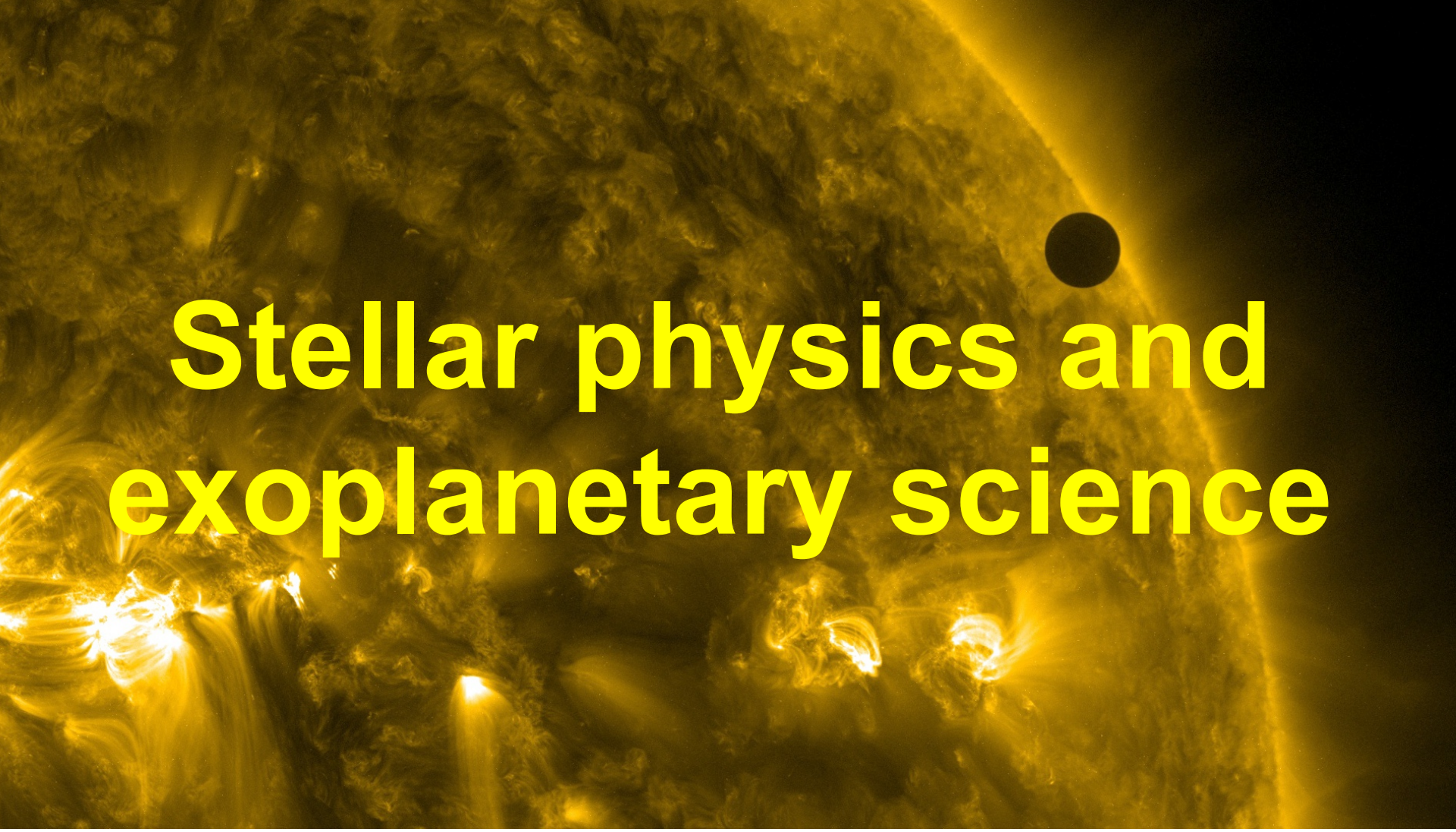


Stellar physics and exoplanetary science

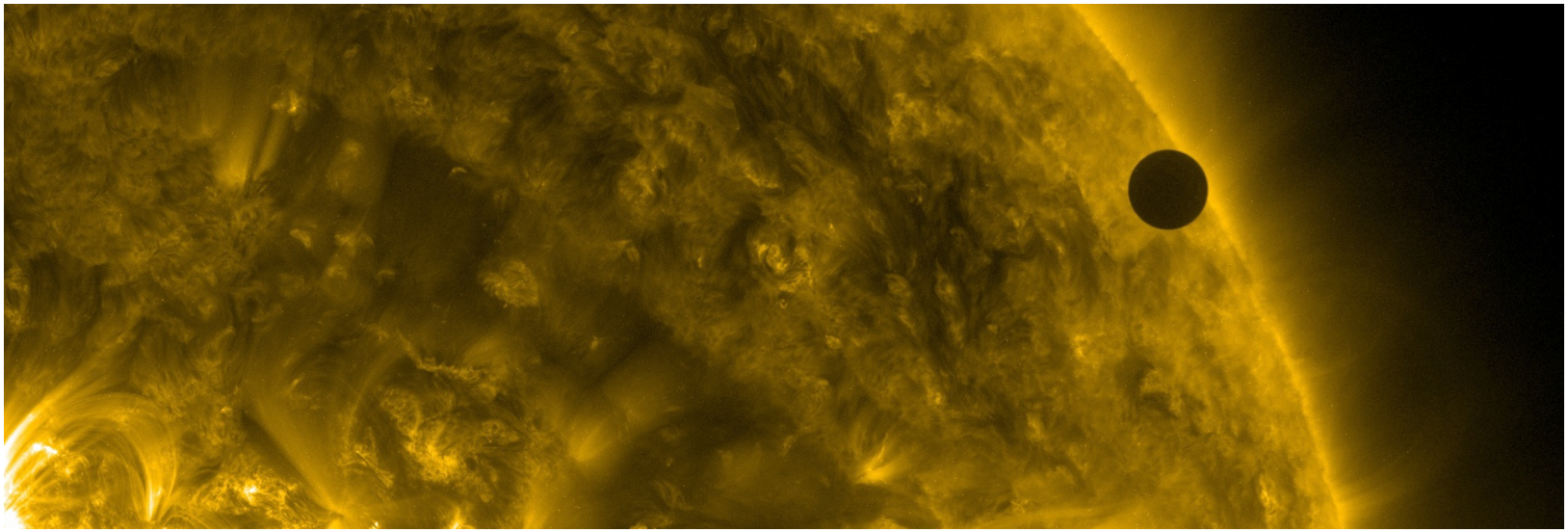
Martin Asplund

THE AUSTRALIAN NATIONAL UNIVERSITY

Australian Government

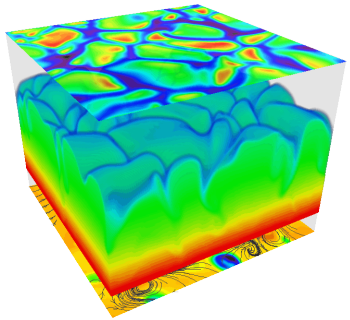
Australian Research Council

Stellar modeling and exoplanets



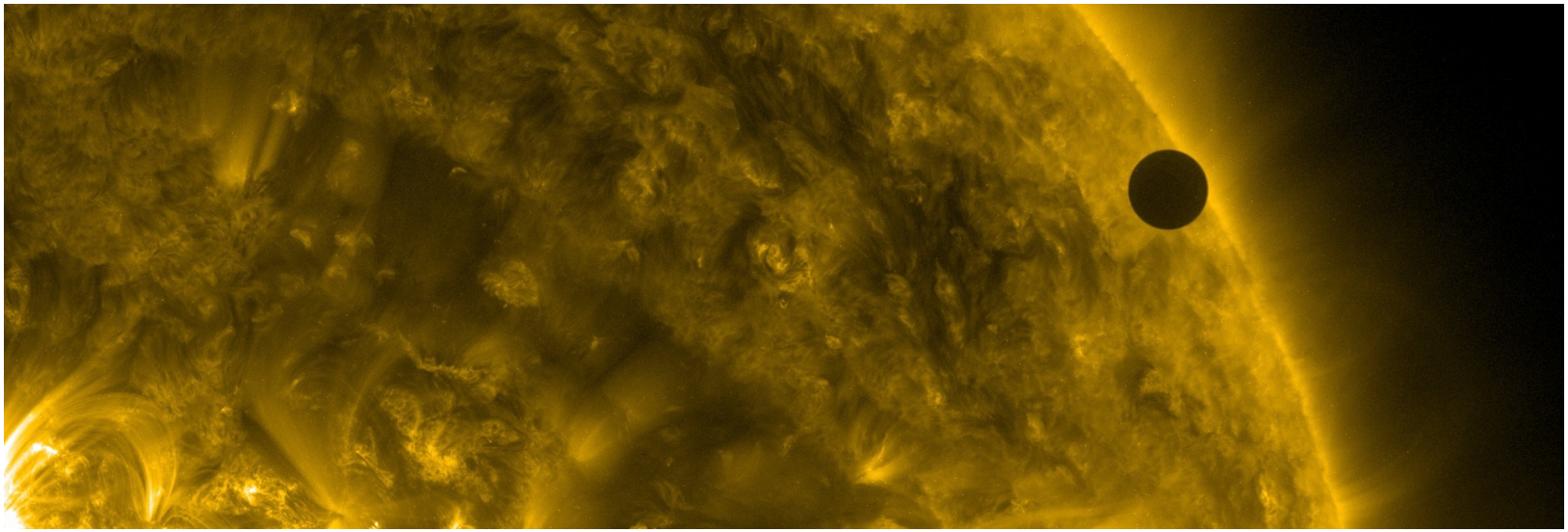
Stars:
Convection
Evolution
Oscillations
Atmospheres
Spectra
Composition

Stellar models



Exoplanets:
Detection
Age
Mass
Radius
Atmospheres
Composition

Stellar modeling and exoplanets



Stars:

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Evolution

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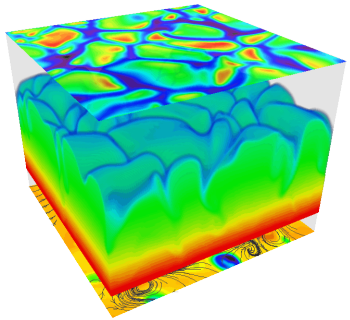


Exoplanets:

Detection

Age

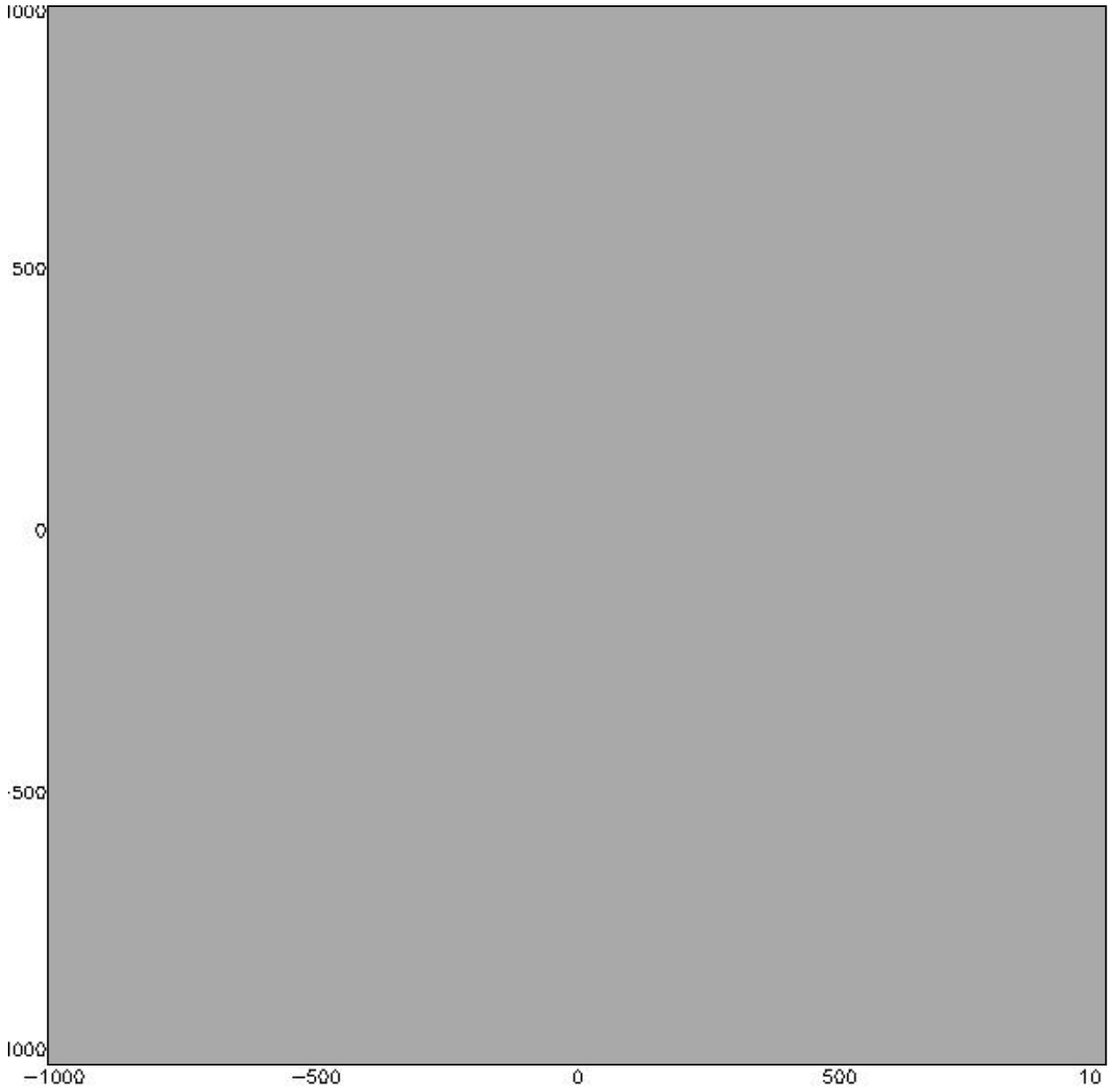
Mass

Radius

Atmospheres

Composition

Stellar surface convection



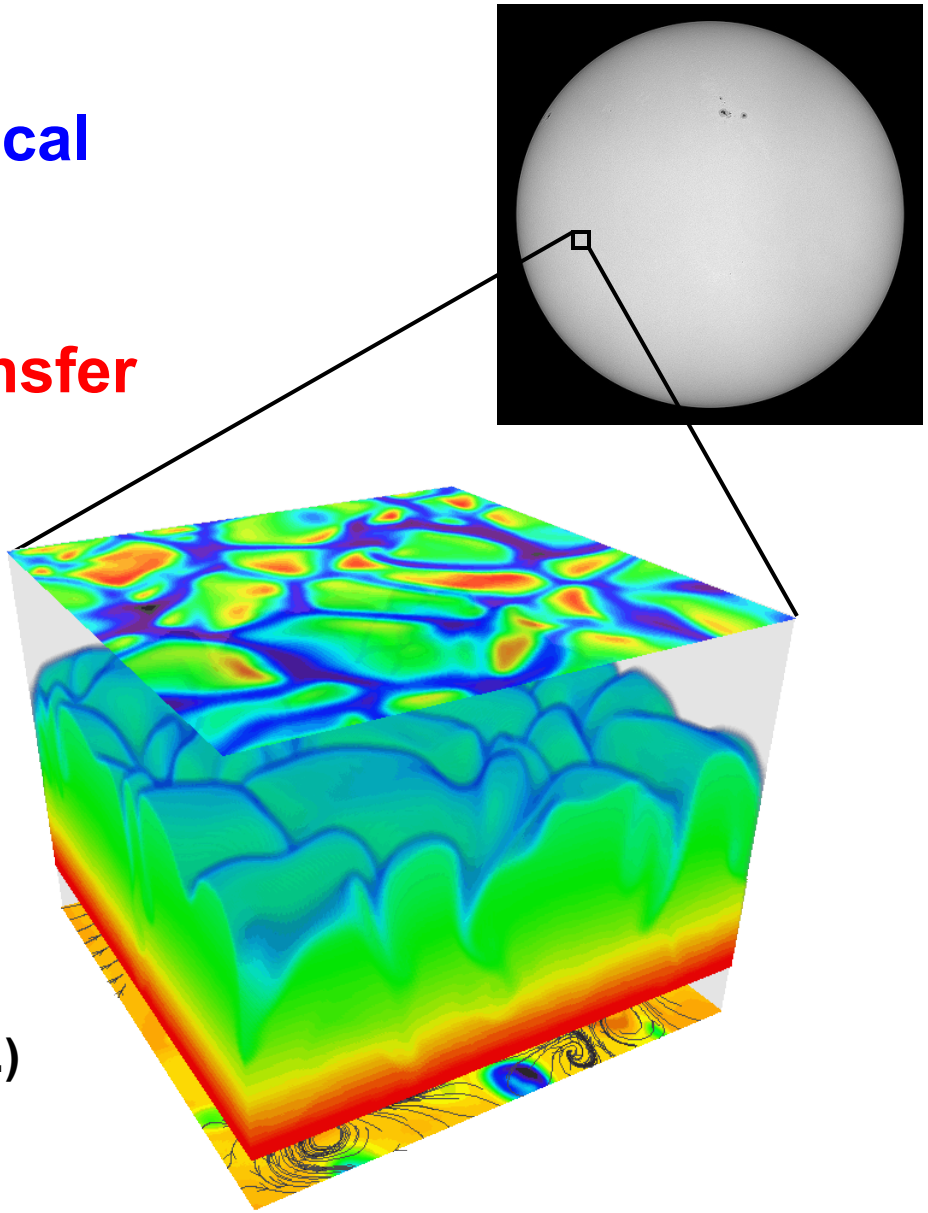
Mats Carlsson (Oslo)

3D stellar atmosphere models

Ingredients:

- **Radiative-hydrodynamical**
- **Time-dependent**
- **3-dimensional**
- **Simplified radiative transfer**

Essentially parameter free

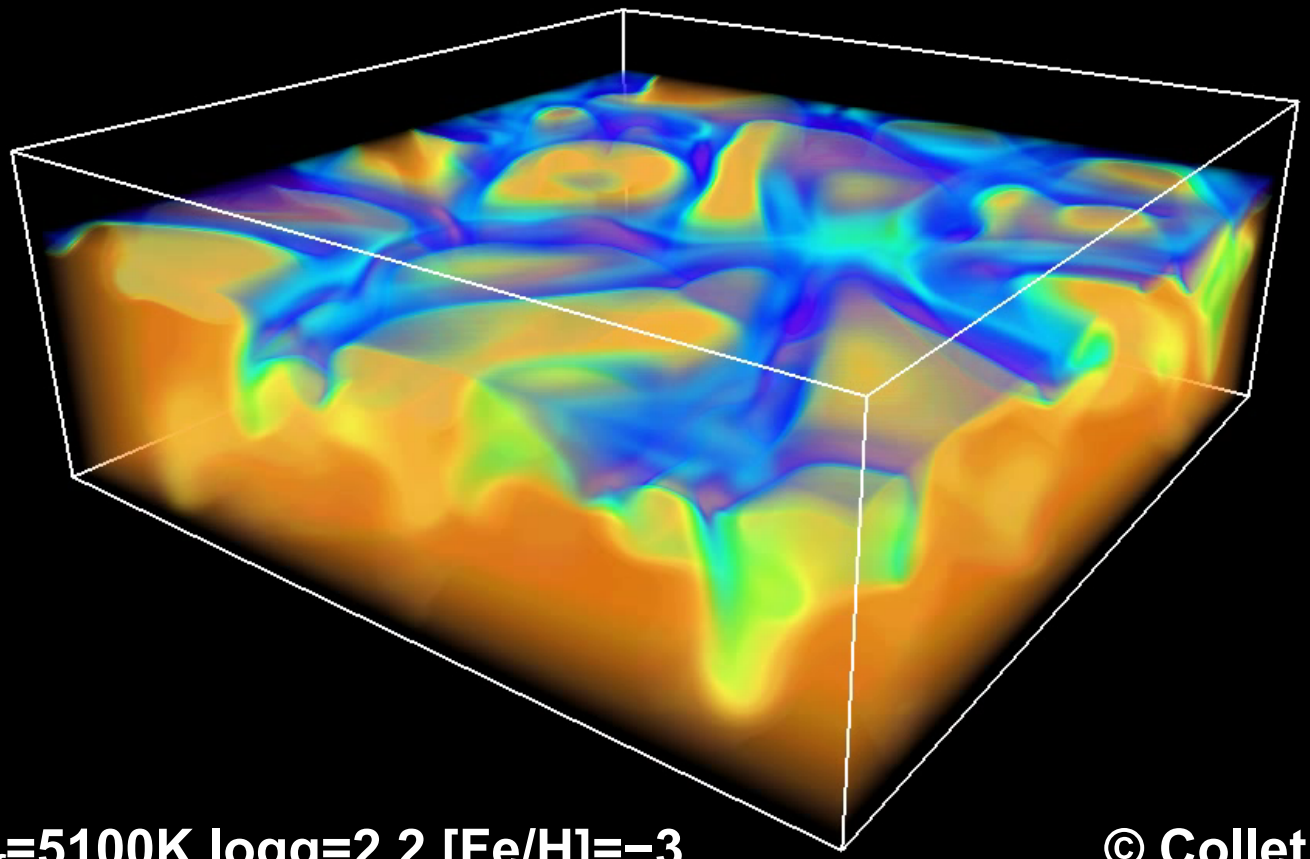


For the aficionados:

Stagger-code (Nordlund et al.)
MHD equation-of-state (Mihalas et al.)
MARCS opacities (Gustafsson et al.)
Opacity binning (Nordlund)

3D atmosphere simulation

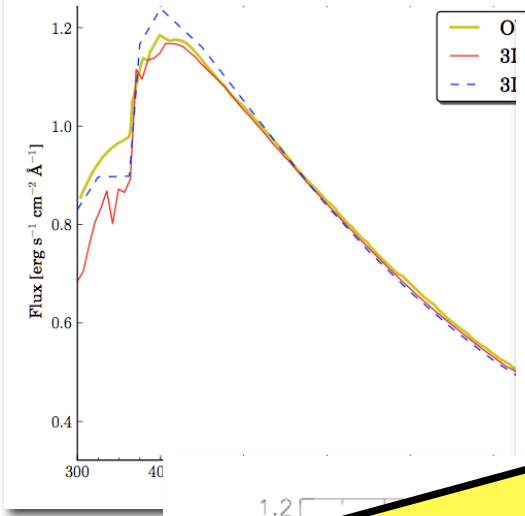
Temporal evolution of entropy in atmosphere of metal-poor red giant



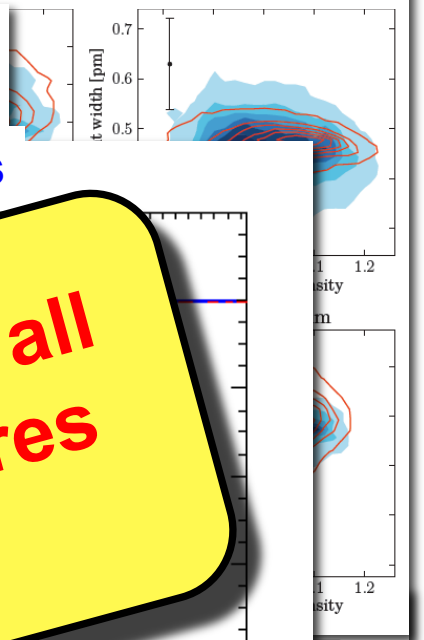
T_{eff}=5100K logg=2.2 [Fe/H]=−3

Observational tests

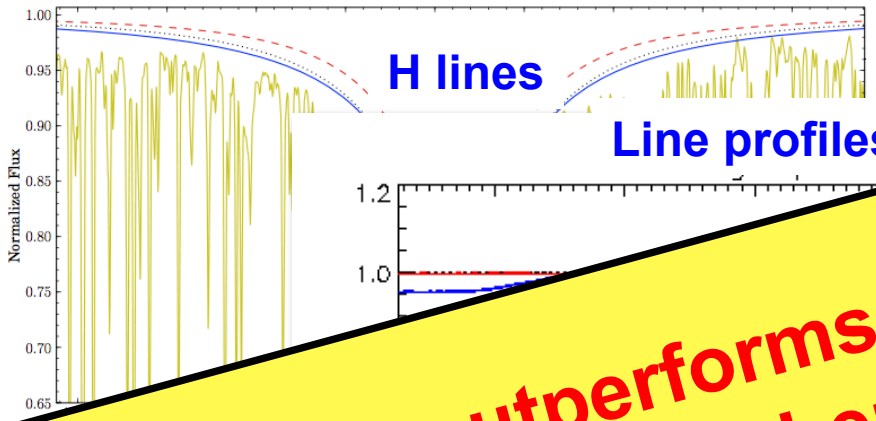
Spectral energy distribution



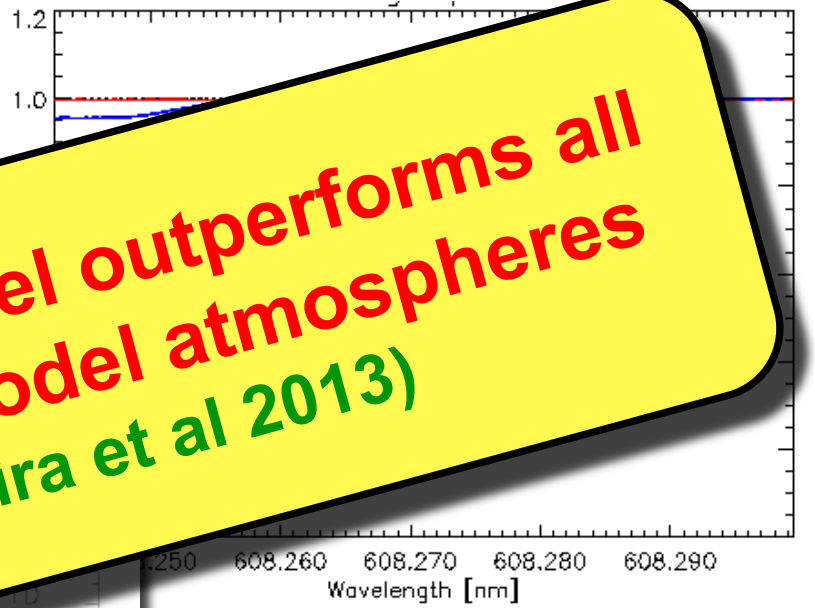
Spatially resolved lines



H lines

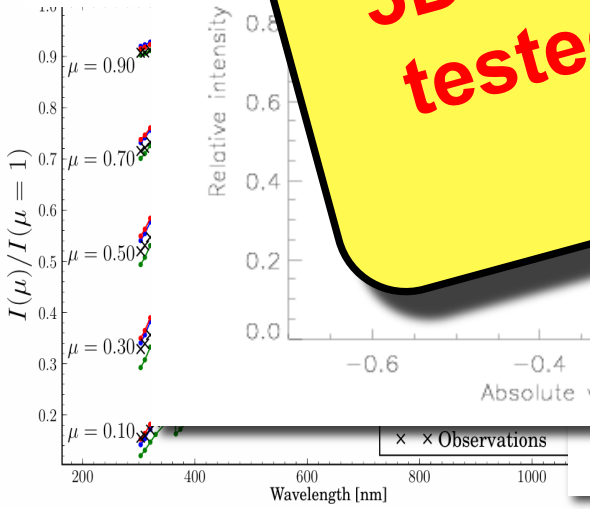


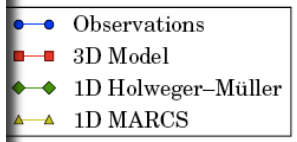
Line profiles

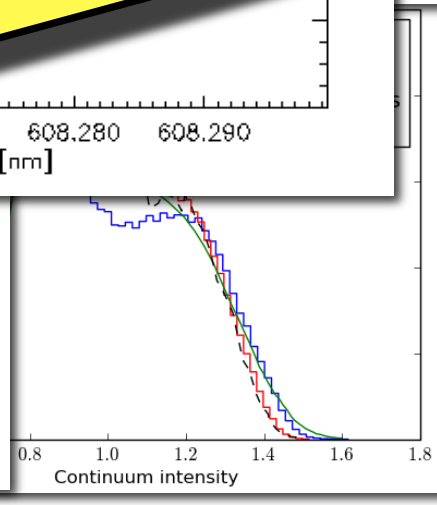


3D solar model outperforms all tested 1D model atmospheres (Pereira et al 2013)

Cent



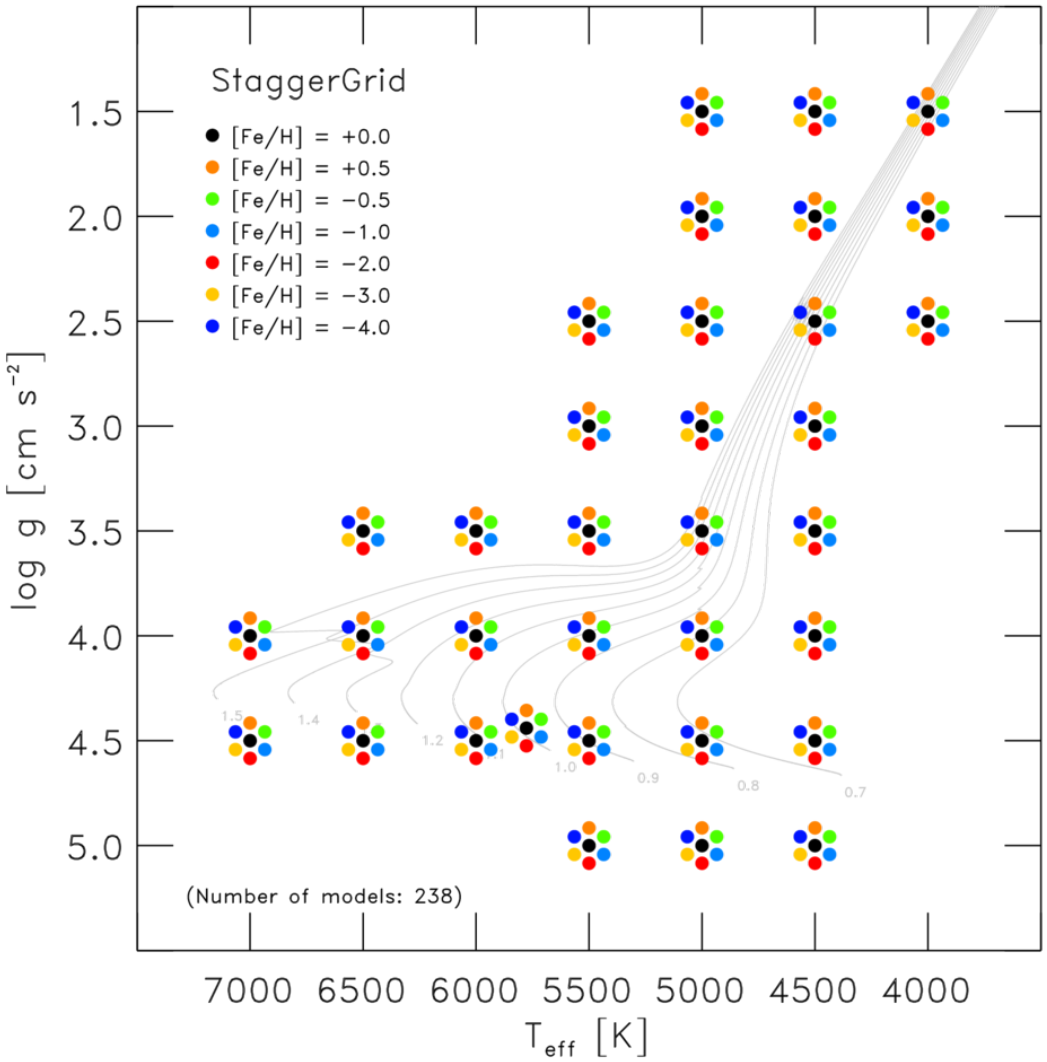




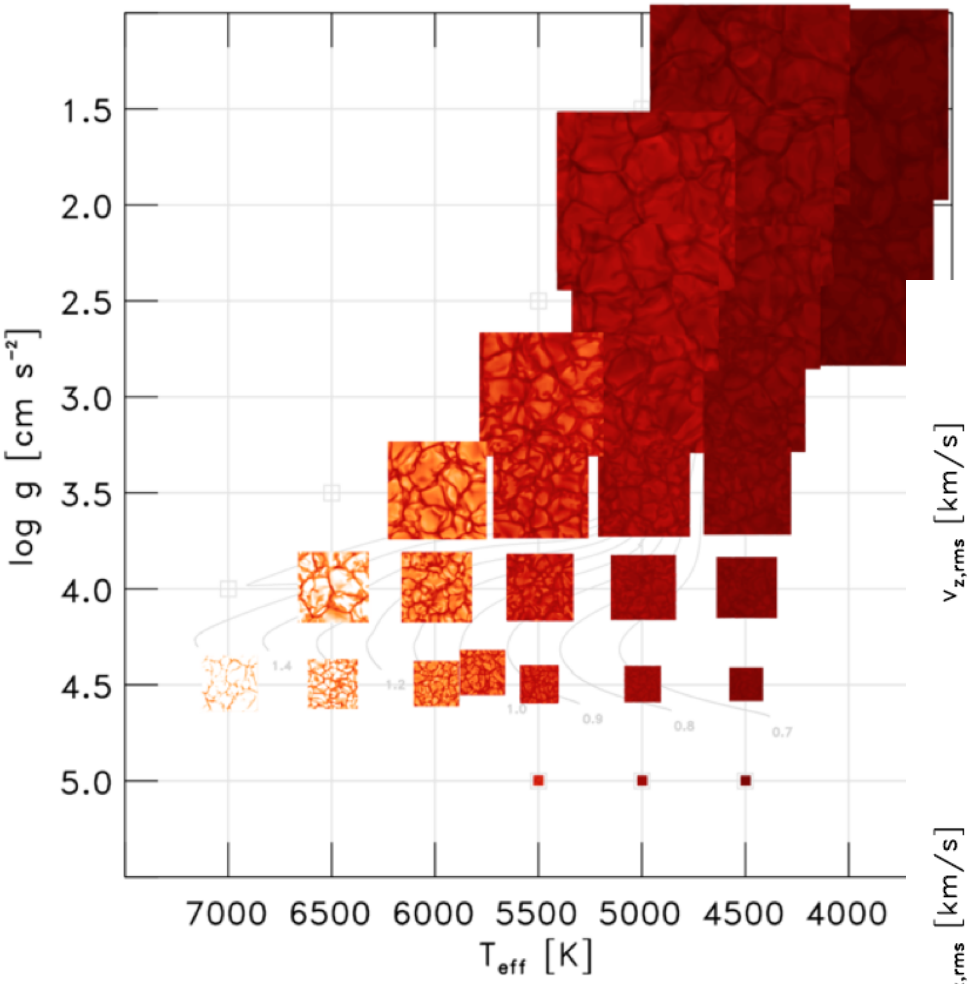
Stagger-grid of 3D stellar models

Magic et al. 2013;
Collet et al. 2012:
3D and <3D> models and fluxes public:

- **Stellar spectroscopy**
- **Stellar evolution**
- **Asteroseismology**
- **Exoplanet searches**
- **Etc, etc**

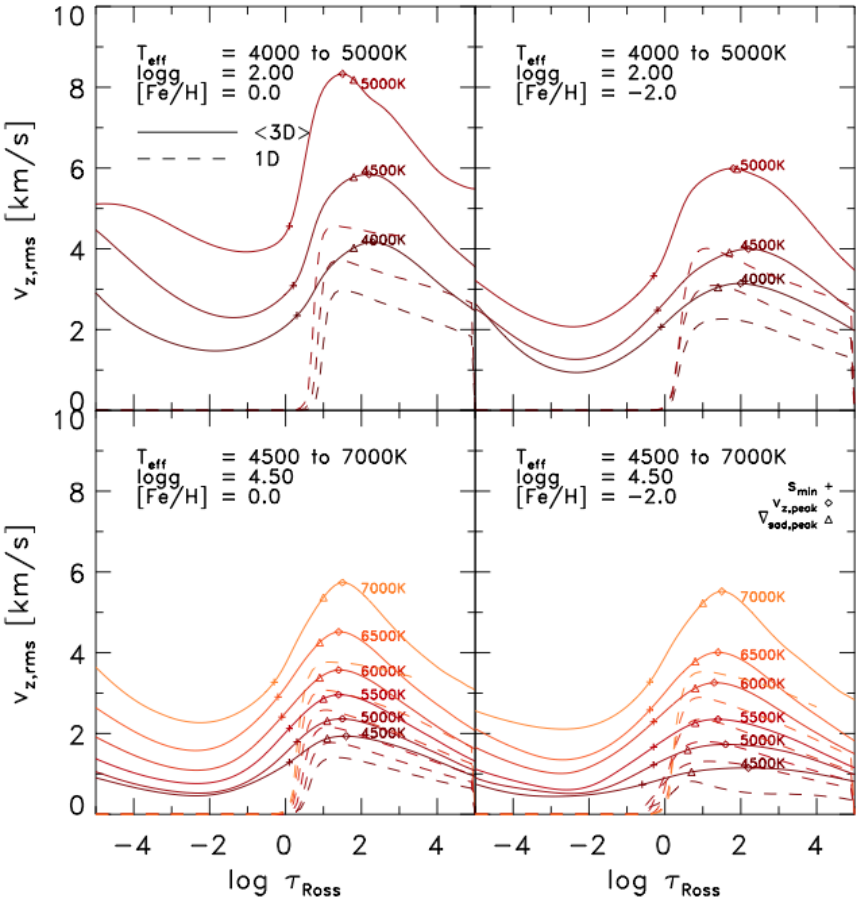


Convection across HR-diagram

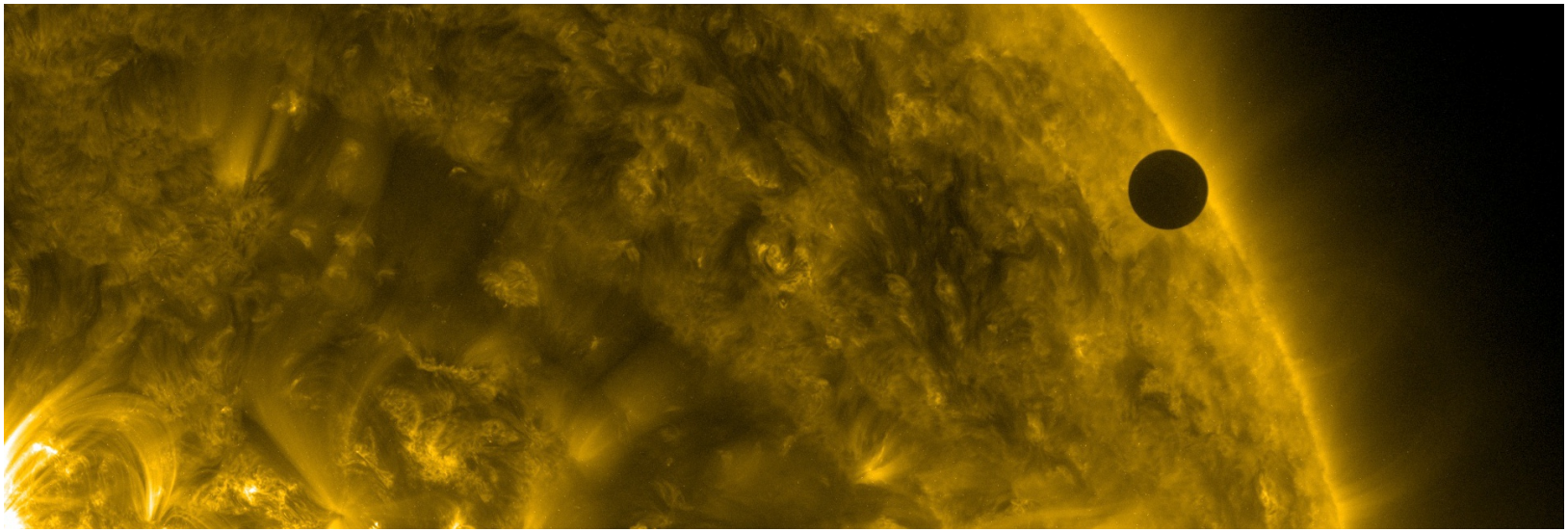


Magic et al. 2013

Convection properties vs stellar parameters



Stellar modeling and exoplanets



Stars:
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Atmospheres
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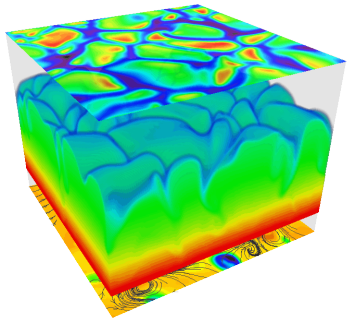
Composition

