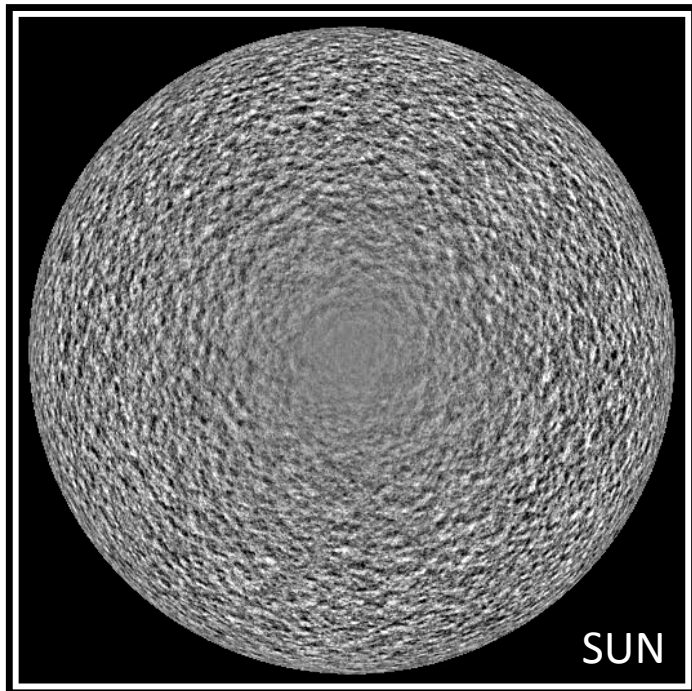
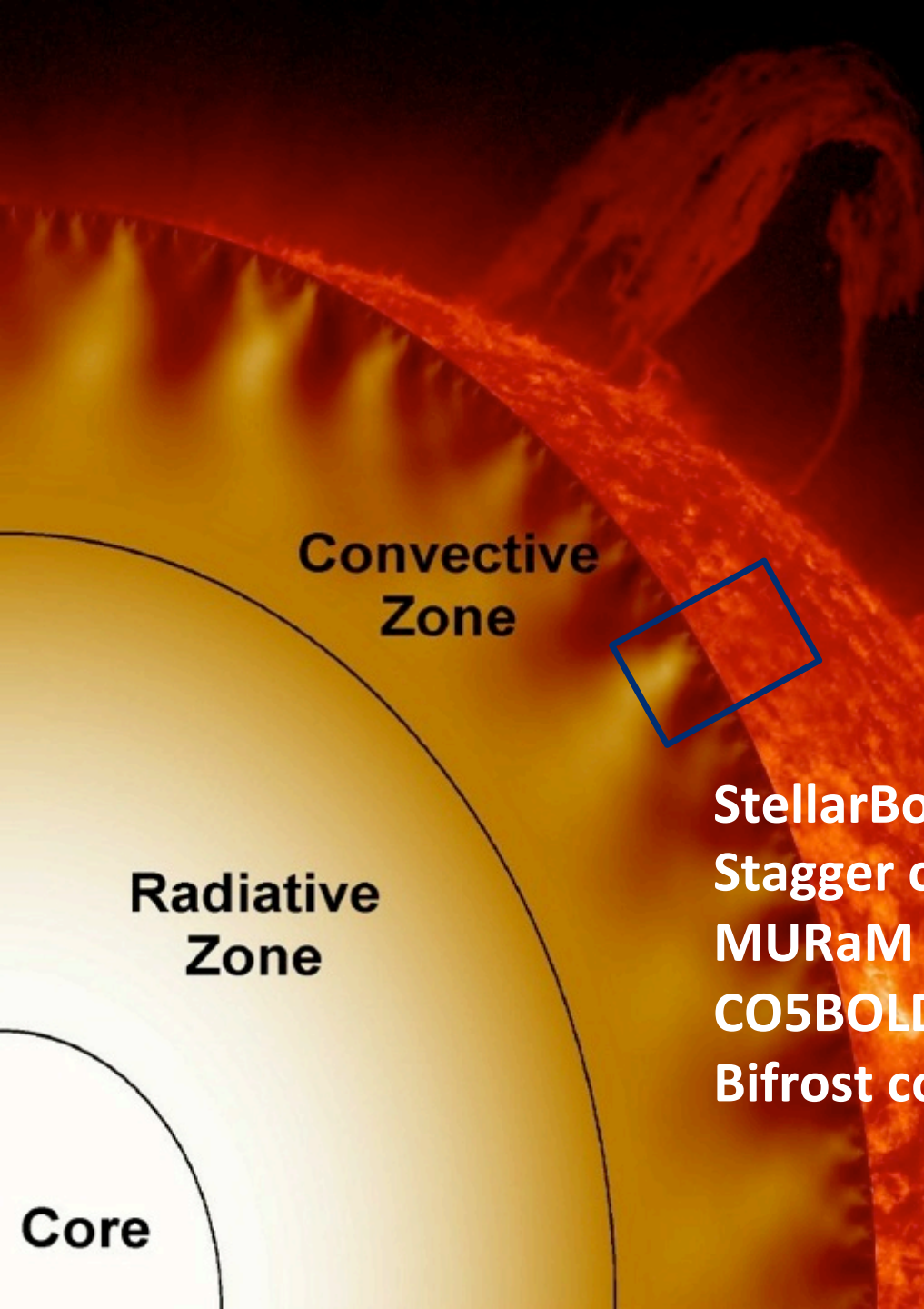


Heliophysics Integrated Modeling: From Sun-Earth to Star-Exoplanet

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- ☀ Compressible fluid flow in a highly stratified medium
- ☀ 3D multi-group radiative energy transfer between the fluid elements
- ☀ A real-gas equation of state
- ☀ Ionization and excitation of all abundant species
- ☀ Small-scale turbulence
- ☀ Magnetic effects

StellarBox code (Wray et al, 2015, 2018)

Stagger code (Galsgaard & Nordlund, 1996)

MURaM code (Vogler, 2003)

CO5BOLD code (Freytag et al., 2002)

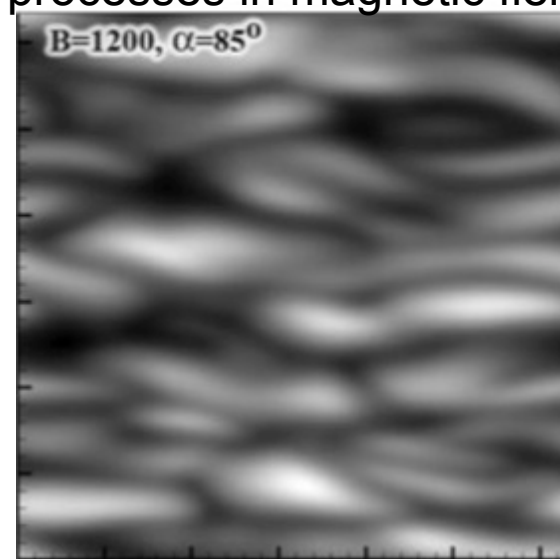
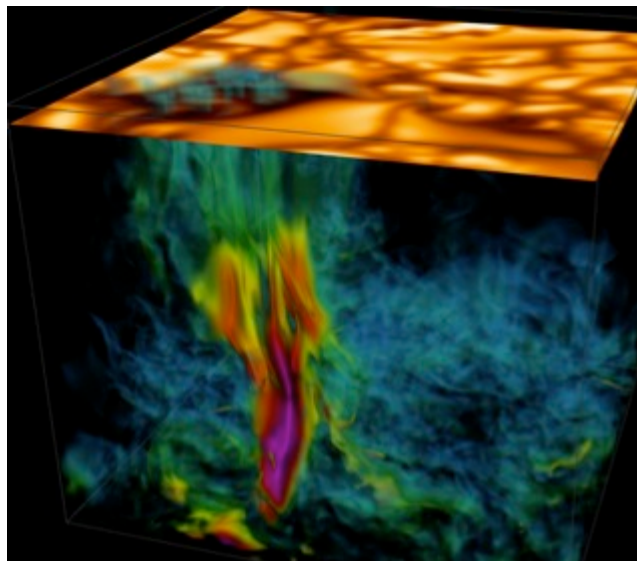
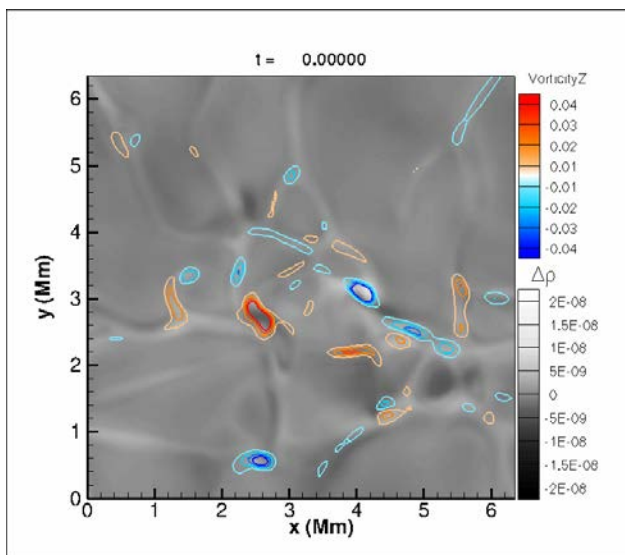
Bifrost code (Gudiksen et al. 2011)

