Tight asteroseismic constraints on core overshooting and diffusive mixing for massive stars

Ehsan Moravveji (KU Leuven)

And special Thanks to:

SEVENTH FRAMEWORK PROGRAMME

Belgian Science Policy Office belspo

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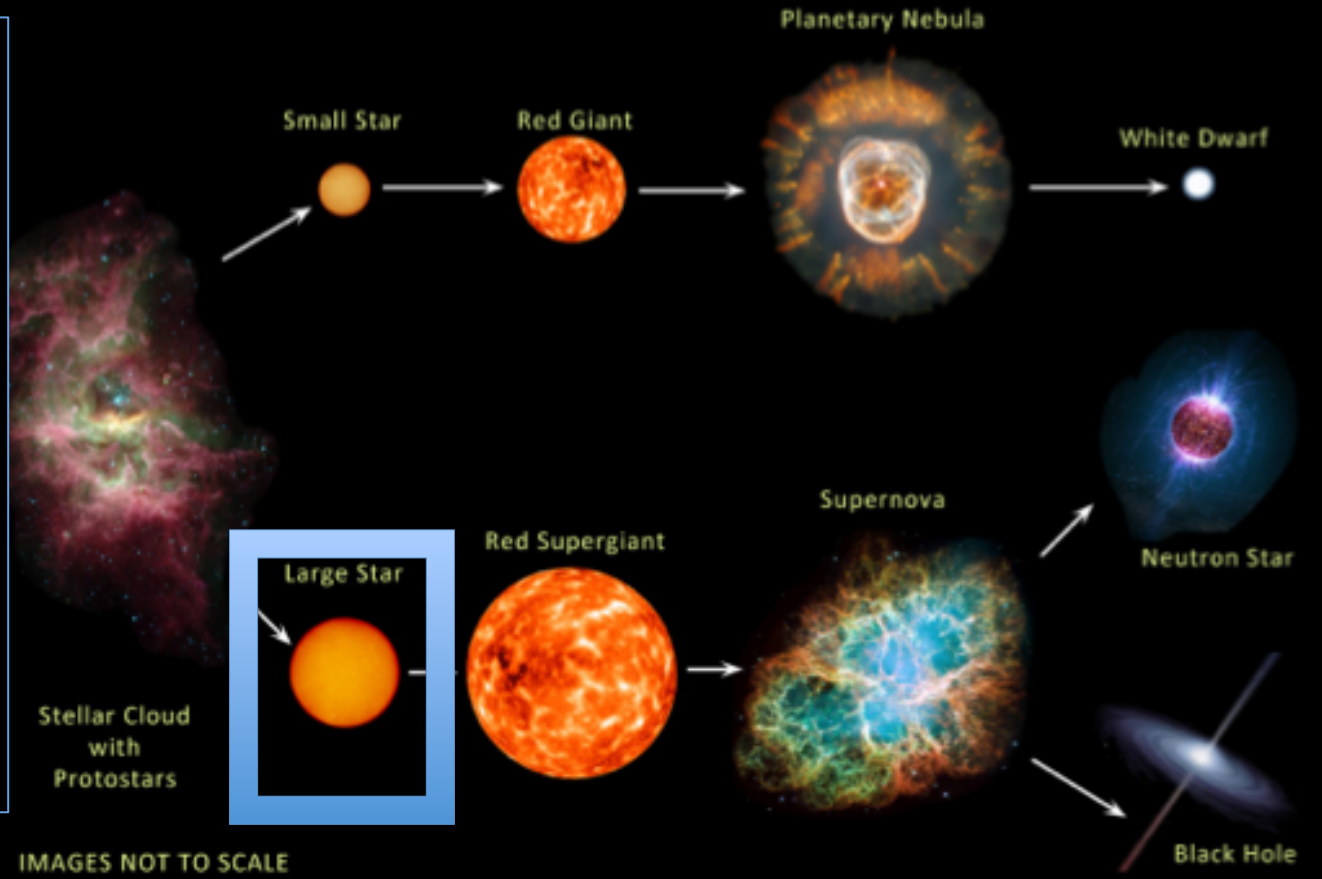
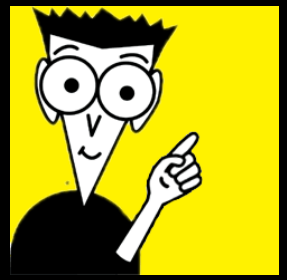
Outline

- Asteroseismology, overshooting and extra diffusive mixing
- Two B-type slow rotators
- Lessons on mixing and overshoot

