Astrosejsmologia

Aleksiej Pamiatnych

Centrum Astronomiczne im. M. Kopernika PAN, Warszawa

Astrosejsmologia – badanie budowy wewnętrznej gwiazd za pośrednictwem analizy widma częstotliwości ich pulsacji.

Dla Ziemi – sejsmologia (analiza drgań, spowodowanych
trzęsieniami ziemi albo wybuchami jądrowymi),
dla Słońca – heliosejsmologia.

CAMK, marzec-czerwiec 2012

Proponowany kalendarz 11 lekcji :

13 marca, wtorek, godz. 10.00 (lekcja 1).
27 marca, wtorek, godz. 10.00 (lekcje 2 i 3).

17 kwietnia, wtorek, godz. 10.00 (lekcje 4 i 5).
24 kwietnia, wtorek, godz. 10.00 (lekcje 6 i 7).

15 maja, wtorek, godz. 10.00 (lekcje 8 i 9).
29 maja, wtorek, godz. 10.00 (lekcje 10 i 11).

12 czerwca, wtorek, godz. 10.00 – zaliczenie (egzamin).

Źródła-podręczniki:

- J. Christensen-Dalsgaard, Stellar oscillations, 2003, 276 stron.
  File JCD_course.pdf.

- C. Aerts, Asteroseismology, 2005, 152 strony.
  File Aerts_course.pdf.

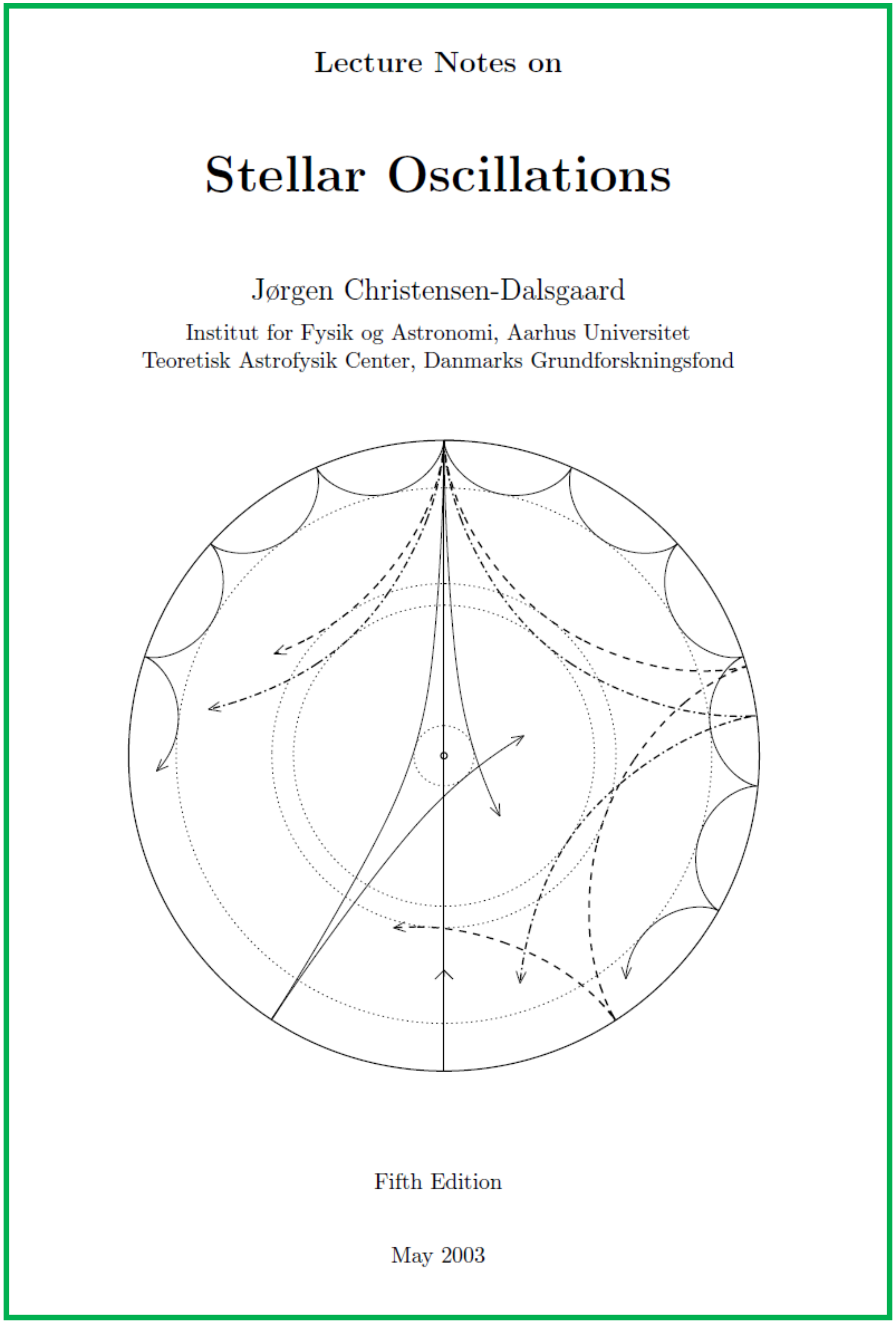
- C. Aerts, J. Christensen-Dalsgaard, D. W. Kurtz,
  Asteroseismology, 2010, Springer, 866 stron.
  Książka.

- A. Gautschy, H. Saio, Stellar pulsations across the HR diagram.
  Part 1: Ann. Rev. Astron. Astrophys., 1995, 33, 75.
  Part 2: Ann. Rev. Astron. Astrophys., 1996, 34, 551.

- C.Aerts et al., The current status of Asteroseismology,
  Solar Phys., 2008, 251, 3 (astro-ph 0803.3527, 25.03.2008)

- Kilka oryginalnych artykułów ostatnich lat.

- W. A. Dziembowski,
  Wykład „Wielomodalne pulsacje gwiazd – asterosejsmologia".



Lecture Notes on

Stellar Oscillations

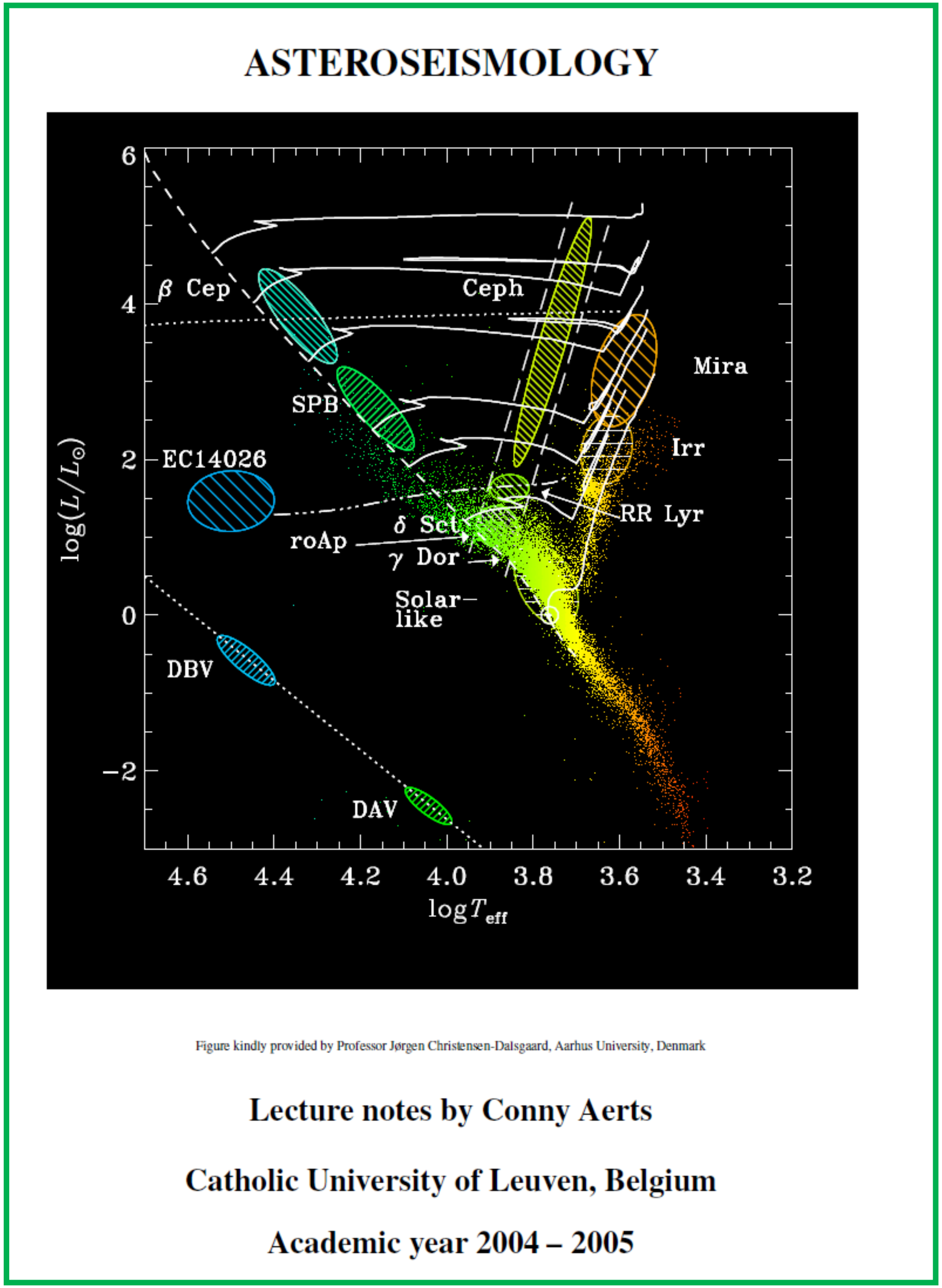
Jørgen Christensen-Dalsgaard

Institut for Fysik og Astronomi, Aarhus Universitet
Teoretisk Astrofysik Center, Danmarks Grundforskningsfond

Fifth Edition

May 2003

1) File JCD_course.pdf



ASTEROSEISMOLOGY

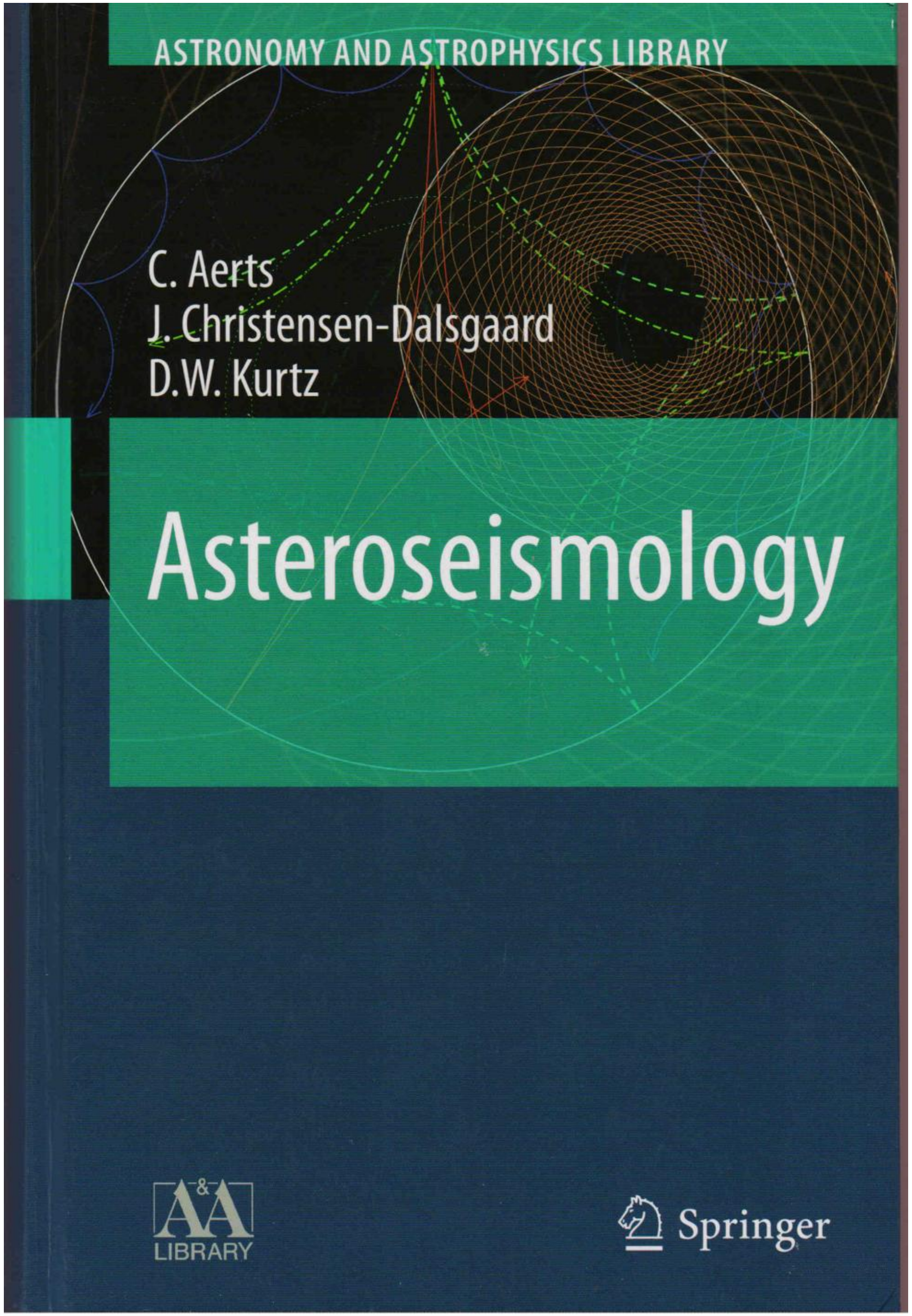
Figure kindly provided by Professor Jørgen Christensen-Dalsgaard, Aarhus University, Denmark

Lecture notes by Conny Aerts

Catholic University of Leuven, Belgium

Academic year 2004 – 2005

2) File astero.pdf, 12.35 Mb



ASTRONOMY AND ASTROPHYSICS LIBRARY

C. Aerts
J. Christensen-Dalsgaard
D.W. Kurtz

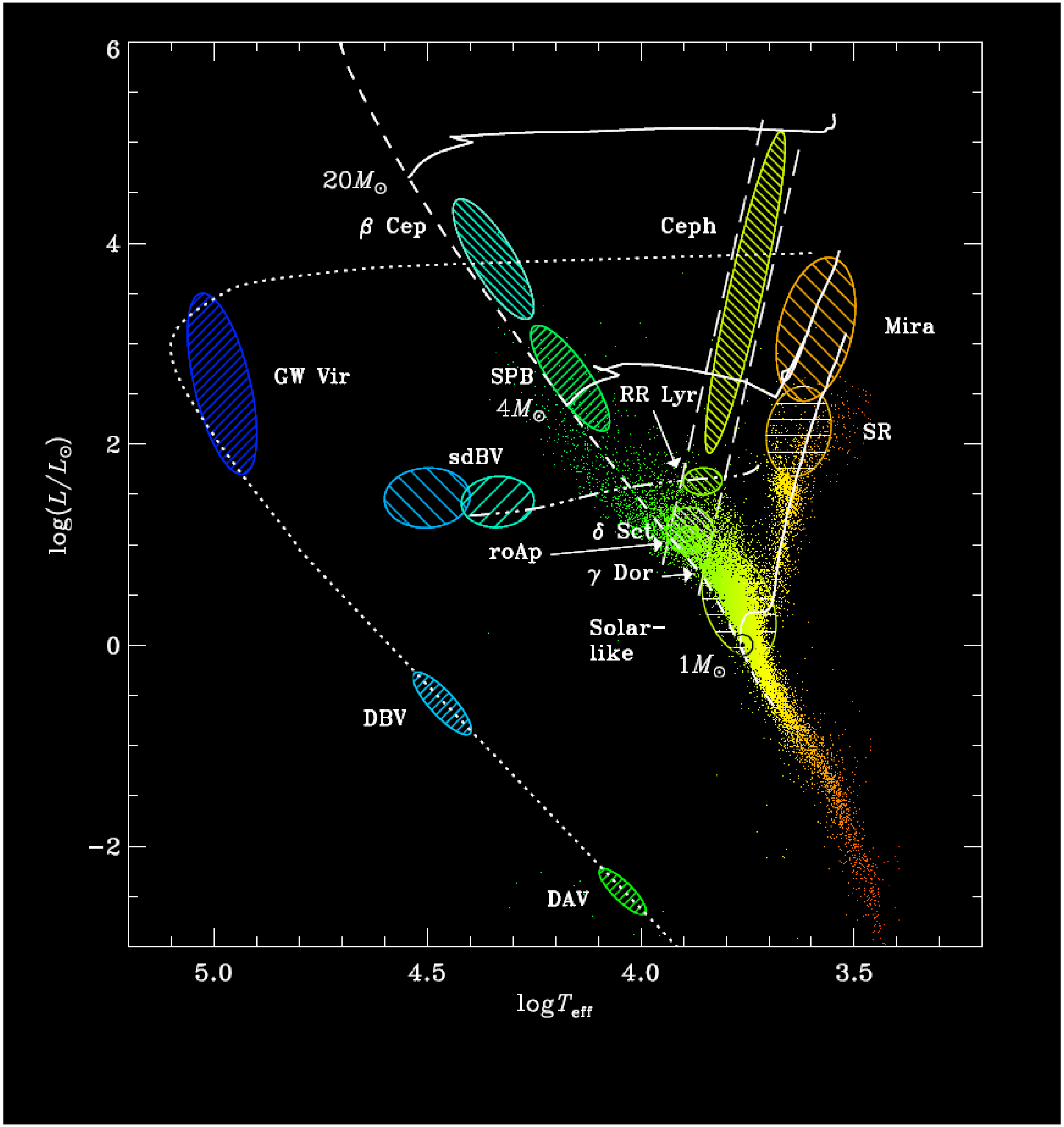
Asteroseismology

A&A LIBRARY

Springer

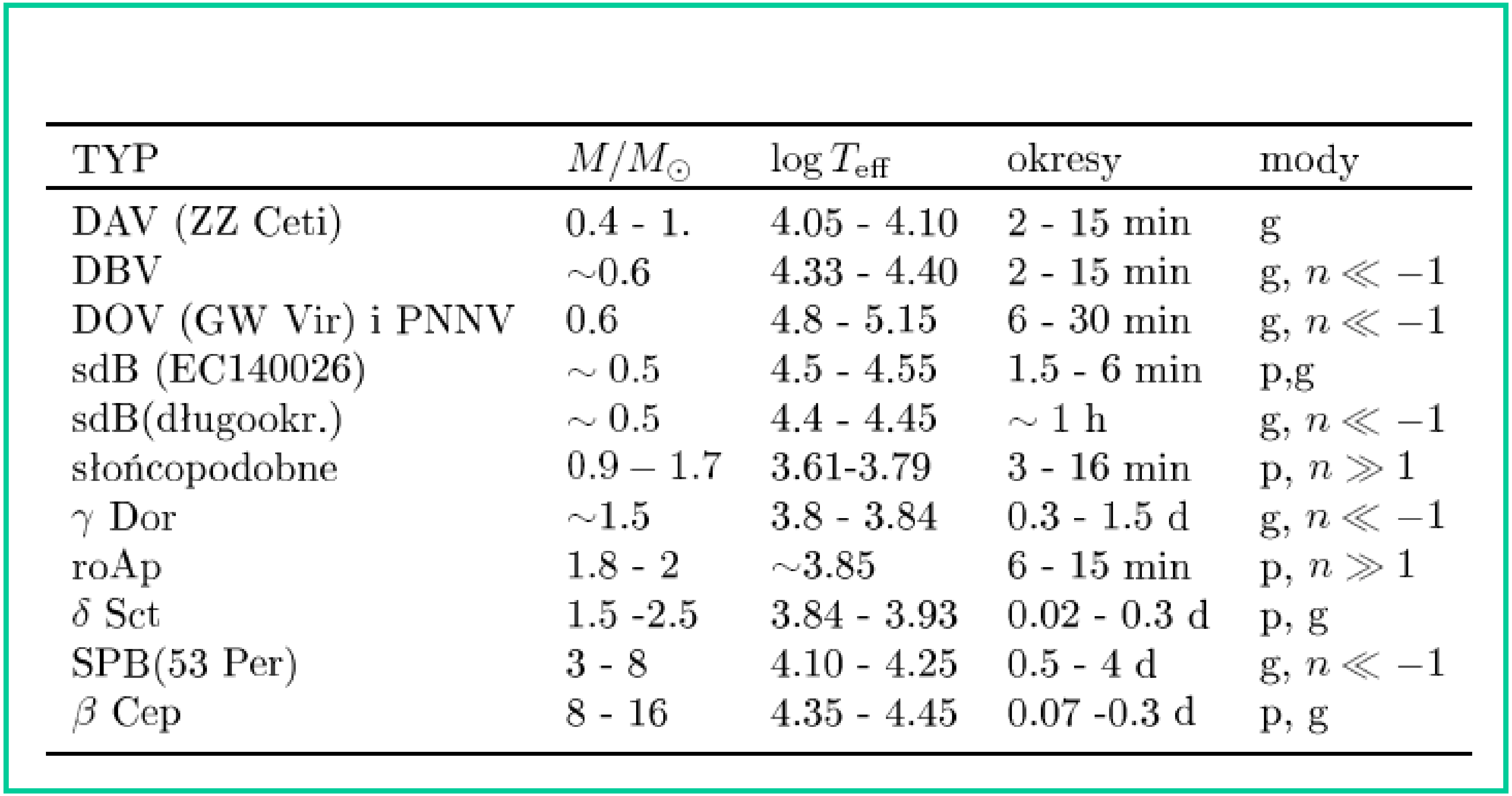
3) Książka, 2010, 866 stron.