3D realistic modeling of the solar dynamics

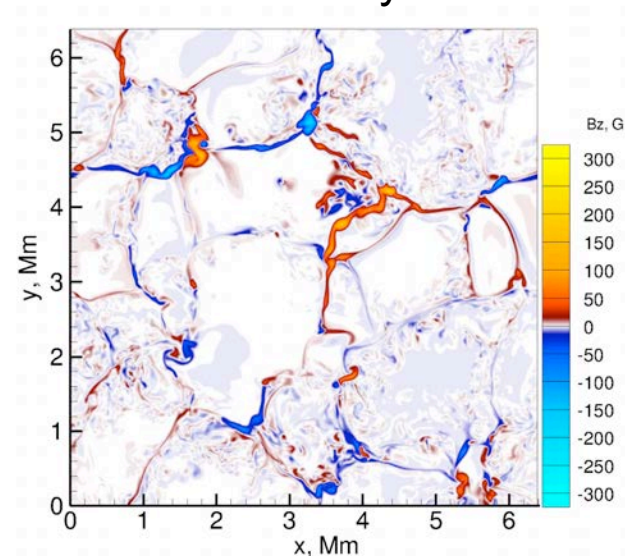
Acoustic waves excitation

Magnetic structures formation

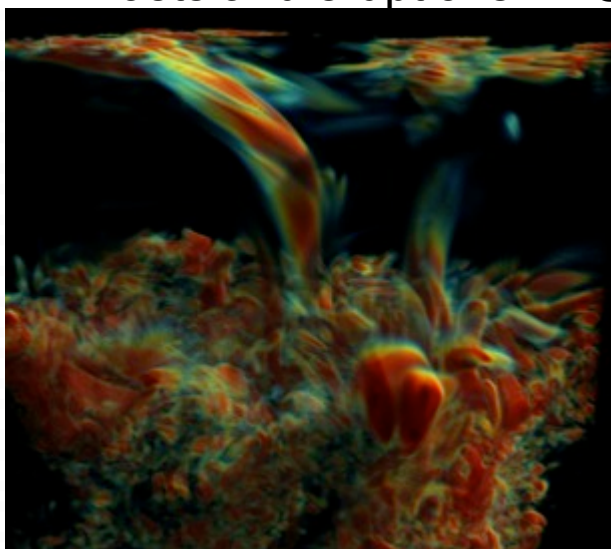
Self organization
processes in magnetic field



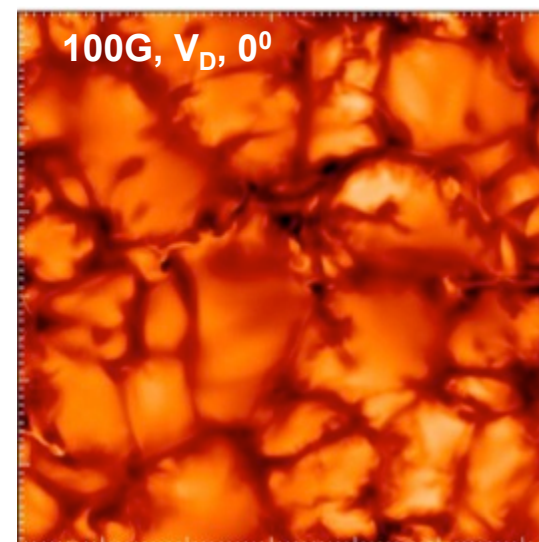
Small-scale dynamo



Jets and eruptions



Spectral lines and observables



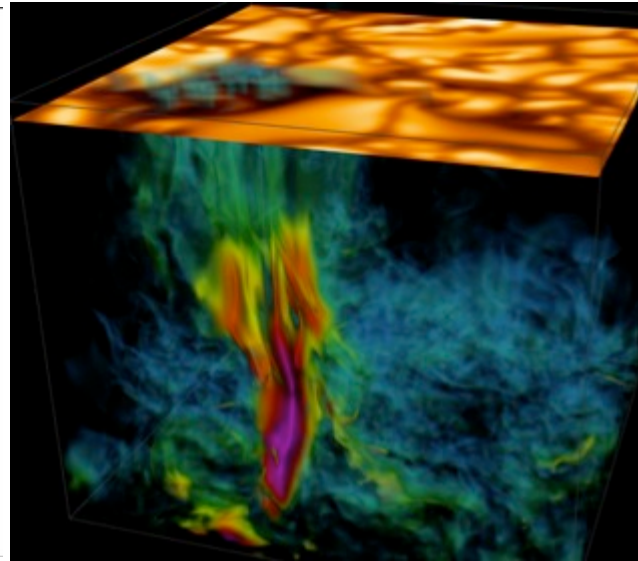
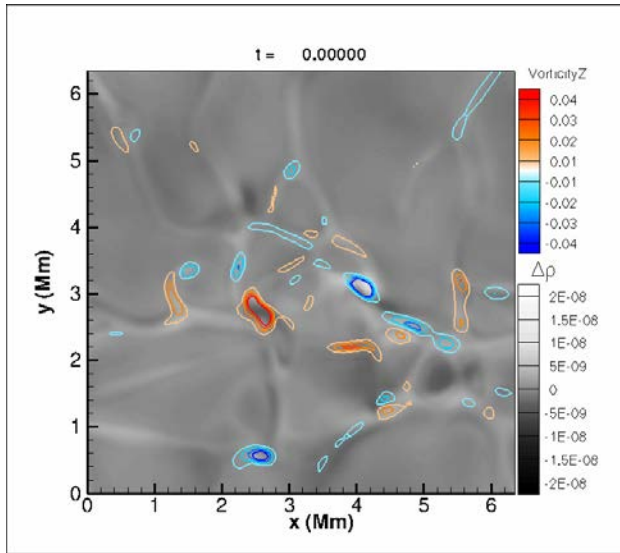
Kitiashvili et al., 2009-2018

