CHARACTERISATION OF STELLAR GRANULATION USING 3D STELLAR ATMOSPHERE MODELS

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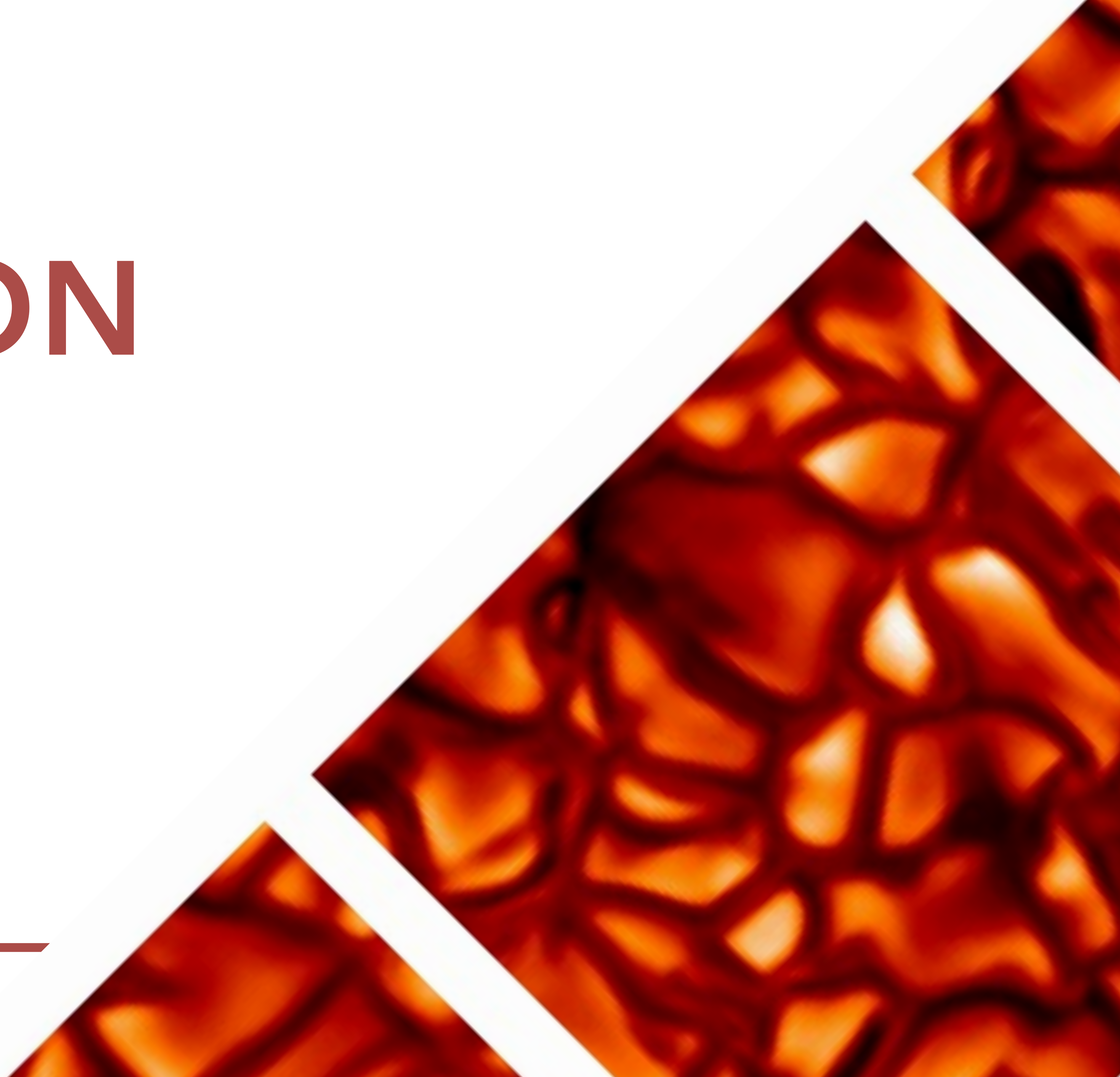
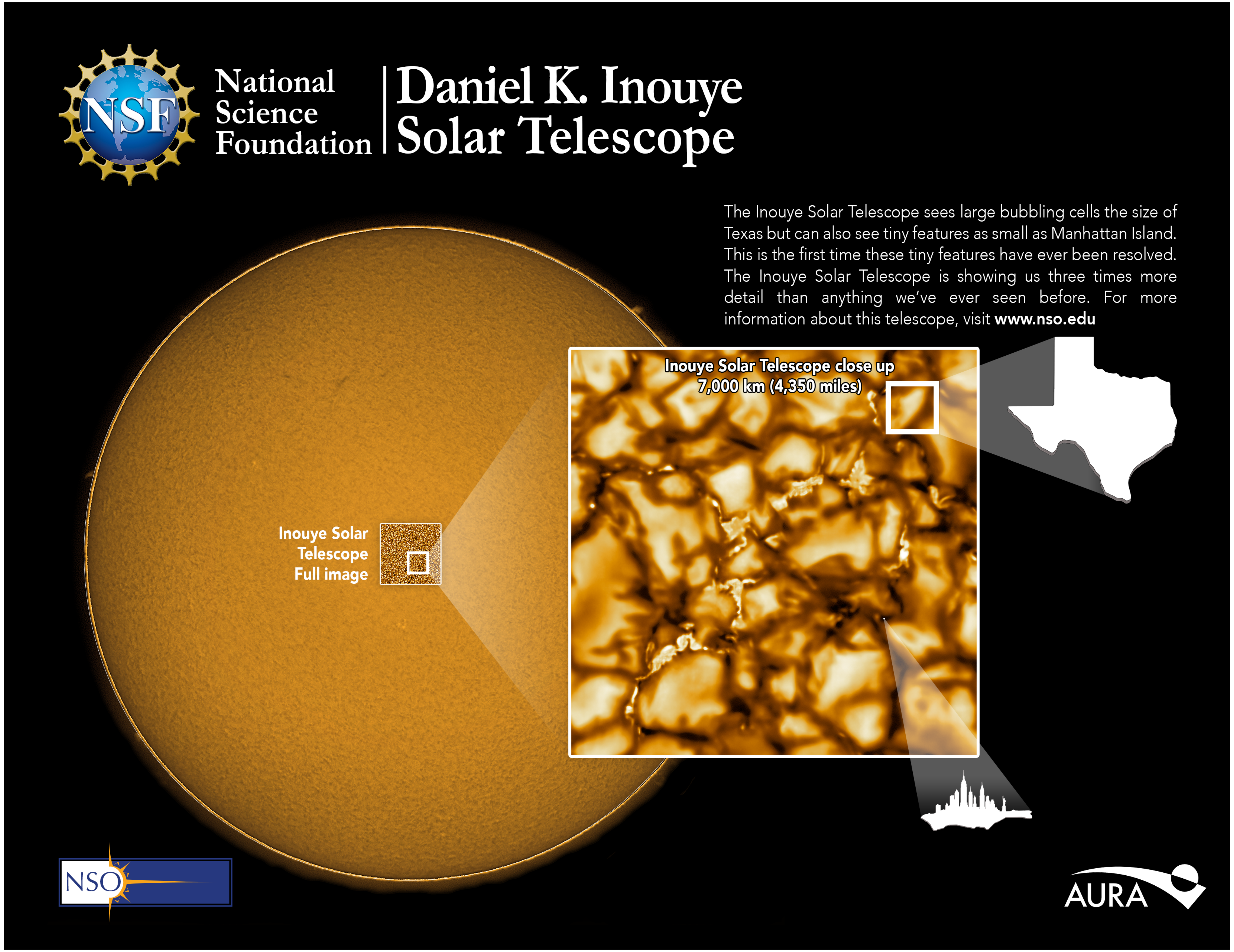
AARHUS
UNIVERSITY

16 March 2023

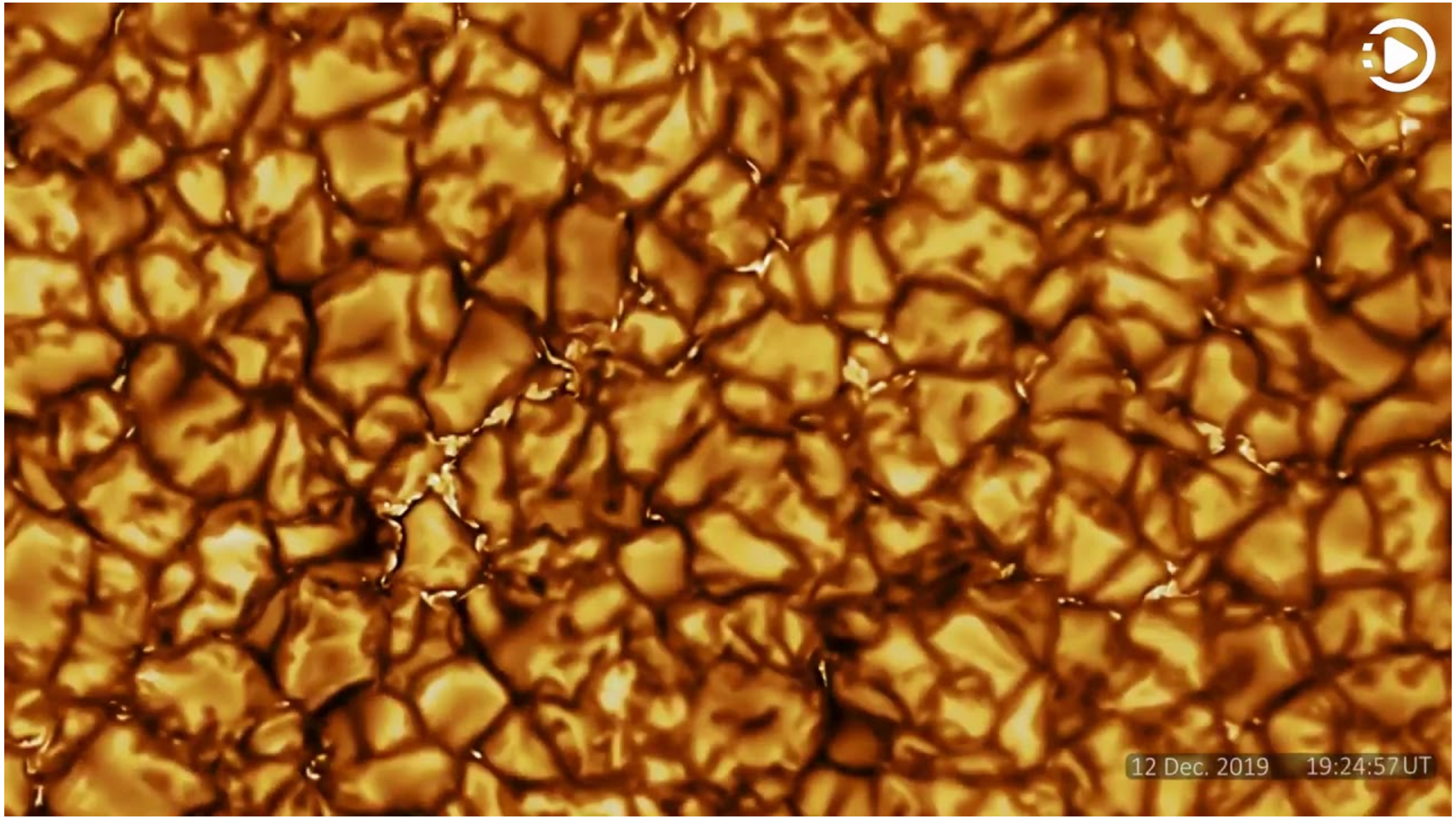
MOTIVATION





Daniel K. Inouye Solar Telescope

The Inouye Solar Telescope sees large bubbling cells the size of Texas but can also see tiny features as small as Manhattan Island. This is the first time these tiny features have ever been resolved. The Inouye Solar Telescope is showing us three times more detail than anything we've ever seen before. For more information about this telescope, visit **www.nso.edu**



Observations made by the Daniel K. Inouye Solar Telescope
Area: 19,000 x 10,700 km

WHY SHOULD WE STUDY GRANULATION?

