What can we learn from asteroseismology of β Cephei stars?

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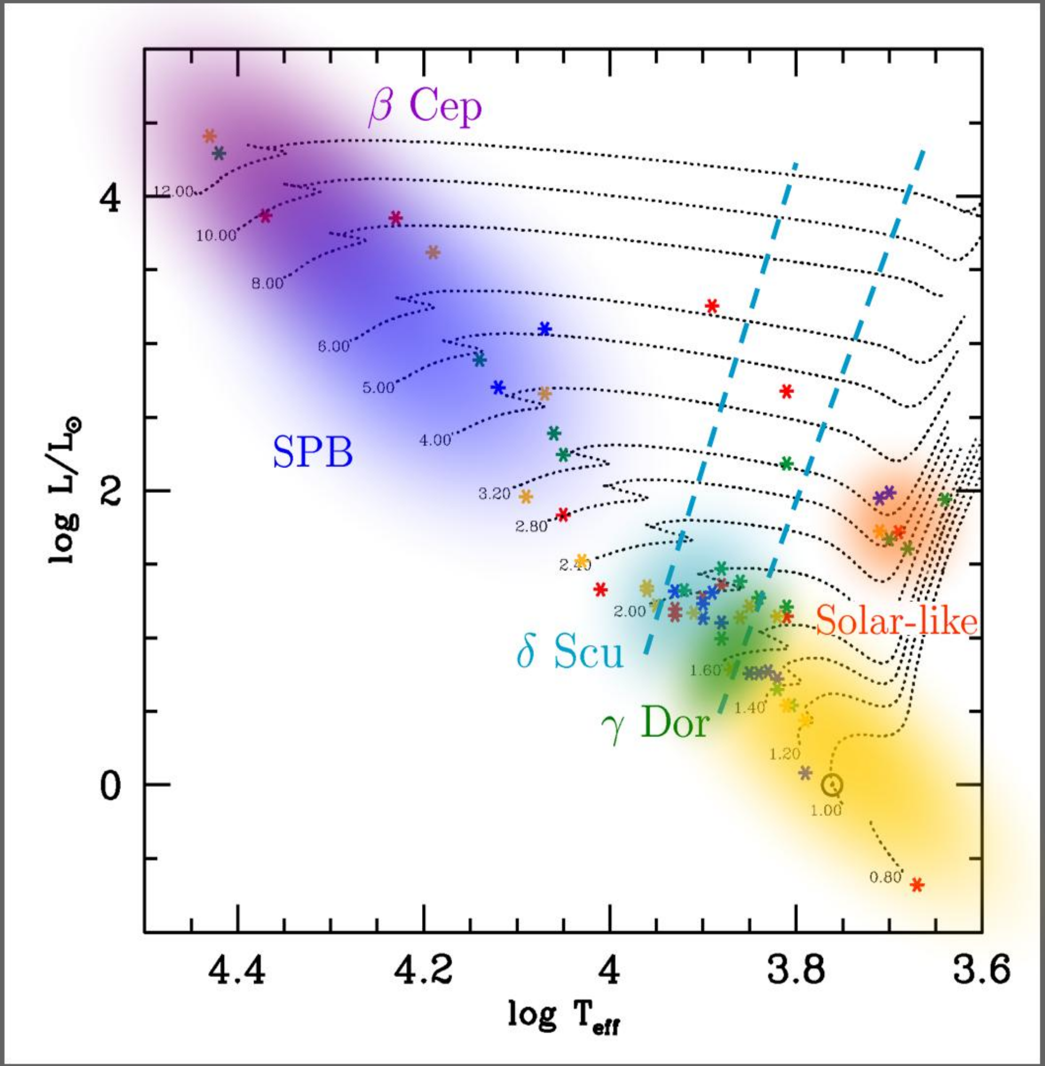
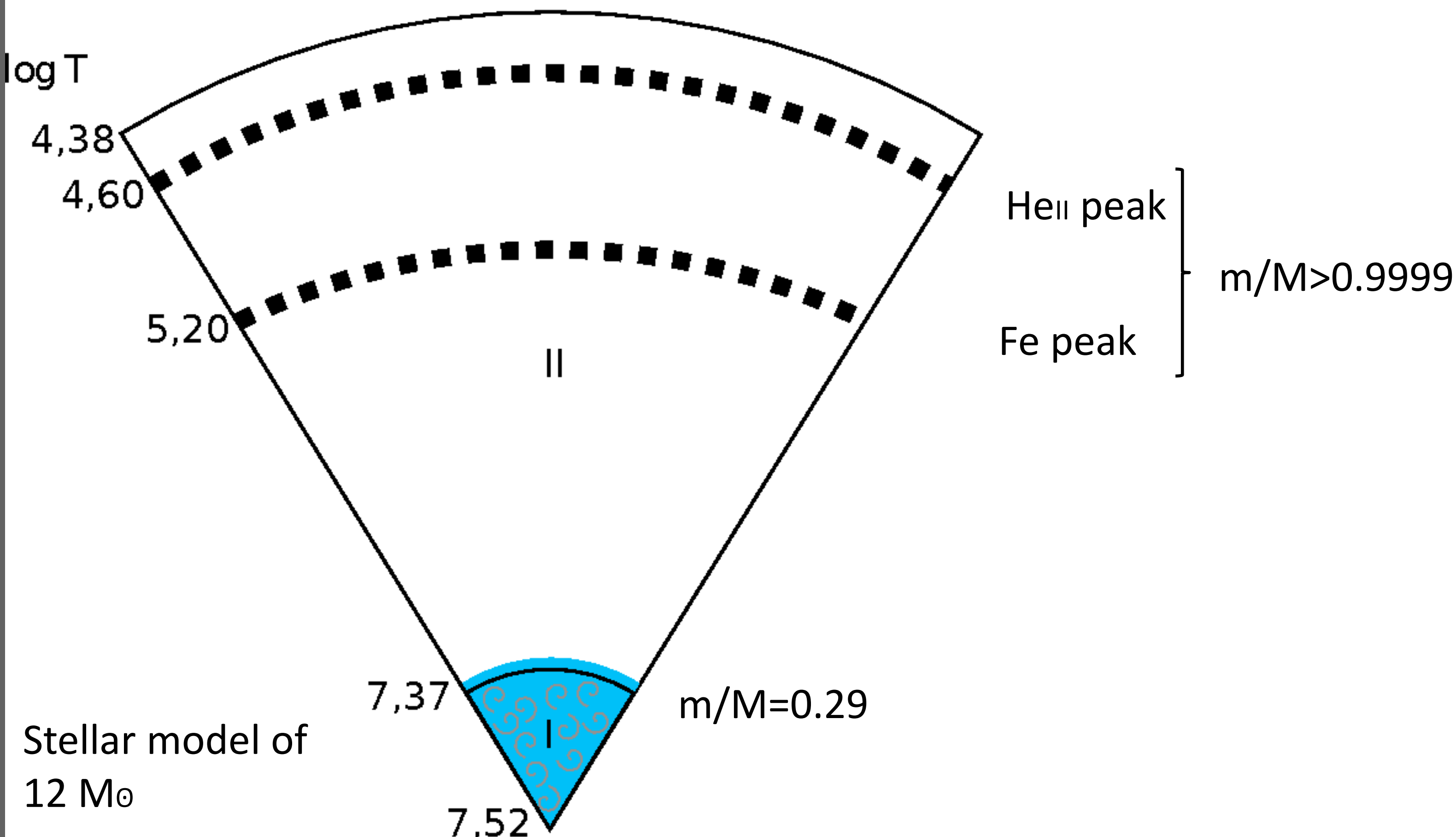
Main-sequence B stars

- Rare objects (~0,125%)
- Masses between 2.5 et 18 M☉
- Rather simple structure



Main-sequence B stars



Stellar model of
12 $M_\odot$

Why looking at these stars?