3D realistic modeling of the solar dynamics

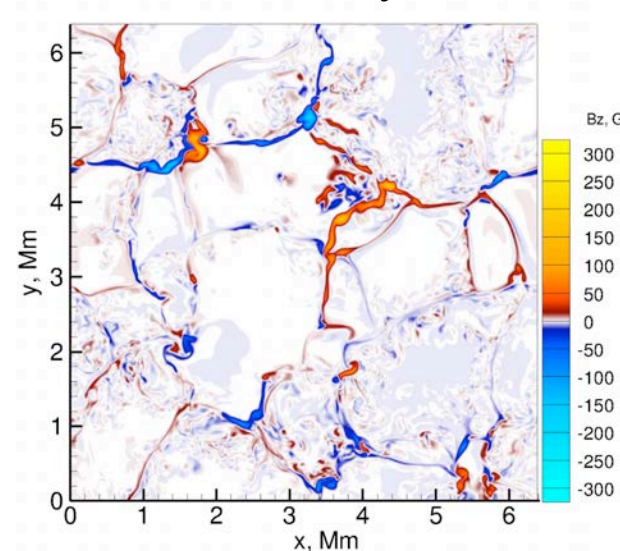
Acoustic waves excitation

Magnetic structures formation

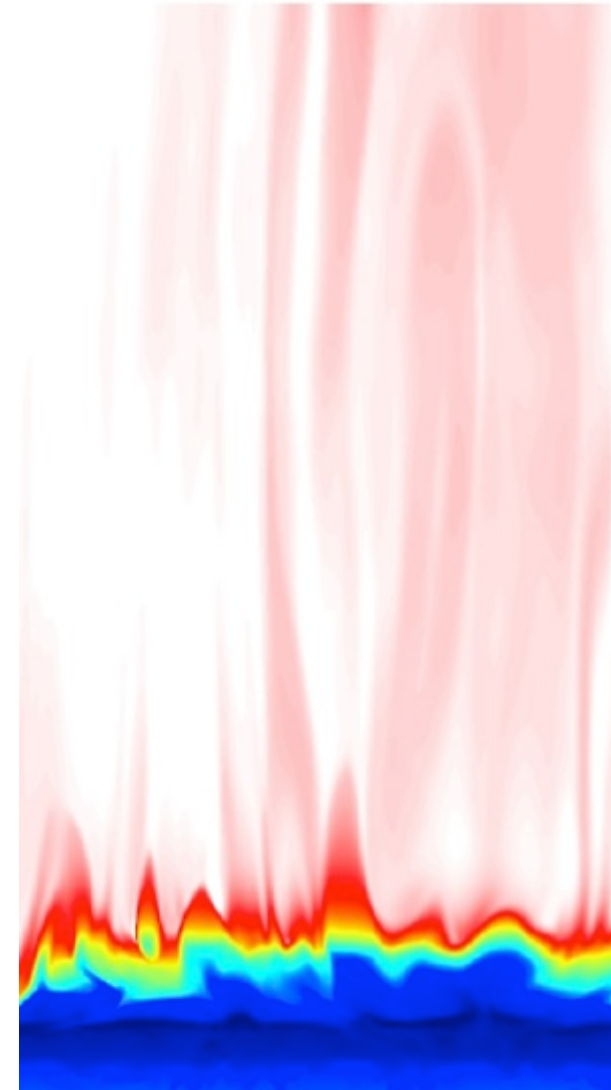
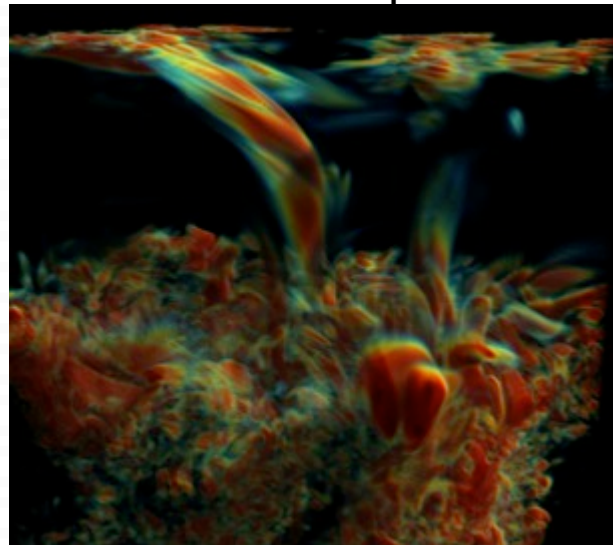
Solar corona structure and dynamics