Pulsating stars in the HRD



JCD 2007, http://user-phys.au.dk/jcd/HELAS/puls_HR/

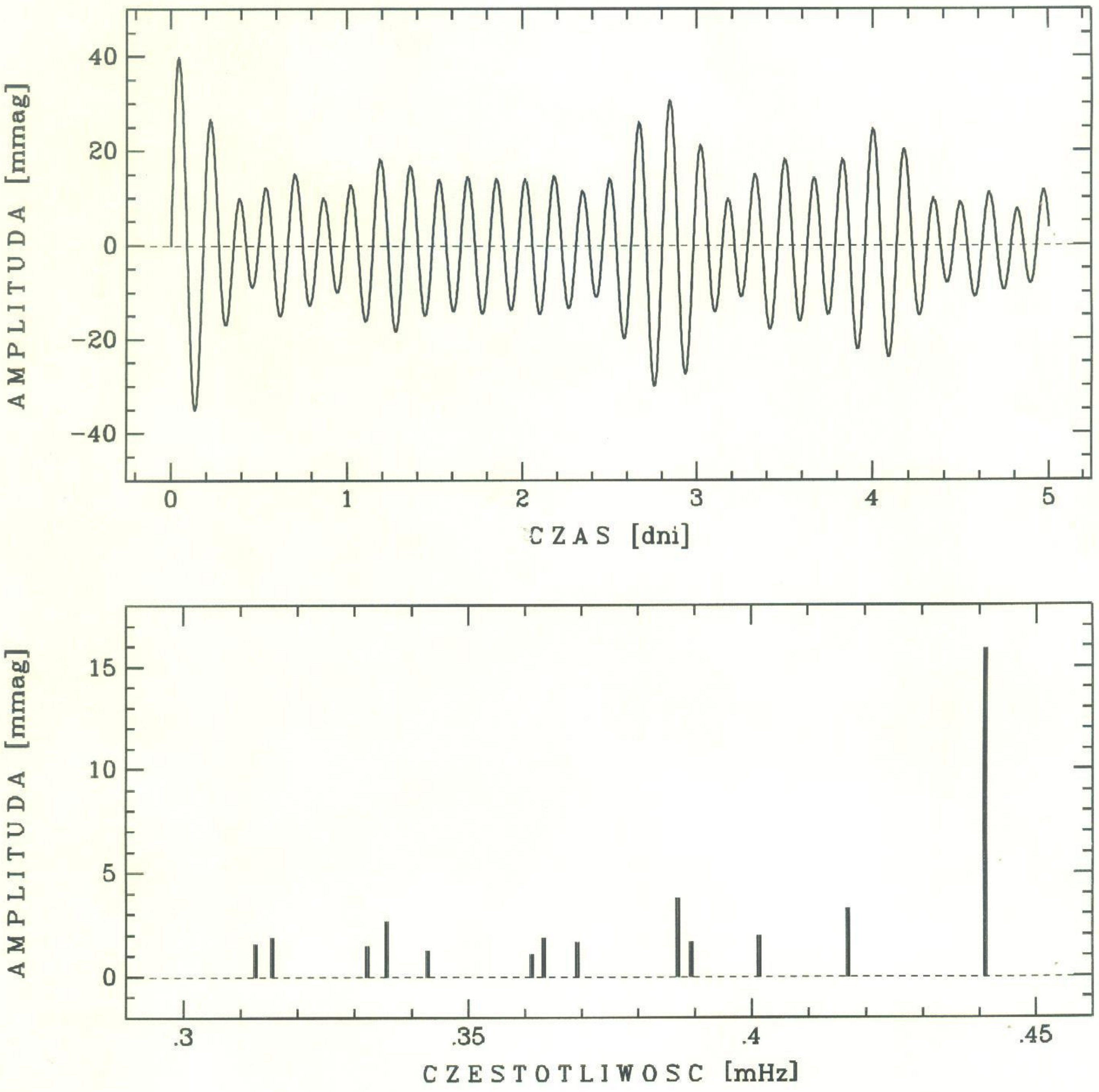
Typy wielomodalnych gwiazd pulsujących



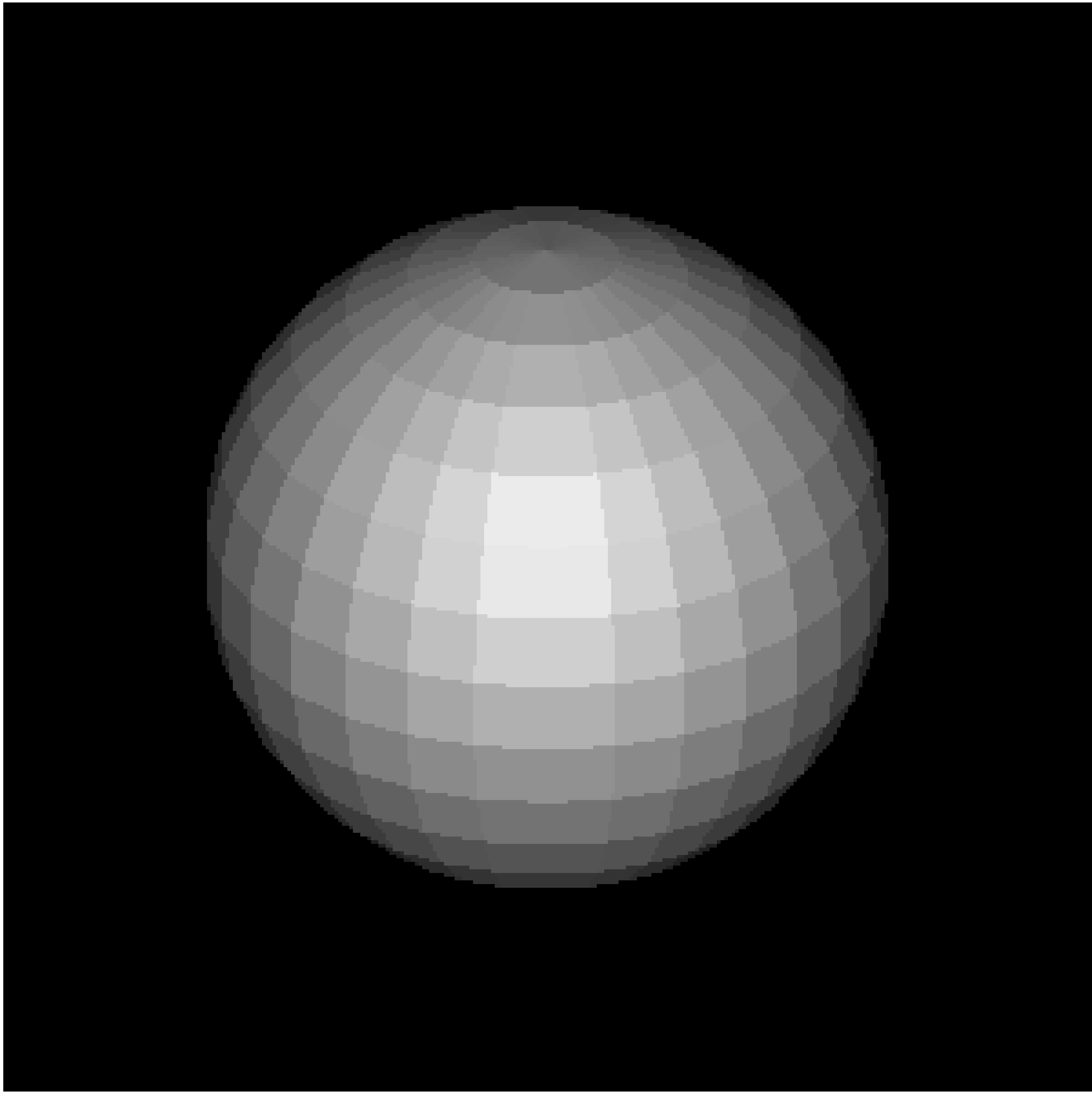
TYP	$M/M_\odot$	$\log T_{\rm eff}$	okresy	mody
DAV (ZZ Ceti)	0.4 - 1.	4.05 - 4.10	2 - 15 min	g
DBV	$\sim$0.6	4.33 - 4.40	2 - 15 min	g, $n \ll -1$
DOV (GW Vir) i PNNV	0.6	4.8 - 5.15	6 - 30 min	g, $n \ll -1$
sdB (EC140026)	$\sim$ 0.5	4.5 - 4.55	1.5 - 6 min	p,g
sdB(długookr.)	$\sim$ 0.5	4.4 - 4.45	$\sim$ 1 h	g, $n \ll -1$
słońcopodobne	$0.9 - 1.7$	3.61-3.79	3 - 16 min	p, $n \gg 1$
γ Dor	$\sim$1.5	3.8 - 3.84	0.3 - 1.5 d	g, $n \ll -1$
roAp	1.8 - 2	$\sim$3.85	6 - 15 min	p, $n \gg 1$
δ Sct	1.5 -2.5	3.84 - 3.93	0.02 - 0.3 d	p, g
SPB(53 Per)	3 - 8	4.10 - 4.25	0.5 - 4 d	g, $n \ll -1$
β Cep	8 - 16	4.35 - 4.45	0.07 -0.3 d	p, g

W. A. Dziembowski

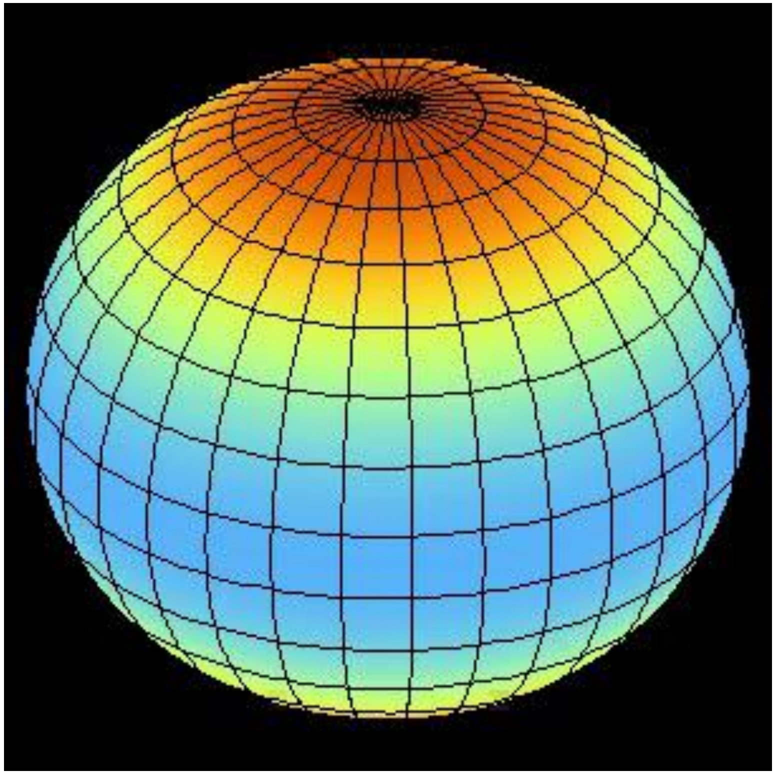
Krzywa zmian blasku i widmo amplitud pusacji gwiazdy XX Pyxidis



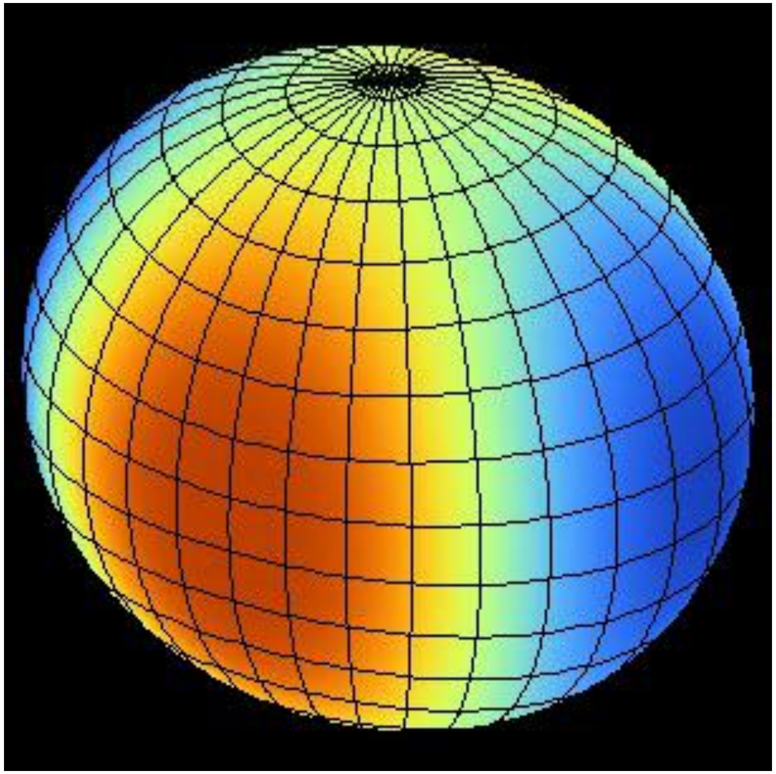
Radialne pulsacje



Non-radial modes: quadrupole modes



$l=2$, $m=0$

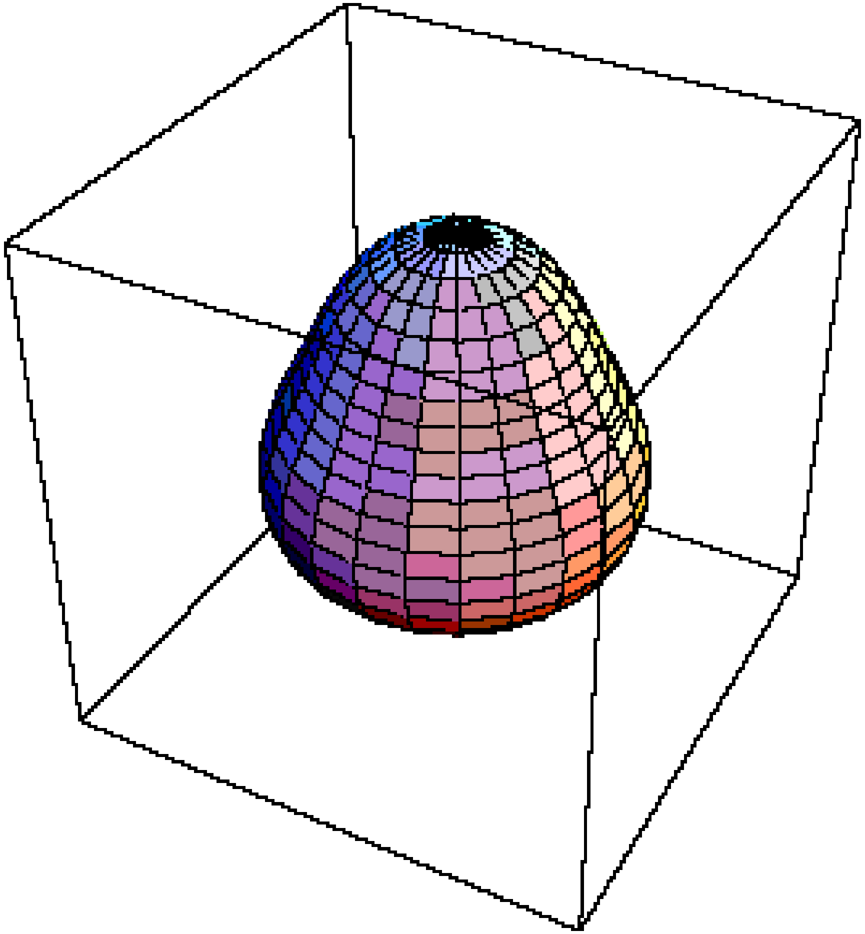


$l=2$, $m=2$

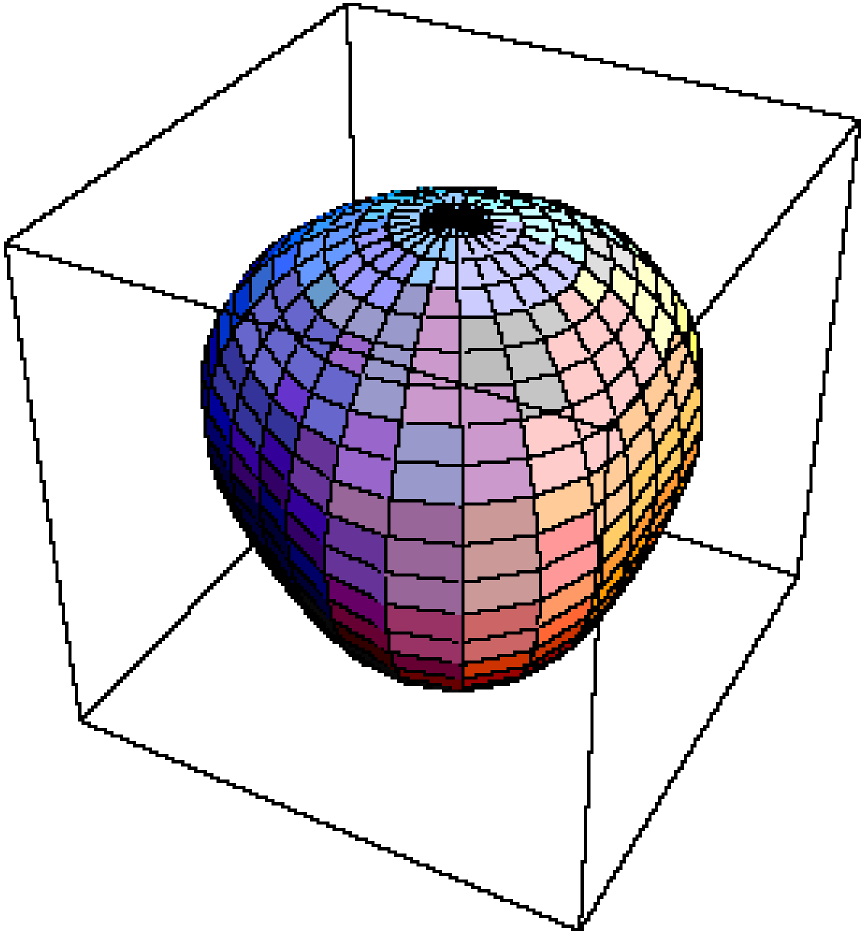
From a course of asteroseismology

Oscylacje nieradialne oktupolowe, *l*=3:

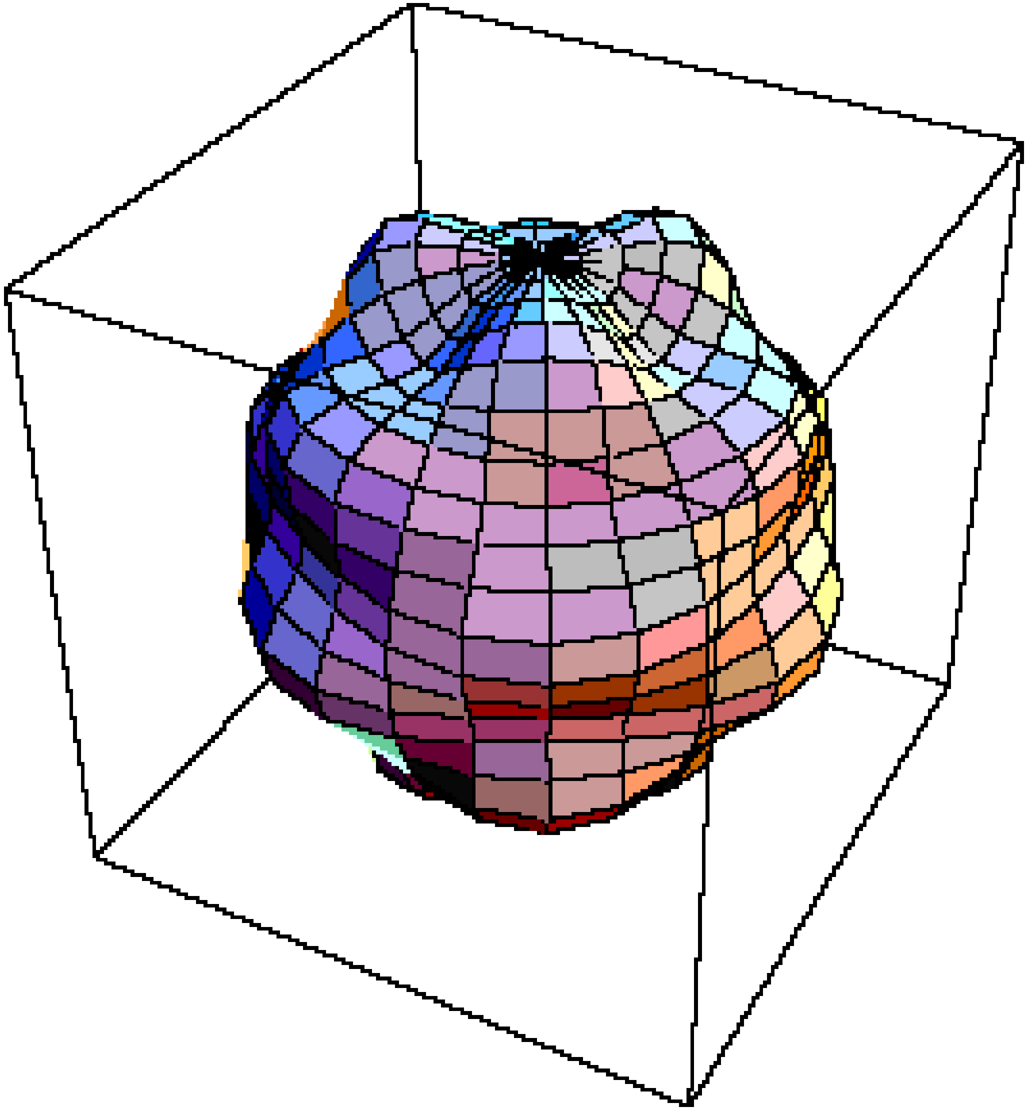
m=0



m=3



Oscylacje nieradialne, *l*=8, m=3:



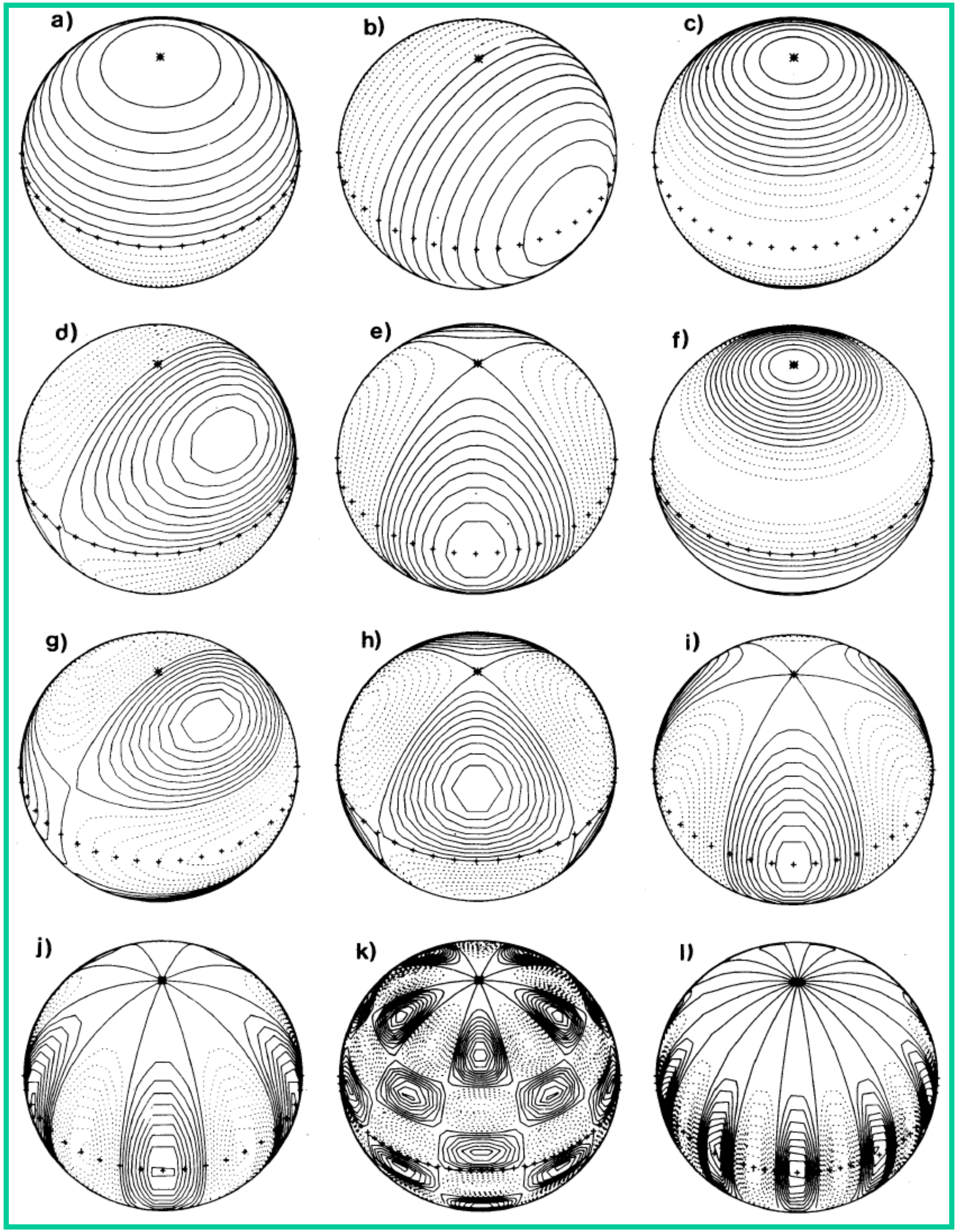
Przykłady geometrii oscylacji nieradialnych:

a) *l*=1, m=0
b) *l*=1, m=1

c) *l*=2, m=0
d) *l*=2, m=1
e) *l*=2, m=2

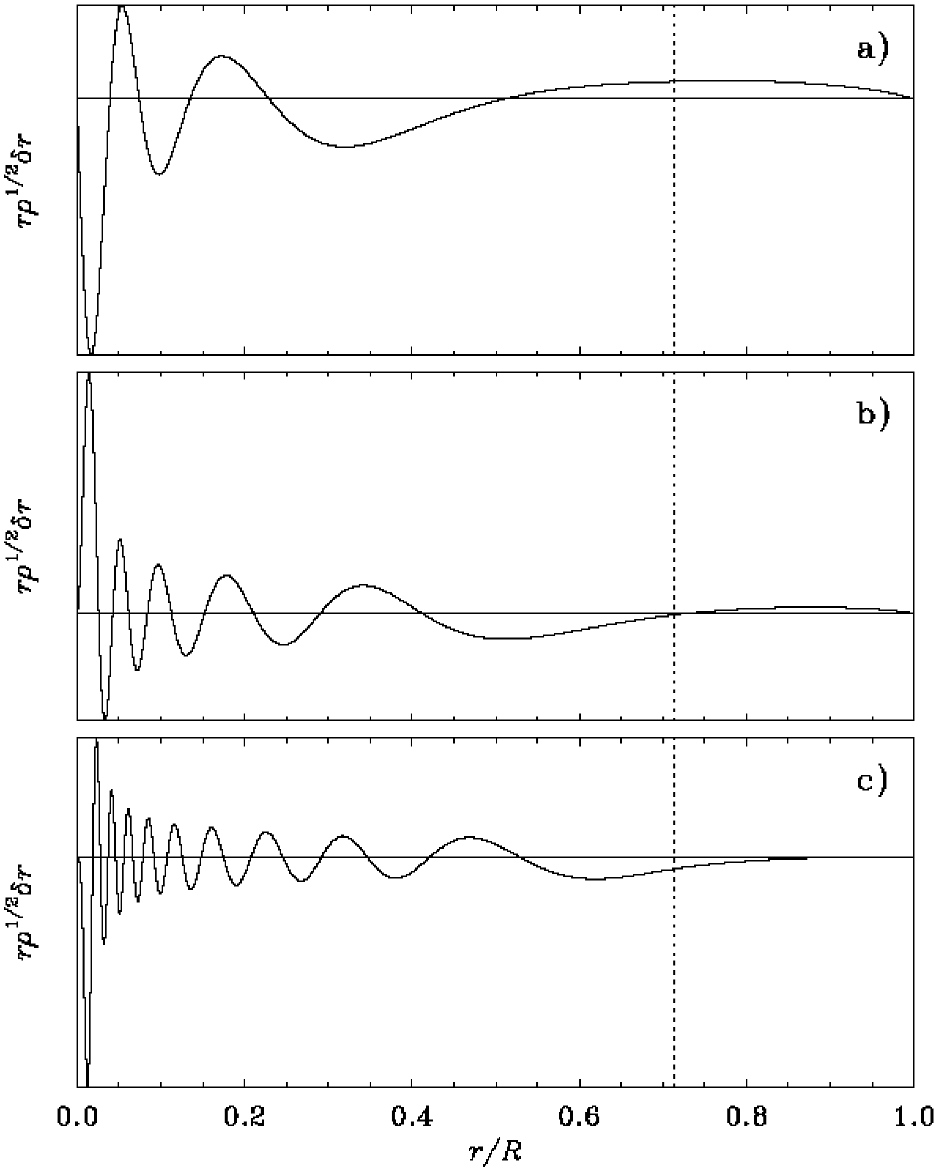
f) *l*=3, m=0
g) *l*=3, m=1
h) *l*=3, m=2
i) *l*=3, m=3

j) *l*=5, m=5
k) *l*=10, m=5
l) *l*=10, m=10



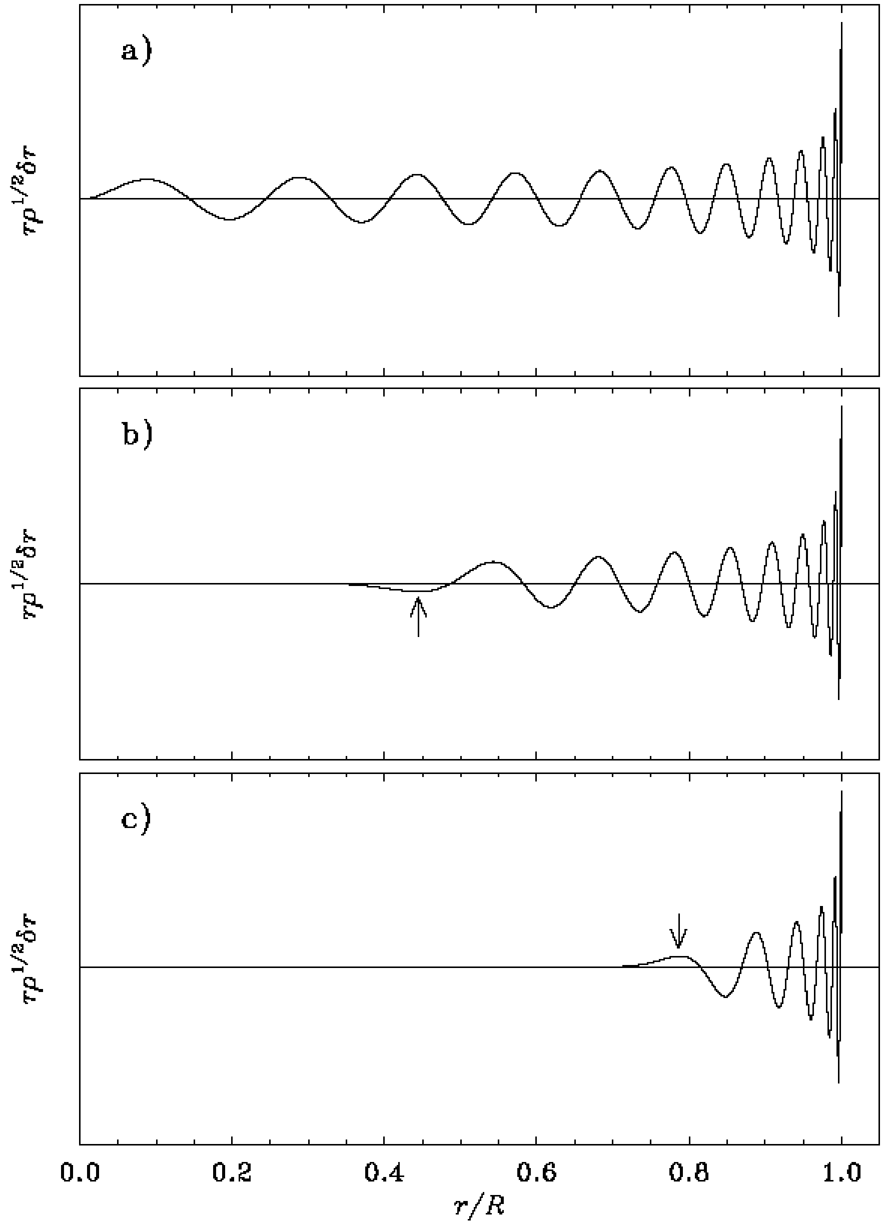
J. Christensen-Dalsgaard

Mody grawitacyjne

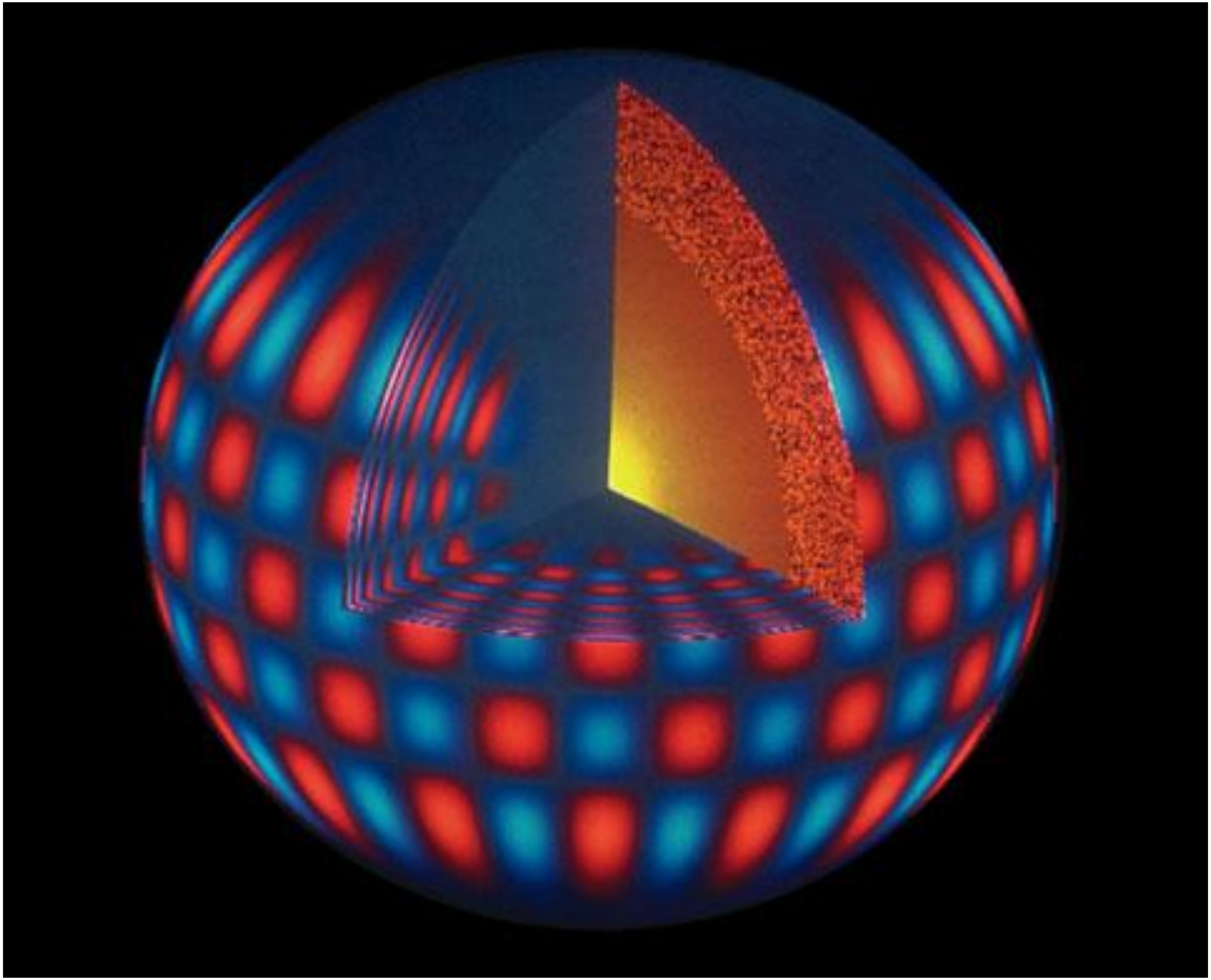


(l,n)=(1,5), (2,10), (4,19), $\nu=100\mu$Hz

Mody akustyczne (ciśnieniowe)



