Seismology Working Group

Evolution and Seismic Tools Activity

Past and present

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and the ESTA Team

Centro de Astrofísica
da Universidade do Porto

ESTA goals

ESTA aims at contributing towards the preparation and exploration of the scientific results of CoRoT. In order to achieve this, the goals set for ESTA include:

- to provide a **grid of reference stellar models and their frequencies** of oscillation.

- to extensively **test, compare and optimize numerical tools** used to calculate:
  - stellar models,
  - oscillation frequencies,
  - and seismic inversions.

ESTA was setup under the *Seismology Working Group* of CoRoT to secure that the interpretation of the data is solely determined by the physics being used.

The ultimate goal of ESTA for CoRoT is to secure that the uncertainties/errors in the models correspond to uncertainties in the frequencies below the expected observational precision.

Adopted strategy

- To make **as much information as possible available** on:
  - evolution codes,
  - seismic codes,
  - data produced by these tools.

- To **initiate coordinated activities**, aiming at inducing the development of the codes and the discussion of the physical assumptions used in these codes, by:
  - setting specific tasks,
  - facilitating the exchange of data,
  - establishing new collaborations.

- To **produce and make available reference data** useful for asteroseismology of stars across the HR diagram, namely:
  - evolution sequences,
  - stellar models,
  - oscillation frequencies.

All information regarding past and ongoing activities, as well as data and documents, are available at the **ESTA Website**:

www.astro.up.pt/corot/

Participants

Belgium:
Andrea Miglio
Josefina Montalban
Arlette Noels
Richard Scuflaire
Anne Thoul

France:
Gabrielle Berthomieu
Matthieu Castro
Marie Jo Goupil
Yveline Lebreton
Pierre Morel
Andy Moya
Phi Nghiem
Pascal Lambert
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Denmark:
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Teresa C. Teixeira

Romenia:
Marian D. Suran

Spain:
Rafael Garrido
Juan Carlos Suarez

Switzerland:
Patrick Eggenberger

United Kingdom:
Ian W. Roxburgh
Michael J. Thompson

Participation is open to all colleagues from *CoRoT contributing countries* willing to join the comparison and having access to an evolution or/and seismic code.

Up-to-date lists of participants and tools are maintained at the ESTA webpage. There is also a distribution list for emails used to exchange news on ESTA related activities.

Evolution Tools

- **ASTEC** - *Aarhus Stellar Evolution Code*
  By: J. Christensen-Dalsgaard
- **ATON** - *Rome Stellar Evolution Code*
  By: P. Ventura et al.
- **CESAM** - *Code d'Evolution Stellaire Adaptatif et Modulaire*
  By: P. Morel & Y. Lebreton
- **CLÉS** - *Code Ligeois d'Evolution Stellaire*
  By: J. Montalban, R. Scuflaire and the BAG
- **FRANEC** - *Pisa Evolution Code*
  By: S. Degl'Innocenti, M. Marconi et al.
- **GARSTEC** - *Garching Stellar Evolution Code*
  By: A. Weiss
- **STAROX** - *Roxburgh's Stellar Evolution Code*
  By: I. Roxburgh
- **TGEC** - *Toulouse-Geneva Evolution Code*
  By: M. Castro et al.
- ...

Seismic Tools

- **ADIPLS** - *Aarhus Adiabatic Pulsation Package*
  By: J. Christensen-Dalsgaard
- **FILOU** - *Meudon Oscillation Code*
  By: J. C. Suarez
- **GraCo** - *Granada Oscillation Code*
  By: R. Garrido & A. Moya
- **LOSC** - *Liège Oscillation Code*
  By: R. Scuflaire and the BAG
- **NOC** - *Nice Oscillations Code*
  By: G. Berthomieu & J. Provost
- **OSCROX** - *Roxburgh's Oscillation Code*
  By: I. Roxburgh
- **POSC** - *Porto Oscillation Code*
  By: M. Monteiro
- ...

Conversion tool

In order of facilitate the comparison and exchange of models a conversion tool has been implemented: **MODCONV**. The objective is to include all formats used within ESTA for producing models and as input for the oscillation codes. More formats will be added as necessary.

The conversions already available are:

```
[12] GONG   -|FGONG   [23] FGONG   -|OSC     [32] OSC -|FGONG
[13]         |OSC     [24]          |AMDL    [34]       |AMDL
[14]         |AMDL    [25]          |FAMDL   [35]       |FAMDL
[15]         |FAMDL   [26]          |SROX    [36]       |SROX

[45] AMDL   -|FAMDL   [62] SROX    -|FGONG
[54] FAMDL -|AMDL     [64]          |AMDL
                      [65]          |FAMDL
```

The possibility to re-mesh the models when formatting the input for the oscillation codes is also being added.

ESTA documents:

- "*Description of the File Formats used within CoRoT/ESTA*" (2005-12-05)

Milestones

The previous reports/events relevant for ESTA are:

- *CoRoT Week 3, Dec. 2002*
  - 1 oral presentation (+ posters)
- *Meeting 1 (CoRoT Week 7)* , Dec. 2004
  - 1 oral presentation (+ 1 discussion + posters)
- *Meeting 2 (CoRoT Week 8)*, May 2005
  - 1 discussion (+ 1 report + posters)
- *Meeting 3 (Workshop in Nice), Sep. 2005*
  - 16 oral presentations + 2 discussions (+ 2 reports)
- *Meeting 4 (Workshop in Aarhus)*, Oct. 2005
  - 17 oral presentations + 2 discussions (+ 2 reports)
- *Meeting 5 (CoRoT Week 9)*, Dec. 2005
  - 4 oral presentations + 2 discussions (+ 1 report + posters)

Several codes have participated in the proposed exercises.

In order to reach the latest results several iterations have been necessary. Almost all **code builders have used this work to correct, develop and optimize** the evolution and seismic codes being compared.

Reference grid of models

In order to define a common reference we have produced reference grids of models and frequencies.

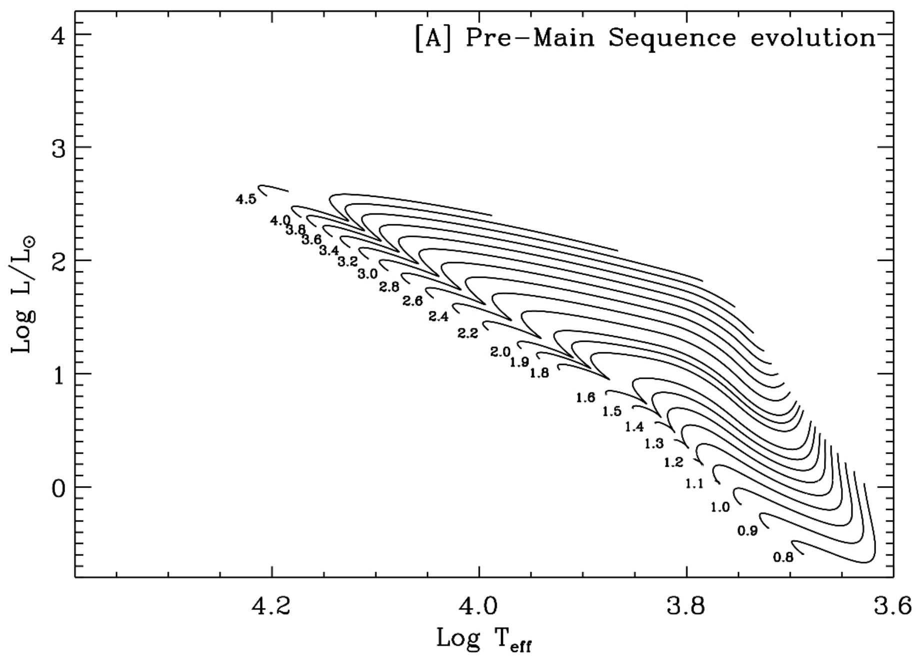
The standard set of physics selected for these reference grids is the following:

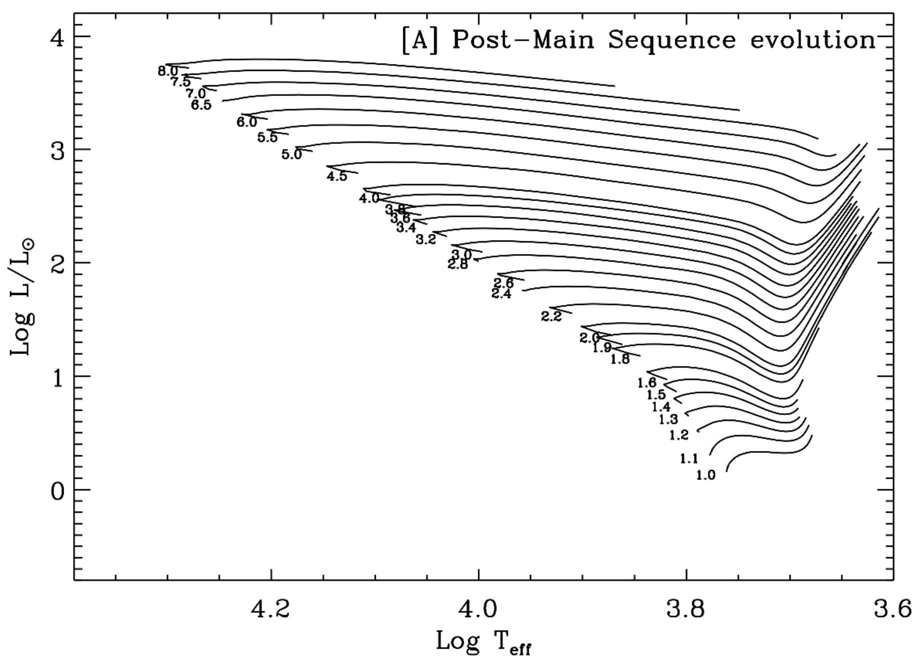
ITEM	Selection	References
EoS	OPAL	Rogers et al. (1996, 2001 Tables)
Opacities	OPAL + AF	Iglesias & Rogers (1996) Alexander & Fergusson (1994)
Reaction rates	NACRE	Angulo et al. (1999)
Convection	MLT (α = 1.6)	Bohm-Vitense (1958) + Henyey et al. (1965)
Overshoot	*none*	-
Diffusion/settling	*none*	-
Mixture	Solar	Grevesse & Noels (1993)
Atmosphere	Grey	Eddington's

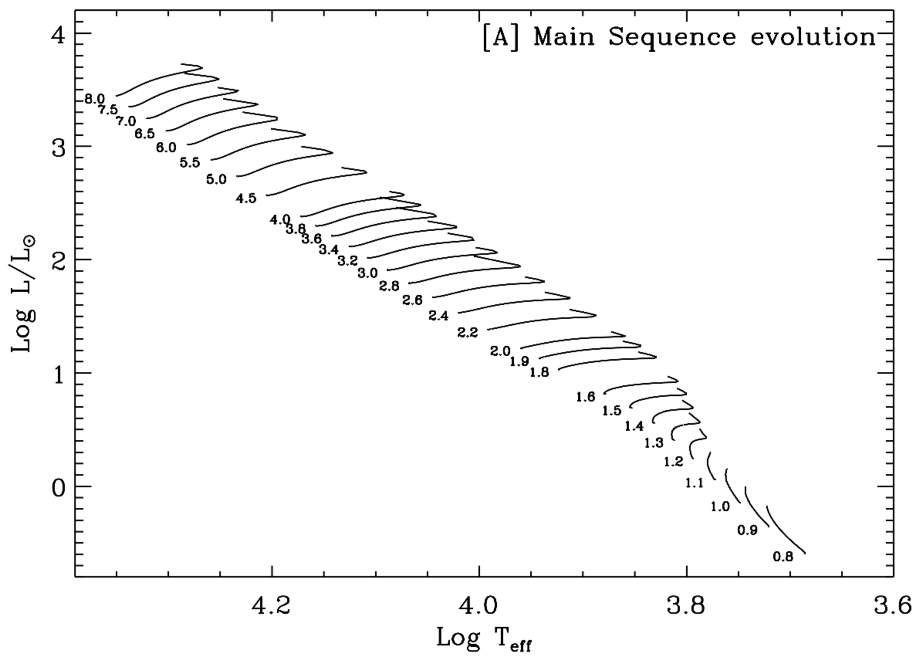
The CESAM grid

The evolutionary sequences and the models have been calculated with **CESAM (2K)** while the frequencies were determined with **POSC**, by Marques, Fernandes & Monteiro.