Small-scale dynamo

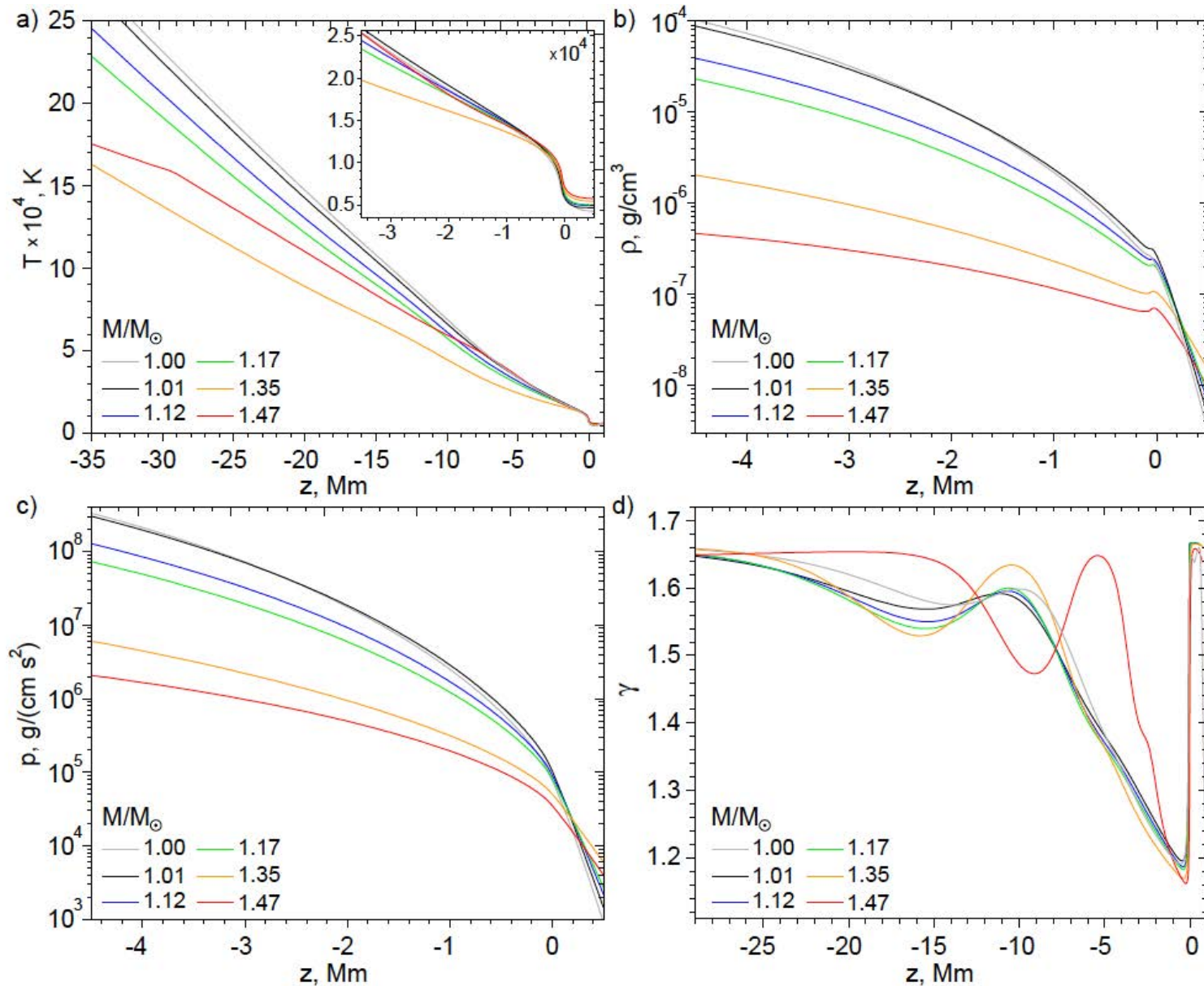


Jets and eruptions

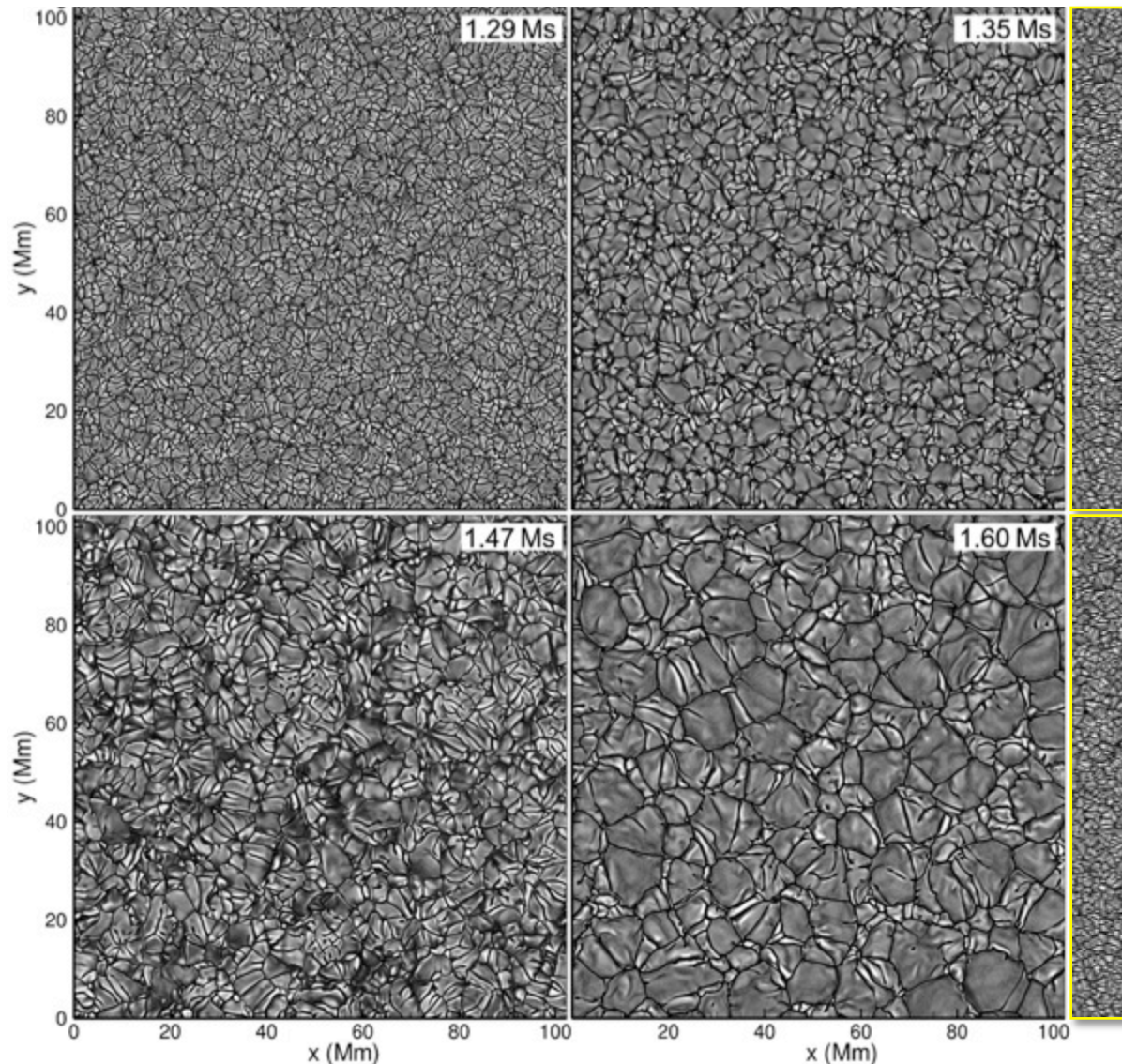


Kitiashvili et al., 2009-2018

Models of interior structure of the stars



Properties of the stellar surface convection



Sun

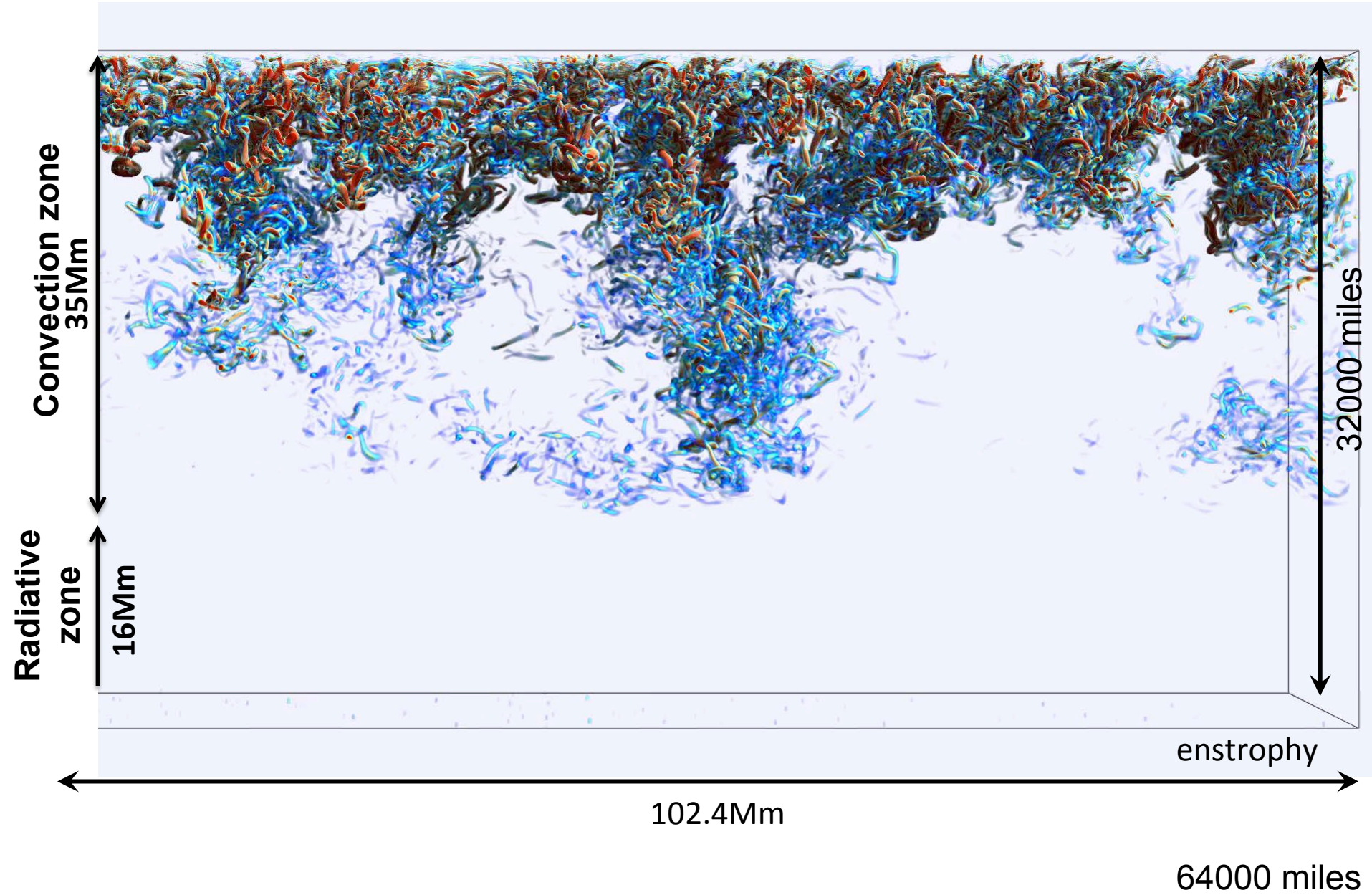
Pressure scale
height at the
photosphere