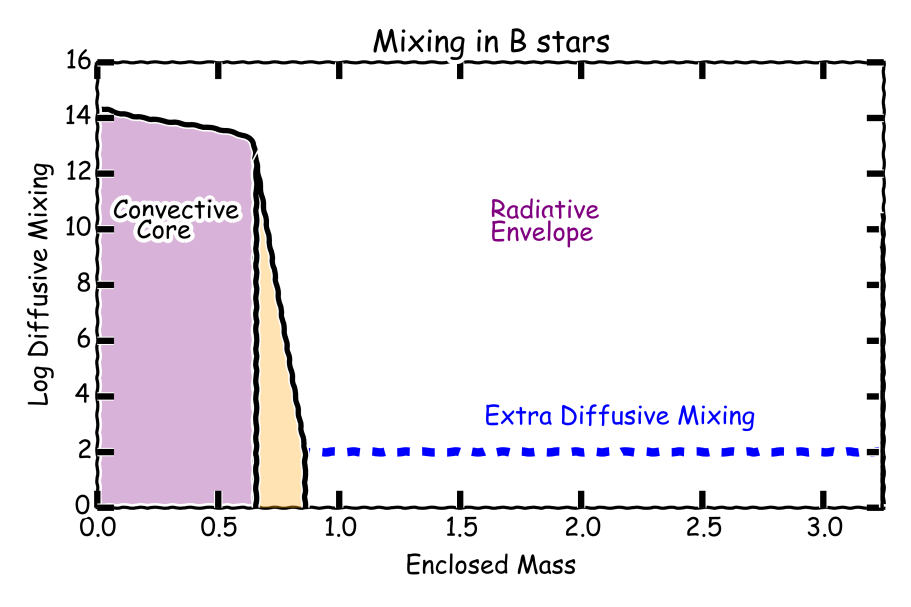


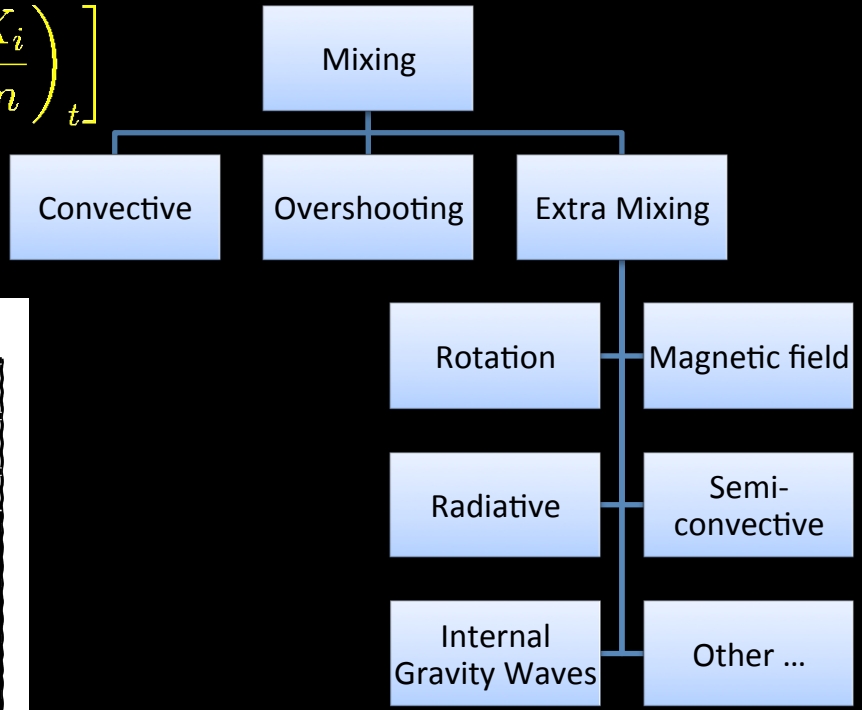


WHAT CAN ASTEROSEISMOLOGY TELL ABOUT MIXING?

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

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





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

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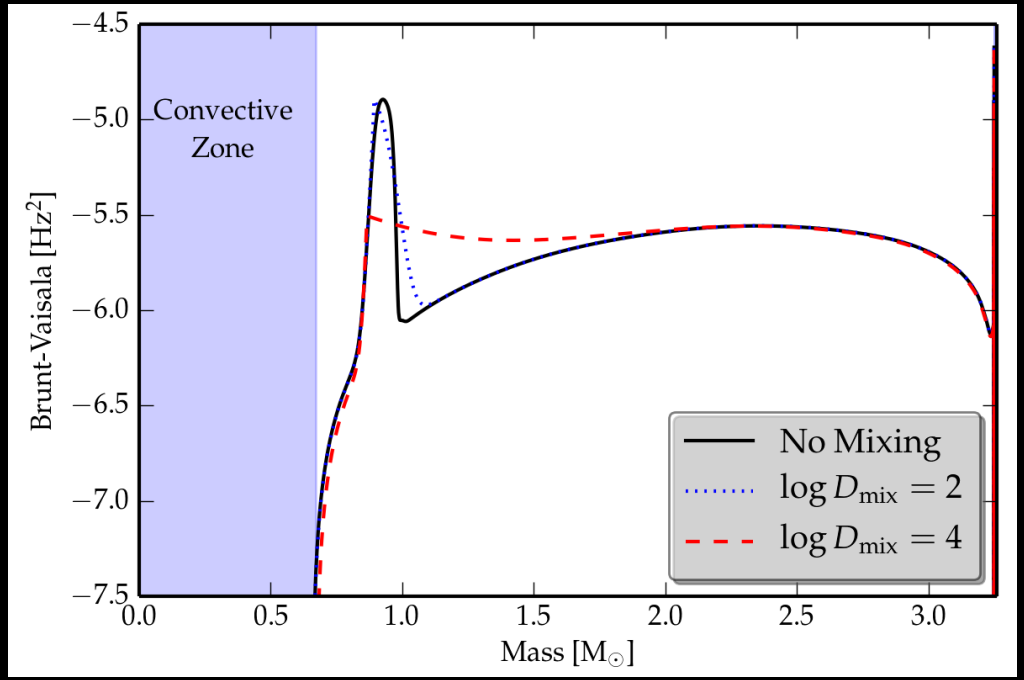
Brunt-Vaisala Frequency: $N^2 \propto (\nabla_{\rm ad} - \nabla_T + \nabla_\mu)$

$$\Delta P_\ell = P_{n+1,\ell} - P_{n,\ell} = \frac{2\pi^2}{\sqrt{\ell(\ell+1)}} \left(\int_{r_1}^{r_2} \frac{N(r)}{r} dr \right)^{-1}$$

Changing D_{mix}:
- which changes ∇_μ
- which changes N^2
- changes frequencies
- changes period spacing

See Tassuol (1980), Miglio et al. (2008), Moravveji (2015, EAS Conf. proc., in press)



