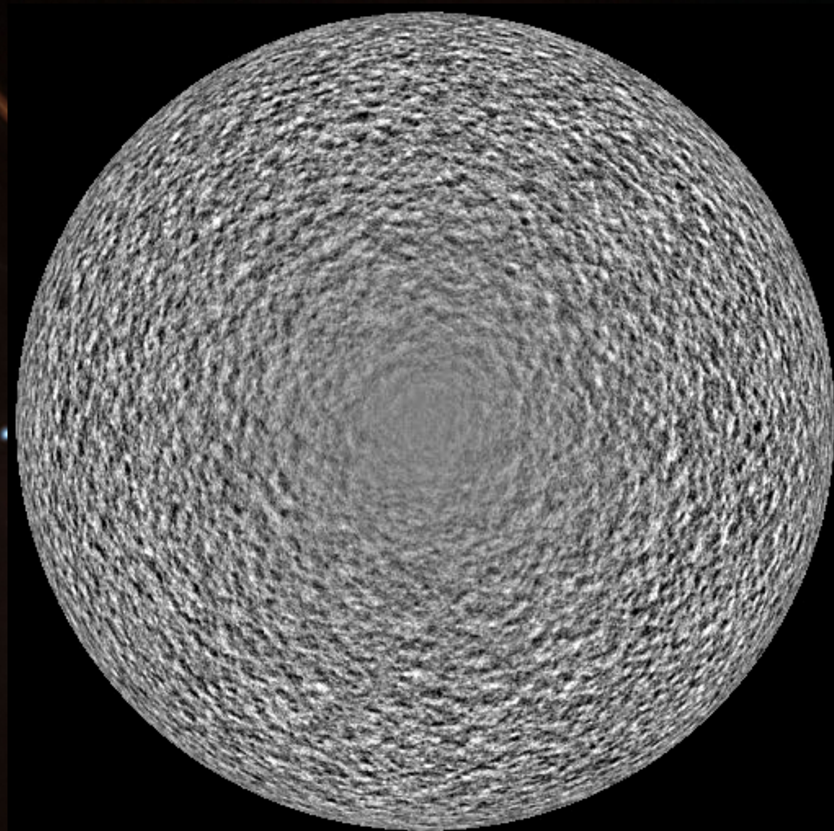
Dynamics of Turbulent Convection in Moderate-Mass Stars



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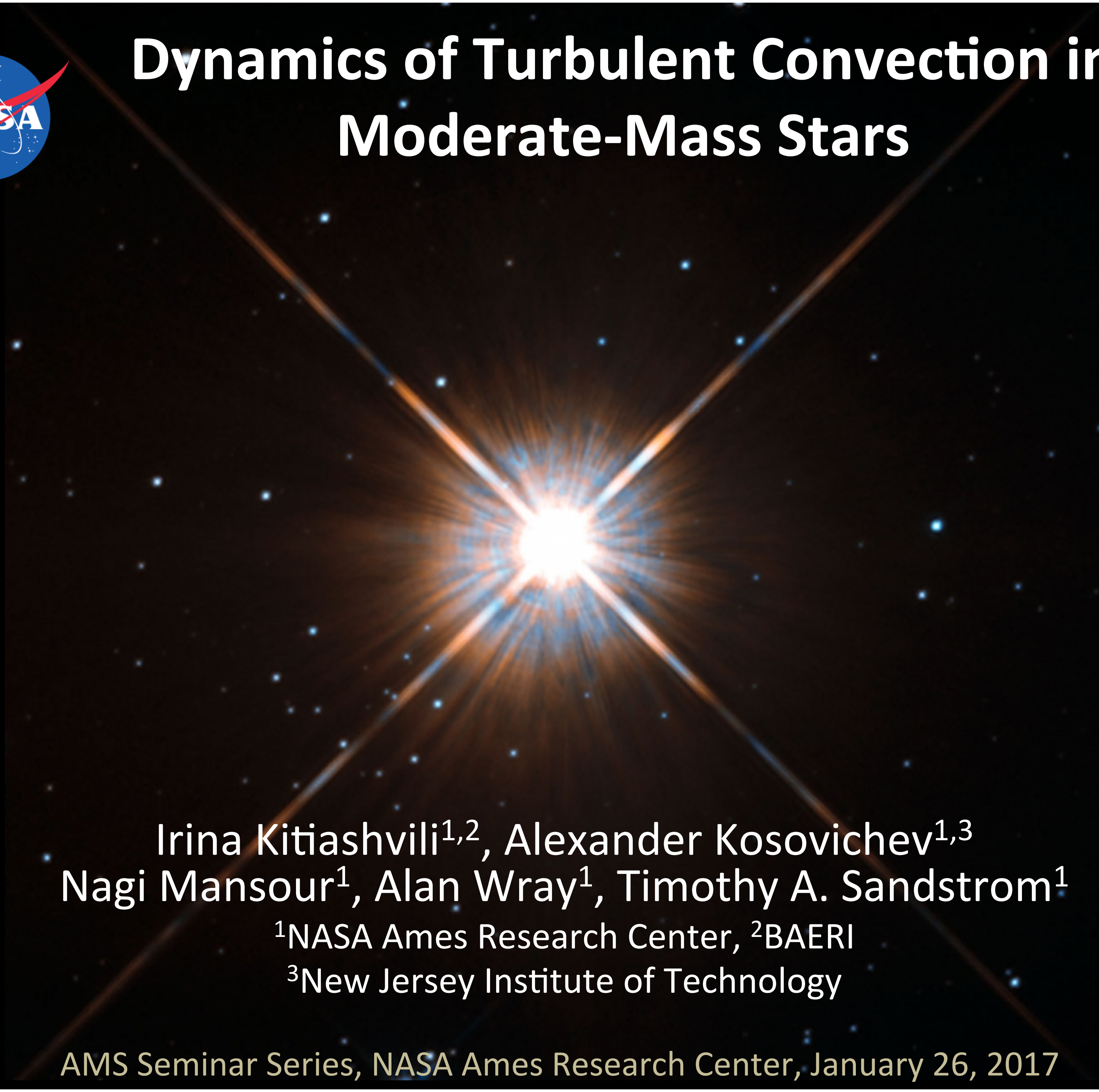
AMS Seminar Series, NASA Ames Research Center, January 26, 2017

Dynamics of Turbulent Convection in Moderate-Mass Stars



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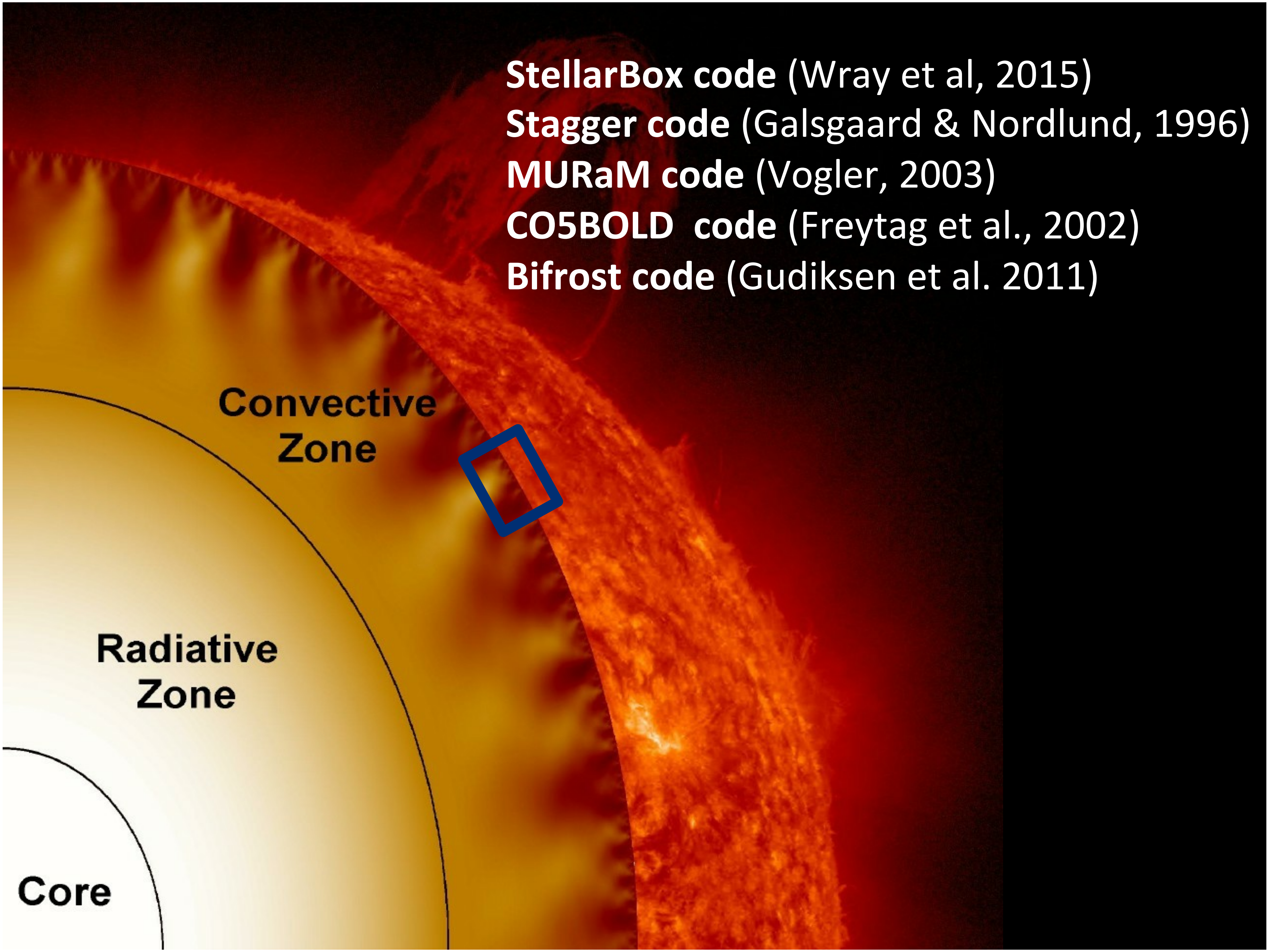
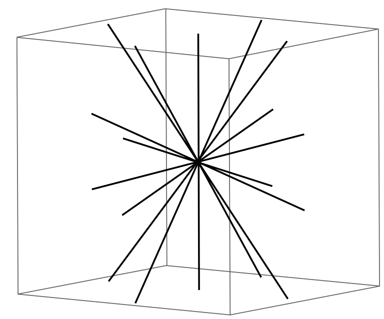

StellarBox code (Wray et al, 2015)
Stagger code (Galsgaard & Nordlund, 1996)
MURaM code (Vogler, 2003)
CO5BOLD code (Freytag et al., 2002)
Bifrost code (Gudiksen et al. 2011)
Convective Zone
Radiative Zone
Core

Numerical Model: Basic characteristic of the code

StellarBox ("SolarBox")

Wray et al., 2015

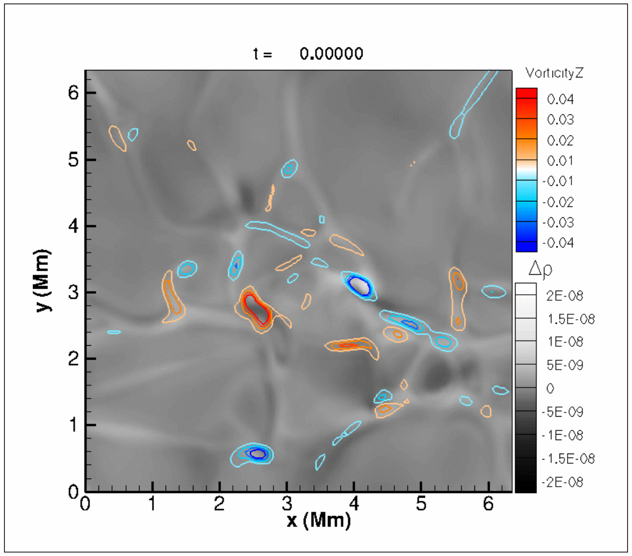


- ✓ 3d rectangular geometry
- ✓ Fully conservative compressible
- ✓ Fully coupled radiation solver:
  - ✧ LTE using 4 opacity-distribution-function bins
  - ✧ Ray-tracing transport by Feautrier method
  - ✧ 18 rays (2 vertical, 16 slanted) angular quadrature
- ✓ Non-ideal (tabular) EOS
- ✓ 4th order Padé spatial derivatives
- ✓ 4th order Runge-Kutta in time
- ✓ Different Turbulence models
  - ✧ LES: Smagorinsky model (and its dynamic procedure)
  - ✧ DNS + Hyperviscosity approach
  - ✧ MHD subgrid models

