Lessons from Asteroseismology of B-Type Dwarfs

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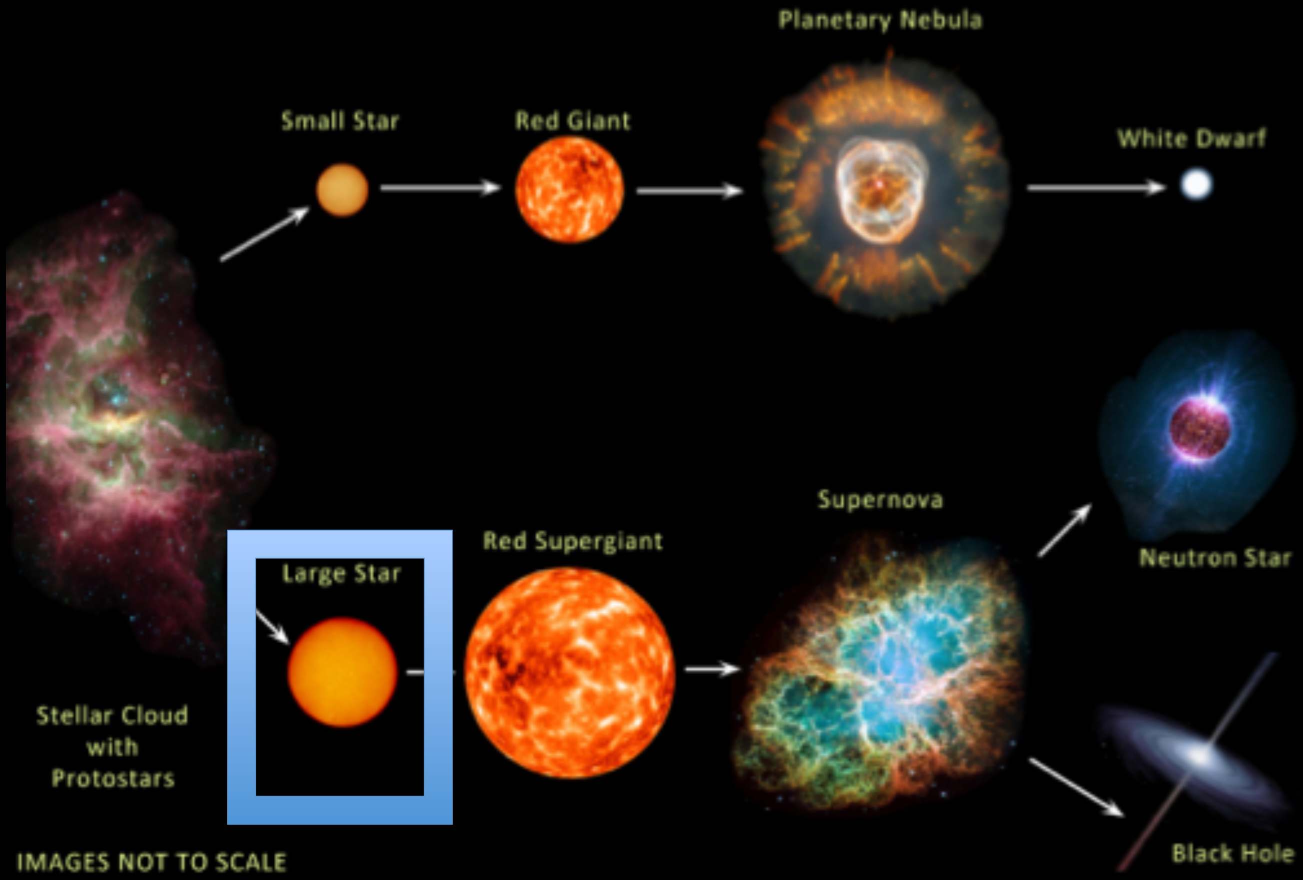
Thanks to: Conny Aerts, Peter I. Papics, Santiago A. Triana & Tamara Rogers

Outline

- Asteroseismology in 5 minutes
- Two B-type slow rotators
- Lessons on mixing and overshoot



What Can Asteroseismology tell about physics of stars?

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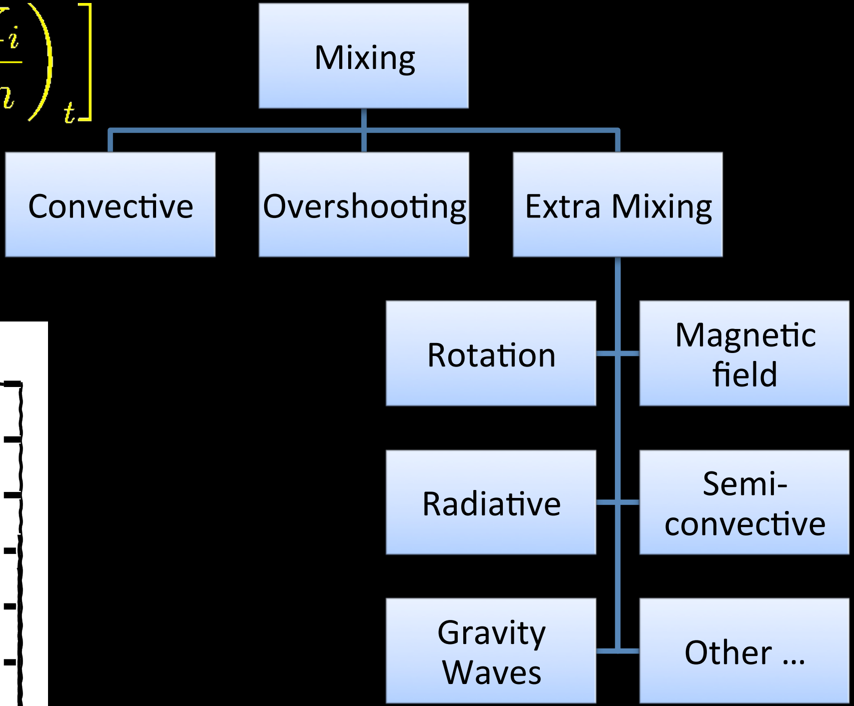
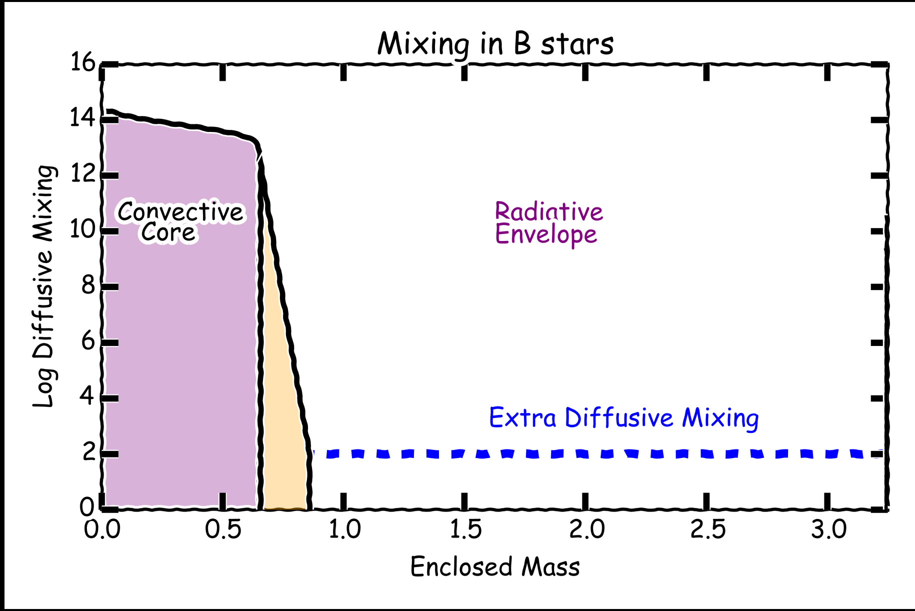
$$\frac{dX_i}{dt} = \left(\frac{dX_i}{dt}\right)_{\mathrm{nuc}} + \frac{\partial}{\partial m}\left[(4\pi r^2\rho)^2 D_{\mathrm{mix}} \left(\frac{\partial X_i}{\partial m}\right)_t\right]$$

