Surface Convection Models

Friedrich Kupka

Max Planck Institute for
Solar System Research, Göttingen

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WP 123200 — Surface Convection (1D — 3D)

Current WP 123200 members / contributors

Martin Asplund
Kévin Belkacem
Elisabetta Caffau
Robert Cameron
Christoffer Karoff
Friedrich Kupka (WP lead)
Hans Ludwig
Réza Samadi
Keivan Stassun
Barry Smalley
Matthias Steffen

Characterization of Convection Signatures

Modelling of the Granulation Background ?

Requests which the work package is expected to deal with, as summarized by Nuccio Lanza (WP 123 000 leader):

How well is granulation characterized by Harvey-type models ?

Can we provide theoretical priors on the parameters of such models of the power spectrum ?

The granulation background can be used to determine log(g). Do 3D RHD recover the results from this method ?

Modelling of the high frequency part of the lightcurve ?

Characterization of Convection Signatures

Modelling of the Granulation Background ?

Compare 3D radiation hydrodynamical simulations covering various spatial resolutions, domain widths, abundances, boundary conditions...

ANTARES models: Friedrich Kupka (+ Daniel Krüger)
CO5BOLD models: Hans Ludwig
MuRAM models: Jesper Schou (+ Robert Cameron)
STAGGER models: Martin Asplund, Yixiao Zhou

critical feedback from Kévin Belkacem (+ Réza Samadi)

for this presentation: thanks to comments from Kévin Belkacem, Hans Ludwig, Jesper Schou, and Yixiao Zhou.

Harvey-Type Profiles I

Original Paper

Representation of "background noise" proposed by J. Harvey (1985), ESASP 235, 199:

$$P(\nu) = \frac{4\sigma^2\tau}{1+(2\pi\nu\tau)^2} \quad (1)$$

Table 1 lists the values that were used in constructing a background noise spectrum estimate for a full-disk observation made with a moderately strong photospheric spectrum line.

Table 1. Basis for solar noise spectrum estimate

Feature	τ (s)	σ_{vert} (m/s)	σ_{horiz} (m/s)	$\sigma_{fulldisk}$ (m/s)
Granulation	372	890	460	0.7
Mesogranulation	10^4	60	0?	0.3
Supergranulation	10^5	30?	150	1.9
Active regions	10^6	200?	100?	3.0

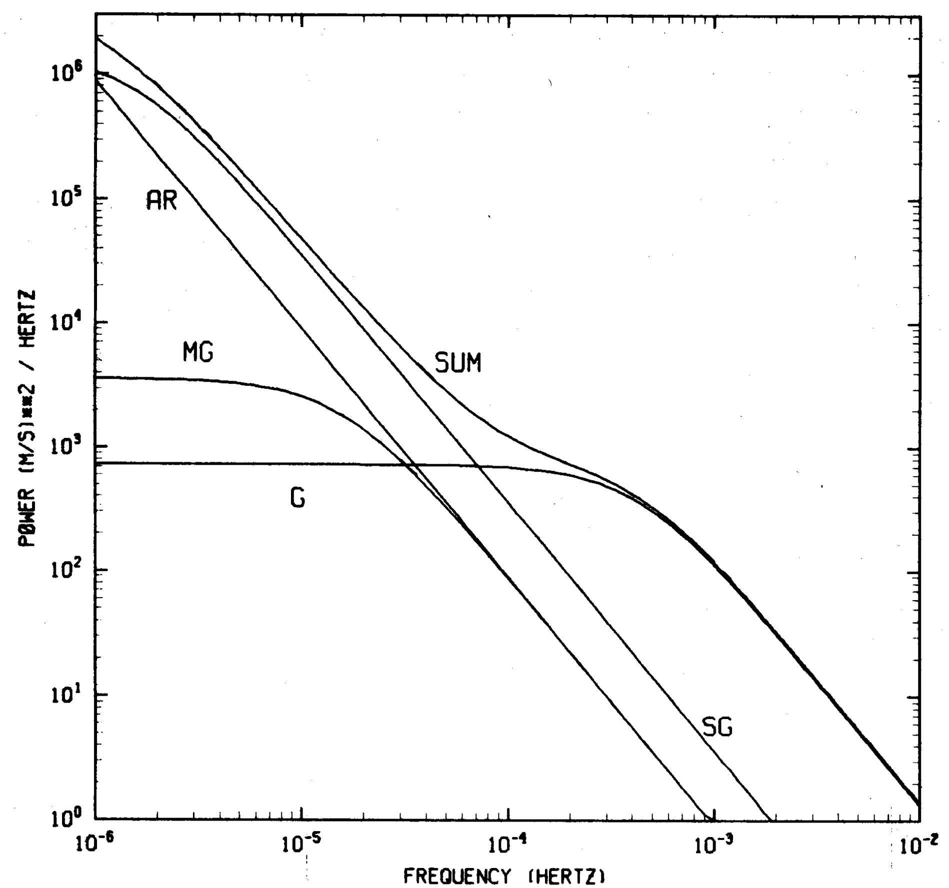


Figure 4. Estimated solar background noise for an observation of Doppler shifts of a moderately strong photospheric spectrum line averaged over the solar disk (G=granulation, MG=mesogranulation, SG=supergranulation, AR=active regions).

Harvey-Type Profiles II

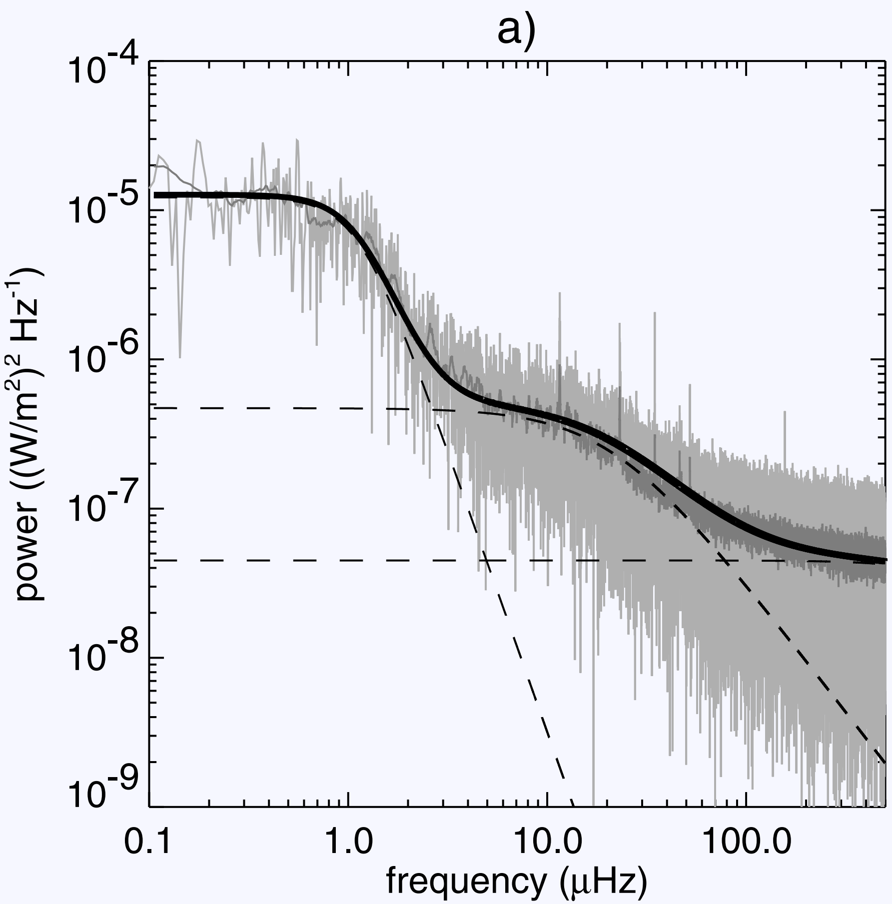
Further developments ...

Super-Lorentzian functions suggested by Andersen et al. (1994), Sol. Phys., 152, 247 as in Aigrain et al. (2004), A&A 414, 1139:

$$P(\nu) = \sum_{i=1}^{N} P_i = \sum_{i=1}^{N} \frac{A_i}{1 + (B_i\, \nu)^{C_i}} \qquad (1)$$

Table 1. Typical timescales for the different of structures on the solar surface.

Component	Timescale B (s)
Active regions	1 to 3×10^7
Super-granulation	3 to 7×10^4
Meso-granulation	$\simeq$8000
Granulation	200 to 500
Bright points	$\simeq$70



Harvey-Type Profiles III

Approaching current models ...

Superposing instrumental noise, granulation and activity background, combined with a model of the power excess hump from p-modes suggested in Kallinger et al. (2014), A&A 570, A41:

In all cases, the power density spectra are modelled by the superposition of instrumental noise[3], the contribution of one to three super-Lorentzian[4] functions, and a power excess hump approximated by a Gaussian,

$$P(\nu) = P_n' + \eta(\nu)^2 \left[\sum_i \frac{\xi_i a_i^2 / b_i}{1 + (\nu/b_i)^{c_i}} + P_g \exp \frac{-(\nu - \nu_{\max})^2}{2\sigma^2} \right], \quad (2)$$

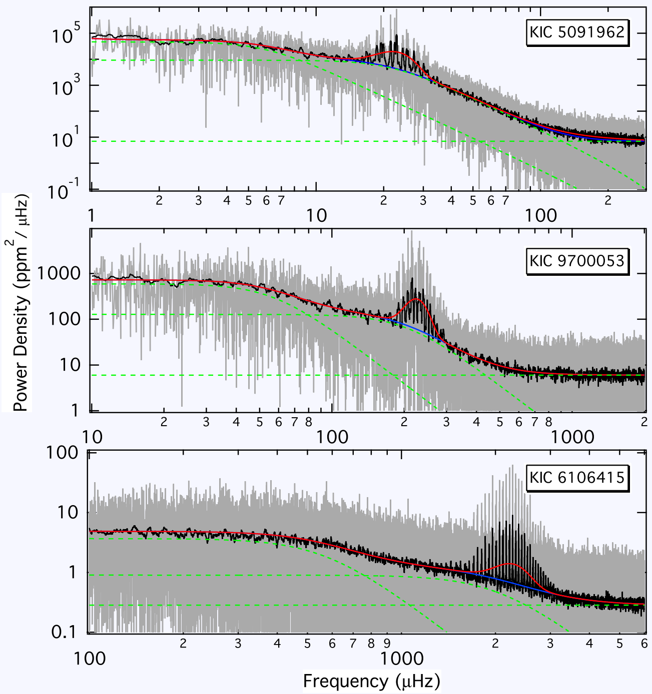


Fig. 7. Power density spectra of three typical stars with $\nu_{\max} \simeq 22$, 220, and 2200 μHz, respectively, showing that all timescales and amplitudes (granulation as well as pulsation) scale simultaneously. Grey and black lines indicate the raw and heavily smoothed spectrum, respectively. The global fit is shown with (red) and without (blue) the Gaussian component. Green lines indicate the individual background and white noise components of the fit.

Basic Simulation Setup

Surface convection zones of main sequence stars

- ➔ surface pressure scale height $P/(\rho g) = H_p \ll R$, the stellar radius
- ➔ simulation box: small fraction of entire convection zone ("box-in-a-star"), for this box: RHD: solve NSE with RT numerically on a grid in space & time.

