Astrophysique Théorique et
Astérosismologie

KITP Conference
The Impact of Asteroseismology
across Stellar Astrophysics
Santa Barbara

Unveiling the internal structure of pulsating massive stars

Mélanie Godart

Marc-Antoine Dupret and Arlette Grotsch Noels

Collaborators: J. Montalban, P. Ventura
and C. Aerts, P. Eggenberger, K. Lefever,, S. Simon Diaz

October, 27 2011

Introduction

Maeder 1981 , Chiosi and Maeder 1986, …

NOW asteoseismology!

Introduction

Massive stars present various kinds of modes:

- β Cephei type modes: low order p- and g-modes
- SPB type modes: high order g-modes
- Strange modes

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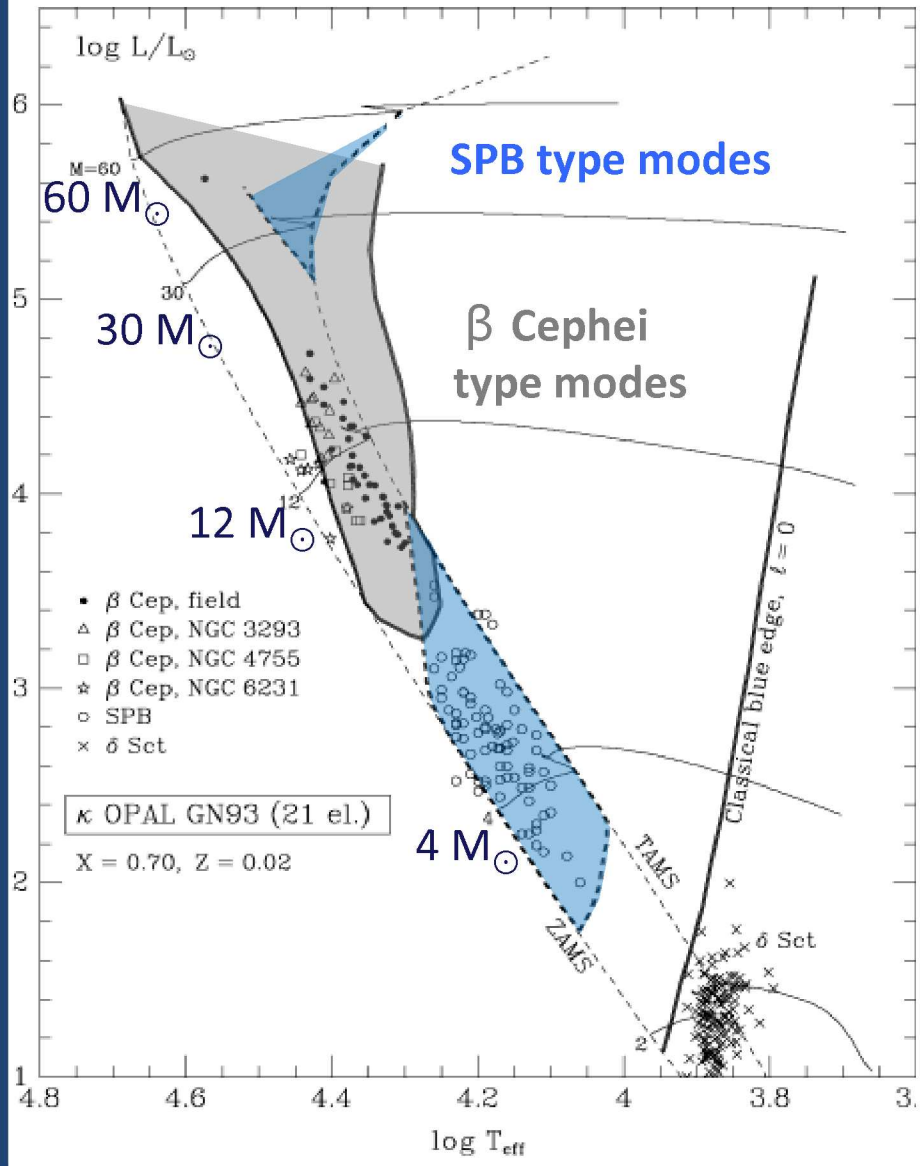
INSTABILITY DOMAINS

WHAT HAS BEEN DONE ?

Pamyatnykh (1993,1999)

Miglio (2007) and Pamyatnykh (2007) with OPAL/OP and GN93/AGS05

Pamyatnykh (1999)



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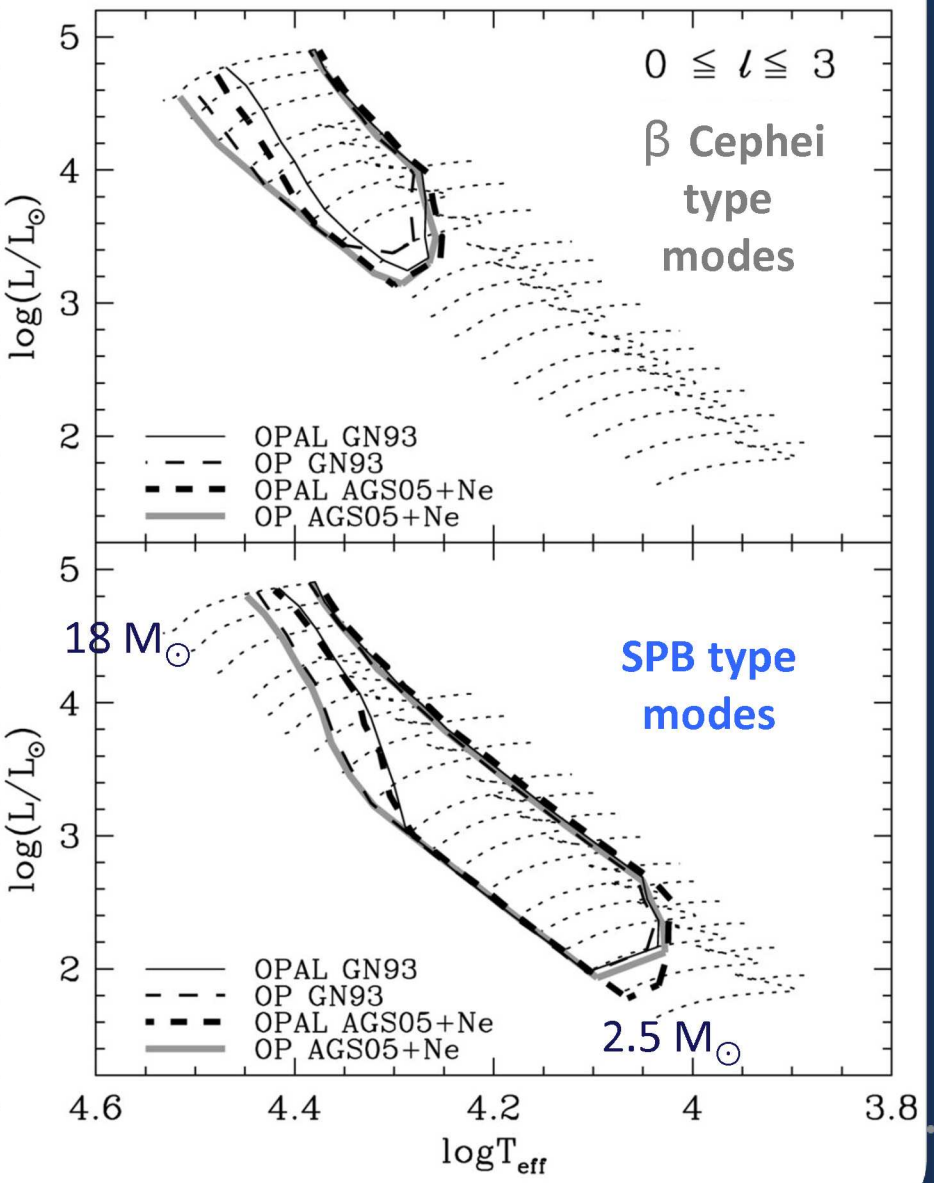

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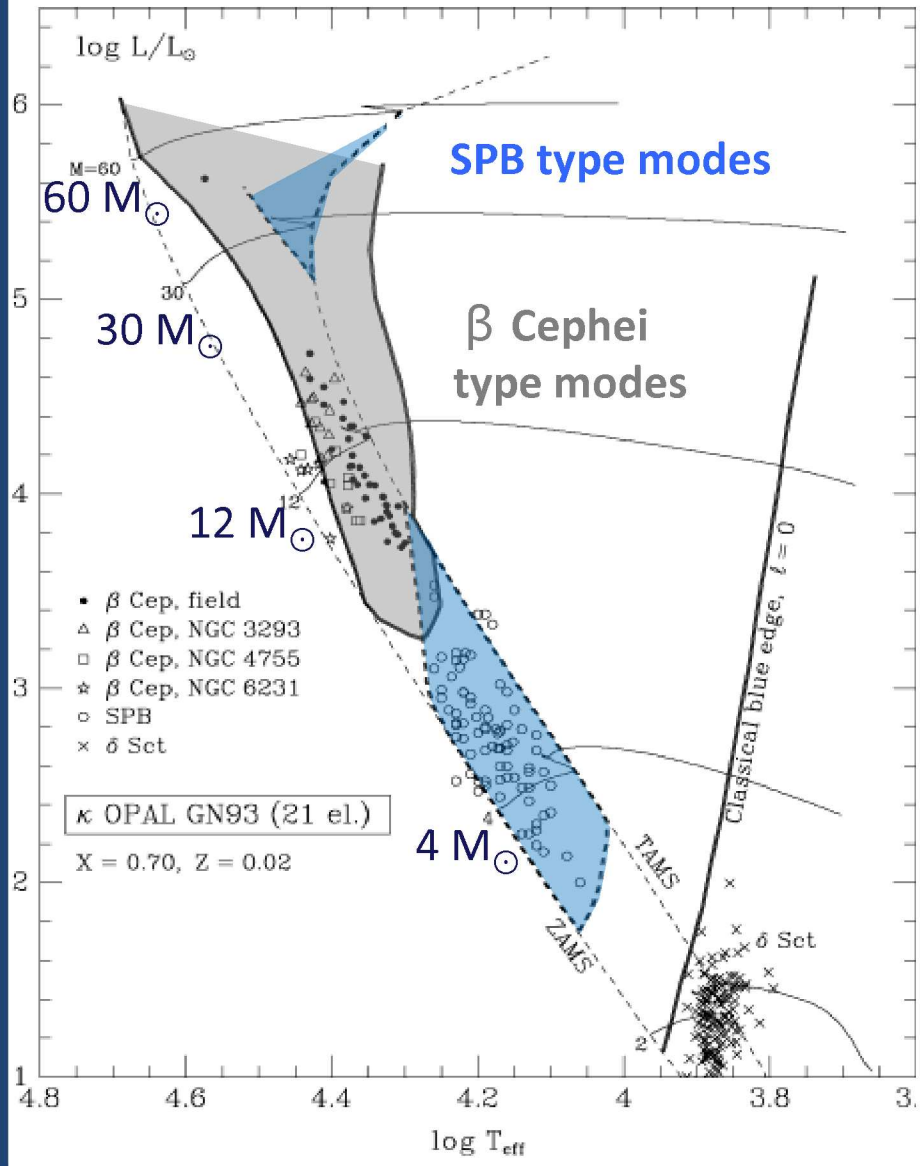
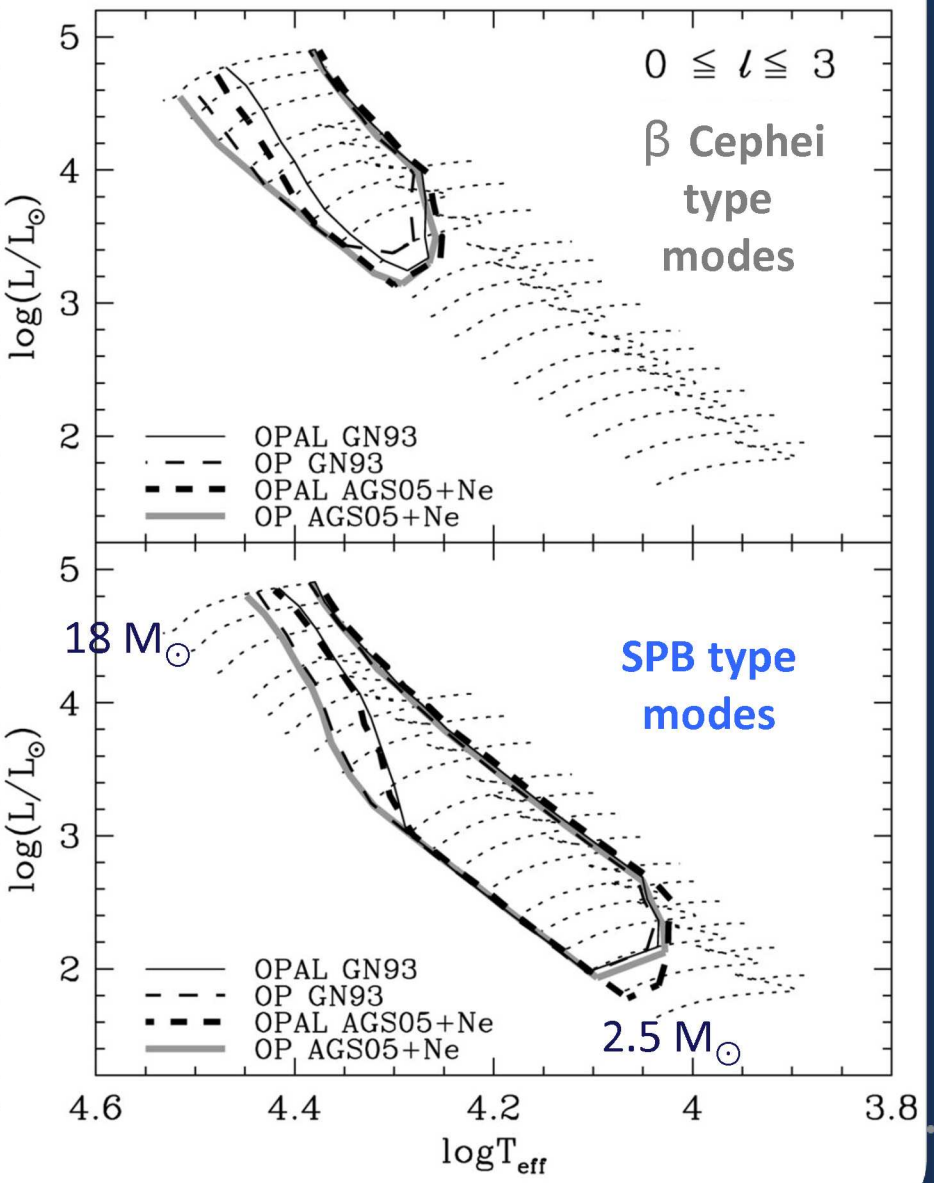