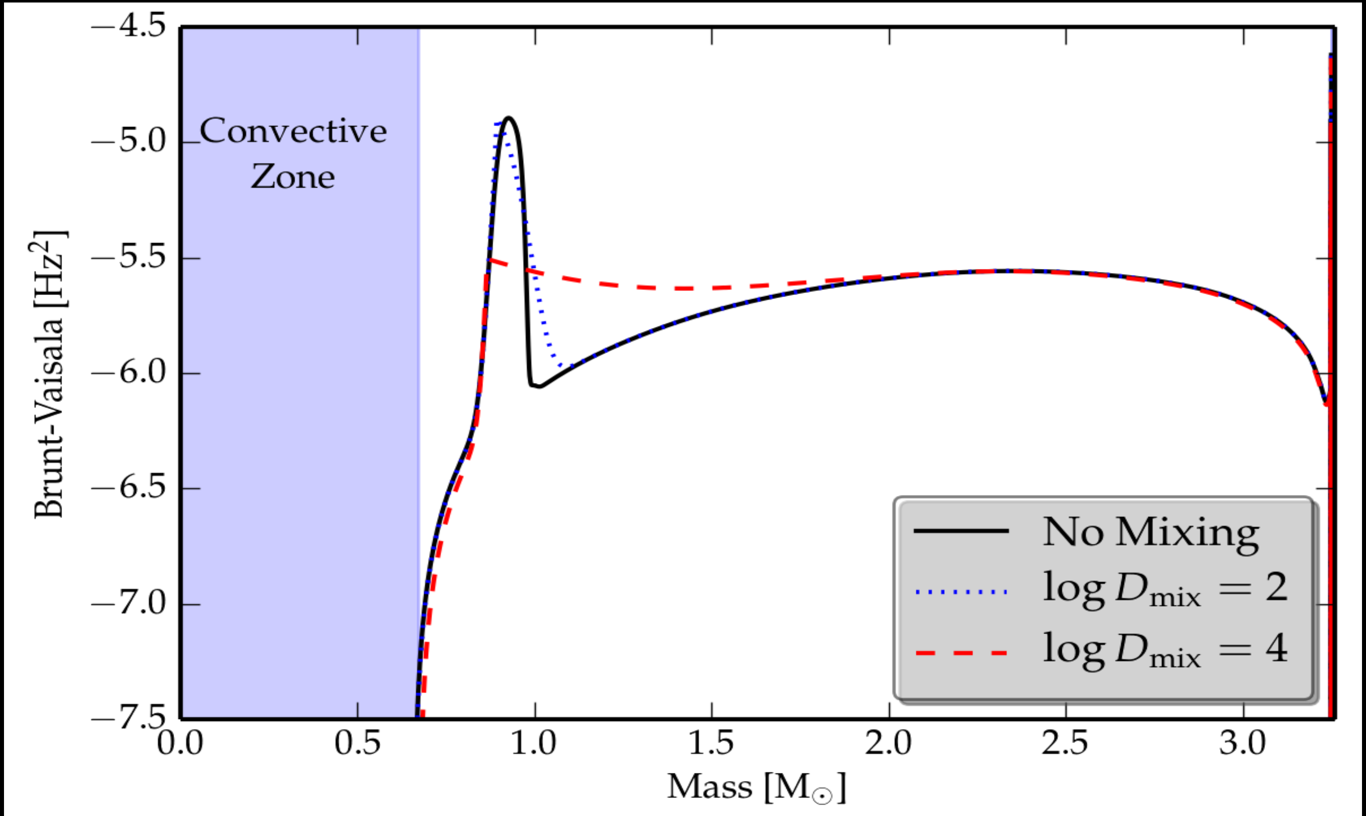
$$D_{\mathrm{mix}} = D_{\mathrm{conv}} + D_{\mathrm{over}} + D_{\mathrm{extra}}$$





Zahn (1992), Heger+ (2000, 2005), Maeder (2009), Mathis+ (2004, 2005)

Brunt-Vaisala Frequency: $N^2 \propto (\nabla_{\rm ad} - \nabla_T + \nabla_\mu)$



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Mixing Signature in high-order gravity modes

For a series of g-modes of any degree, el:

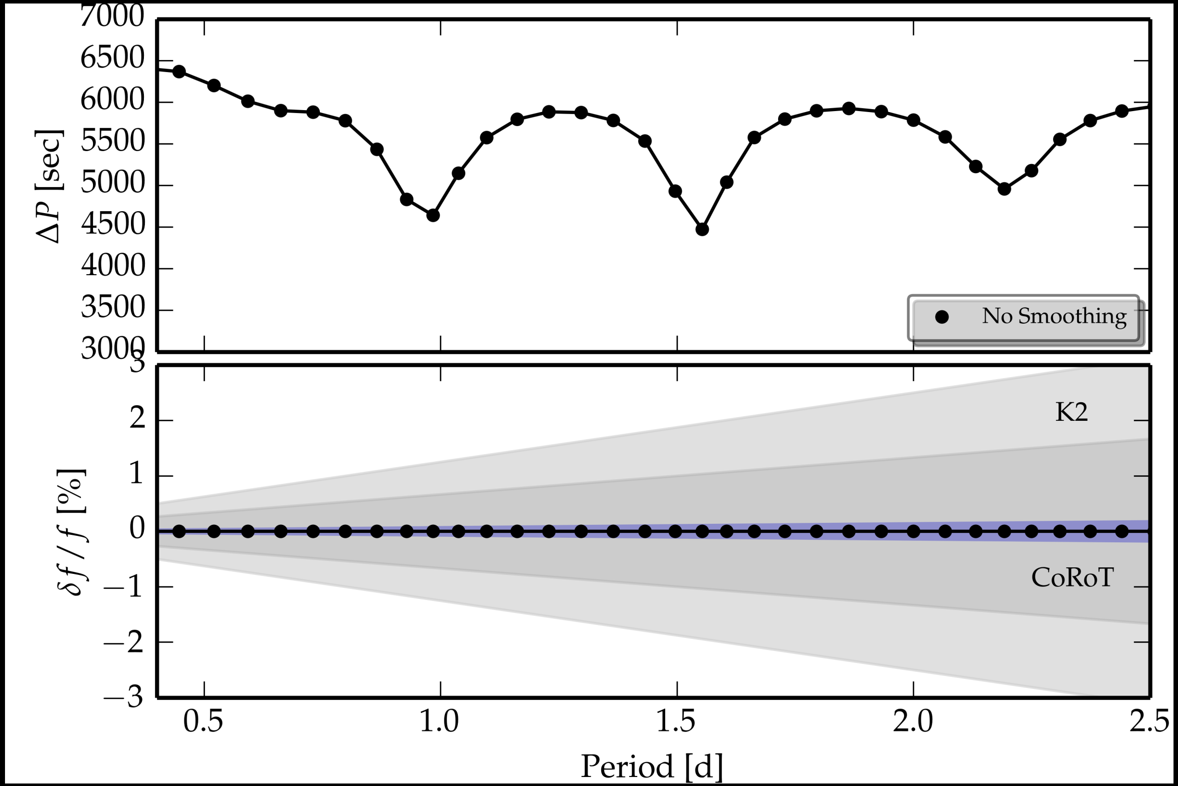
$$P_{n,\ell} = 1/f_{n,\ell},$$

$$\Delta P_n = P_{n+1} - P_n,$$

$$T_{\mathrm{K2}} \sim 90\text{ days},$$

$$T_{\mathrm{CoRoT}} \sim 130\text{ days},$$

$$T_{\mathrm{Kepler}} \sim 1460\text{ days}.$$



Tassoul (1980), Miglio+2008, Ostensen+2014, Van Reeth+2015

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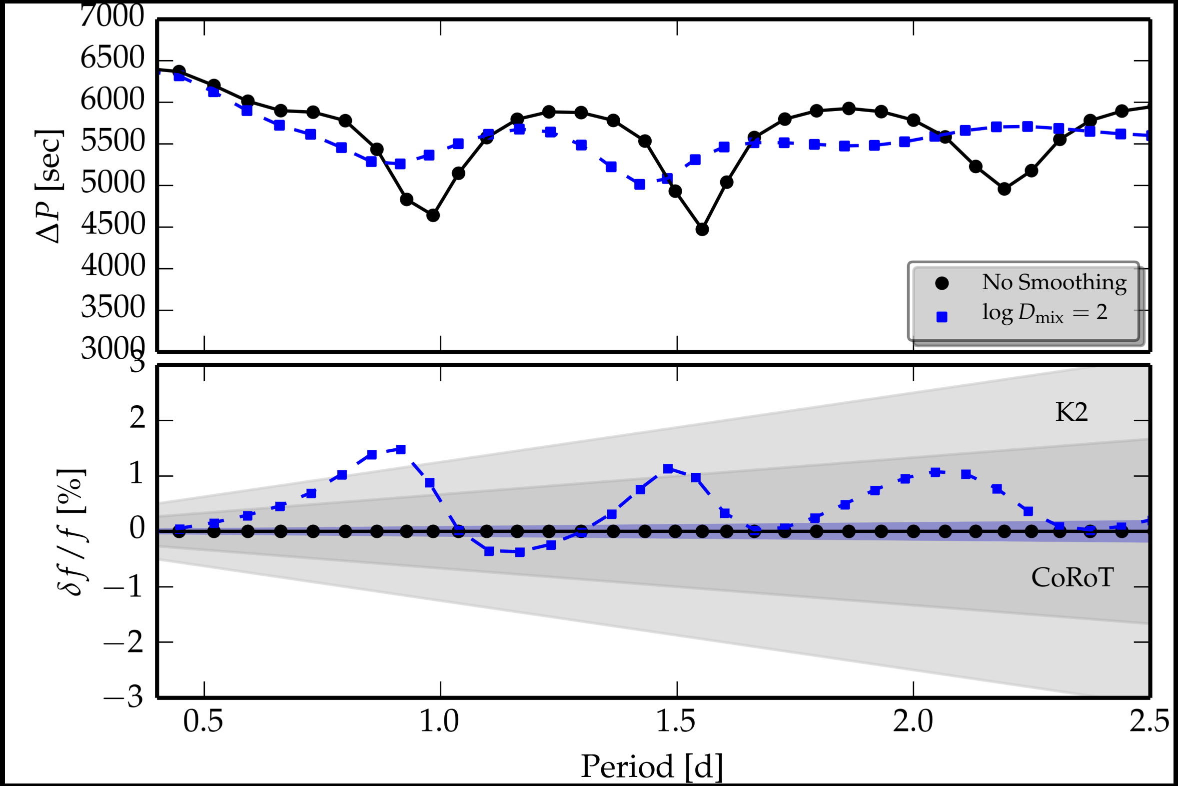