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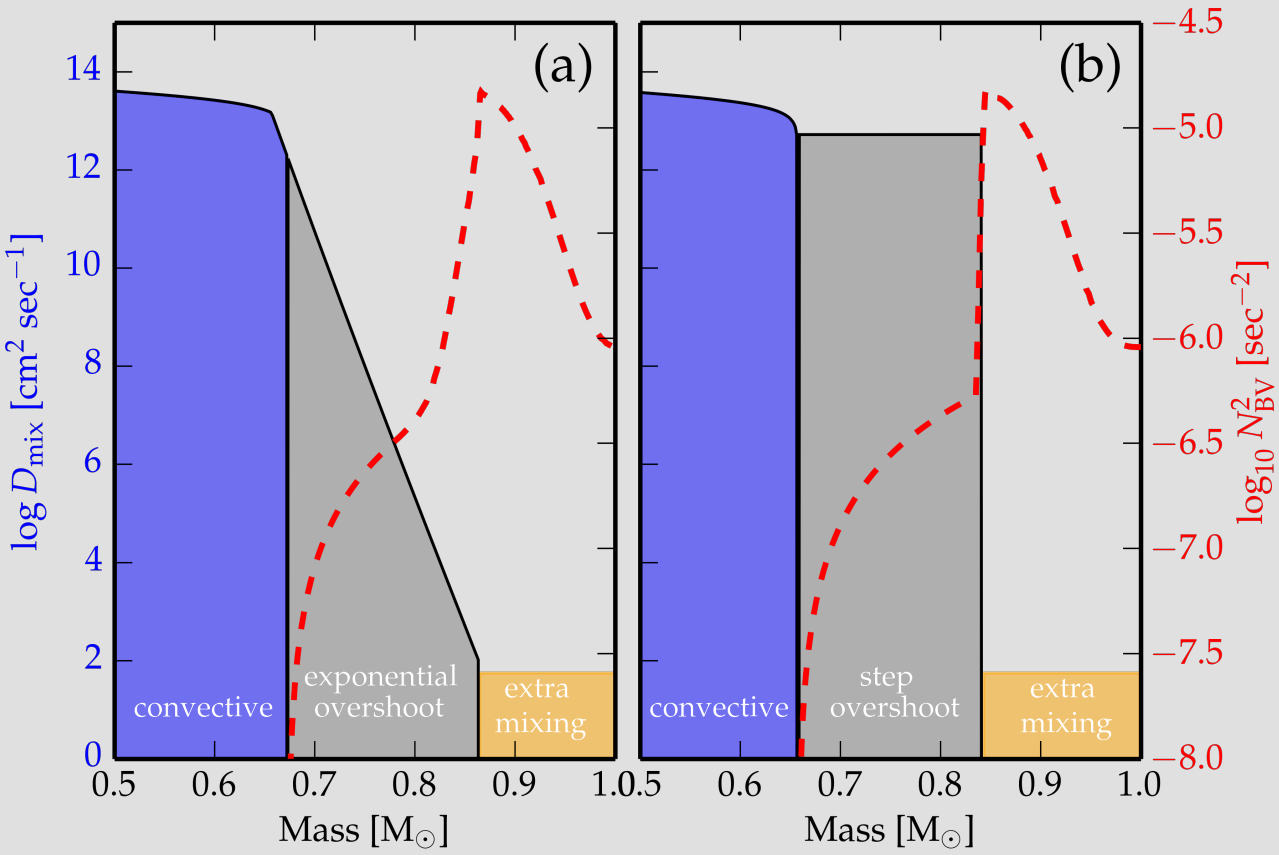
Adopted Mixing Scheme

Convective Core Overshoot:

(a) Exponential Overshoot
(b) Step-Function Overshoot

+ Extra Mixing in the radiative envelope

$$N^2 \propto (\nabla - \nabla_{\rm ad} + \nabla_\mu)$$



See Moravveji (2015, EAS conf. proc.)

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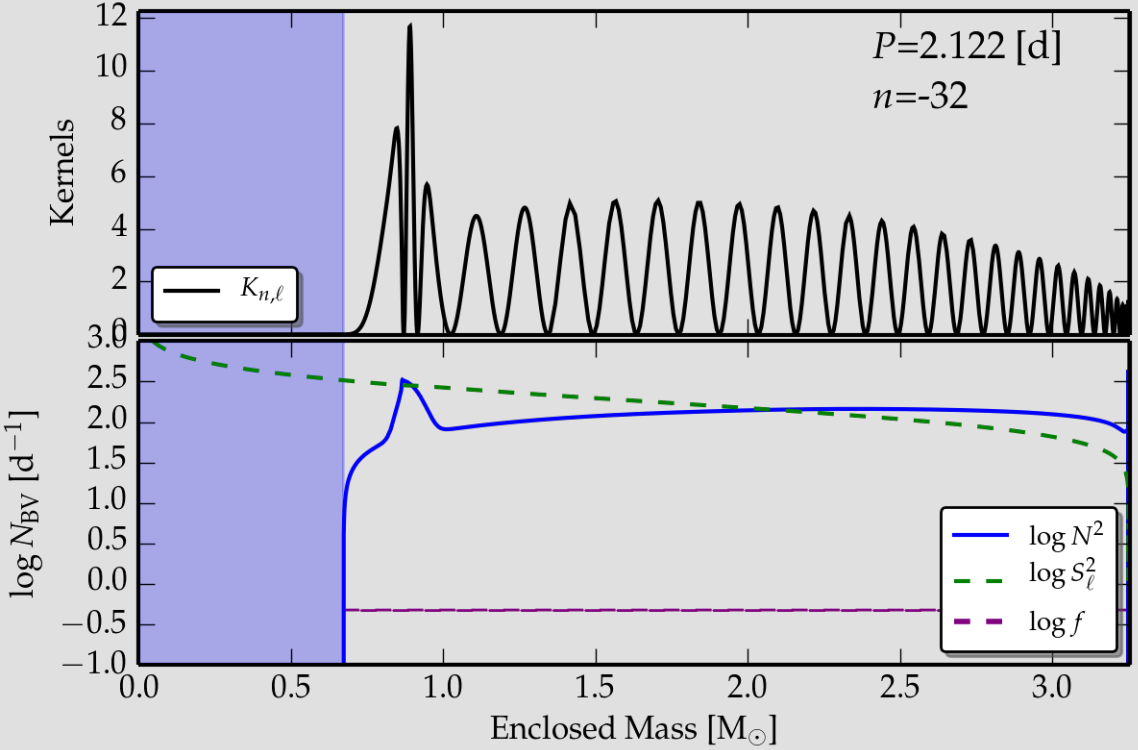
Kernels and Mode Trapping

- High-order g-modes get trapped in μ-gradient layer [1,2]
- Sizeable amplitude in the overshoot layer [2, 3]
- Unravel thermal and chemical stratification in the μ-gradient and overshoot layer [3, 4]

$$\int_0^\infty K_{n,\ell}\, dr = 1$$



[1] Aerts et al. (2010), [2] Dziembowski & Paymatnykh (1991), [3] Moravveji (2015, EAS conf. proc.), [4] Viallet et al. (2015)