Miglio (2007)

+ Pamyathnykh (2007)



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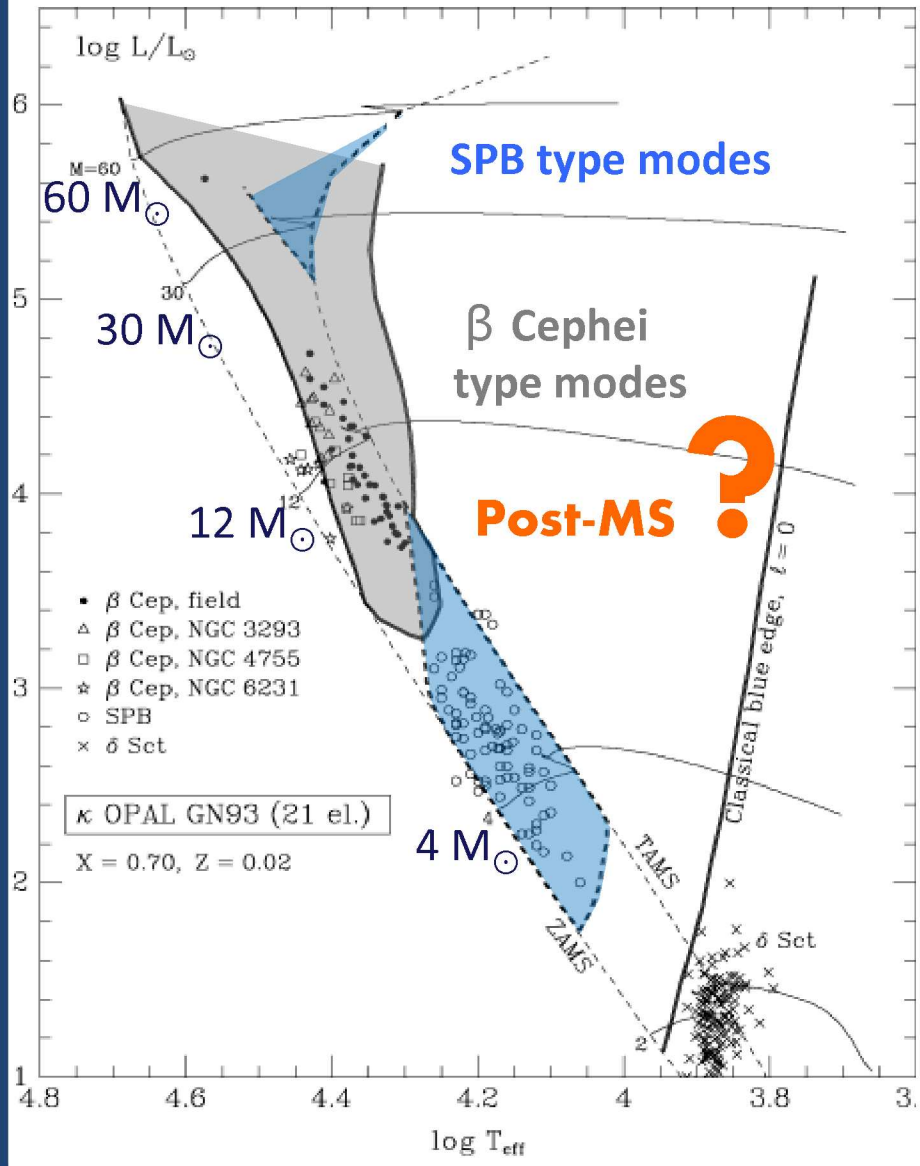

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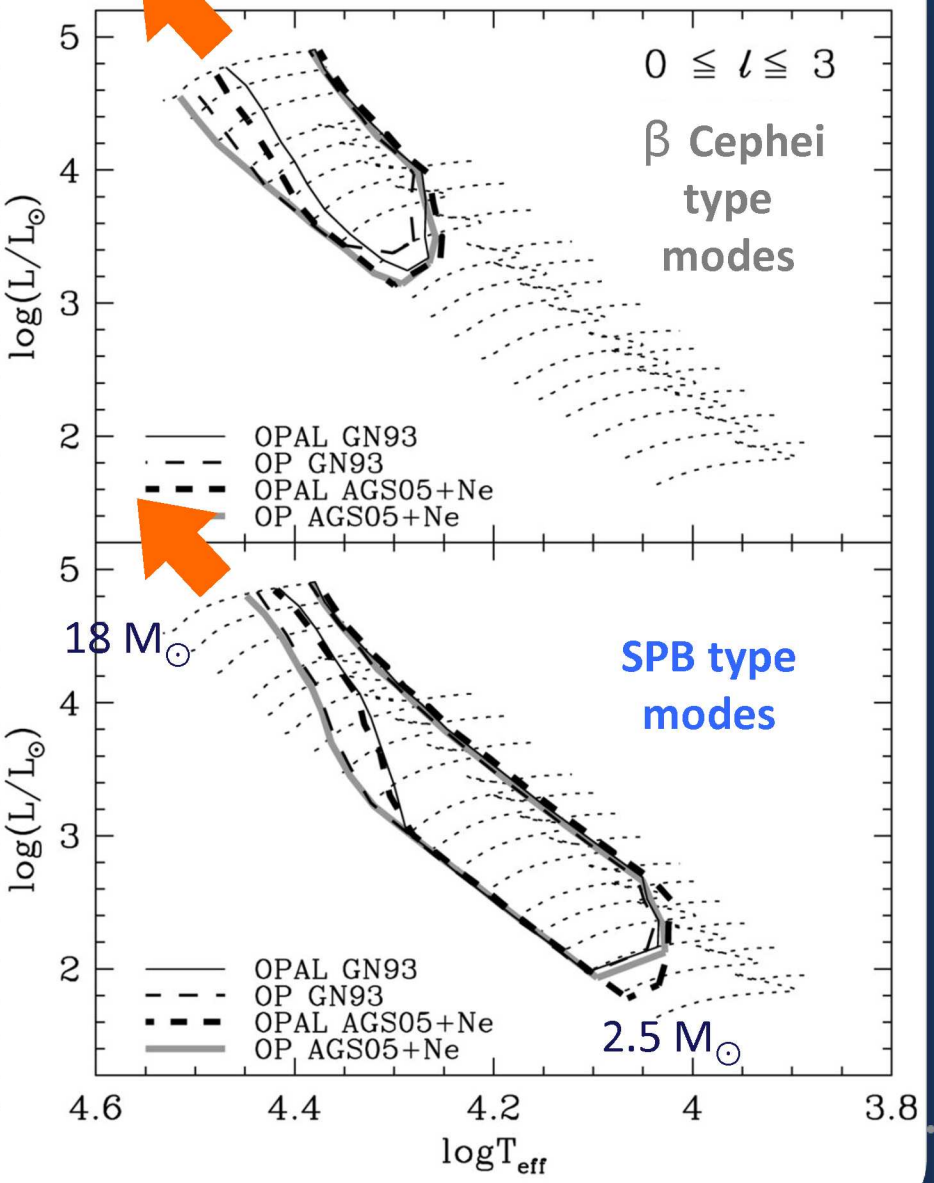

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MS for high order g-modes

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2 – 18 $M_\odot$

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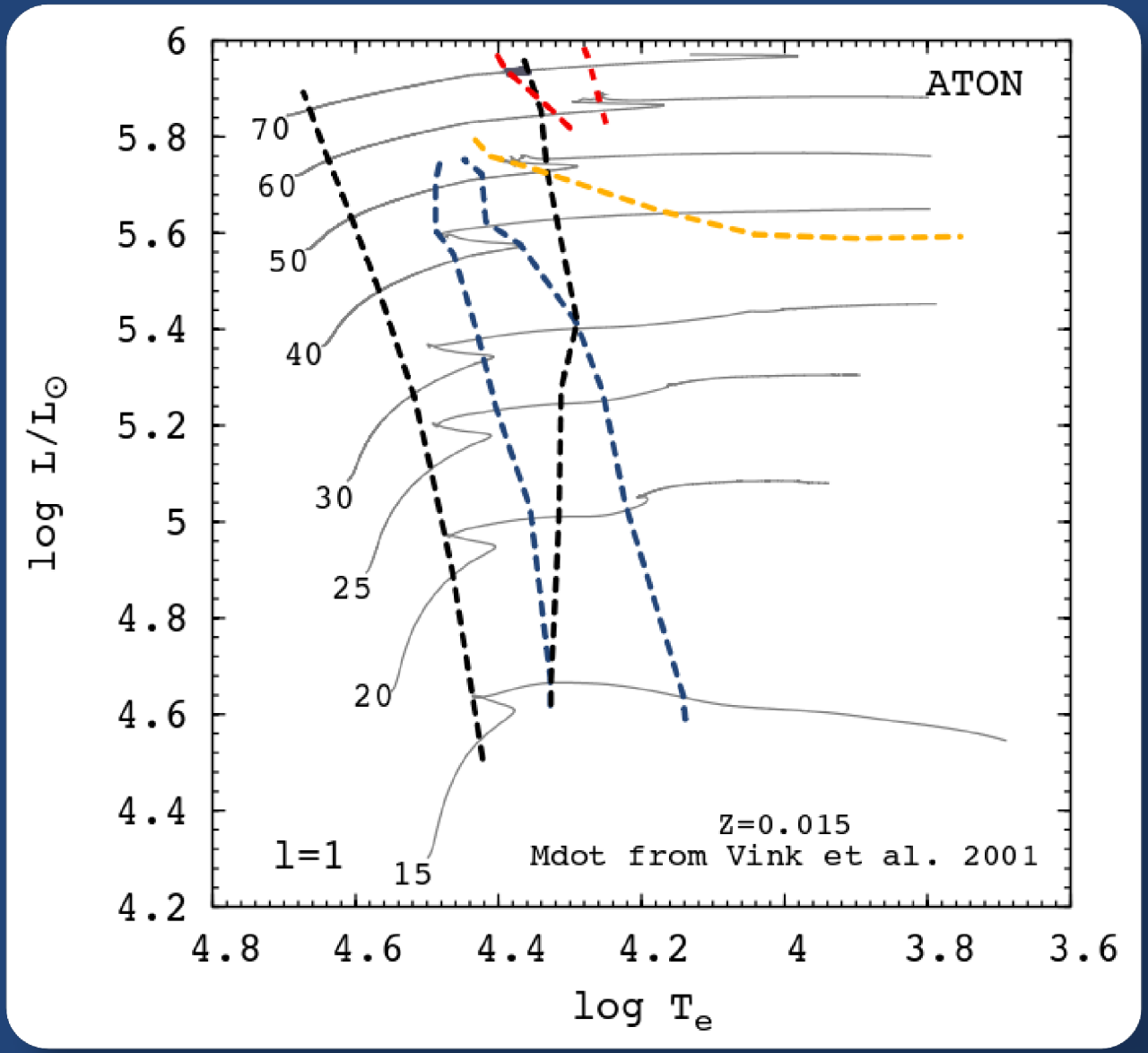
LARGER MASSES, POST-MS

stellar models ATON evolution code (Ventura et al. 2008)

non-adiabatic frequencies and excitation MAD (Dupret et al. 2003)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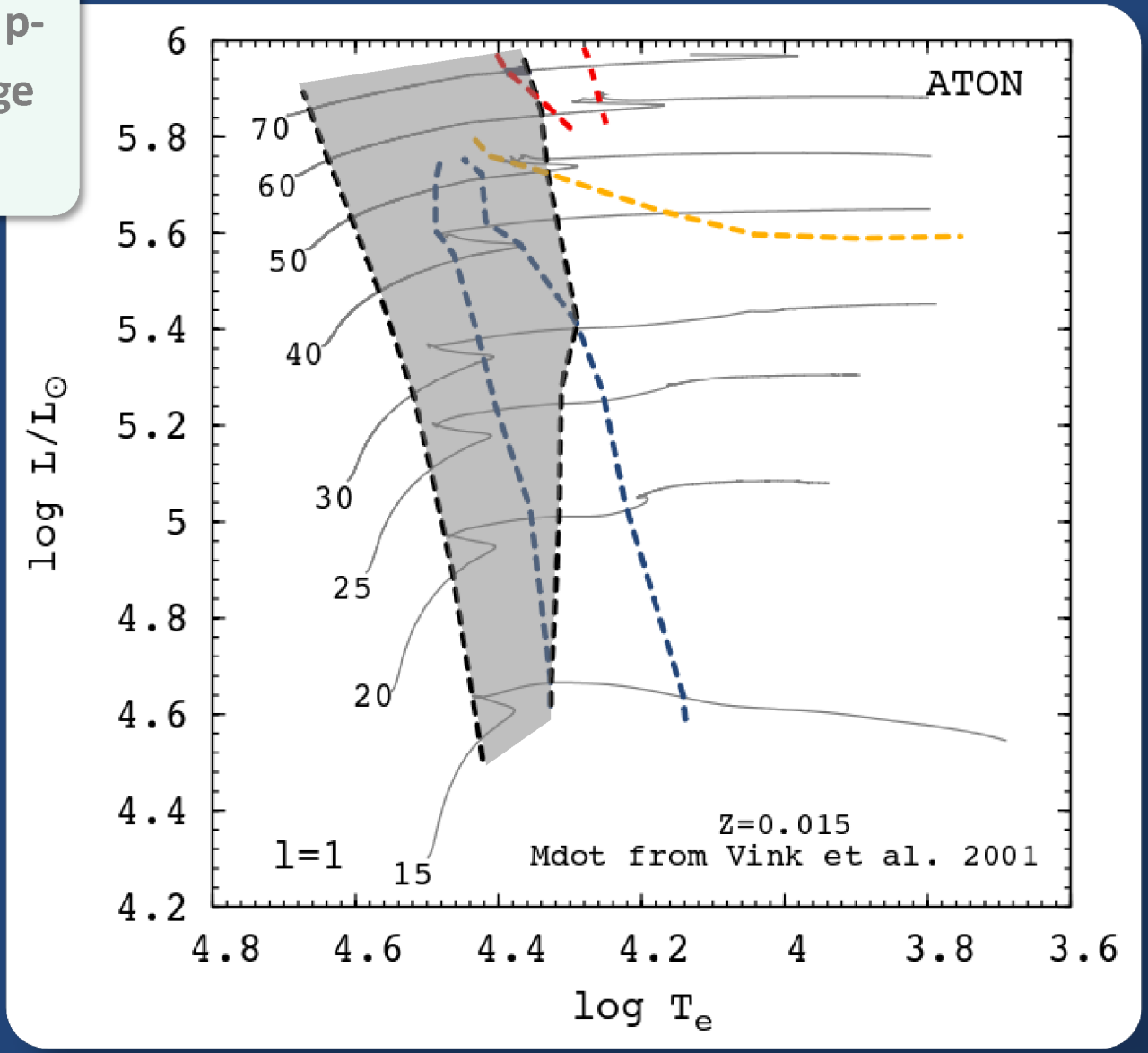
Low order p- and strange modes