All data (sequences, selected models and their frequencies) are available for download from the ESTA webpage. Additional models and frequencies can be provided on request.







Definition of Tasks

In order to organize the activities on code optimization different tasks have been organized:

- **Task 1** - on model comparison

  The goal is to compare the evolution codes for representative values of stellar mass and age in order to achieve an acceptable level of consistency between different codes.

  - Step 1 has been completed (see the posters)
  - But further work is needed, so we will continue…

- **Task 2** - on frequency comparison

  The goal is to compare the seismic codes for relevant stellar models to secure an accurate calculation of the oscillation frequencies.

  - Step 1 has been initiated (see the posters)
  - Several work packages have been defined for the near future.

Task 1 - model comparison

Under this task a few **specific, fully identified, stellar cases** have been proposed to compare the evolution codes.

The physical assumptions proposed as the reference for the comparison have been defined and stellar models at different stages of evolution have been identified in order to cover as much as possible a representative range of stellar mass and age.

The comparison has addressed **how the physics and the numerical implementation of the physics may affect the result of different codes**. Discrepancies are to be used to optimize and develop the codes in order to produce consistent outputs between codes.

Both the global stellar parameters of the selected models and their interior structure have been compared. The evolutionary sequences leading to each model and the seismic properties are also compared under this Task.

Further details are given at the following webpage:

www.astro.up.pt/corot/compmod/task1.html

Targets

These targets correspond to seven specific **fully identified stellar cases**, covering a representative range in stellar masses, ages and composition.

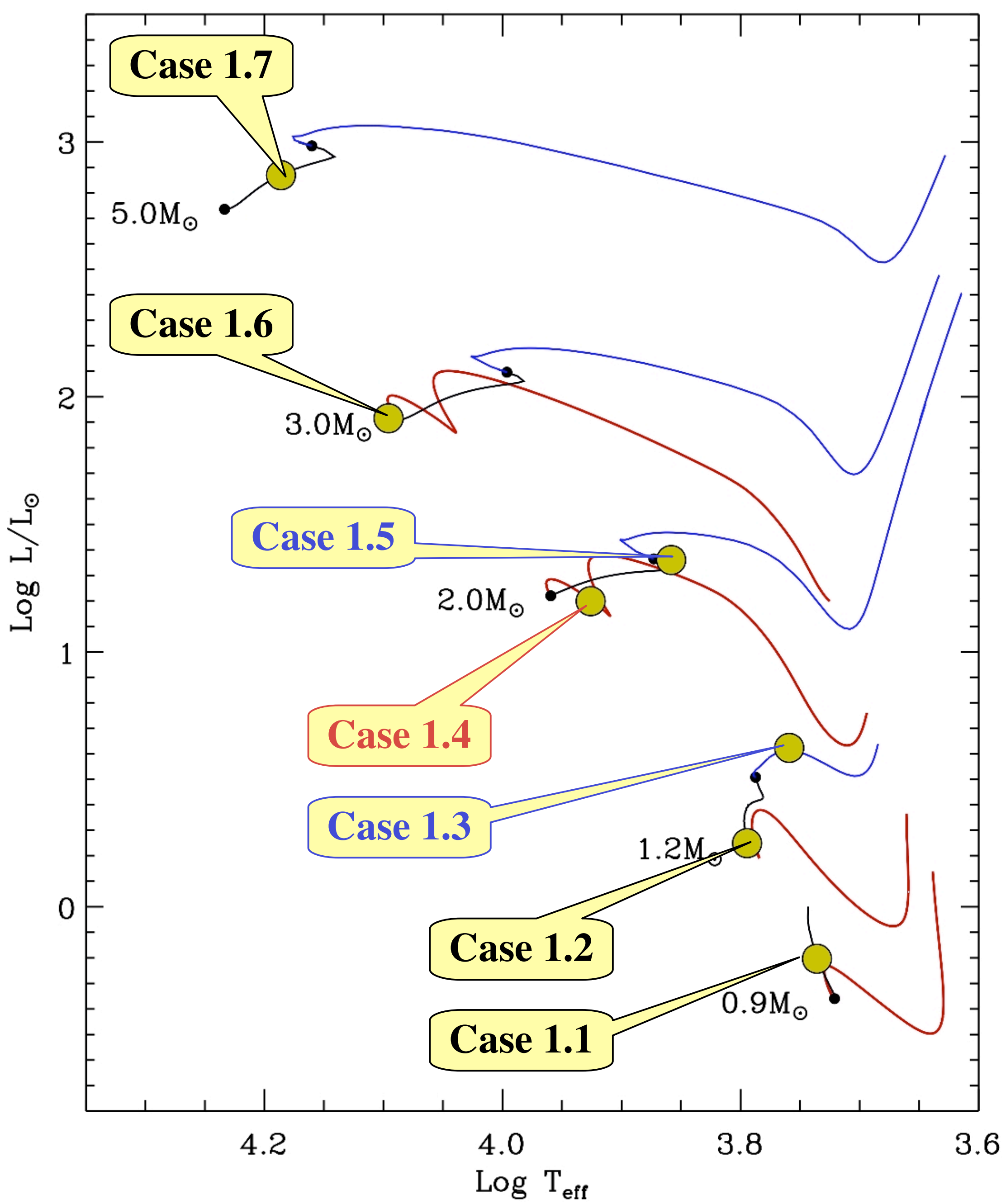
Case	$M/M_{\odot}$	Y_0	Z_0	α_{OV}	X_C	T_C	$M_{He,Cor}$	State
1.1	0.9	0.28	0.02	-	0.35	-	-	MS
1.2	1.2	0.28	0.02	-	0.69	-	-	ZAMS
1.3	1.2	0.26	0.01	-	-	-	$0.1M_{\odot}$	PostMS
1.4	2.0	0.28	0.02	-	-	$1.9\ 10^7$	-	PreMS
1.5	2.0	0.26	0.02	0.15	0.01	-	-	TAMS
1.6	3.0	0.28	0.01	-	0.69	-	-	ZAMS
1.7	5.0	0.28	0.02	-	0.35	-	-	MS

$M_{He,Cor}$ ⇨ mass of the central region where $X<0.01$

HR diagram

Case	X_C	T_C	$M_{He,Cor}$
1.1	0.35	-	-
1.2	0.69	-	-
1.3	-	-	$0.1M_\odot$
1.4	-	$1.9\ 10^7$	-
1.5	0.01	-	-
1.6	0.69	-	-
1.7	0.35	-	-

The work presented here is also discussed in two posters shown here.



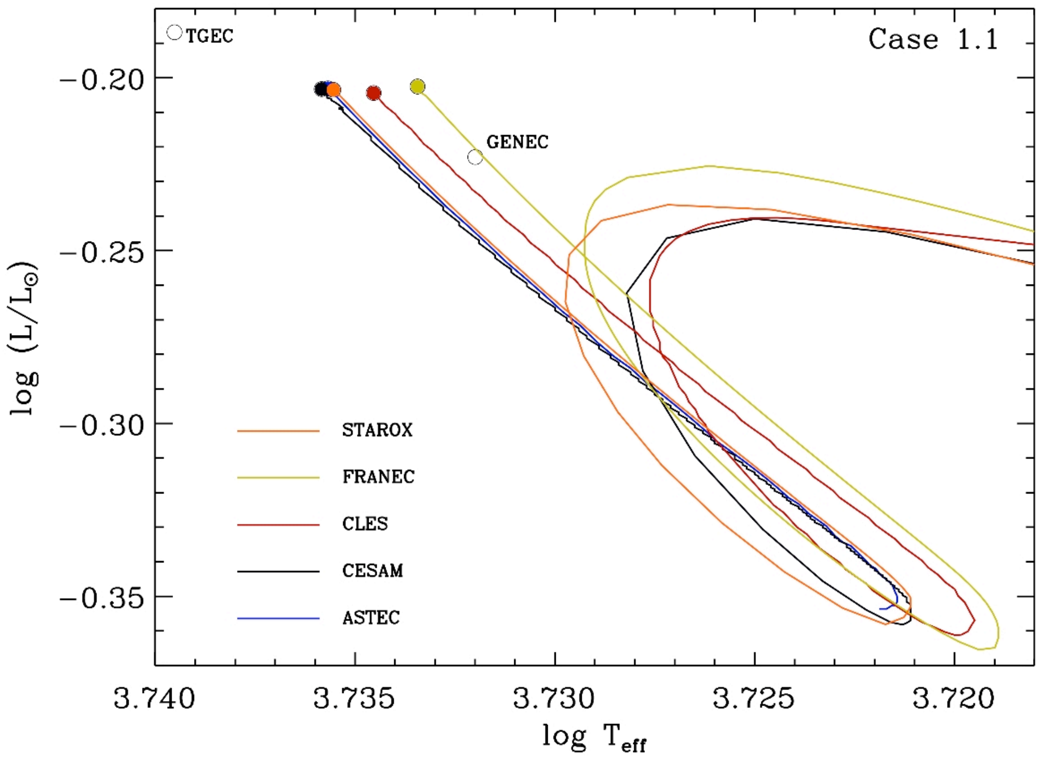
Reference physics

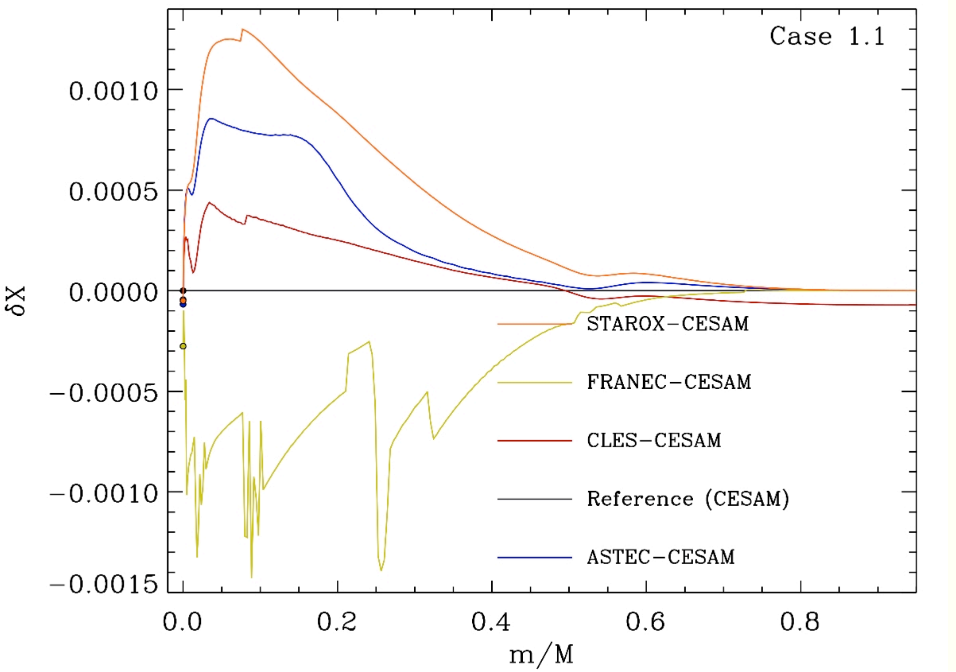
ITEM	Selection	References
EoS	OPAL	Rogers et al. (1996, 2001 Tables)
Opacities	OPAL + AF	Iglesias & Rogers (1996) Alexander & Fergusson (1994)
Reaction rates	NACRE	Angulo et al. (1999)
Convection	MLT (α = 1.6)	Bohm-Vitense (1958) + Henyey et al. (1965)
Overshoot	*none or* α_{ov}=0.15	Fully mixed + adiabatic stratification
Diffusion/settling	*none*	-
Mixture	Solar	Grevesse & Noels (1993)
Atmosphere	Grey	Eddington's

