Coupling 3D atmospheres into 1D stellar models

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Introduction

The 3D simulations

- Simulations of stellar atmospheres
- Constructed solving the time-dependant hydrodynamic equations of mass, momentum, and energy conservation
- Coupled to 3D radiative transfer equations to model the interaction between radiation and plasma
- No free-parameters, convection arises naturally

Introduction

The 3D simulations

- Computationally expensive: follow processes that occur in dynamical timescales (e.g., convection)
- Not suited for following nuclear timescales (e.g., stellar evolution)
- We want to used them to improve our 1D evolutionary calculations
- How can we couple their predictions to our simplified model of the outer stellar layers?

Introduction

Convective transport: mixing length theory

- It assumes a bubble travels a characteristic distance and then dissolves
- The mixing length parameter scales this distance
- The temperature gradient in convective instability is calculated after some geometrical assumptions and defining the mixing length parameter

$$\ell = \alpha_{\mathrm{mlt}} H_P$$

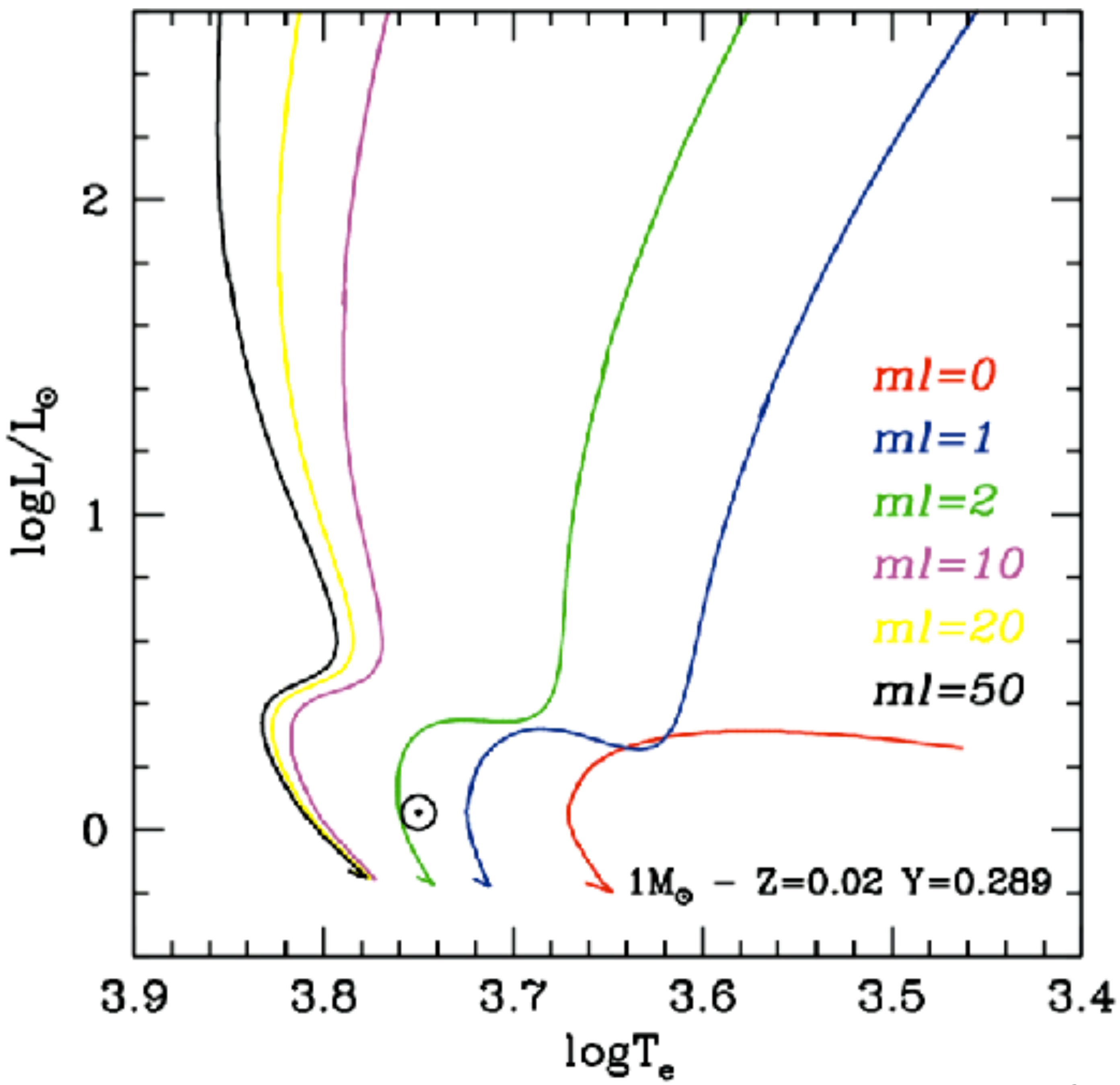
Introduction

Convective transport: the Sun

- The mixing length parameter is normally calibrated to reproduce solar properties
- Standard Solar Model (SSM): evolve a fully homogeneous 1 $M_\odot$ model from the pre-MS to solar age
- SSM must match solar radius, luminosity, and surface metals-to-hydrogen ratio at the solar age
- Three adjustable parameters: initial composition and mixing-length parameter

