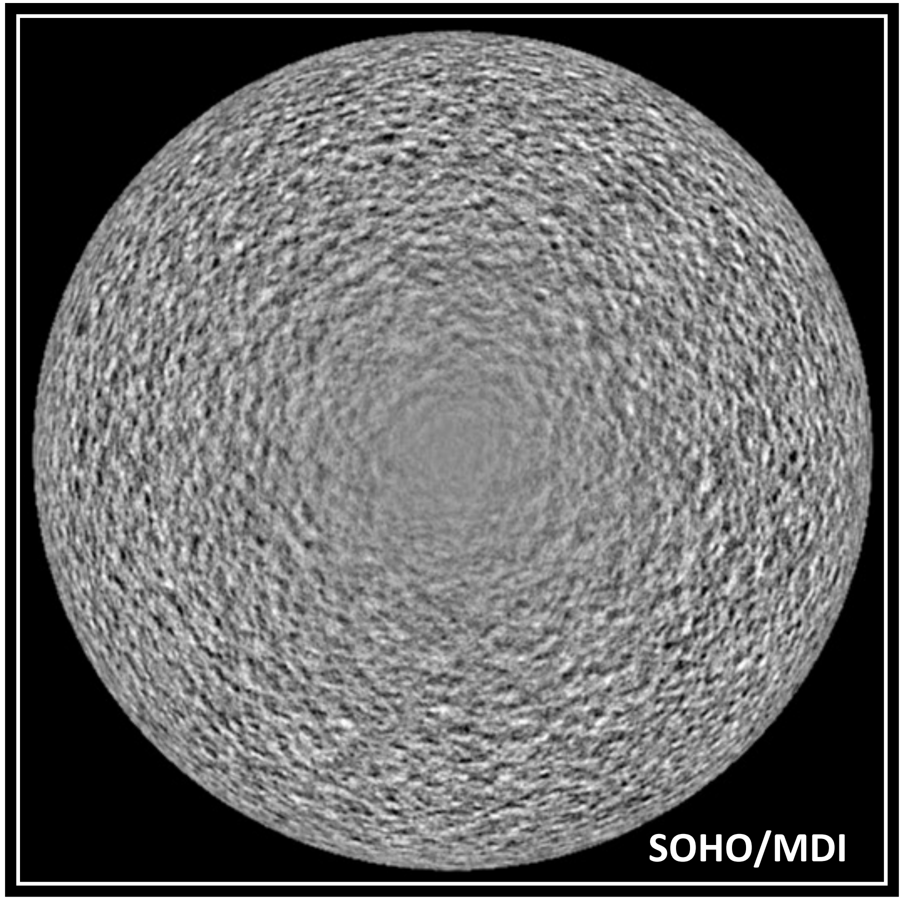
Advances in 3D Realistic Modeling of Solar-type Stars to Study Stellar Jitter and Photospheric and Subsurface Dynamics

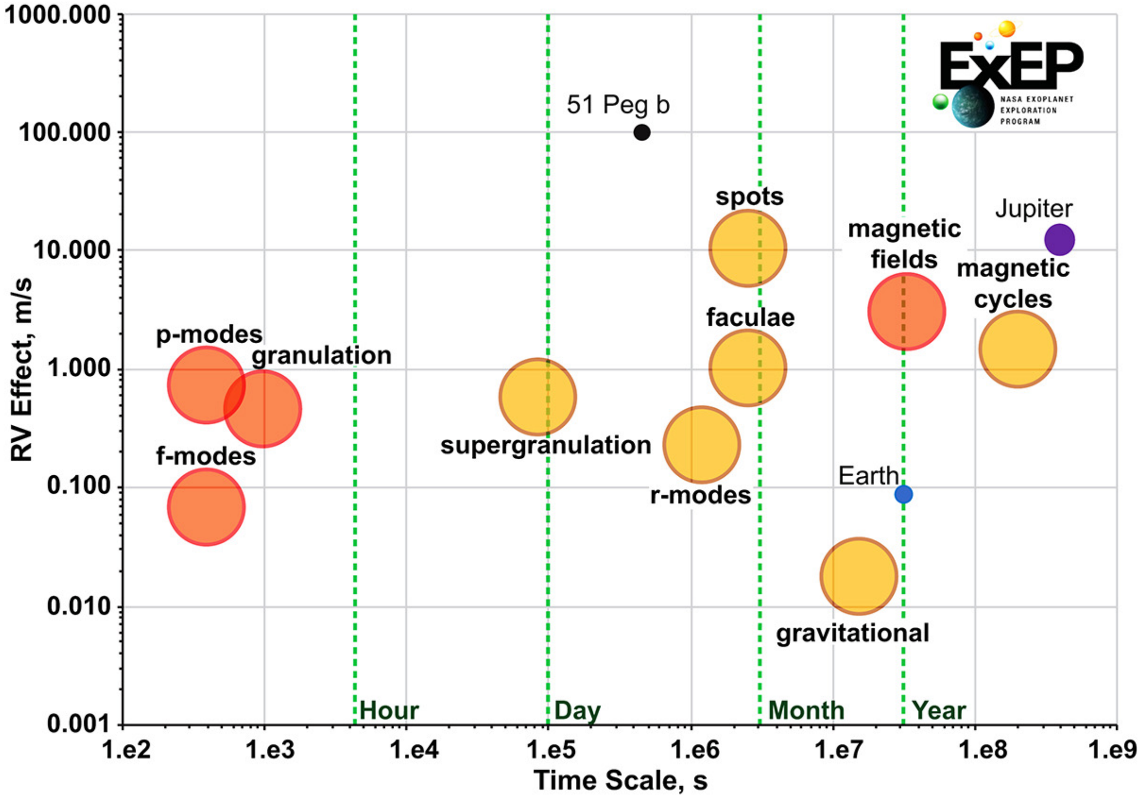
Irina Kitiashvili[1], Alan Wray[1], Sage Li[1,2], Samuel Granovsky[1,3], Kyla Mullaney[1,4]

[1]NASA Ames Research Center, [2]Georgia Institute of Technology,
[3]New Jersey Institute of Technology, [4]University of Chicago