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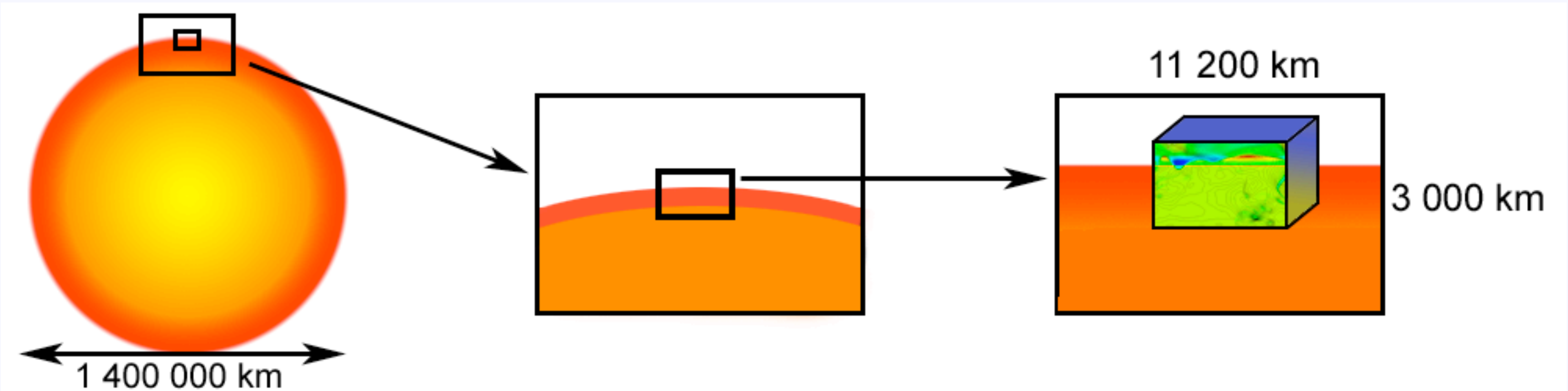


(illustration by courtesy of F. Zaussinger)

- ➔ Compute mean structure. Allow 3D-1D patching.
- ➔ Improve 1D models. Near surface effect.
- ➔ Characterize surface convection: granulation background.
- ➔ Investigate radial p-modes (vertical box modes excited in the simulations).

Simulations

simulation	$N_x \times N_y \times N_z$	size [Mm^3]	$h_{\rm vert}$ [km]	$h_{\rm hor}$ [km]	time [s]	rate [Hz]	mixture
STAGGER ApJ 880	230 × 240 × 240	3.8 × 6.0 × 6.0	7.05–32.63	25.0	86400	1/30	AGSS09
ANTARES cosc13	350 × 170 × 170	3.88 × 6.0 × 6.0	11.1	35.3	40012	1/15.84	GN93
ANTARES wide4	405 × 510 × 510	4.45 × 18.0 × 18.0	11.1	35.3	12420	1/8.54	GN93
CO5BOLD n53	150 × 140 × 140	2.27 × 5.6 × 5.6	15.1	40.0	52210	1/10	H01
CO5BOLD n94	165 × 400 × 400	3.15 × 11.2 × 11.2	12.0–28.2	28.0	8330	1/10	GS98+AGS05
CO5BOLD model D	150 × 189 × 189	8.4 × 18.6 × 18.6	16.1–283.8	98.4	264000	1/10	GS98+AGS05
CO5BOLD model G	300 × 378 × 378	8.4 × 18.6 × 18.6	8.38–141.9	49.2	132000	1/10	GS98+AGS05
MuRAM case 10	300 × 200 × 200	6 × 12 × 12	20	60.0	3591850	∼ 1/71.84	?
MuRAM case 11	600 × 400 × 400	6 × 12 × 12	10	30.0	703020	∼ 1/34.33	?

Table of Basic Simulation Data

Note that these simulations have originally been computed for various applications:

ANTARES cosc13: p-mode damping & work integrals (Belkacem et al. 2019, A&A 625, A20)
wide4: automatic granule identification (Leitner et al. 2017, ApSS 362, 181, Lemmerer et al. 2017, A&A 598, A126)

CO5BOLD model D & G: adiabaticity of solar RHD (Ludwig 2019, workshop @ Exeter)
n53 & n94: general purpose models (Ludwig 2004, 2019)

MuRAM case 10 & 11: study near-surface effect on osc. frequ. (Schou & Birch, A&A, subm.)

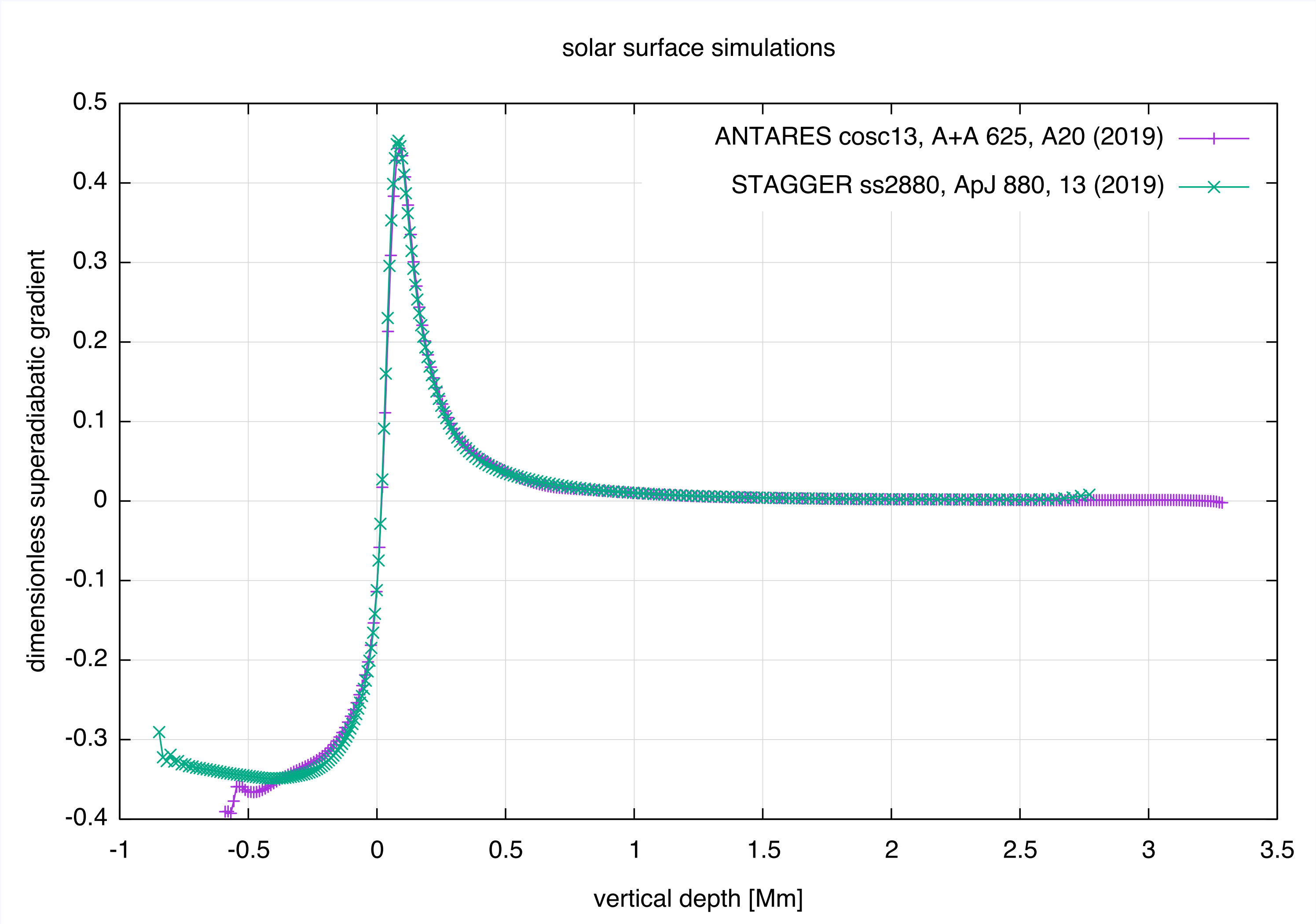
STAGGER ss2880: semi-analytical models of p-mode excitation & damping (Zhou et al. 2019, ApJ 880, 13)

Effective temperatures and detailed chemical composition vary! Below, in all cases: vertical coordinate has been shifted to have <T(0 Mm)>=$T_{\rm eff}$ (MuRAM). Layers above ➔ x < 0 Mm.

Comparing Mean Structure I

Superadiabatic gradient

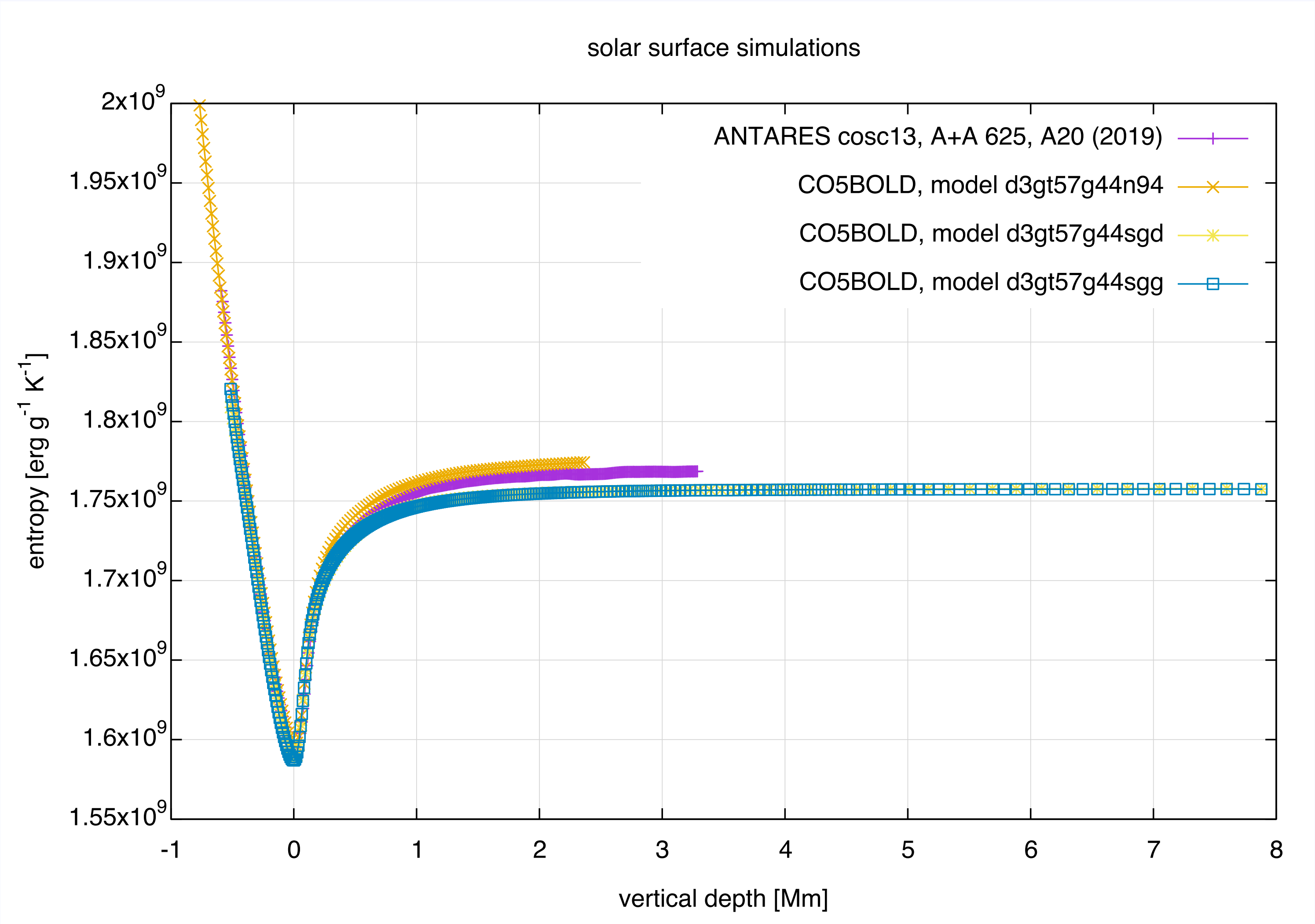
Good agreement at similar spatial resolution despite different chemical composition if x > -0.1Mm (T_{eff}=5773 K for ss2880 / STAGGER, 5750 K for cosc13 / ANTARES).



