Massive Star Asteroseismology

Ehsan Moravveji

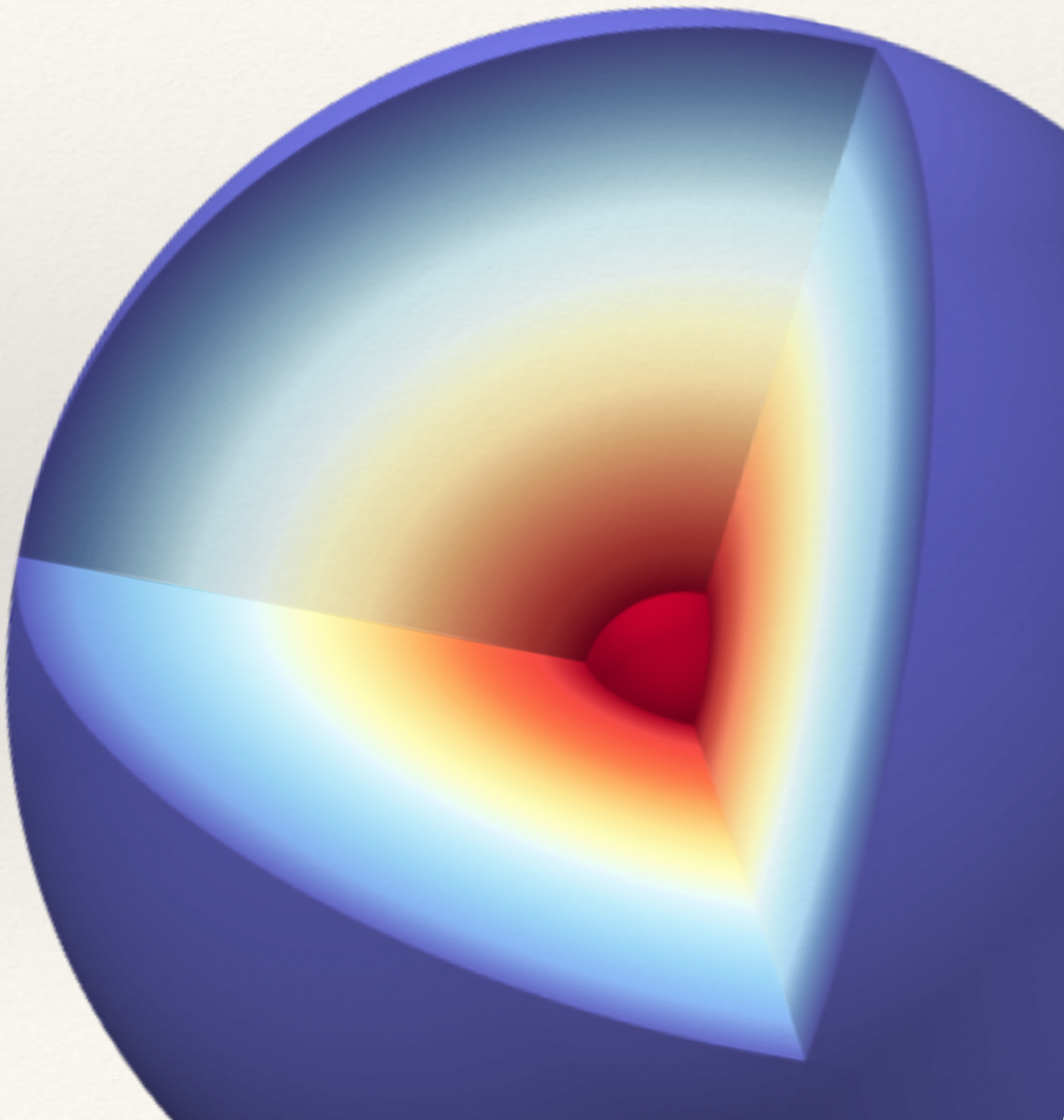
Now: Marie Curie Fellow (KU Leuven)

Soon: Joining BinCosmos (Amsterdam)

SEVENTH FRAMEWORK PROGRAMME

KATHOLIEKE UNIVERSITEIT LEUVEN

Waves Probe the Interior



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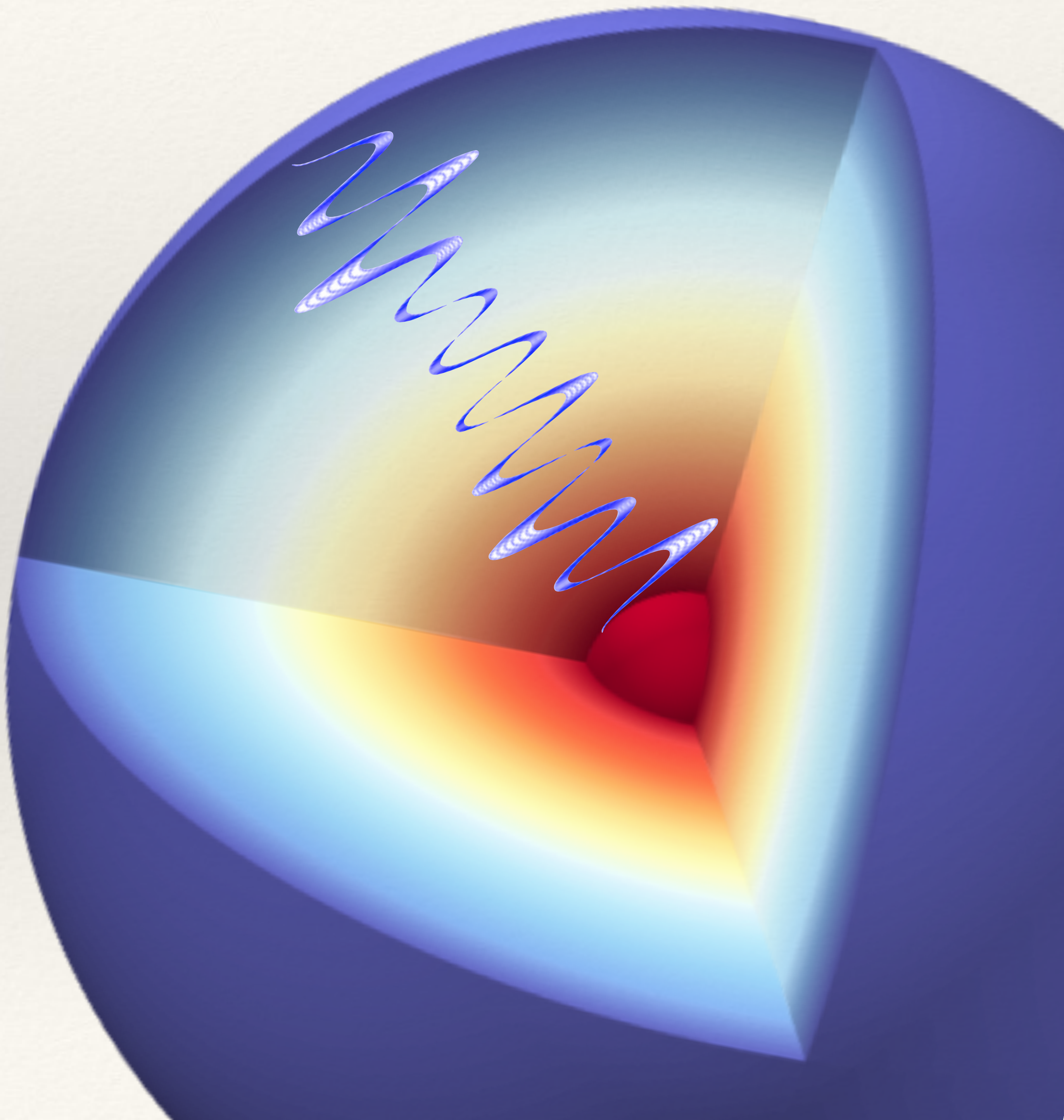
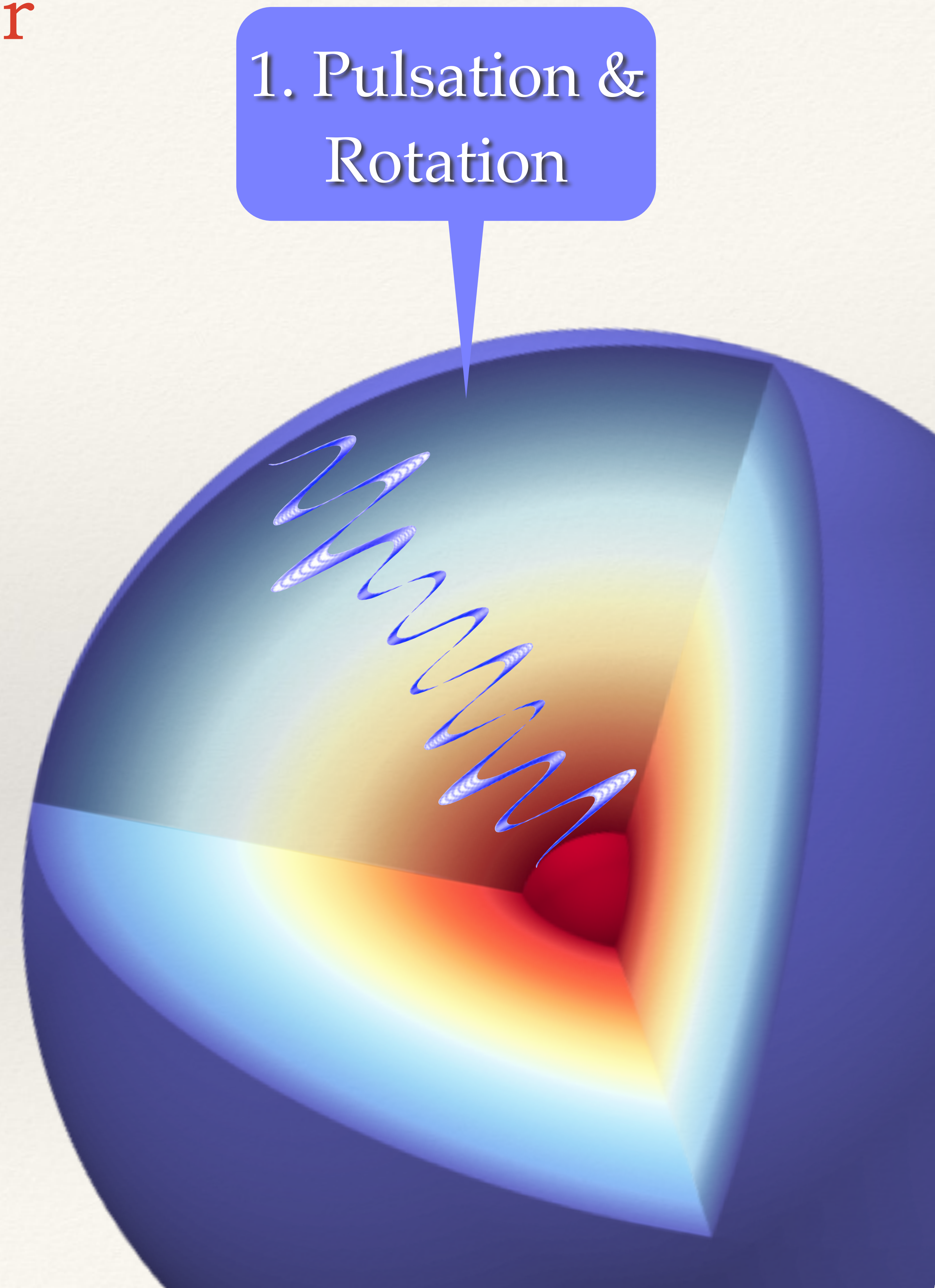
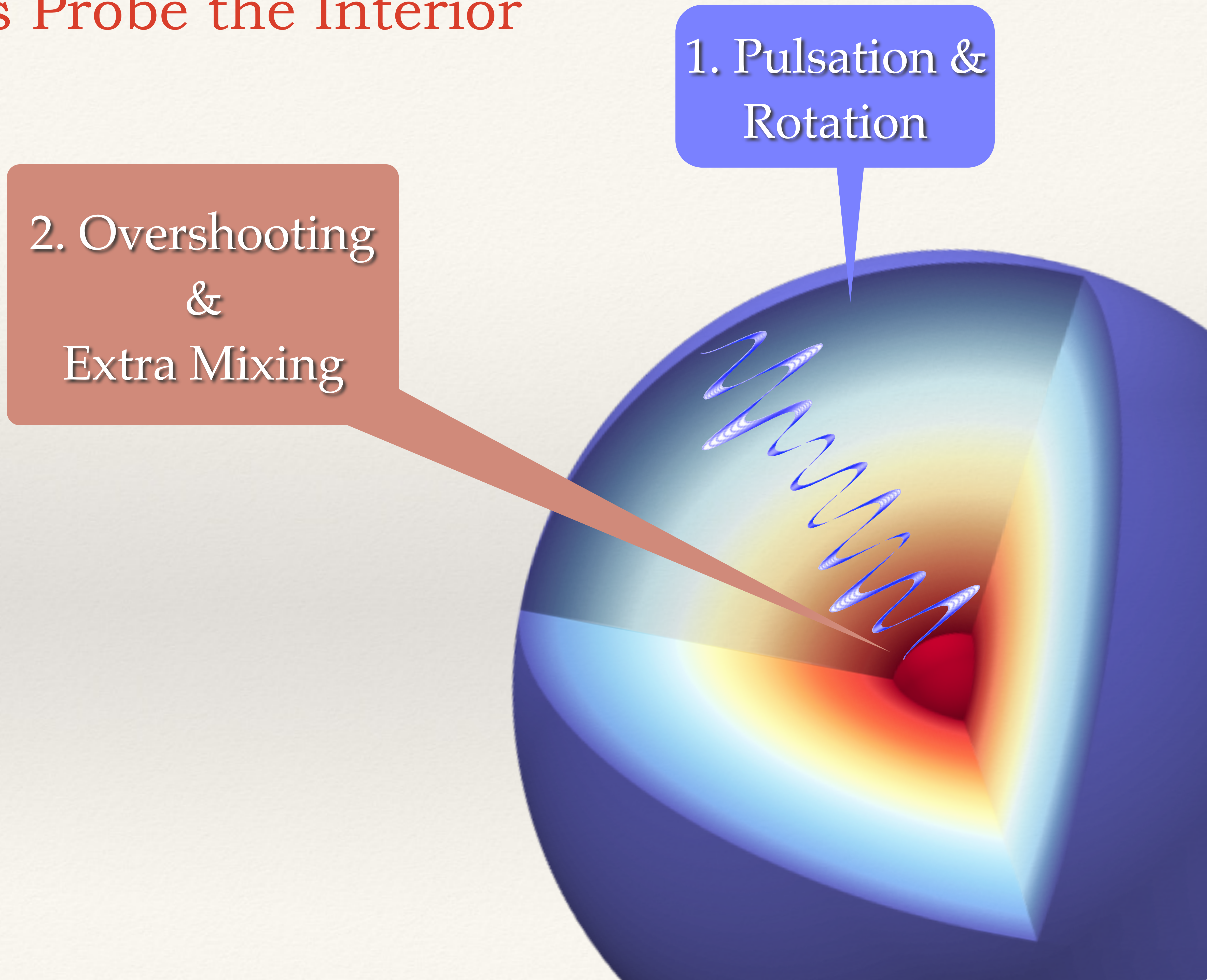