Stellar models



Exoplanets:
Detection
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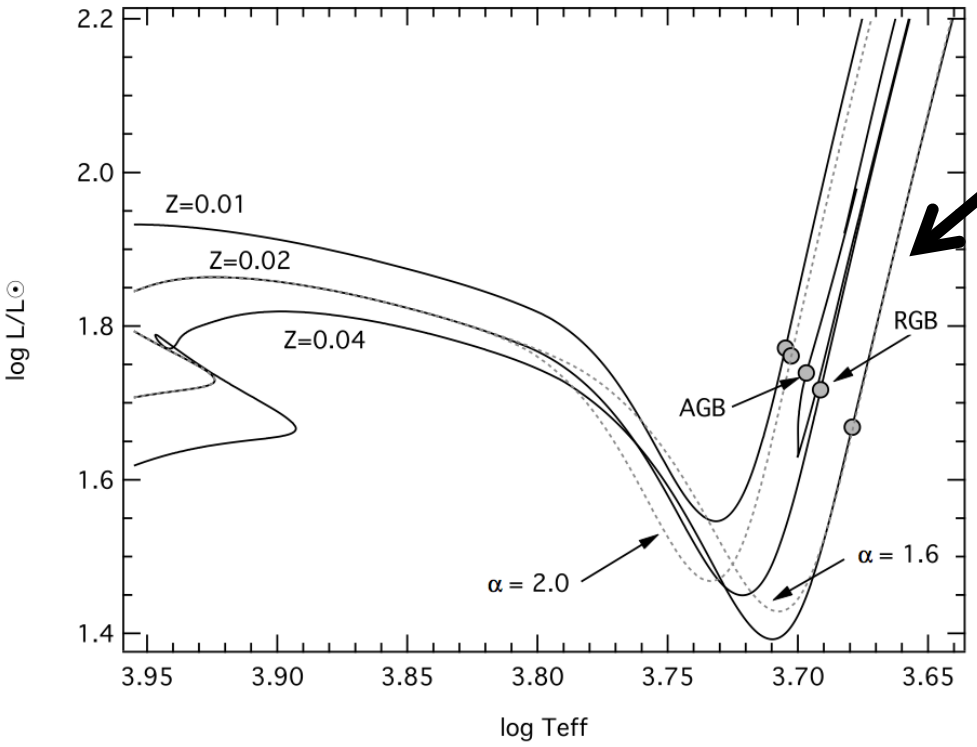
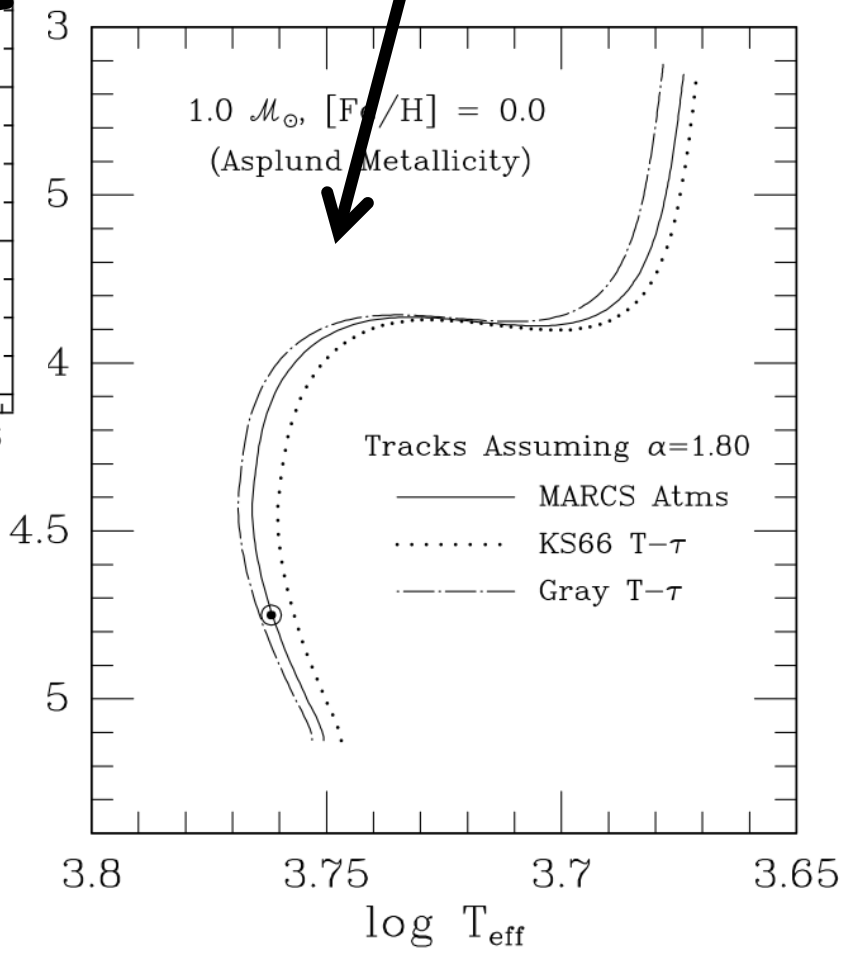
Stellar evolution



Kallinger et al. 2010

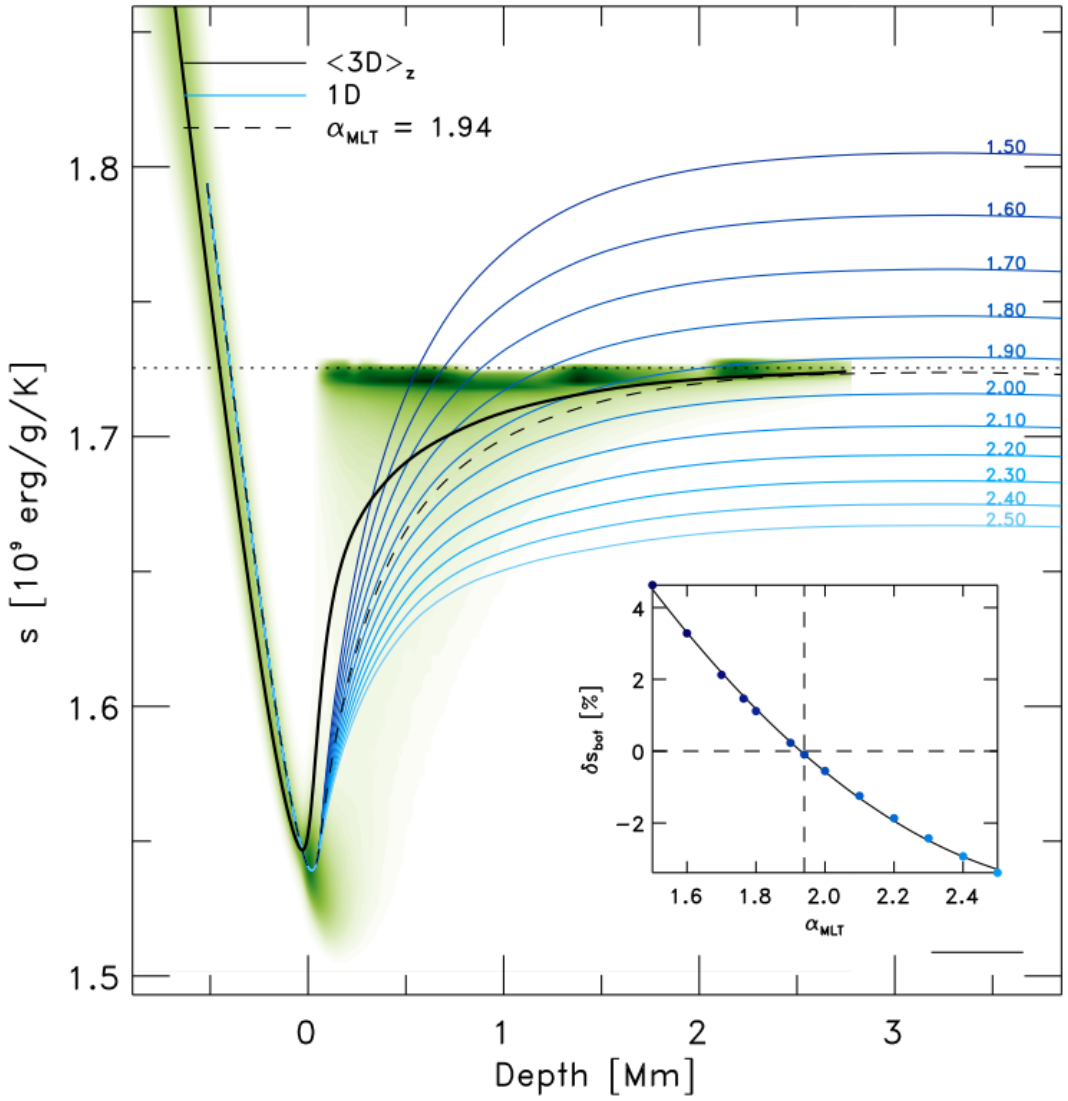
Mixing length theory

Atmosphere



vandenBerg et al. 2008

Calibrating mixing length theory



Magic et al. 2015:

Calibration of MLT with evolution models with different α_{MLT} to match entropy at depth

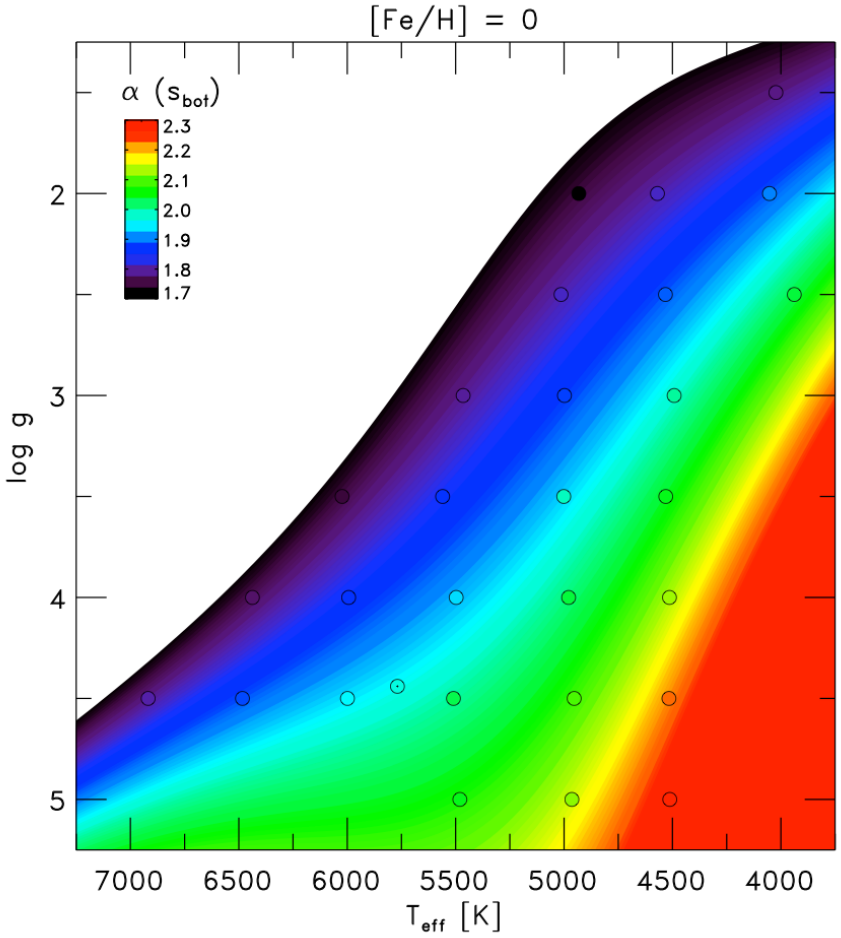
Note: Stellar evolution models should have identical microphysics as 3D surface models

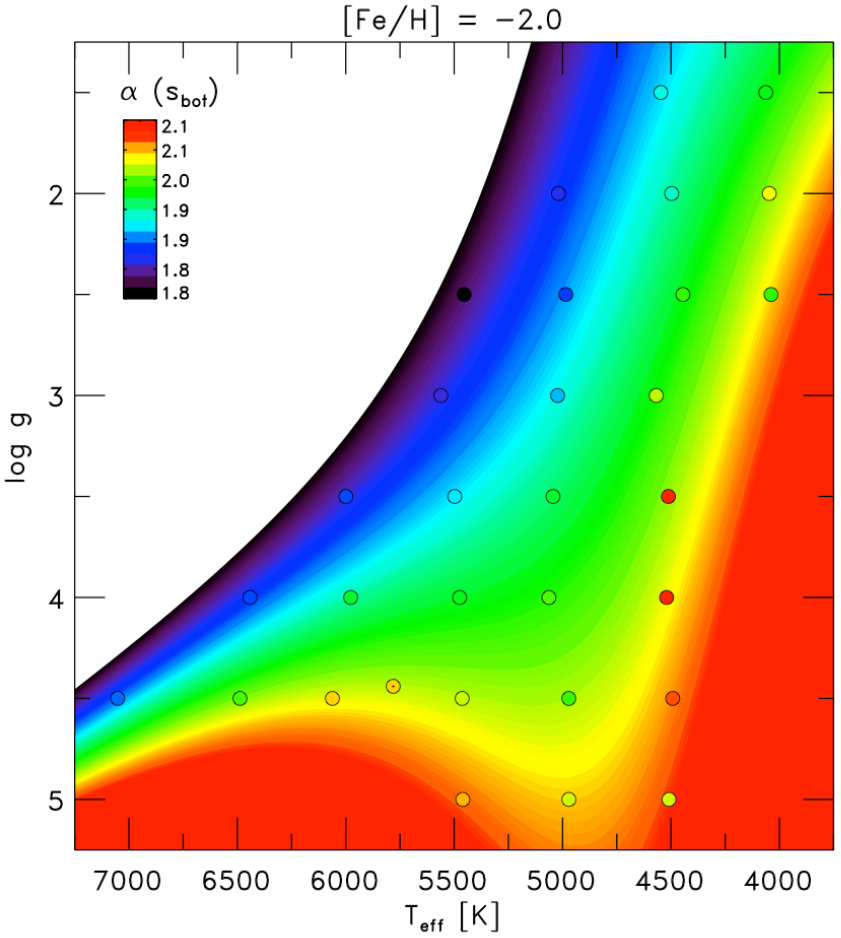
Predicted variations of α_{MLT}

Magic et al. (2015):

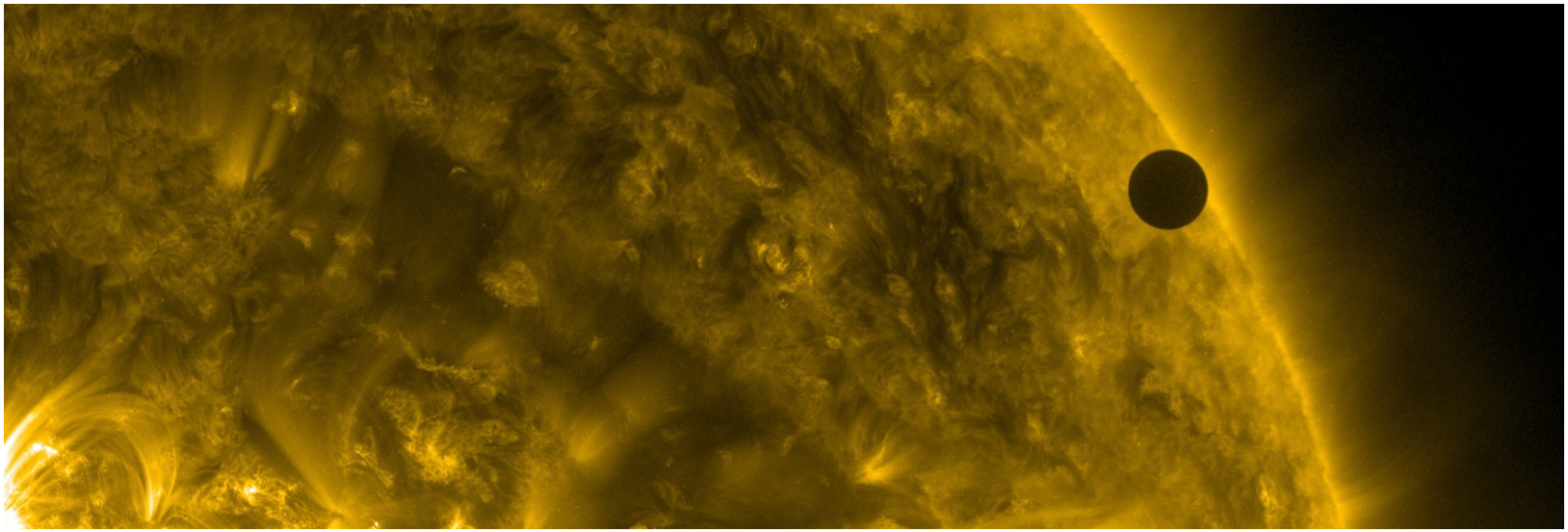
Similar α_{MLT} along evolutionary tracks

Varying α_{MLT} with stellar mass





Stellar modeling and exoplanets



Stars:
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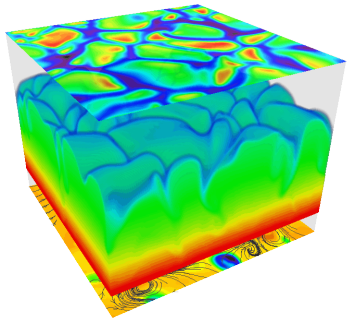
Stellar models



Exoplanets:
Detection
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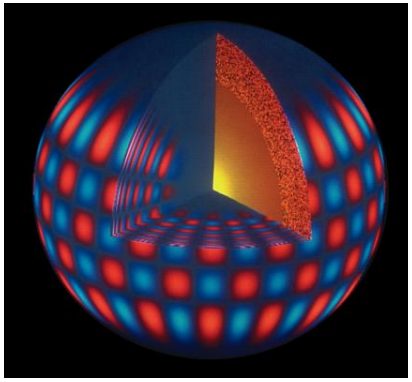
Asteroseismology

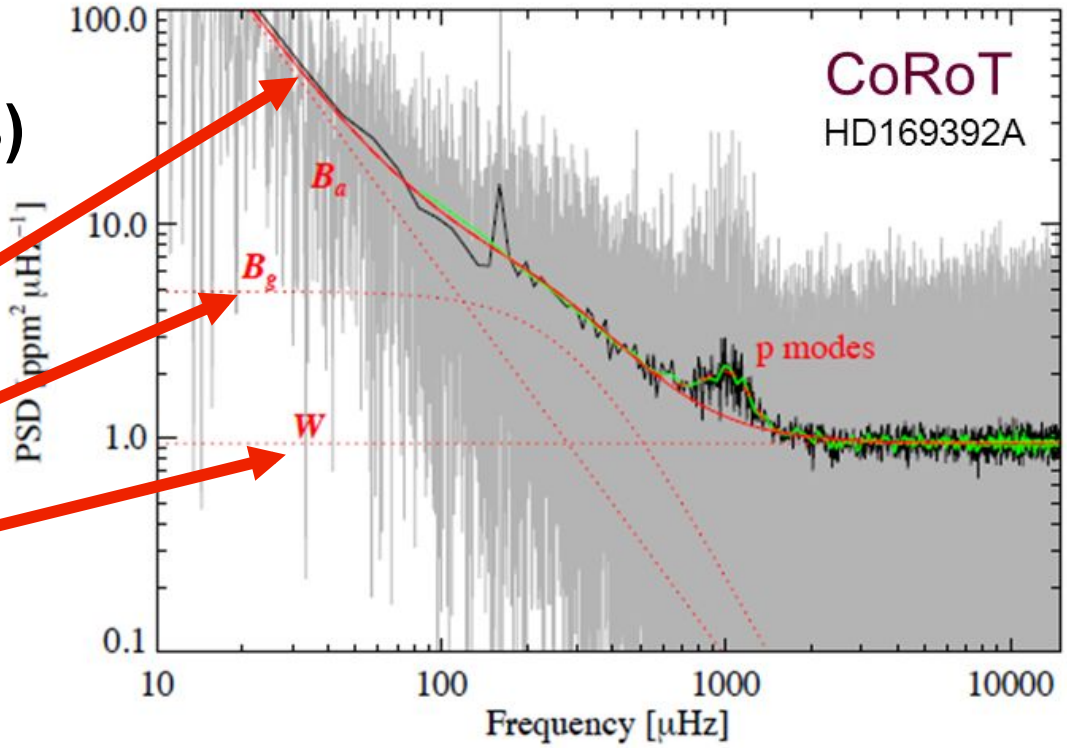


Exoplanets ♥ Asteroseismology

Asteroseismology ⇒ Stellar radius + mass
⇒ Planetary radius + mass
See Daniel Huber's talk