(l,n)=(0,23), (20,17), (60,10), $\nu=3300\mu$Hz



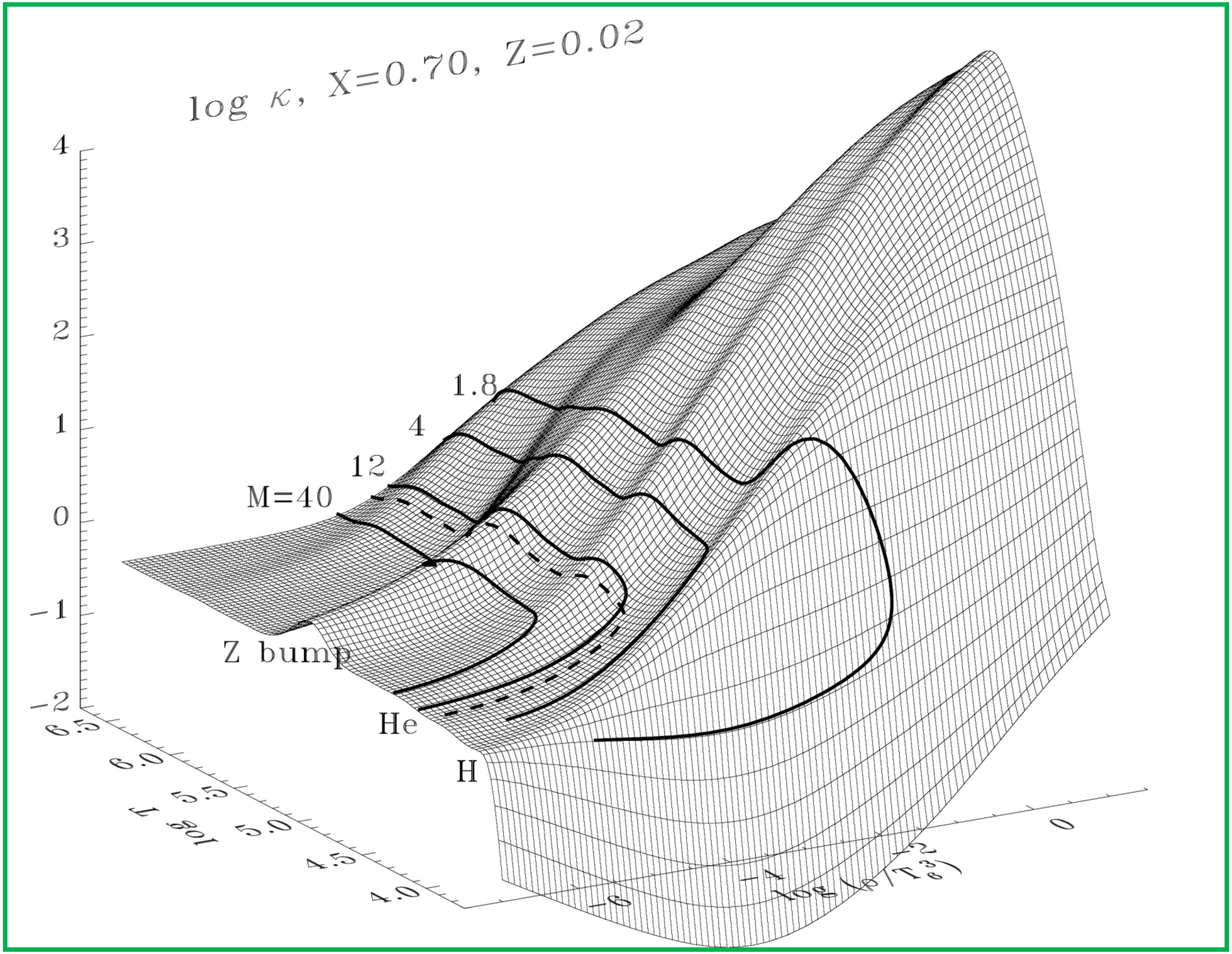
Two examples of asteroseismic modelling

- β Cep, SPB and δ Sct instability domains in the HR diagram.
  Hybrid stars (with both β Cep and SPB pulsations)

- **ν Eridani** – a slow rotating hybrid star

- **44 Tauri** – a very slow rotating δ Sct star

Opacity behaviour at astrophysical conditions [κ OPAL 1996]



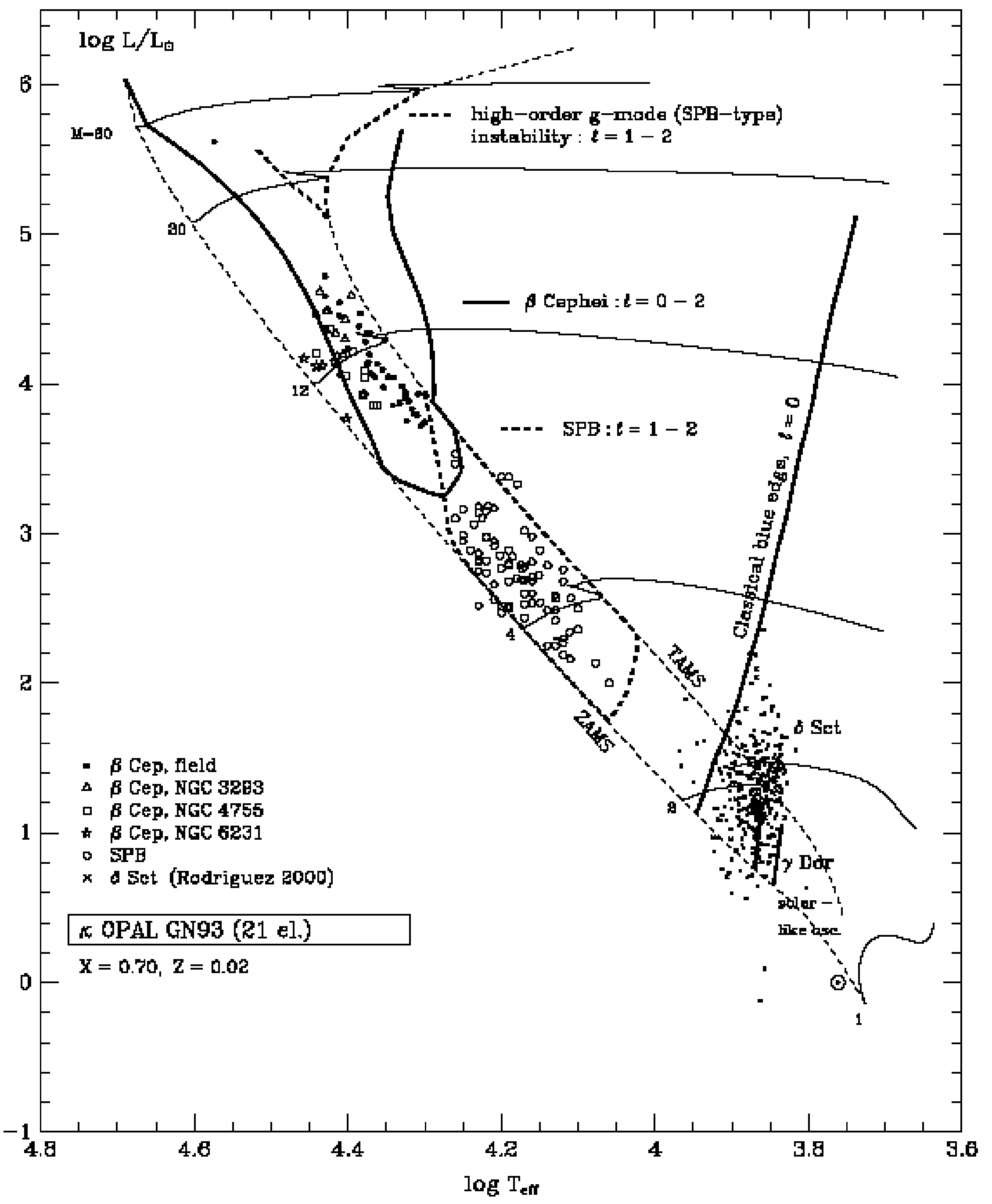
Pamyatnykh, 1999, Acta Astronomica, 49, 119

κ OPAL GN93 (Livermore, 1996):

Instability domains

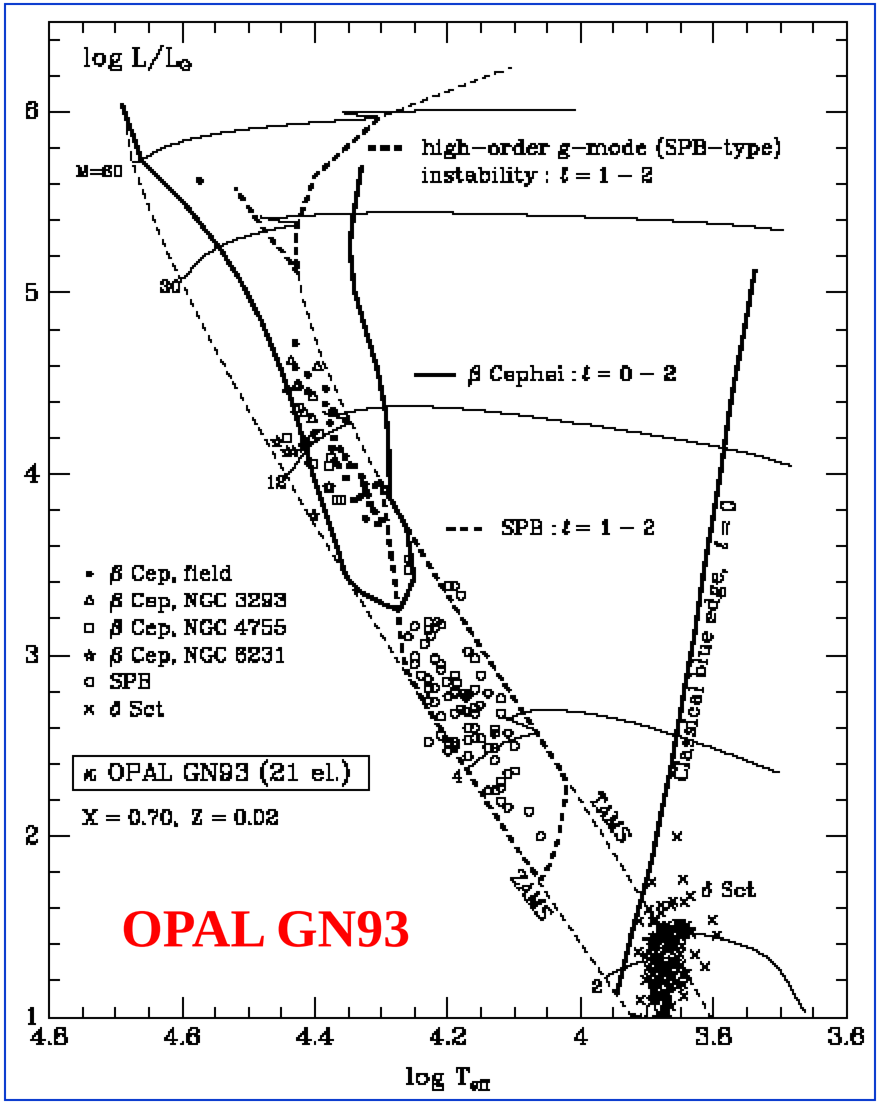
in the Upper MS

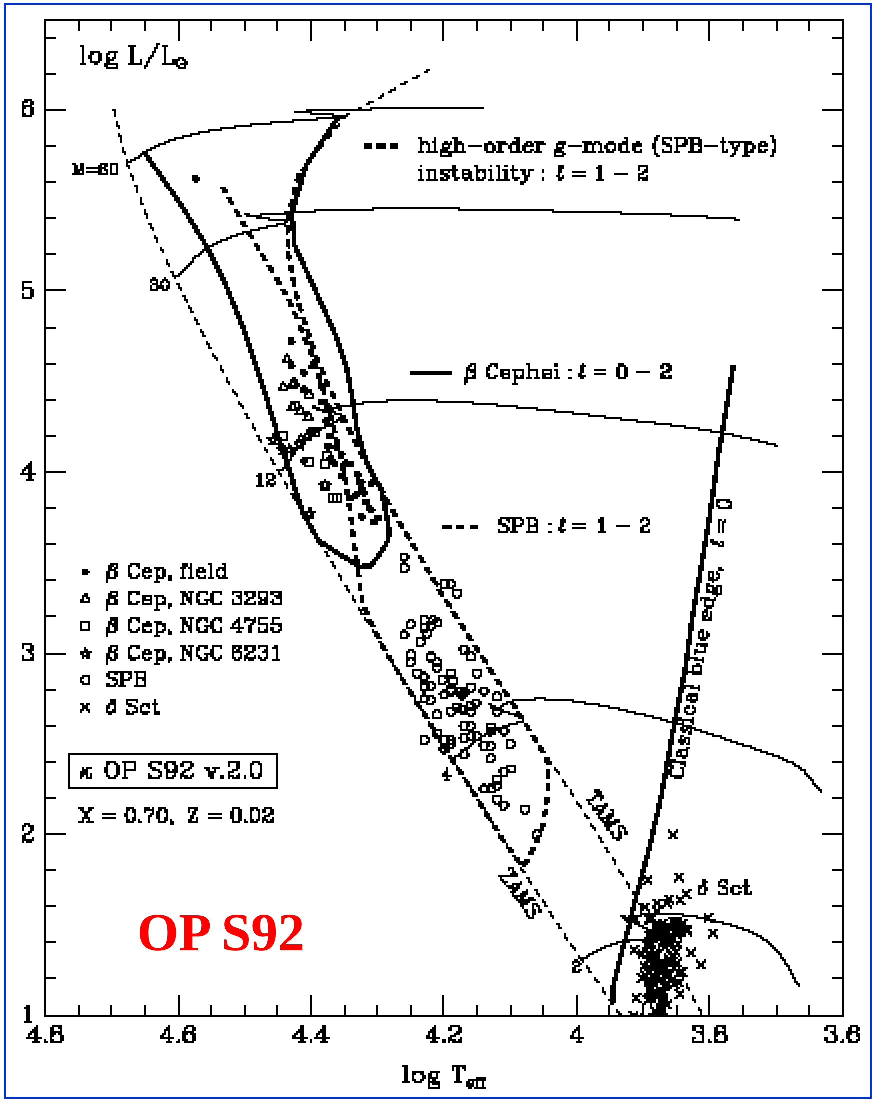
X=0.70, Z=0.02



Pamyatnykh, 1999, Acta Astr., 49, 119

Instability domains in the Upper Main Sequence: OP *vs* OPAL





Hybrid pulsations (overlap of β Cep and SPB domains) are sensitive to the opacity choice

Pamyatnykh, 1999, Acta Astr., 49, 119

Four stars in the HRD:

12 Lacertae

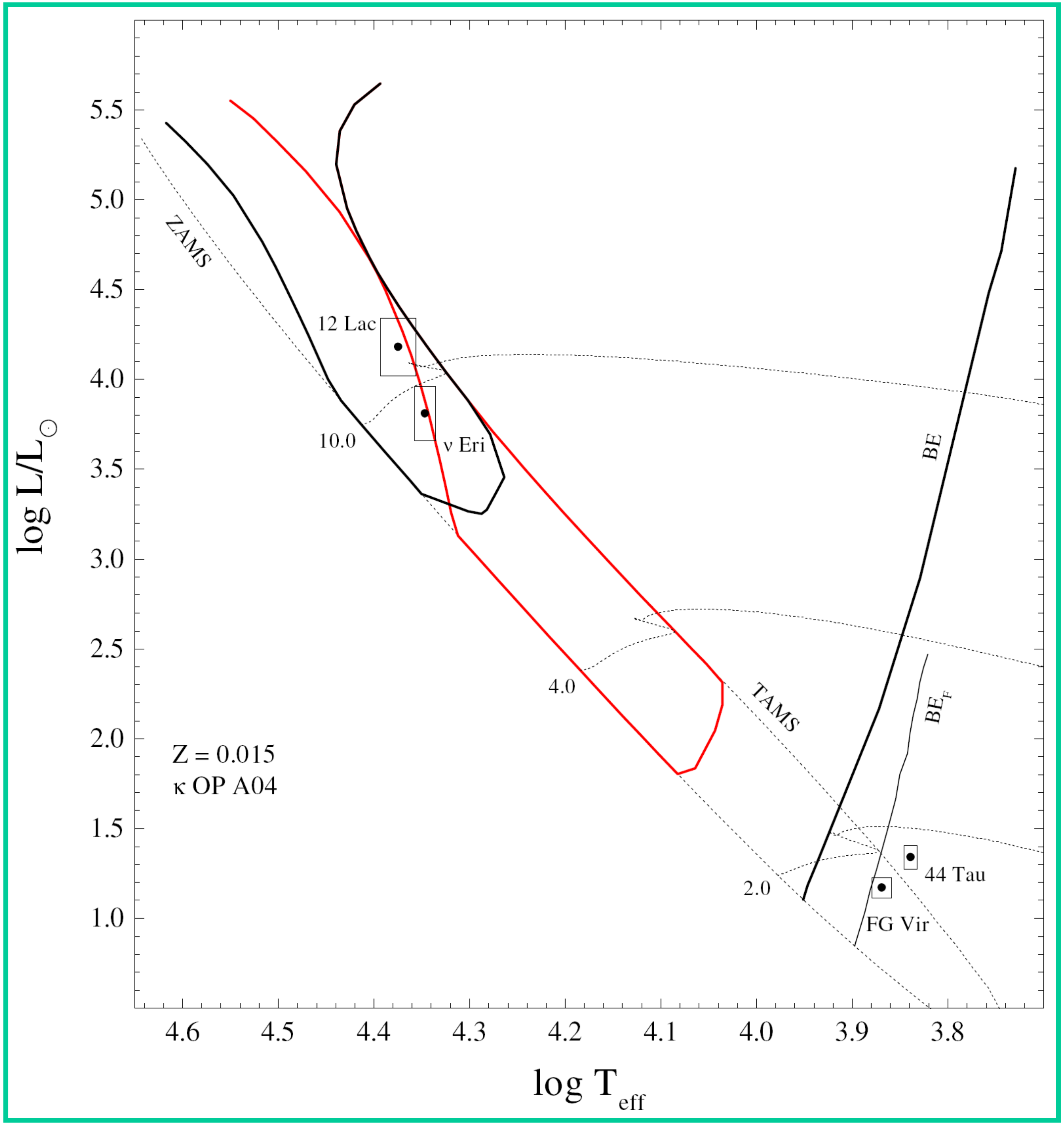
ν Eridani

44 Tauri

FG Vir

β Cep and SPB instability domains,

Blue Edge of the Classical instability strip

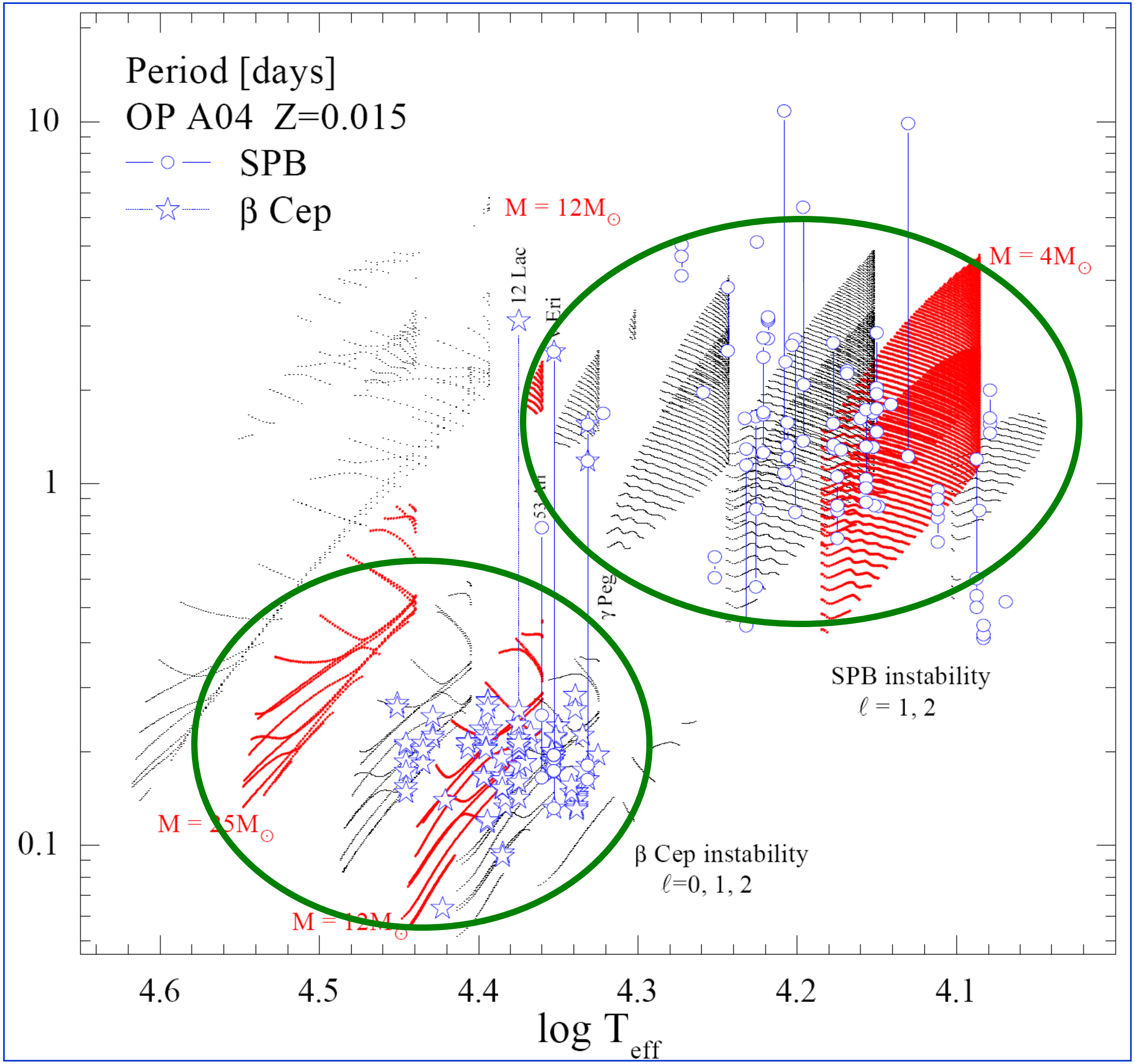


Periods of observed β Cep and SPB stars in domains of theoretical periods of unstable modes

κ OP A04

Z=0.015

Some hybrid stars (with both β Cep and SPB pulsations) are clearly seen

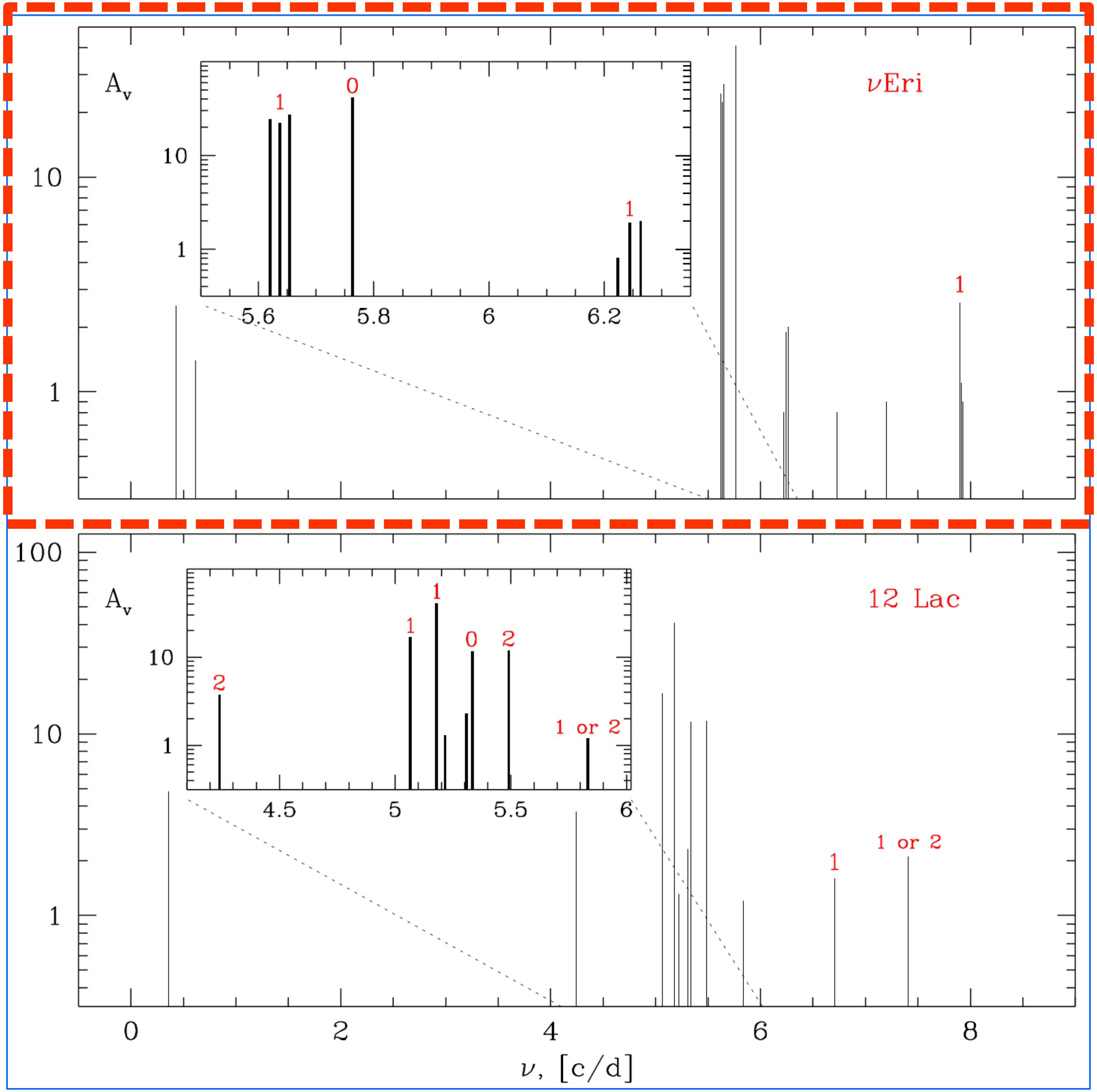


Zdravkov & Pamyatnykh 2008

ν Eridani

14 frequencies (degree *l* is identified for 8 of them),
Sp B2 III,
mV = 3.920,
π = 5.56 +- 0.88 mas,
Vrot = 6 km/s (SIMBAD: Vsini = 7, 20, 25 km/s),
[m/H] = 0.05 +- 0.09,
Teff = 22200 +- 600 K

Oscillation spectra of ν Eri and 12 Lac

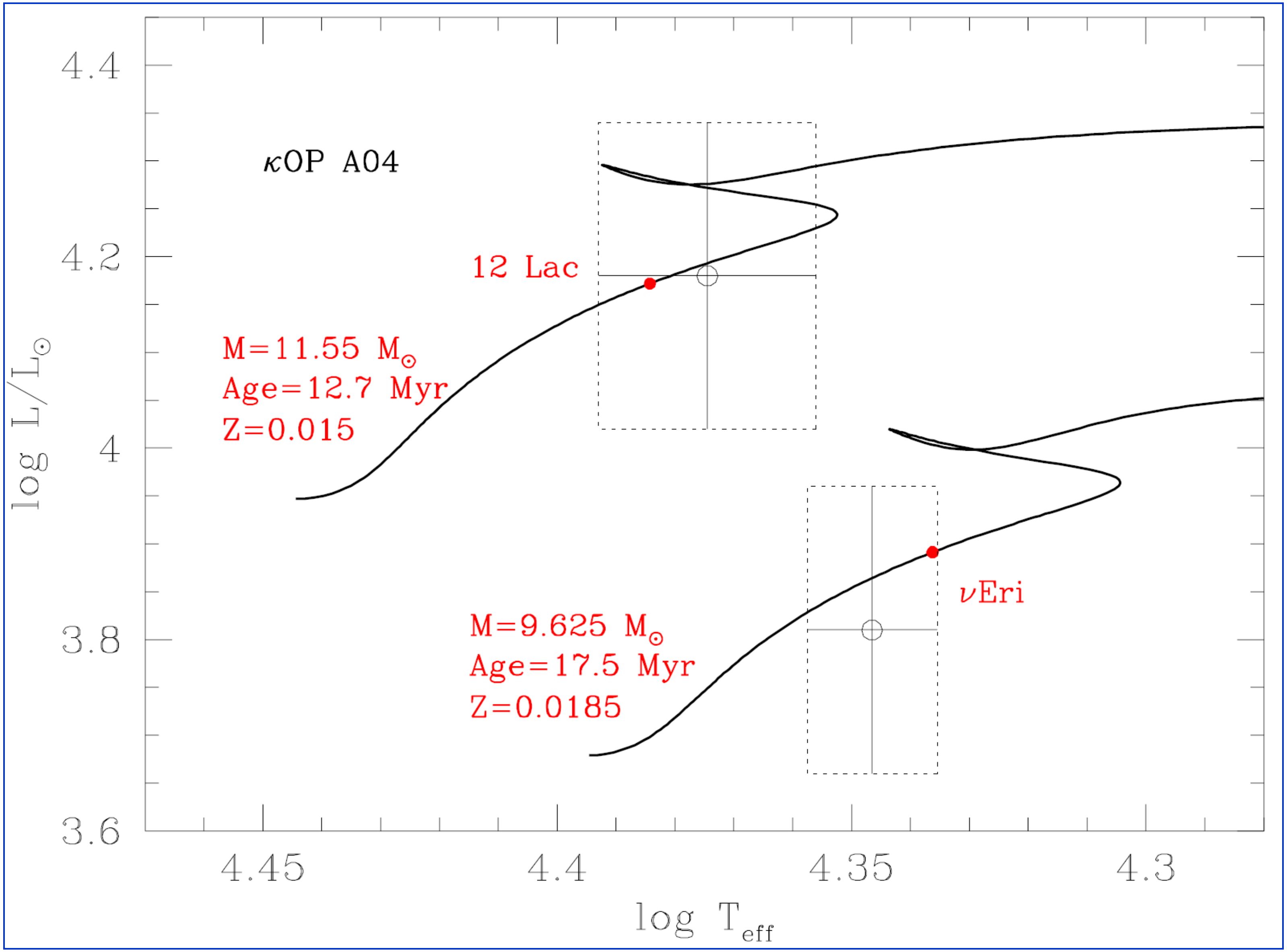


ν Eri:
Jerzykiewicz et al. 2005

12 Lac:
Handler et al. 2006

Dziembowski &
Pamyatnykh 2008

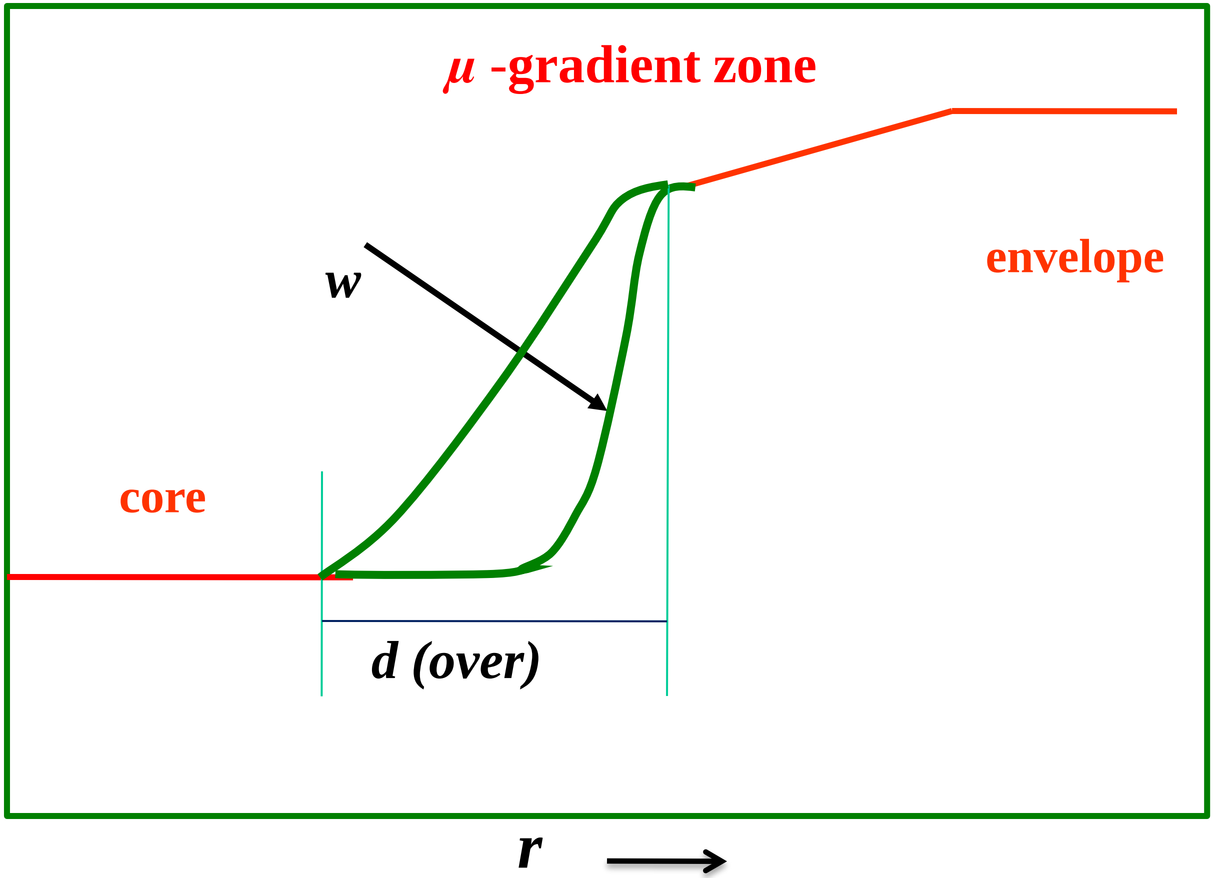
ν Eri and 12 Lac in the theoretical H-R diagram Red points mark fitted models (3 frequencies for ν Eri are fitted)