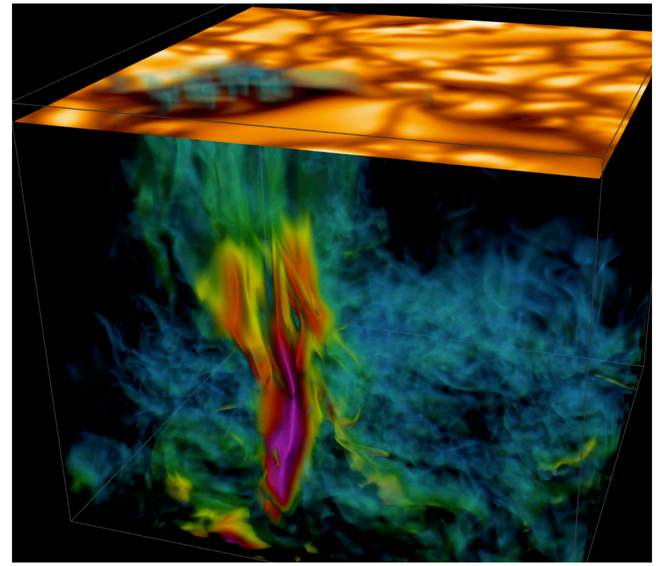
We use a 3D non-linear radiative MHD code developed for simulating the upper solar convection zone and lower atmosphere. This code takes into account several physical phenomena: compressible fluid flow in a highly stratified medium, 3D multi-group radiative energy transfer between the fluid elements, a real-gas equation of state, ionization and excitation of all abundant species, and magnetic effects. A unique feature of this code is implementation of various subgrid scale turbulence models. We adopted the most widely used subgrid-scale Smagorinsky model (Smagorinsky,1963) in the compressible formulation (Germano et al.,1991).