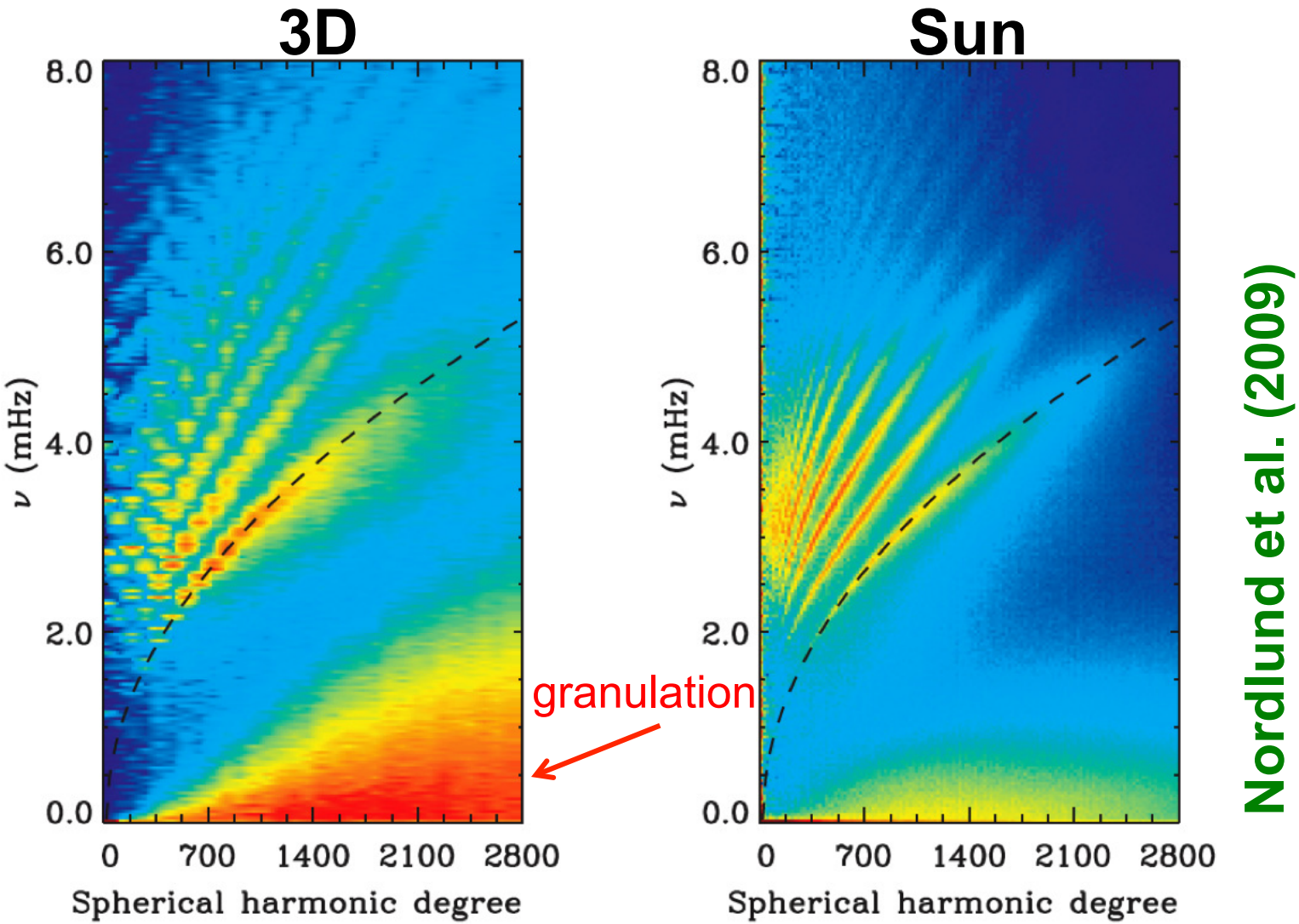
Solar-like oscillations:
Sound waves (p-modes)
Driven by convection

Background:
Activity
Granulation
White noise



Solar oscillations

P-modes driven by convective motions near surface



P-mode frequencies: 1D

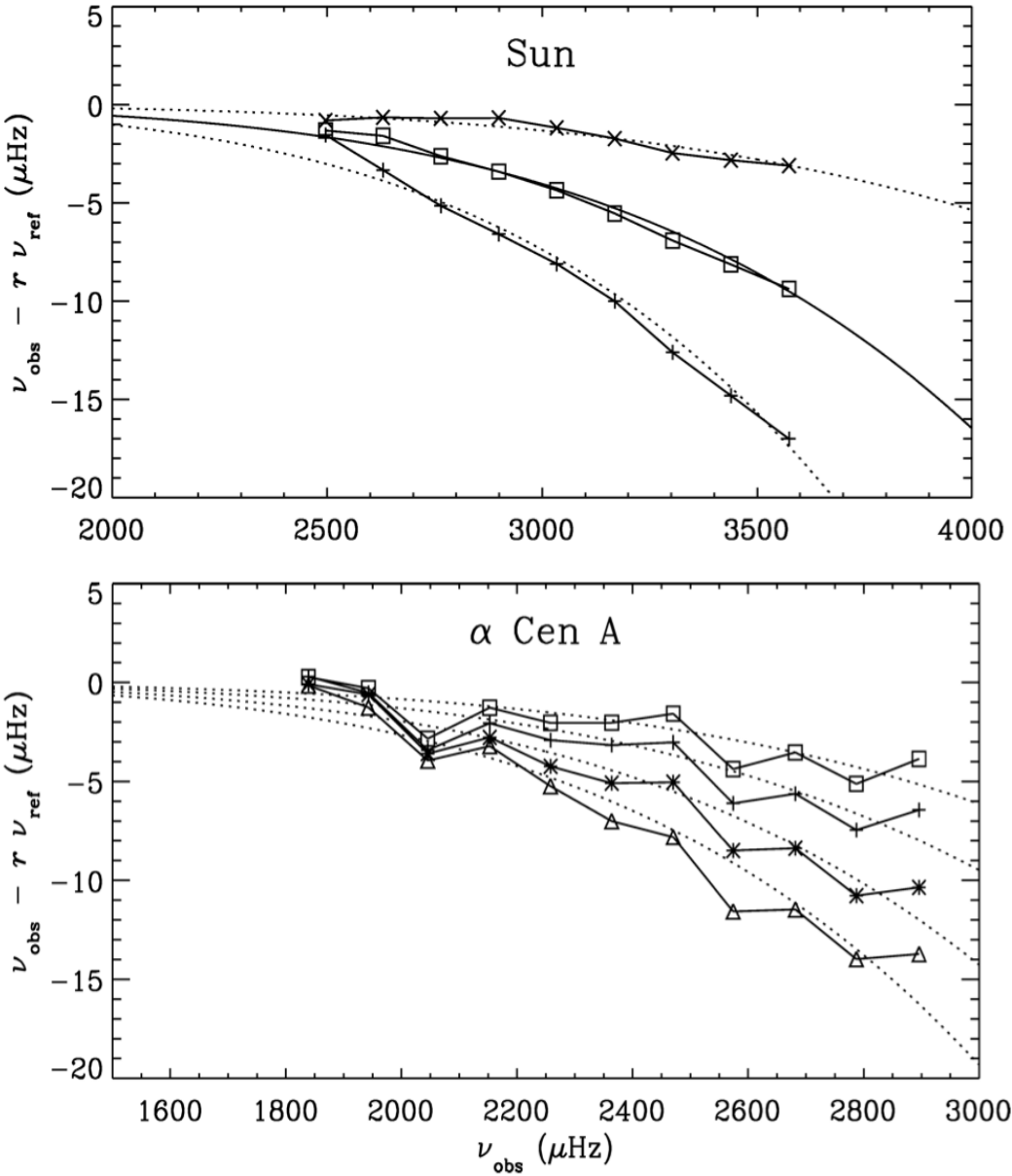
Wrong frequencies predicted with 1D stellar models

Correct for "surface effects":

$$\nu_{\rm obs}(n) - \nu_{\rm best}(n) = a\left[\frac{\nu_{\rm obs}(n)}{\nu_0}\right]^b$$

calibrated on Sun only (Kjeldsen et al. 2008)

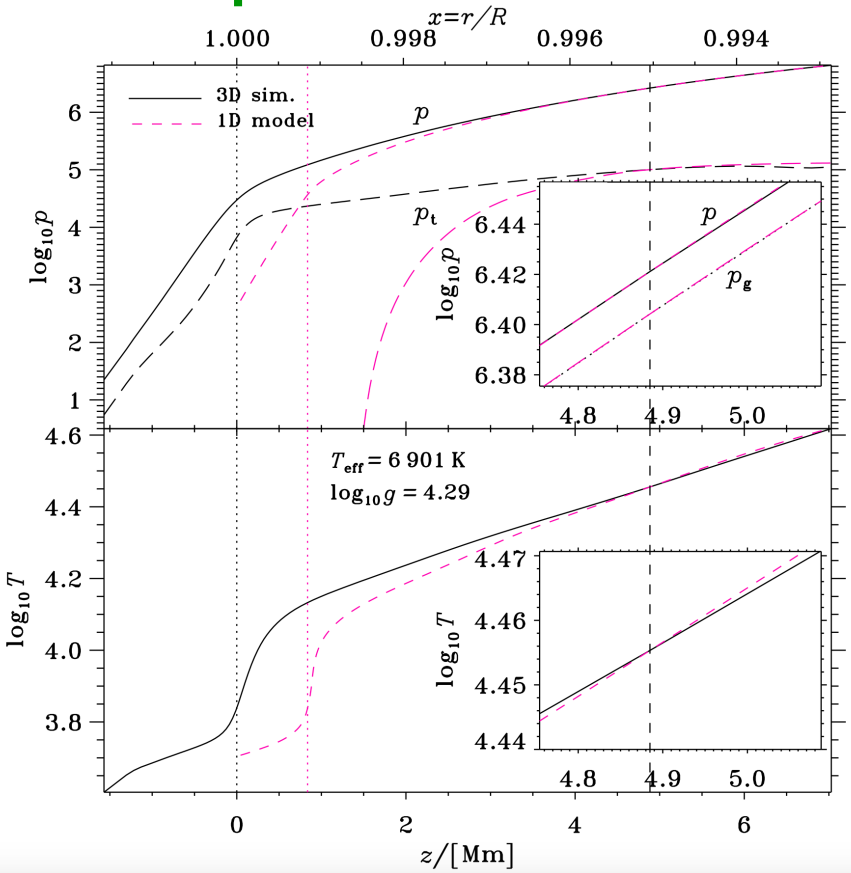
Be careful when doing asteroseismology with individual frequencies!

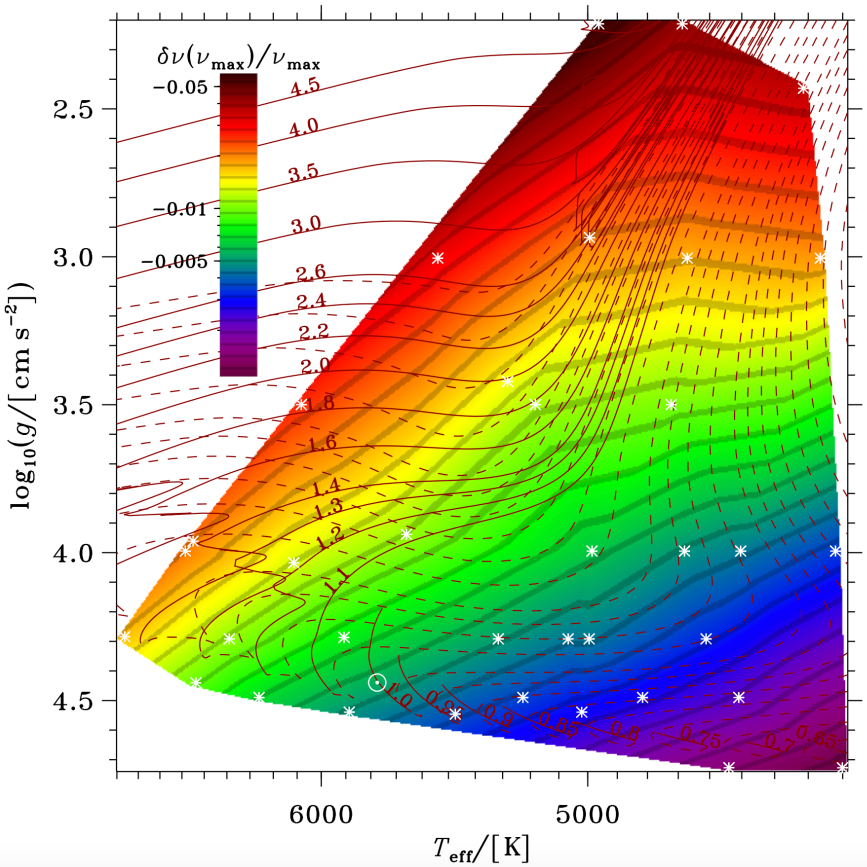


1D models with <3D> surface

3D models can't predict all modes due to finite simulation box
⇒ Patch 1D interior models with average $\langle 3D \rangle_{xy,t}$ models
⇒ Larger atmospheric extension + spatial inhomogenities
⇒ Oscillation frequencies shifted: "surface effects"

Trampedach et al. 2017

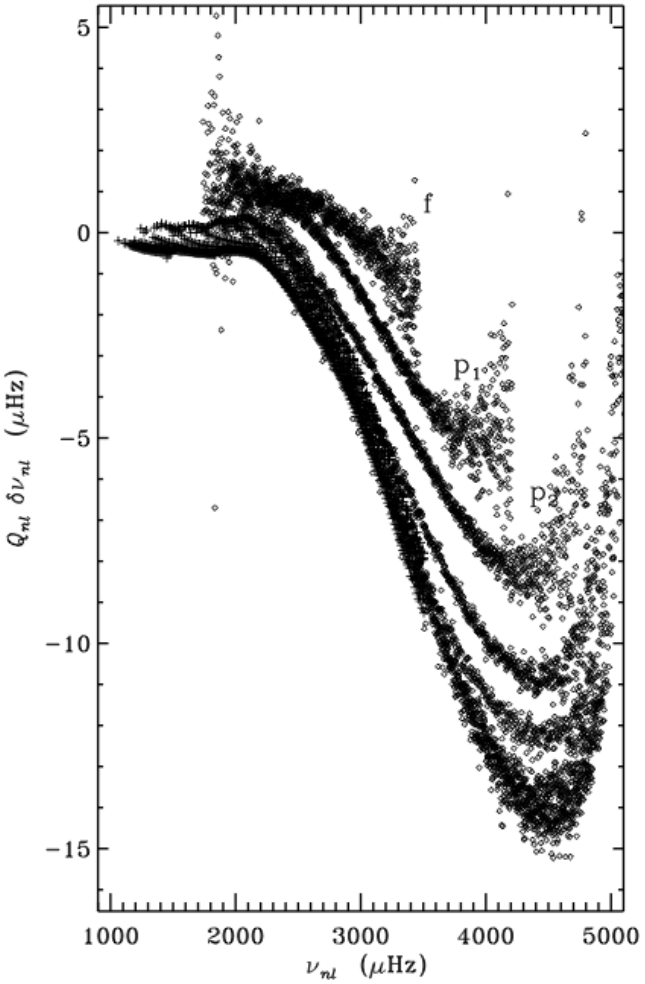




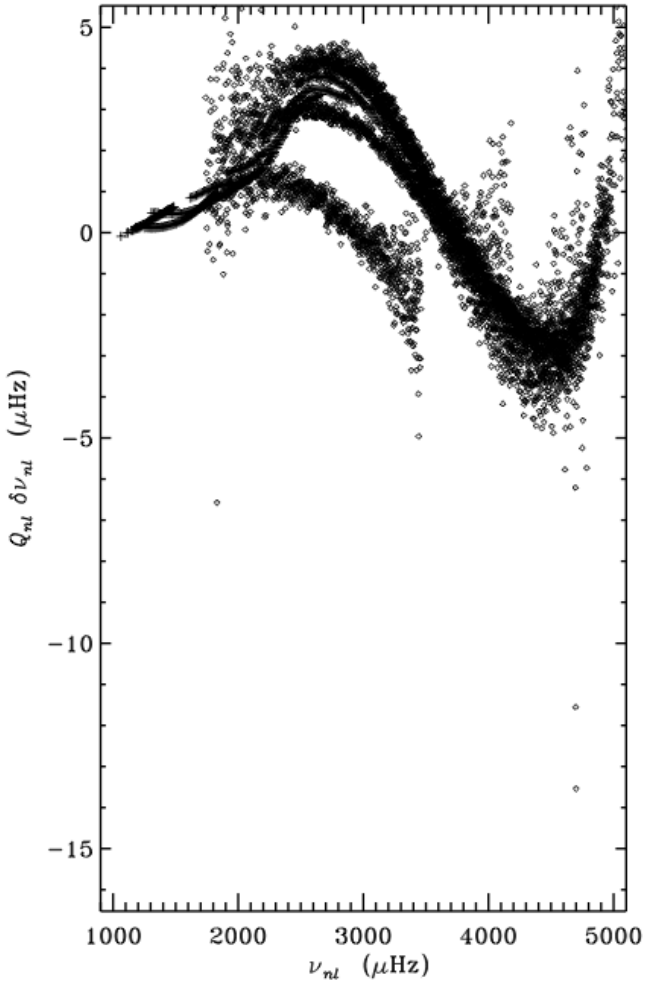
P-mode frequencies: <3D>

P_{turb} and horizontal fluctuations increase scale height (acoustic cavity) and lowers p-mode frequencies

Sun - 1D

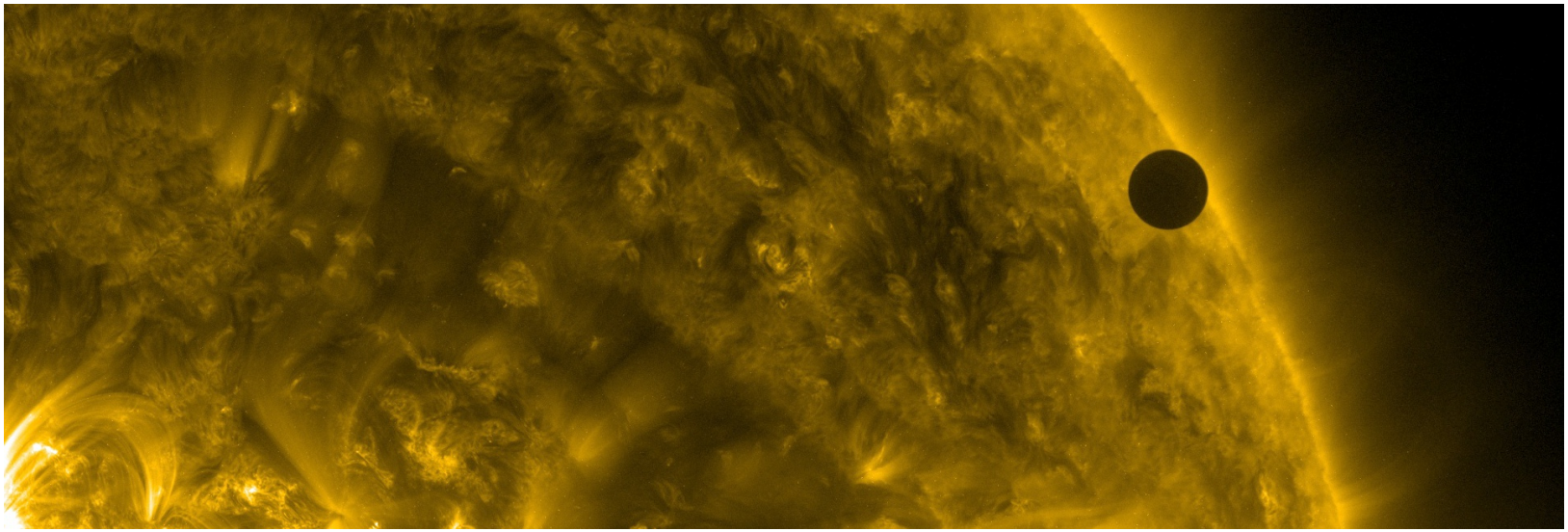


Sun - <3D>



Nordlund et al. (2009)