Dziembowski & Pamyatnykh 2008

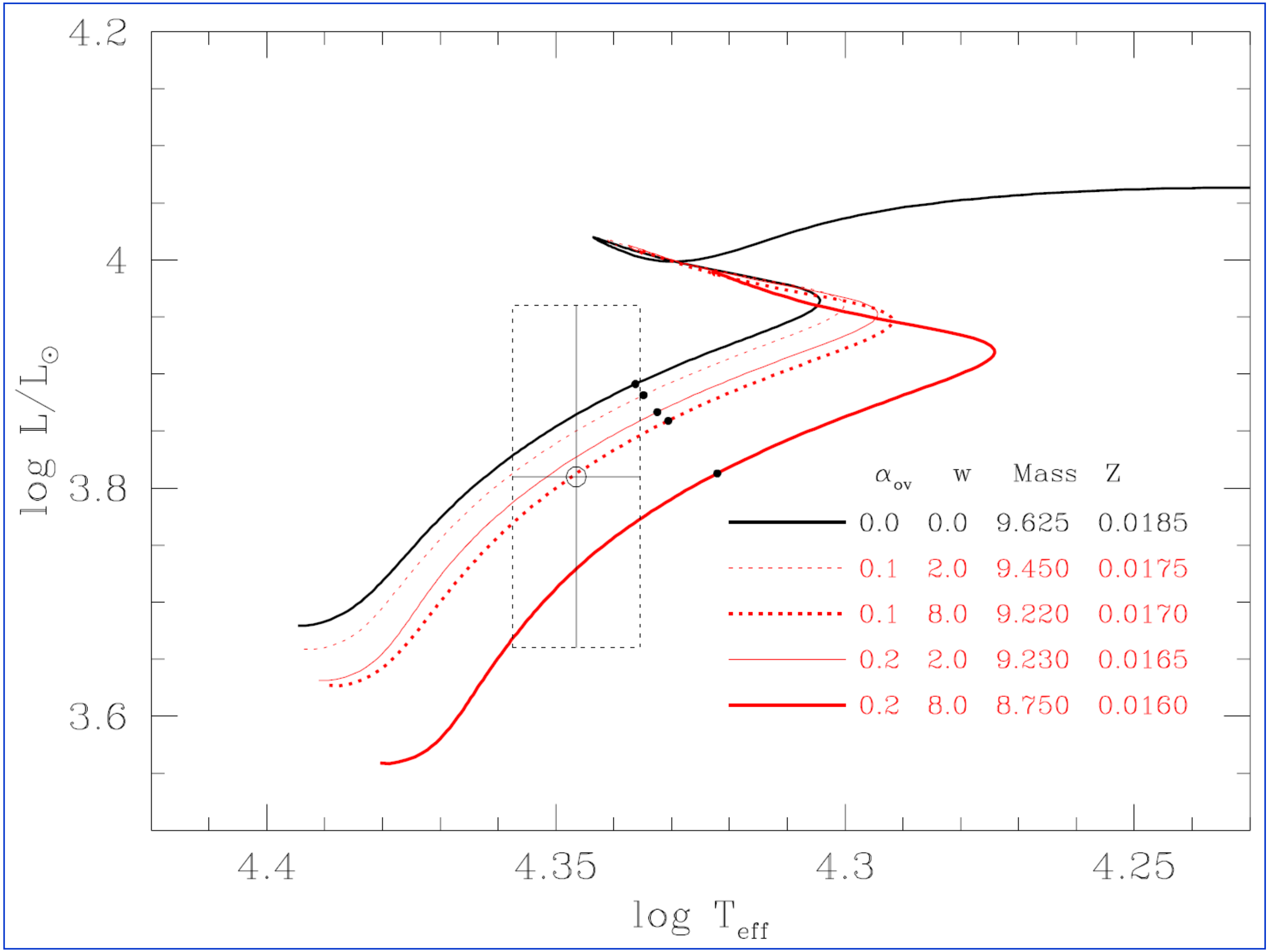
Testing overshooting

Two-parametric overshooting



Dziembowski 2008

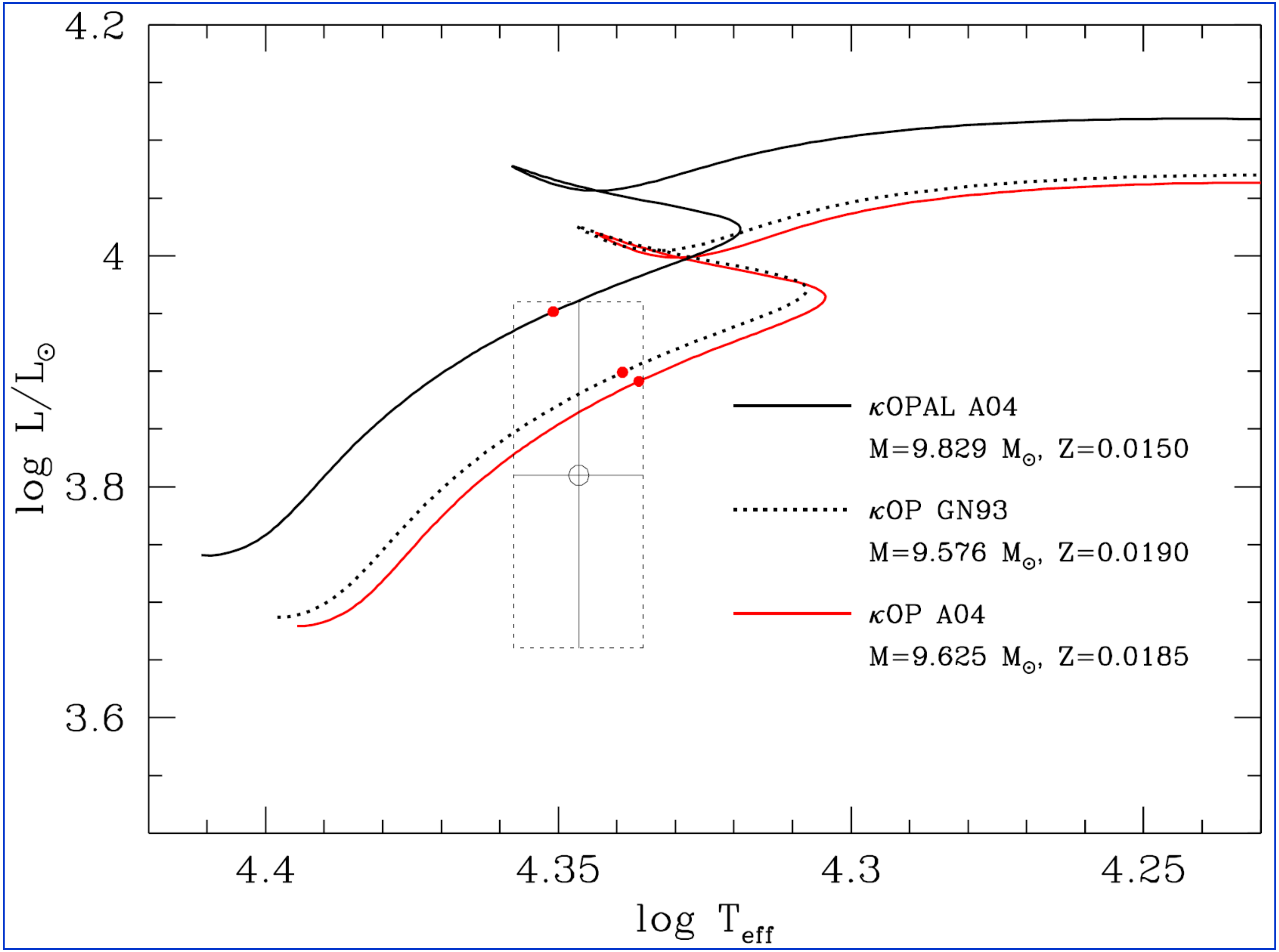
Seismic models of ν Eri for different overshooting parameters in the H-R diagram



Dziembowski & Pamyatnykh 2008

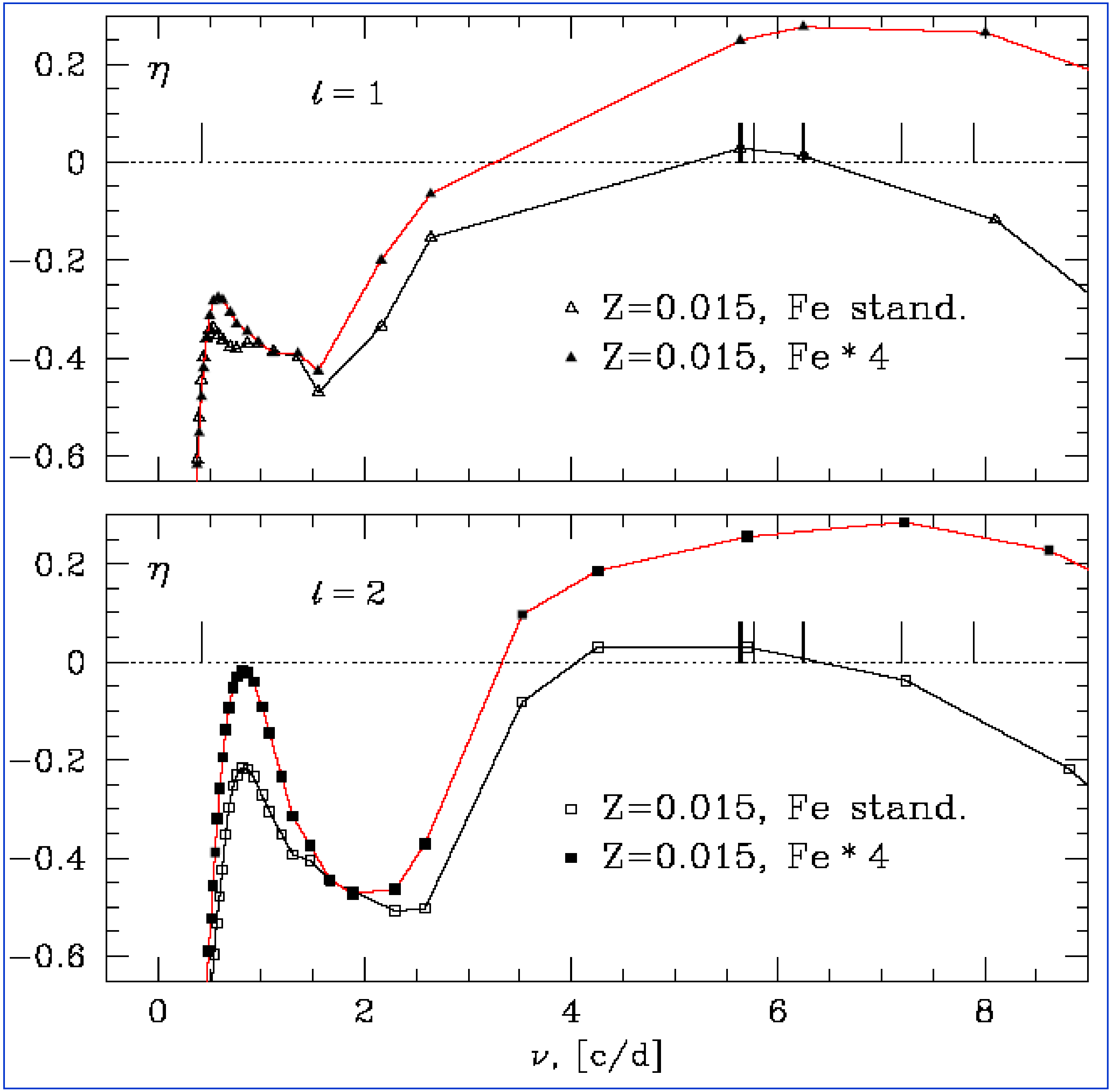
Testing opacity

Seismic models of ν Eri for different opacities and mixtures in the H-R diagram



Dziembowski & Pamyatnykh 2008

$$\eta = \frac{W}{\int_0^1 \left| \frac{\mathrm{d}W}{\mathrm{d}r} \right| \mathrm{d}r}$$



Instability coefficient in a standard model and in the model with the Fe accumulation in the driving zone

OPAL opacity in both cases

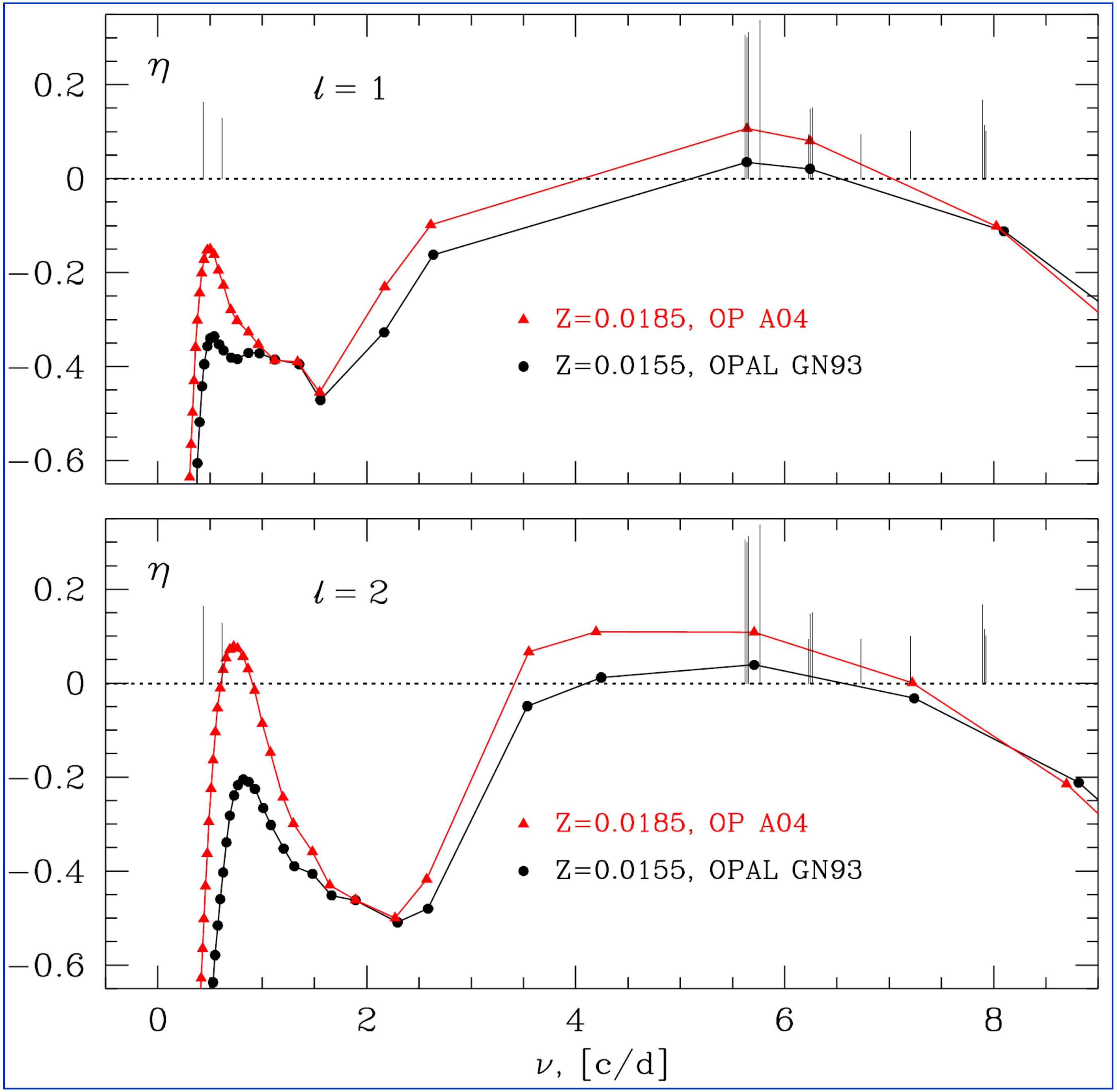
η > 0 for unstable modes

Pamyatnykh, Handler, Dziembowski 2004

$$\eta = \frac{W}{\int_0^1 \left| \frac{\mathrm{d}W}{\mathrm{d}r} \right| \mathrm{d}r}$$

Instability coefficient in models computed with OPAL and OP opacities

$\eta > 0$ for unstable modes

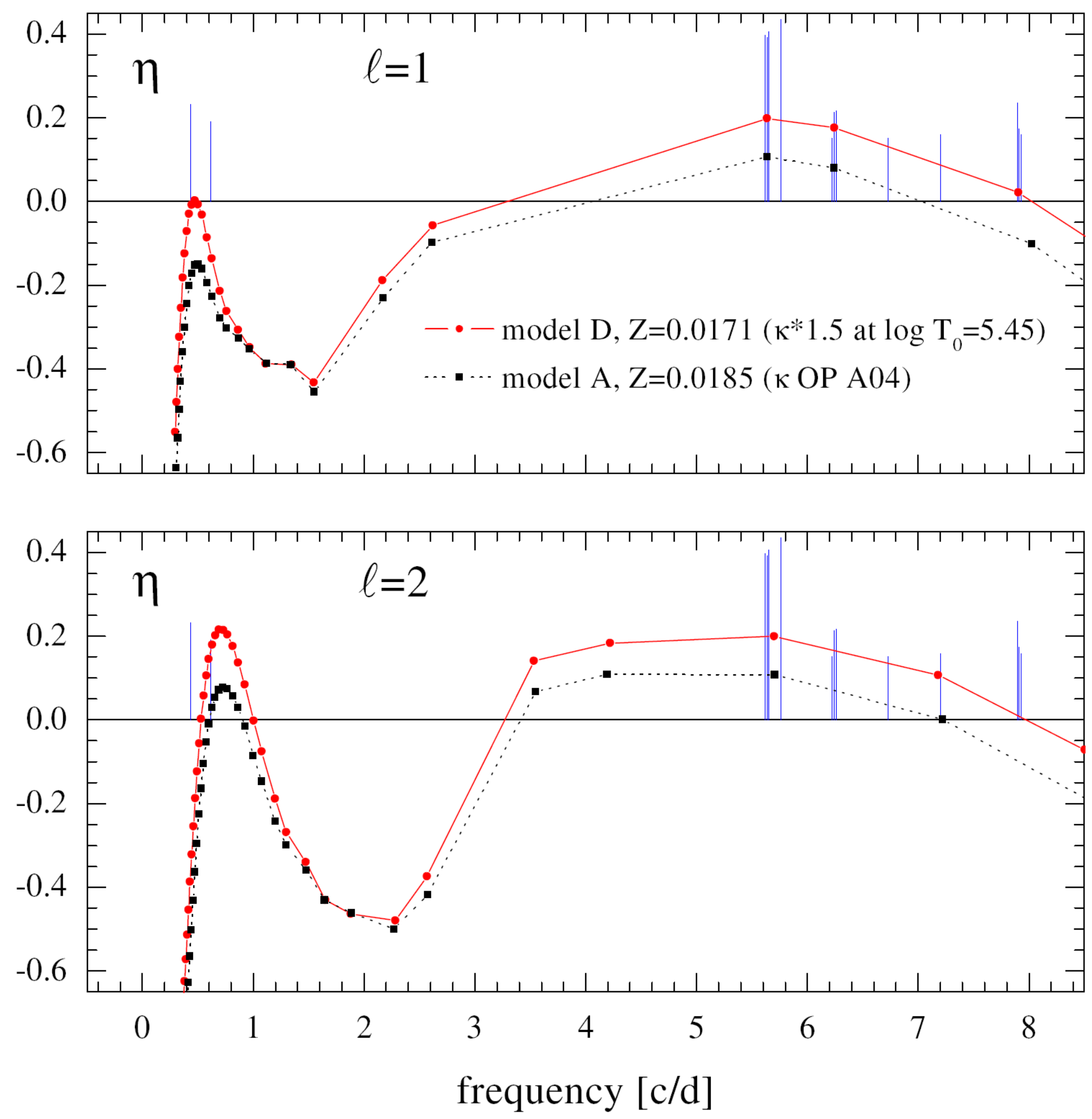


Dziembowski, Pamyatnykh 2008

$$\eta = \frac{W}{\int_0^1 \left| \frac{\mathrm{d}W}{\mathrm{d}r} \right| \mathrm{d}r}$$

