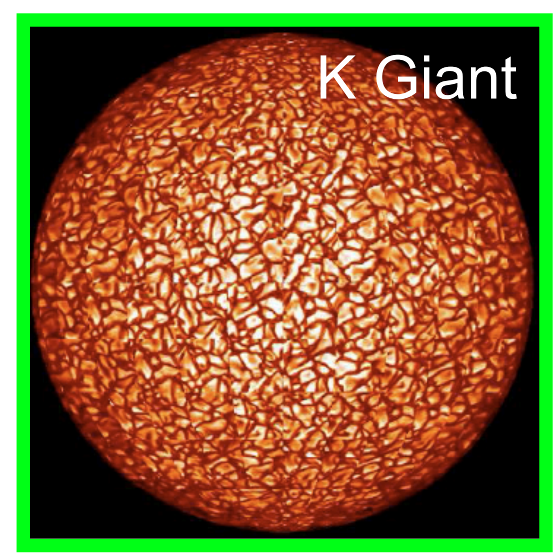
Semi-global models of stellar surfaces

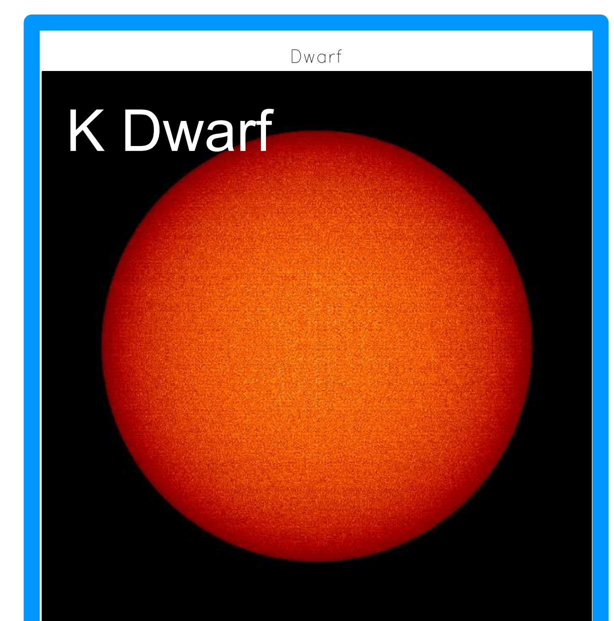
Over 200 3D surface convection simulations of FGK stars (Stagger-grid, Magic et al. 2013)





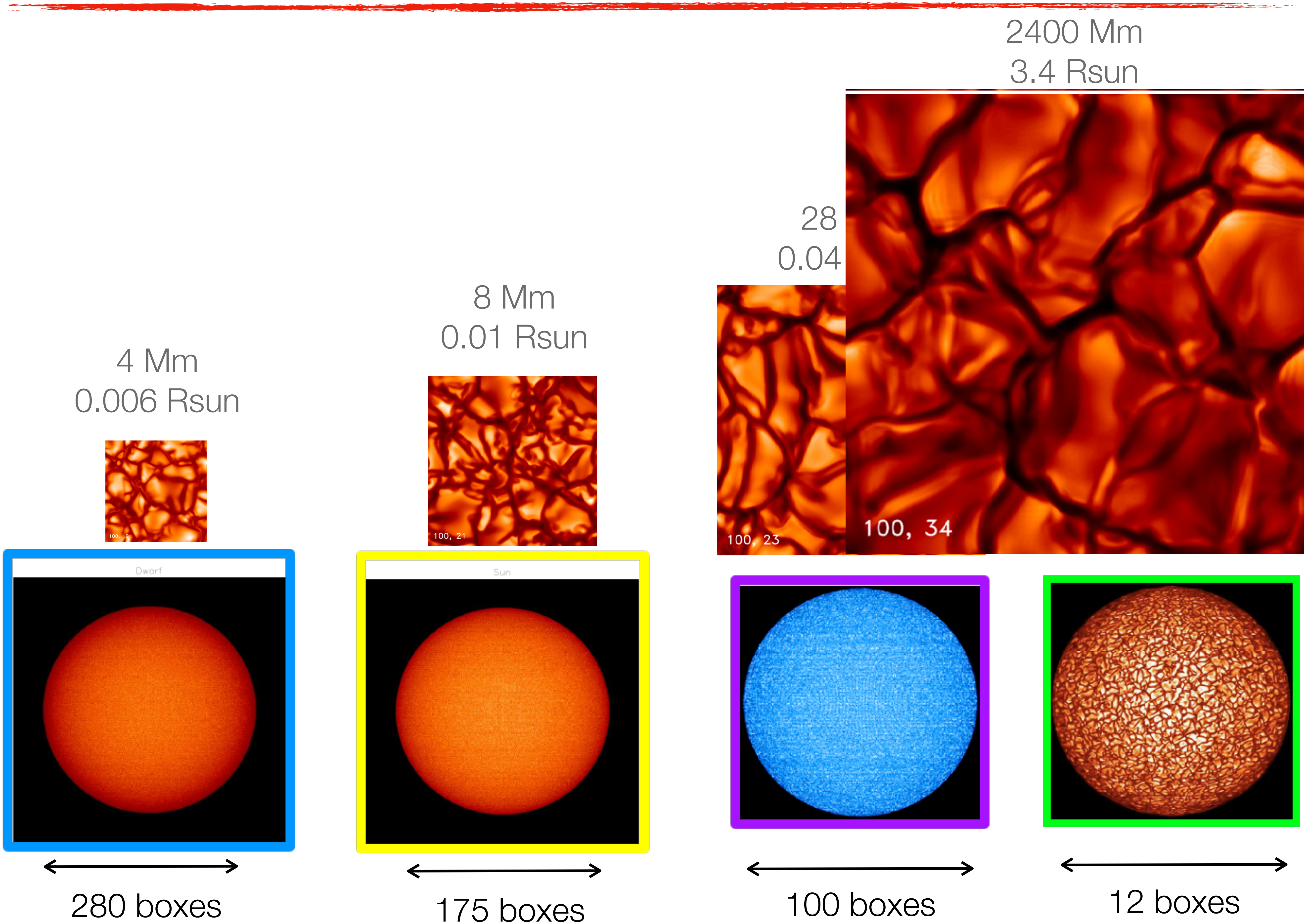




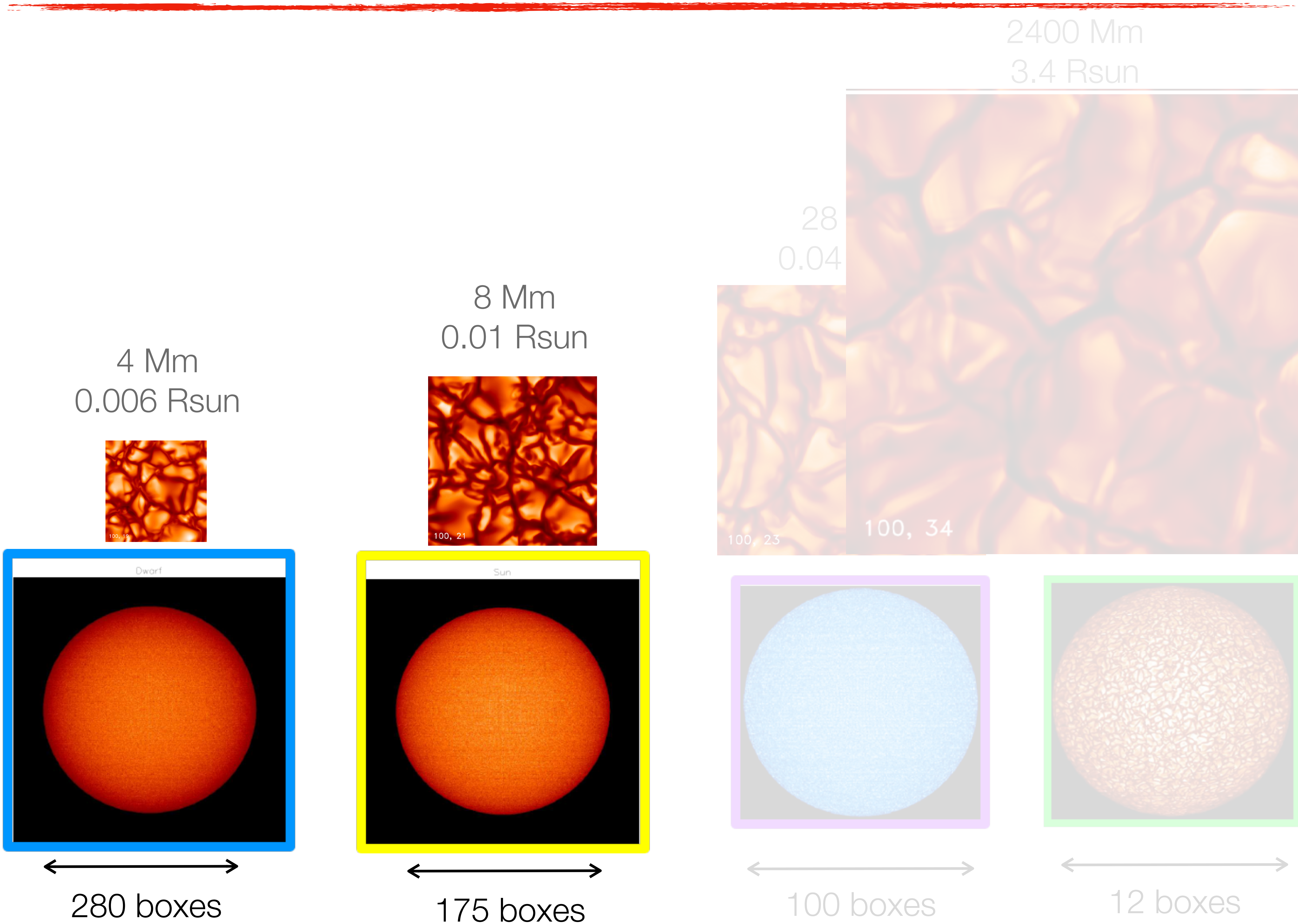


Chiavassa et al., A&A 2017, 2014, 2012, 2010; Bigot et al. 2006, 2011

Semi-global models of stellar surfaces



Semi-global models of stellar surfaces



Stellar photometric variability

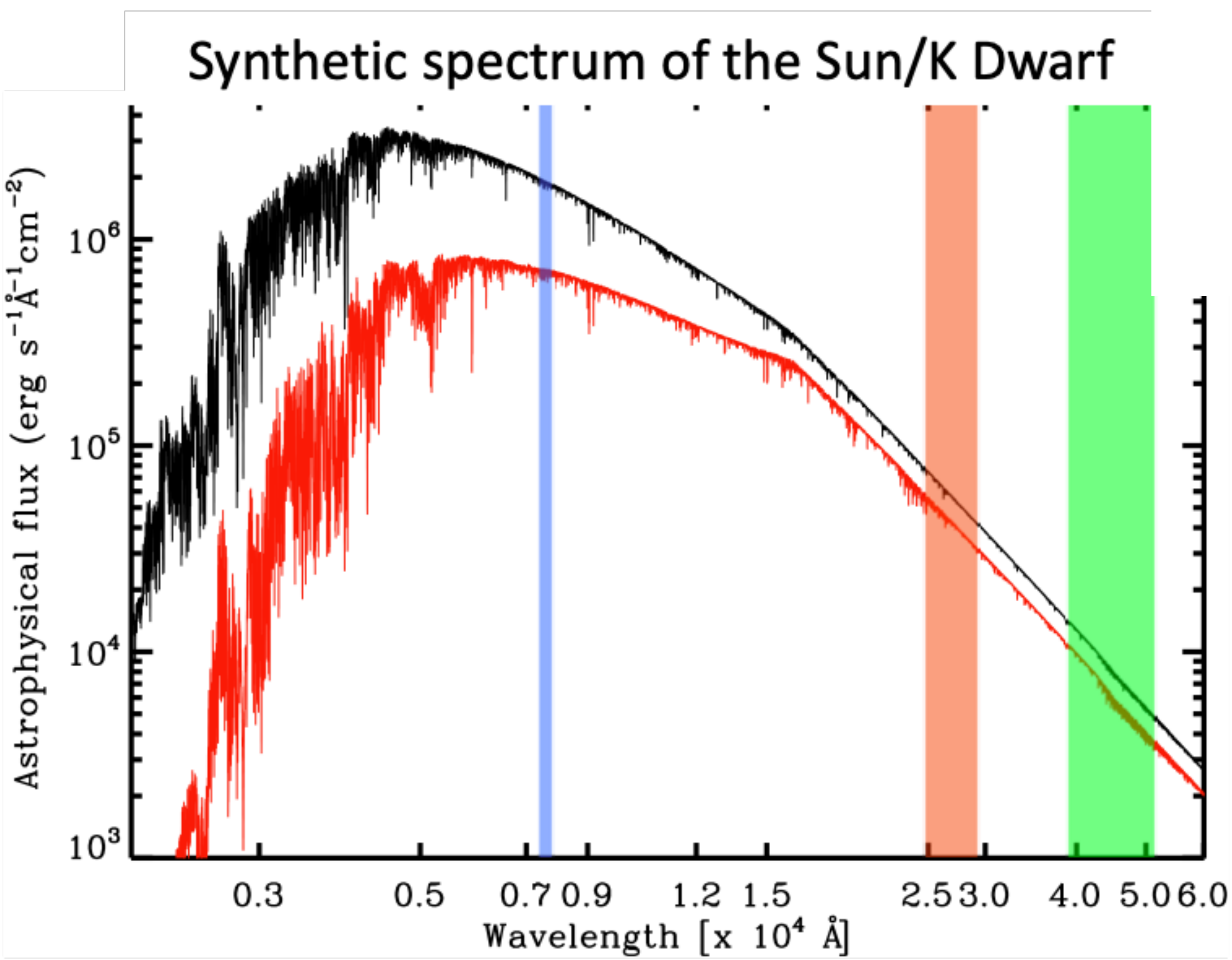
$$\varphi_\star = I_\star(\lambda) \cdot$$

R = spectral resolution

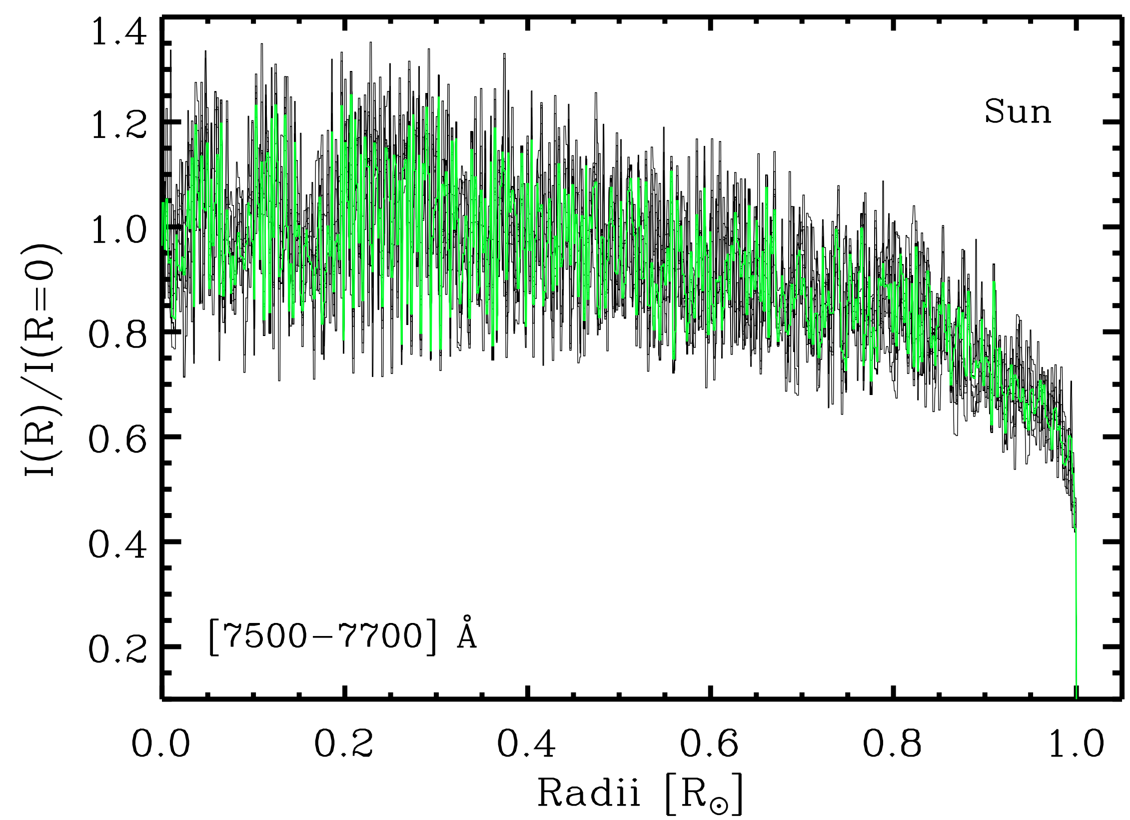
S = 7844 cm of surface collector for a 100 cm dia

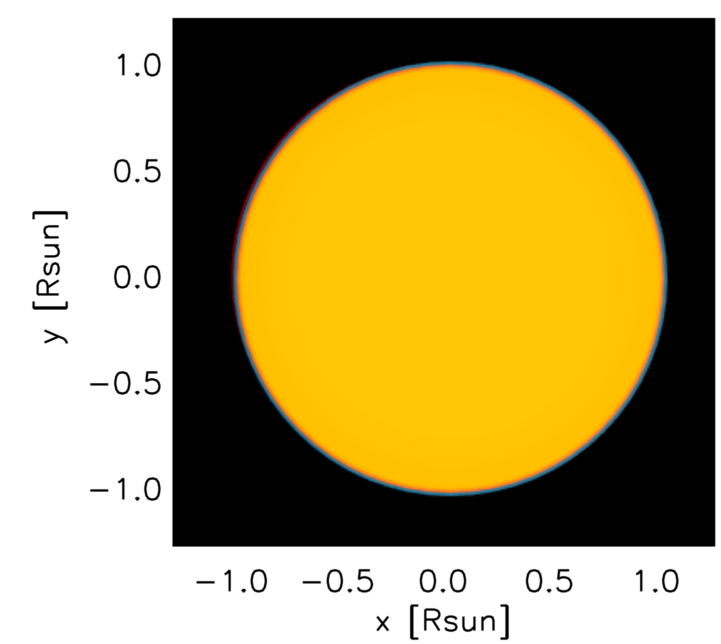
ε = 0.15 electron/photon net efficency

Δt = 7 hours



Synthetic Sun

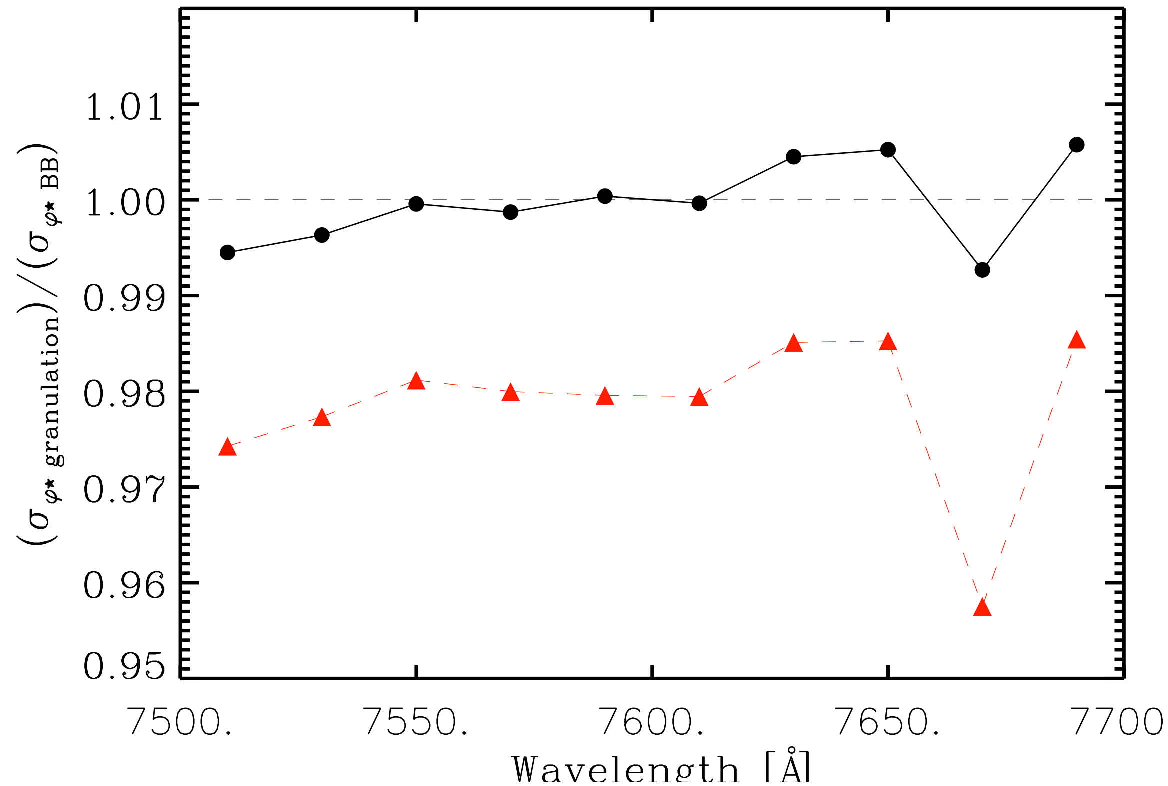




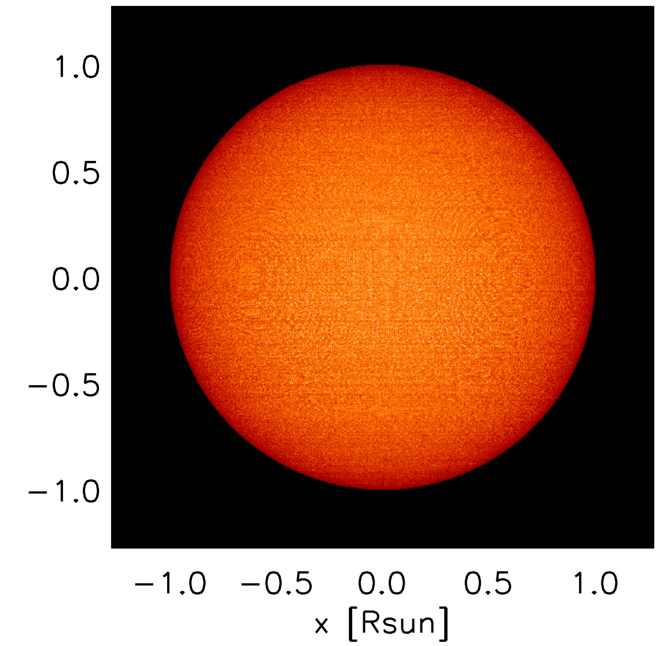
Stellar photometric variability

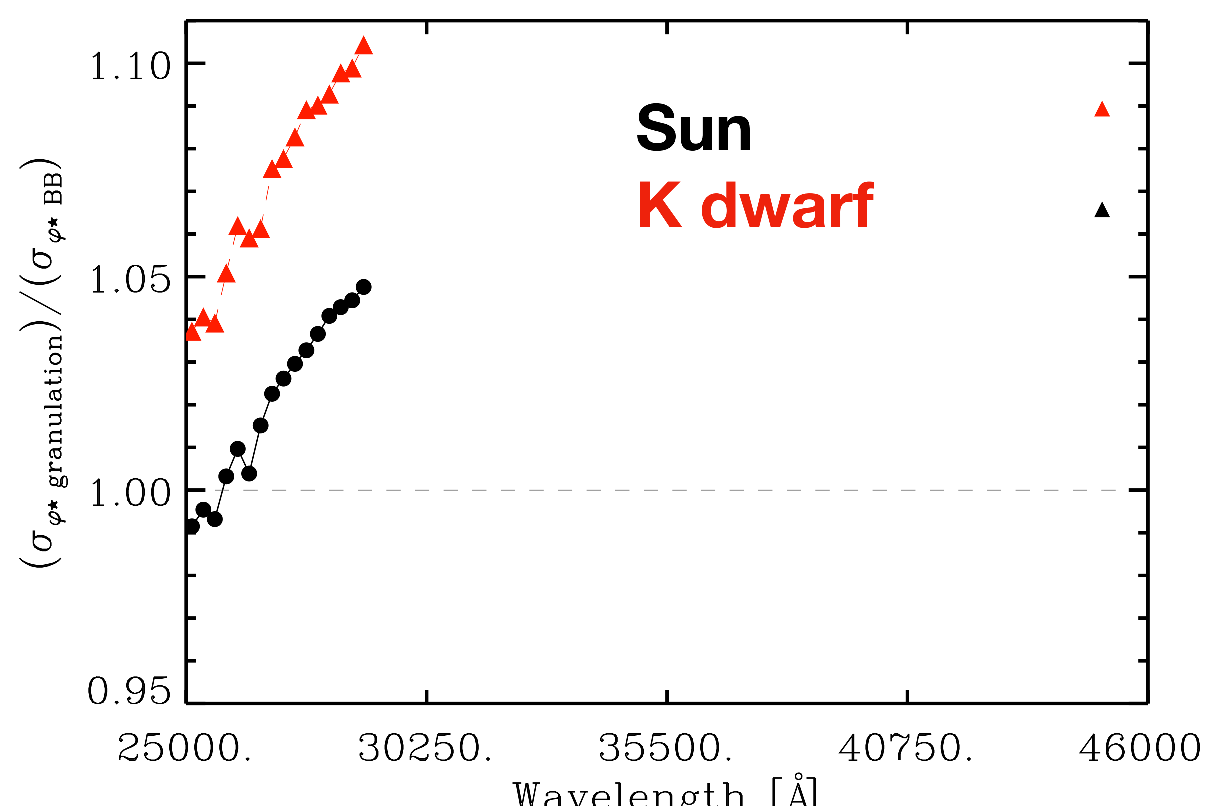
Granulation affects the photon noise in various wavelength ranges compared to the black-body (BB).

Uncertainties based on the BB can overestimate or underestimate the uncertainties, depending on the wavelength range considered

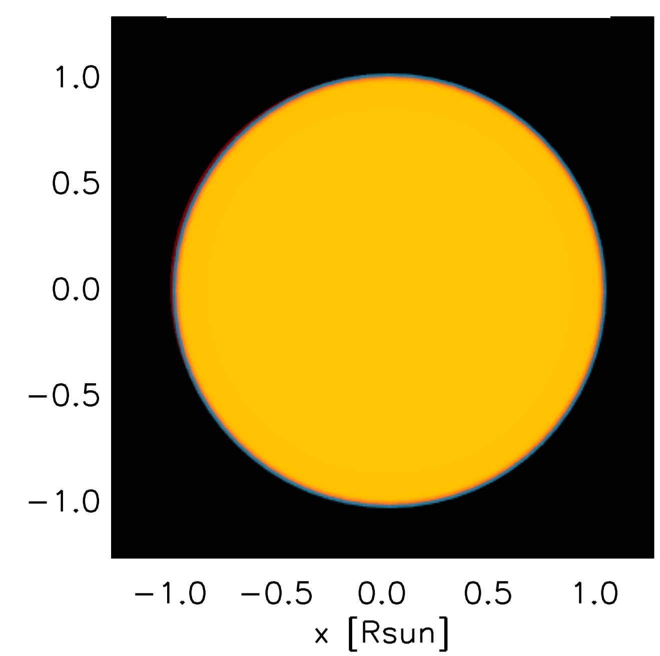


Synthetic Sun



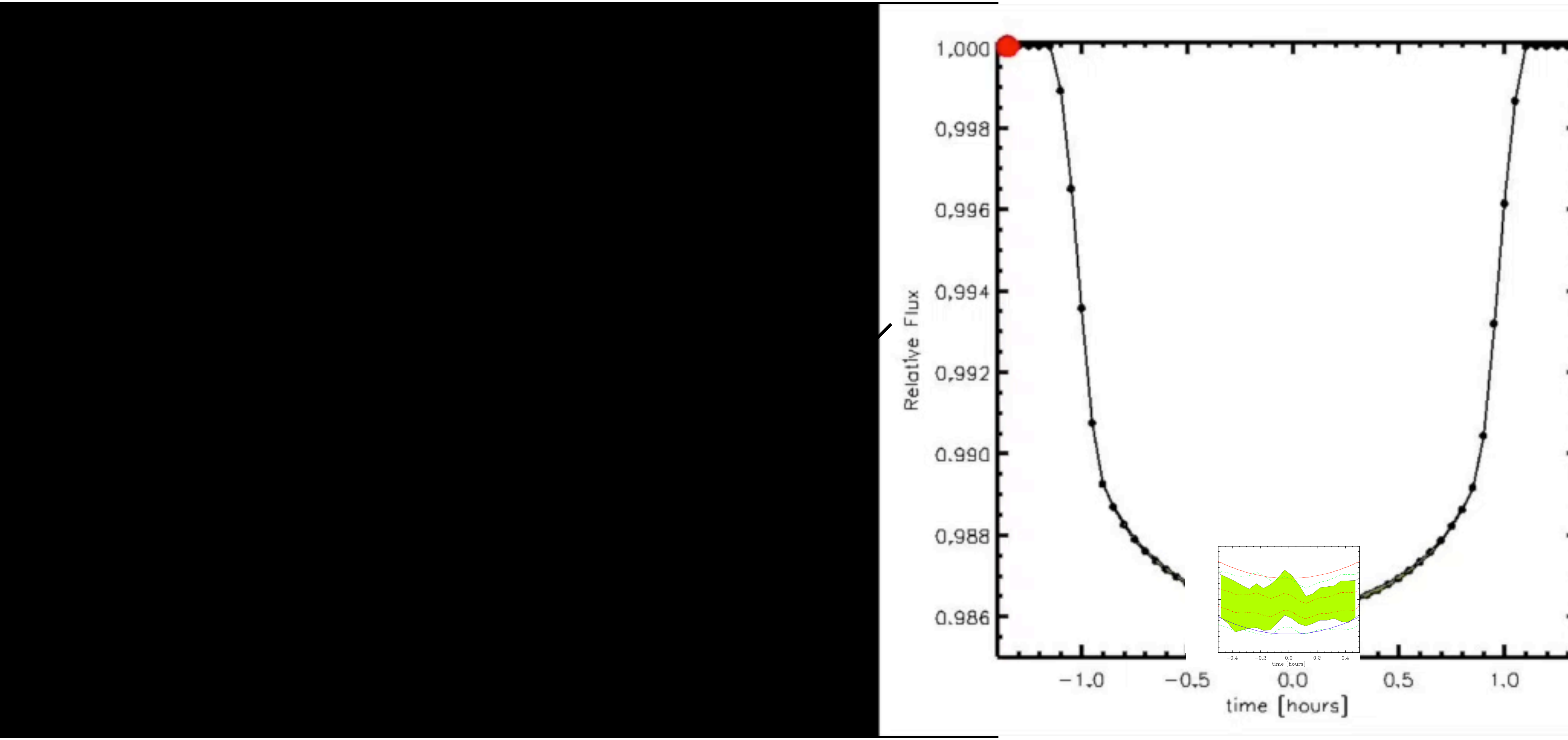


Black Body



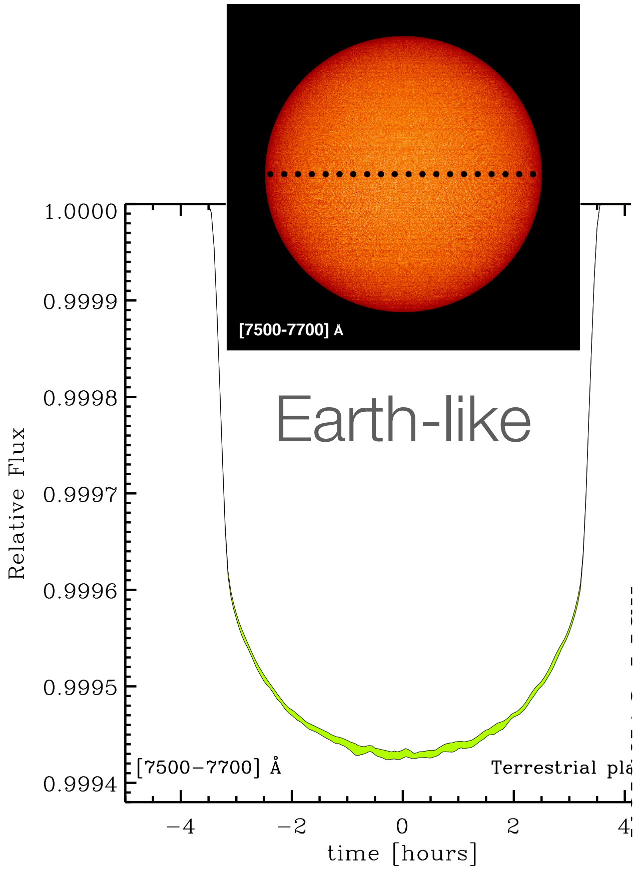
Chiavassa et al., A&A 2017

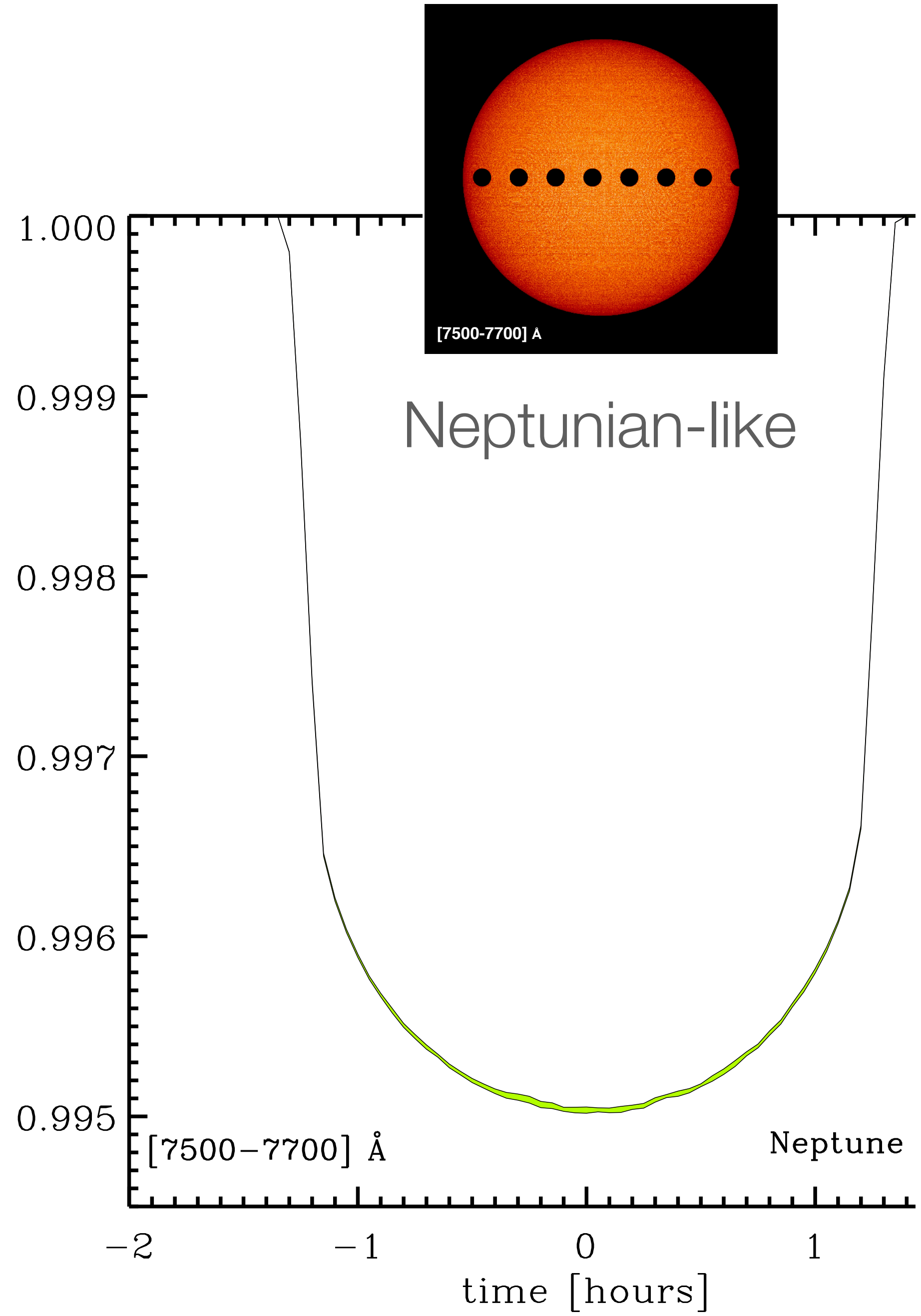
Synthetic transit for different planet sizes