Contamination of the Radial Velocity Signal with Stellar Jitter

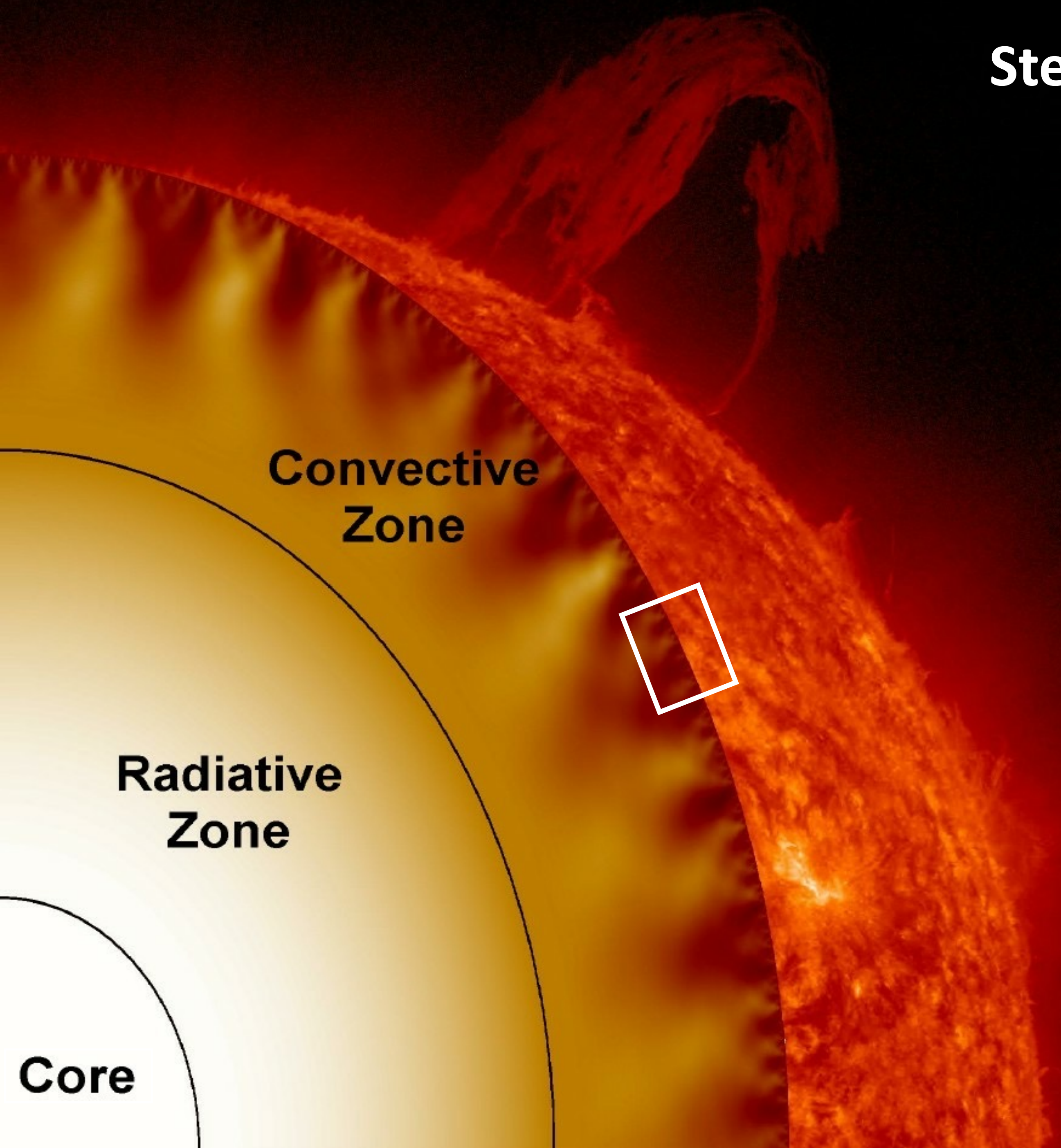


SOHO/MDI Dopplergram averaged over 30-min



Schematic representation of correlated noise sources in the RV measurements originating from stellar surface convection and magnetic activity (modified from NASA EPRV working group report).

StellarBox code (Wray et al., 2015; 2018)



- Compressible plasma flows in a highly stratified medium
- 3D multi-group radiative energy transfer between the fluid elements
- Real-gas equation of state
- Ionization and excitation of all abundant species
- Small-scale turbulence
  - LES: Smagorinsky model (including its dynamic form)
  - DNS + Hyperviscosity approach
  - MHD subgrid models
- Magnetic effects
- Rotation
- Internal structure
- Opacity tables

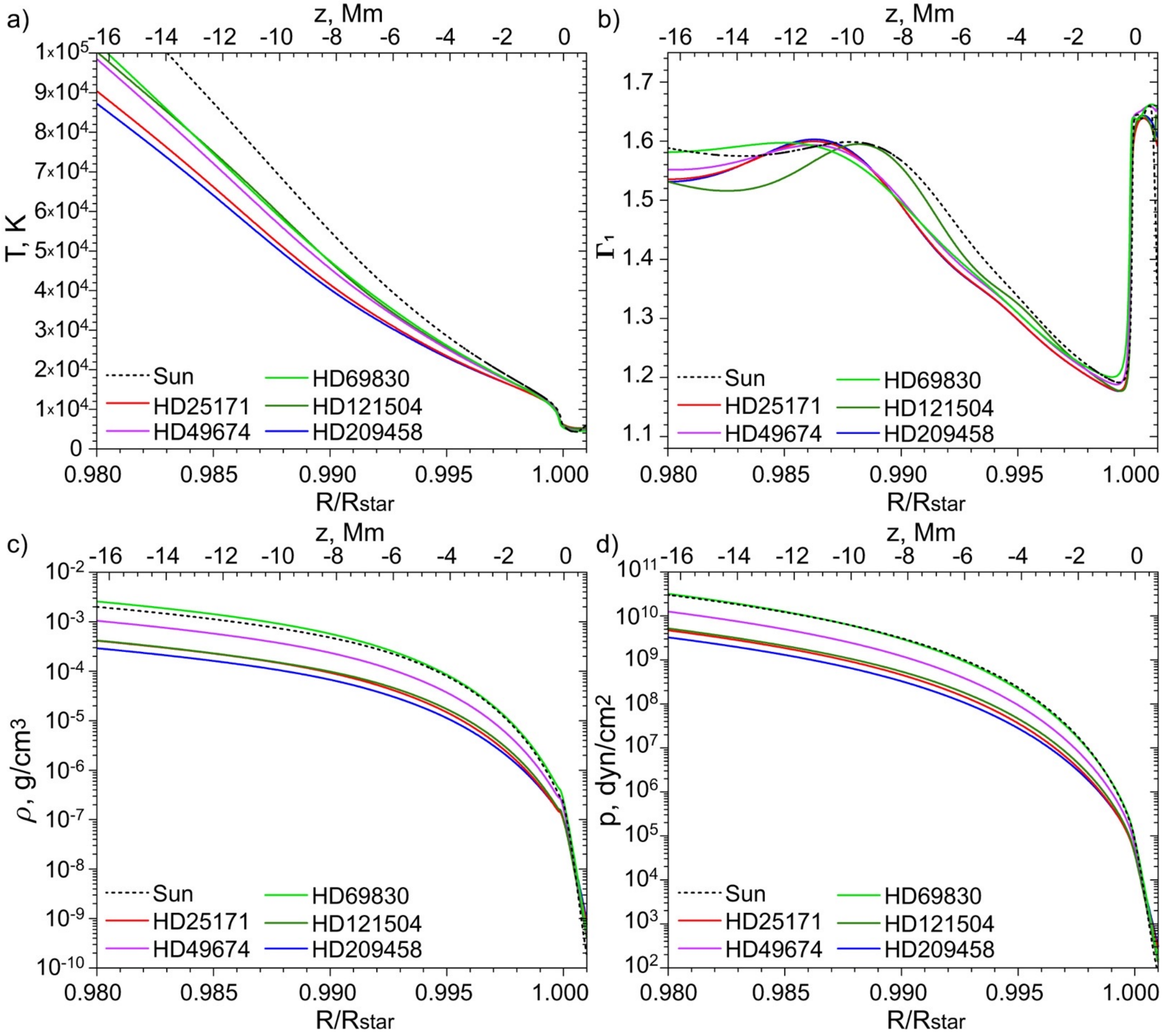
StellarBox code (Wray et al., 2015; 2018)

Target Stars

Star	Mass	log(g)
HD209458	1.05	4.314
HD121504	1.18	4.355
HD25171	1.08	4.329
HD49674	1.00	4.408
HD69830	0.87	