Introduction

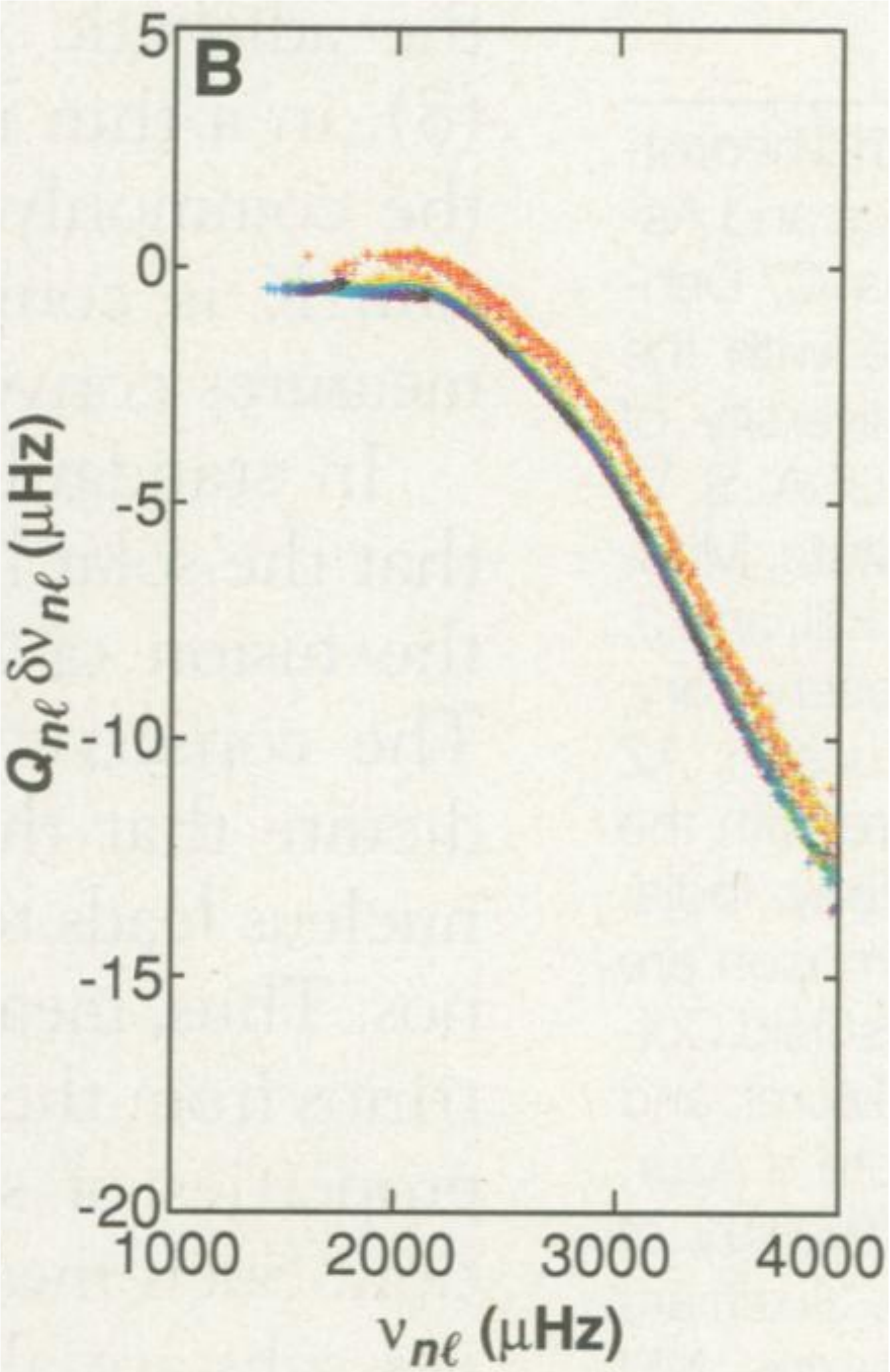
The temperature scale



Courtesy of S. Cassisi

Introduction

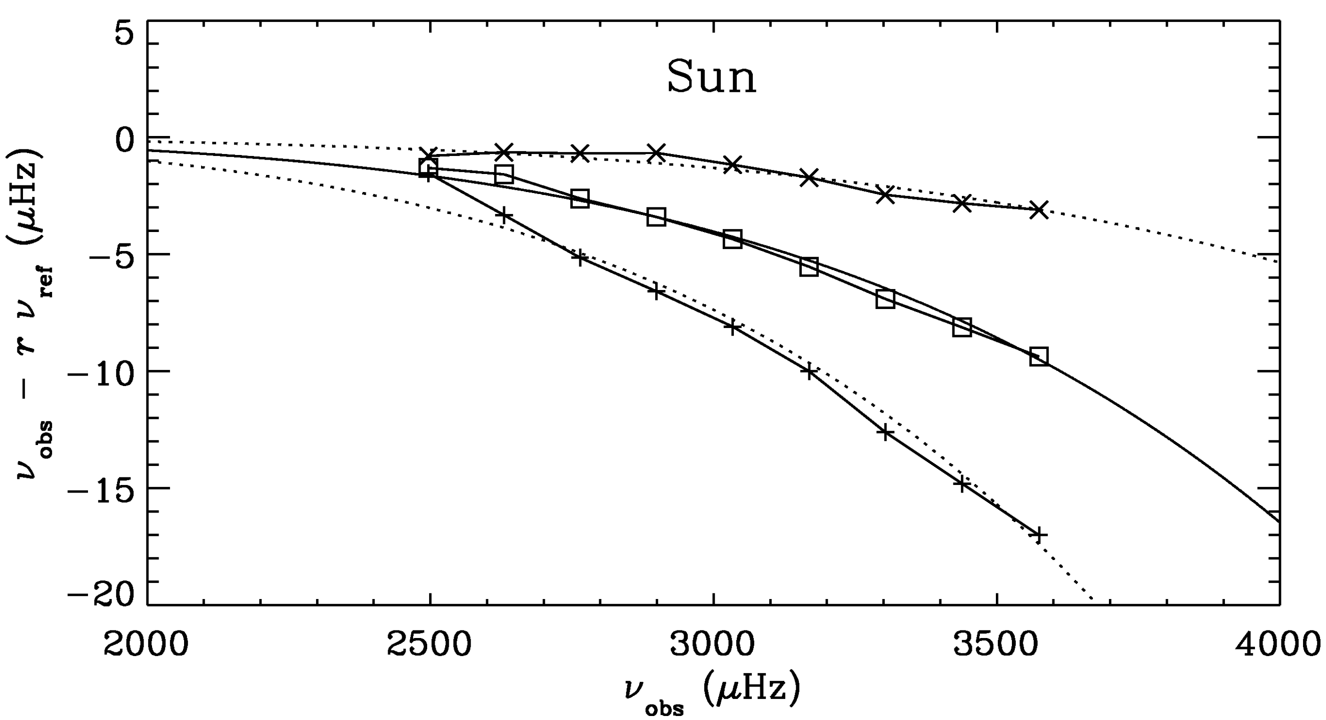
The surface effect



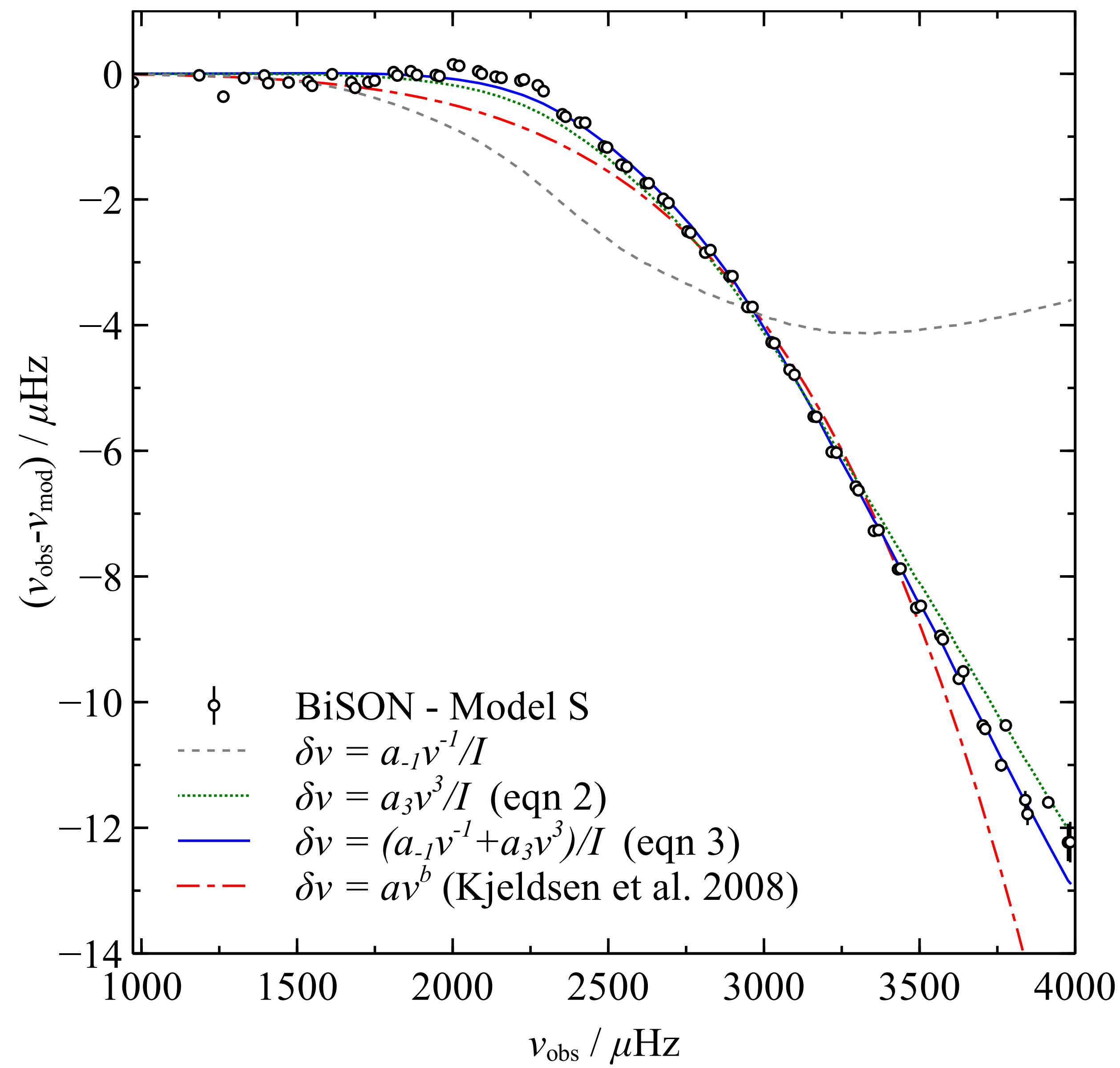
Christensen-Dalsgaard et al. 1996

Introduction

The surface effect



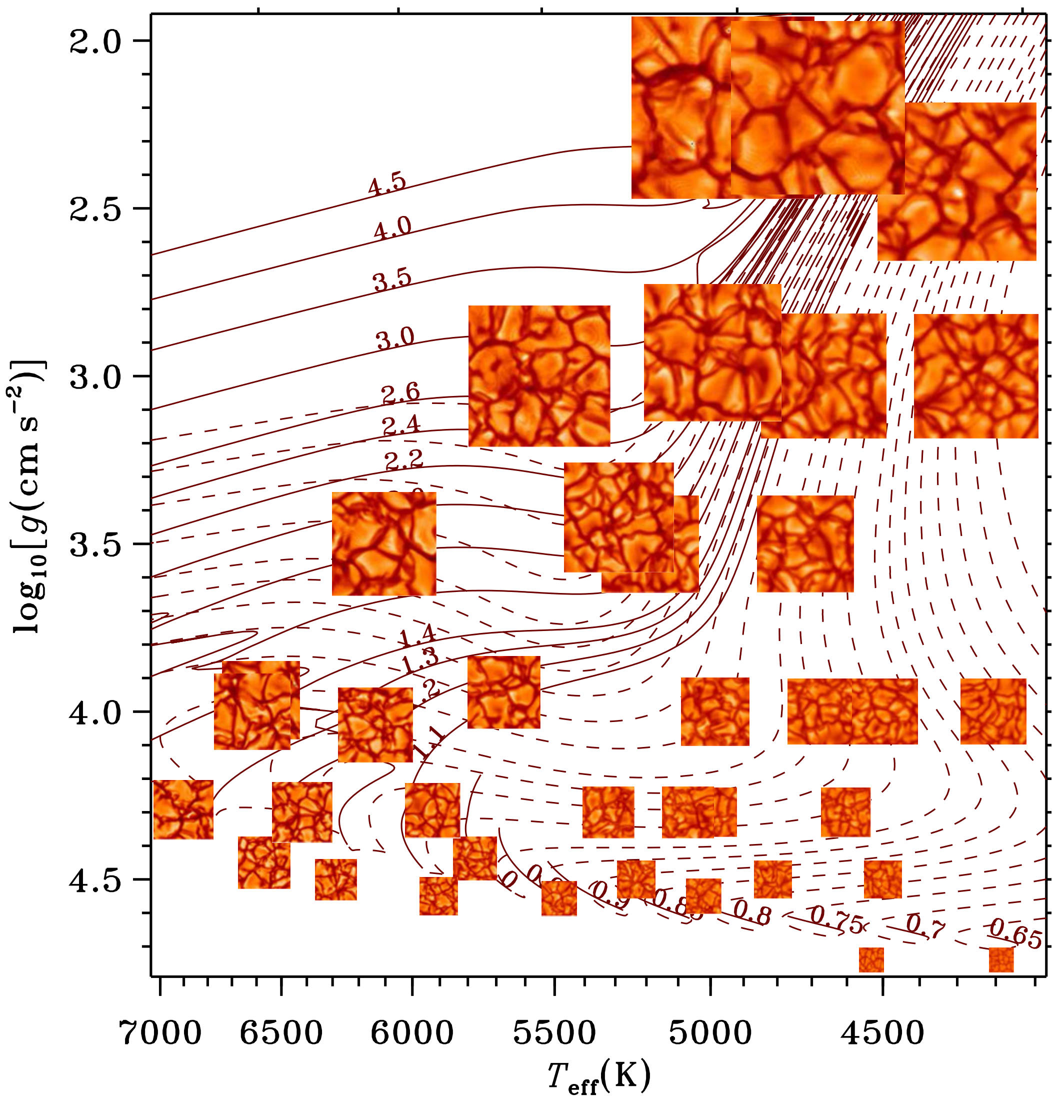
Kjeldsen et al. 2008



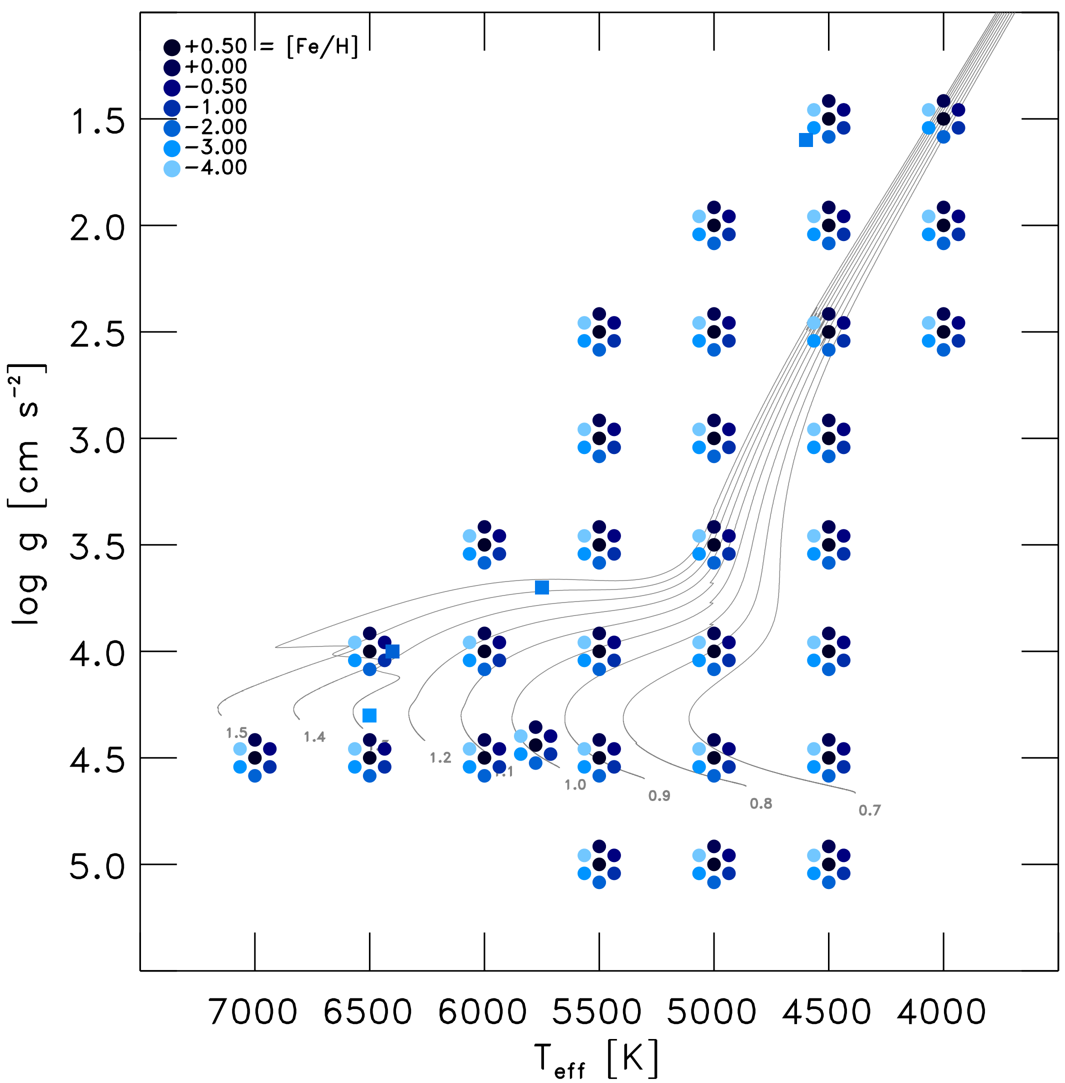
Ball & Gizon 2014

Grids of 3D simulations

Examples: what is available



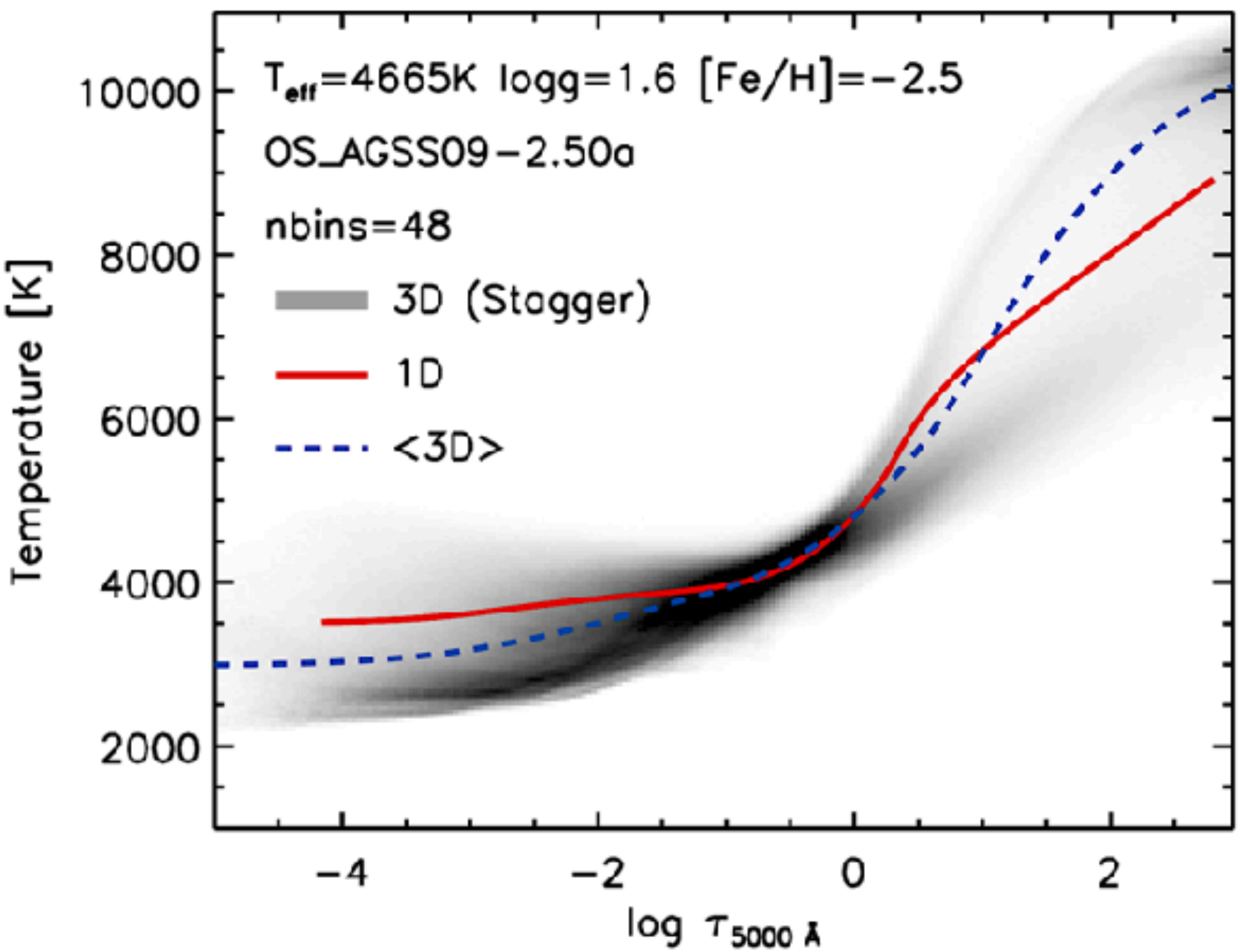
Trampedach et al. 2014



Magic et al. 2013

Grids of 3D simulations

Mean stratifications



Courtesy of R. Collet

Coupling 3D to 1D

A rapidly developing field

- Use mean 3D stratifications to calibrate free parameters (mixing length)
- Use boundary conditions and T-τ relations from the 3D simulations
- Use patched models for specific simulations (no time evolution)
- The stellar models of the future: on-the-fly patching of 3D mean structures