- Interaction with the interstellar medium (stellar winds)
- Real chemical element factories
- Define the mass range in which stars end their life by a core-collape supernova

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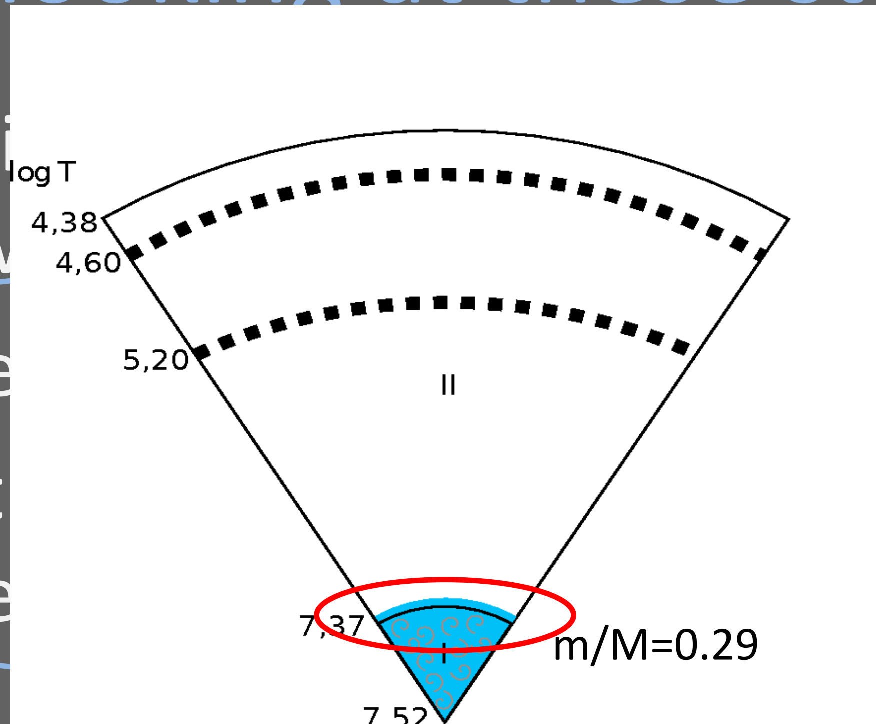


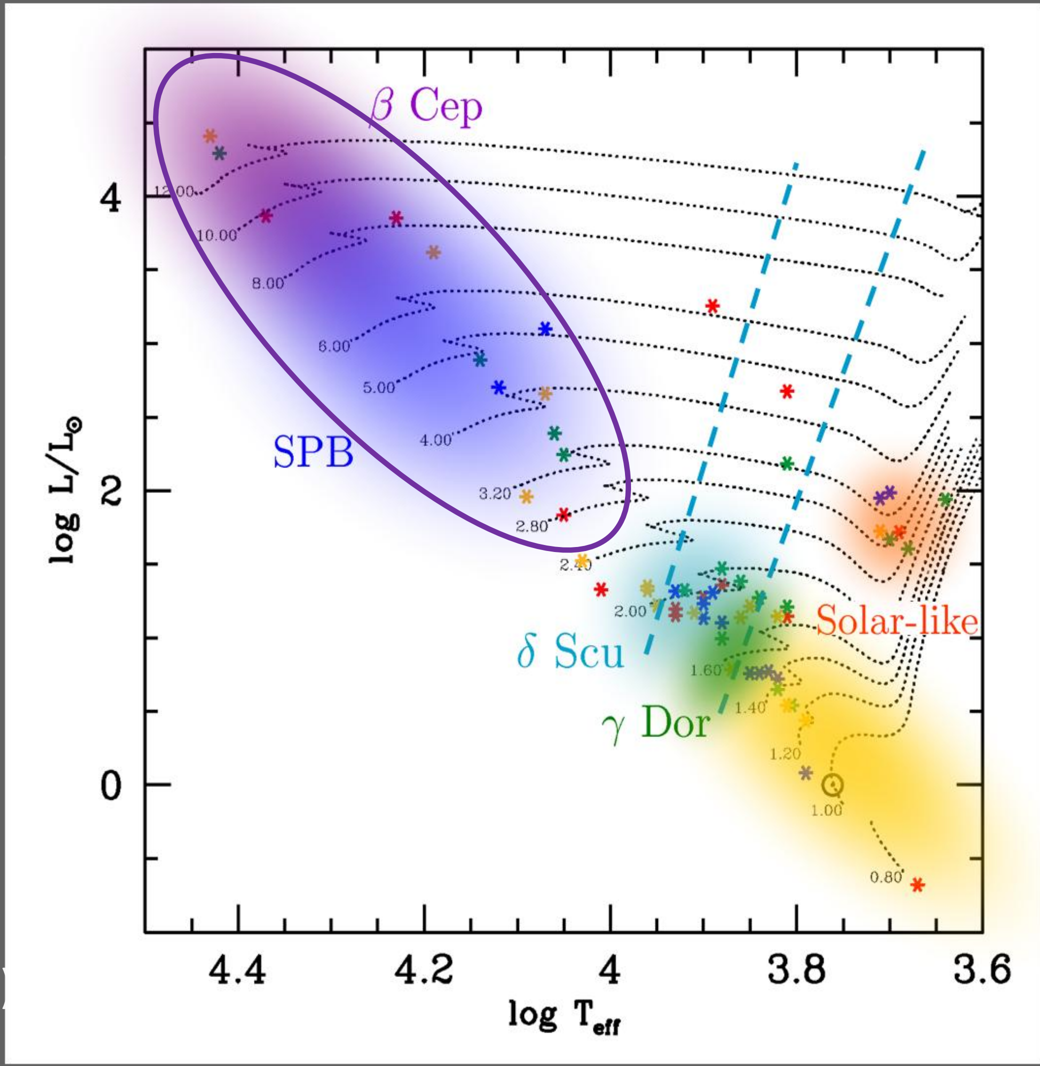
A lot of uncertainties, among which size of the central mixed region during the main sequence

Main-sequence pulsating B-type stars

β Cephei: ~8 to 18 M⊙
- low-order p and g mode
- P from 2 to 8 hours

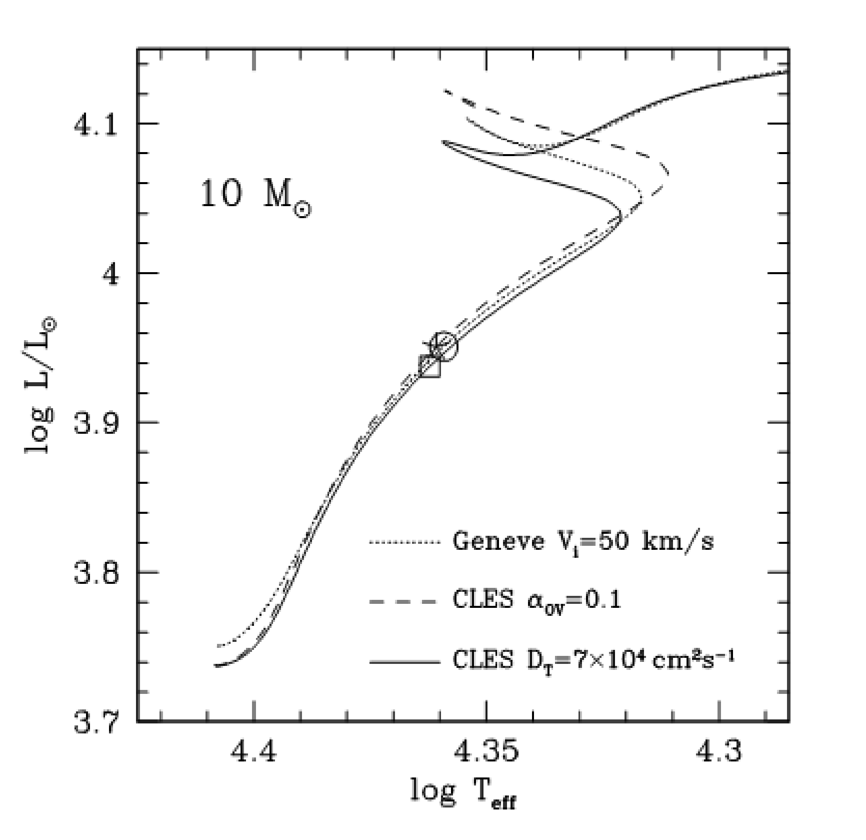
SPB: ~2.5 to 8 M⊙
- high-order g modes
- P from 1 to 3 days

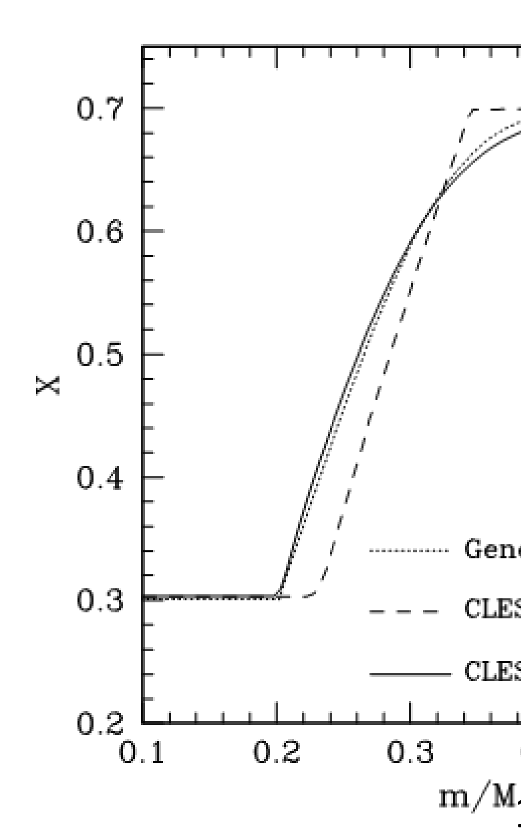
κ mechanism activated by the Fe-group opacity peak
(Moskalik & Dziembowski 1992; Dziembowski, Moskalik & Pamyatnykh 1993)