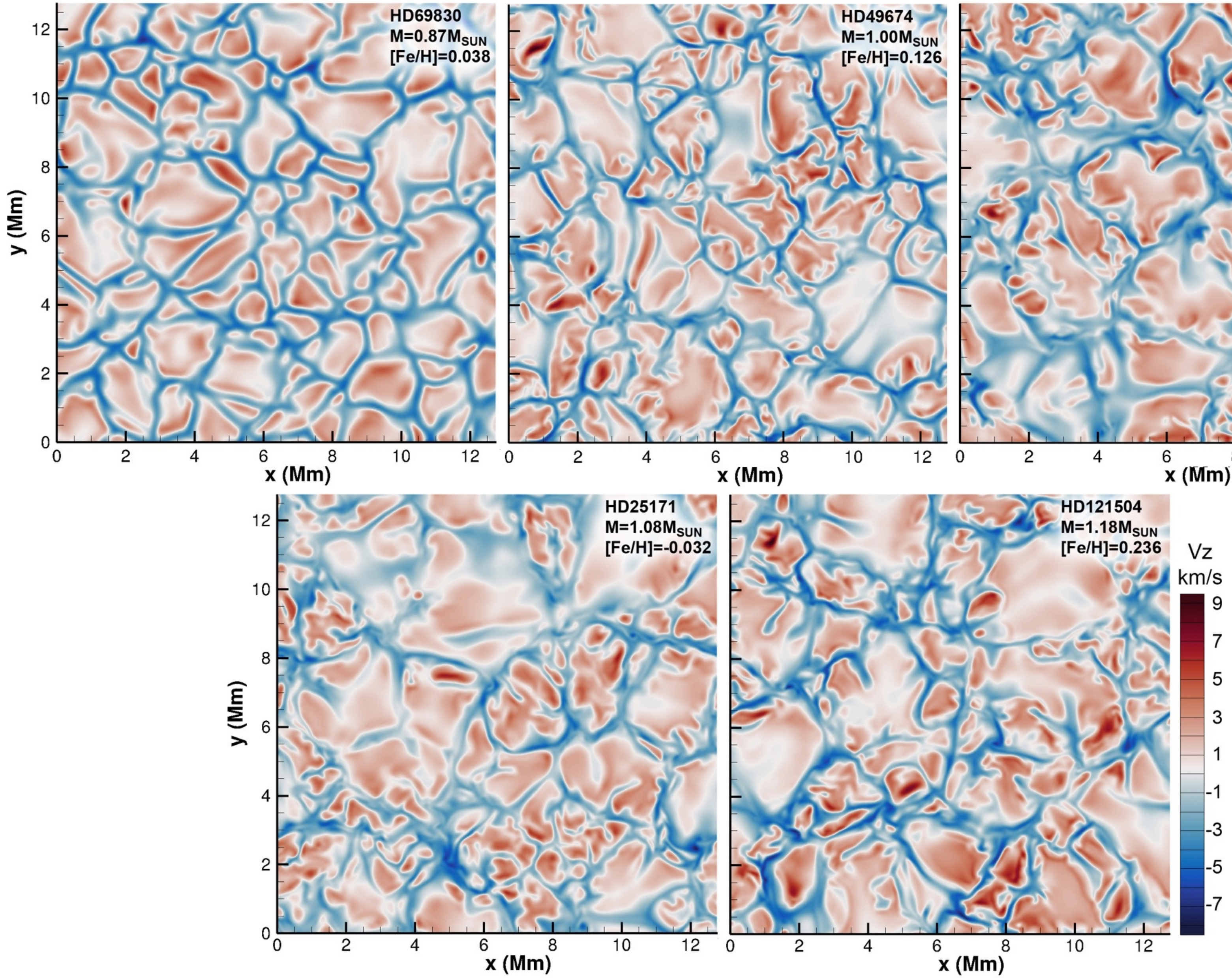
- Compressible plasma flows in a highly stratified medium
- 3D multi-group radiative energy transfer between the fluid elements
- Real-gas equation of state
- Ionization and excitation of all abundant species
- Small-scale turbulence
  - LES: Smagorinsky model (including its dynamic form)
  - DNS + Hyperviscosity approach
  - MHD subgrid models
- Magnetic effects
- Rotation
- Internal structure
- Opacity tables

Initial conditions



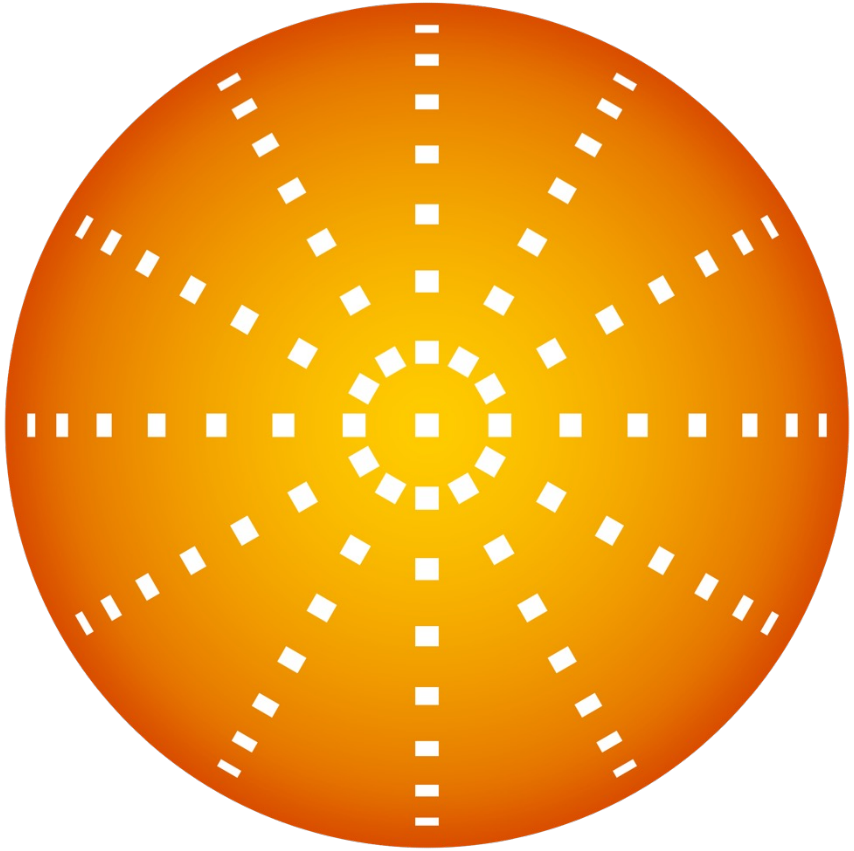
The initial conditions are obtained using the MESA code (Paxton et al. 2011)

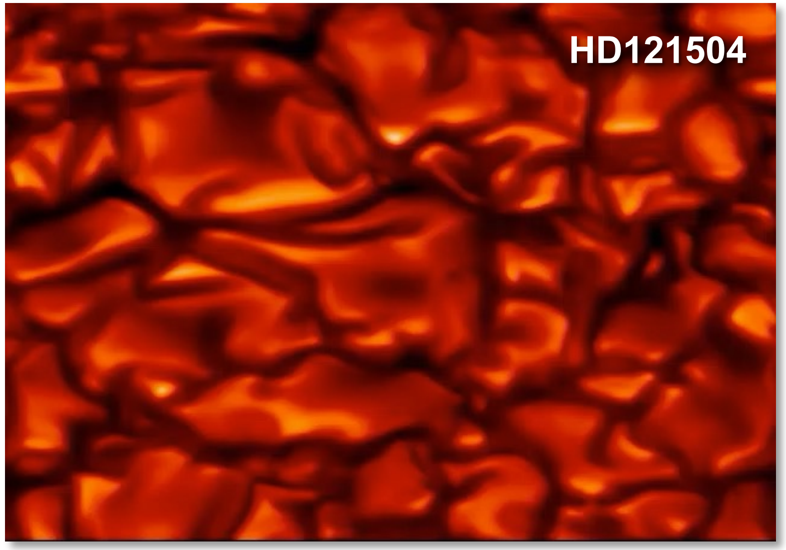
Granulation structure of the solar-type stars



Our simulations show that the granulation structure on solar-type stars may be quite different from the solar granulation, and thus requires detailed modeling.