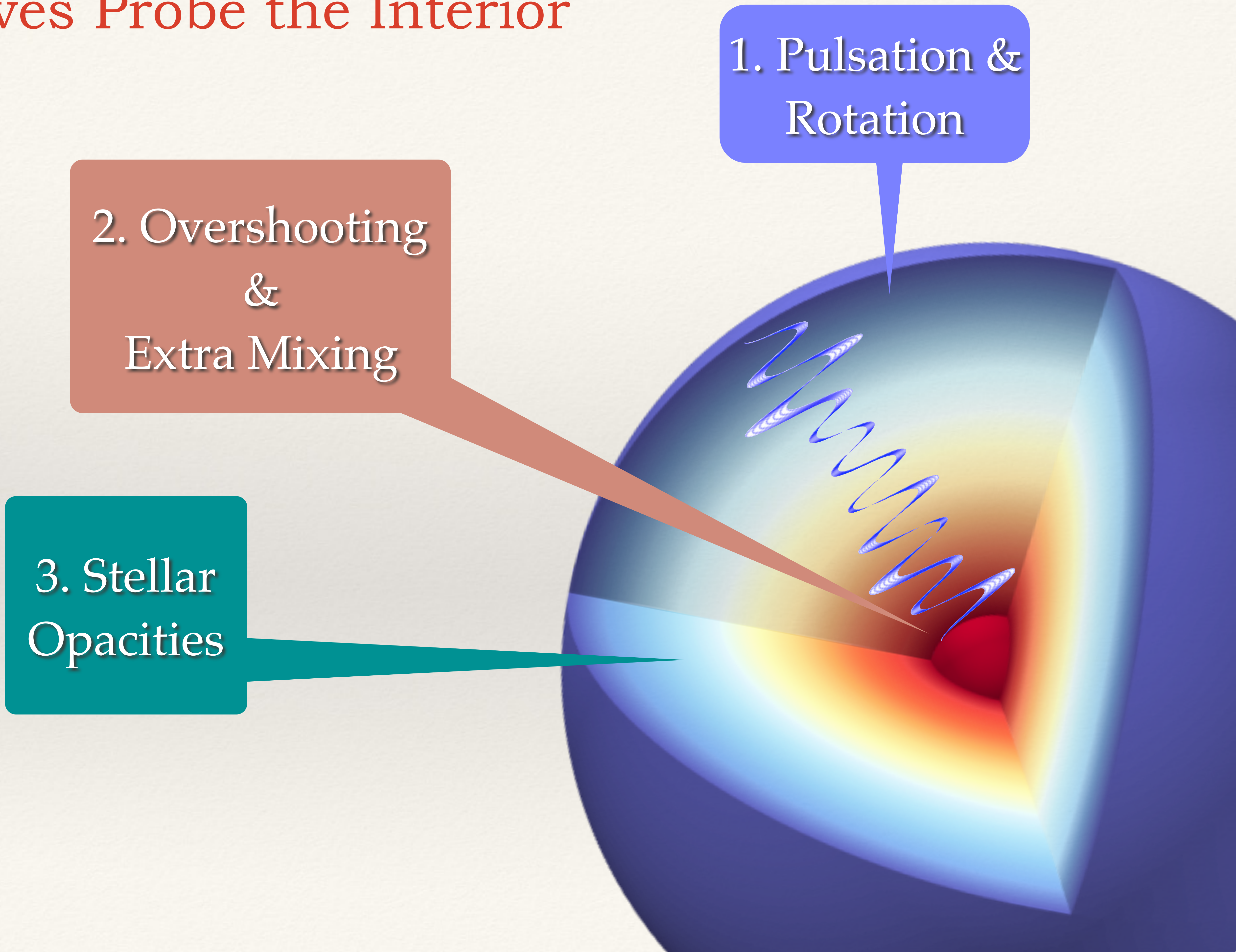
Waves Probe the Interior



Waves Probe the Interior

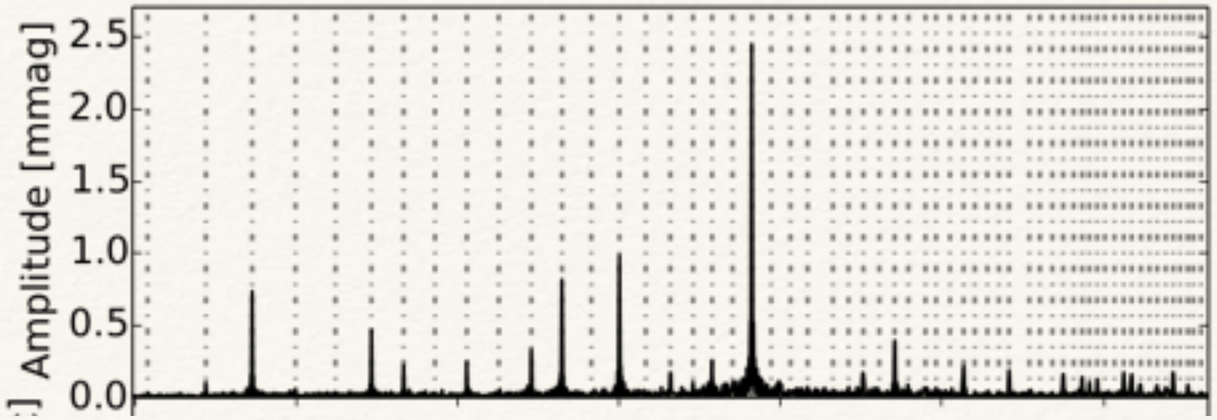


Waves Probe the Interior

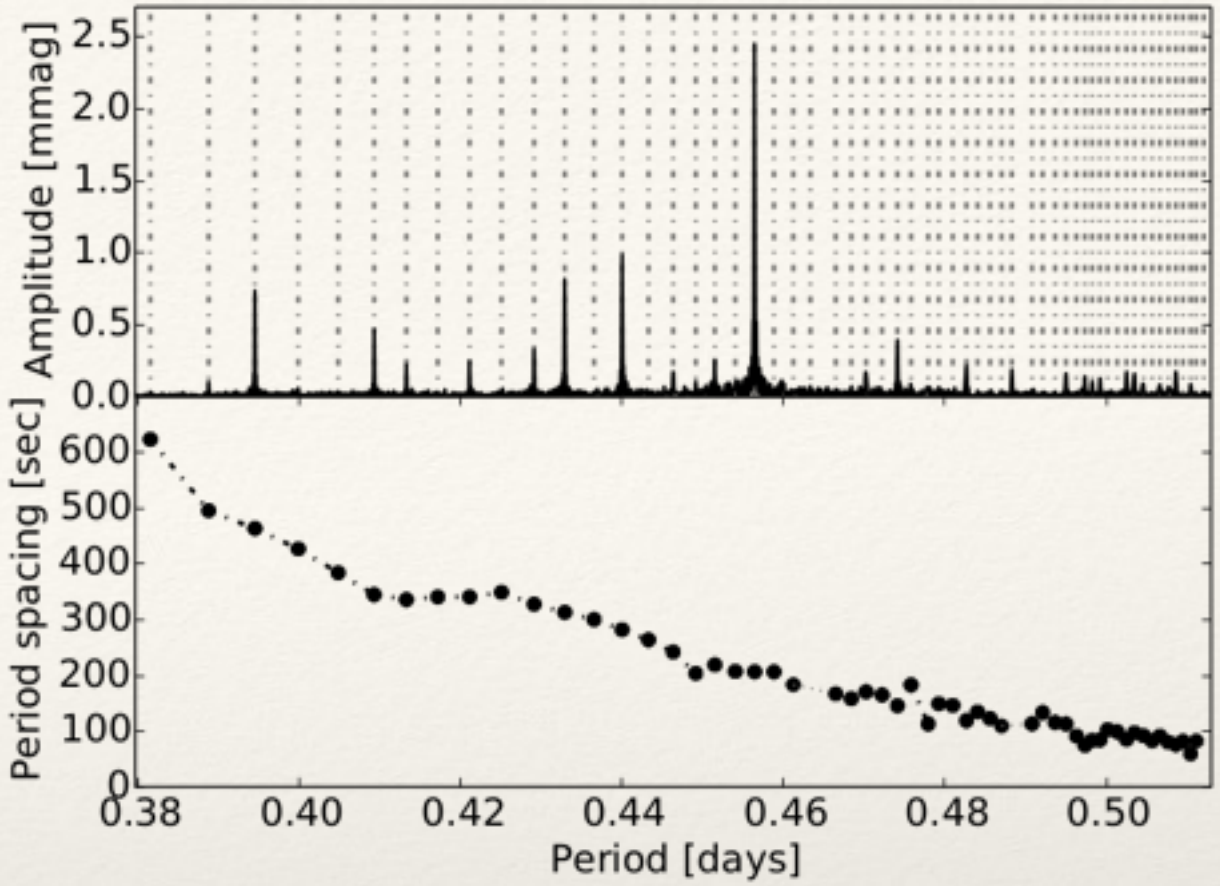


Part I:
Pulsations and AM Transport

Period Spacing

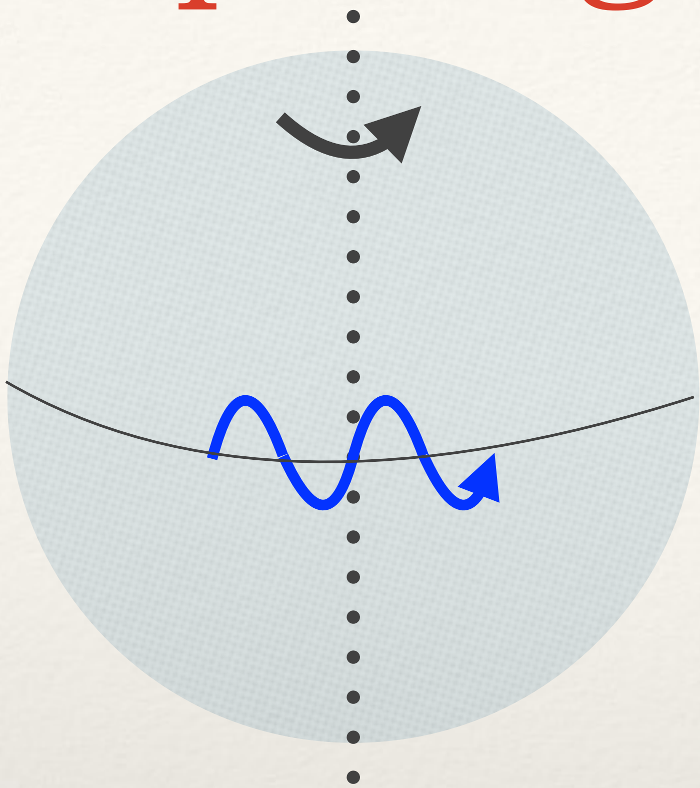


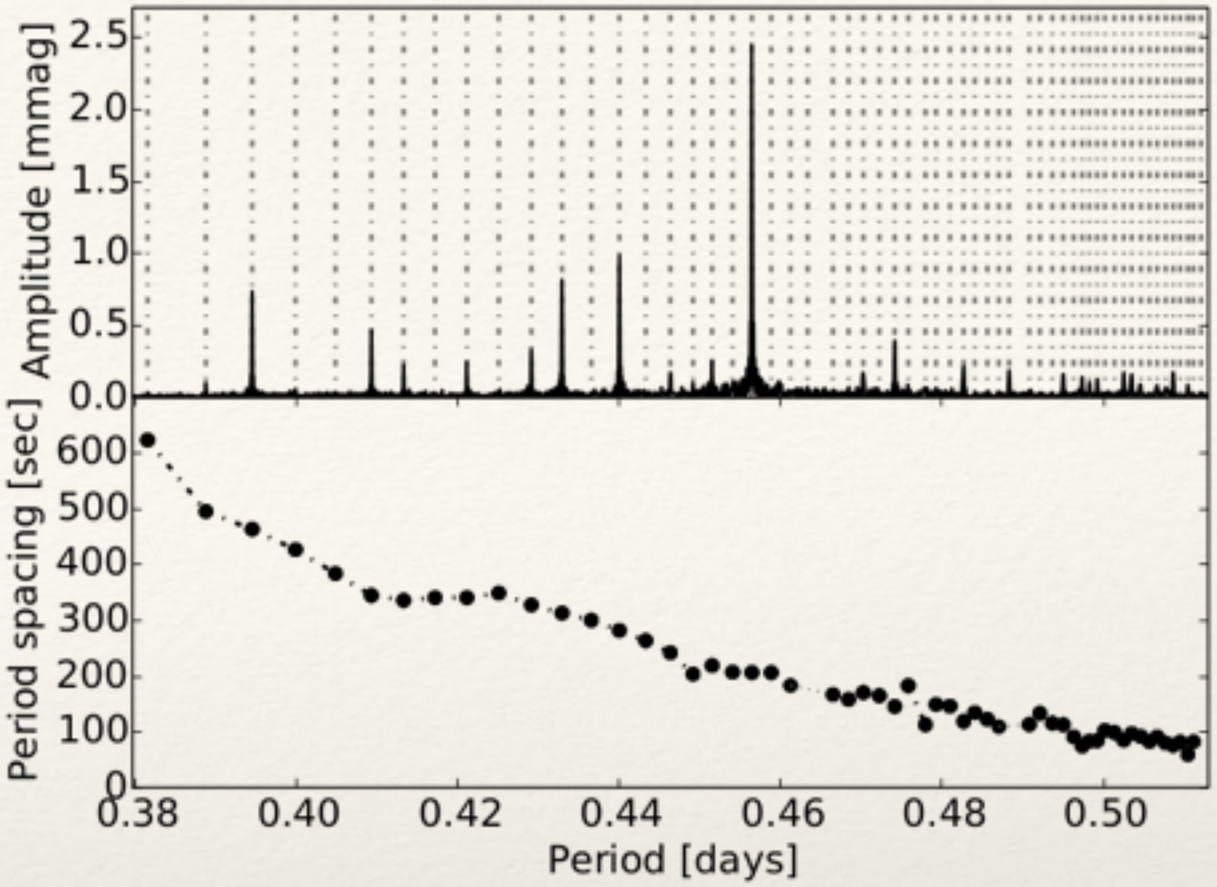
Period Spacing



Period Spacing

Prograde

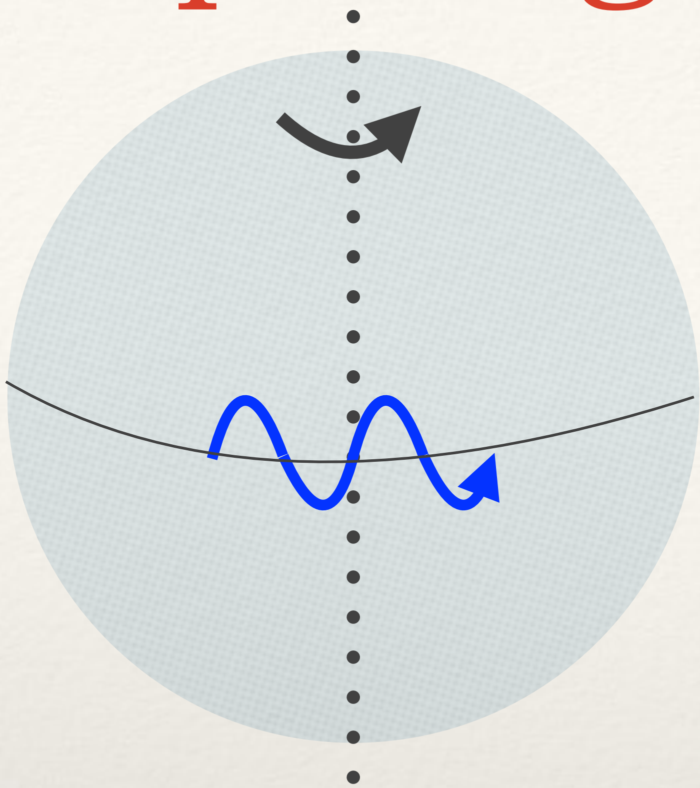




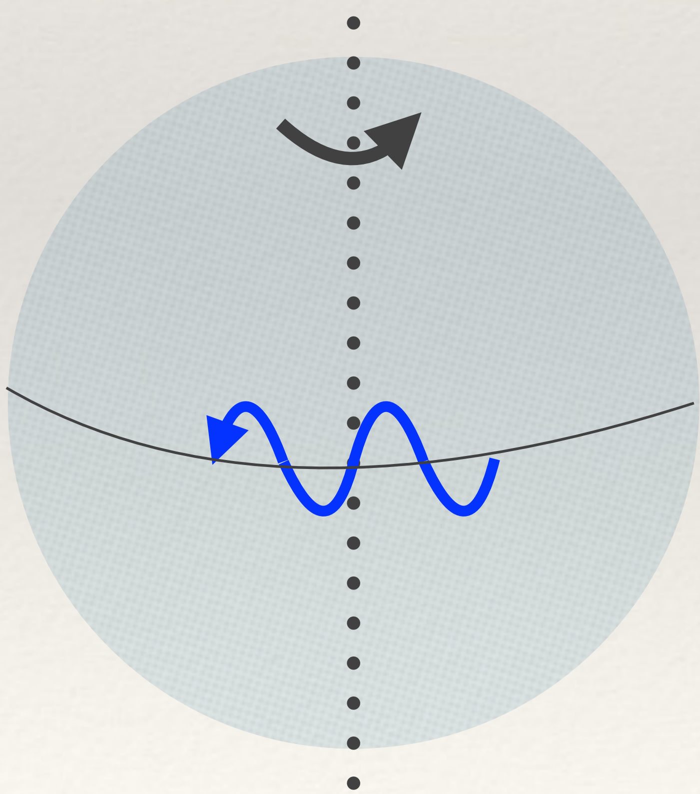
Van Reeth et al. (2015a, 2015b, 2016)

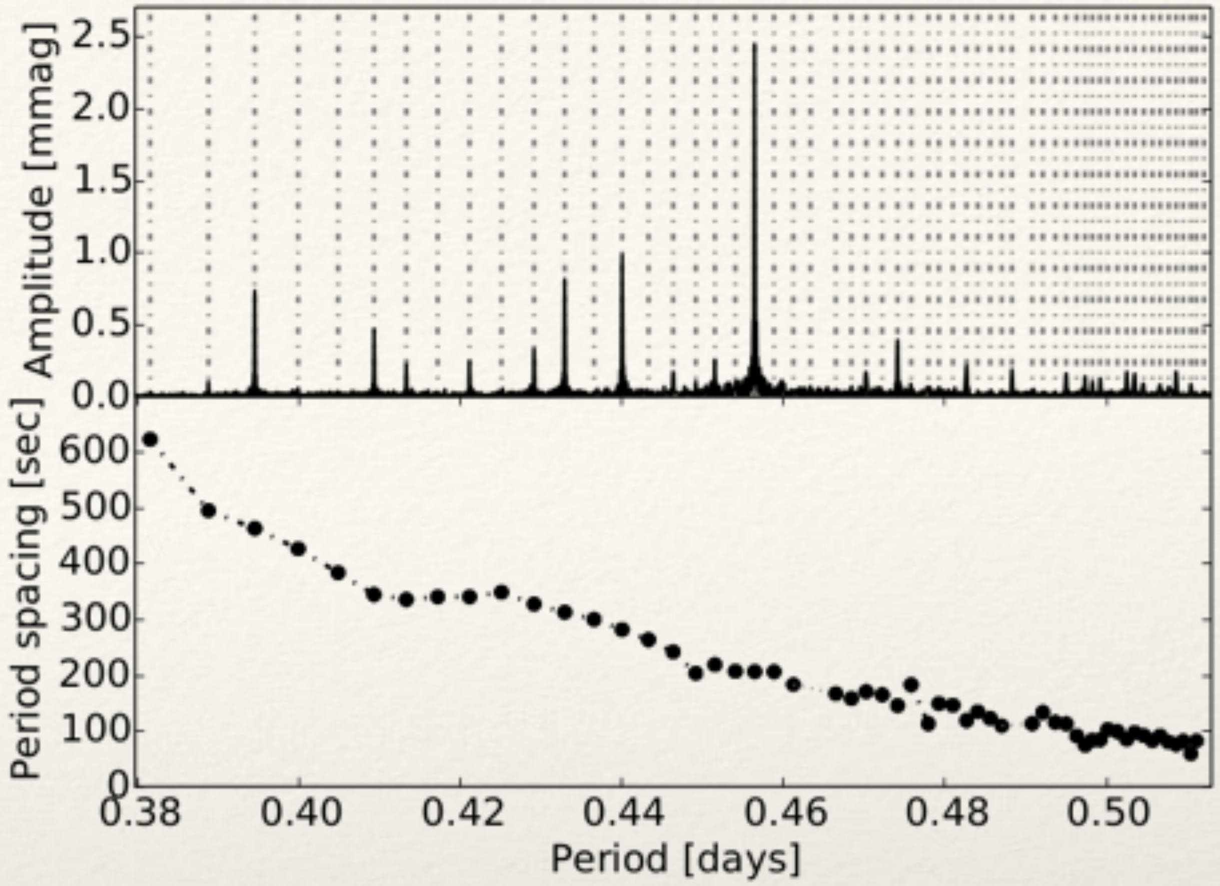
Period Spacing

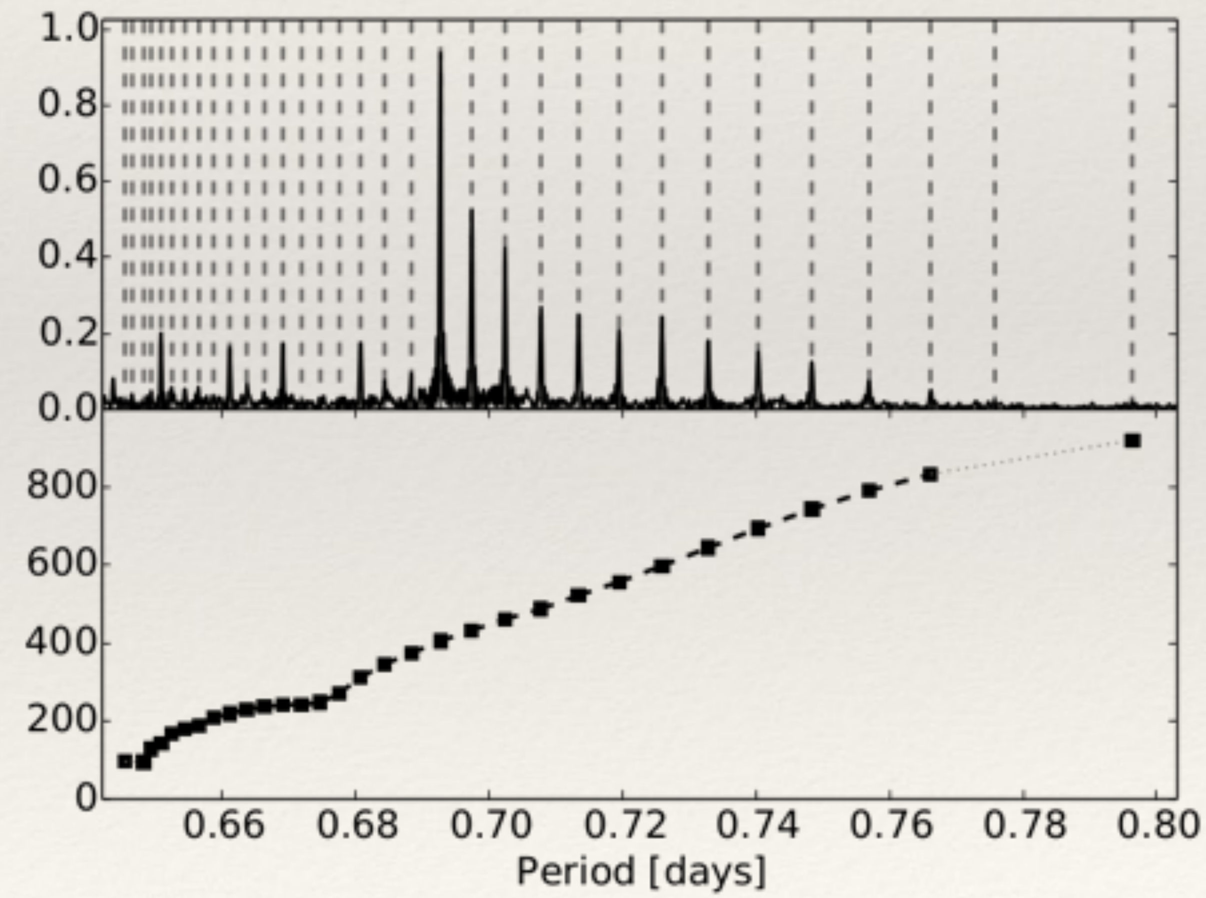
Prograde



Retrograde



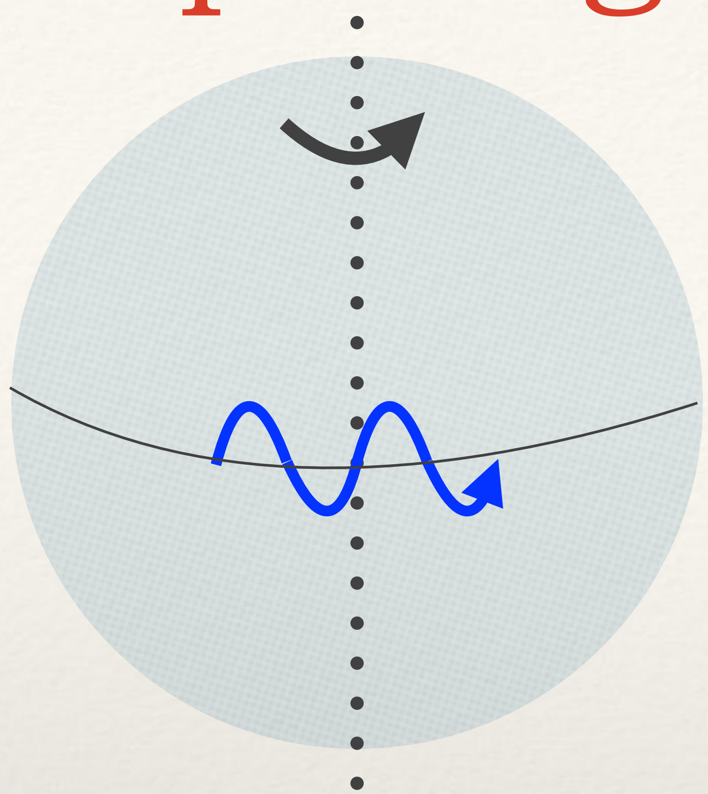




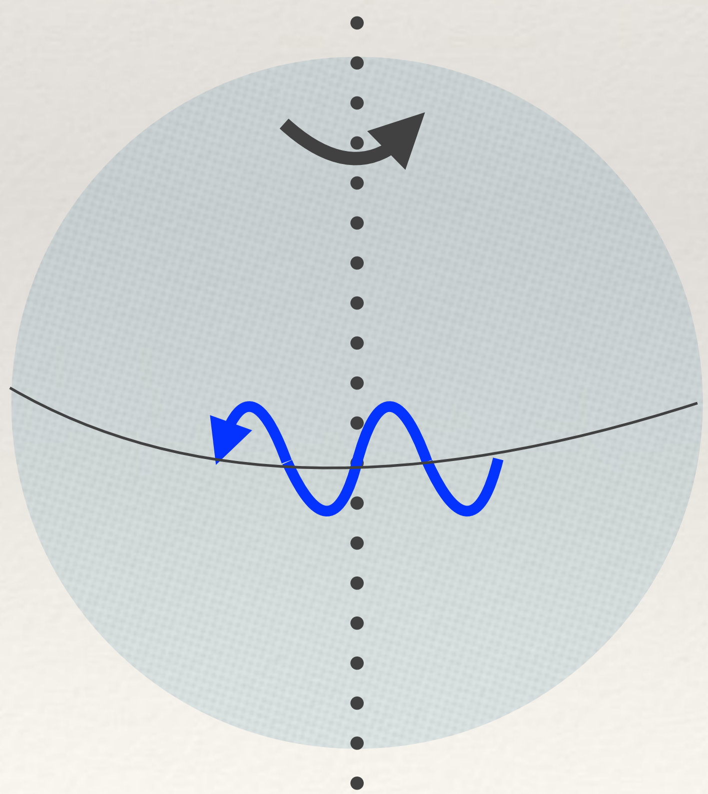
Van Reeth et al. (2015a, 2015b, 2016)