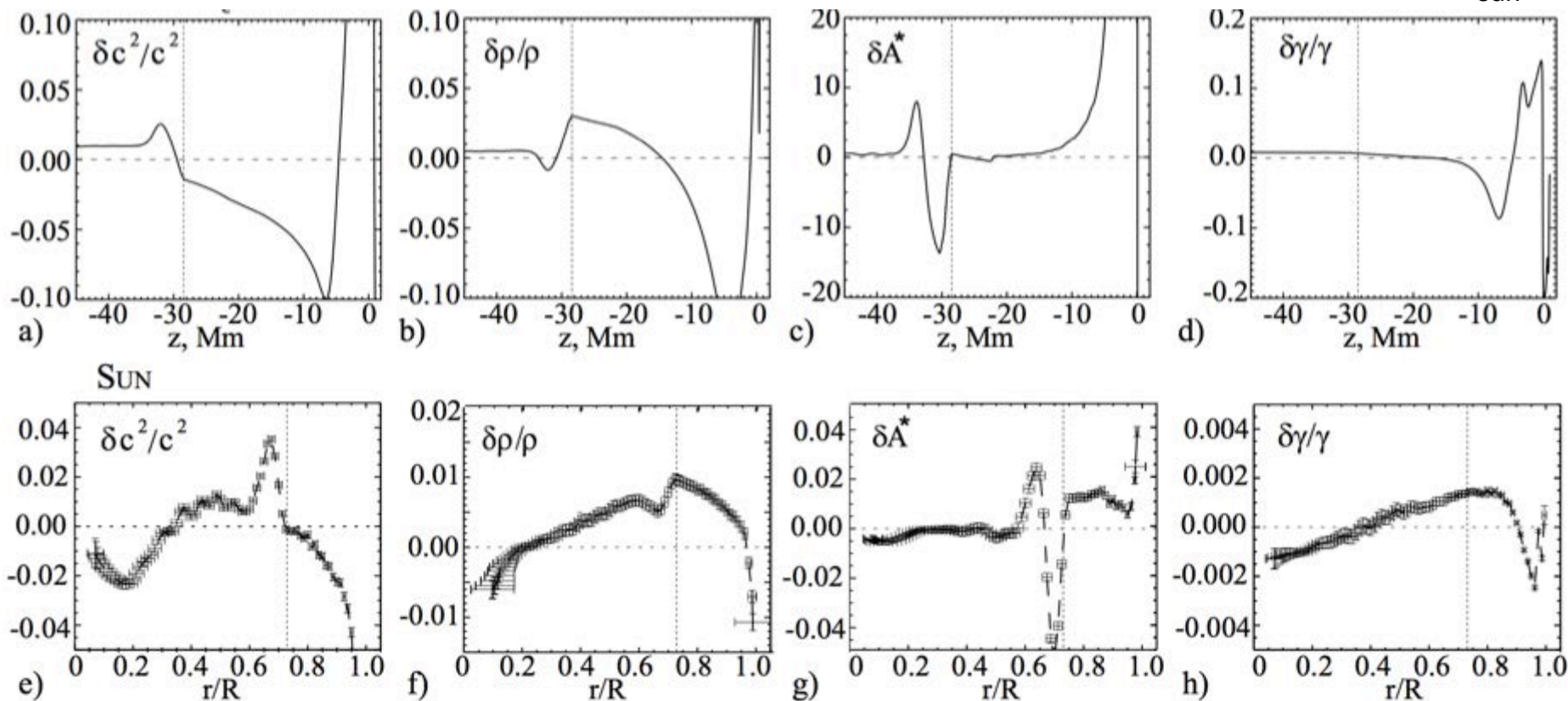
M, M_{\odot}	H_p, km
1.00	140
1.17	173
1.29	236
1.35	267
1.47	270
1.60	359

Distribution of the vertical velocity, revealing changes in the granulation structure, and formation of multi-scale convective cells.

StellarBox code (Wray et al., 2018)

$M=1.47M_{\text{sun}}$





The deviations between the 3D simulation and 1D model of a star with mass $M=1.47 M_{\text{sun}}$ as a function of depth, $z=r-R$, for: a) the squared sound speed, $\delta c^2/c^2$; b) density, $\delta \rho/\rho$; c) the Ledoux parameter of convective stability, A^* ; and d) the adiabatic exponent, γ . Panels e-h) show the corresponding deviations of the solar properties obtained by helioseismology inversion (Kosovichev 1999, 2011) from the 1D standard solar model (Christensen-Dalsgaard et al. 1996). Vertical dotted lines show the location of the bottom boundary of the convection zone.

Proxima Centauri

	Age,Gyr	Log(L)	Log(g)	Teff	Y _{surf}	Z _{surf}	R
Observations	4.85-8.8	-2.75	5.1-5.5	2700-3100	0.278	0.029	0.141-0.145
MESA model	4.85	-2.773	5.153	2985	0.278	0.029	-0.154
MESA model	8.8	-2.772	5.154	2985	0.278	0.029	-0.154