Stellar modeling and exoplanets



Stars:

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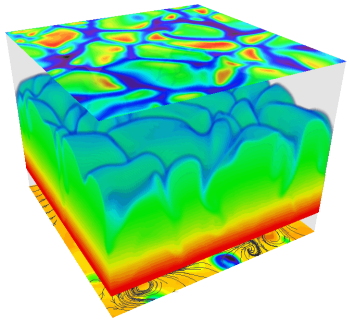
Stellar models



Exoplanets:

Detection
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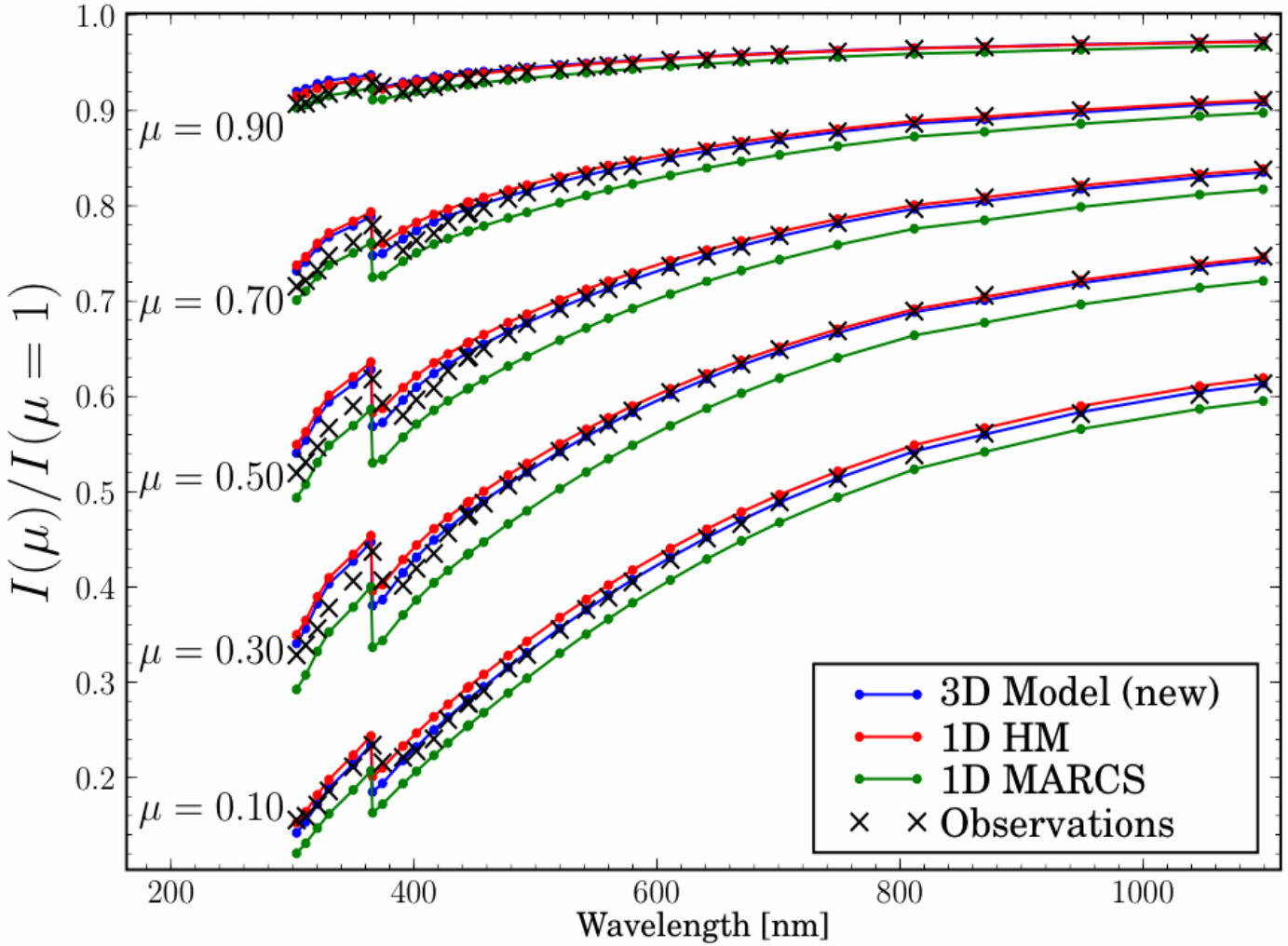
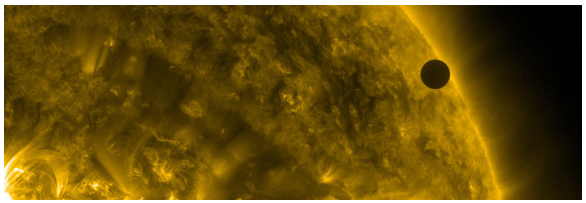
Temperature structure

3D model atmospheres have different T(tau) than 1D

⇒ Different spectra and limb darkening



Limb-darkening and transits

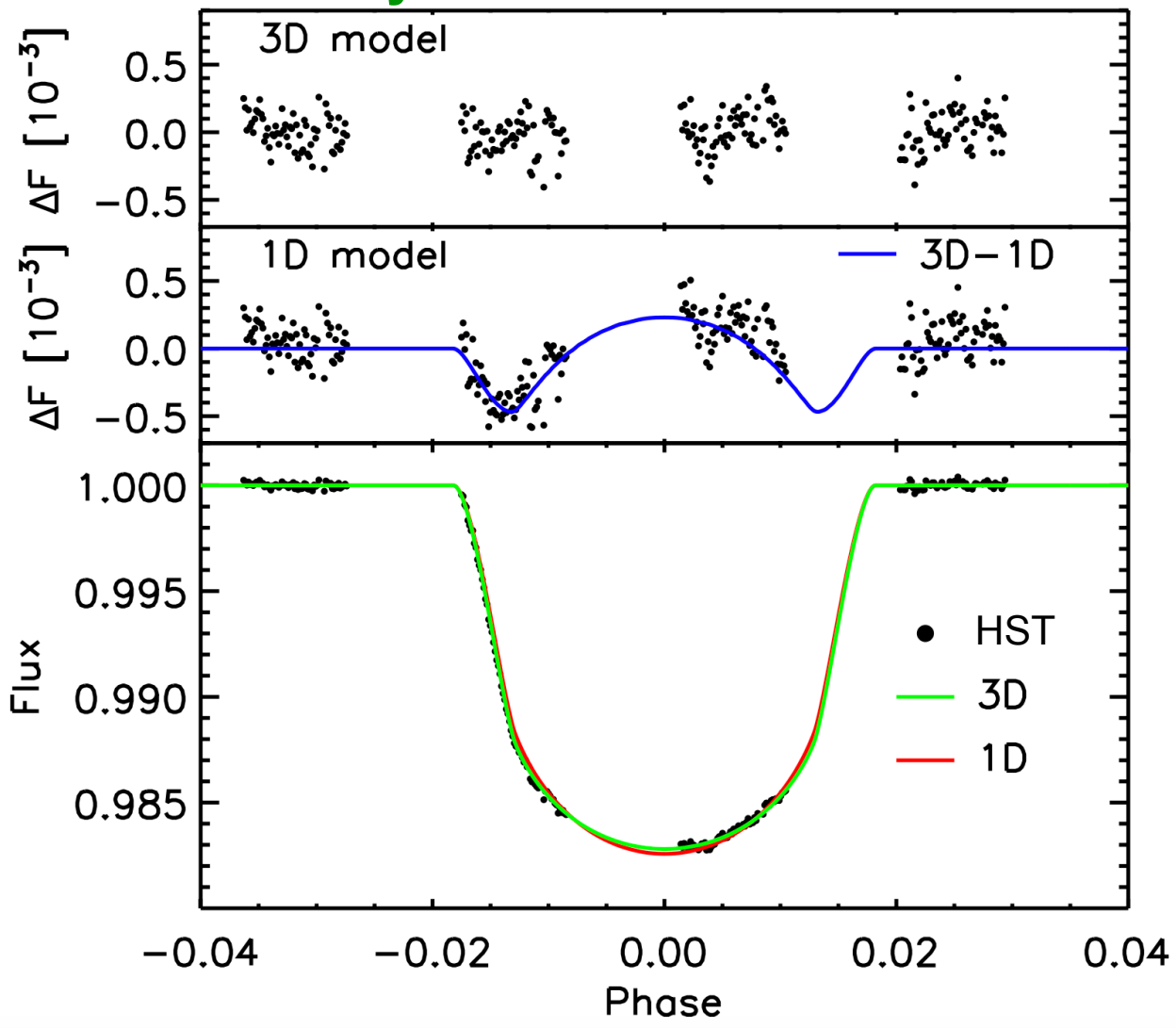


Shallower T-gradient

Different transit light curves

Better agreement with observations in 3D

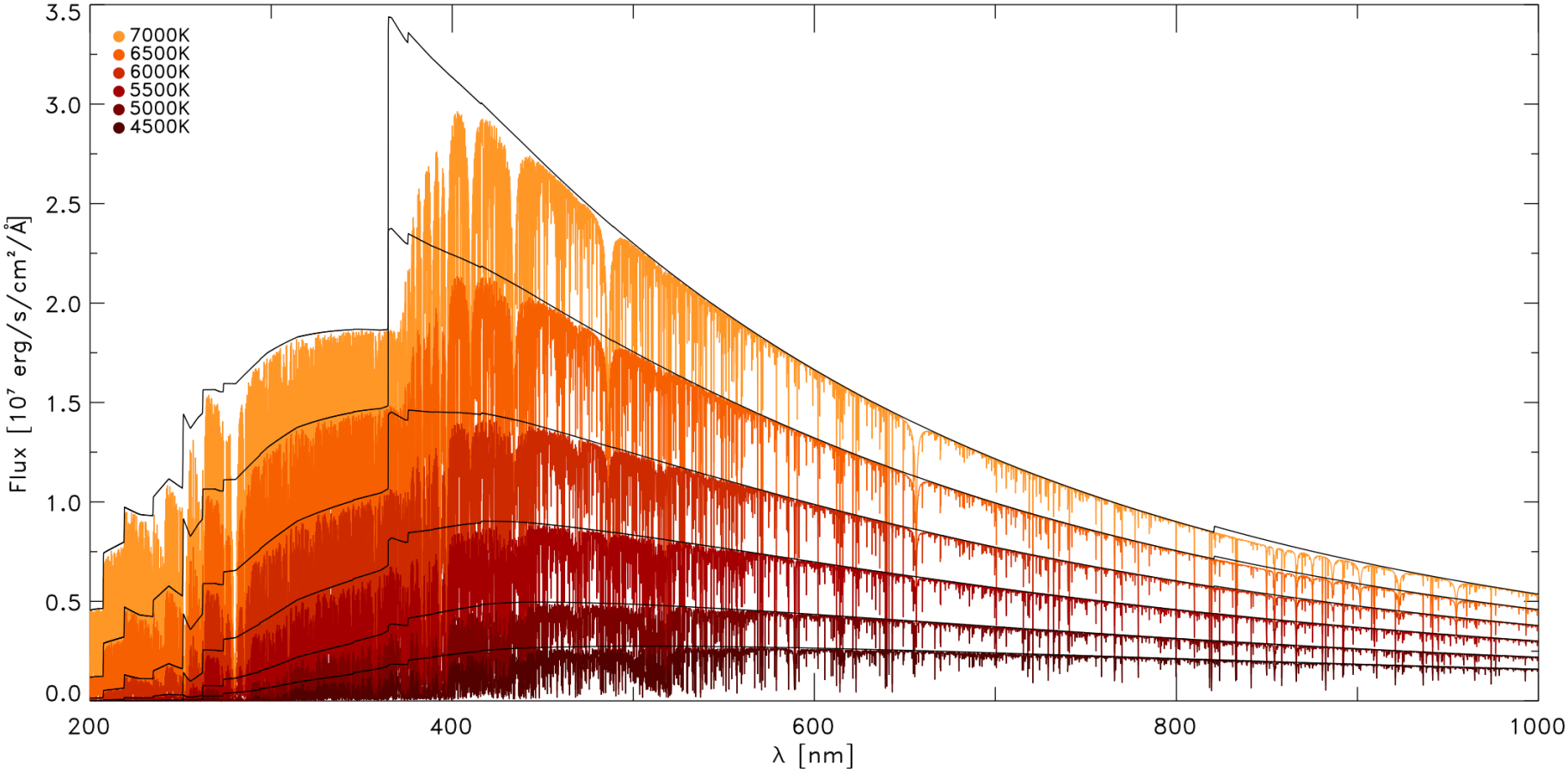
Hayek et al. 2012: HD209458



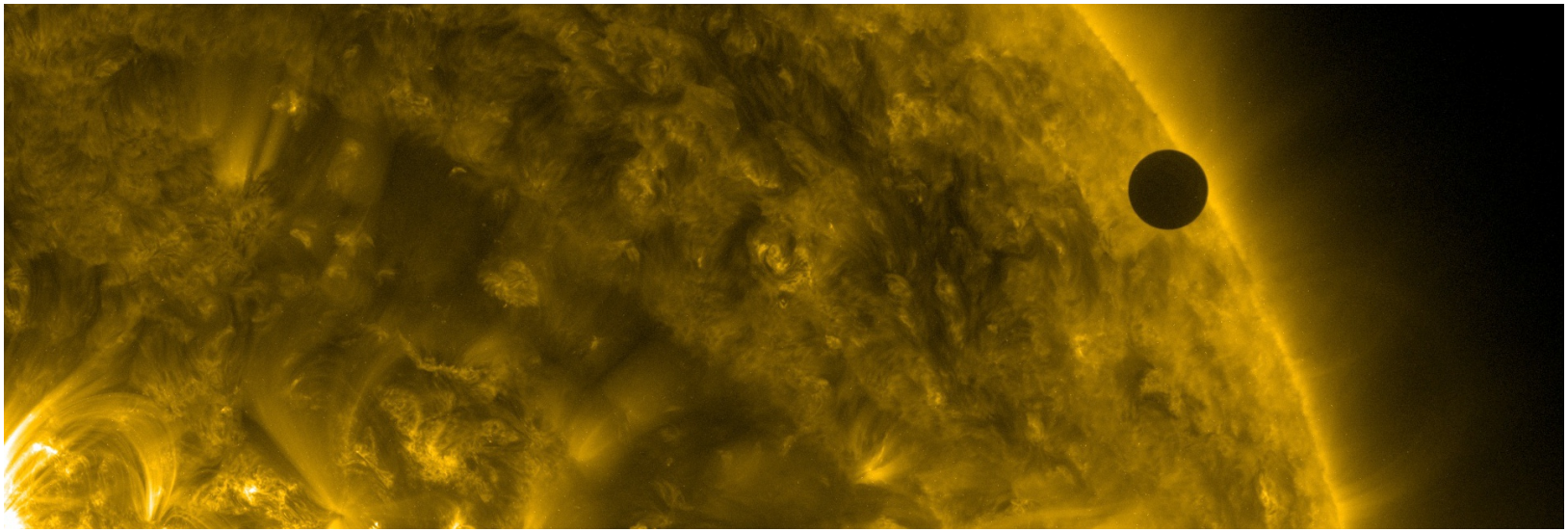
3D spectra and limb-darkening

Magic et al. 2015, Chiavassa et al. 2017:

Predicted stellar spectra, colours, limb-darkening and convective line shifts for full grid of Stagger 3D models of FGK stars publicly available



Stellar modeling and exoplanets



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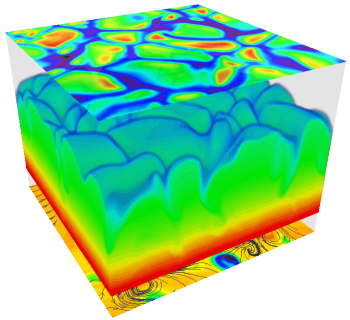

Exoplanets:

Detection
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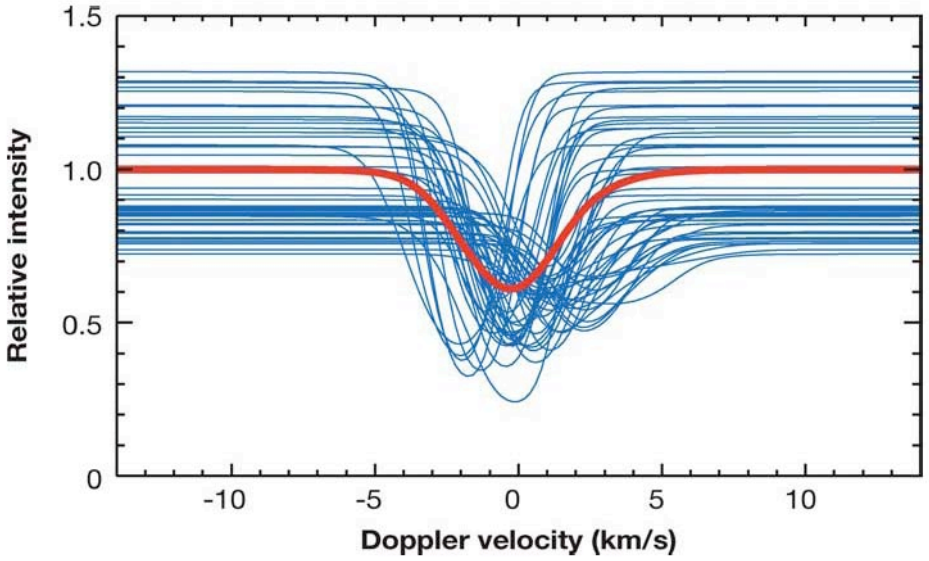
Stellar spectroscopy in 3D



Stellar radiation and stellar atmosphere interconnected:

⇒ Non-local & non-linear

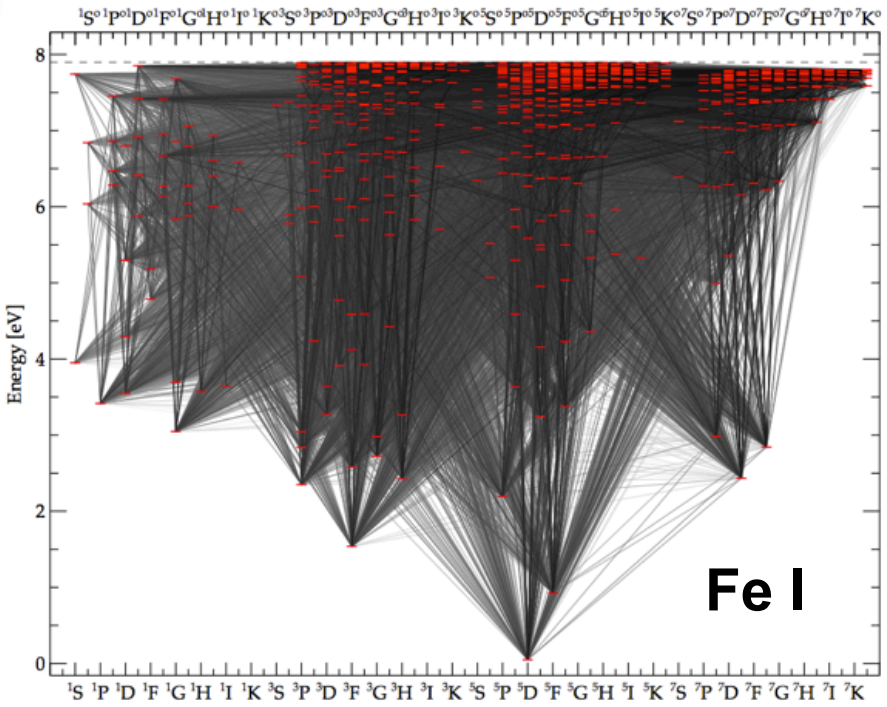
⇒ "Everything depends on everything, everywhere"