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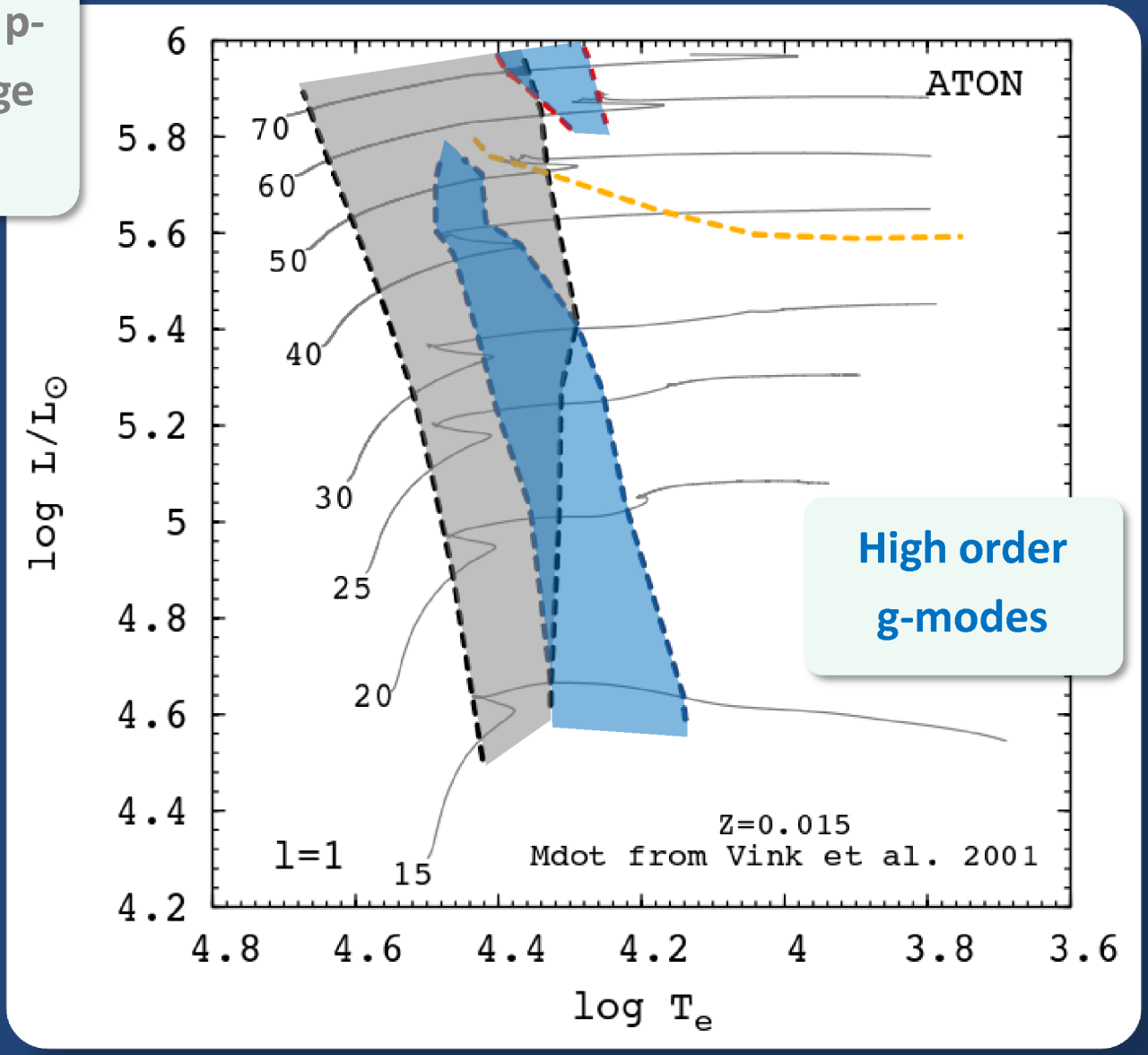

High order g-modes

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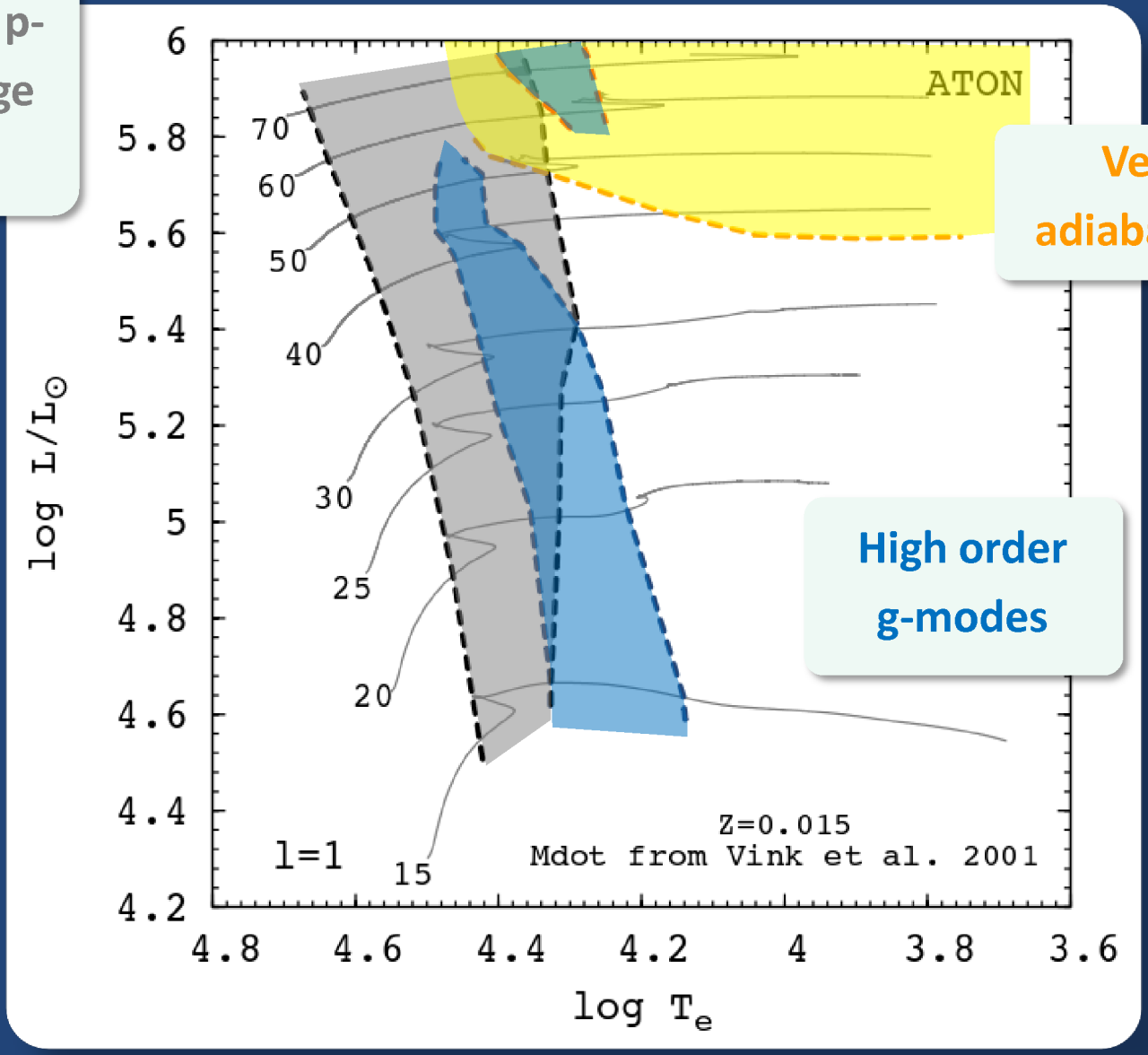
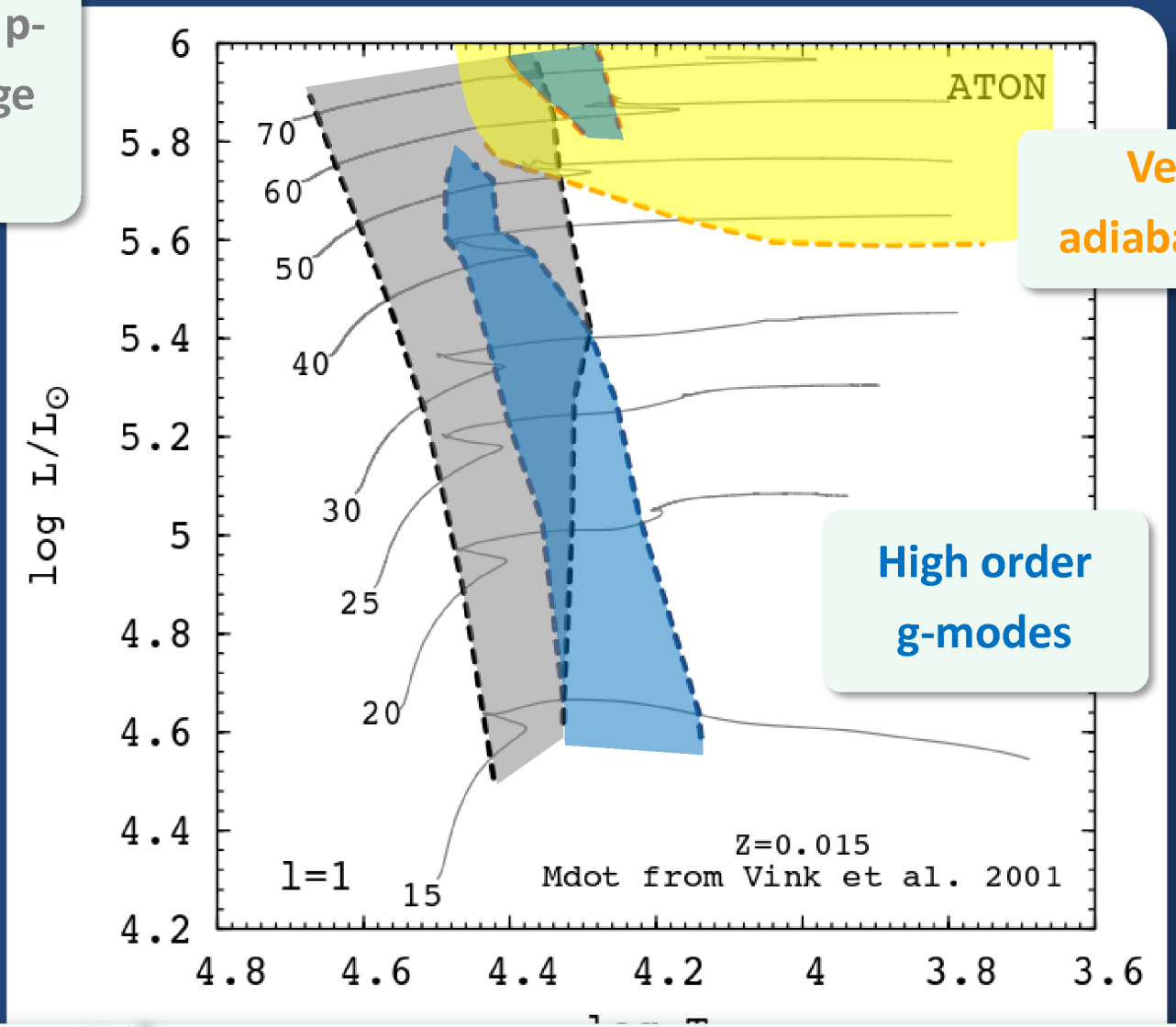


Very non-adiabatic modes

High order g-modes

Low order p- and strange modes



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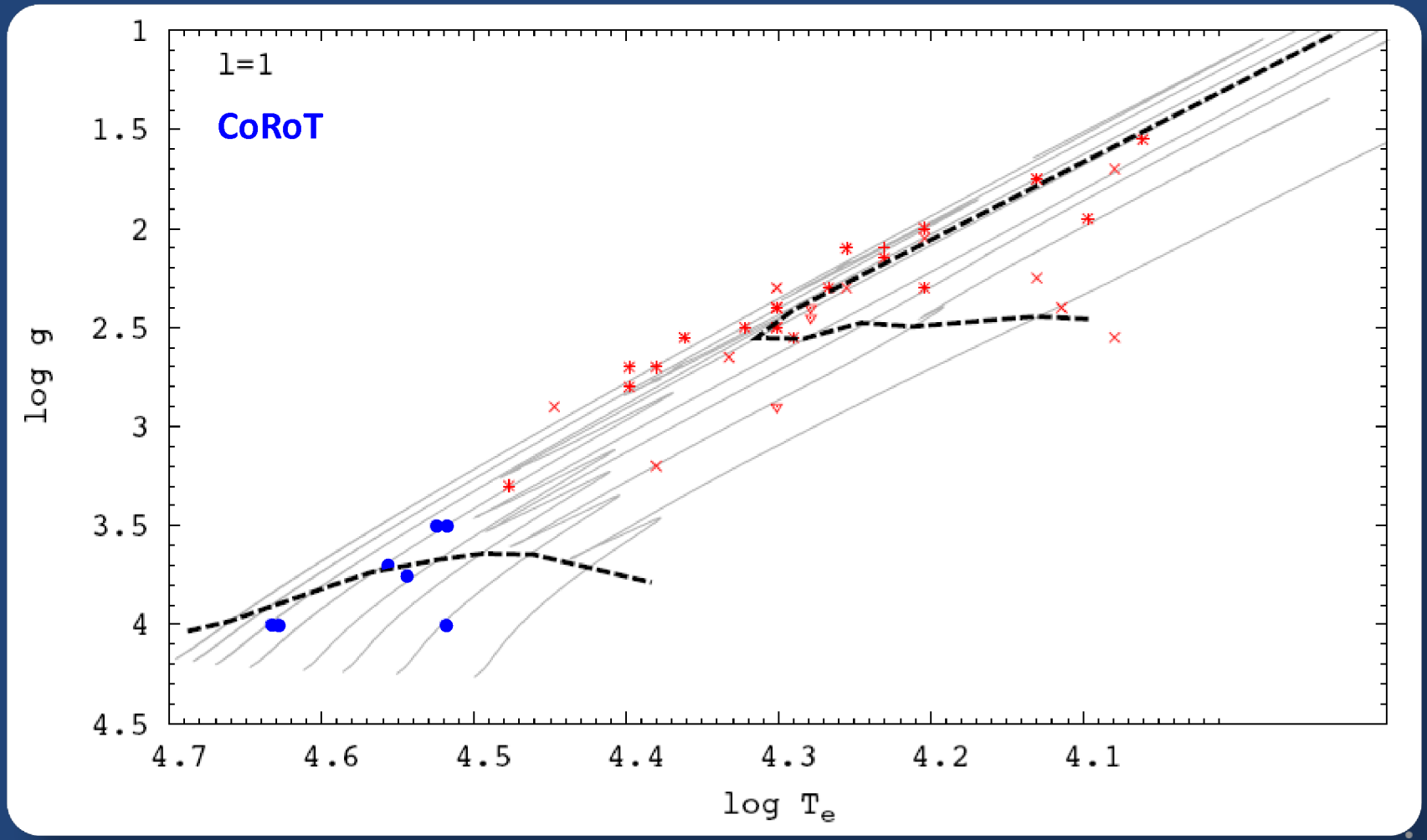
High order g-modes

