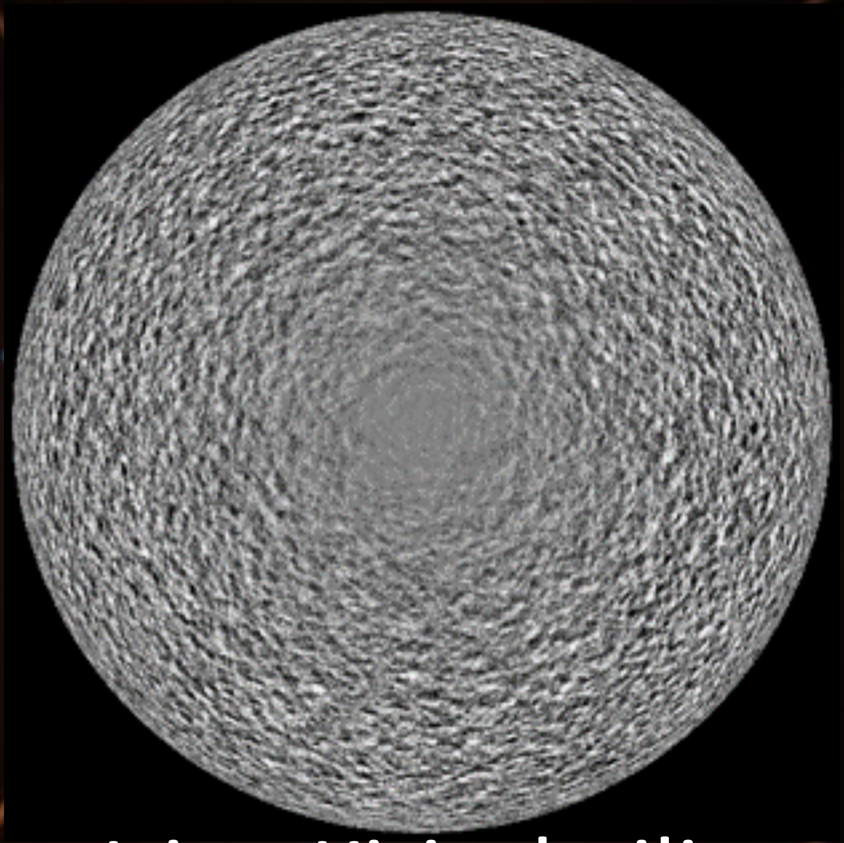
Concepts of Solar and Stellar Convection and Dynamos



Irina Kitiashvili

NASA Ames Research Center

Concepts of Solar and Stellar Convection and Dynamos

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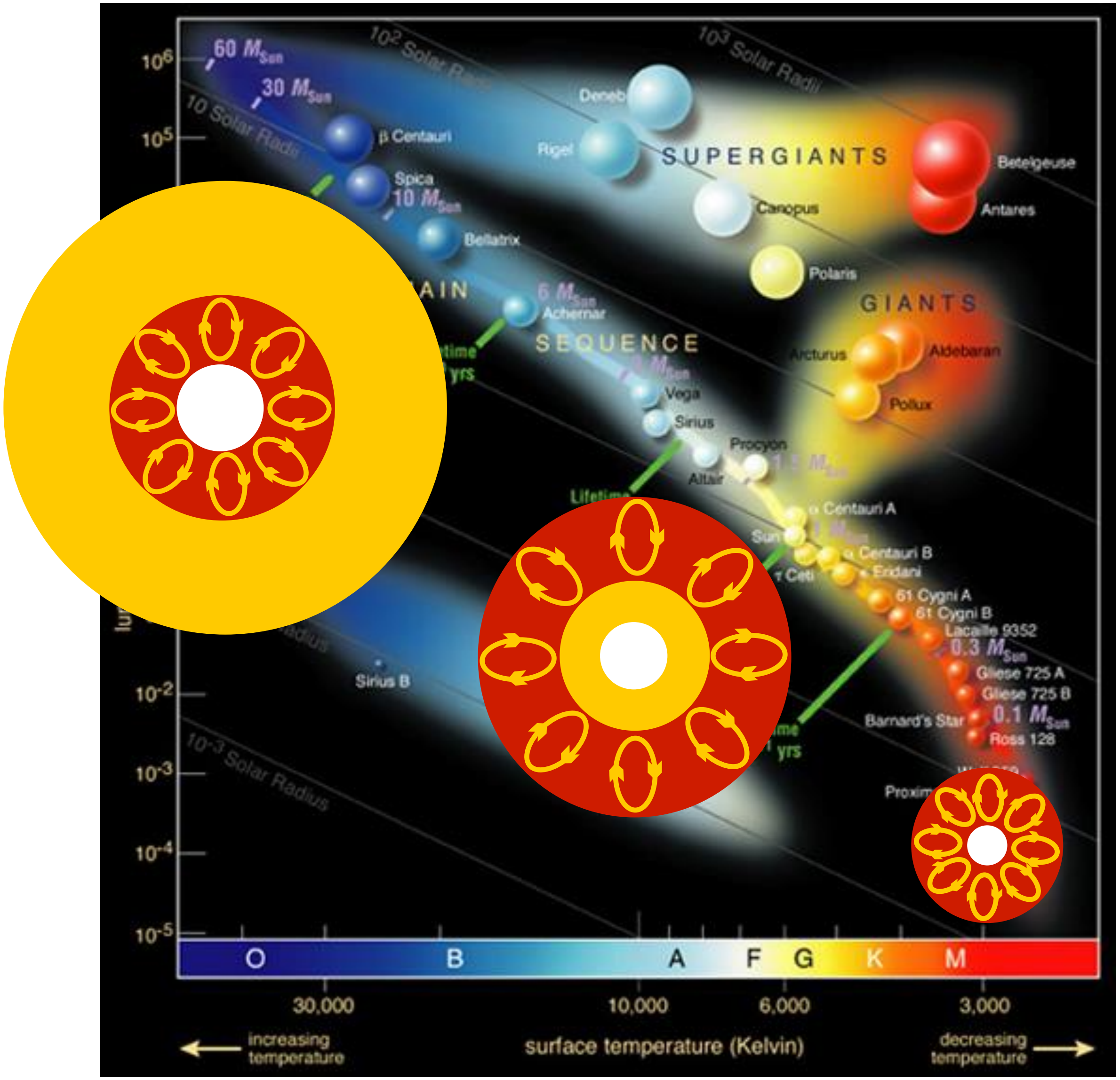
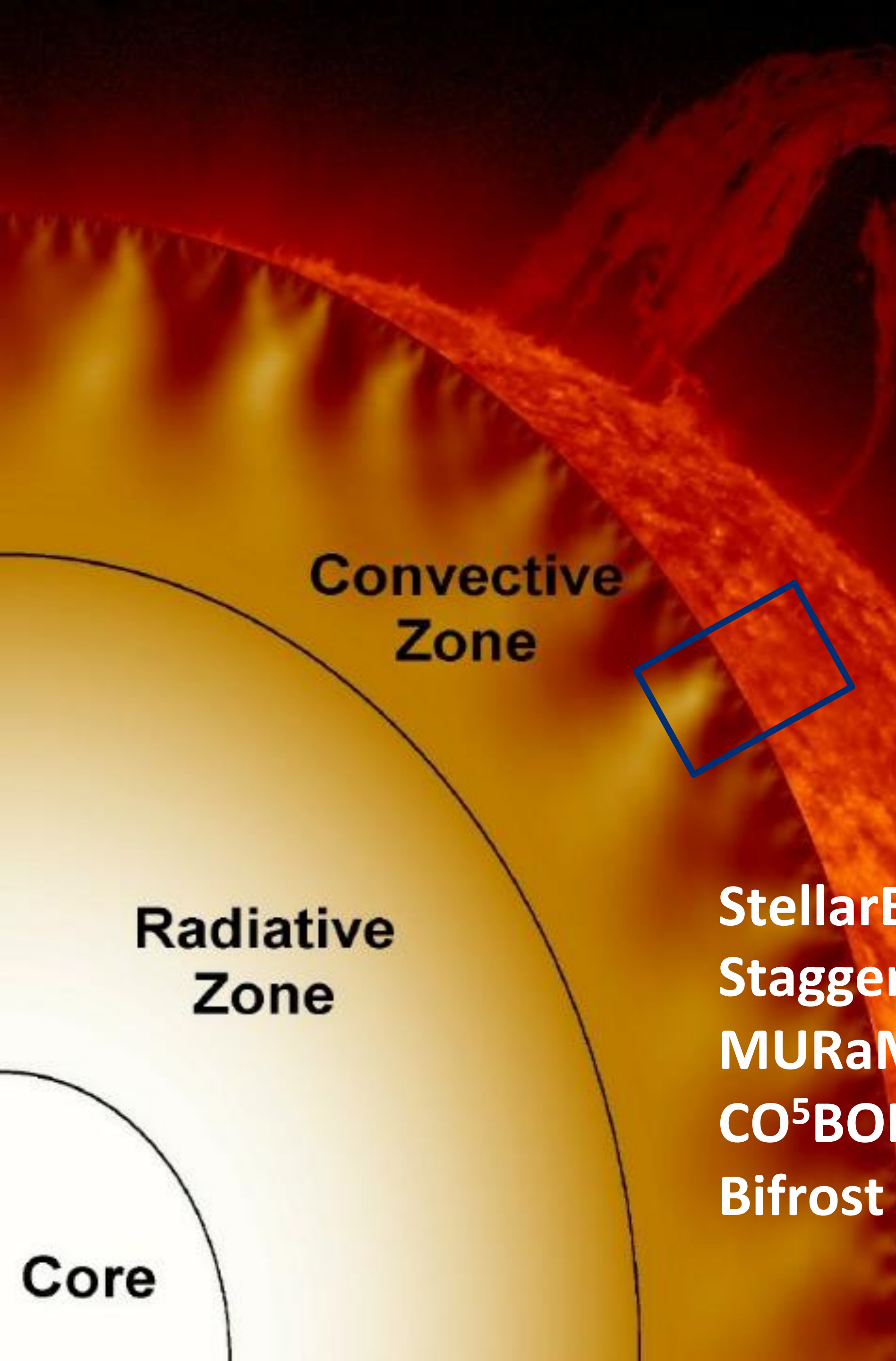
Hertzsprung–Russell diagram



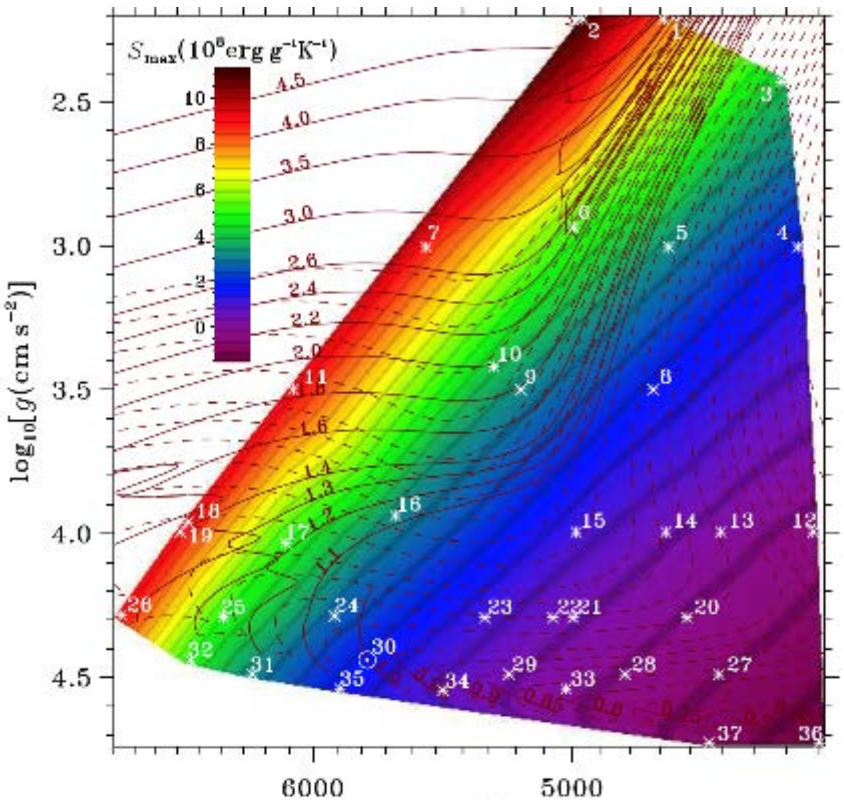
Credit: ESO



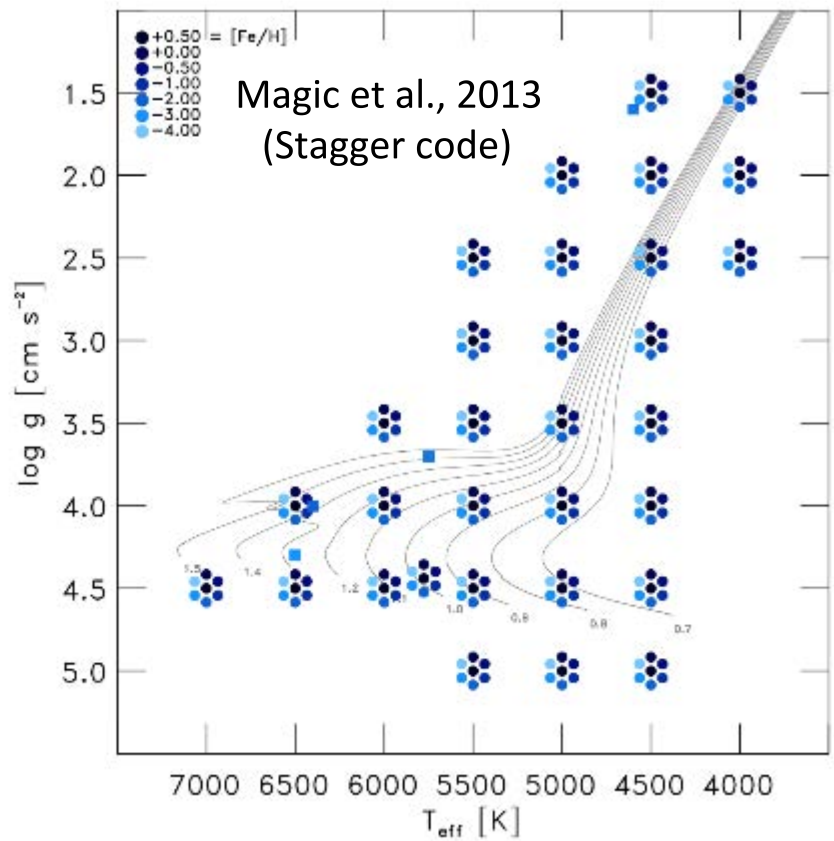
- Compressible fluid flow in a highly stratified medium
- 3D multi-group radiative energy transfer between the fluid elements
- Real-gas equation of state
- Ionization and excitation of all abundant species
- Small-scale turbulence
- Magnetic effects