Comparing Mean Structure II

Specific entropy

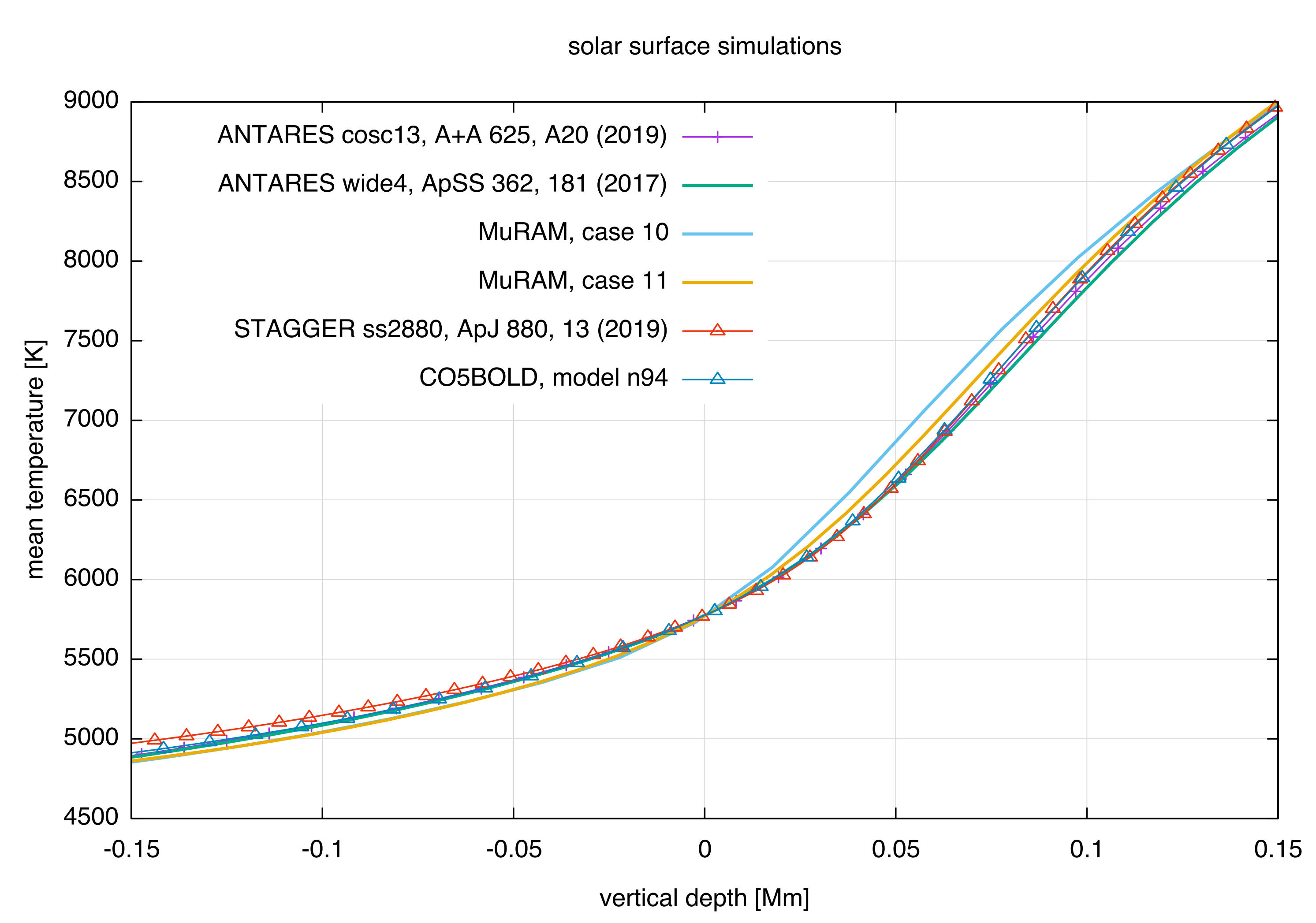
Agreement in photosphere & around superadiabatic peak, shift in interior plateau: starting models / input entropies (models D, G: grey; n94 and cosc13: non-grey).



Comparing Mean Structure III

Mean temperature in superadiabatic layer

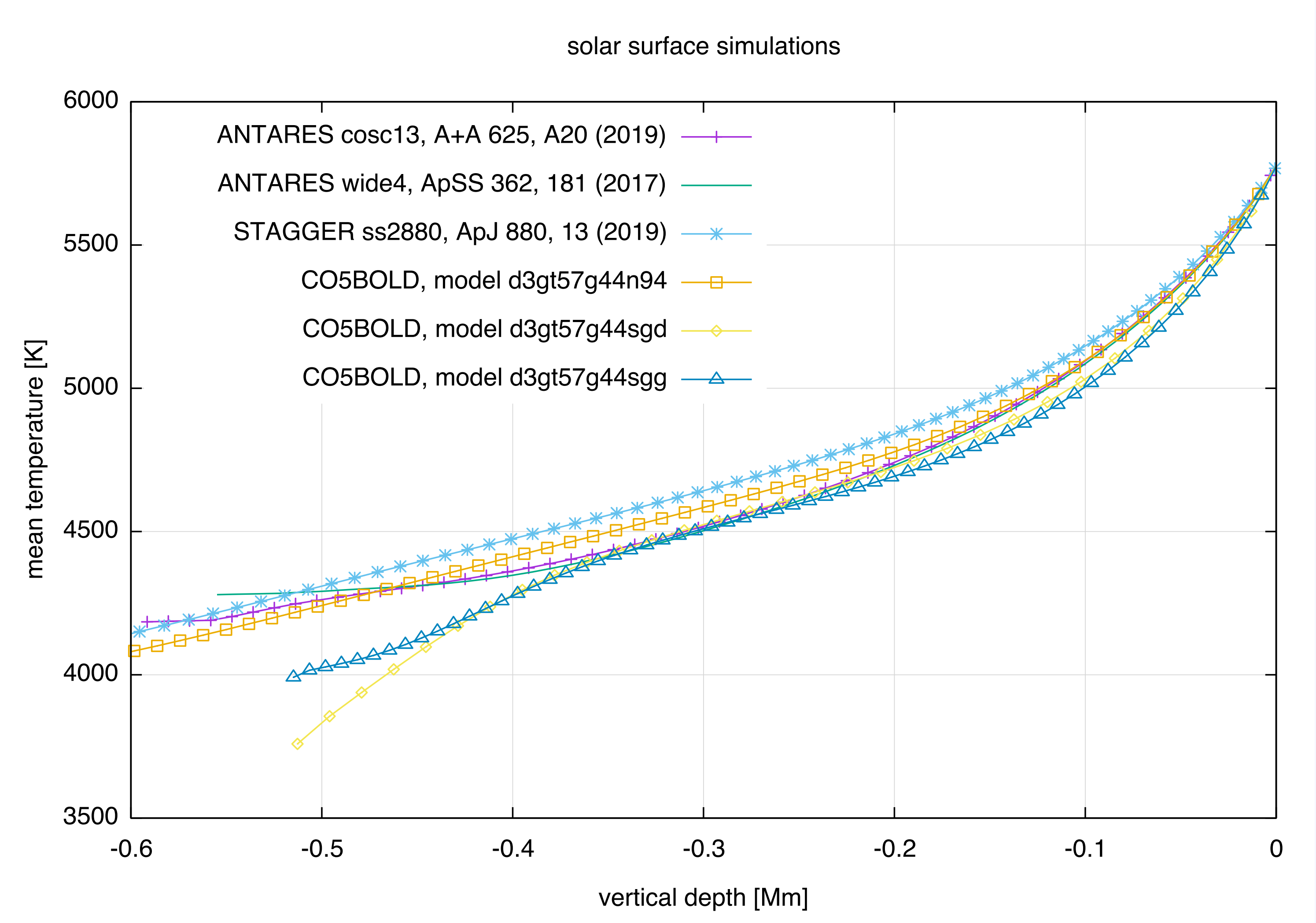
Good agreement among all four codes having "standard resolution" (h_{vert} ~ 10 km, $h_{horizontal}$ ~ 30 km). Compare MuRAM cases ➔ similar effect for CO5BOLD cases.



Comparing Mean Structure IV

Mean temperature in the photosphere

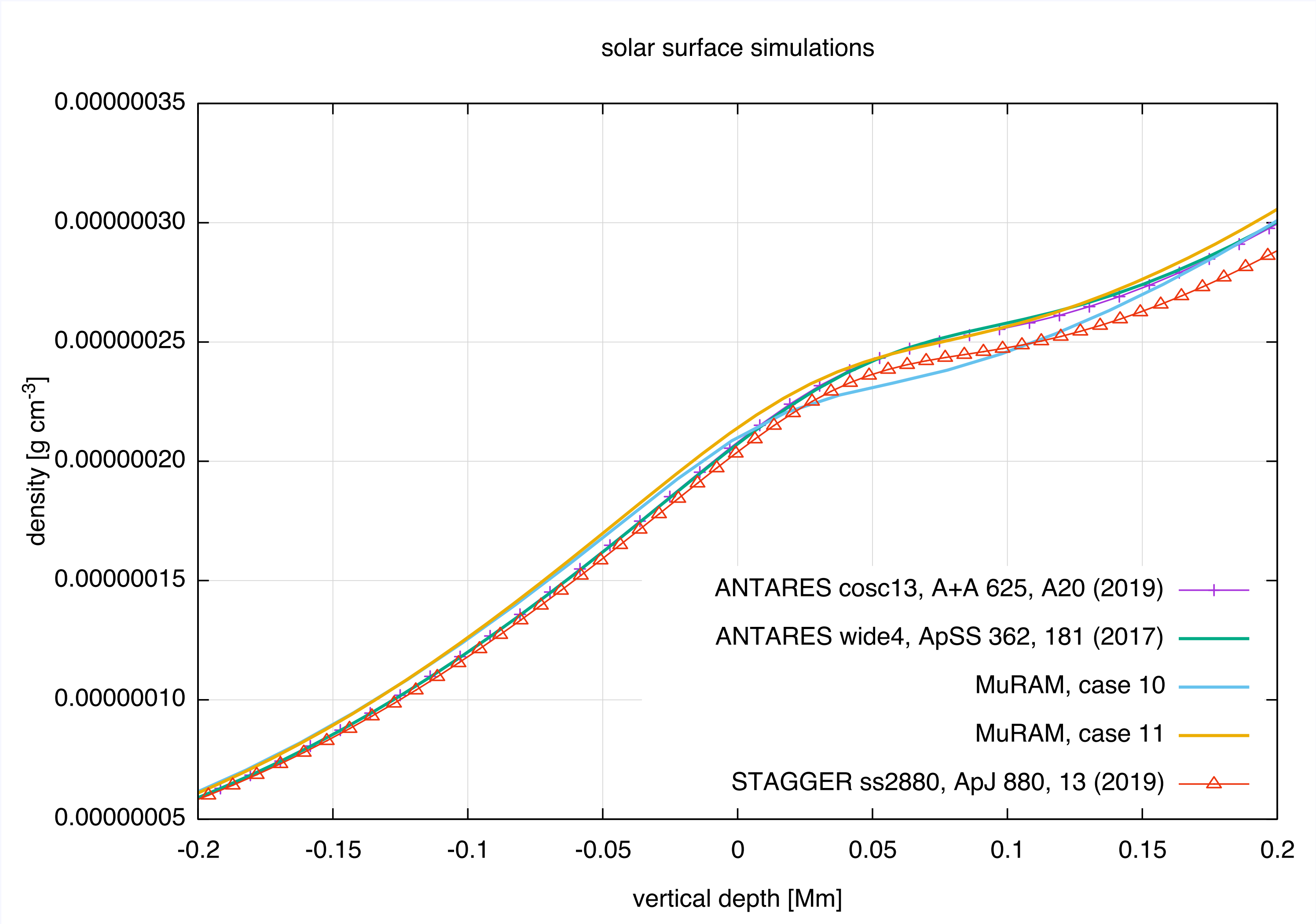
Differences due to chemical composition (STAGGER / AGSS09 abundances) as well as grey vs. non-grey radiative transfer (models D&G) (and presumably also T_{eff}).