More detailed specifications of the physics have been provided in:

`http://www.astro.up.pt/corot/compmod/docs/Task1_Roadmap.pdf`

Case 1.1

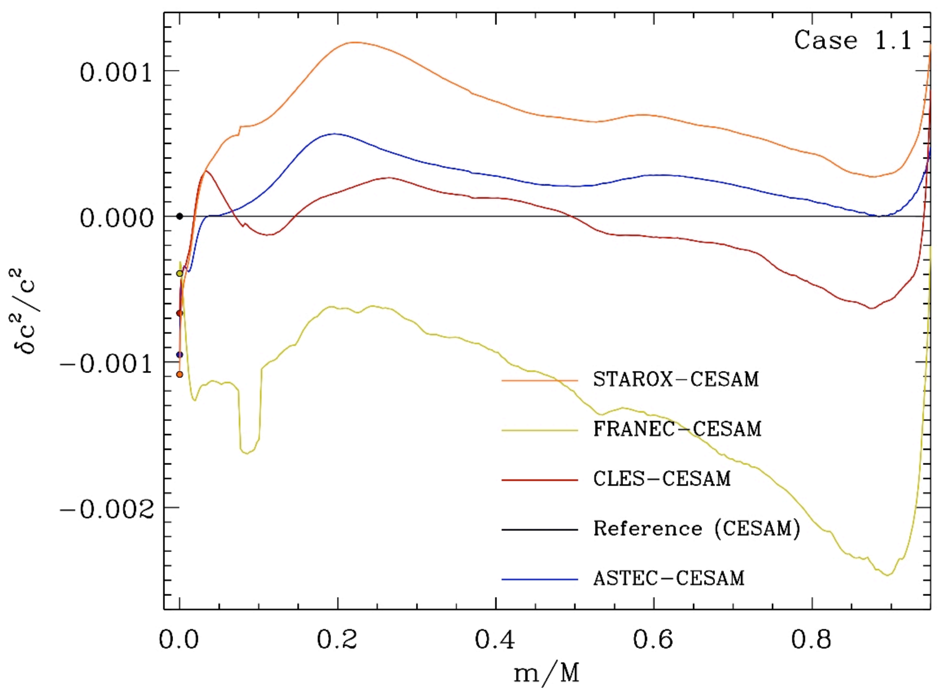




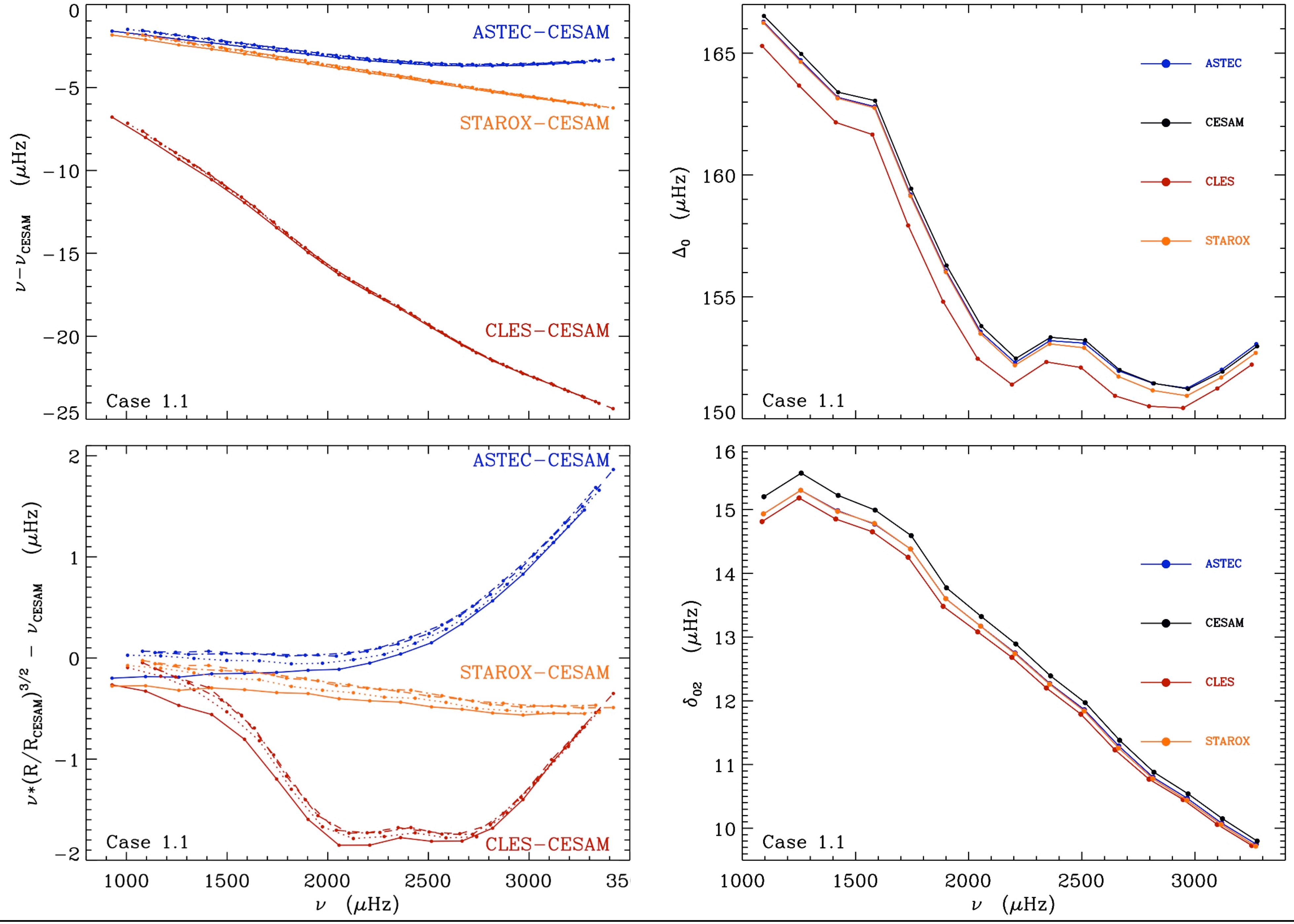
Main sequence (middle) model:

$M = 0.9\ M_{\odot}$

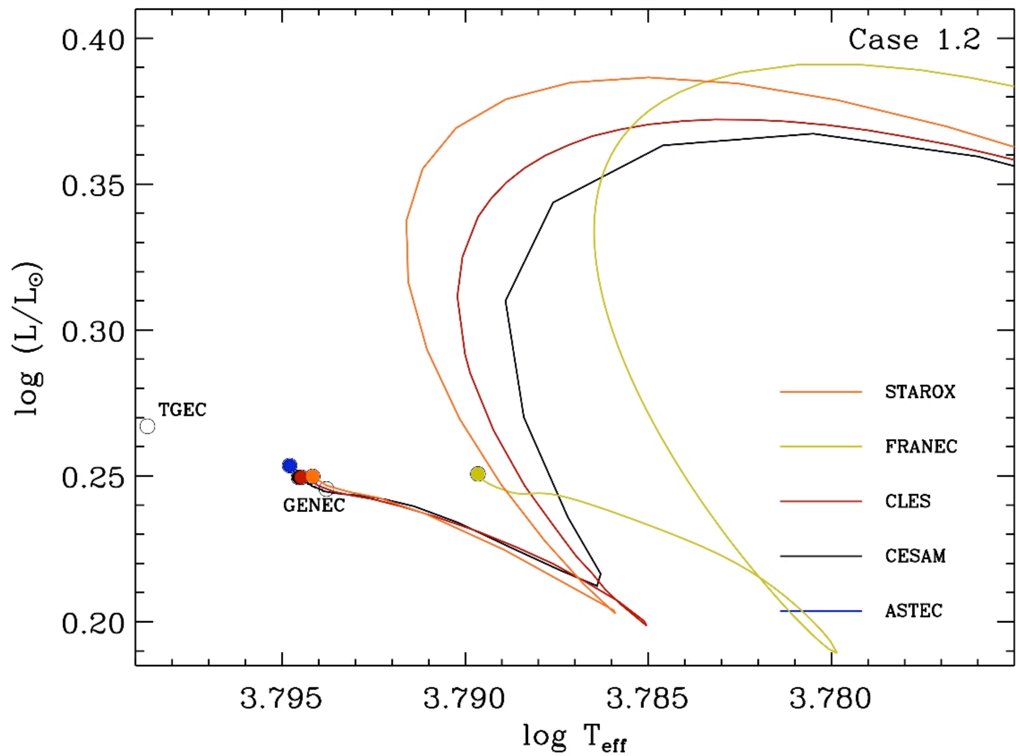
Code	Age	R/Rsun	L/Lsun	Teff	Tc/10^7	rhoc
ASTEC	6 709.1	0.8925	0.6265	5 441.0	1.4466	151.42
CESAM	6 782.0	0.8916	0.6262	5 443.0	1.4480	150.91
CLES	6 895.2	0.8958	0.6246	5 426.7	1.4470	150.90
FRANEC	6 839.0	0.8997	0.6273	5 413.0	1.4460	151.00
GENEC	7 024.0	0.8871	0.5985	5 395.0	1.4330	149.90
STAROX	6 674.5	0.8926	0.6259	5 439.3	1.4463	151.79
TGEC	6 539.0	0.8942	0.6504	5 489.3	1.4577	153.94
Spread (%)	7.2%	1.4%	8.3%	1.7%	1.7%	2.7%
	3.3%	0.5%	0.3%	0.3%	0.1%	0.6%