Solar turbulent dynamics

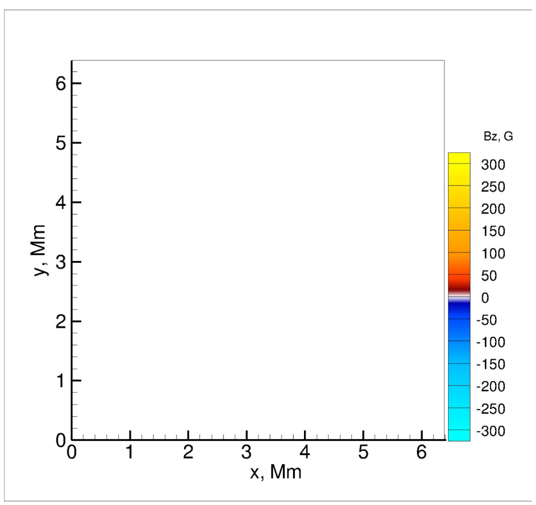
Acoustic waves excitation



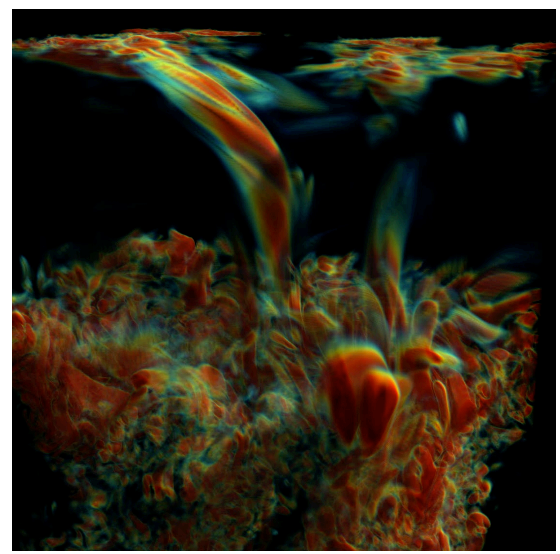
Pores formation



Small-scale dynamo

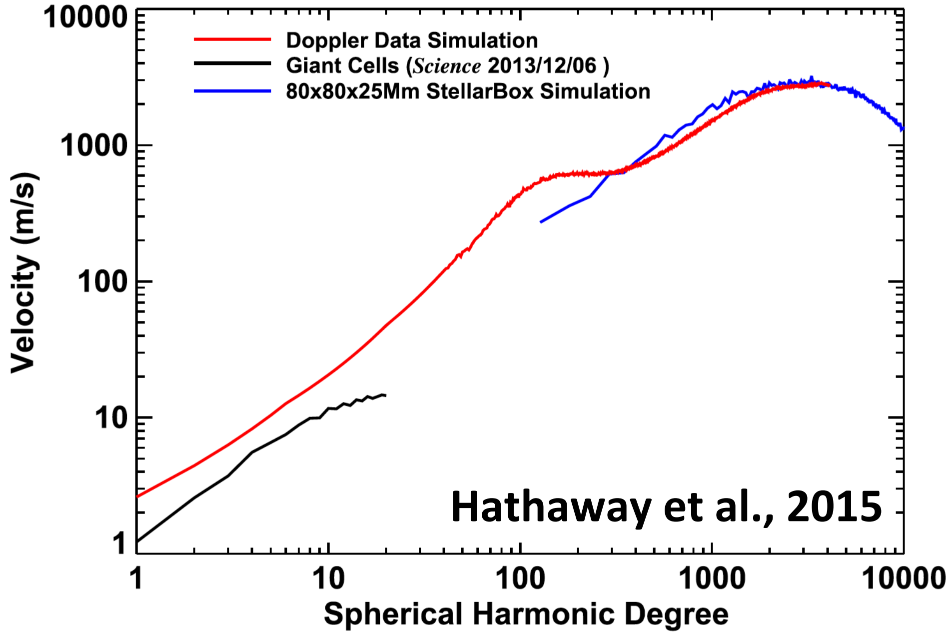


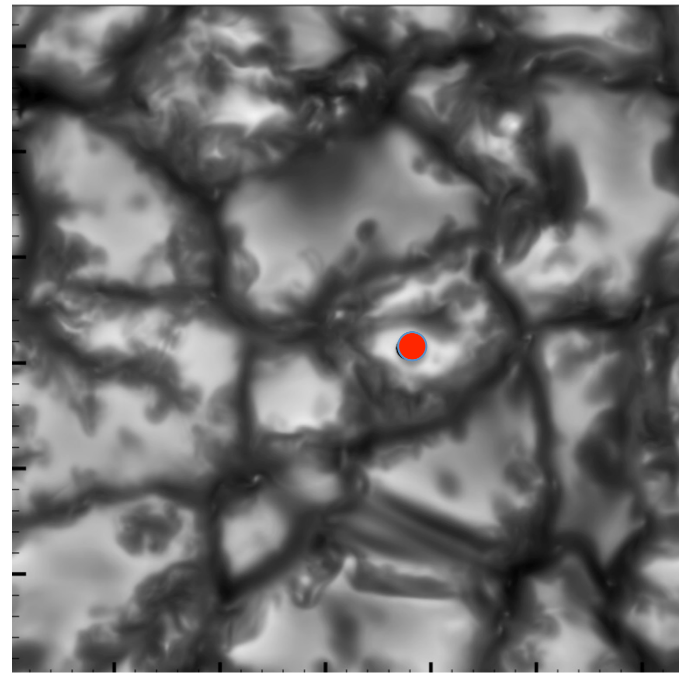
Jets and eruptions

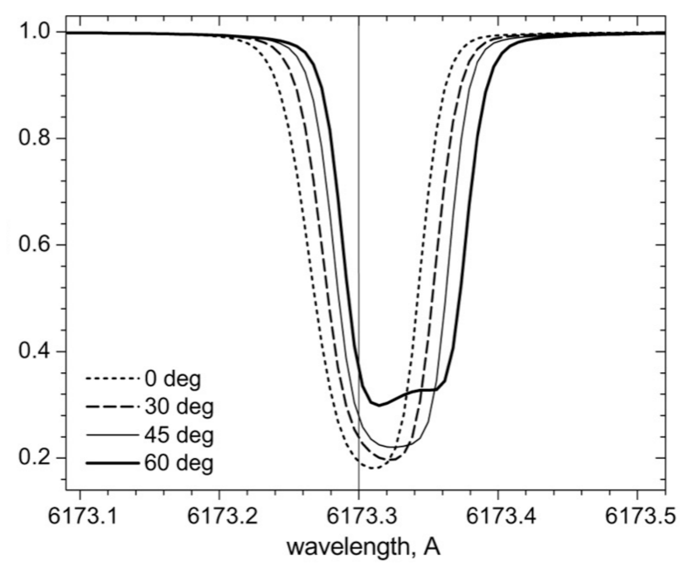


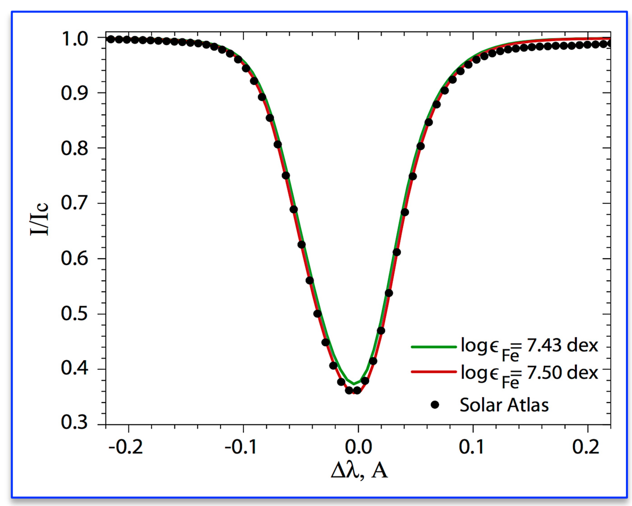
Kitiashvili et al., 2010-2015

Solar Magnetoconvection

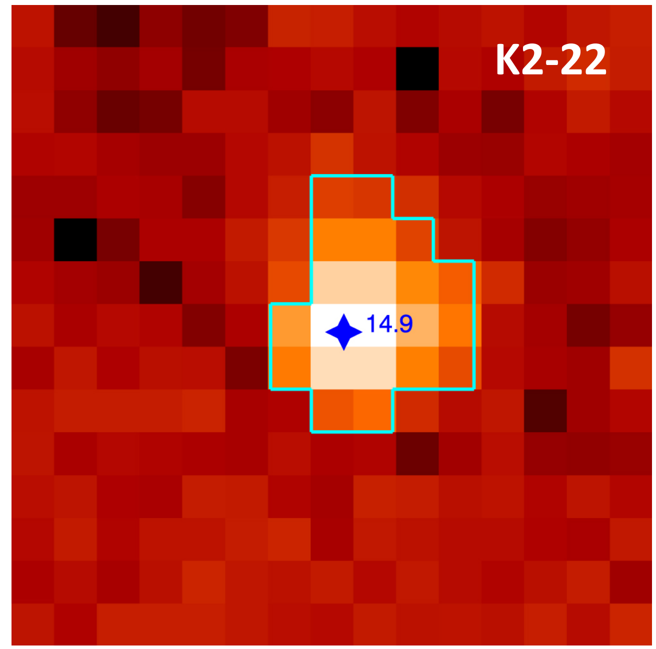








Stellar Observations

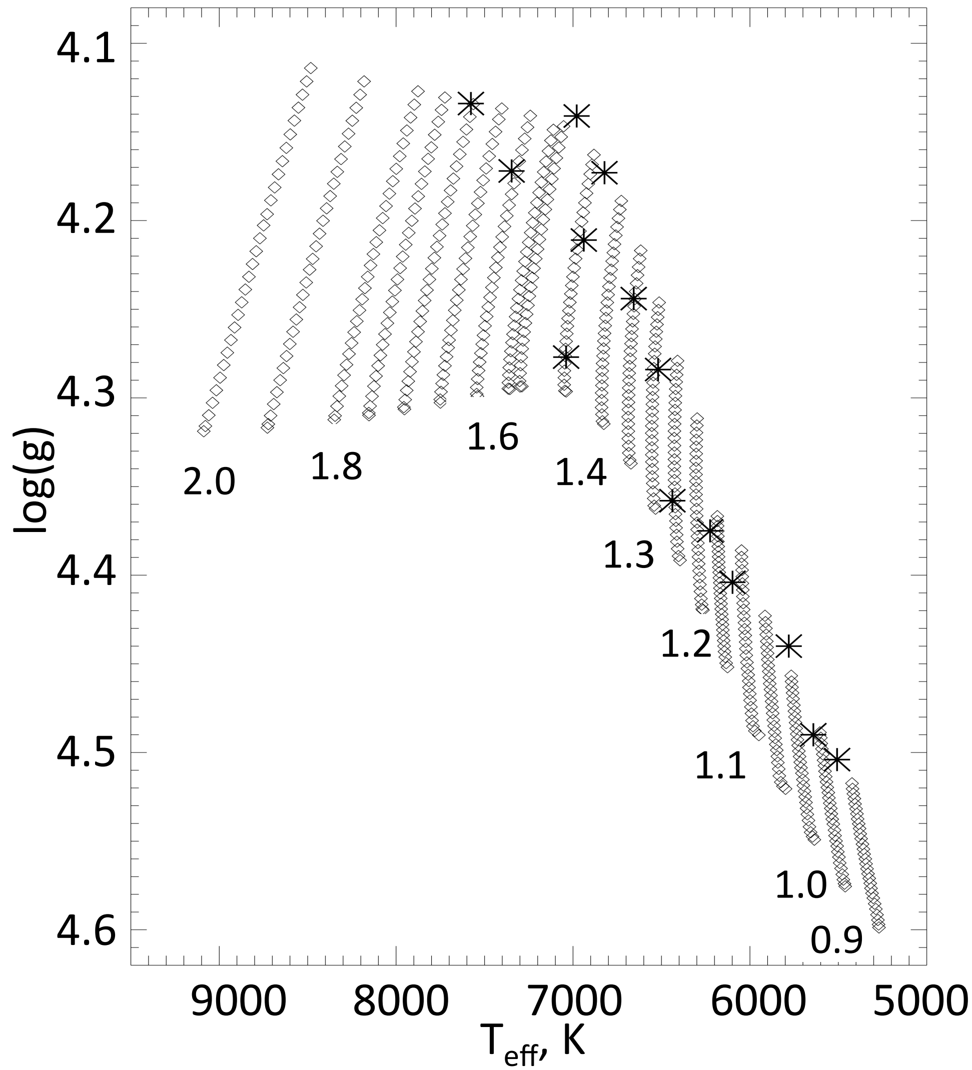


Sanchis-Ojeda et al., 2015

Stellar Models

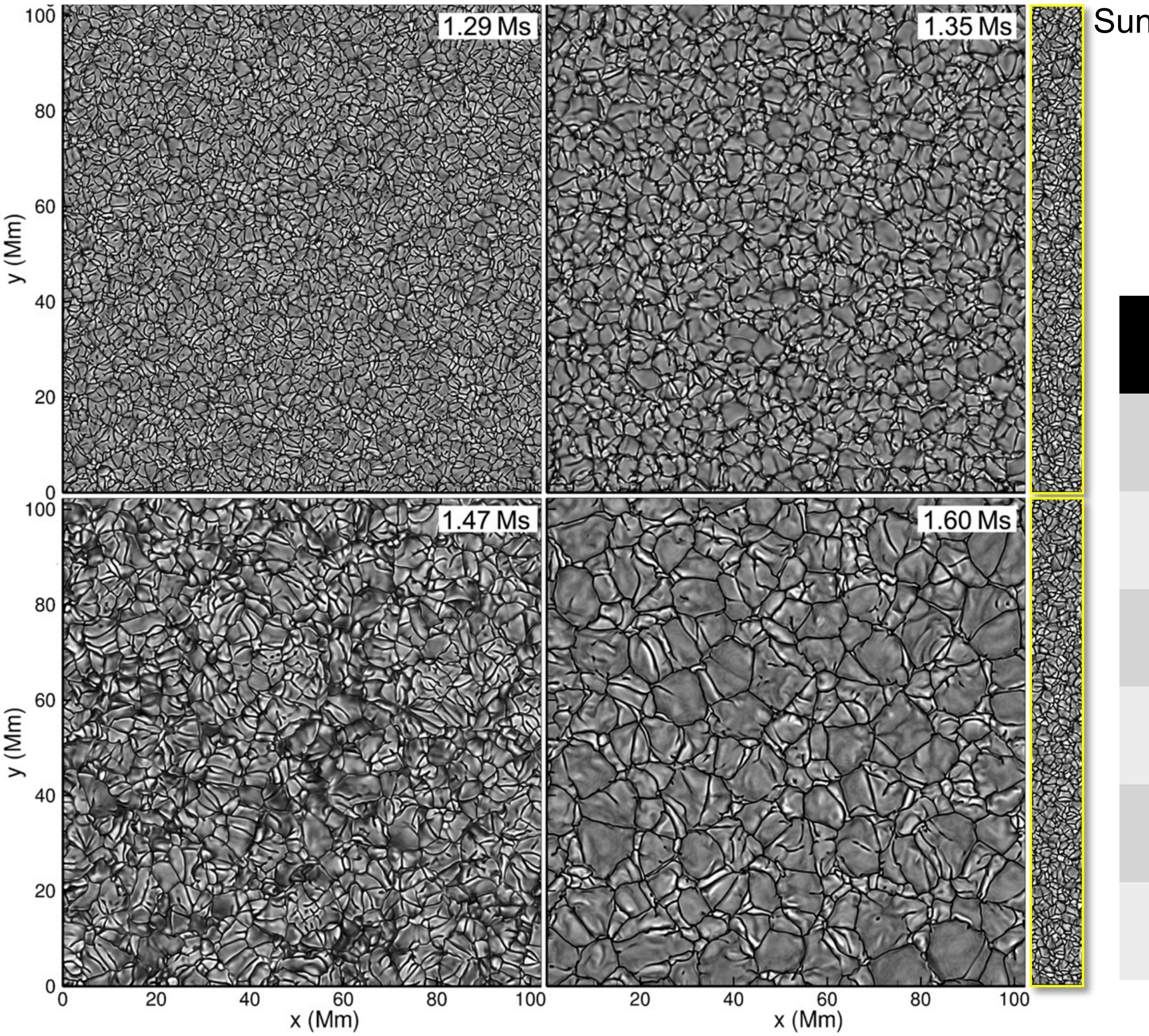
Kepler Targets

Kepler ID	Teff	Log G	Mass
11244118	5507	4.504	0.94
3427720	5780	4.44	1.01