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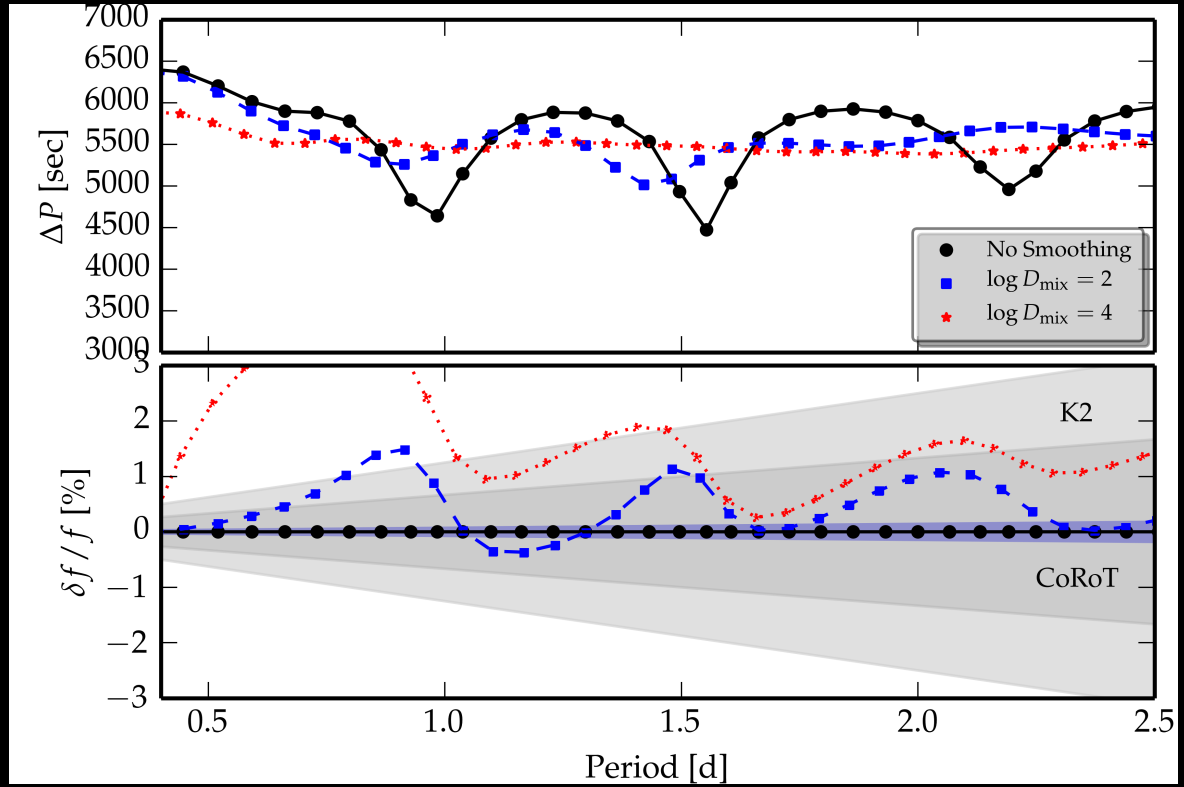
Mixing Signature in high-order gravity modes

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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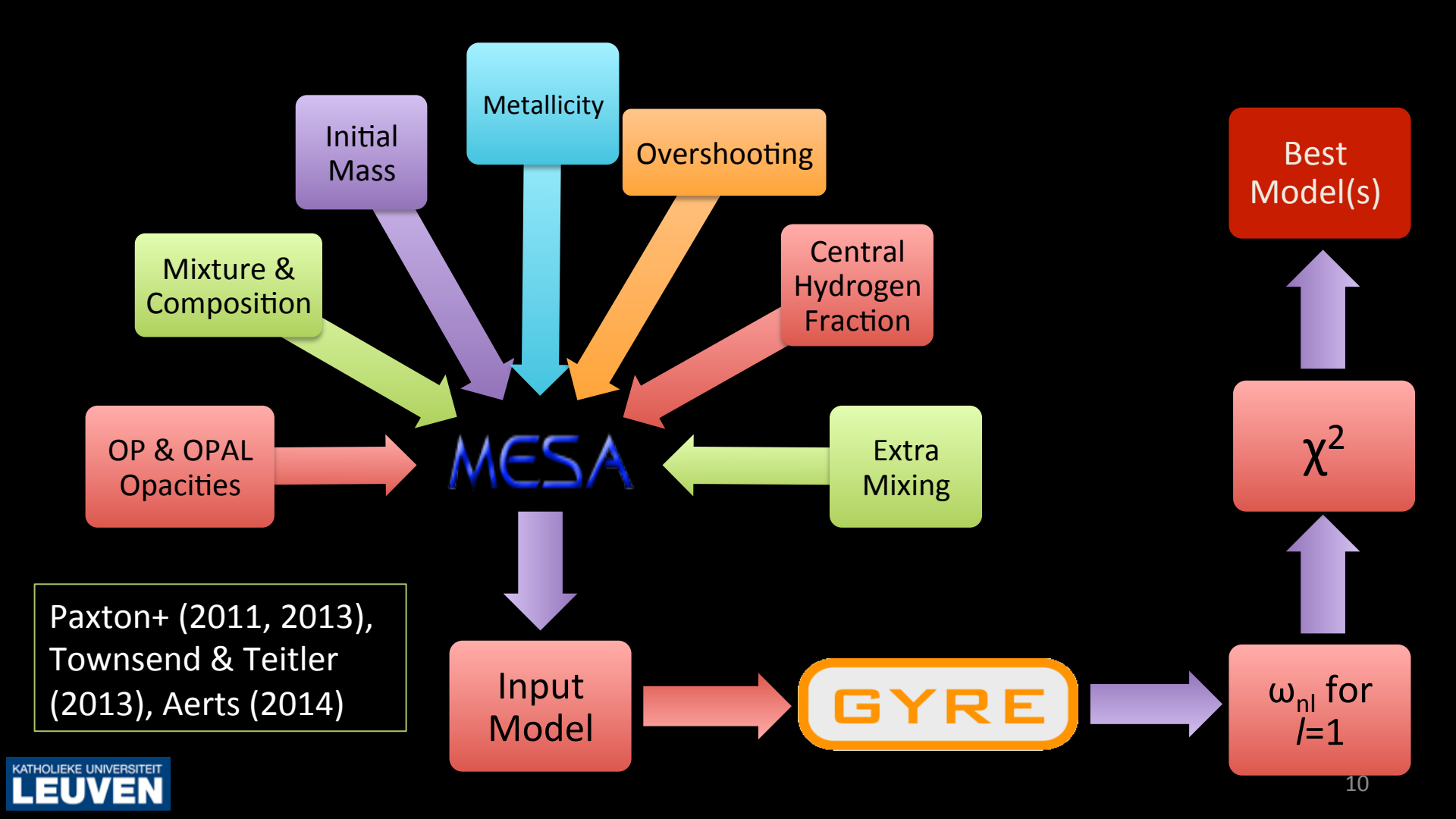
HOW TO DO IT?