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Coupling 3D to 1D

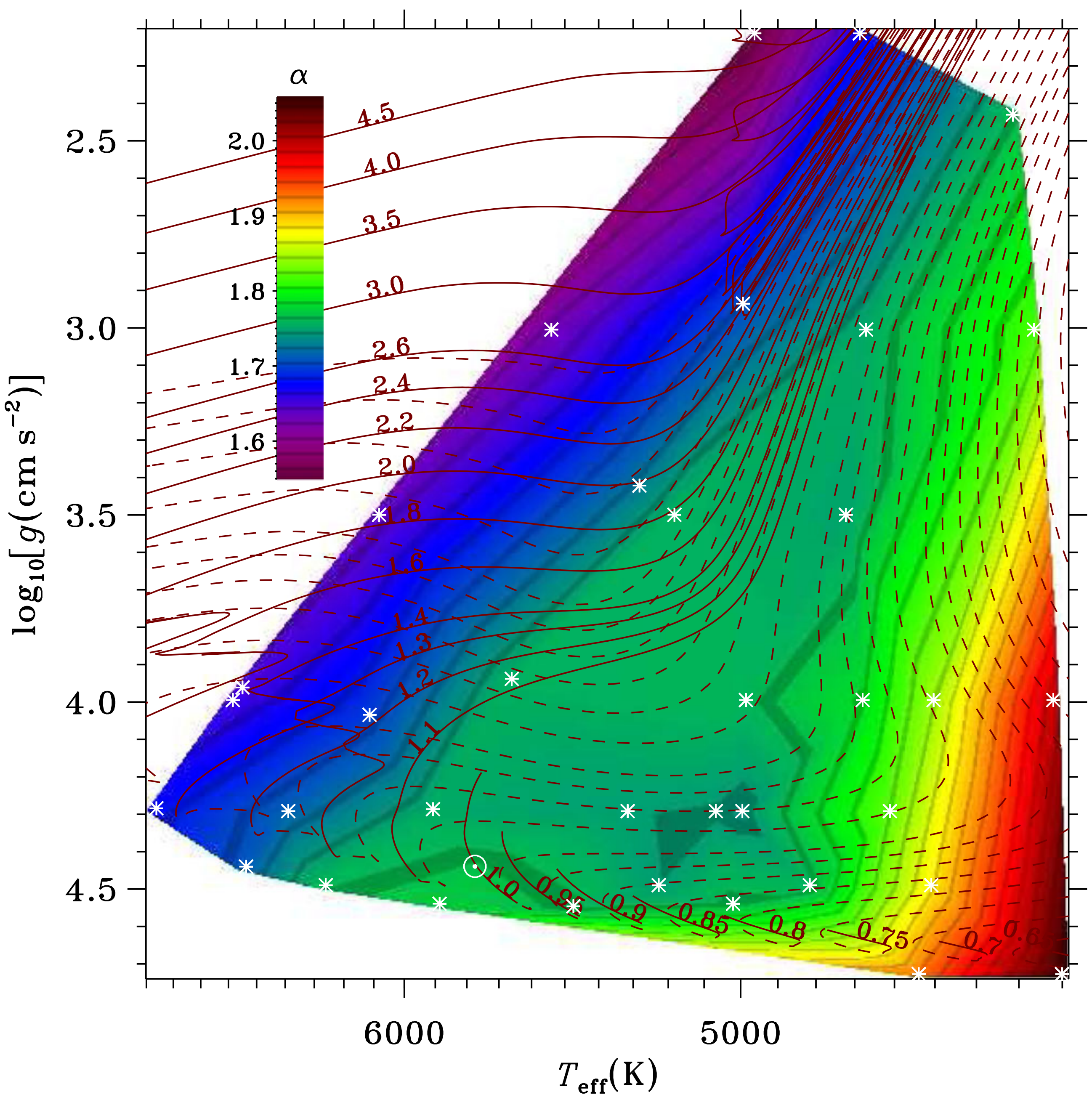
Calibrating the mixing length

- Produce 1D envelope structures with as similar input physics as the simulations as possible
- Vary the mixing length in the 1D structure to match thermodynamical quantities at the bottom of the simulation (e.g., entropy, temperature)
- Result: temperature, gravity, and metallicity dependant mixing-length parameter

Ludwig et al. 1999
Trampedach et al. 2014
Magic et al. 2015

Coupling 3D to 1D

Calibrating the mixing length



Trampedach et al. 2014

Calibrating the mixing length

Appendix B: Functional fits

Similar to Ludwig et al. (1999), we performed functional fits of the mixing length parameters and the mass mixing length parameter with the $T_{\rm eff}$ and $\log g$ for the different metallicities individually. We transformed the stellar parameters with $x = (T_{\rm eff} - 5777)/1000$ and $y = \log g - 4.44$, and fitted the values with a least-squares minimization method for the functional basis

$$f(x, y) = a_0 + (a_1 + (a_3 + a_5 x + a_6 y)\, x + a_4 y)\, x + a_2 y. \quad \text{(B.1)}$$

The resulting coefficients, a_i, are listed in Table B.1.

Table B.1. Coefficients a_i of the linear function f (Eq. (B.1)) for $\alpha_{\rm MLT}(s_{\rm bot})$, $\alpha_{\rm MLT}(\Delta s)$, and $\alpha_{\rm m}$ for different metallicities.

Value	[Fe/H]	a_0	a_1	a_2	a_3	a_4	a_5	a_6	rmsΔ	maxΔ
$\alpha_{\rm MLT}(s_{\rm bot})$	+0.5	1.973739	–0.134290	0.163201	0.032132	0.046759	–0.025605	0.052871	0.022	0.040
	+0.0	1.976078	–0.110071	0.175605	0.003978	0.103336	–0.058691	0.080557	0.017	0.038
	–0.5	1.956357	–0.133645	0.133825	0.027491	0.049125	–0.048045	0.057956	0.027	0.042
	–1.0	1.969945	–0.143710	0.149004	0.001154	0.052837	–0.033471	0.037823	0.020	0.058
	–2.0	2.010997	0.012308	0.160894	–0.041272	0.180486	–0.059577	0.074409	0.033	0.067
	–3.0	2.133974	0.053307	0.222283	–0.192920	0.225412	–0.064937	0.027230	0.066	0.149
$\alpha_{\rm MLT}(\Delta s)$	+0.5	2.060065	–0.075697	0.183750	0.018061	0.160931	–0.110880	0.164789	0.063	0.091
	+0.0	2.077069	–0.079283	0.153376	0.041062	0.098795	–0.108972	0.137377	0.075	0.139
	–0.5	2.080653	–0.117156	0.139250	0.105874	0.063015	–0.104596	0.143233	0.095	0.206
	–1.0	2.131896	–0.135578	0.195694	0.039771	0.109232	–0.074565	0.110530	0.054	0.096
	–2.0	2.229049	–0.068633	0.248141	–0.043729	0.229523	–0.088846	0.112805	0.056	0.136
	–3.0	2.324527	–0.011662	0.293515	–0.171136	0.305021	–0.112595	0.077837	0.109	0.248

Magic et al. 2015

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Coupling 3D to 1D

The T-τ relations

- From the same calibration to extract the mixing-length, one can obtain the average temperature stratification
- This is given in terms of a generalised hopf function, and requires a change in the boundary condition
- Can be consistently implemented in 1D calculations together with the variable mixing-length

Salaris & Cassisi 2015
Mosumgaard et al. 2018

Coupling 3D to 1D

The T-τ relations

$\tau = \tau_{surf}$

Atmosphere

$$T(\tau) = T_{hopf}(\tau)$$

$\tau = \tau_{eff}$

Stellar interior

$$\alpha_{MLT} = K_{MLT}\,\alpha_{MLT}(T_{eff}, \log g)$$
$$\nabla_{rad} = \widetilde{\nabla}_{rad}[1 + q'(\tau)]$$