4076177	6098	4.404	1.12
10119517	6225	4.375	1.17
6131093	6438	4.358	1.25
11138047	6519	4.284	1.29
11342880	6657	4.244	1.35
6306896	6822	4.173	1.45
11649699	6939	4.211	1.46
9962653	7039	4.277	1.47
5466537	6979	4.141	1.52
8677585	7347	4.172	1.6
10451090	7577	4.134	1.7



Calculated with the stellar evolution code CESAM (Morel 1997; Morel & Lebreton 2008)

Properties of the stellar surface convection



Pressure scale height at the photosphere

M, M_S	Hp, km
1.00	140
1.17	173
1.29	236
1.35	267
1.47	270
1.60	359

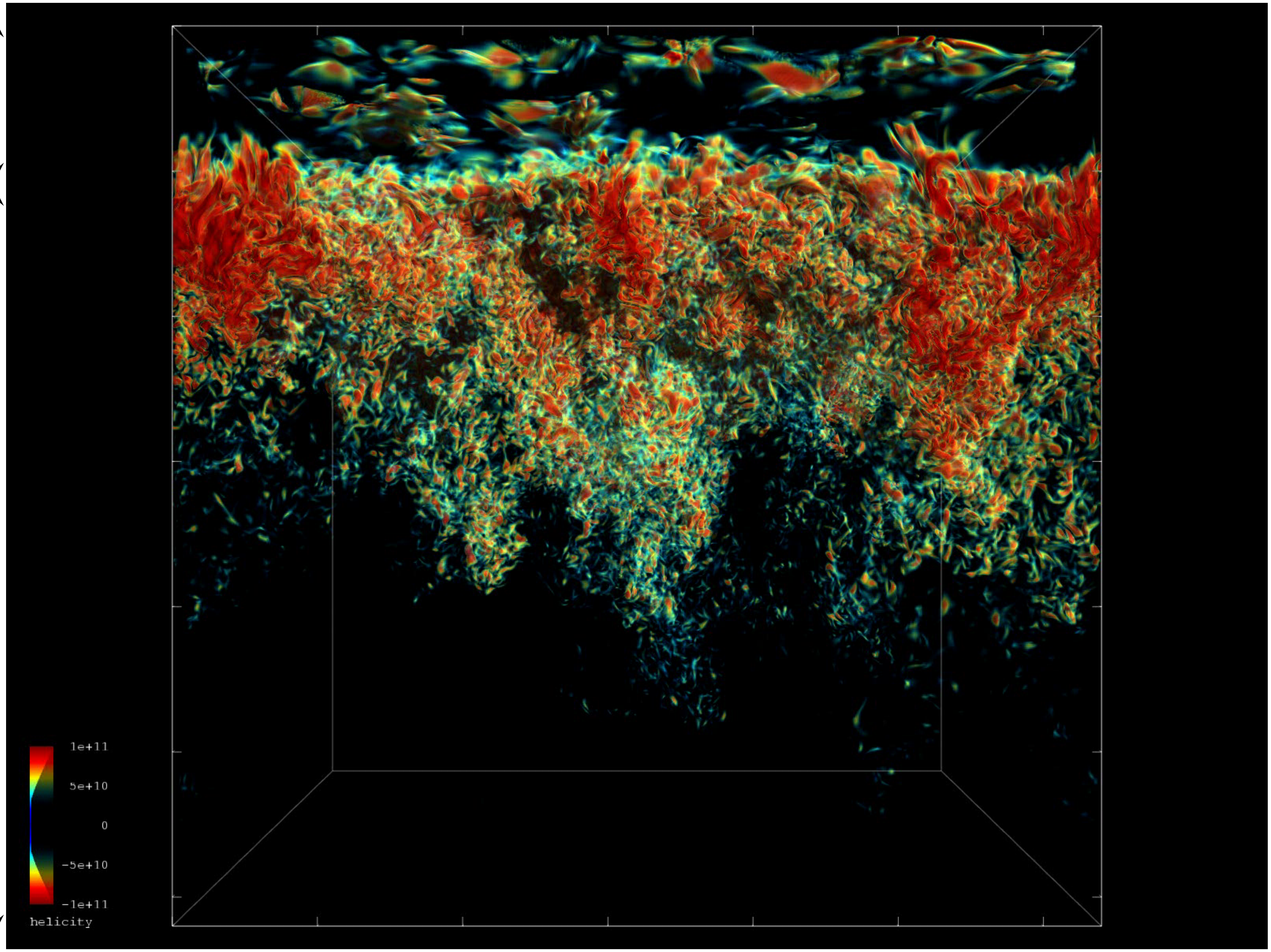
Distribution of the vertical velocity, revealing changes in the granulation structure, and formation of multi-scale convective cells.