To be compared with Saio 2011, MNRAS

Main sequence massive CoRoT stars: low order p- and g-modes



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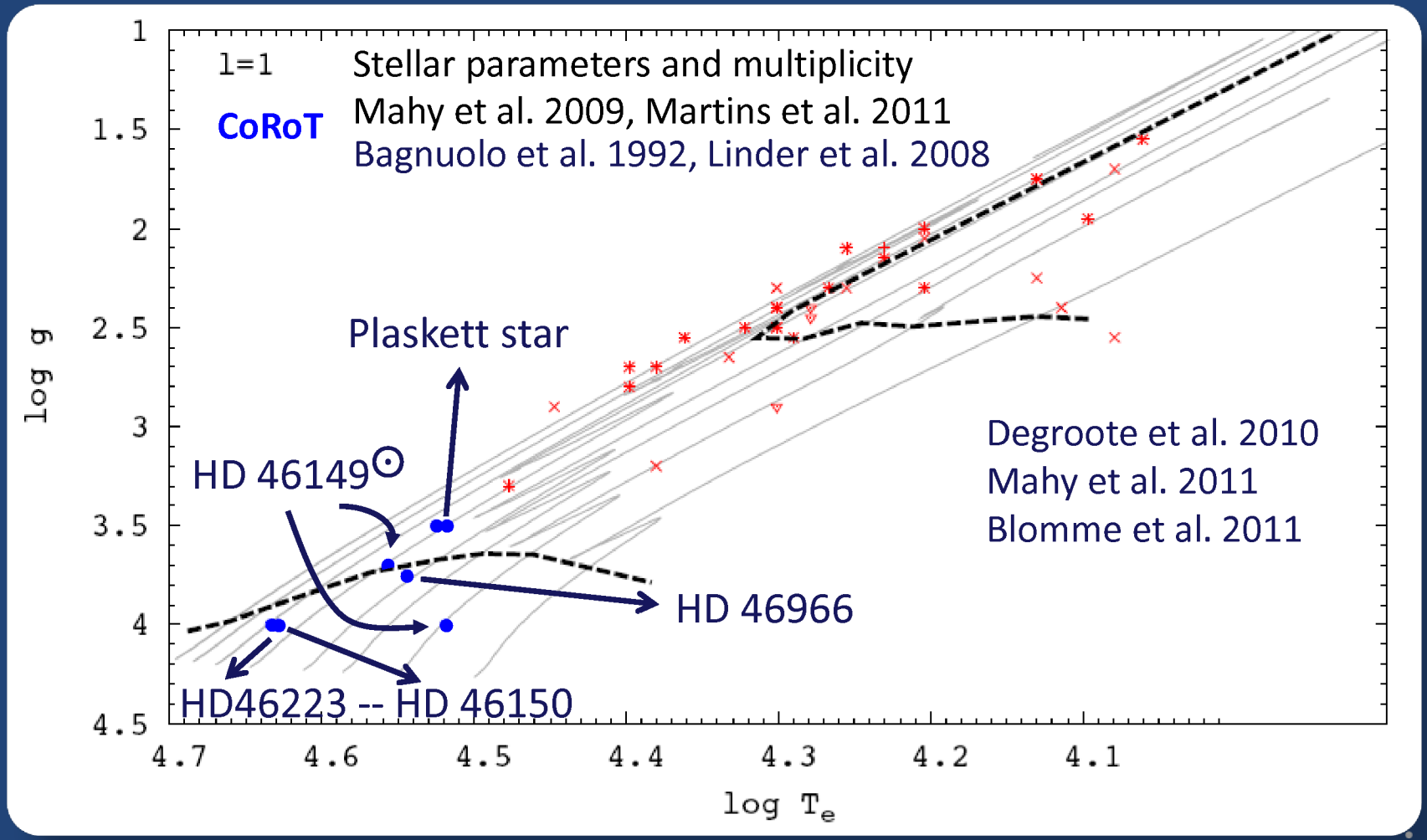


PROBE DEEPEST LAYERS

Post-main sequence massive stars: high order g-modes

Godart et al. 2009

post-MS

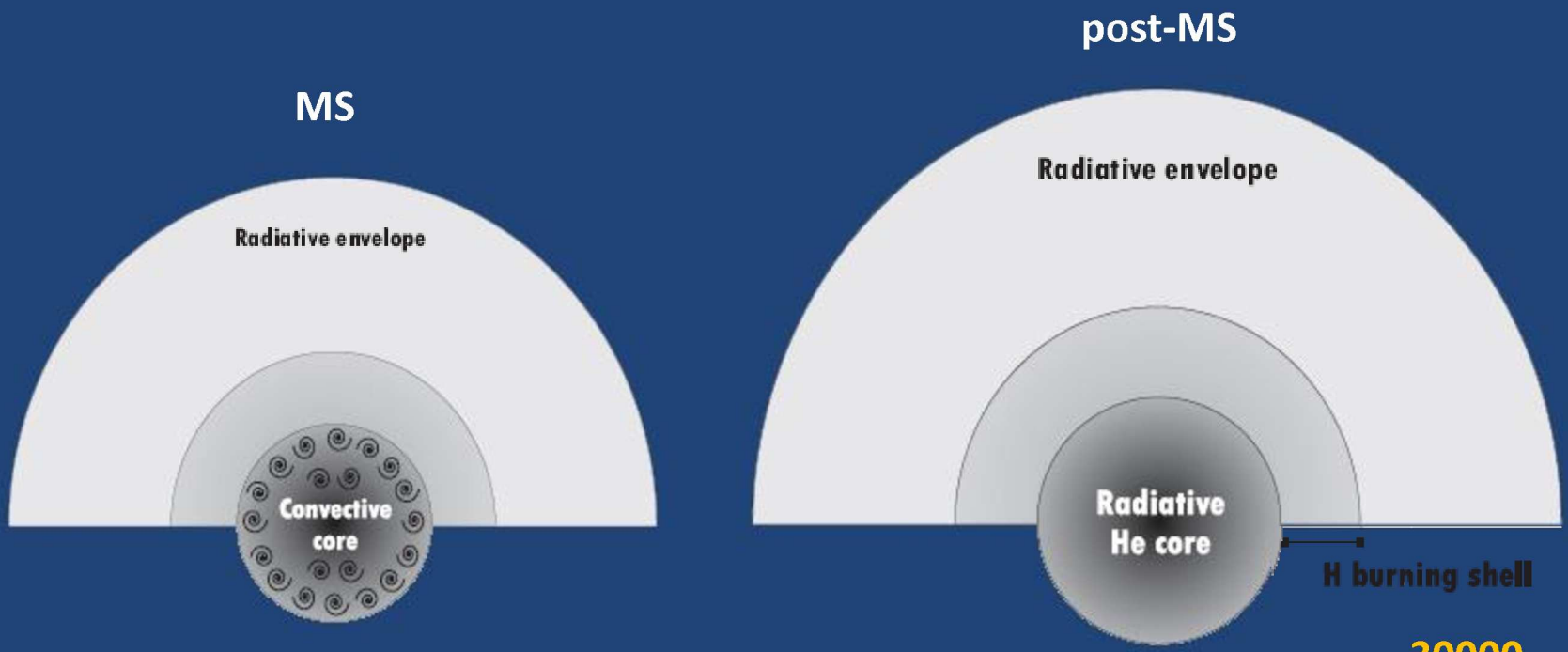
MS

Convective core

Radiative envelope

Radiative core

Radiative envelope



High ρ contrast

30000

Large N frequency

$$N^2 \simeq \frac{g^2 \rho}{P}[\nabla_{ad} - \nabla + \nabla_\mu]$$

Strong radiative damping
No g-modes !!

$$k_r = \sqrt{\ell(\ell+1)}\ \frac{N}{(\sigma r)}$$

Post-main sequence massive stars: high order g-modes

This is the case for SPB stars

BUT **g-modes observed in massive post-MS stars:**

Post-main sequence massive stars: high order g-modes

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◇ 48 frequencies ($\lesssim$ 2.8 c/d, ampl~ mmag) in HD 163899 (Saio et al. 2006)

- B2 Ib/II (Schmidt & Carruthers 1996)
- observed by MOST during 37 days

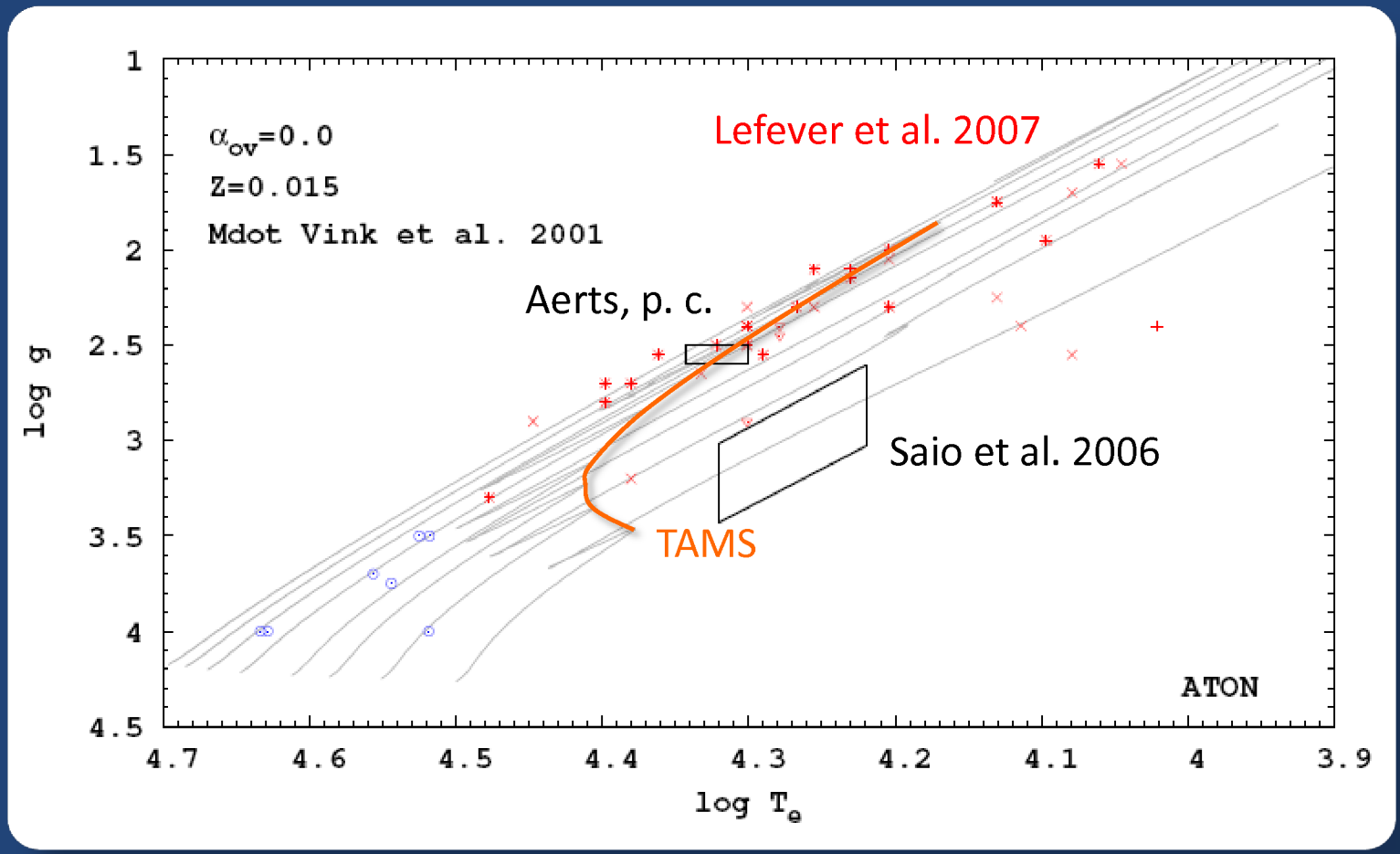
p and g-mode pulsations

Slowly pulsating B supergiants
SPBsg
(Saio et al. 2006)