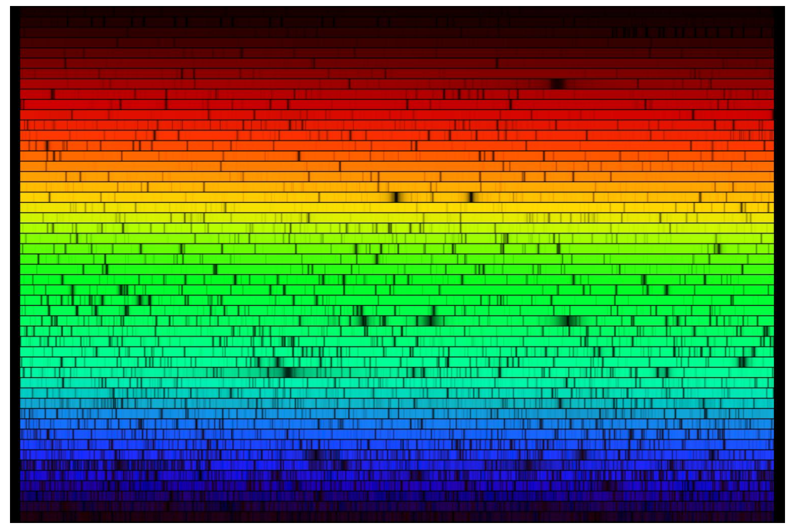
Exoplanet detection

Stellar noise in light curve and radial velocities

↓

Exoplanet characterization

Spectroscopy



Abundance determination

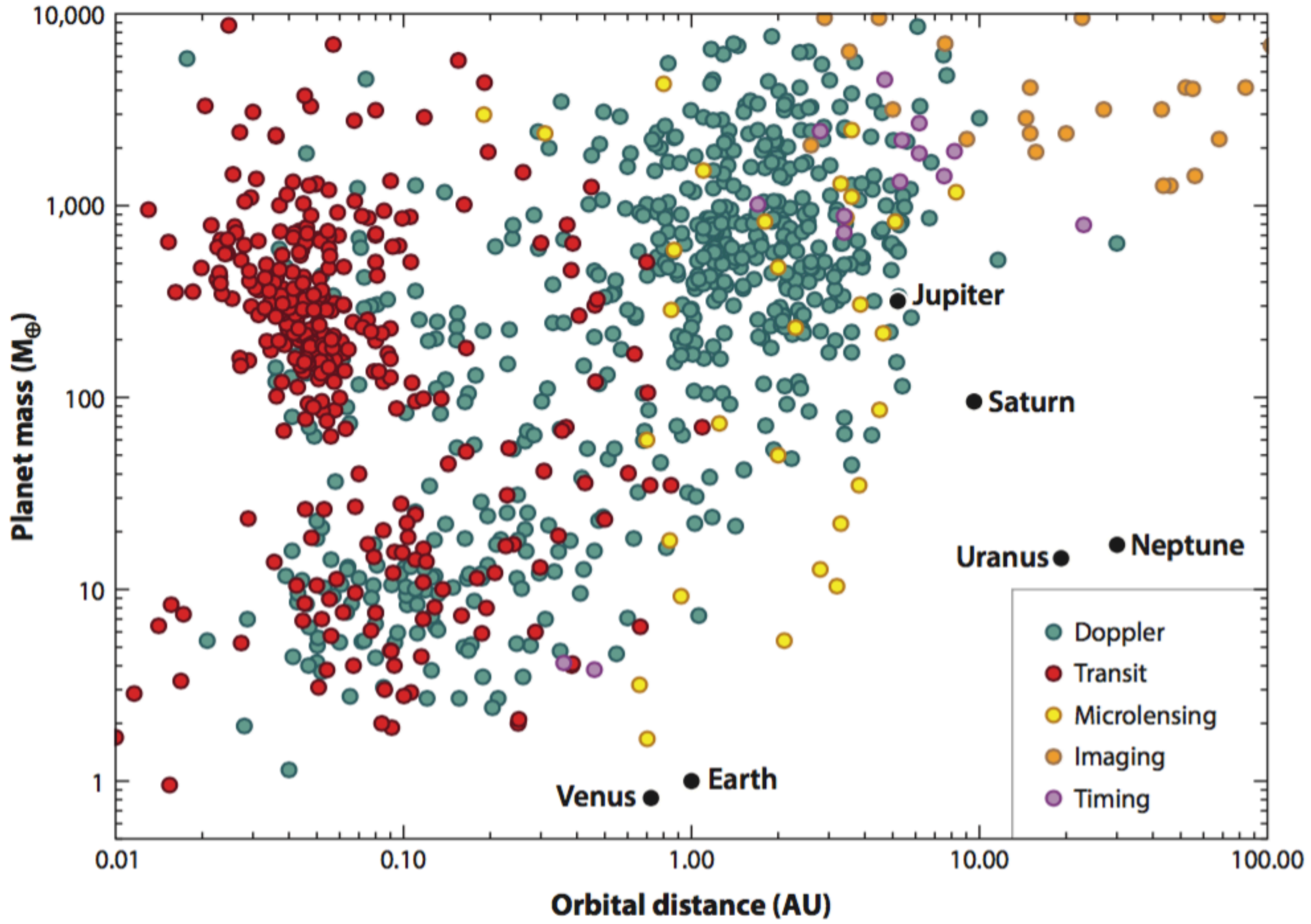
Stellar characterization

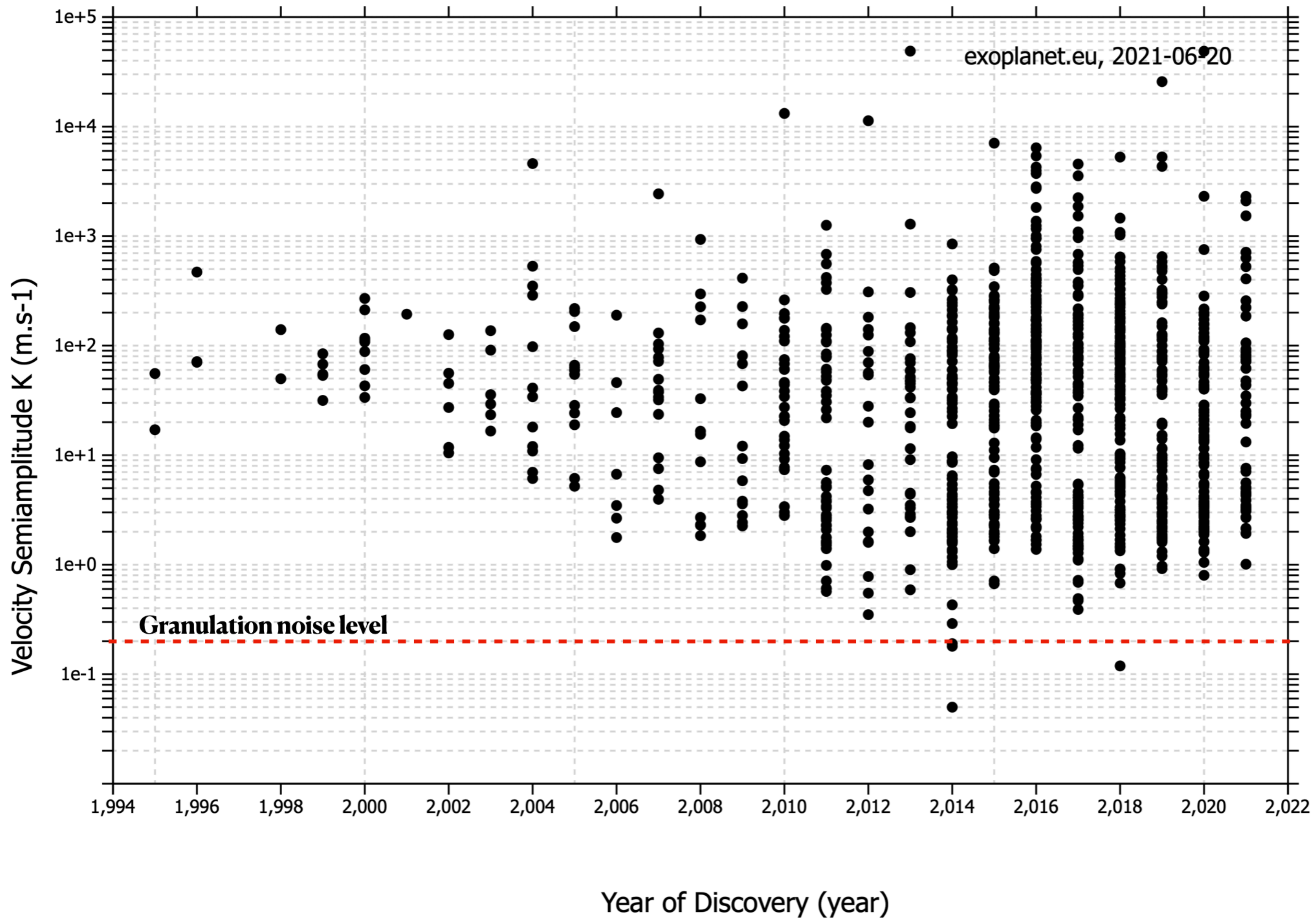
Galactic Archeology

Asteroseismology

Stellar characterization

EXOPLANET DETECTION

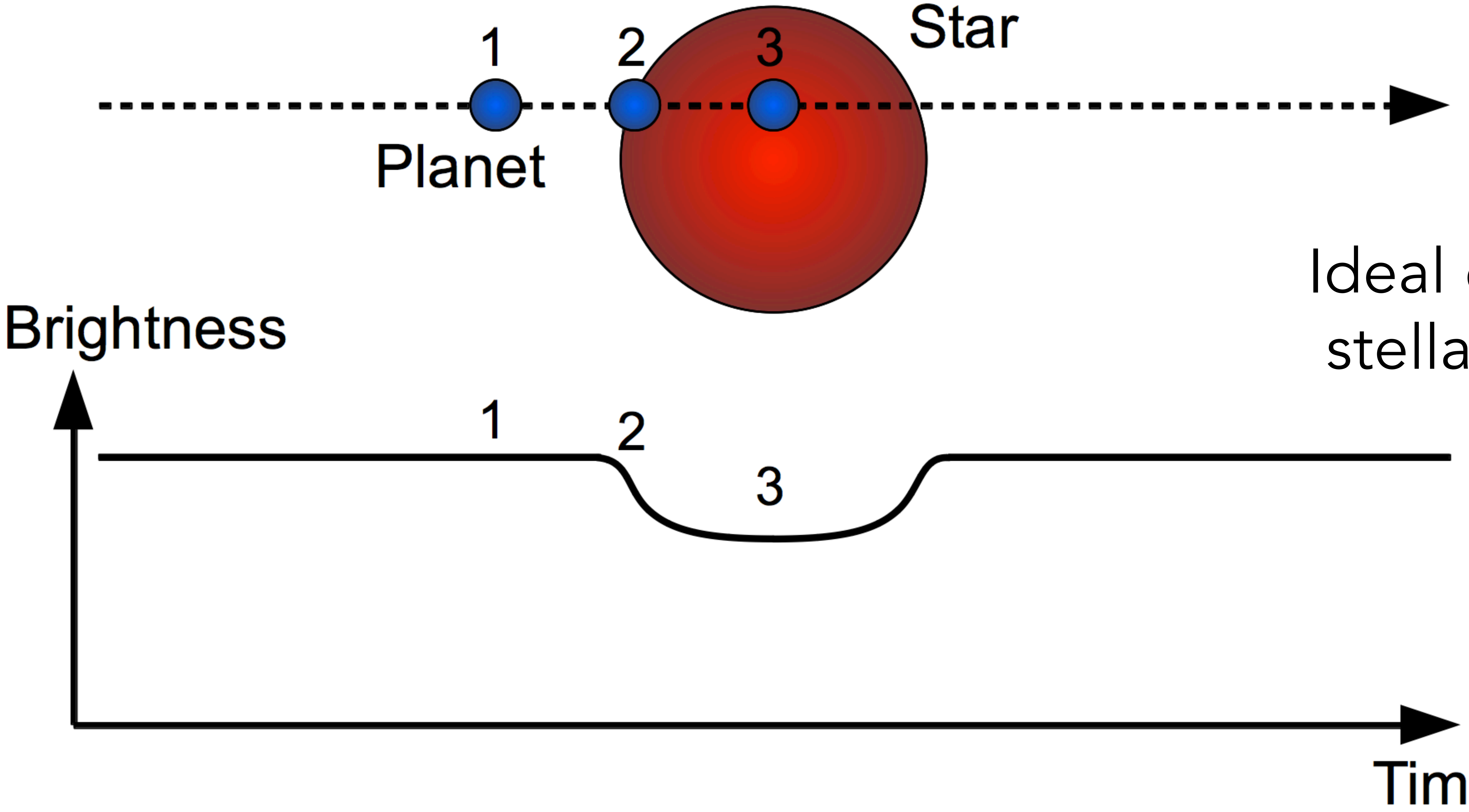




Credits: Joshua Winn and Daniel Fabrycky

Credits:exoplanets.eu

EXOPLANET DETECTION



Ideal case: no stellar noise!

IN REAL DATA:
PLANET + STELLAR NOISE

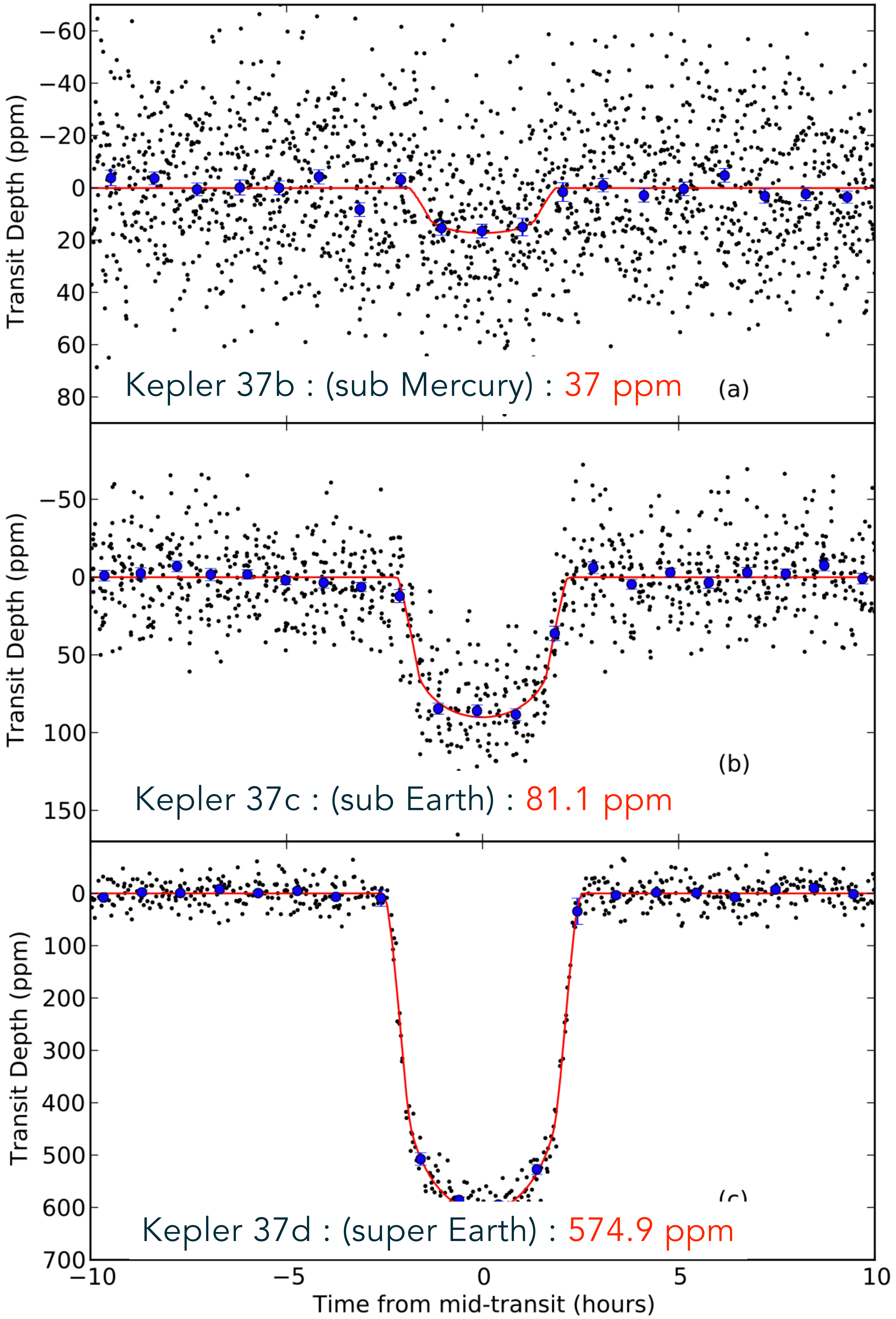
Noise: is <u>mainly</u> due to convection

Transit depths can be comparable to stellar convective fluctuations

Solar granulation **noise**: ~ **50 ppm**

Stellar granulation **noise**: **30 - 500 ppm**

We need to <u>understand</u> and <u>account for</u> the convective noise in both the detection and characterization of exoplanets.



Kepler 37:
Teff = 5417 K
logg = 4.57

Credits: Barclay et al. 2013

CURRENT CHALLENGES

Transits, RVs are affected by **stellar noise**

Amplitudes: 50-500 ppm

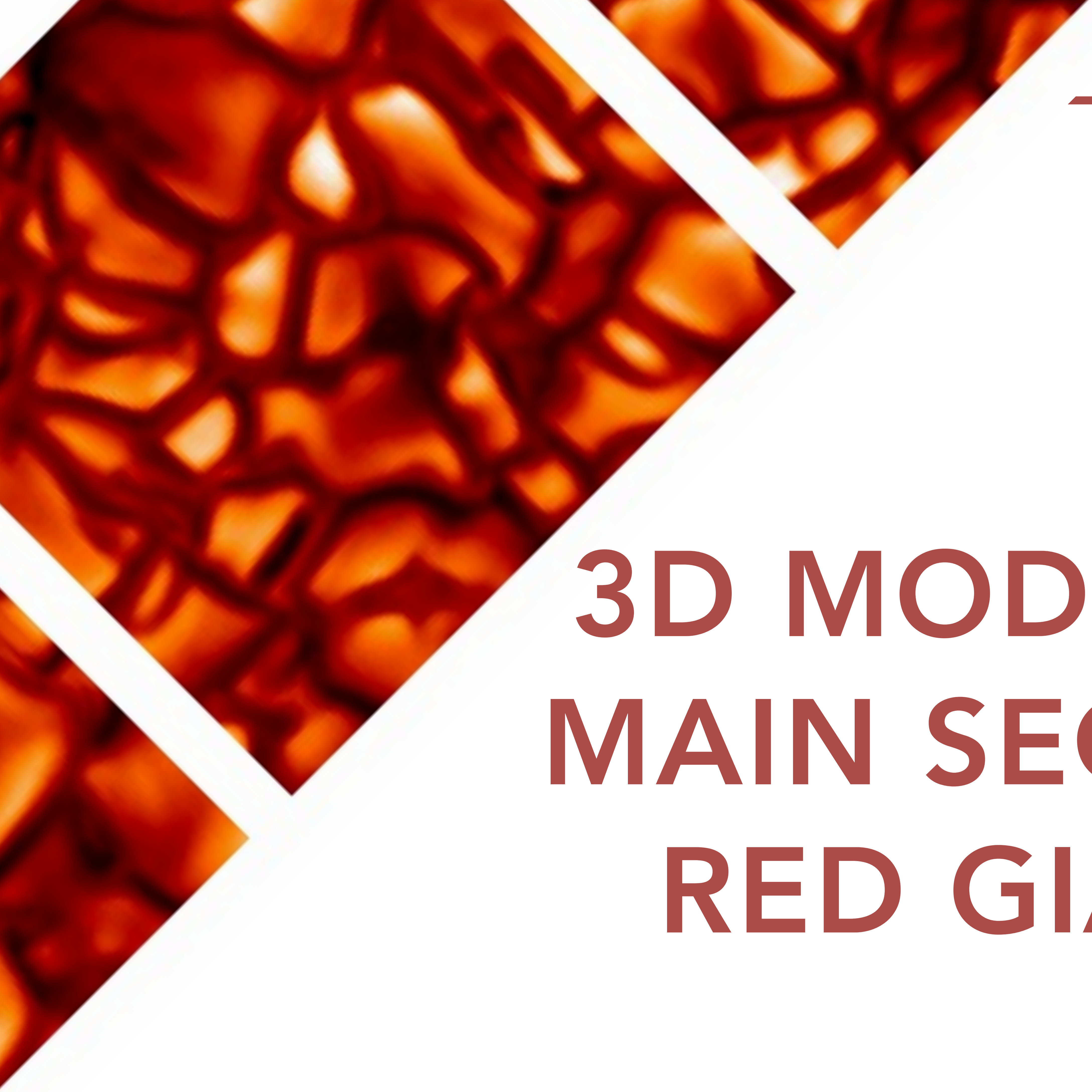
Timescales: minutes-hours

Uncertainties in exoplanet parameters:

radii and masses
(Meunier et al. 2020, Sulis et al. 2020)