StellarBox code

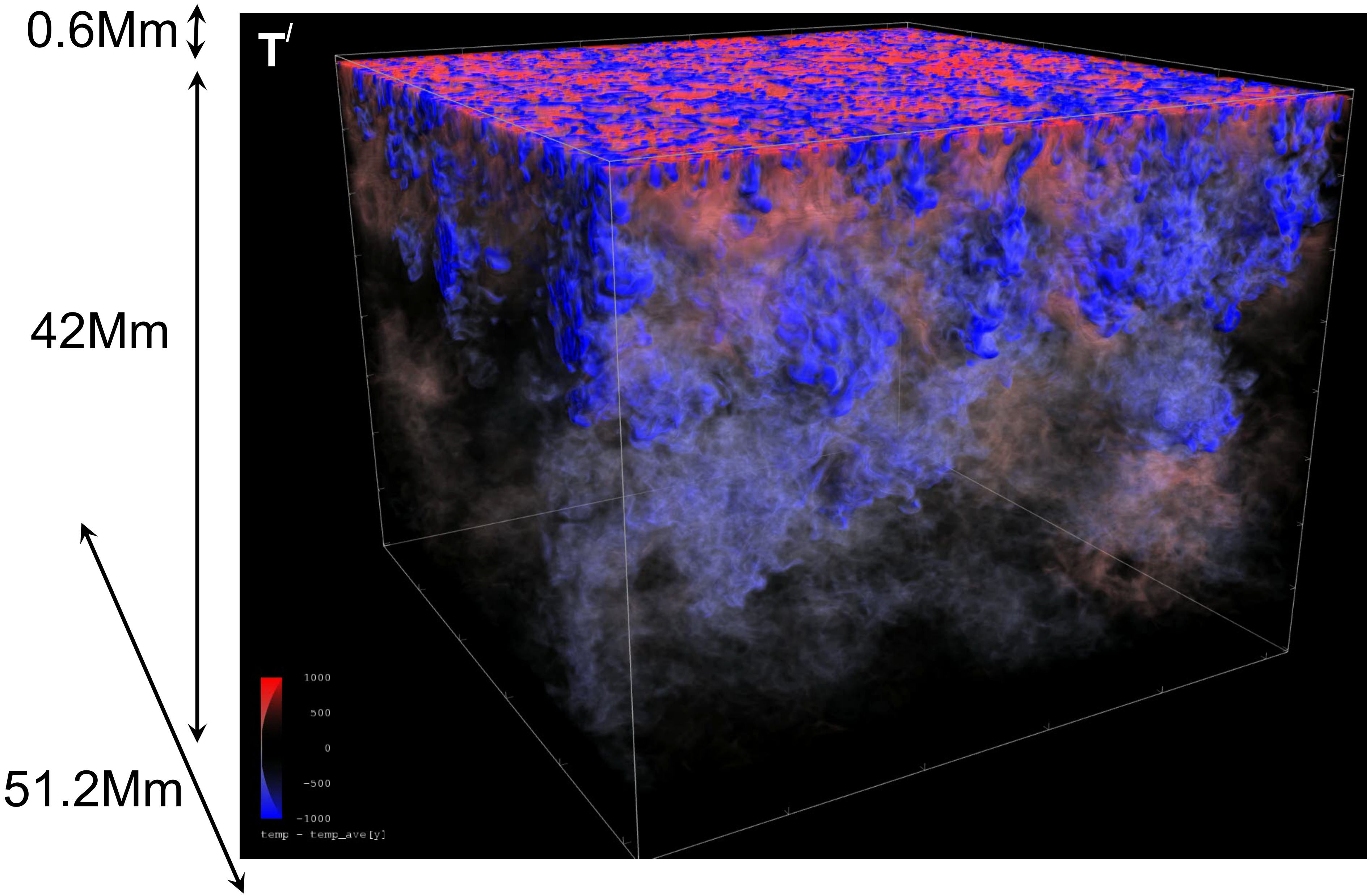
Subsurface Stellar Dynamics: 1Ms

1Mm

5.2Mm

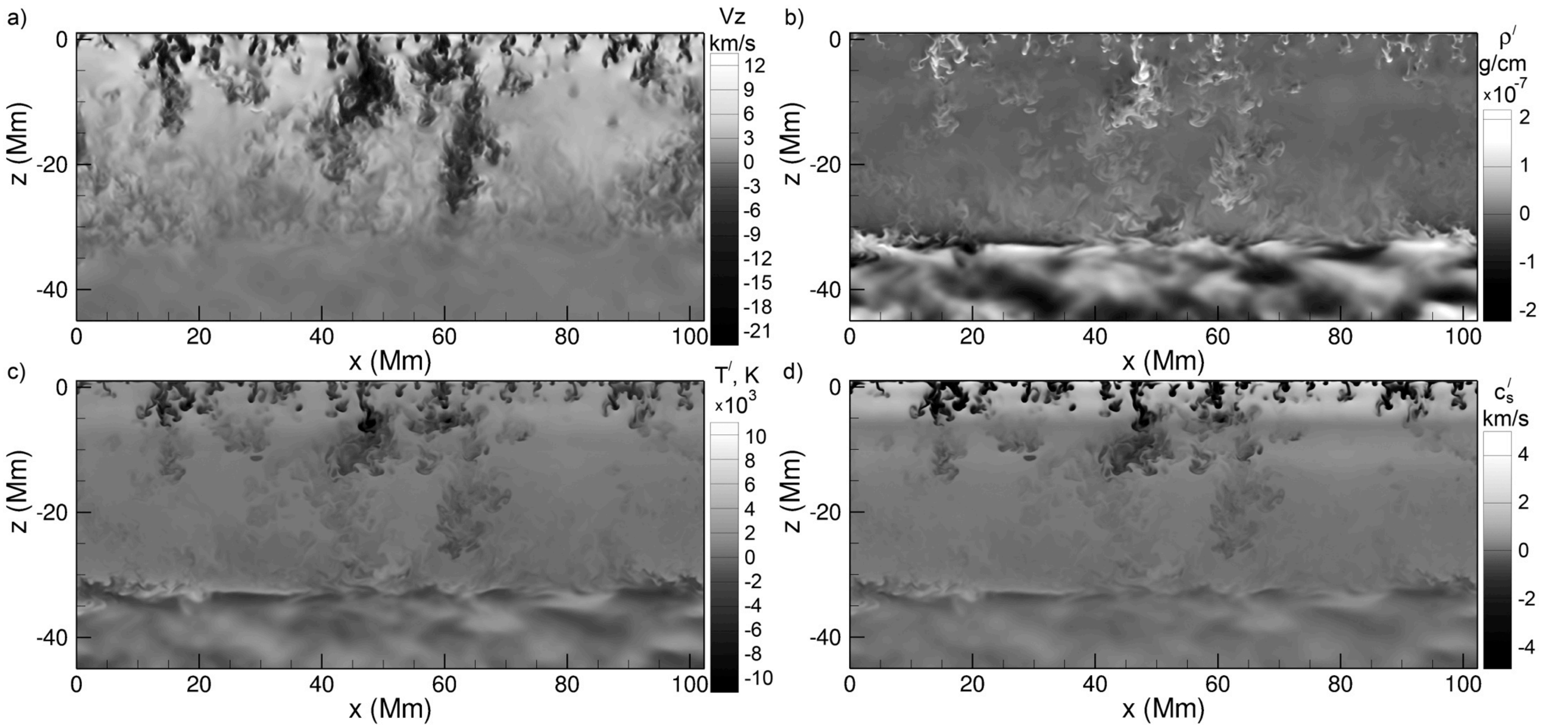


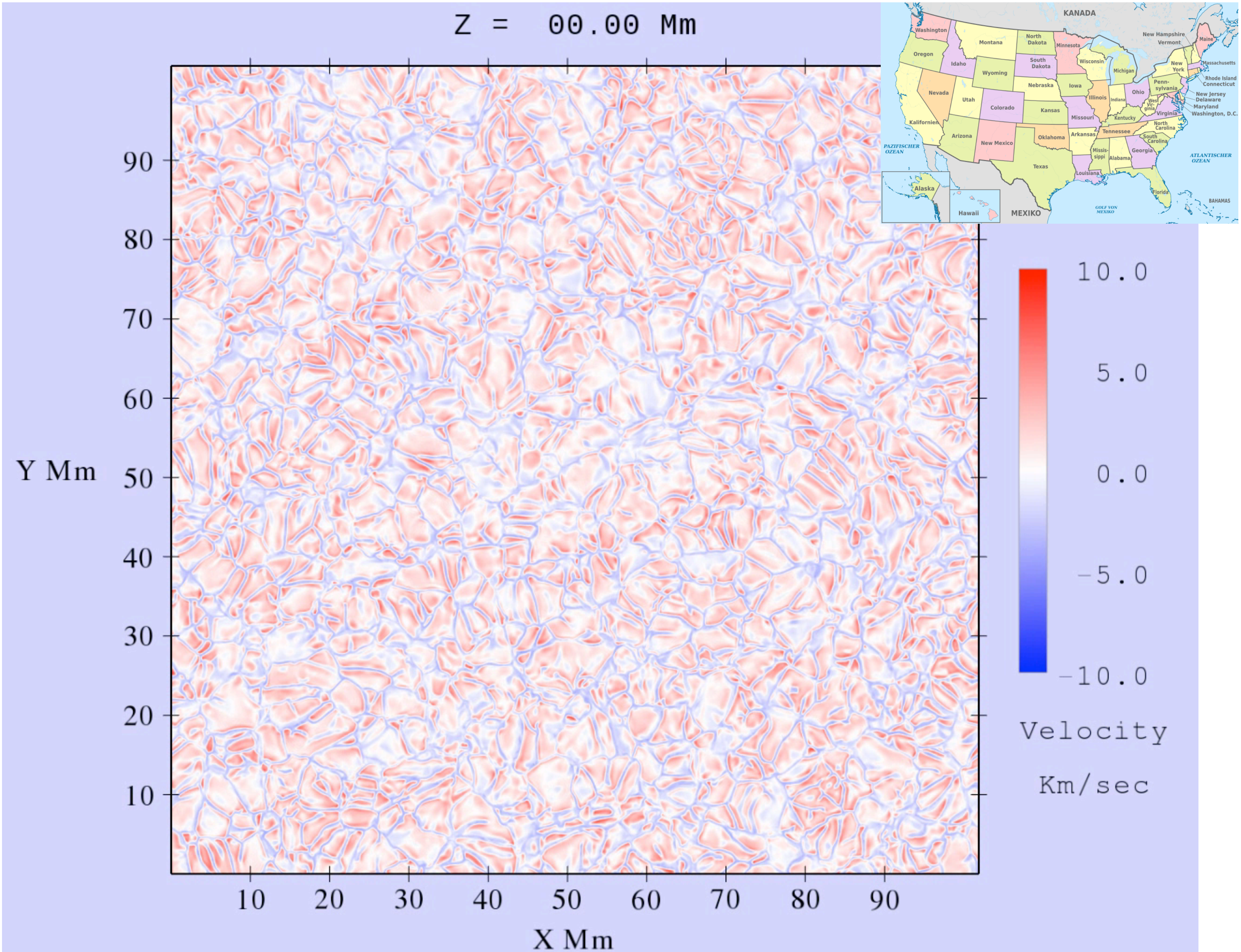
Subsurface Stellar Dynamics: 1.35Ms



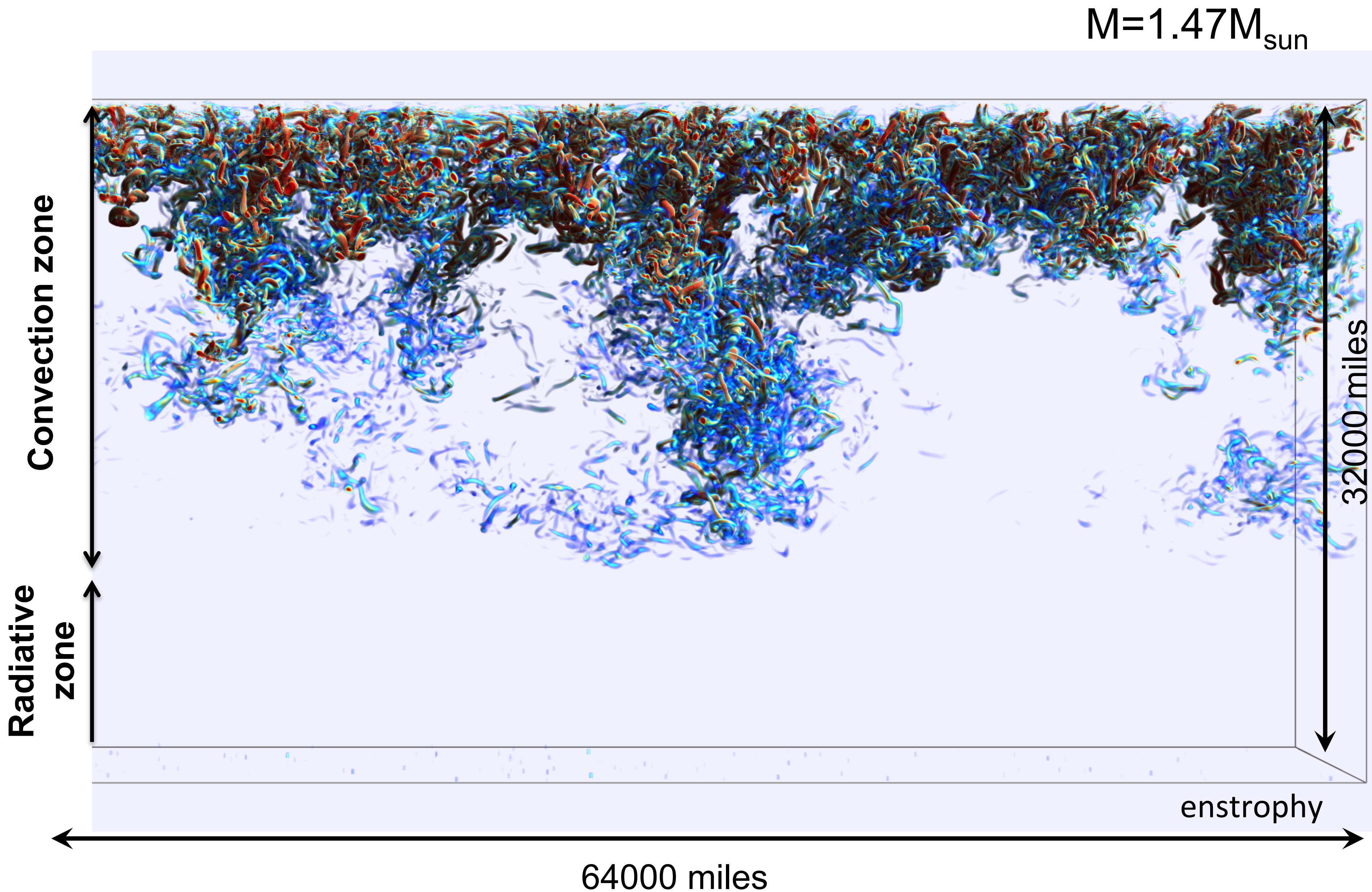
KIC9962653, M=1.47M_{SUN}

Vertical slice through the computational domain shows:
a) vertical velocity, b) density, c) temperature and d) sound speed perturbations from the stellar photosphere to the radiative zone.
Large-scale density fluctuations in the radiative zone are caused by internal gravity waves (g-modes) excited by convective overshooting.

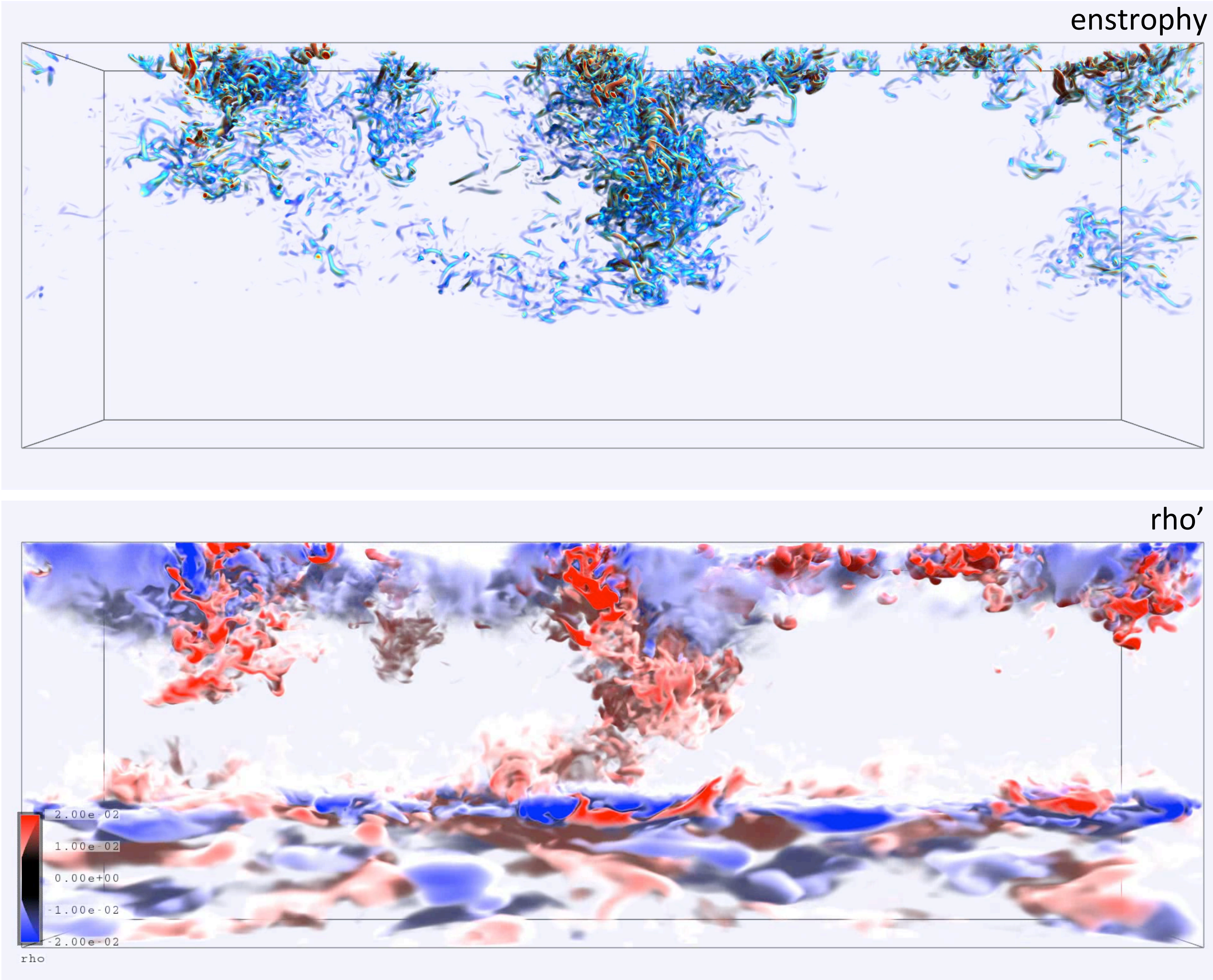




Z = 00.00 Mm
Y Mm
X Mm
10
20
30
40
50
60
70
80
90
10.0
5.0
0.0
−5.0
−10.0
Velocity
Km/sec
KANADA
Washington
Oregon
Idaho
Montana
North Dakota
South Dakota
Minnesota
Wyoming
Nebraska
Iowa
Wisconsin
Michigan
Nevada
Utah
Colorado
Kansas
Illinois
Indiana
Ohio
Kalifornien
Arizona
New Mexico
Oklahoma
Missouri
Kentucky
Arkansas
Tennessee
Texas
Louisiana
Missis-sippi
Alabama
Georgia
Florida
North Carolina
South Carolina
Virginia
West Virginia
Penn-sylvania
New York
New Hampshire
Vermont
Maine
Massachusetts
Rhode Island
Connecticut
New Jersey
Delaware
Maryland
Washington, D.C.
PAZIFISCHER OZEAN
ATLANTISCHER OZEAN
GOLF VON MEXIKO
BAHAMAS
MEXIKO
Alaska
Hawaii