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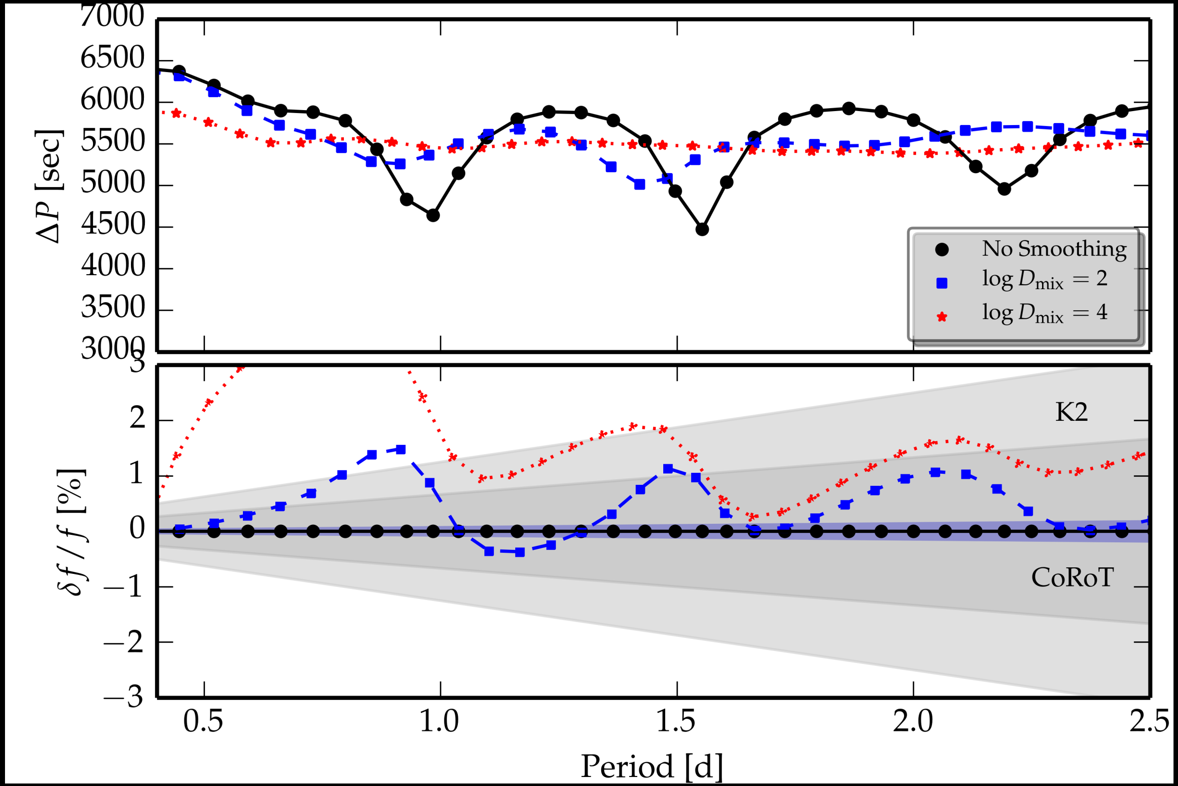


Tassoul (1980), Miglio+2008, Ostensen+2014, Van Reeth+2015

How to Do it?

$$\chi^2_{red} = \frac{1}{19 - 4} \sum_{i=1}^{19} \frac{(f_i^O - f_i^C)^2}{\sigma_i^2}$$

Observed Modes

- Mass
- Metallicity, Z
- Age, X_c
- Overshooting, f_{ov}

or

Semi-Convection, α_{sc}

ω_{nl} for l=1

χ^2

Best Model(s)

Paxton+ (2011, 2013), Townsend & Teitler (2013), Aerts (2014)

Applications to two stars

Two Slowly Rotating and Pulsating B-Type Dwarfs

KIC 10526294 (B8 V)

T_{eff} = 11 500 ± 500 K

log g = 4.2 ± 0.2 dex

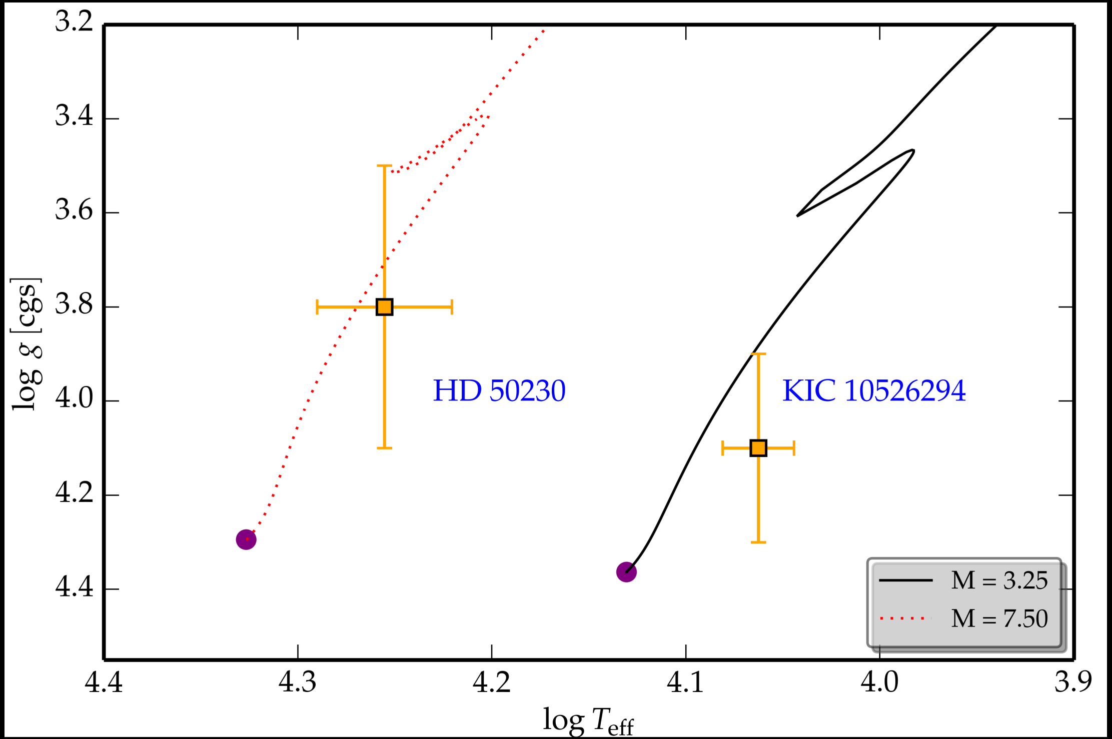
V sin i < 18 km/sec

HD 50230 (B3 V)

T_{eff} = 18 000 ± 1500 K

log g = 3.8 ± 0.3 dex

V sin i ≈ 6 km/sec



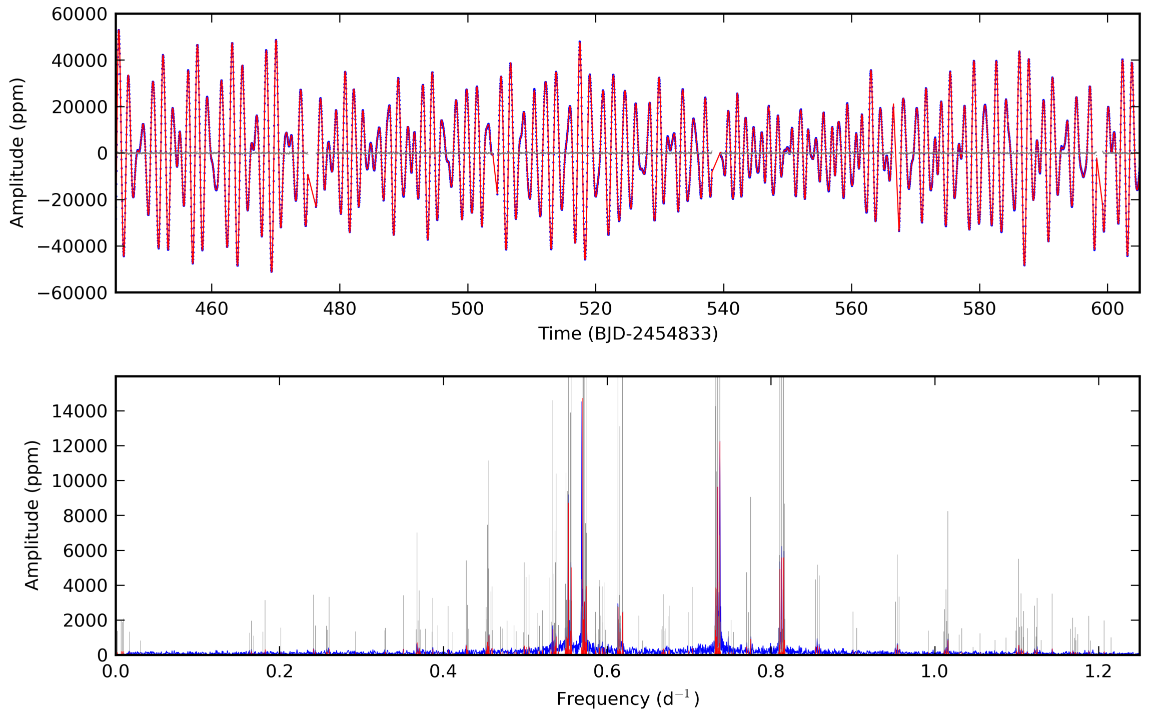
The *Kepler* Target (I)

KIC 10526294 (B8 V)

T_{eff} = 11 500 ± 500 K
log g = 4.2 ± 0.2 dex
V sin i < 18 km/sec

T_{Kepler} = 1420 days
19 consecutive dipole g-mode triplets!