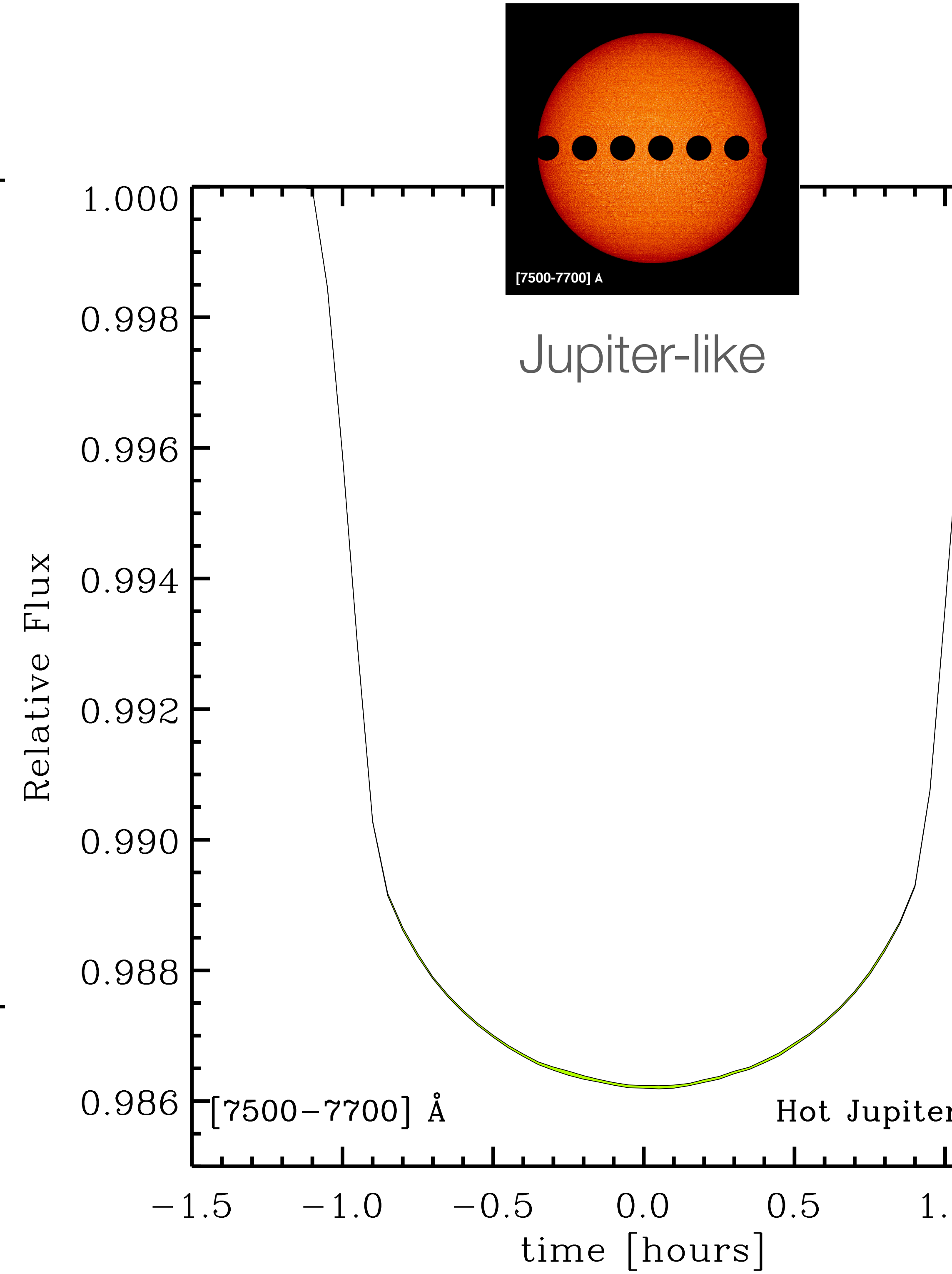


Sun and Hot Jupiter synthetic transit in (Chiavassa, Caldas, Selsis et al. 2017)
Timescale of the granulation: 5-10 minutes
Transit time: 1.8 hours

Synthetic transit for different planet sizes





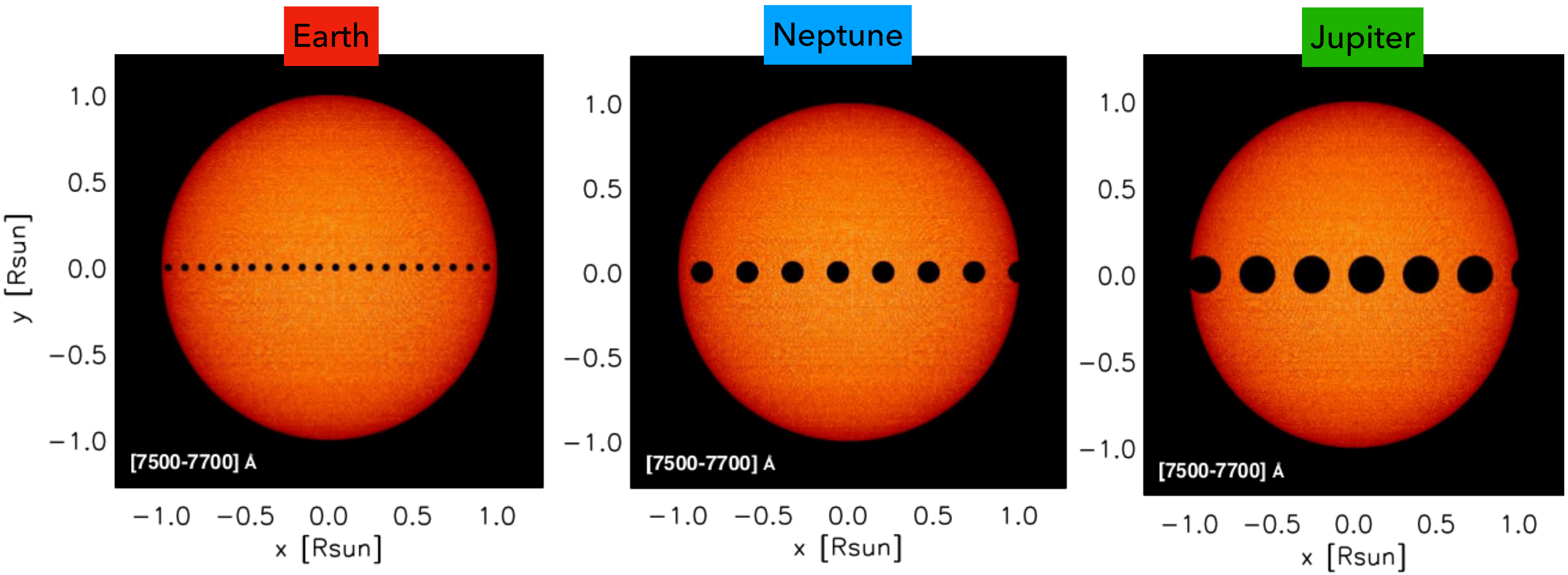


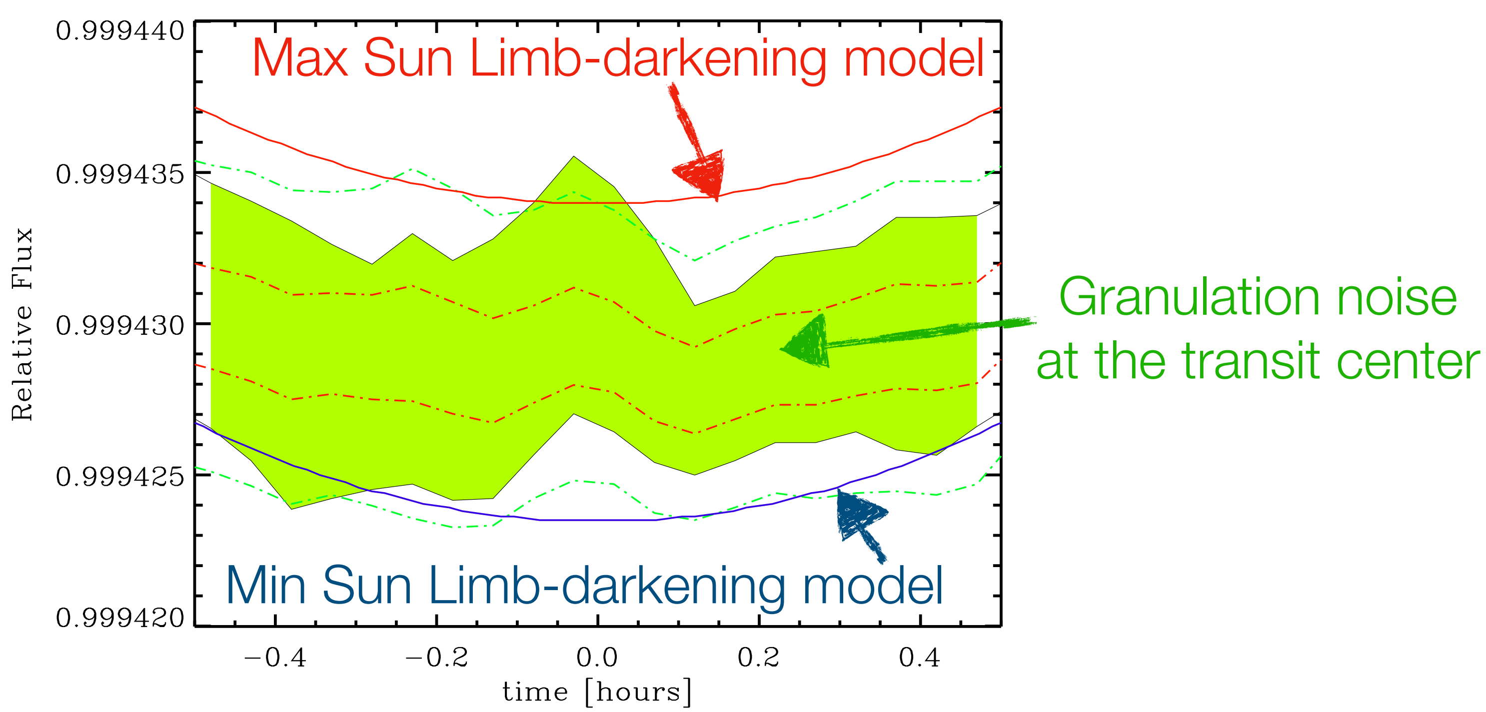
3.5 part per million

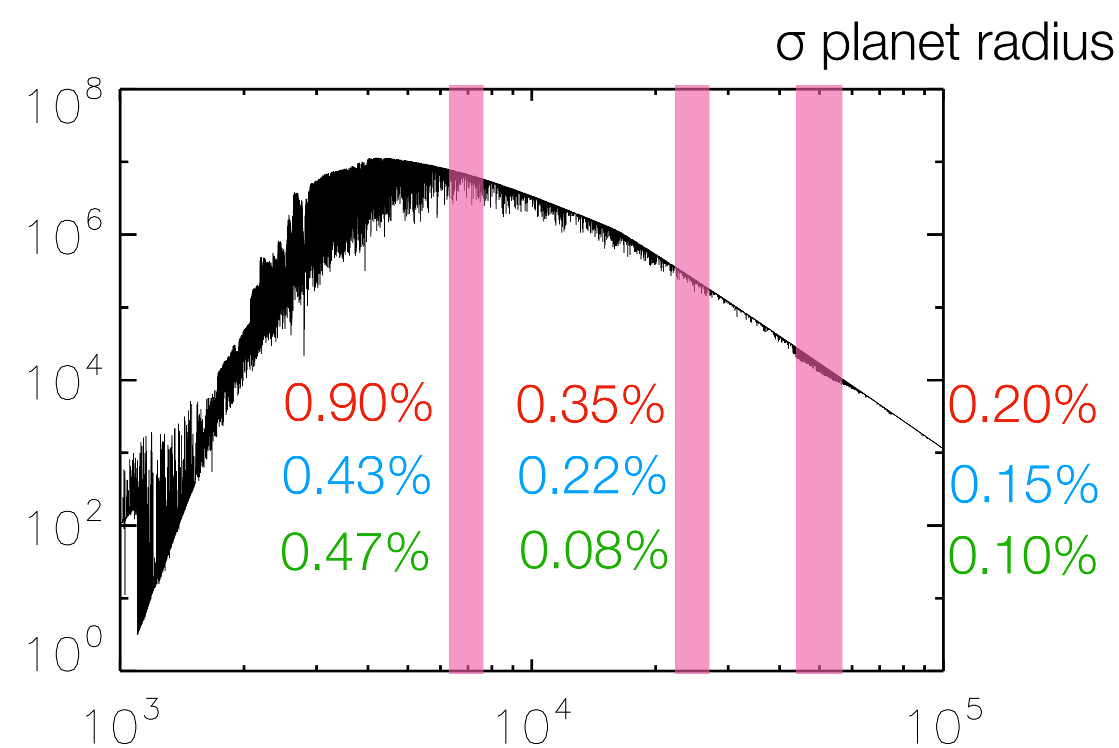
7.4 part per million

15.9 part per million

Synthetic transit for different planet sizes

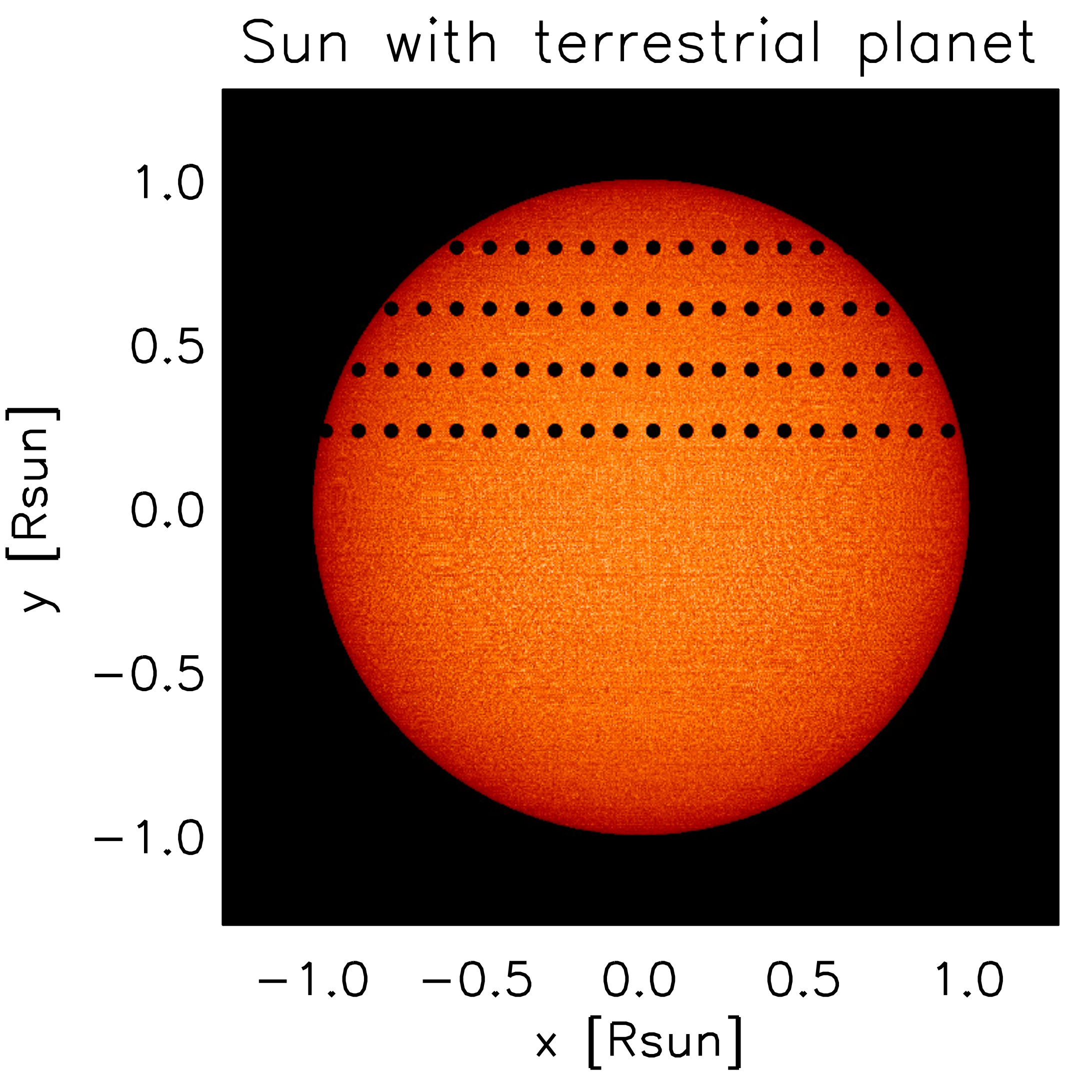


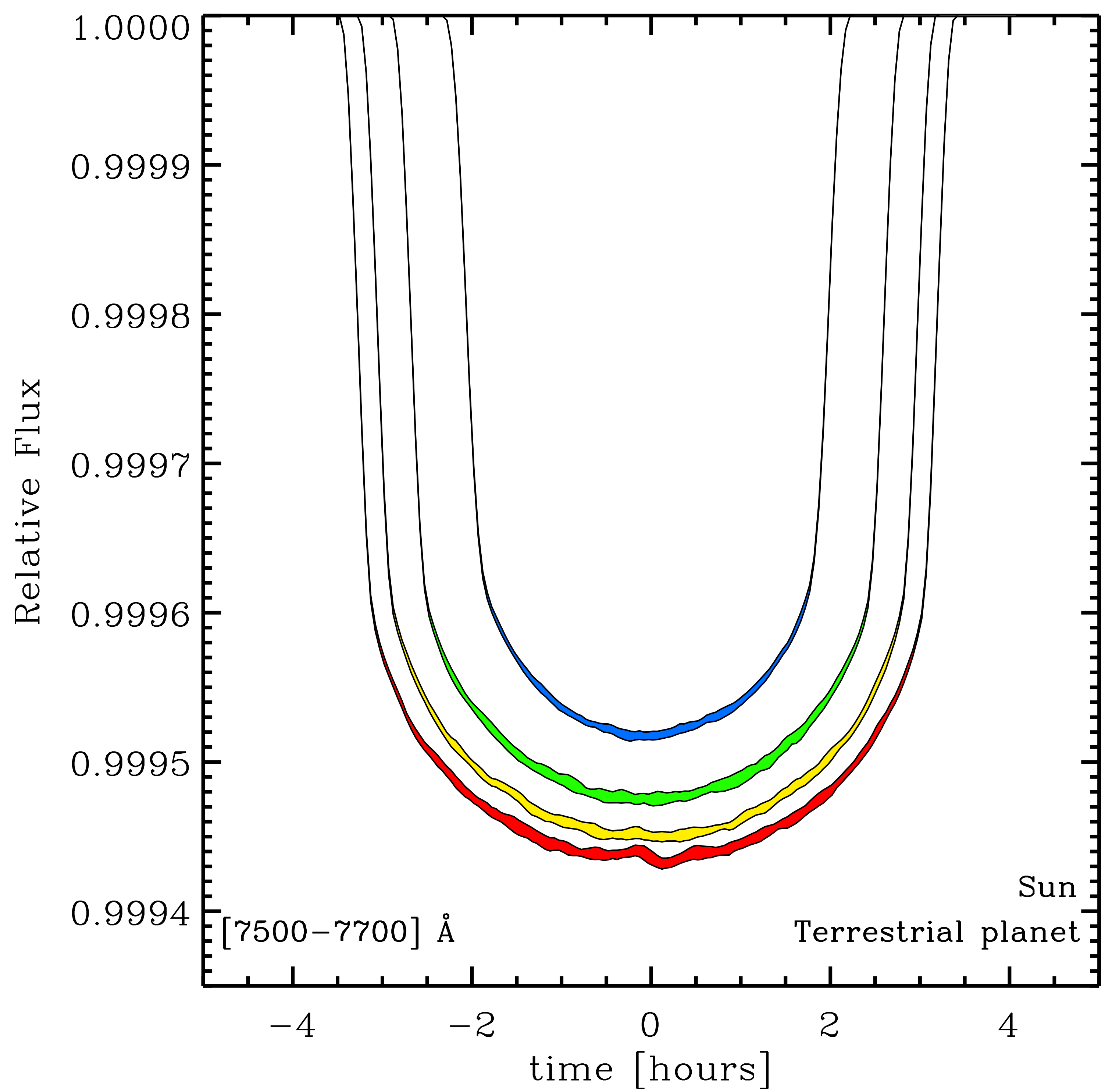




Chiavassa, Caldas, Selsis et al. 2017

Synthetic transit for different planet sizes

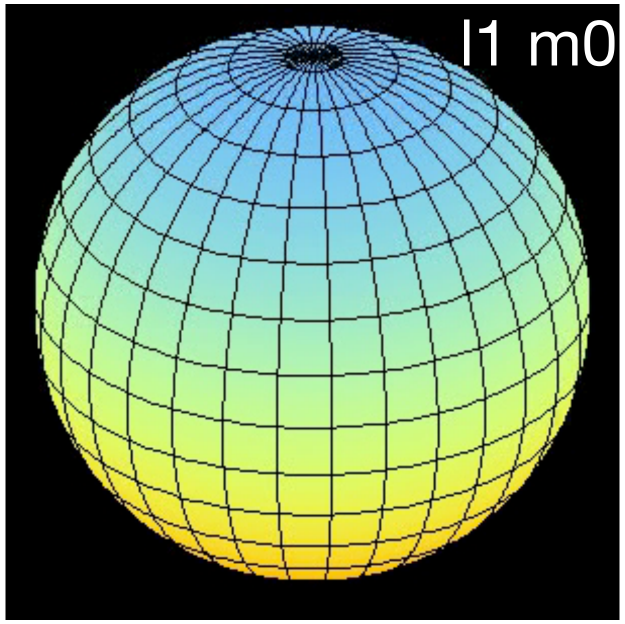


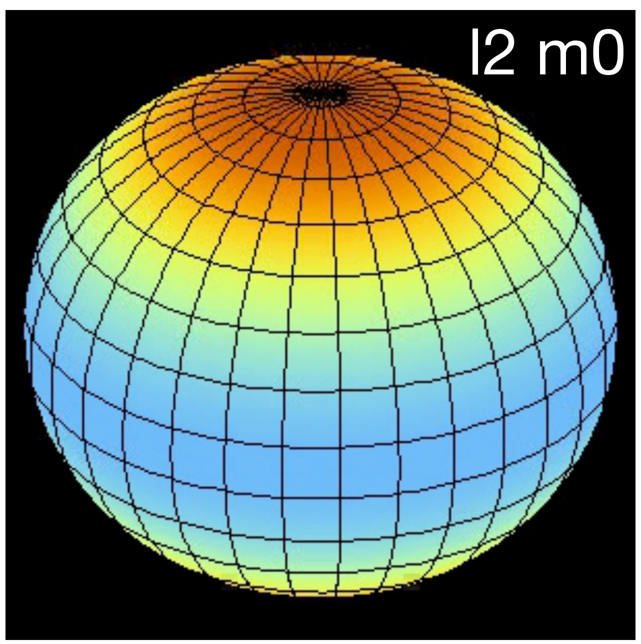


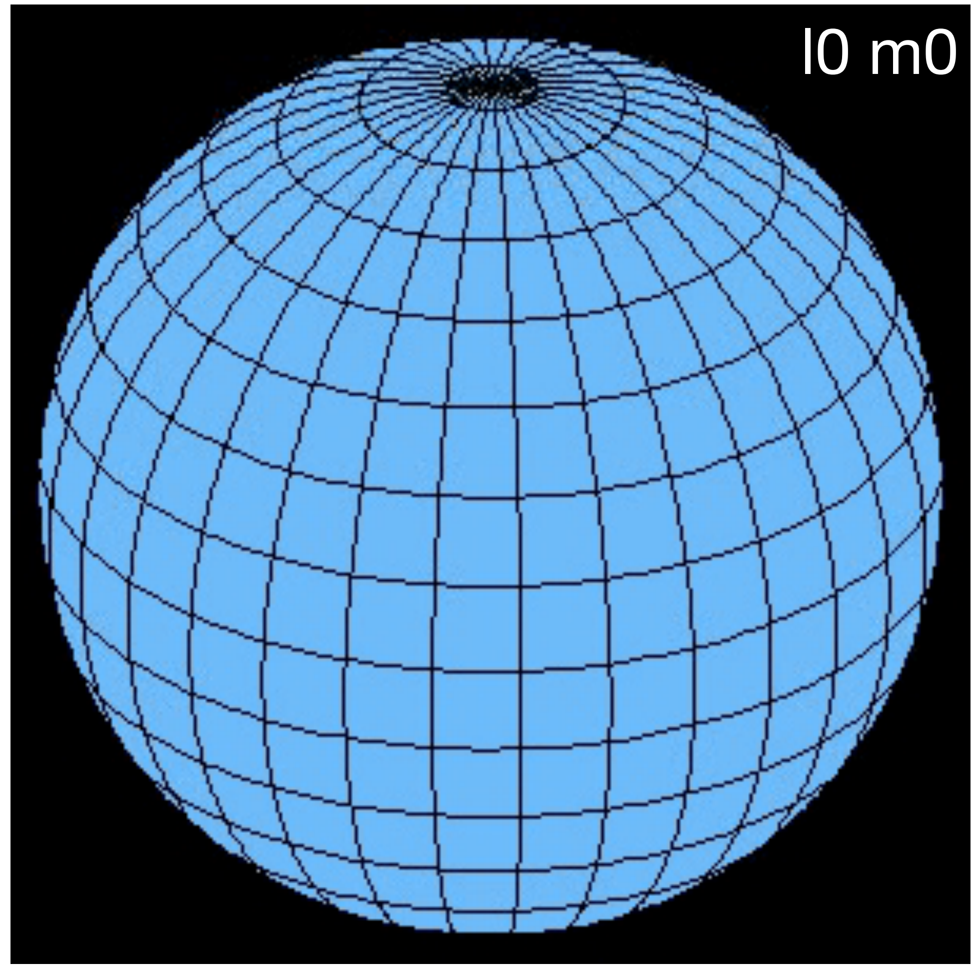
Similar behavior of fluctuations for Terrestrial planet at different inclination (from 6.3 to 3.0 part per-million from top to bottom)

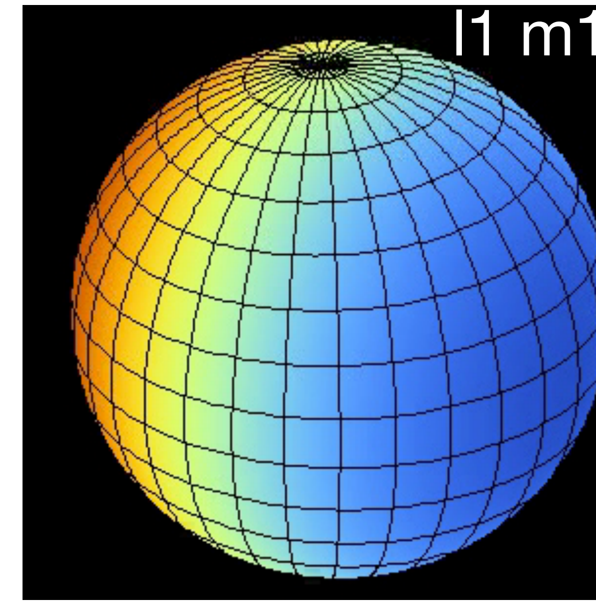
Brightness and velocity variability

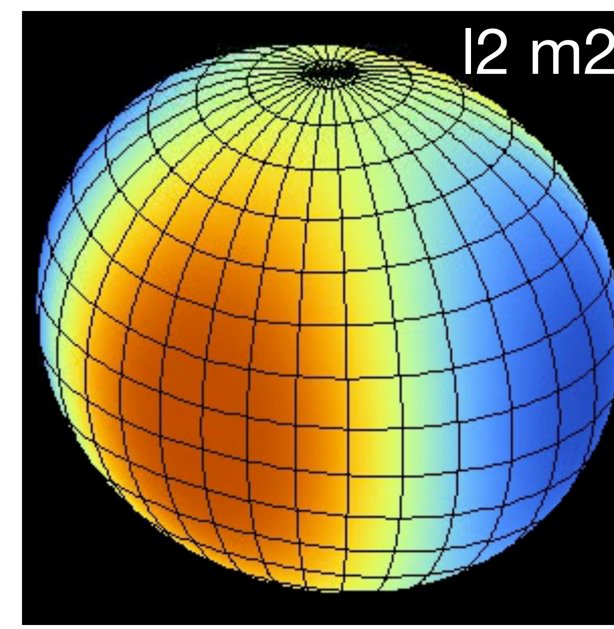
Pulsating star











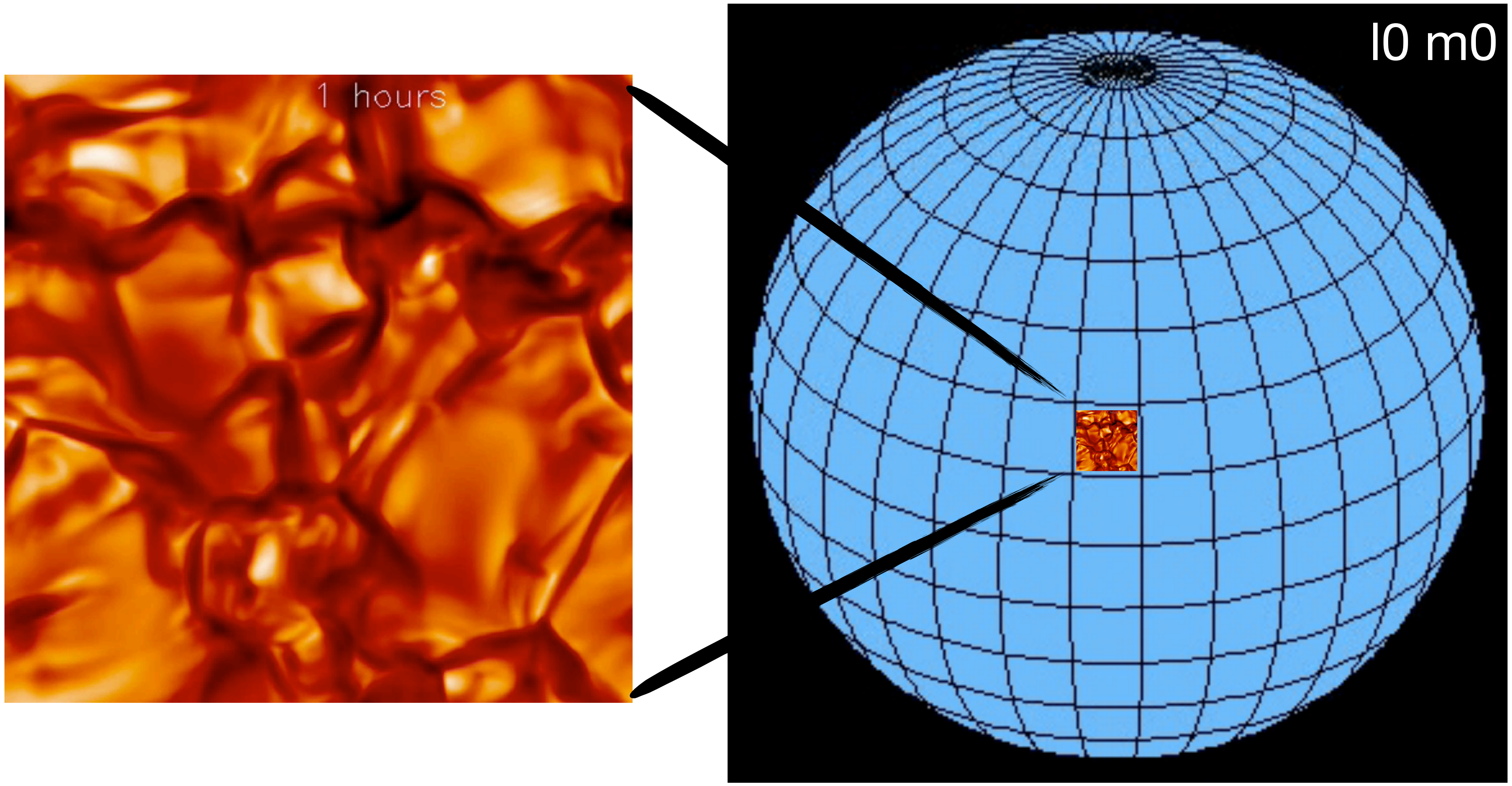
Example of solar spherical harmonics
blue: approaching the observer
red: moving away

Garcia et al. 2014

Pulsating star - star in which variability is due to pulsations, i.e. acoustic and/or gravity waves propagating in its envelope and interior.

Changes of the brightness and/or the radial velocity are the observed evidences of pulsations.

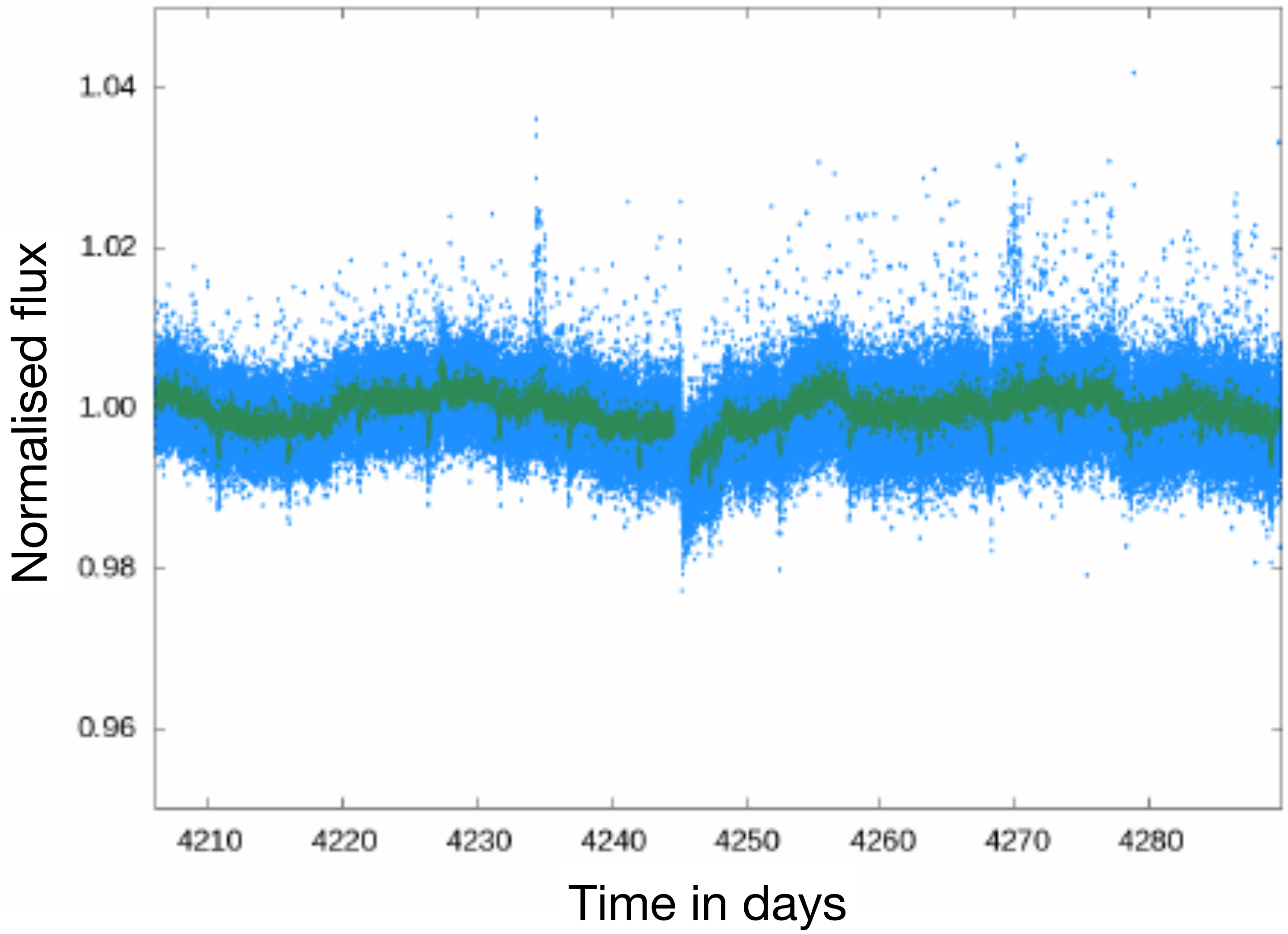
Pulsating star



These waves are generated by a stochastic velocity field in the near-surface convection, where turbulent close to the speed of sound. These waves propagate into the interior and produce the standing waves.