StellarBox code (Wray et al, 2015, 2018)
Stagger code (Galsgaard & Nordlund, 1996)
MURaM code (Vogler, 2003)
CO^{5}BOLD code (Freytag et al., 2002)
Bifrost code (Gudiksen et al. 2011)

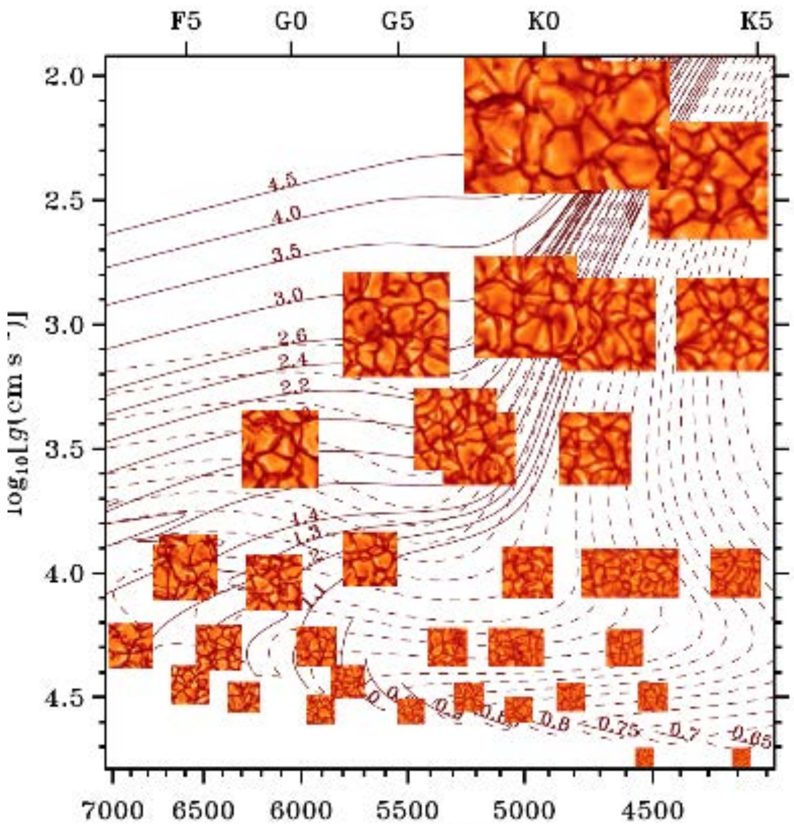
3D stellar convection as a grid of stellar parameters



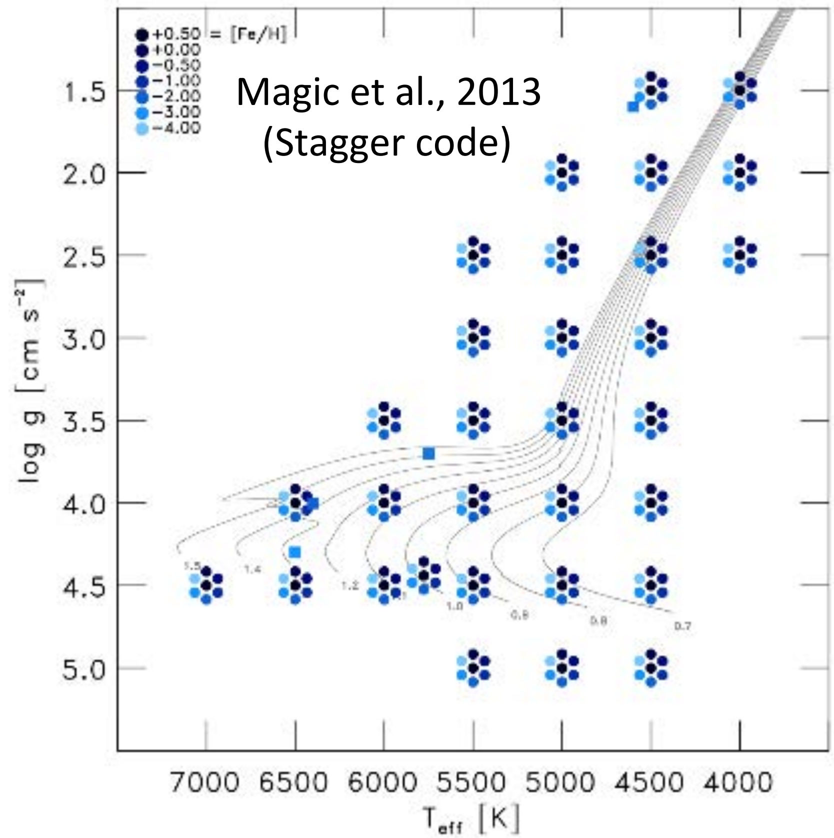
Trampedach et al., 2013, 2014



3D stellar convection as a grid of stellar parameters



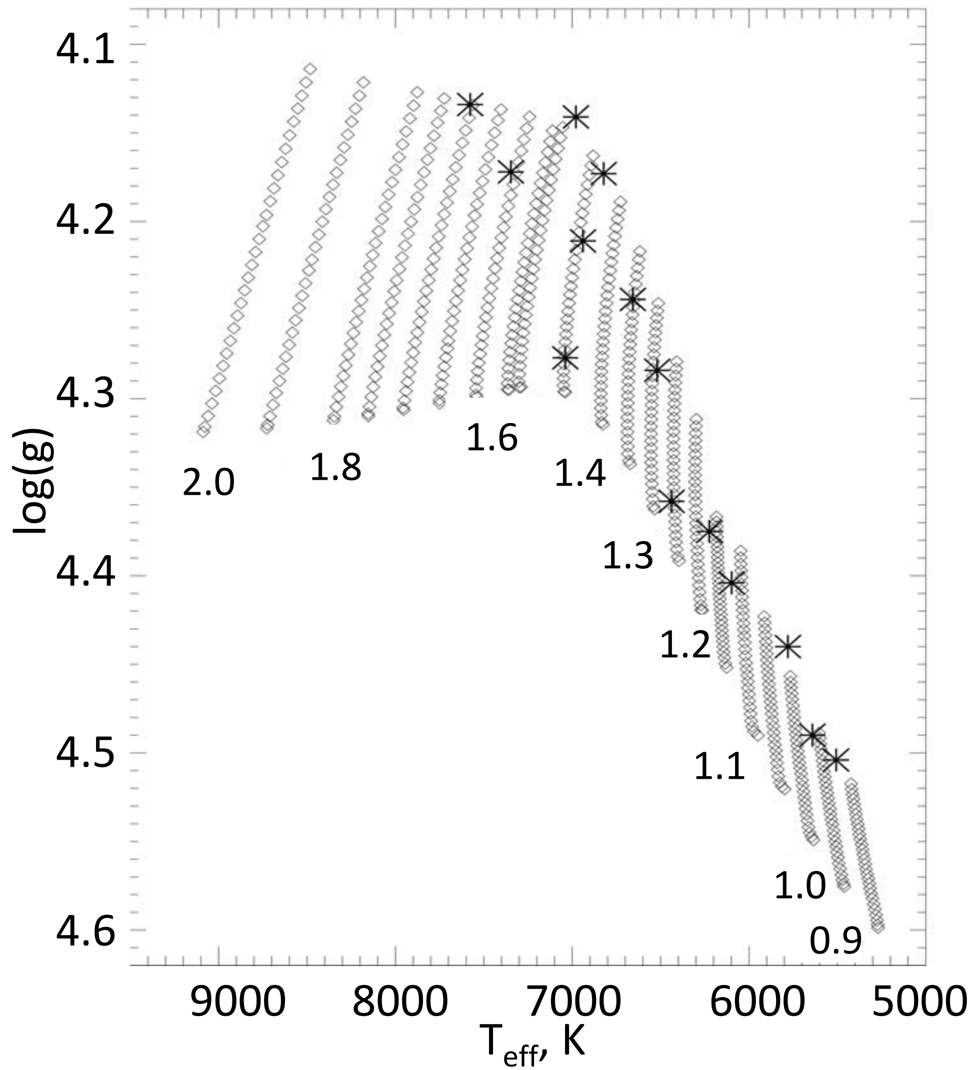
Trampedach et al., 2013, 2014



Stellar Models

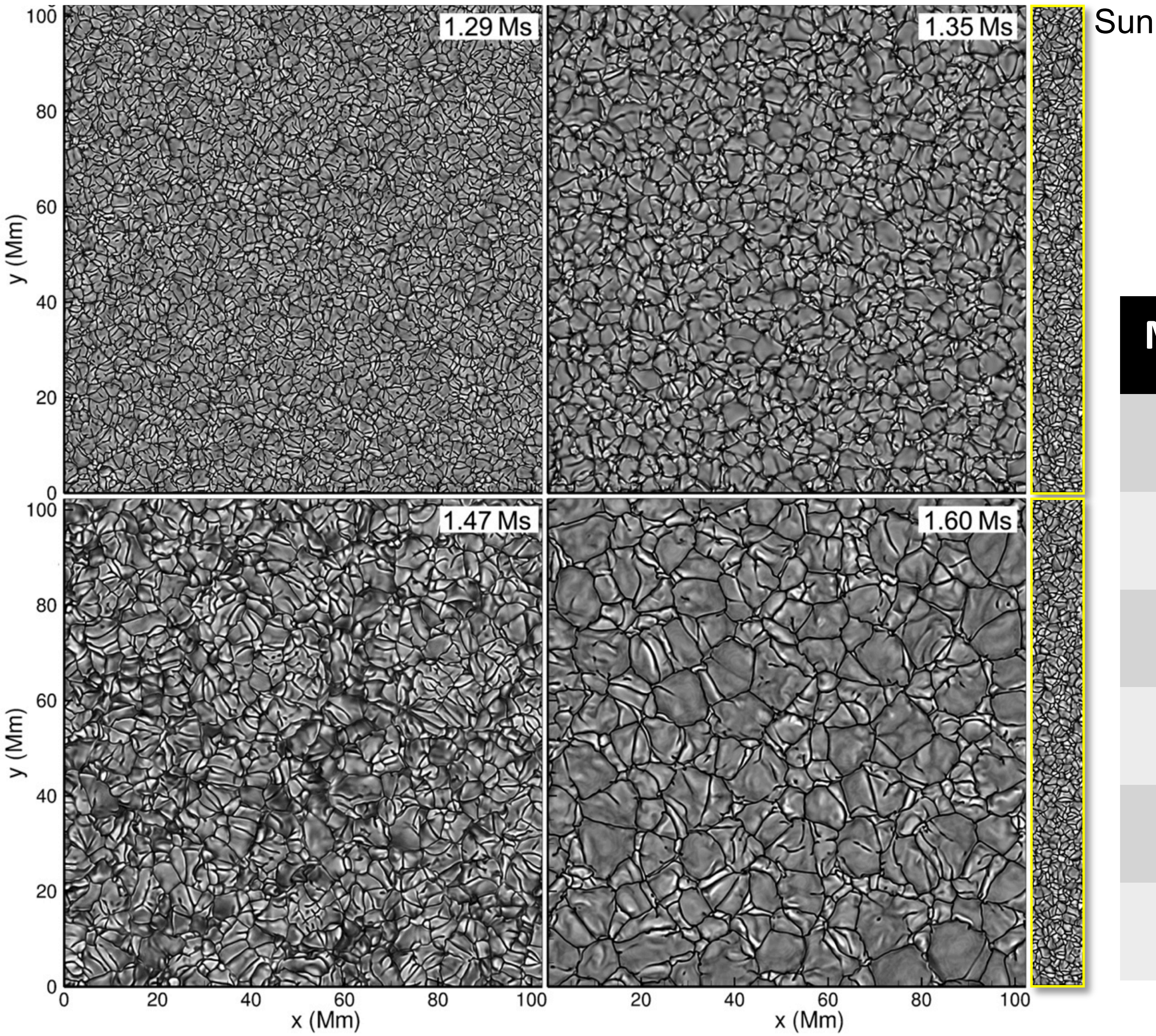
Kepler Targets

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 stellar surface convection



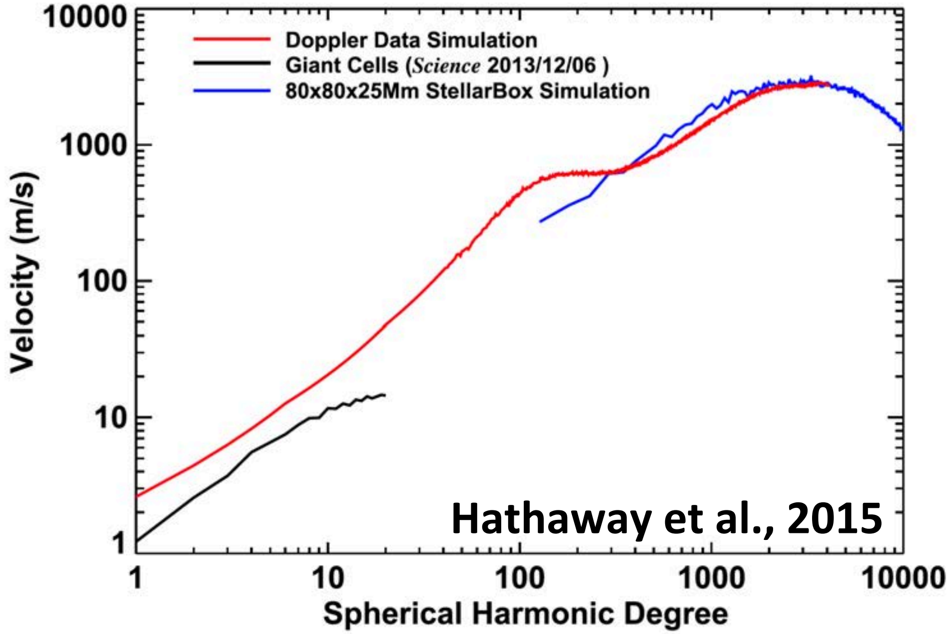
Pressure scale-height at the photosphere