Comparing Mean Structure V

Mean density around the superadiabatic peak

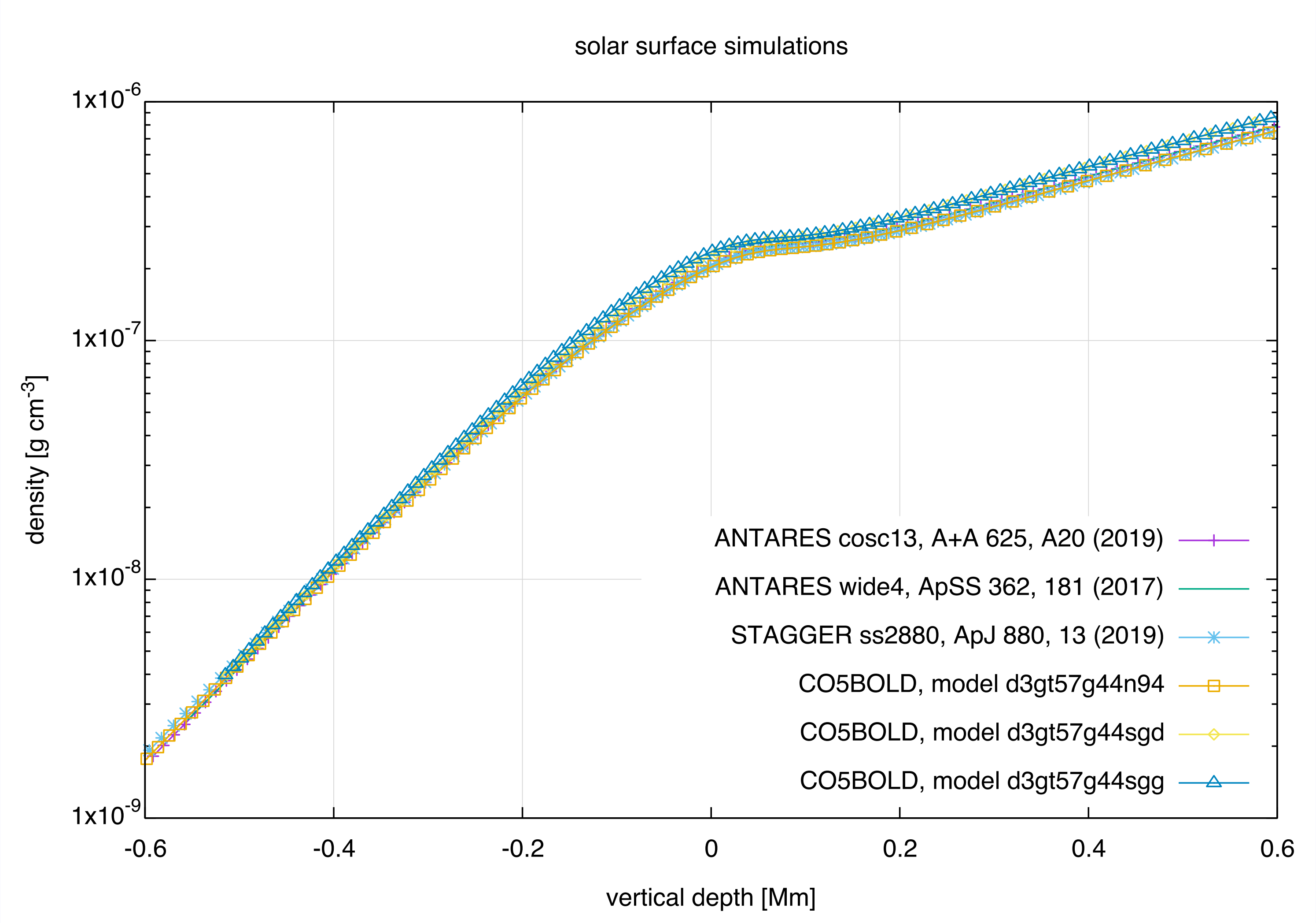
Small differences due to chemical composition (STAGGER / AGSS09 abundances), spatial resolution & velocity profile (MuRAM case 10 & 11).



Comparing Mean Structure VI

Mean density around the superadiabatic peak

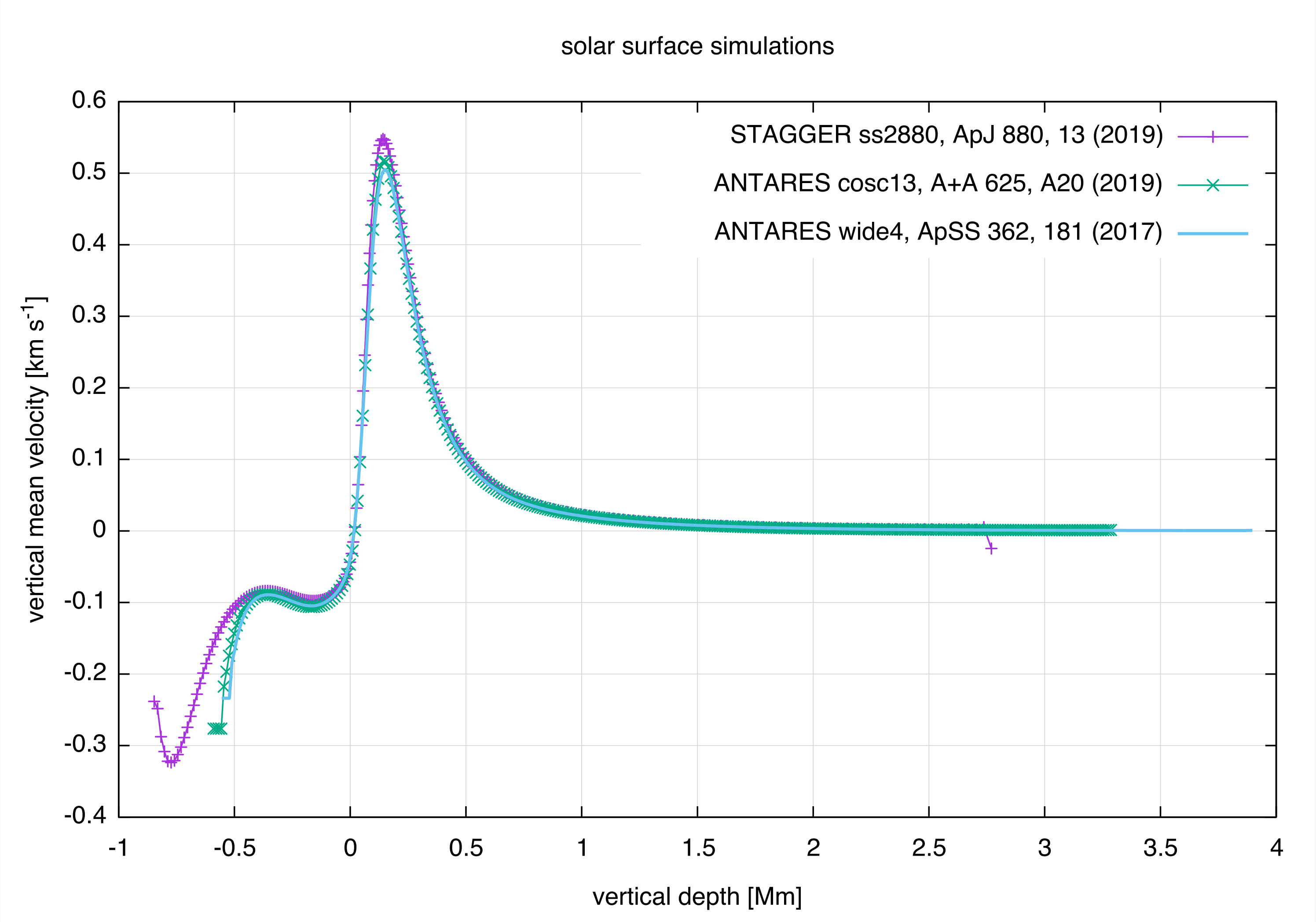
Small differences due to chemical composition, spatial resolution & velocity profile, slightly larger ones from grey vs. non-grey (CO5BOLD models D & G vs. n94).



Comparing Mean Structure VII

Time and horizontally averaged mean vertical velocity

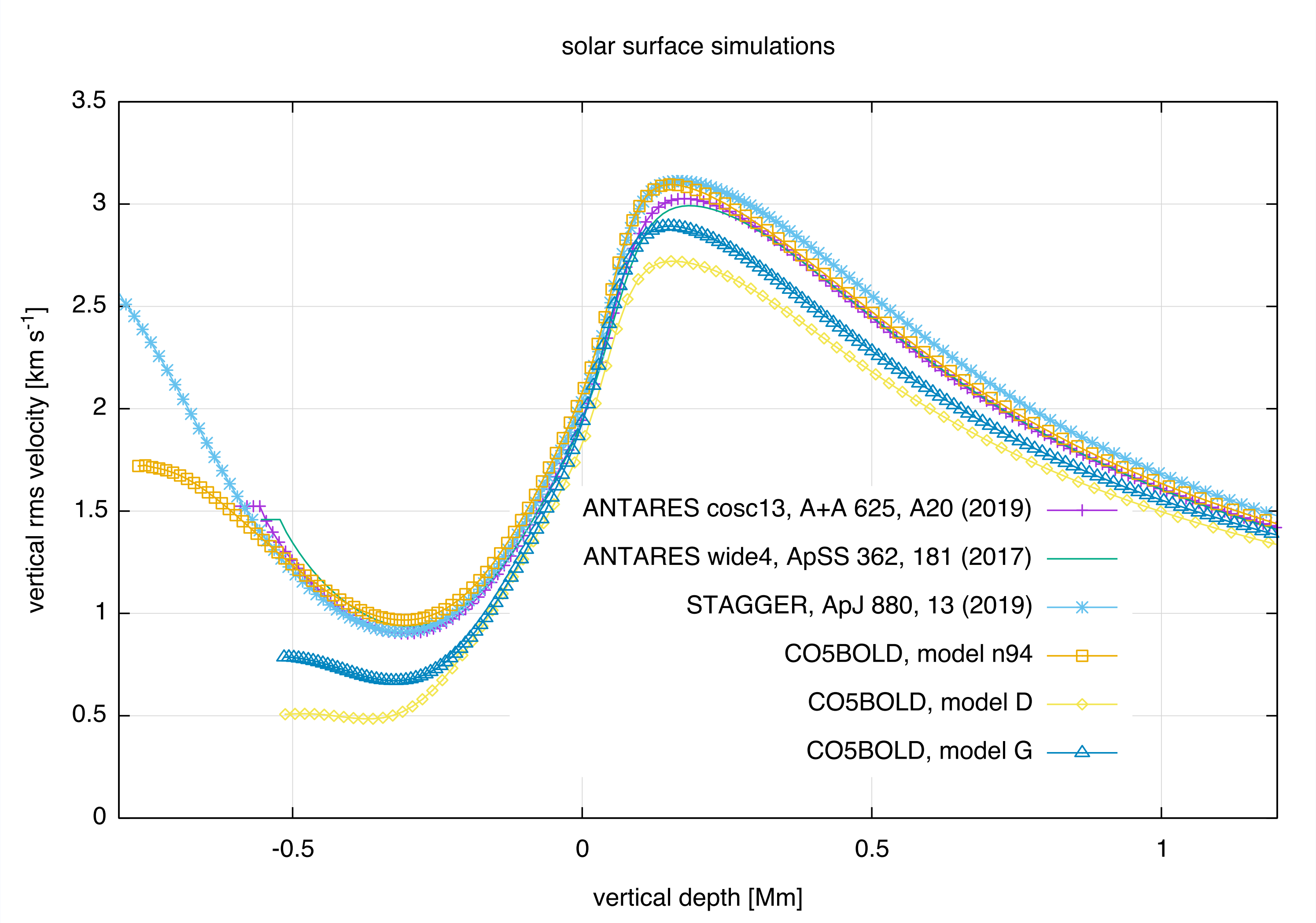
Small differences: density differences at 200 km (STAGGER / AGSS09 abundances), boundary conditions < -300 km. Horizontal box width plays no role (minimum: 6 Mm).