Extra-mixing near the convective core

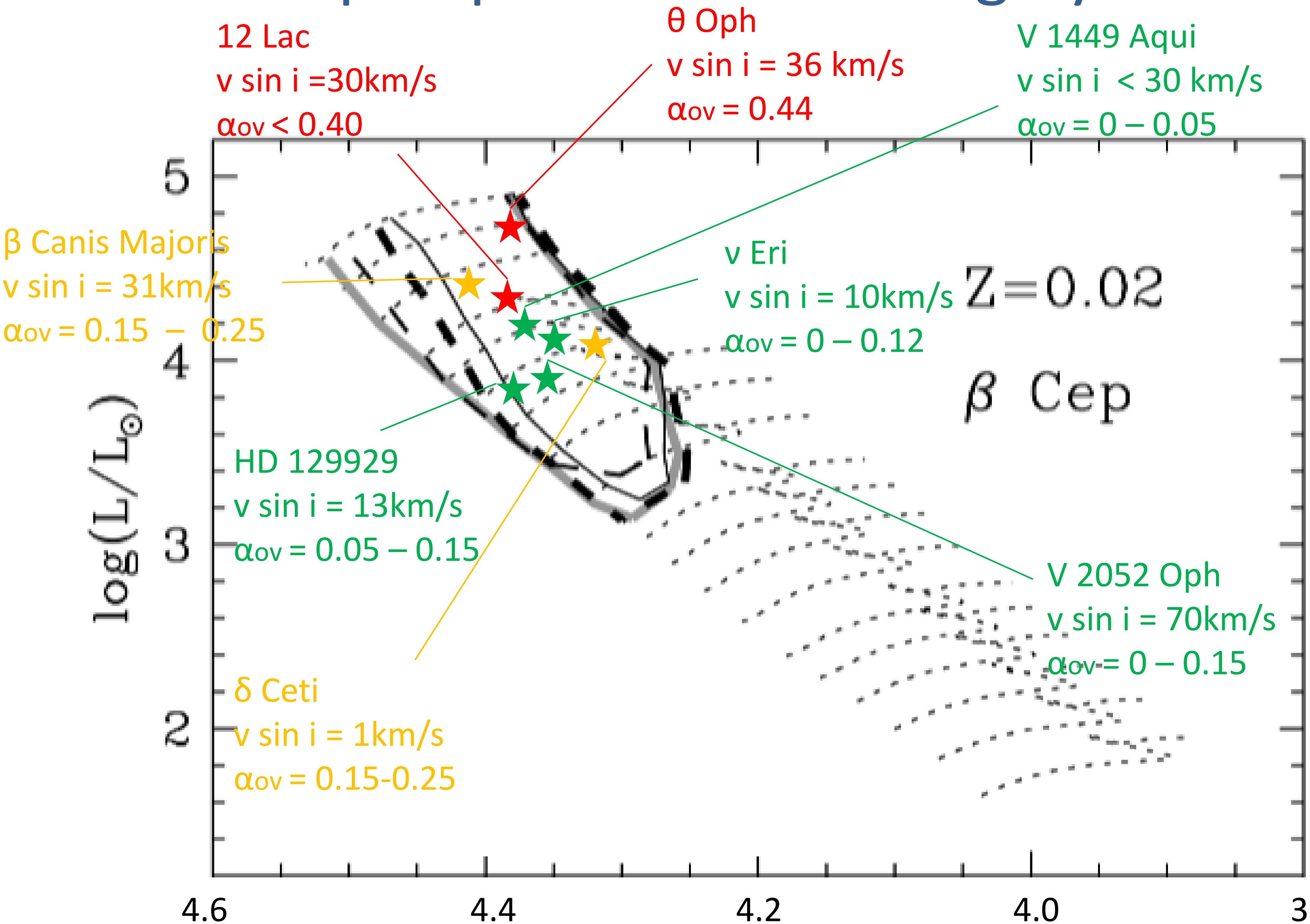
- Instantaneous mixing: overshooting, expressed in Hp (e.g. : Maeder 1975 ; Bressan et al. 1981)
- Diffusive mixing : e.g. rotation (meridional circulation + shear ; e.g. : Pinsonneault et al. 1991 ; Maeder & Zahn 1998 ; Meynet & Maeder 2000, and ref. therein)





10 M⊙ β Cephei model

Several β Cephei stars thoroughly studied



Refs: Aerts et al. 2003, 2004; Dupret et al. 2004 ; Thoul et al. 2004; Handler et al. 2004 ; Aerts et al. 2004 ; De Ridder et al. 2004 ; Pamyatnykh et al. 2004 ; Aerts et al. 1994 ; Shobrook et al. 2006 ; Mazumdar et al. 2006 ; Aerts et al. 1992, 2006 ; Belkacem et al. 2009 ; Degroote et al. 2009 ; Aerts et al. 2011 ; Handler et al. 2006 ; Desmet et al. 2007; Desmet et al. 2009 ; Handler et al. 2005; Briquet et al. 2005; Briquet et al. 2007 ; Neiner et al. 2003 ; Morel et al. 2006 ; Handler et al. 2012 ; Briquet et al. 2013

- Broad range of overshooting values, no connection with v sin i.
  What is actually measured?

$\Rightarrow$ Series of « Hare and Hound » exercises

(see e.g. Thoul et al. 2003)

– A model is defined by M, X, Z, age, α_{ov} : degeneracy affecting these parameters?

– Accuracy of the retrieved stellar parameters

We use forward approach modelling

- Based on a seismic merit function (m=0) :

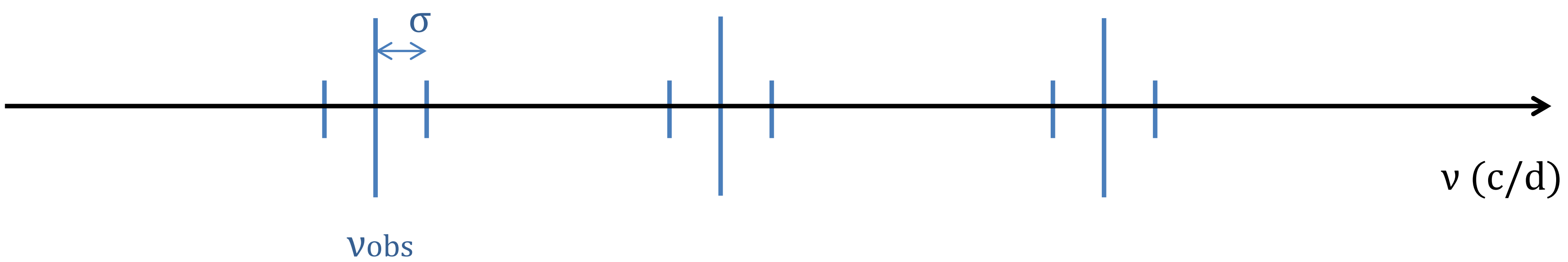
$$\chi^2 = \frac{1}{N_{\mathrm{obs}}} \sum_{i=1}^{N_{\mathrm{obs}}} \frac{(\nu_{\mathrm{obs,i}} - \nu_{\mathrm{th,i}})^2}{\sigma_i^2}$$

- Computed on a pre-computed grid (Briquet et al. 2009) of adiabatic frequencies for stellar models:

Parameter	Range	Step
M (in $M_\odot$)	7.6 – 18.6	0.1
X	0.68 – 0.74	0.02
Z	0.010 – 0.018	0.002
α_{ov}	0 – 0.50	0.05