⇒ 3D non-LTE line formation

3D non-LTE now possible:

- **Complex atoms: Fe**
  Amarsi et al. 2017
- **>10^5 stars: GALAH survey**
  Amarsi et al. 2018

More accurate stellar parameters and abundances



The solar yardstick

Z	Element	Photosphere	Meteorites	Z	Element	Photosphere	Meteorites
1	H	12.00	8.22 ± 0.04	44	Ru	1.75 ± 0.08	1.76 ± 0.03
2	He	[10.93 ± 0.01]	1.29	45	Rh	0.91 ± 0.10	1.06 ± 0.04
3	Li	1.05 ± 0.10	3.26 ± 0.05	46	Pd	1.57 ± 0.10	1.65 ± 0.02
4	Be	1.38 ± 0.09	1.30 ± 0.03	47	Ag	0.94 ± 0.10	1.20 ± 0.02
5	B	2.70 ± 0.20	2.79 ± 0.04	48	Cd		1.71 ± 0.03
6	C	8.43 ± 0.05	7.39 ± 0.04	49	In	0.80 ± 0.20	0.76 ± 0.03
7	N	7.83 ± 0.05	6.26 ± 0.06	50	Sn	2.04 ± 0.10	2.07 ± 0.06
8	O	8.69 ± 0.05	8.40 ± 0.04	51	Sb		1.01 ± 0.06

Asplund et al. 2009, ARAA, 47, 481;
Scott et al. 2015ab; Grevesse et al. 2015:
3D-based analysis of all elements
Statistical and systematic errors included in total uncertainties

25	Mn	5.43 ± 0.04	5.48 ± 0.01	69	Tm	0.10 ± 0.04	0.12 ± 0.03
26	Fe	7.50 ± 0.04	7.45 ± 0.01	70	Yb	0.84 ± 0.11	0.92 ± 0.02
27	Co	4.99 ± 0.07	4.87 ± 0.01	71	Lu	0.10 ± 0.09	0.09 ± 0.02
28	Ni	6.22 ± 0.04	6.20 ± 0.01	72	Hf	0.85 ± 0.04	0.71 ± 0.02
29	Cu	4.19 ± 0.04	4.25 ± 0.04	73	Ta		−0.12 ± 0.04
30	Zn	4.56 ± 0.05	4.63 ± 0.04	74	W	0.85 ± 0.12	0.65 ± 0.04
31	Ga	3.04 ± 0.09	3.08 ± 0.02	75	Re		0.26 ± 0.04
32	Ge	3.65 ± 0.10	3.58 ± 0.04	76	Os	1.40 ± 0.08	1.35 ± 0.03

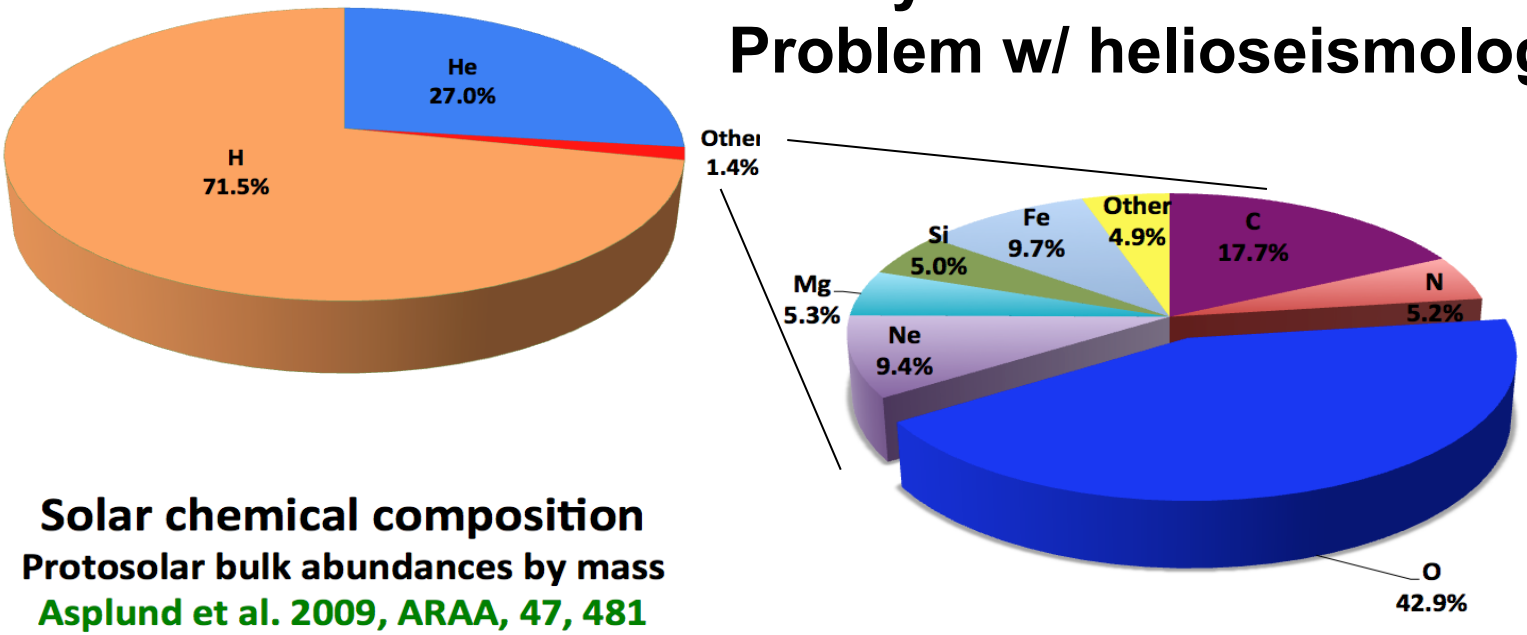
Sun has a subsolar metallicity

~~Z=0.021~~ (Anders & Grevesse 1989)

Z=0.014±0.002 (Asplund et al. 2009)

Mainly ~40% decrease in CNO

Problem w/ helioseismology!



Solar chemical composition

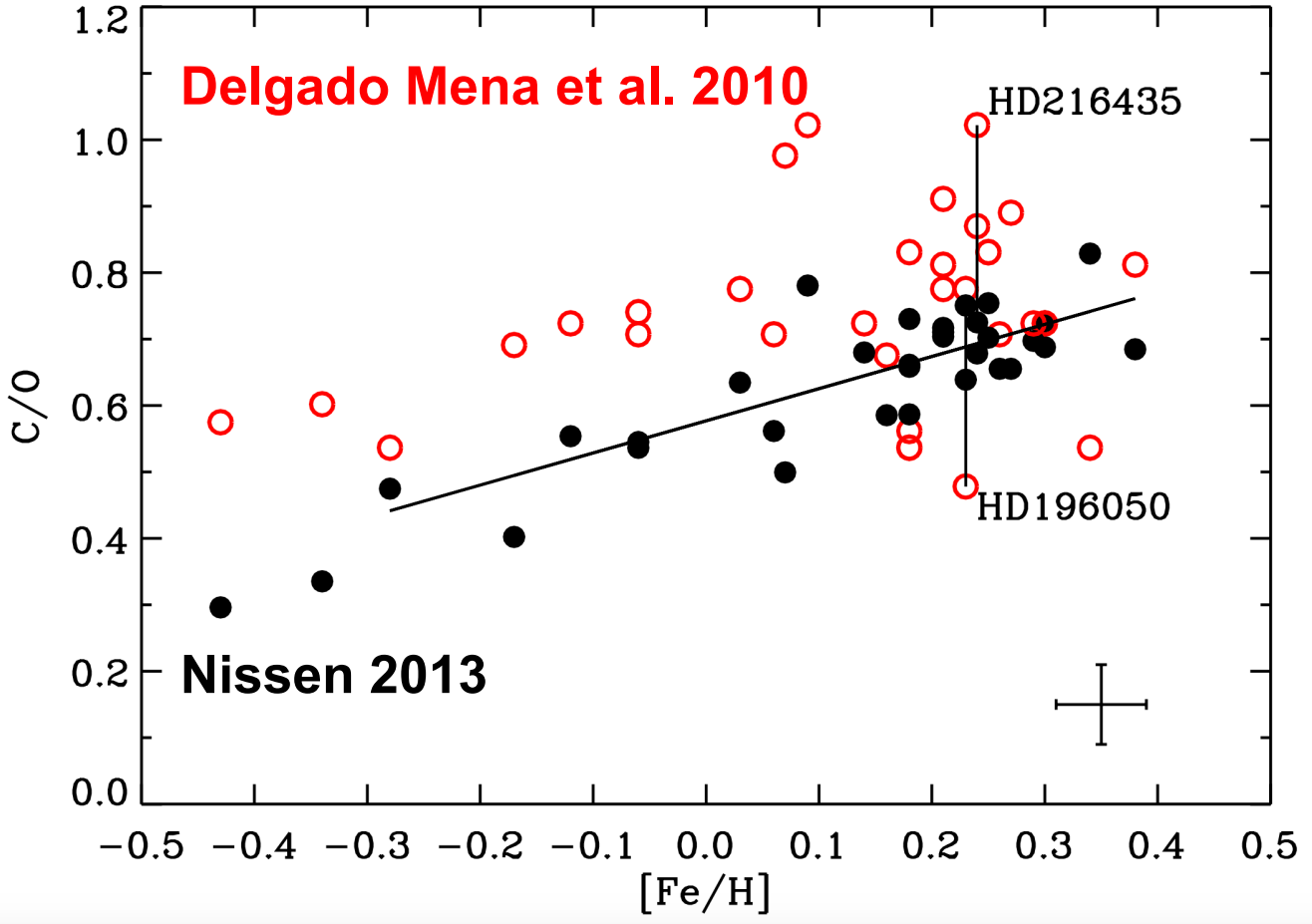
Protosolar bulk abundances by mass

Asplund et al. 2009, ARAA, 47, 481

Stellar abundances as proxies

Bond et al. 2010: C/O, Mg/Si critical for planet formation
Nissen 2013: Small C/O ratios with little cosmic scatter

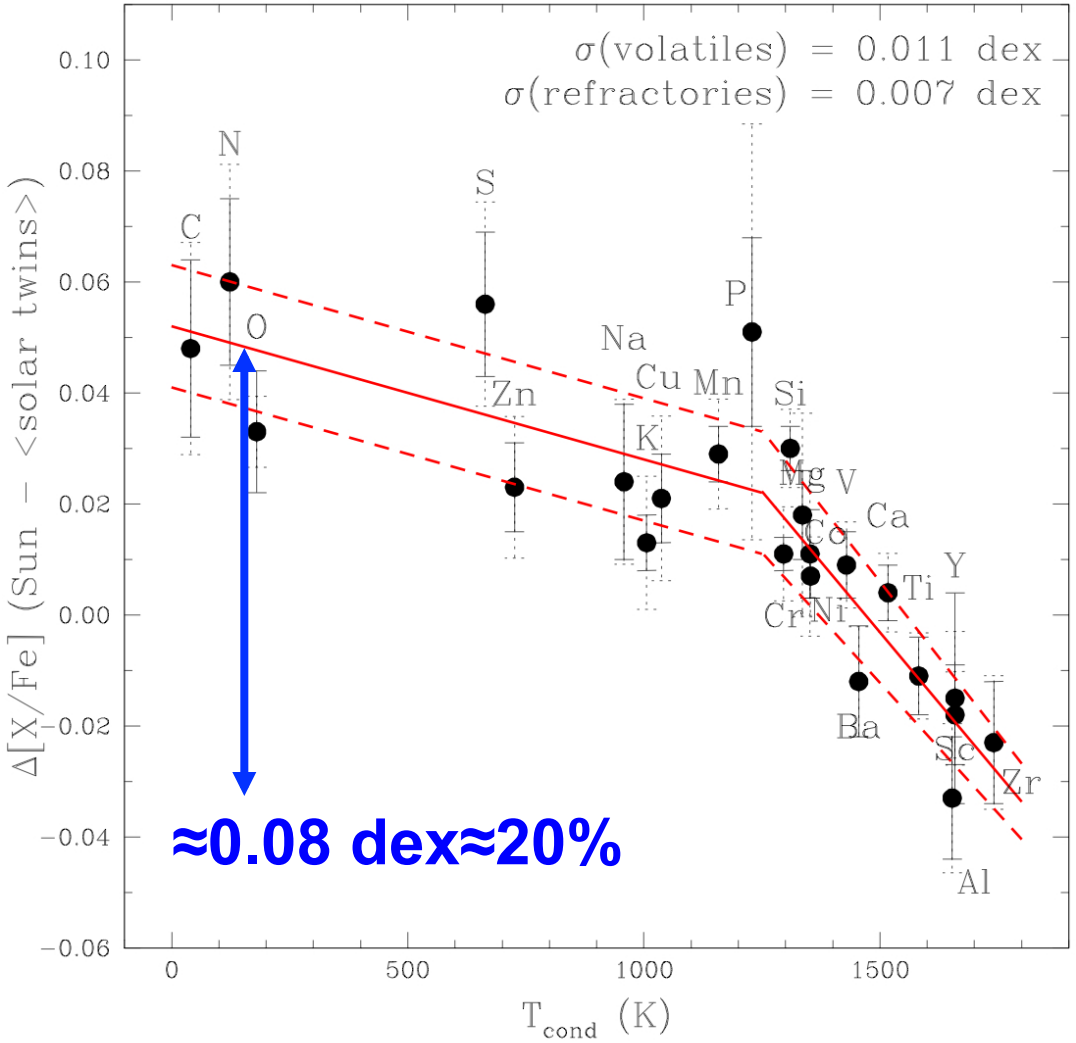
See Megan Bedell's talk!



Beware: Forbidden and permitted CI and OI lines with different systematic effects
⇒ 3D non-LTE

What about other Suns?

Melendez et al. 2009: Sun vs solar twins



Chemical signature of (terrestrial?) planet formation

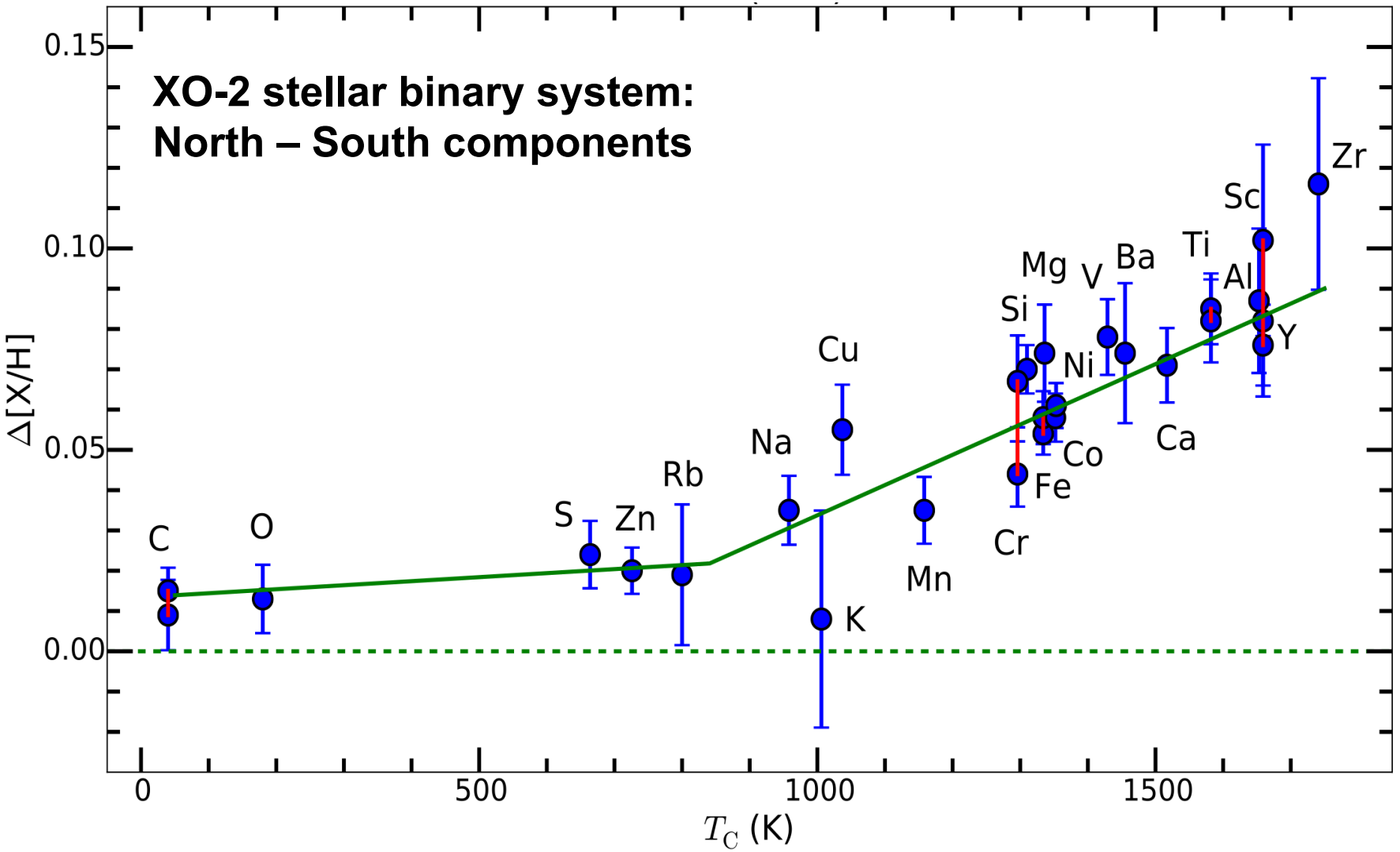
Sun is unusual but not unique (~15%)

See Megan Bedell's talk for an update!

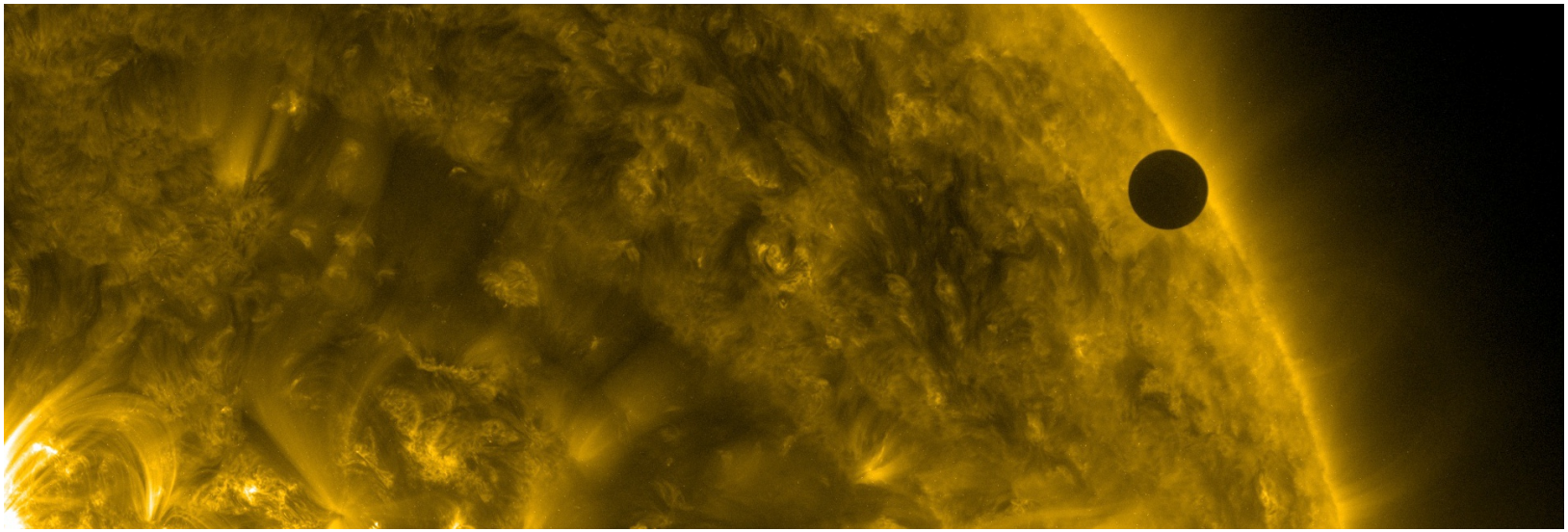
Precision spectroscopy critical!