Comparing Mean Structure VIII

Time and horizontally averaged vertical root mean square velocity

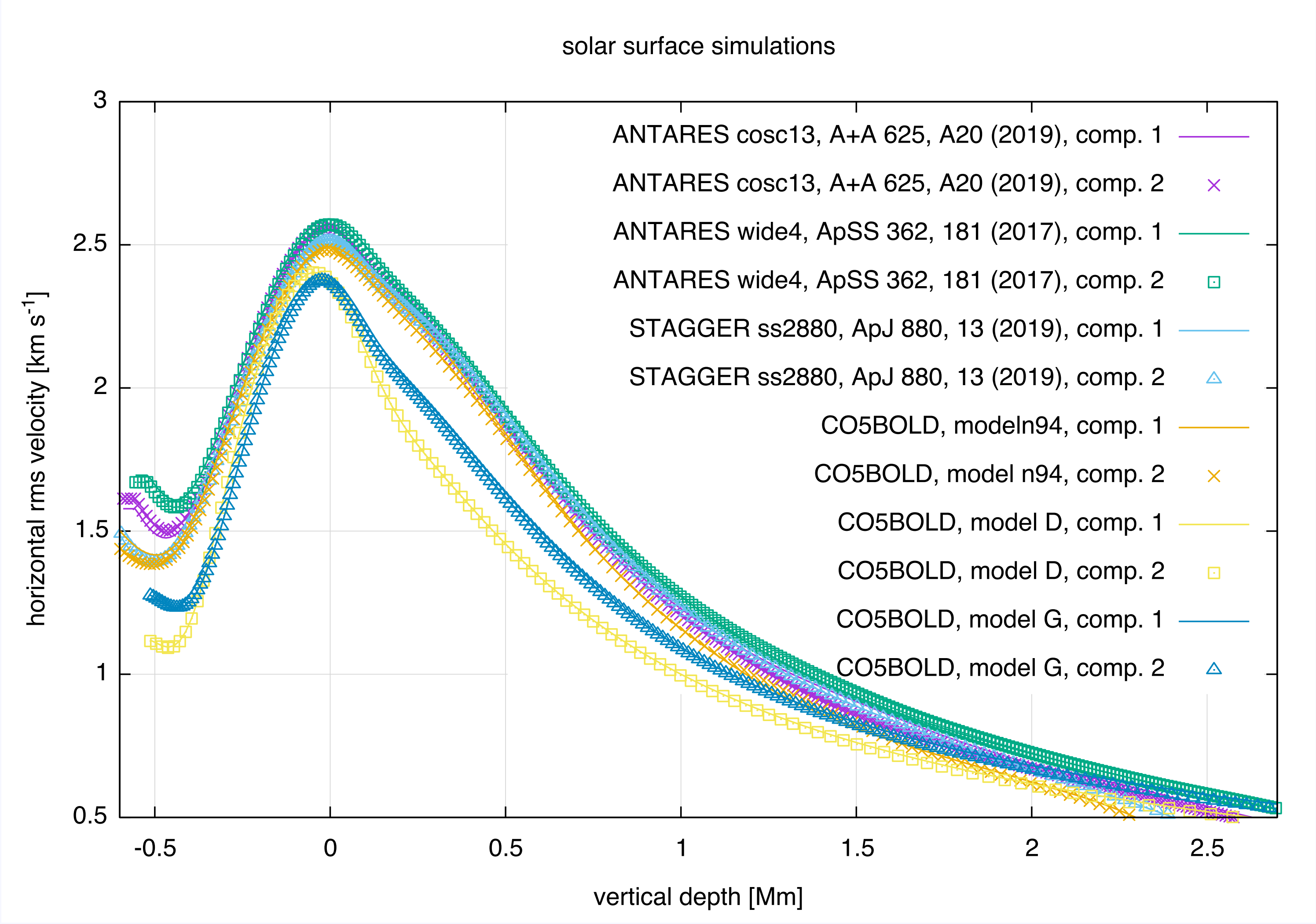
Difference for x > -0.3 Mm due to resolution/RT (CO5BOLD models D&G), followed by density differences (ANTARES models: GN93 comp.). Model width not important.



Comparing Mean Structure IX

Time and horizontally averaged horizontal RMS velocity

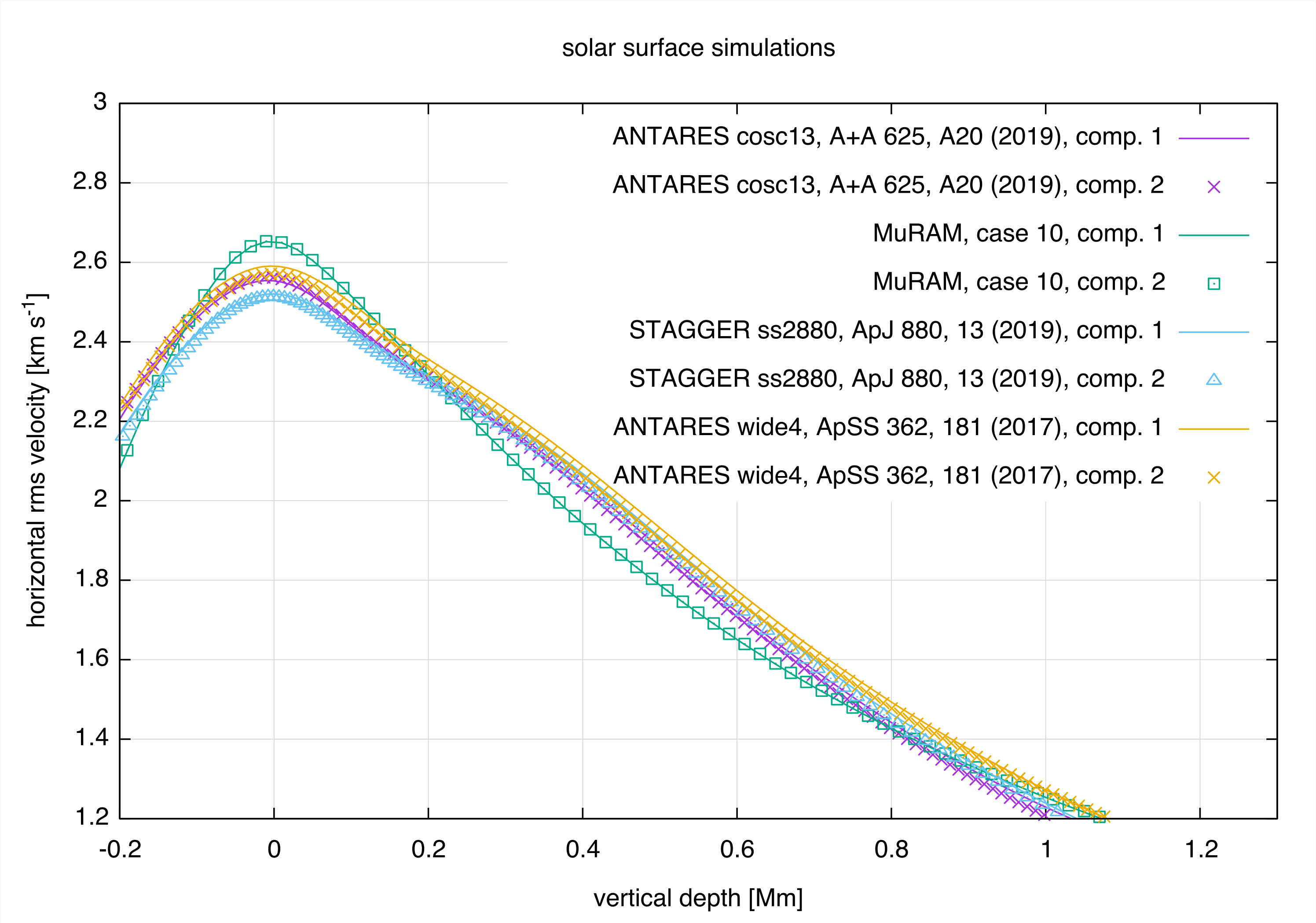
Main differences similar to vertical RMS velocity. Small differences: numerics (ANTARES vs. CO5BOLD & STAGGER ?). Very small ones: directions (comp. 1 & 2).



Comparing Mean Structure X

Time and horizontally averaged horizontal RMS velocity

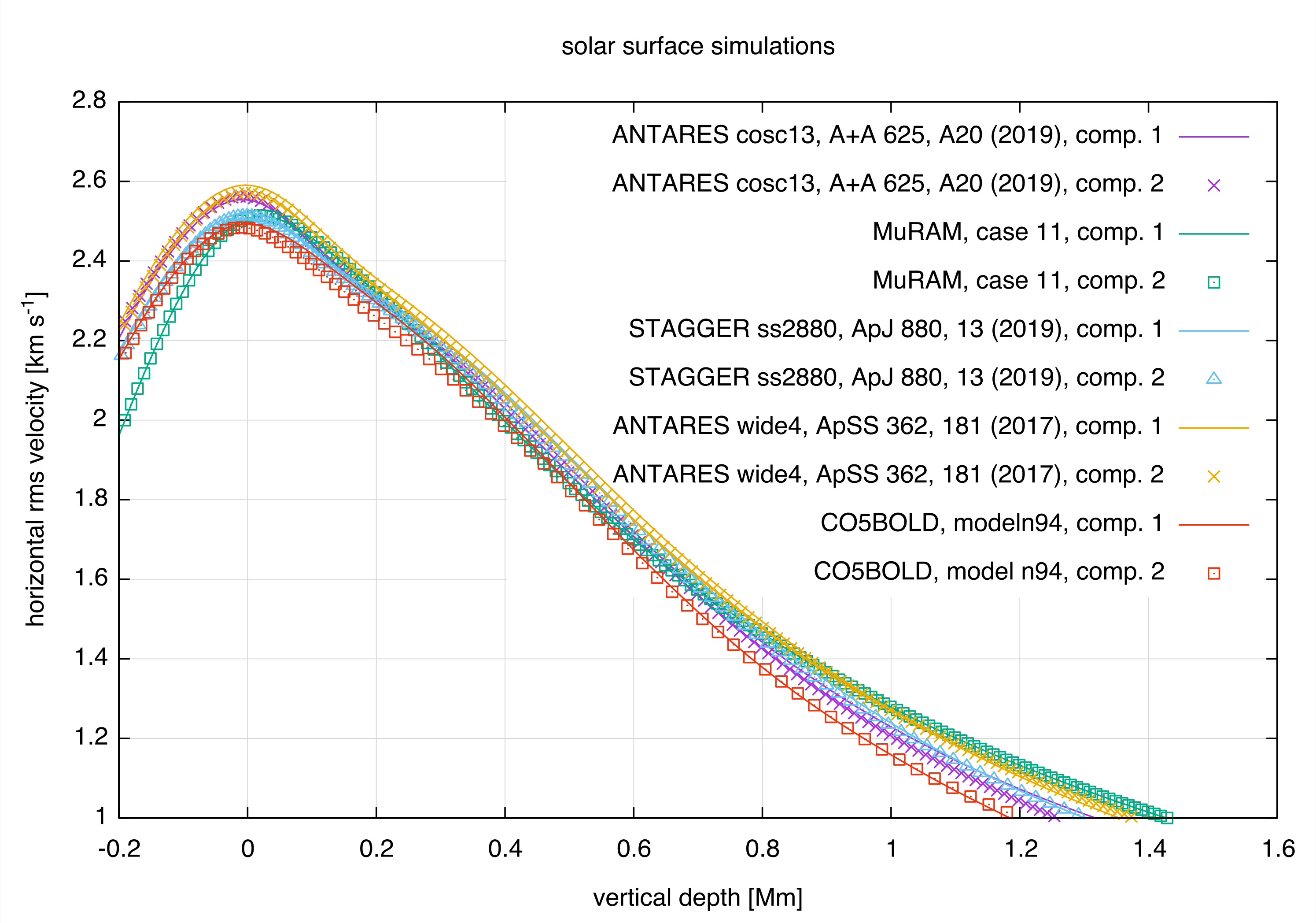
Zoom-in to make this more visible and also including the moderate resolution MuRAM case 10 for comparison (clear deviations of up to 0.1 km/s).