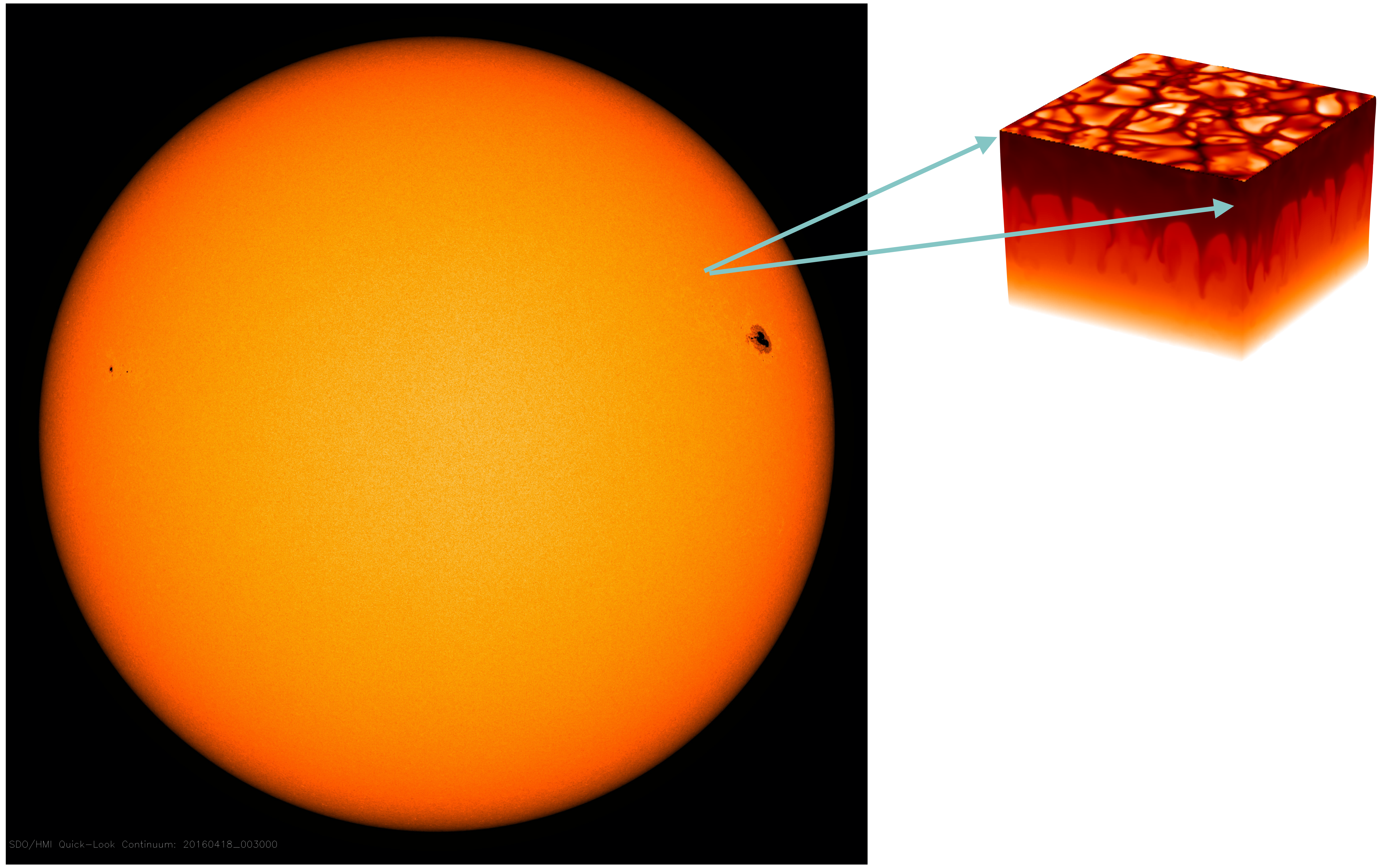
Difficult to estimate the composition of the planet

IN ORDER TO DETECT AND CHARACTERIZE EXOPLANETS ACCURATELY, WE NEED TO MODEL THE STELLAR BRIGHTNESS VARIATIONS



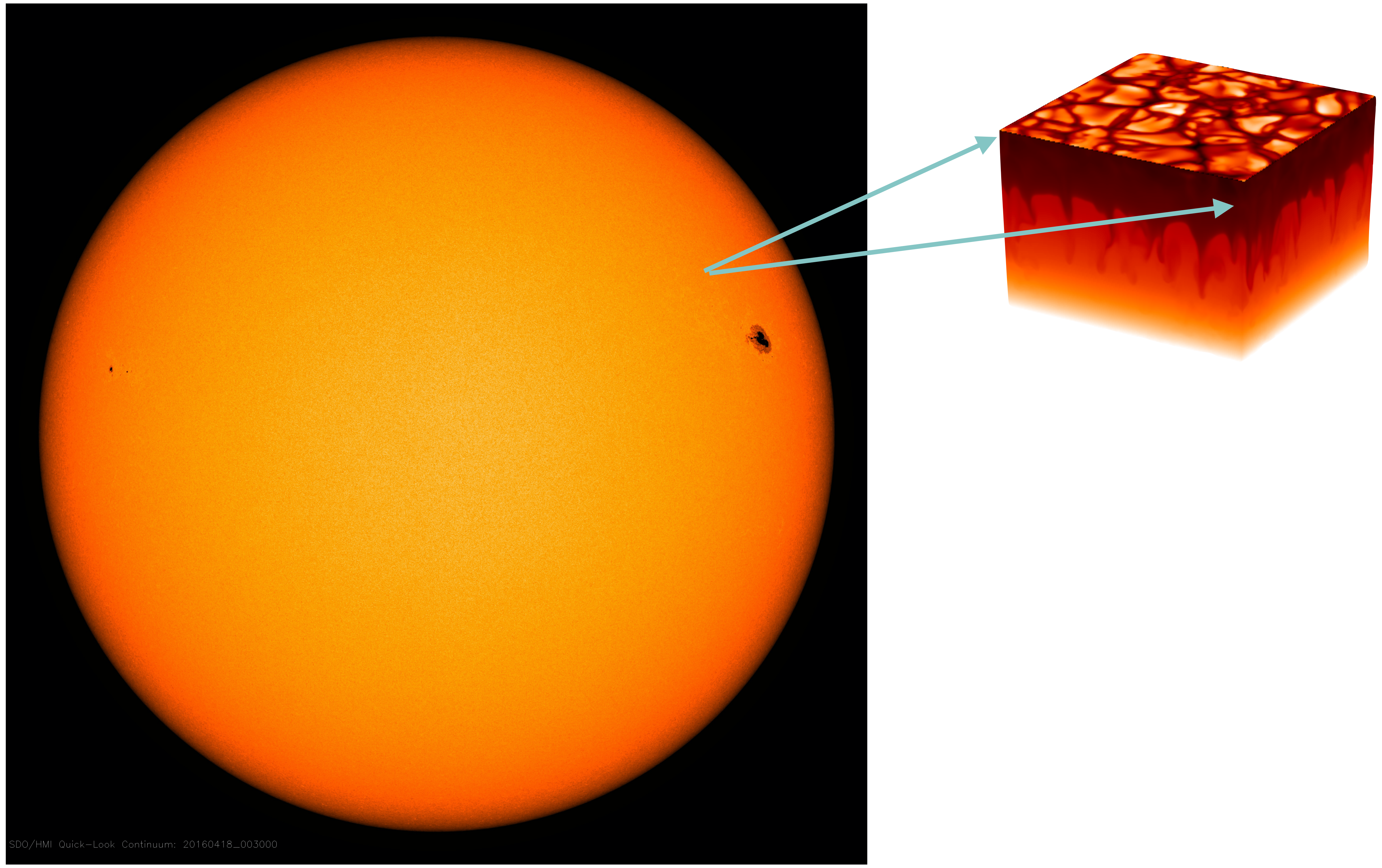
3D MODELS FROM THE MAIN SEQUENCE UP TO RED GIANT BRANCH

3D STELLAR ATMOSPHERE MODELS



- Box-in-a-star model!
- Top of the convective zone, superadiabatic region, photosphere
- **Composition**: 17 most abundant elements
- Solution of the **mass**, **energy**, and **momentum** conservation
- Convection emerges naturally

3D STELLAR ATMOSPHERE MODELS



Six main variables: density, energy, momenta (in every direction), temperature and surface intensity.

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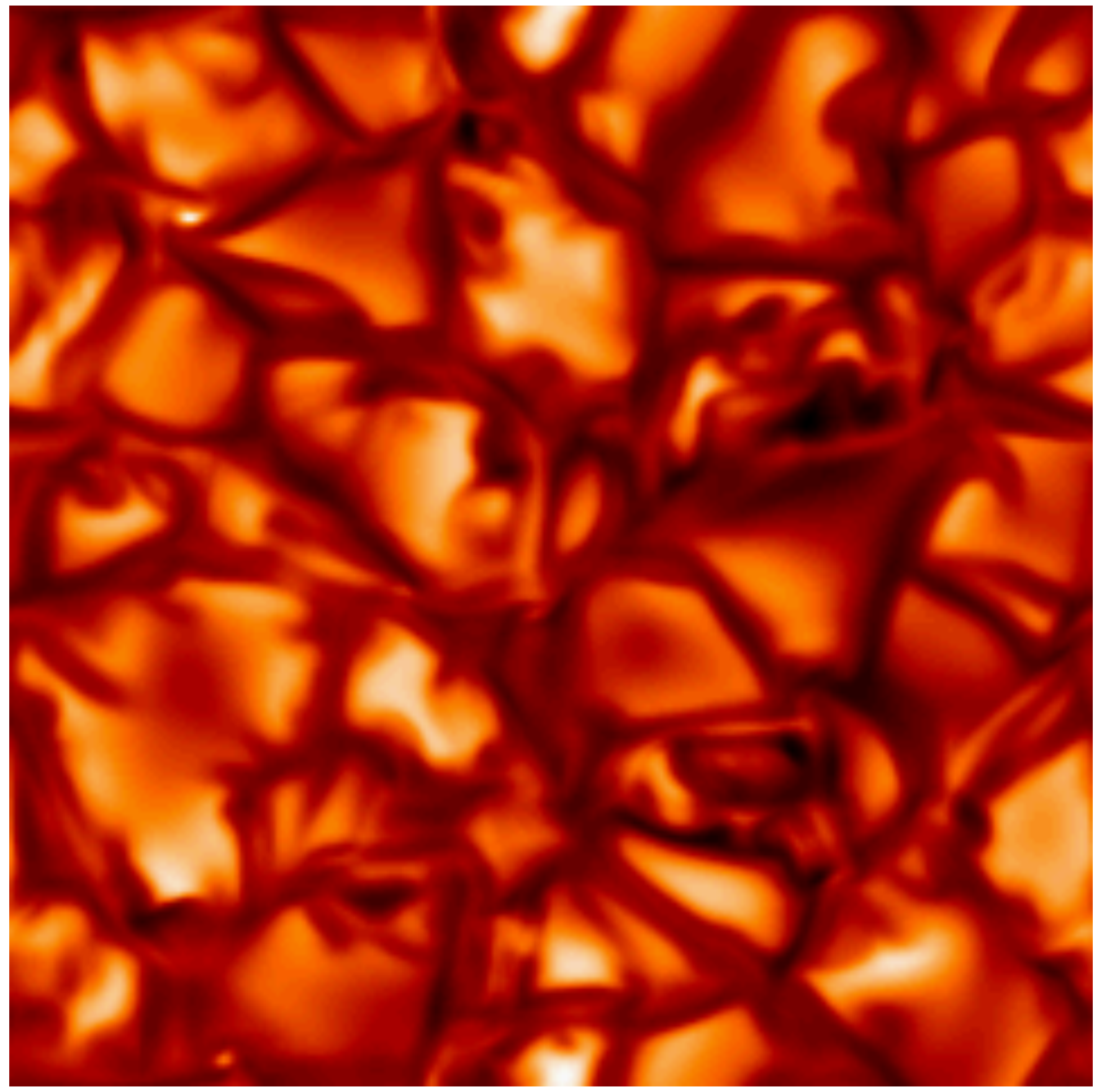
Other variables are obtained with the Equation of state.