Initial Mass
Metallicity
Overshooting
Mixture & Composition
Central Hydrogen Fraction
OP & OPAL Opacities
MESA
Extra Mixing
Best Model(s)
χ^2
Input Model
GYRE
ω_{nl} for l=1
Paxton+ (2011, 2013), Townsend & Teitler (2013), Aerts (2014)

$$\chi^2_{\text{red}} = \frac{1}{19 - 5} \sum_{i=1}^{19} \frac{(f_i^{(\text{obs})} - f_i^{(\text{mod})})^2}{\sigma_i^2}$$

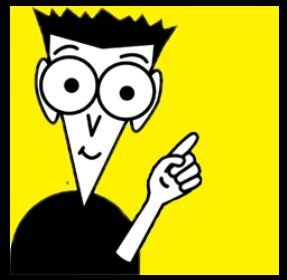
Observed Modes

- Mass
- Metallicity, Z
- Age, X_c
- Overshooting, f_{ov}
- Extra diffusive mixing D_{mix}

Best Model(s)

χ^2

ω_{nl} for l=1

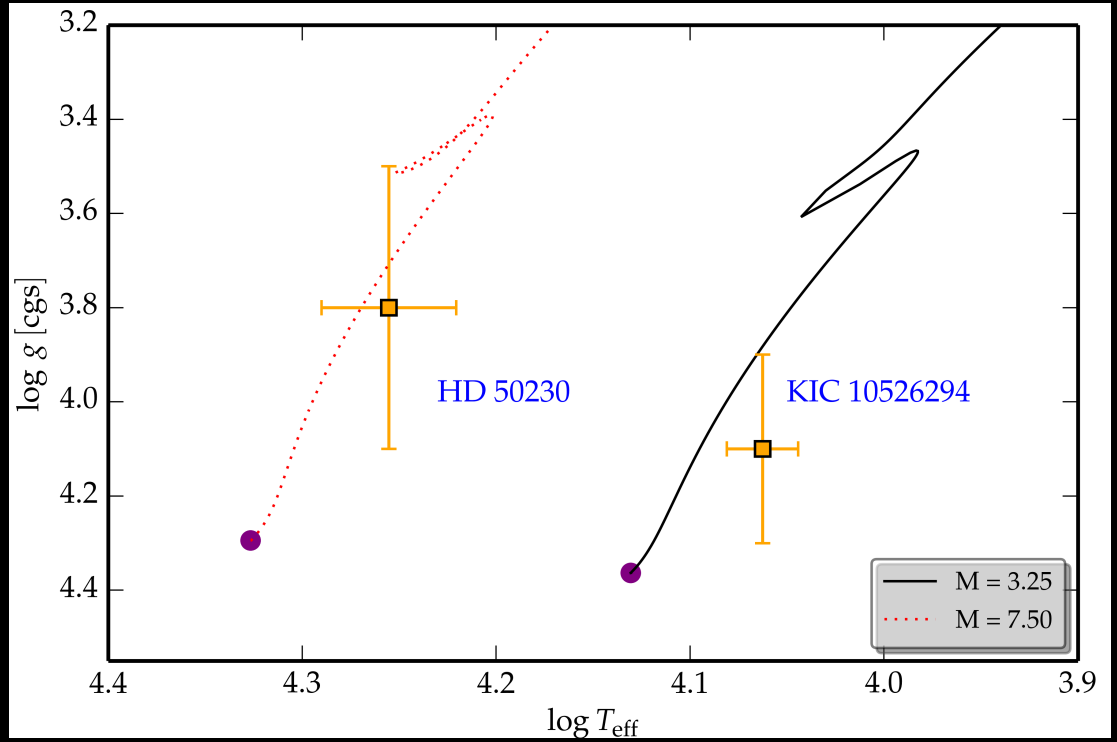


APPLICATIONS TO TWO STARS

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



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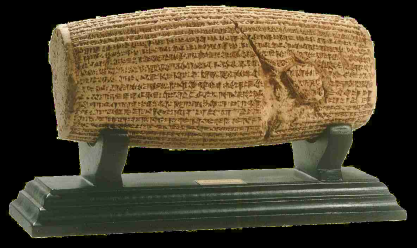
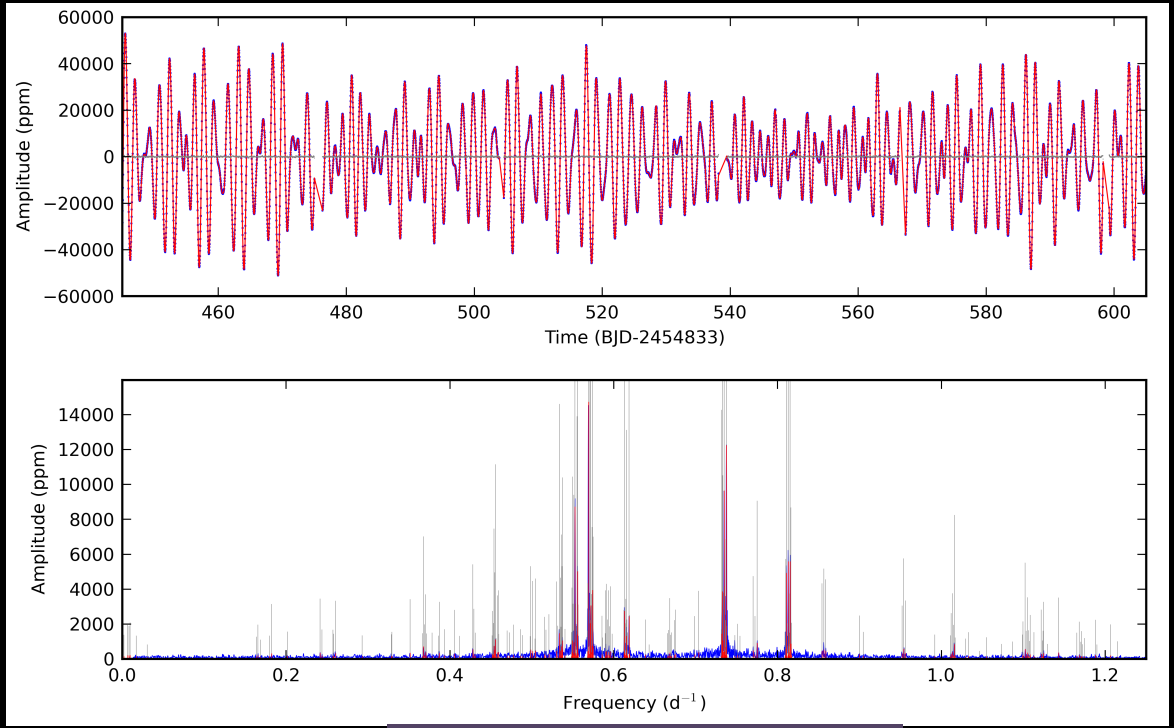
KIC 10526294



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!