Comparing Mean Structure XI

Time and horizontally averaged horizontal RMS velocity

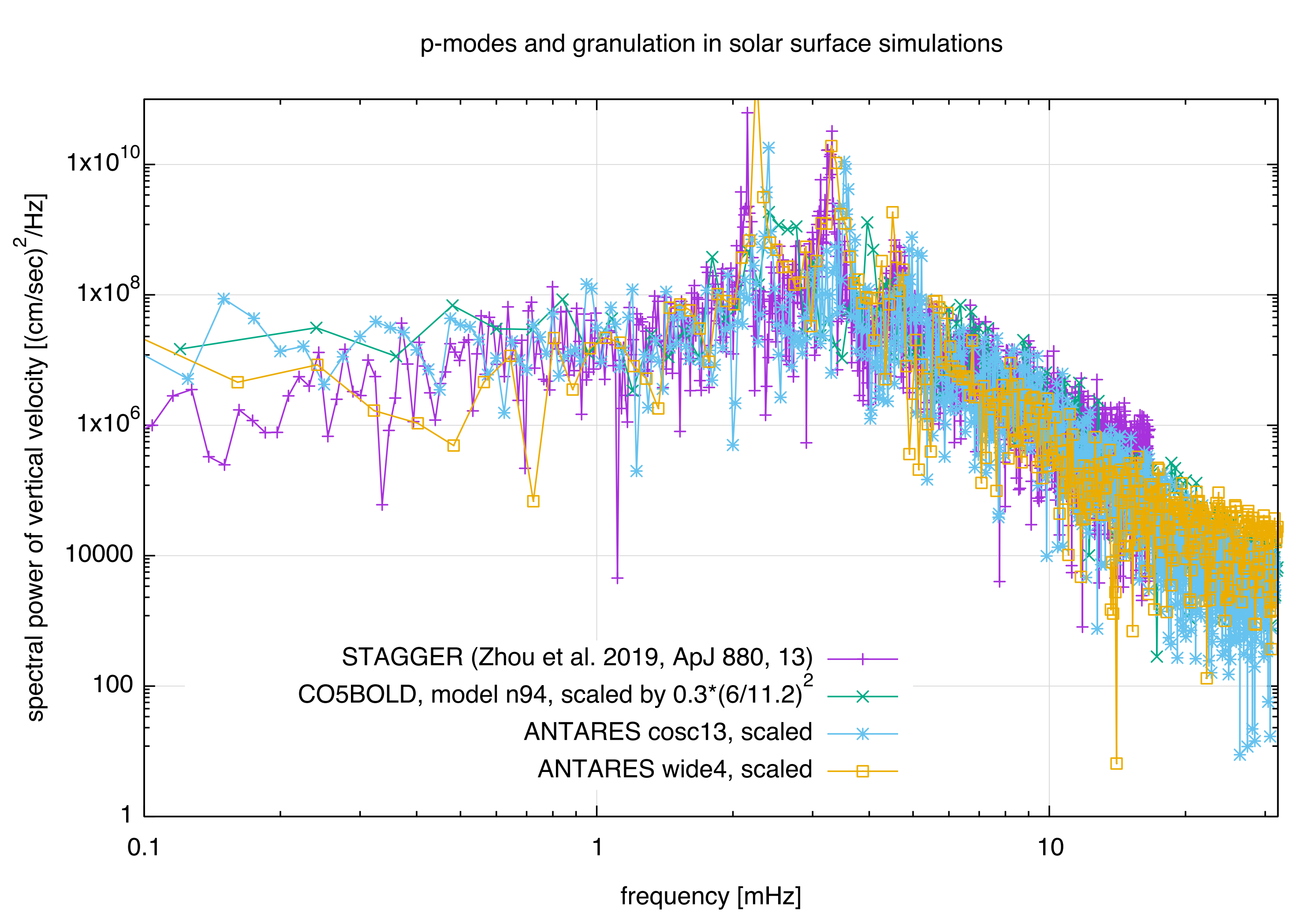
Zoom-in to make this more visible and now including the standard resolution MuRAM case 11 for comparison (much smaller differences except for the photosphere).



Comparing Power Spectra from 3D RHD I

Horizontally averaged vertical velocity time series power spectrum

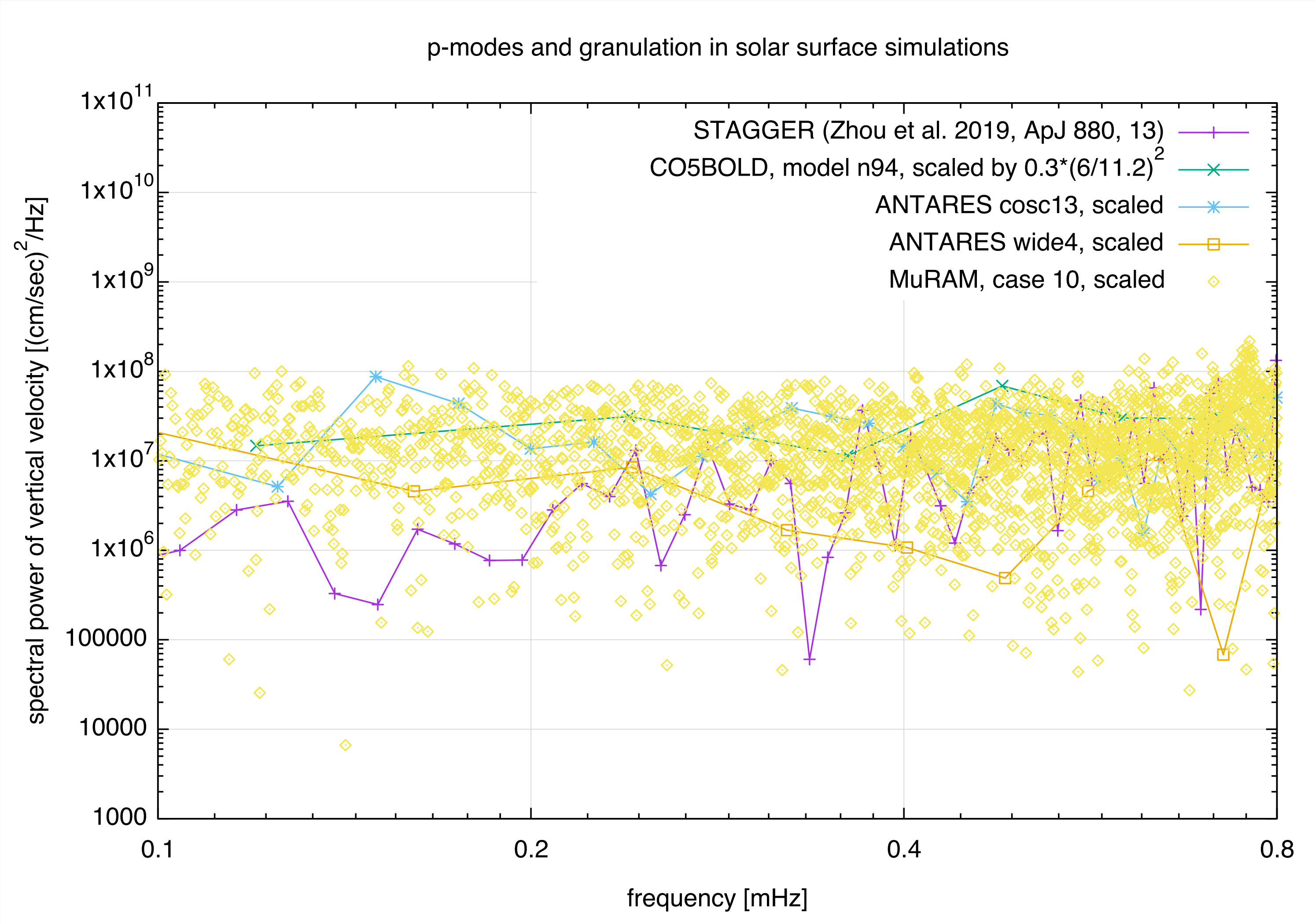
Layer: <T>=T_{eff}. Normalized @ [1,2] mHz. 2...3 p-modes. Low frequency power drop (ss2880): origin? For >5 mHz: effect of sampling rate (ss2880), domain width (wide4)!



Comparing Power Spectra from 3D RHD II

Horizontally averaged vertical velocity time series power spectrum

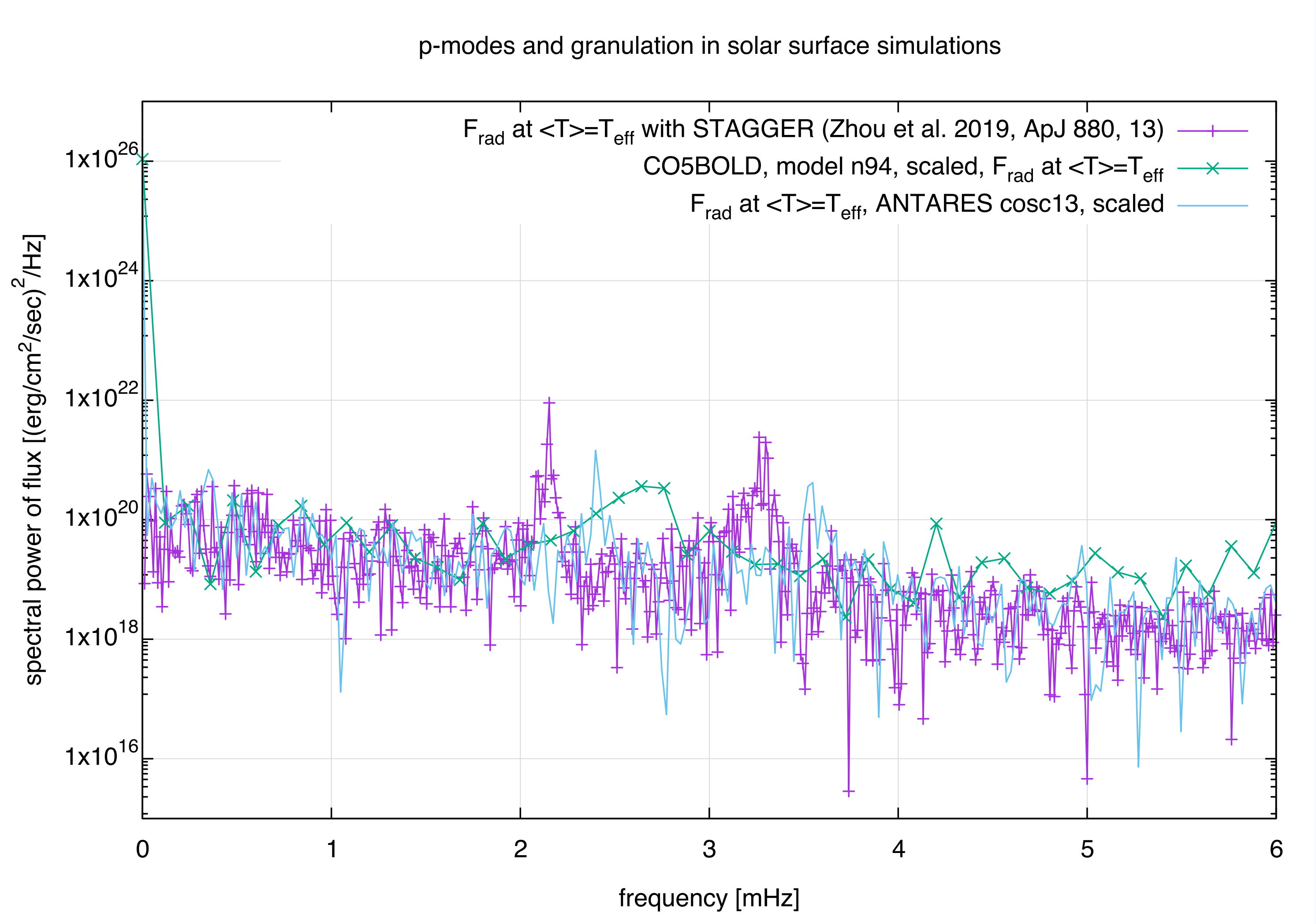
Low frequency range: MuRAM case 10 covers 36.5 days of solar time. It has a node placed 2 Mm above the surface (like ANTARES; CO5BOLD & STAGGER: anti-nodes).