Papics & Moravveji et al. (2014)
Morevveji et al. (2015)
Triana et al. (2015, submitted)



The *Kepler* Target (II)

KIC 10526294 (B8 V)

T_{eff} = 11 500 ± 500 K
log *g* = 4.2 ± 0.2 dex
V sin *i* < 18 km/sec

T_{Kepler} = 1420 days
19 consecutive dipole g-mode triplets!

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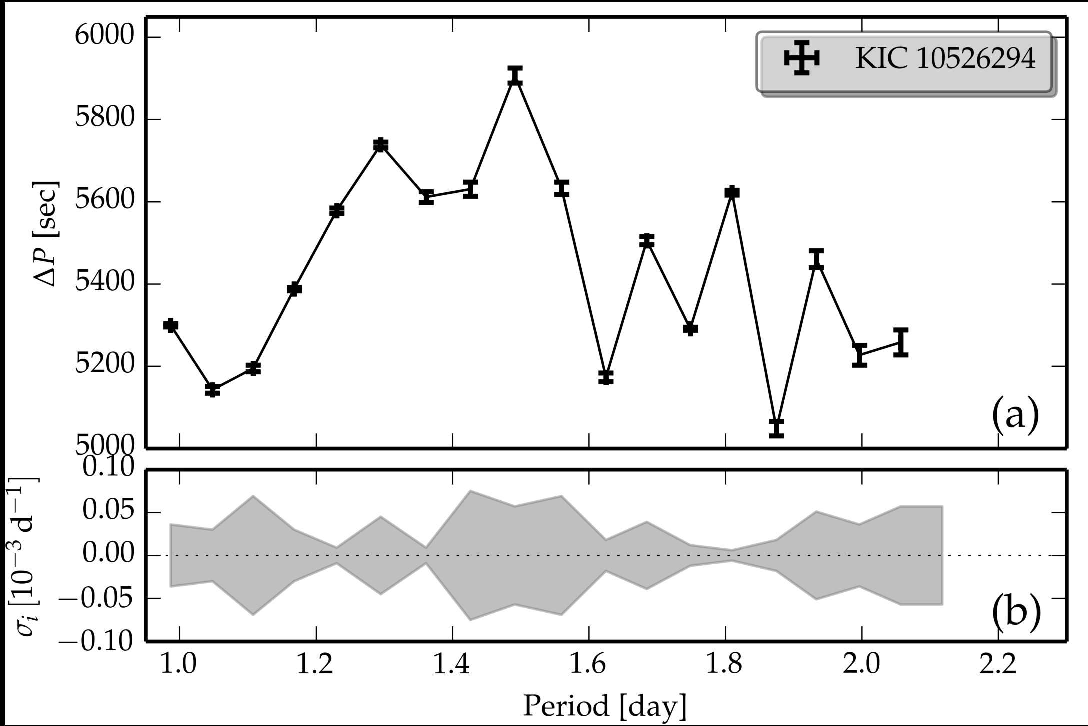
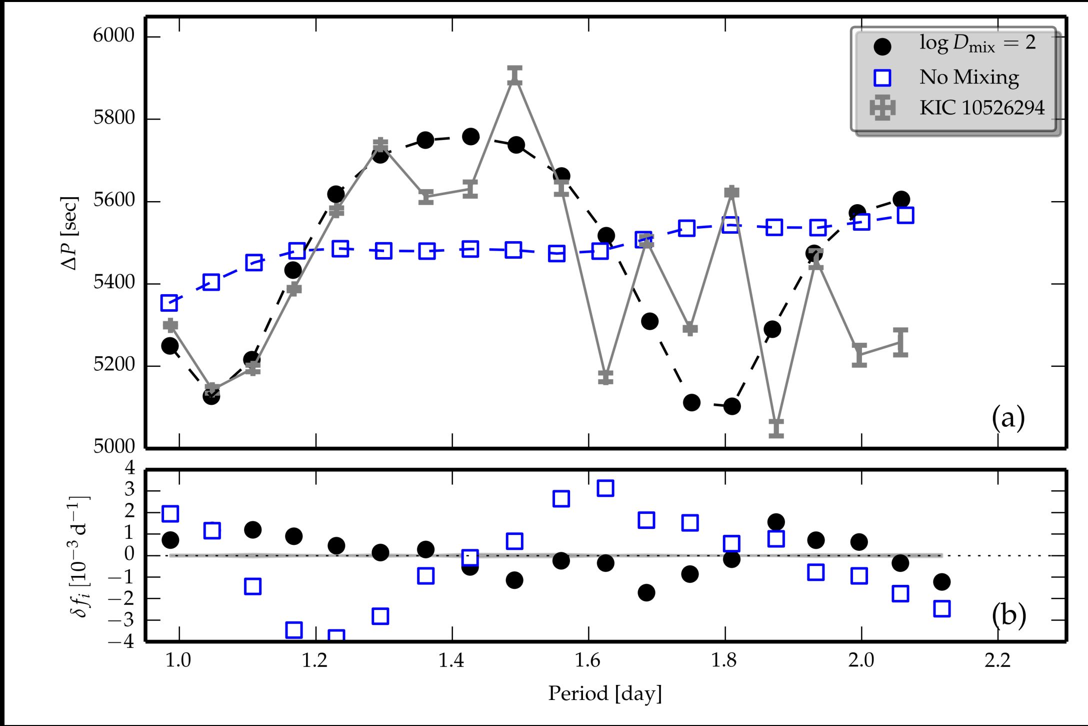


The *Kepler* Target (III)

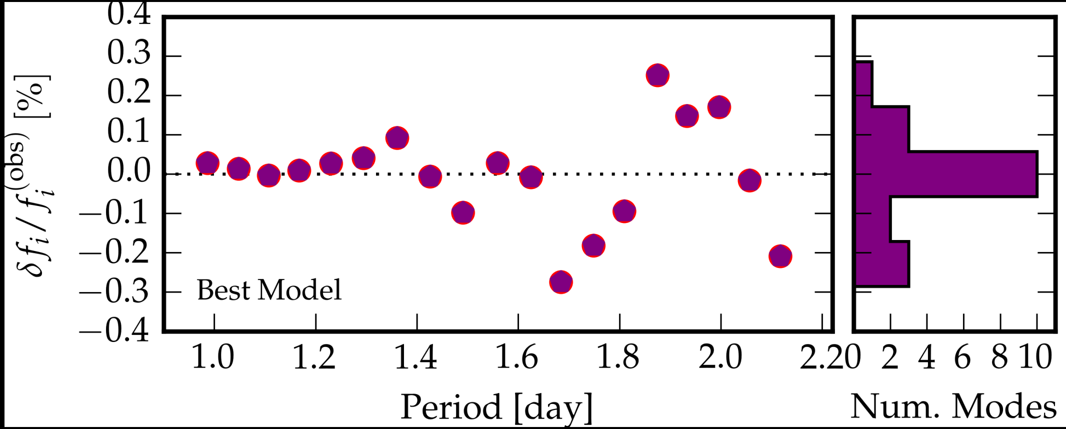
KIC 10526294 (B8 V)

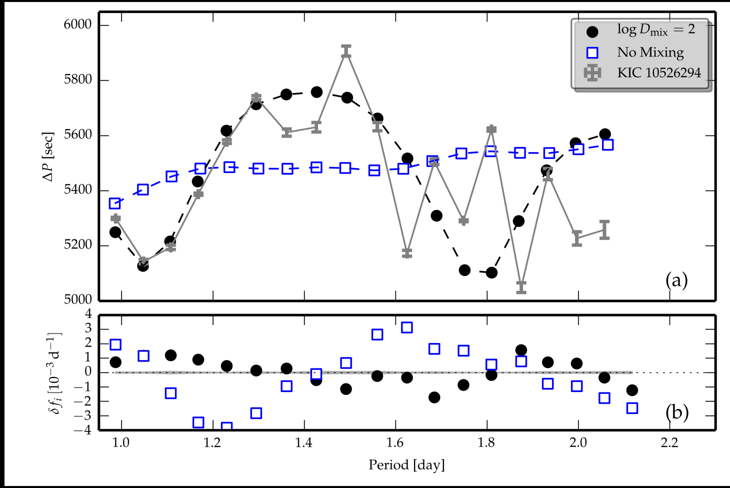
Test of extra mixing:
Chi-square improves by a factor of 11

Papics & Moravveji et al. (2014)
Morevveji et al. (2015)
Triana et al. (2015, submitted)



The *Kepler* Target (IV)





KIC 10526294 (B8 V)

Morevveji et al. (2015, A&A)

The *Kepler* Target (V)

KIC 10526294 (B8 V)

Test of Overshoot prescription:

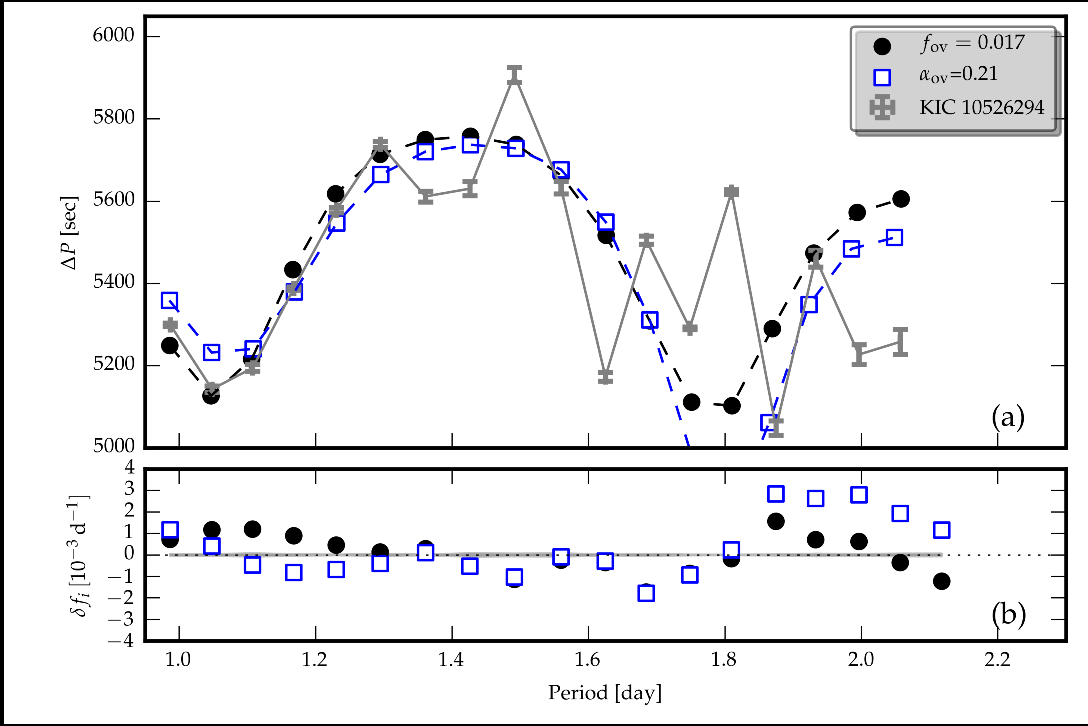
- Step-function overshoot
- Exponentially decaying

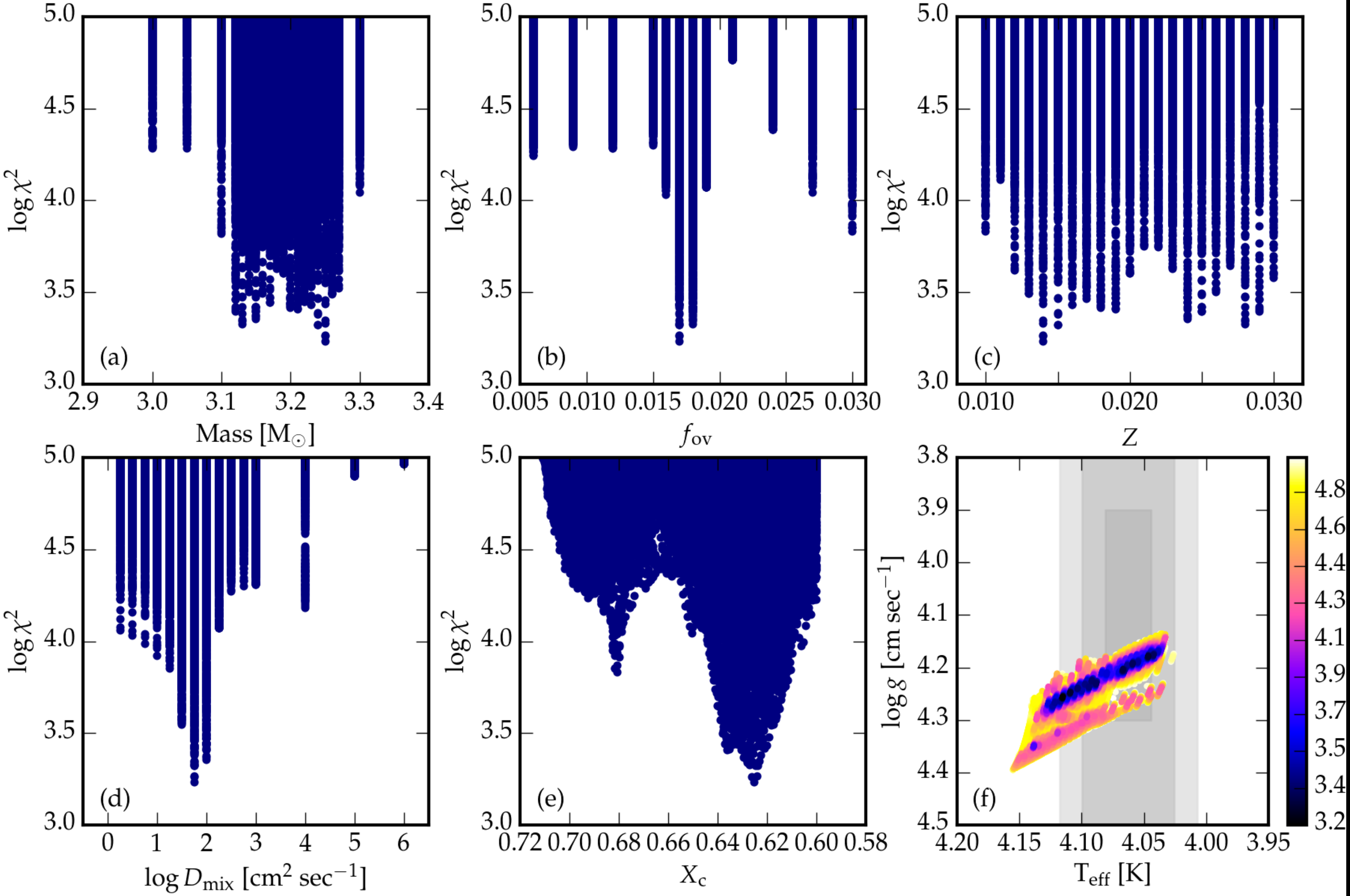
$$D_{\rm over} = D_{\rm conv}$$

OR

$$D_{\rm over} = D_{\rm conv} \exp\left(\frac{2r}{f_{\rm ov}\, H_p}\right)$$

Morevveji et al. (2015, A&A)





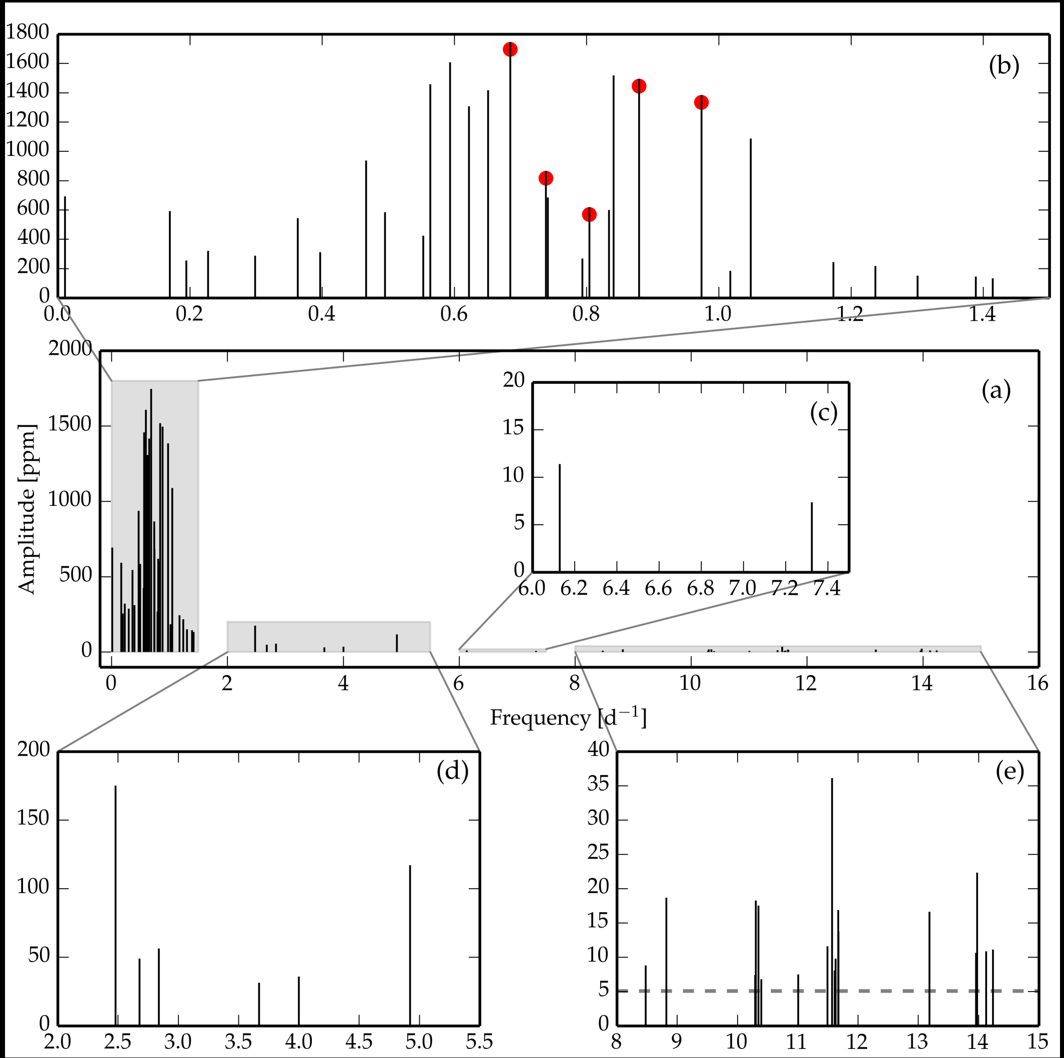
(a)
(b)
(c)
(d)
(e)
(f)
log χ²
Mass [M☉]
f_ov
Z
log D_mix [cm² sec⁻¹]
X_c
T_eff [K]
log g [cm sec⁻¹]