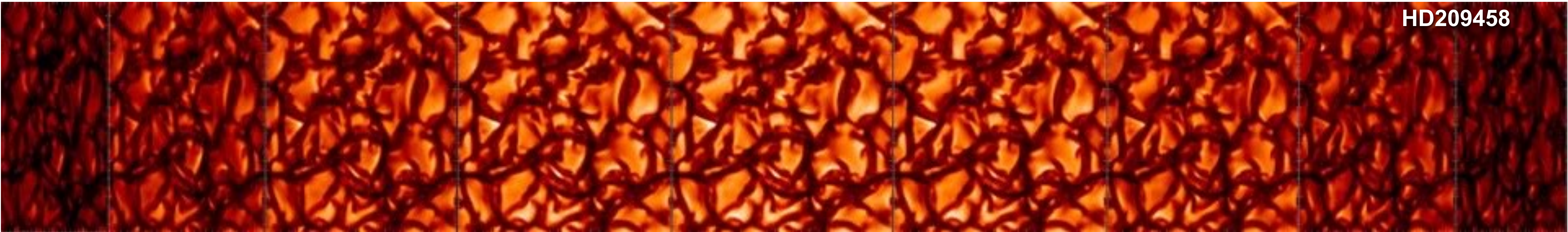
Modeling of Stellar Jitter



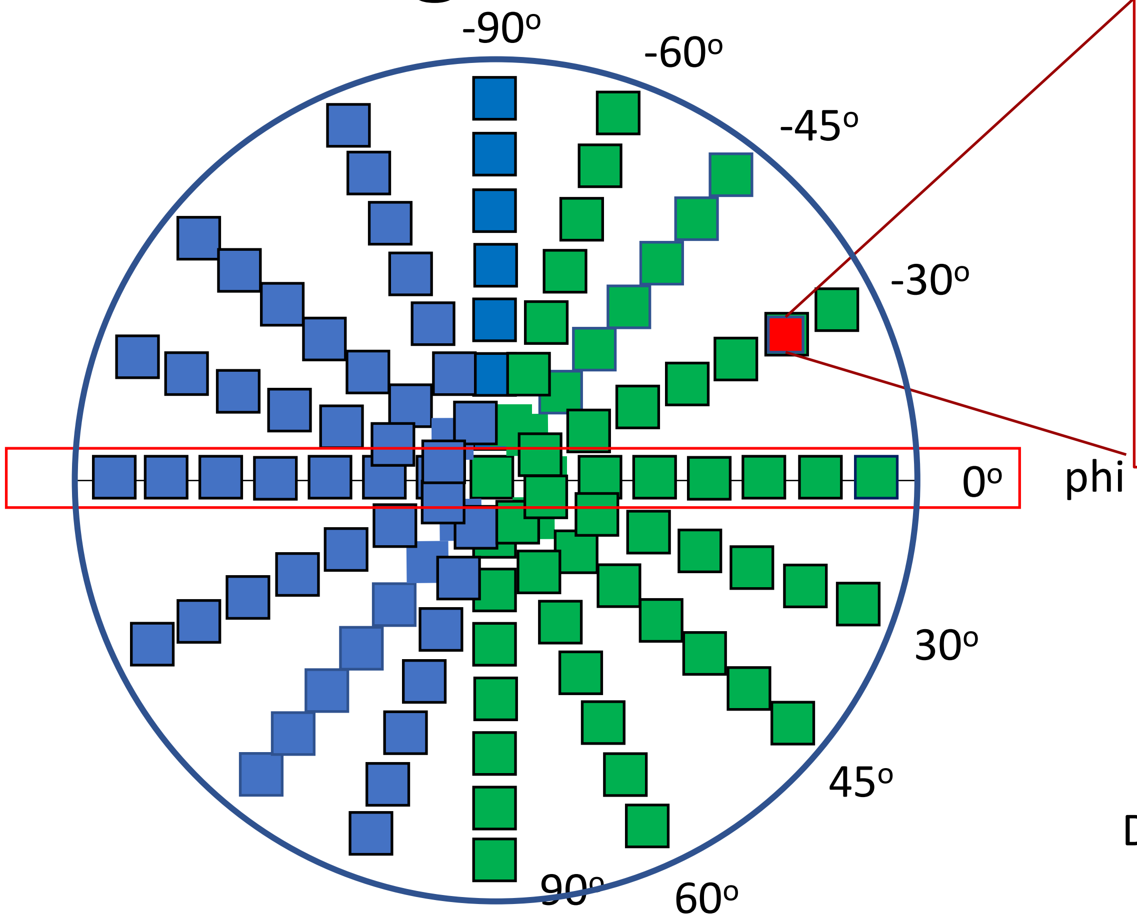


Synthetic image (Fe I, 6173A) of HD121504 planet-host star shows granulation dynamics of the photosphere at 45 degrees from the disk center.

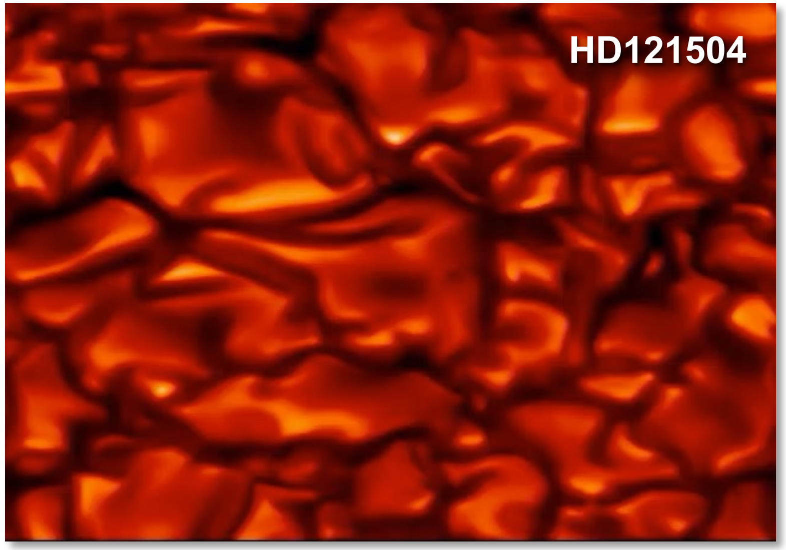
Dravins et al., 2017; 2018; 2021;
Cegla et al., 2012; 2013; 2018; 2019



Modeling of Stellar Jitter

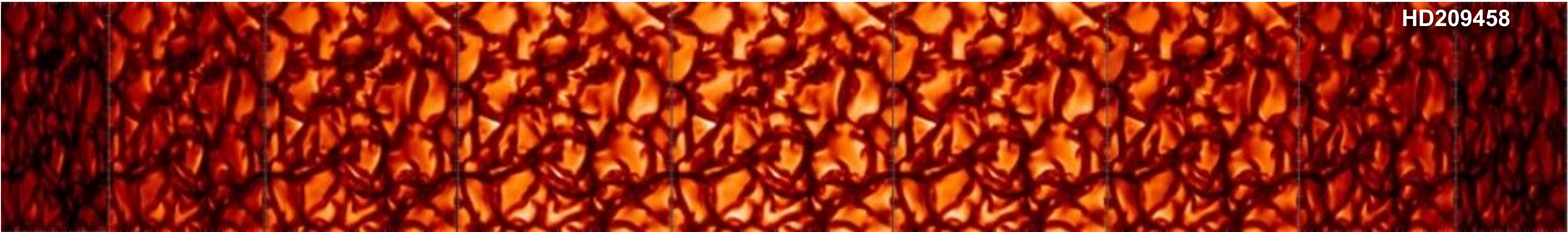


- 3D time-series of ultra-high spectral resolution data
- Line profile
- Doppler shift
- Line depth
- Bisector