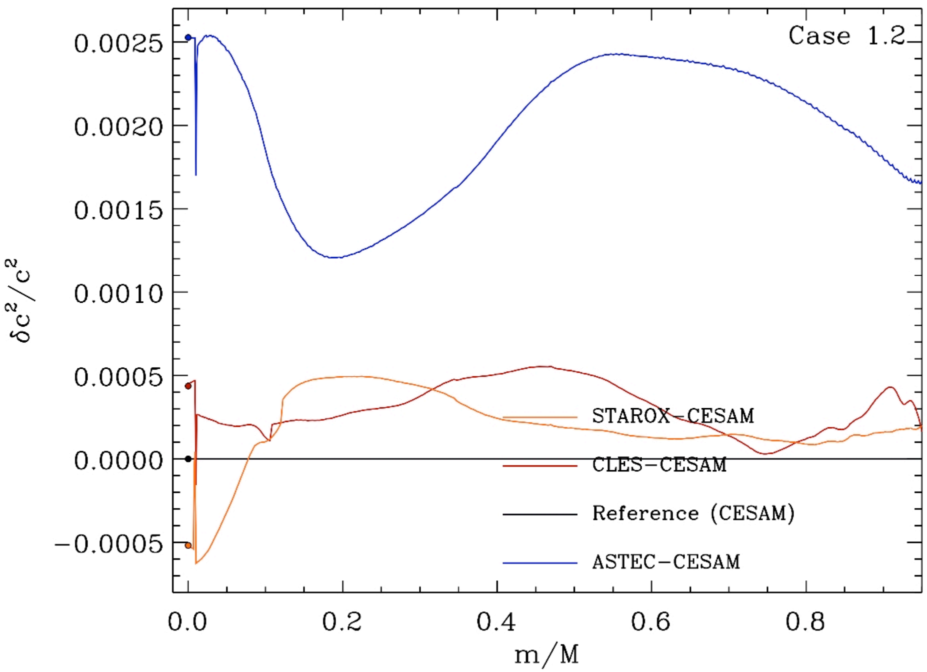


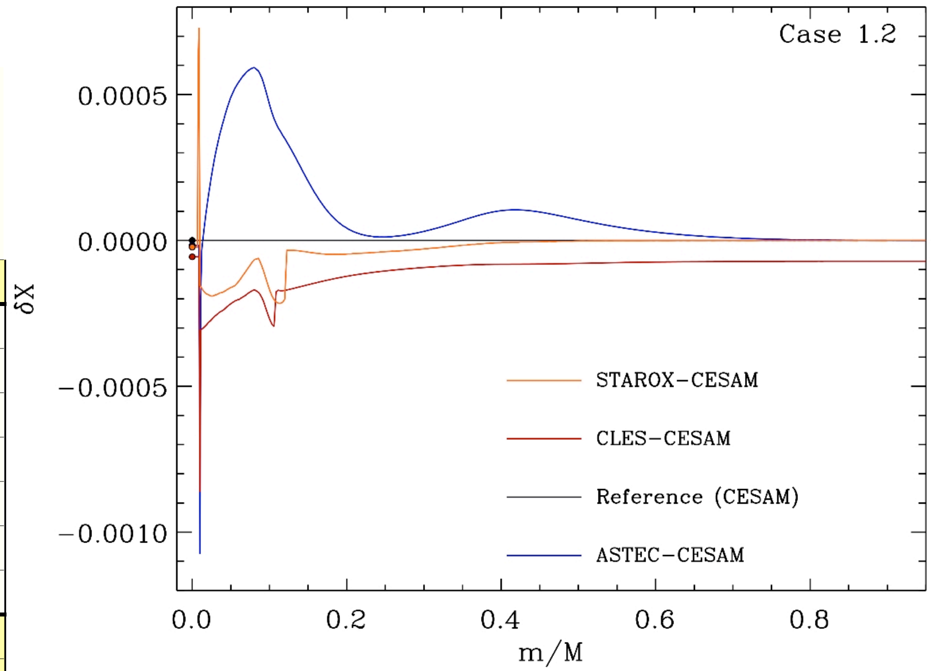
Case 1.1 - Seismic properties



Case 1.2





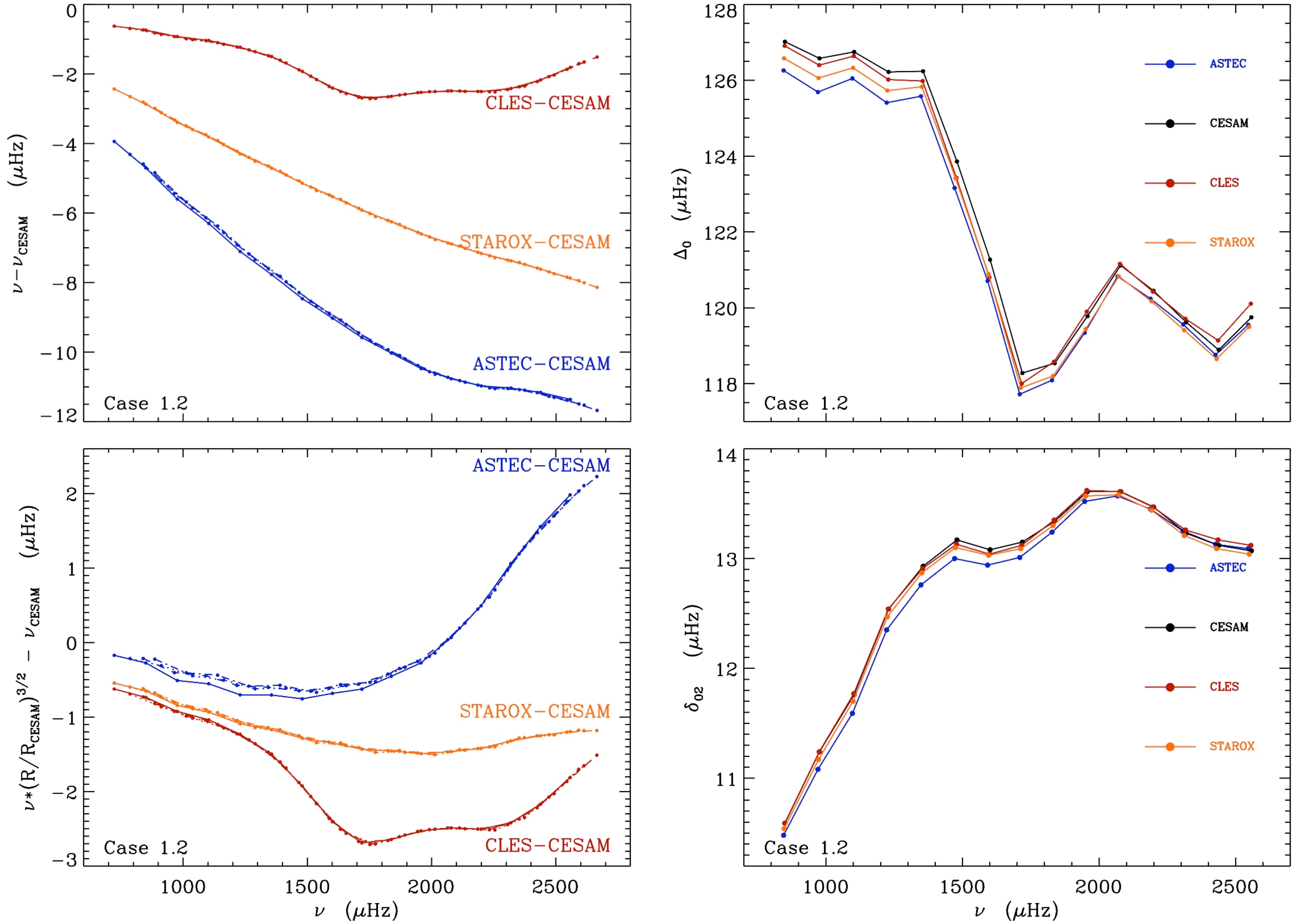


Main sequence (ZAMS) model:

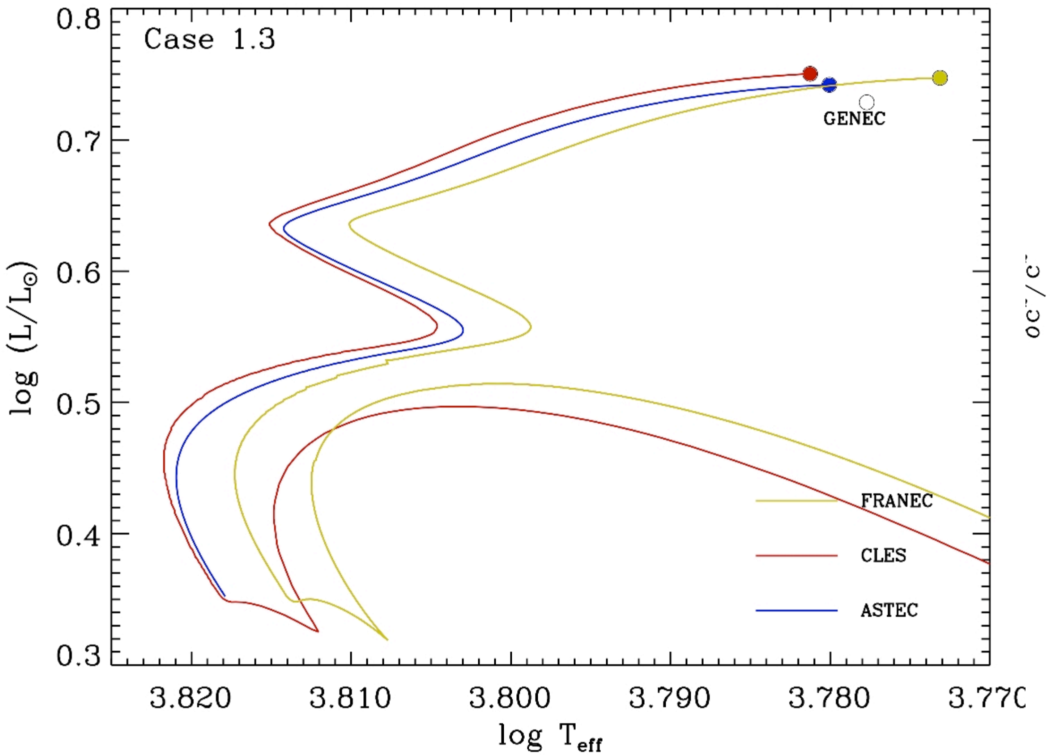
$M = 1.2\ M_\odot$

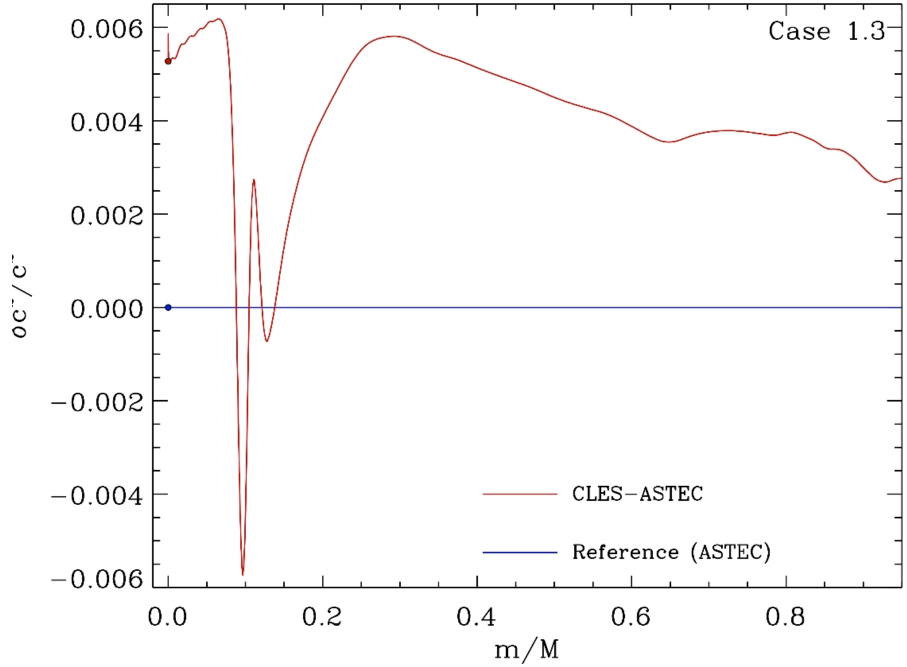
Code	Age	R/Rsun	L/Lsun	Teff	Tc/10^7	rhoc
ASTEC	74.59	1.1499	1.7929	6,234.4	1.5805	87.233
CESAM	96.71	1.1459	1.7762	6,230.9	1.5766	86.647
CLES	102.92	1.1463	1.7764	6,229.8	1.5759	86.524
FRANEC	99.10	1.1700	1.7810	6,161.0	1.5750	86.690
GENEC	79.00	1.1440	1.7600	6,220.0	1.5730	86.340
STAROX	101.45	1.1483	1.7775	6,225.4	1.5758	86.841
TGEC	106.00	1.1483	1.8493	6,290.4	1.5894	88.306
Spread (%)	34.8%	2.2%	4.9%	2.1%	1.0%	2.3%
	31.9%	0.3%	0.9%	0.1%	0.3%	0.8%