3D STELLAR ATMOSPHERE MODELS

Dwarf star

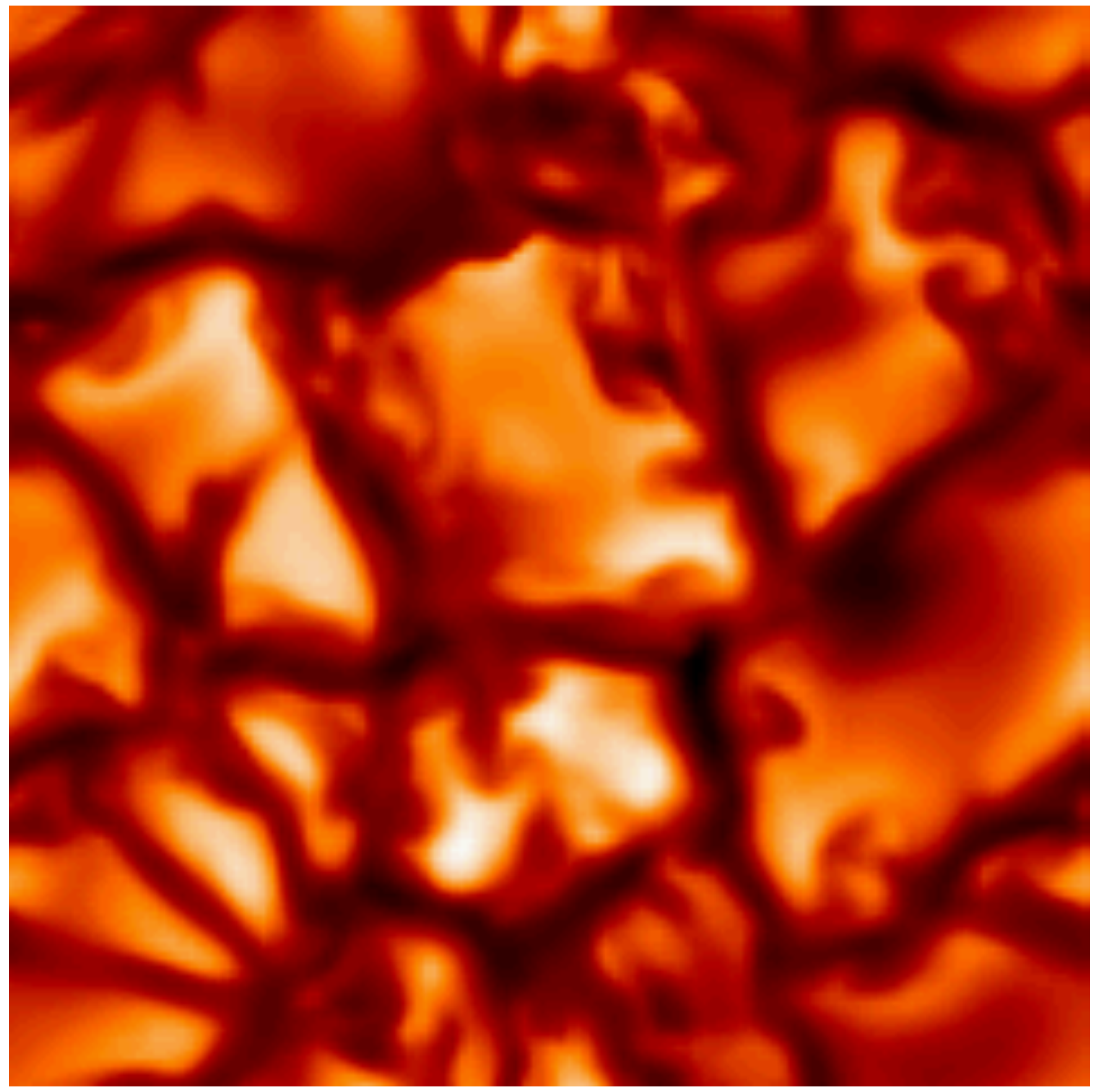
5500 K, logg = 5, [Fe/H] = 0.0



2 Mm x 2 Mm

Solar simulation

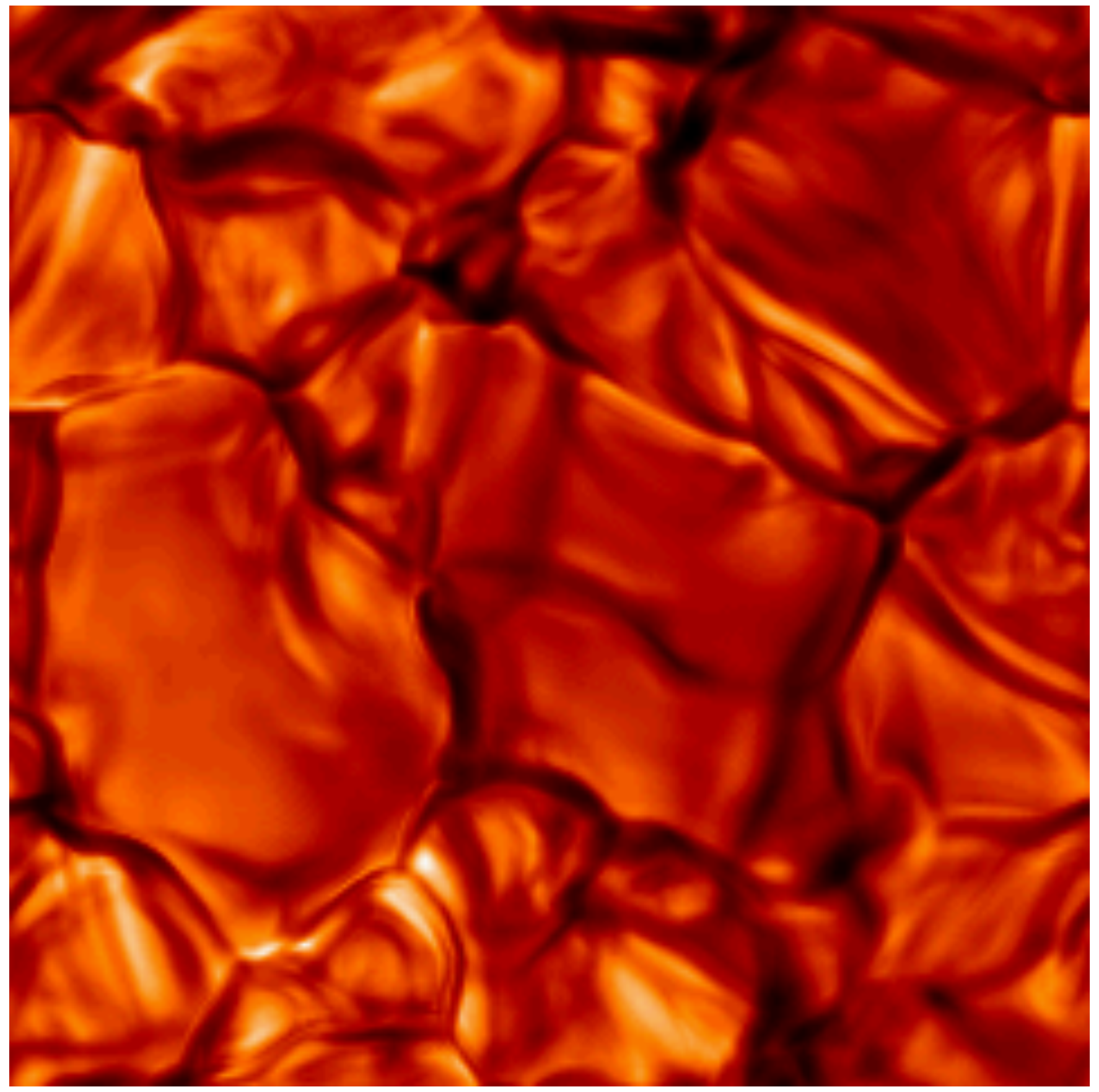
5777 K, logg = 4.4, [Fe/H] = 0.0



8 Mm x 8 Mm

Red giant

5000 K, logg = 2, [Fe/H] = 0.0



3500 Mm x 3500 Mm

3D STELLAR ATMOSPHERE MODELS

Dwarf star

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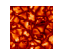

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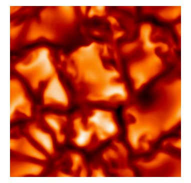

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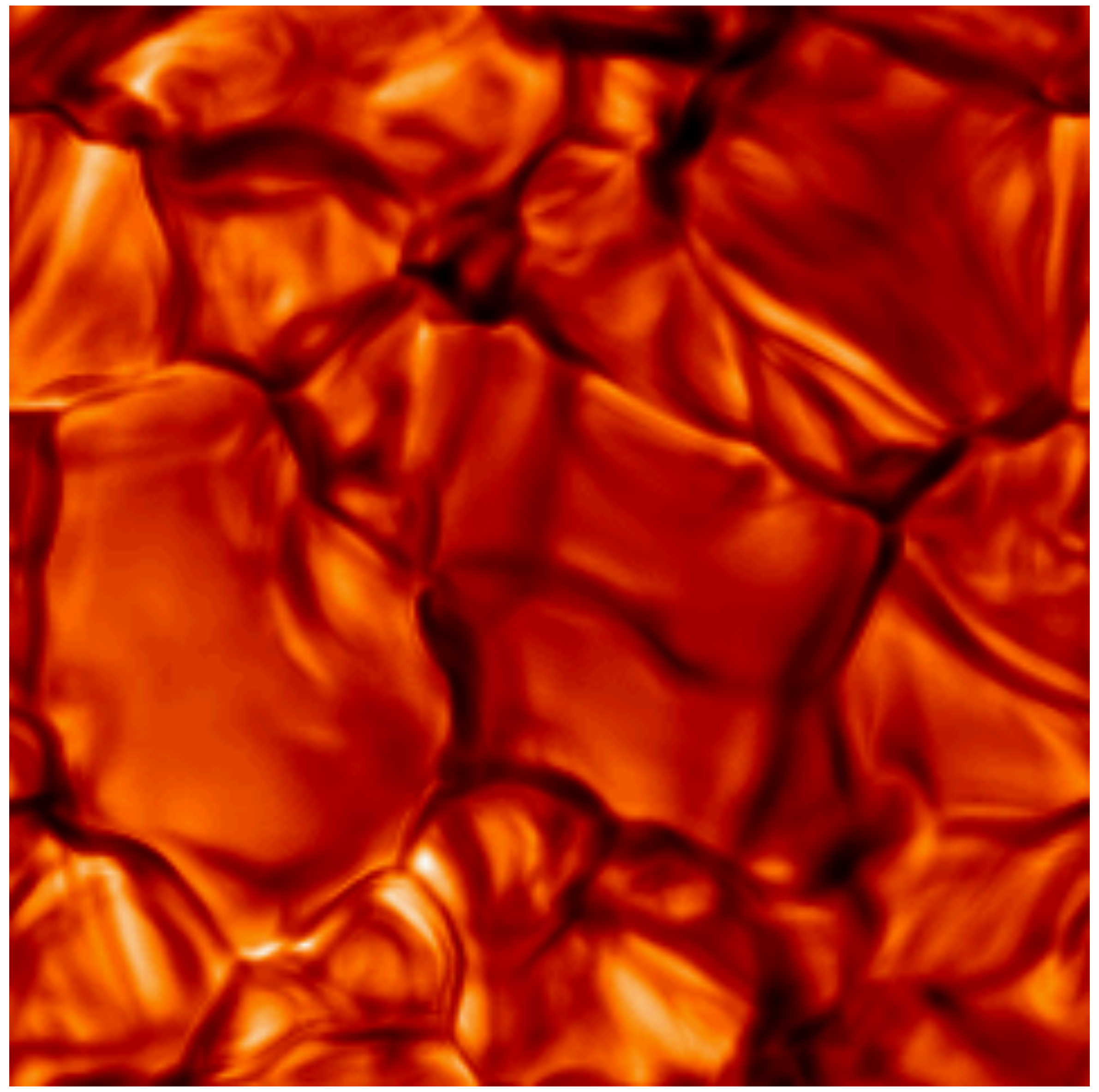


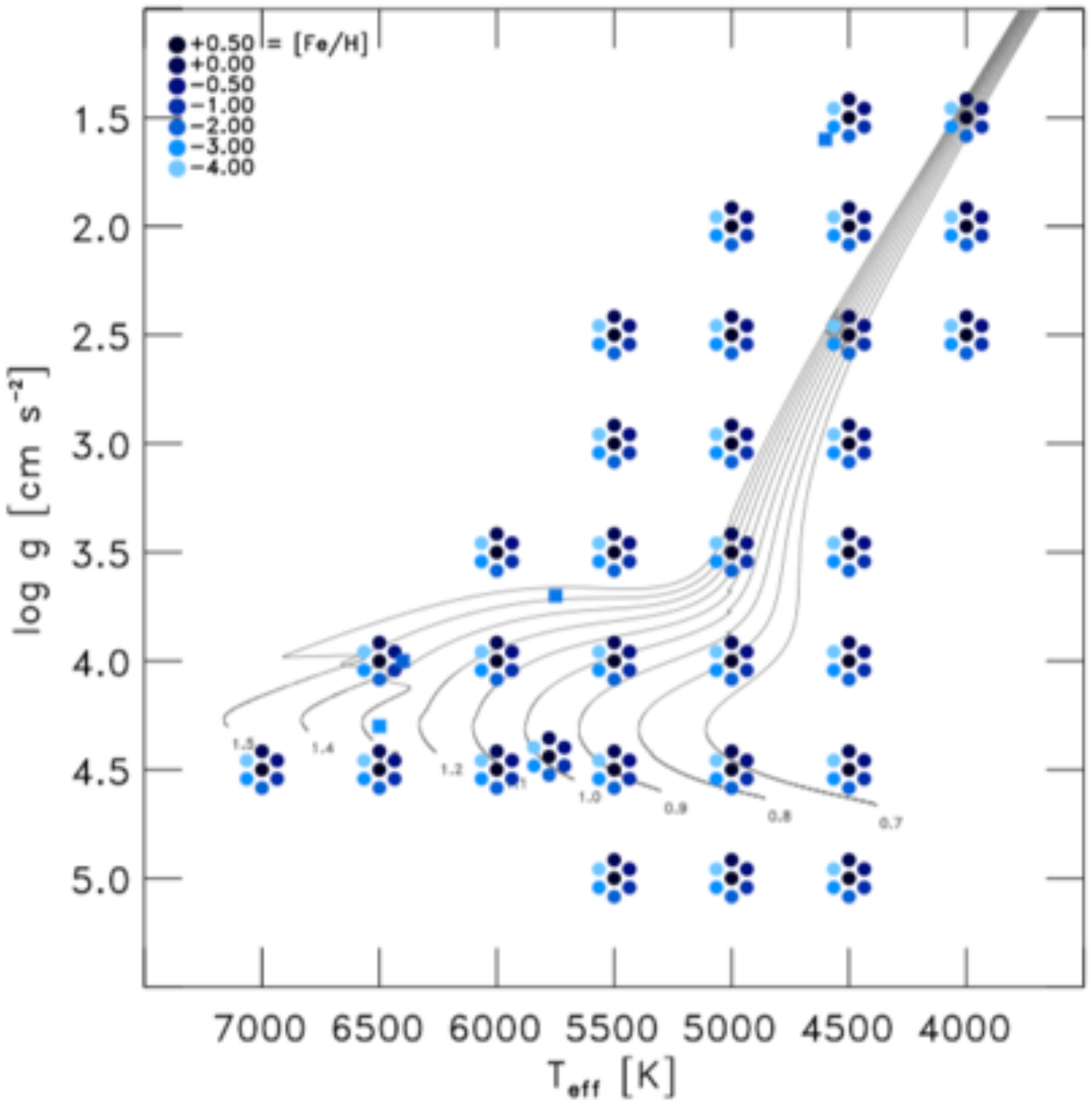
3500 Mm x 3500 Mm

ORIGINAL STAGGER GRID

- 217 models + 3 reference stars

- Main sequence, turn-off point, red giant branch

- Models defined by 3 stellar parameters: **effective temperature, surface gravity,** and **metallicity**



Magic et al. 2013

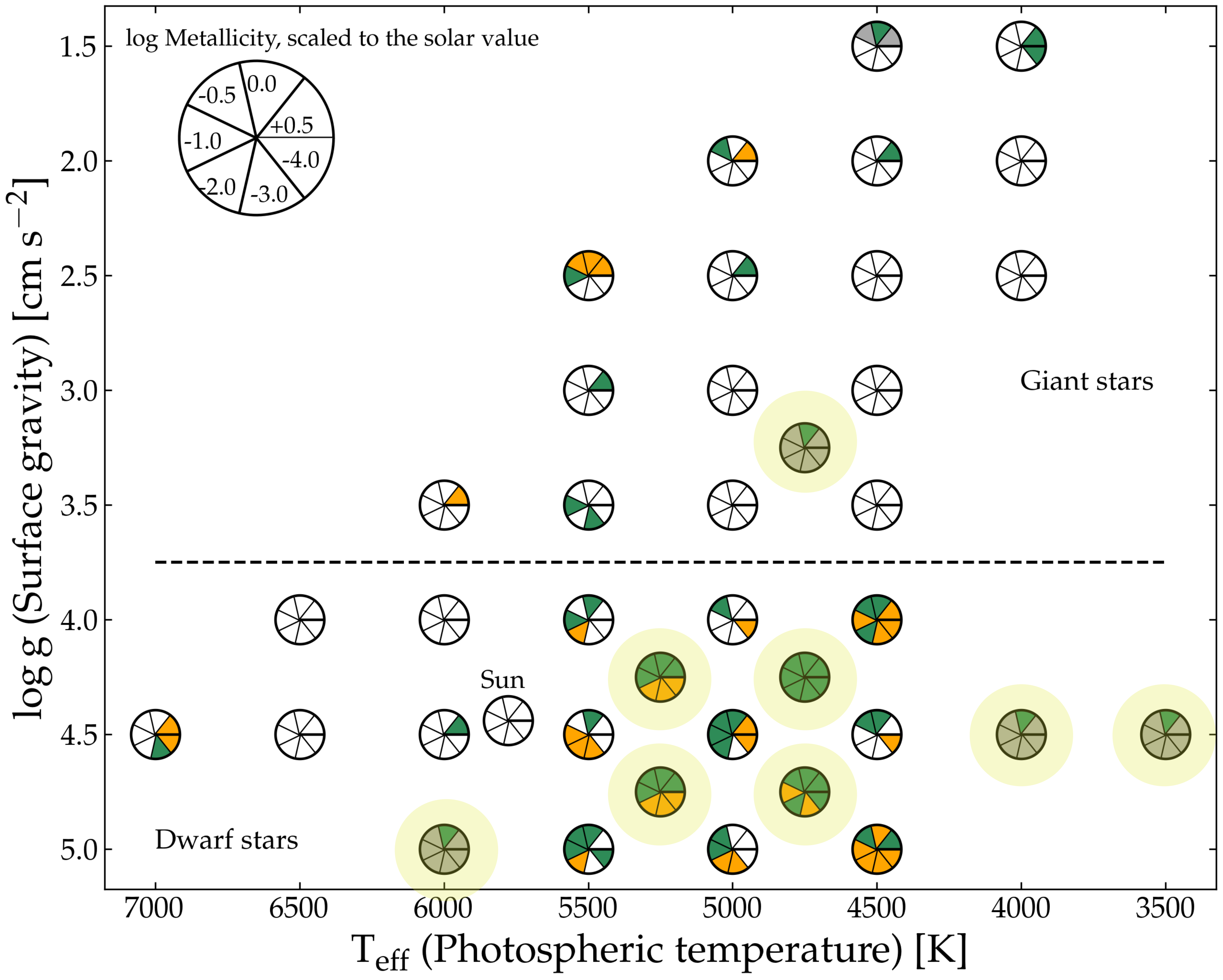
AN EXTENDED AND REFINED STAGGER GRID

Improve models and create new ones, mainly for PLATO purposes

Rodríguez Díaz et al. In prep.