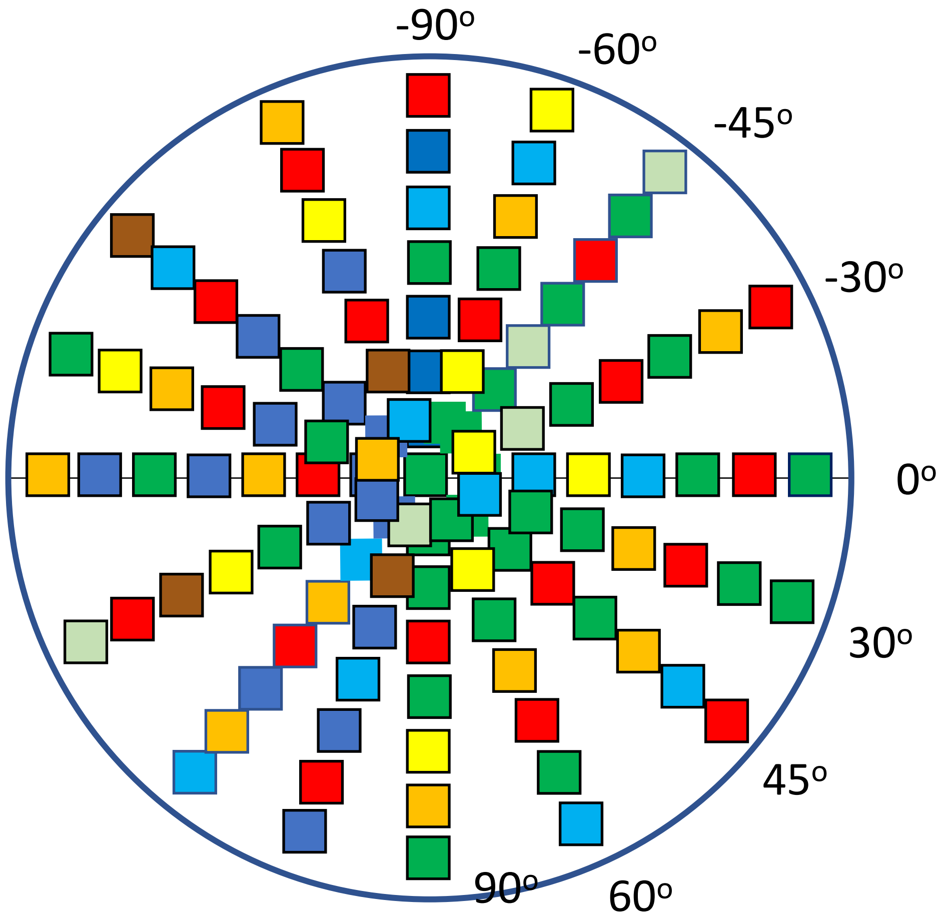


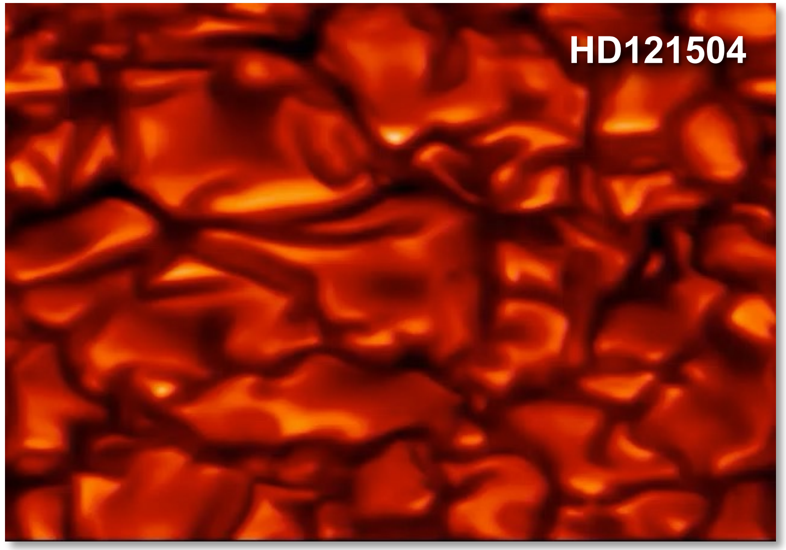
Synthetic image (Fe I, 6173A) of HD121504 planet-host star shows granulation dynamics of the photosphere at 45 degrees from the disk center.