- With or without considering classical parameters (log g – Te) a posteriori

- Monte-Carlo simulations implemented to derive theoretical uncertainties



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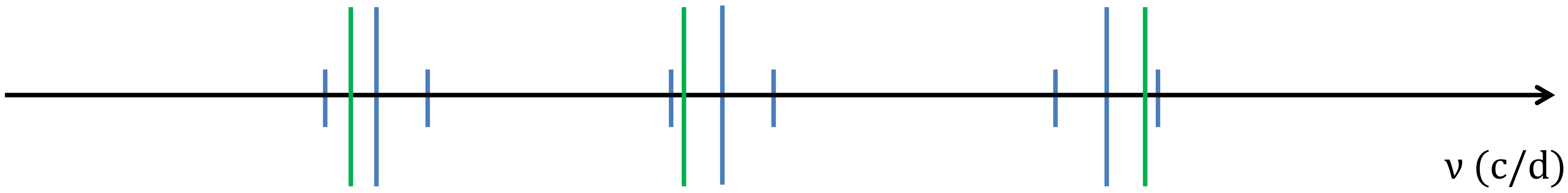

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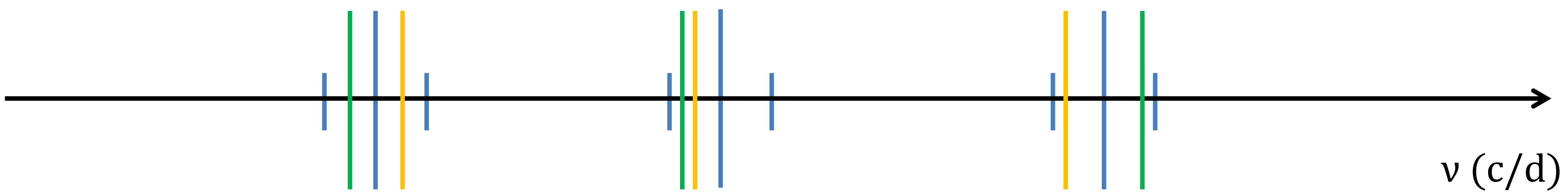


x 1000 (=Nsim)

« Hare and Hound » exercises

Several stellar models used as synthetic « observed » stars (the hare)

Mass	Xc	Mixture	Opacity	Overshooting	Turbulent mixing
9-14 M⊙	0.20-0.50	GN93/AGS05	OP/OPAL	0-0.2	Y/N

How inferences depends on:

- Number of frequencies required
  - 3 to 5 frequencies, with identified ℓ
- Micro-physics :
  - GN93 vs AGS05
- Macro-physics :
  - turbulent diffusive mixing vs instantenous mixing

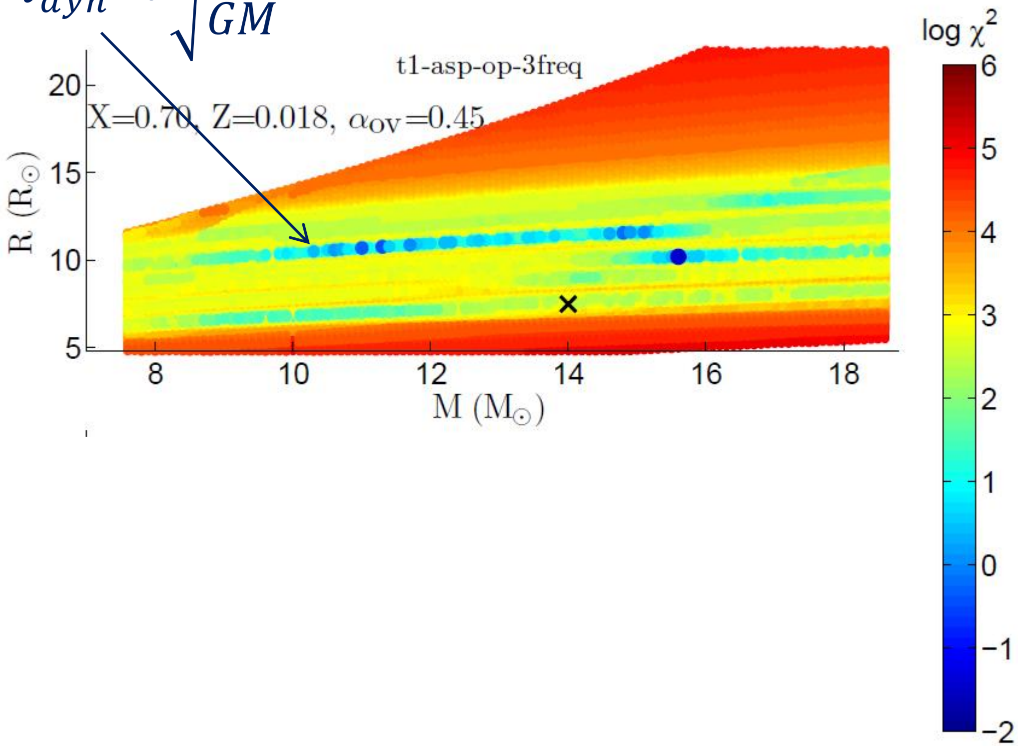
i. Analysing the role of seismic constraints

Input model (« observed » star)	Fitting models
AGS05/OP	AGS05/OP

- t1, 3 frequencies, ℓ known (0,1,2)

$\tau_{dyn} \propto \sqrt{\frac{R^3}{GM}}$

Global minimum

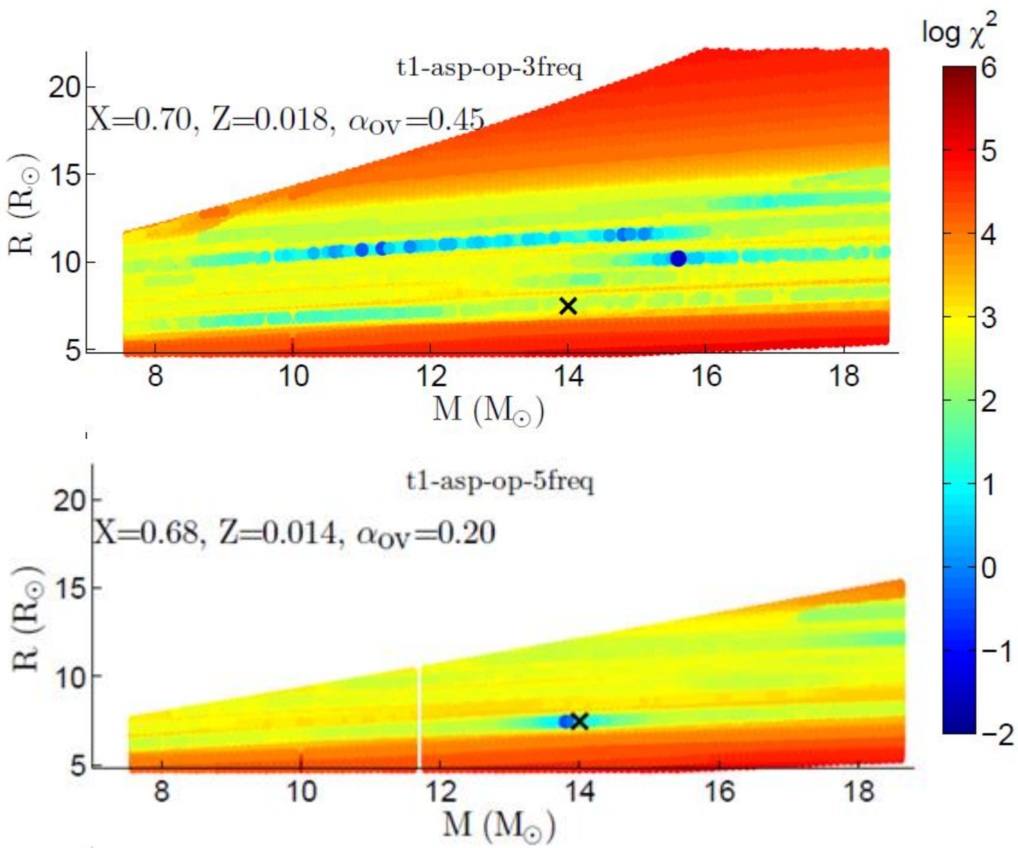


Parameter	Input t1	Fitting model 3 freq.
M (M⊙)	14	15.6
R (R⊙)	7.48	10.18
X	0.70	0.70
Z	0.014	0.018
α_{ov}	0.20	0.45
Xc	0.288	0.237

Input model (« observed » star)	Fitting models
AGS05/OP	AGS05/OP

- t1, 5 frequencies, ℓ known (0,1,2)

Global minimum



Parameter	Input t1	Fitting model 5 freq.
M (M⊙)	14	13.8
R (R⊙)	7.48	7.45
X	0.70	0.68
Z	0.014	0.014
α_{ov}	0.20	0.20
Xc	0.288	0.274