◇ Lefever et al. (2007) sample B supergiants

suggest non-radial pulsations excited by the κ-mechanism

Post-main sequence massive stars



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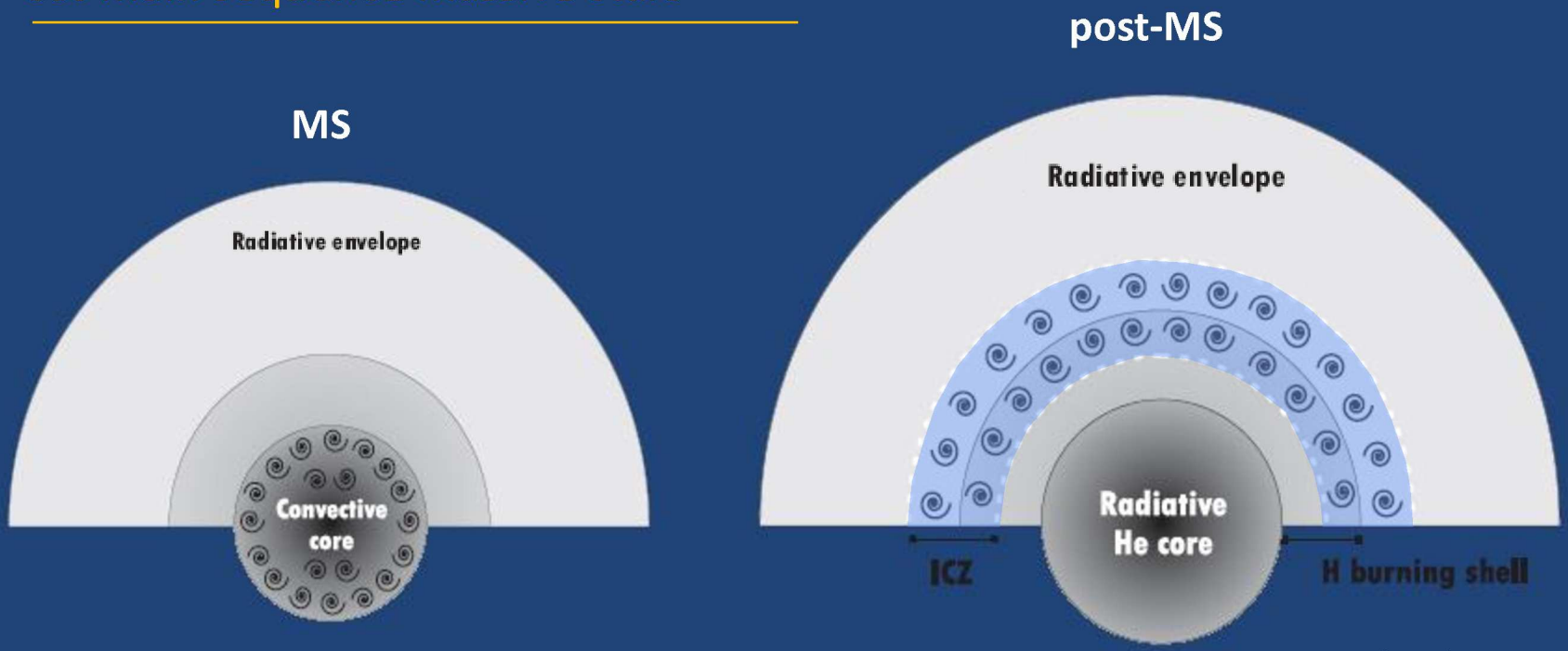
g-modes observed ? thanks to ICZ !

Post-main sequence massive stars



Intermediate convective zone (ICZ) in which g-modes are evanescent prevents the modes from entering the core (Saio et al. 2006)

K-mechanism drives the mode in the superficial layers

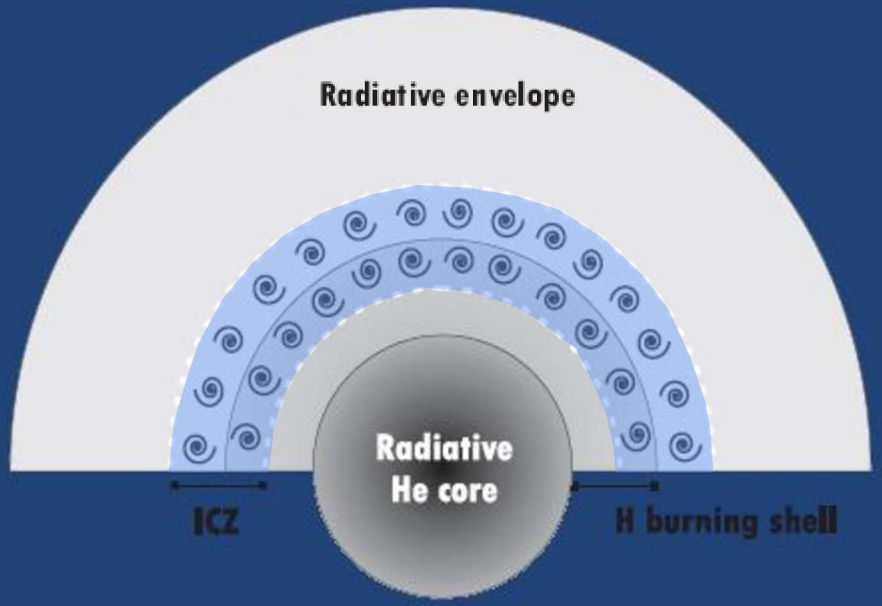
Post-main sequence massive stars

G-modes observed

BUT Large k

Numerical method ?

post-MS



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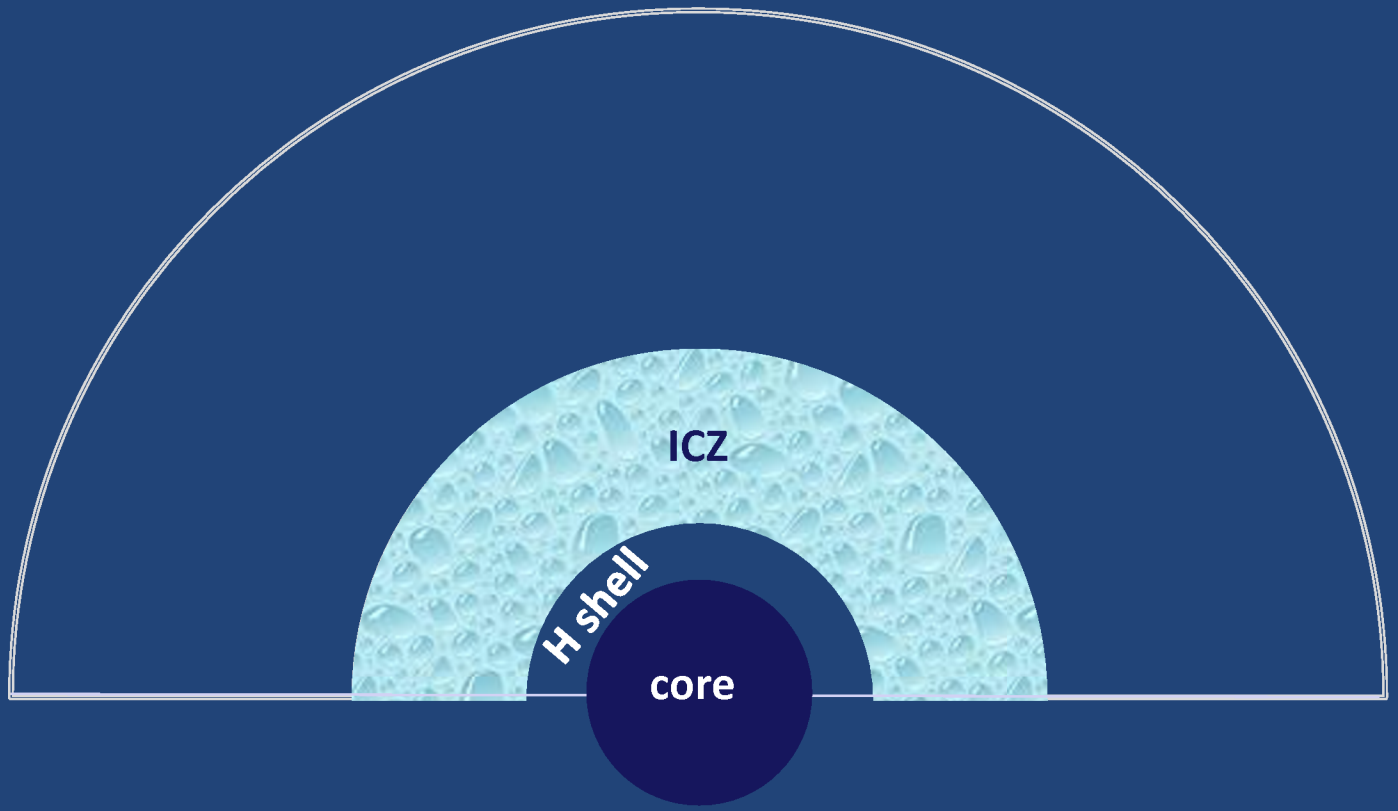
physical factors
MASS LOSS, OVERSHOOTING
can prevent the ICZ

(Godart et al. 2009)

Numerical method

- Stellar models: ATON evolution code (Ventura et al. 2008)
- Non-adiabatic frequencies: MAD (Dupret et al. 2003)



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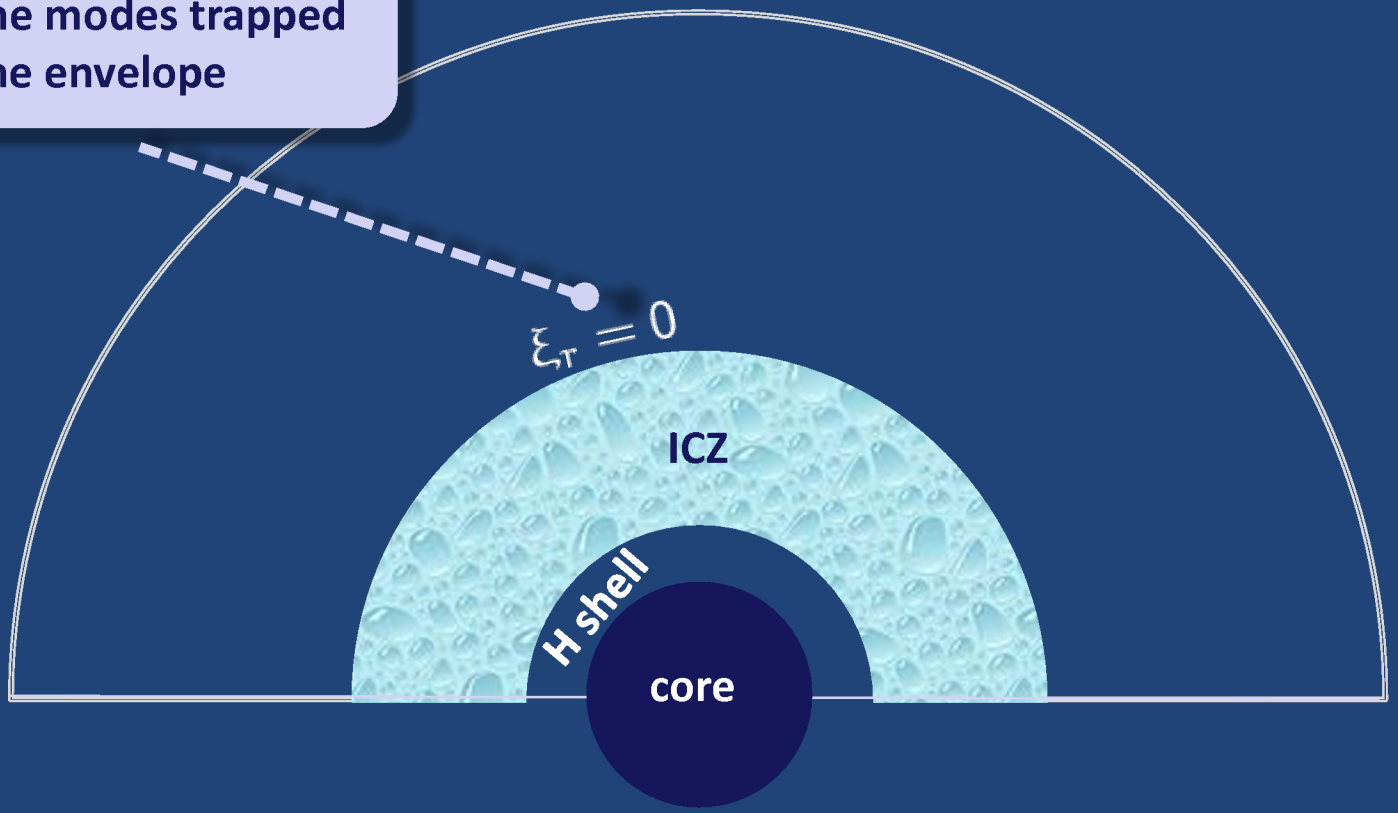

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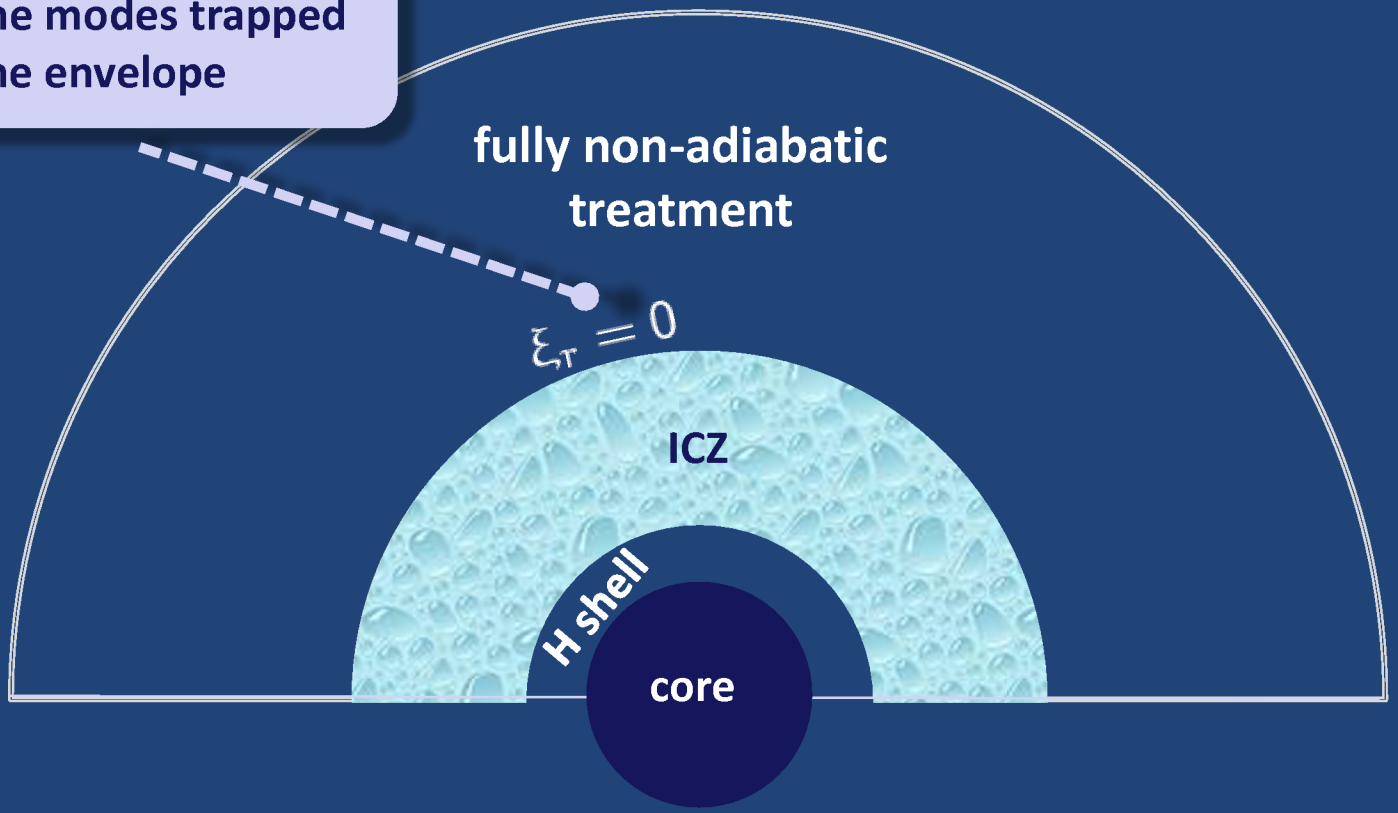