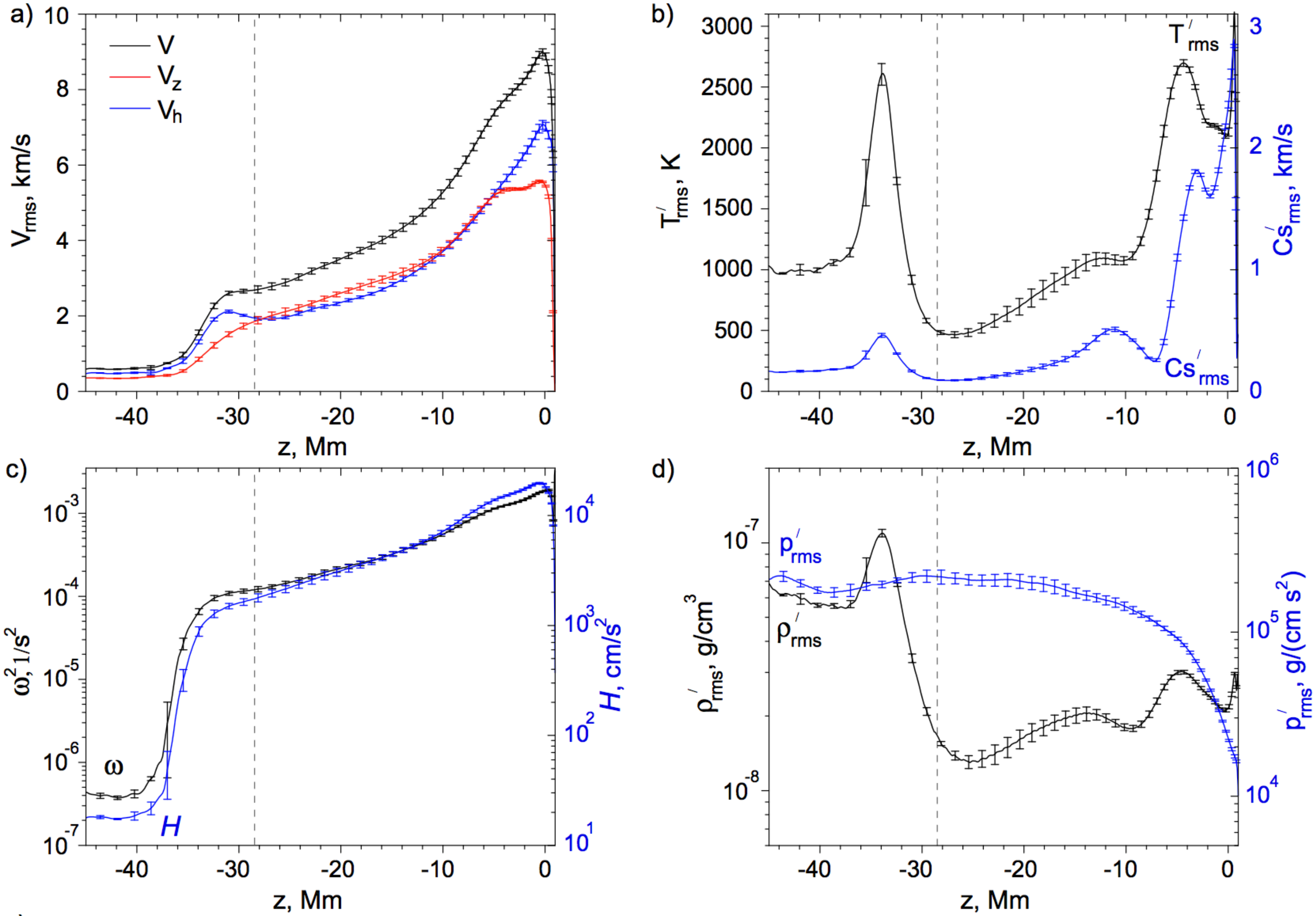


M=1.47M$_{sun}$
Convection zone
Radiative zone
32000 miles
enstrophy
64000 miles

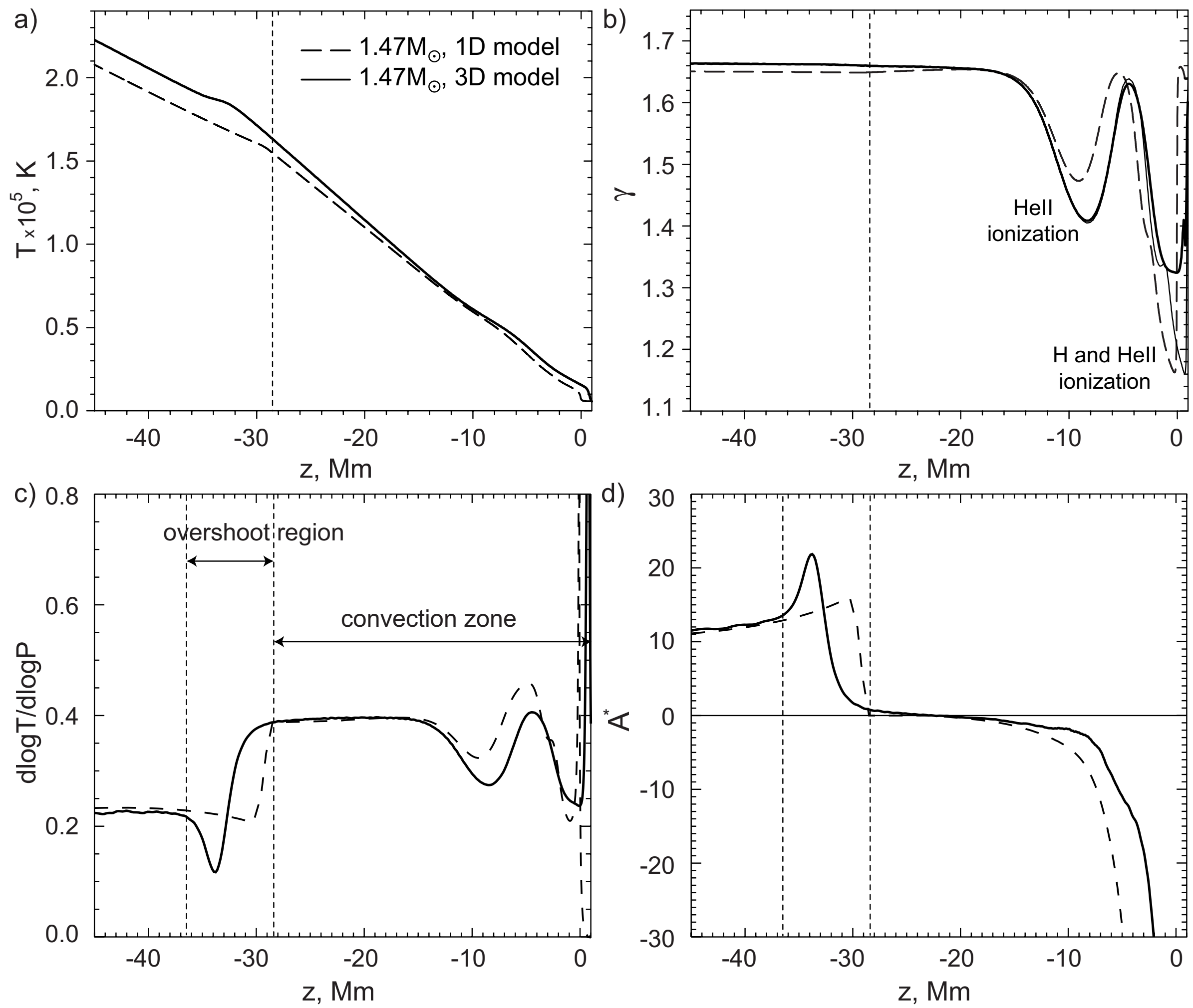


enstrophy
rho’
2.00e-02
1.00e-02
0.00e+00
-1.00e-02
-2.00e-02
rho

M=1.47M_{sun}

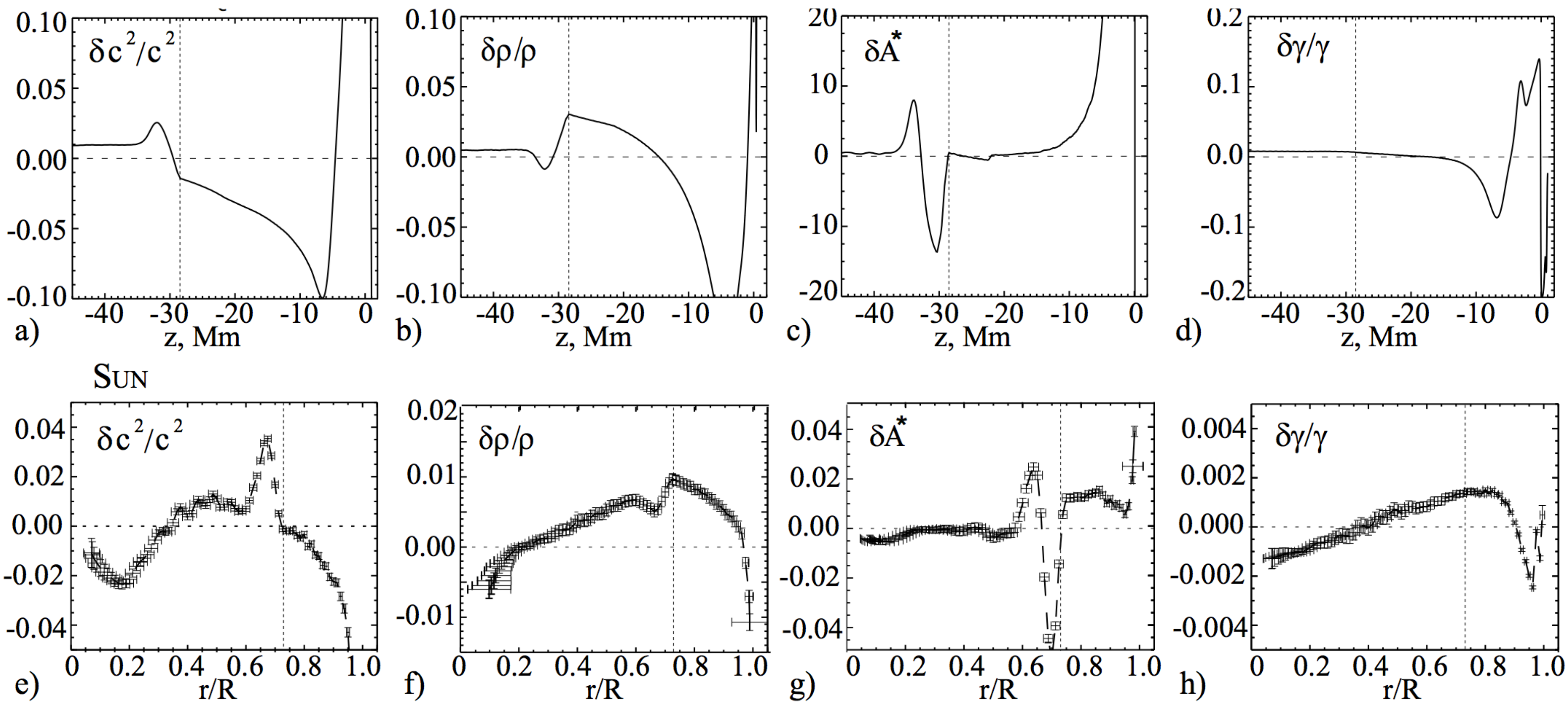


Vertical profiles, obtained from the 3D numerical simulation of a 1.47 M_{sun} F-type star: a) *rms* of velocity V (black), vertical Vz (red) and horizontal Vh (blue) components of velocity; b) *rms* of temperature $T^{/}$ (black) and sound speed $c_s^{/}$ (blue) perturbations; c) enstrophy ω (black) and helicity *H* (blue); d) *rms* of density $\rho\eta o^{/}$ (black) and gas pressure $p^{/}$ (blue) perturbations.
Vertical dashed lines indicate the bottom boundary of the convection zone of the corresponding 1D stellar model: z_{cz}=-28.5 Mm.



Comparison of the 1D interior structure of a moderate mass star ($M=1.47M_{sun}$) calculated from mixing-length theory and from the 3D simulation: a) the temperature, T; b) the adiabatic exponent, γαμμα; c) the temperature gradient, $\nabla = \frac{d\log T}{d\log P}$; d) the Ledoux parameter of convective stability $A^* = \frac{1}{\gamma}\frac{d\log P}{d\log r} - \frac{d\log \rho}{d\log r}$