Model 10: 4.85Gy

H1=0.6933

H2=2.3621E-17

He3=0.0017

He4=0.2760

Li7=2.3113E-17

Be7=4.7685E-25

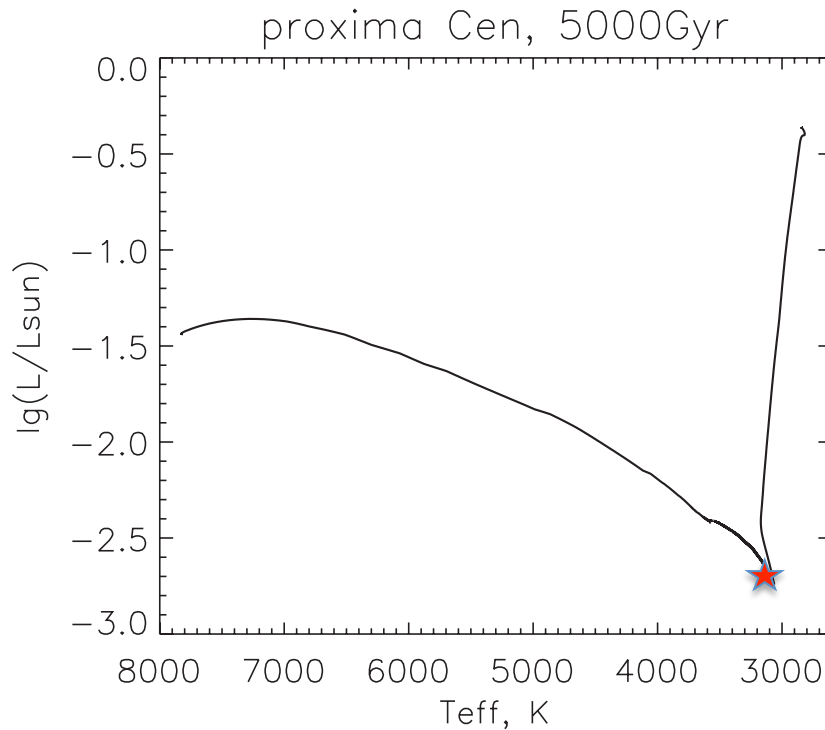
C12=0.00499

N14=0.0015

O16=0.0136

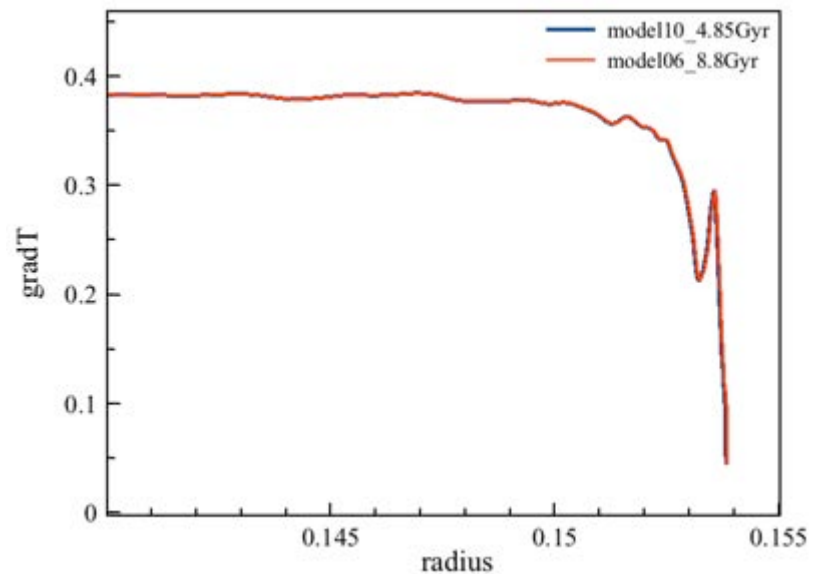
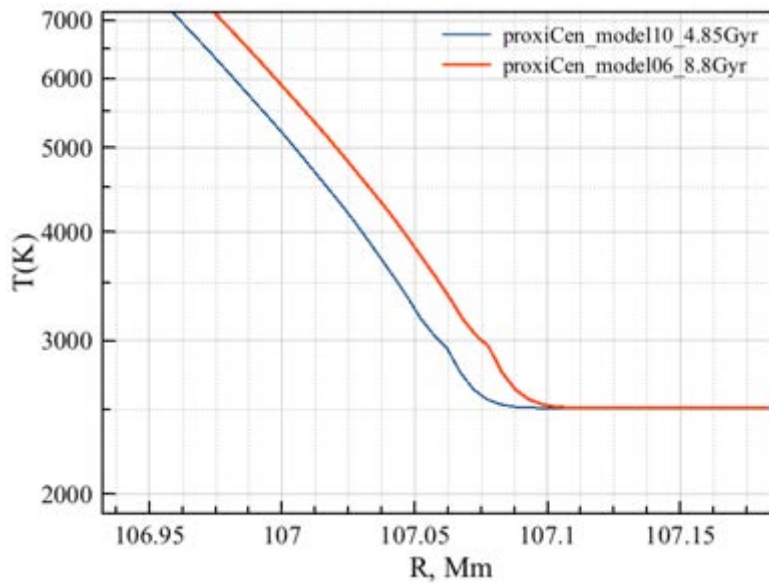
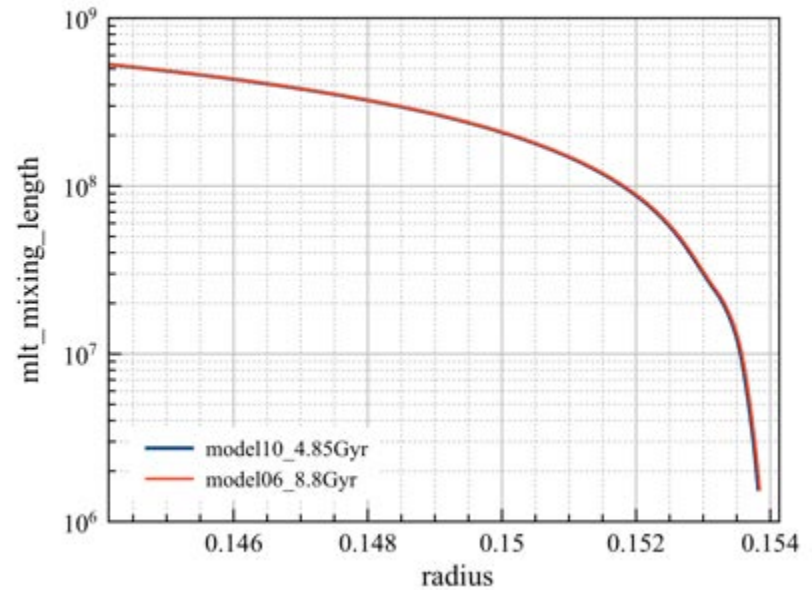
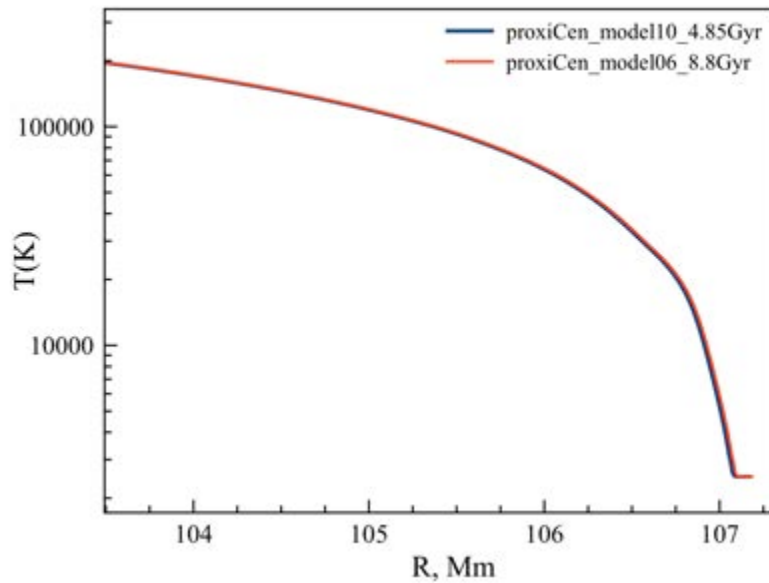
Ne20=0.0030

Mg24=0.0059



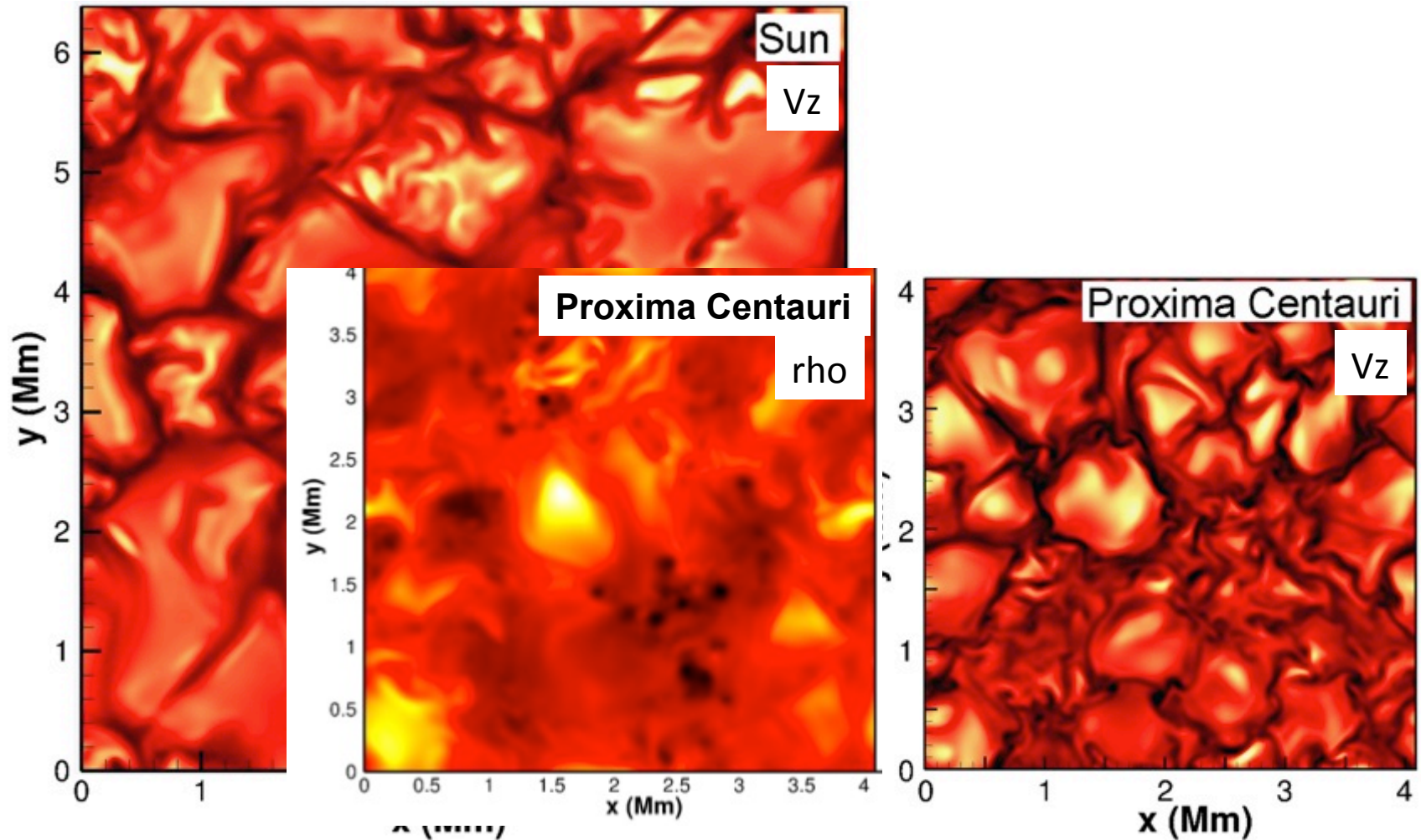
Proxima Centauri

MESA code: Initial conditions, 1D model



Proxima Centauri

StellarBox code: HD, 3D model



How Experience of studying the solar dynamics can be used for improving exoplanets detection?