Dravins et al., 2017; 2018; 2021; Cegla et al., 2012; 2013; 2018; 2019



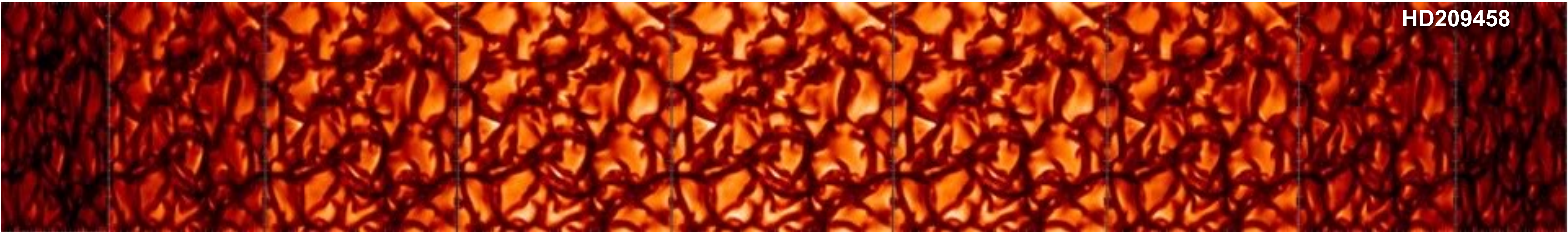
Modeling of Stellar Jitter



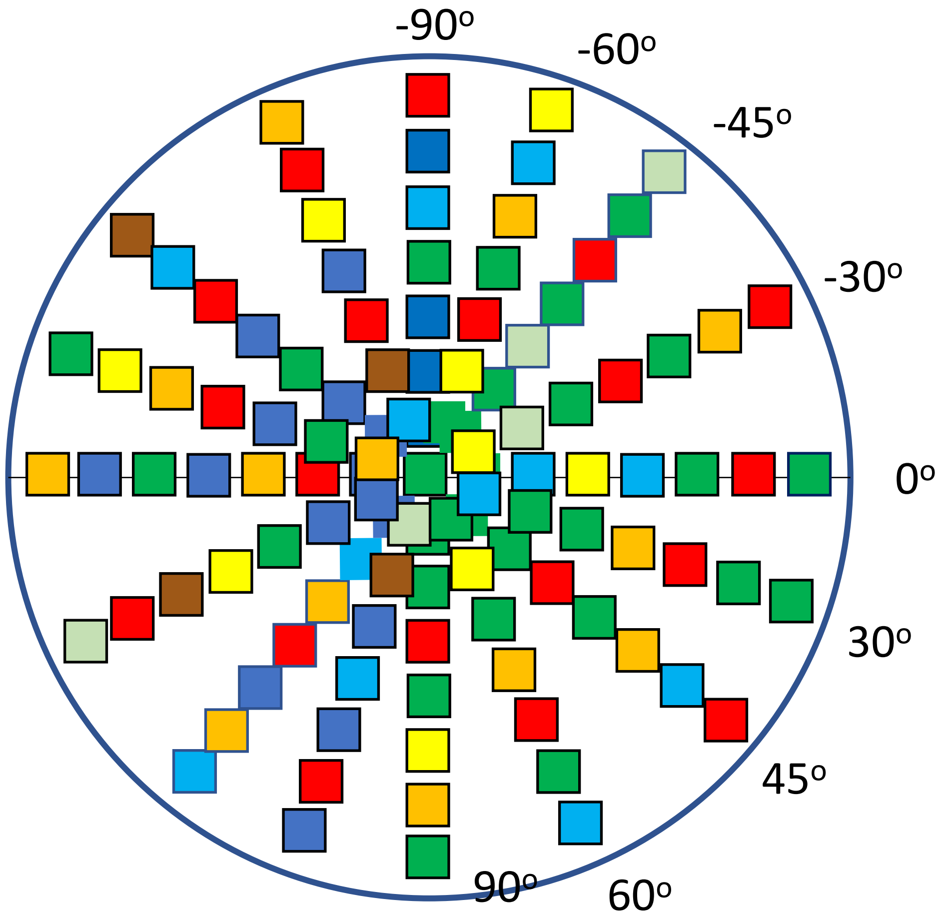


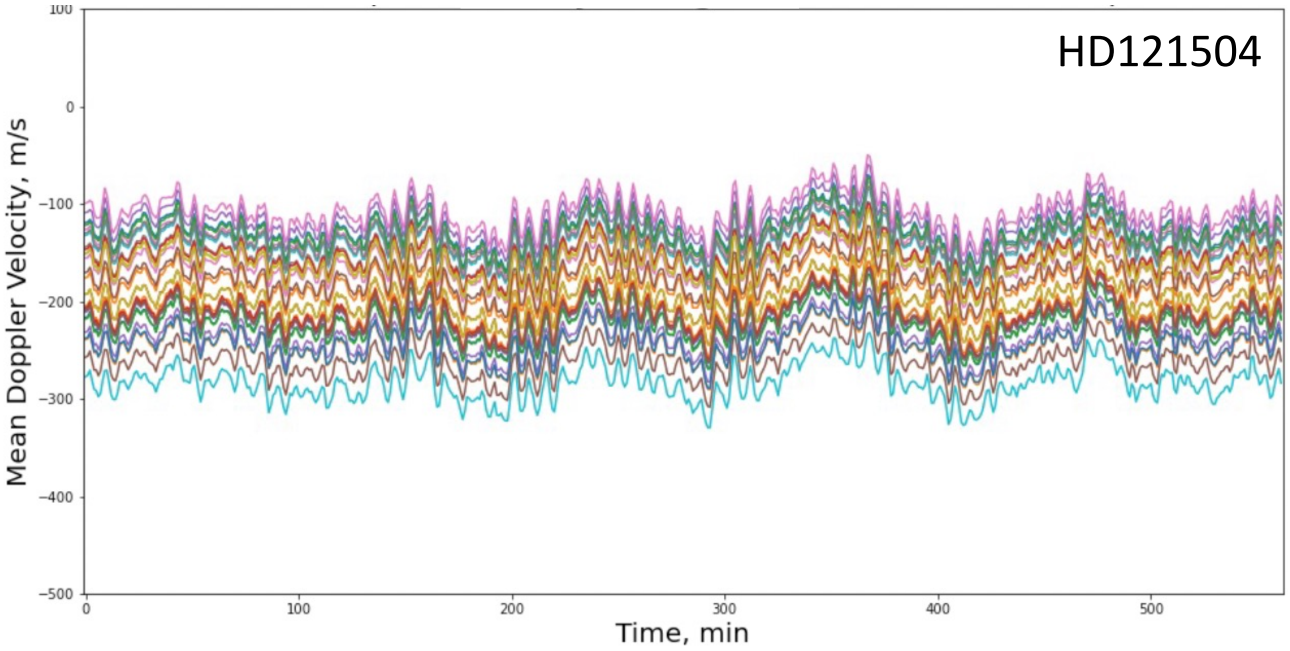
Synthetic image (Fe I, 6173A) of HD121504 planet-host star shows granulation dynamics of the photosphere at 45 degrees from the disk center.

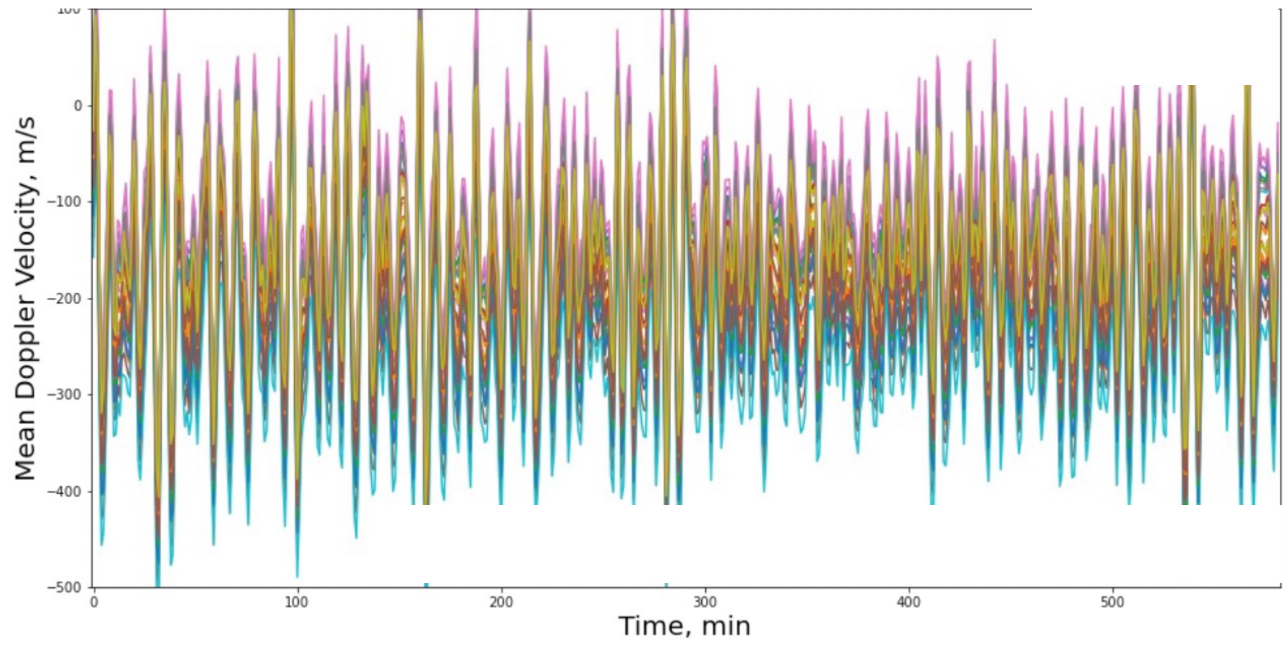
Dravins et al., 2017; 2018; 2021; Cegla et al., 2012; 2013; 2018; 2019