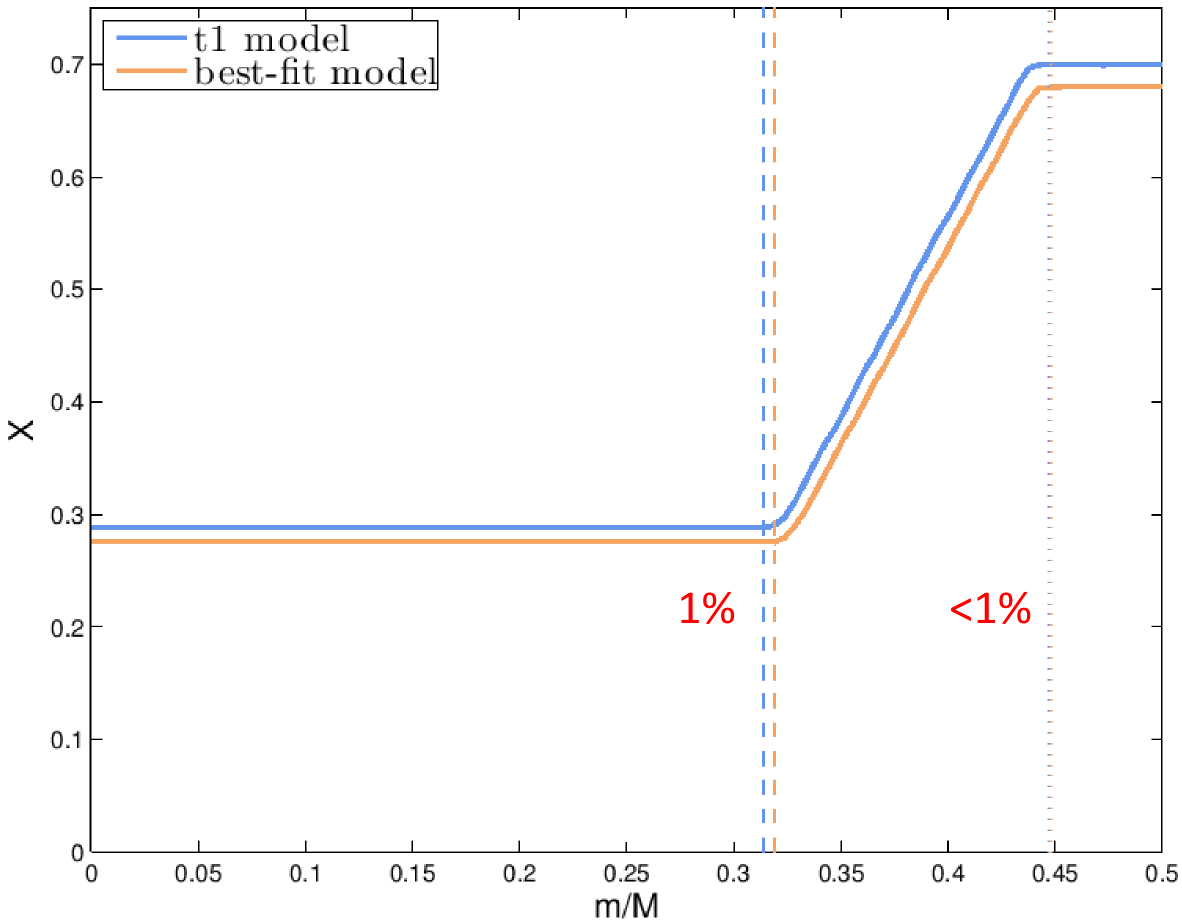
Input model (« observed » star)	Fitting models
AGS05/OP	AGS05/OP

- Errors on the parameters from the MC simulations

Parameter	**Input**	**Uncertainty 3 freq.**	**Uncertainty 5 freq.**
M ($M_\odot$)	14	23%	1%
R ($R_\odot$)	7.48	31%	1%
X	0.70	6%	6%
Z	0.014	29%	14%
α_{ov}	0.20	50%	25% (grid limit)
Xc	0.288	9%	11%

Input model (« observed » star)	Fitting models
AGS05/OP	AGS05/OP

5 freq.



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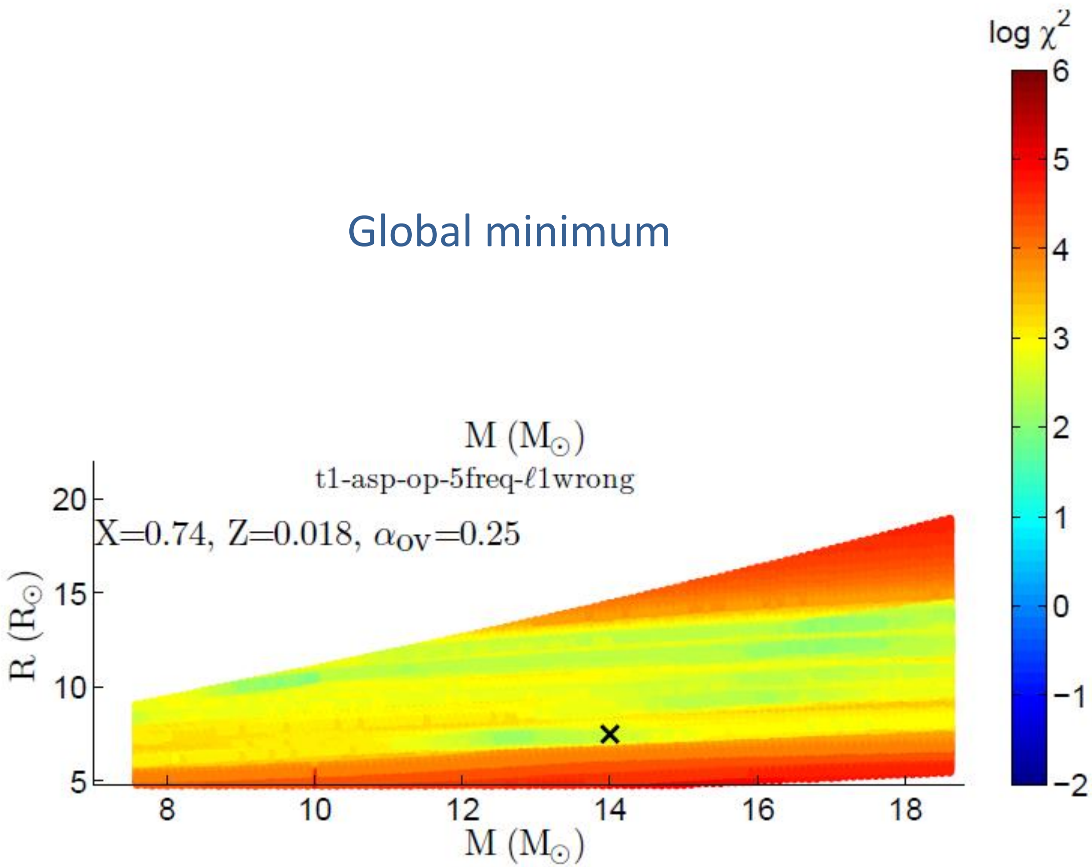
Input model (« observed » star)	Fitting models
AGS05/OP	AGS05/OP