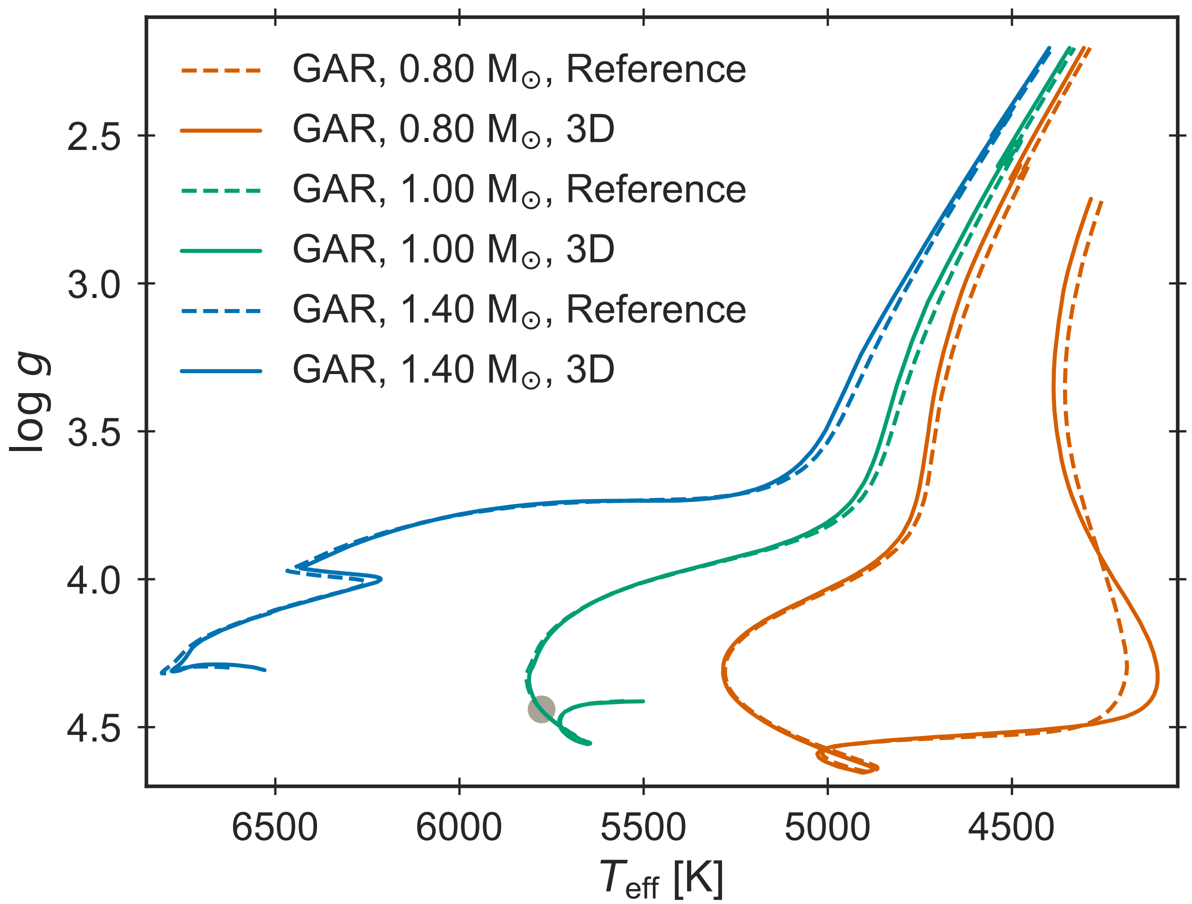
$\tau = 10$

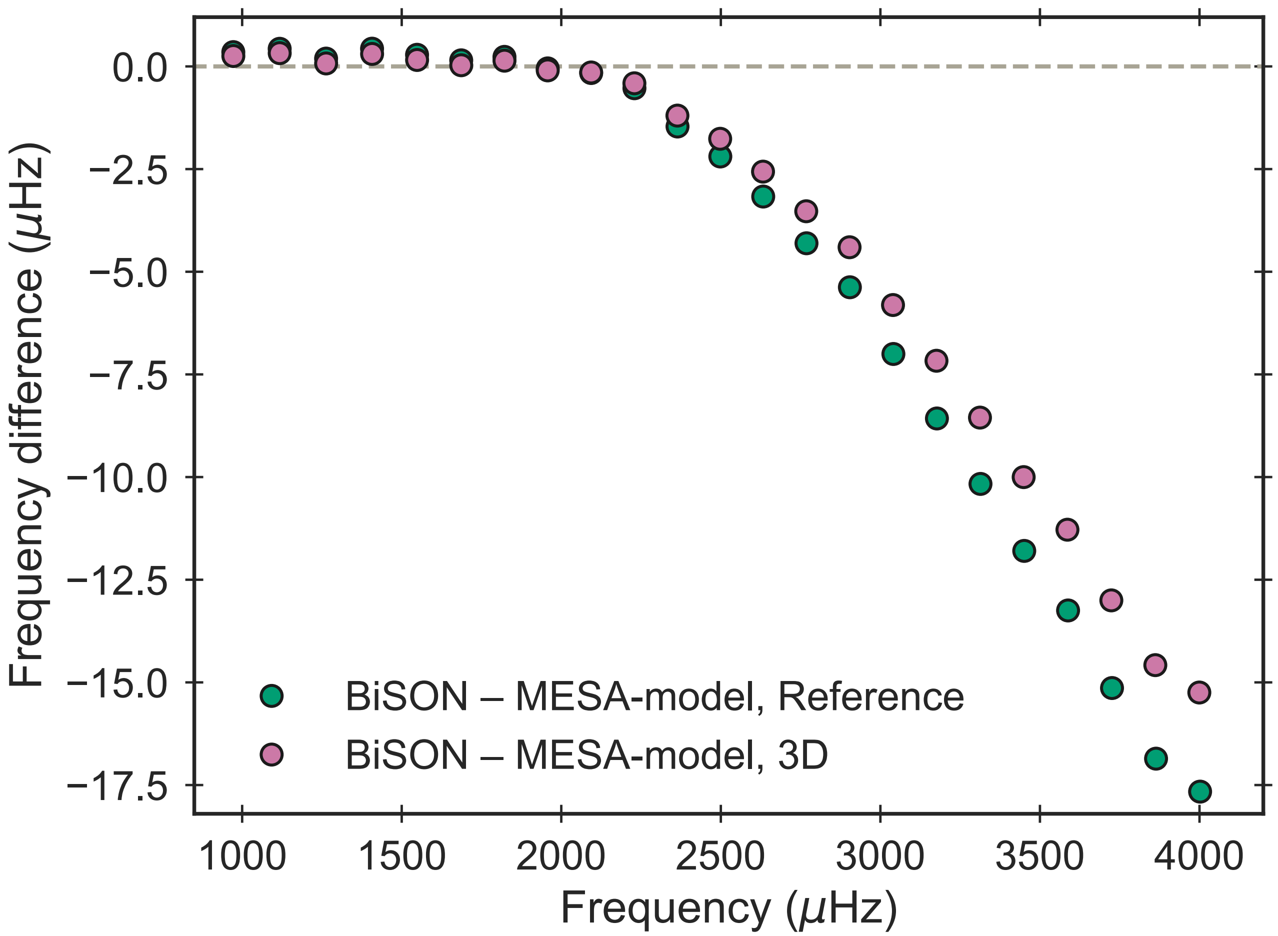
$$\alpha_{MLT} = K_{MLT}\,\alpha_{MLT}(T_{eff}, \log g)$$
$$\nabla_{rad} = \widetilde{\nabla}_{rad}$$

Salaris & Cassisi 2015
Mosumgaard et al. 2018

Coupling 3D to 1D

The T-τ relations





Mosumgaard et al. 2018

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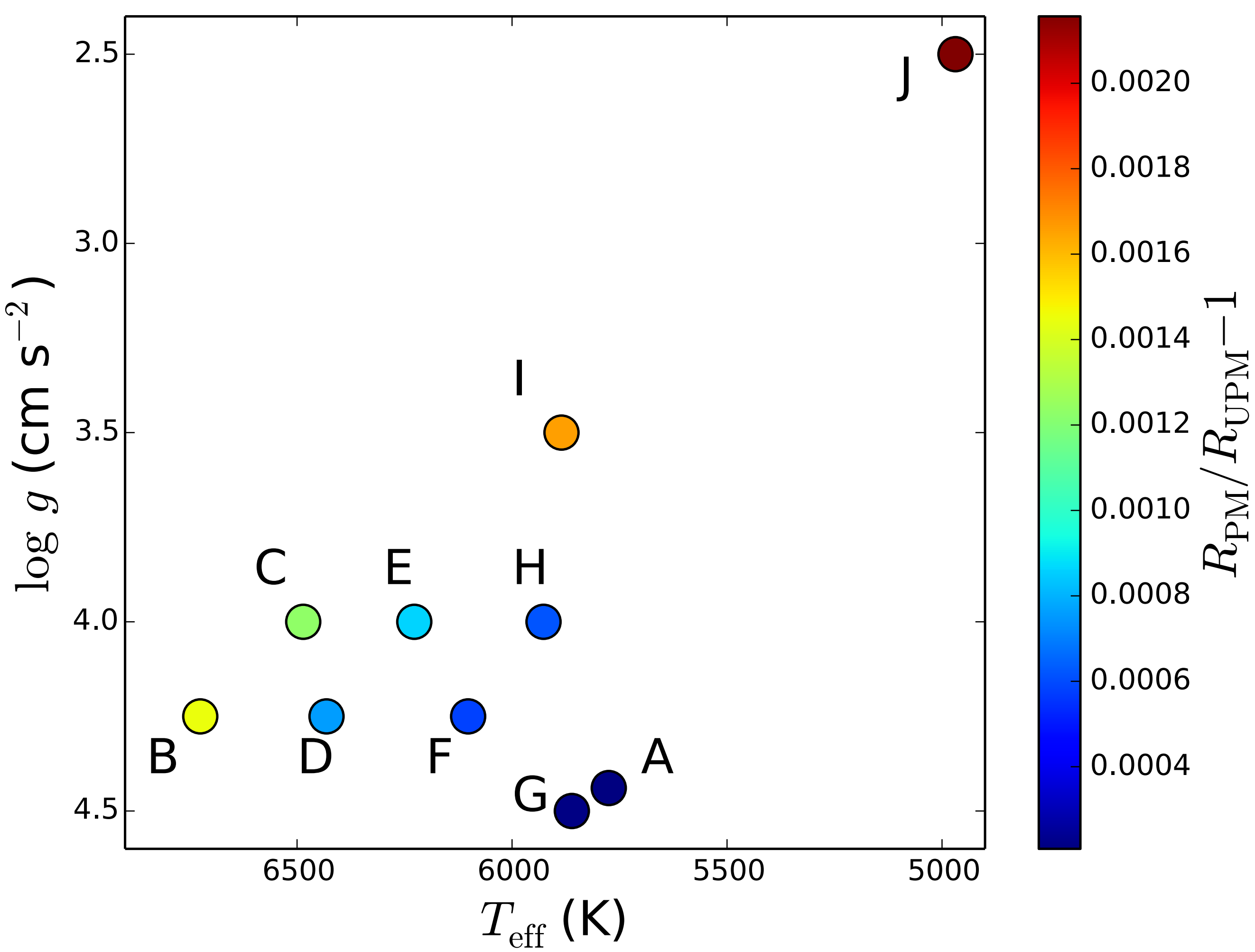
Coupling 3D to 1D

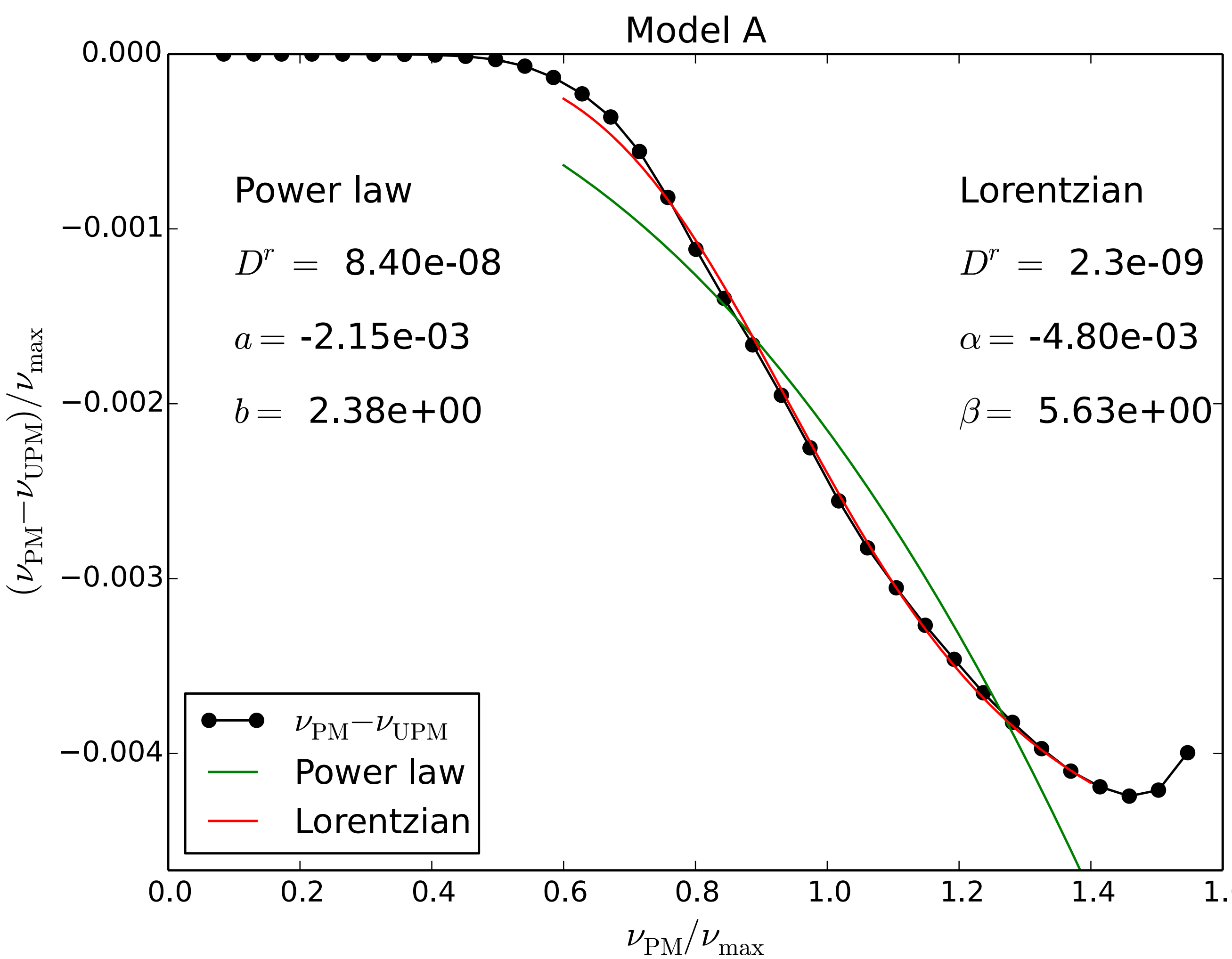
Patched models

- Compute a 1D structure that matches the simulation's Teff and log(g) modifying mass and age
- Fit a quantity at the bottom of the simulation (e.g., pressure or temperature) varying the mixing length
- Peel-off outer layers and use the mean 3D stratification for temperature, pressure, density, etc.