Comparing Power Spectra from 3D RHD III

Horizontally averaged radiative flux time series power spectrum

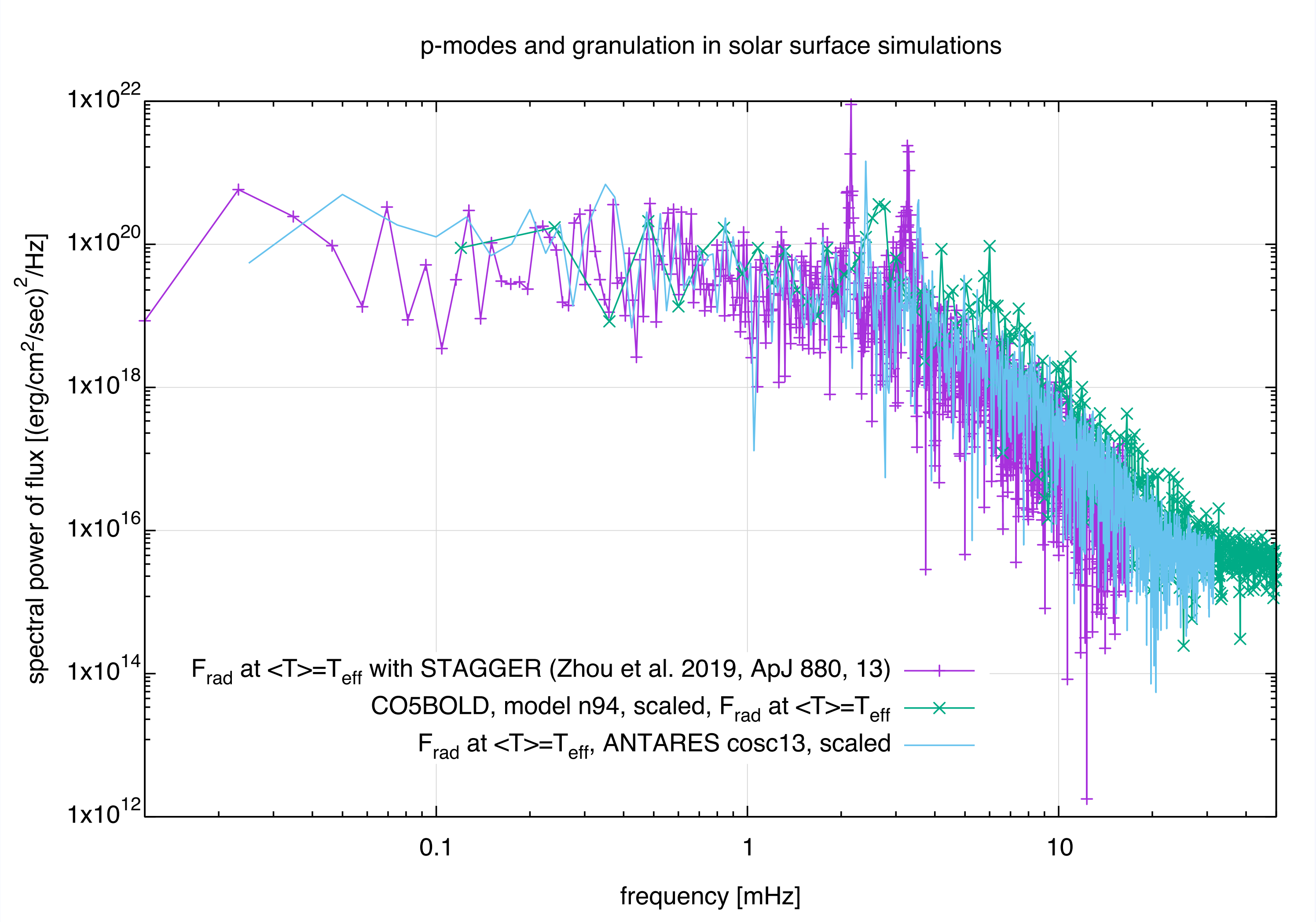
Here, F_{rad} has also been evaluated at <T(0)>=T_{eff}. Scaled to match in 1-2 mHz range. At least 2 p-modes visible for each of them. No power drops at low frequencies.



Comparing Power Spectra from 3D RHD IV

Horizontally averaged radiative flux time series power spectrum

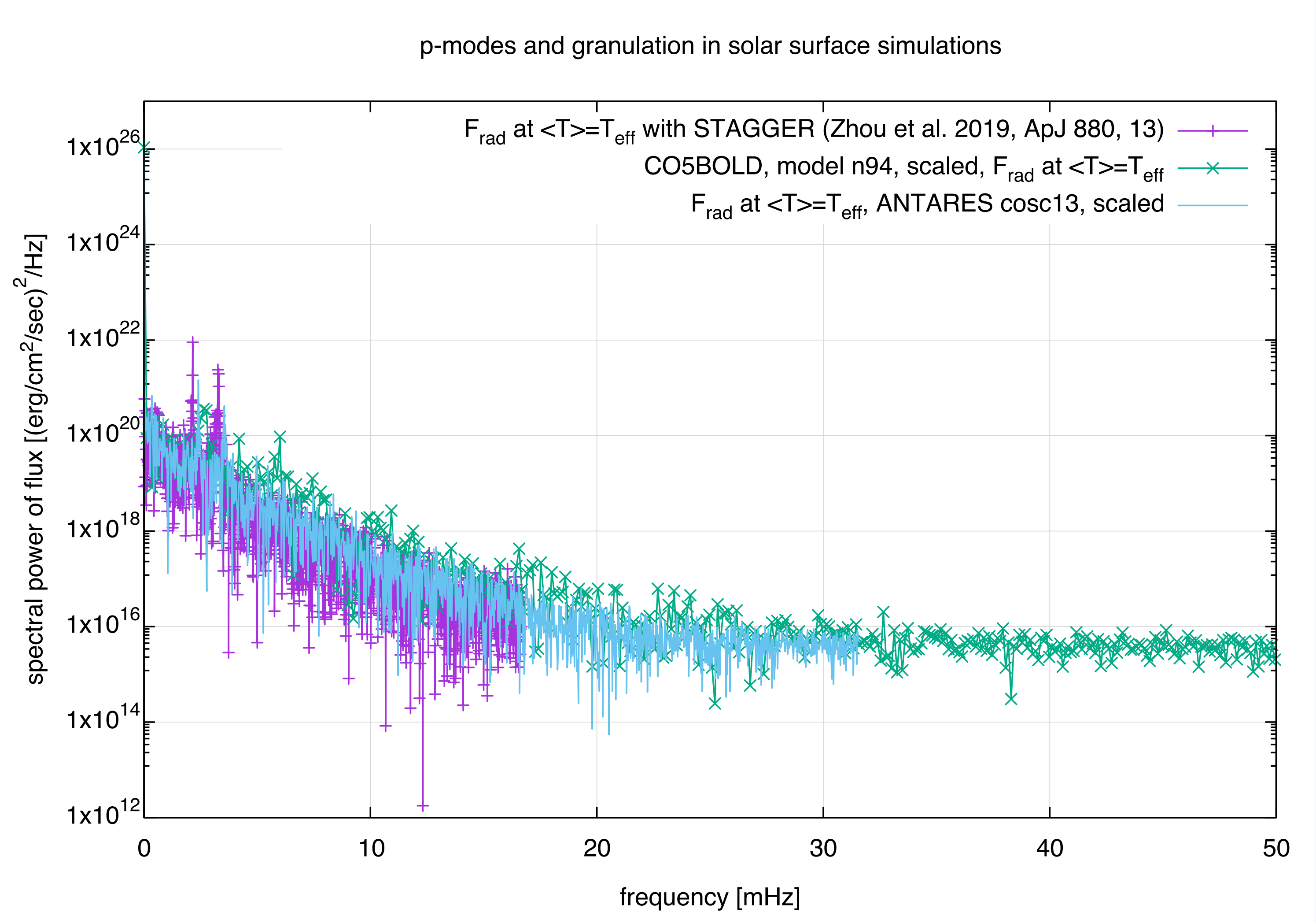
Power distribution of ANTARES cosc13 and STAGGER ss2880: similar resolution and width, different abundances. CO5BOLD n94: more high frequency power (box width?).



Comparing Power Spectra from 3D RHD V

Horizontally averaged radiative flux time series power spectrum

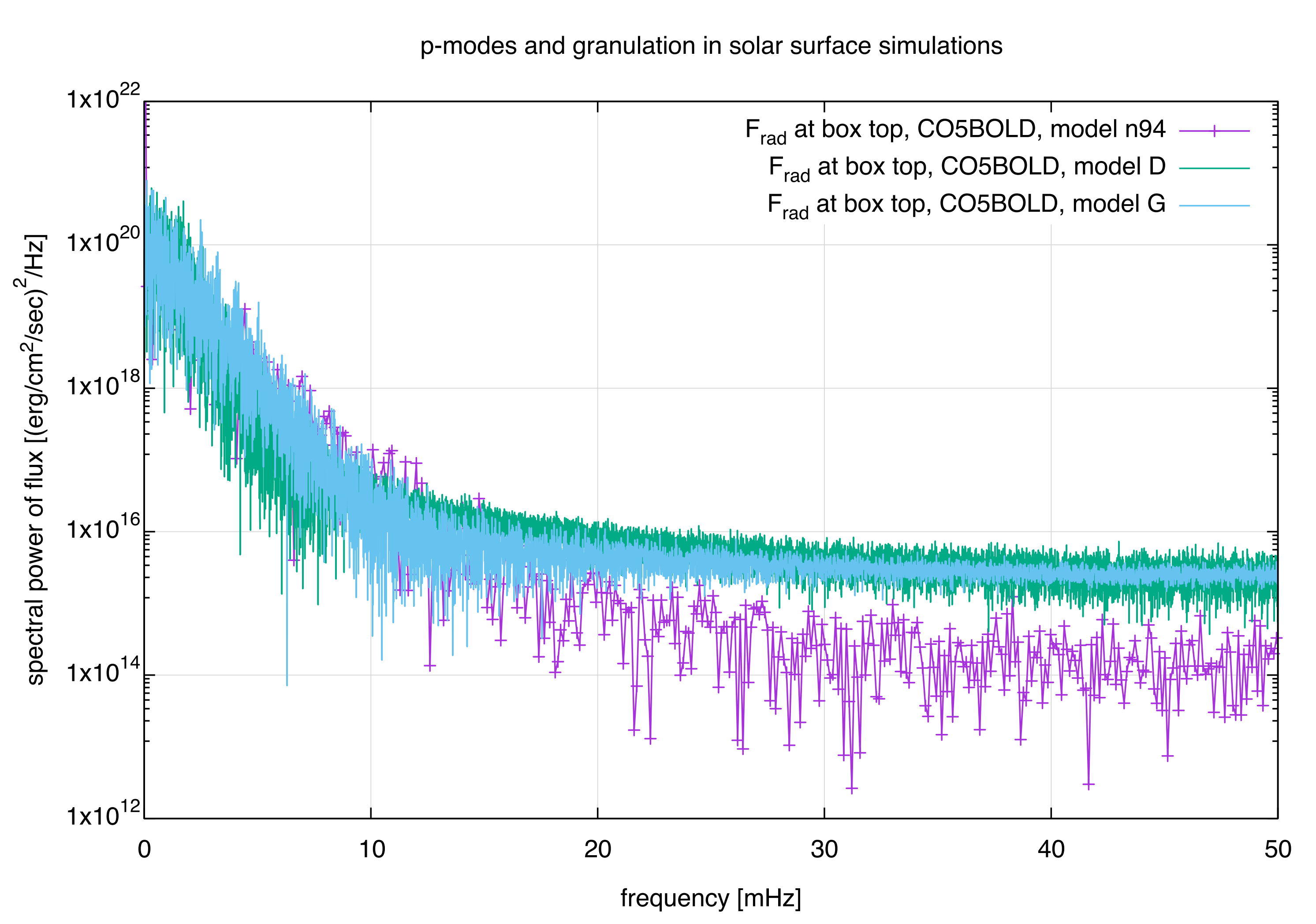
Contrary to the velocity power spectrum there is no pile up of power at 16 mHz for STAGGER ss2880. Slightly higher power in CO5BOLD n94 at high frequencies.



Comparing Power Spectra from 3D RHD VI

Horizontally averaged radiative flux time series power spectrum

For F_{rad} evaluated @ top, standard resolution model n94: more power at 6-12 mHz, less at >15 mHz (box width vs. grey RT). Effect of resolution between models D & G.



Comparing Power Spectra from 3D RHD VII

Horizontally averaged radiative flux time series power spectrum

Relative intensity variations evaluated @ top, models G (green, moderate resolution) & D (black, low resolution),18 Mm wide, smoothed signal: influence of resolution.