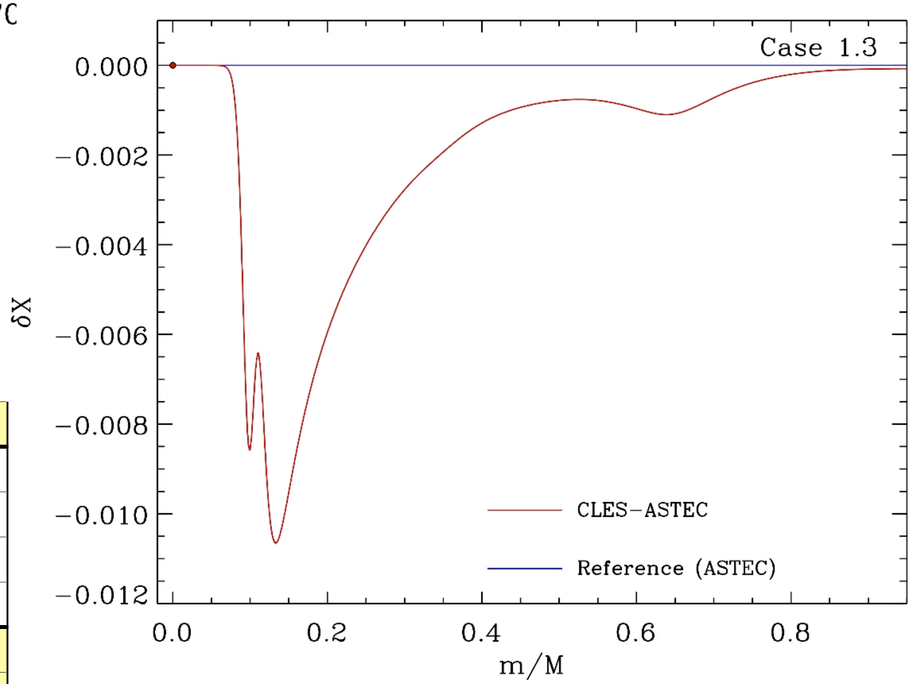
Case 1.2 - Seismic properties



Case 1.3





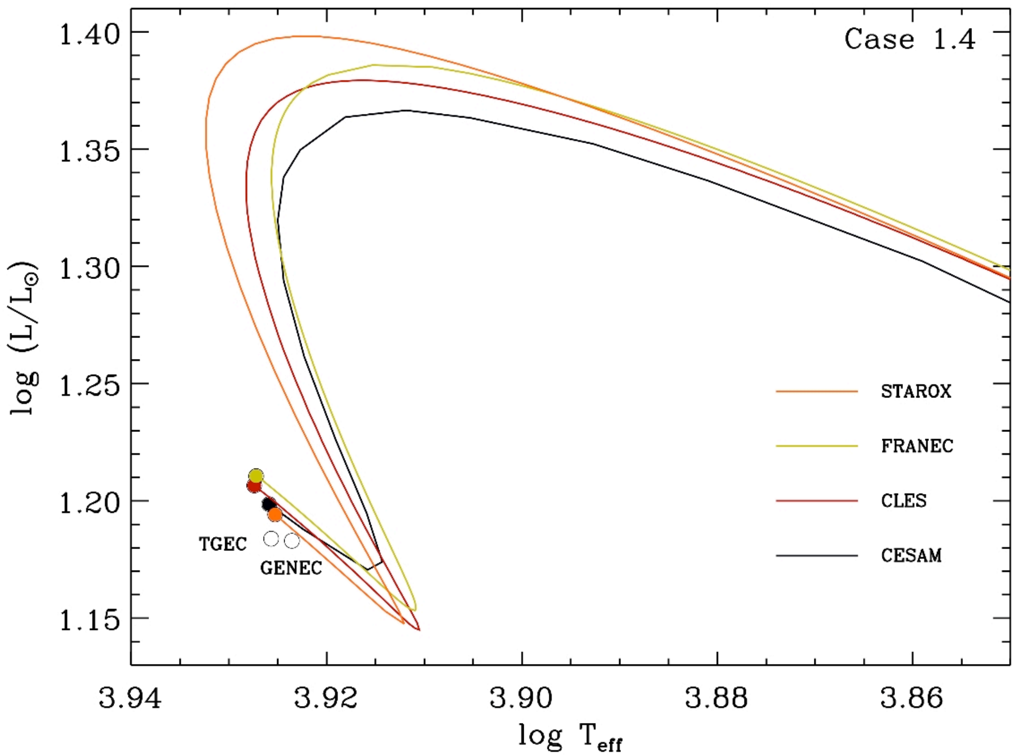


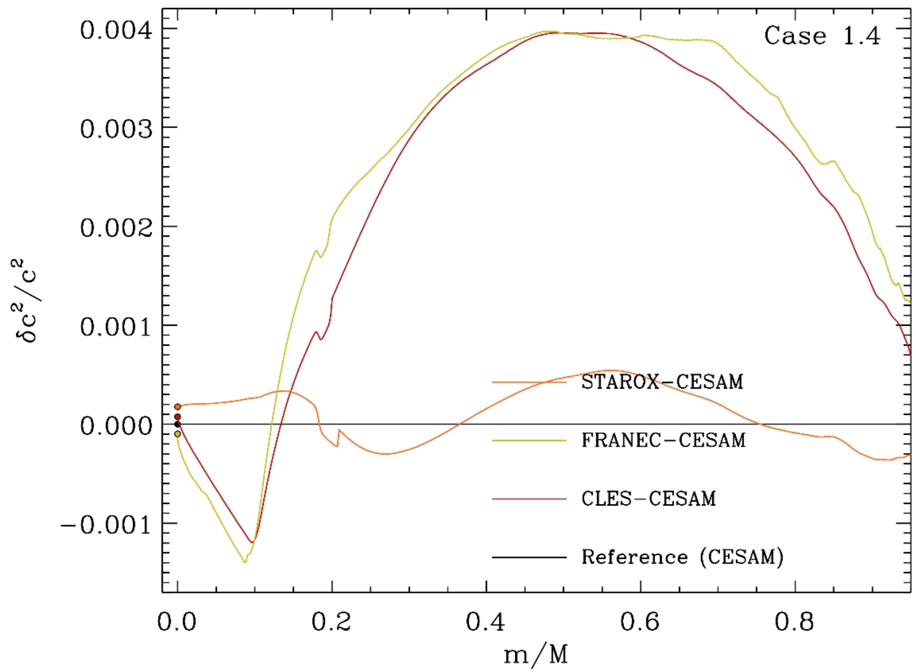
Post-main sequence model:

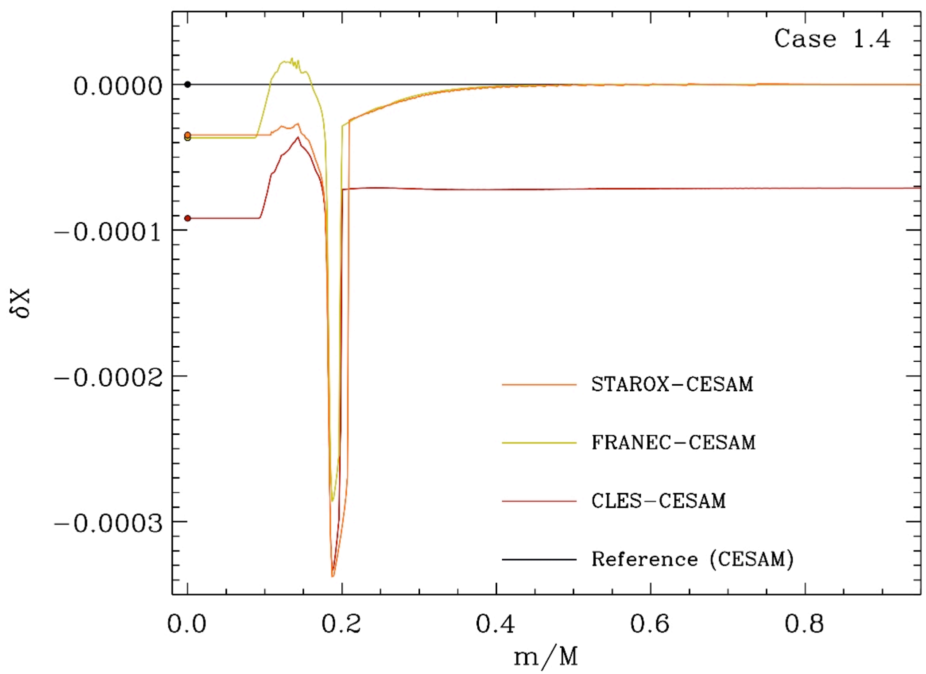
$M = 1.2\ M_\odot$

Code	Age	R/Rsun	L/Lsun	Teff	Tc/10^7	rhoc
ASTEC	4 322.8	2.1594	5.5200	6 026.4	2.1845	3253.27
CLES	4 454.0	2.1683	5.6278	6 043.2	2.2013	3107.53
FRANEC	4 278.0	2.2376	5.5880	5 931.0	2.1950	3280.00
GENEC	4 511.0	2.1490	5.3530	5 994.0	2.1940	3288.00
Spread (%)	5.3%	4.0%	5.0%	1.9%	0.8%	5.6%
	3.0%	0.4%	1.9%	0.3%	0.8%	4.6%

Case 1.4





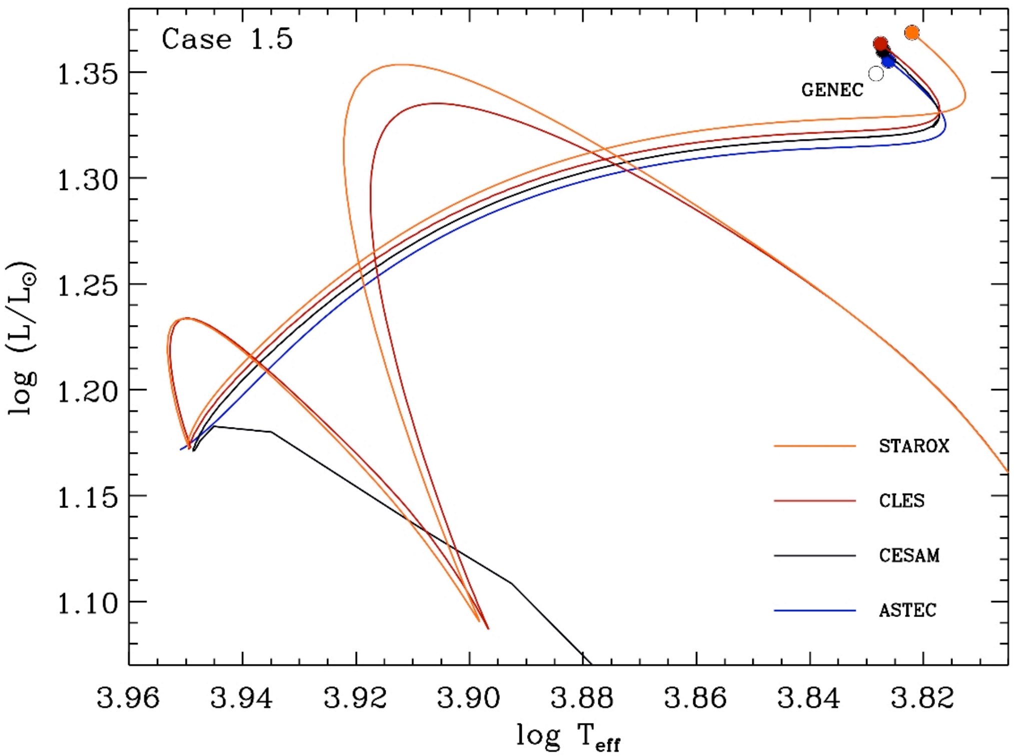


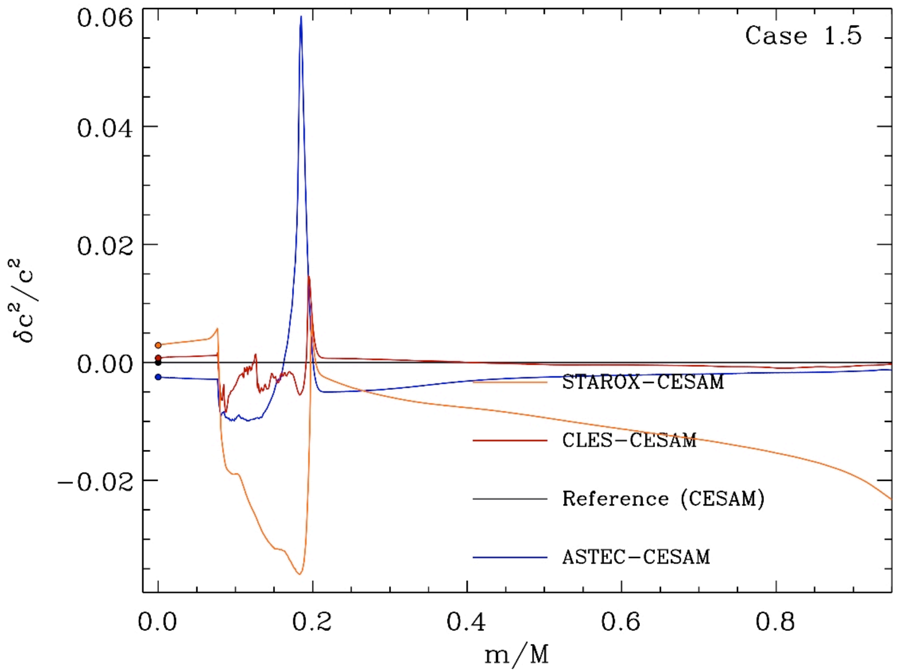
Pre-main sequence model:

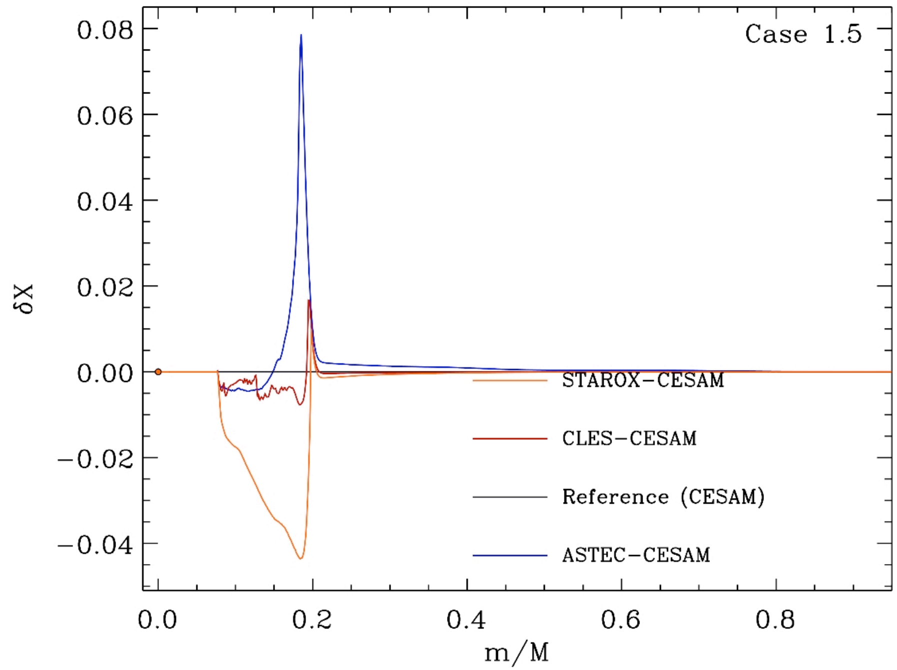
$M = 2.0\ M_\odot$

Code	Age	R/Rsun	L/Lsun	Teff	Tc/10^7	rhoc
CESAM	7.043	1.8663	15.798	8,431.3	1.8996	49.224
CLES	7.579	1.8705	16.091	8,460.7	1.9000	49.890
FRANEC	7.814	1.8760	16.240	8,457.0	1.8970	50.030
GENEC	7.685	1.8530	15.240	8,386.0	1.9000	48.900
STAROX	8.292	1.8623	15.639	8,419.3	1.9000	49.199
TGEC	7.200	1.8387	15.271	8,427.0	1.8914	46.864
Spread (%)	16.3%	2.0%	6.4%	0.9%	0.5%	6.5%
	16.3%	0.4%	2.9%	0.5%	0.0%	1.4%

Case 1.5





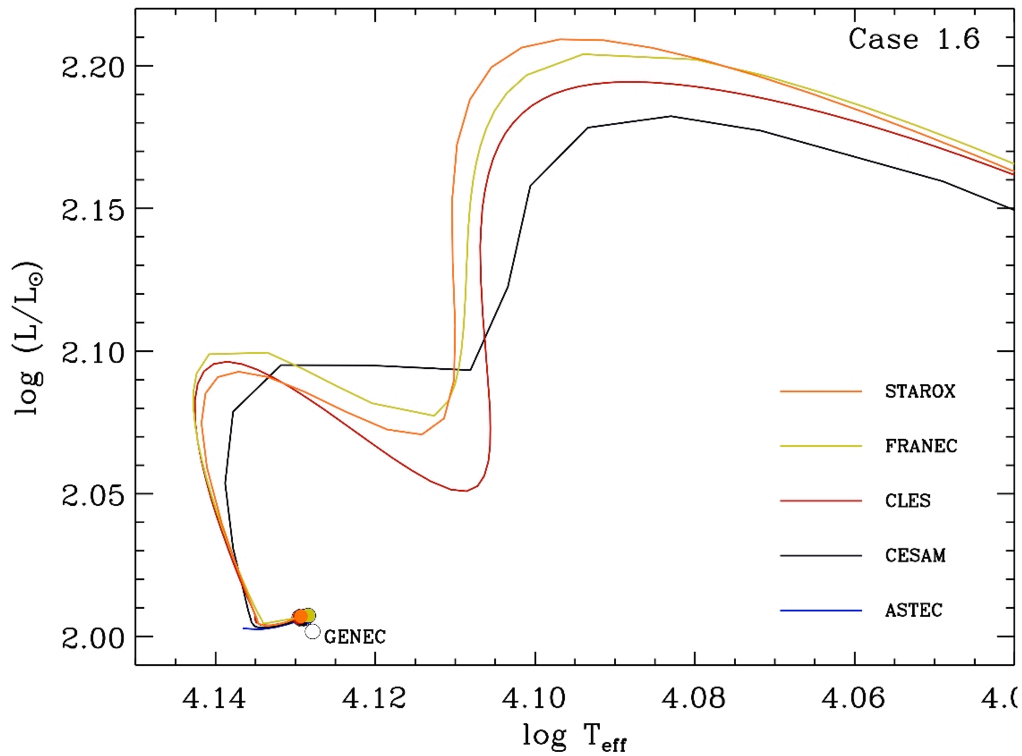


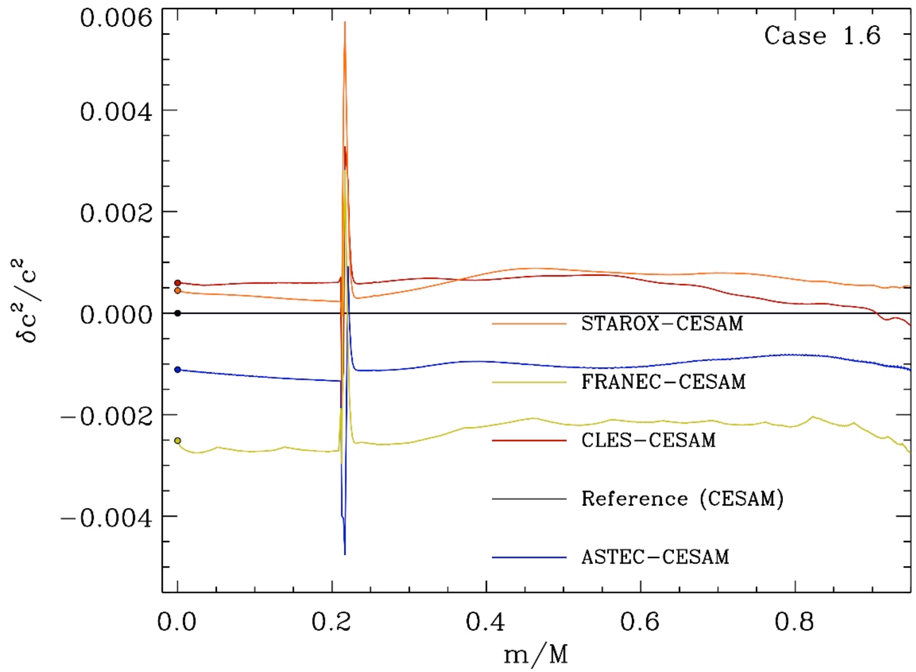
End of the main sequence (TAMS) model:

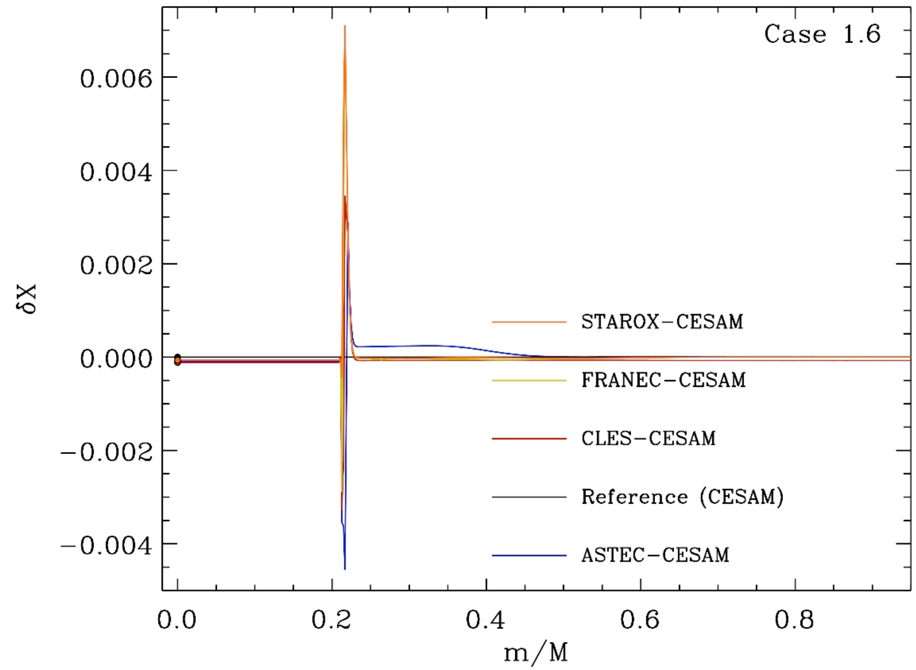
$M = 2.0\ M_\odot$

Code	Age	R/Rsun	L/Lsun	Teff	Tc/10^7	rhoc
ASTEC	1,175.4	3.5390	22.668	6,701.2	2.7869	130.900
CESAM	1,184.1	3.5427	22.909	6,715.5	2.7937	131.757
CLES	1,202.4	3.5491	23.090	6,722.6	2.7971	131.684
GENEC	1,189.0	3.4780	22.350	6,735.0	2.7940	131.700
STAROX	1,207.7	3.6627	23.369	6,637.4	2.8024	131.832
Spread (%)	**2.7%**	**5.2%**	**4.5%**	**1.5%**	**0.6%**	**0.7%**
	2.7%	**3.4%**	**3.0%**	**1.3%**	**0.6%**	**0.7%**