Coupling 3D to 1D

Patched models

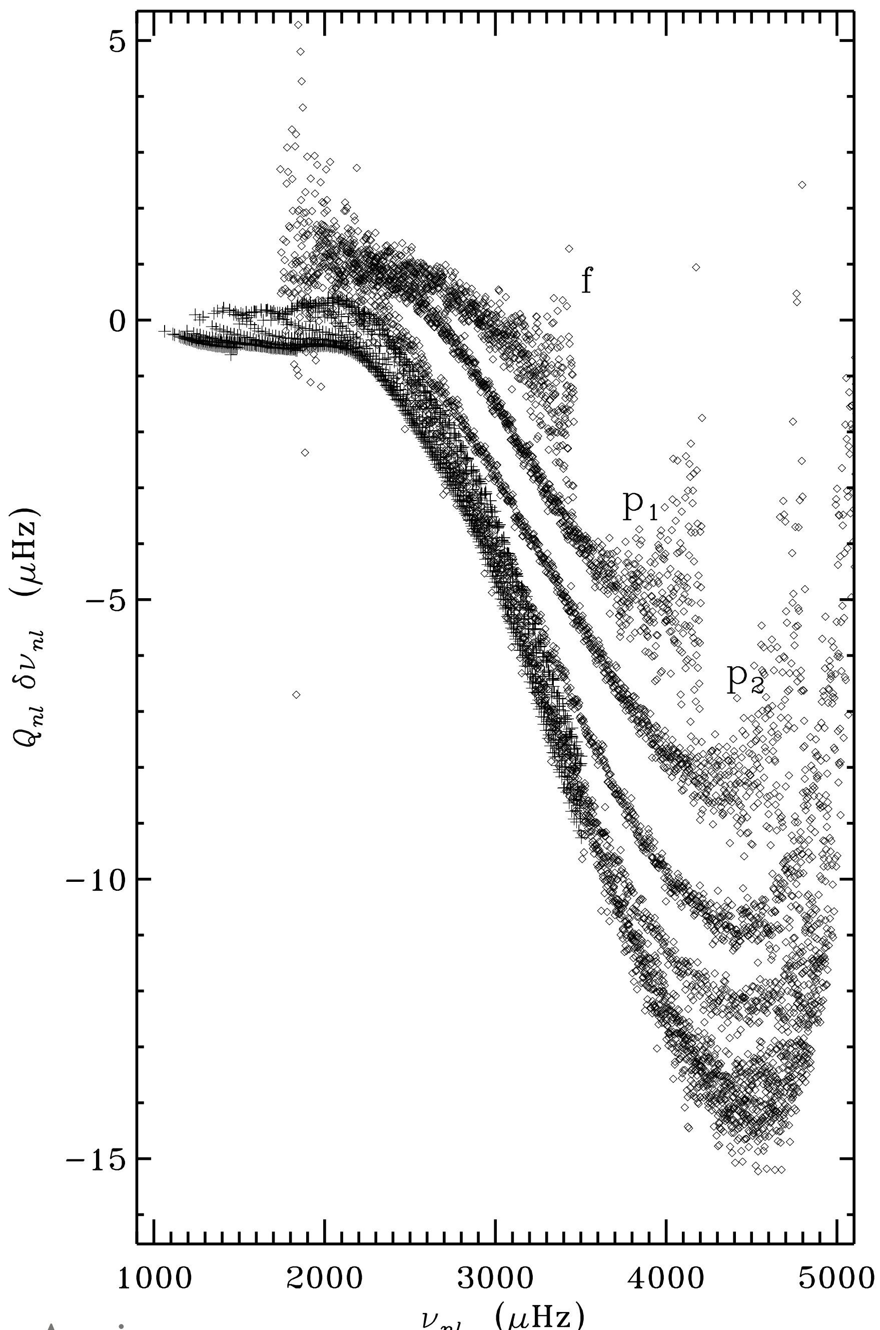


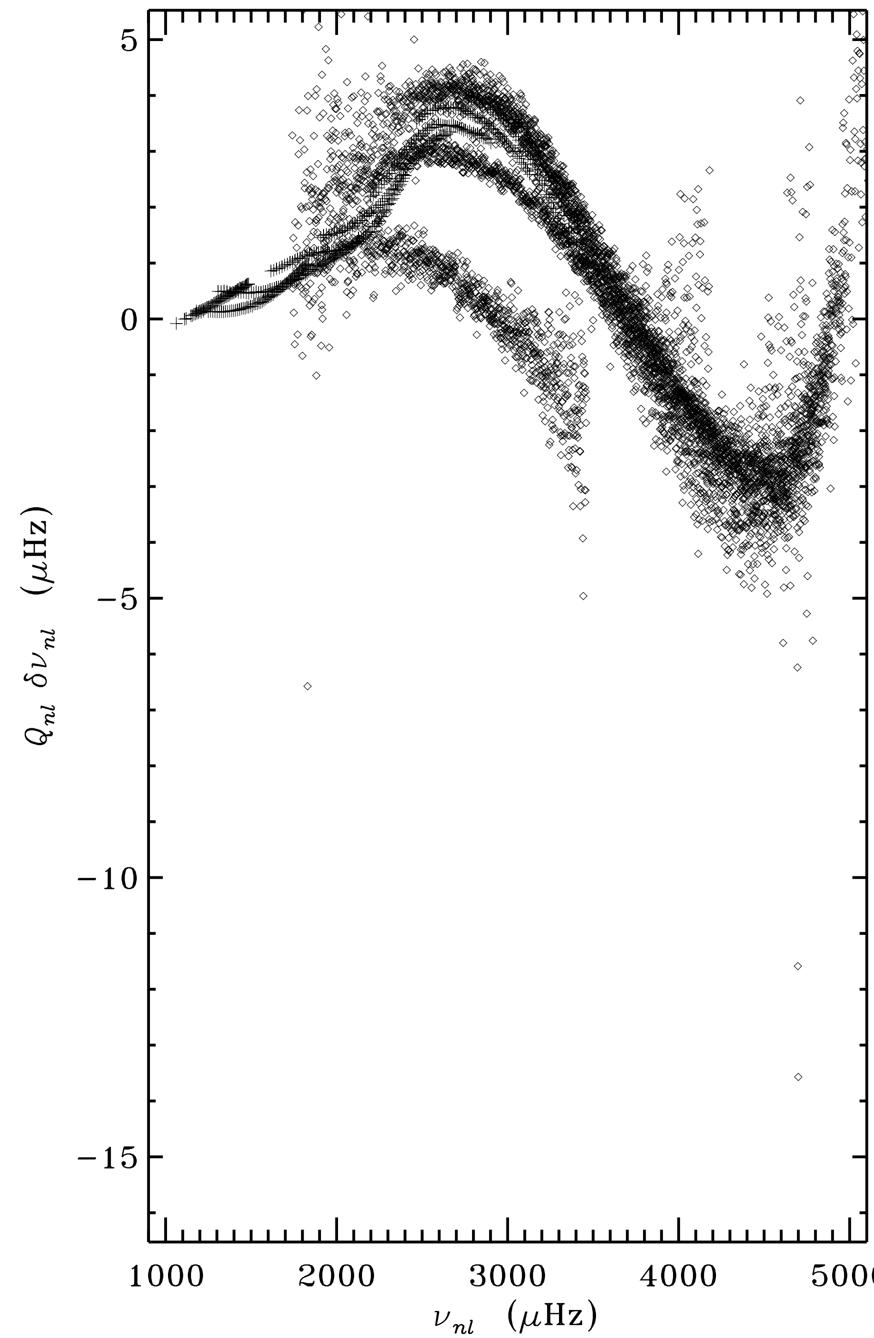


Sonoi et al. 2015

Coupling 3D to 1D

Patched models

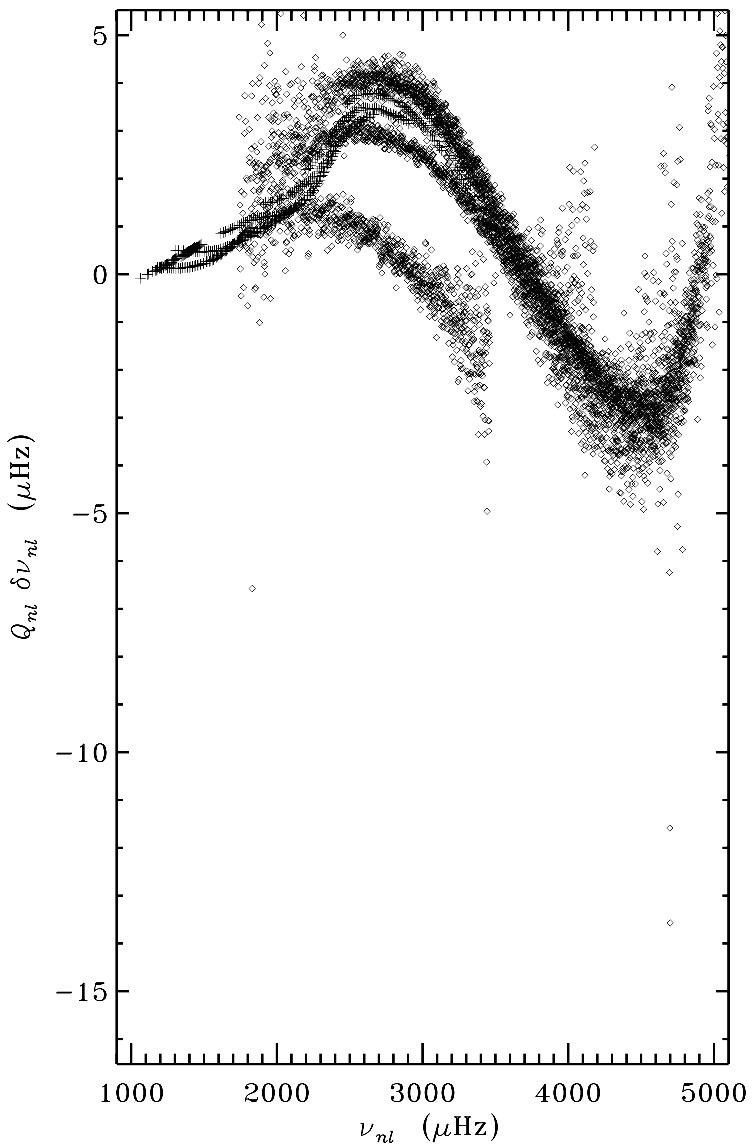


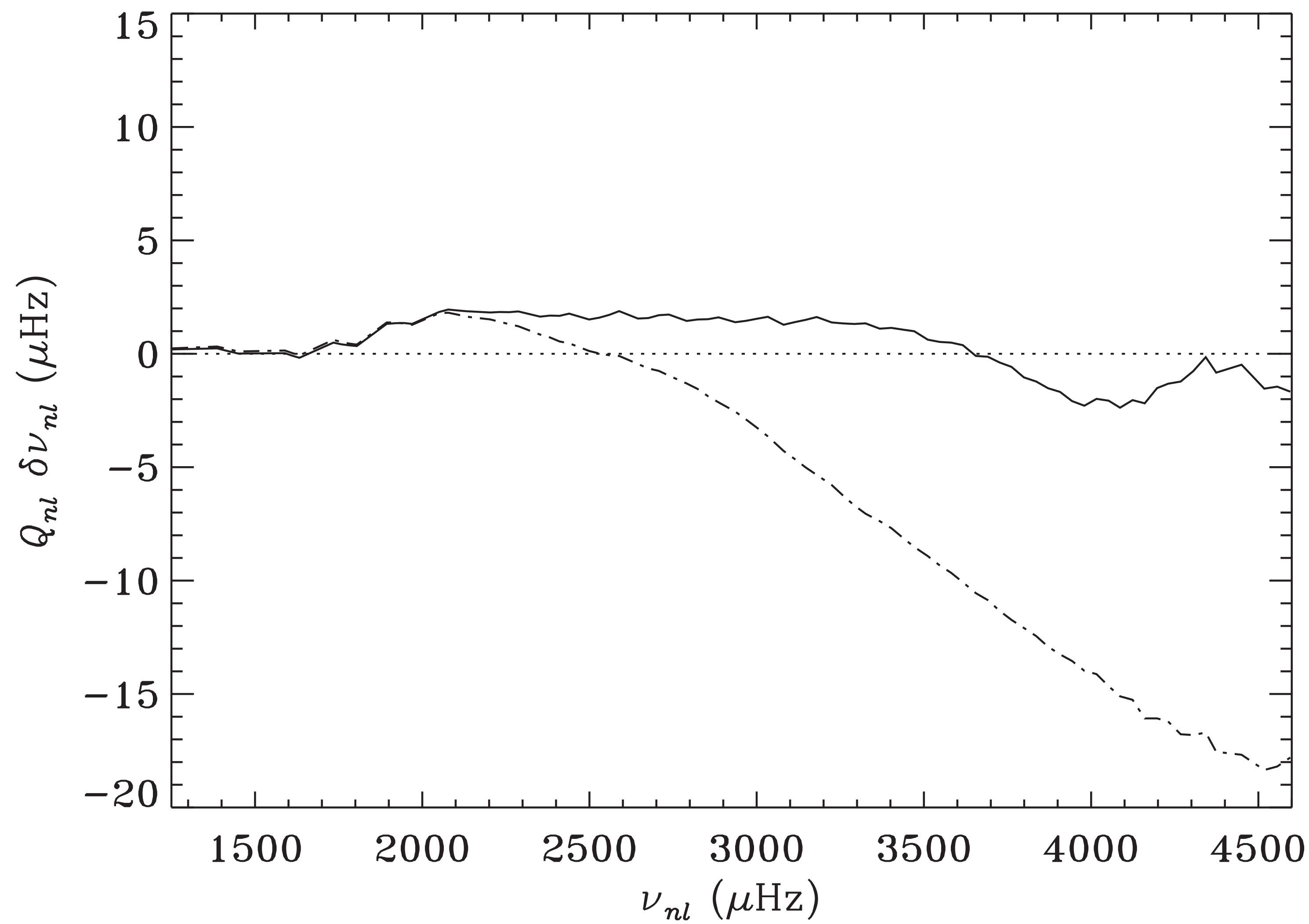


Rosenthal et al. 1999

Coupling 3D to 1D

Patched models





Houdek et al. 2017

Coupling 3D to 1D

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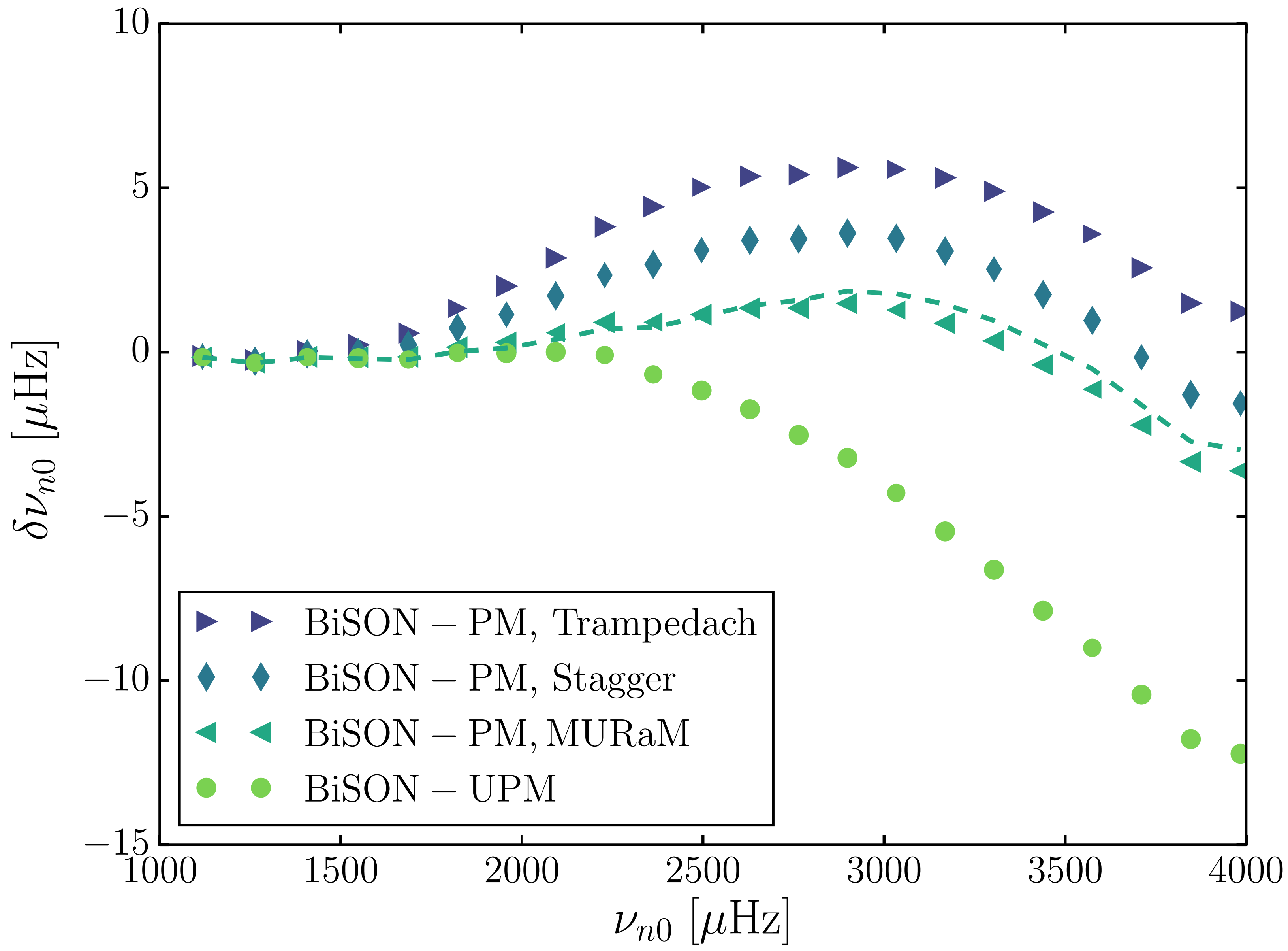