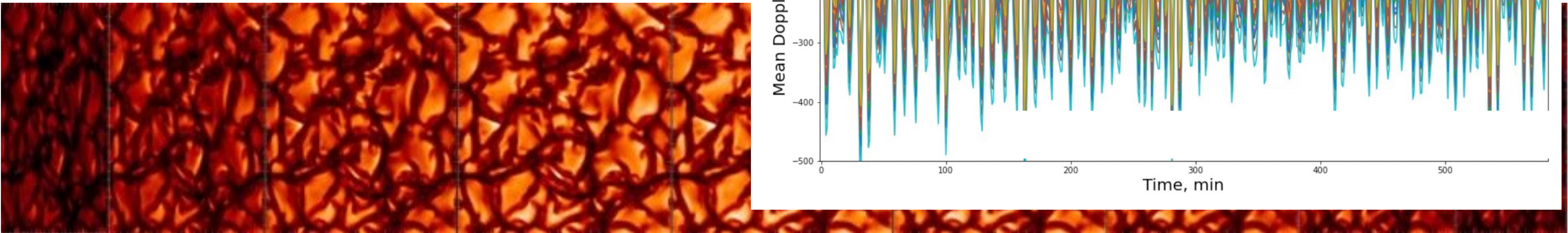


Modeling of Stellar Jitter

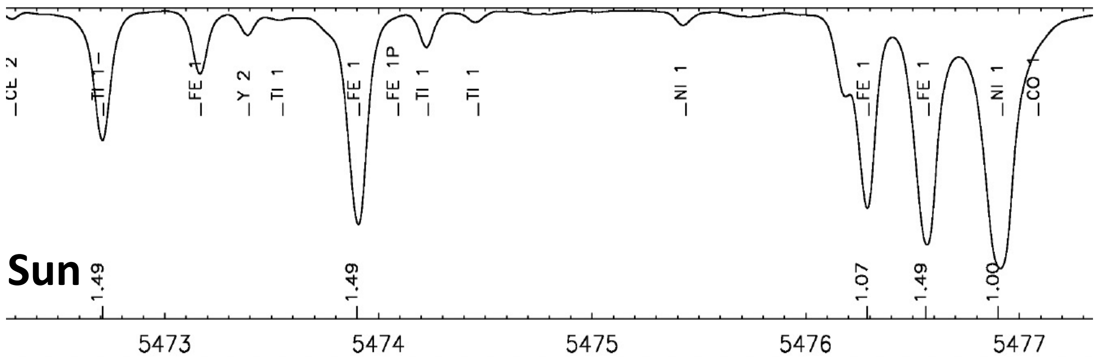


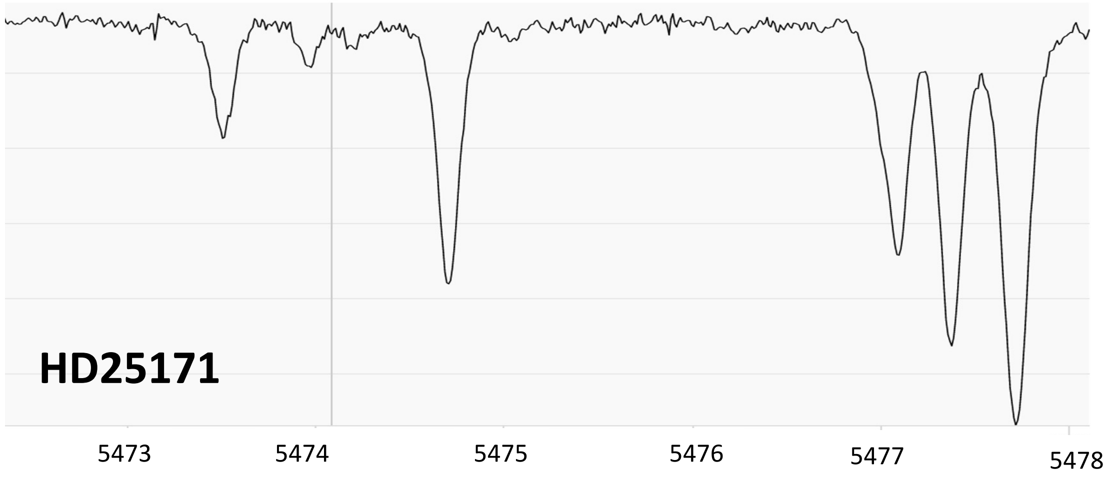




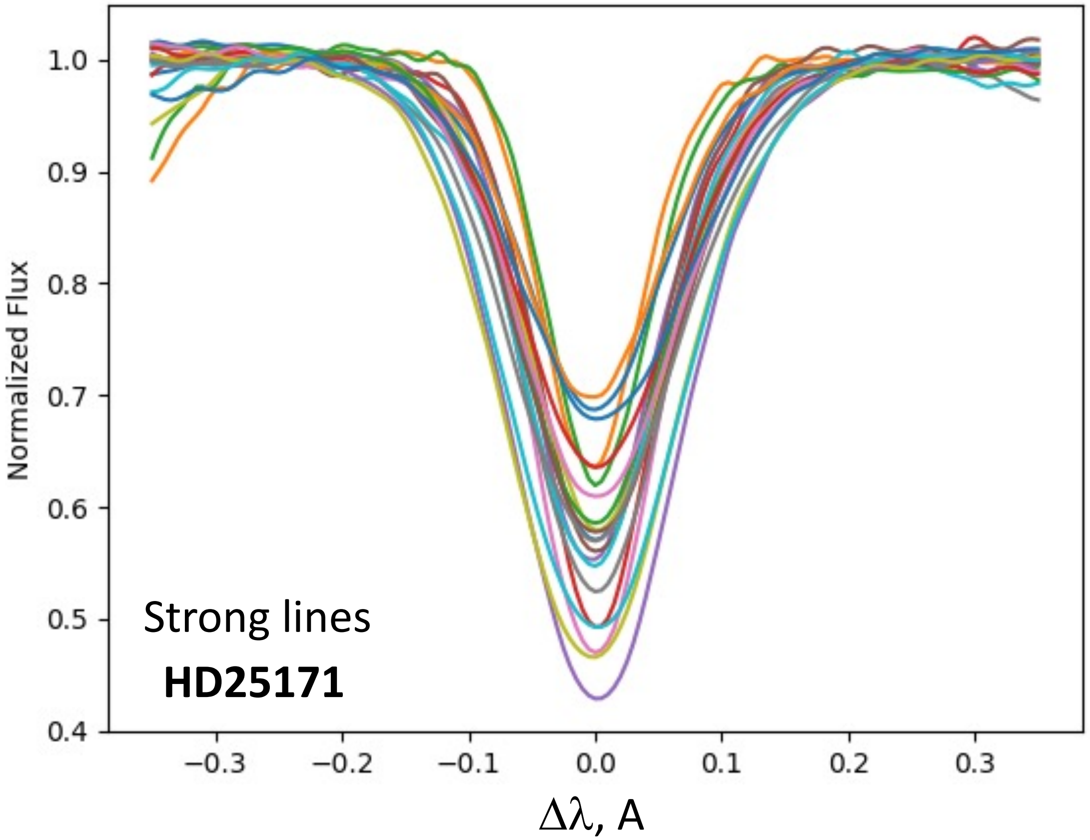


Model calibration: absolute abundances



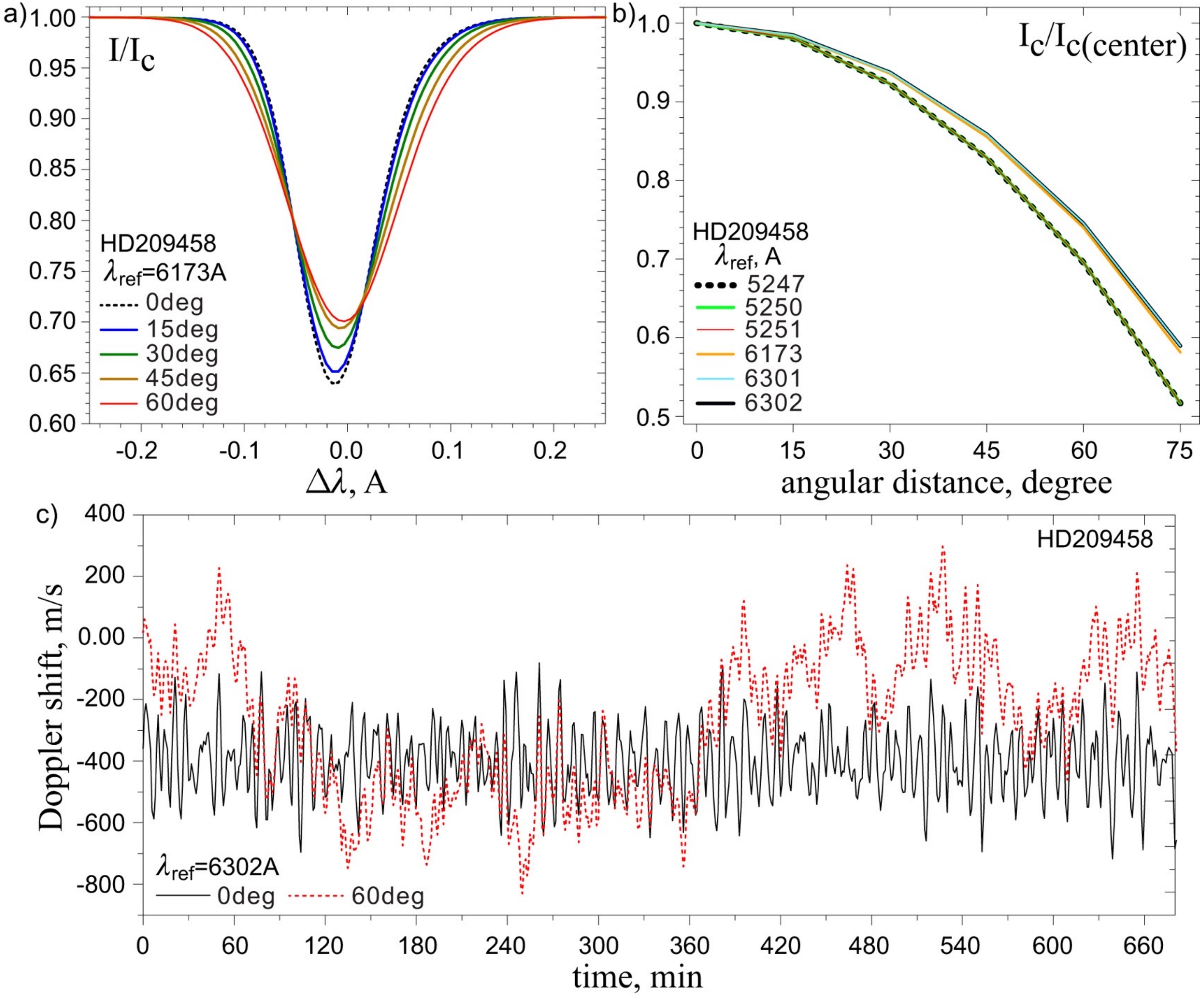


HARPS/ESO Science Archive Facility



Selected 20 weak and 20 strong iron lines to perform synthesis

Planet-hosting star HD209458: center-to-limb effects



Center-to-limb effects:

a) changes in the spectral line (λref=6173A) at different distances from the disk center;