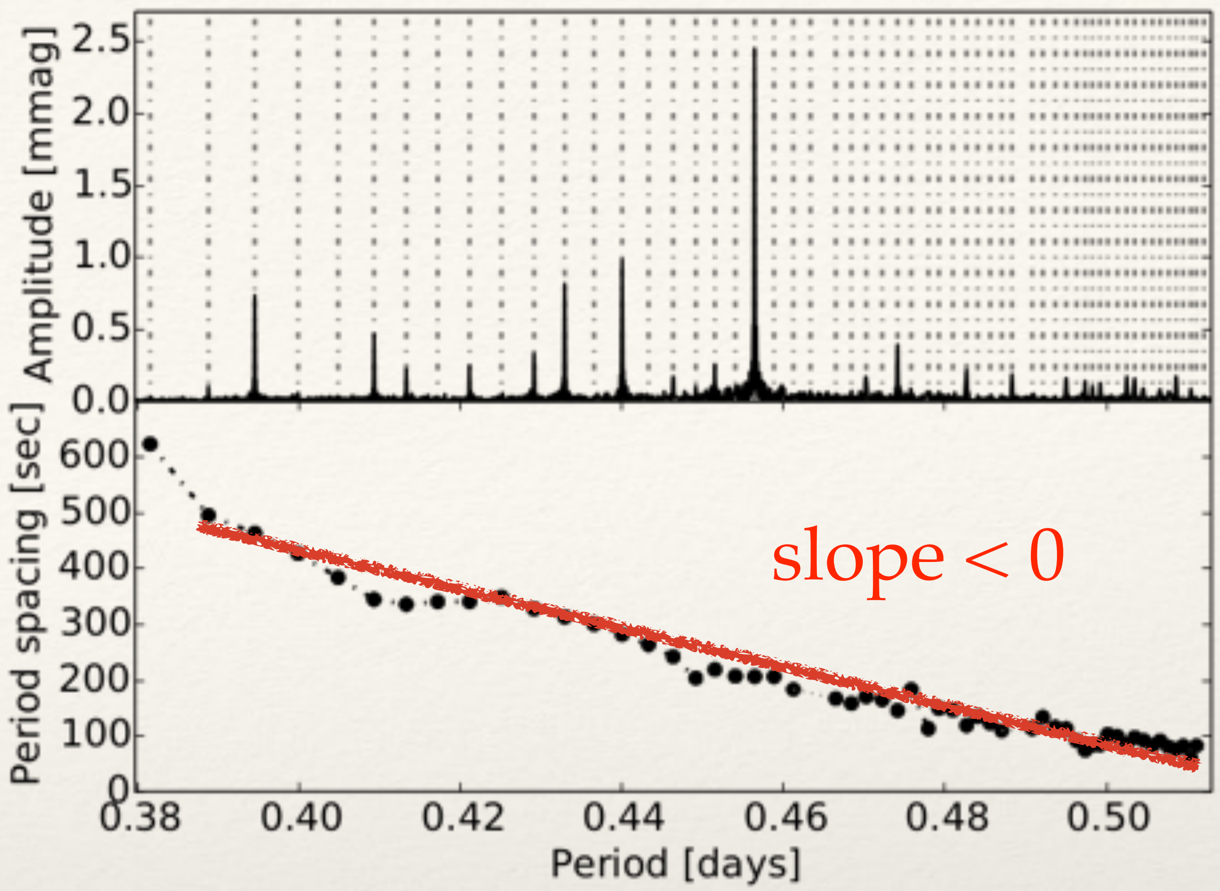
Period Spacing

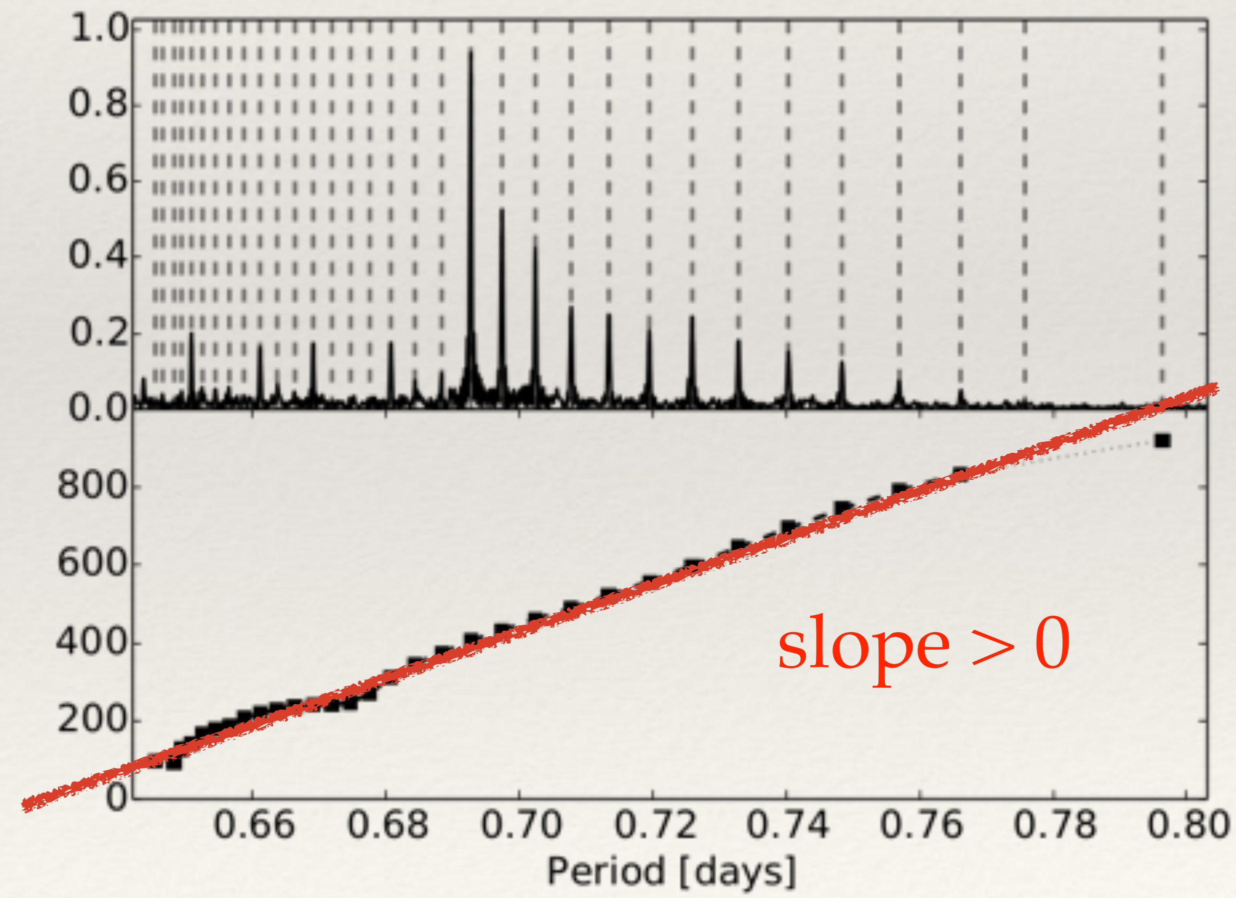
Prograde



Retrograde

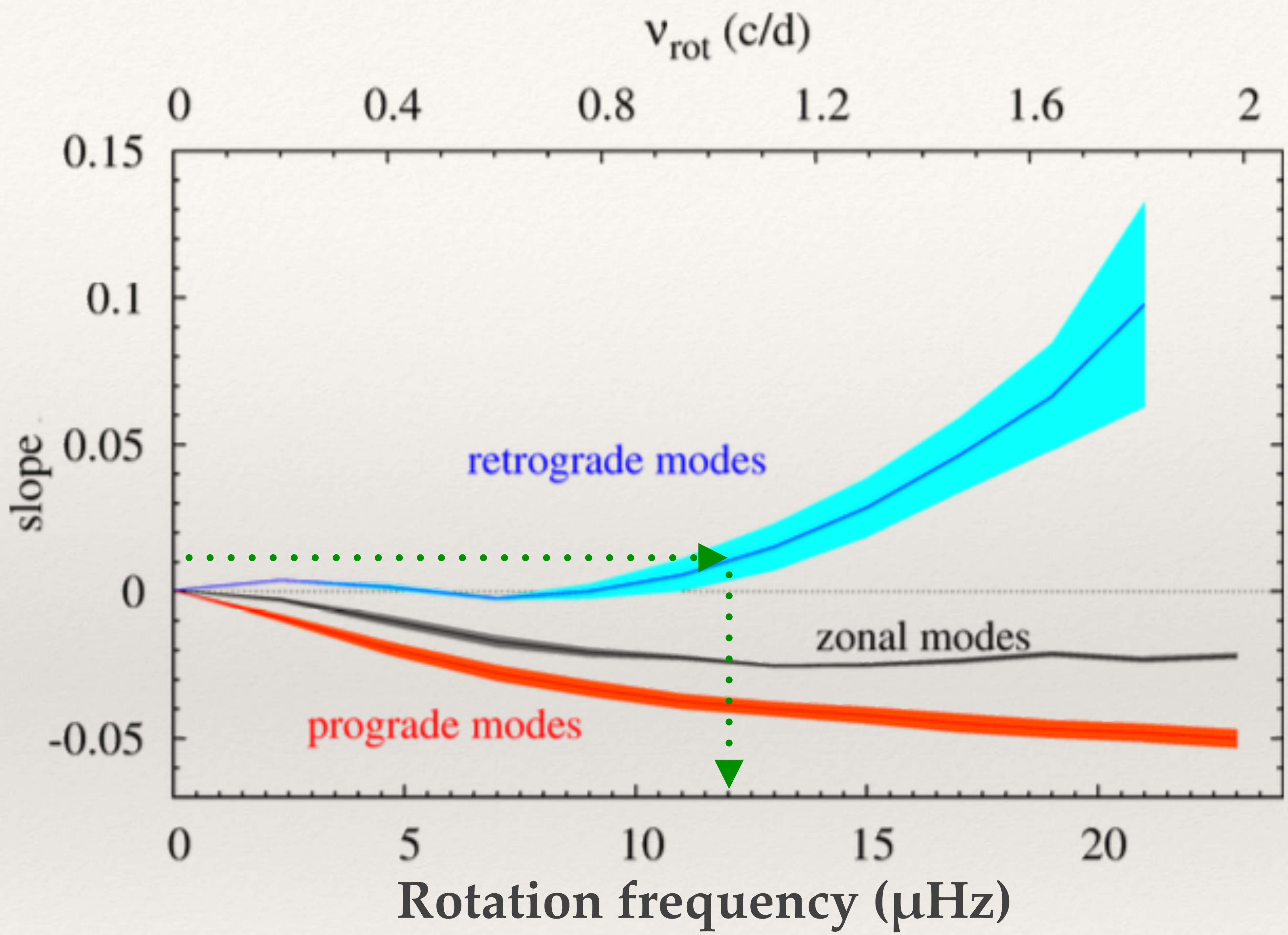






Van Reeth et al. (2015a, 2015b, 2016)

Measuring Rotation Frequency



Ouazzani+(2017), Prat+(2015, 2017)

☞ See the talk by Daniel Reese

AM Transport by Waves

Sub-surface mean-flow by:
- IGW
- p- and g-modes

Prograde: **extract** AM locally, when excited.
Retrograde: **deposit** AM locally, when excited.

AM Transport by Waves

Sub-surface mean-flow by:
- IGW
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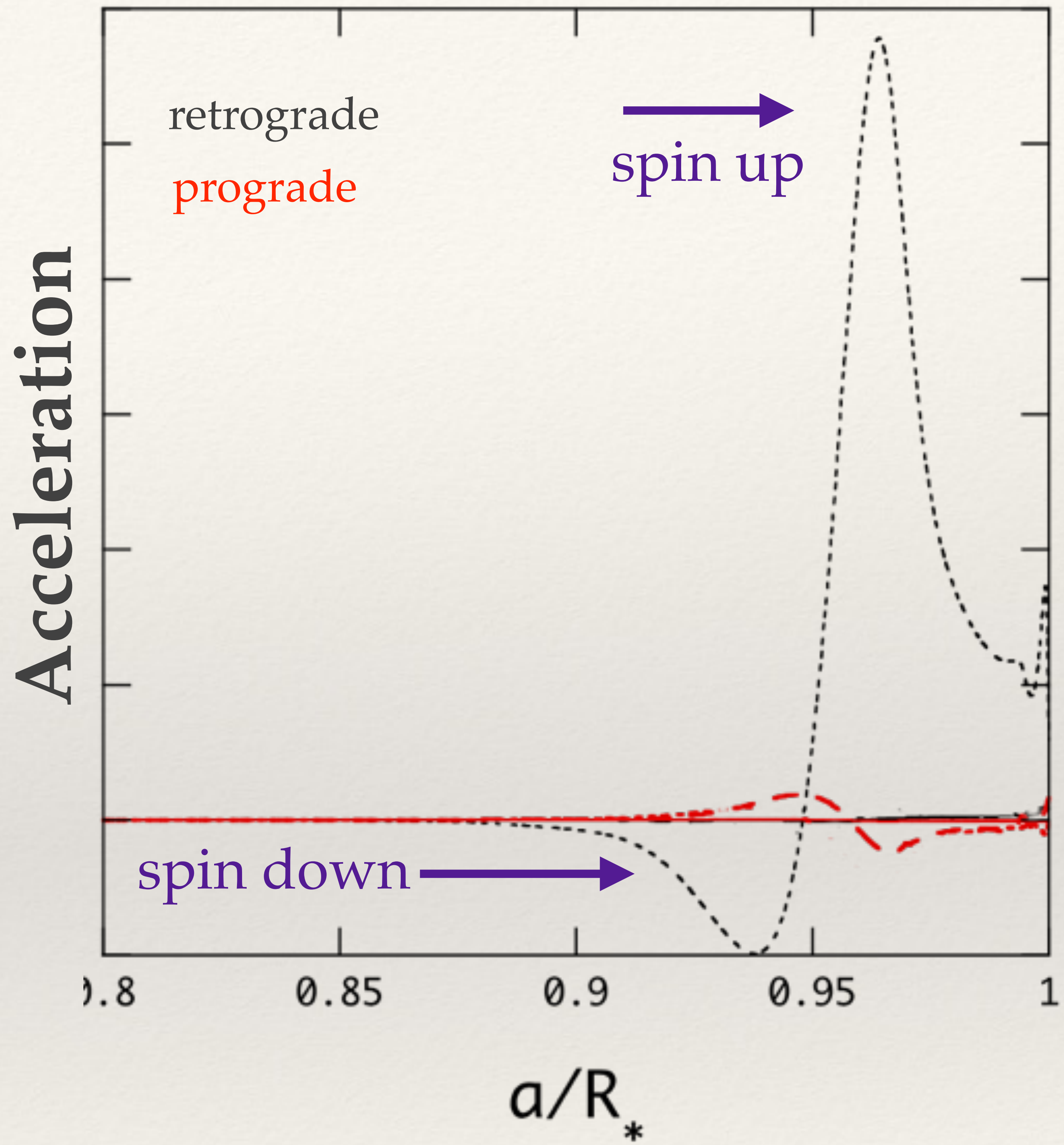
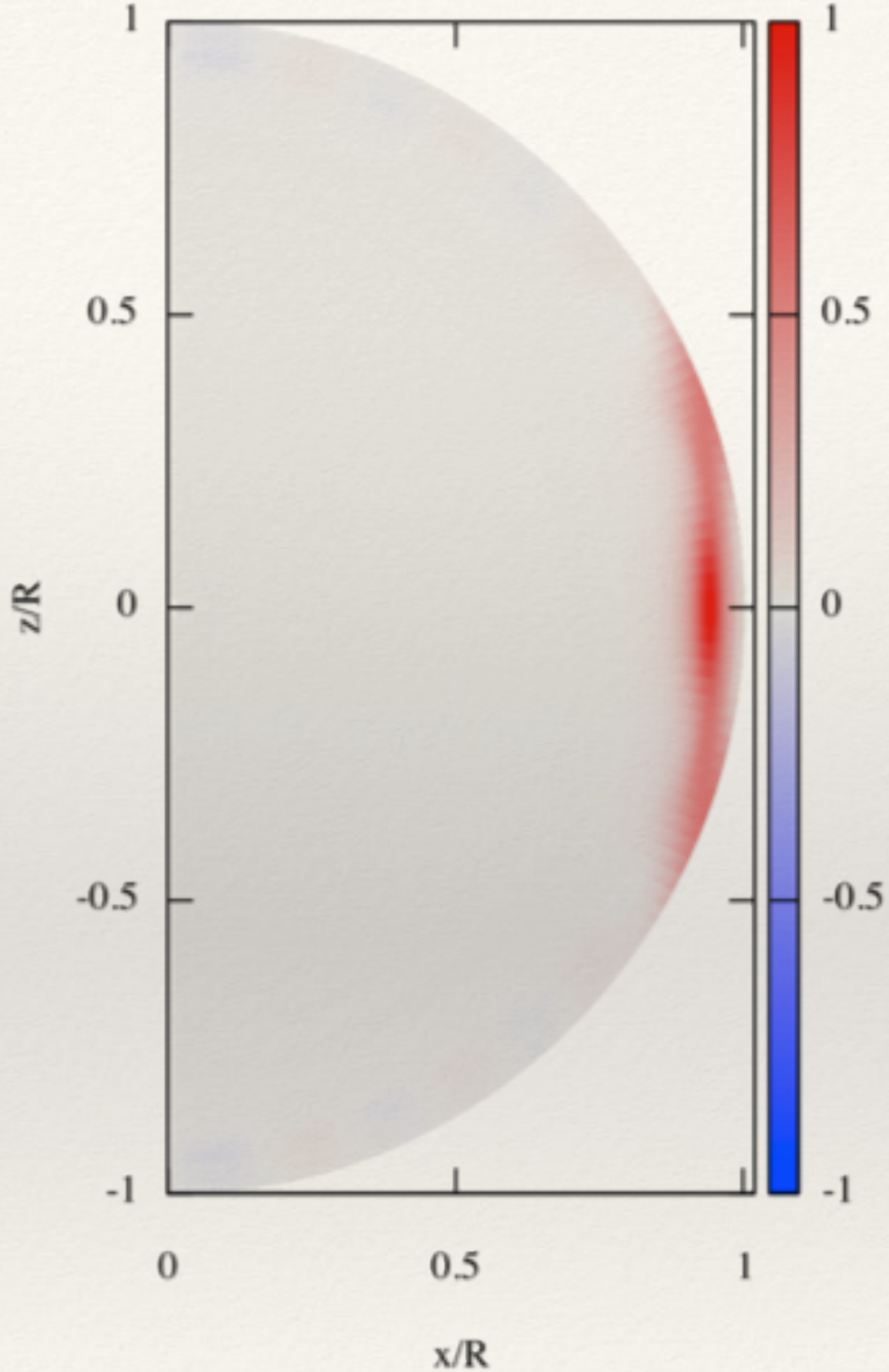


Lee, Neiner & Mathis (2014, 2016)
☞ see the talk by Tami Rogers

AM Transport by Waves



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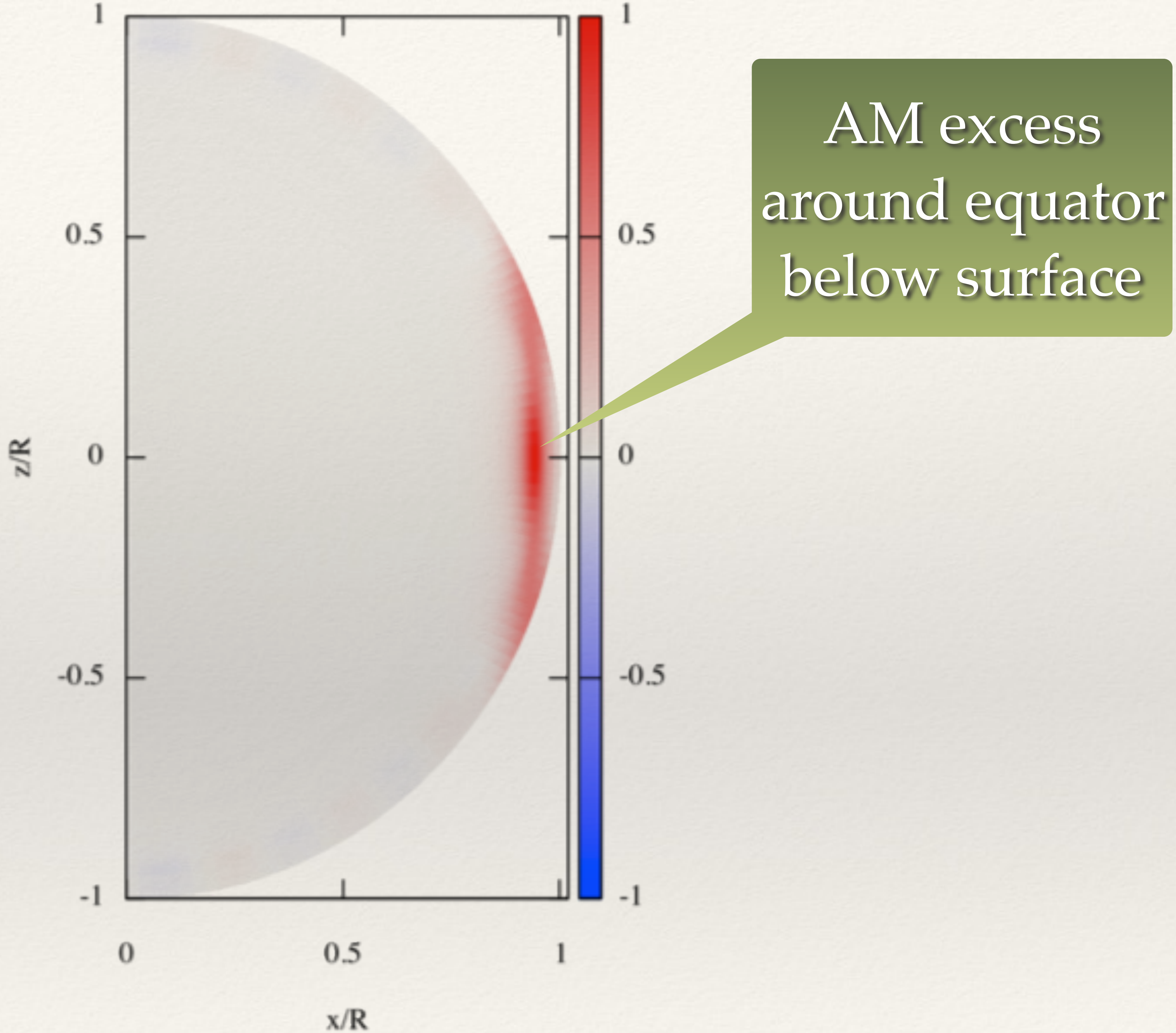
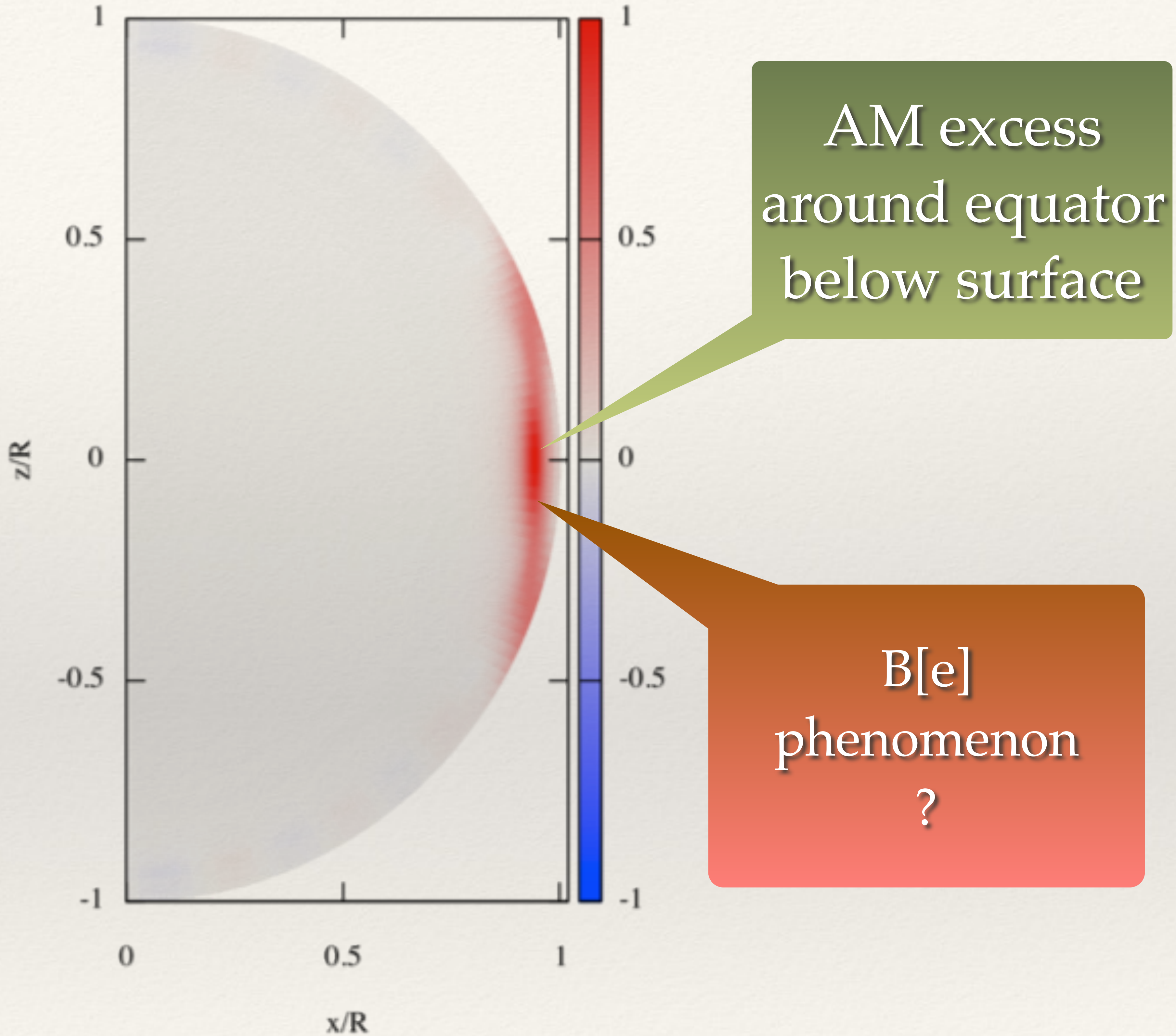
AM Transport by Waves



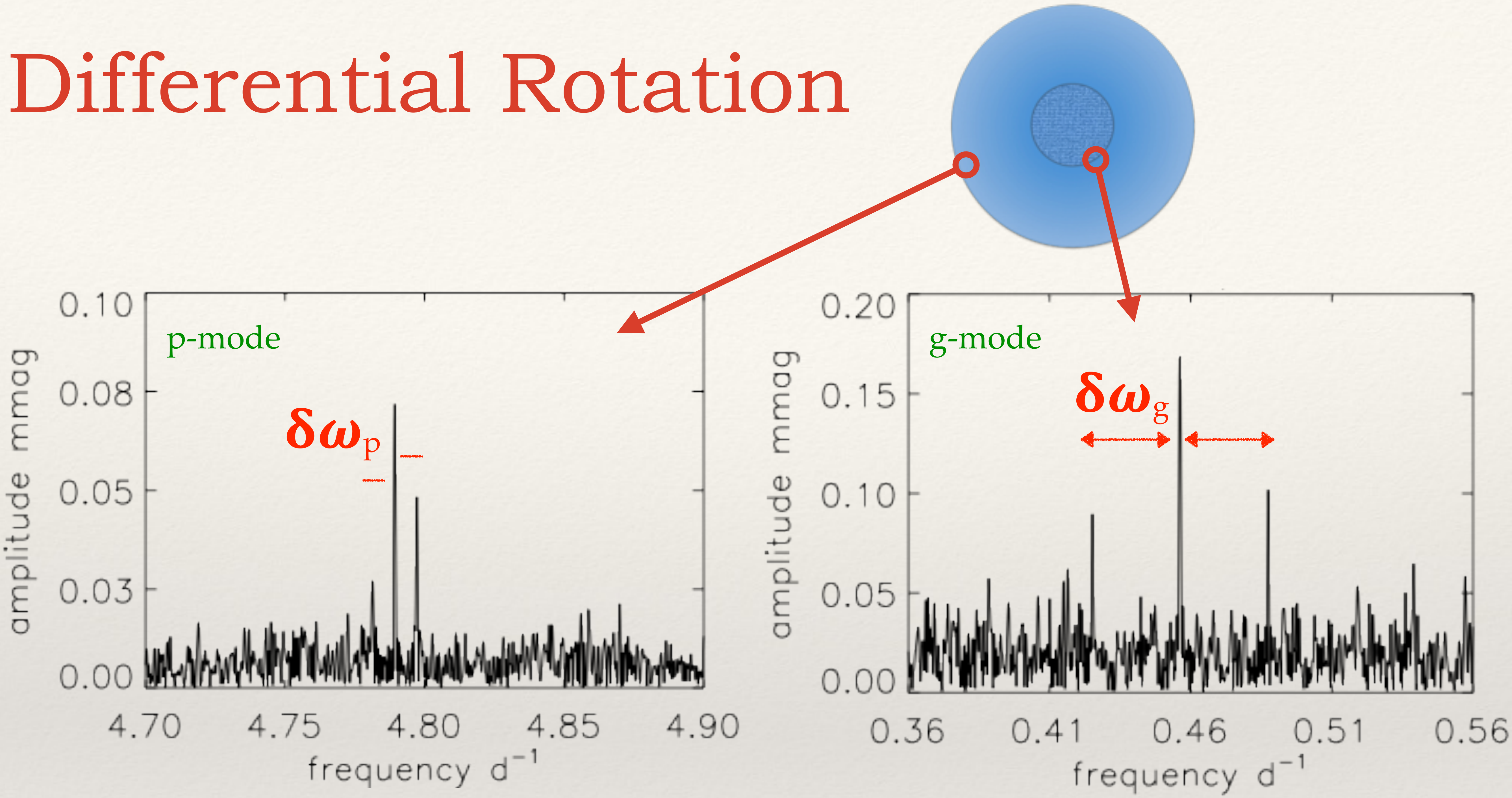
Lee, Neiner & Mathis (2014, 2016)