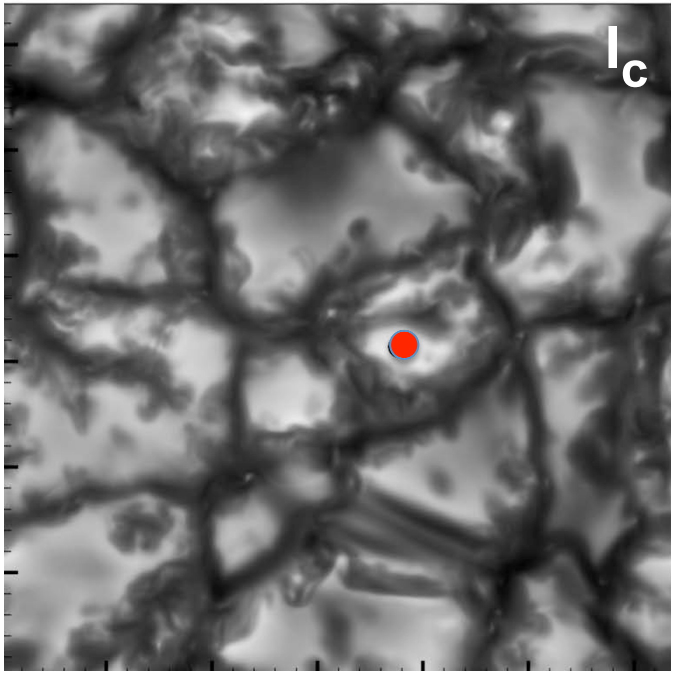
M, M_{Sun}	H_p, km
1.00	140
1.17	173
1.29	236
1.35	267
1.47	270
1.60	359

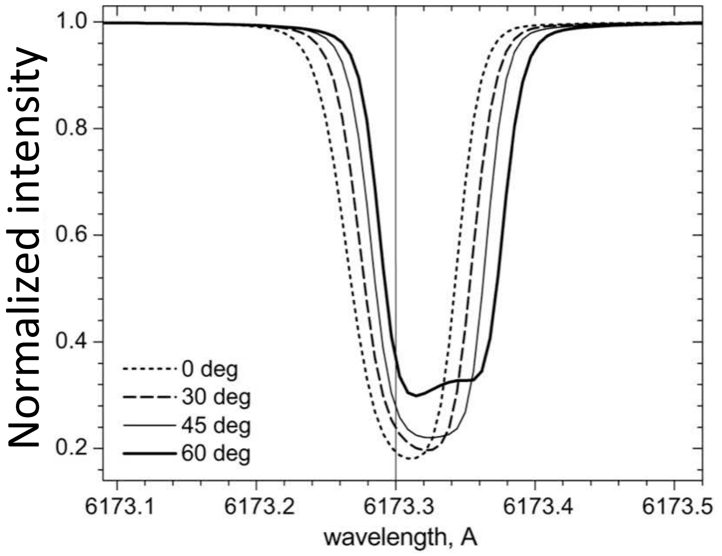
Distribution of vertical velocity, revealing changes in granulation structure and formation of multi-scale convective cells with increasing mass