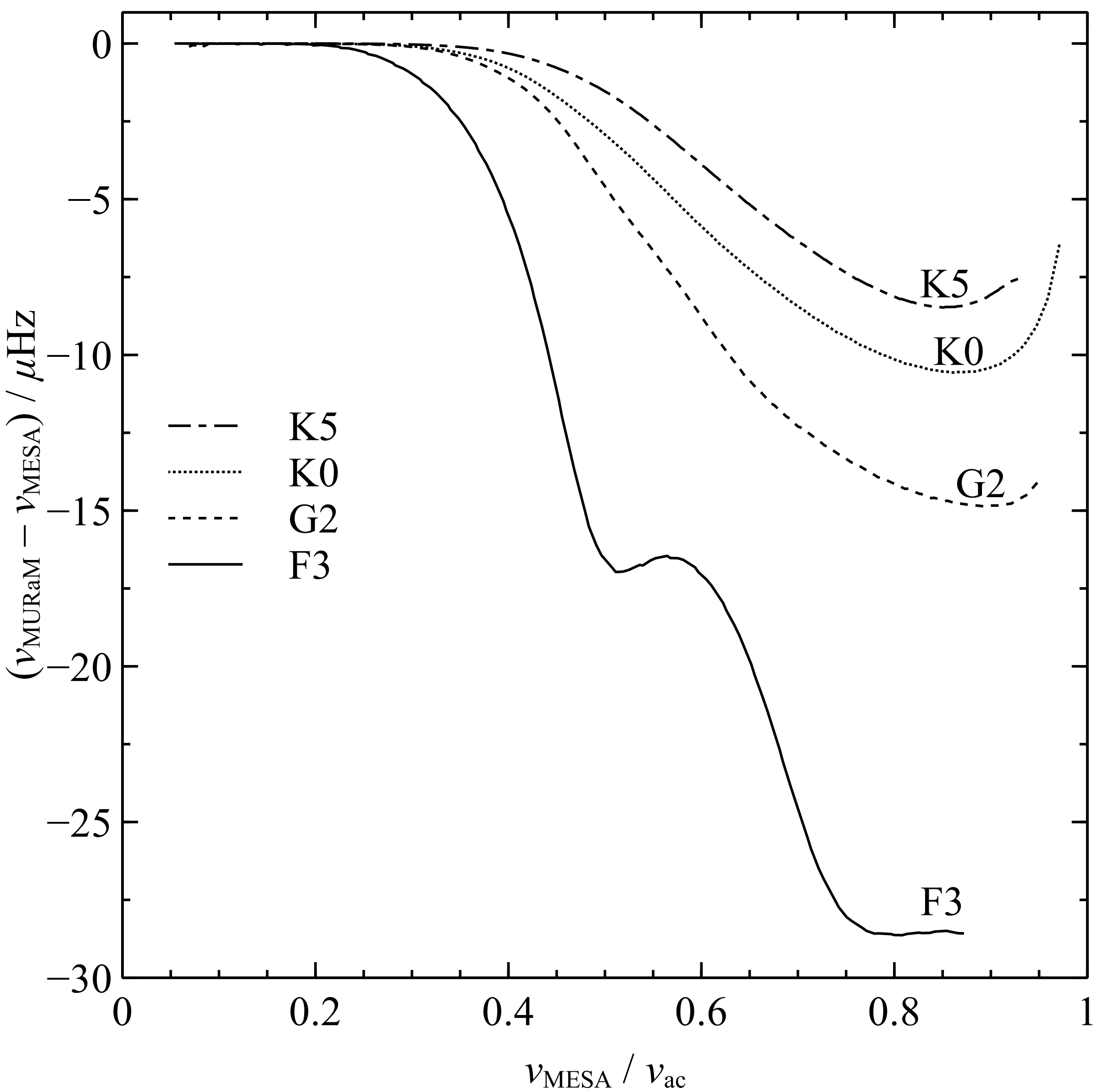
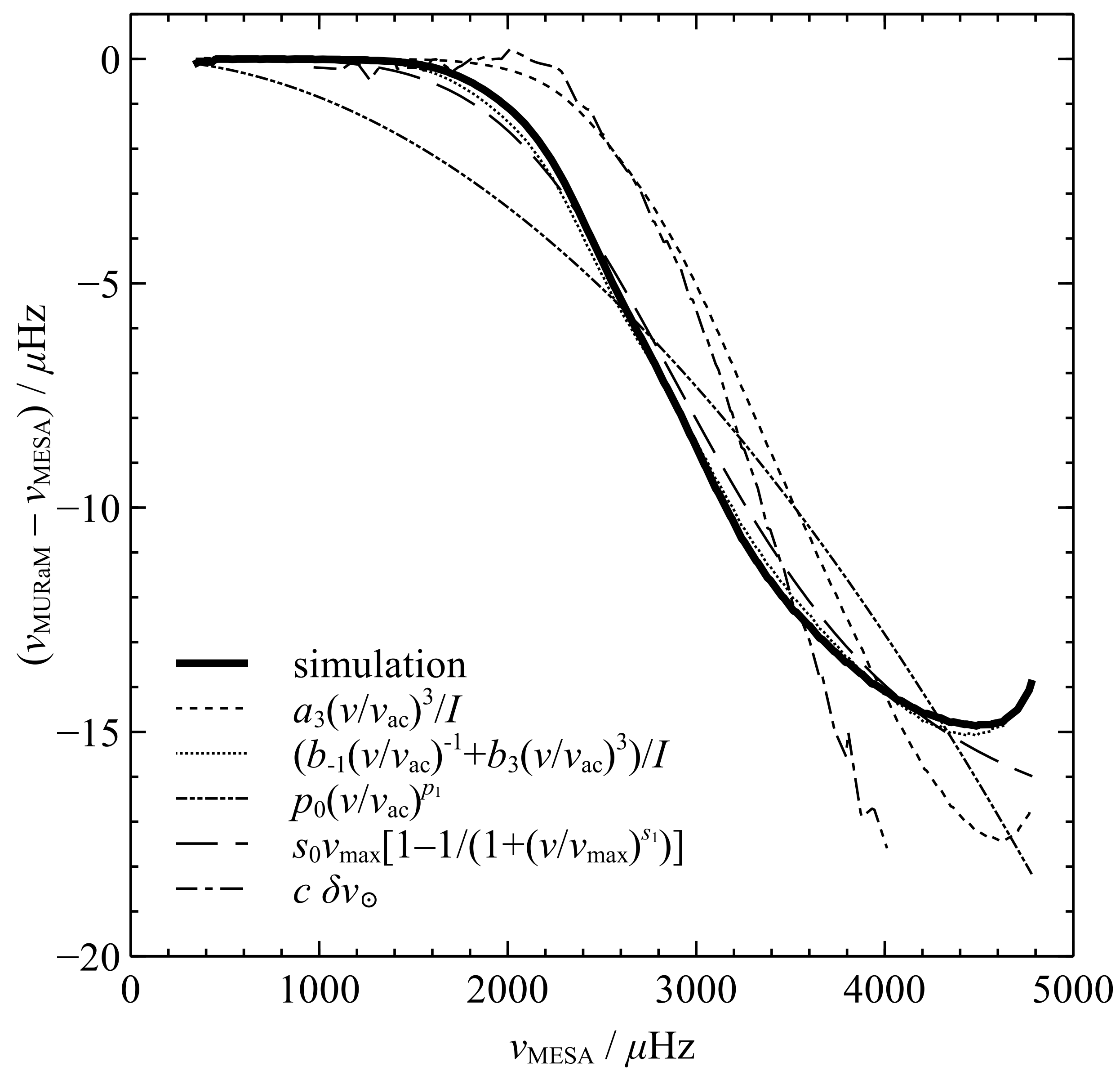


Jørgensen et al. 2017

Coupling 3D to 1D

Patched models: results

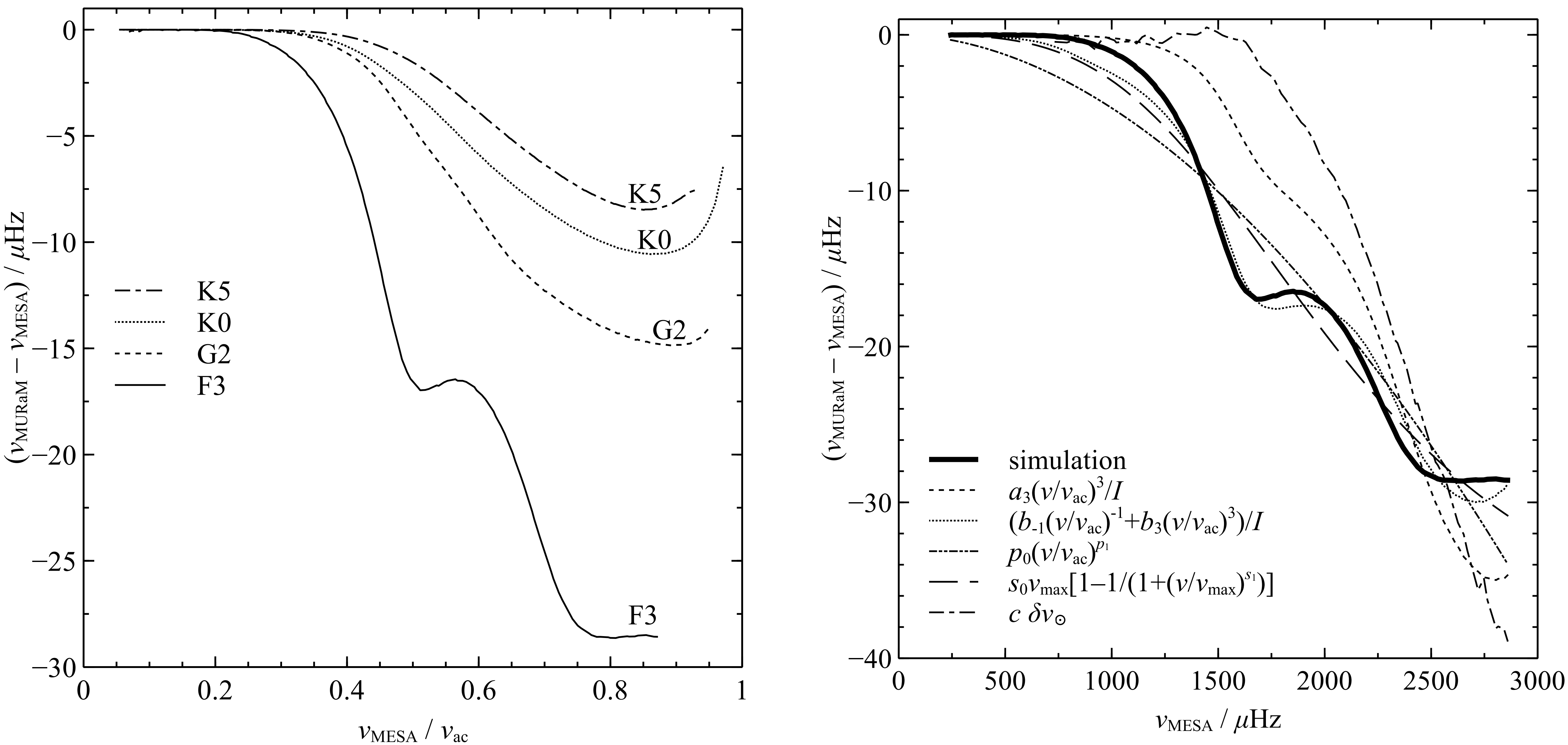




Ball et al. 2016

Coupling 3D to 1D

Patched models: results



Ball et al. 2016

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The stellar models of the future