AM Transport by Waves



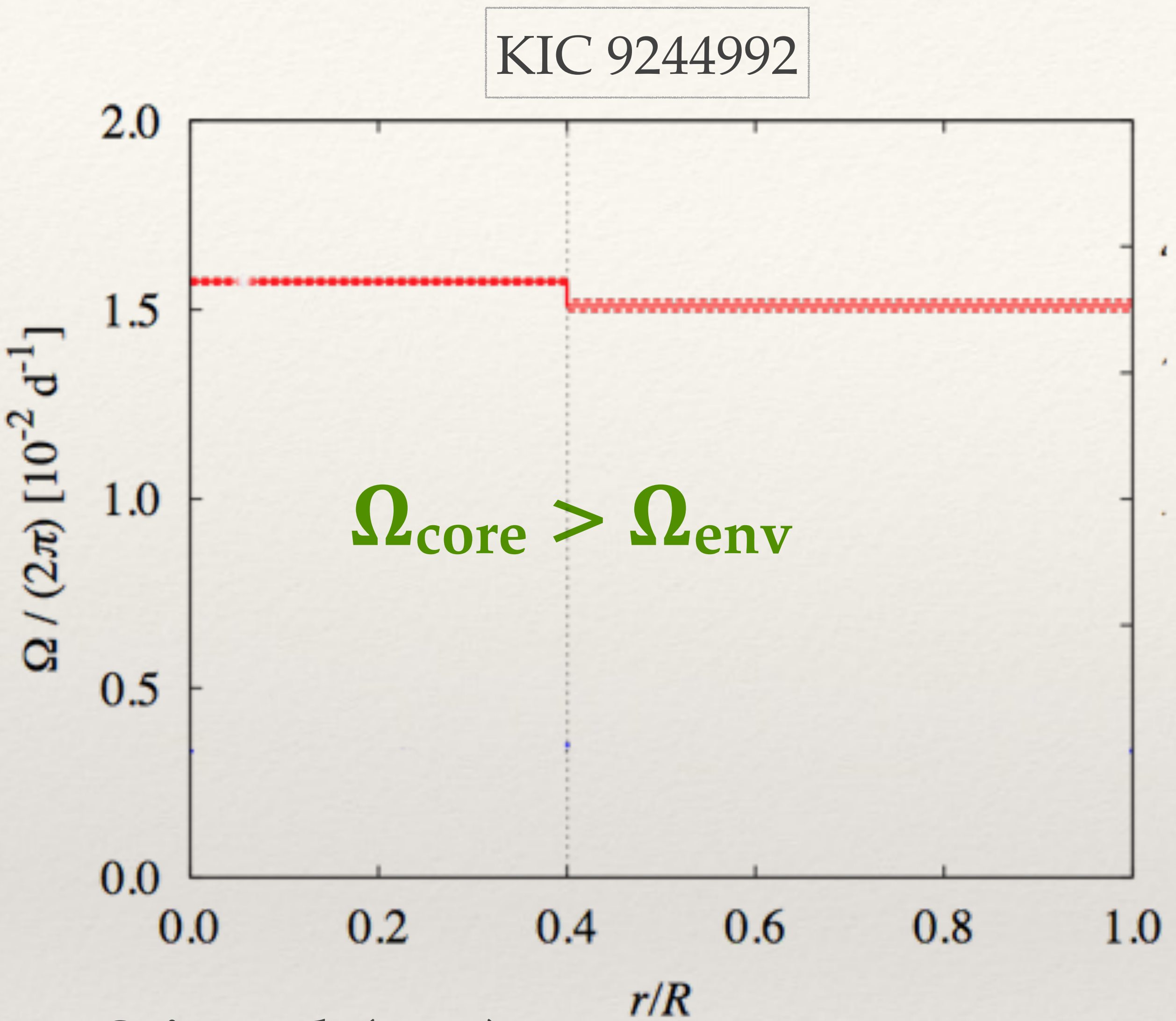
Lee, Neiner & Mathis (2014, 2016)

Differential Rotation



Two F-type *Kepler* hybrid pulsators,
near TAMS, slow rotators
(**Kurtz+ 2014, Saio+ 2015**)

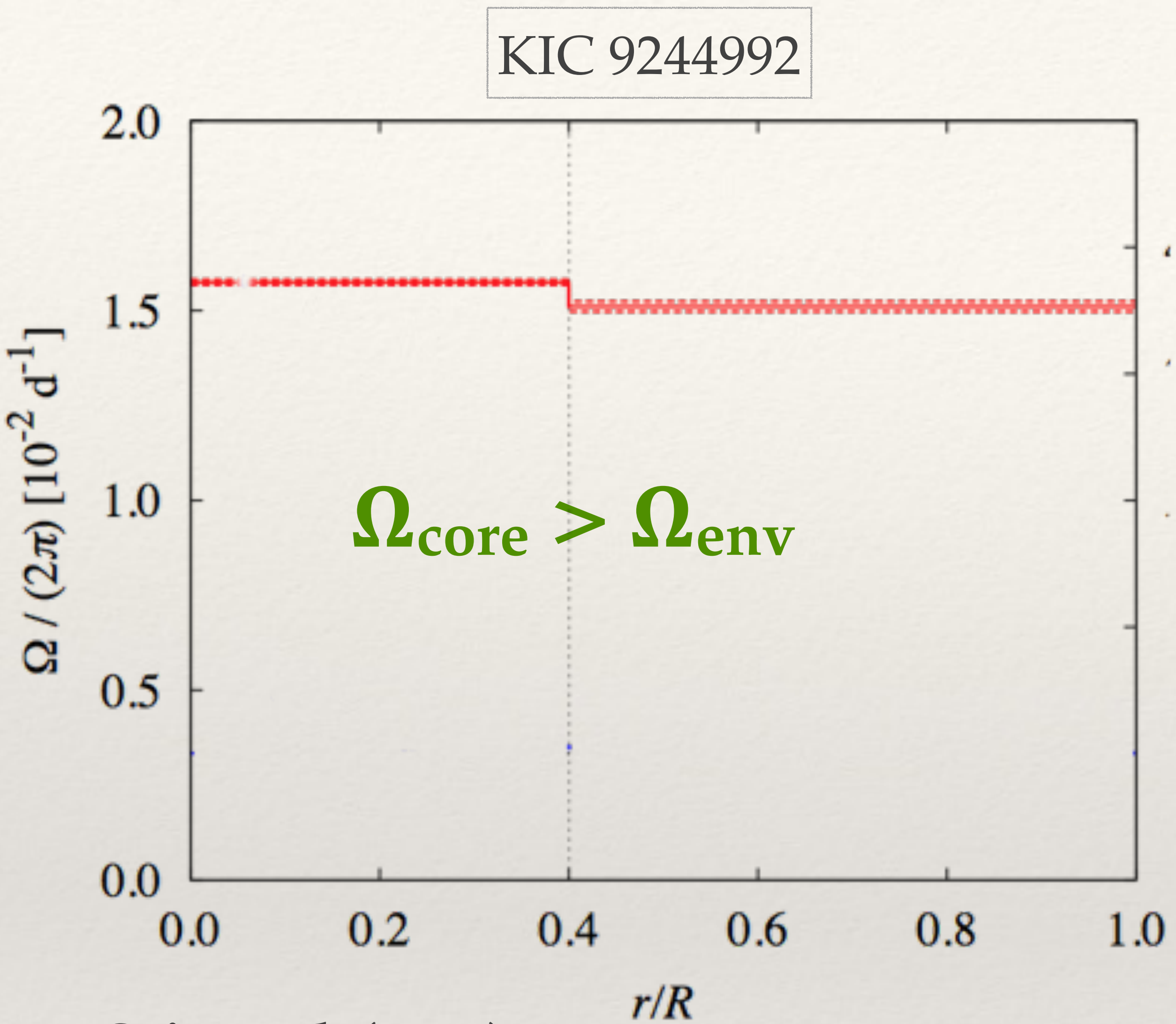
Differential Rotation



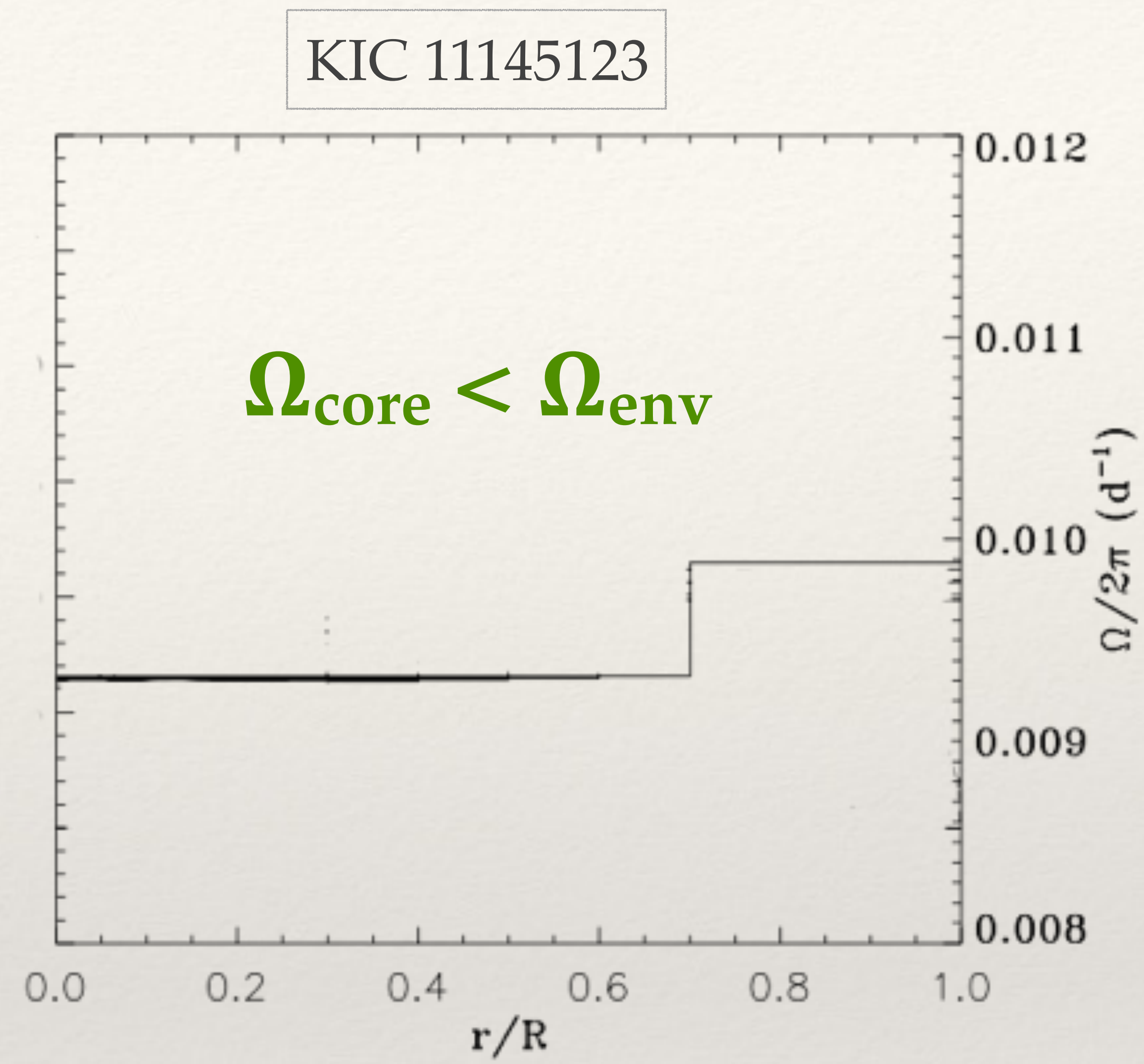
Saio et al. (2015)

Almost rigid rotation at TAMS:
Strong AM transport needed

Differential Rotation



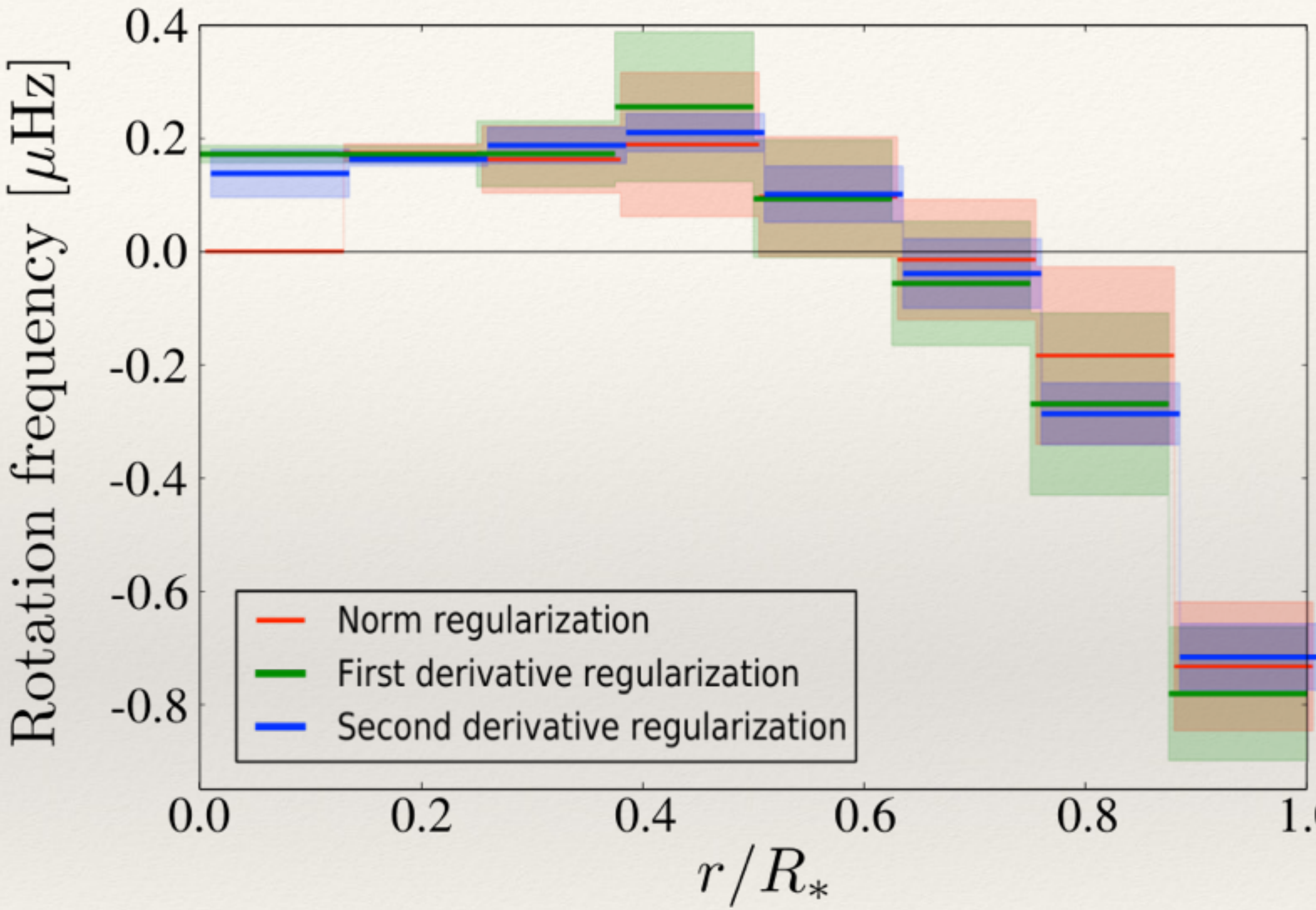
Saio et al. (2015)



Kurtz et al. (2014)

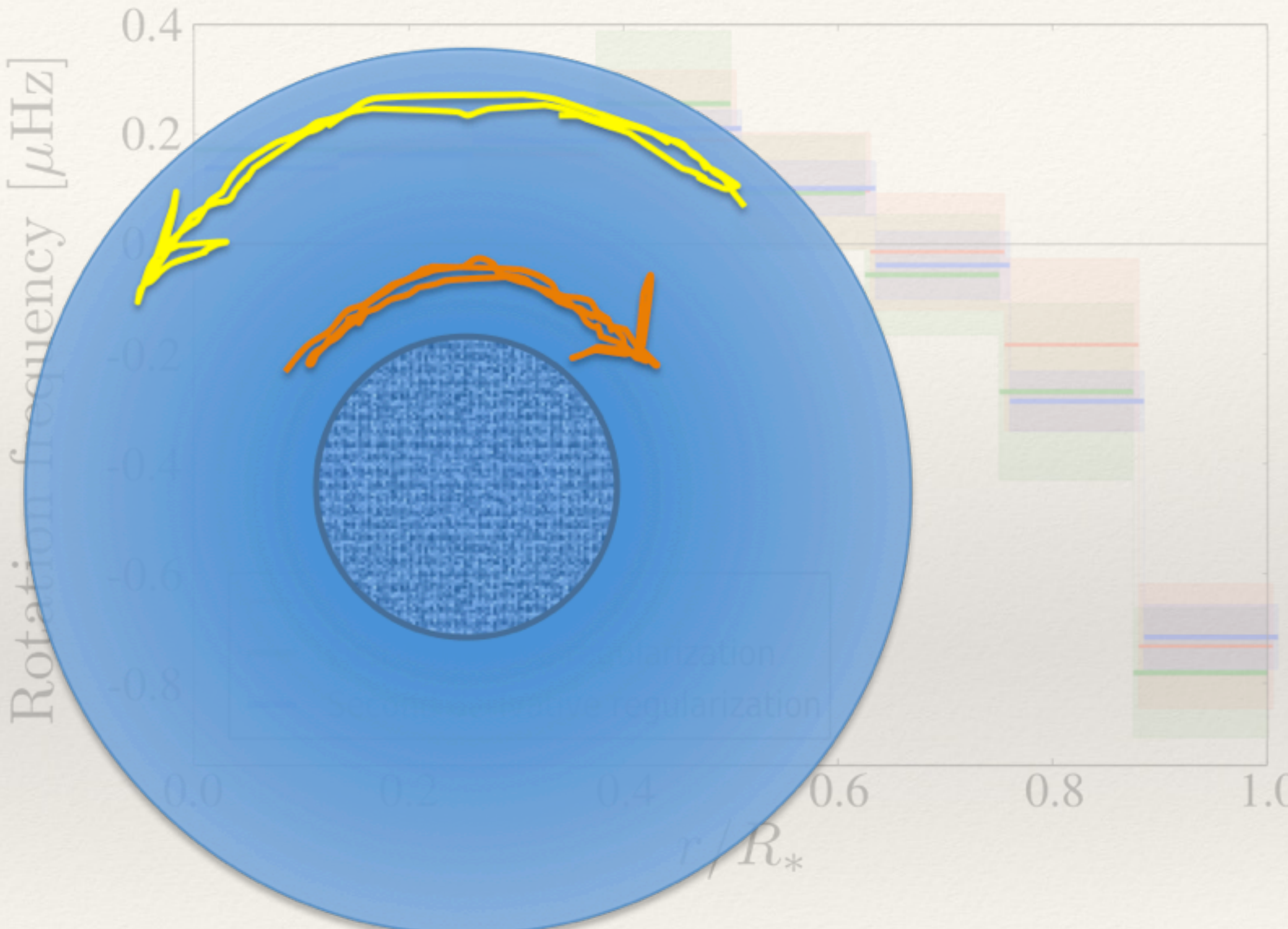
Almost rigid rotation at TAMS:
Strong AM transport needed

Counter-Rotating Envelope



Triana, Moravveji+ 2015, Rogers 2015

Counter-Rotating Envelope

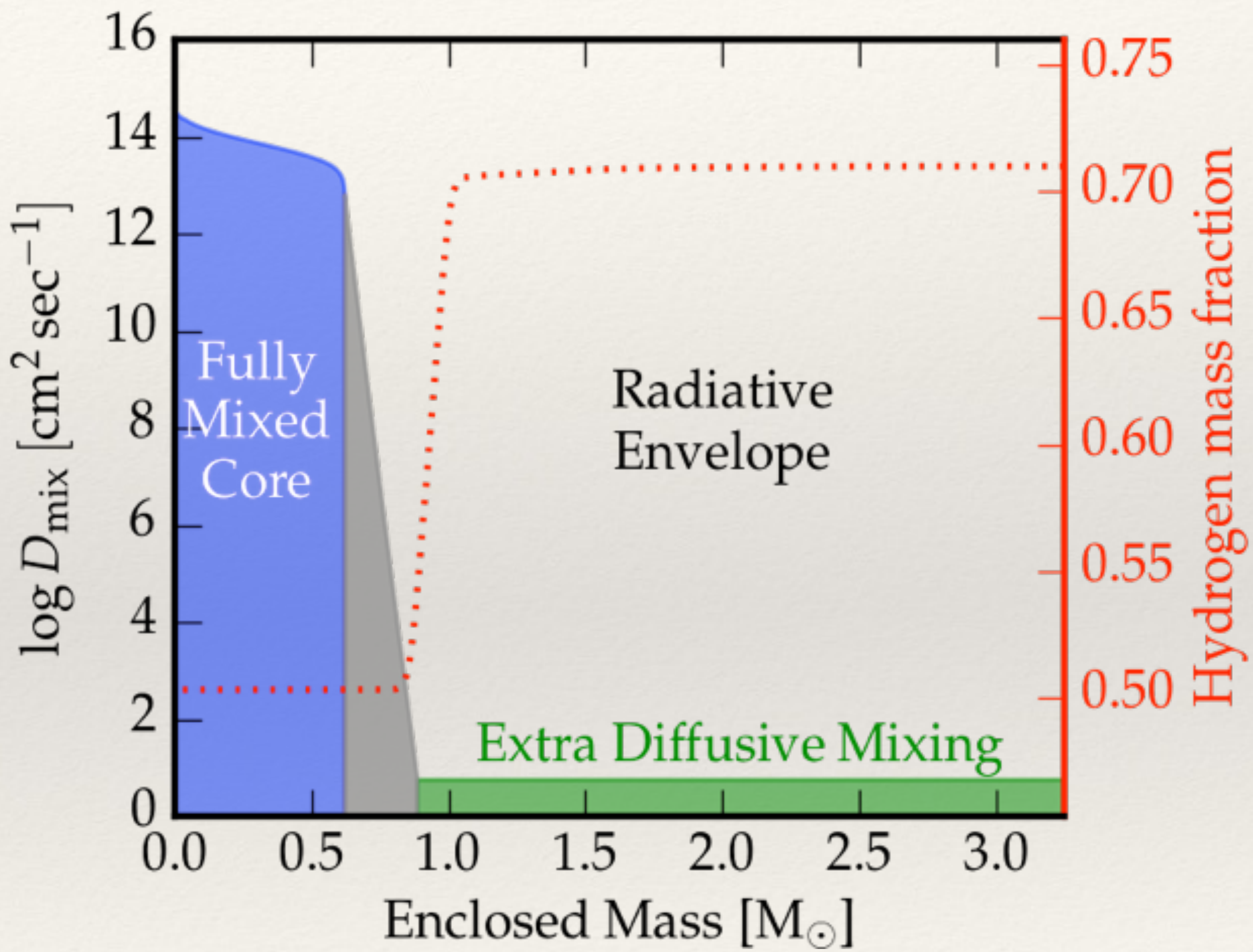


Triana, Moravveji+ 2015, Rogers 2015

Part II:
Overshooting & Extra Mixing

Core Overshooting & Extra Mixing

See: Miglio+ (2008), Schmid & Aerts (2016) Deheuvels+ (2016), Dziembowski+ (1991),