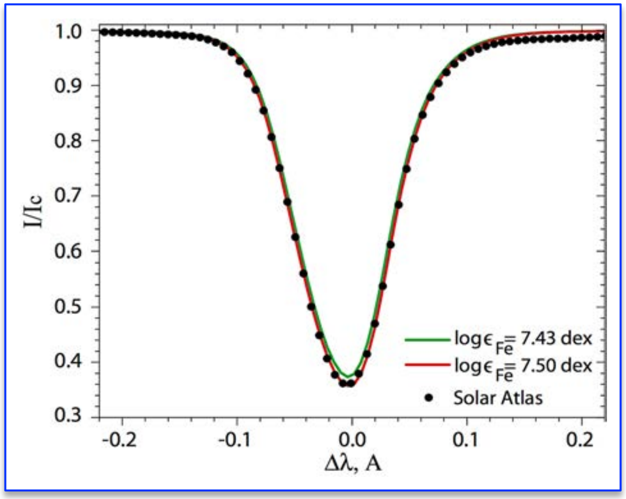
StellarBox code

Observations vs. models

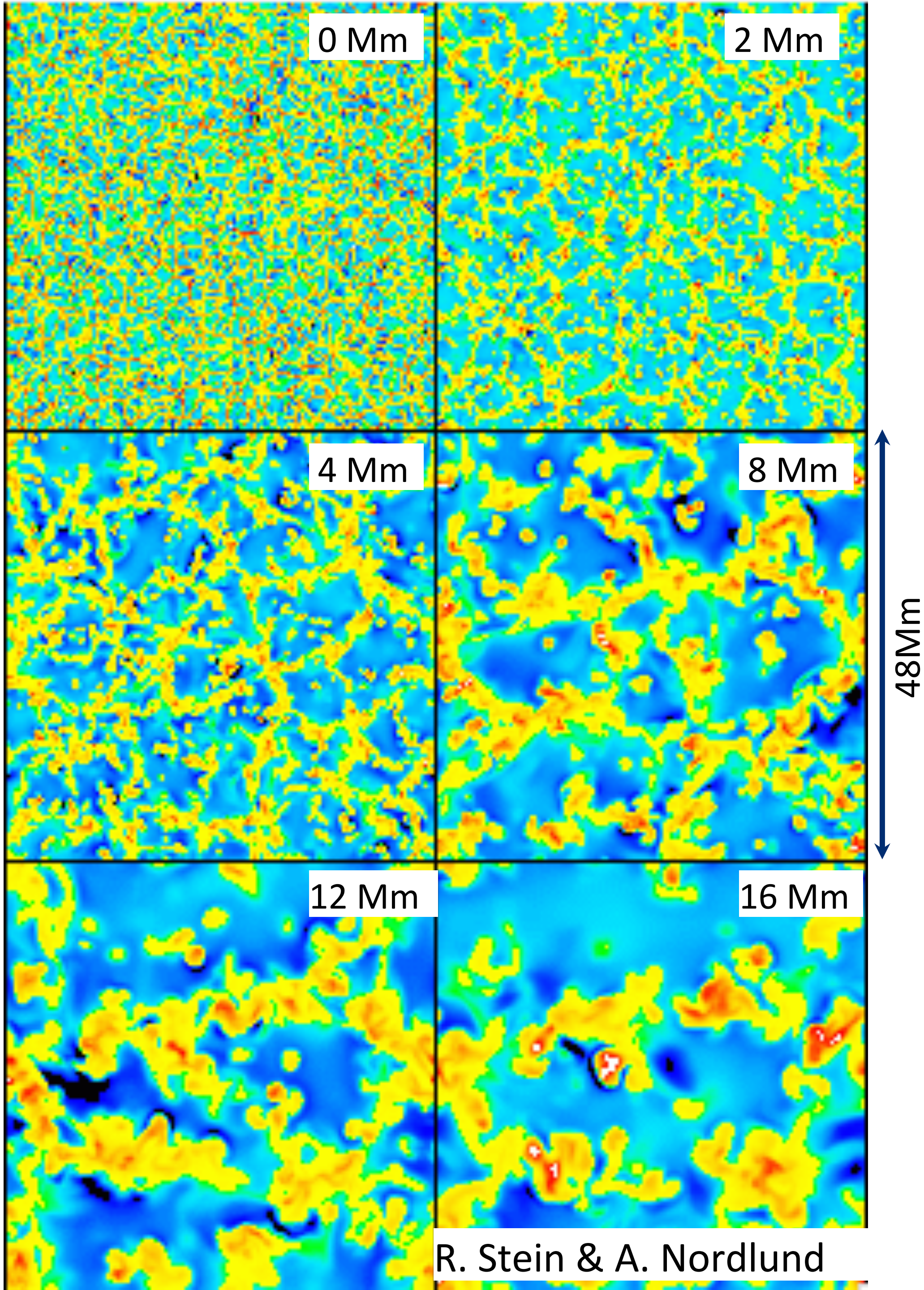








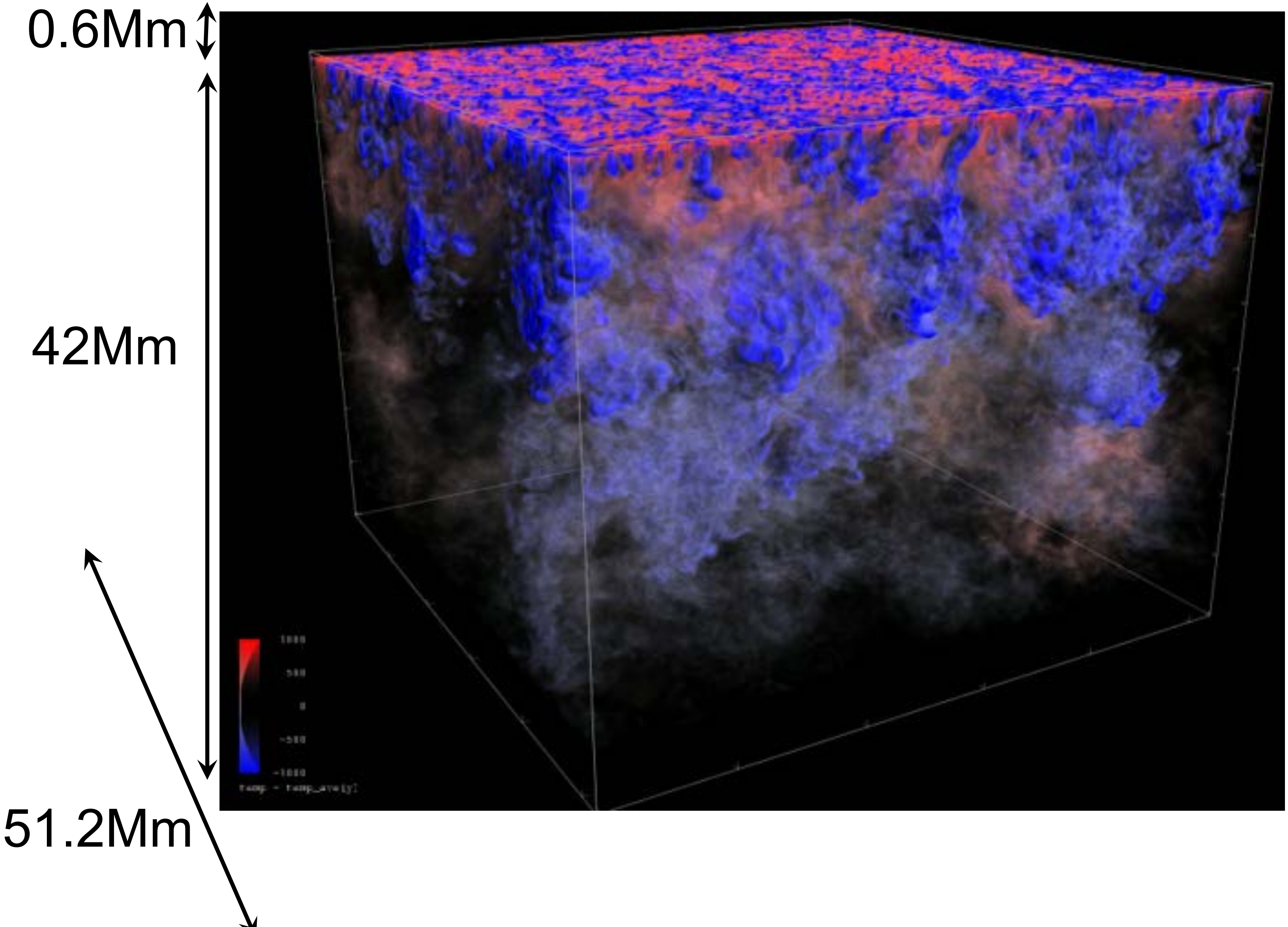
Kitiashvili et al., 2015

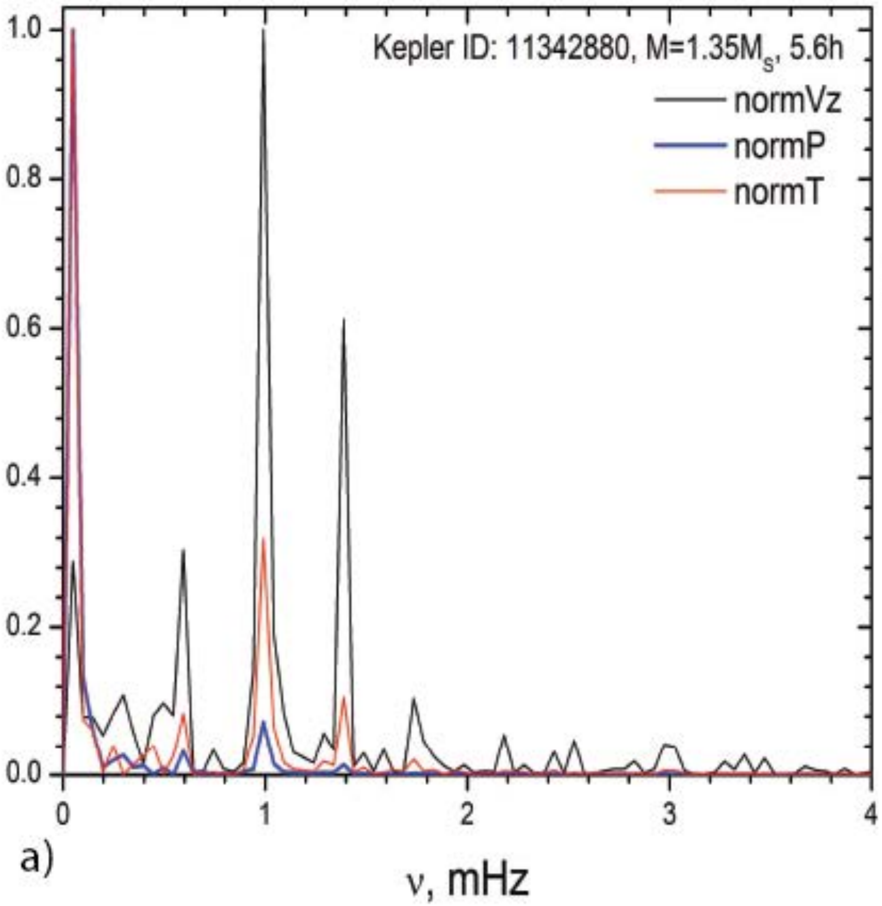


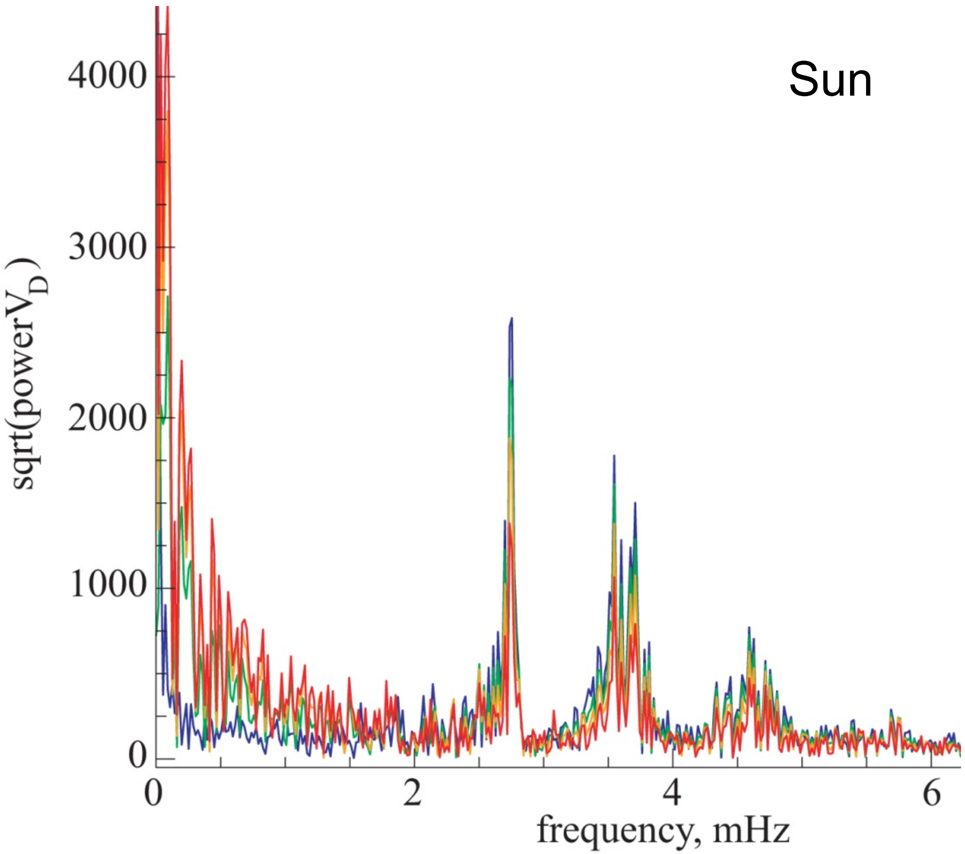
Vertical velocity at the visible surface and at 2, 4, 8, 12, and 16 Mm below the surface.

Green and blue are upflows; yellow and red are downflows.

Subsurface Stellar Dynamics: 1.35M_{Sun}







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

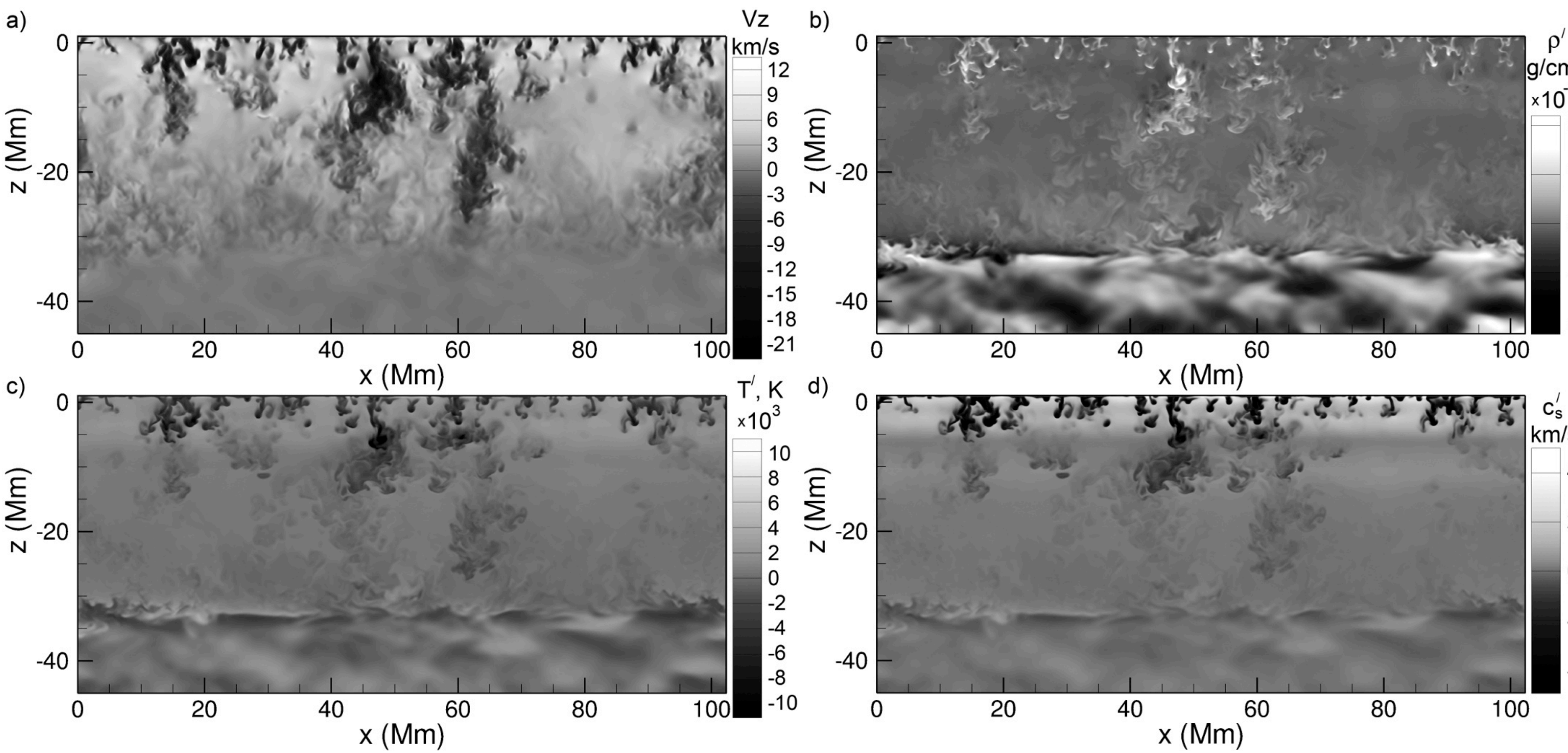
Power spectrum of low-degree (radial) solar oscillations for Doppler shift at different angular distances from the disc center (blue) to 60 deg (red).

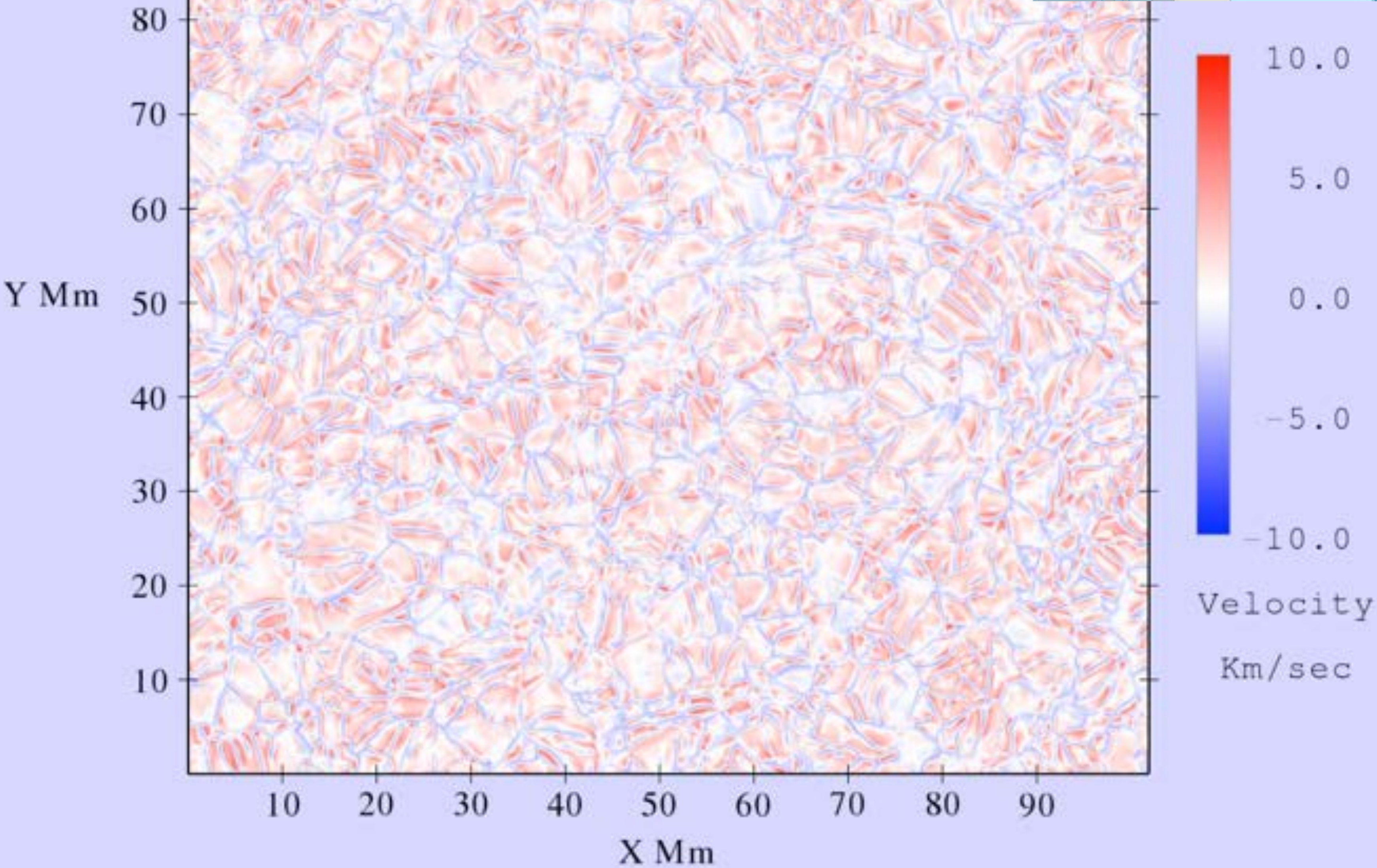
KIC9962653, M=1.47M_{SUN}

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.