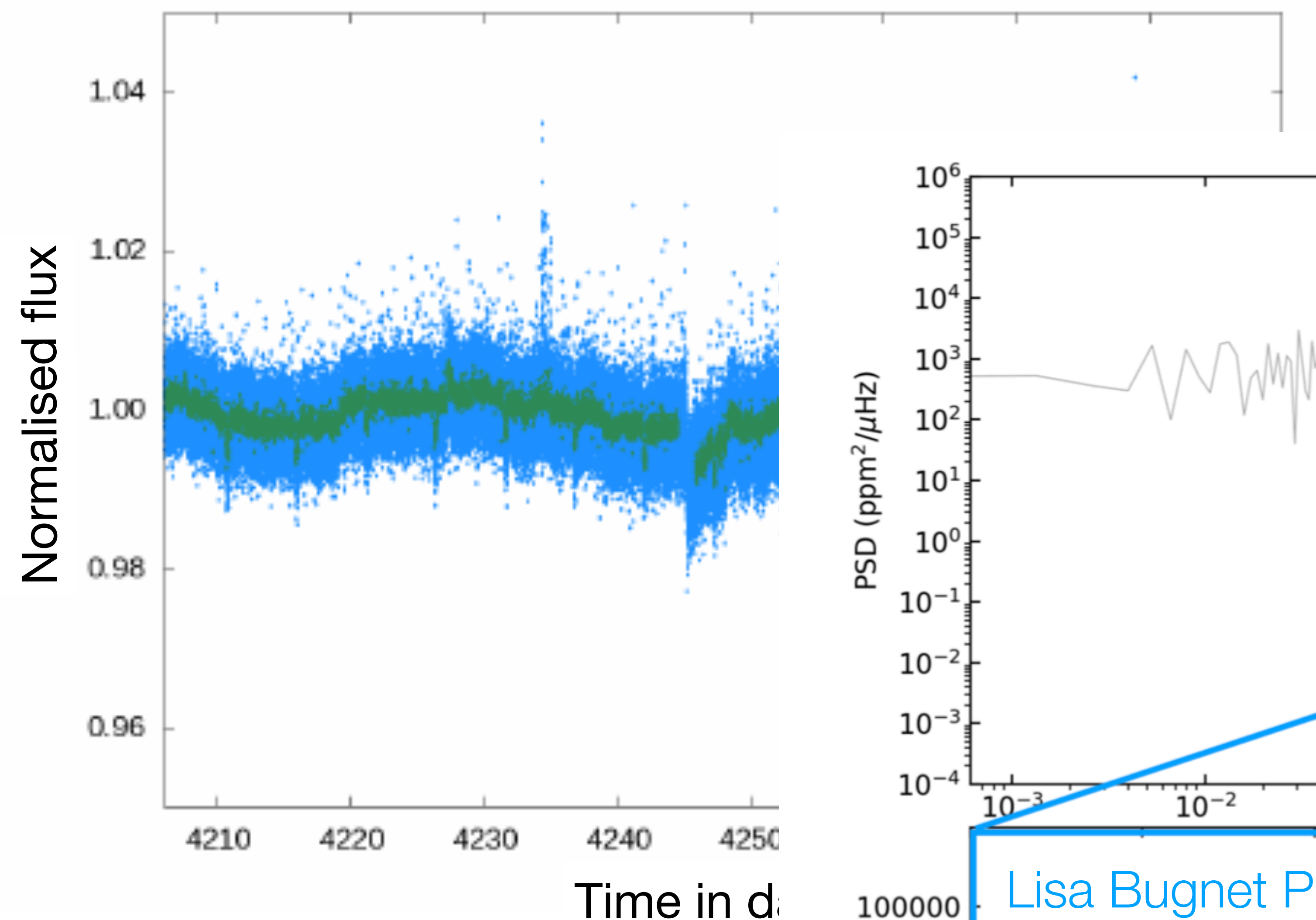
Pulsating star

CoRoT 28b light curve (Crabrera et al. 2015)

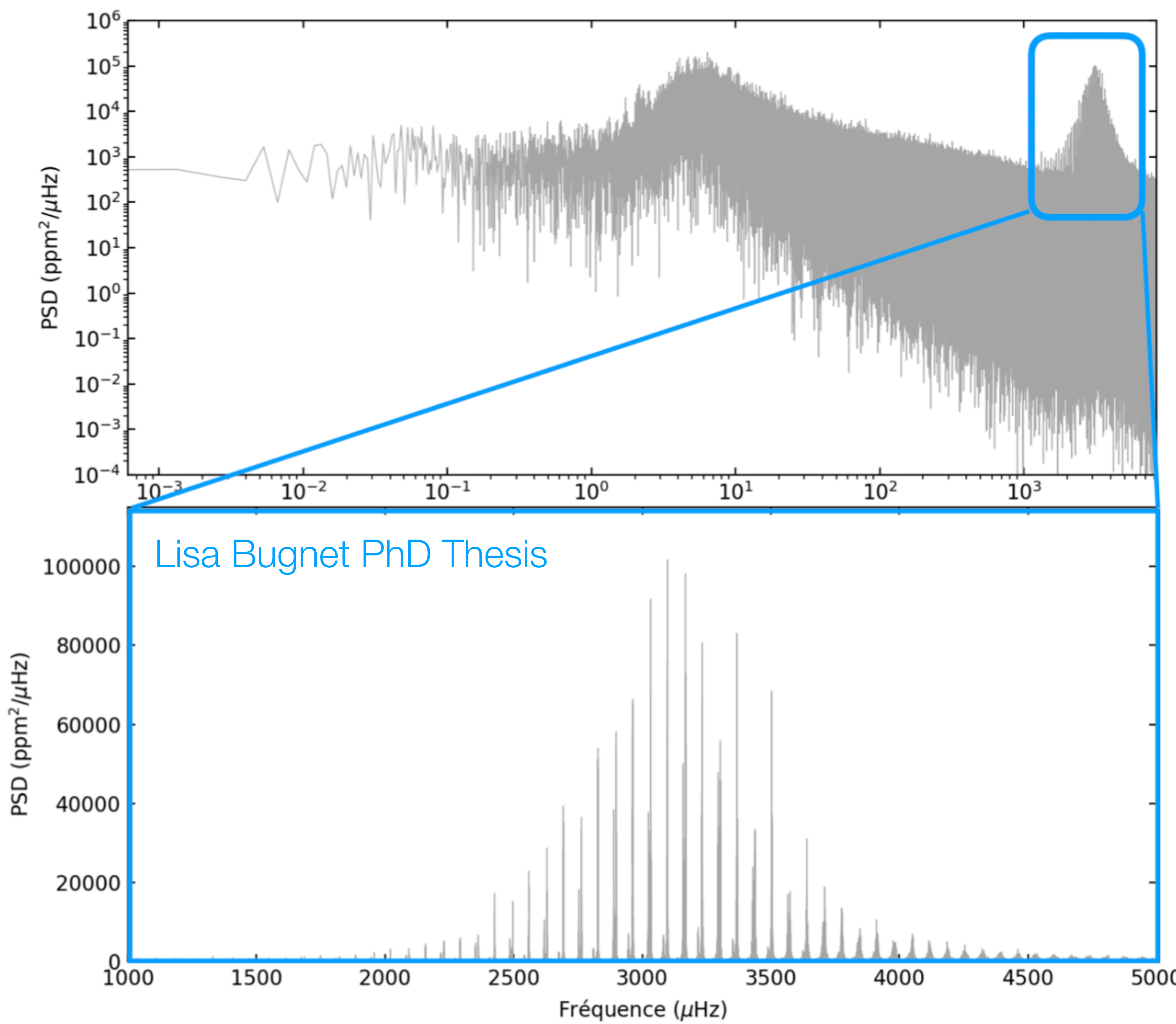


Pulsating star

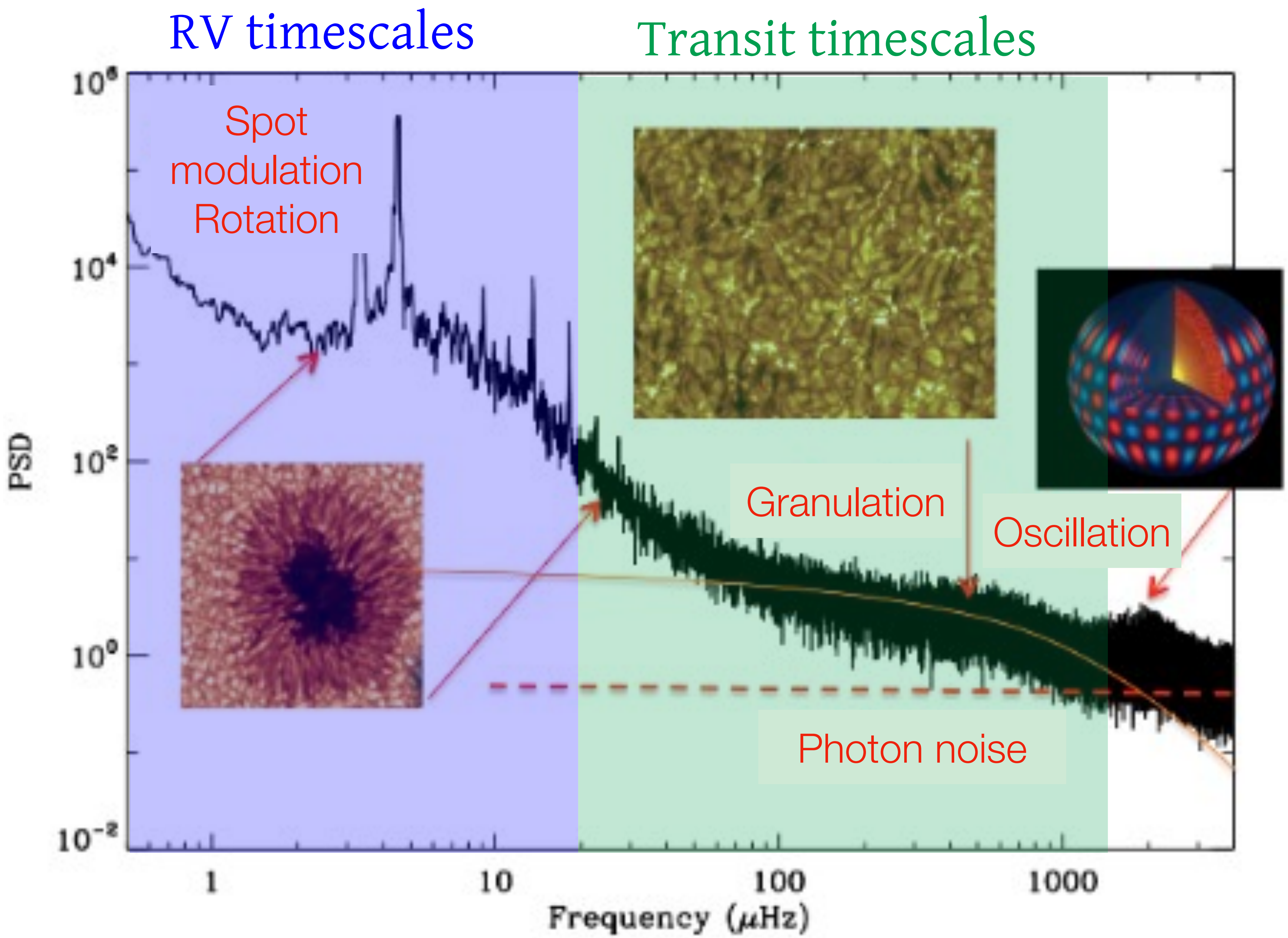
CoRoT 28b light curve (Crabrera et al. 2015)



power spectral density (PSD) of the Sun (data GOLF@SoHO)

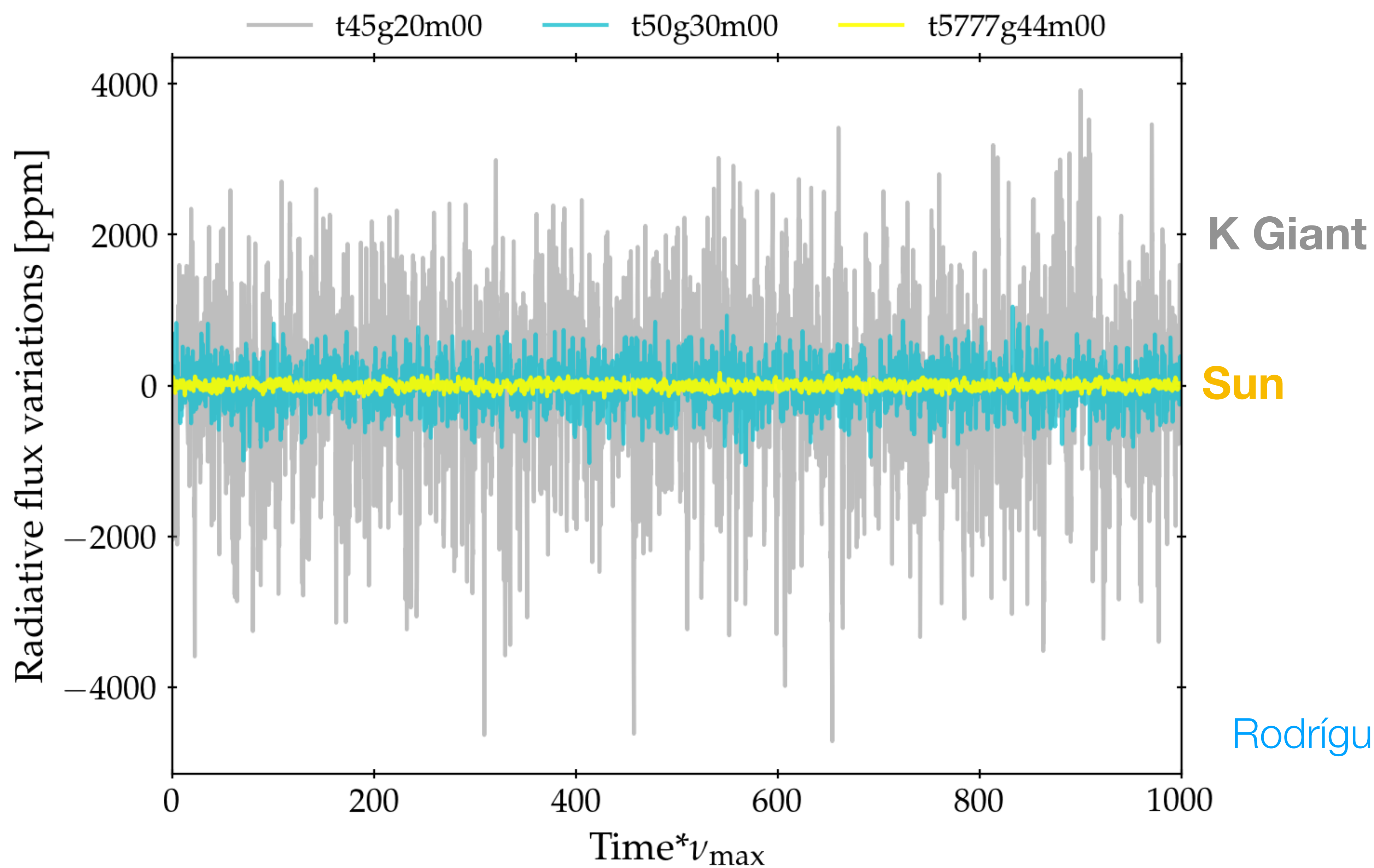


Pulsating star



KIC 3733735 (F5iV-V star), figure adapted from Garcia et al. 2014

Brightness - 1st example

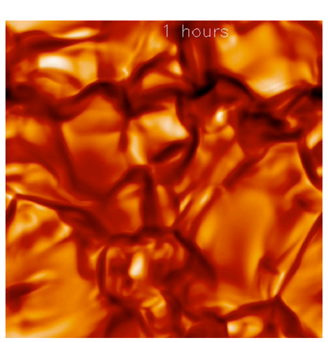


Detecting an Earth
- 12 hours transit
- 9 m/s in amplitude
- 84 ppm

Perryman 2018

Rodríguez Díaz et al. 2022

Sun granules



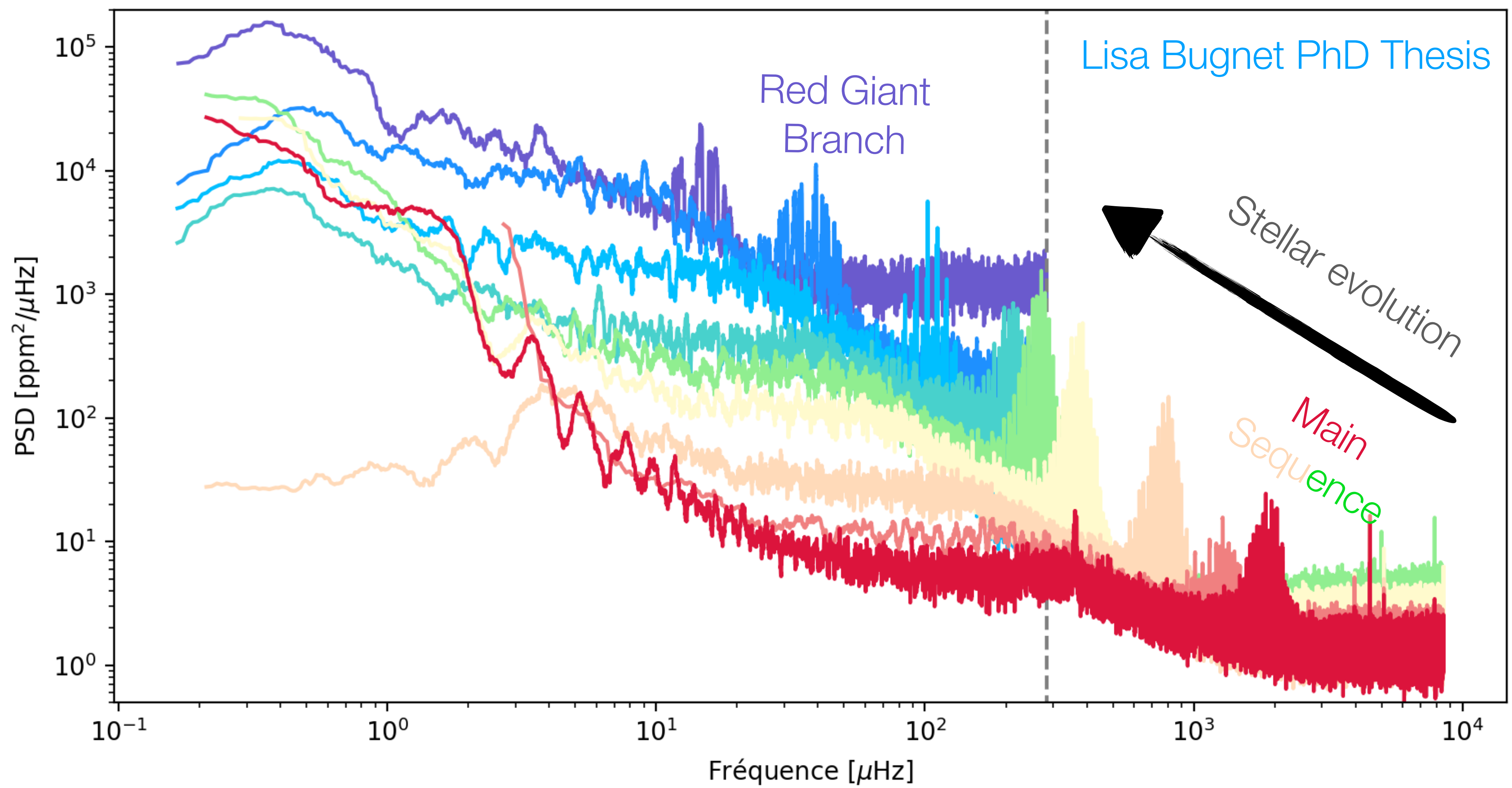
~1 Mm in size
- 5-10 minutes in time
- 40-80 cm/s in amplitude
- 10-300 ppm

Rodríguez Díaz et al. 2022
Chiavassa et al. 2018

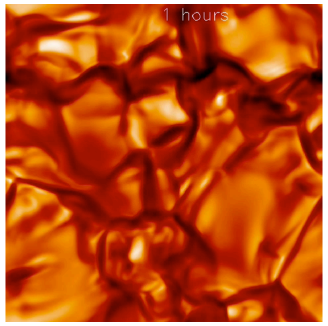
K Giant granules

~600 Mm in size
- hours to days in time
- 200-300 m/s in amplitude
- 1000-2000 ppm

Brightness - 1st example



Sun granules



~1 Mm in size

- 5-10 minutes in time
- 40-80 cm/s in amplitude
- 10-300 ppm

Granule sizes depend on pressure scale height and, in particular, on surface gravity

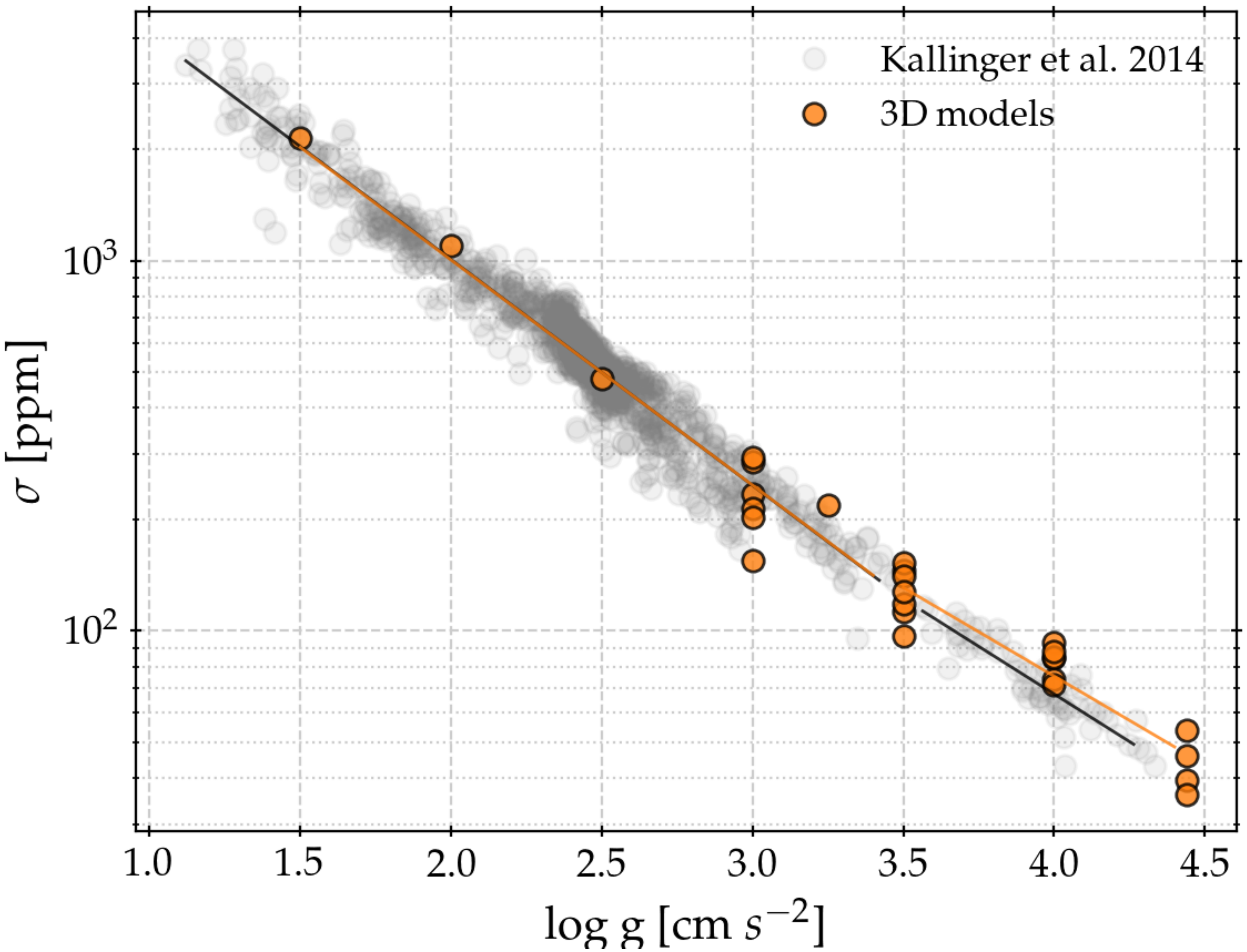
Rodríguez Díaz et al. 2022
Chiavassa et al. 2018

K Giant granules

~600 Mm in size

- hours to days in time
- 200-300 m/s in amplitude
- 1000-2000 ppm

Brightness - 1st example

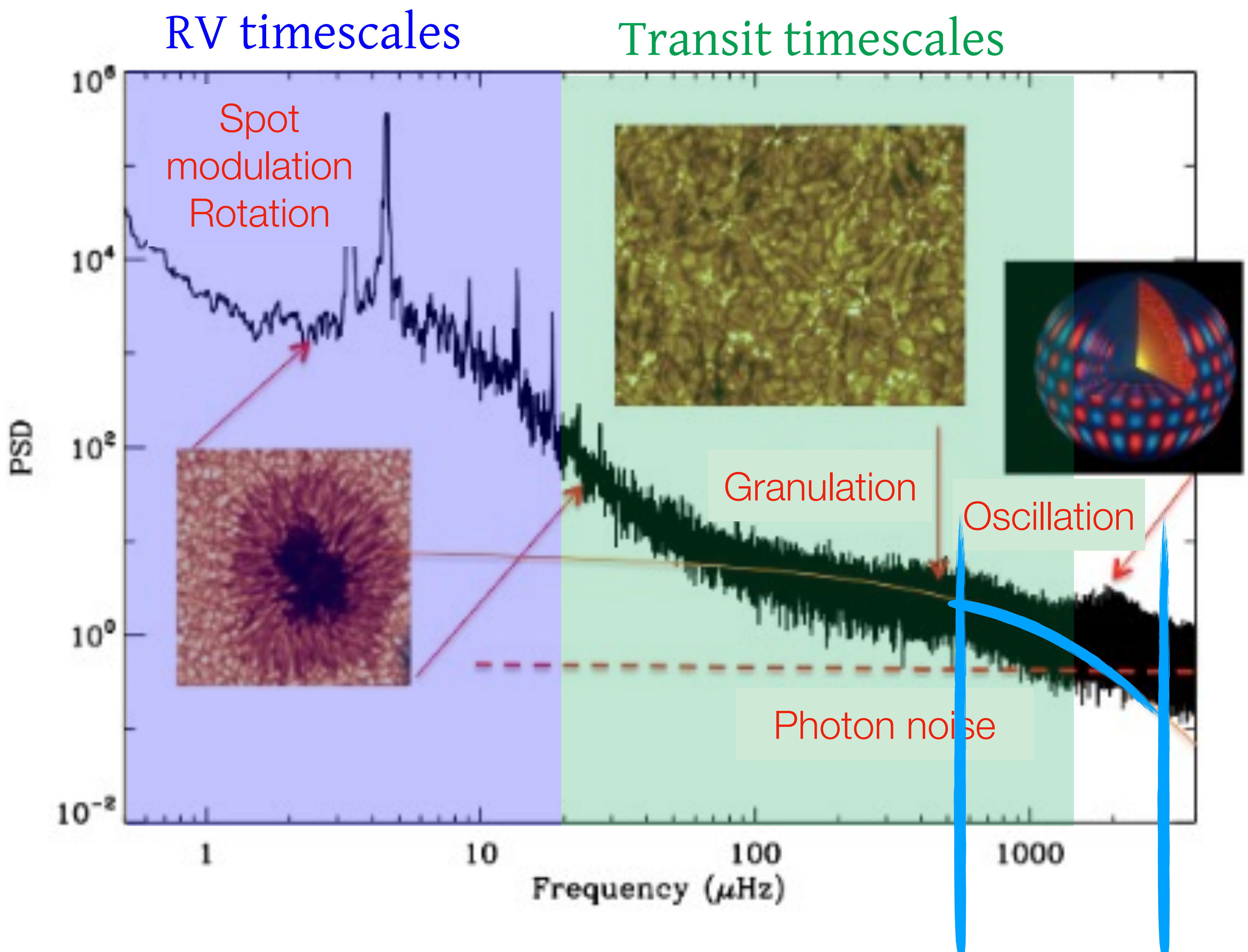


Synthetic granulation properties have been compared to a large sample of Kepler stars (gray).

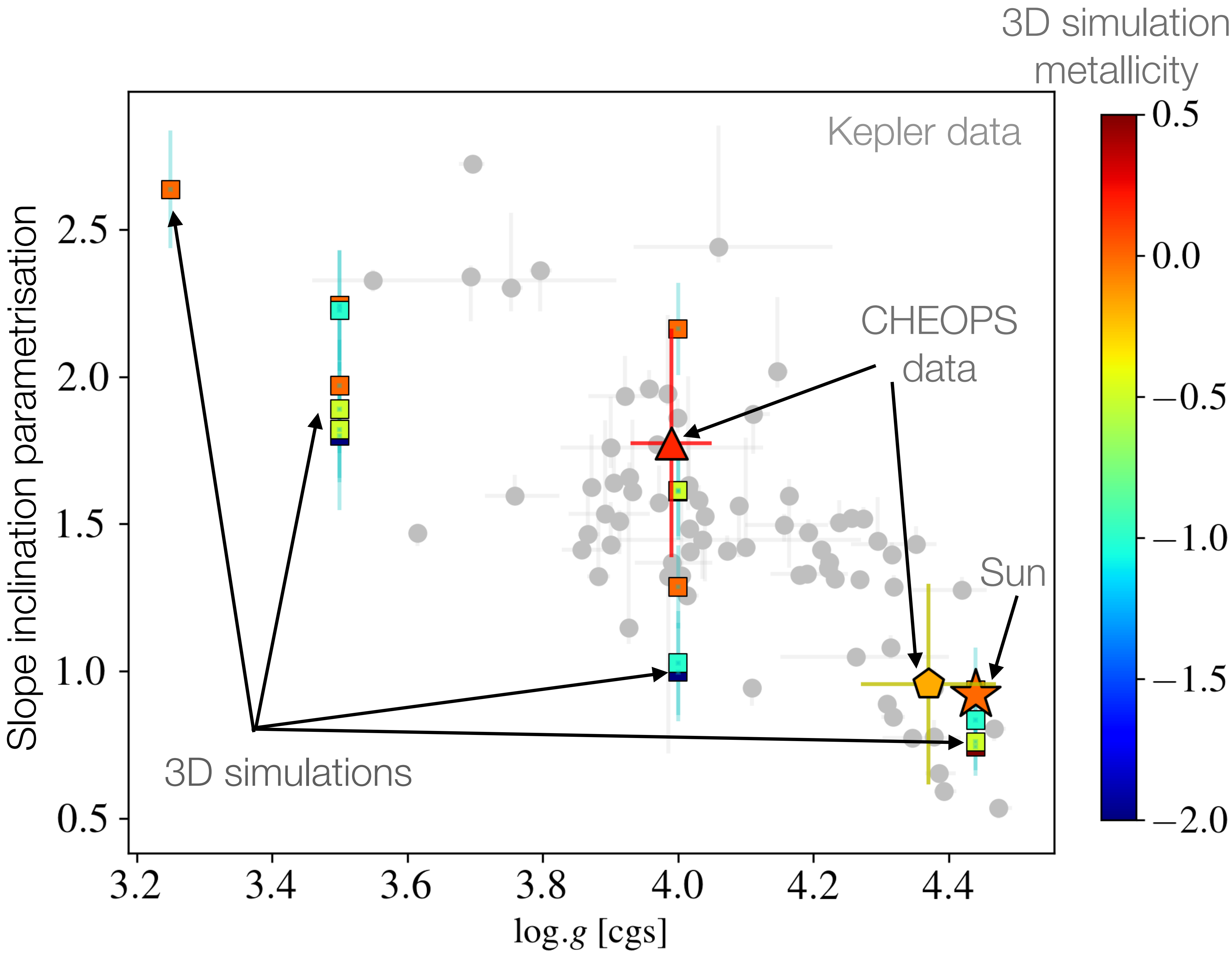
3D stellar atmosphere (yellow points) reproduce granulation properties of stars across the HR diagram,