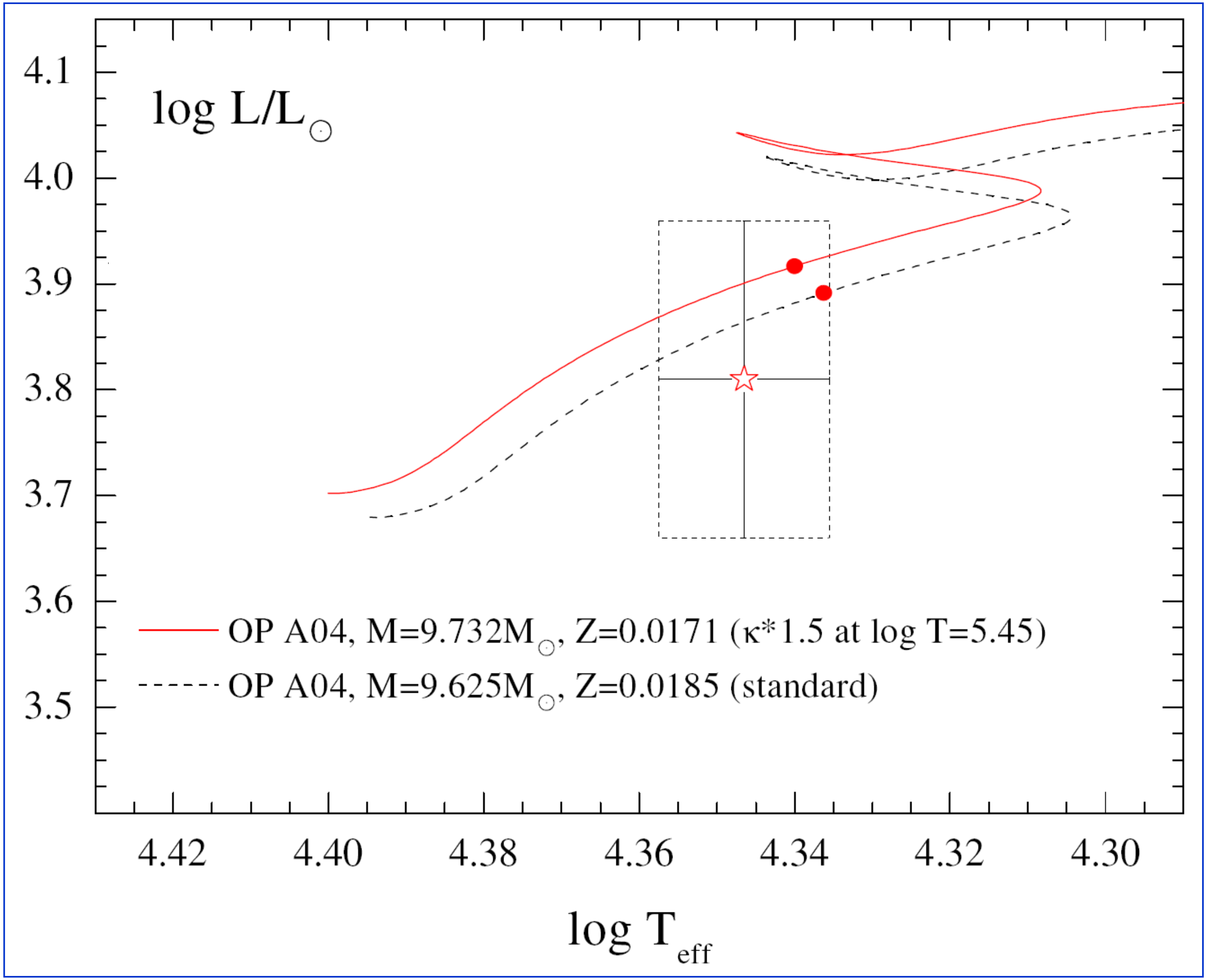
Instability coefficient in a standard model and in the model with enchanced opacity in the Z bump region

$\eta > 0$ for unstable modes



Zdravkov & Pamyatnykh 2008

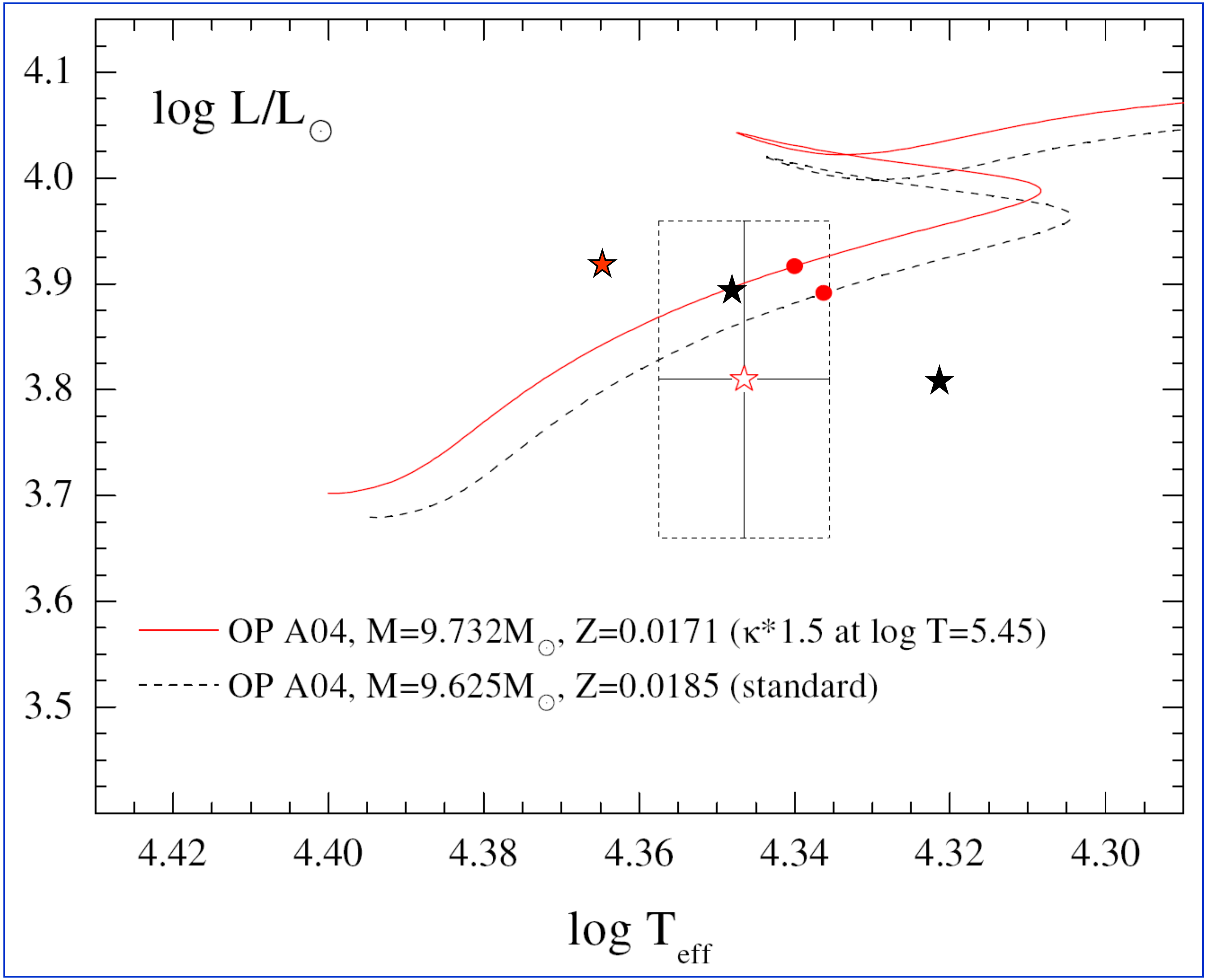
ν Eri : a standard model and the model with enchanced Z bump opacity



Zdravkov & Pamyatnykh 2008

ν Eri : a standard model and the model with enchanced Z bump opacity

★ - nonstandard models of Ausseloos et al. (2004)

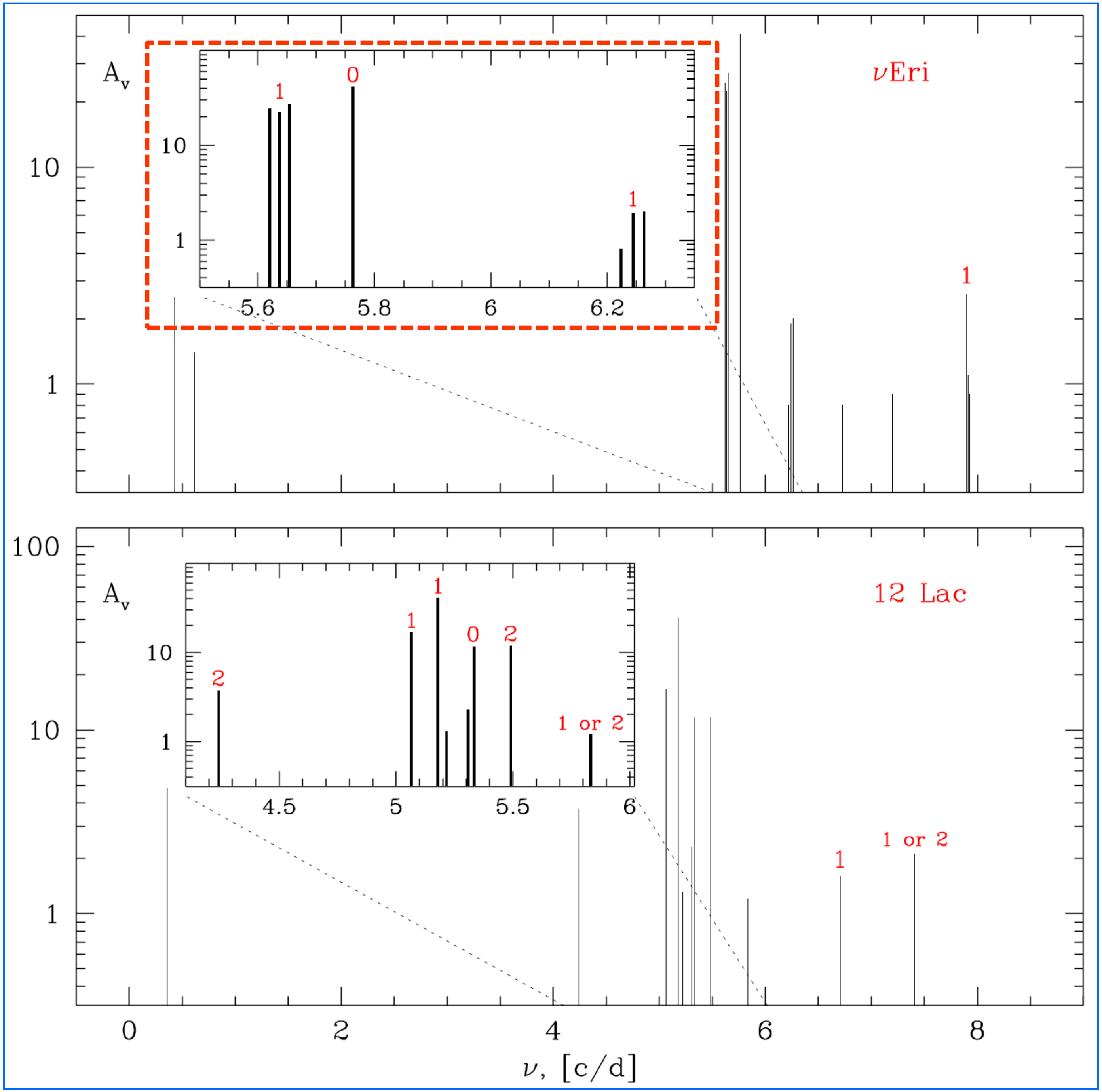


Zdravkov & Pamyatnykh 2008

Testing rotation in interiors

Oscillation spectra of ν Eri and 12 Lac

Two rotationally splitted triplets of *l* = 1 modes (g1 and p1)

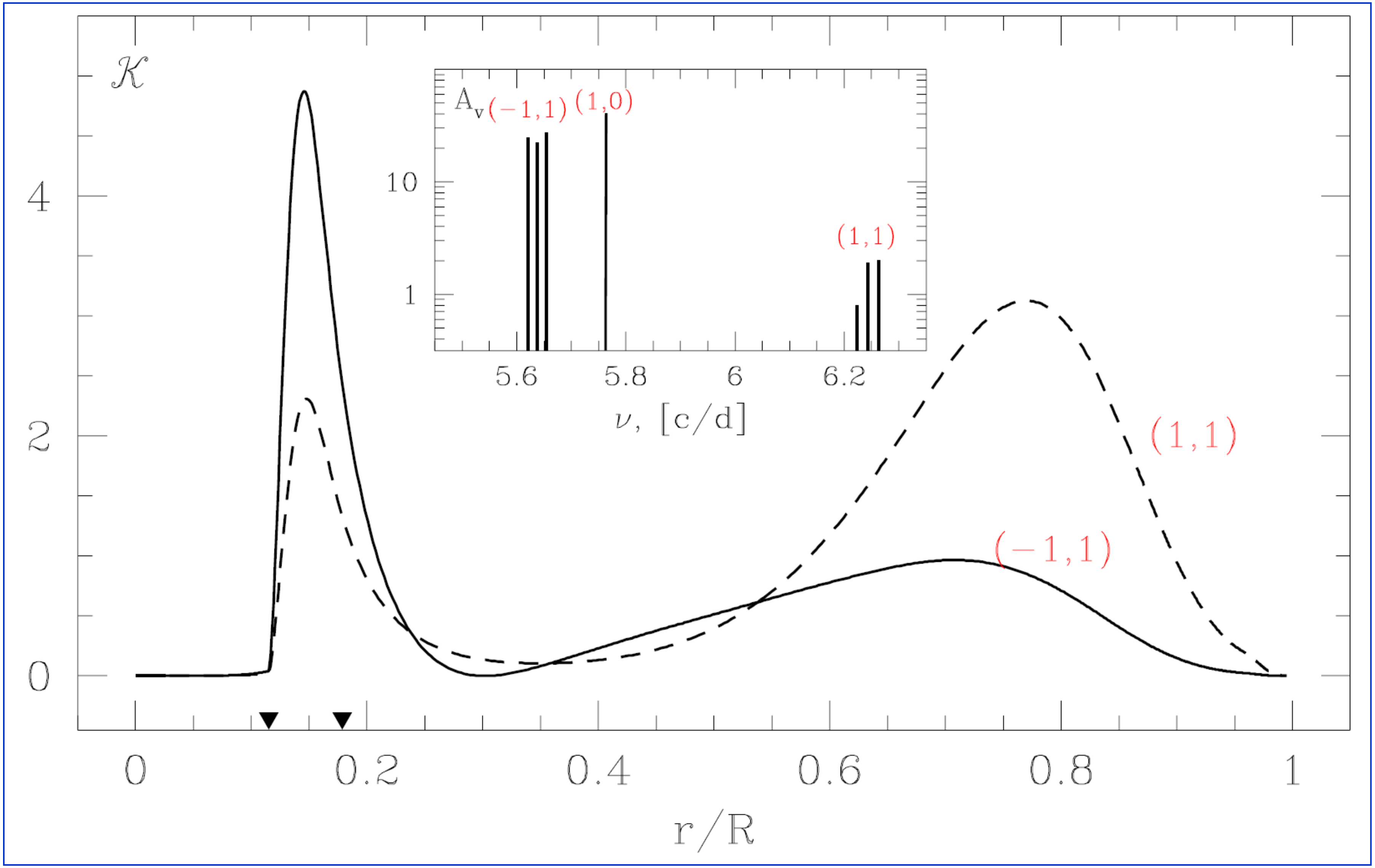


Dziembowski & Pamyatnykh 2008

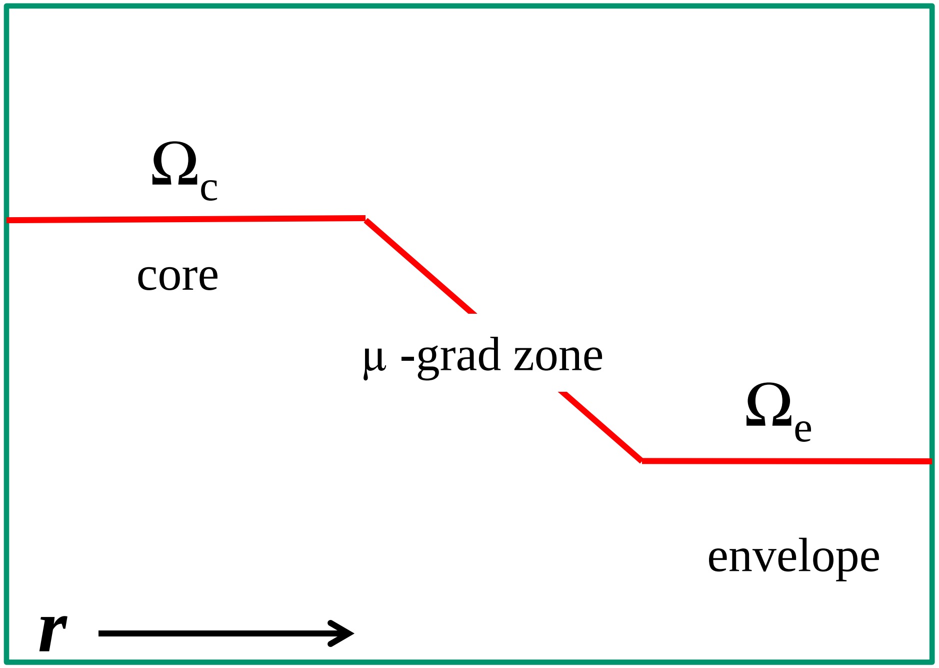
ν Eri: the splitting kernels for two normal modes:
***l* = 1, g1 (solid line), *l* = 1, p1 (dashed line).**
Triangles mark boundaries of the μ-gradient zone.

$$S \equiv 0.5(\nu_+ - \nu_-) = \int_0^1 dx\mathcal{K}(x)\Omega/2\pi$$

S_g=0.017, S_p=0.020 c/d



Simple rotation law



Results:
$V_{rot} = 6$ km / s
$\Omega_{core} = 5 * \Omega_{envelope}$

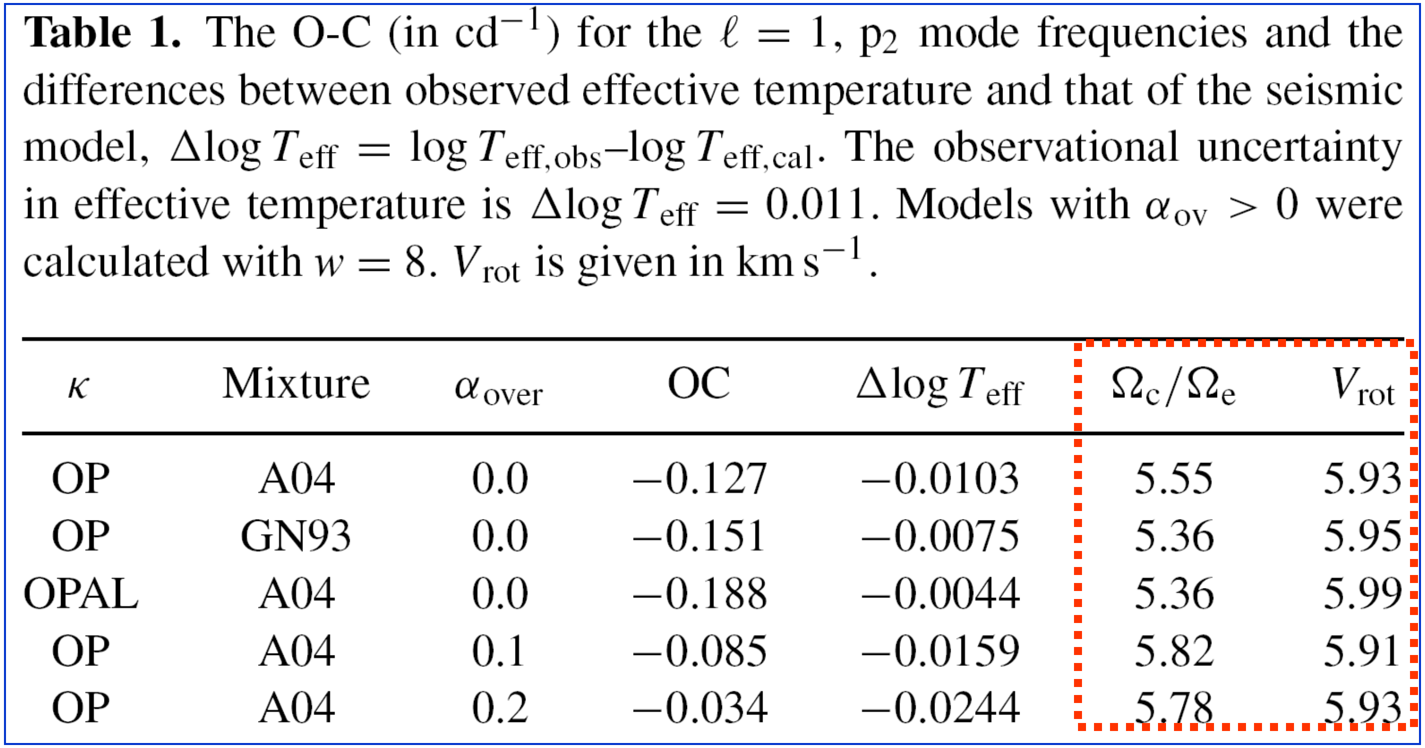


Table 1. The O-C (in cd^{-1}) for the $\ell = 1$, p_2 mode frequencies and the differences between observed effective temperature and that of the seismic model, $\Delta \log T_{\rm eff} = \log T_{\rm eff,obs} - \log T_{\rm eff,cal}$. The observational uncertainty in effective temperature is $\Delta \log T_{\rm eff} = 0.011$. Models with $\alpha_{\rm ov} > 0$ were calculated with $w = 8$. $V_{\rm rot}$ is given in $\mathrm{km\,s^{-1}}$.