Case 1.6





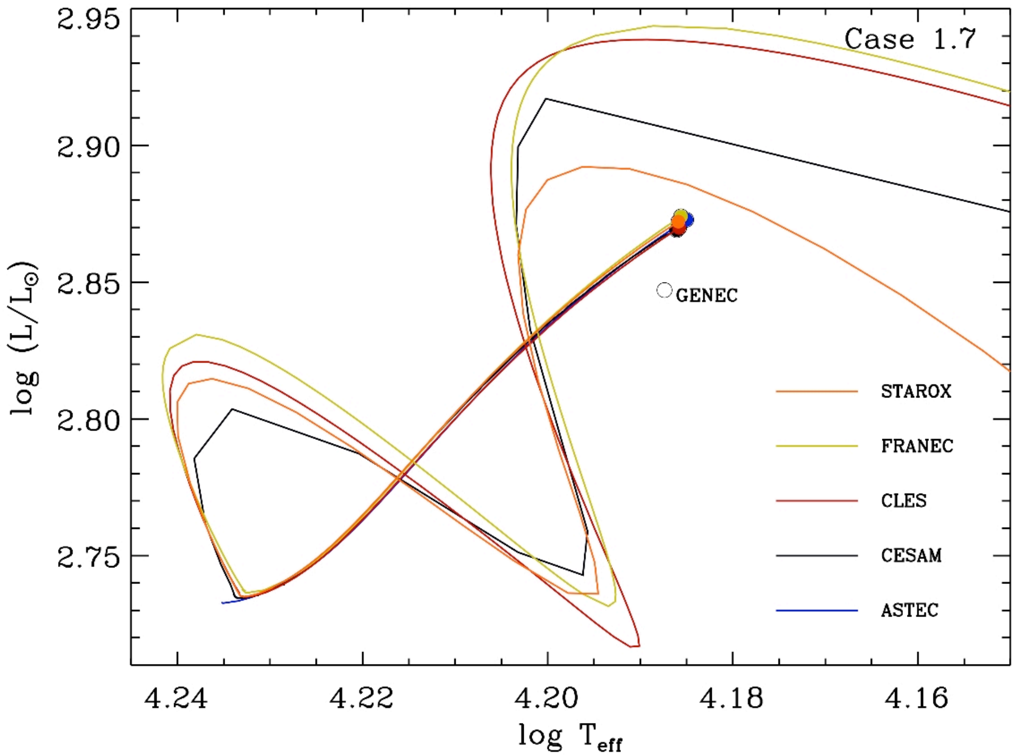


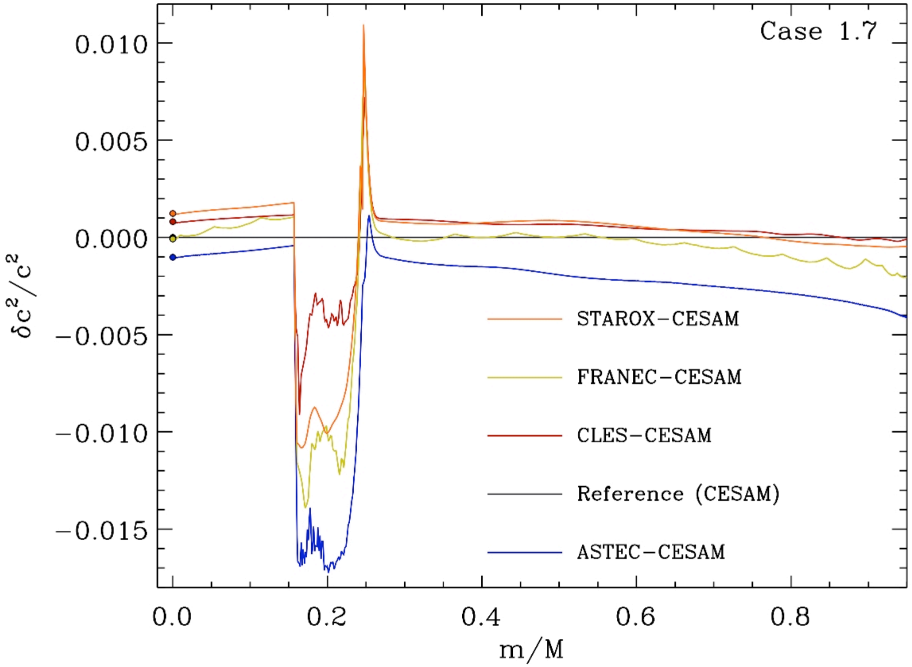
Main sequence (ZAMS) model:

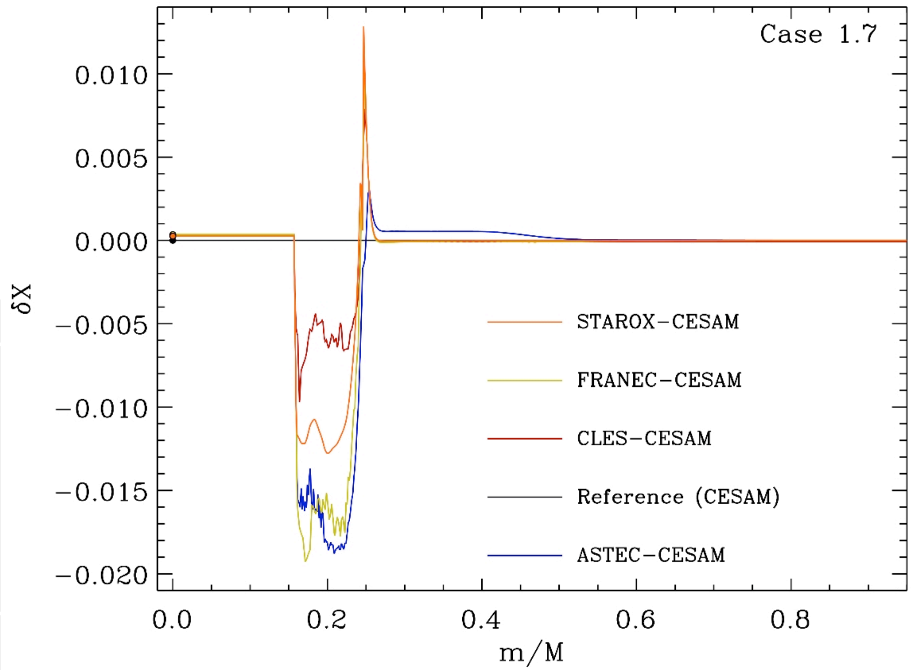
$M = 3.0\ M_\odot$

Code	Age	R/Rsun	L/Lsun	Teff	Tc/10^7	rhoc
ASTEC	13.32	1.8588	101.52	13,451	2.4834	42.937
CESAM	14.47	1.8539	101.41	13,466	2.4859	43.043
CLES	14.76	1.8526	101.54	13,475	2.4860	43.021
FRANEC	14.86	1.8590	101.70	13,440	2.4810	42.880
GENEC	14.77	1.8560	100.40	13,423	2.4880	42.600
STAROX	14.46	1.8552	101.64	13,468	2.4872	43.166
Spread (%)	10.9%	0.3%	1.3%	0.4%	0.3%	1.3%
	10.3%	0.3%	0.2%	0.2%	0.2%	0.5%

Case 1.7







Main sequence (middle) model:

$M = 5.0\ M_\odot$

Code	Age	R/Rsun	L/Lsun	Teff	Tc/10^7	rhoc
ASTEC	56.37	3.8888	746.09	15,312	2.8321	19.600
CESAM	55.94	3.8539	739.62	15,348	2.8358	19.760
CLES	56.53	3.8622	741.06	15,339	2.8374	19.777
FRANEC	56.86	3.8750	748.20	15,332	2.8360	19.730
GENEC	52.74	3.7340	703.20	15,395	2.8650	19.520
STAROX	55.60	3.8708	744.95	15,342	2.8384	19.761
Spread (%)	7.5%	4.1%	6.2%	0.5%	1.2%	1.3%
	1.7%	0.9%	0.9%	0.2%	0.2%	0.9%

Comparison - internal structure

Results for the comparison of the internal structure (when excluding the atmosphere) for $m<0.95M$:

Δ_{max}	δX	$\delta c^2/c^2$
1.1 ($0.9M_\odot$, MS)	**0.0015**	**0.0025**
1.2 ($1.2M_\odot$, ZAMS)	**0.0011**	**0.0026**
1.3 ($1.2M_\odot$, PostMS)	**0.011**	**0.0063**
1.4 ($2M_\odot$, PreMS)	**0.00034**	**0.004**
1.5 ($2M_\odot$, TAMS)	**0.08**	**0.06**
1.6 ($3M_\odot$, ZAMS)	**0.0075**	**0.0078**
1.7 ($5M_\odot$, MS)	**0.019**	**0.018**

Most evident problems (to be solved!):

- edge of convective regions (and in particular with overshoot and semi-convection)
- near-surface layers and atmosphere

Task 2 - frequency comparison

In this task, **particular types of stellar pulsators** are study in order to quantify the uncertainty on the predicted seismic parameters for these stars.

Models and frequencies, as calculated by different codes, are produced in order to quantify the range of solutions found for the frequencies in each class of pulsators.

Andy Moya leads this task whose objective is to compare the frequencies as calculated by different seismic codes for the same model. The goal is to establish the numerical accuracy of the seismic codes and their sensitivity to some of the calculation parameters.

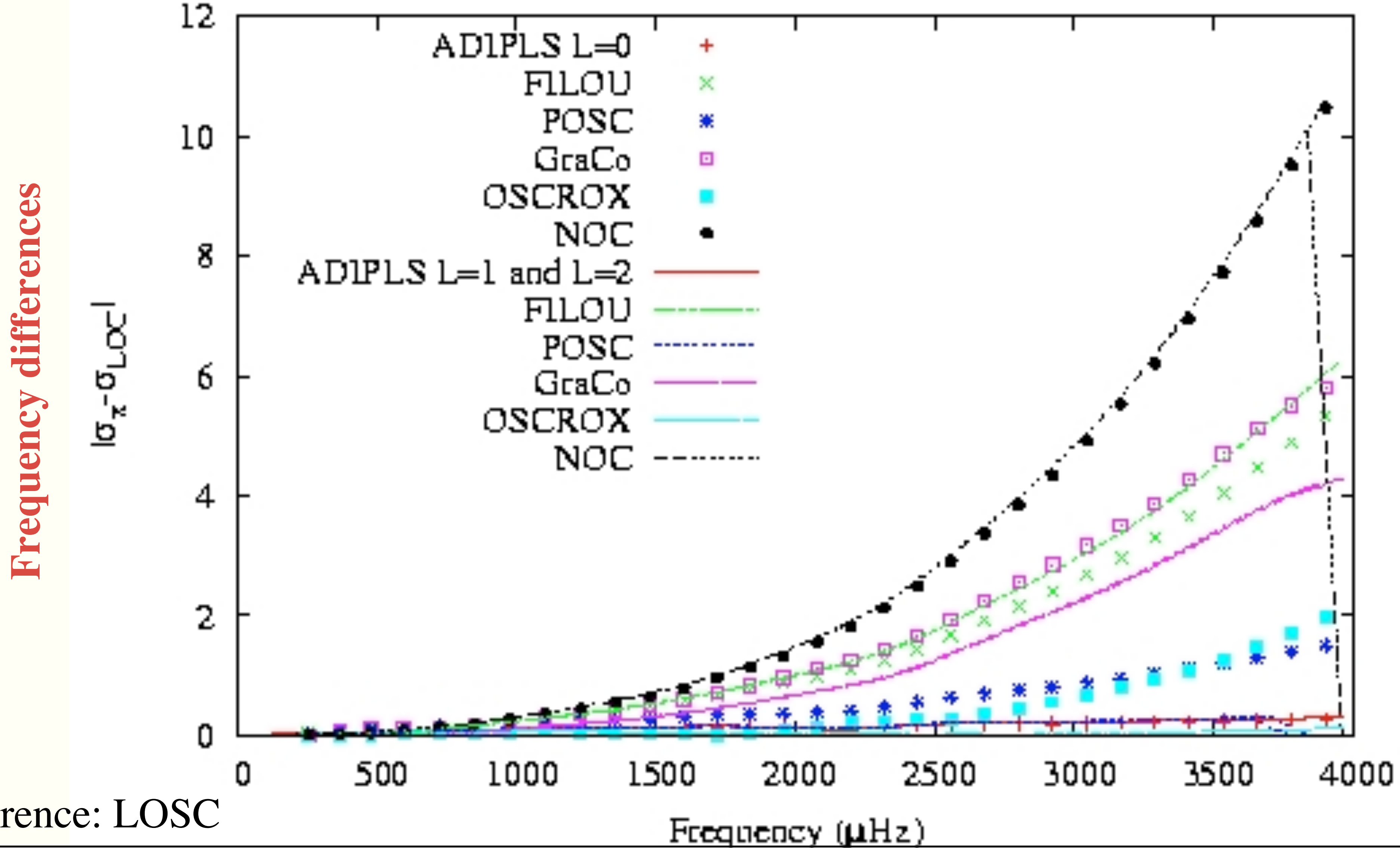
A preliminary comparison for Task 2 have been presented and discuss in this meeting. The results shown on Tuesday by Andy Moya (also available as a poster) have been produced using a **1.2 $M_{\odot}$ model in the main sequence**.