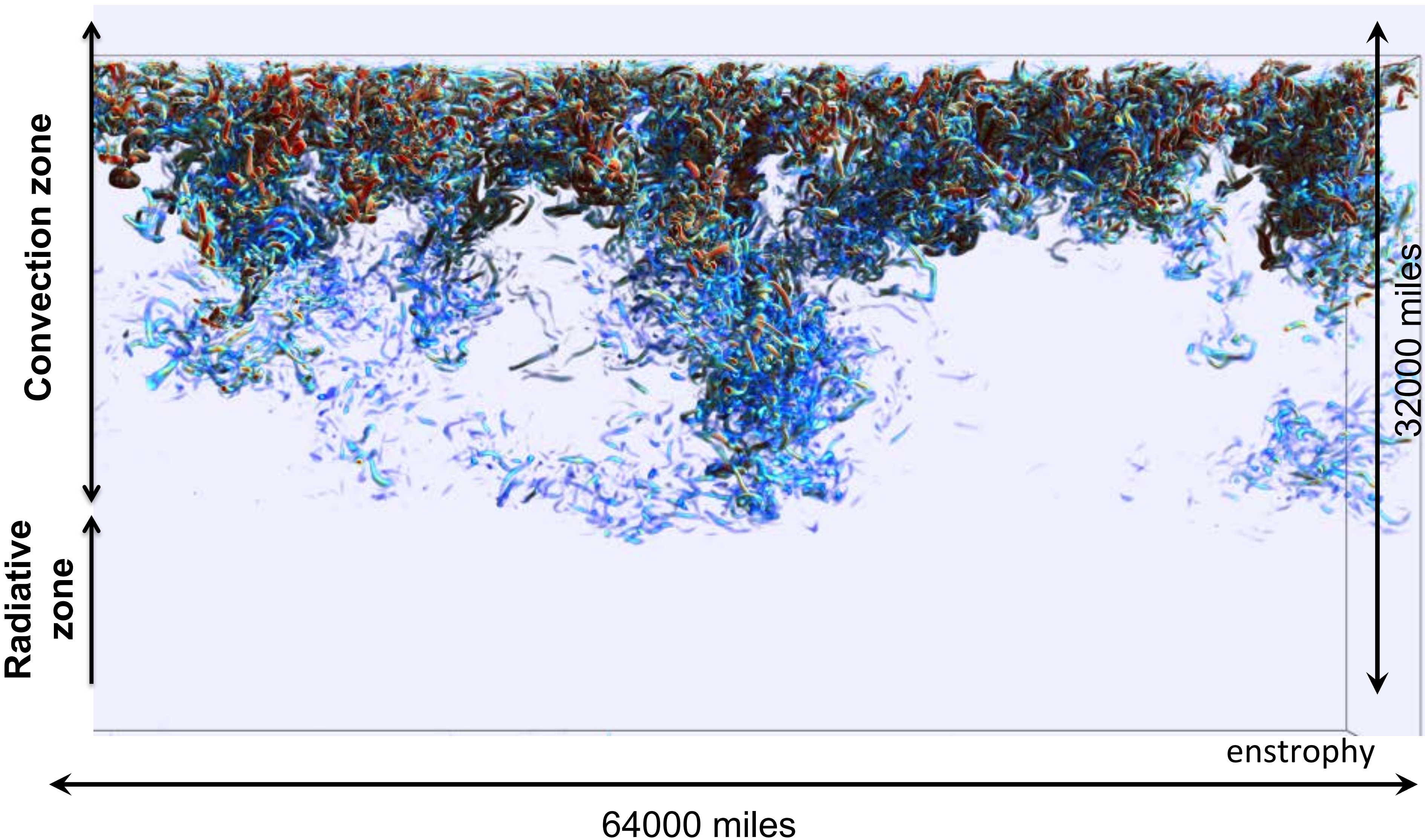



Z = 00.00 Mm
Y Mm
X Mm
10
20
30
40
50
60
70
80
90
10.0
5.0
0.0
-5.0
-10.0
Velocity
Km/sec

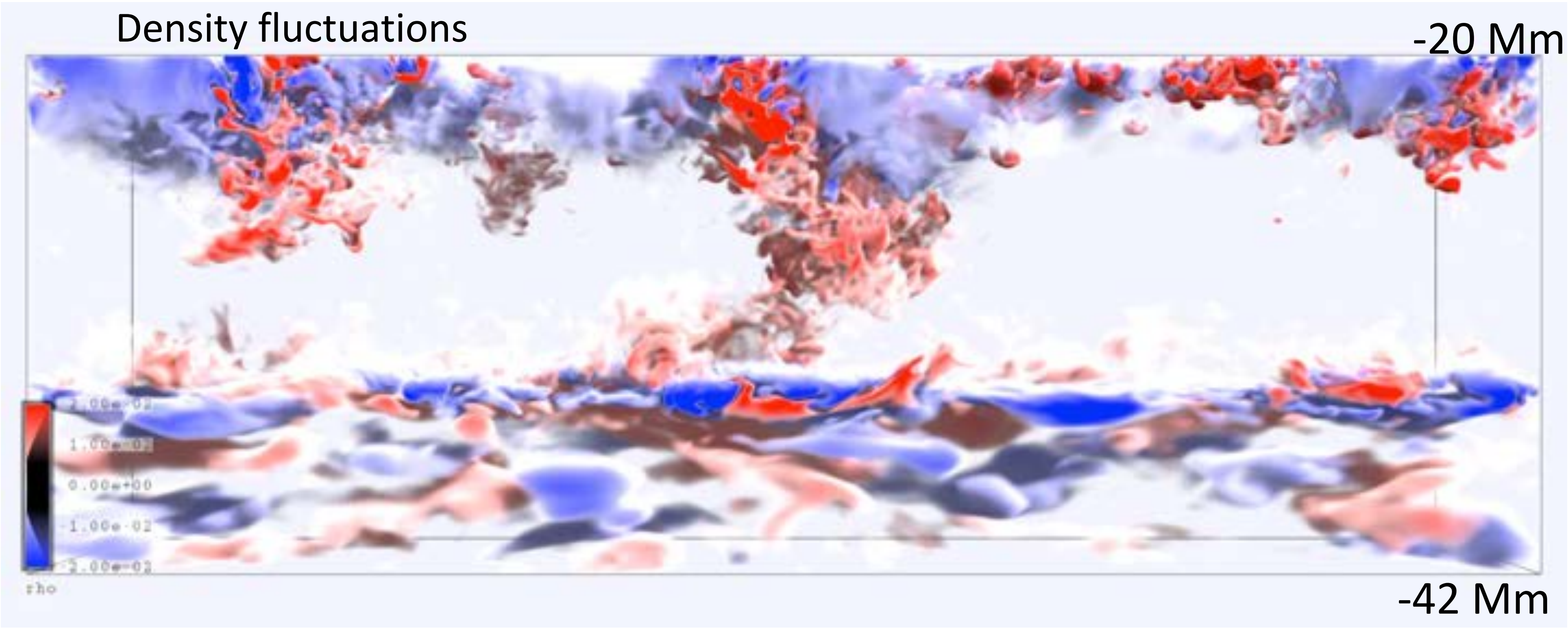

KANADA
Washington
Montana
North Dakota
Minnesota
Oregon
Idaho
South Dakota
Wyoming
Wisconsin
Michigan
New York
Nevada
Utah
Colorado
Nebraska
Iowa
Illinois
Ohio
Kalifornien
Kansas
Missouri
Kentucky
Virginia
Arizona
New Mexico
Oklahoma
Arkansas
Tennessee
North Carolina
South Carolina
Texas
Georgia
Alabama
Louisiana
Florida
Alaska
Hawaii
MEXIKO
New Hampshire
Vermont
Maine
Massachusetts
Rhode Island
Connecticut
New Jersey
Delaware
Maryland
Washington, D.C.
ATLANTISCHER OZEAN
PAZIFISCHER OZEAN
BAHAMAS

Convection zone dynamics

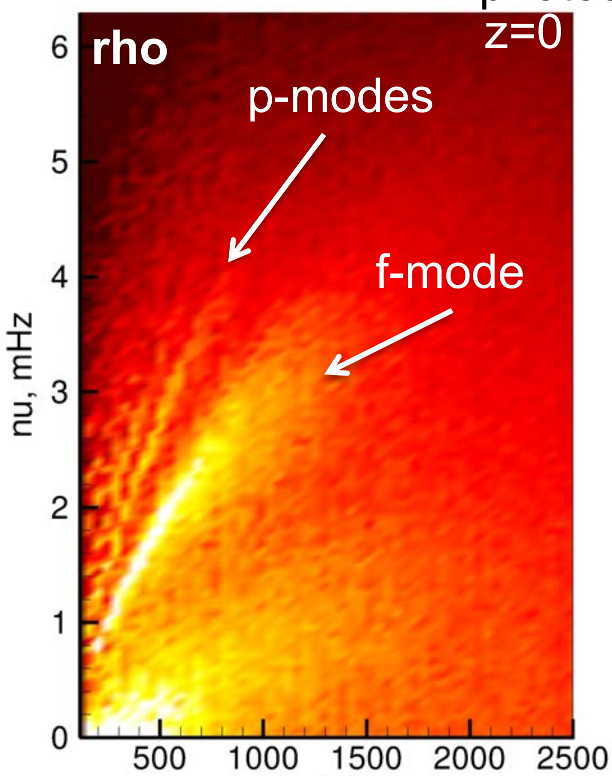
M=1.47M_{sun}

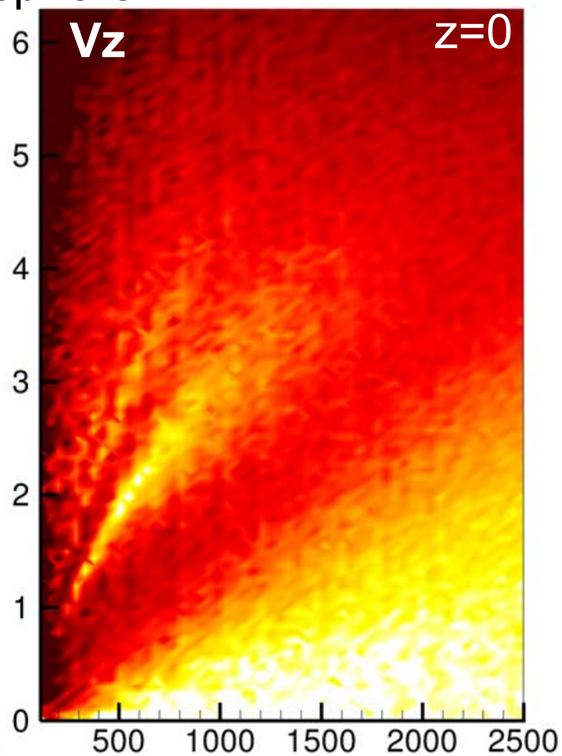


Overshoot layer



photosphere

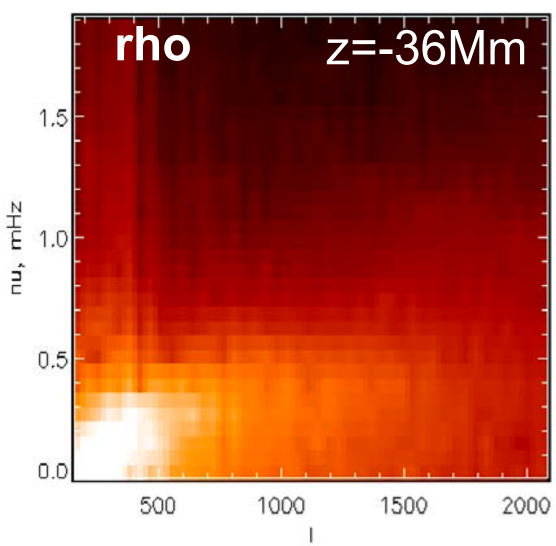


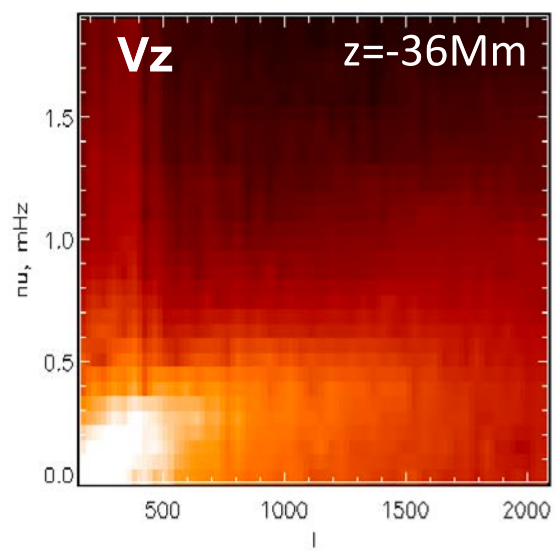


$M=1.47M_{sun}$

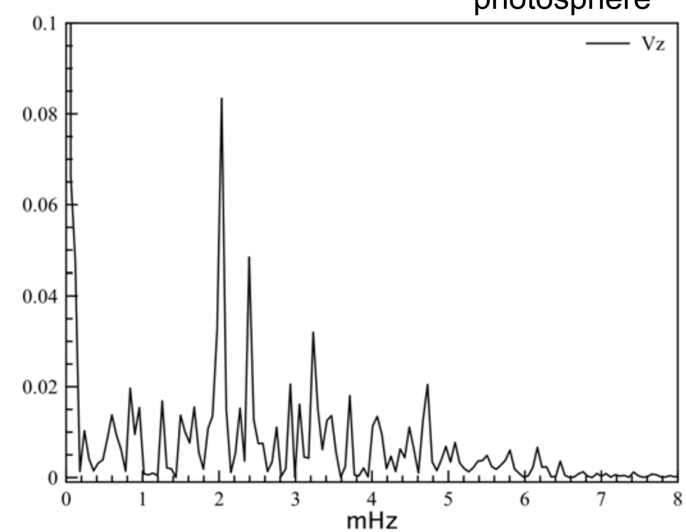
Angular degree (*l*) - frequency (n) diagram, obtained from numerical StellarBox simulations for a 1.47 M_{Sun} Kepler target star.