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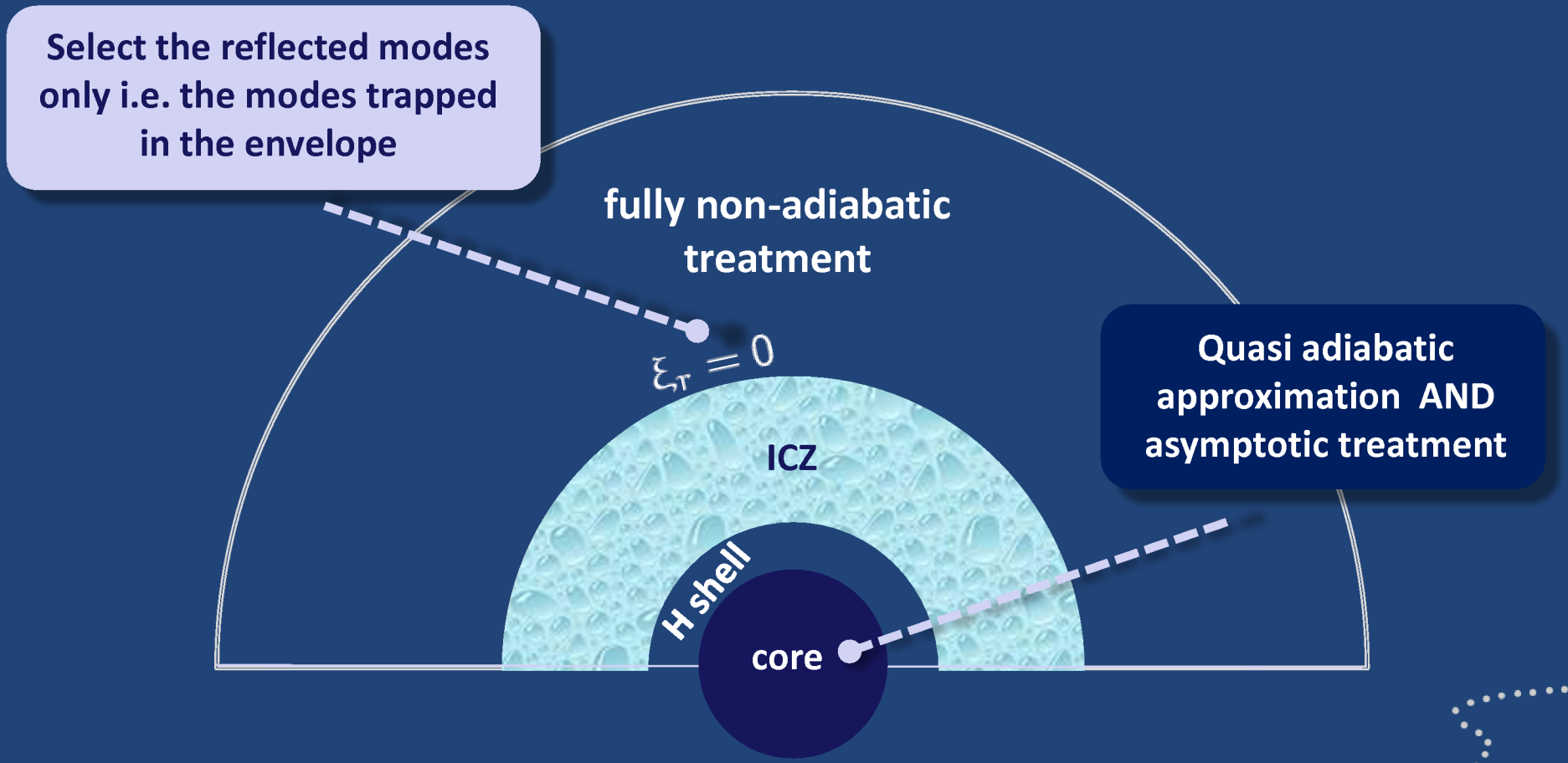
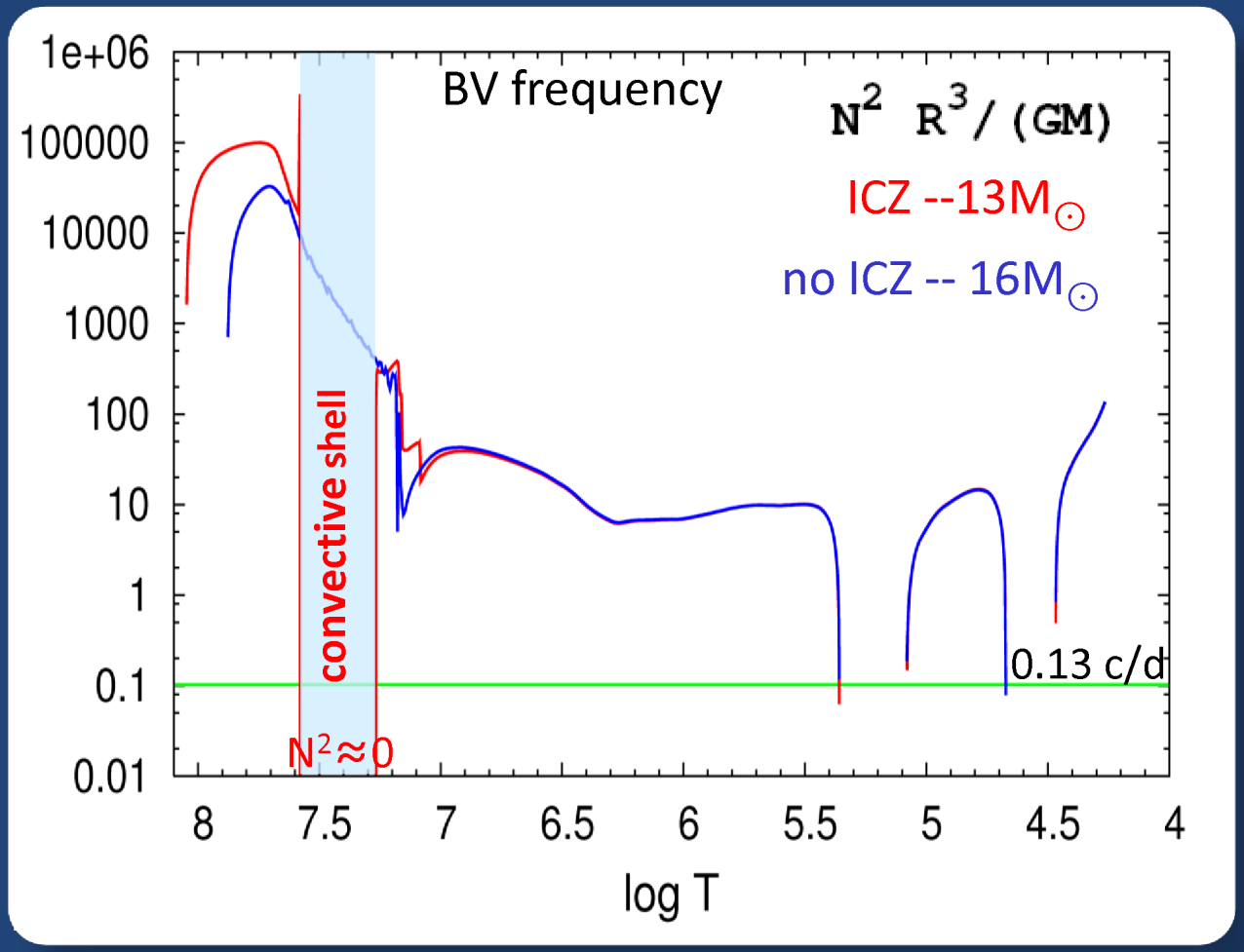
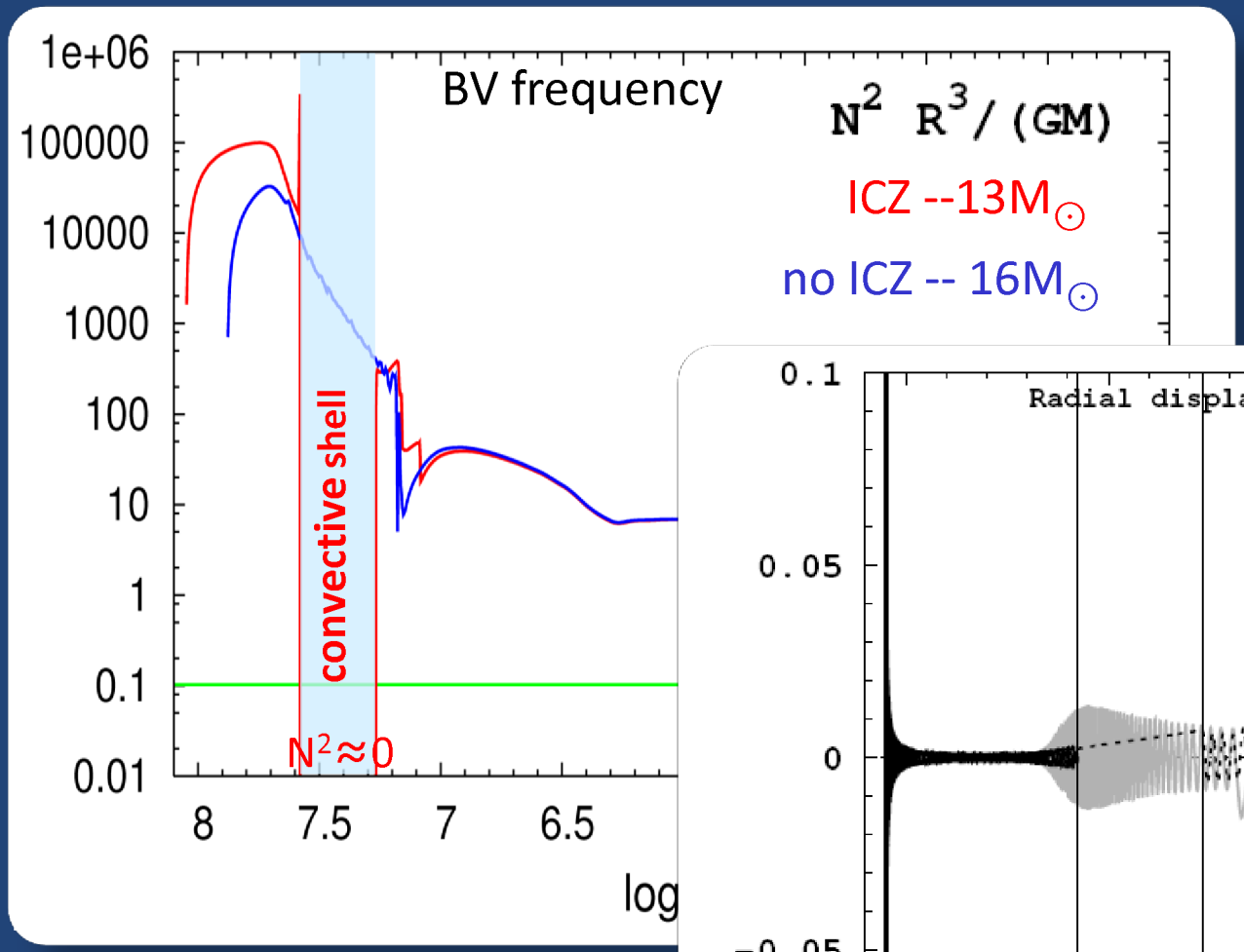