Rodríguez Díaz et al. 2022

Brightness - 2nd example



Brightness - 2nd example

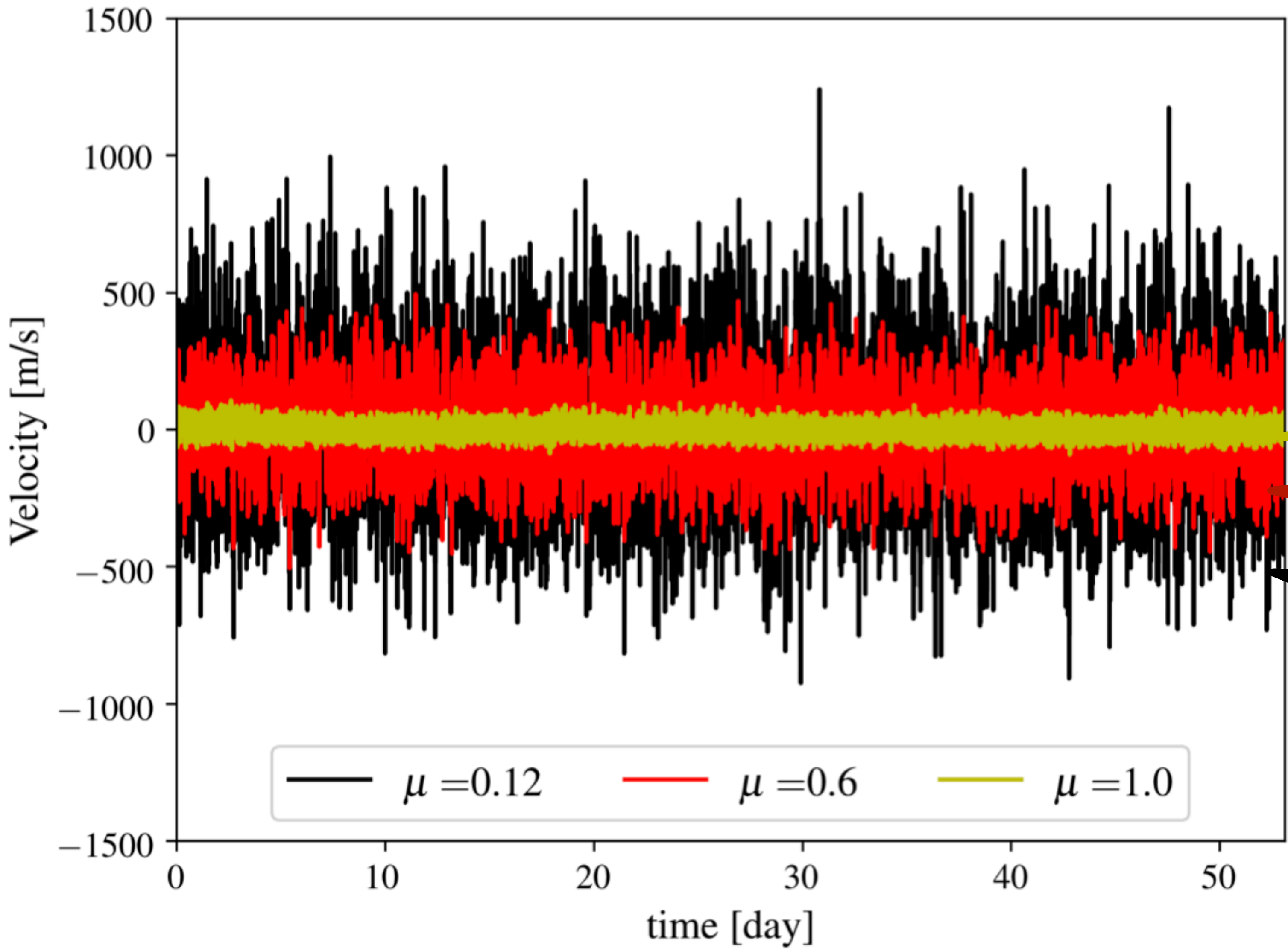


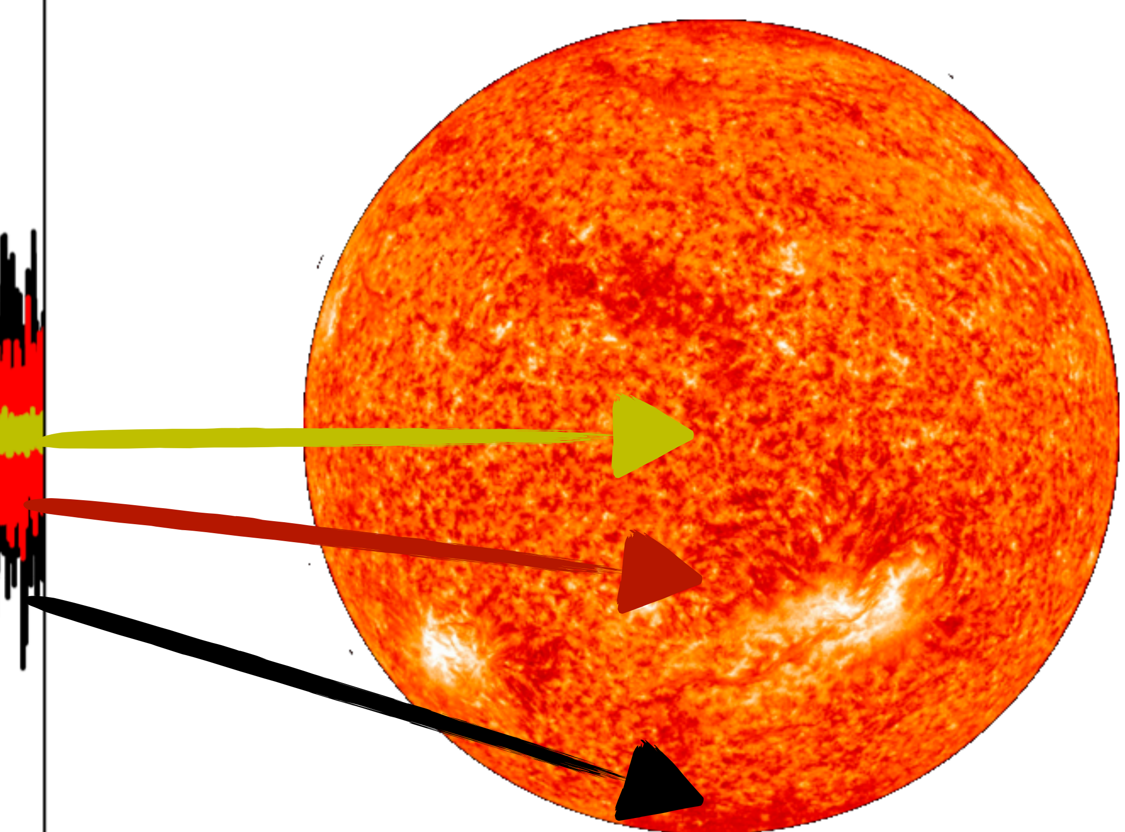
3D simulations reproduce the granulation slope in Kepler and CHEOPS data. The predicted granulations properties are real

Sulis et al. 2022 (submitted)

Velocity - 1st example

3D simulations data velocity for the Sun at different inclinations in the rage of GOLF@SoHO

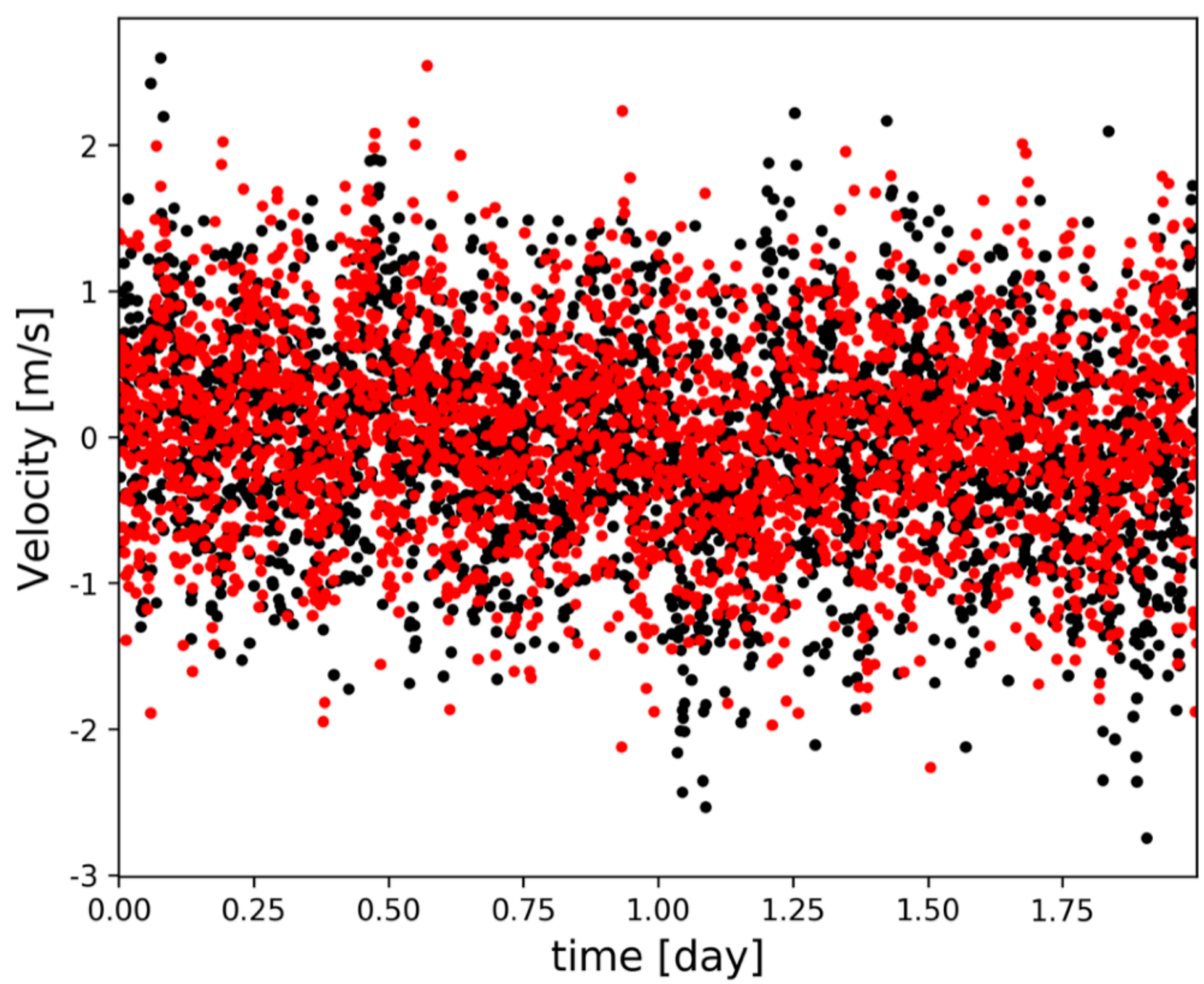




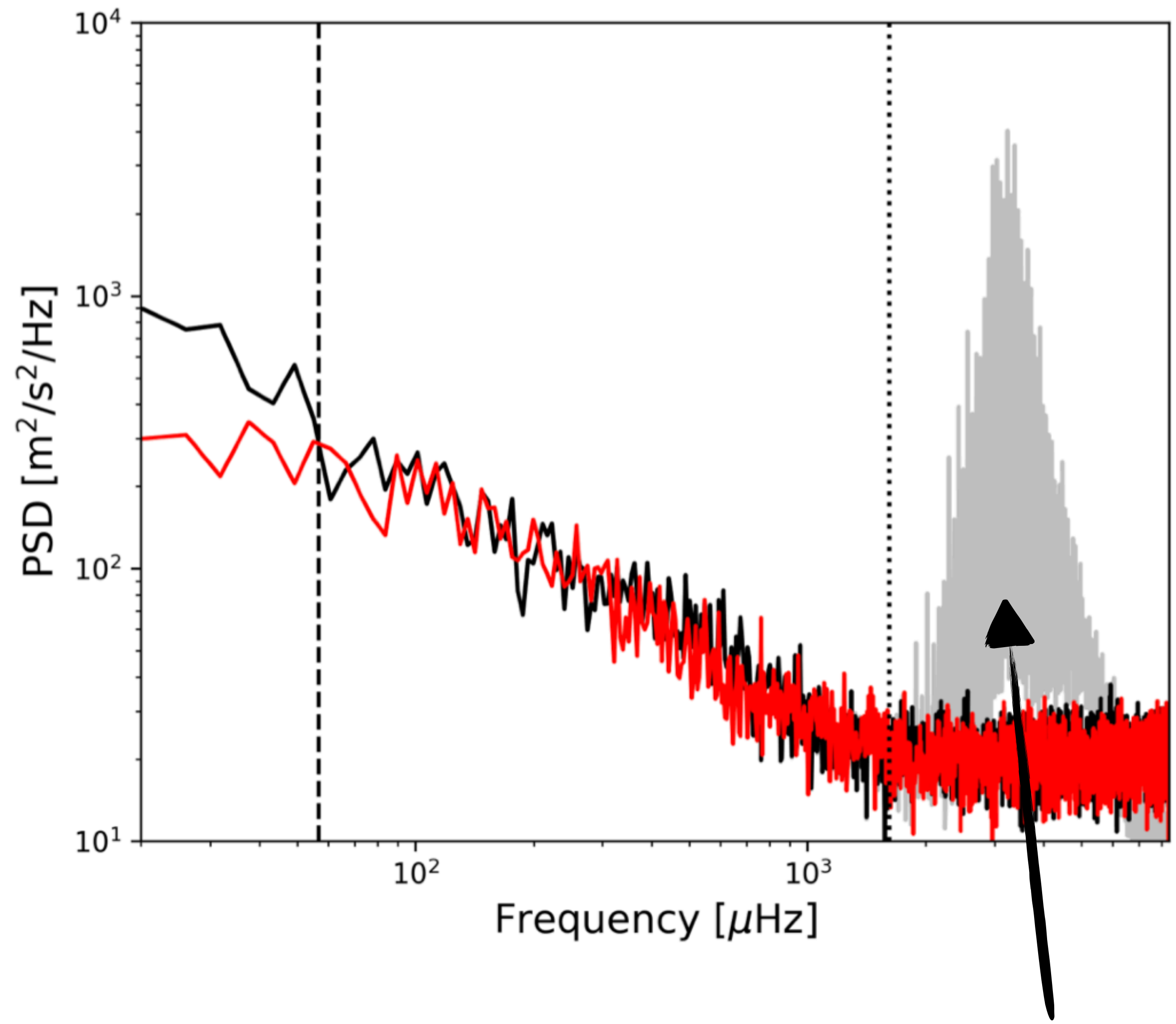
Sulis et al. 2020

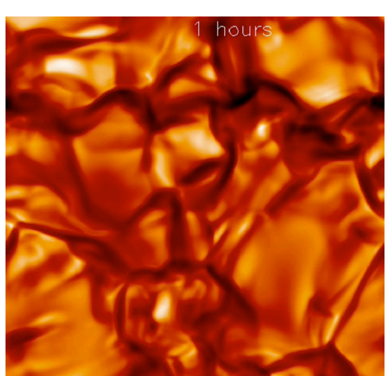
Velocity - 1st example

Observed Sun velocity fluctuations (black points)



Associated periodograms (2 days of observations)





Synthetic velocities (red points)

3D simulations produce reliable synthetic time series of the convective noise affecting RV data. Crucial to derive the intrinsic noise level in the detection of exoplanets down to the cm/s level

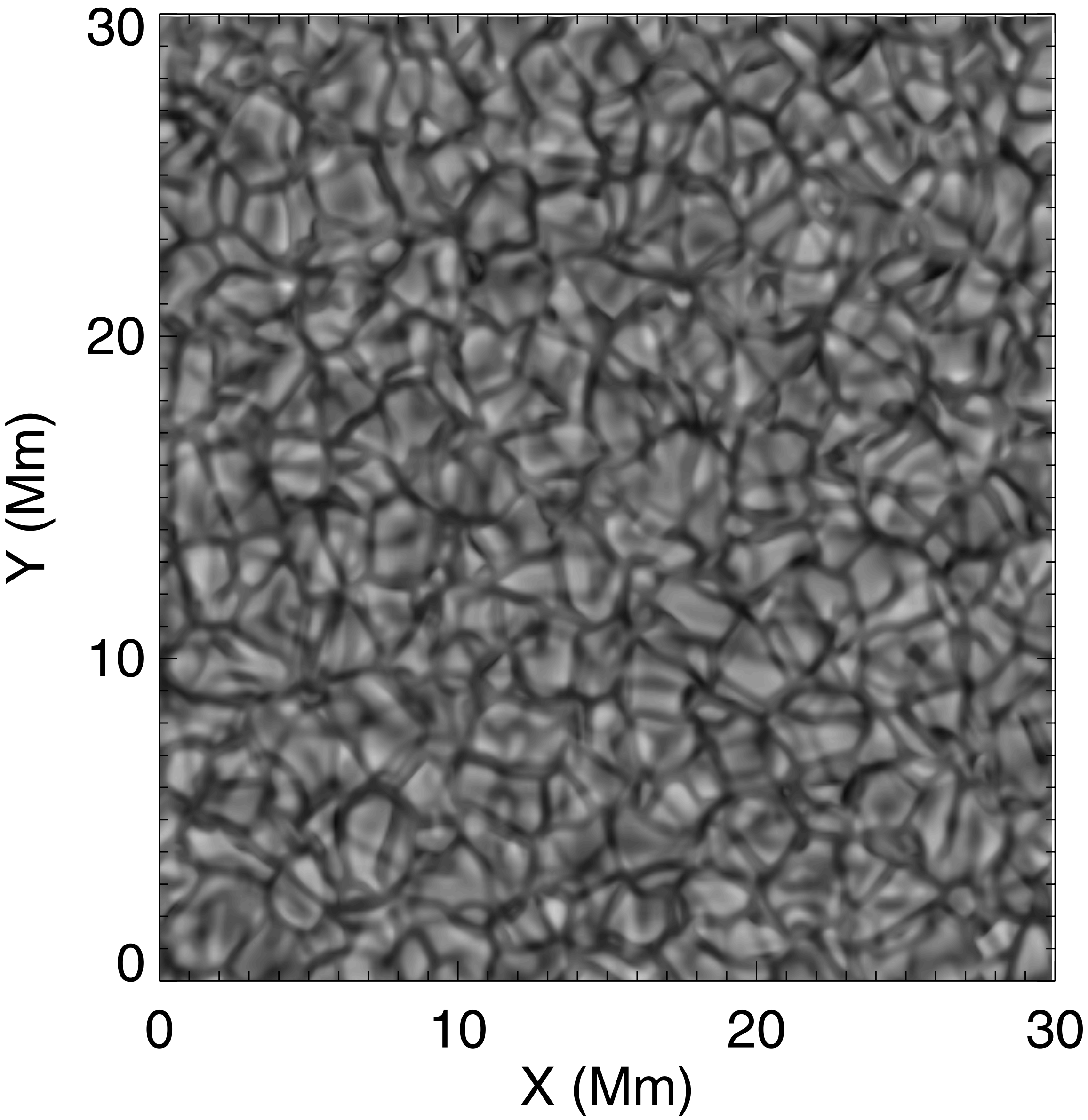
Observed acoustic modes

Sulis et al. 2020

Velocity - 2nd example

3D simulation of the solar granulation (Rieutord et al. 2002)

Segmentation technique



Meunier et al. 2015

Velocity - 2nd example

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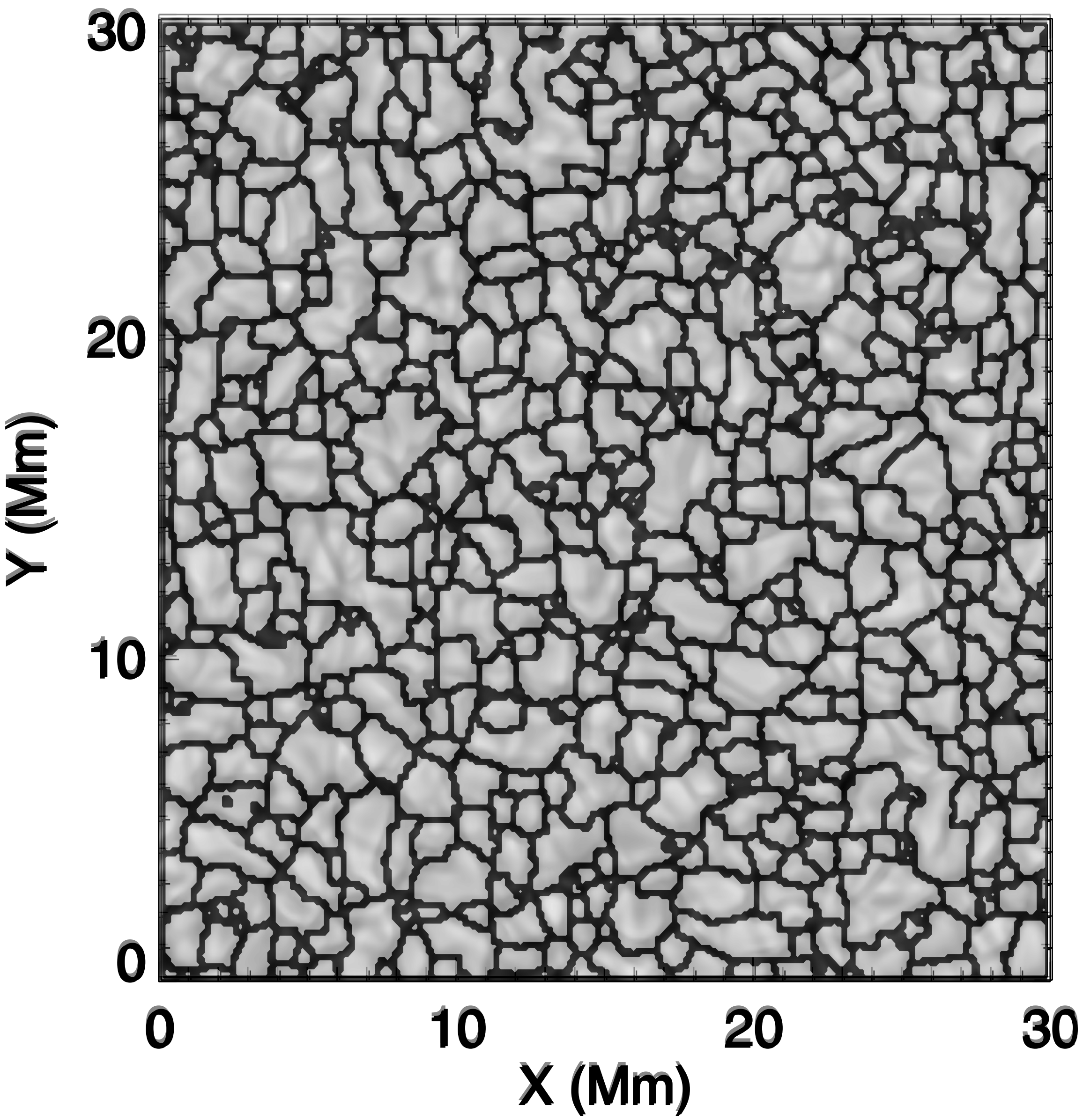
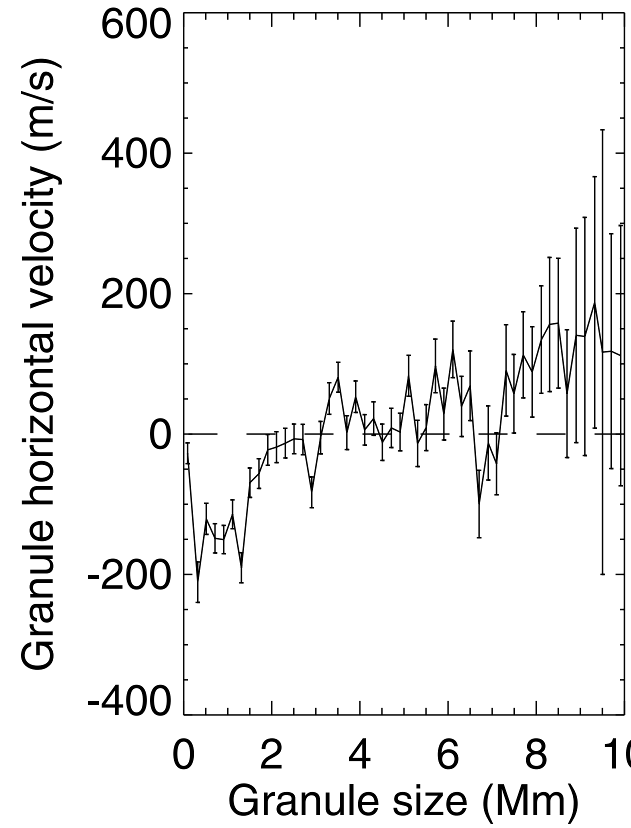
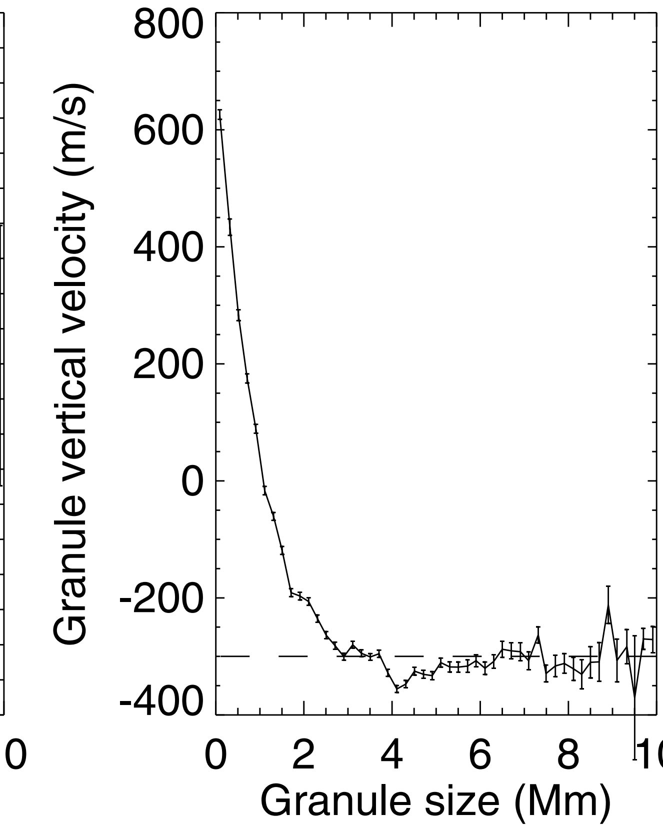
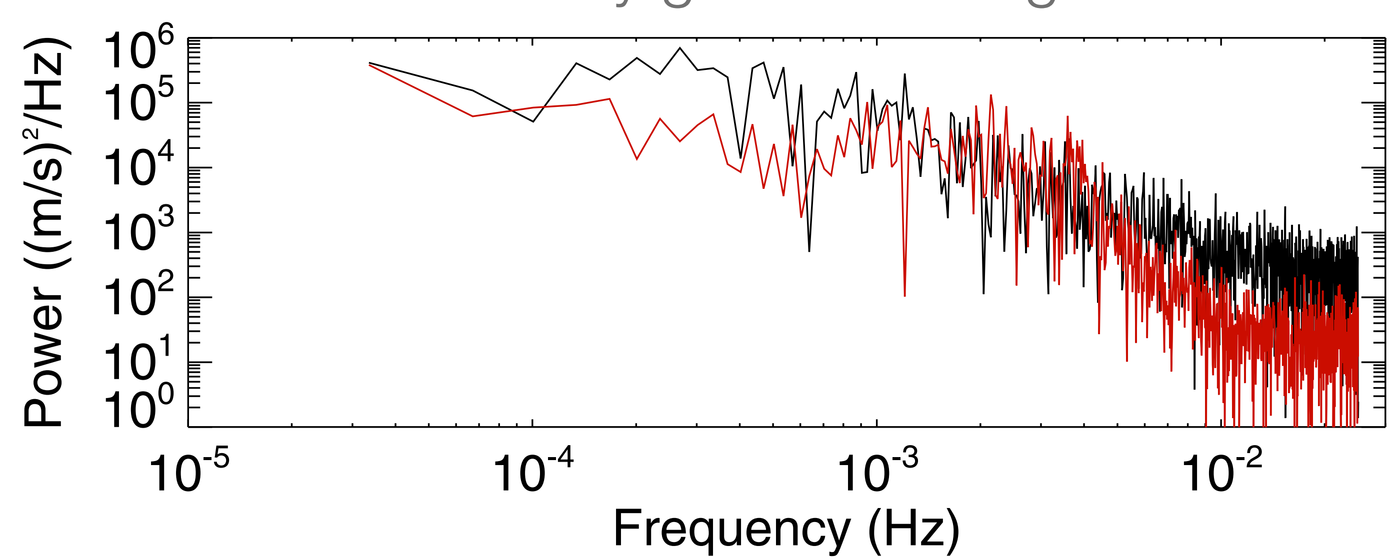


Granulation velocity properties extracted





Radial velocity granulation signature



Granulation and mesogranulation predictions to drive observing strategies

Meunier et al. 2015

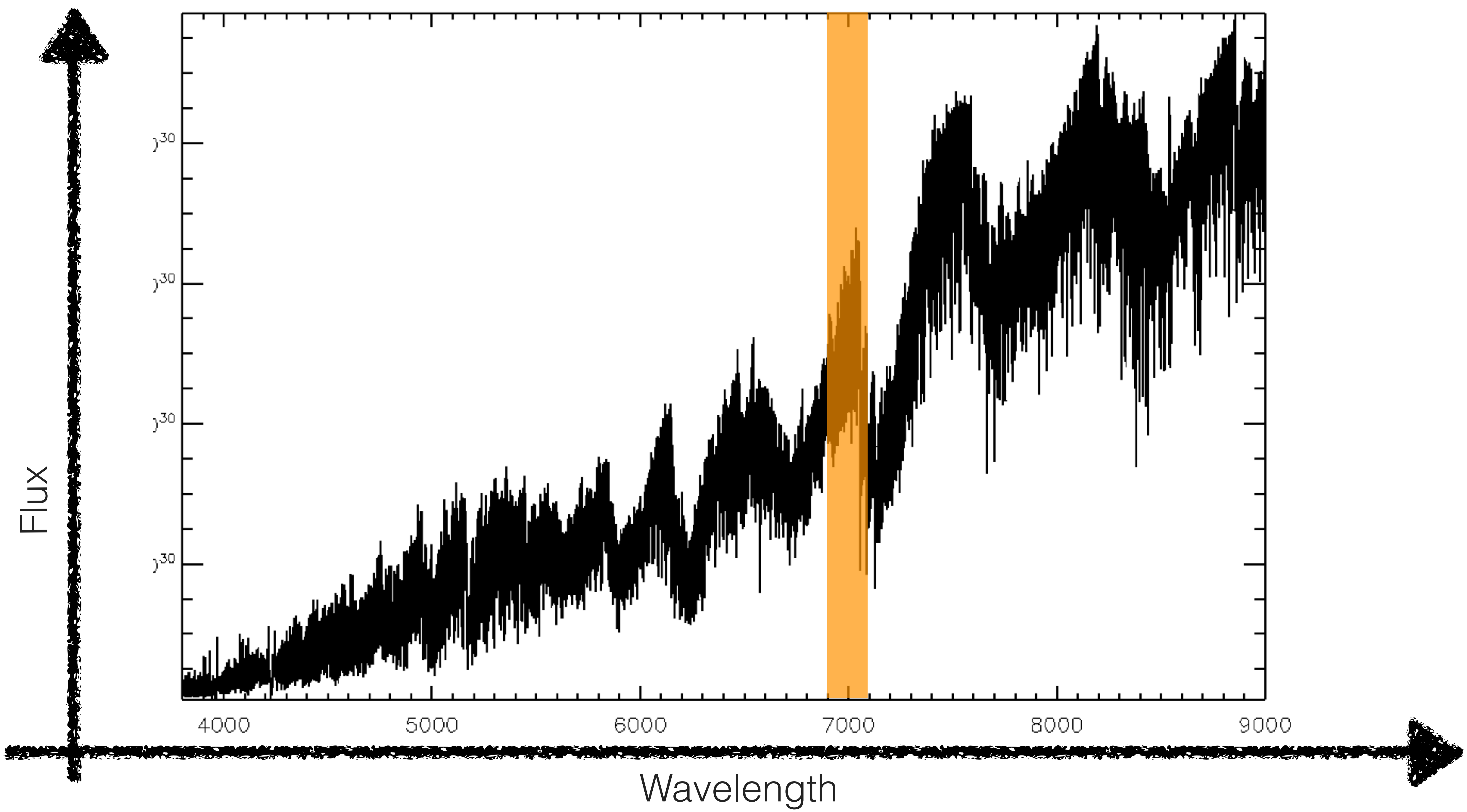
High spectral resolution

Basic concepts in spectroscopy: resolution

Spectral resolution (Δλ) versus resolving power (λ/Δλ)

Spectrographs are characterised by a ~constant resolving power R=λ/Δλ

This translates into a variable spectral resolution Δλ according to wavelength λ



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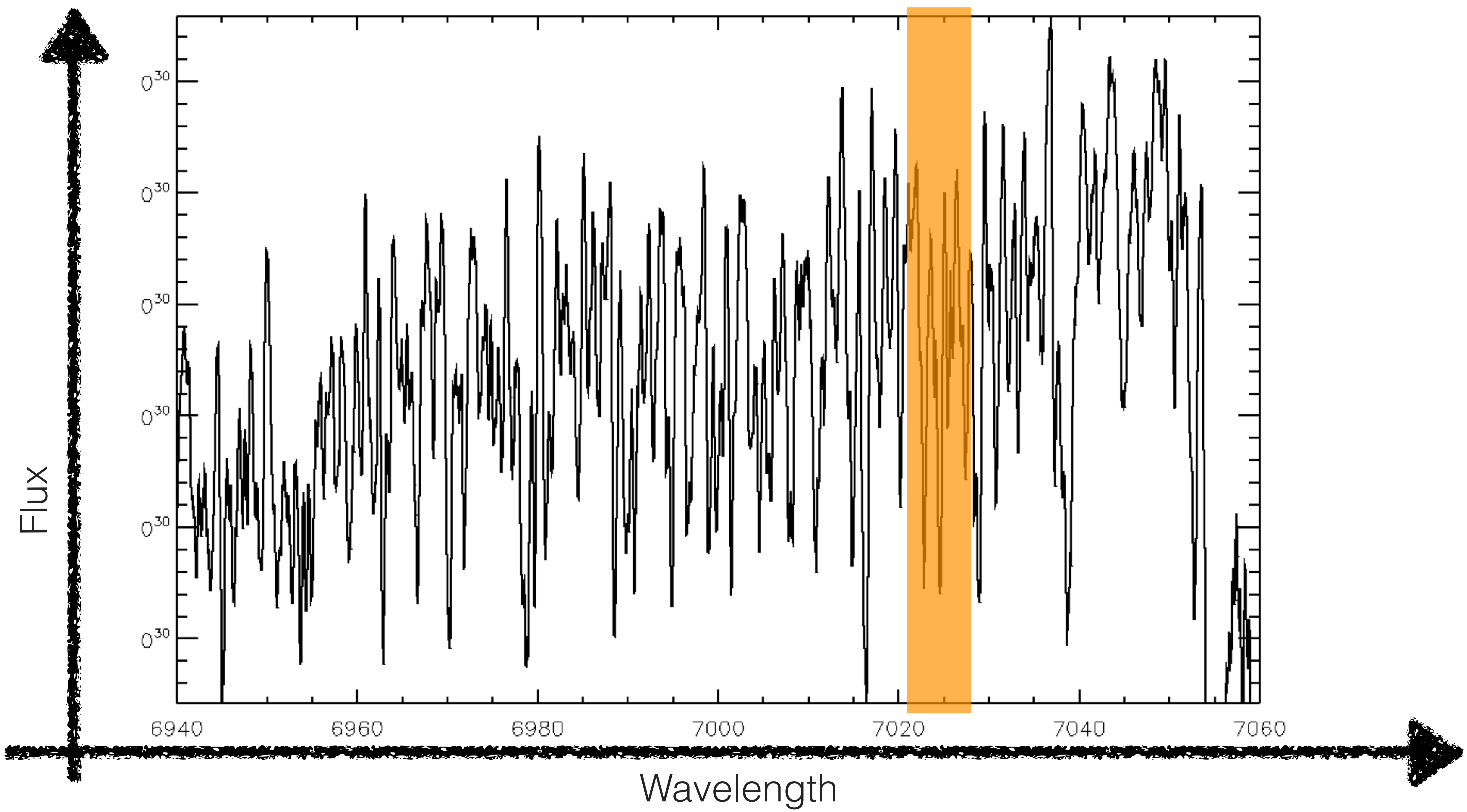