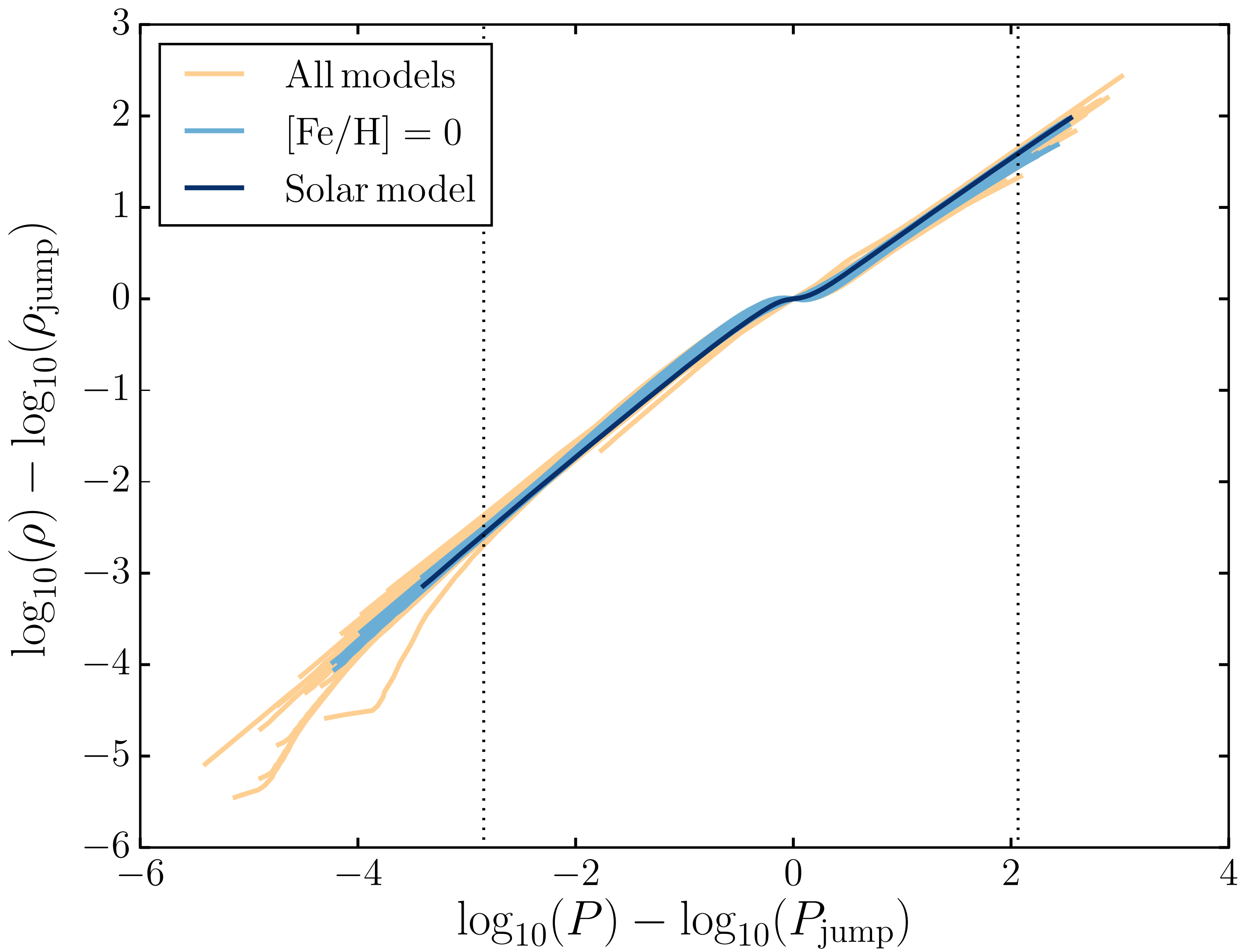
Interpolation

- To use 3D averages on the fly, we need them at any given point in the Teff/log(g) plane
- Is this feasible? Can we safely interpolate across 3D stratifications?
- Yes, as log(ρ) as a function of log(P) looks similar across the 3D grid.
- A jump in density occurs close to the surface, corresponding to a local minima in dlog(ρ)/dlog(P)

Jørgensen et al. 2017

The stellar models of the future

Interpolation



Jørgensen et al. 2017

The stellar models of the future

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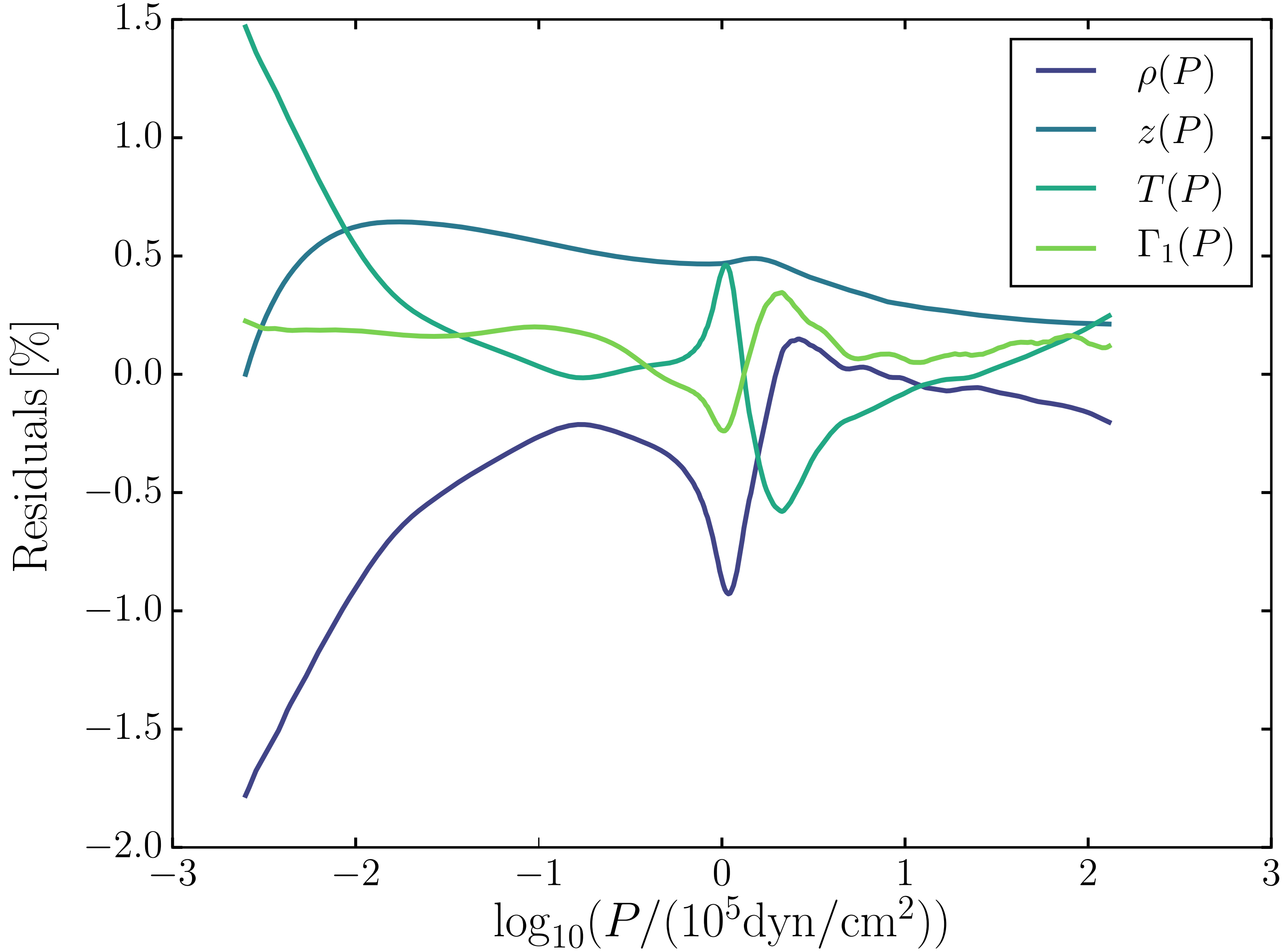

Jørgensen et al. 2017

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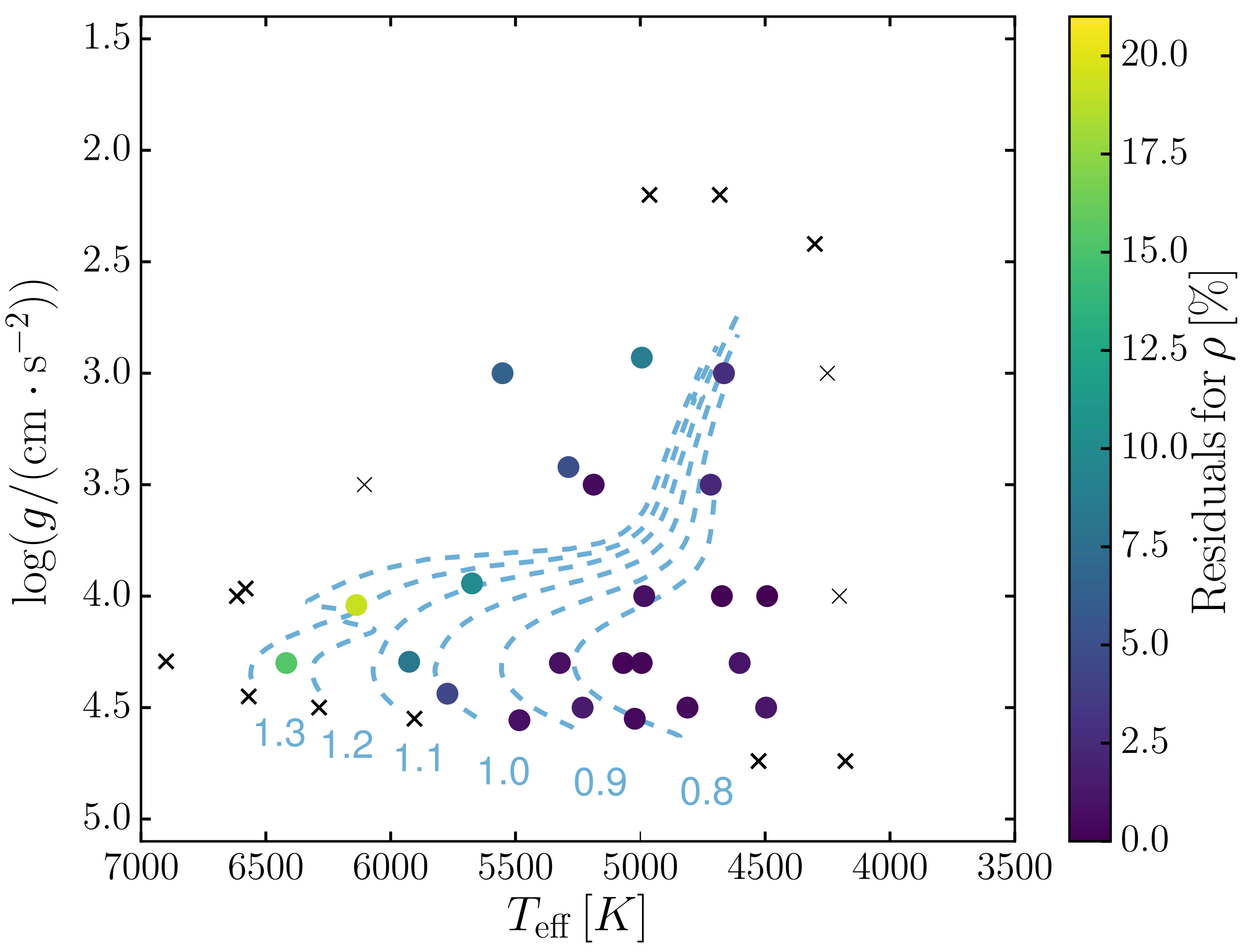
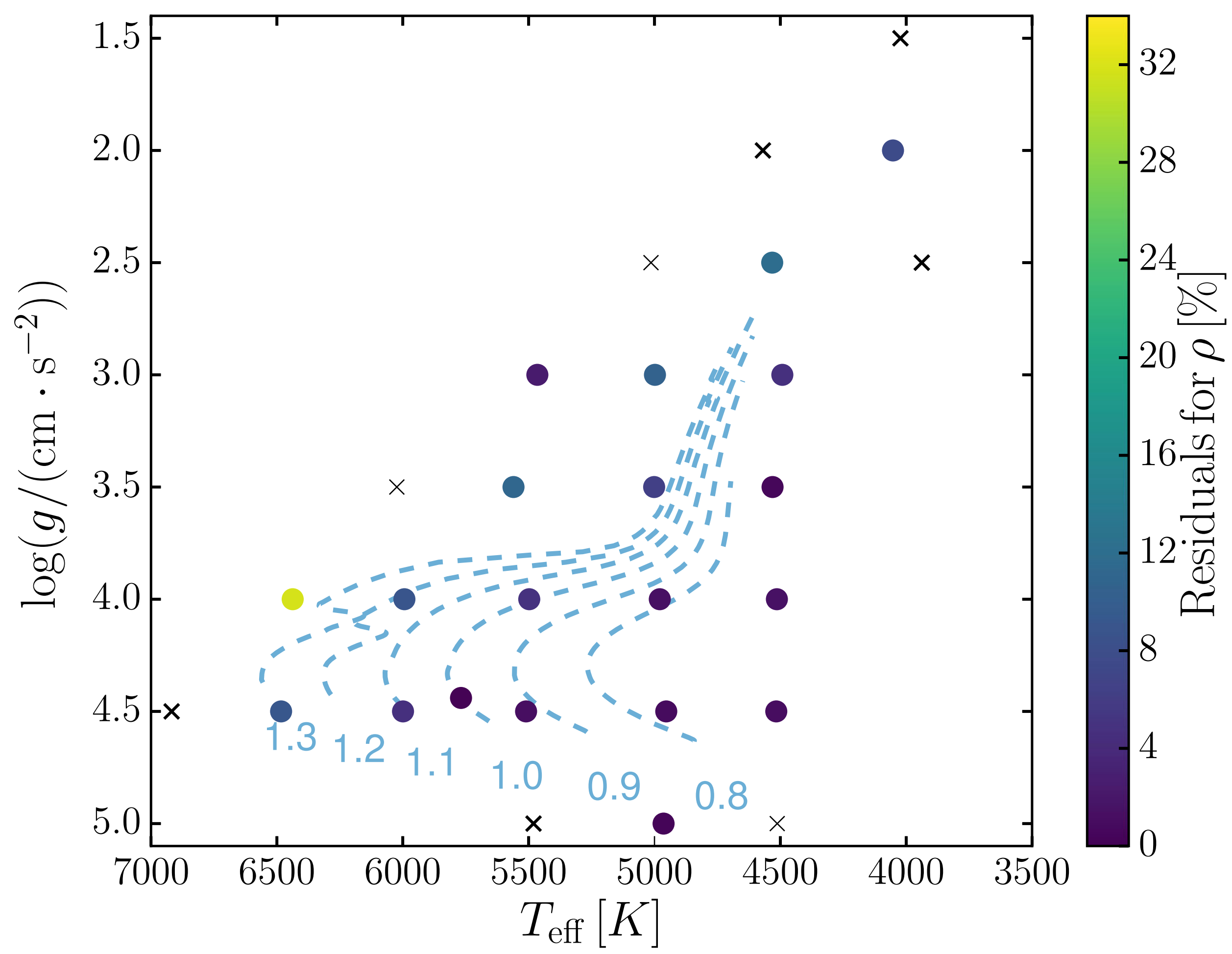