Planet signature in (some) binaries

Ramírez et al. 2015:



Stellar physics and exoplanets



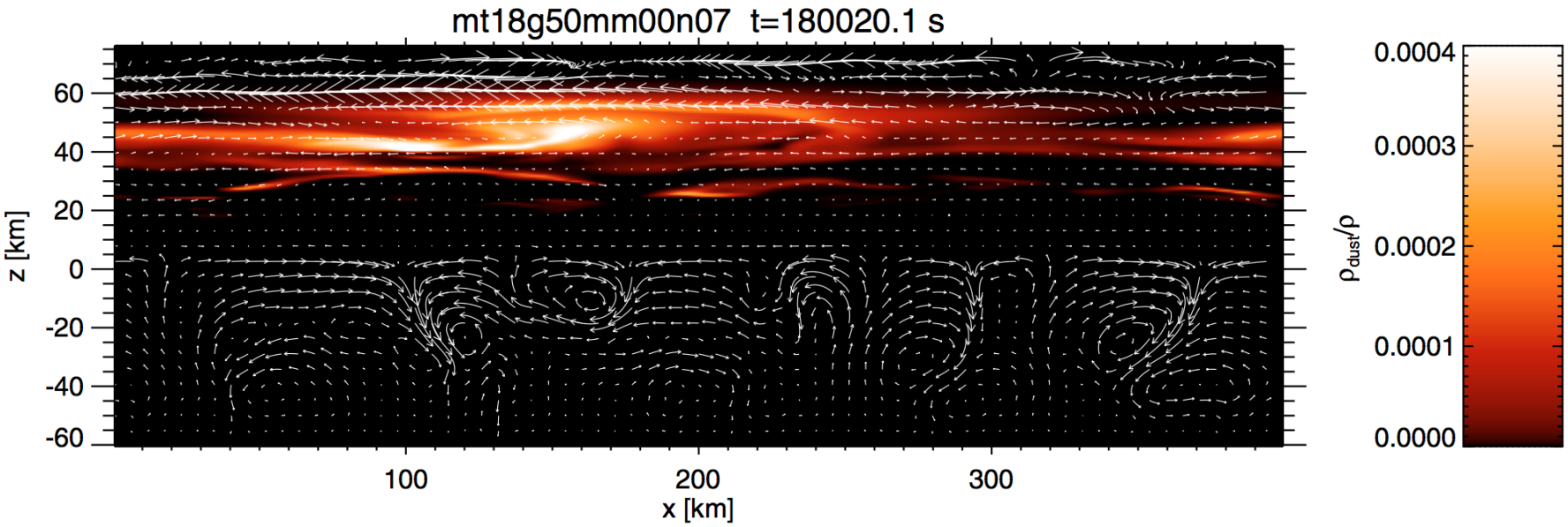
Stars:

Convection
Evolution
Oscillations
Atmospheres
Spectra
Composition

Exoplanets:

Detection
Age
Mass
Radius
Atmospheres
Composition

Brown dwarfs



Freytag et al. (2010)

2D radiative-hydrodynamical models of brown dwarfs

Dust formation included but without nucleation

Dust clouds in higher layers maintained by gravity waves

Variability on short time-scales

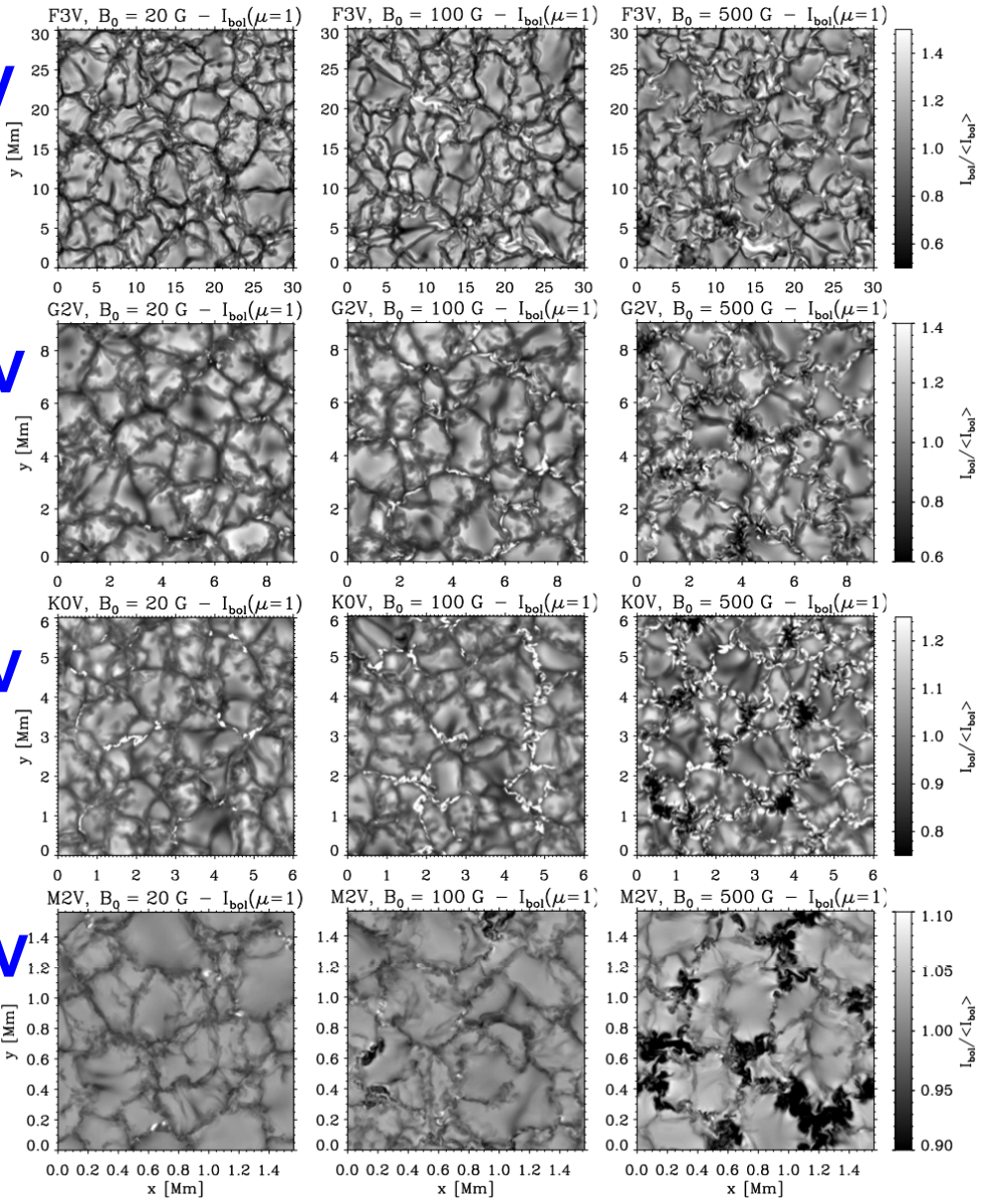
What about magnetic fields?

Beeck et al. (2015)

Granulation pattern changes: bright and dark features

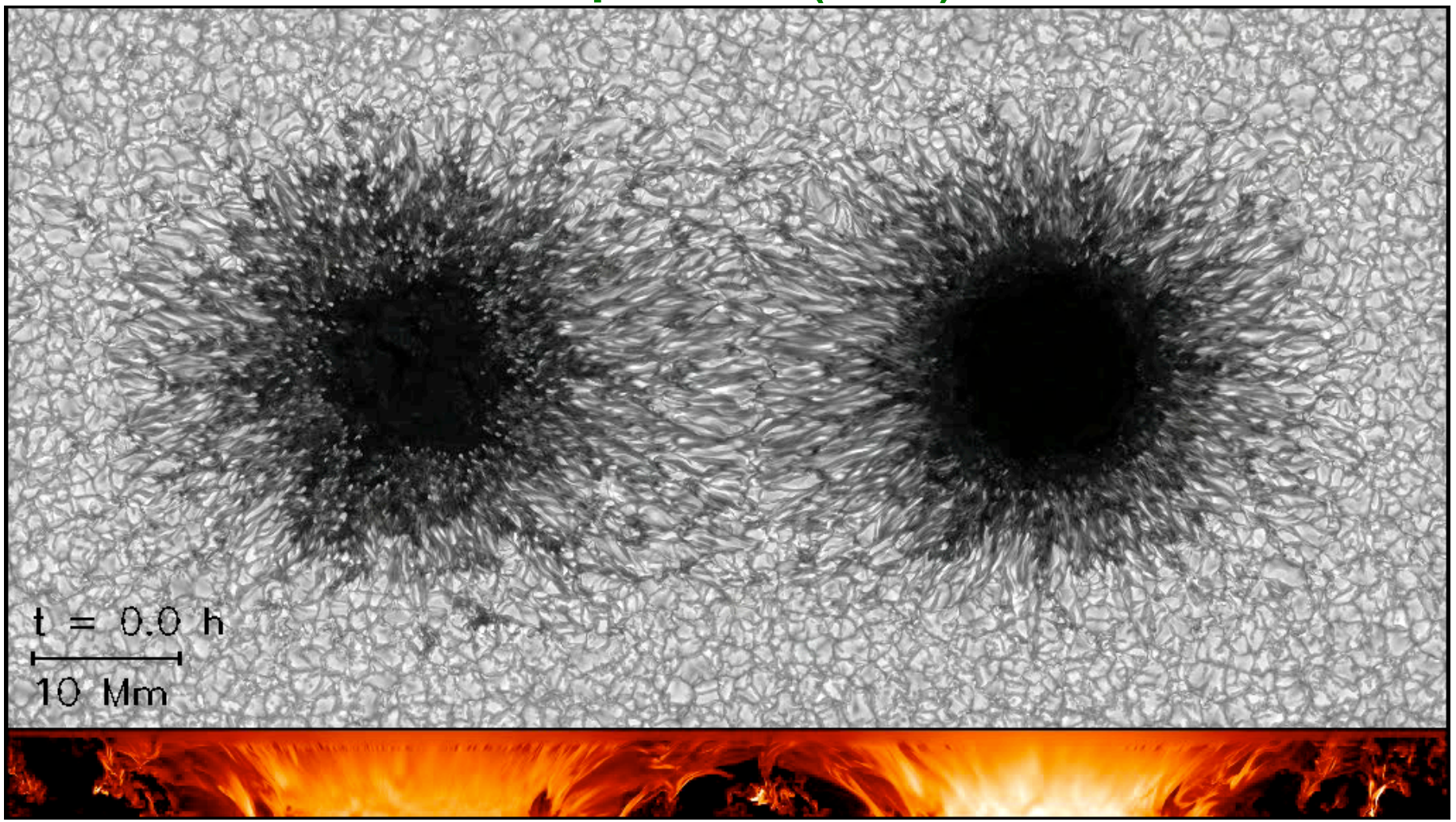
Higher temperatures in upper atmospheres

To do: systematically explore HR-diagram with more realistic magnetic field configurations



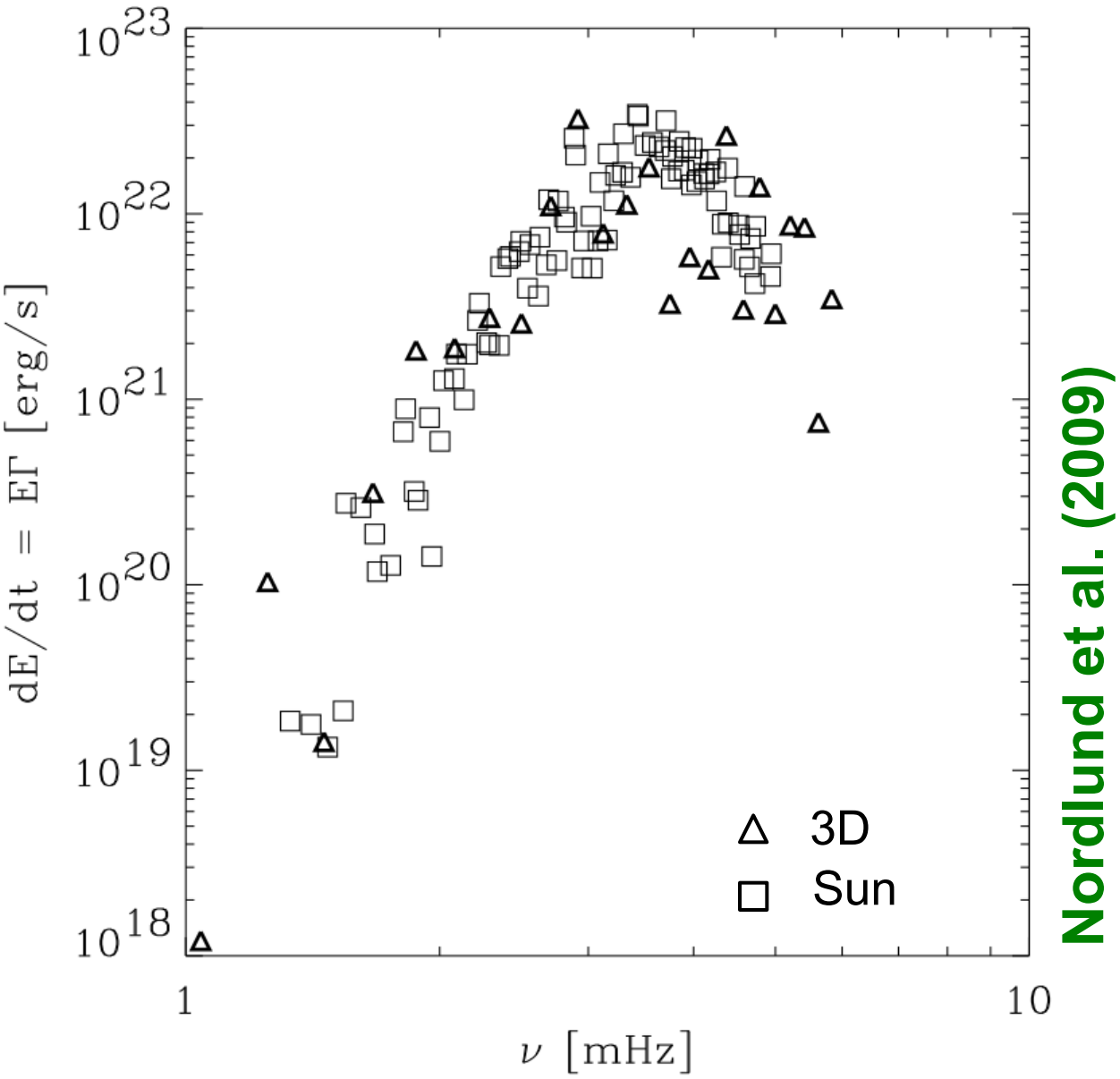
Sunspot models

Rempel et al. (2013)

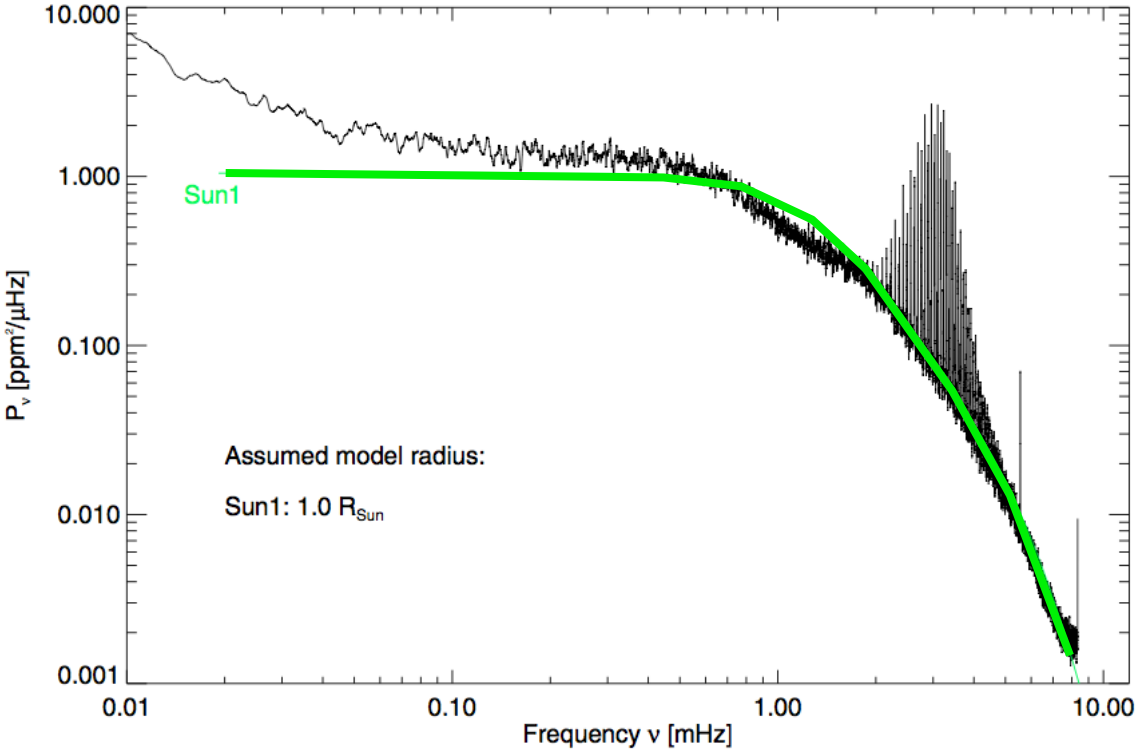


Note: imposed sunspot structure beforehand

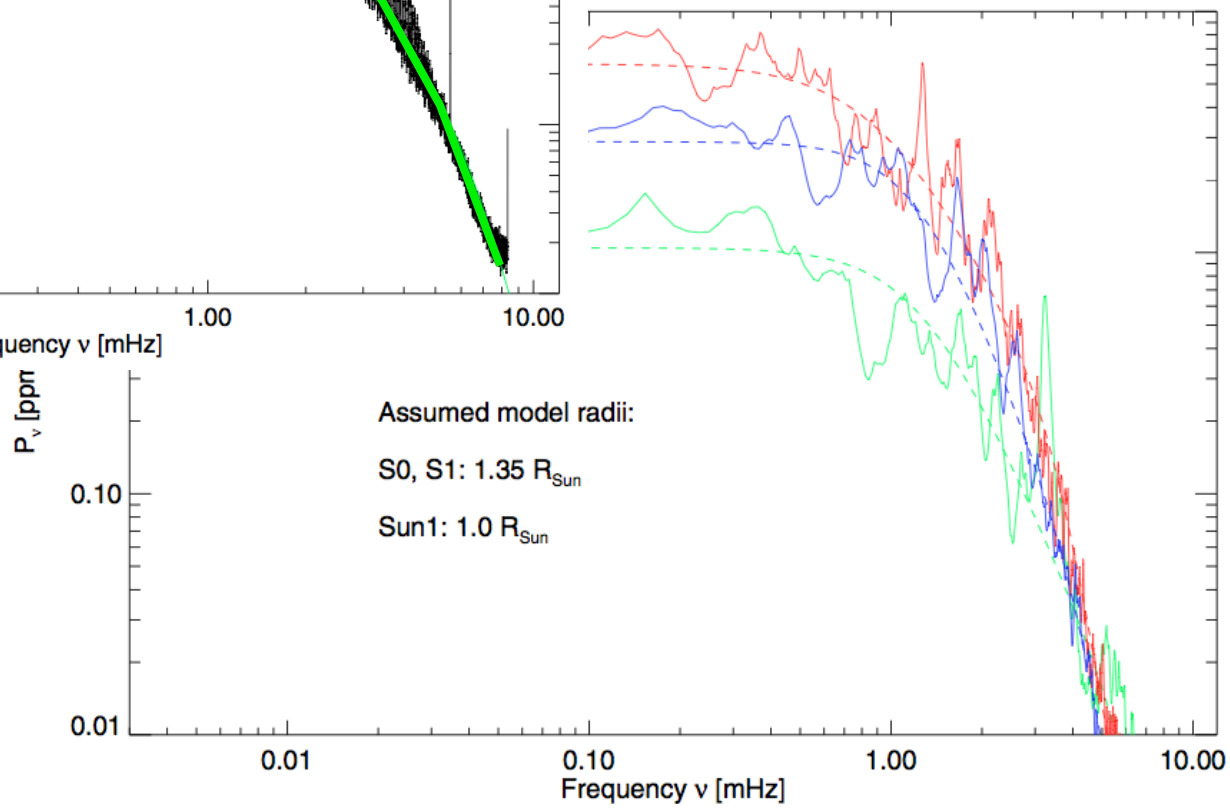
Excitation of solar p-modes



Granulation background

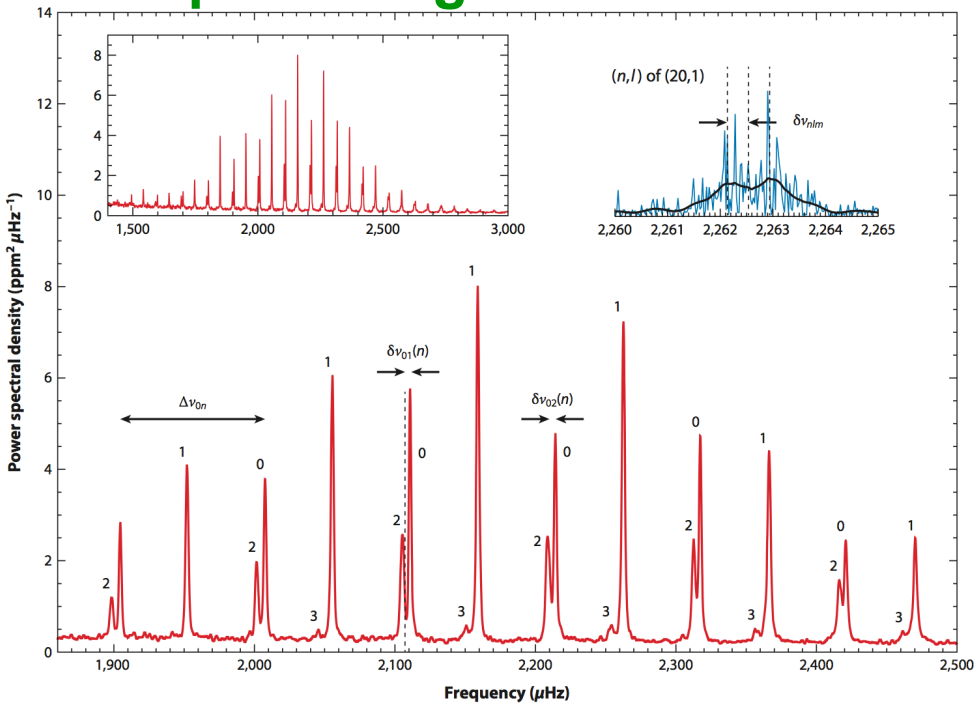


Ludwig et al. 2009: Granulation power from 3D models agree well with observations