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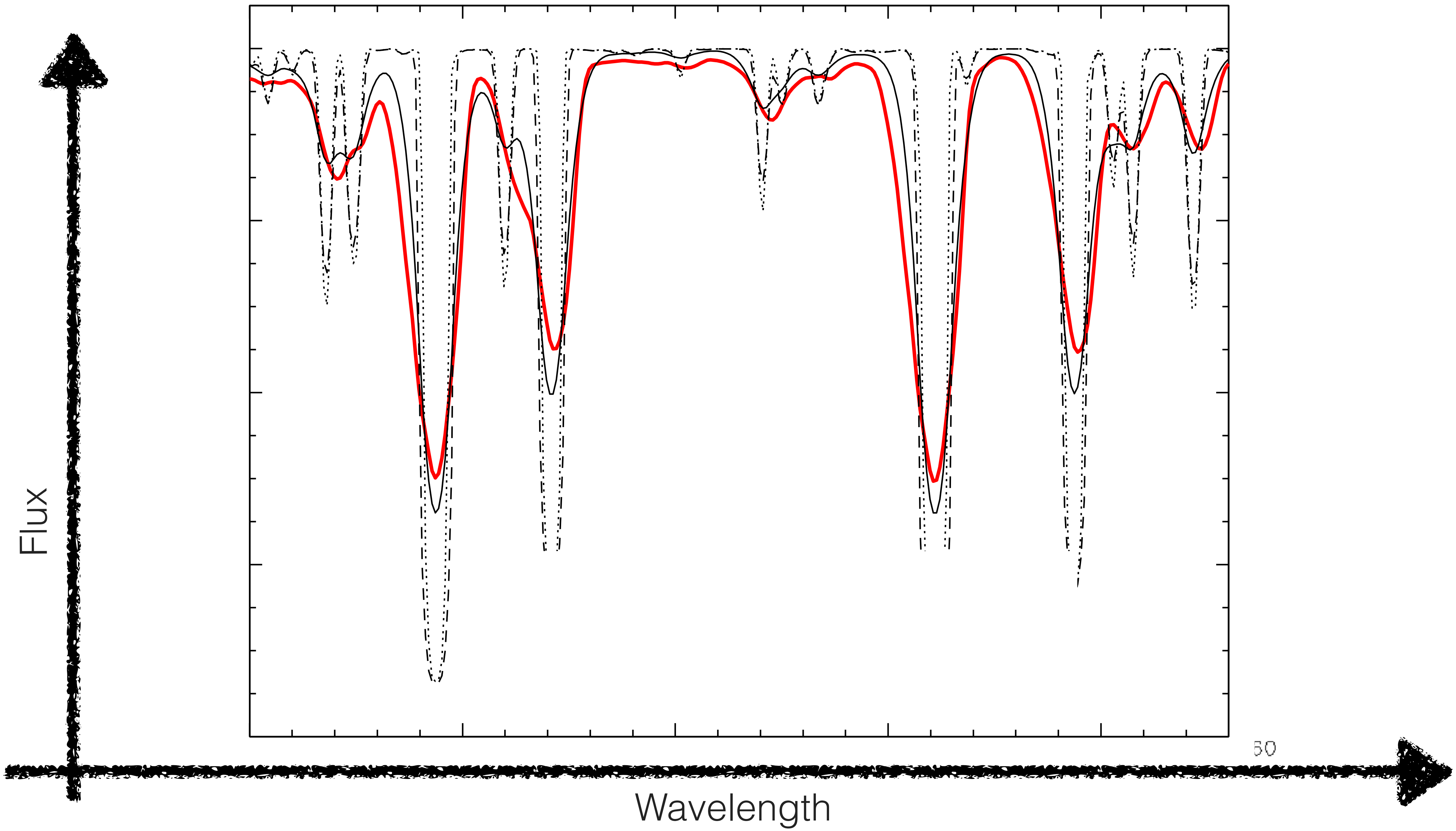
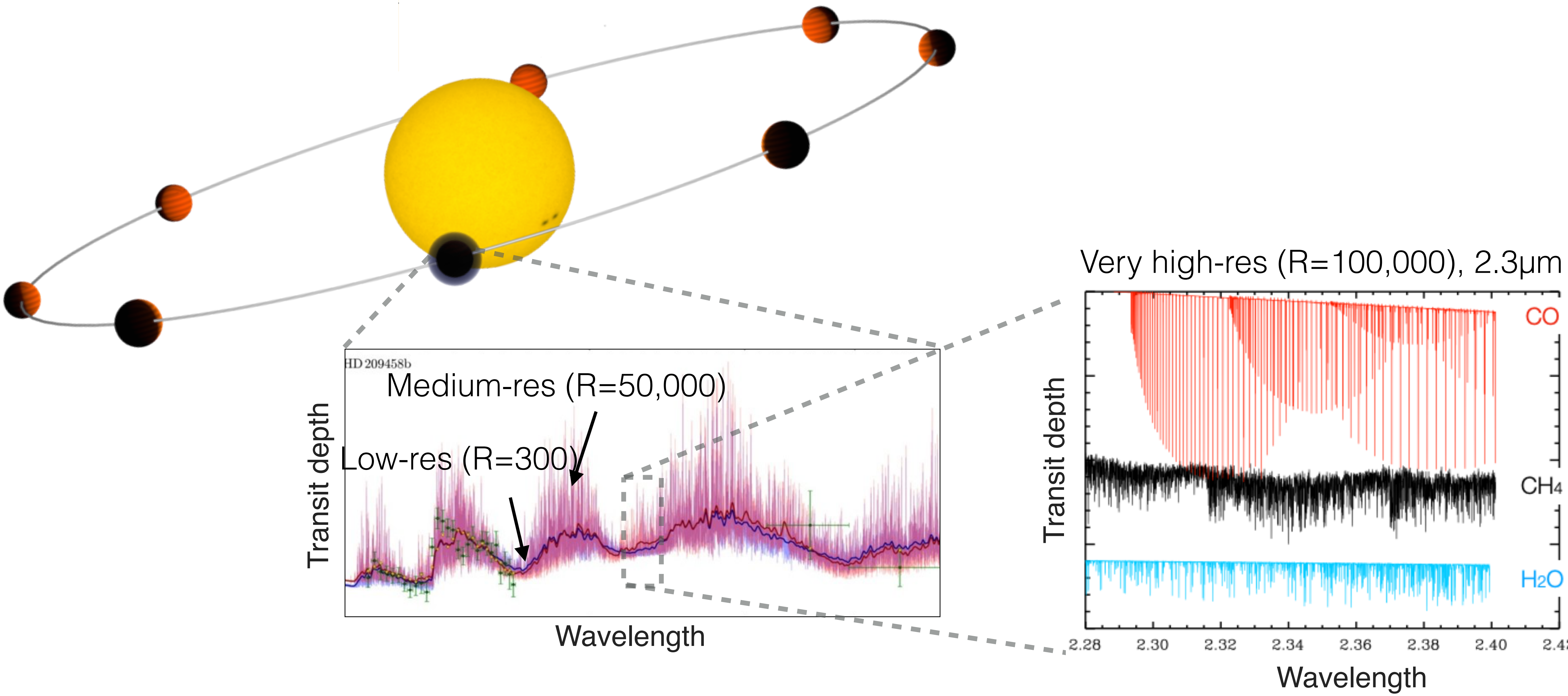
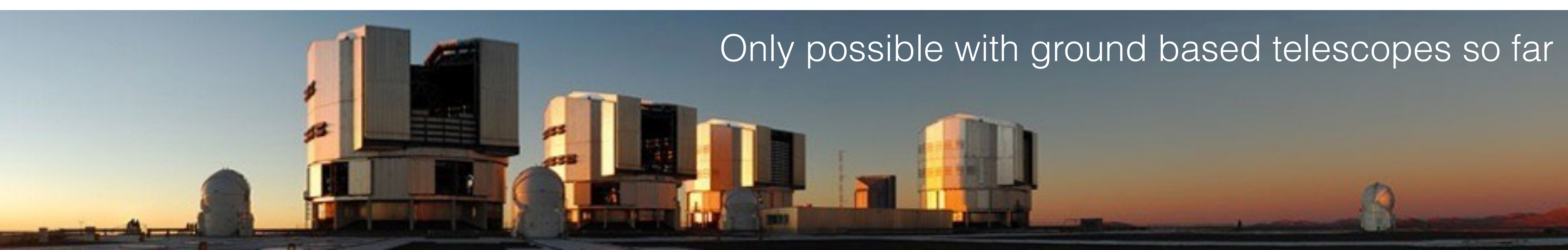


Exoplanets at high spectral resolution



Each species has a unique pattern of spectral lines
Species can be "matched" line by line to templates, e.g. via cross correlation



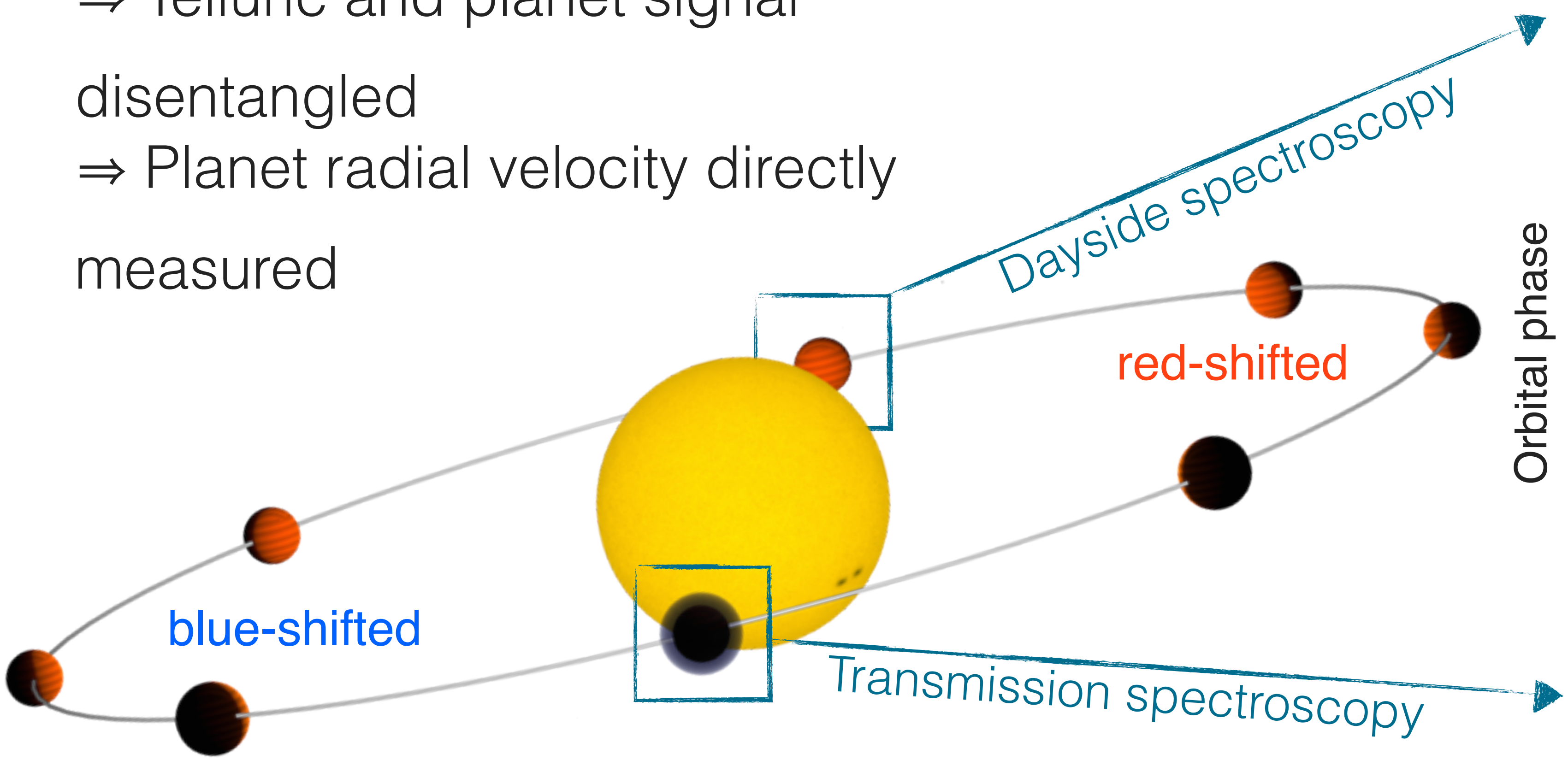
Time-differential high-dispersion spectroscopy

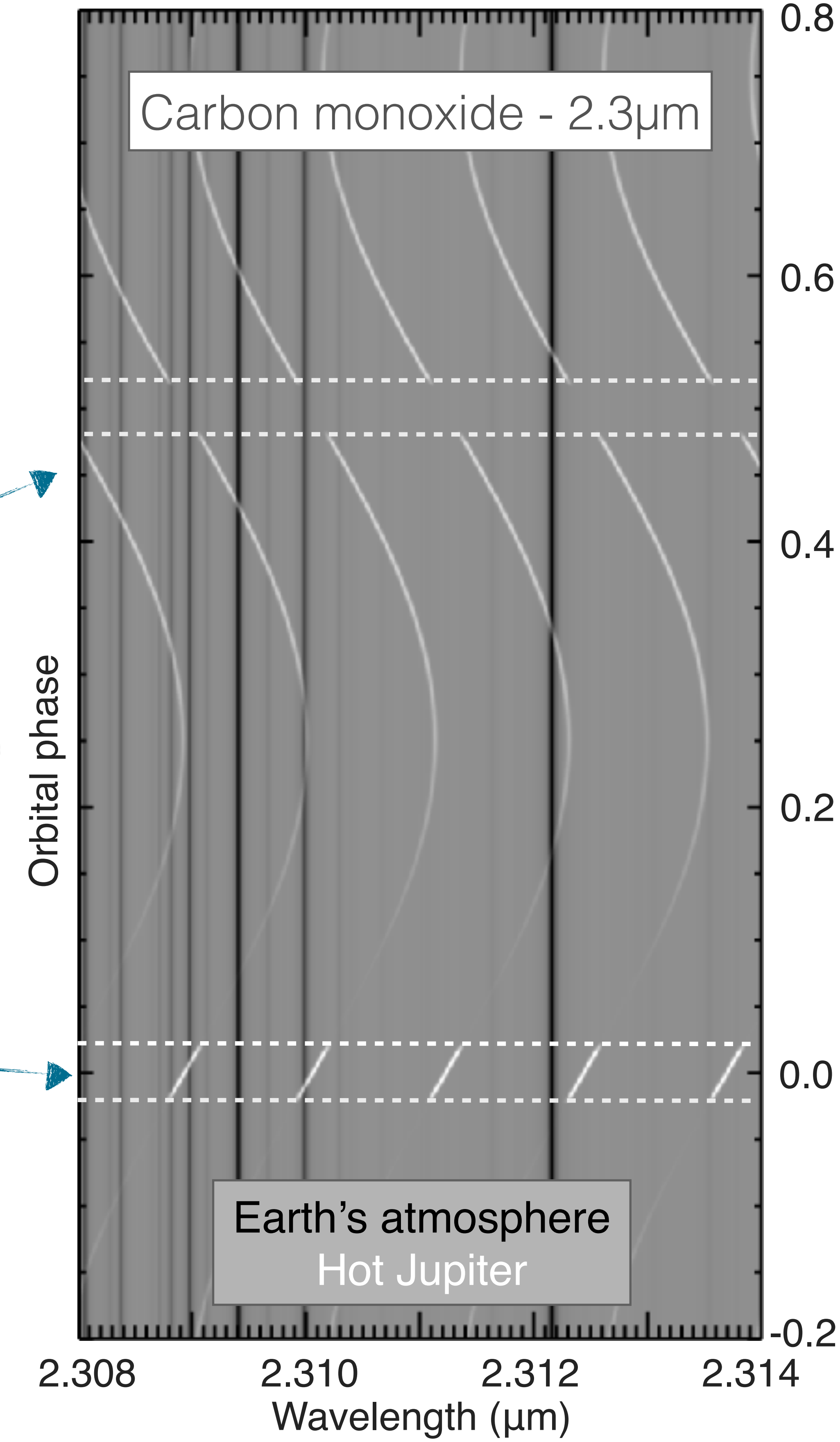
Hot Jupiters: detectable change in radial velocity during a few hours of observations
(Planet: 10-100 km/s; Star: 10-100 m/s)

Vice-versa lines formed in the Earth's atmosphere are completely stationary

⇒ Telluric and planet signal disentangled

⇒ Planet radial velocity directly measured

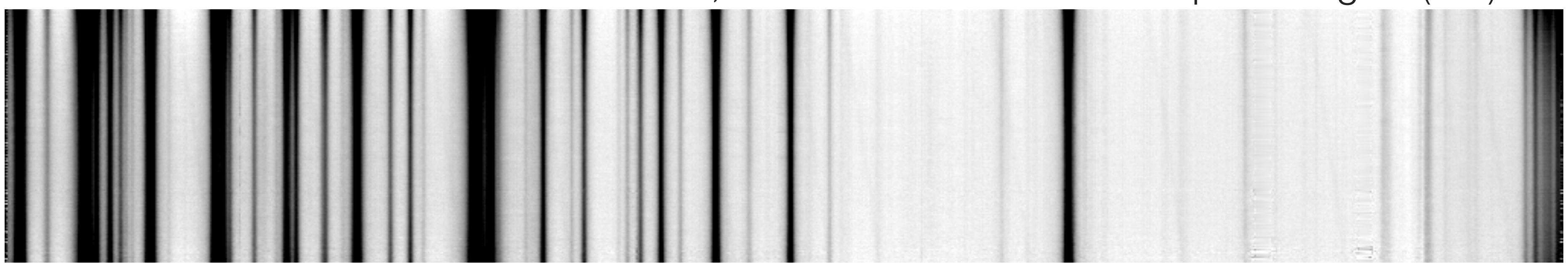




Snellen et al. 2010

Time-differential high-dispersion spectroscopy

CRIRES Observations of HD189733, 5 hours of real data + 20x planet signal (CO)



Step 1

Removing 3D stellar spectrum

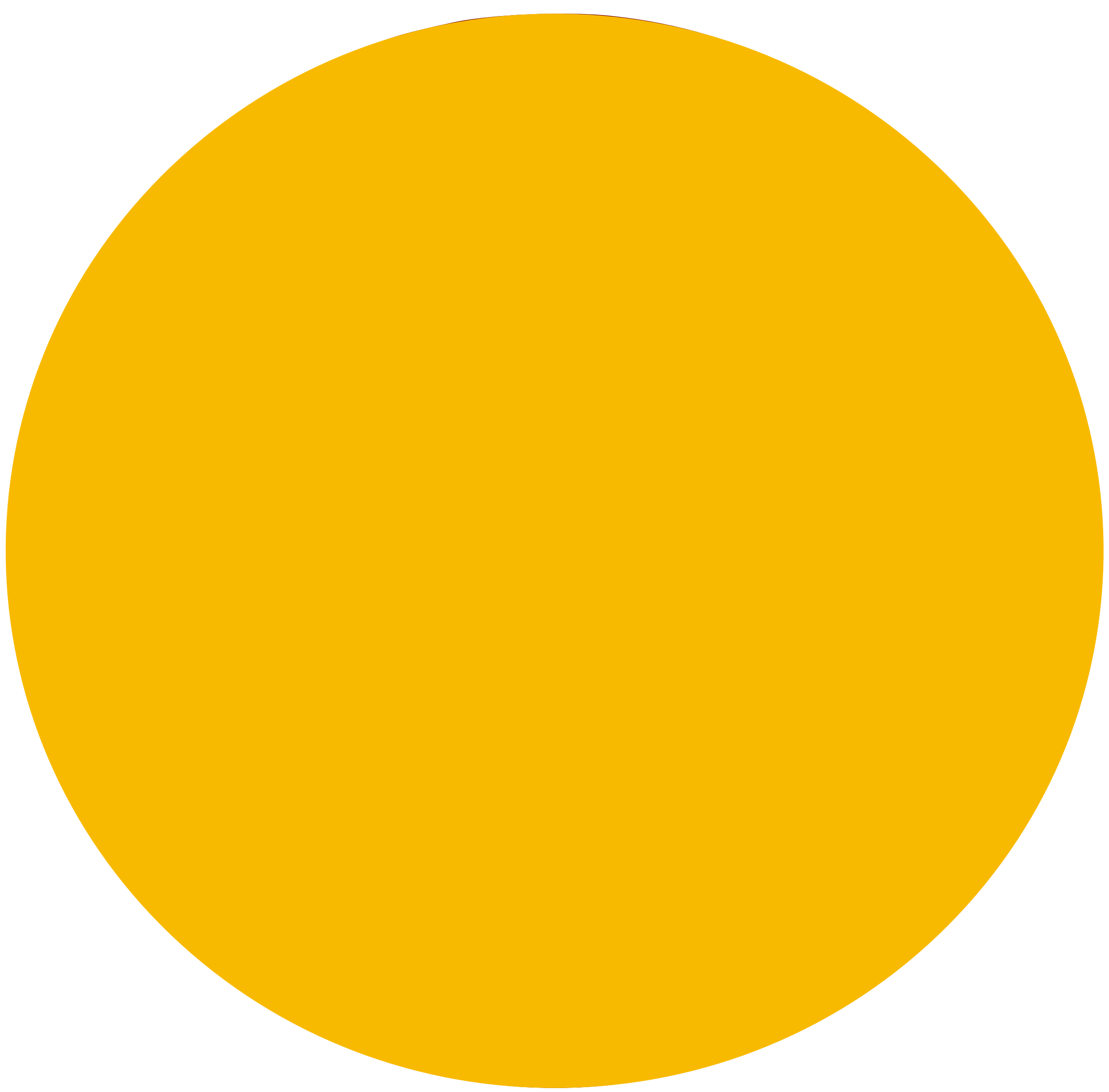
Step 2

But…

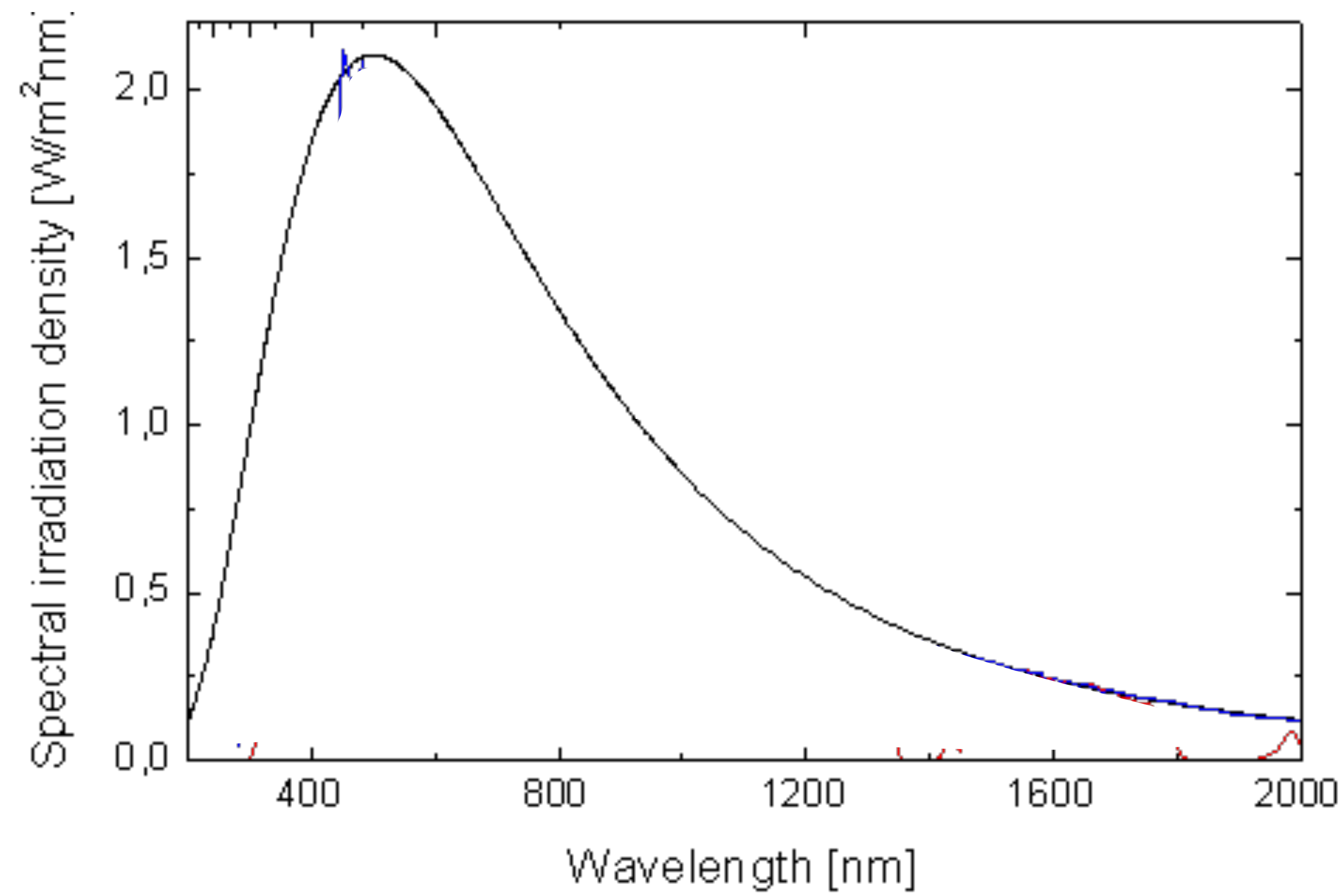
Brogi et al. 2016, ApJ, 817, A106

Caveats: stars are not black bodies

An (approximative) star…



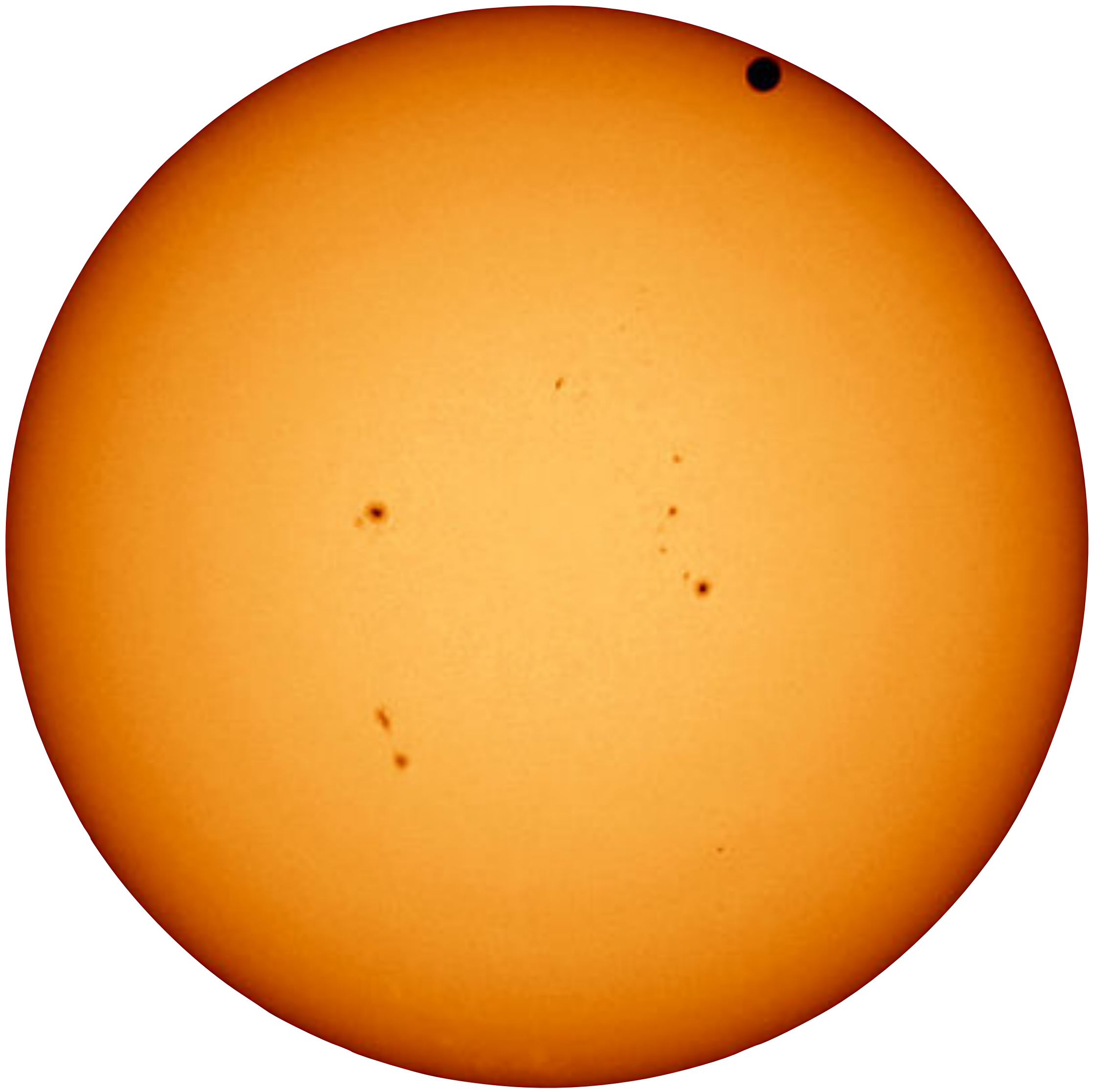
An (approximative) stellar spectrum as a Black Body…



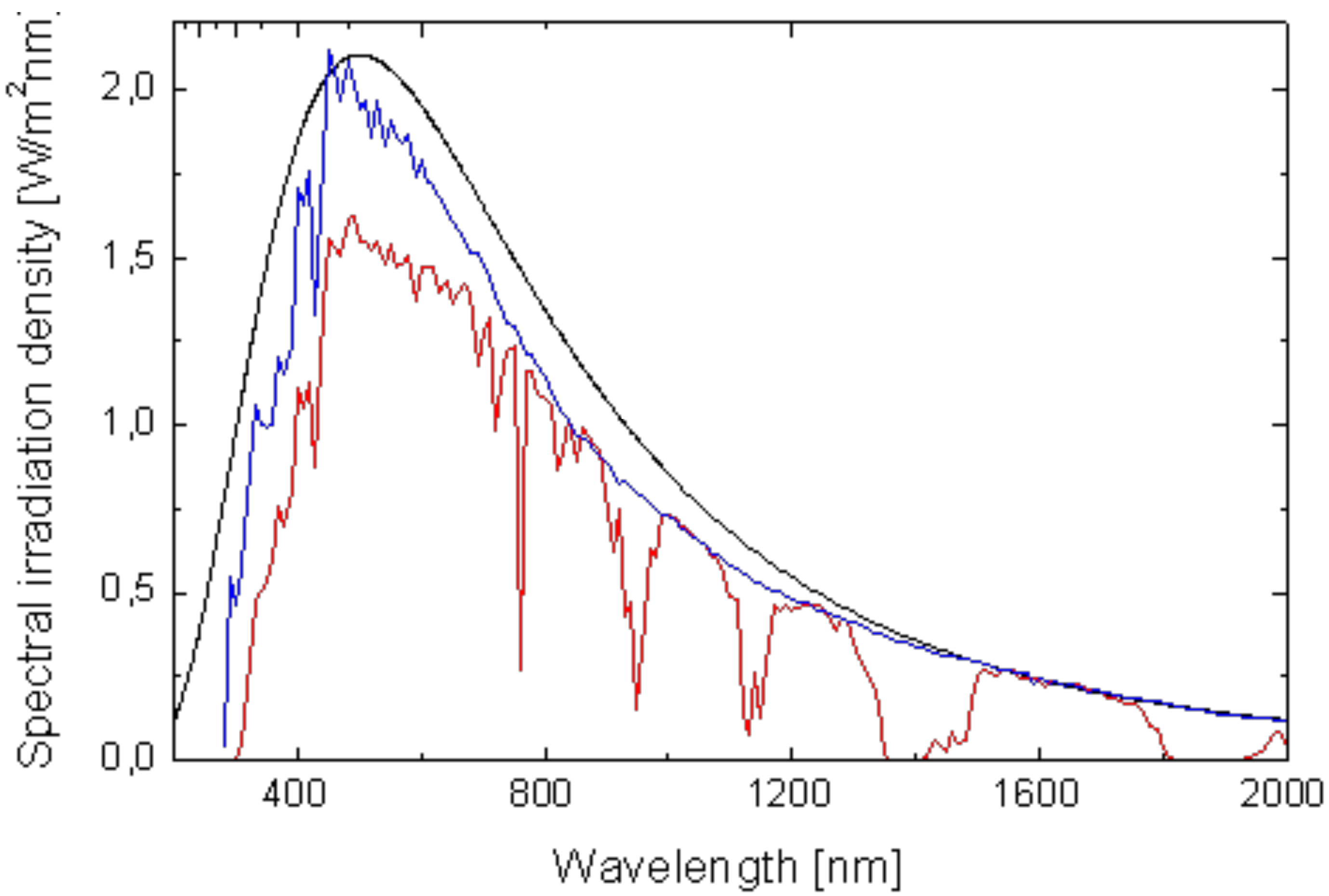
… But the very reality is different…

Caveats: stars are not black bodies

An (approximative) star…

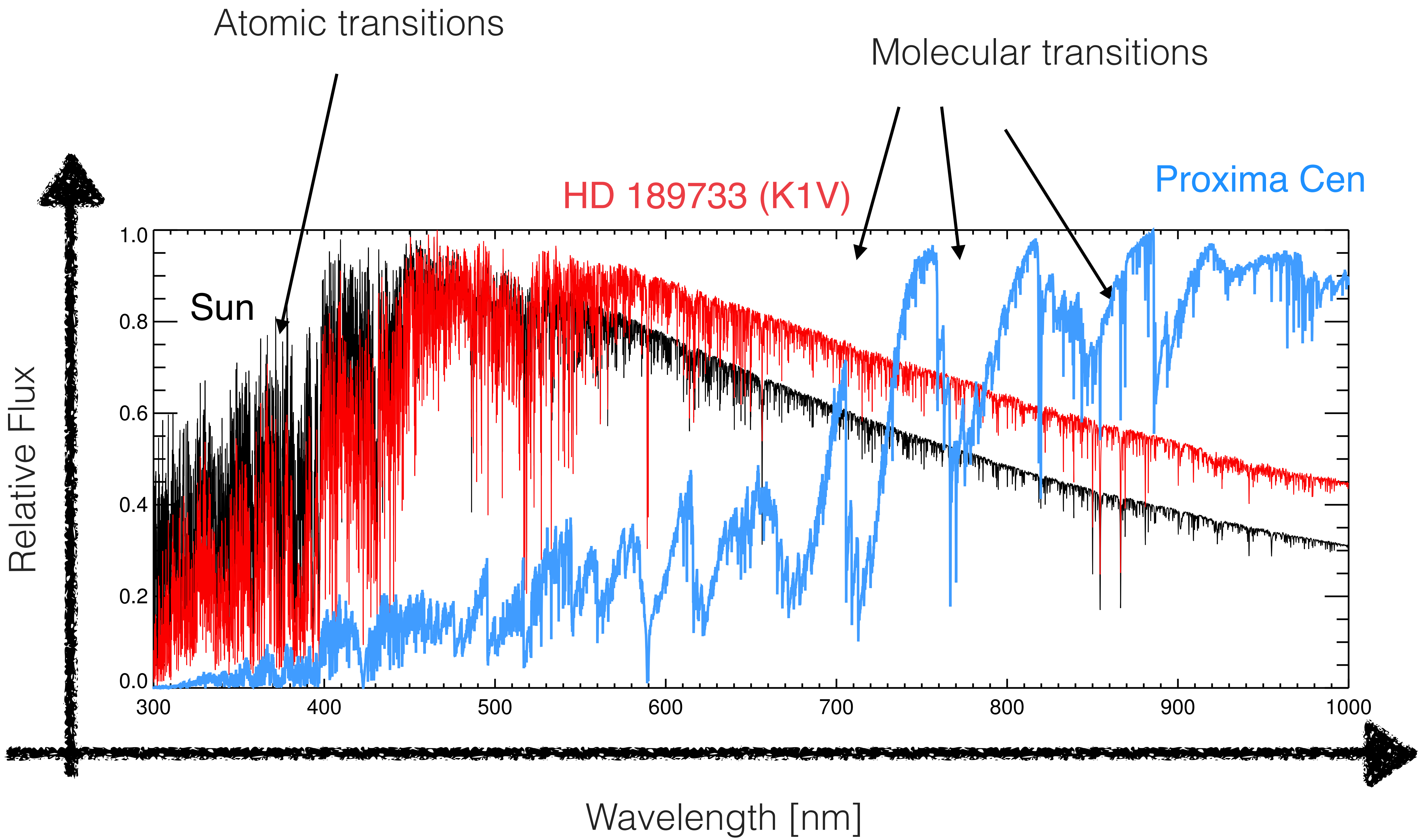


An (approximative) stellar spectrum as a Black Body…



… But the very reality is different…

Caveats: stars are not black bodies



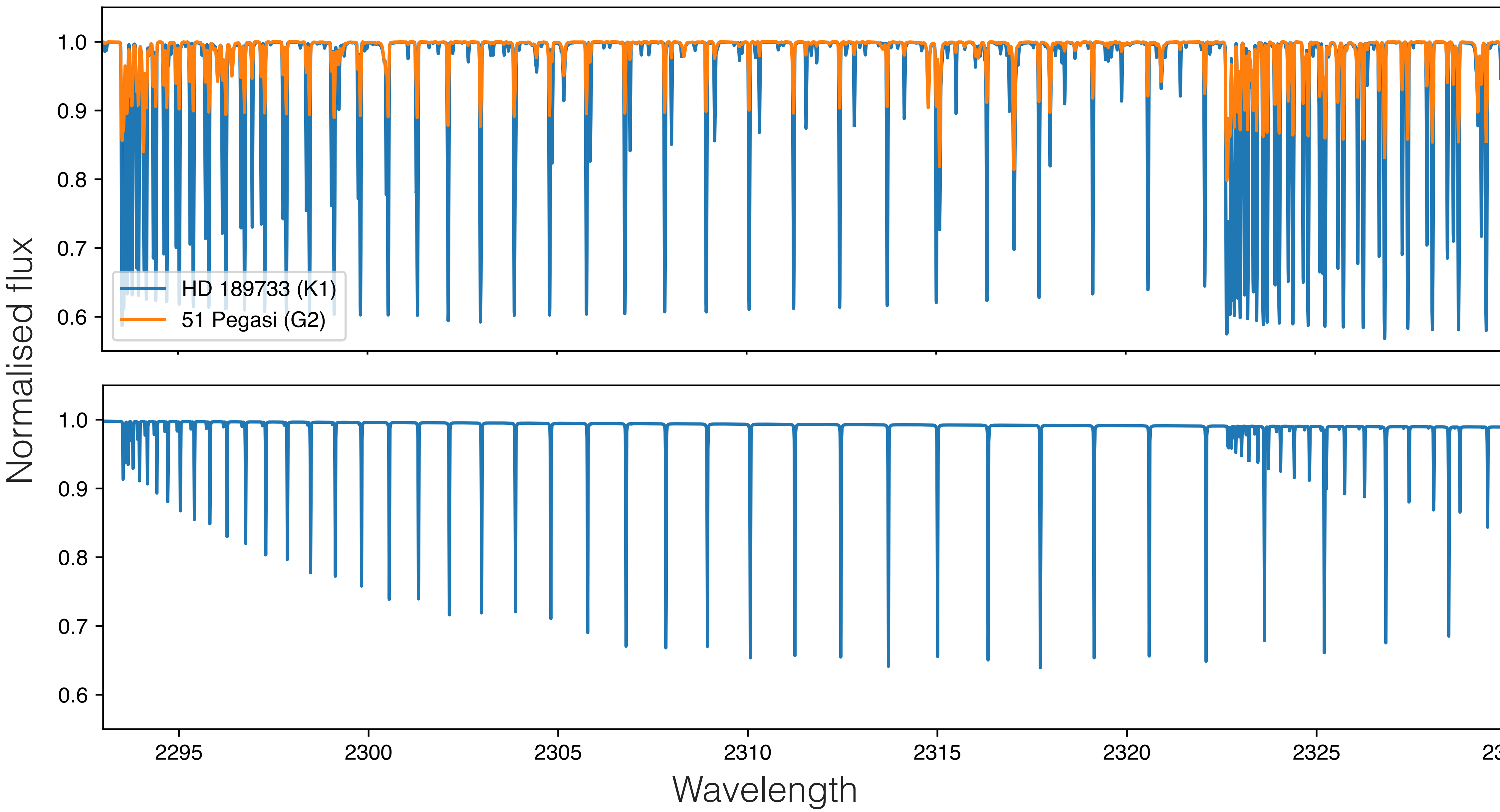
Spectral lines are formed by different atoms / molecules vs. temperature

Spectral lines are formed at various depths

Spectral lines are formed at various points on a rotating stellar surface

Caveats: planets have spectral lines as in stars

Stars and hot Jupiters can have "similar" spectra: CO spectral type G or later type
Or TiO and H_2O for Cooler stars.