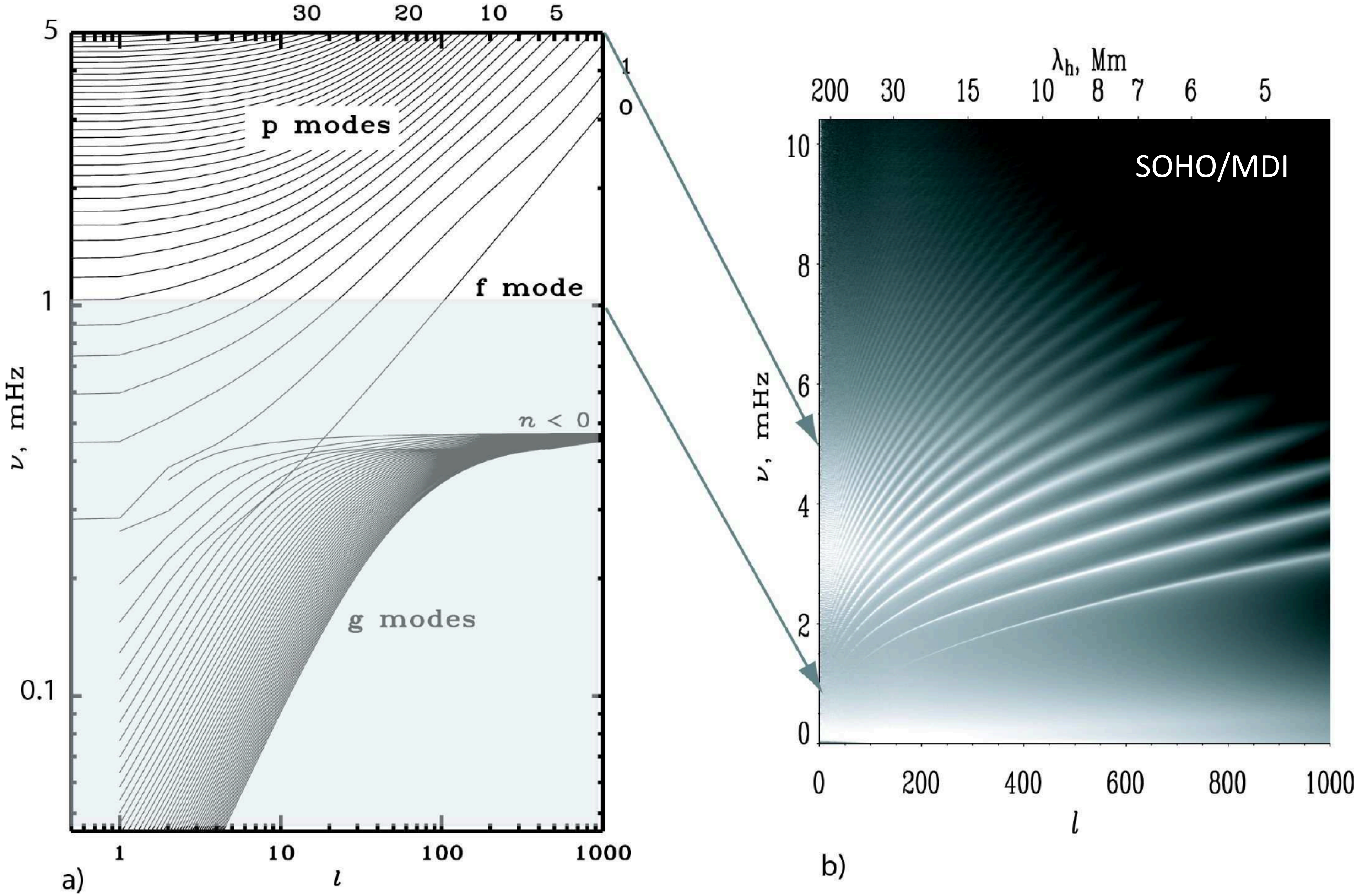
$1.47M_{sun}$



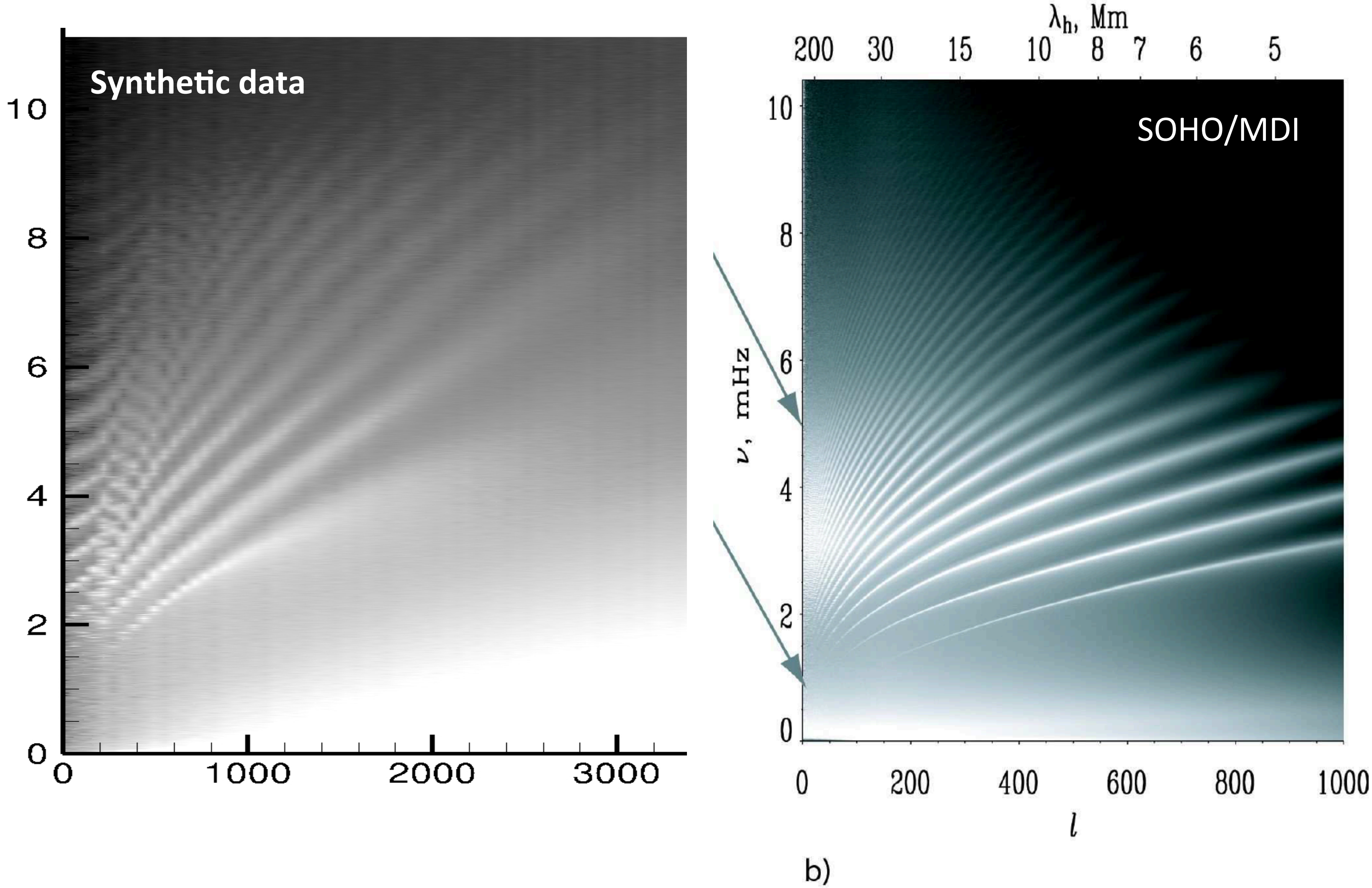
The deviations between the 3D simulation and 1D model of a star with mass M=1.47 M_{sun} as a function of depth, z=r-R, for: a) the squared sound speed, $\delta c^2/c^2$; b) density, $\delta\rho/\rho$; c) the Ledoux parameter of convective stability, A*; and d) the adiabatic exponent, γ. Panels e-h) 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.