Jørgensen et al. 2017

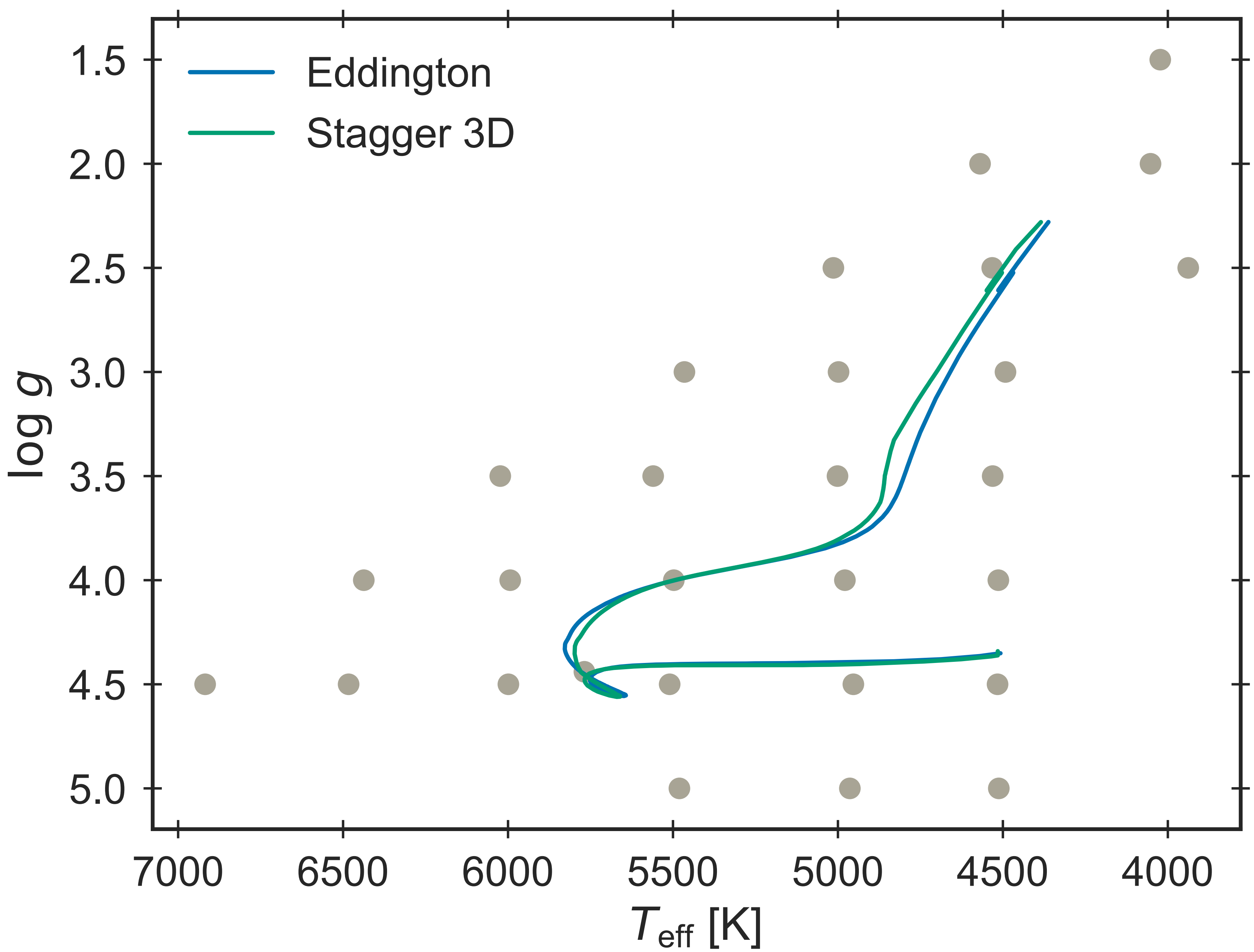
Disclaimer

- All work done by Andreas Jørgensen and Jakob Mosumgaard
- Preliminary results, many tests in progress
- Successfully patched 3D averages to 1D evolution on-the-fly

Jørgensen et al. 2018, in prep
Mosumgaard et al. 2018, in prep

The stellar models of the future

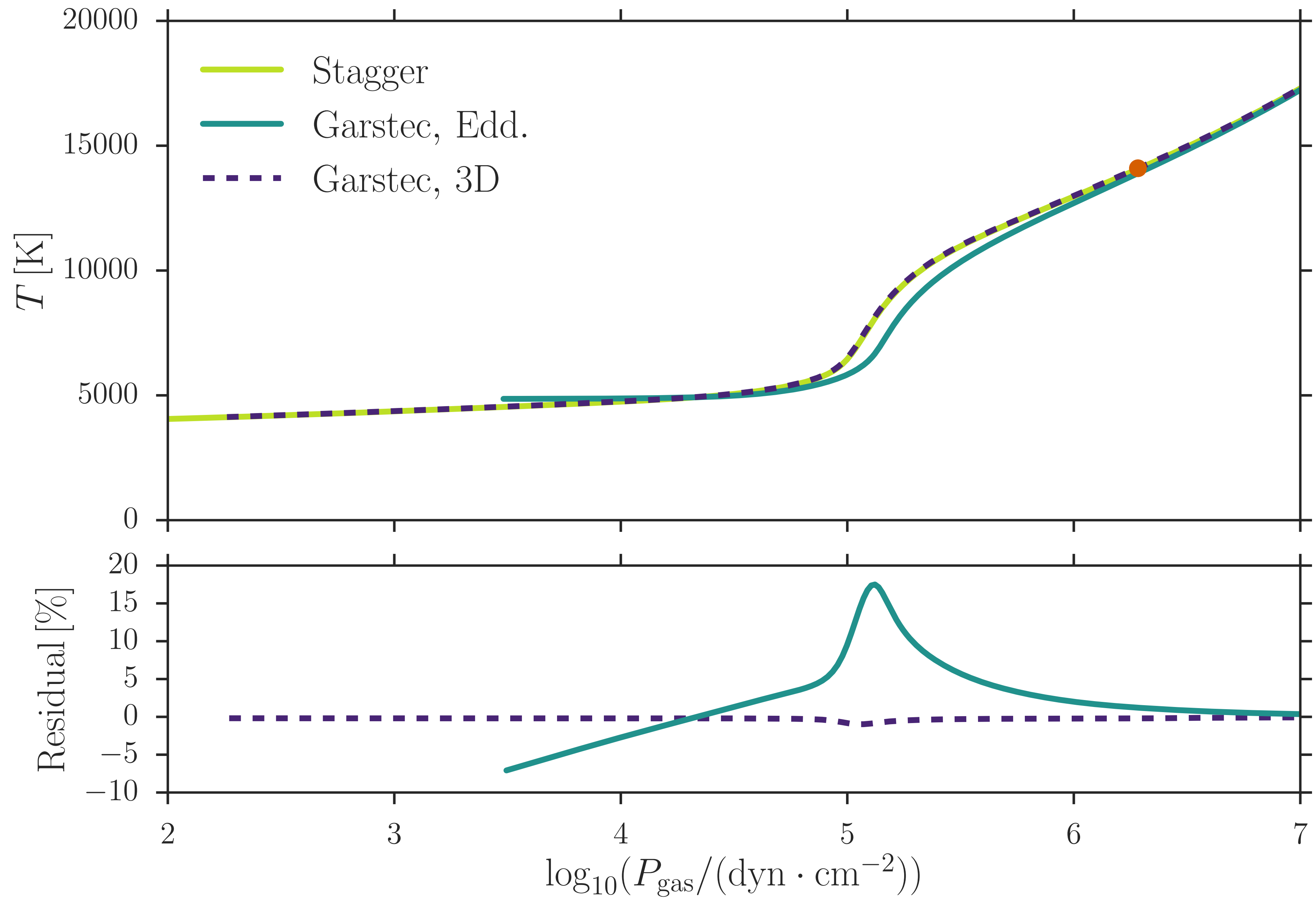
Evolution



Jørgensen et al. 2018, in prep
Mosumgaard et al. 2018, in prep

The stellar models of the future

Solar model



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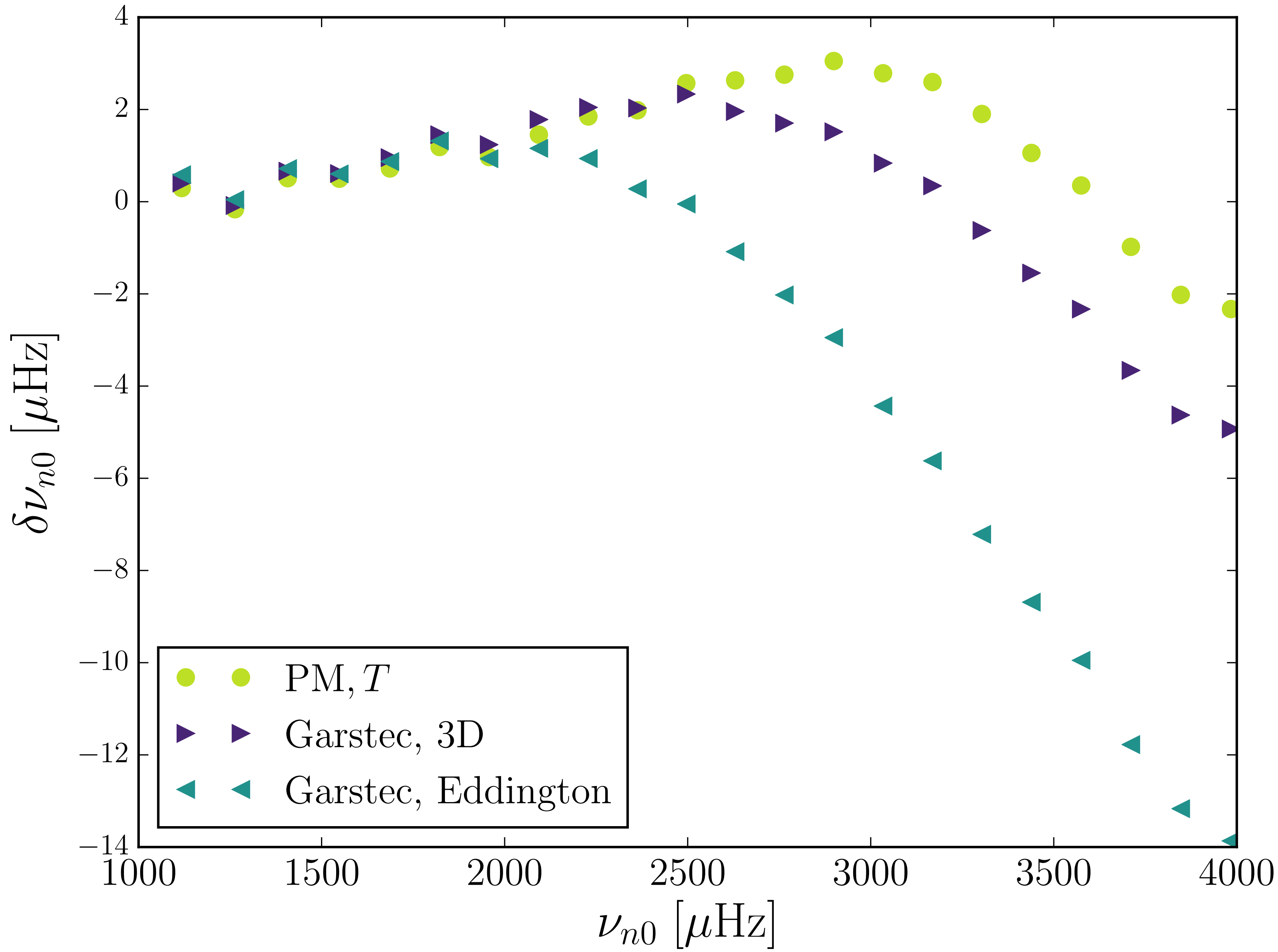
The stellar models of the future

Solar model



Jørgensen et al. 2018, in prep
Mosumgaard et al. 2018, in prep

Conclusions and outlook

Coupling 3D simulations to 1D evolution

- Can be done on-the-fly
- Still many aspects to be explored (e.g., best way to interpolate 3D structures, role of turbulent pressure, interpolation in metallicity, and many more)
- Need for more simulations: require finer sampling in some regions of the Teff/log(g) plane
- Future is promising, and should be available in time for Plato

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