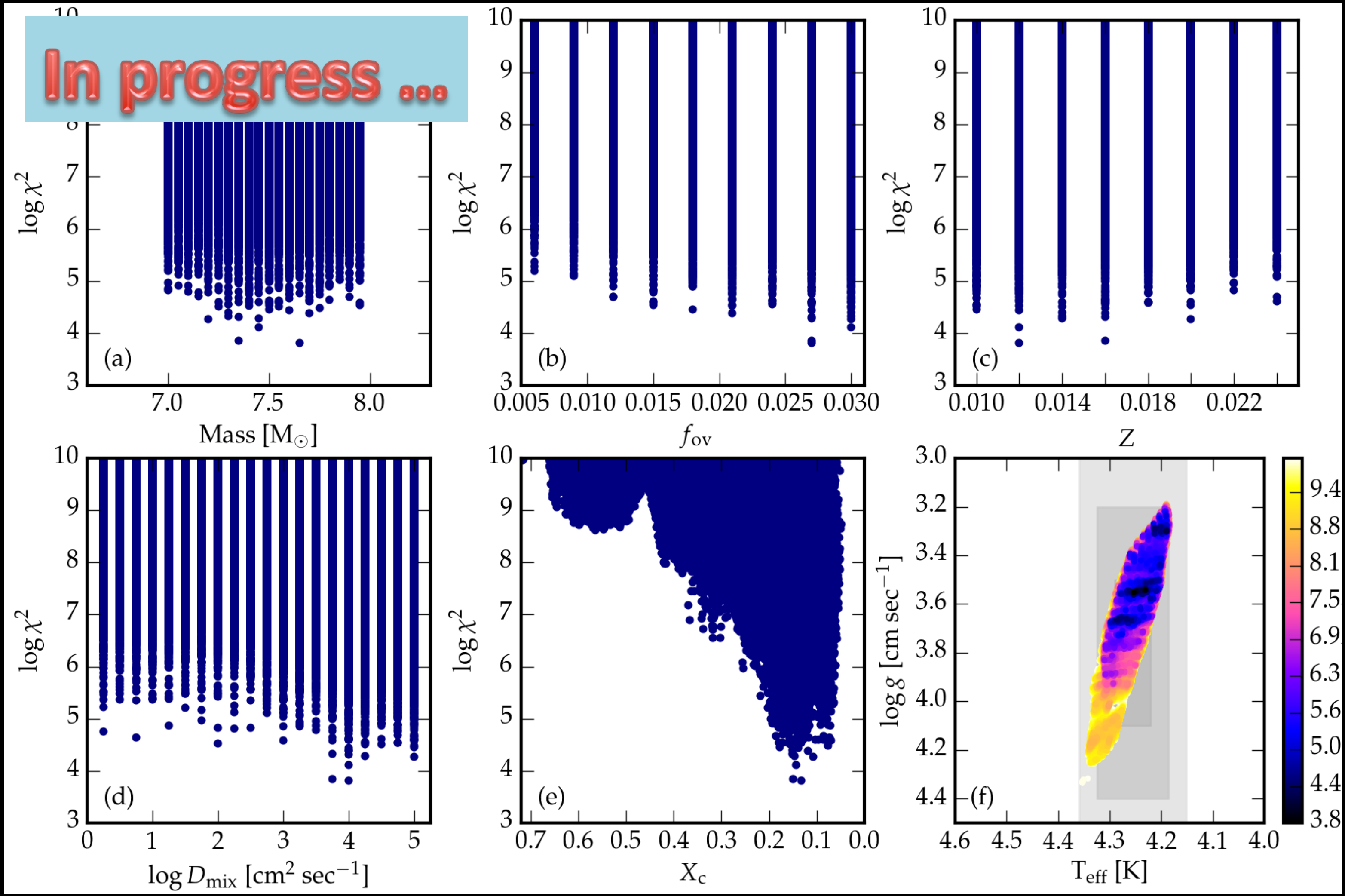
HD 50230 (B3 V)

T_{eff} = 18 000 ± 1500 K
log g = 3.8 ± 0.3 dex
V sin i ≈ 6 km/sec

T_{CoRoT} = 137 days
5 consecutive dipole g-modes + a lot of low-order p-modes

Degroote et al. (2010, Nature, 2012),
Moravveji & Aerts (2015, in preparation)




In progress ...
(a)
log χ²
Mass [M☉]
(b)
f_ov
(c)
Z
(d)
log D_mix [cm² sec⁻¹]
(e)
X_c
(f)
log g [cm sec⁻¹]
T_eff [K]

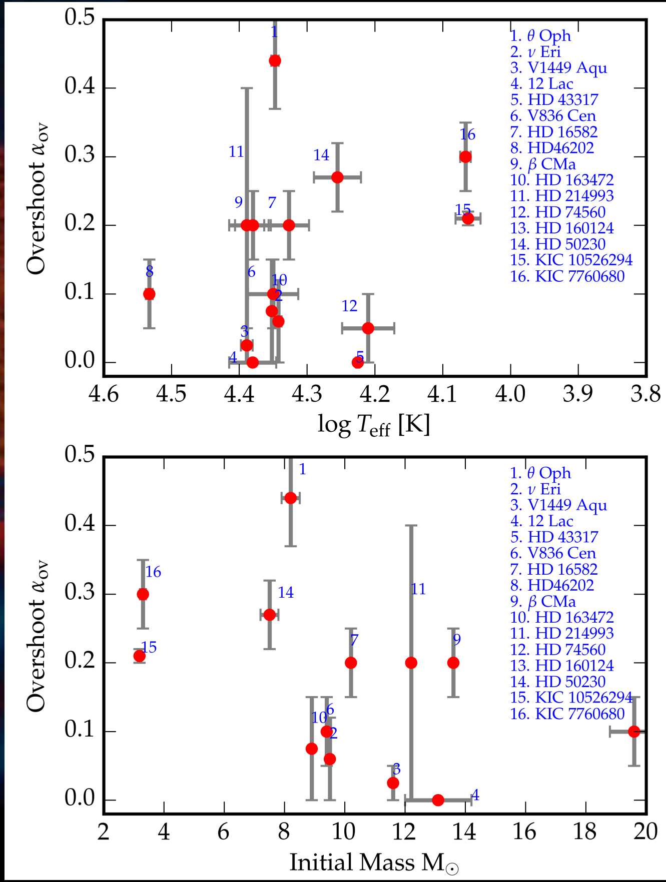
Physics of “less”-Evolved Stars

a) Asteroseismology can quantify overshooting and mixing in (B-type) stars

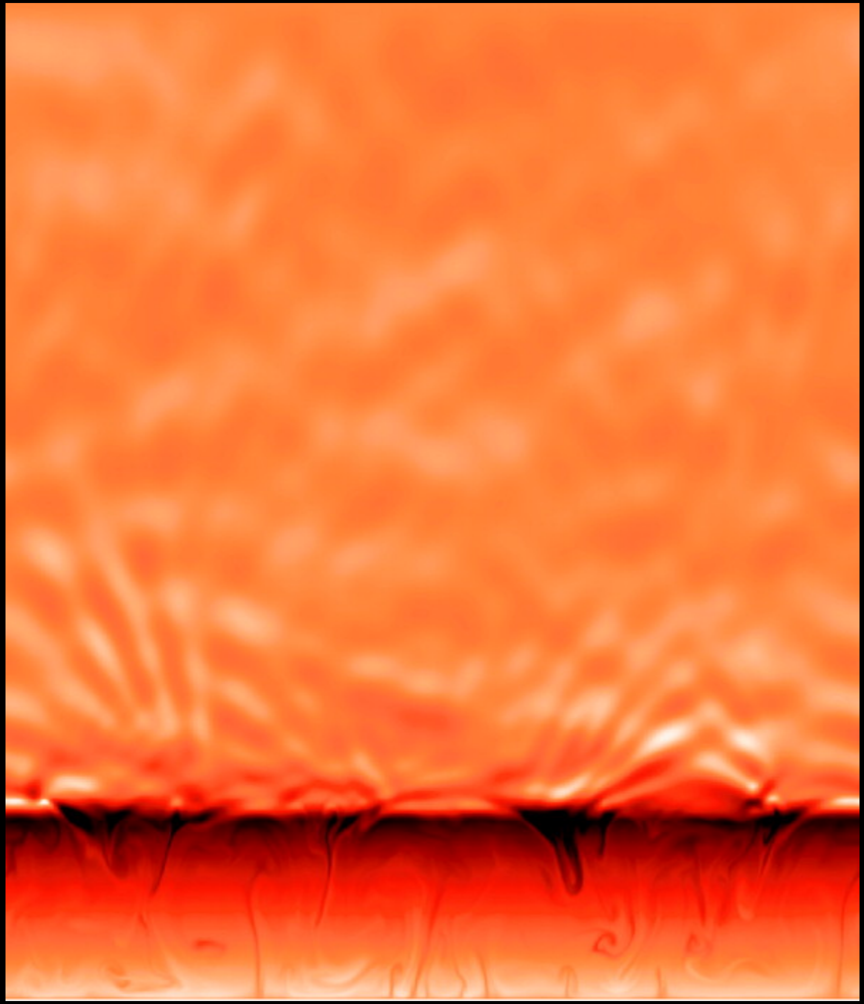
b) Overshoot from the core is perhaps smooth (exponential?)