In radiative zone

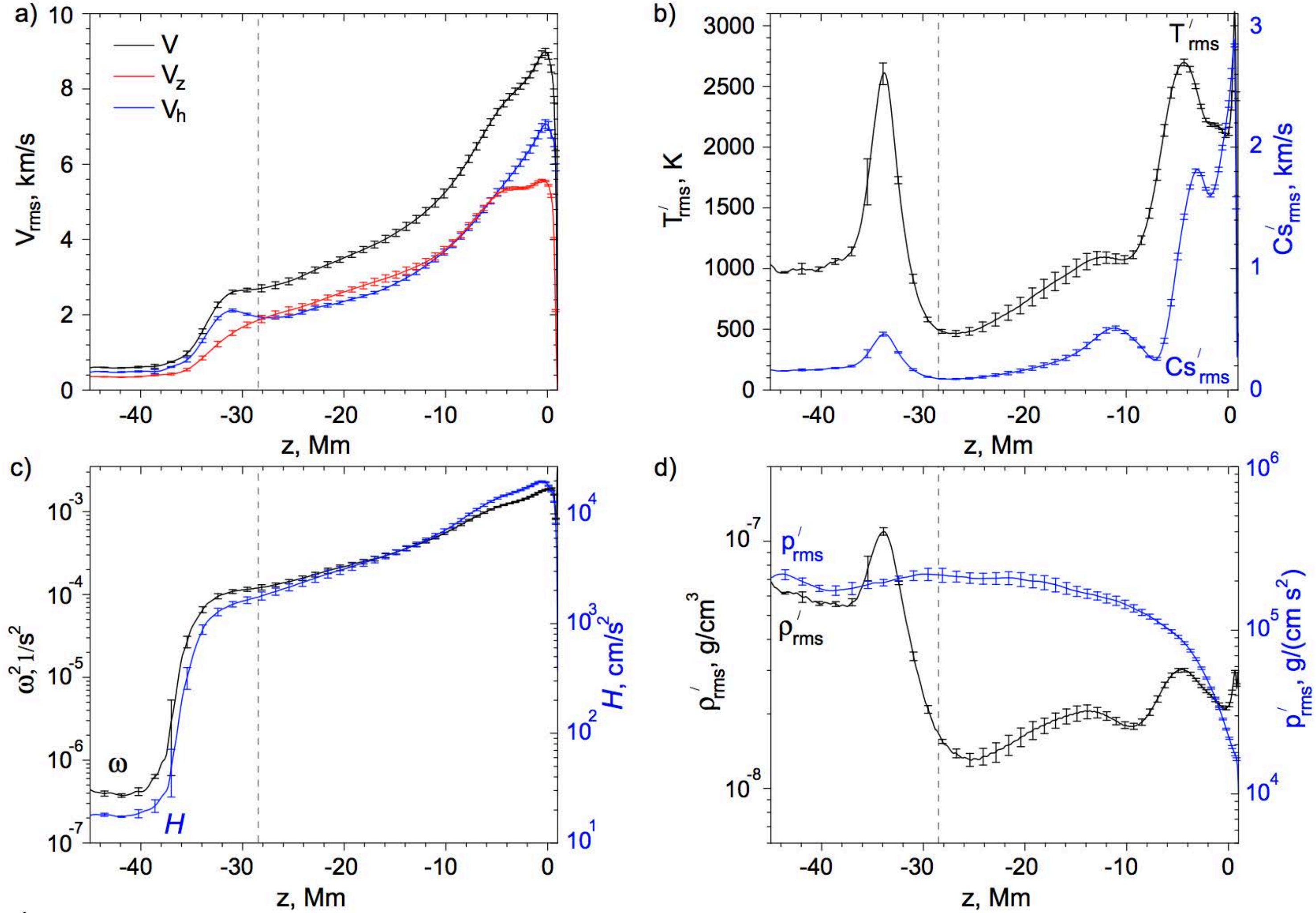




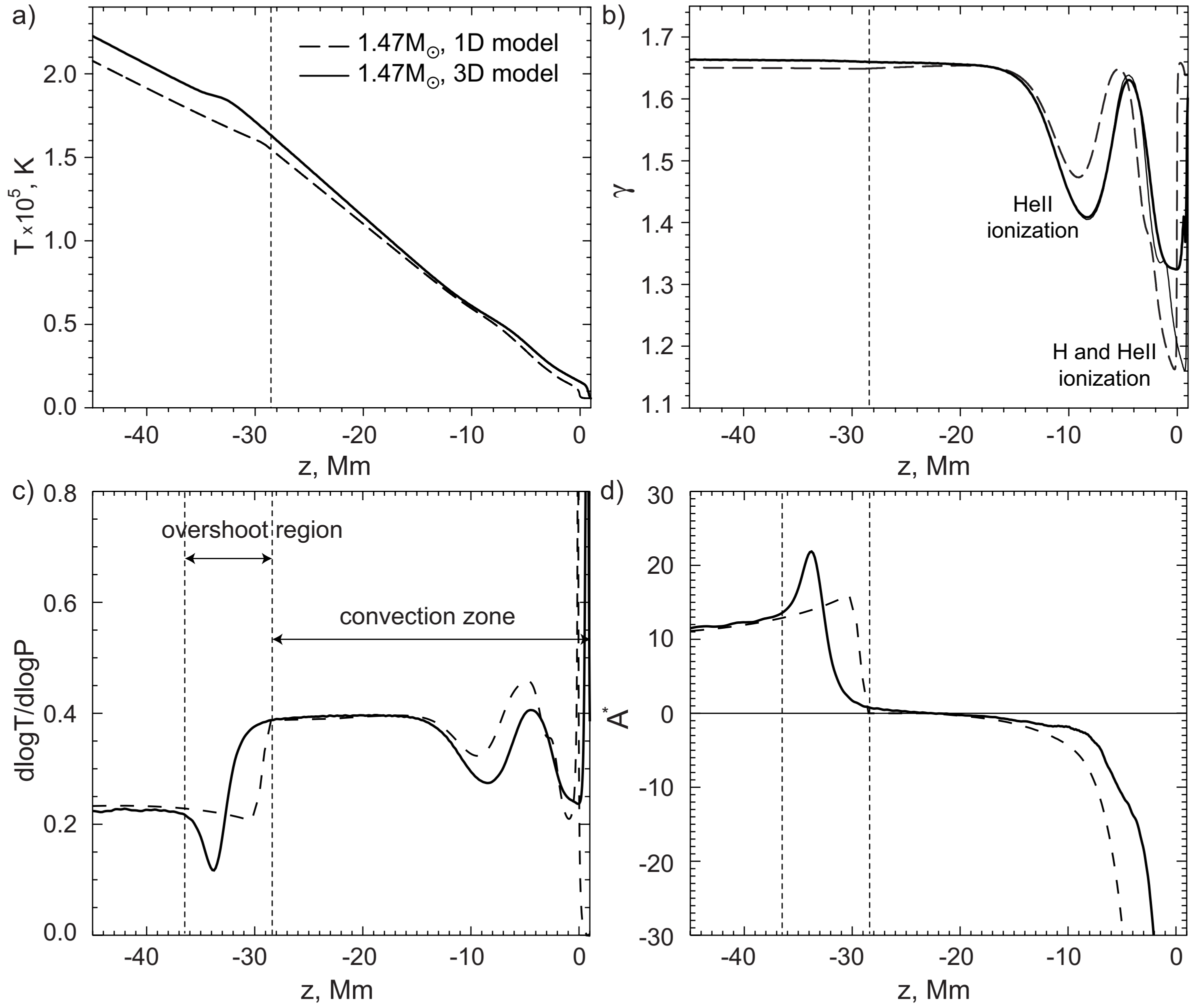
photosphere



M=1.47M$_{Sun}$



Vertical profiles, obtained from a 3D 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 w (black) and
helicity *H* (blue); d) *rms* of density r′ (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.



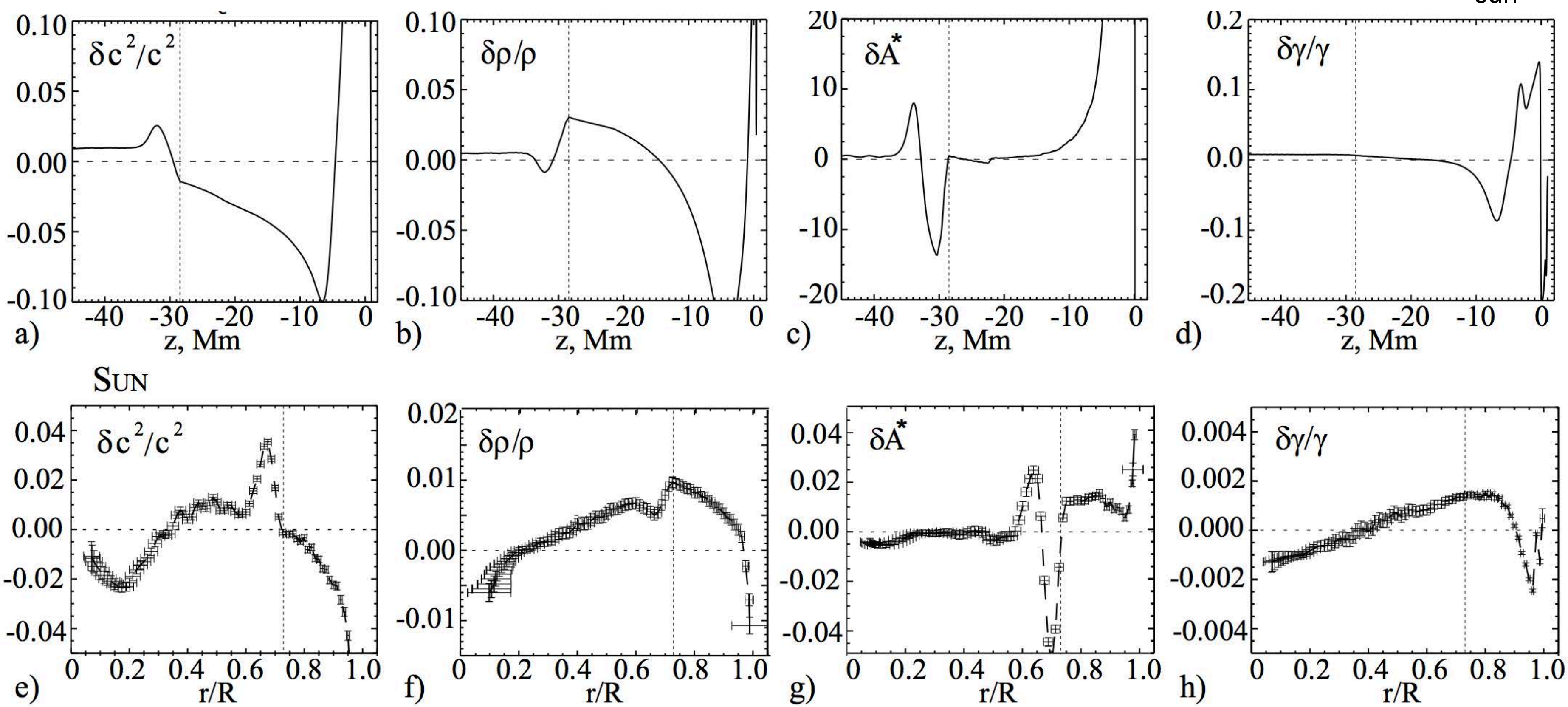
Comparison of the interior structure of a moderate mass star ($M=1.47M_{sun}$) calculated from 1-D mixing-length theory and from a 3D simulation: a) temperature, T; b) adiabatic exponent, g;

c) the temperature gradient, $\nabla = \frac{d\log T}{d\log P}$;

d) Ledoux parameter of convective stability $A^* = \frac{1}{\gamma}\frac{d\log P}{d\log r} - \frac{d\log \rho}{d\log r}$

Kitiashvili et al., 2016
Trampedach et al., 2018

$1.47 M_{sun}$

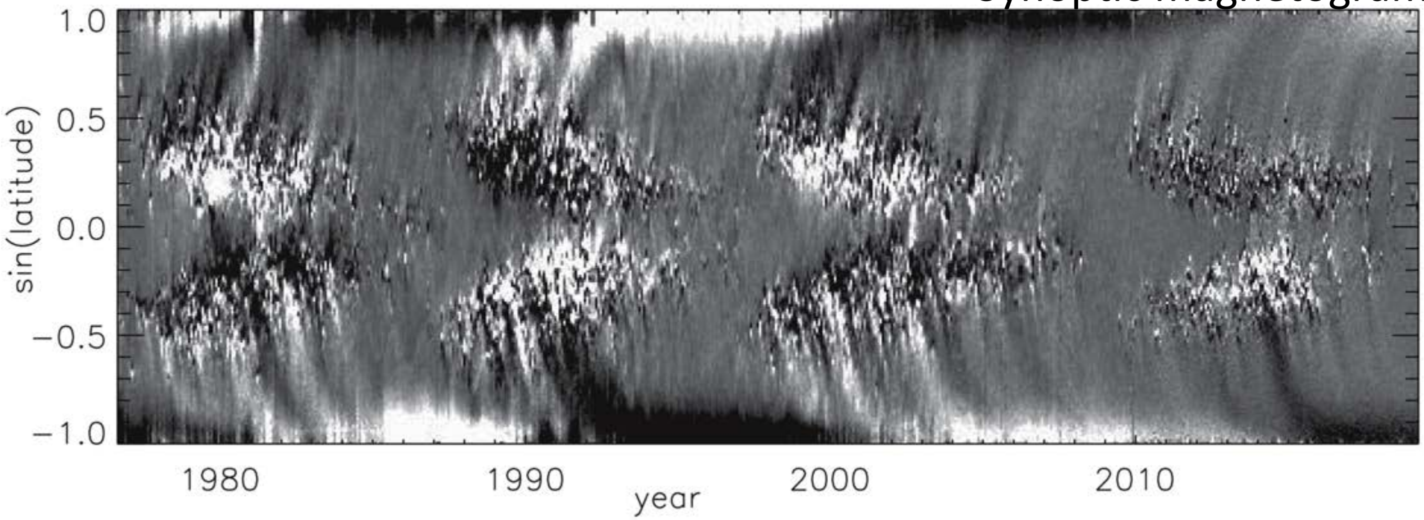


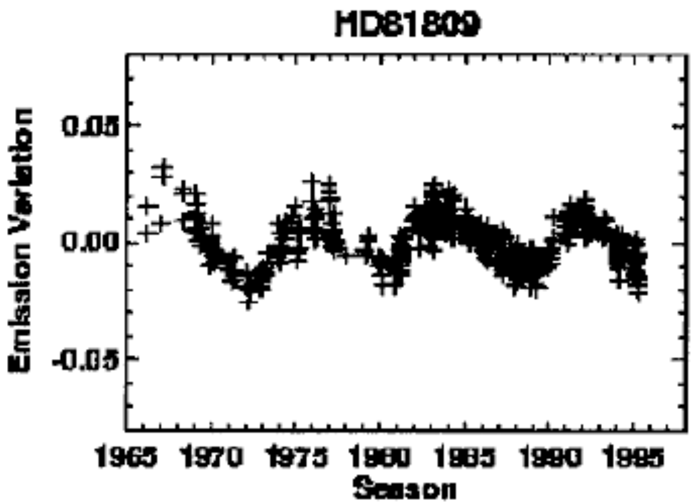
Deviations between the 3D simulation and 1D model of a star with mass M=1.47 M_{sun} as a function of depth, z=r-R, for: a) the sound speed squared, dc^2/c^2; b) density, dr/r; c) Ledoux parameter of convective stability, A*; and d) adiabatic exponent, g.
Panels e-h show the corresponding deviations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