Stars at 5500K
and 5000K

Hot Jupiter
at T=1,800K

Caveats: planets have spectral lines as in stars

Stars and hot Jupiters can have “similar” spectra: CO spectral type G or later type
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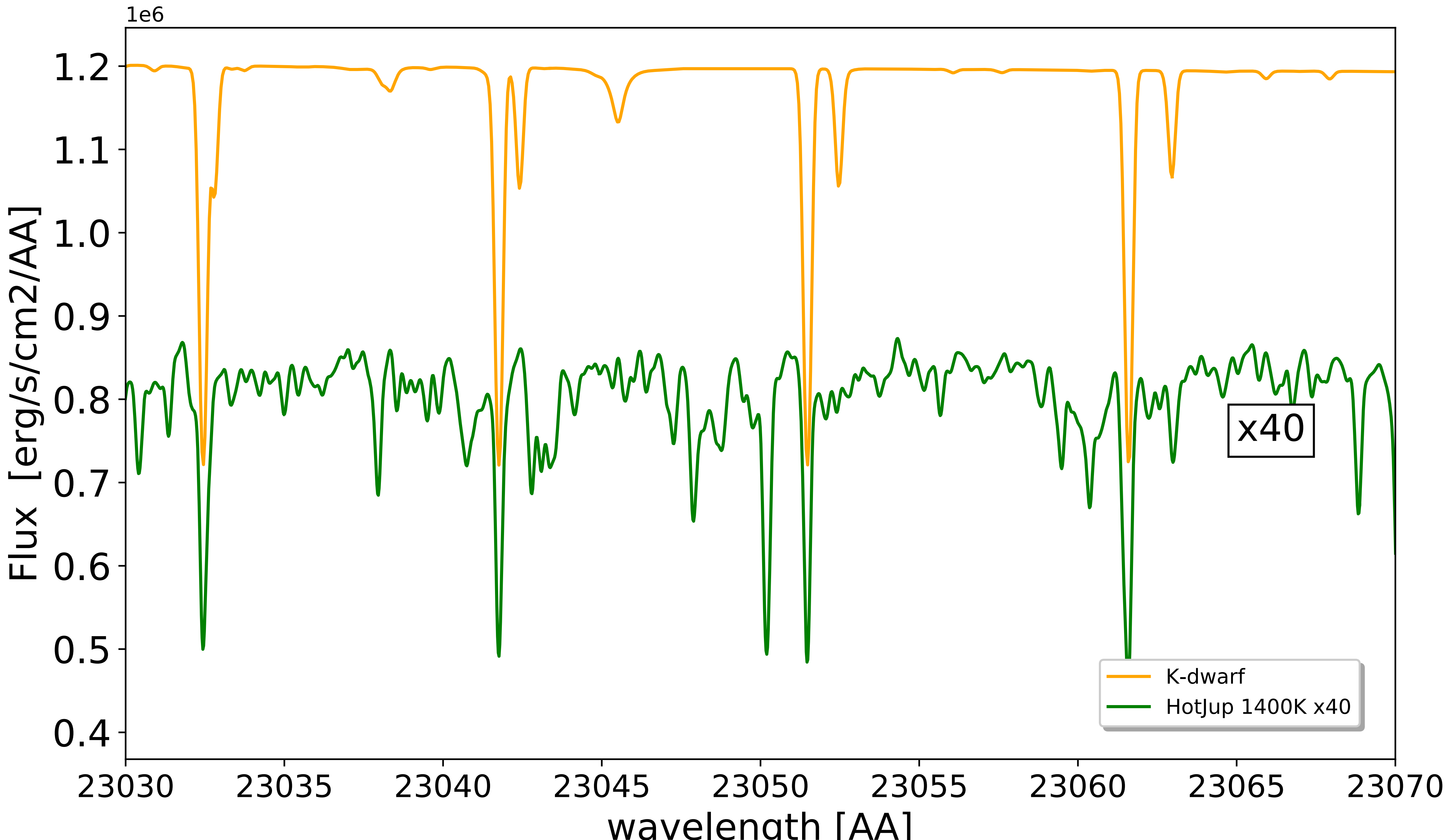

M. C. Maimone PhD Thesis (on going)

Caveats: planets have spectral lines as in stars

Stars and hot Jupiters can have “similar” spectra: CO spectral type G or later type
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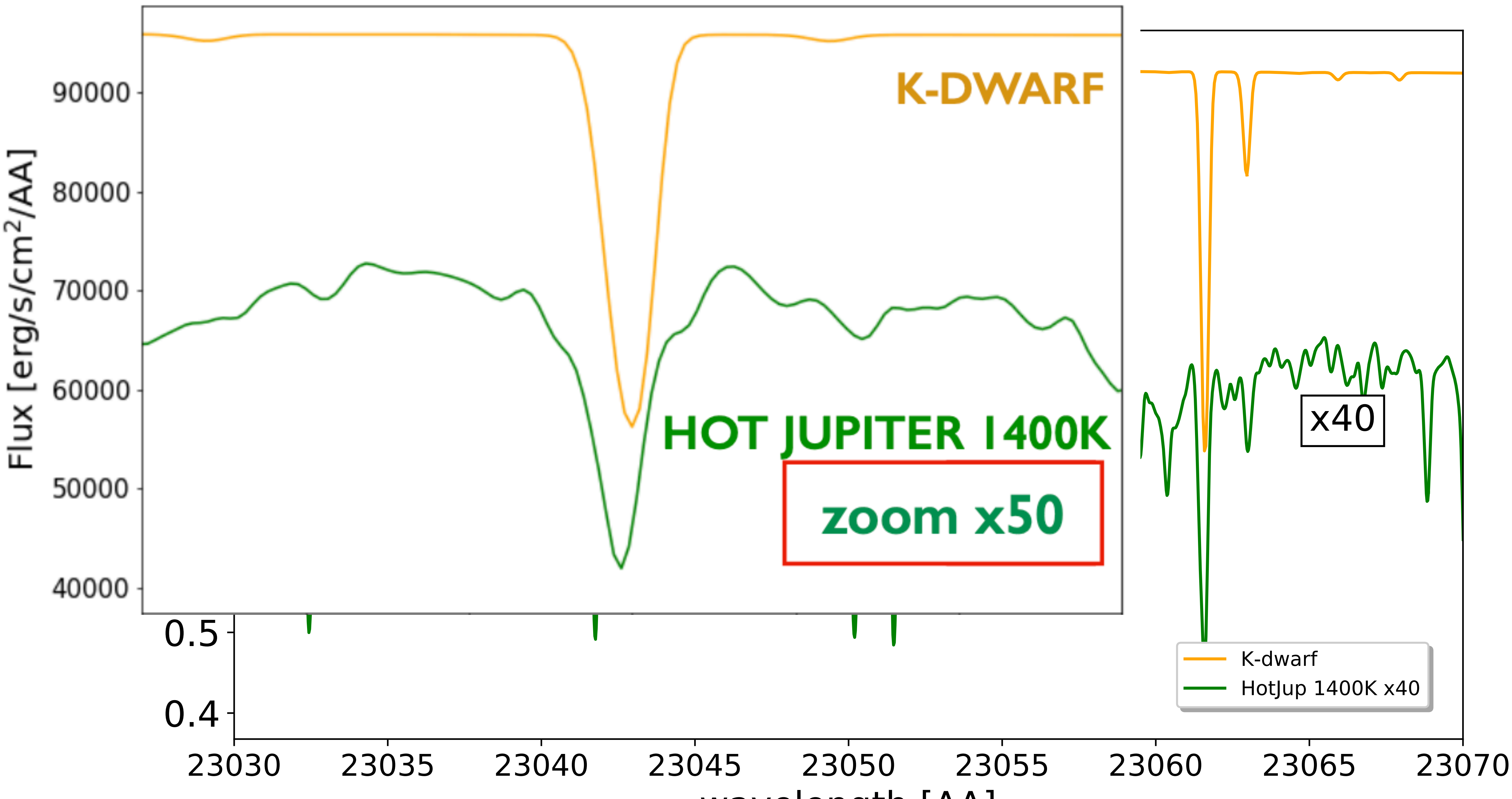
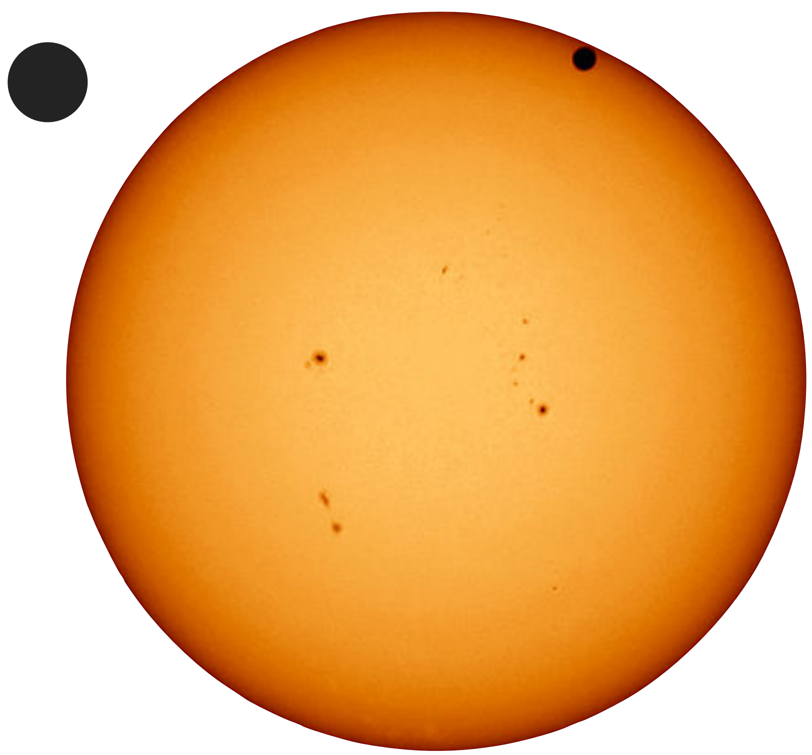


M. C. Maimone PhD Thesis (on going)

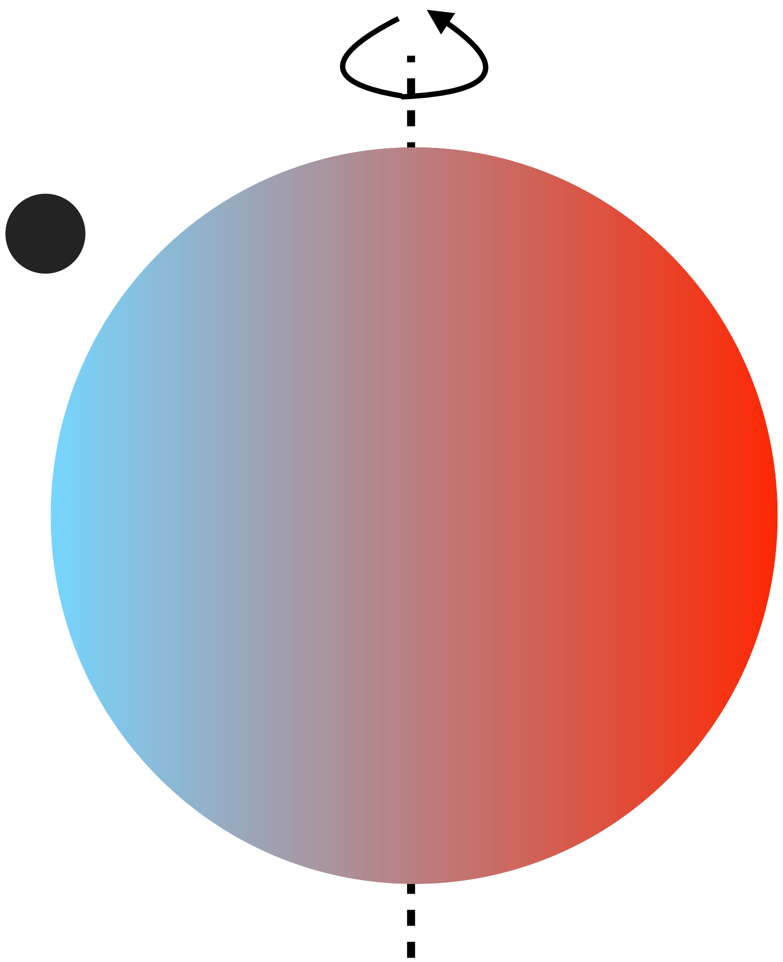
Caveats: stars can distort the planet signal

Stellar intensities vary according to distance from centre (limb darkening)
Stars are rotating with a spin-orbit angle that can be non-zero



Centre-to-limb variations

A transiting planet blocks regions of the stellar surface with different intensities

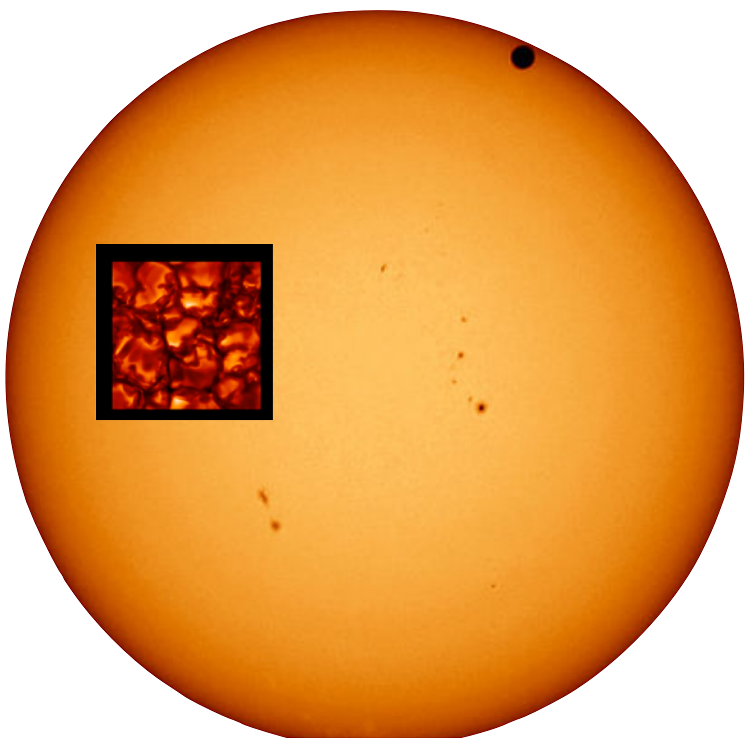


Rossiter-McLaughlin effect

A transiting planet blocks regions of the stellar surface with different rotation

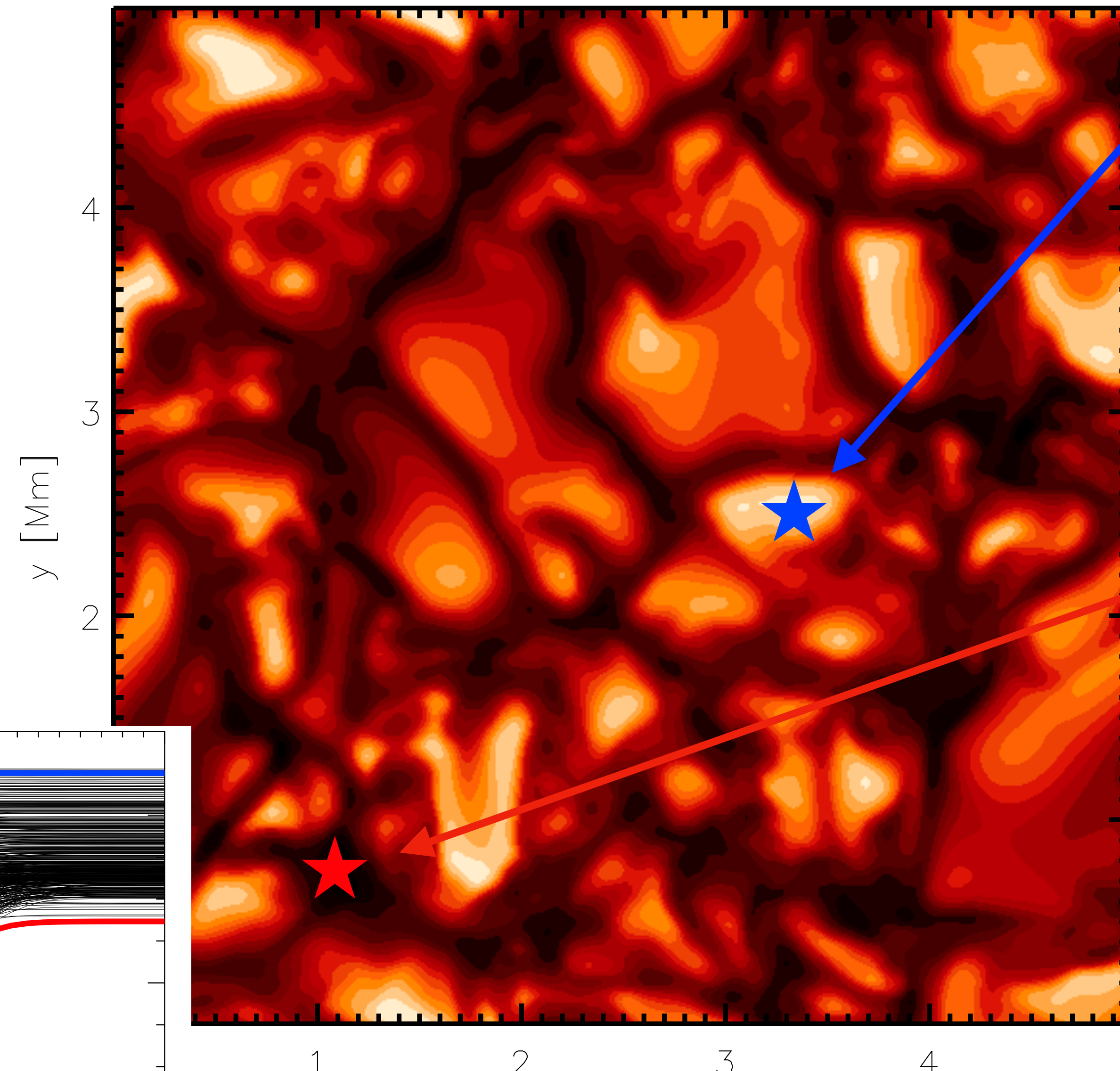
If uncorrected, stellar residuals during transit can dominate the cross correlation signal

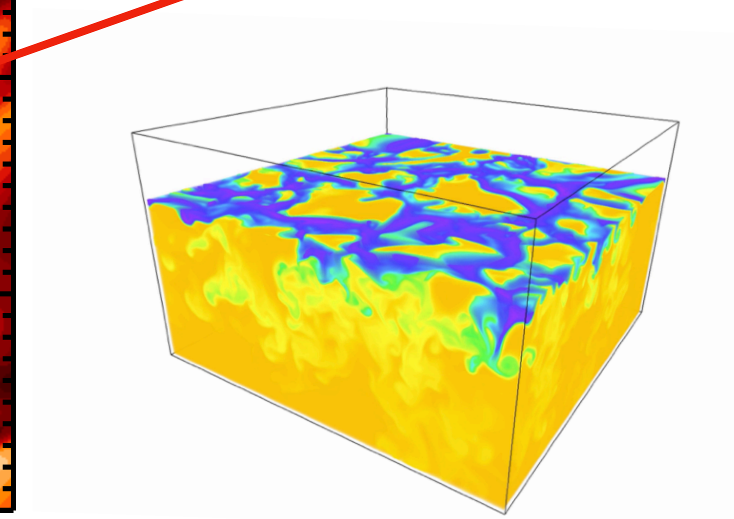
Caveats: stars have a convective pattern



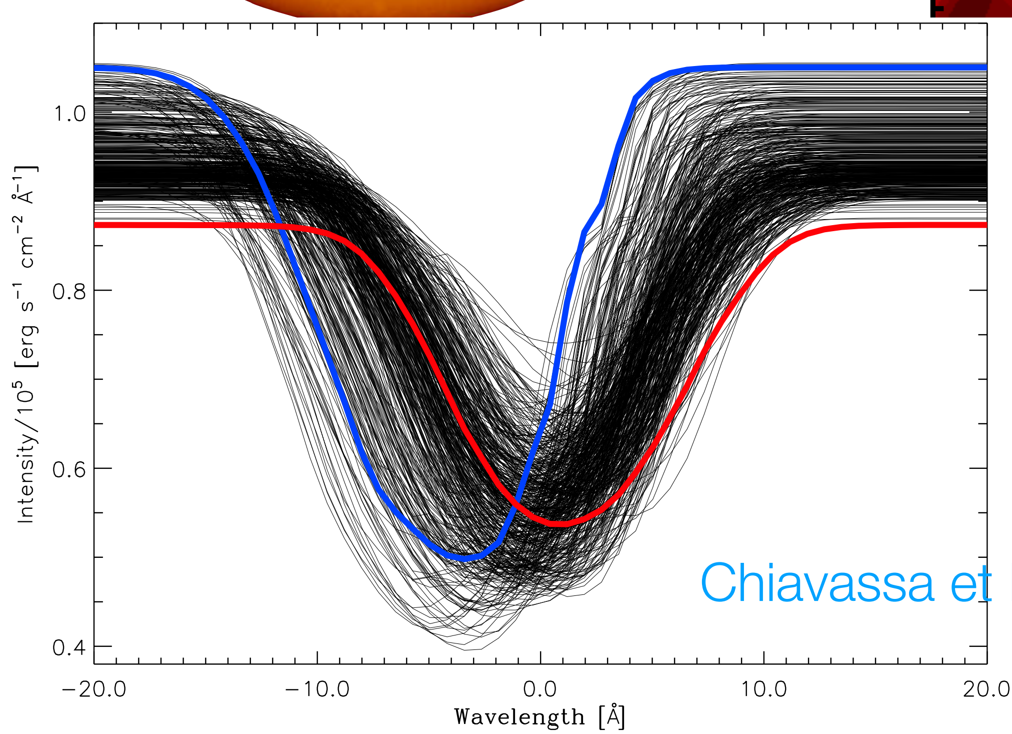
Rising column of material (blue-shifted, hotter)

Descending column of material (red-shifted, cooler)





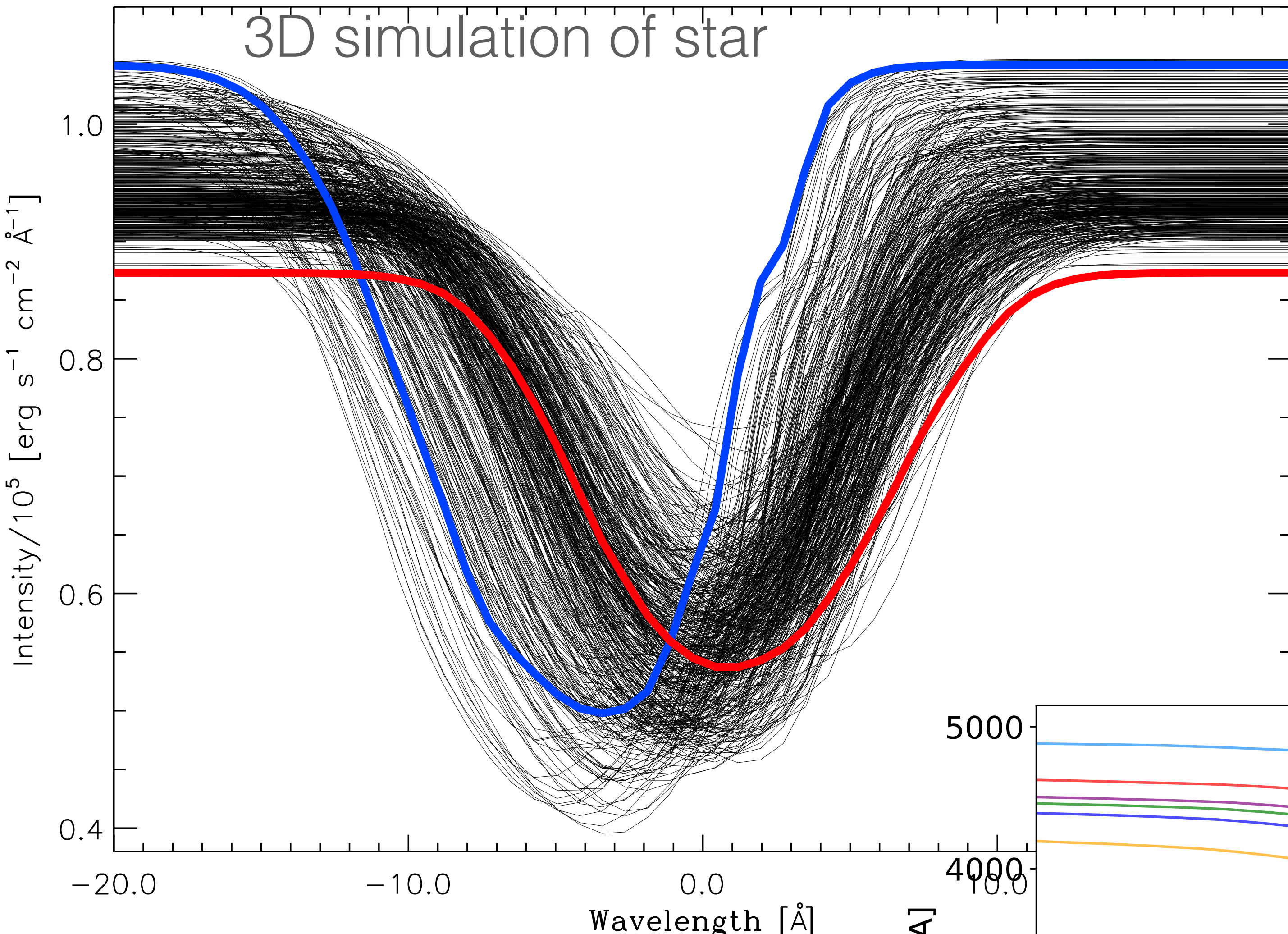
3D radiative hydrodynamical simulations



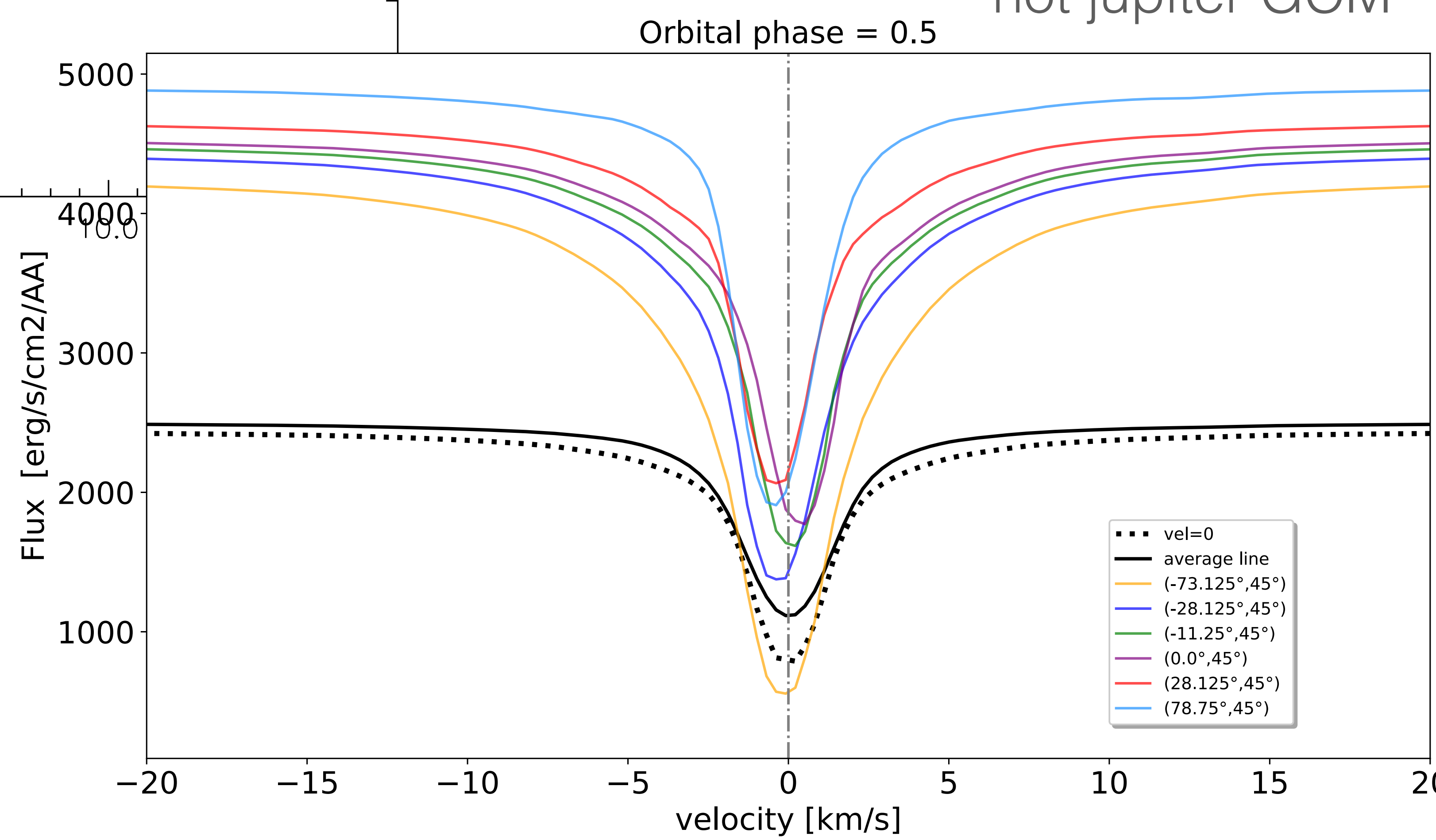
Chiavassa et Brogi 2019

Caveats: stars have a convective pattern

Synthetic CO line from
3D simulation of star



Synthetic CO line from
hot jupiter GCM

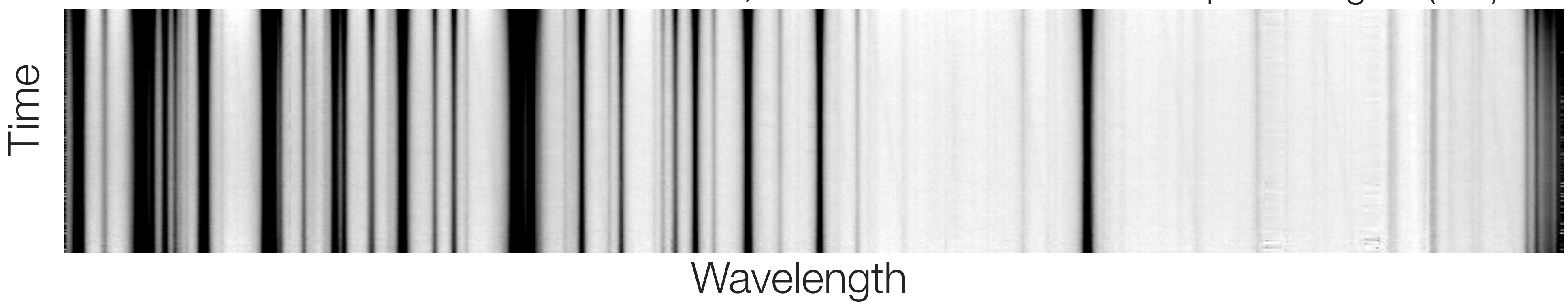


Different physical origins but
similar spanning velocity
ranges

M. C. Maimone PhD Thesis (on going)

Time-differential high-dispersion spectroscopy

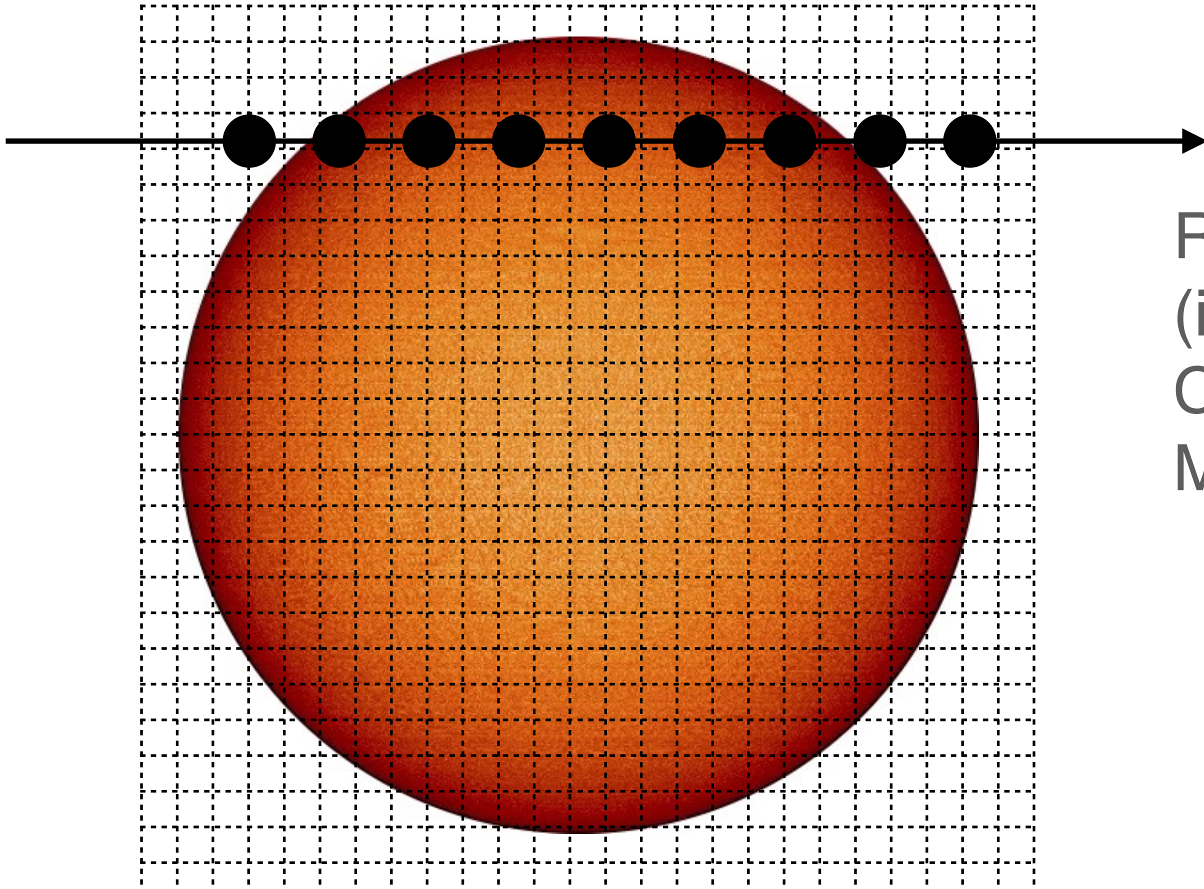
CRIRES Observations of HD189733, 5 hours of real data + 20x planet signal (CO)