Asteroseismic scaling relations

Chaplin & Miglio 2013



Large frequency separation:

$$\Delta\nu \propto \bar{\rho}^{1/2}$$

Frequency maximum power:

$$\nu_{\max} \propto \nu_c$$

Departures from scaling relations for stars different from the Sun?
e.g. $T_{\rm eff}$, log*g*, [Fe/H]

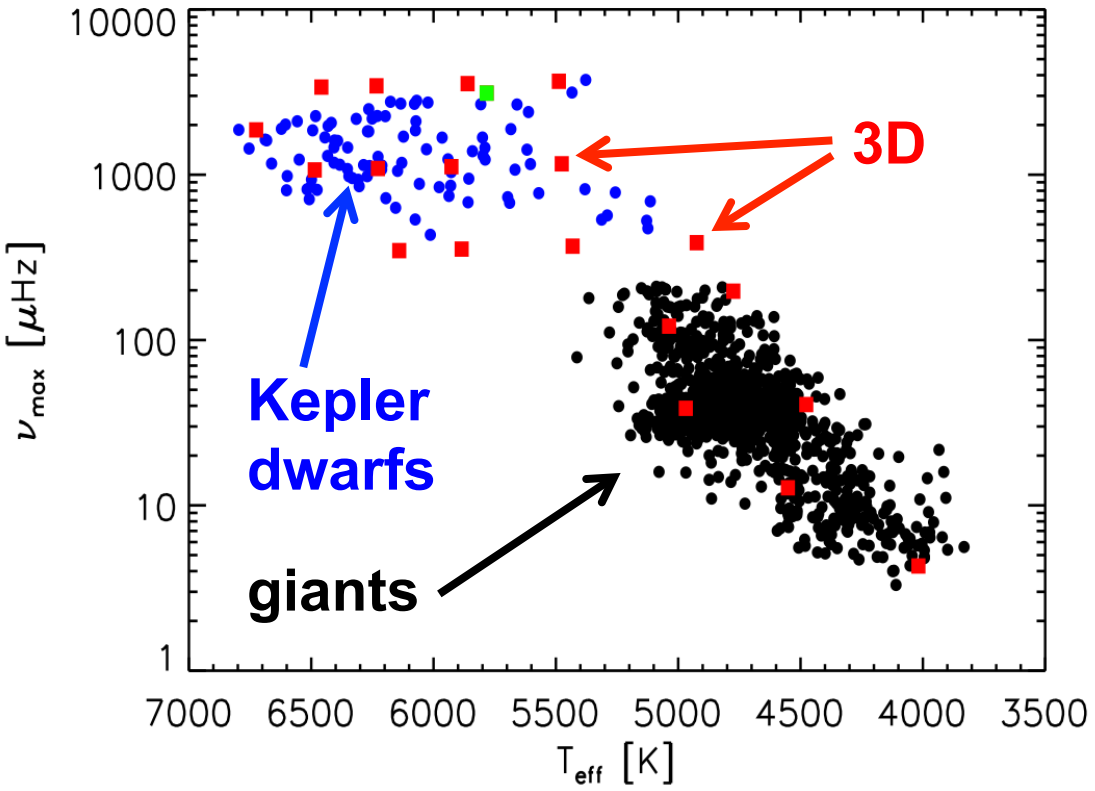
$$\left(\frac{R}{R_\odot}\right) \simeq \left(\frac{\nu_{\max}}{\nu_{\max,\odot}}\right)\left(\frac{\langle\Delta\nu_{nl}\rangle}{\langle\Delta\nu_{nl}\rangle_\odot}\right)^{-2}\left(\frac{T_{\rm eff}}{T_{\rm eff,\odot}}\right)^{0.5},$$

$$\left(\frac{M}{M_\odot}\right) \simeq \left(\frac{\nu_{\max}}{\nu_{\max,\odot}}\right)^{3}\left(\frac{\langle\Delta\nu_{nl}\rangle}{\langle\Delta\nu_{nl}\rangle_\odot}\right)^{-4}\left(\frac{T_{\rm eff}}{T_{\rm eff,\odot}}\right)^{1.5},$$

Global scaling relations

$$\Delta\nu \propto \bar{\rho}^{1/2} \quad \Rightarrow \quad \Delta\nu = \frac{(M/M_\odot)^{1/2}}{(R/R_\odot)^{3/2}}\Delta\nu_\odot$$

$$\nu_{\rm max} \propto \nu_{\rm c} \quad \Rightarrow \quad \nu_{\rm max} = \frac{M/M_\odot}{(R/R_\odot)^2\sqrt{T_{\rm eff}/T_{\rm eff,\odot}}}\nu_{\rm max,\odot}$$



Belkacem et al. (2013)

Dispersion due to Mach number:

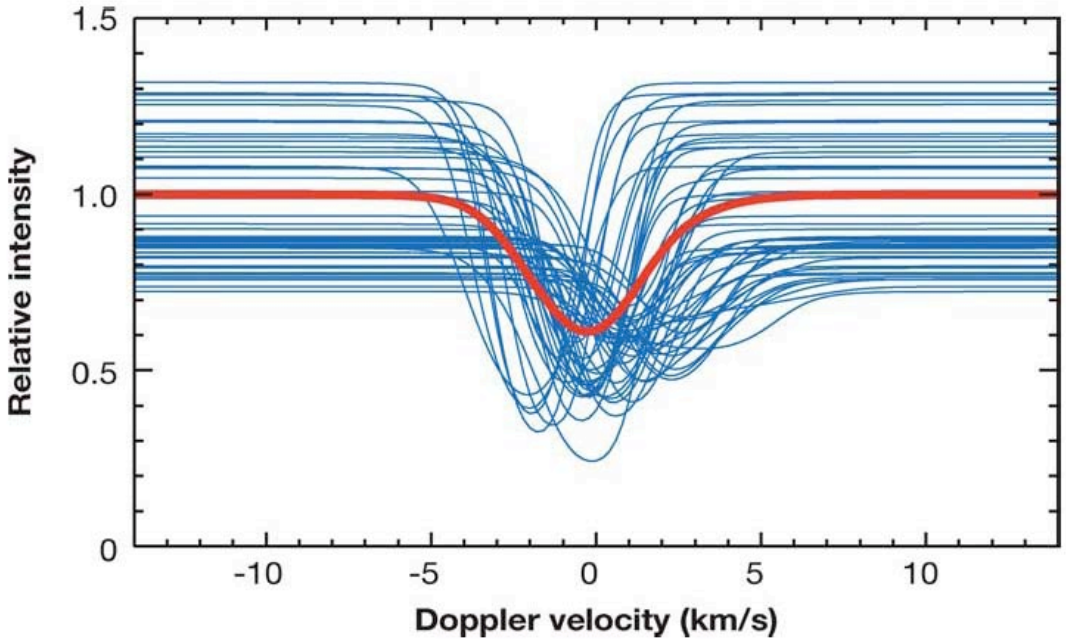
3D:

$$\nu_{\rm max} \propto \mathcal{M}_a^{2.7}\nu_{\rm c}$$

MLT:

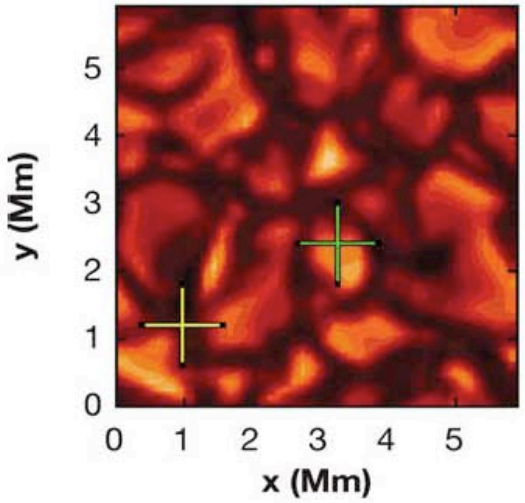
$$\nu_{\rm max} \propto \mathcal{M}_a^{3}\nu_{\rm c}$$

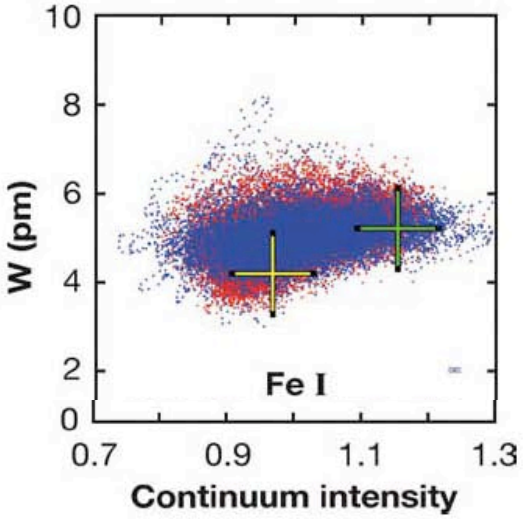
Spatially resolved lines



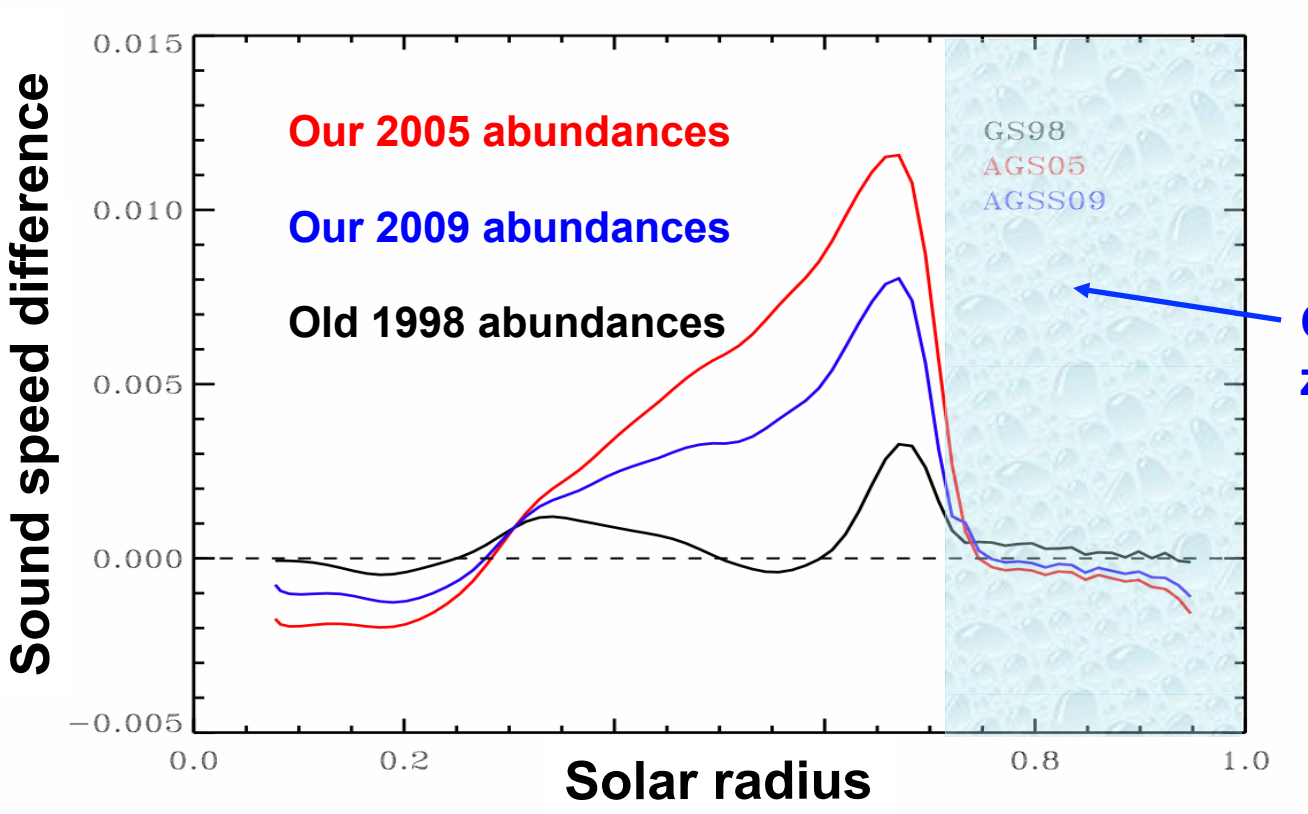
Line profiles vary tremendously across the solar surface

3D model describes observations very well in most cases





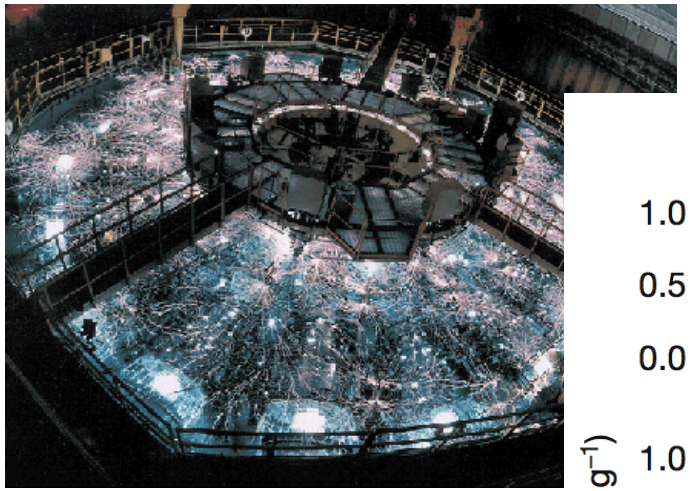
Trouble in paradise



Solar interior models with new abundances are in conflict with helioseismology

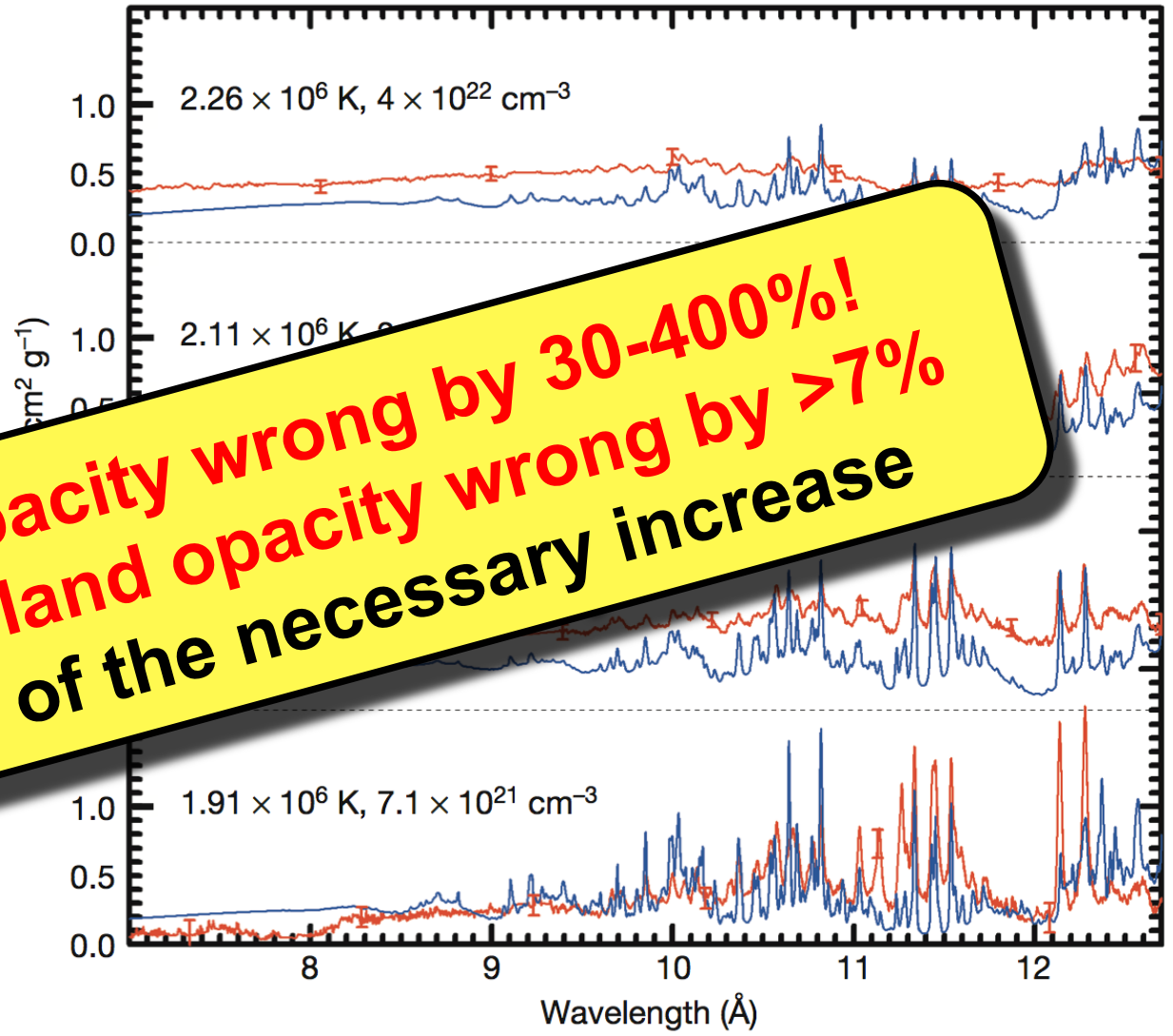
- **Wrong sound speed**
- **Wrong depth of convection zone: R=0.723 vs 0.713±0.001**
- **Wrong surface helium abundance: Y=0.235 vs 0.248±0.004**

Missing opacity



Measurements of opacities at conditio the botto convectio using San Pinch facil

Bailey et al. (2015)



Fe opacity wrong by 30-400%!
Rosseland opacity wrong by >7%
Half of the necessary increase