Work with Lionel Bigot, Cis Lagae (Stockholm), Anish Amarsi, Karin Lind (Stockholm), Regner Trampedach, Remo Collet

Yellow: models we are currently working on
Green: improved models
Grey: non-existent models
White: rest of the models from Magic et al. 2013.



CHARACTERISATION OF STELLAR GRANULATION

Rodríguez Díaz et al. 2022

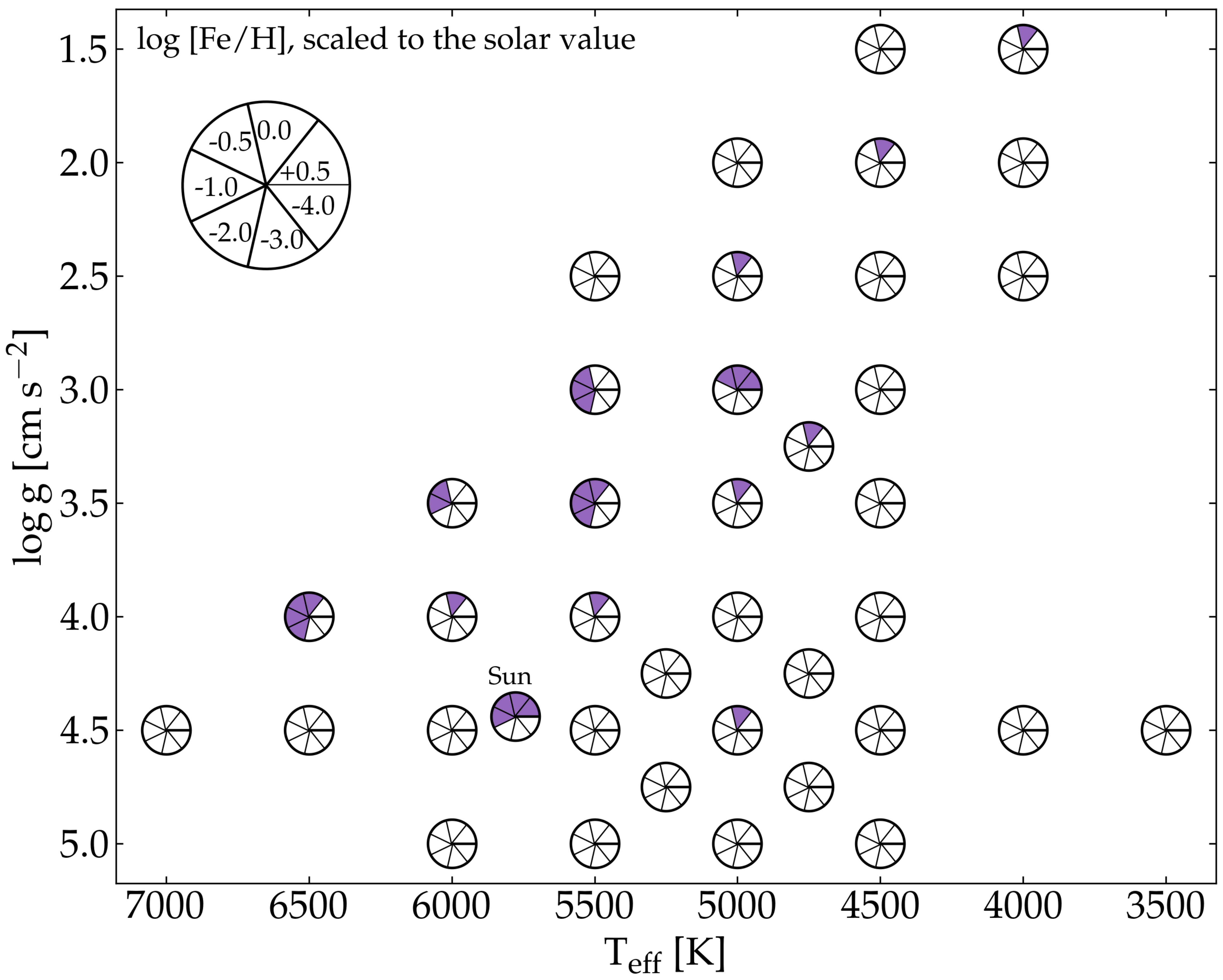
Work with Lionel Bigot, Víctor Aguirre Børsen-Koch, Thomas Kallinger,
Jakob Lysgaard Rørsted, Mikkel Lund, Sophia Sulis, David Mary

AN EXTENDED AND REFINED STAGGER GRID

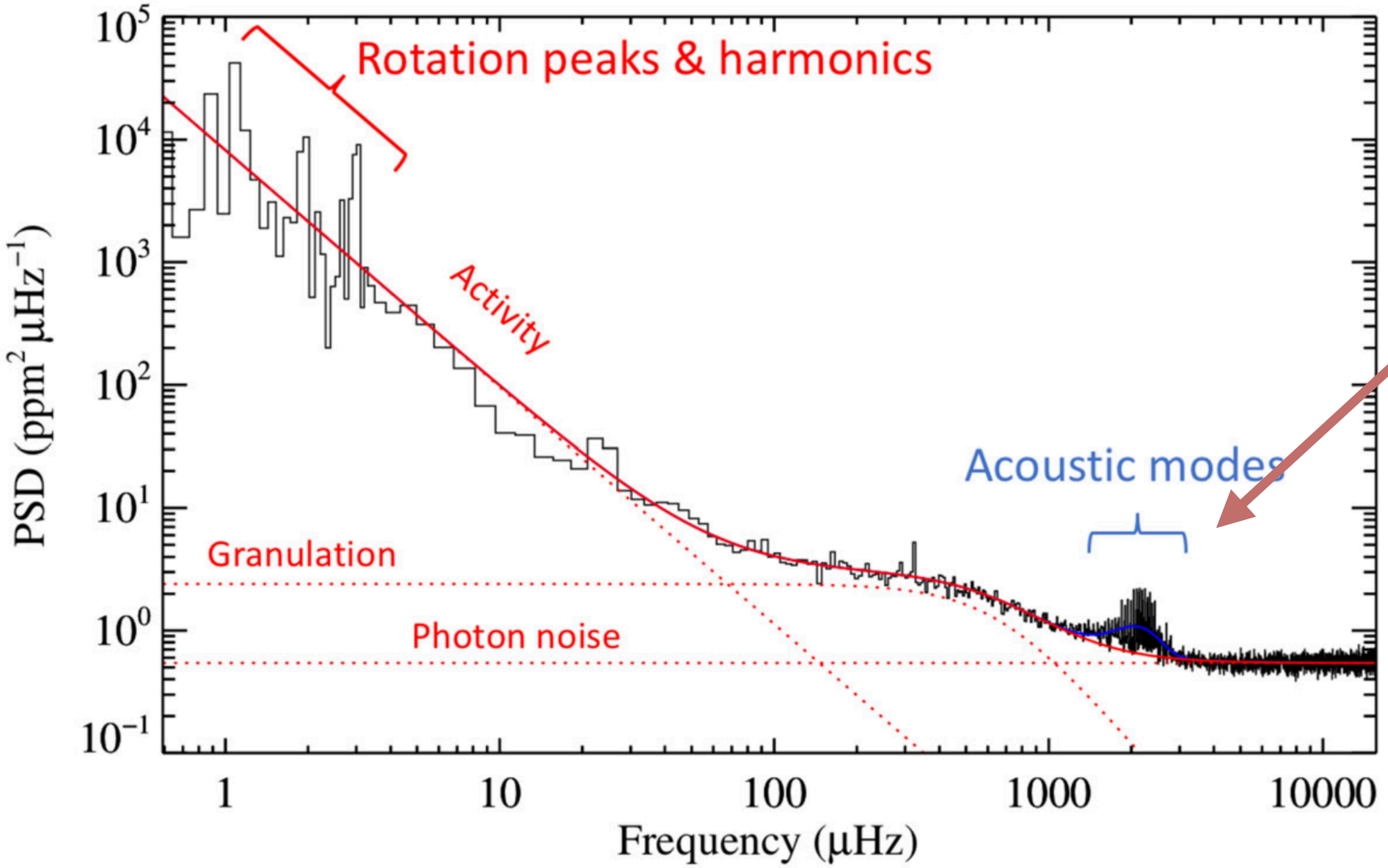
Models selected to cover a wide range in ν_{max}: peak-frequency of the solar-like oscillations

$$\nu_{max} \propto \left(\frac{g}{g_\odot}\right)\left(\frac{T_{eff,\odot}}{T_{eff}}\right)^{1/2}\left(\frac{\mu}{\mu_\odot}\right)^{1/2}$$

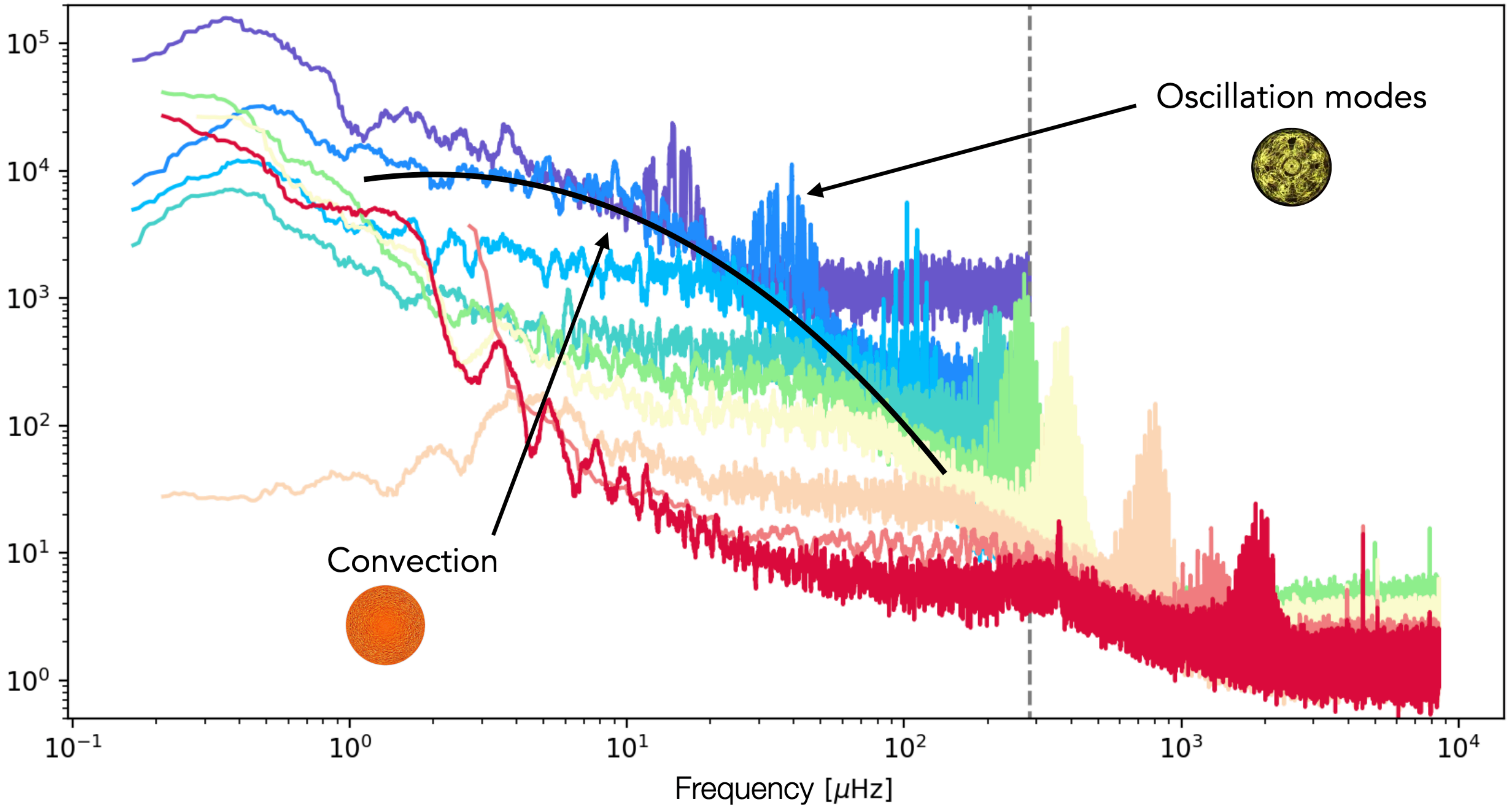
Very long time series, with the same physical setup



ν_{max}: peak-frequency of the solar-like oscillations



Credits: Rafael García et al. 2019 (in Ballot et al. 2011)



Credits: Lisa Bugnet

TIME SERIES FROM 3D MODELS

t45g20m00

T_{eff}: 4500 K, logg = 2.0, [Fe/H] = 0.0

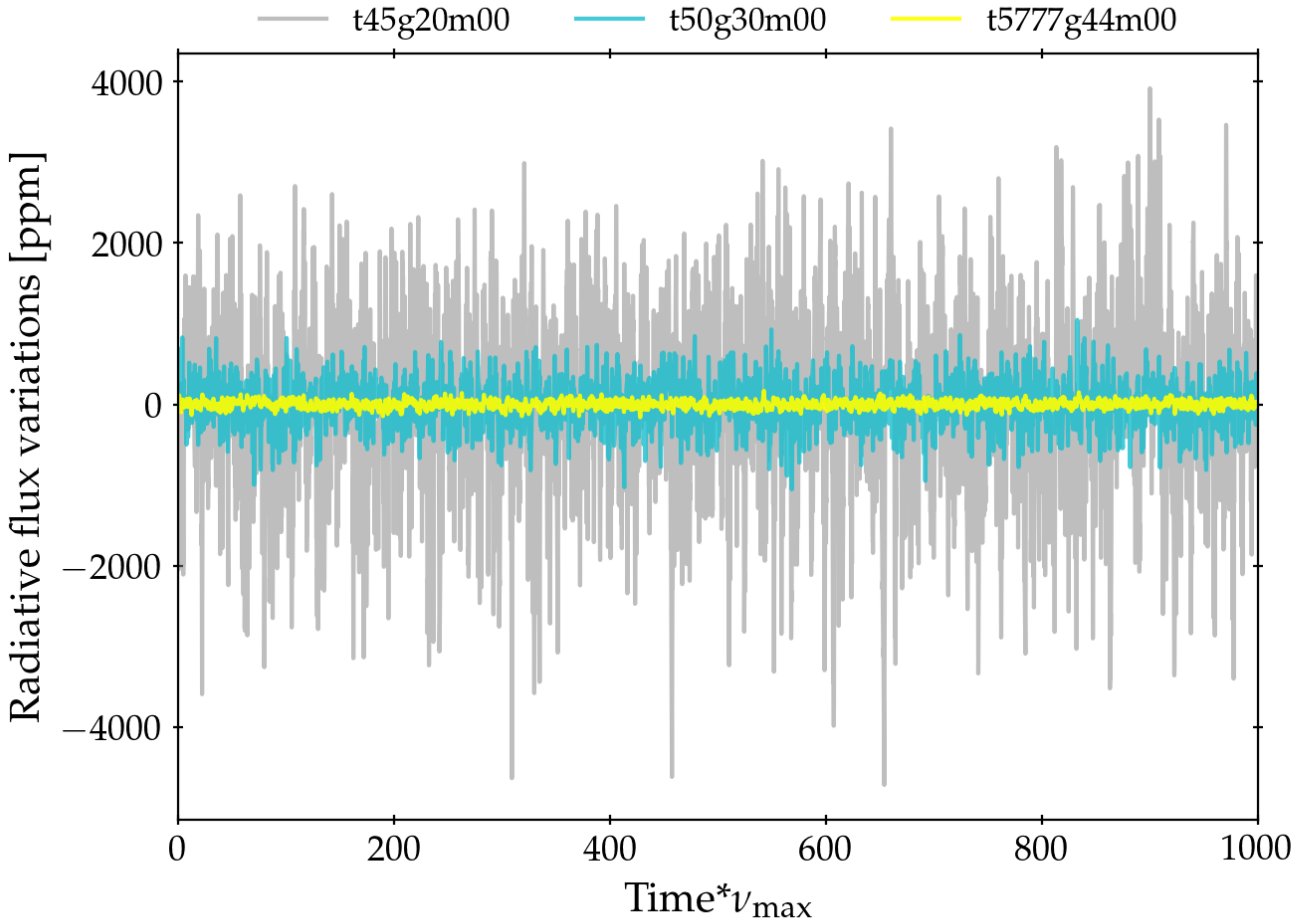
t50g30m00

T_{eff}: 5000 K, logg = 3.0, [Fe/H] = 0.0

t5777g44m00

T_{eff}: 5777 K, logg = 4.44, [Fe/H] = 0.0

Granulation amplitude changes!