Moravveji+ (2015, 2016)

Core Overshooting & Extra Mixing

See: Miglio+ (2008),
Schmid & Aerts (2016)
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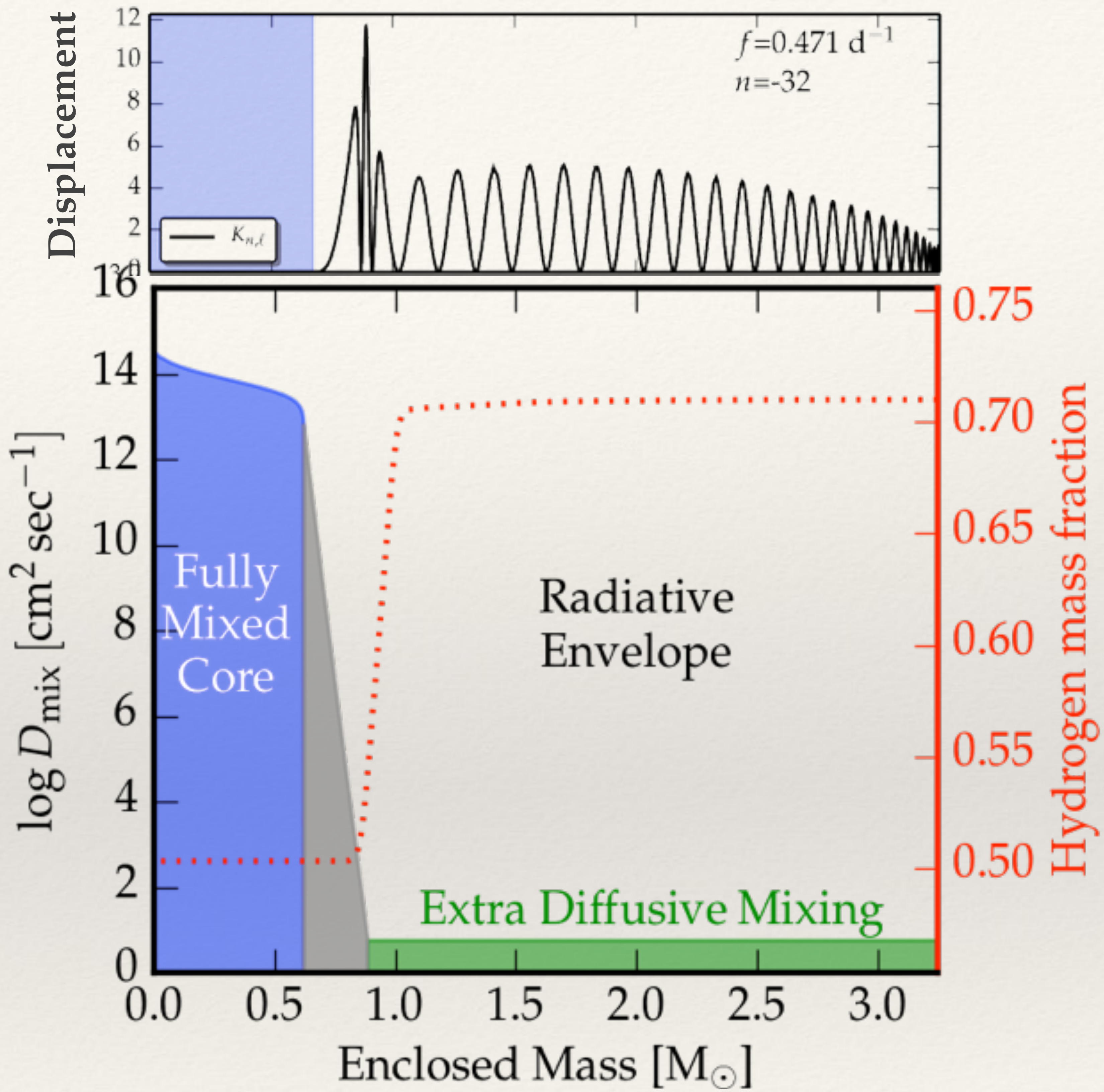
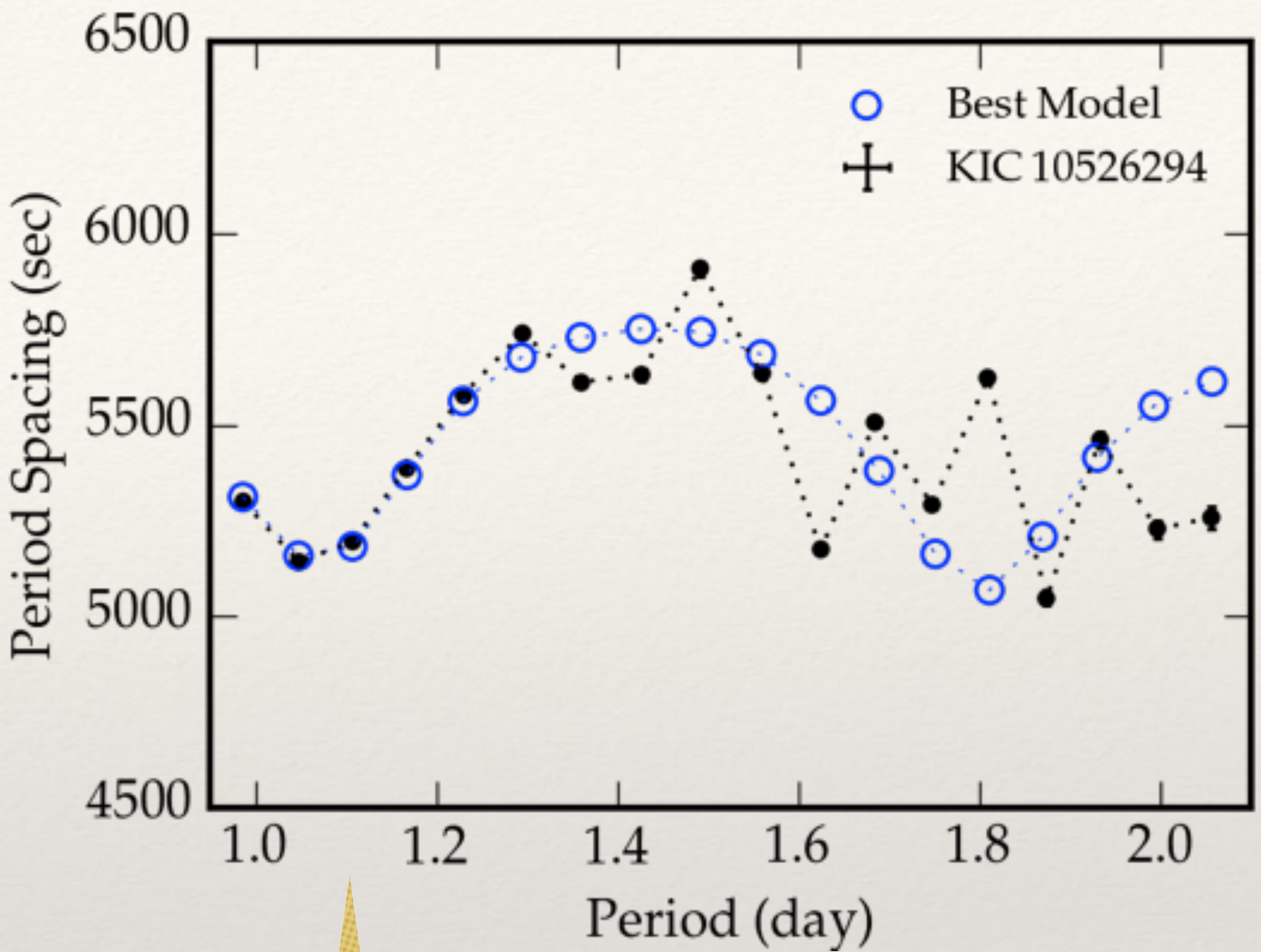


Moravveji+ (2015, 2016)

Core Overshooting and Extra Mixing

Kepler B8V star
19 g-mode triplets
Near ZAMS
Very slow rotator ($P_{rot} \approx 188$ days)

Mass	Overshoot	$\log(D_{mix})$
3.25	0.017 ± 0.001	1.75 ± 0.25



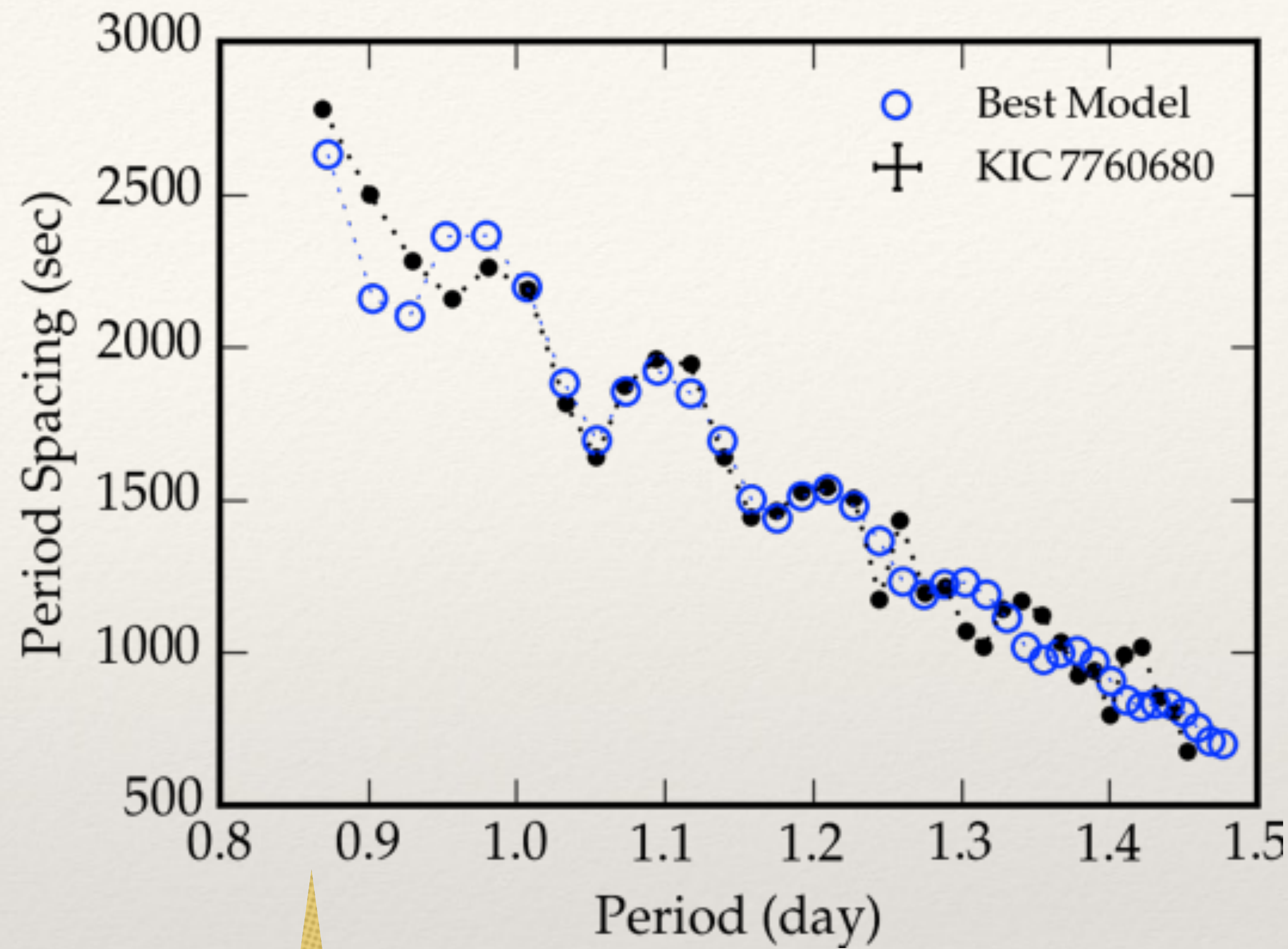
The counter-rotating star!

Papics+ 2014, **Moravveji+ 2015**

Core Overshooting and Extra Mixing

Kepler B8V star
36 g-mode $(\ell, m) = (1, +1)$
Moderate rotator ($P_{rot} \approx 2.2$ days)

Mass	Overshoot	$\log(D_{mix})$
3.25	0.024 ± 0.001	0.75 ± 0.25



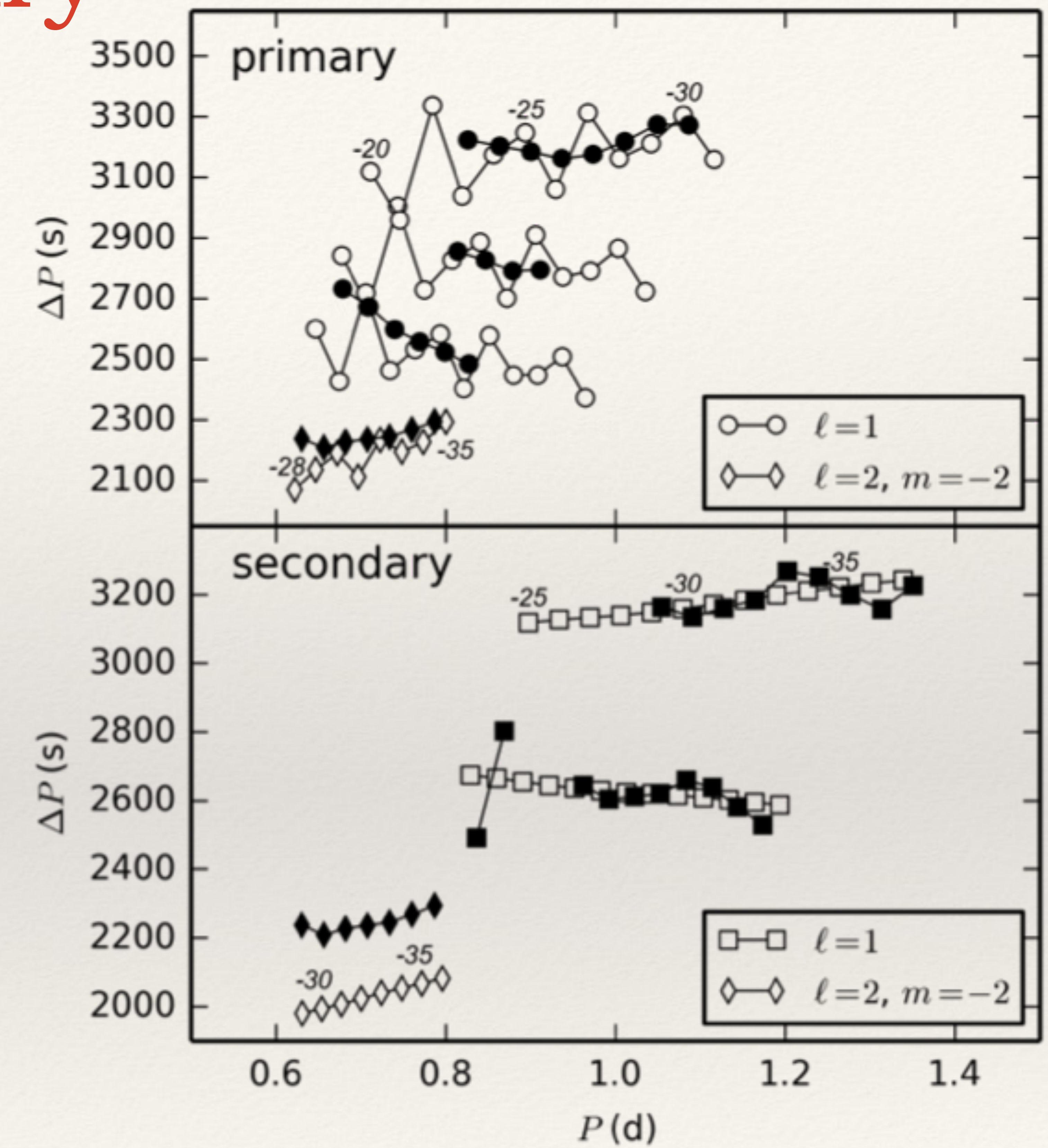
Rotates at 26% Roche break up

Papics+ 2015, **Moravveji+ 2016**

Pulsating Binary

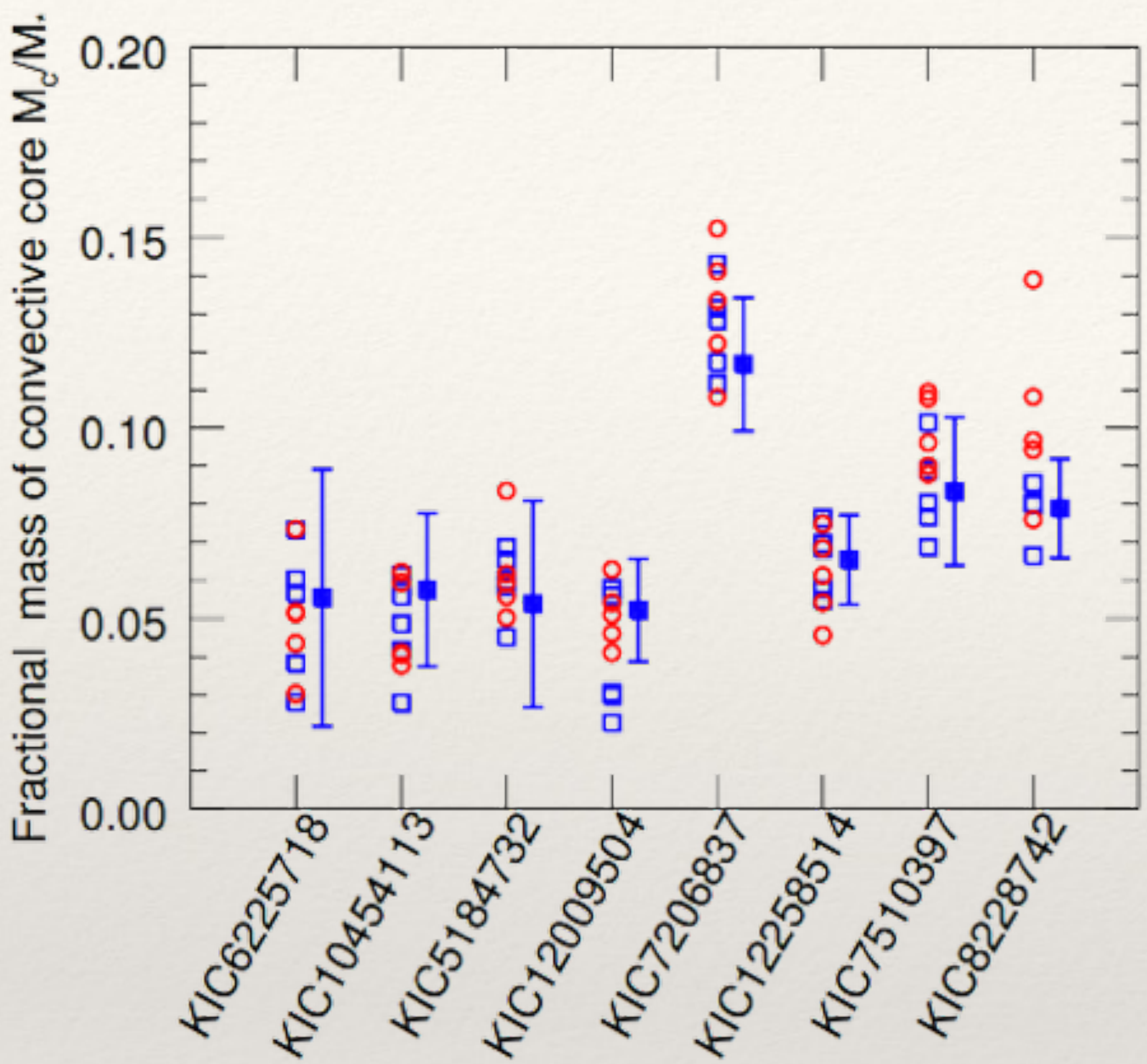
(F+F) Kepler SB2 binary system
both component are pulsating
hybrid: p-modes + g-modes

Mass	Overshooting	$\log(D_{\mathrm{mix}})$
1.82	0.008	0.25
1.76	0.005	1.75



Schmid+ (2015, 2016), Keen+ (2015)

Overshooting for $1.1 \lesssim M/M_\odot \lesssim 1.5$



Deheuvels+ (2016), Claret & Torres (2016)