Use observations and realistic-type simulations of the Sun

Jimenez et al. 1986: 15m/s variations in presence active regions

Deming et al. 1987: found RV signatures of supergranulation from spectra of integrated sunlight

Dumusque et al., 2015 (HARPS-N)

Haywood et al., 2016 (SDO/HMI and HARPS)

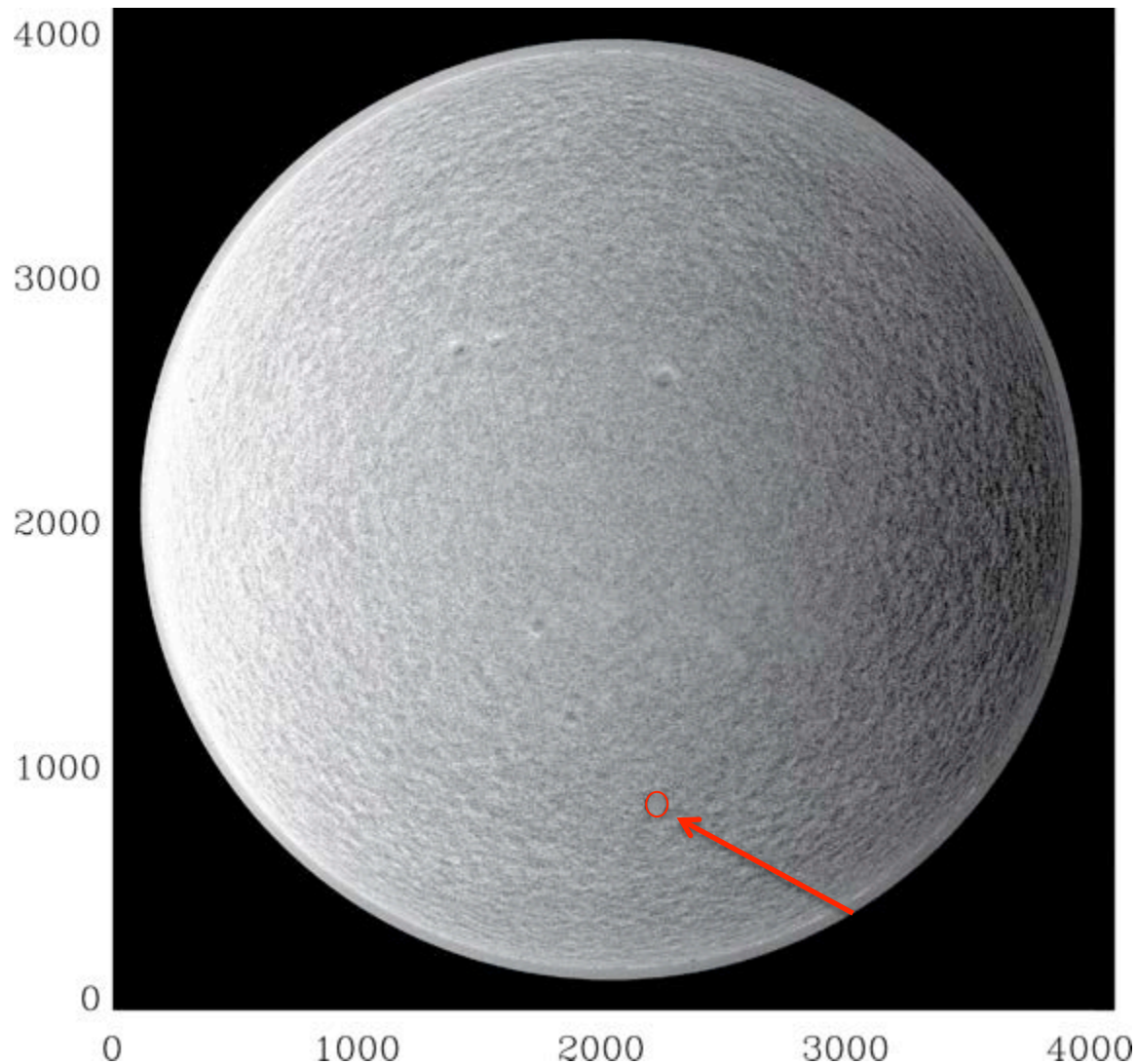
Vidotto et al., 2016 (SDO/HMI, SOLIS/NSO)

Lanza et al., 2016 (HARPS & HARPS-N)

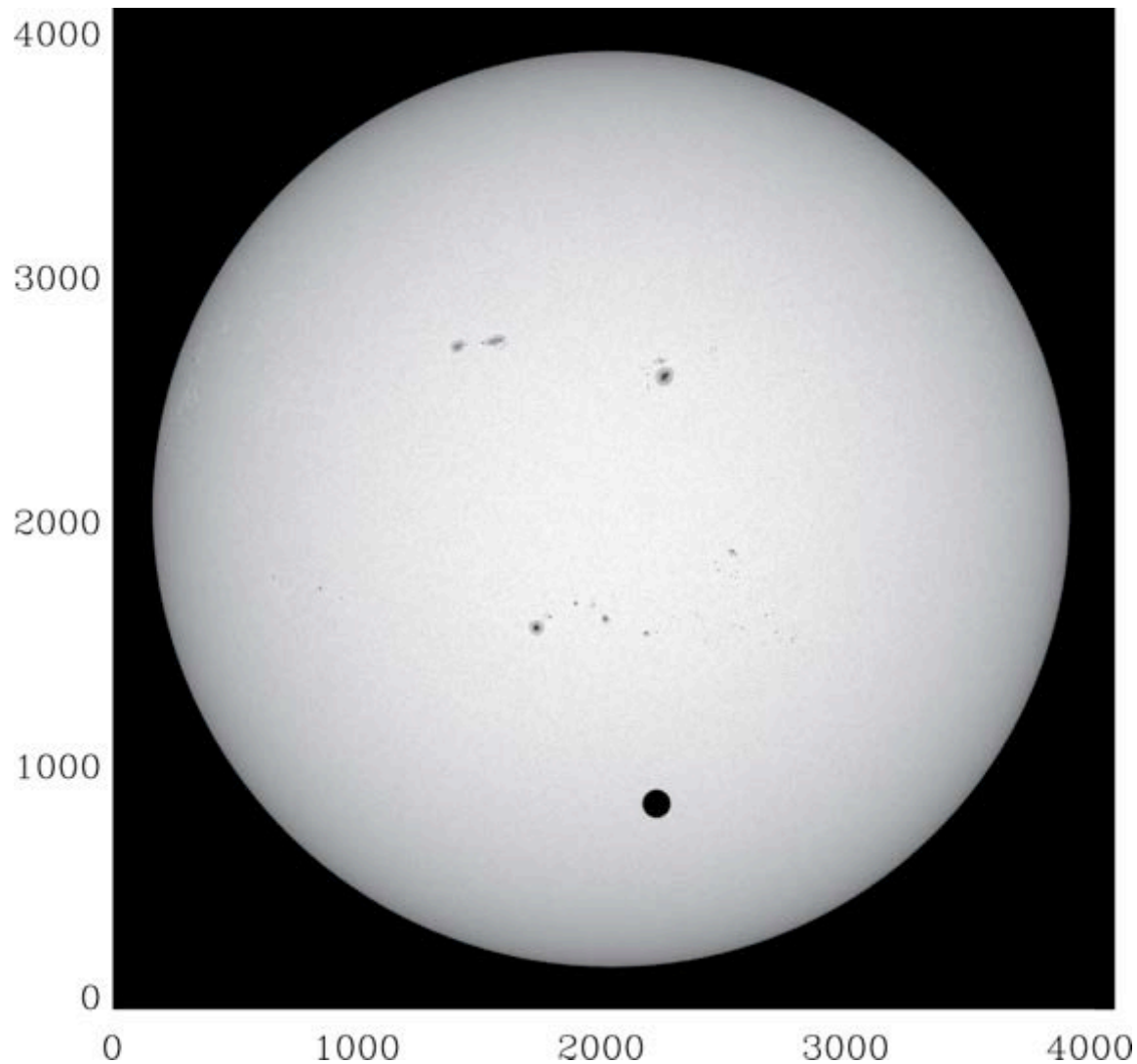
Lemke & Reiners, 2016 (FTS observations)