PROPERTIES OF GRANULATION NOISE

Standard deviation

$\sigma_{box} = \sqrt{\langle \mathscr{F}^2 \rangle - \langle \mathscr{F} \rangle^2}$, where $\mathscr{F}$ is the bolometric radiative flux

From a small box to the whole star

Scale by the number of granules: $\sigma = \sigma_{box}\sqrt{N^{-1}}$,
with $N = 2\pi R_\star^2 / l^2$.

Following Trampedach 1998, Ludwig 2006

$R_\star$: stellar radius

l: length of one horizontal side of the 3D models

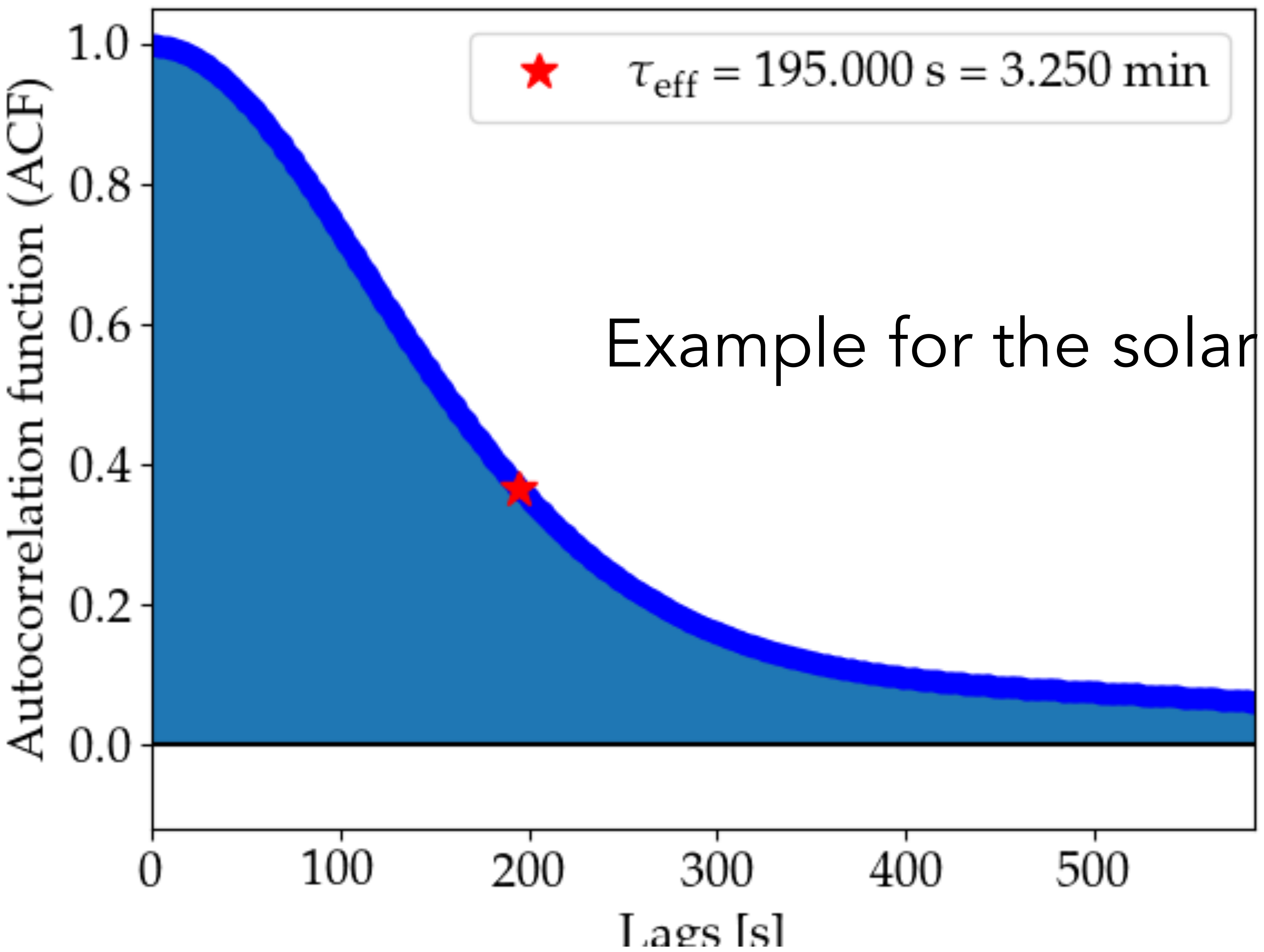
PROPERTIES OF GRANULATION NOISE

Characteristic time scale

Using the autocorrelation function

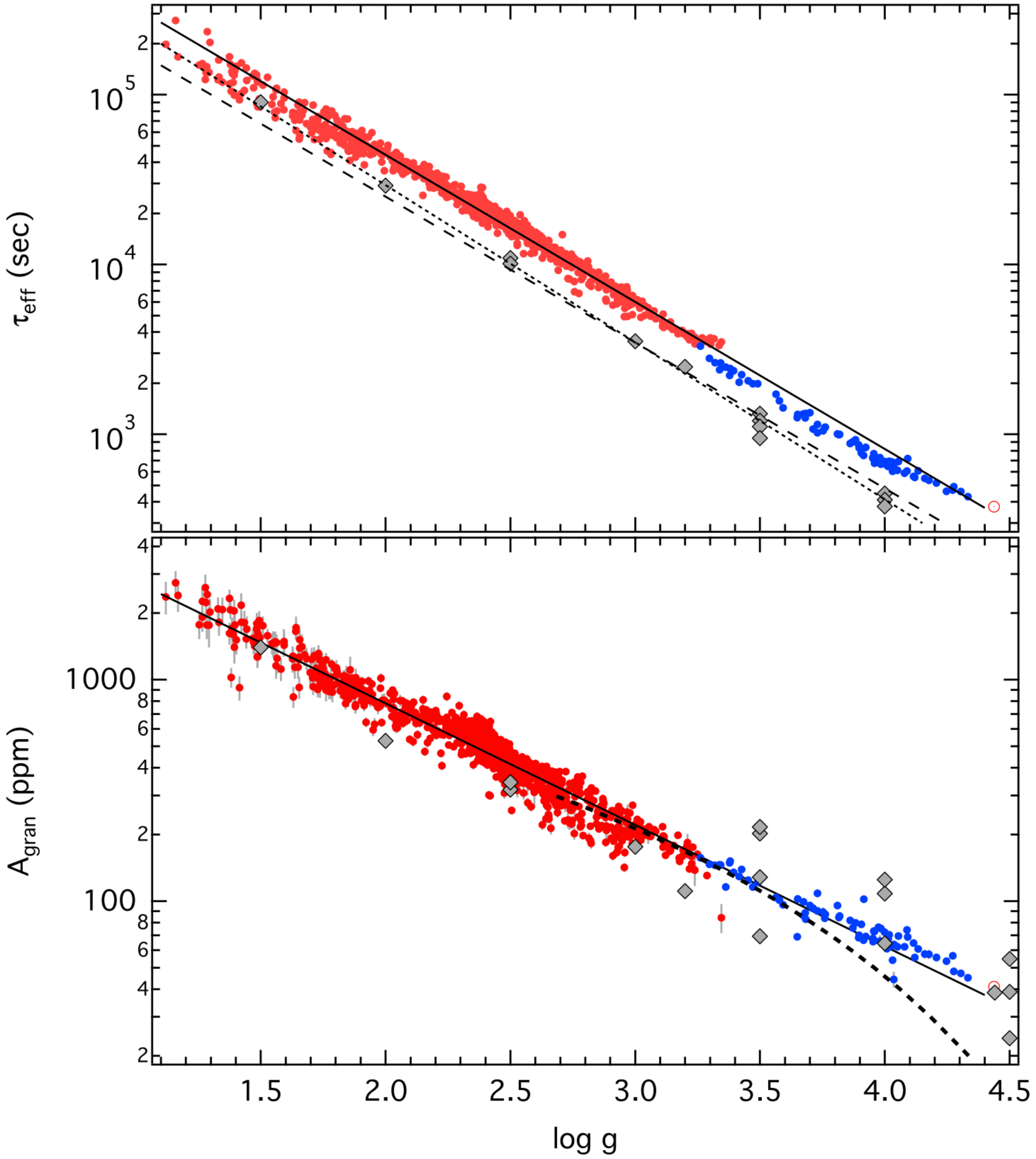
Following Mathur et al. 2011, Samadi et al. 2013, Kallinger et al. 2014

Computed as the e-folding time of the ACF (i.e. when the ACF drops by a factor of e^{-1}).



Example for the solar model

CHARACTERIZATION OF GRANULATION NOISE



Credits: Kallinger et al. 2014

Kepler sample from *Kallinger et al. 2014*. Stellar parameters were derived with scaling relations.

Red: long cadence data.
Blue: short cadence data.
Grey: *Samadi et al. 2013*.
3D models from the CIFIST grid.

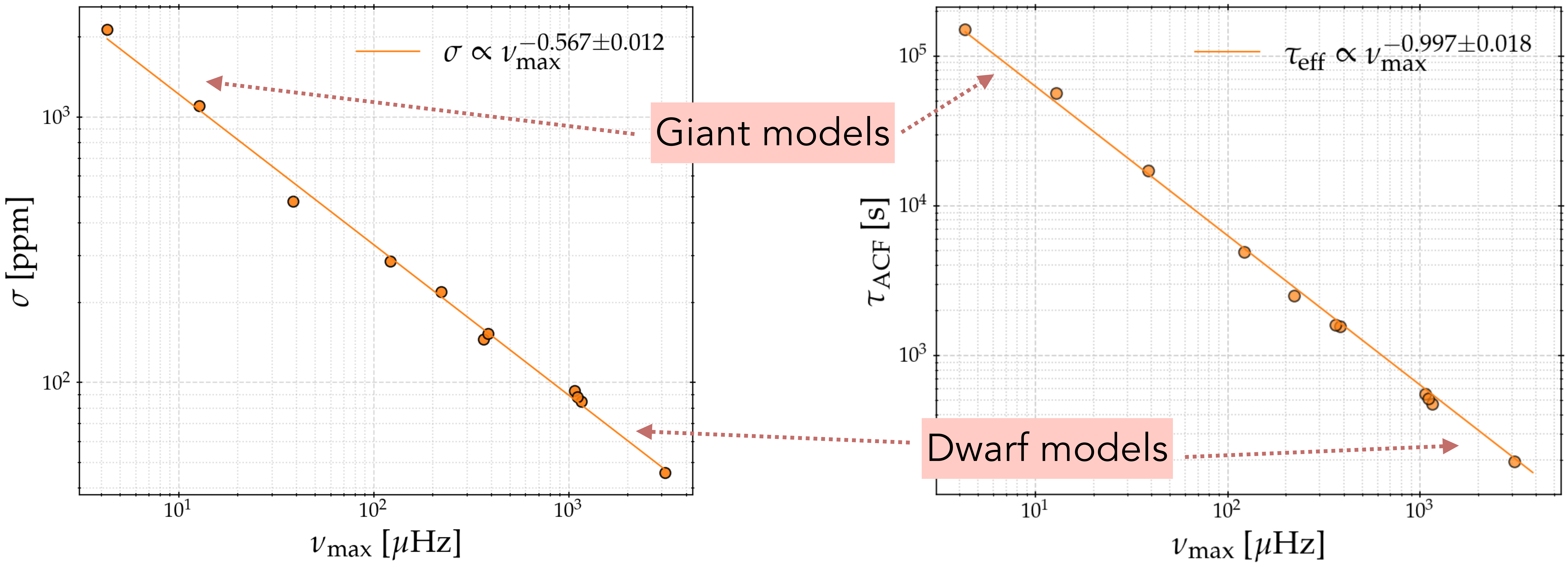
- Predictions from 3D models **did not reproduce** the observed data.
- Offset in timescales, and large spread in granulation noise.

Y-axes are in log-scale!

More studies: Ludwig et al. 2009, Mathur et al. 2011, Bastien et al. 2016, Kallinger et al. 2016, Pande et al. 2018

THIS WORK - 3D MODELS AT SOLAR METALLICITY

Very nice correlation with ν_{max} at solar metallicity!