Step 1

Brogi et al. 2016, ApJ, 817, A106

Time-differential high-dispersion spectroscopy

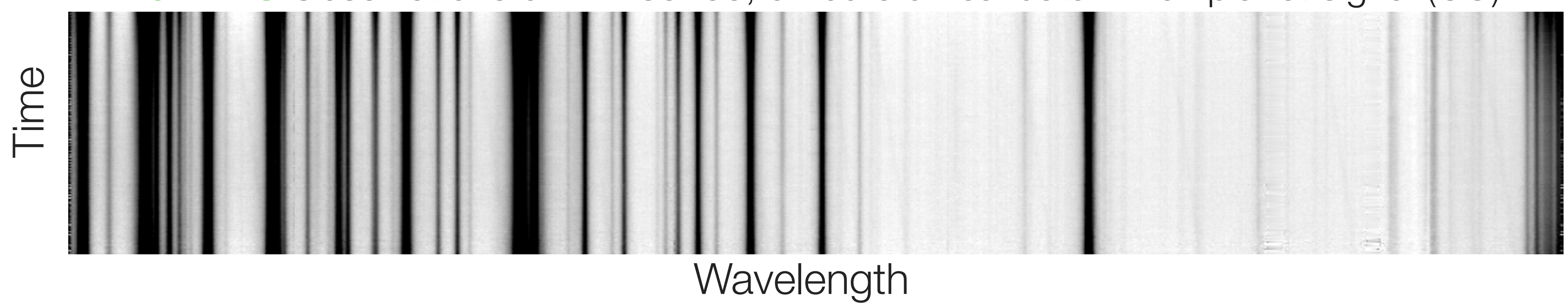


Removing 3D stellar spectrum (incorporating, convection signature, Center to Limb and Rossiter-McLaughlin effects)

Step 2

Time-differential high-dispersion spectroscopy

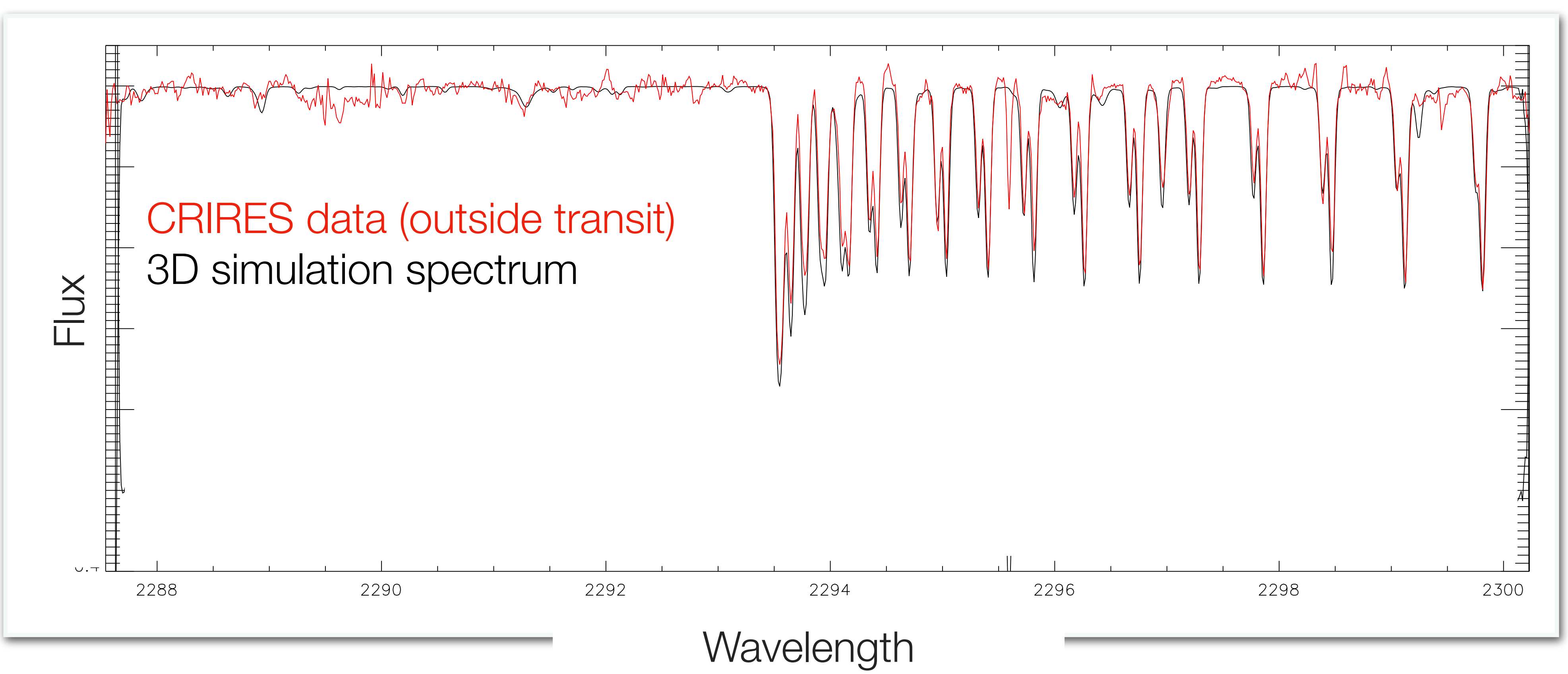
CRIRES Observations of HD189733, 5 hours of real data + 20x planet signal (CO)

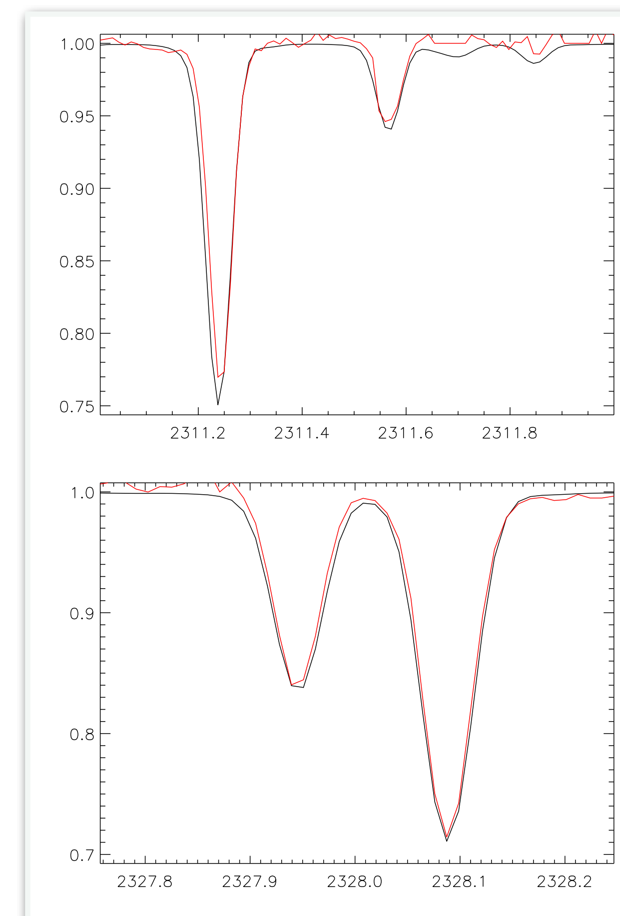


Step 1

Step 2

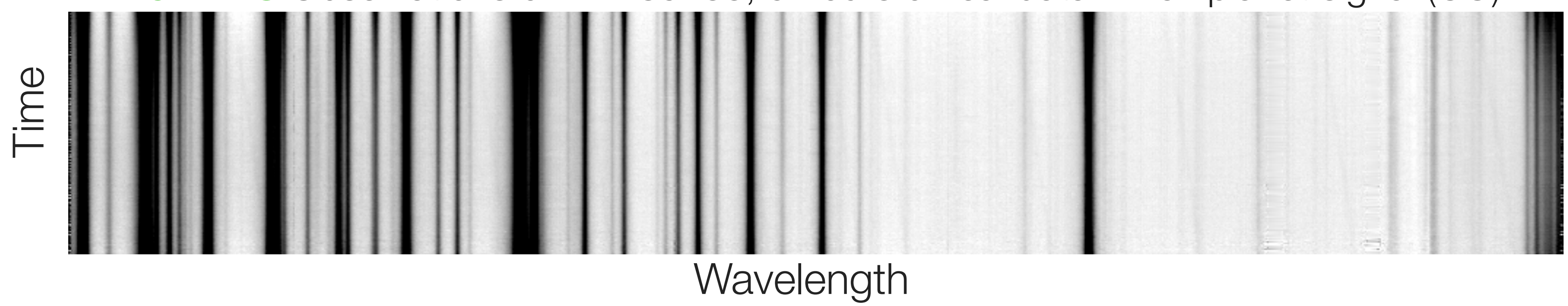
Removing 3D stellar spectrum (incorporating RM and Center to Limb and Rossiter-McLaughlin effects)





Time-differential high-dispersion spectroscopy

CRIRES Observations of HD189733, 5 hours of real data + 20x planet signal (CO)



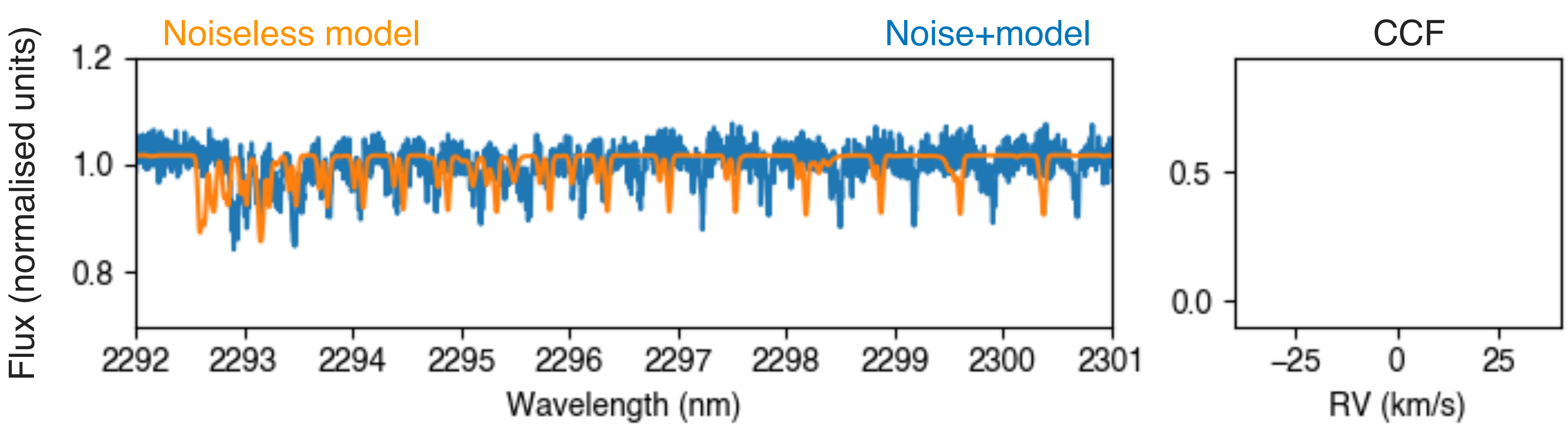
Step 1

Removing 3D stellar spectrum (incorporating RM and Center to Limb and Rossiter-McLaughlin effects)

Step 2

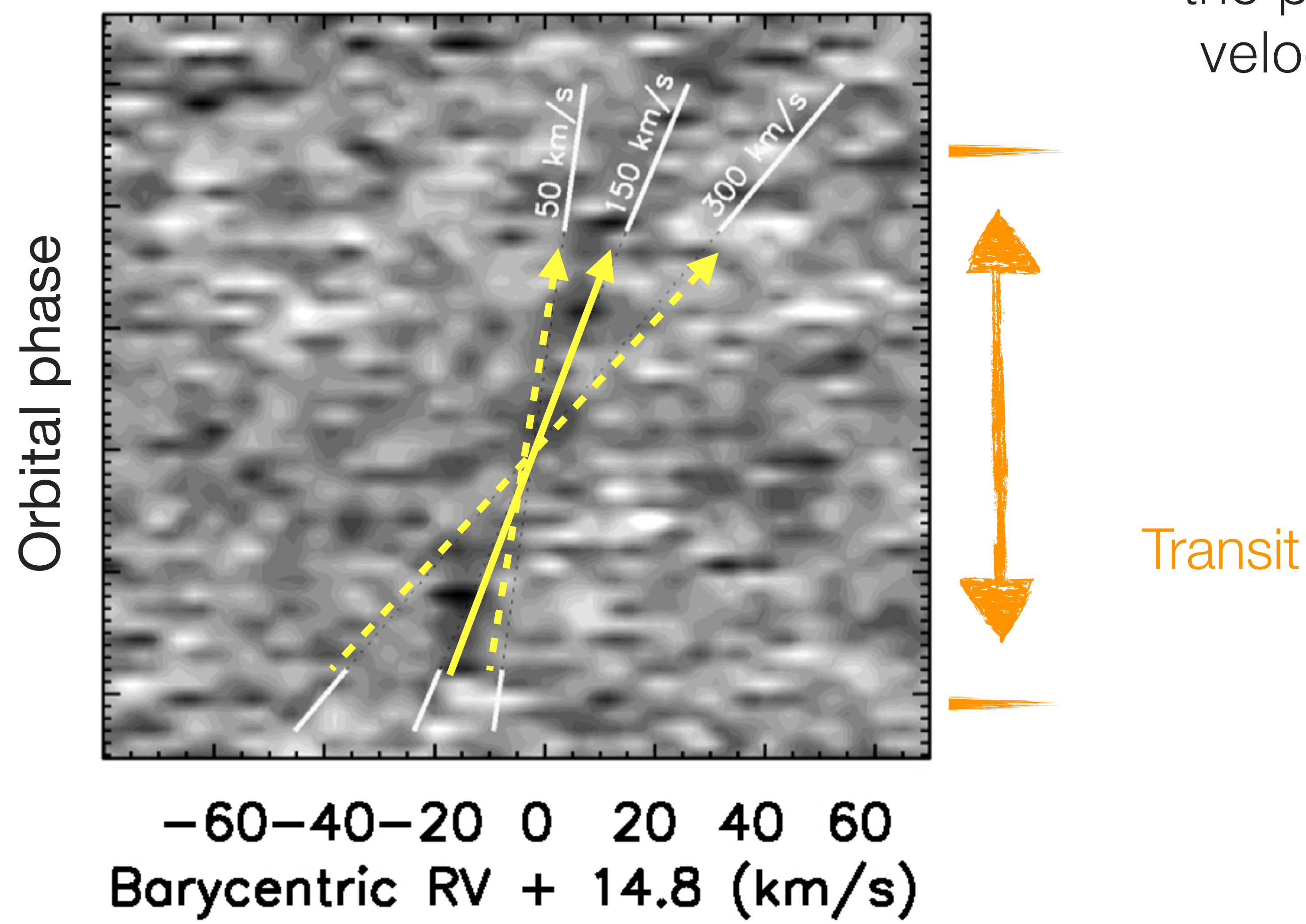
Removing "static" telluric lines and cross-correlate with 1D planet models

Step 3

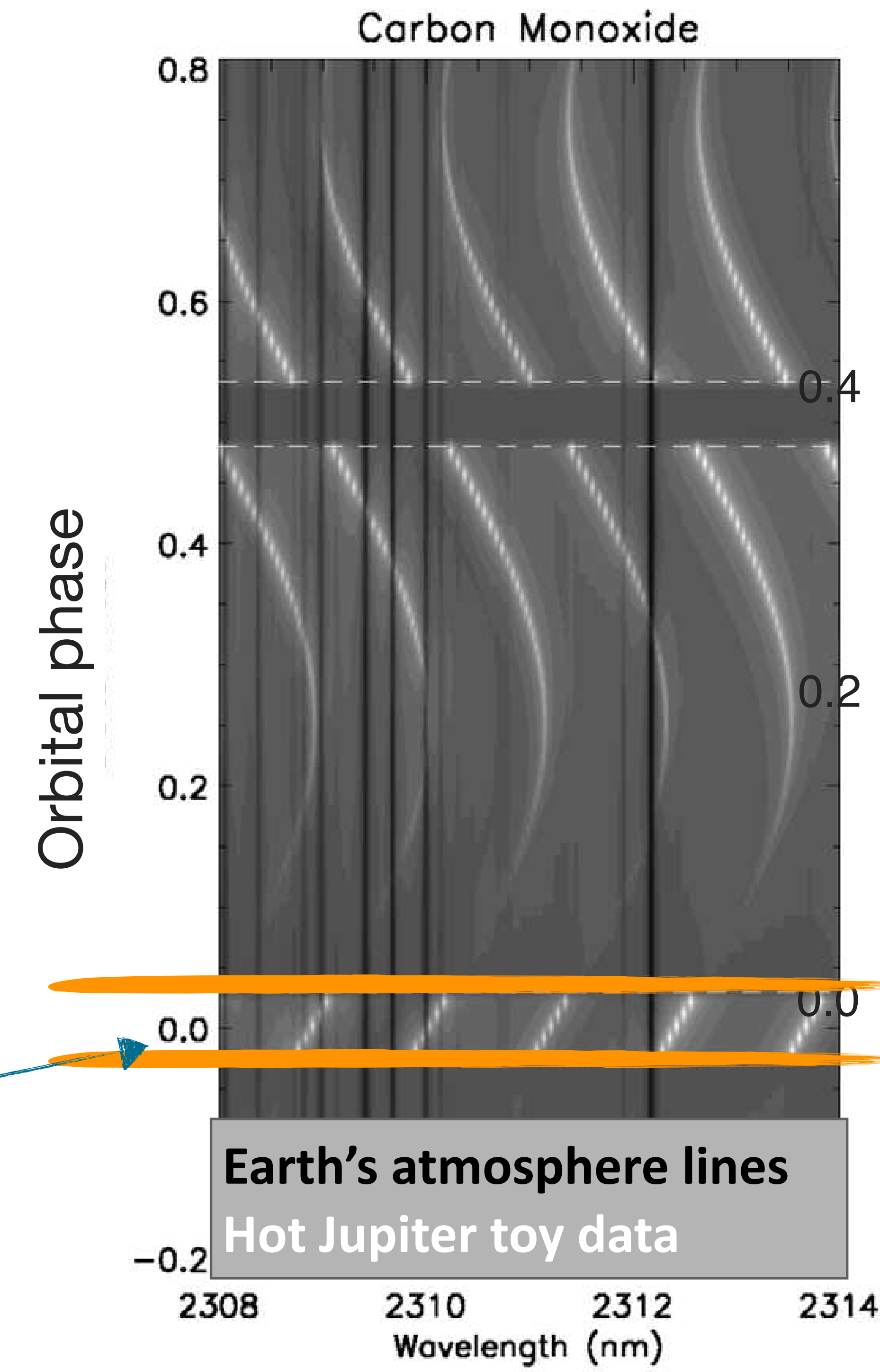


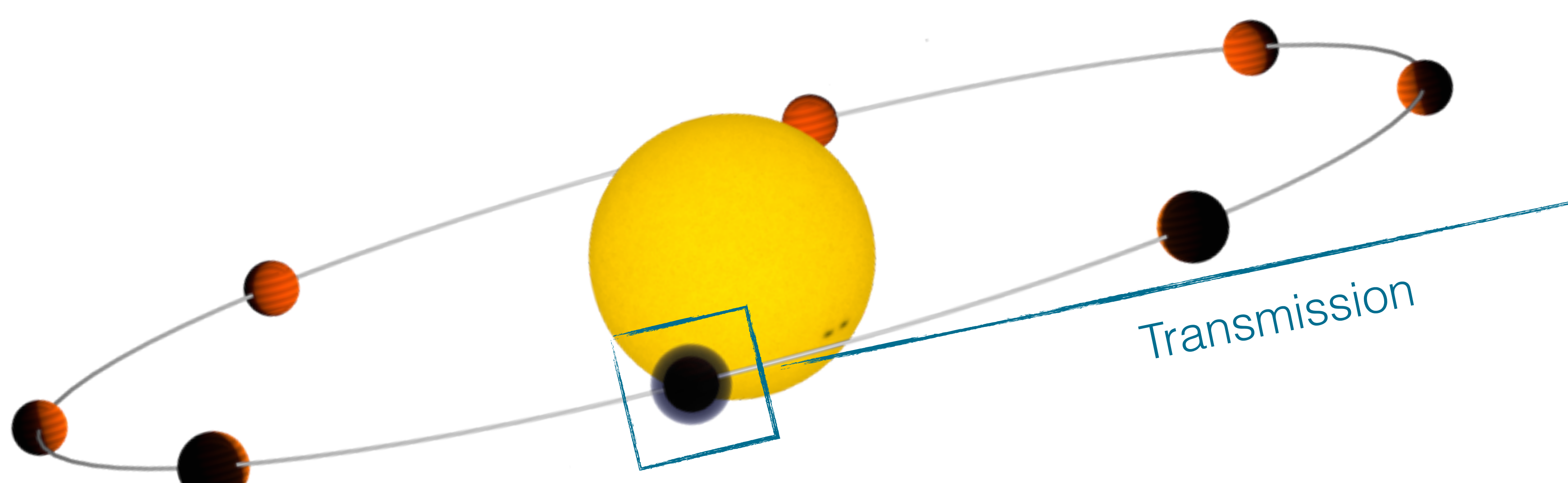
Time-differential high-dispersion spectroscopy

Cross-correlation matrix
CC(Radial Velocity, time)

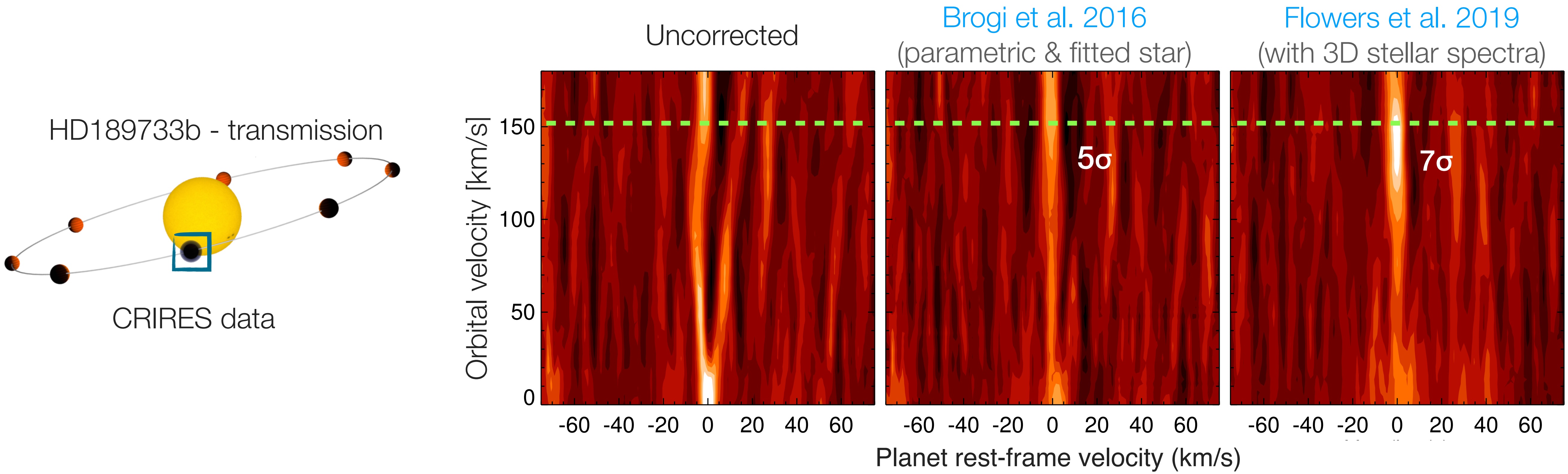


The peak CC tracks the planet radial velocity in time

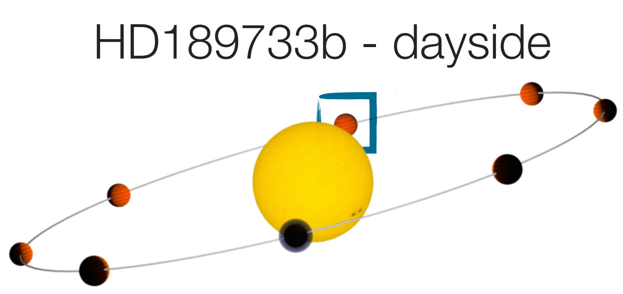


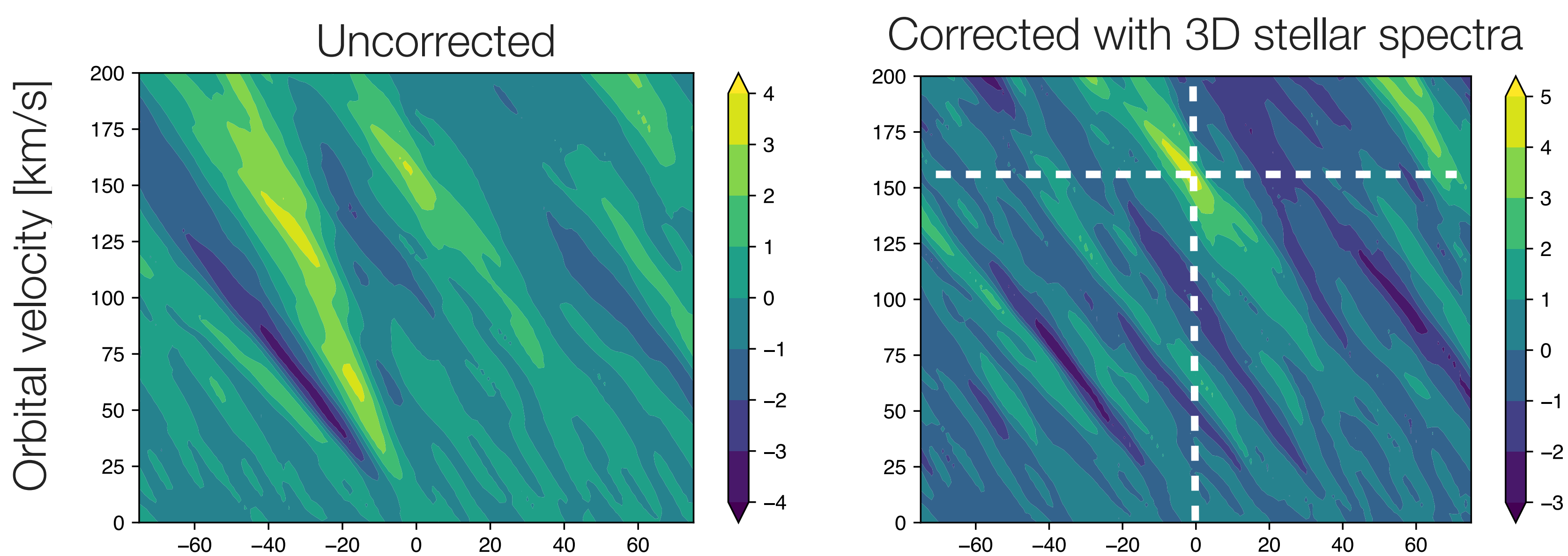


Snellen et al. 2010



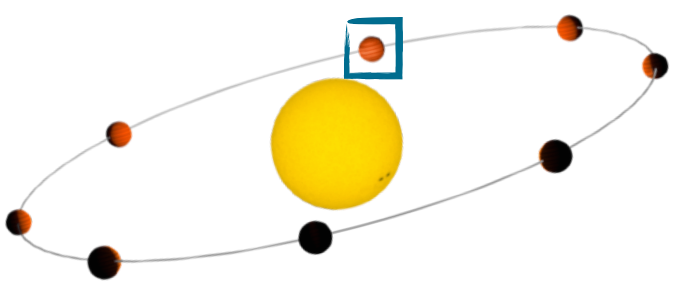
Chiavassa & Brogi 2019, A&A, 631, A100





Chiavassa & Brogi 2019, A&A, 631, A100

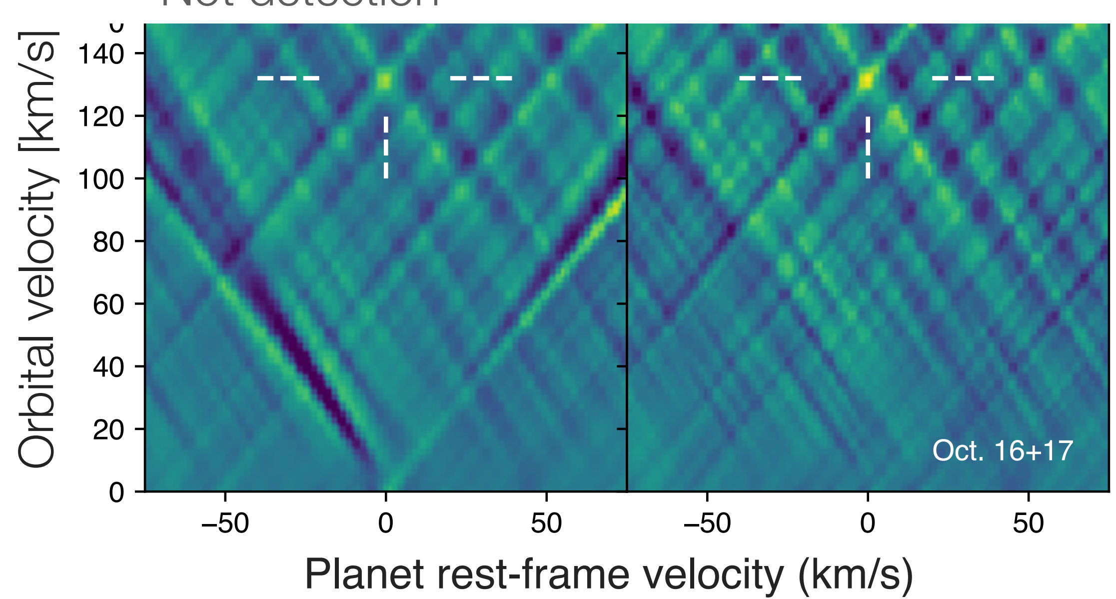
51 Peg - dayside (not transiting)



Chiavassa & Brogi 2019, A&A, 631, A100

Brogi et al. 2013
(parametric & fitted star)
Not detection

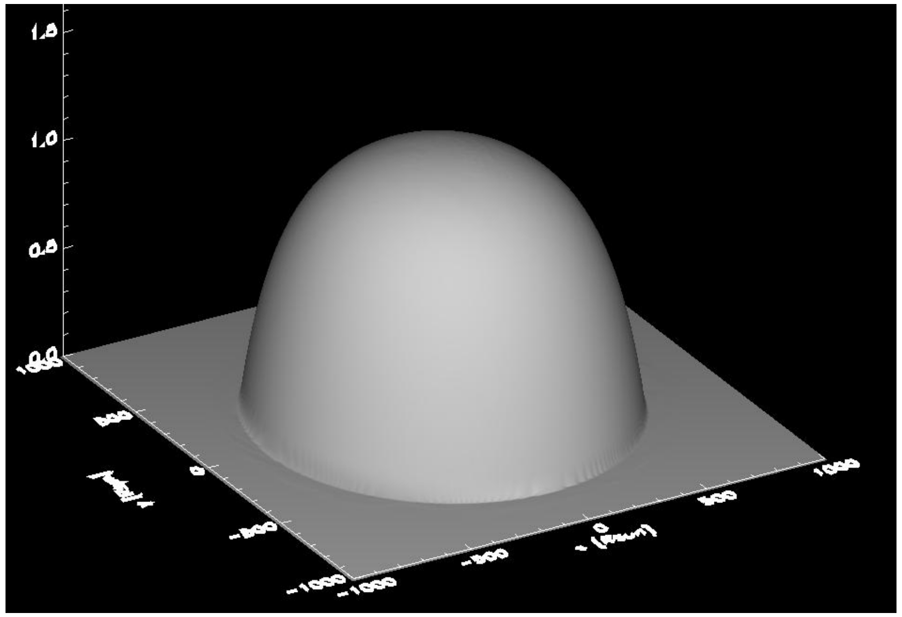
Clear detection with 3D stellar spectra correction



What is better in the framework of planets?
1D or 3D models for stars?