Cegla et al., 2013, 2016

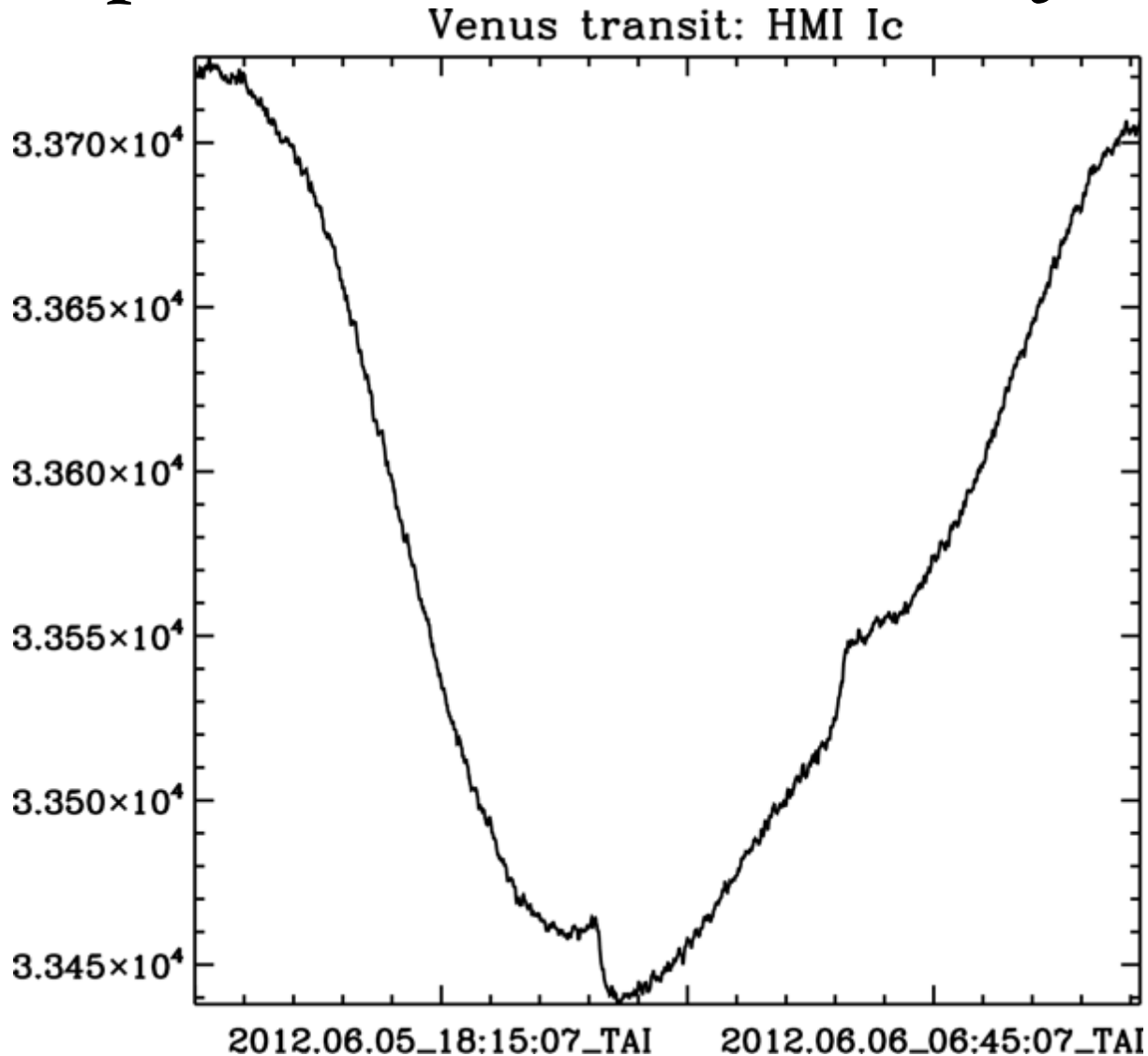
Example: Venus Transit, 5 – 6 June 2012



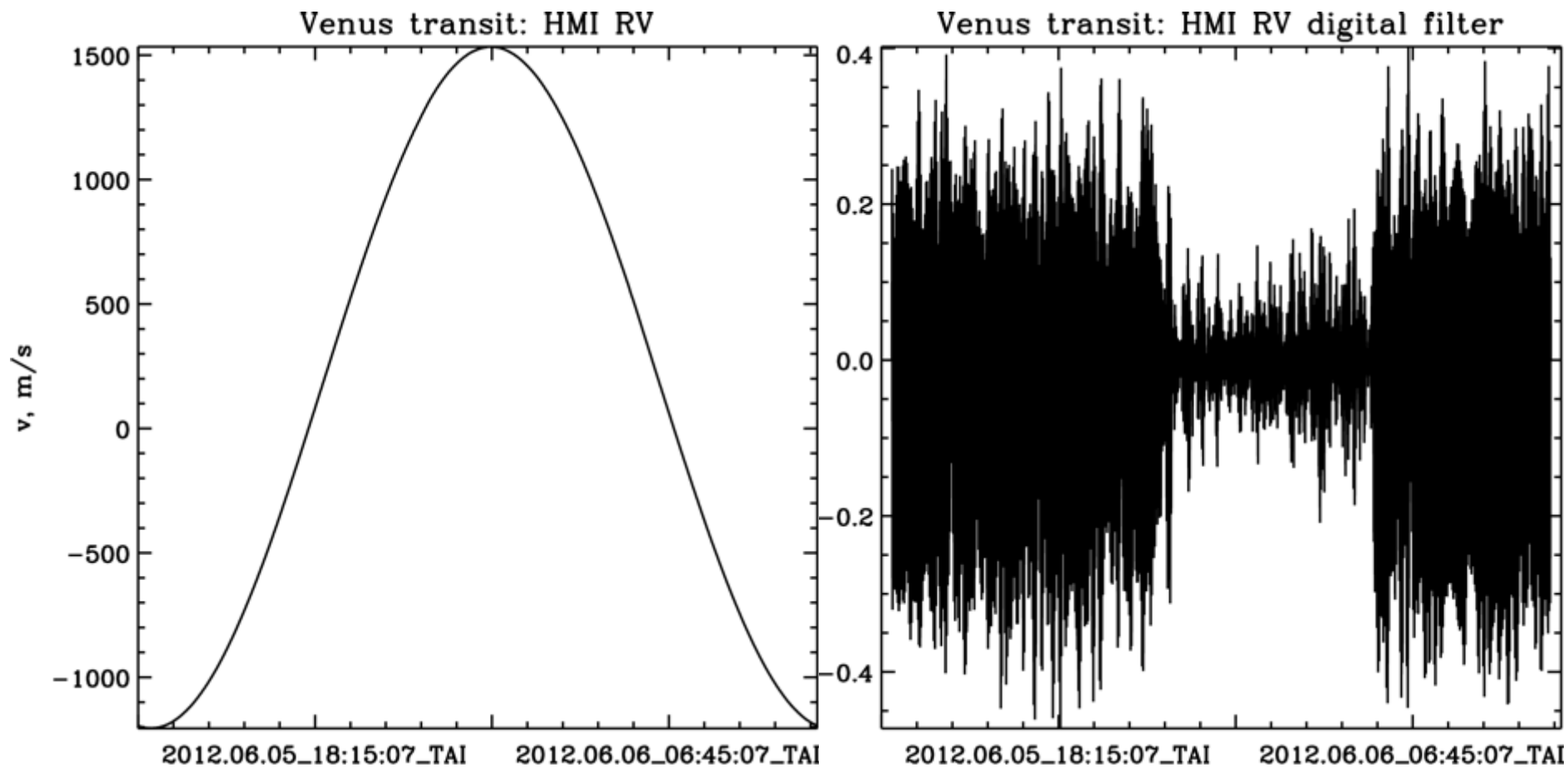
Example: Venus Transit, 5 – 6 June 2012



Example: Venus Transit, 5 – 6 June 2012



Example: Venus Transit



Conclusions

- Because of complexity of the physics of stellar surface and subsurface layers, 'ab initio' (or 'realistic'), numerical simulations based on first principles become a primary tool of theoretical modeling.
- Our investigation of main-sequence stars has shown that the dynamics of stellar convection dramatically changes among stars of different mass. The convection zone is shallower for more massive stars, the turbulent convection becomes more vigorous with plasma motions reaching supersonic speeds and multi-scale convective cells structures, which can be quite different from the granulation and supergranulation known from solar observations. Convective downdrafts in intergranular lanes between granulation clusters reach speeds of more than 20km/s, can penetrate through the whole convection zone, hit the radiative zone, and form a 8Mm thick overshoot layer.
- For stars with $M > 1.35M_{\odot}$ the convection zone is relatively shallow, and the high-resolution simulations domain cover its whole depth range including a convectively stable layer of the radiative zone. This allows us to investigate the physics of overshooting and turbulent mixing, as well as excitation of internal gravity waves at the bottom of the convection zone.
- New modeling effort of Proxima Centauri ($0.123M_{\odot}$) shows dramatic difference from the solar convection structure, in which a relatively weak turbulence near the stellar photosphere is accompanied by supersonic flows.
- Future developments include 3D radiative simulations of stellar convection zones and atmospheres of stars of different mass and age, taking into account effects of magnetic field and rotation as well as characterization of influence of the turbulent surface plasma on stellar observations, such as the stellar jitter, which will help to improve detection of Earth-size planets.