BV frequency
$N^2 R^3 / (GM)$
ICZ --13$M_\odot$
no ICZ -- 16$M_\odot$
convective shell
$N^2 \approx 0$
0.13 c/d
1e+06
100000
10000
1000
100
10
1
0.1
0.01
8
7.5
7
6.5
6
5.5
5
4.5
4
log T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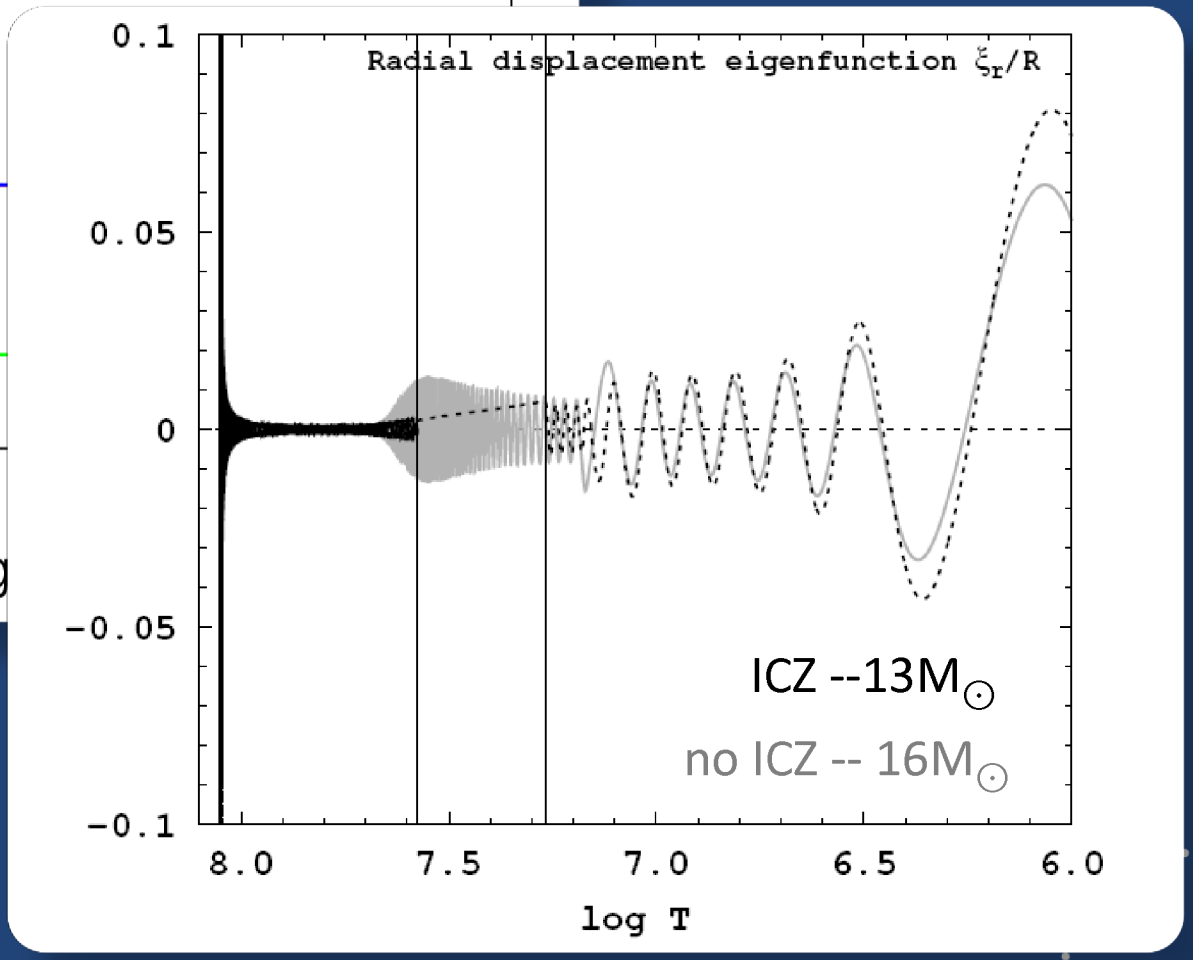
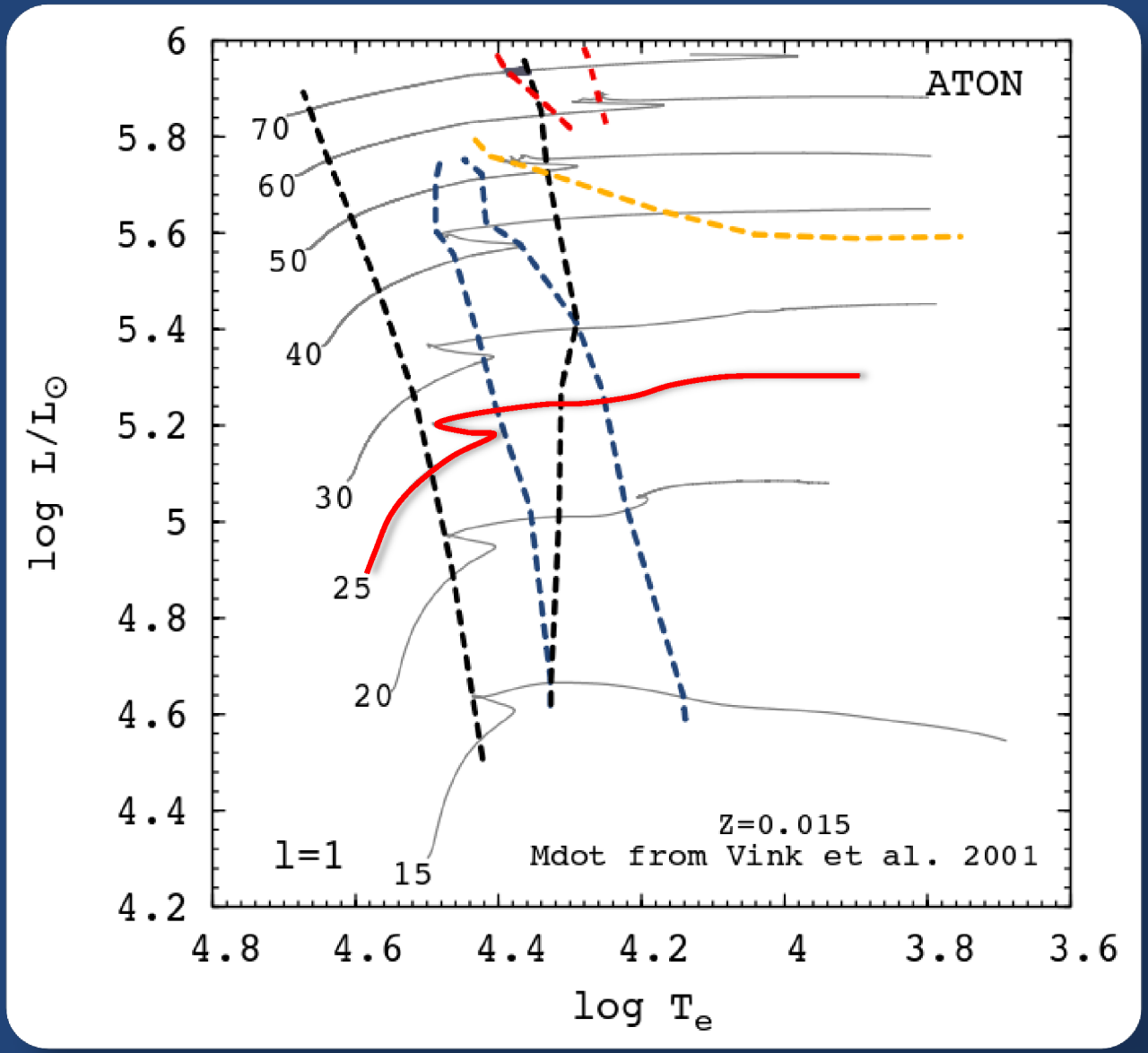

Radial displacement eigenfunction ξ_r/R
ICZ --13$M_\odot$
no ICZ -- 16$M_\odot$
0.1
0.05
0
−0.05
−0.1
8.0
7.5
7.0
6.5
6.0
log T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Z=0.015
Mdot from Vink et al. 2001
log L/L⊙
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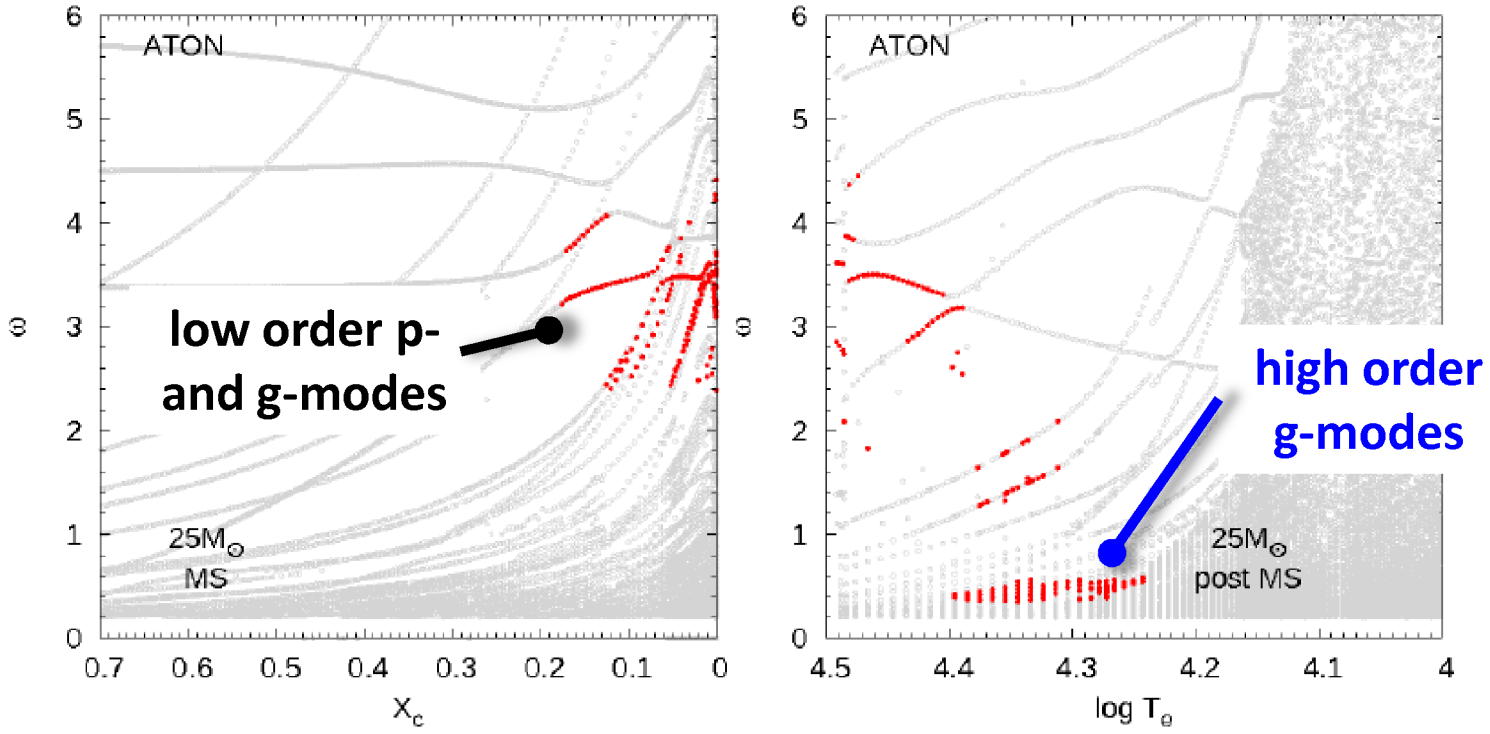
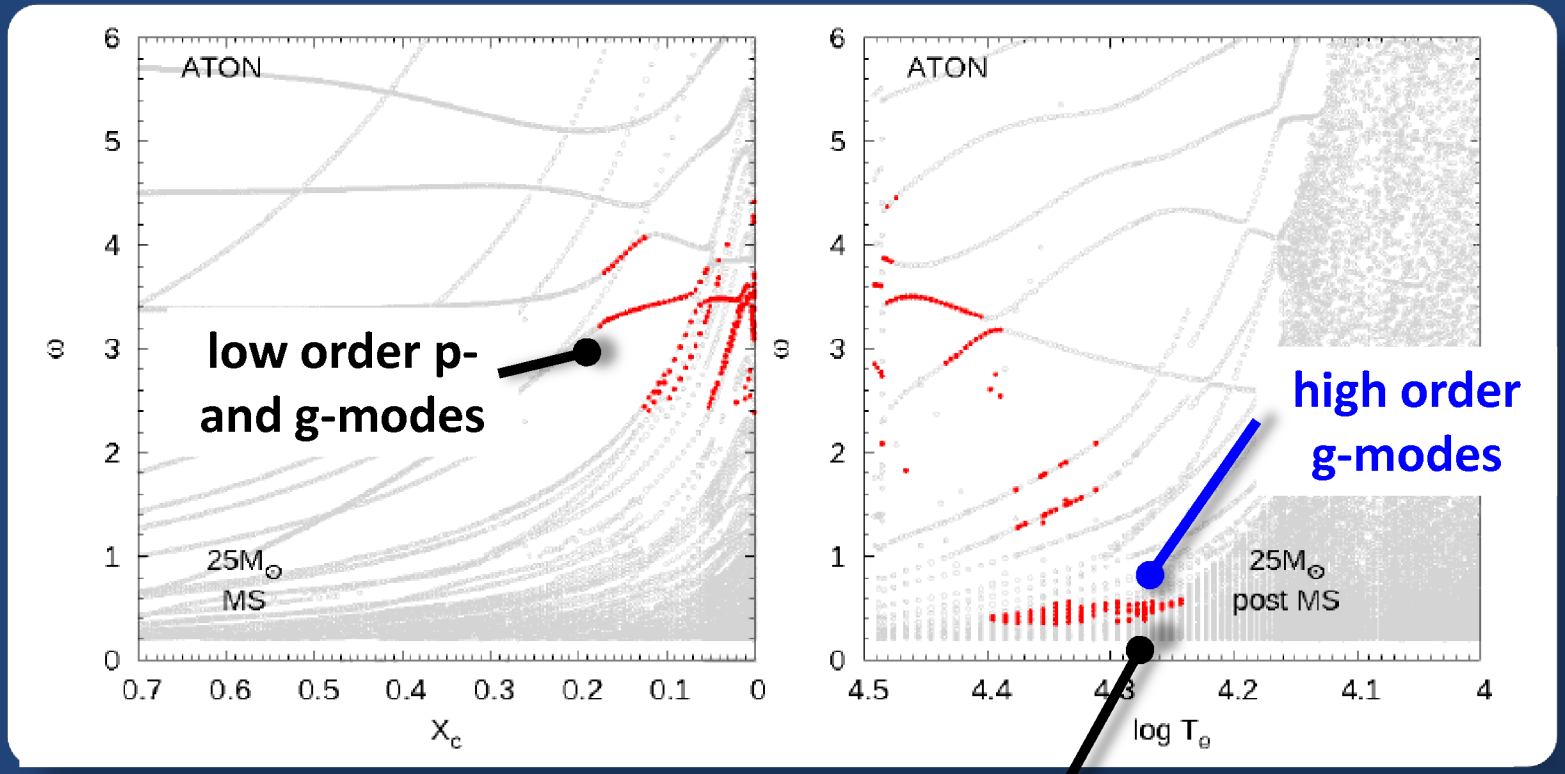
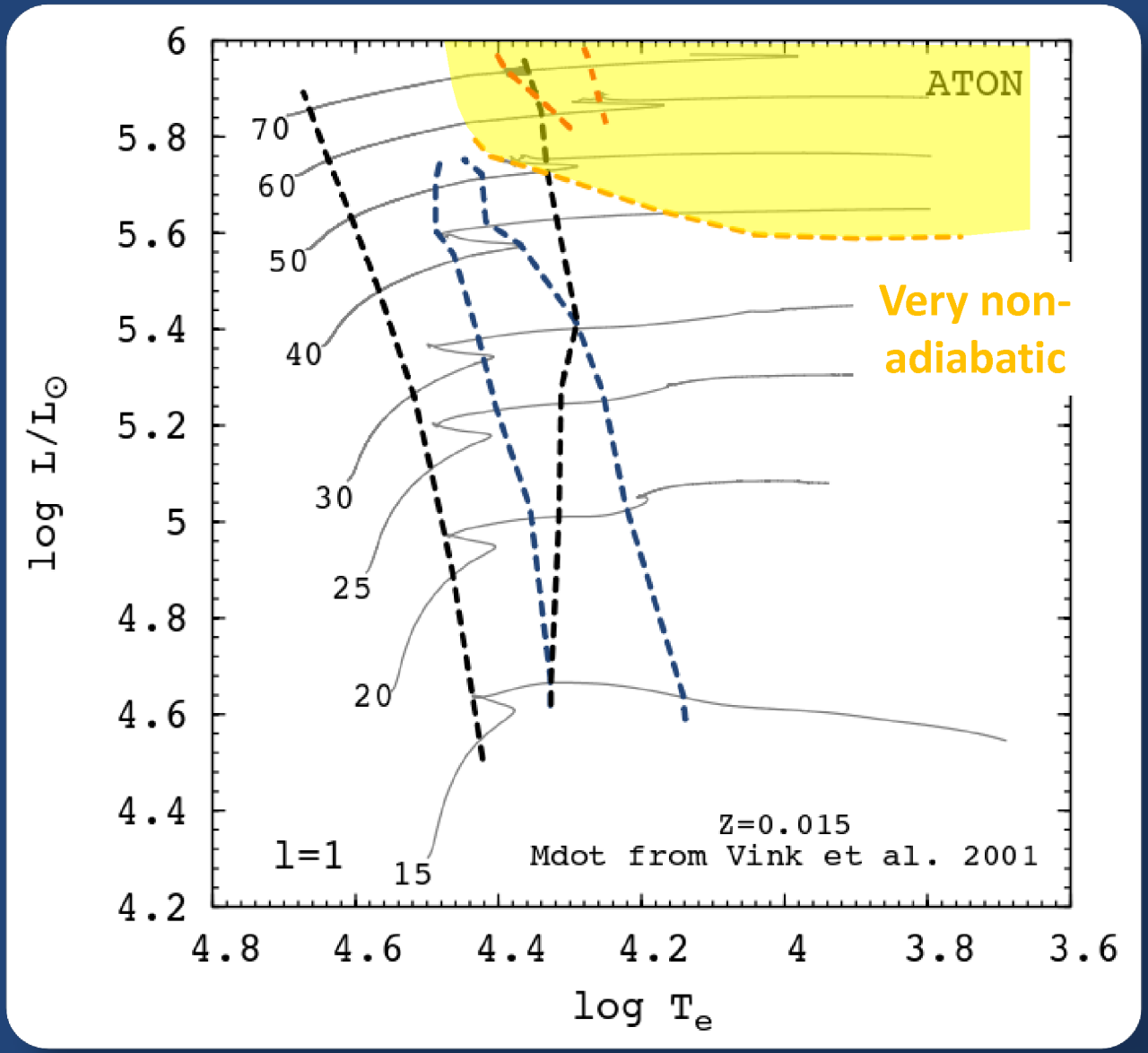