- t1, 5 frequencies, ℓ known, 1 misidentification

Global minimum

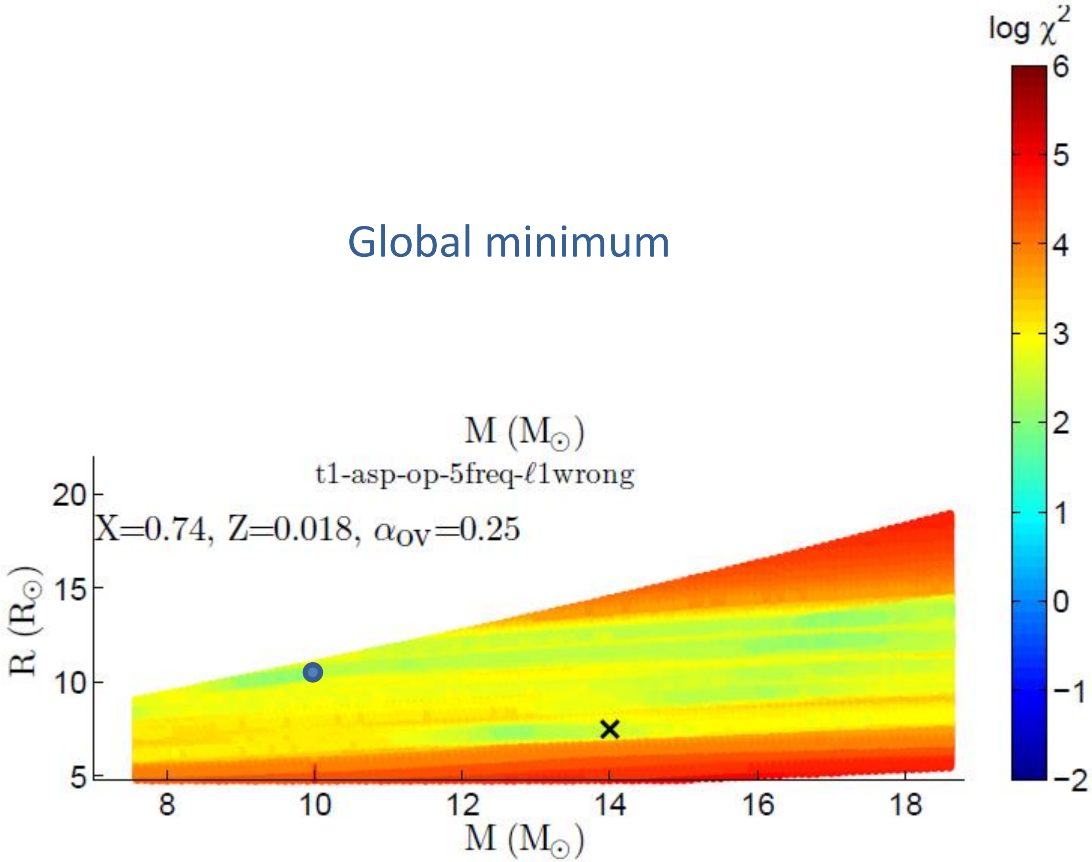


Parameter	Input	Fitting model
M (M⊙)	14	10.10
R (R⊙)	7.48	10.45
X	0.70	0.74
Z	0.014	0.018
α_{ov}	0.20	0.25
Xc	0.288	0.004

Input model (« observed » star)	Fitting models
AGS05/OP	AGS05/OP

- t1, 5 frequencies, ℓ known, 1 misidentification

Global minimum

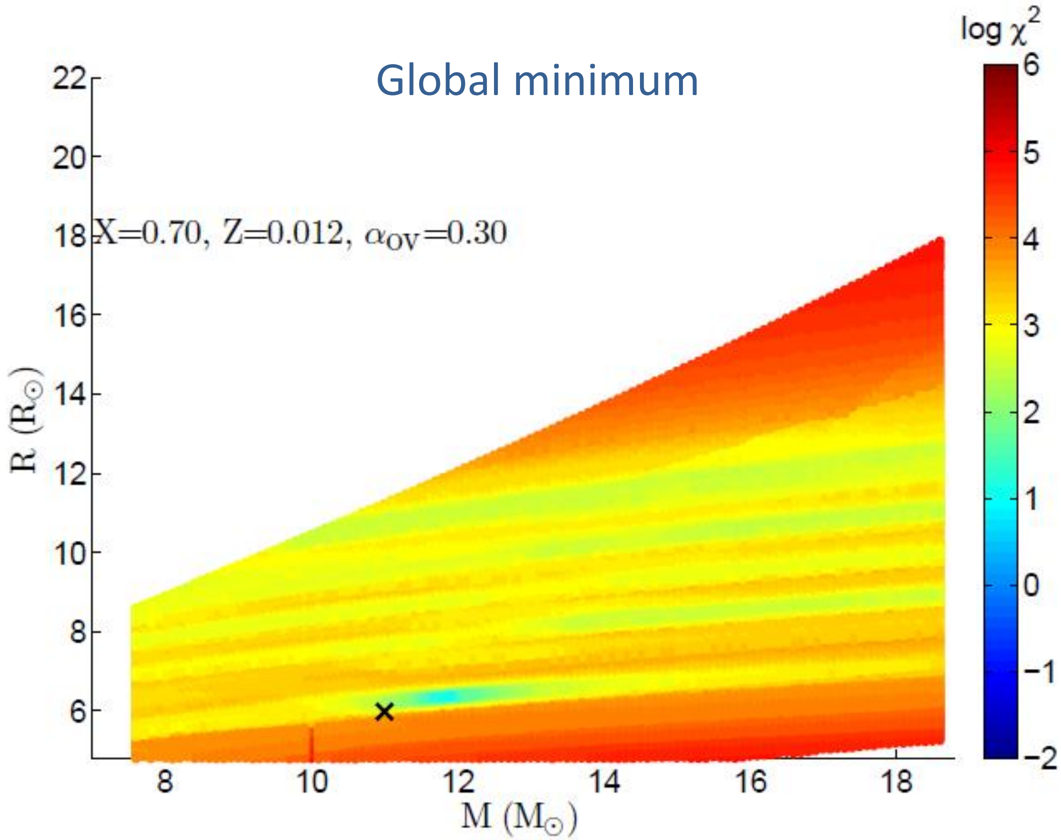


Parameter	Input	Fitting model
M (M⊙)	14	10.10
R (R⊙)	7.48	10.45
X	0.70	0.74
Z	0.014	0.018
α_{ov}	0.20	0.25
Xc	0.288	0.004

ii. The hare star and the theoretical hound grid present a different <u>micro-physics</u>

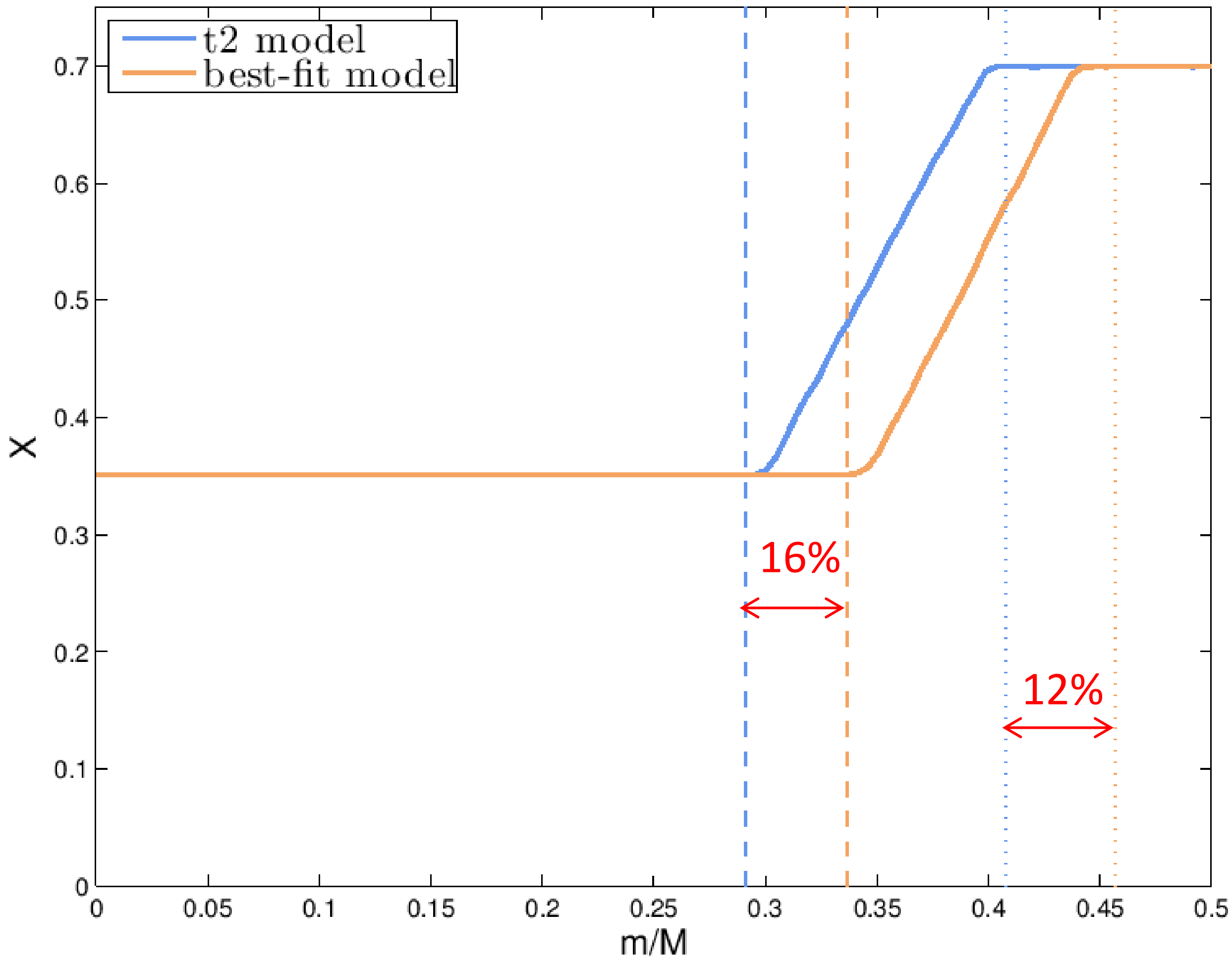
Input model (« observed » star)	Fitting models
GN93/OP	AGS05/OP