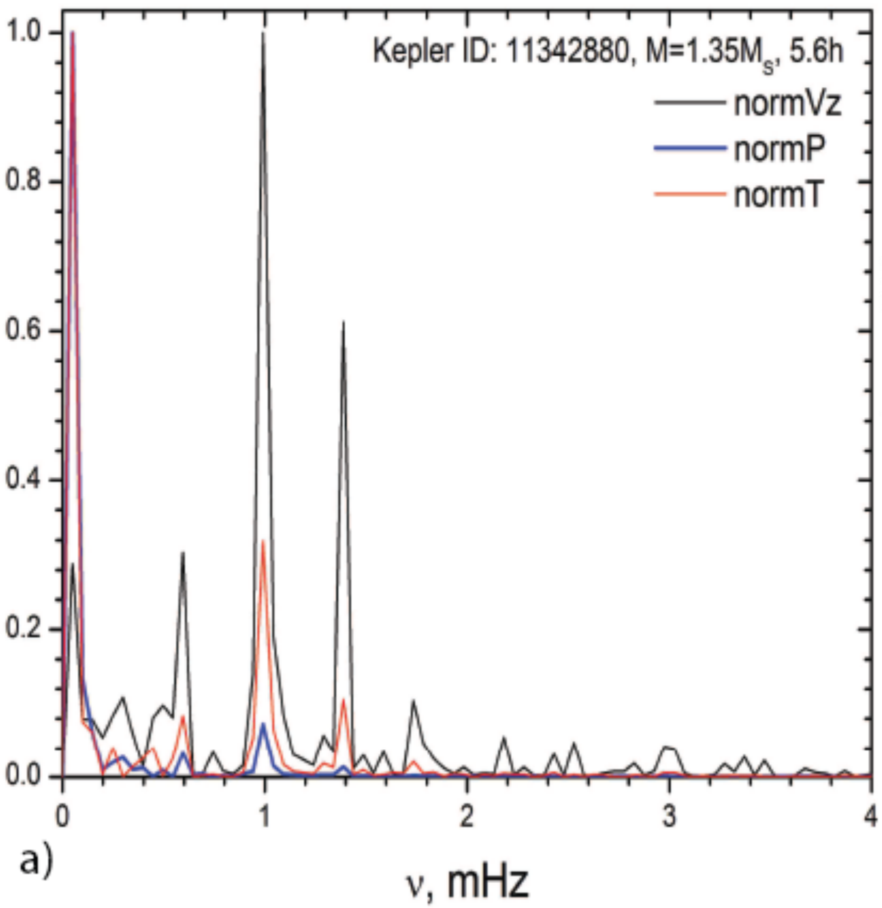
Kitiashvili et al., 2016

Oscillations: Sun

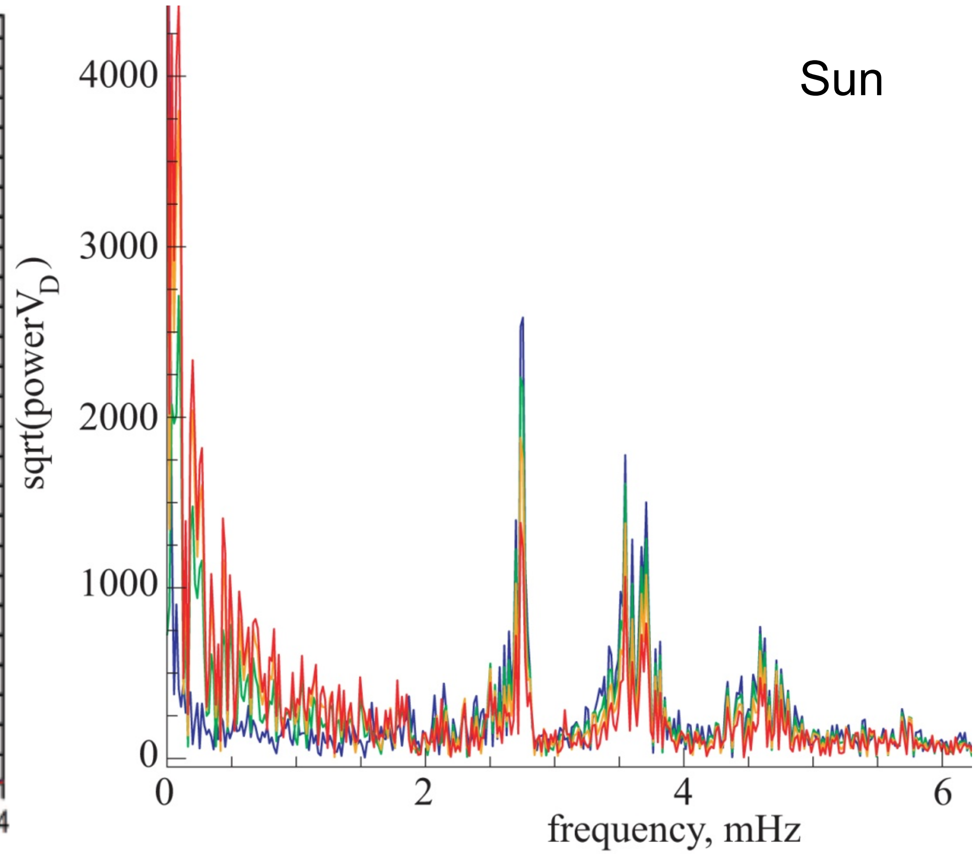


Oscillations: Sun

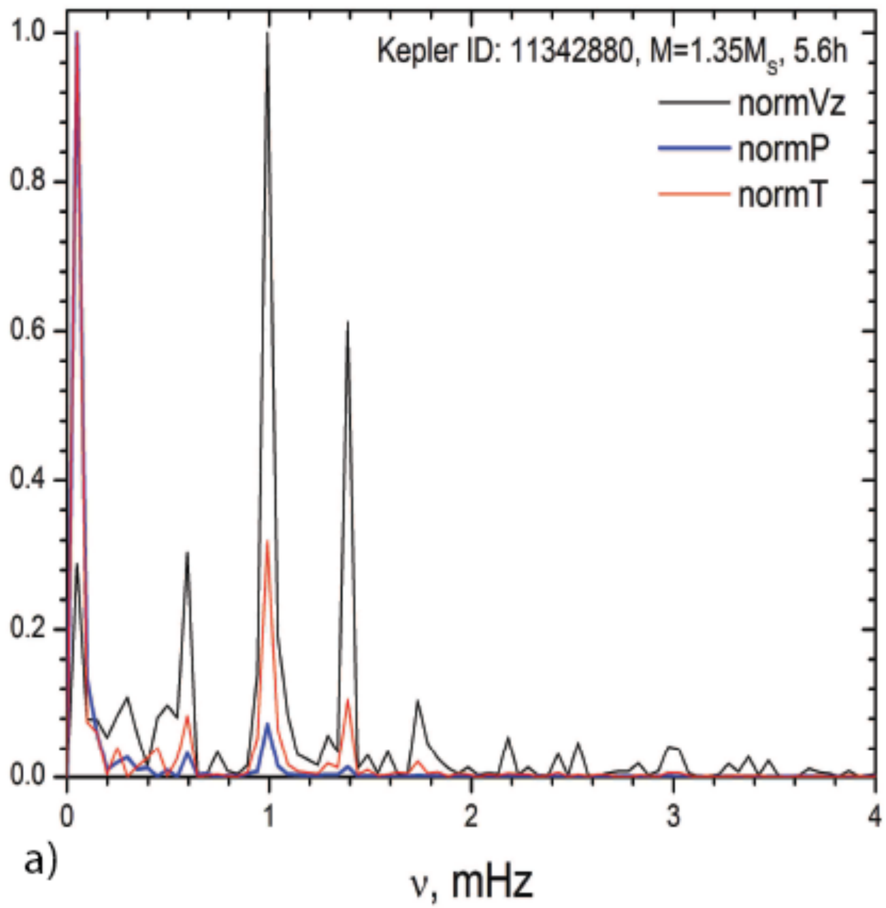


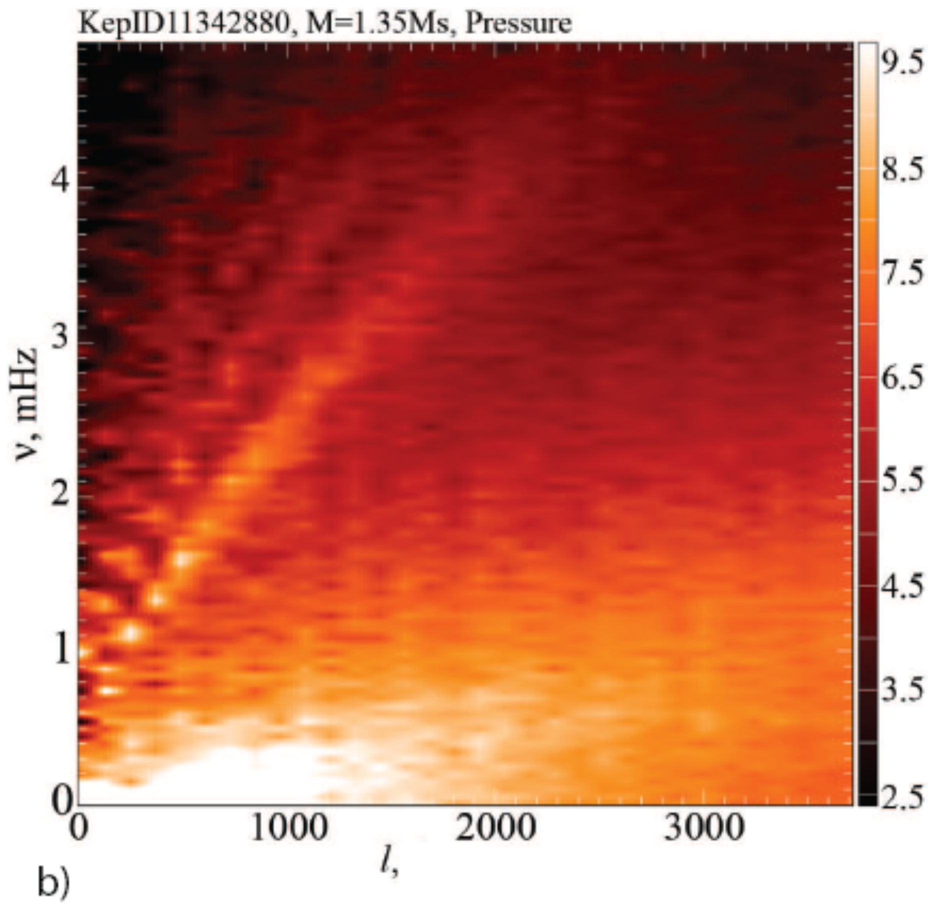


Power spectrum of low-degree (radial) stellar oscillations for vertical velocity Vz, pressure P, and temperature T



Power spectrum of low-degree (radial) solar oscillations for Doppler shift on different angular distances from the disc center (blue) to 60 deg (red).

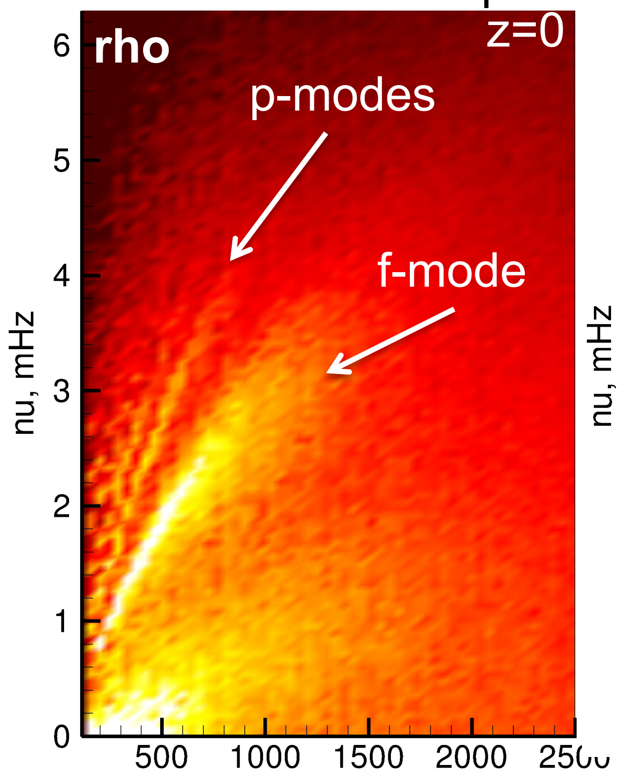


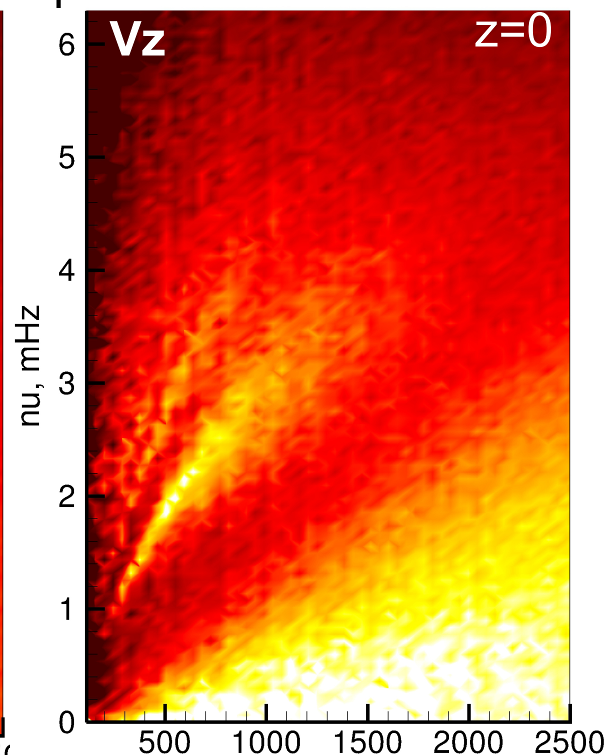


Power spectrum of low-degree (radial) stellar oscillations for vertical velocity Vz, pressure P, and temperature T

Angular degree (*l*) - frequency (ν) diagram, obtained from the 3D numerical StellarBox simulations for a model of 1.35 Ms Kepler target star.

photosphere

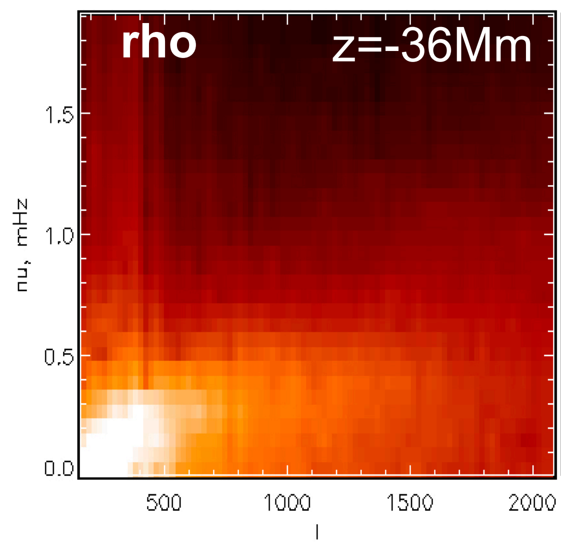


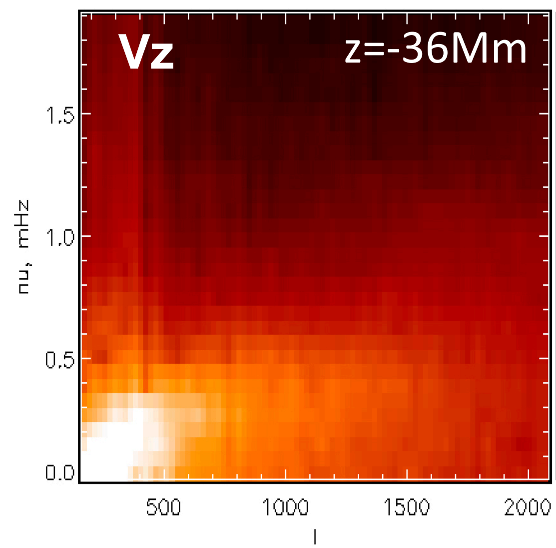


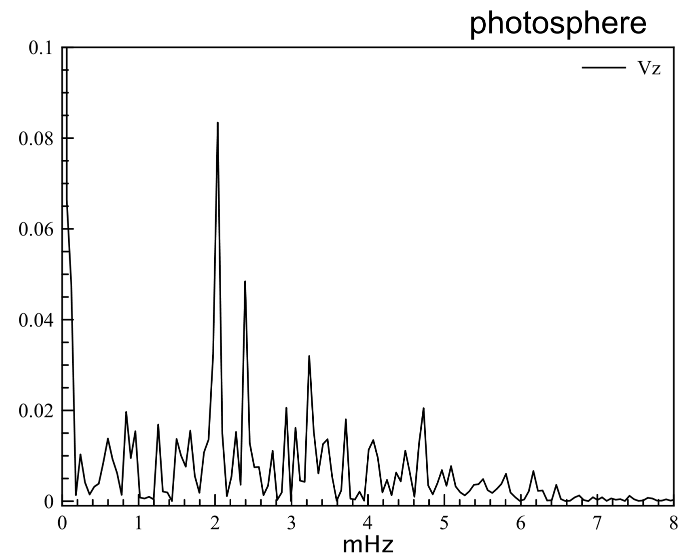
M=1.47M_{sun}

Angular degree (l) - frequency ($\nu\upsilon$) diagram, obtained from the 3D numerical StellarBox simulations for a model of 1.47 Ms Kepler target star.

In radiative zone







Conclusions

- Our investigation of main-sequence stars has shown that the dynamics of stellar convection dramatically changes as the stellar mass increases.
- For stars with M > 1.35Ms the convection zone is relatively shallow, and the simulation domain covers its whole depth range and a convectively stable layer of the radiative zone. This allowed us to investigate the physics of overshooting, turbulent mixing and excitation of internal gravity waves at the bottom of the convection zone.
- Realistic 3D radiative simulations of moderate-type stars have revealed a self-organized clustering process in which ‘small’ and ‘large’ granules cluster.
- Comparison of the mean structure profiles from 3D simulations with the corresponding 1D standard stellar model shows an increase of the stellar radius by ~800km, as well as significant changes in the thermodynamic structure and turbulent properties of the ionization zones.
- Convective downdrafts in the intergranular lanes between granulation clusters reach speeds of more than 20km/s, penetrate through the whole convection zone, hit the radiative zone, and form a 8Mm thick overshoot layer.
- It is demonstrated that the deviations of the mean structure of the 3D model from the 1D standard model of the same mass and composition are qualitatively similar to the deviations for the Sun found by helioseismology from SOHO mission data.

Future plans

Investigate:

- effects of various LES turbulence models (Smagorinski model, dynamic model, hyperviscosity) on the energy transport and dynamics of stellar convection simulations;
- effects of rotation: generation of subsurface shear and meridional flow;
- magnetic field generation by local dynamo on solar-type stars;
- effects of surface convection on the RV method of detection of Earth-type planets;
- radiative MHD models of the Proxima Centauri star and HD185351.