See: Papics et al. (2014, A&A)
Moravveji et al. (2015, A&A)
Triana et al. (2015, ApJ)



See the talk by Santiago

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Observed Period Spacing

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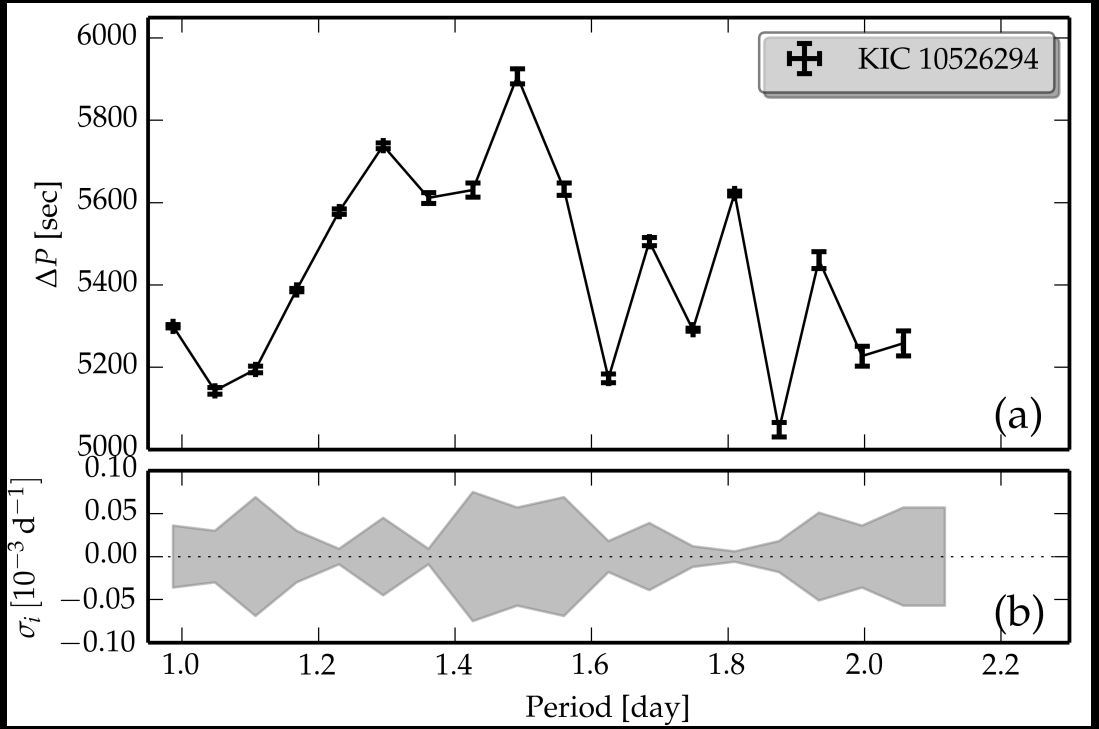

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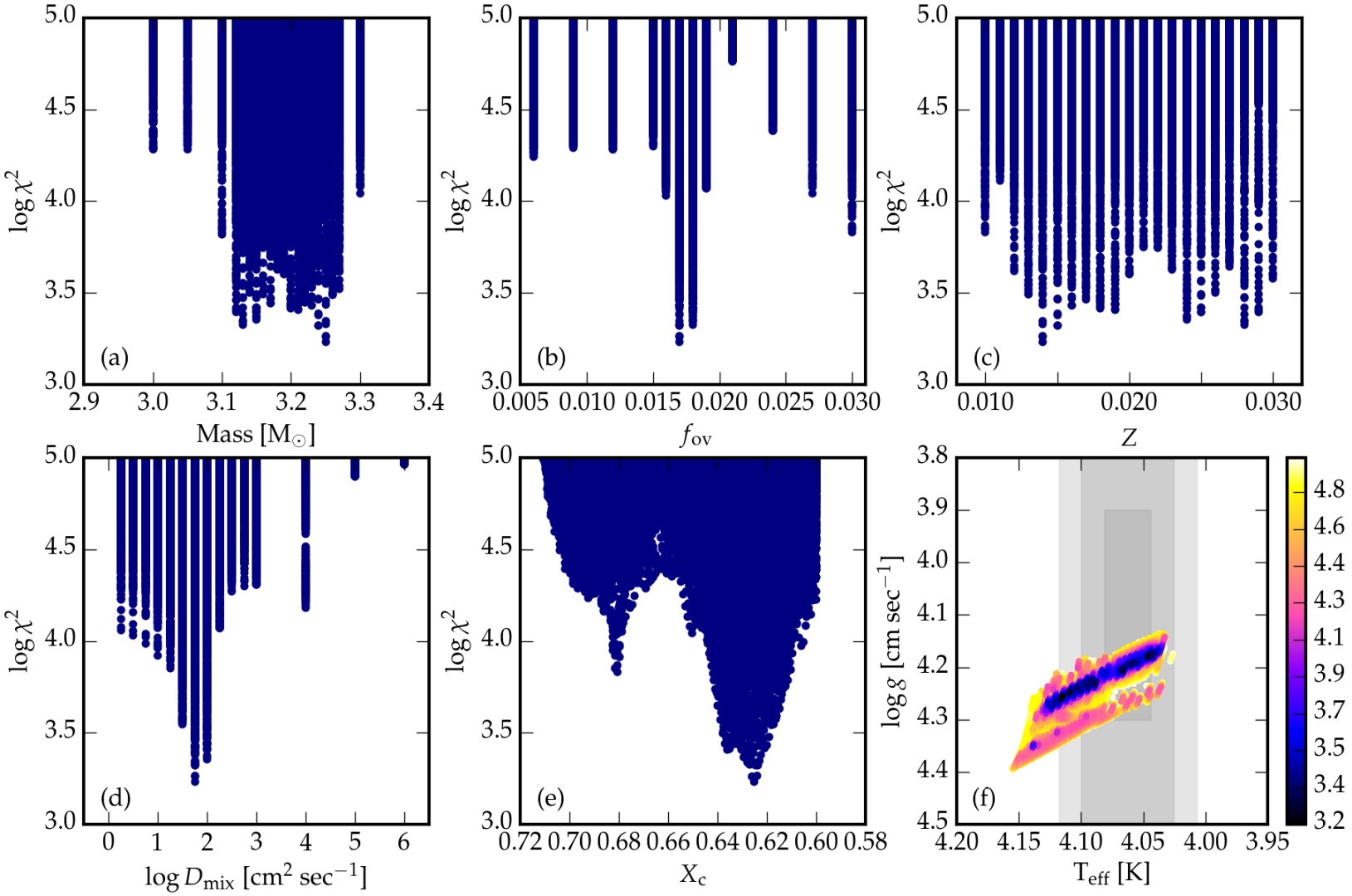