- t2, 6 frequencies, ℓ known (0,1,2)



Parameter	Input	Fitting model
M ($M_\odot$)	11	11.4
R ($R_\odot$)	5.98	6.07
X	0.70	0.70
Z	0.016	0.012
α_{ov}	0.20	0.30
Xc	0.351	0.354

Input model (« observed » star)	Fitting models
GN93/OP	AGS05/OP



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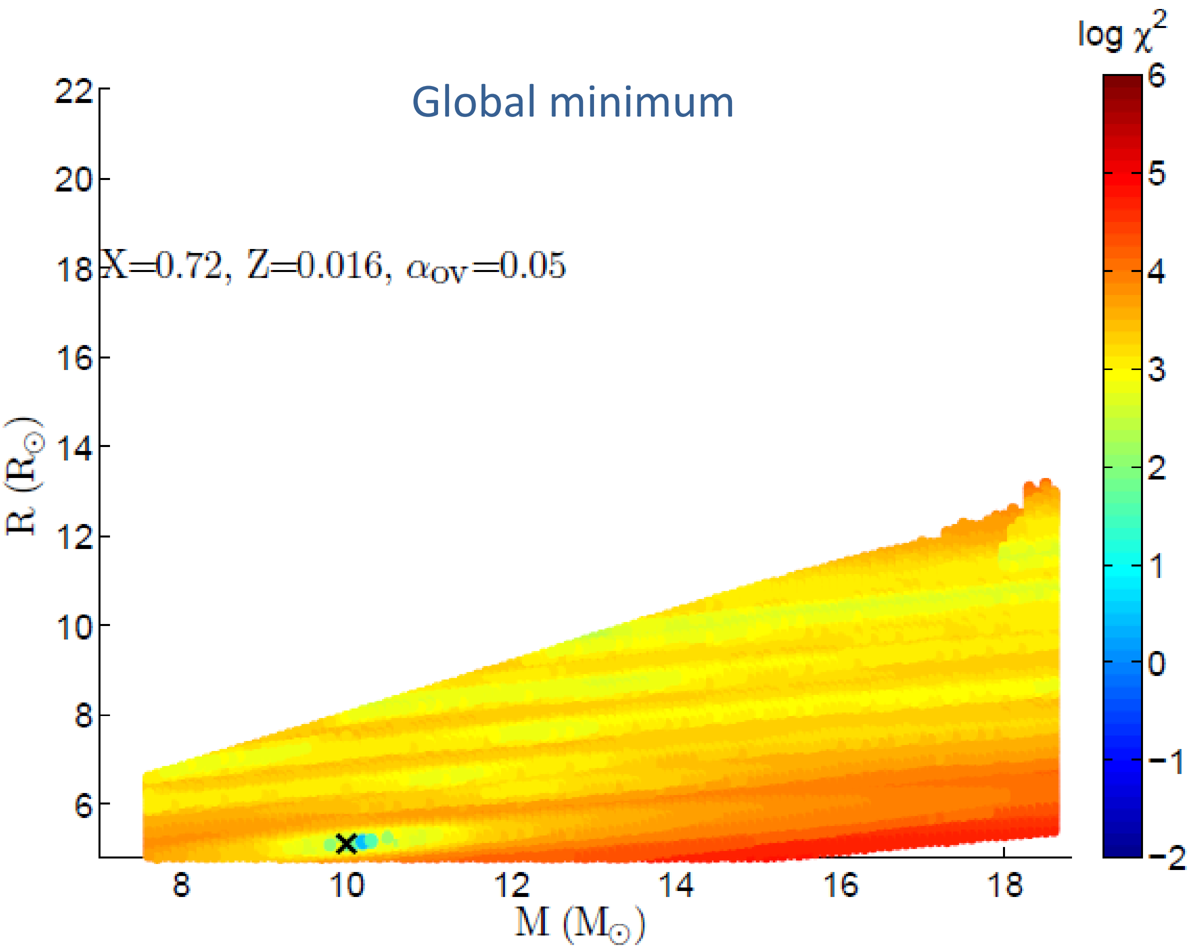
iii. The hare star and the theoretical hound grid present a different macro-physics

Input model (« observed » star)	Fitting models
AGS05/OP + diffusive mixing	AGS05/OP

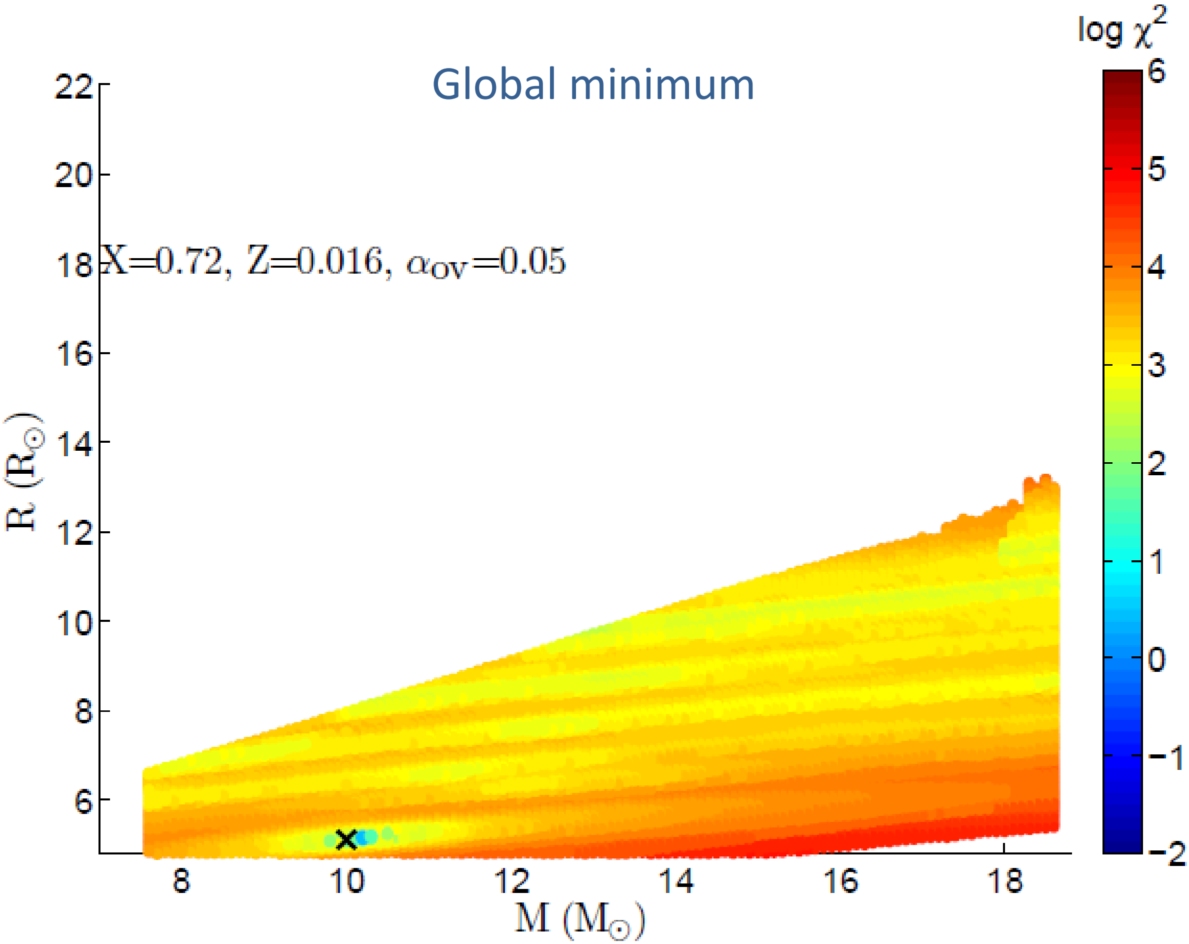
- t6, 8 frequencies, ℓ known (0,1,2)



Parameter	Input	Fitting model
M (M⊙)	10	10.2
R (R⊙)	5.12	5.16
X	0.70	0.72
Z	0.014	0.016
α_{ov}	0.05*	0.05
Xc	0.388	0.419

Input model (« observed » star)	Fitting models
AGS05/OP + diffusive mixing	AGS05/OP

- t6, 8 frequencies, ℓ known (0,1,2)