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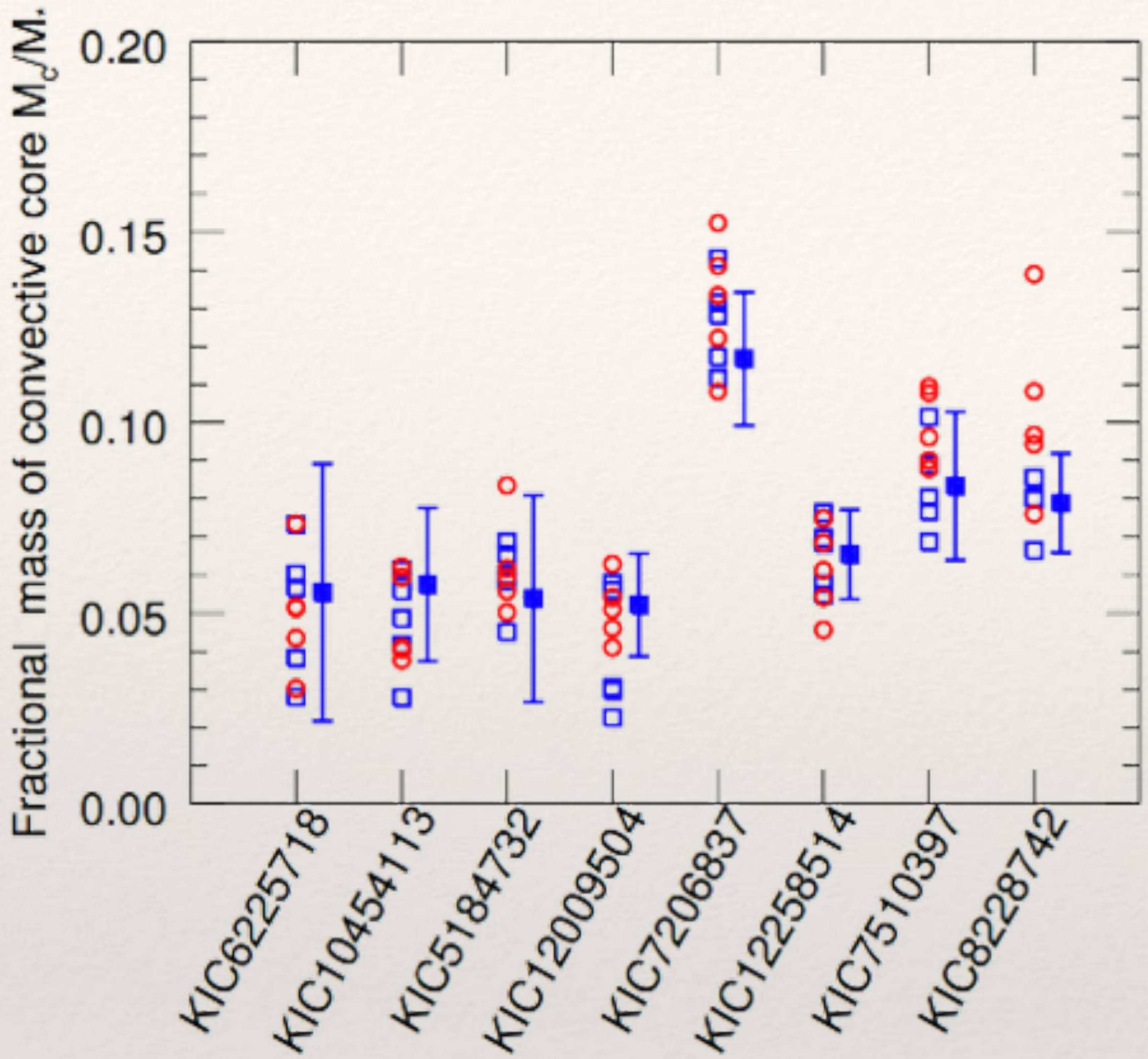
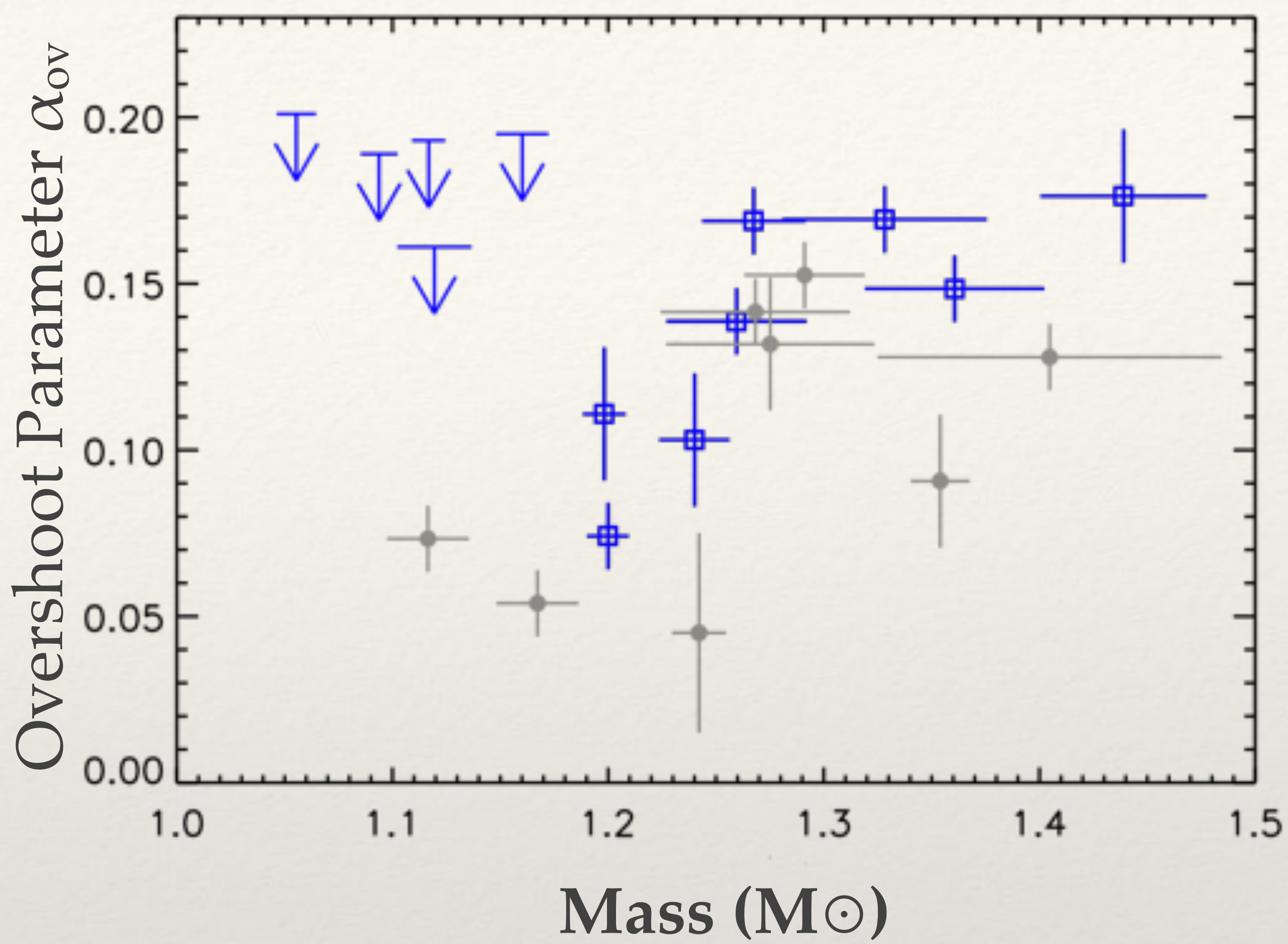


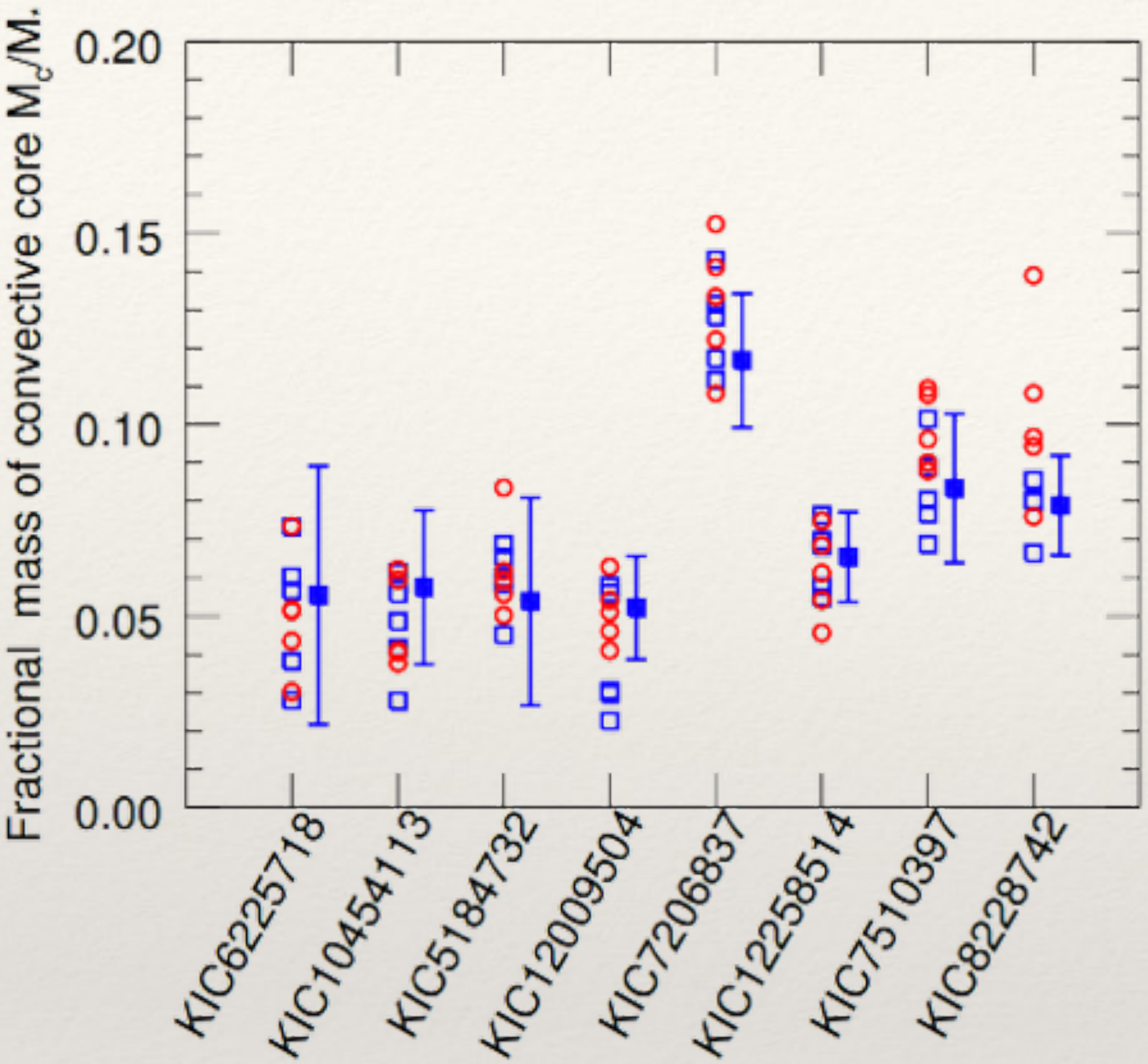


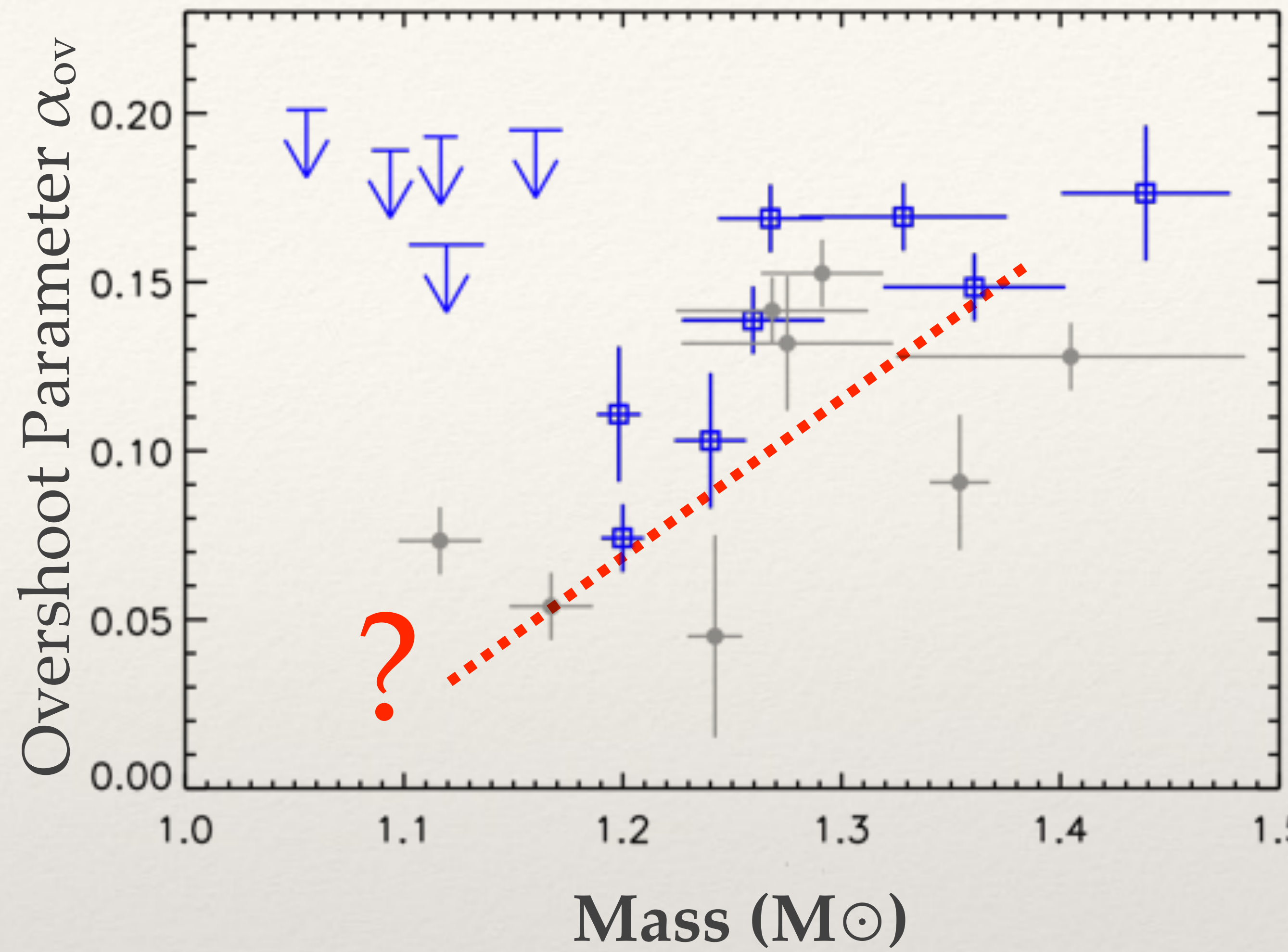
Grey: Incl. Atomic Diffusion

Blue: Without

Deheuvels+ (2016), Claret & Torres (2016)

Overshooting for $1.1 \lesssim M/M_\odot \lesssim 1.5$





Grey: Incl. Atomic Diffusion
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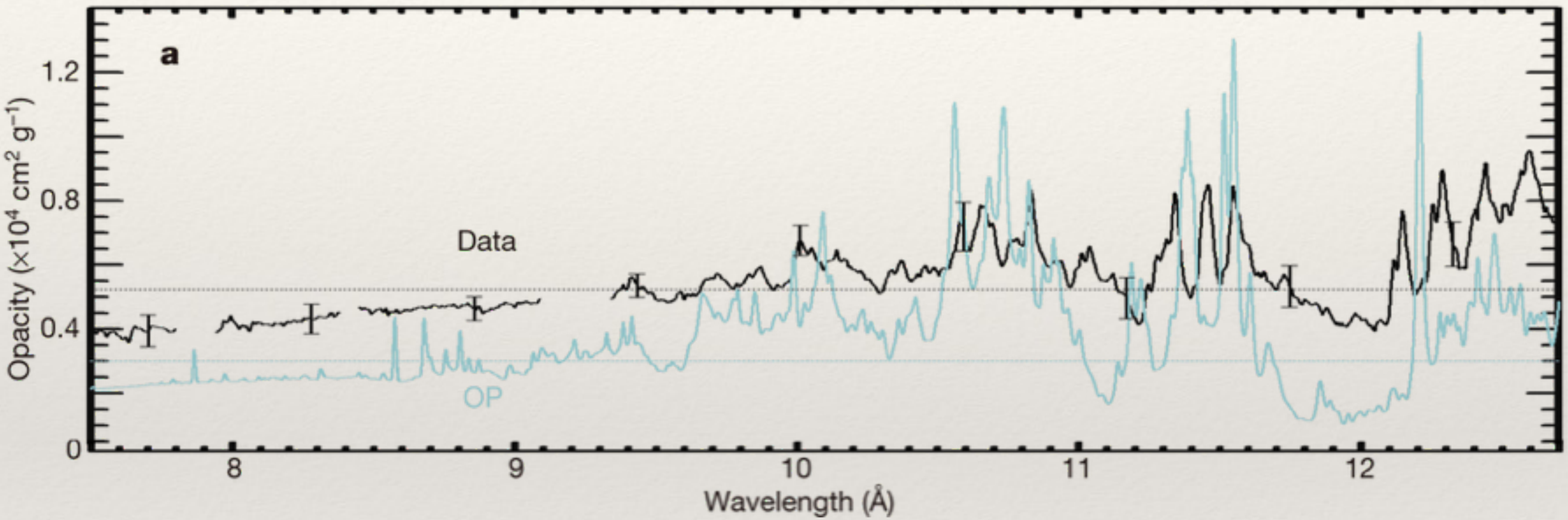
Deheuvels+ (2016), Claret & Torres (2016)

Part III:
Stellar Opacities

Iron-Bump Opacity

Direct experiment: 75% increase

Numerical calculations: Iron ~ 50% to 100% and, Nickel ~ 500% increase

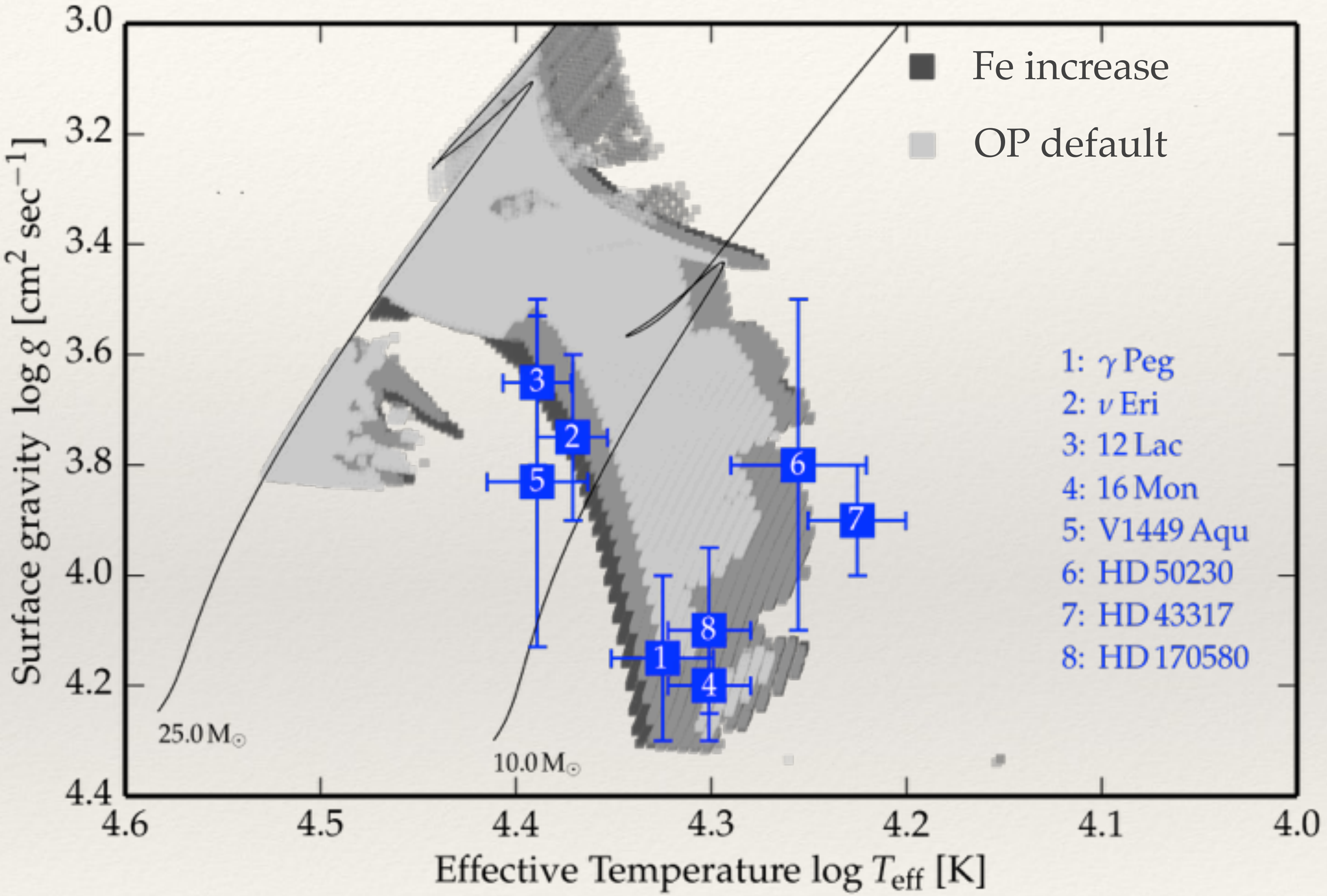


Bailey+ (2015, Nature), Mondet+ (2015), Turck-Chieze+ (2016)

☞ see talk by Matteo Cantiello

Iron-Bump Opacity

Instability strip of hybrid SPB/β Cep stars depends on Fe/Ni opacity

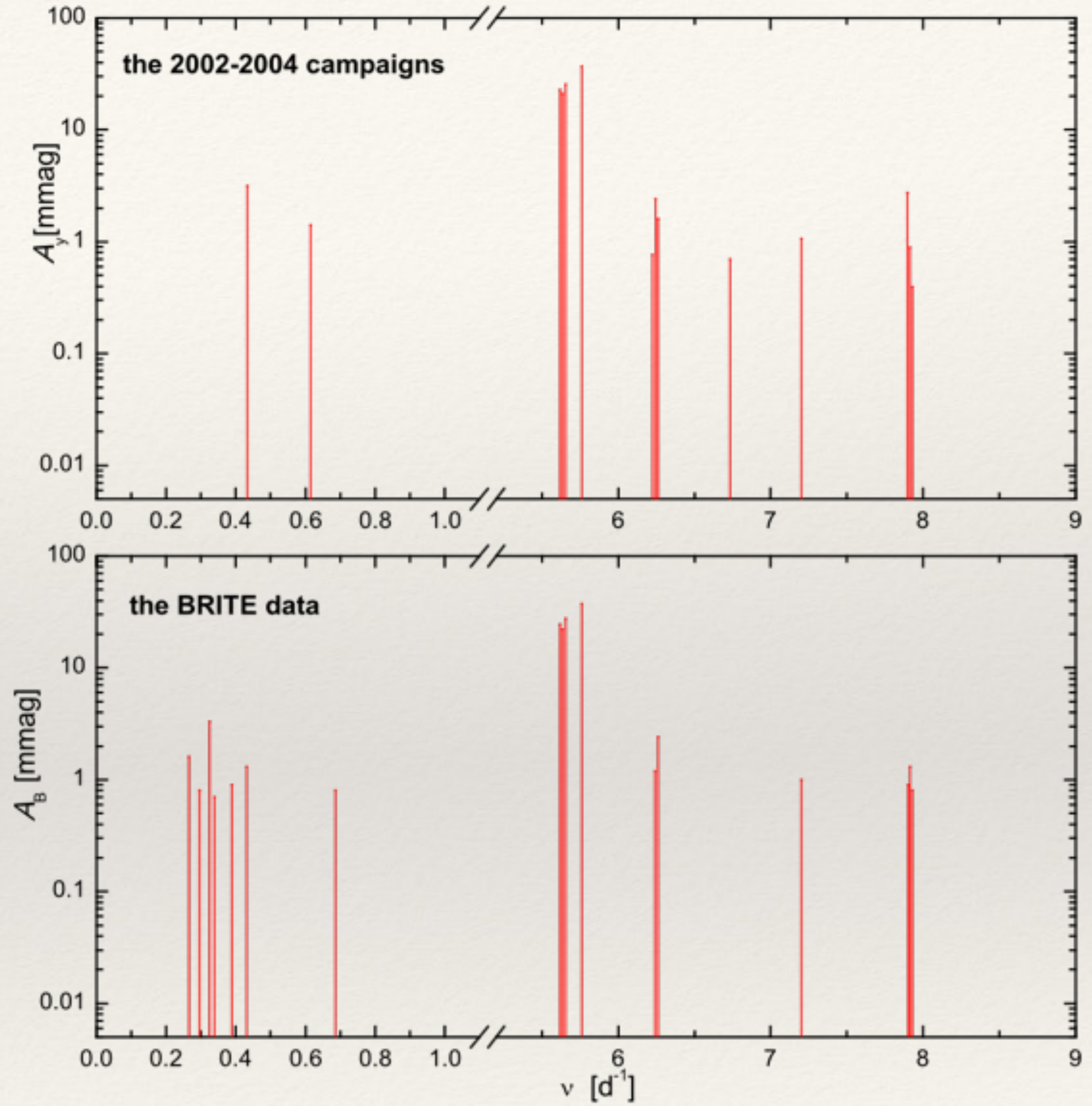


Moravveji (2015)

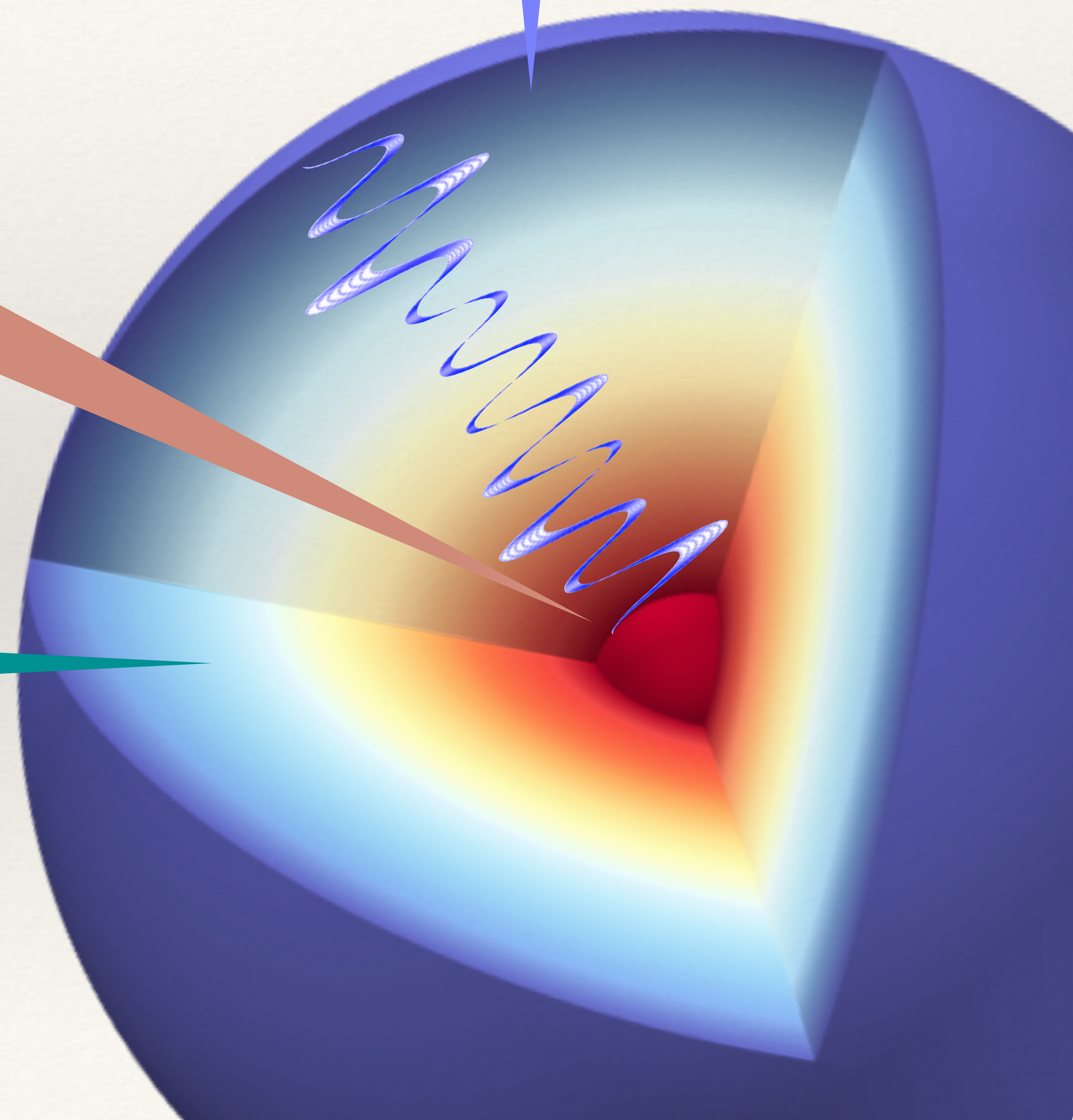
Iron-Bump Opacity

ν Eri has additional g-modes!