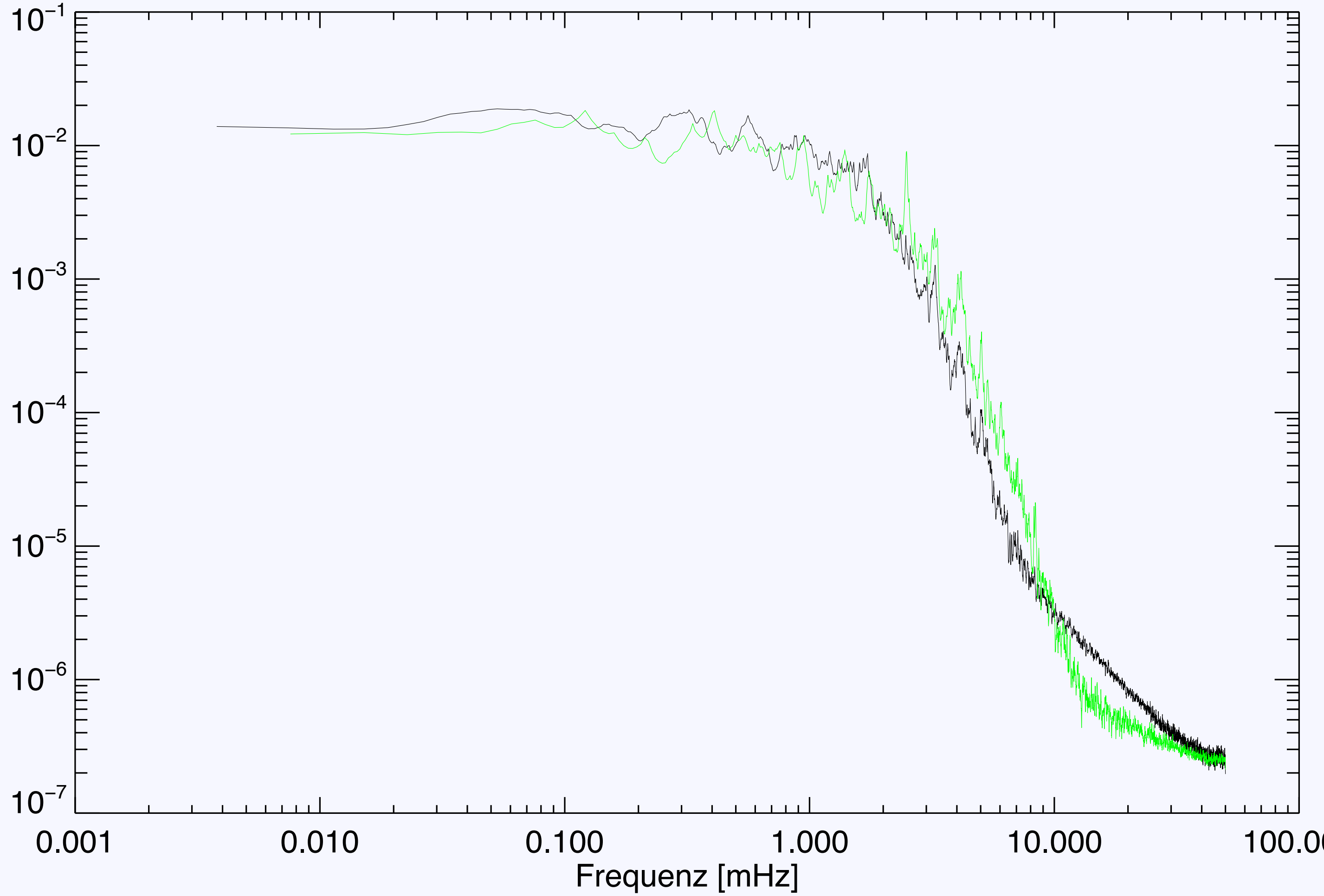


figure by courtesy of H.-G. Ludwig

Comparing Power Spectra from 3D RHD VIII

Horizontally averaged radiative flux time series power spectrum

Relative intensity variations evaluated @ top, similar resolution, 5.2 Mm width (model n53, black) vs. 18 Mm width (models G, green). For > 12 mHz: duration or width?

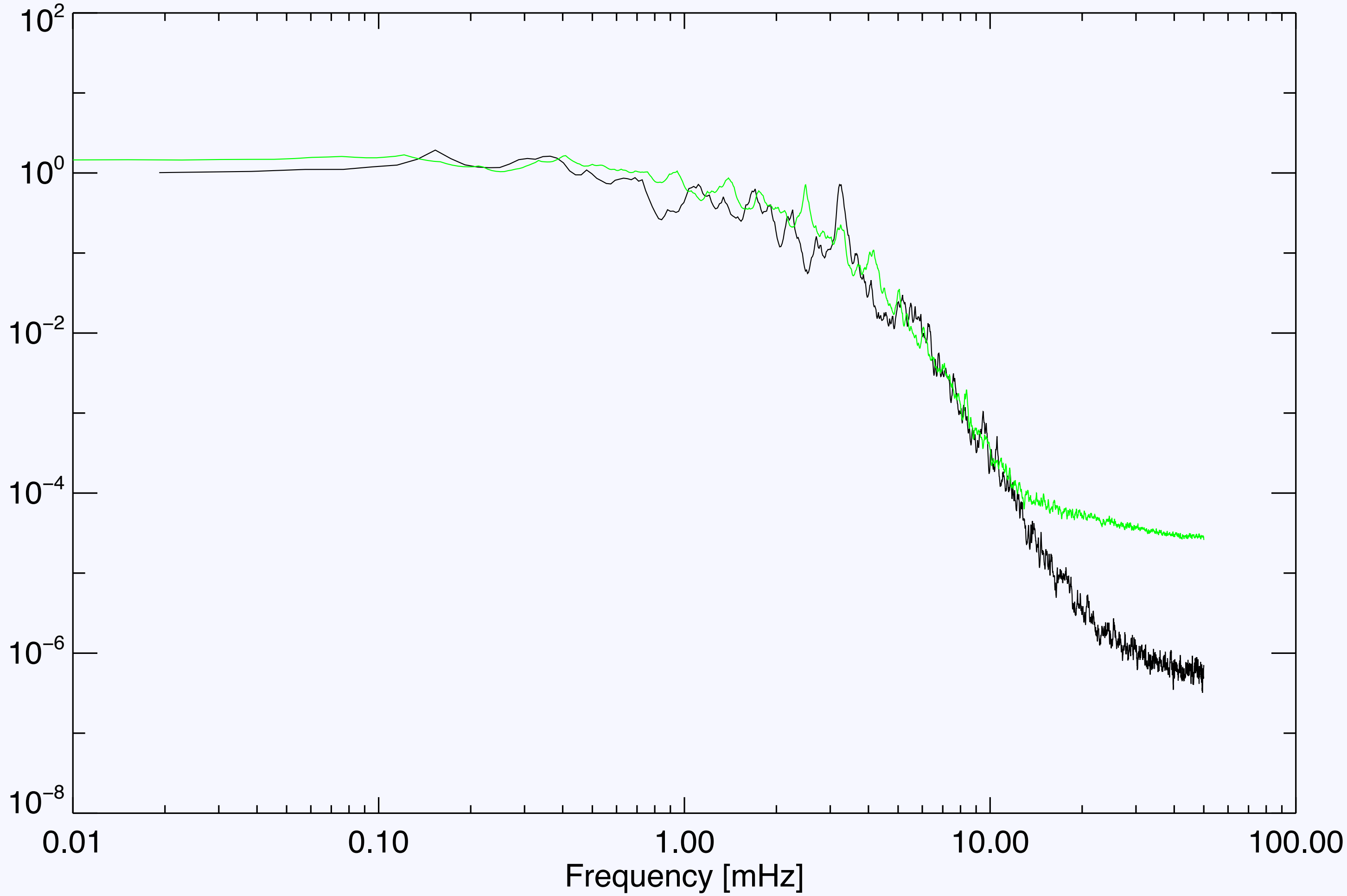


figure by courtesy of H.-G. Ludwig

Suggestion for High Frequency Behaviour

Horizontally averaged radiative flux time series power spectrum

Red: relative intensity variations evaluated @ top for the simulation of a K giant with CO5BOLD. Black: fit to data with p-mode, dot-dashed: p-mode subtracted.

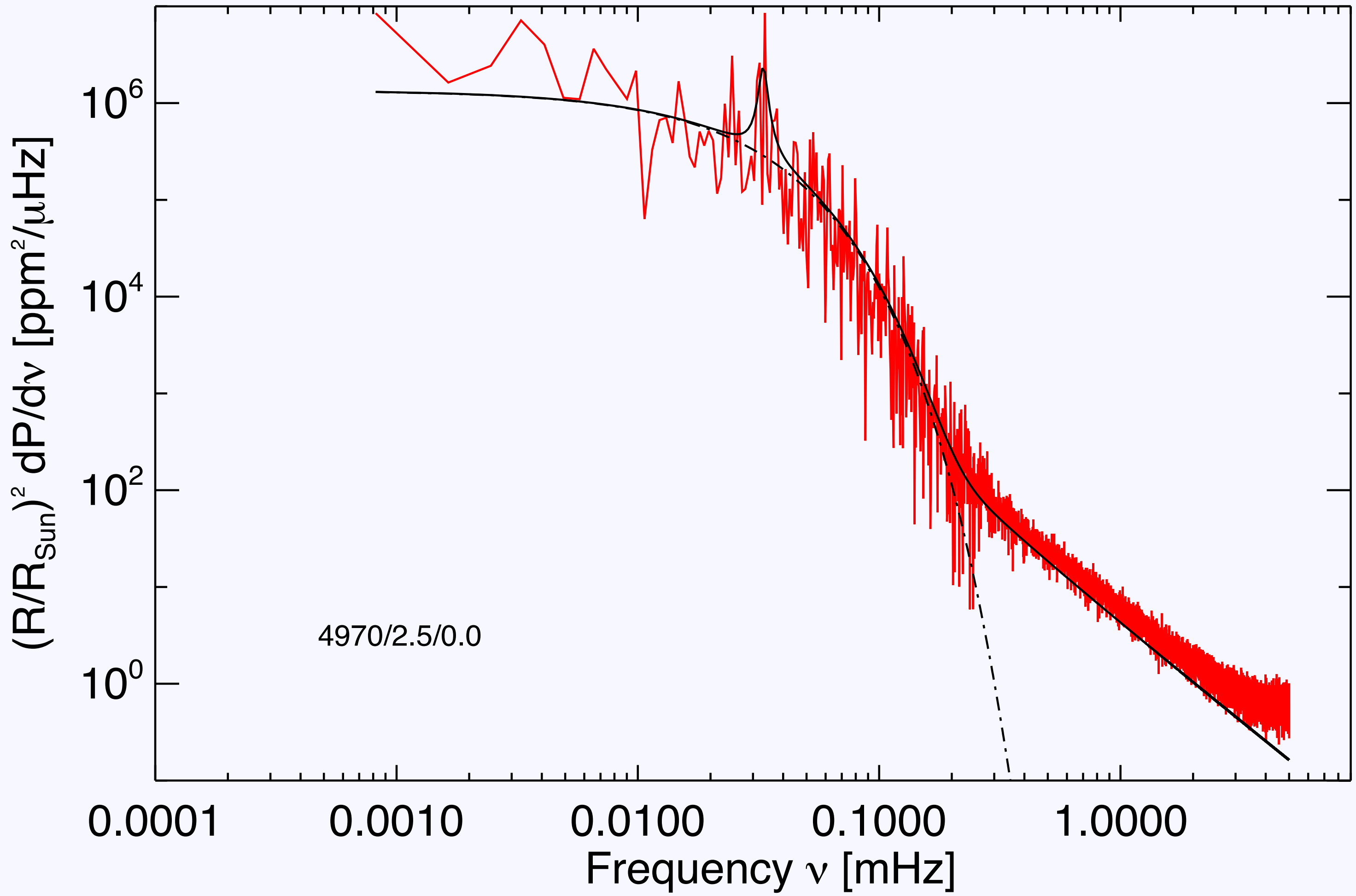


figure by courtesy of H.-G. Ludwig

Summary and Next Steps I

Lessons learned (with scales & rates for the Sun)

- Detailed chemical composition and numerical scheme (as long as its spatial order exceeds 2, for limiting numerical dissipation) less important.
- Reasonable agreement from 0.6 mHz to 12 mHz between ANTARES, CO5BOLD, and STAGGER for power in vertical velocity and radiative flux for standard resolution models ($h_{vertical} \sim 10$ km, $h_{horizontal} \sim 30$ km).
- Consider long (& wide, ≥18 Mm) simulations) to characterize 12-40 mHz range (realistic distribution of small / short-lived granules? p-mode(s) wings?).
- High enough output cadence mandatory: at least 16 sec, better ~10 sec.
- Need good spatial resolution ("standard resolution") to properly characterize the region from 6 to 12 mHz (resolution of 3D RHD abundance studies).
- For velocity power spectra in the frequency domain < 0.6 mHz the detailed top boundary condition may and the simulation time certainly does matter.

Summary and Next Steps II

Next steps

- Perform dedicated simulations fulfilling all these constraints
- Compare them among each other to probe the stability of their results
- Compare with solar data
- Repeat this procedure for stars other than the Sun
- Analyze signal contributions from 3D RHD point of view
- In parallel answering the questions originally posed:
  - Harvey-like profiles or alternatives ?
  - Provision of theoretical priors ?
  - log(g) measurements from granulation background: characterizations of uncertainties
  - High frequency parts of lightcurves ?
- 3D RMHD as next iteration (Low frequency contributions? High frequency?)

...THANK YOU FOR YOUR TIME !