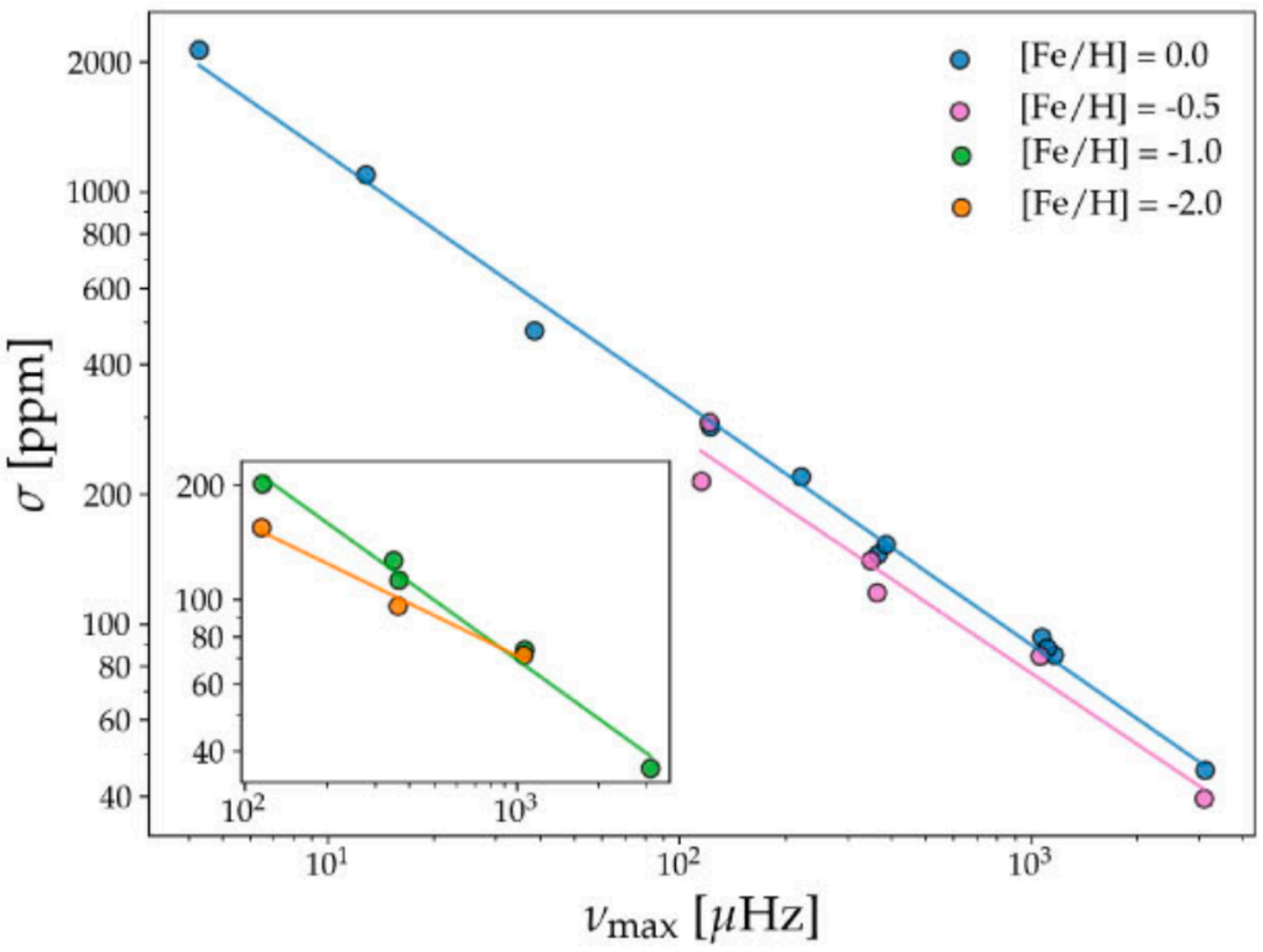


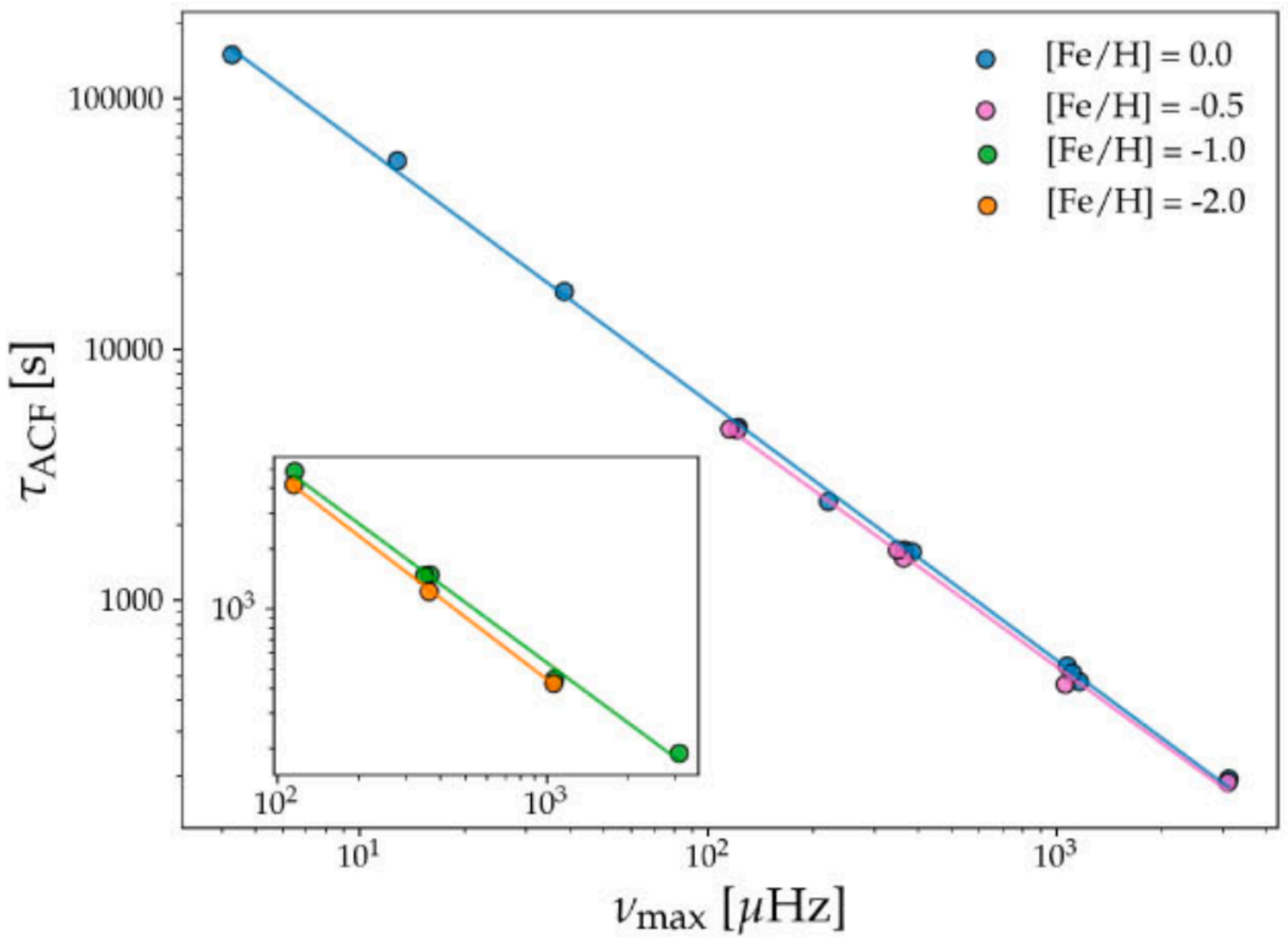
Giant models

Dwarf models

THIS WORK - METALLICITY DEPENDANCE

Scaling relations for each metallicity: different parameters!

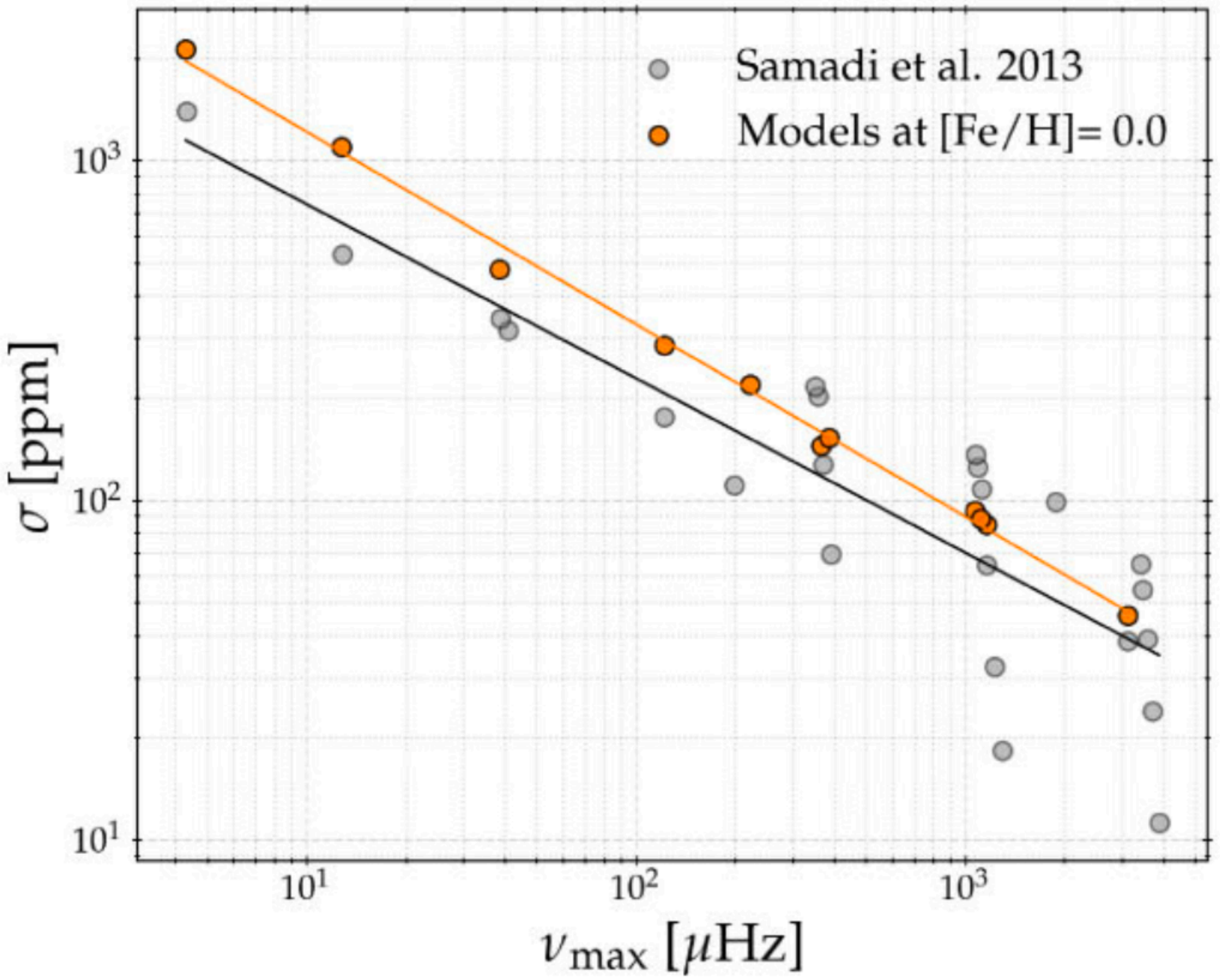


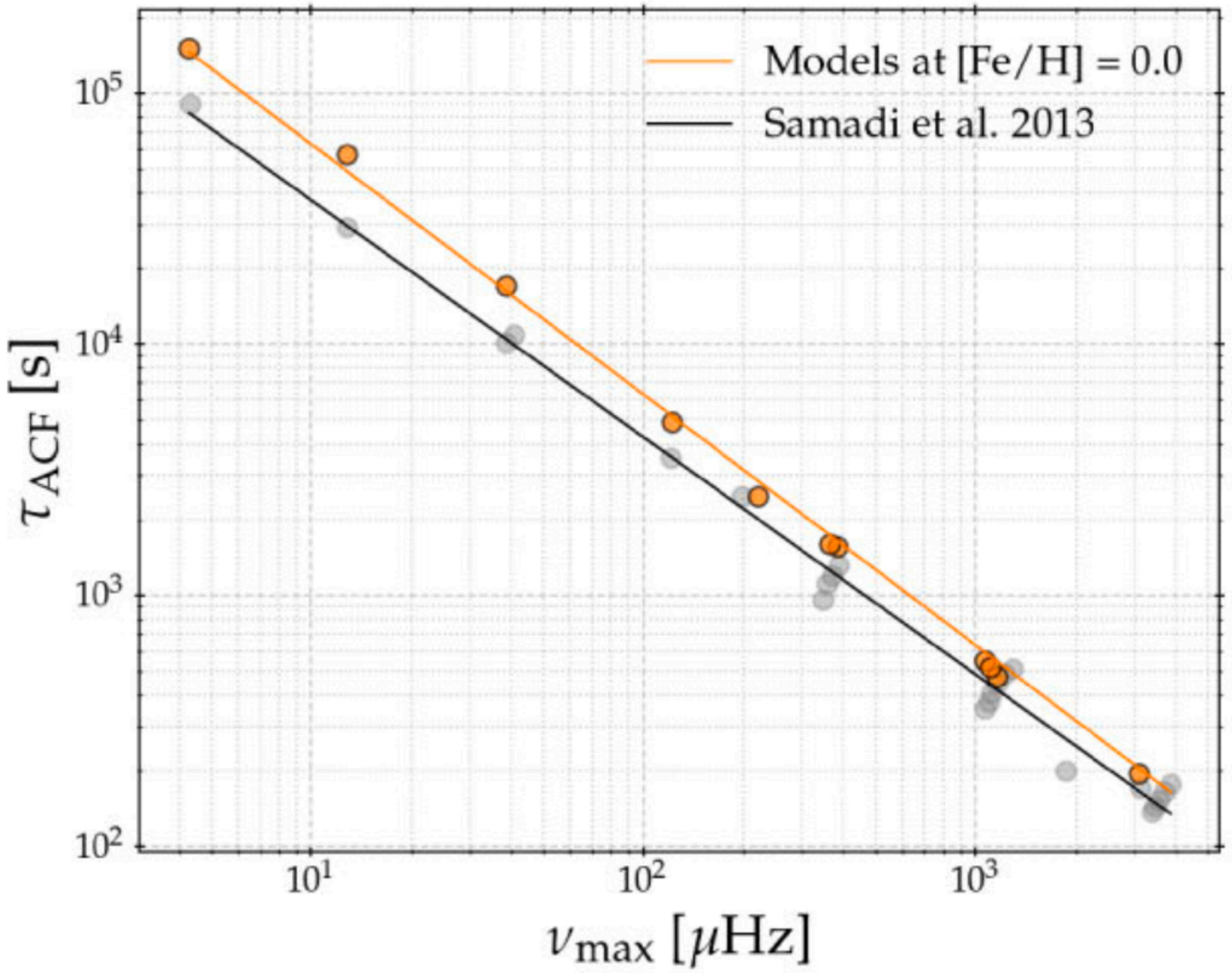


COMPARISON WITH SAMADI ET AL. 2013

3D models from STAGGER // 3D models from CO$_5$BOLD
Long time series // Short time series

The relations are not the same. Scatter is not present in our study!