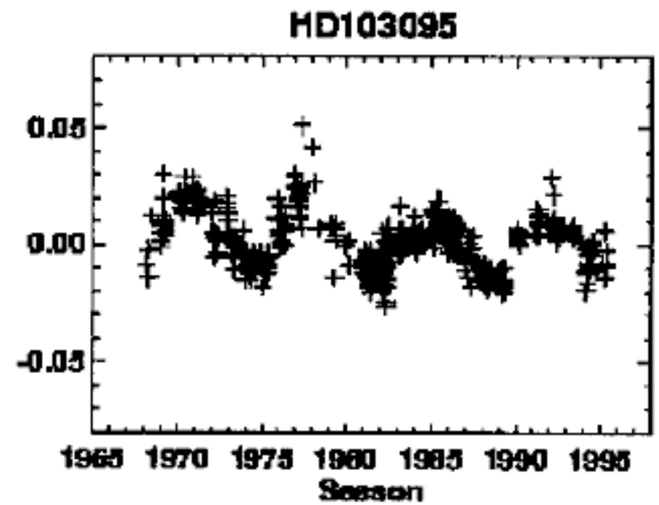
Kitiashvili et al., 2016

Multiscale dynamo process

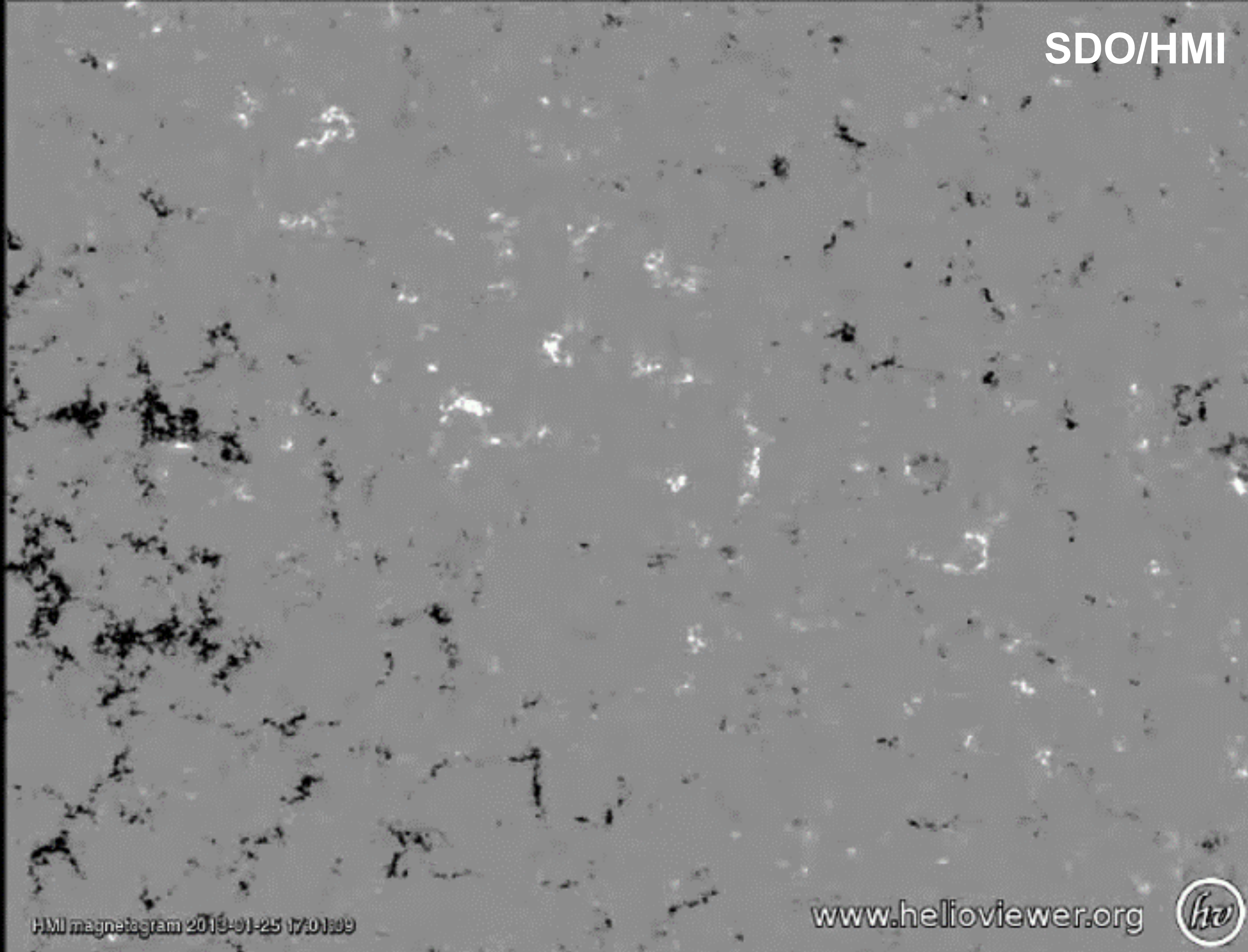
Synoptic magnetogram



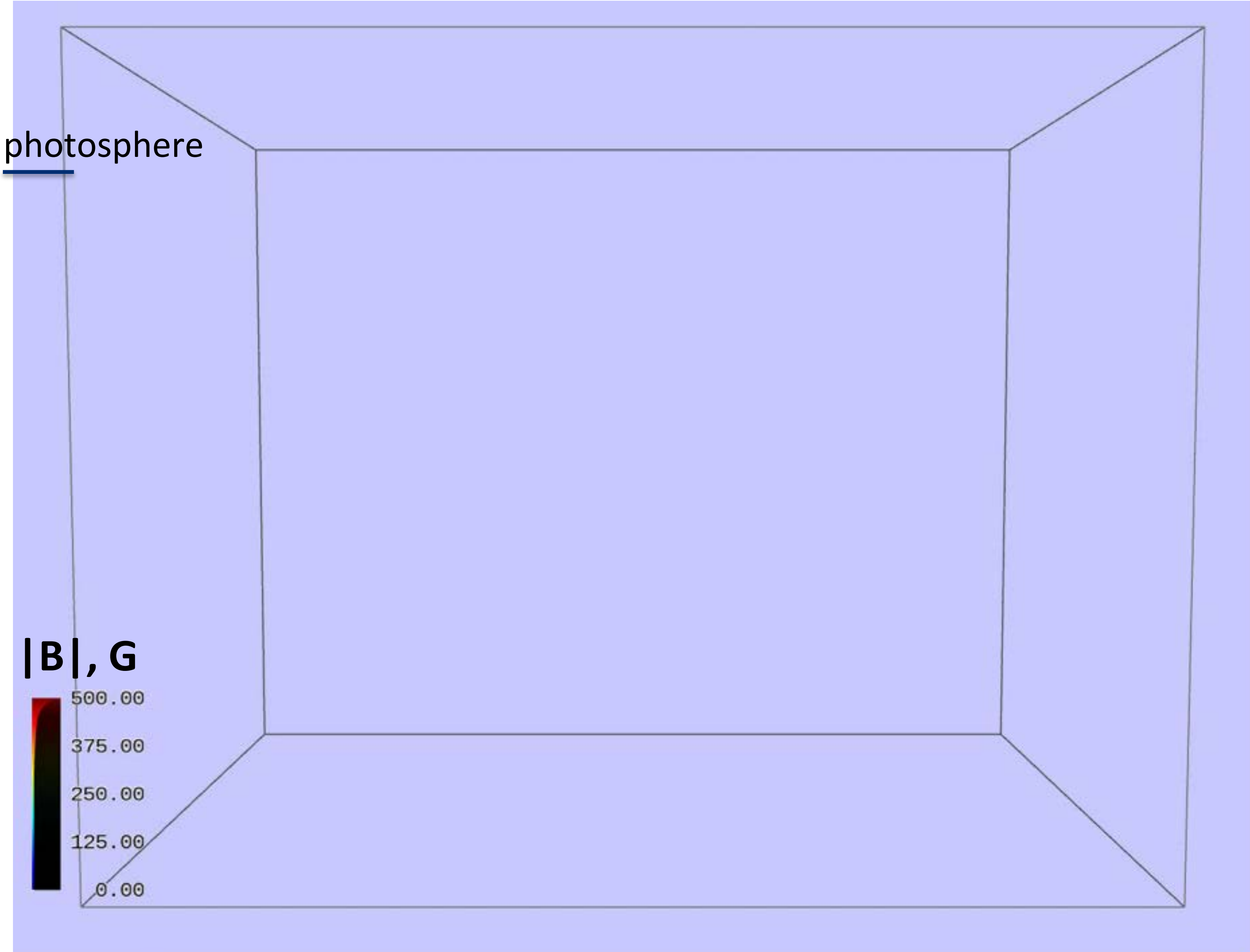




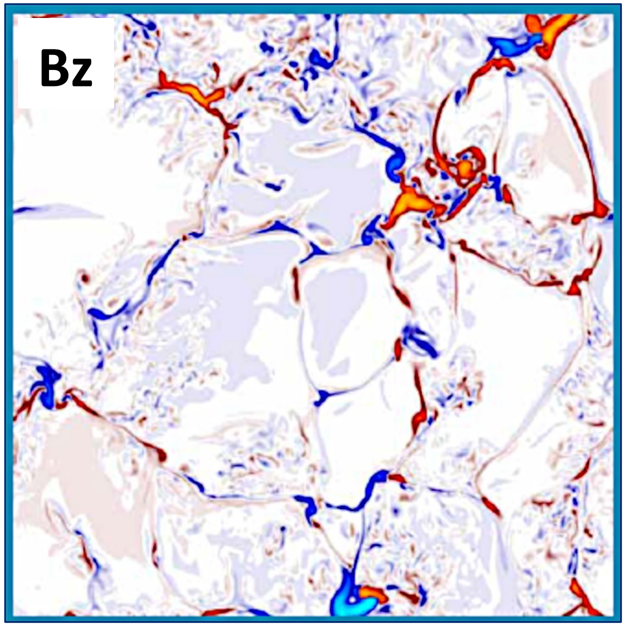
(Radick, 2000; Berdyugina 2005)