c) General picture is forming …

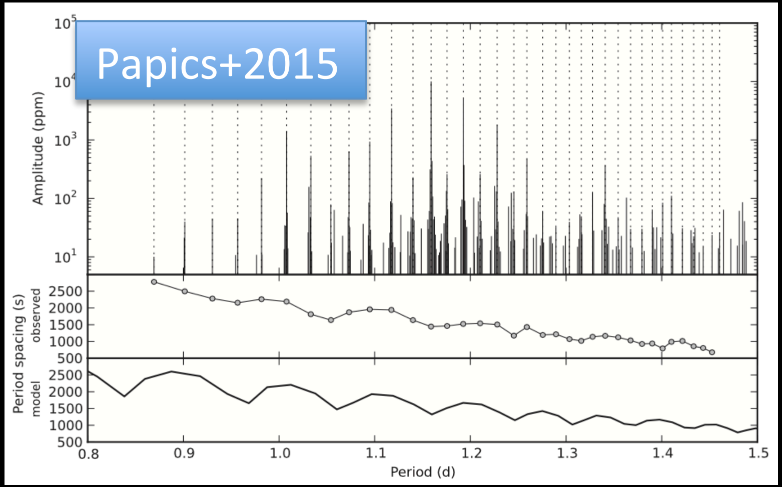
d) Extra Mixing [$10^2 – 10^4$ cm^2/sec] is essential, even for non-rotating stars

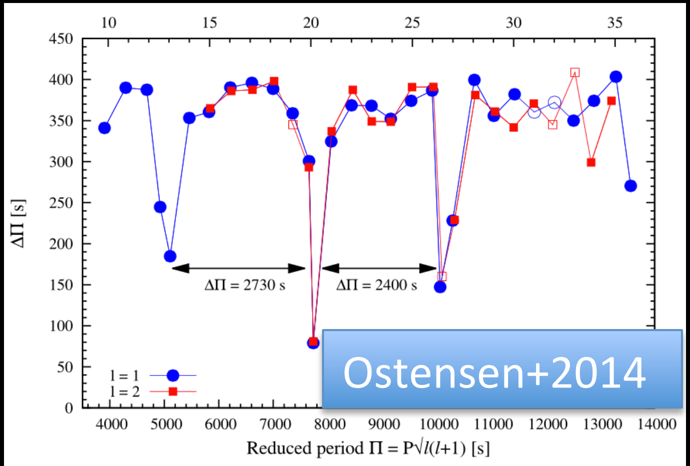


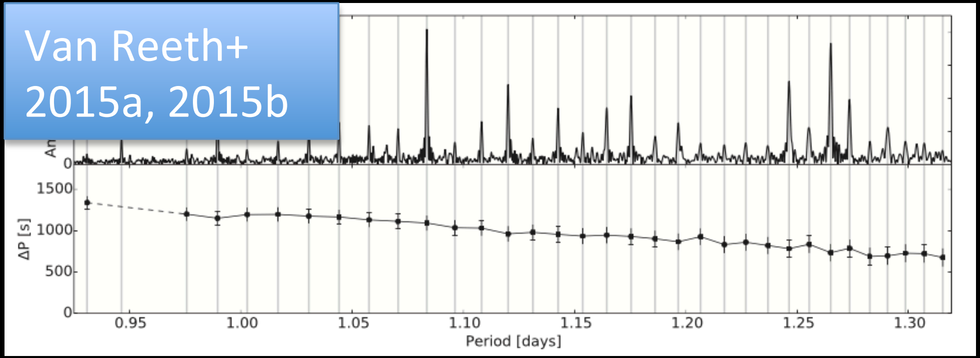
see Rogers & Glatzmaier (2005, ApJ), Meaking & Arnett (2007)



Period Spacing in Other Stars: Few Examples







Grid Parameters

Parameter	From	To	Stepsize
Mass	3.0	3.30	0.05 or 0.01
Z	0.010	0.030	0.001
Overshoot	0.000	0.030	0.003 or 0.001
Log Mixing	0	6	1.0 or 0.25
Center H	0.71	0.60	0.001

Physical Ingredients:

- Mass
- Metallicity
- Opacity: OP and OPAL
- Mixing? Yes/No
- Mixing values
- Age
- Mixture: Nieva & Przybilla (2012)
- Asplund et al. (2009)
- Asplund et al. (2005) + Cunha et al. (2006)
- Overshoot option: step-function versus exponential decay
- Overshoot value

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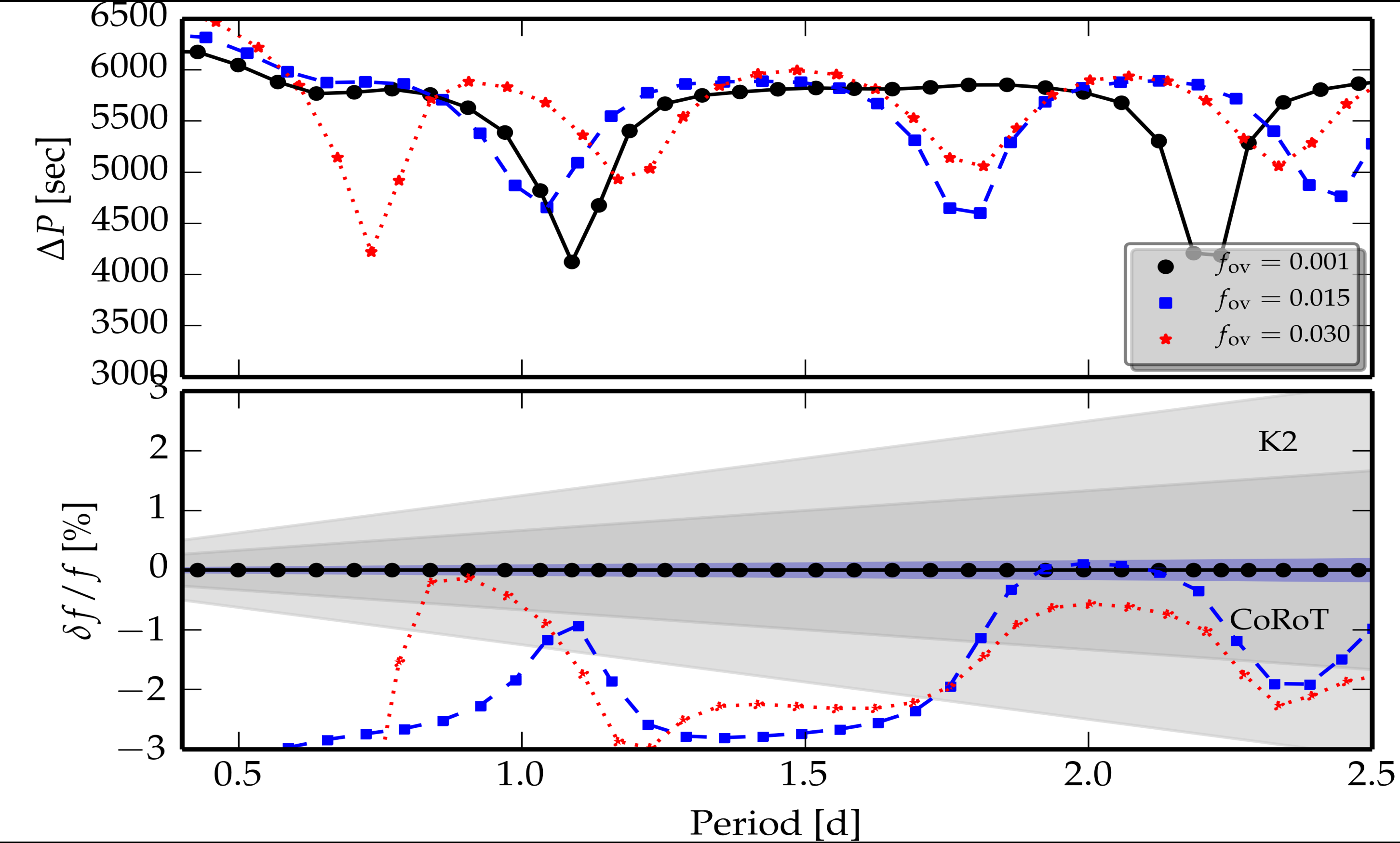