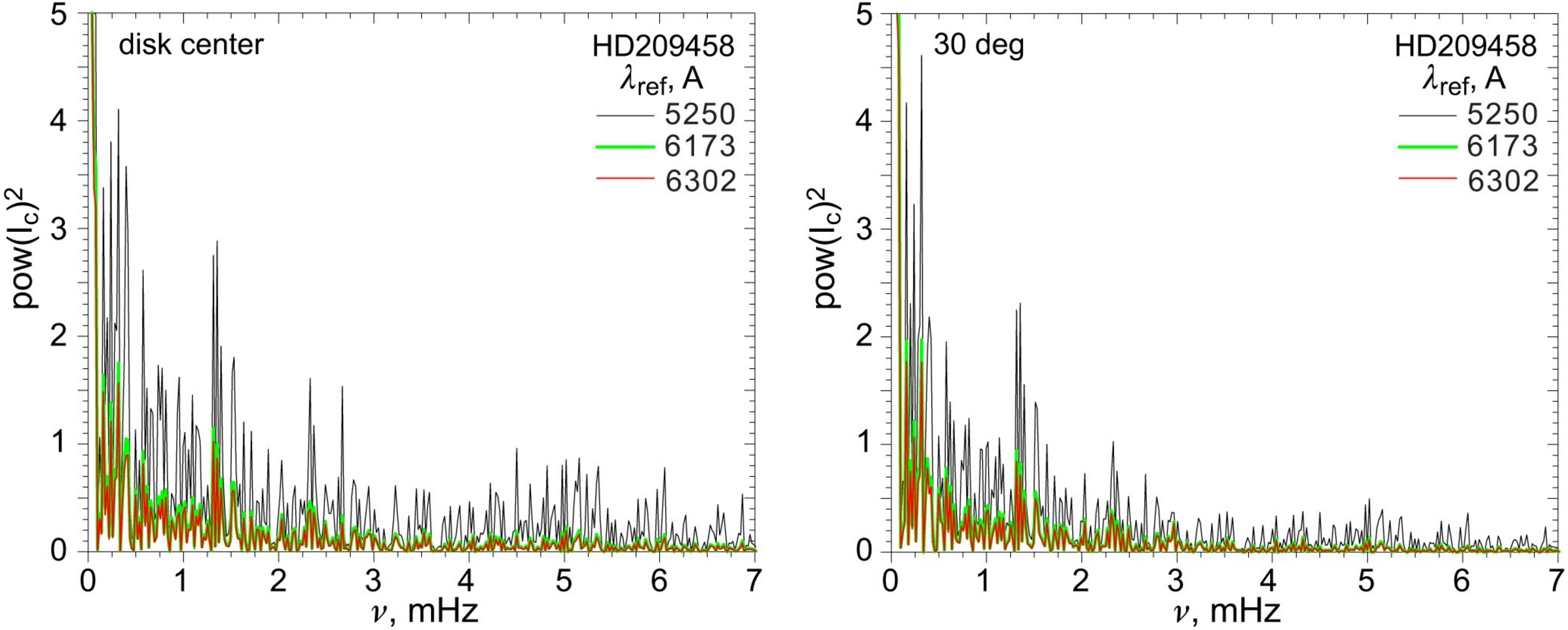
b) limb darkening profiles for six FeI lines;

c) Doppler shift variations as a function of time at the stellar disk center (black solid curve) and at 60 degrees from the disk center (red dotted curve).


HD209458
Stellar surface dynamics
reconstructed from synthetic
continuum intensity patches

Planet-hosting star HD209458: oscillations

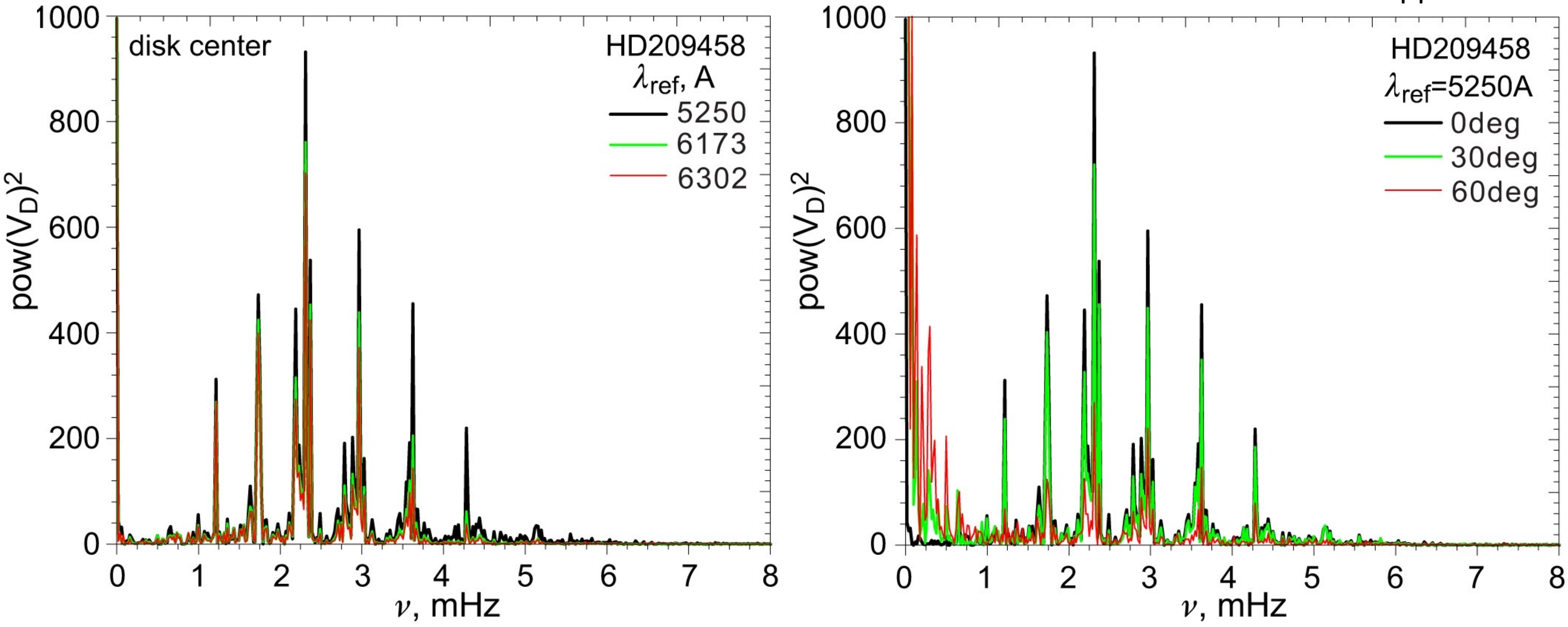
Continuum intensity



The power spectral density obtained from synthetic spectra of HD209458. The power spectral density of continuum intensity is shown for the disc center (left) and 30 degrees longitude (right).

Planet-hosting star HD209458: oscillations

Doppler shift



The power spectral density of the Doppler-shift corresponds to the simulated continuum intensity at the disk center computed from three spectral lines (left), and for three distances from the disk center (0, 30, and 60 degrees) for the single line 5250A (right).

Conclusions

The initial results of our modeling of the solar-type stellar dynamics have allowed us to investigate the nature of stellar jitter and to develop data-characterization and filtering techniques for robust detection of Earth-mass exoplanets.

- **We have performed 3D radiative hydrodynamic simulations of convection for a series of solar-type stars with various mass and metallicity.**
- **Developed a data modeling pipeline for massive line synthesis and computation of observables at different locations over the stellar disks.**
- **Computed synthetic spectroscopic observables of several target stars. Calibration of numerical models according to the available high-resolution spectroscopic observations have been performed.**
- **The results reproduce variations of spectral lines caused by convective motions and oscillations and allow us to investigate physical properties such as oscillation power spectra, center-to-limb variations of spectral line profiles, and convective blue shift, and start the development of physics-based filtering procedures.**

Our current and future efforts are focused on producing longer time series of high-resolution hydrodynamic and MHD models and investigate techniques for filtering photospheric disturbances in spectroscopic observations.

❖ **The work is supported by the NASA Extreme Precision Radial Velocity Foundation Science**