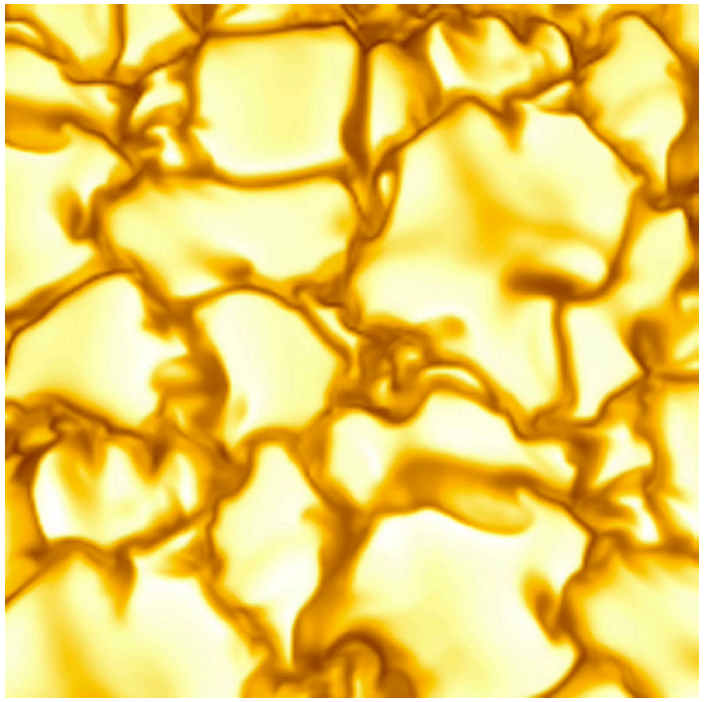
1D versus Multi-D

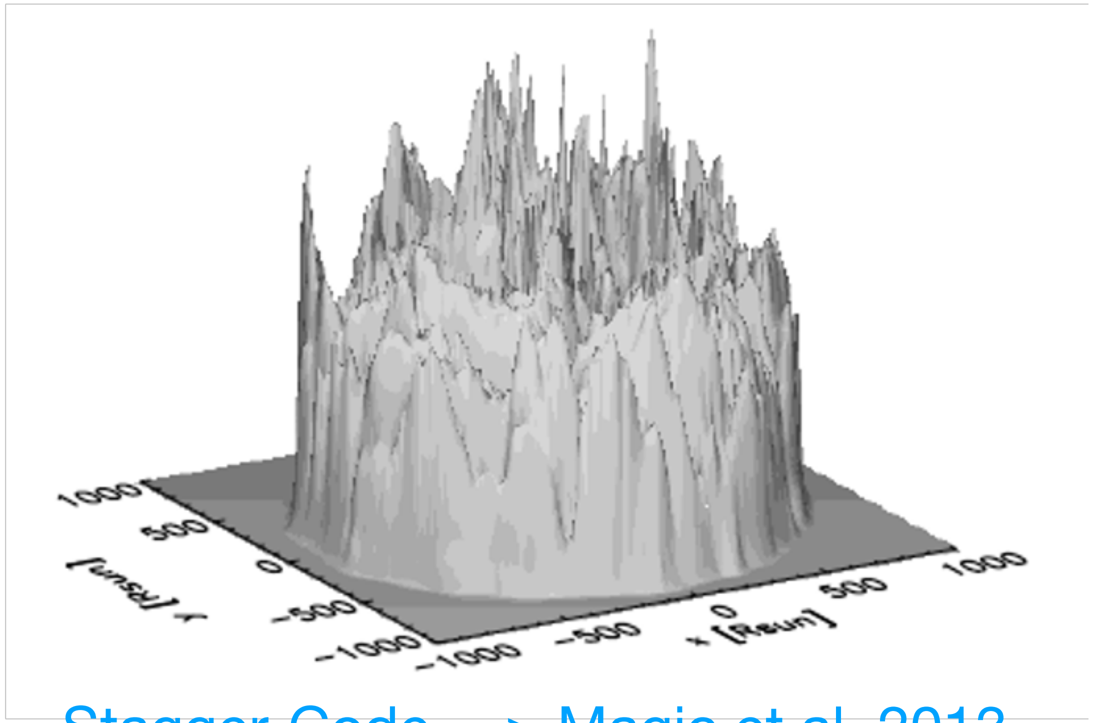
1D, since 1970…



ATLAS —> Kurucz et al. 2005
MARCS models —> Gustafsson et al. 2008
PHOENIX models —> Husser et al. 2013

Multi-D, since 1990…





Stagger-Code —> Magic et al. 2013
CO5BOLD —> Ludwig et al. 2009
MURaM —> Beeck et al. 2013

1D versus Multi-D

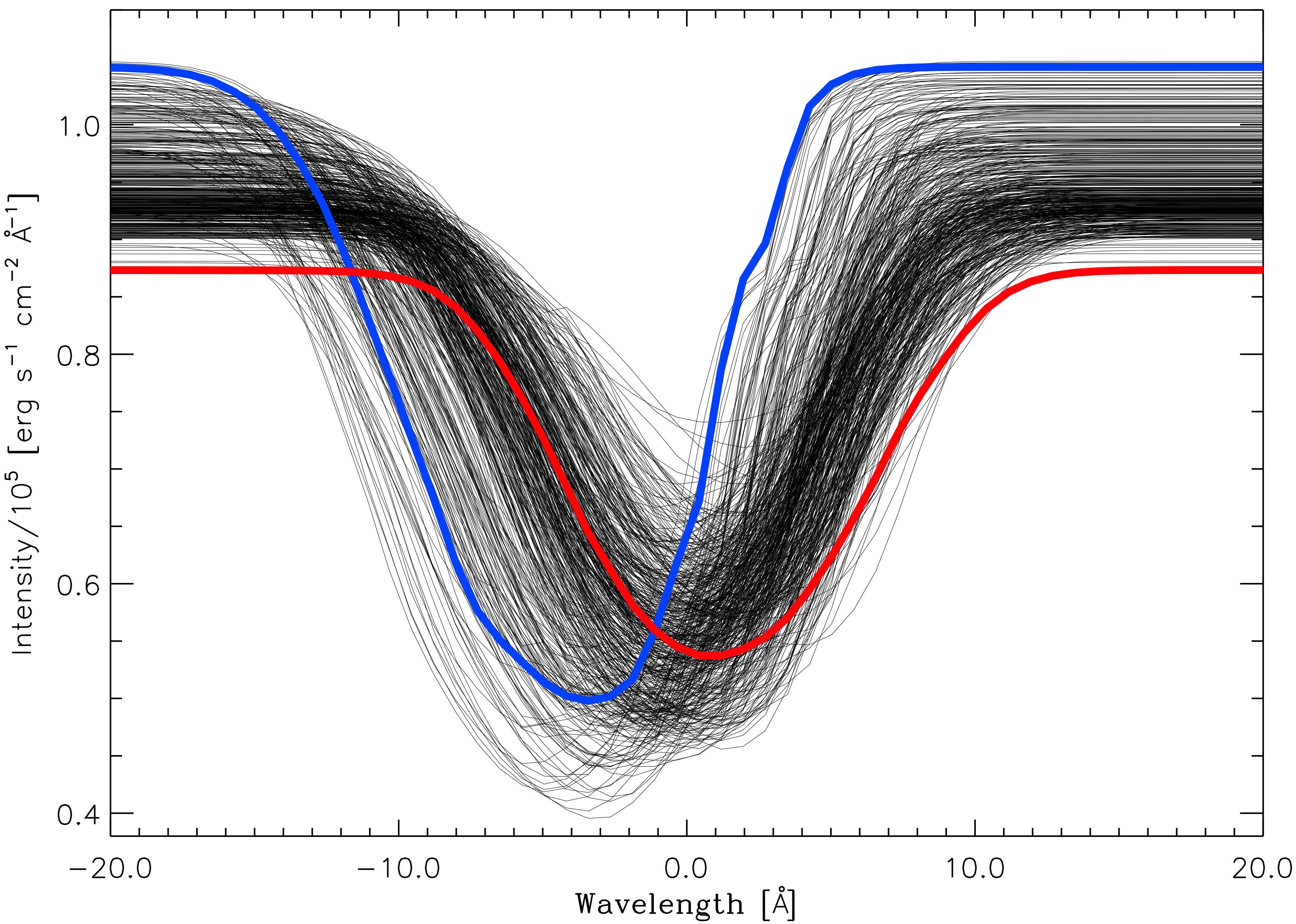
1D, since 1970…

- ☑ Detailed radiative transfer (hundreds thousand) of points from UV to far-IR
- ☑ Non Local Thermal Equilibrium possible (NLTE)
- ☑ CPU friendly, but can machine learning do better?
- ☑ Large grids available
- ☐ (Most of them) hydrostatic
- ☐ Time independent
- ☐ Free parameters (MLT, micro-macro-)

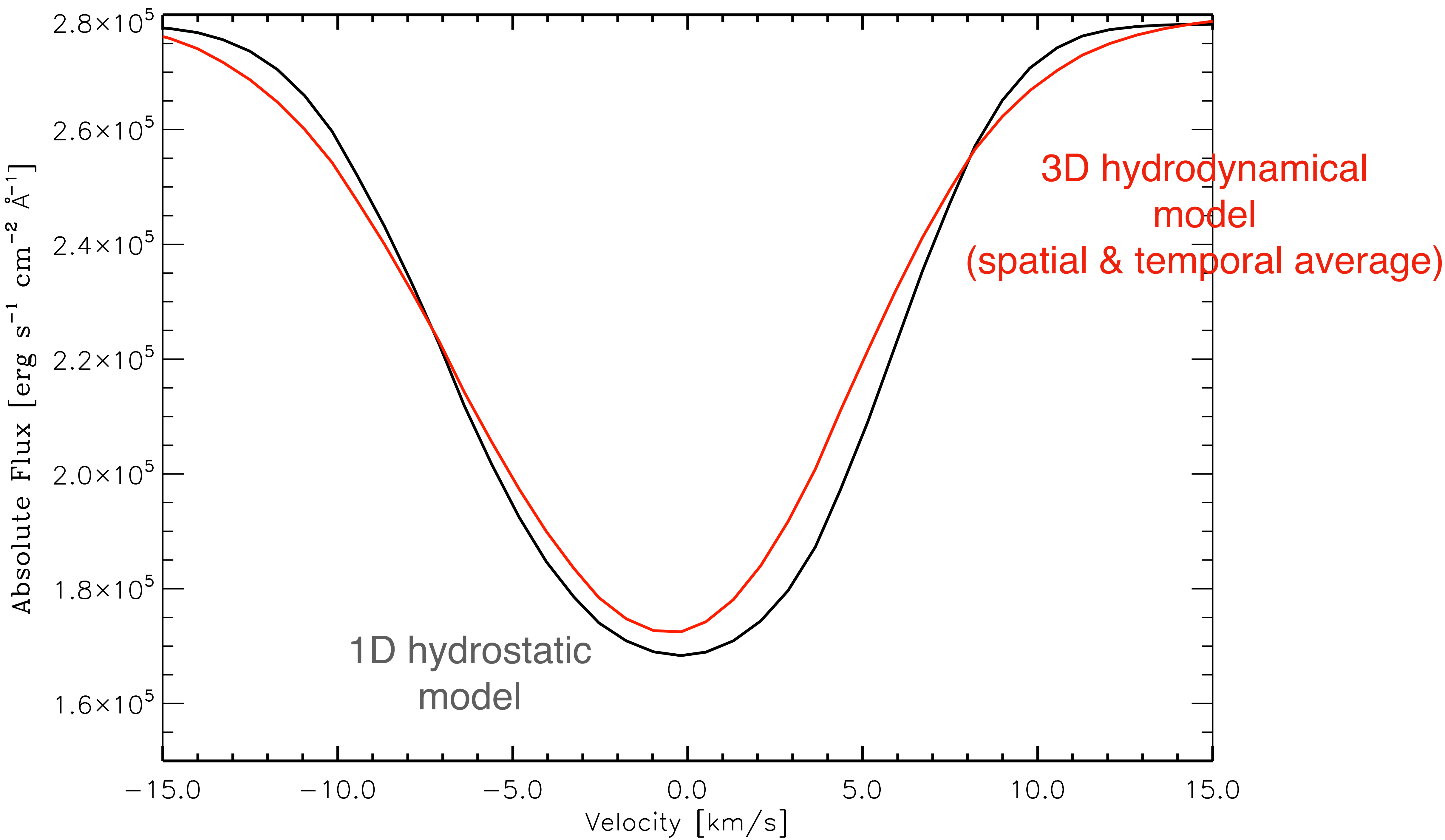
Multi-D, since 1990…

- ☑ Possible to follow the fluid across several pressure scale height. In the outer layers important for : (i) sphericity of the surface/granules, (ii) shocks, (iii) stratifications and inhomogenities
- ☑ Coupling Hydrodynamics with non local Radiation transport. Crucial in the lower density layers where flux forms
- ☑ ab initio, no fudge parameters to mimic (e.g., MLT, micro- macro-turbulence)
- ☑ Time dependent
- ☐ Time consuming. Actual architecture is MPI (Stagger-code) or MPI+OpenMP hybrid (Co5bold). Few hours for Sun, weeks for RSG/AGB
- ☐ Radiative transfer limited (5-24 bins). Need for detailed post processing
- ☐ Only Local Thermal Equilibrium (LTE)

1D versus Multi-D: spectral line positions and shape

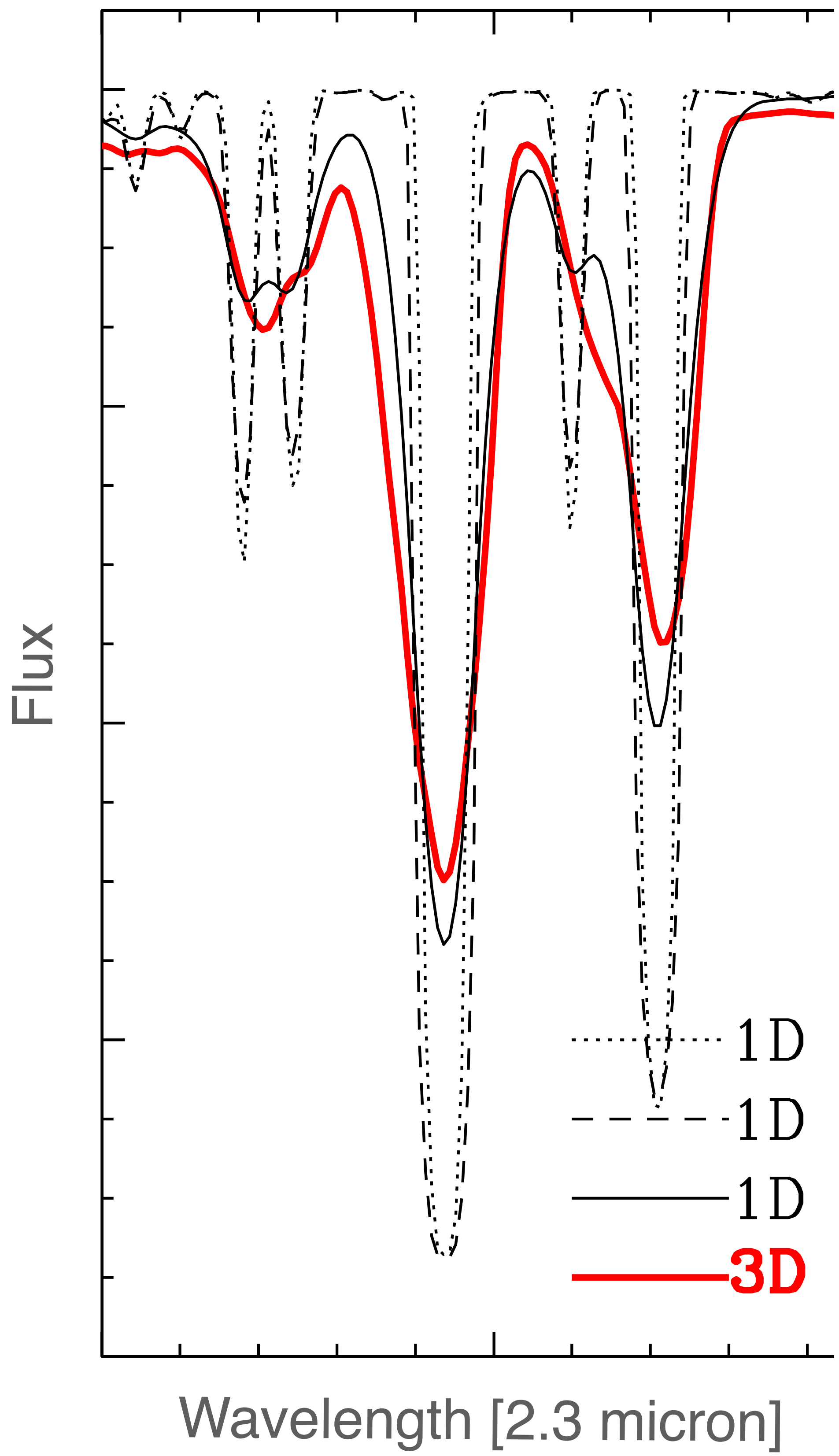


1D versus Multi-D: spectral line positions and shape



IMPACT on: Bisector, position, shape and temporal evolution

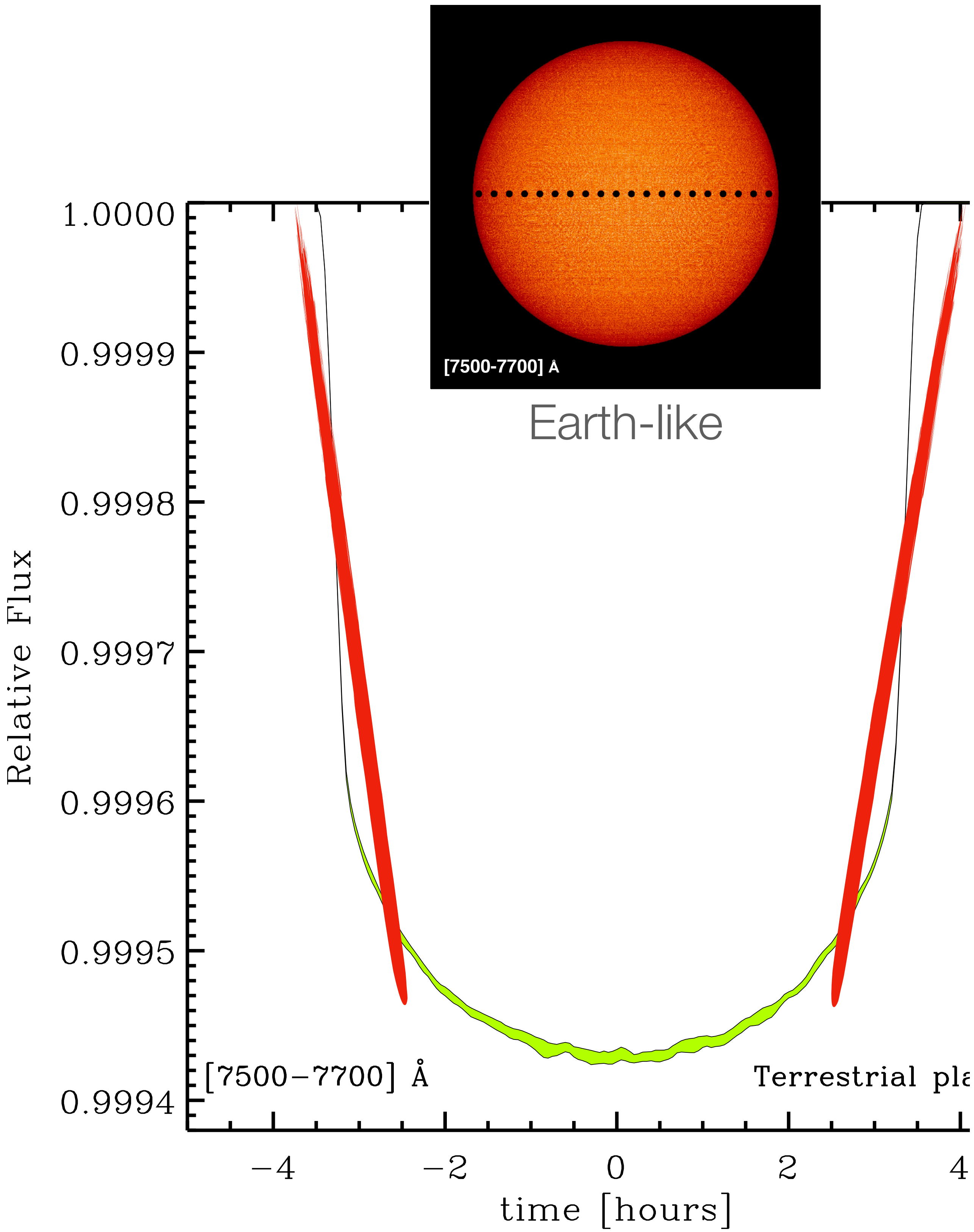
1D versus Multi-D: spectral line positions and shape

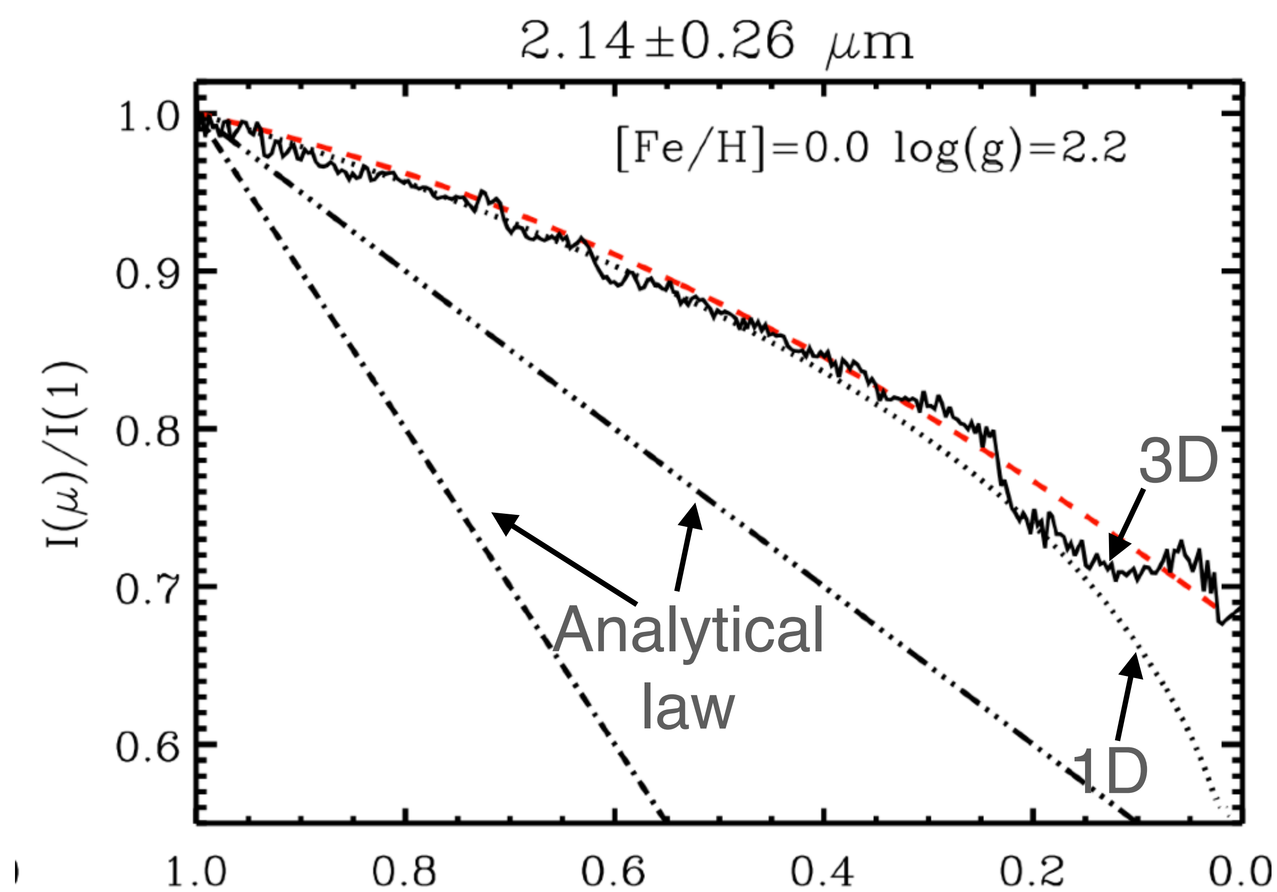


Because of the gas turbulence, also the line depth is different in 3D and 1D.
This is largely dependent on stellar parameters and spectral line excitation energy

IMPACT on: the selection of spectral line in masks at different depth and for different stellar types

1D versus Multi-D: limb darkening





The intensity distribution in 3D is different from the 1D or analytical approximation. And as a function of wavelength

IMPACT on: the ingress and egress as well as the starting time of the transit

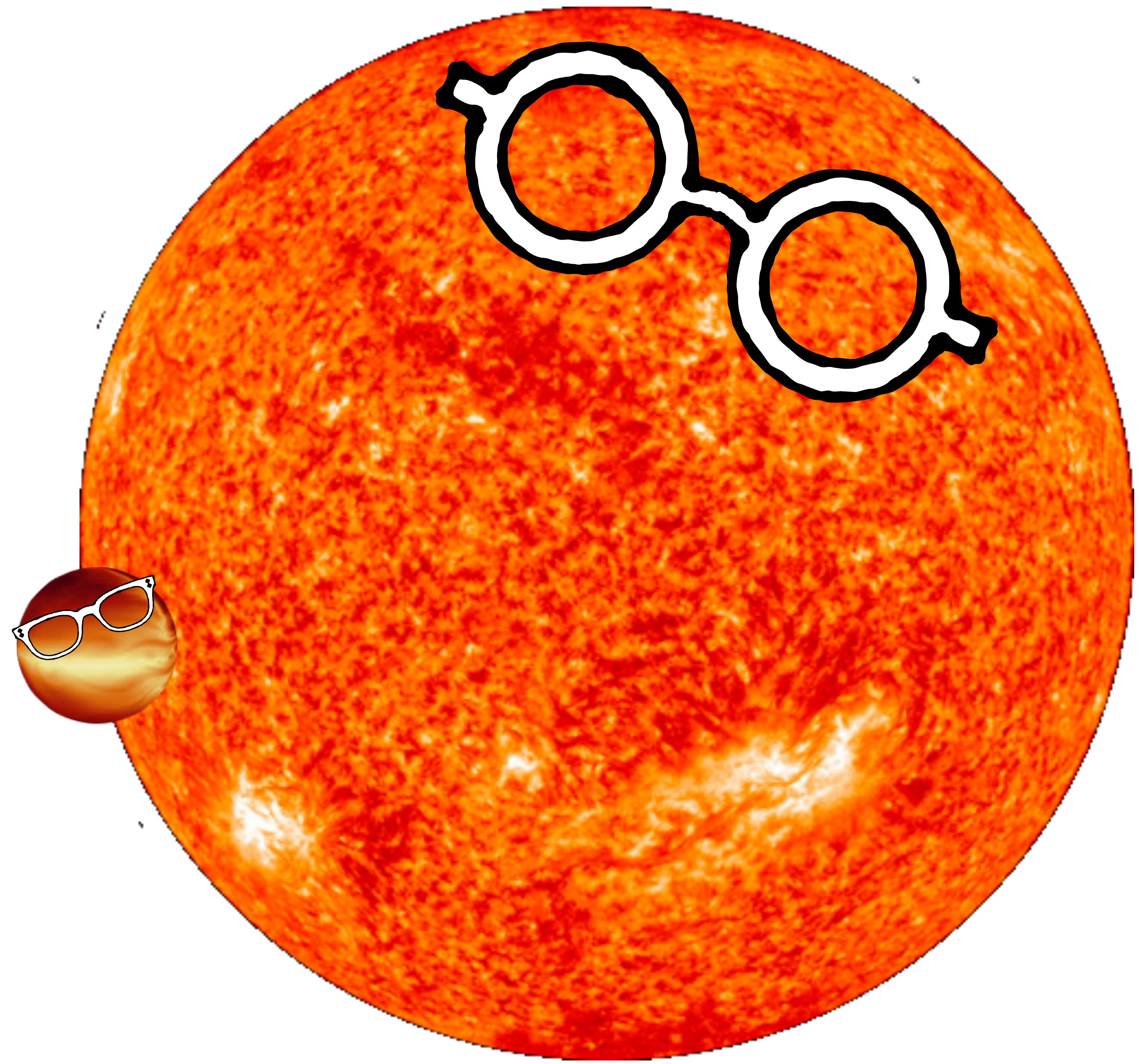
In conclusion …

From the planet point of view:

- the star is the noise, and the stellar spectra need modelling to be processed

From the stellar point of view:

- the "noise" is the signal of stellar dynamics and key point for studying its physical properties
- the planet transits represent and relevant source of information for the star



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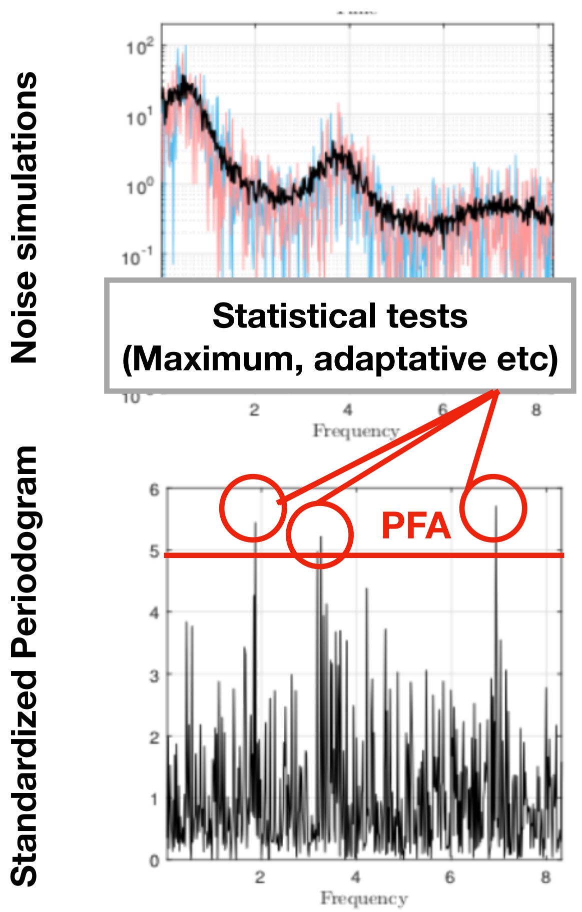
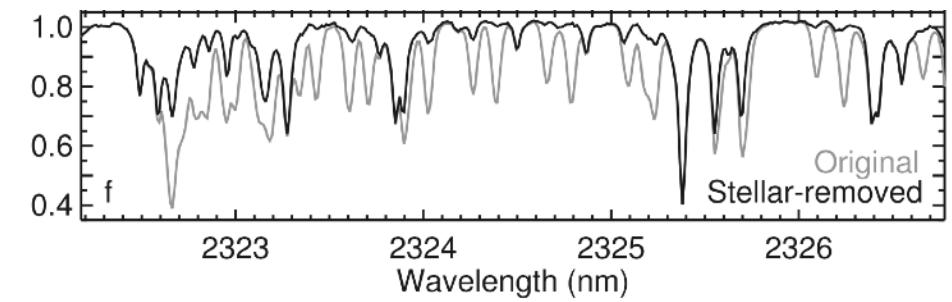
https://lagrange.oca.eu/fr/andrea-chiavassa/

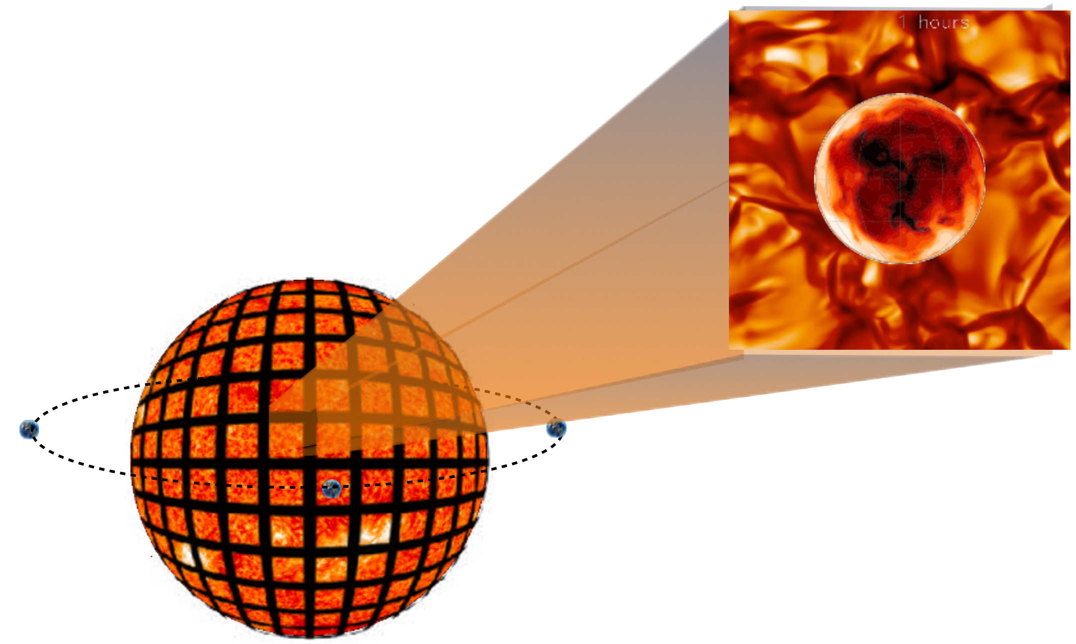
In a nutshell: Stellar Convection, a « noise » for planet detection & characterization

Standardisation of the periodogram for RV search
(Sulis, Mary, Bigot, IEEE, 2017)
A new semi-supervised method
(Sulis, Mary, Bigot+ 2022)



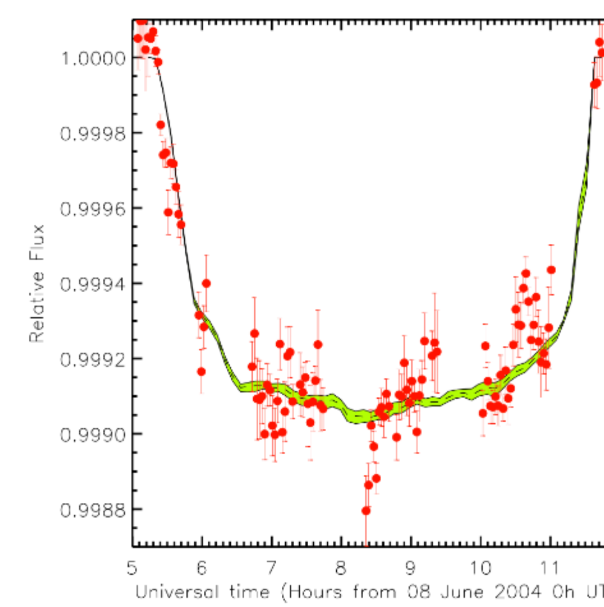
Planetary spectra « depolluted » from 3D stellar spectra
(Chiavassa & Brogi 2019)



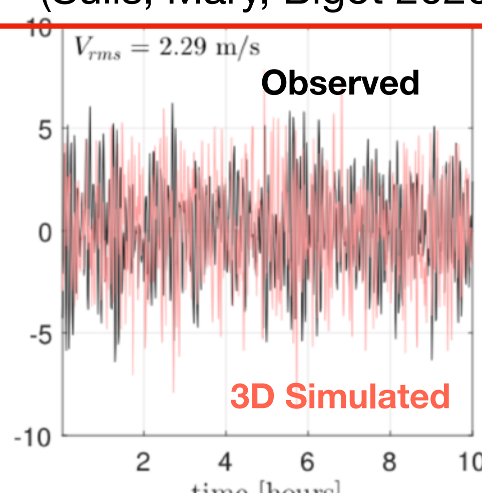


Simultaneous stellar and planetary dynamics in transit emission spectroscopy
(Maimone, Chiavassa, Leconte+ PhD)

Stellar noise effects on transit curves
(Chiavassa+, 2017)



3D Simulation Solar convective noise
(Sulis, Mary, Bigot 2020)



Convective noise across HR diagram
(Rodriguez Diaz et al. 2022)