SDO/HMI
HMI magnetogram 2013-01-25 17:01:09
www.helioviewer.org
hv

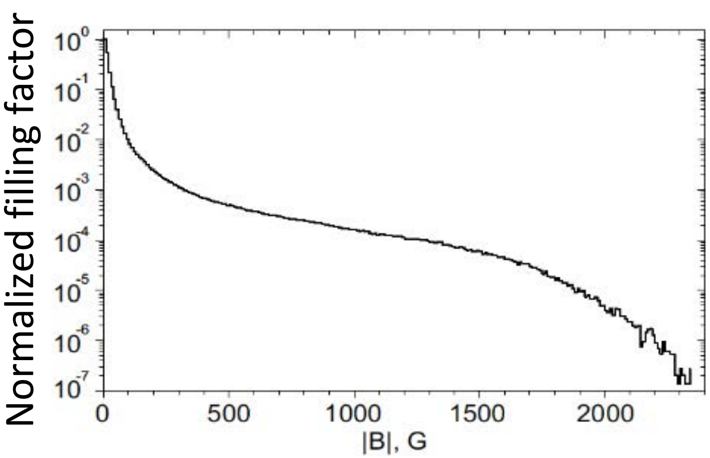
Small-scale (turbulent) dynamo



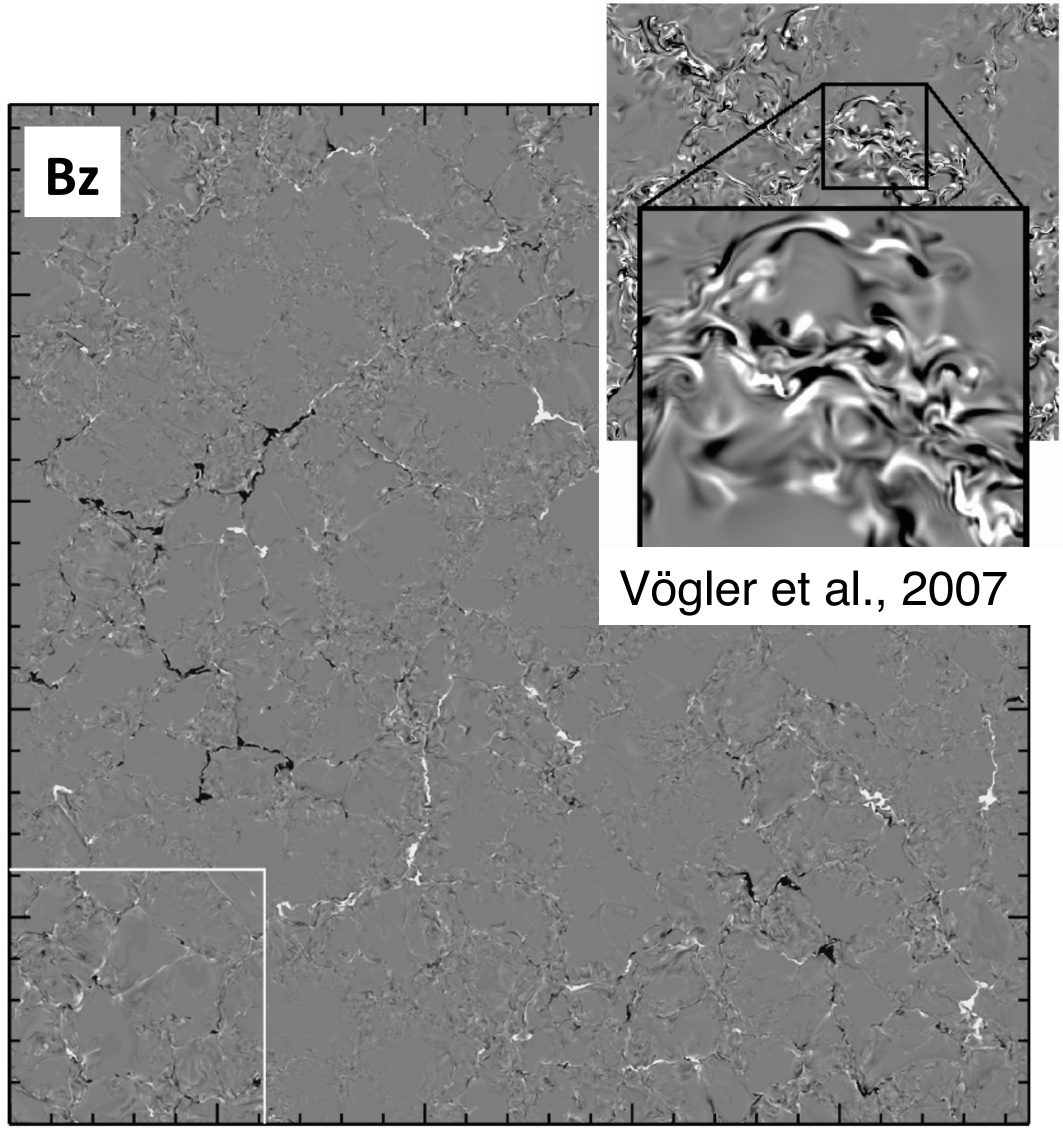
Magnetic field distribution at the photosphere



The blue-red color scale corresponds to magnetic field strengths from -300 to 300 G. The typical size of the magnetic structures is 100 – 300 km.



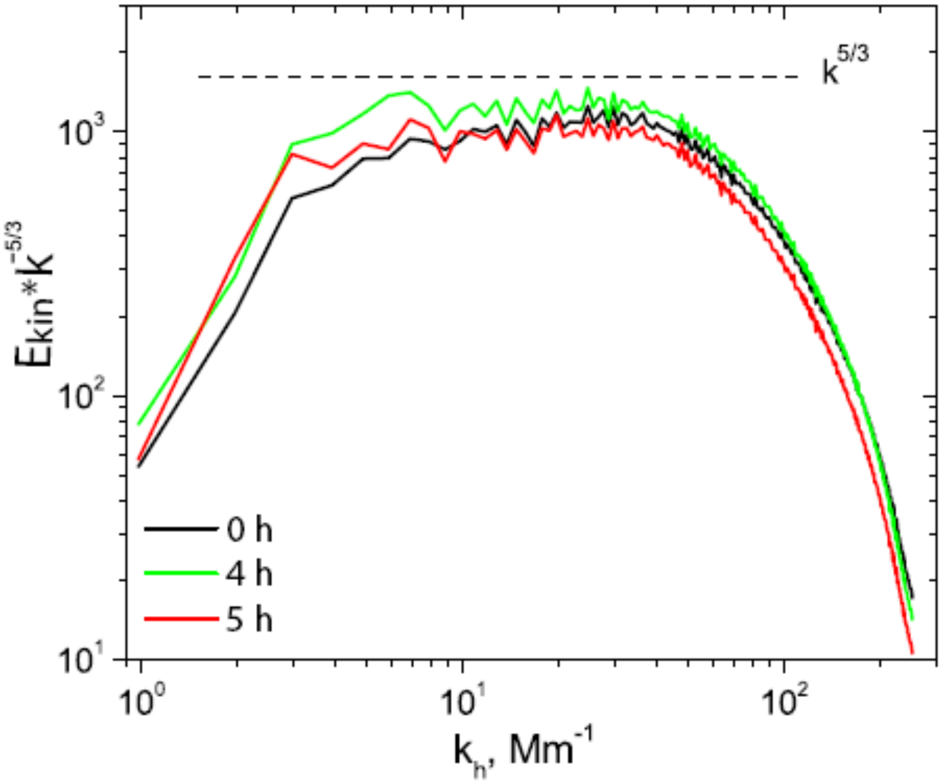
Kitiashvili et al., 2015



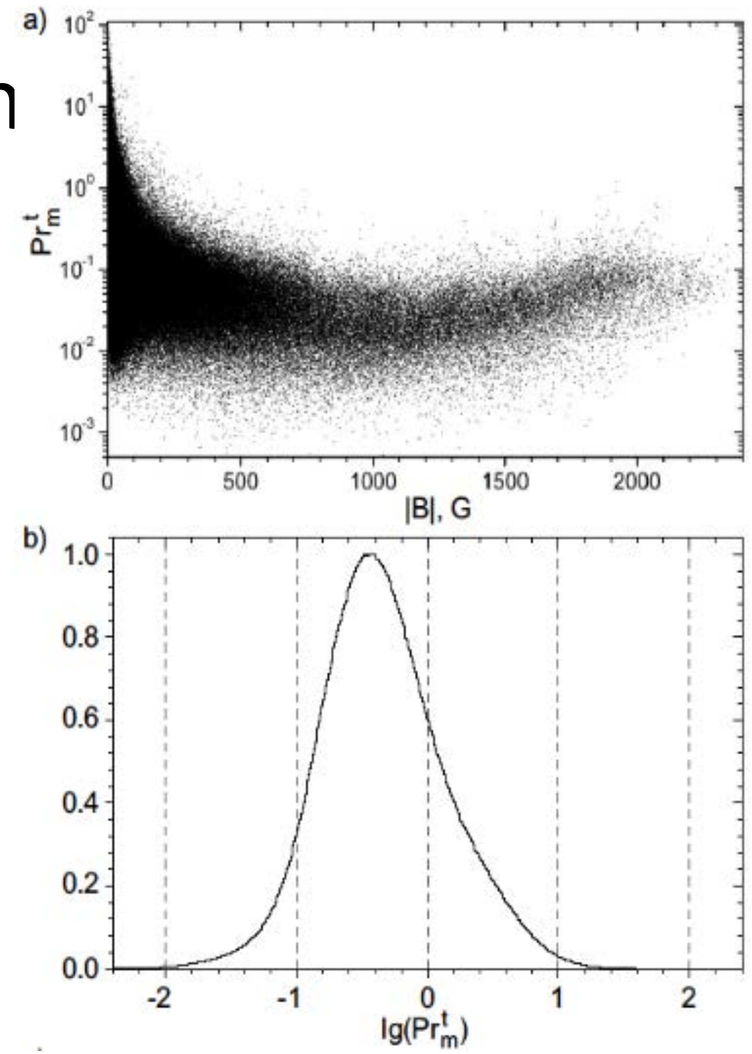
Vögler et al., 2007

Rempel 2014

Magnetic field generation in the surface layers

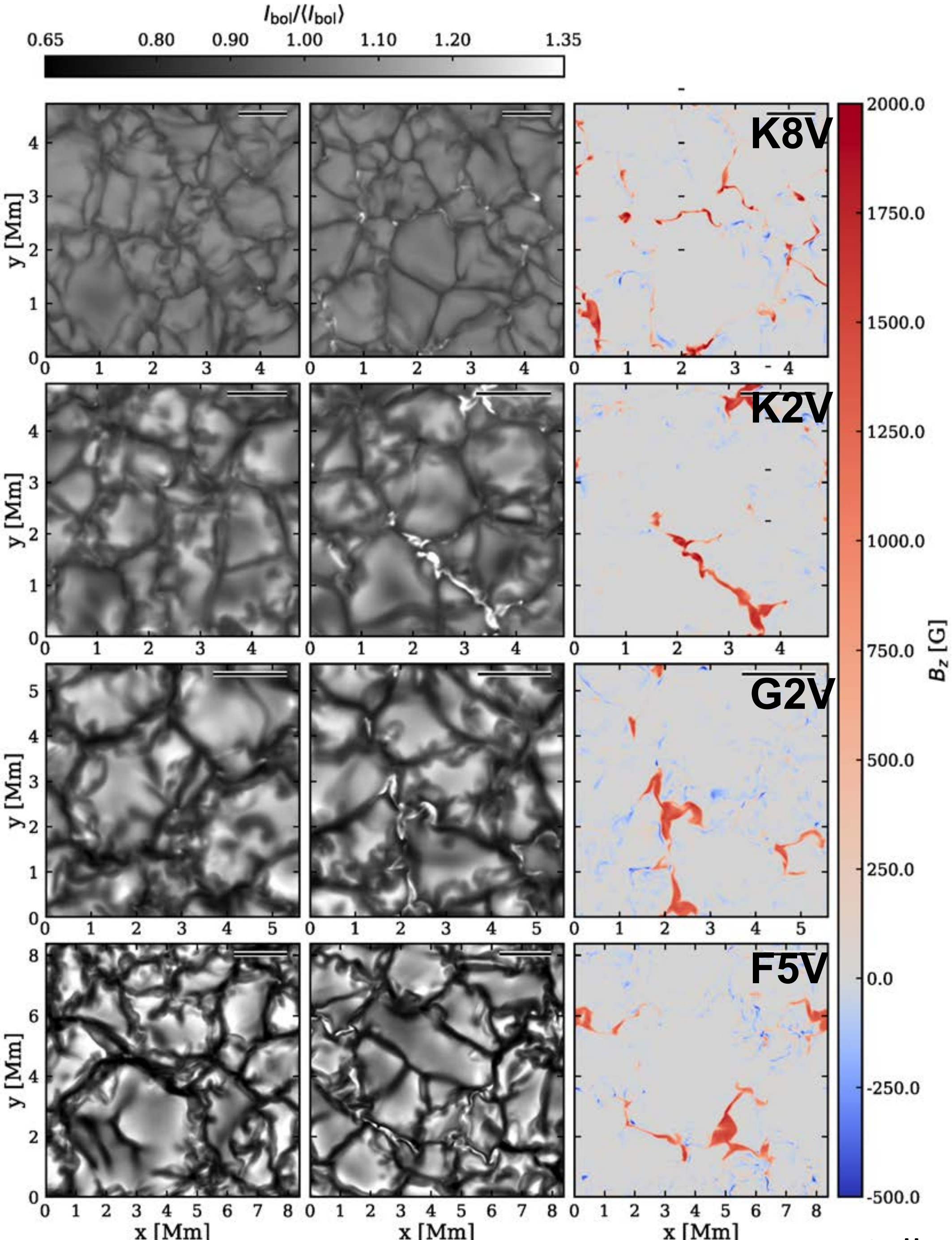


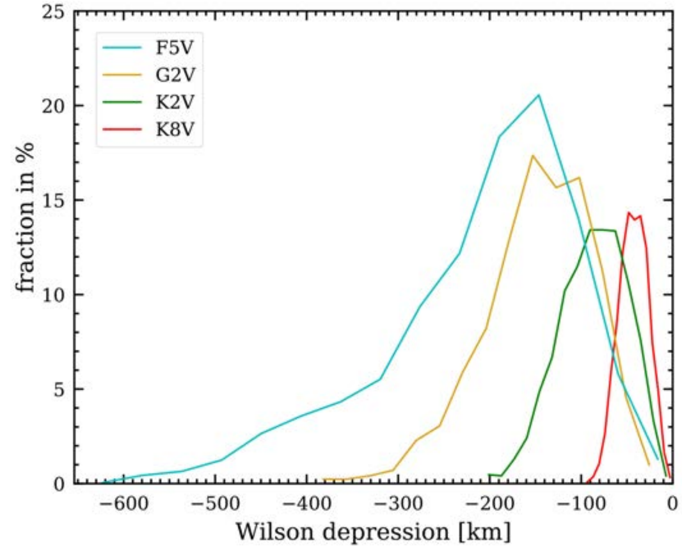
Velocity horizontal power spectrum



a) Statistical distribution of magnetic field strength (|**B**|) vs. turbulent magnetic Prandtl number (Pm^t).
b) Probability distribution function (PDF) of the turbulent Prandtl number. $Pm^t = n^t/h_m^t$

Modeling magnetic fields on other stars





Histograms of the Wilson depressio

Bolometric radiation of non-magnetic simulations (left column) and of the magnetic simulations (middle column), normalized to their respective mean intensities

Salhab et al. 2018

Conclusions

- *"Ab initio" (or "realistic") simulations based on first principles are now a primary tool for modeling stellar surface and subsurface physics.*

- *Convective structure in main-sequence stars dramatically changes as the stellar mass increases.*
  - The convection zone shrinks and becomes more vigorous, with plasma motions reaching supersonic speeds, and develops multi-scale convective cell structures quite different from solar granulation and supergranulation.

- *For $M > 1.35M_{Sun}$ the convection zone is relatively shallow, and simulations can cover it in its entirety plus a convectively stable layer of the radiative zone.*
  - This allows investigation of overshooting, turbulent mixing, and excitation of internal gravity waves at the bottom of the convection zone.

- *The presence of small-scale magnetic fields can impact the observed bolometric intensity and flux.*