Further details on this Task are given at the following webpage:

www.astro.up.pt/corot/compfreqs/task2.html

Step 1 - frequency differences

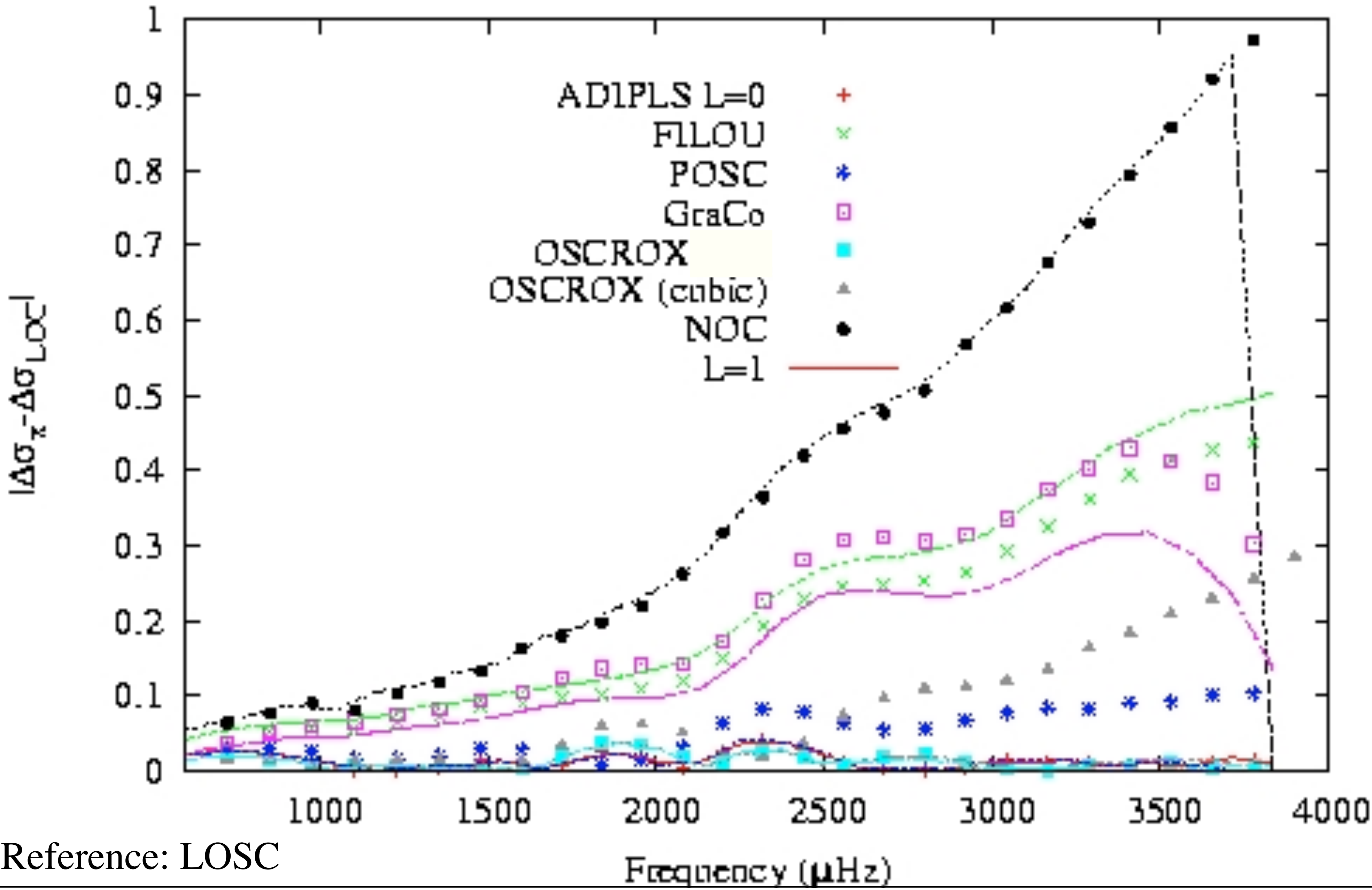
The model has been provided in a mesh with ~900 points. The frequencies were calculated for the mesh provided. In some cases Richardson extrapolation has been used for determining the frequencies.



Reference: LOSC

Step 1 - large frequency separations

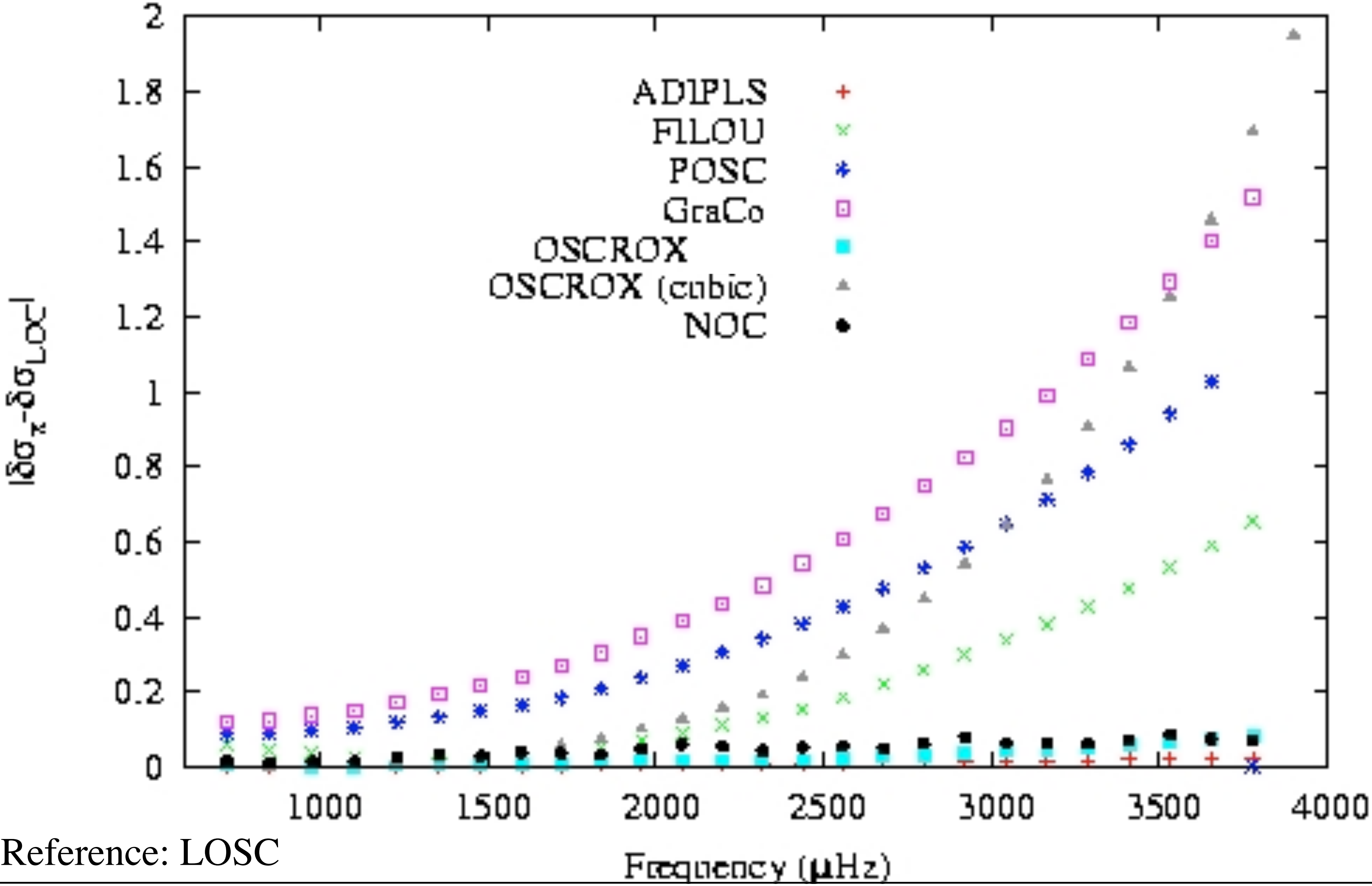
Differences in the large frequency separations for l=0 (dots) and l=1 (lines)



Reference: LOSC

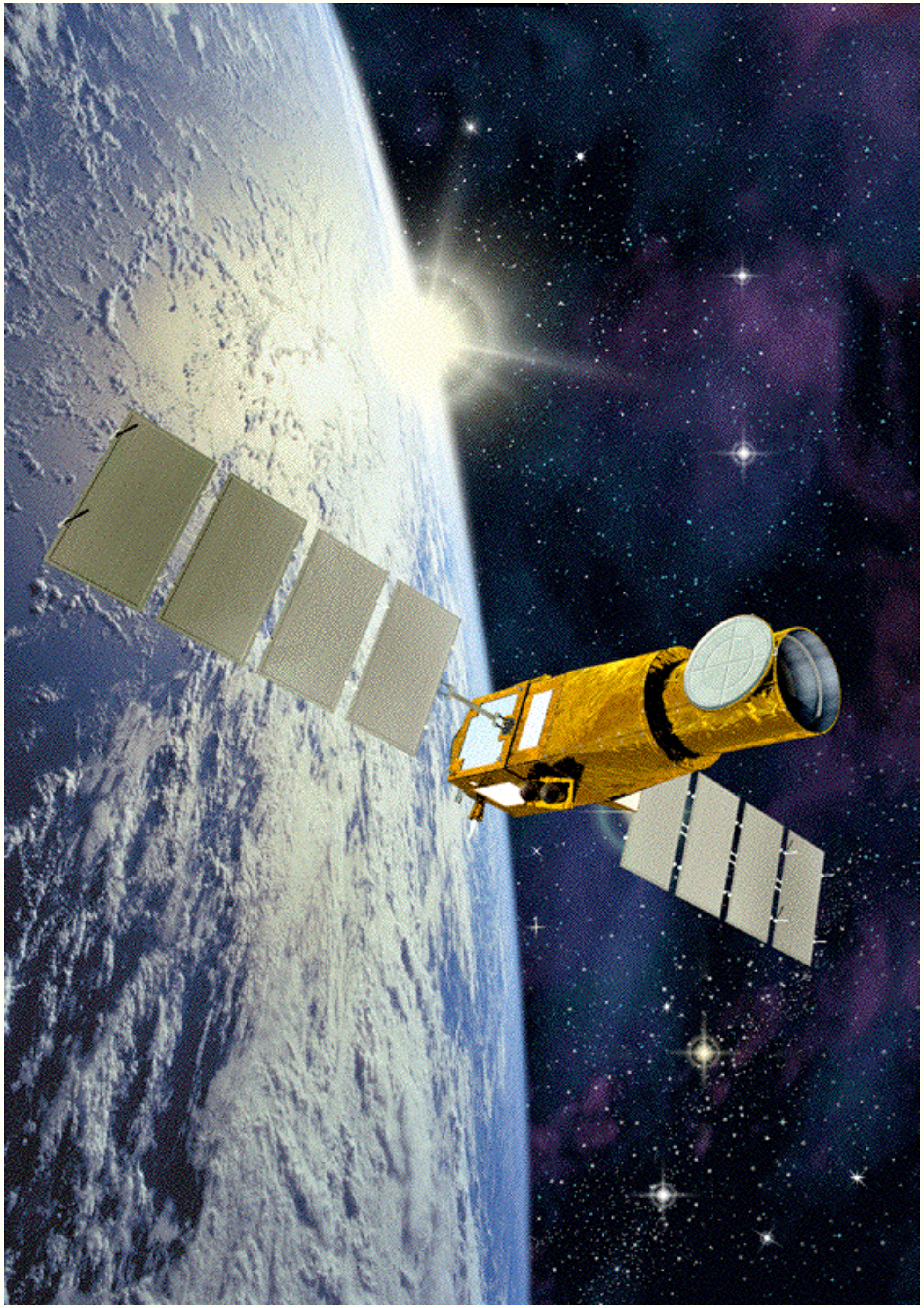
Step 1 - small frequency separations

Differences in the small frequency separations for l=0,2



Reference: LOSC

The end



All information about ESTA (data, documents, ongoing activities, results, publications, etc) are made available at:

www.astro.up.pt/corot/

If you have suggestions, data, information, documents, requests, etc, relevant for ESTA please contact me at:

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