Daszynska-Daszkiewicz+ (2017)
☞ see talk by Gerald Handler



Asteroseismology Teaches Us …

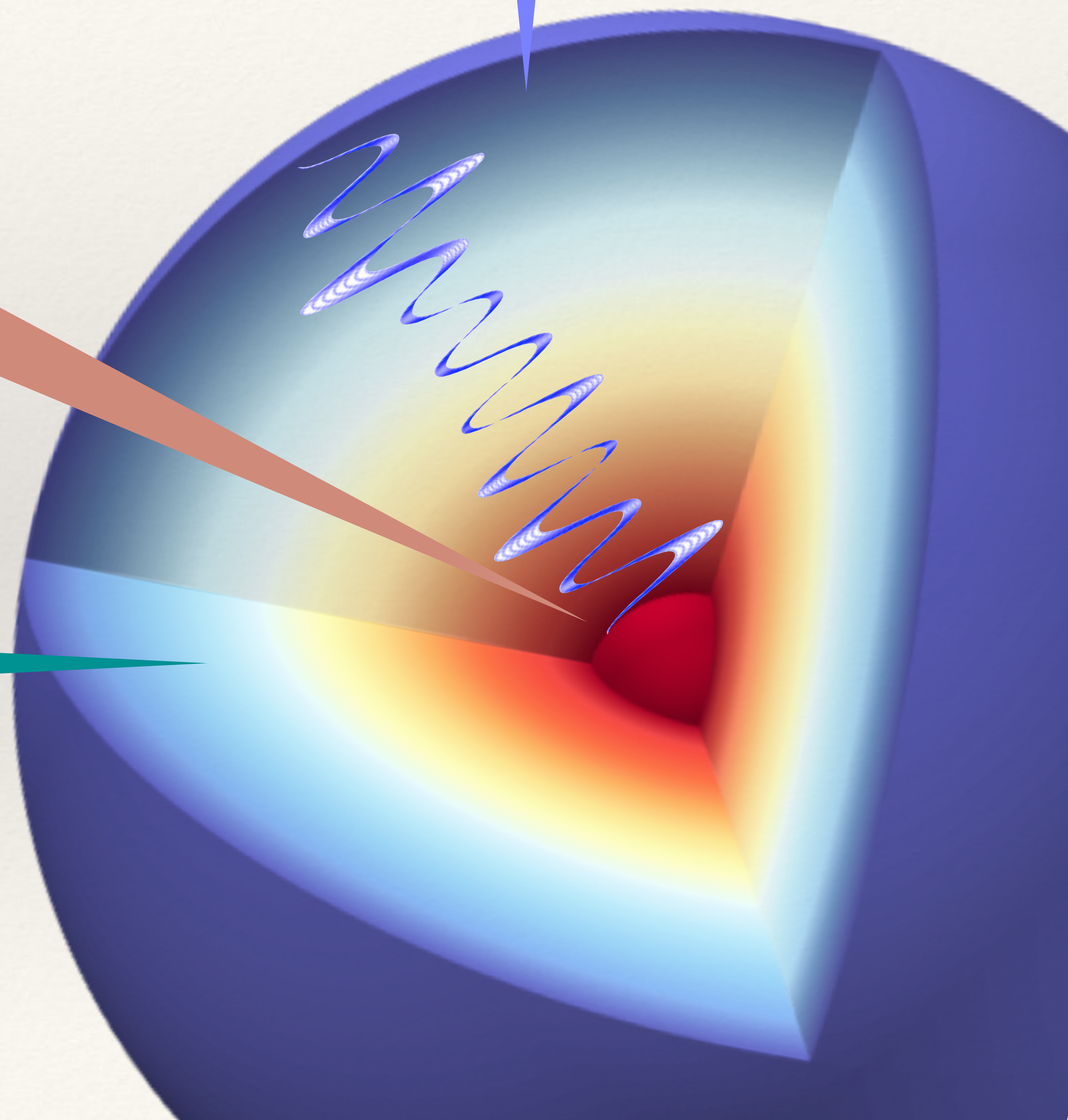


Asteroseismology Teaches Us …

1. Pulsation & Rotation

2. Overshooting & Extra Mixing

3. Stellar Opacities



For further discussions:
email: ehsan.moravveji@kuleuven.be
Skype ID: e-moravveji

Bouabid et al. (2013): Period Spacing and the Traditional Approximation of Rotation

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

$$= \frac{2\pi^2}{\sqrt{\lambda(\ell, m, s)} \int N \, d\ln r \left(1 + \frac{1}{2}\frac{d\ln\lambda}{d\ln s}\right)},$$

$$s = \frac{2\nu_{\mathrm{rot}}}{\nu},$$

$$\lambda \to \ell(\ell+1) \quad \text{for} \quad \nu_{\mathrm{rot}} \to 0.$$

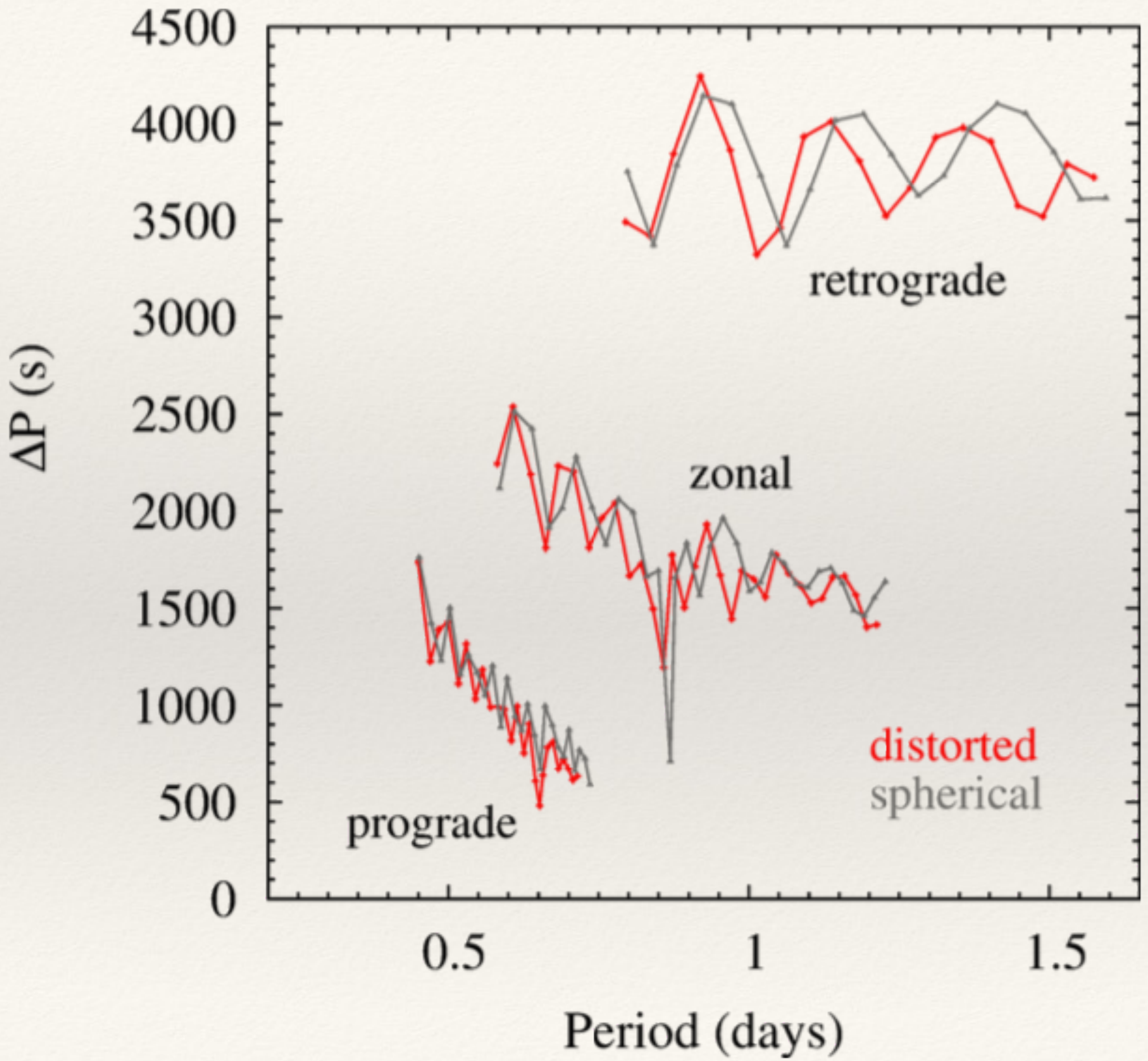
Prat et al. (2017): Period Spacing including Coriolis & Centrifugal Forces

$$\Delta\Pi \simeq \frac{2\int_0^{r_s} \frac{N_0}{r}\mathrm{d}r}{m\Omega\left(\tilde{n}+\frac{3}{4}\right)^2}\frac{1+\frac{\sigma}{2}}{\sqrt{1+\sigma}},$$

where

$$\sigma = \frac{(2\tilde{\ell}+1)f\pi\left(\tilde{n}+\frac{3}{4}\right)}{m^2\int_0^{r_s}\frac{N_0}{r}\mathrm{d}r} \gg \frac{2\tilde{\ell}+1}{m}.$$

Impact of Centriufugal distortion on the Period Spacing Slope

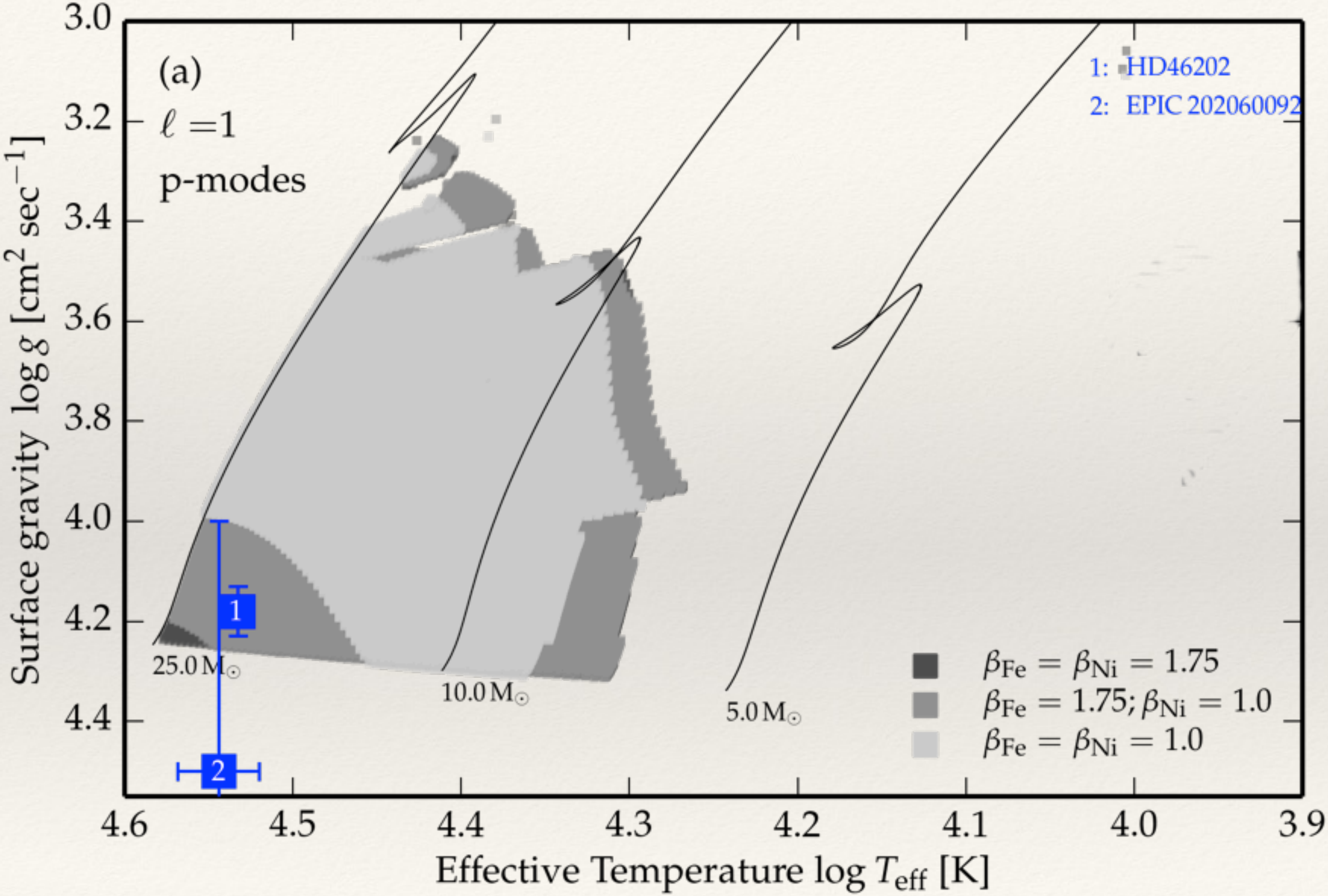


The predicted Rosseland mean opacities for iron are lower than the measured Rosseland mean values by 1.75, 1.67, 1.53, 1.75, and 1.57 for the OP, SCRAM, OPAS, ATOMIC, and SCO-RCG models, respec-

respectively). Focusing on iron, the individual contribution we calculated is 40% higher than the value deduced from OP data.

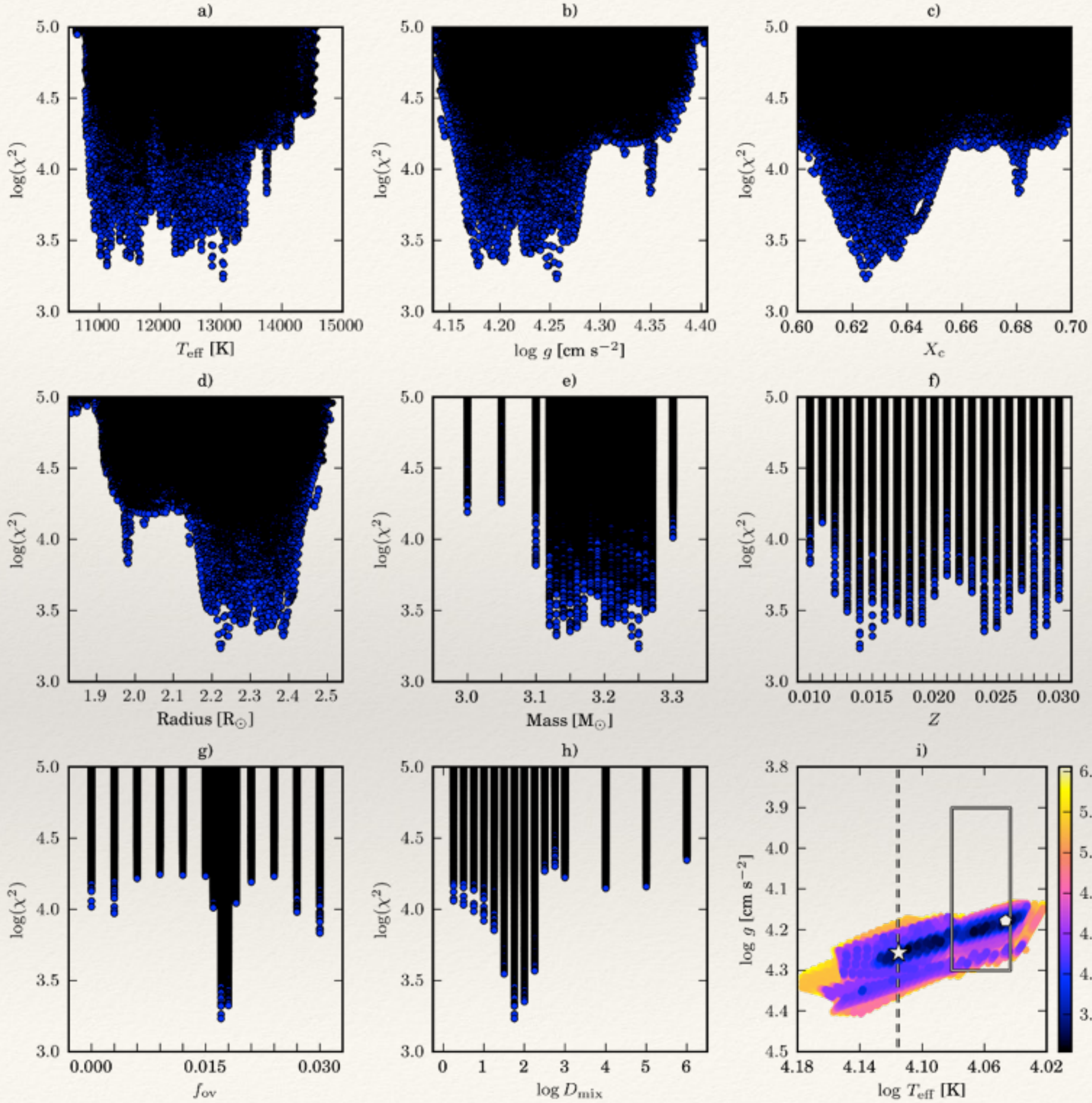
An increase of up to a factor of 2 for the Rosseland mean opacities from the OP tables for iron is suggested by the present study and up to a factor of 6 for nickel. The origin of the

New Instability Strips (>75% Fe opacity) by Moravveji (2015)



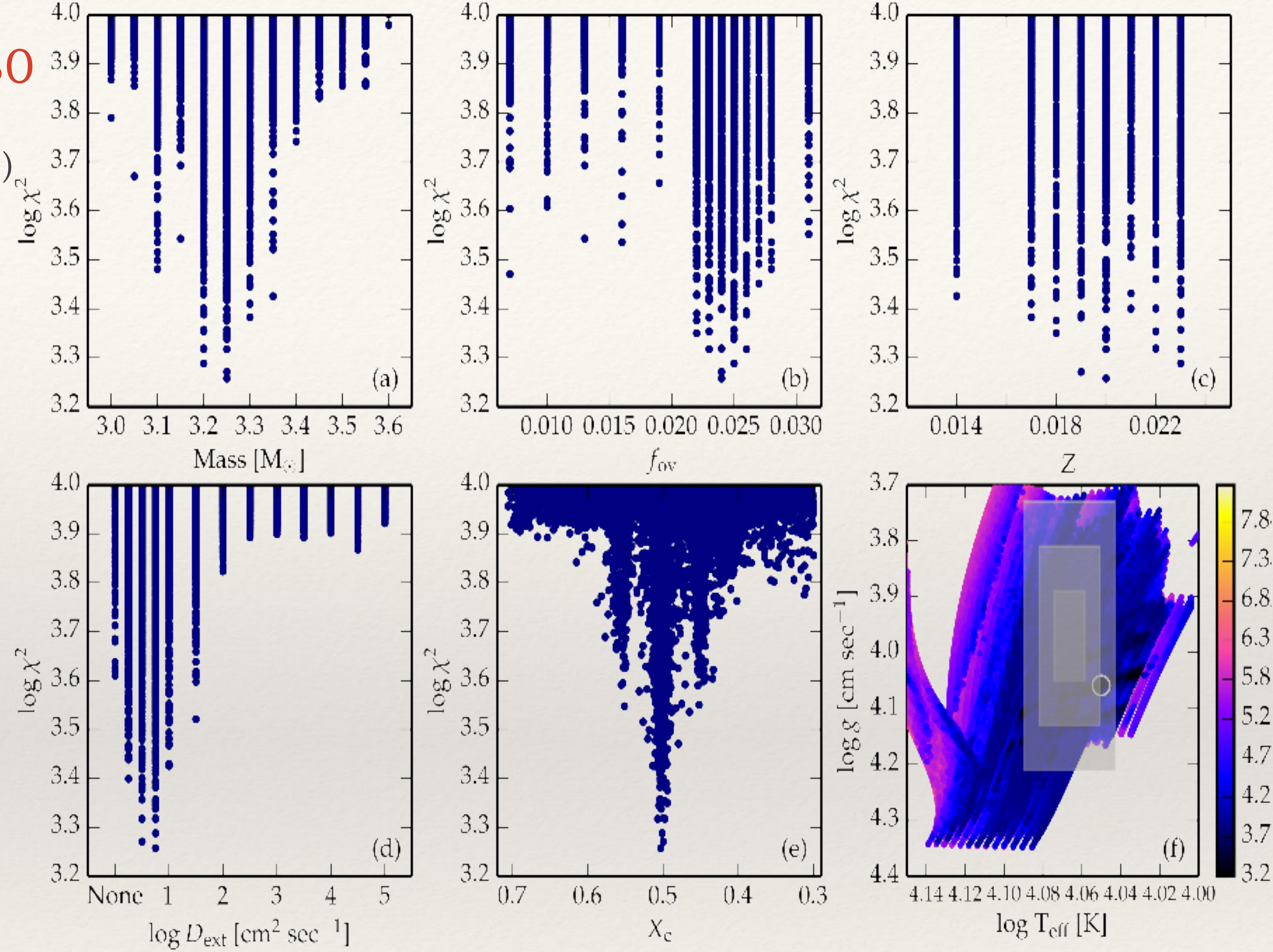
KIC 10526294

Moravveji+ (2015)