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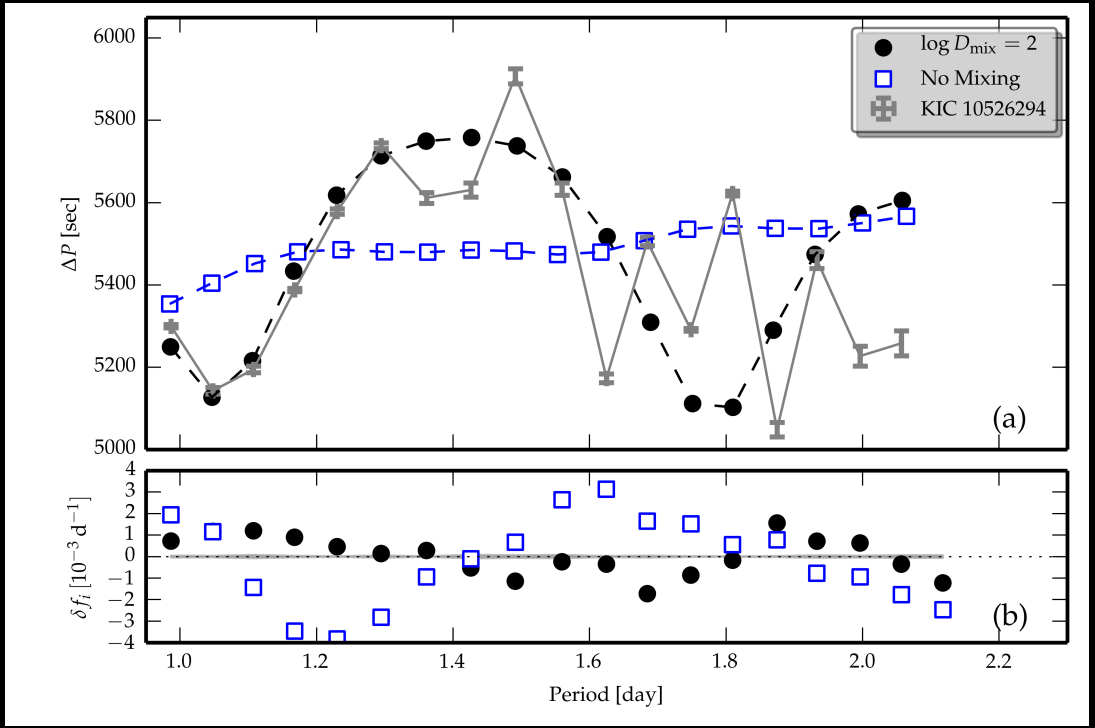
To Mix or Not to Mix?

KIC 10526294 (B8 V)
Test of extra mixing:
By using extra diffusive mixing, Chi-square improves by a factor of ~11.

Morevveji et al. (2015, A&A)



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Step vs. Exponential Overshoot

KIC 10526294 (B8 V)

Test of Overshoot prescription:

- Step-function overshoot
- Exponentially decaying

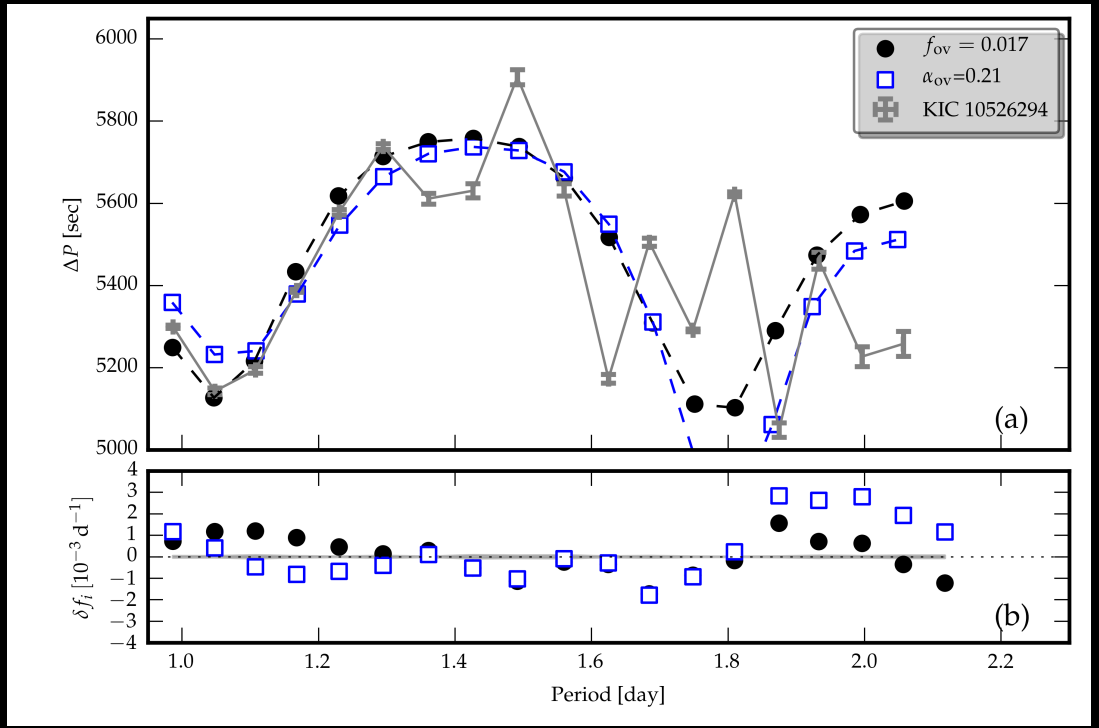
$$D_{\rm over} = D_{\rm conv}$$

OR

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

See: Morevveji et al. (2015)

Viallet et al. (2015, A&A)



$$\alpha_{\rm ov} \approx 10\, f_{\rm ov}$$

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HD 50230 (B3 V)