Parameter	Input	Fitting model
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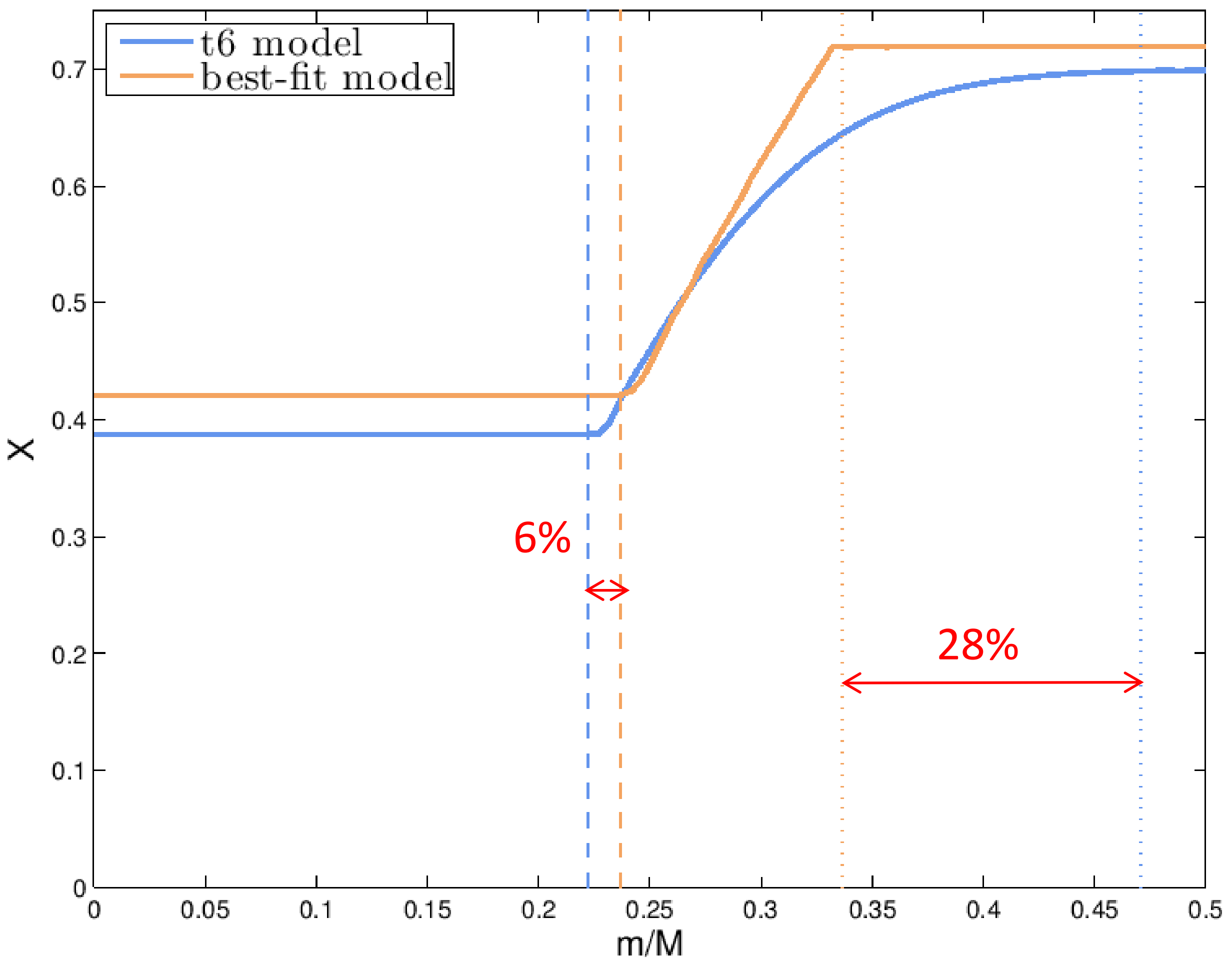
Input model (« observed » star)	Fitting models
AGS05/OP + diffusive mixing	AGS05/OP



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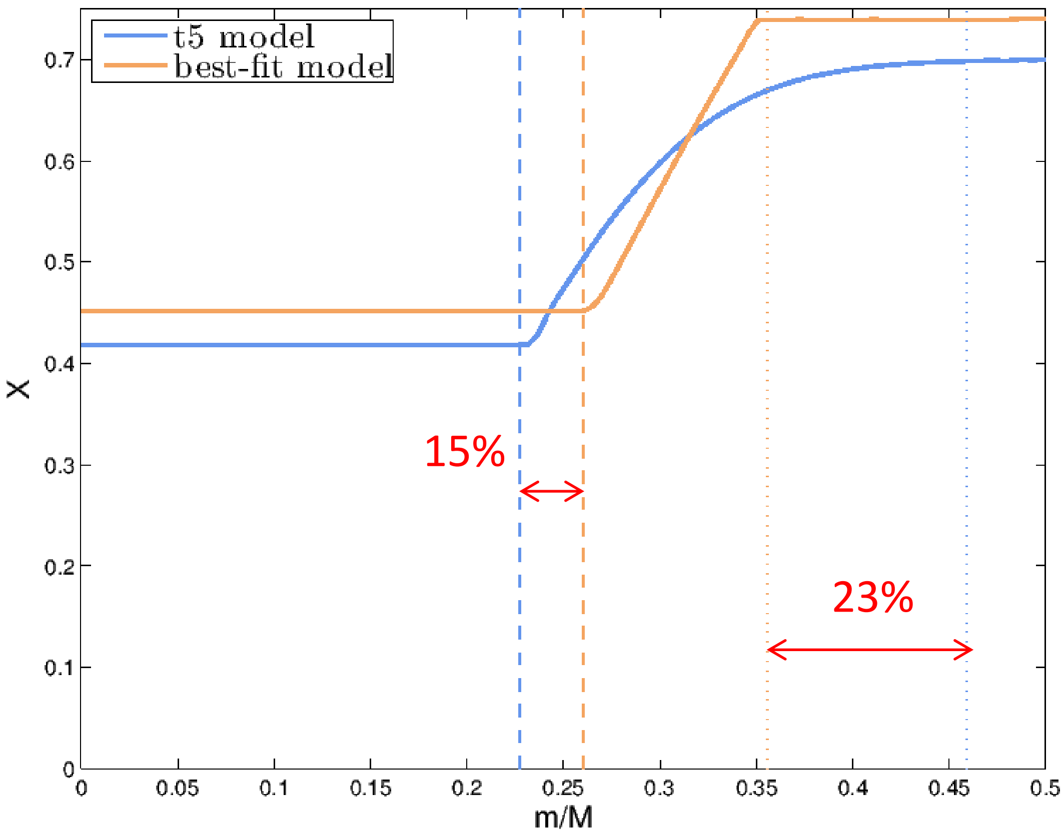
iv. The hare star and the theoretical hound grid present different <u>micro- and macro-physics</u>

Input model (« observed » star)	Fitting models
GN93/OPAL + diffusive mixing	AGS05/OP

- t5, 8 frequencies from mixed modes mainly trapped in the g mode cavity, ℓ known (0,1,2)



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Parameter	Input	Fitting model
M (M⊙)	10	10.8
R (R⊙)	5.24	5.38
X	0.70	0.74
Z	0.020	0.018
α_{ov}	0.10*	0.10
Xc	0.418	0.450

Conclusion

- When physics of the target star and theoretical models are the same:

  - 3 frequencies (with known ℓ) provide insufficient constraints
  - 4 to 5 frequencies with known ℓ lead to accurate seismic inferences
  - central mixed region correctly determined in terms of m/M

- When micro-physics is different:

  - degeneracy on M-X-Z-α_{ov}
  - central mixed region not constrained in terms of m/M

$\Rightarrow$Need of complementary observations, in particular individual abundances

- When macro-physics is different:
  - in our tests, the nature of extra-mixing is undetermined

  $\Rightarrow$ Trying to introduce a new parameter to fit

- Perspective: new observational campaigns

- A few β Cephei stars of interest:
  - ν Eri (De Ridder et al. 2004)
    13 frequencies, 7 with identified ℓ:
    1 $\ell 0$, 6 $\ell 1$ (5 are members of rotational triplets)
  - θ Oph (Briquet et al. 2007)
    7 frequencies with identified ℓ:
    1 $\ell 0$, 3 $\ell 1$ (triplet), 3 $\ell 2$ (part of a quintuplet)
  - HD 129929 (Dupret et al. 2004)
    6 frequencies with identified ℓ:

    1 $\ell 0$, 3 $\ell 1$ (triplet), 2 $\ell 2$ (part of a quintuplet)
  - 12 Lac (Desmet et al. 2009)
    10 frequencies, 4 with identified ℓ:

    1 $\ell 0$, 2 $\ell 1$ (triplet?), 1 $\ell 2$

Thank you!