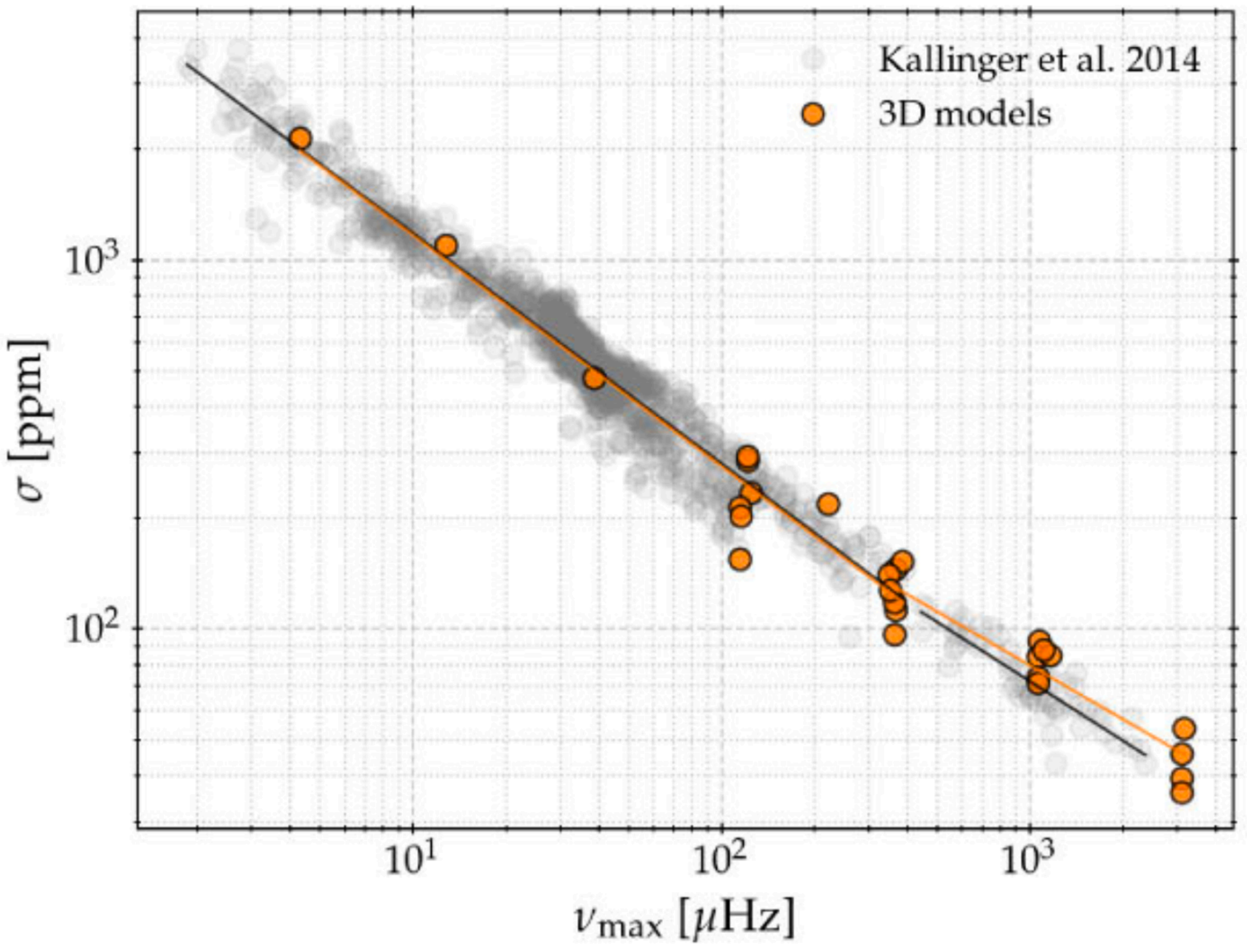


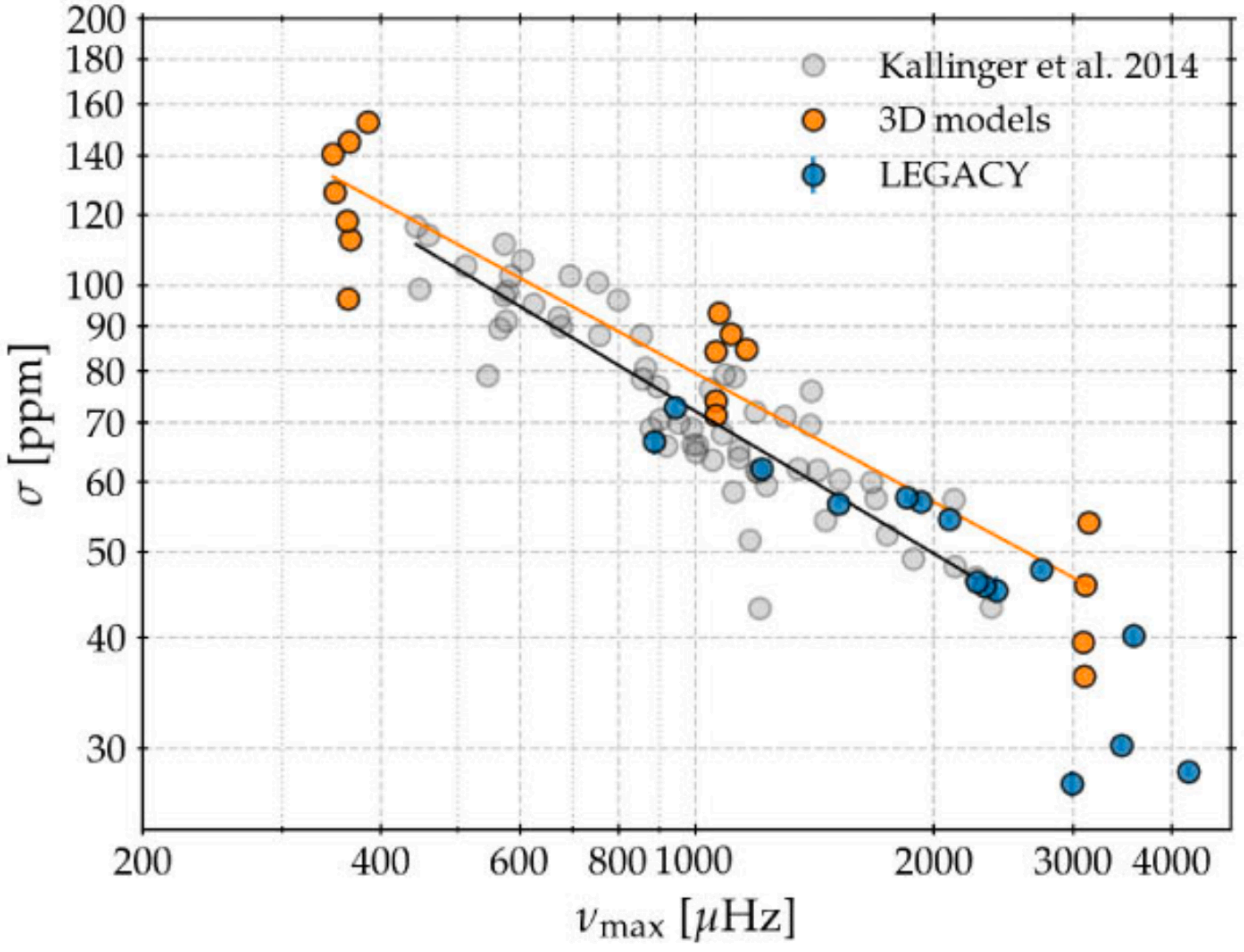
COMPARISON WITH OBSERVATIONAL DATA

Sample of Kepler stars from Kallinger et al. 2014

Selected stars from the LEGACY sample (Lund et al. 2017)

Two different trends, but models follow the observations!



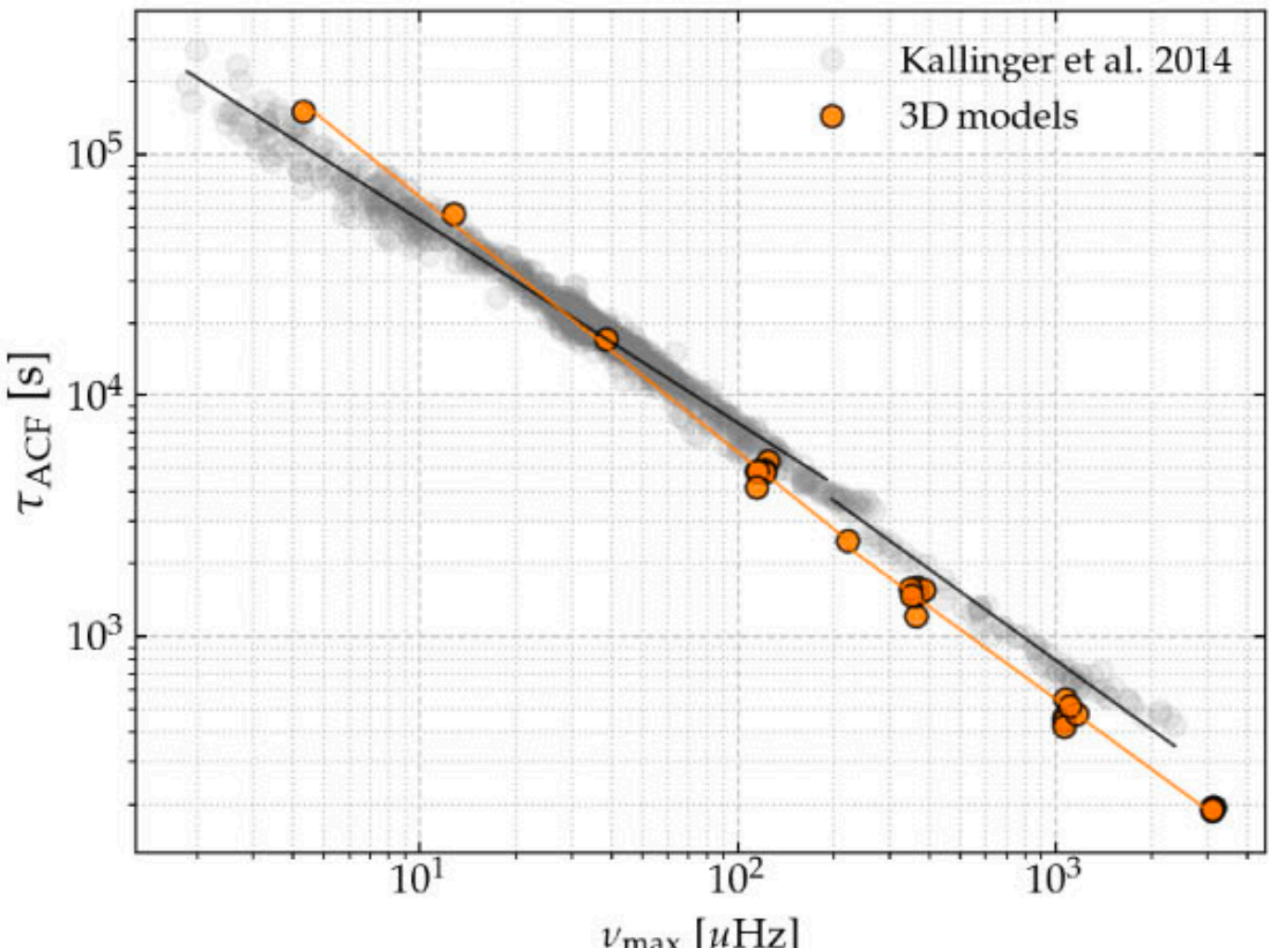


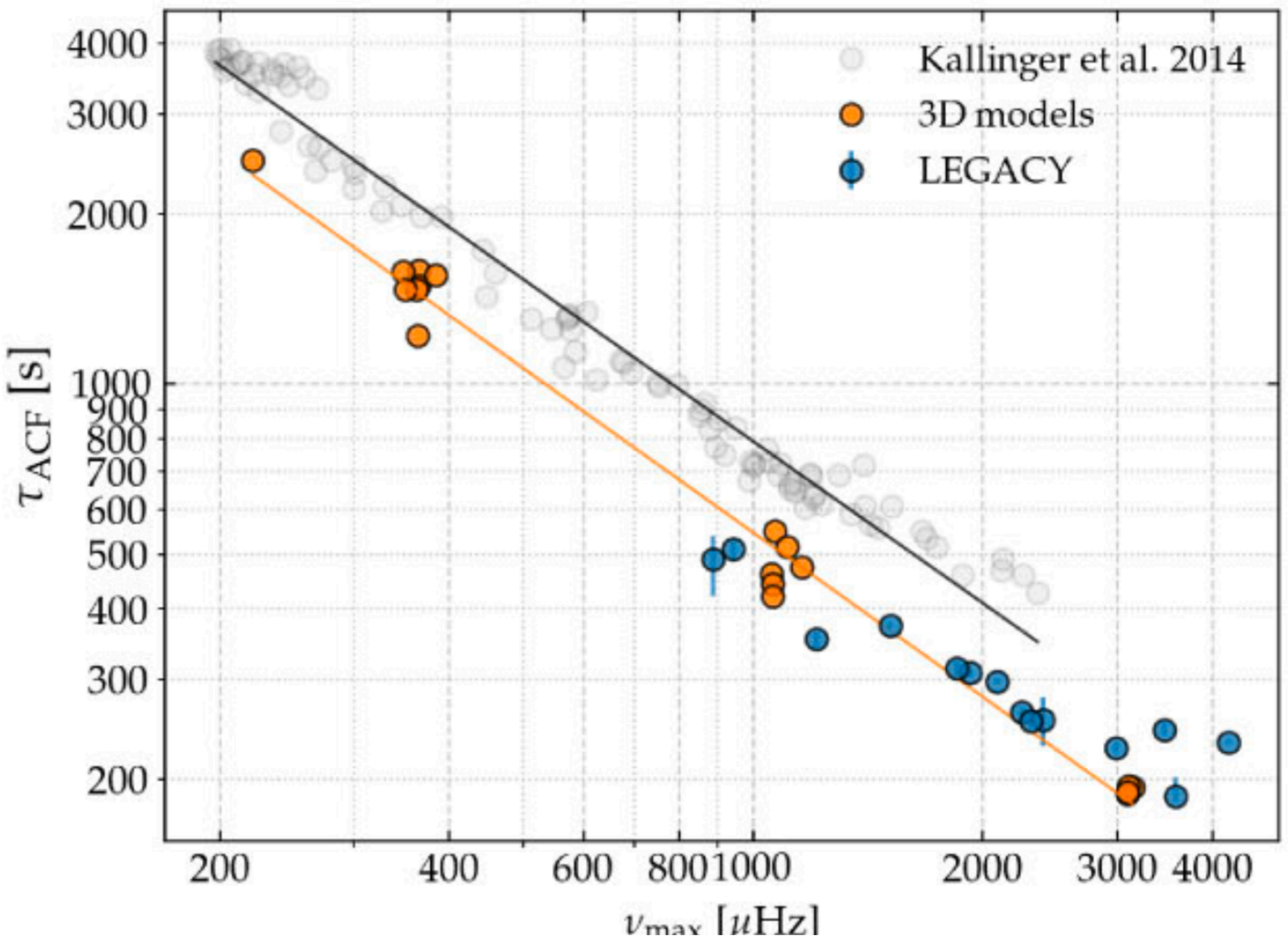
COMPARISON WITH OBSERVATIONAL DATA

Sample of Kepler stars from Kallinger et al. 2014

Selected stars from the LEGACY sample (Lund et al. 2017)

Offset might be due to the determination of stellar parameters, but good fit overall!

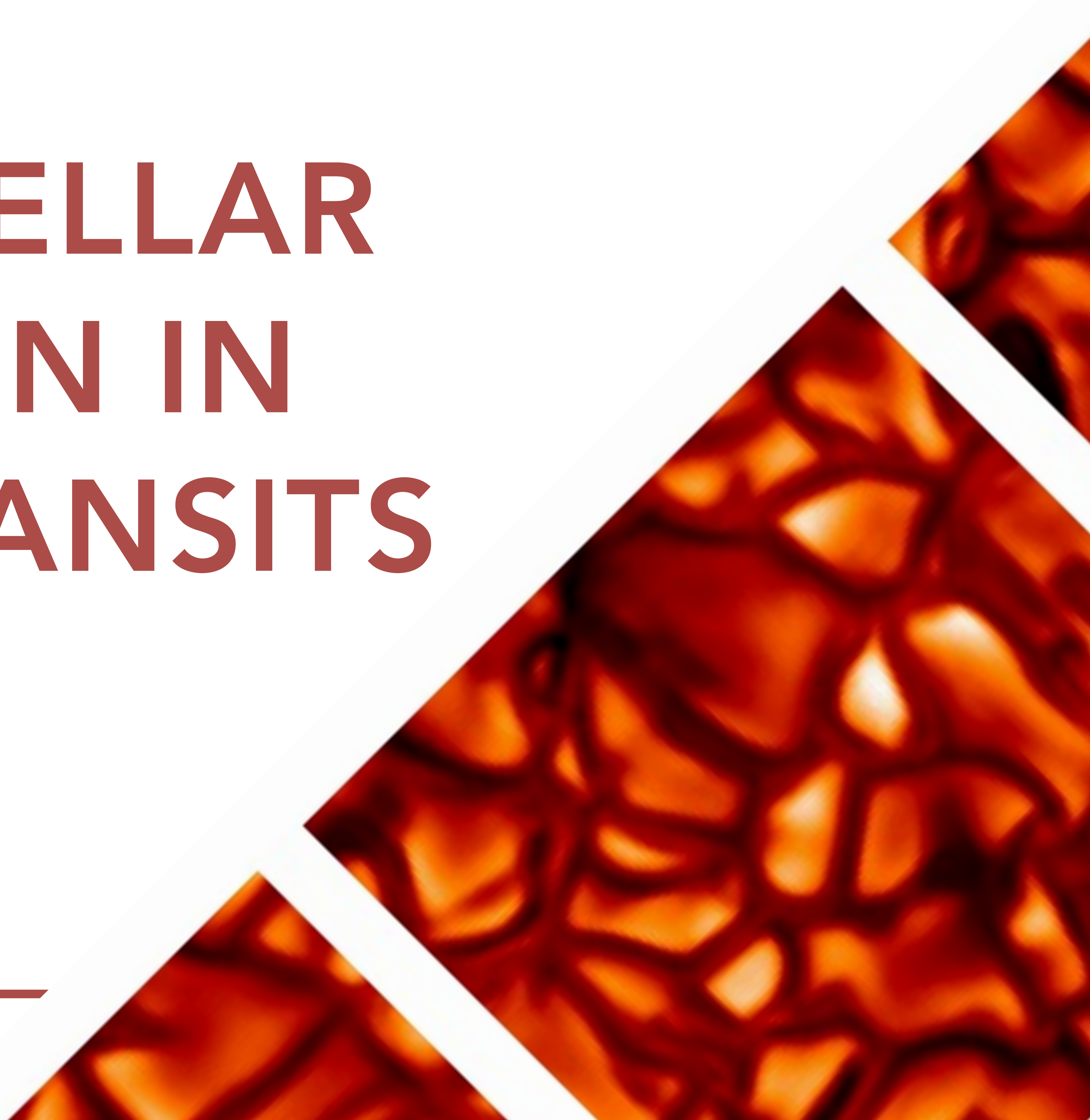




EFFECT OF STELLAR GRANULATION IN PLANETARY TRANSITS

Rodríguez Díaz in prep.

Work with Lionel Bigot, Suzanne Aigrain, Víctor Aguirre Børsen-Koch



CONCLUSIONS

We are working on an **extended** and **refined** version of the **STAGGER grid.**

We derived **scaling relations** between **granulation properties** and ν_{max} using 3D models.

They **reproduce observations** very well.

Metallicity effect was quantified.

We are studying the **effect** of **convection**/granulation on **light curves** and **exoplanet parameters**.