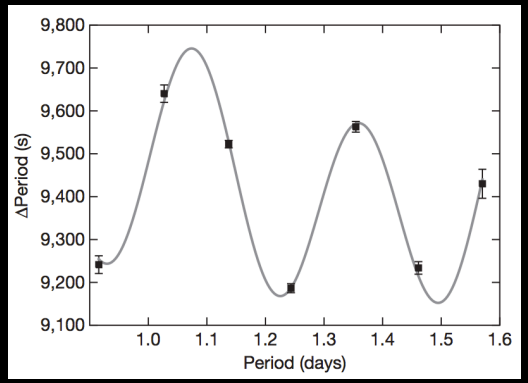
T_{eff} = 18 000 ± 1500 K

log g = 3.8 ± 0.3 dex

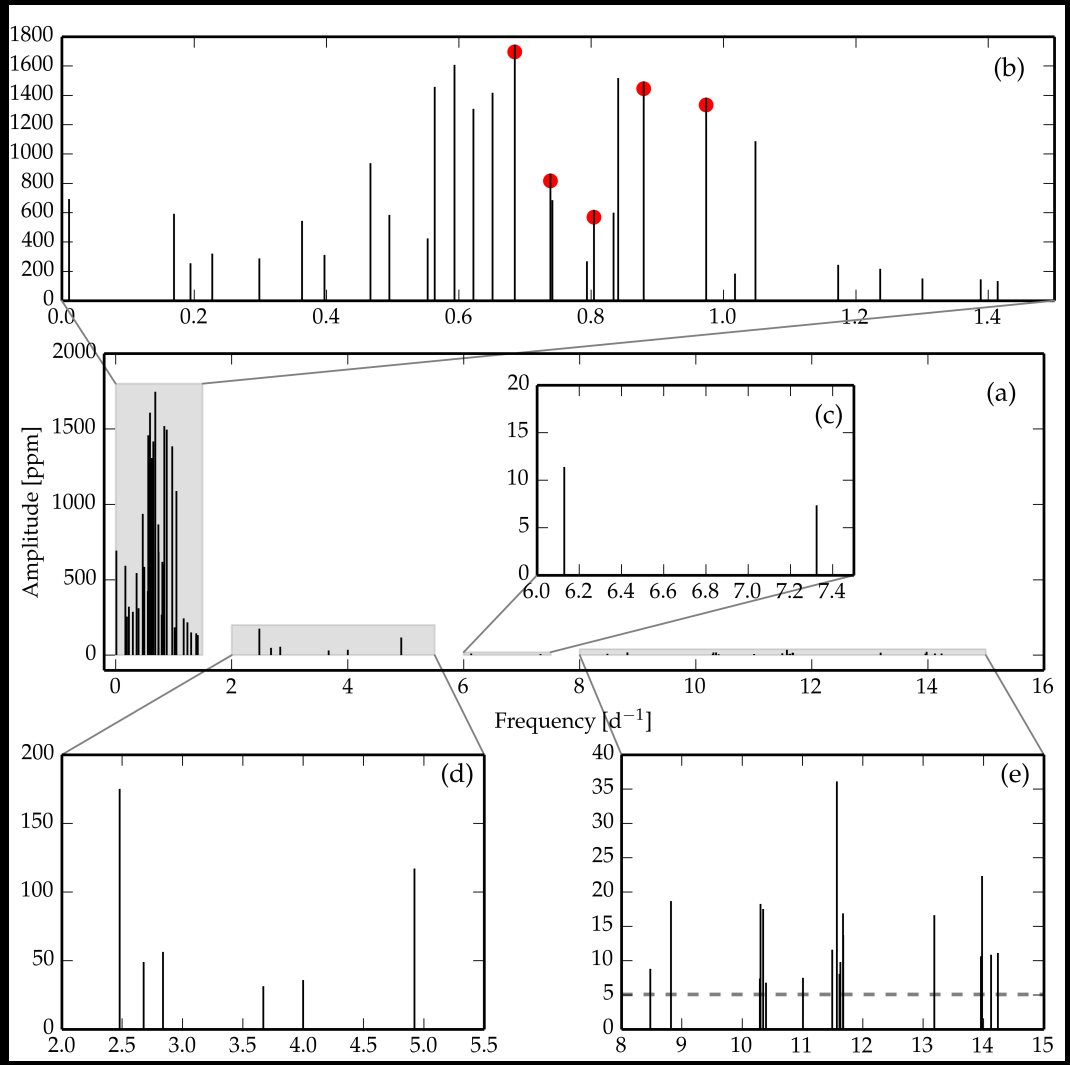
V sin i ≈ 6 km sec^{-1}

T_{CoRoT} = 137 days

5 consecutive dipole g-modes + a lot of low-order p-modes



See: Degroote et al. (2010, Nature, 2012); Moravveji & Aerts (2015, in prep.)



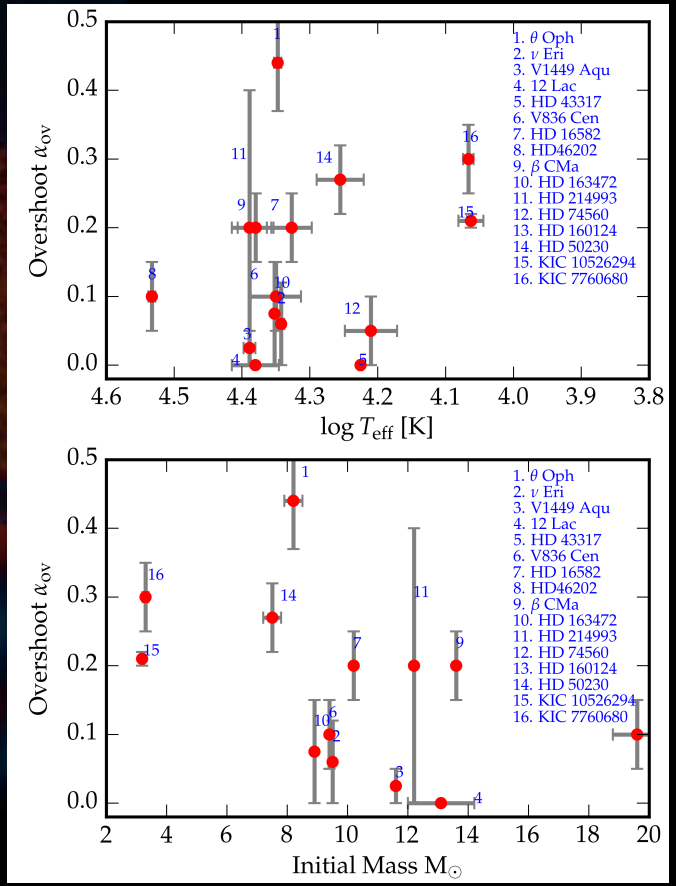
ASTEROSEISMOLOGY AND DEEP MIXING

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

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

c) General picture is forming [1] … Many B-stars with K2 in near future

d) Extra Mixing [10^2 – 10^4 cm^2 sec^{-1}] is essential, even for non-rotating stars



[1] Aerts (2013)

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