6500
6000
5500
5000
4500
4000
3500
3000
ΔP [sec]
$f_{\rm ov} = 0.001$
$f_{\rm ov} = 0.015$
$f_{\rm ov} = 0.030$
3
2
1
0
−1
−2
−3
δf / f [%]
K2
CoRoT
0.5
1.0
1.5
2.0
2.5
Period [d]

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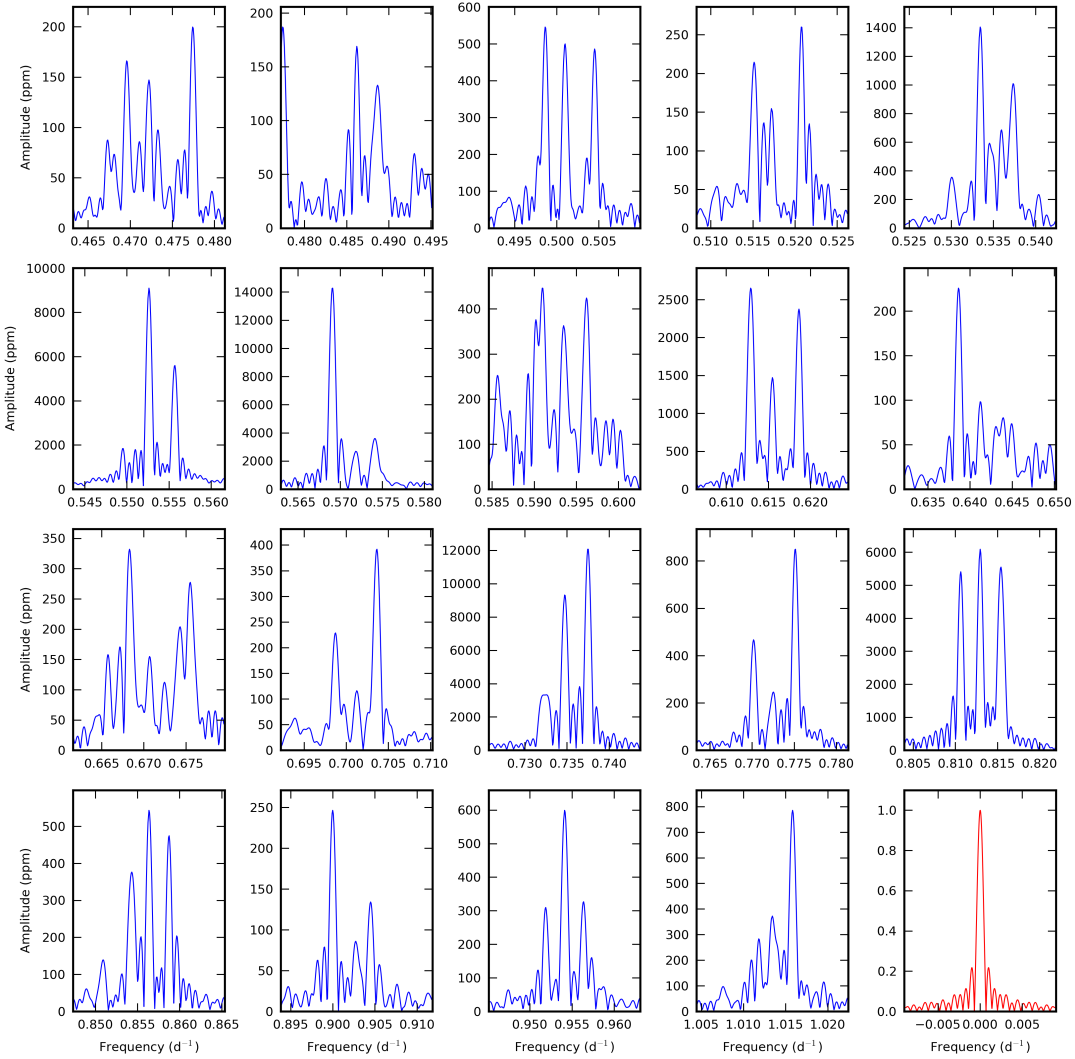
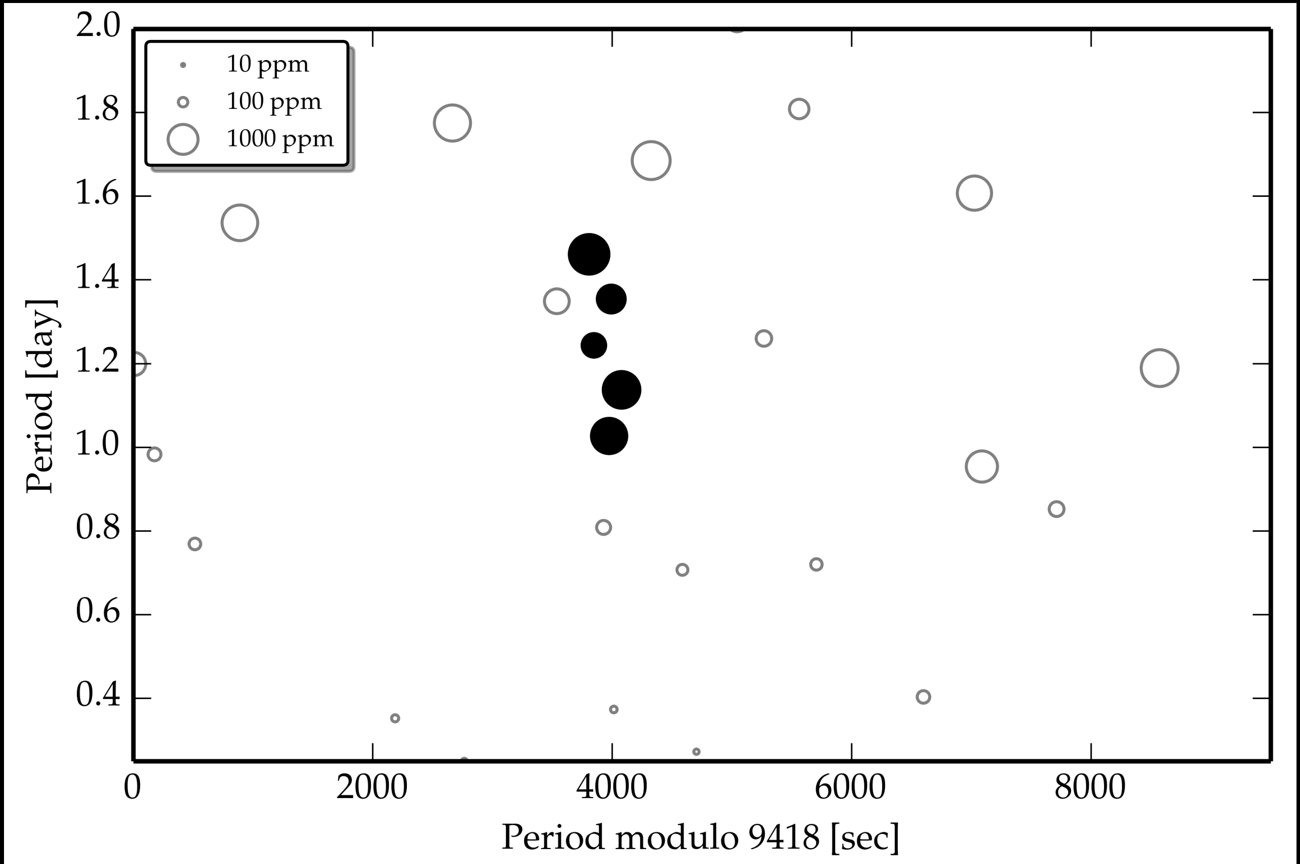
KIC 10526294 Splittings



Echelle Diagram
HD 50230



Parameters of the best models

#	Grid	Opacity	Mixture	Mass [$M_\odot$]	X_{ini}	Z_{ini}	X_c	f_{ov} or α_{ov}	$\log D_{mix}$ [$cm^2\ s^{-1}$]	χ^2_{red}	χ^2_{P14}
1	Basic	OPAL	NP12	3.20	0.71	0.020	0.693	0.000	—	18 192	10.9
2	Composition	OPAL	NP12	3.15	0.69	0.010	0.662	0.030	—	11 402	23.3
3	Evolved	OPAL	NP12	3.50	0.71	0.010	0.254	0.030	2	23 199	21.8
4	**Mixing+Fine**	**OPAL**	**NP12**	**3.25**	**0.71**	**0.014**	**0.627**	**0.017**	**1.75**	**1 711**	**1.42**
5	Mixture	OPAL	A09	3.18	0.71	0.021	0.640	0.018	2.00	2 500	3.60
6	Mixture	OPAL	A05+Ne	3.20	0.71	0.013	0.641	0.018	2.00	5 905	4.53
7	Mixture	OP	NP12	3.24	0.71	0.014	0.636	0.017	1.75	3 034	5.23
8	Mixture	OP	A09	3.22	0.71	0.015	0.638	0.018	2.00	2 348	3.23
9	Mixture	OP	A05+Ne	3.17	0.71	0.012	0.632	0.018	1.75	3 249	2.90
10	Step Overshoot	OPAL	NP12	3.19	0.71	0.019	0.628	0.21	1.75	3 792	5.54
11	Metallicity	OPAL	NP12	3.13	0.71	0.028	0.628	0.018	1.75	2 187	2.32