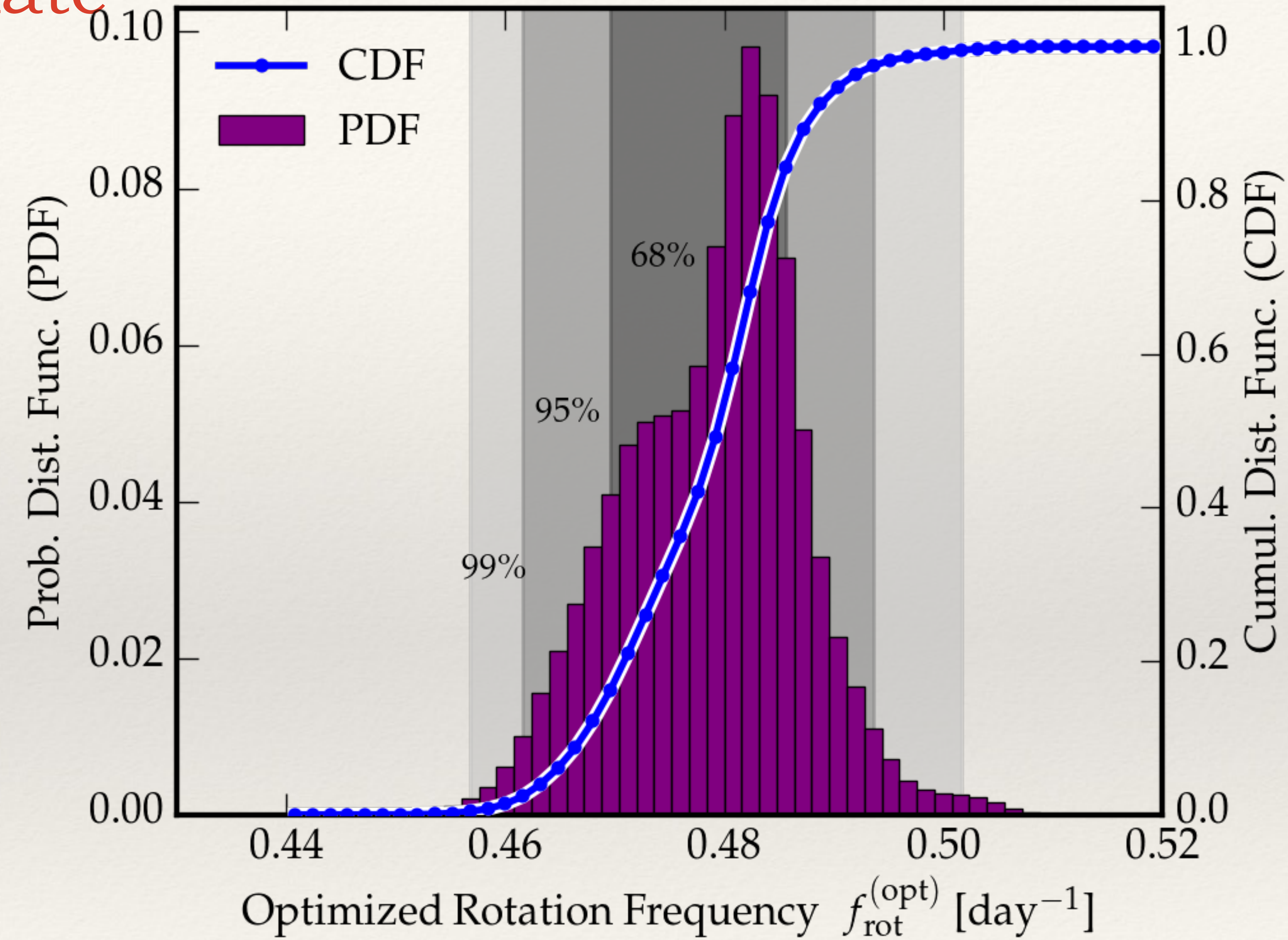


KIC 7760680

Moravveji+ (2016)



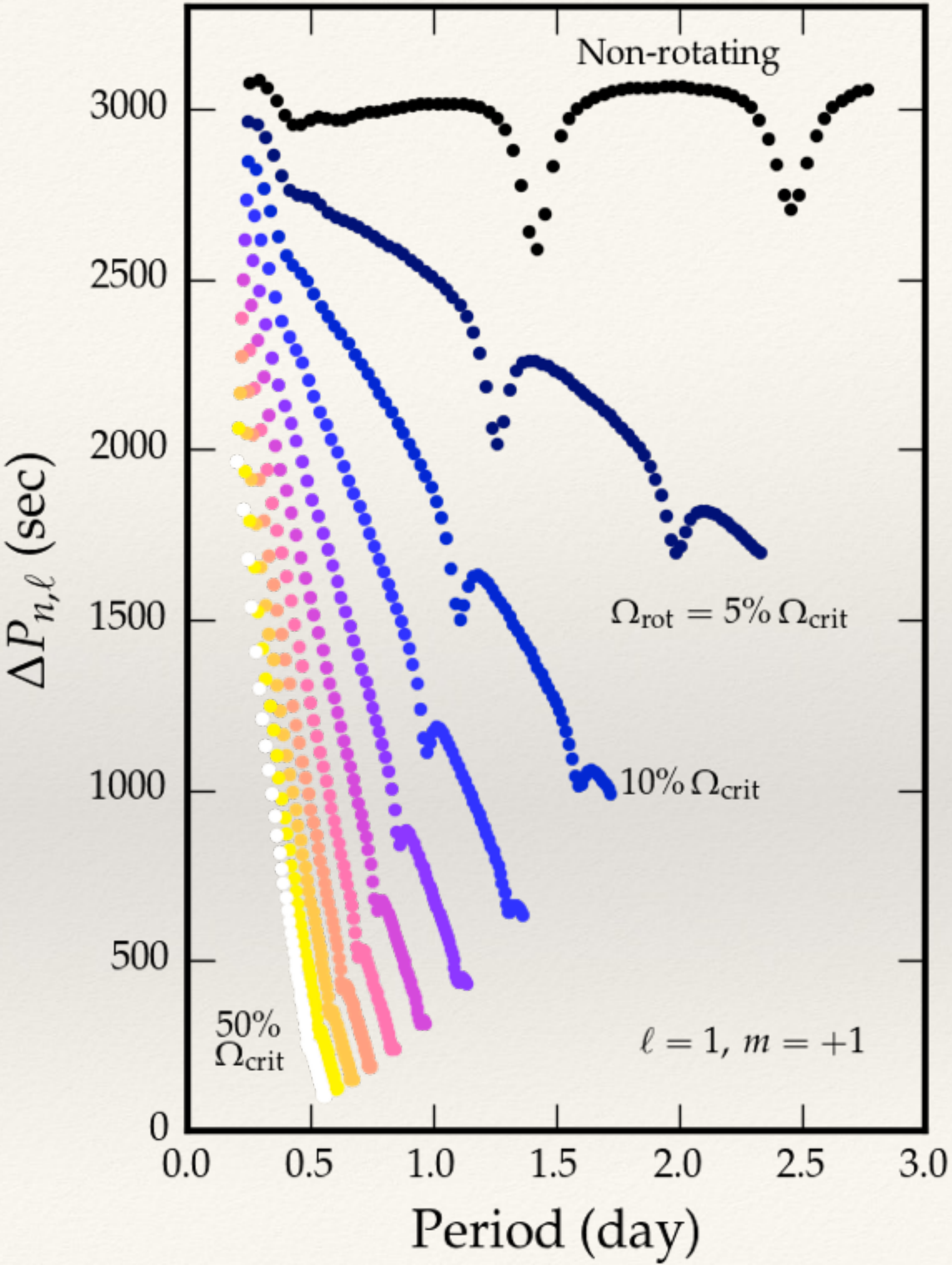
KIC 7760680 Rotation Rate



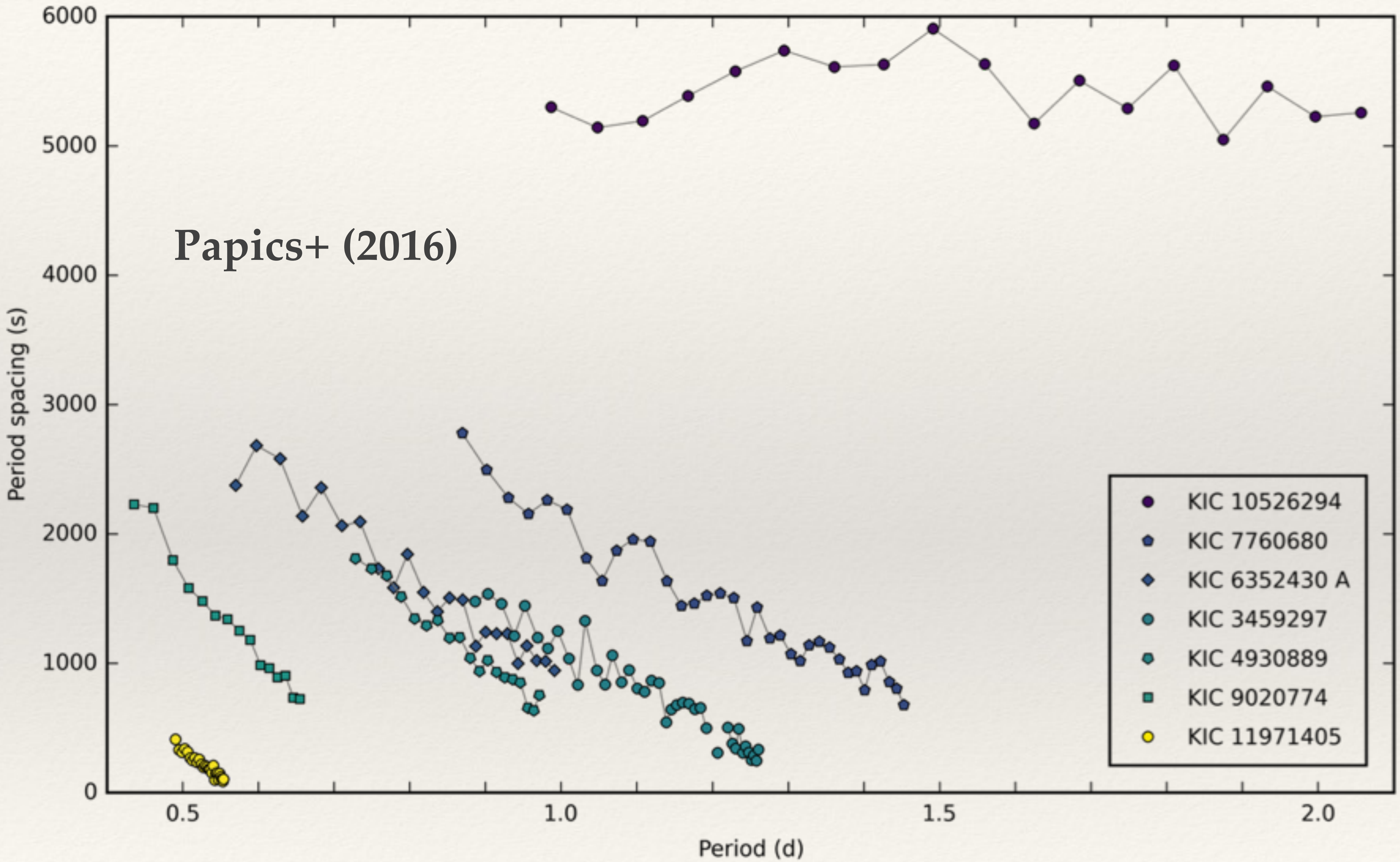
Moravveji, Townsend+ (2016)

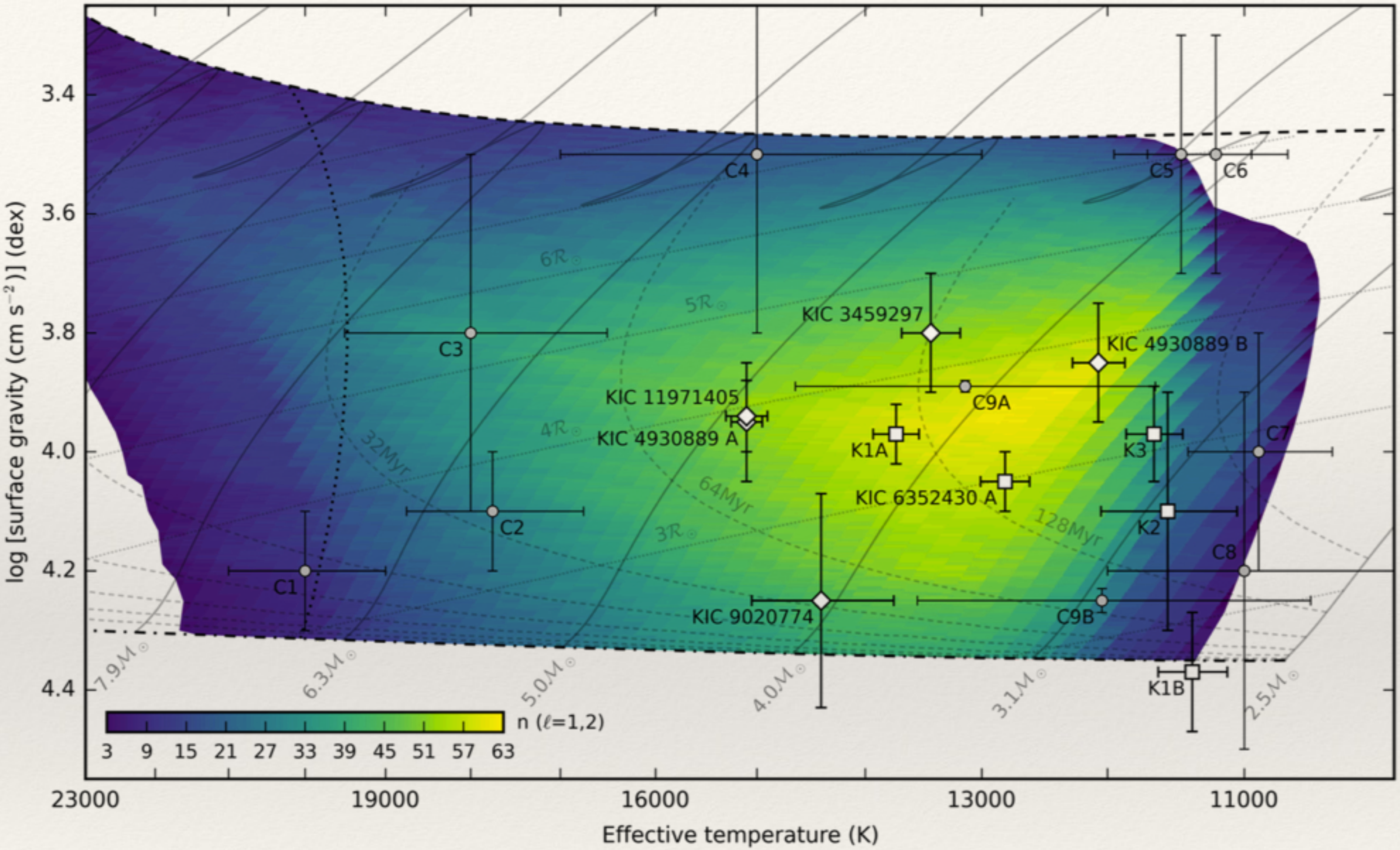
Rotation and the Slope of Period Spacing

Input Model:
1.4 Msun
No extra mixing
Moderate overshoot
Core hydrogen: 0.50



More Period Spacings

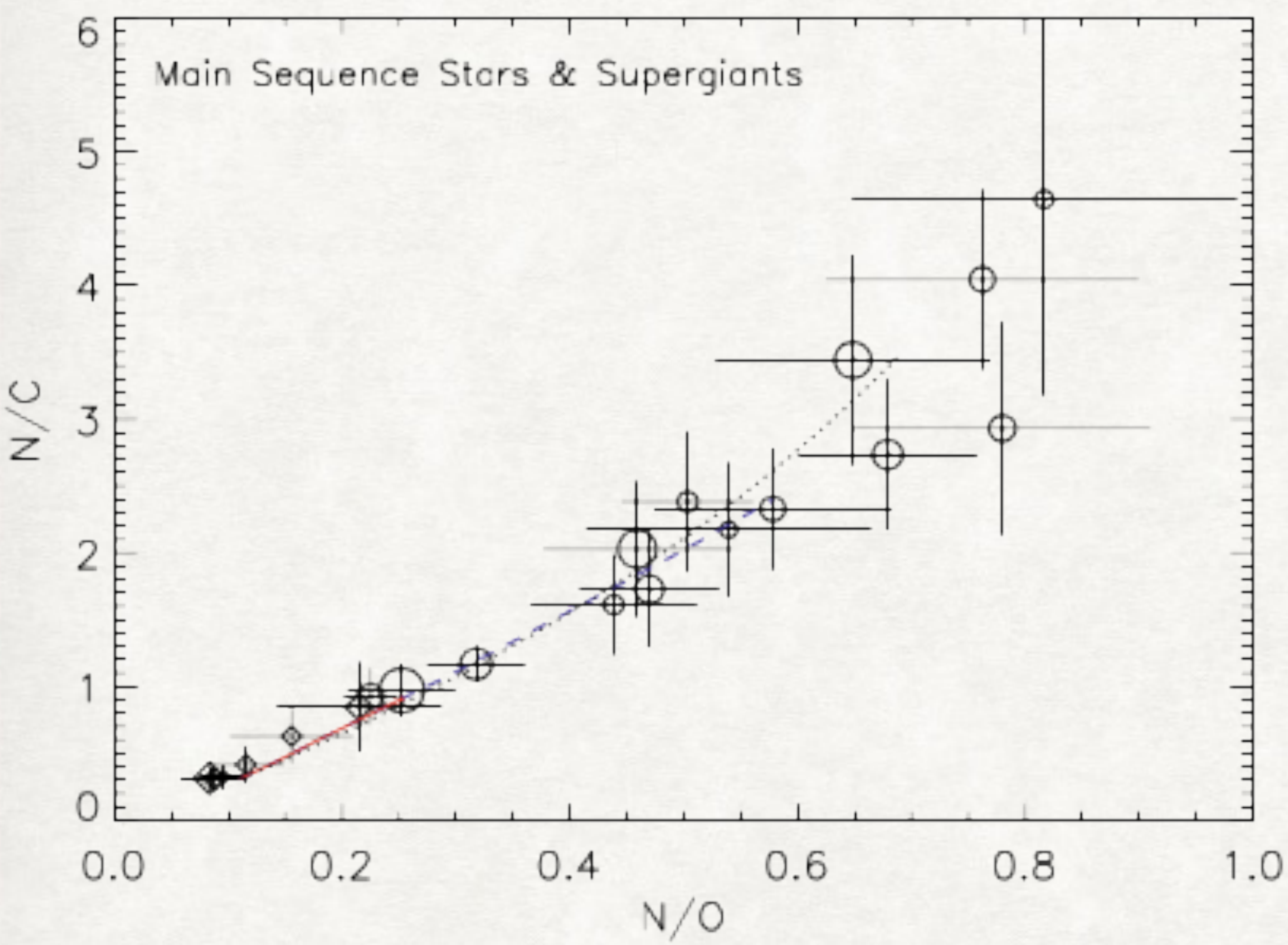




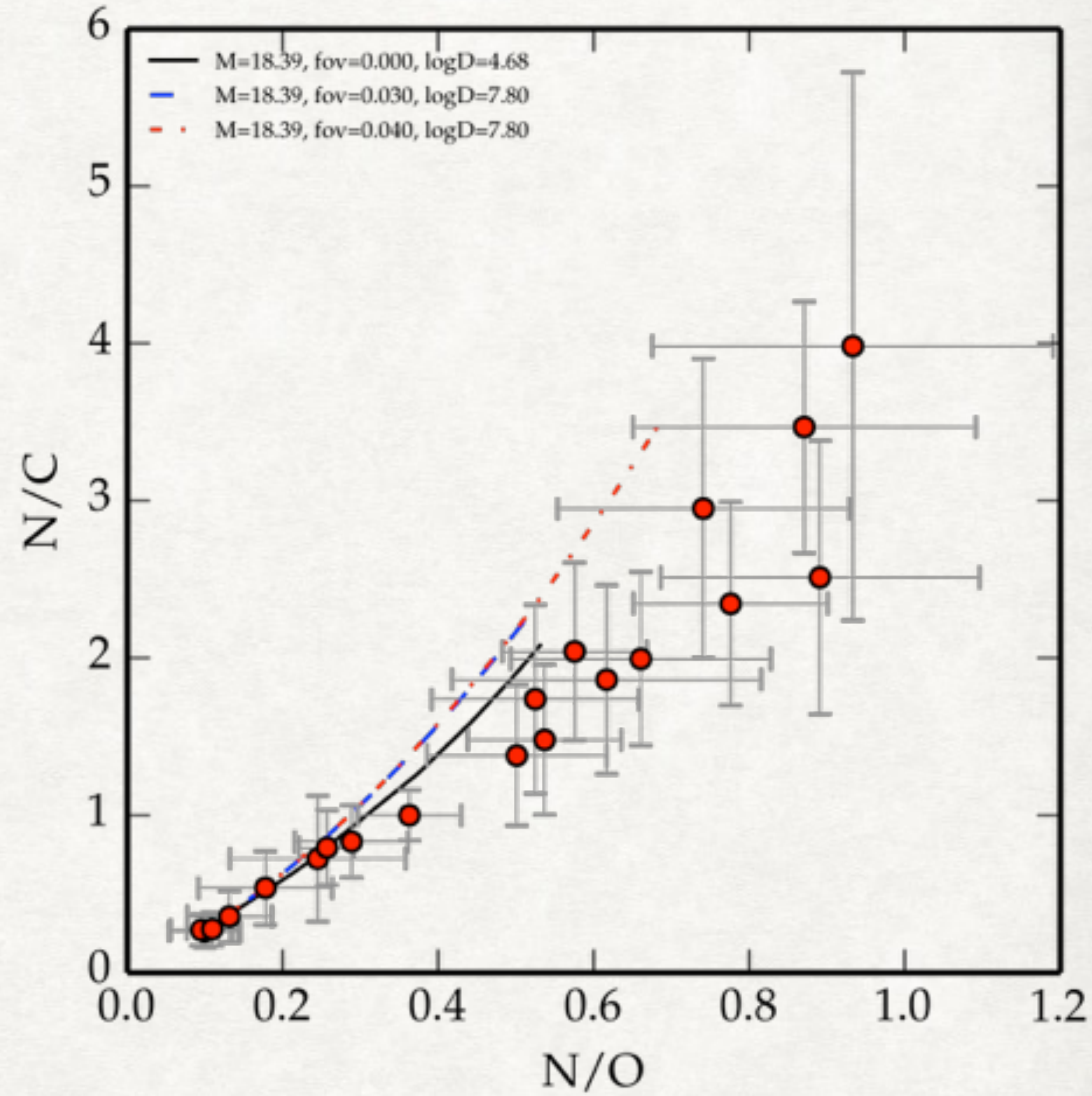
log [surface gravity (cm s^{-2})] (dex)
Effective temperature (K)
3.4
3.6
3.8
4.0
4.2
4.4
23000
19000
16000
13000
11000
C1
C2
C3
C4
C5
C6
C7
C8
C9A
C9B
K1A
K1B
K2
K3
KIC 3459297
KIC 4930889 B
KIC 11971405
KIC 4930889 A
KIC 6352430 A
KIC 9020774
6R⊙
5R⊙
4R⊙
3R⊙
32Myr
64Myr
128Myr
7.9M⊙
6.3M⊙
5.0M⊙
4.0M⊙
3.1M⊙
2.5M⊙
n (ℓ=1,2)
3
9
15
21
27
33
39
45
51
57
63

Papics+ (2016)

MIXING



Przybilla et al. (2010) using GENEVA rotating models



My results using core overshooting and extra diffusive mixing