ATON
low order p- and g-modes
25M⊙ MS
ω
X_c
ATON
high order g-modes
25M⊙ post MS
log T_e



Strong radiative damping

→ small range of excited high order g-modes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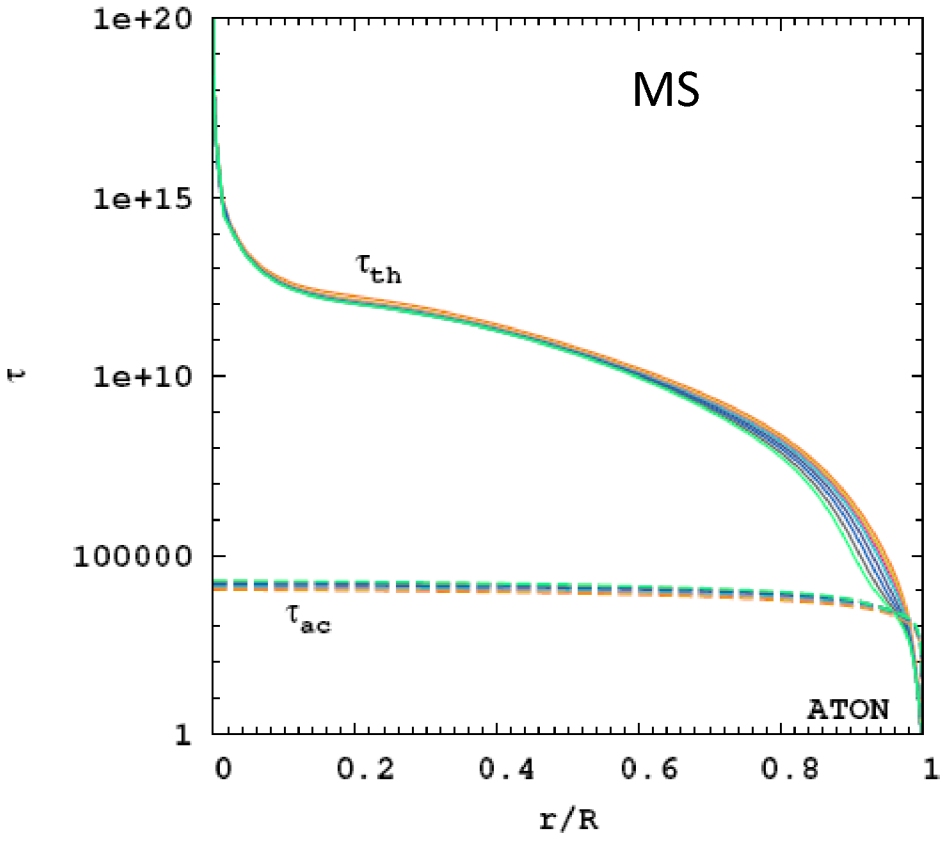
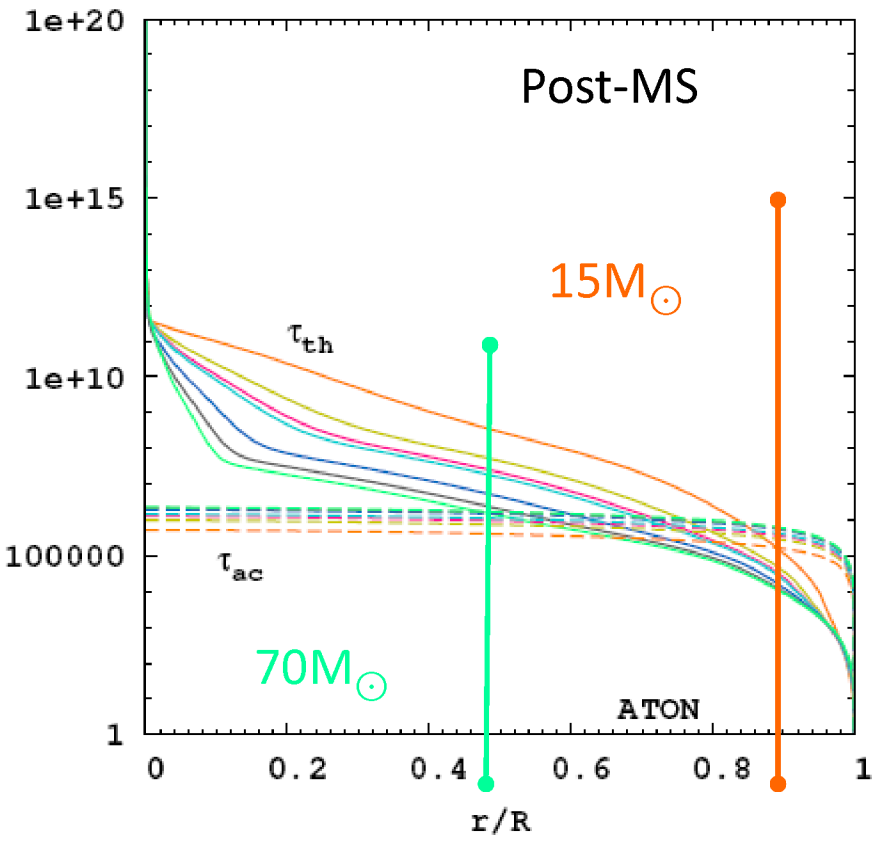
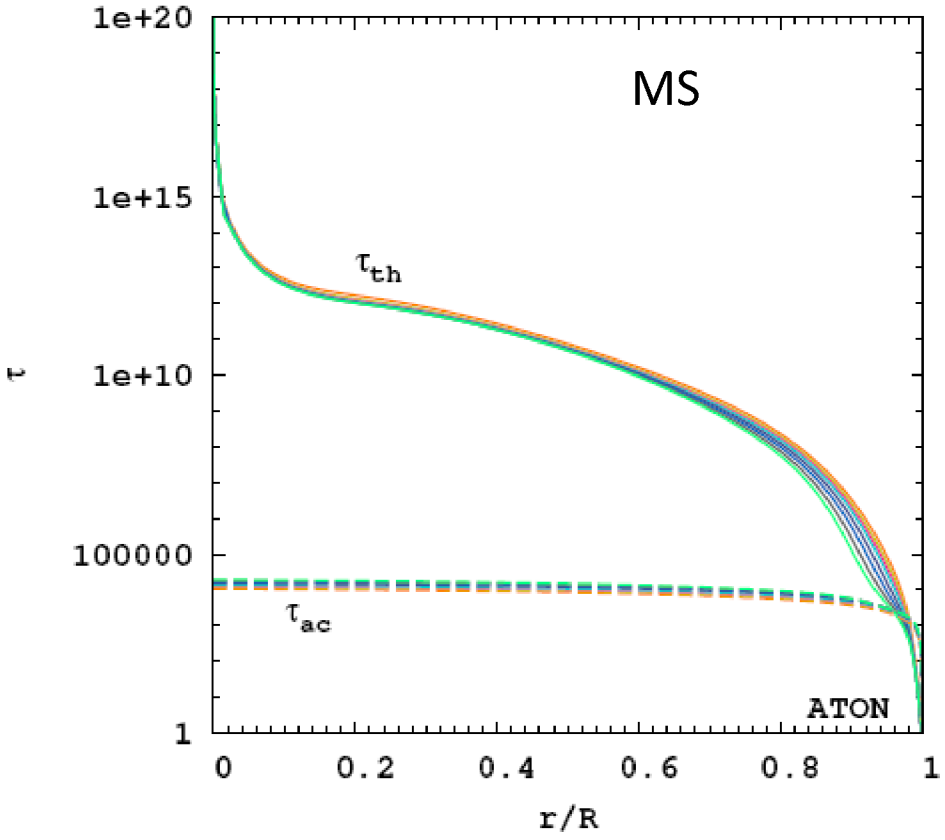
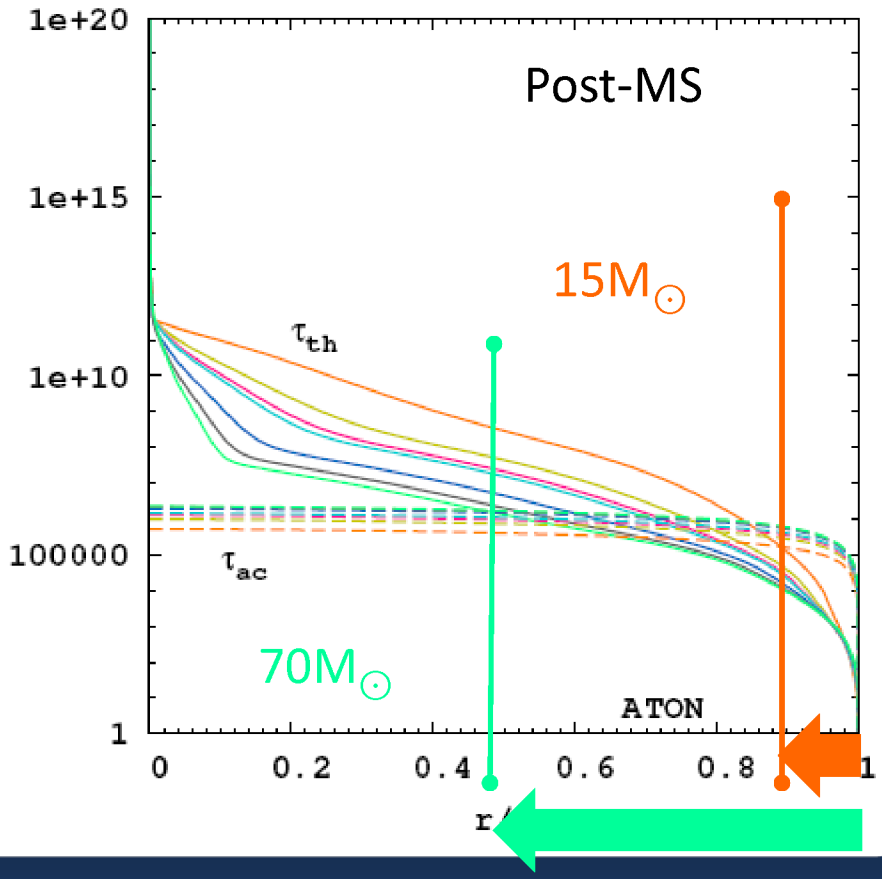




$$\tau_{ac} = \int_r^R \frac{dr}{c} \qquad \tau_{th} = \int_r^R \frac{c_v\, T}{L}\, 4\,\pi\, r^2\, \rho\, dr$$





non-adiabatic region

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Conclusions and perspectives

Asteroseismology of massive stars → probe physical phenomenon

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Asteroseismology of massive stars ➡ **probe physical phenomenon**

Deep layers

high order g-modes

Intermediate Convective Zone ➡ evolution

Mass loss, mixing and chemical profile

Superficial layers

Strange modes

Density inversion region

➡ opacity profile

Temperature inversion region

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New development

Extra broadening produced by pulsation modes
(Lucy 1976, Aerts et al. 2009)

Simon-Diaz 2010, 2011