κ	Mixture	$\alpha_{\rm over}$	OC	$\Delta \log T_{\rm eff}$	Ω_c/Ω_e	$V_{\rm rot}$
OP	A04	0.0	−0.127	−0.0103	5.55	5.93
OP	GN93	0.0	−0.151	−0.0075	5.36	5.95
OPAL	A04	0.0	−0.188	−0.0044	5.36	5.99
OP	A04	0.1	−0.085	−0.0159	5.82	5.91
OP	A04	0.2	−0.034	−0.0244	5.78	5.93

Dziembowski, Pamyatnykh 2008

Summary of results for ν Eridani

- ν Eri has 14 independent modes, the strongest one is the radial fundamental mode, most of the others are *l* = 1 modes.

- Peaks at 0.432 and 0.614 c/d correspond to high-order g-modes (SPB-type pulsations). ν Eri – a hybrid star.

- Rotational splitting of two *l*=1 modes (g1 and p1) can be used to infer information on internal rotation. The core rotates approximately 5 times faster than the envelope.

- Overshooting from the convective core seems to be ineffective in ν Eri, but the estimate critically depends on the Teff determination.

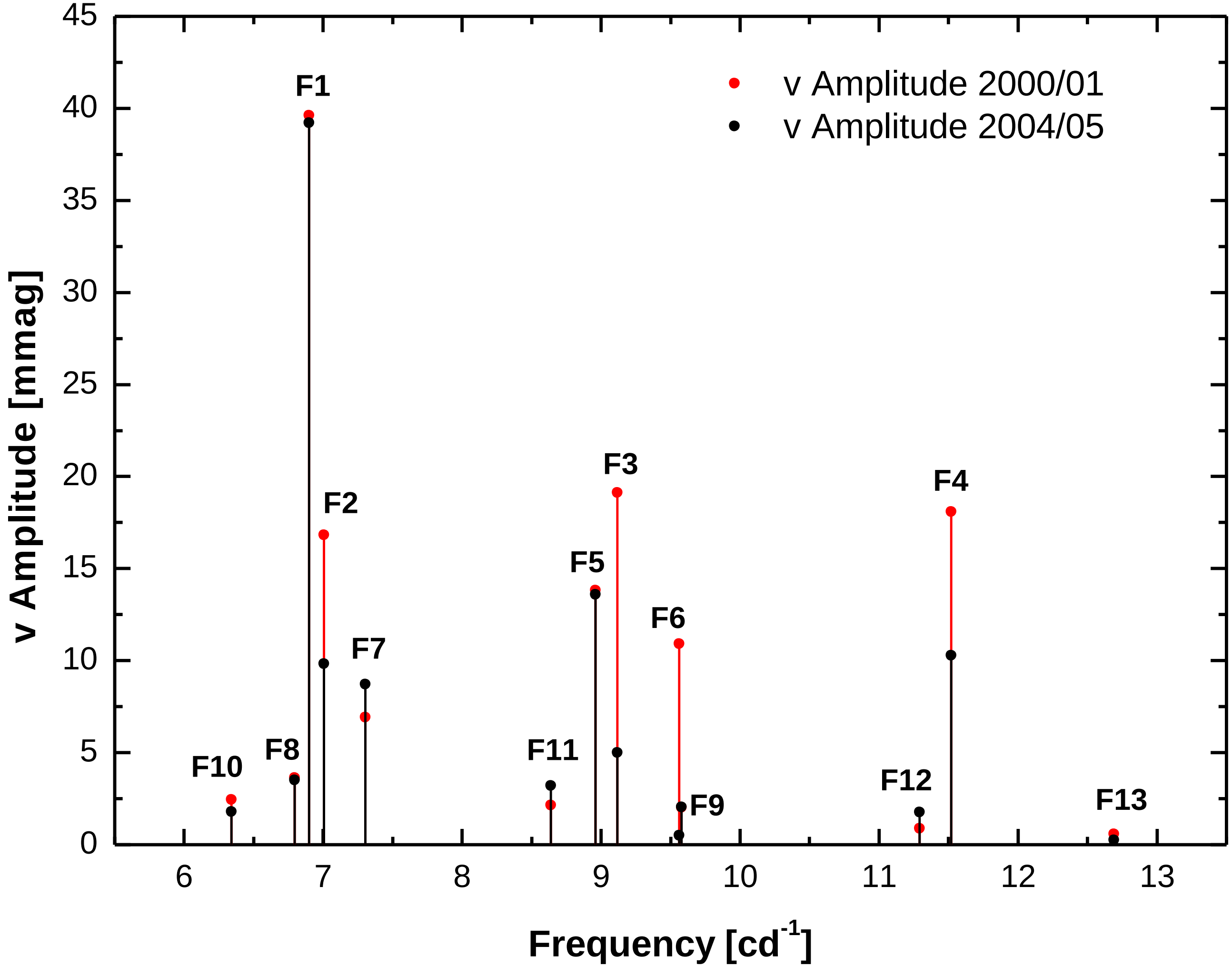
- For standard opacities modes at lowest and highest observed frequencies are stable. An additional opacity enchancement around Z bump region may solve the problem.

- A new way of probing opacity.

44 Tauri

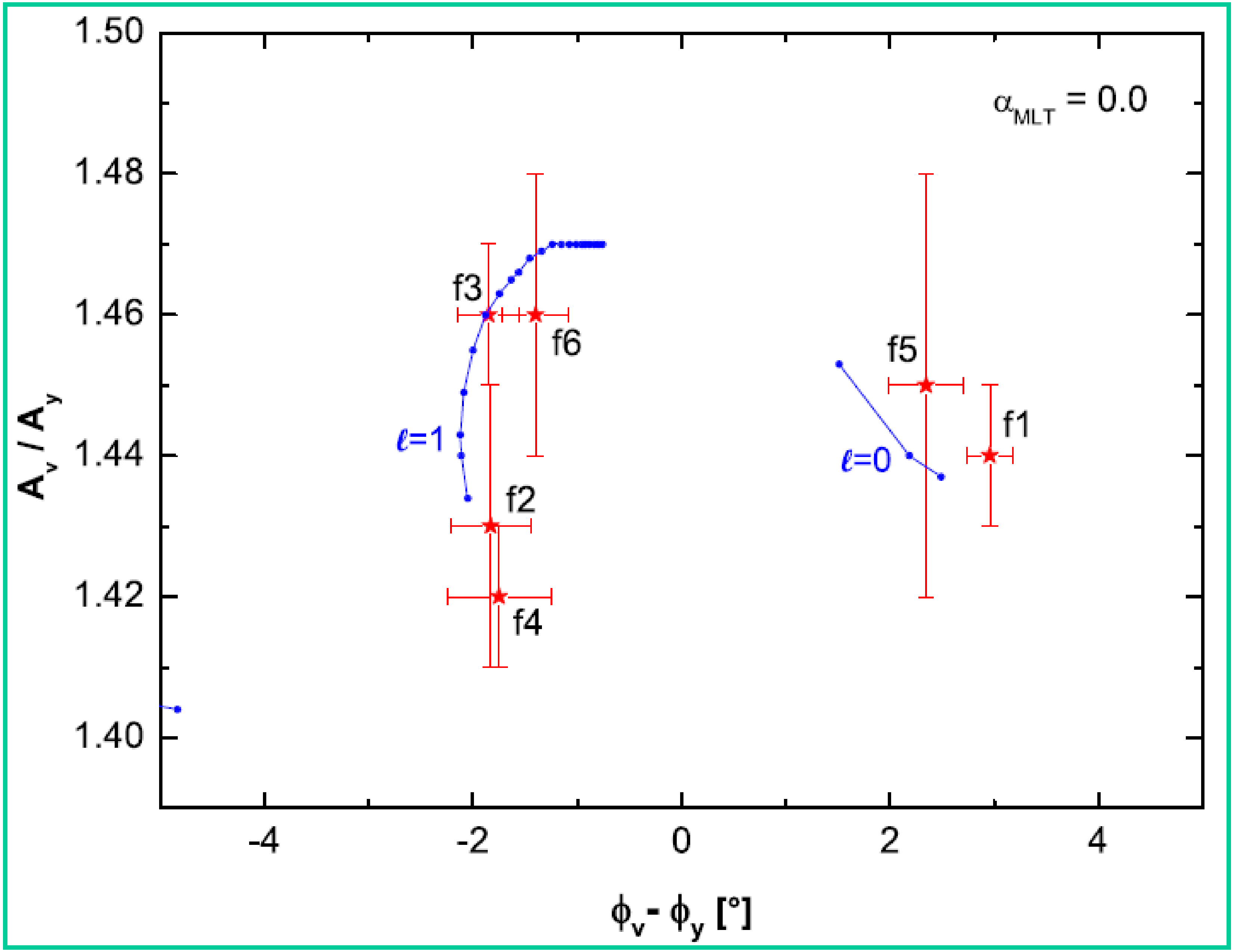
15 frequencies (degree *l* is identified for 10 of them),
Sp F2 IV-V,
mV = 5.399,
p = 16.72 +- 0.93 mas,
Vrot = 3 +- 2 km/s,
[m/H] = approx 0.0,
Teff = 6900 +- 100 K,
log g = 3.6 +- 0.1

44 Tau

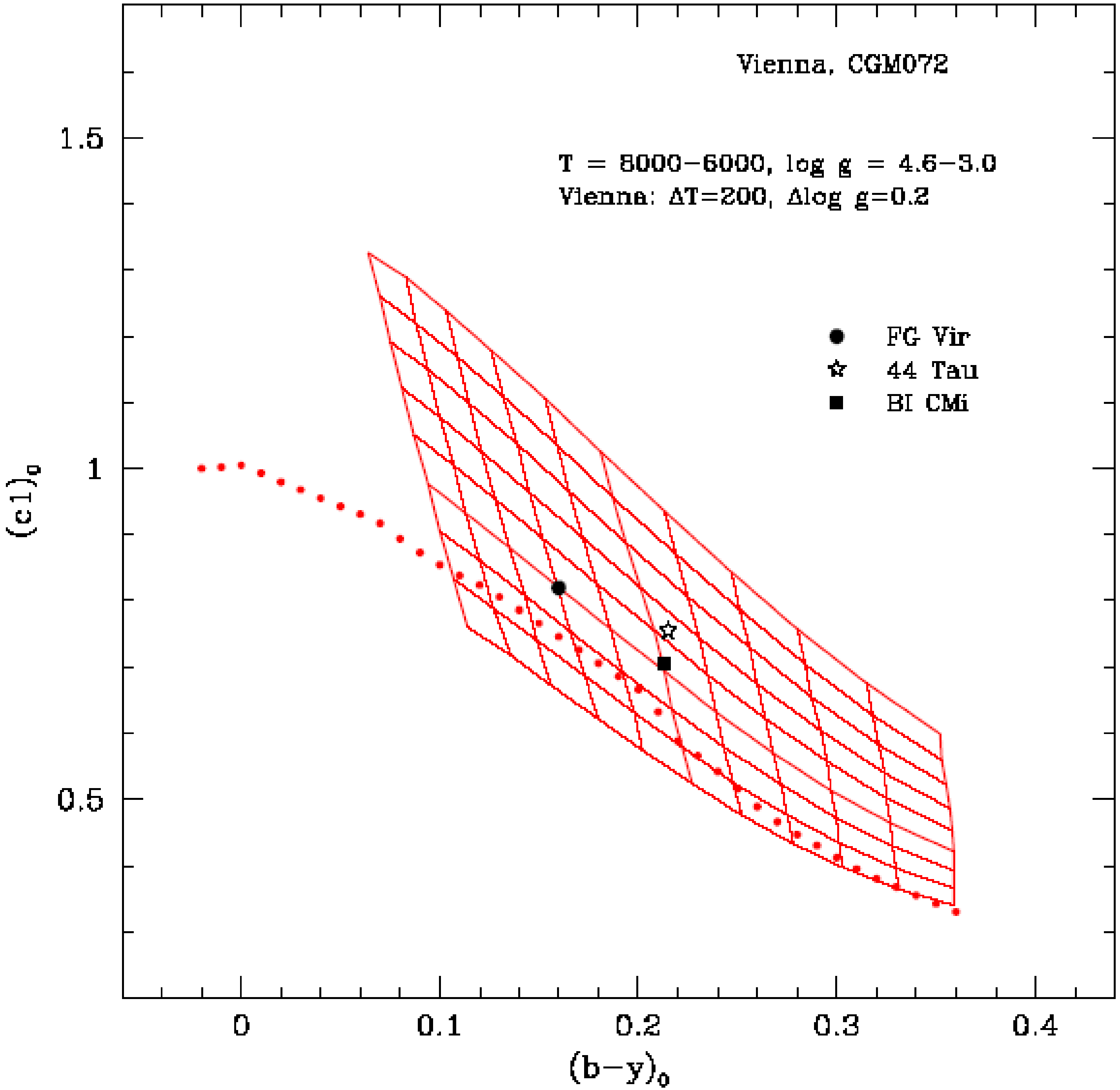


Lenz et al. 2008

44 Tau, mode identification



Lenz et al. 2008

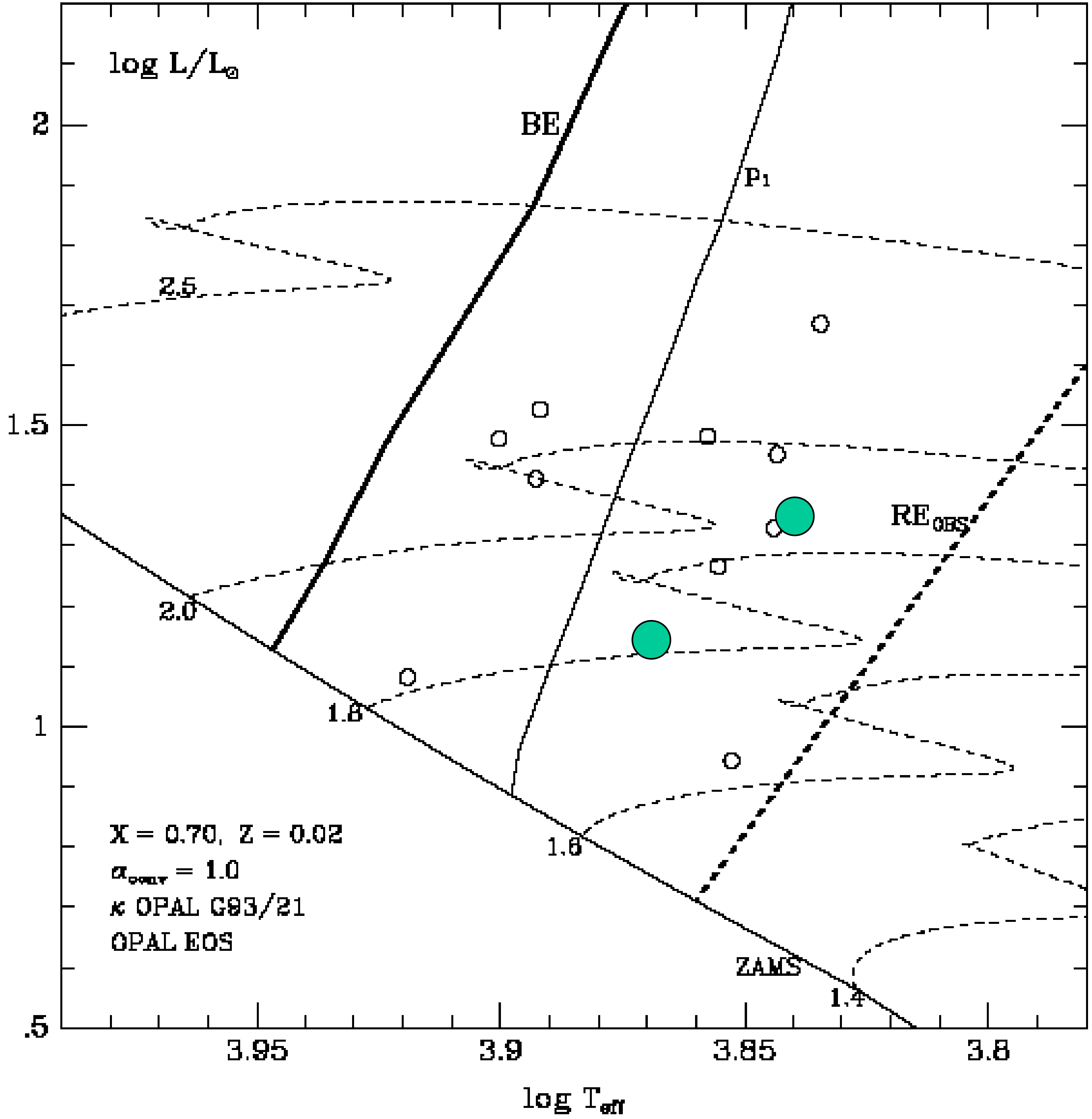

Vienna, CGM072
T = 8000−6000, log g = 4.6−3.0
Vienna: ΔT=200, Δlog g=0.2
● FG Vir
☆ 44 Tau
■ BI CMi
1.5
1
0.5
(c1)$_0$
0
0.1
0.2
0.3
0.4
(b−y)$_0$

FG Vir (MS)

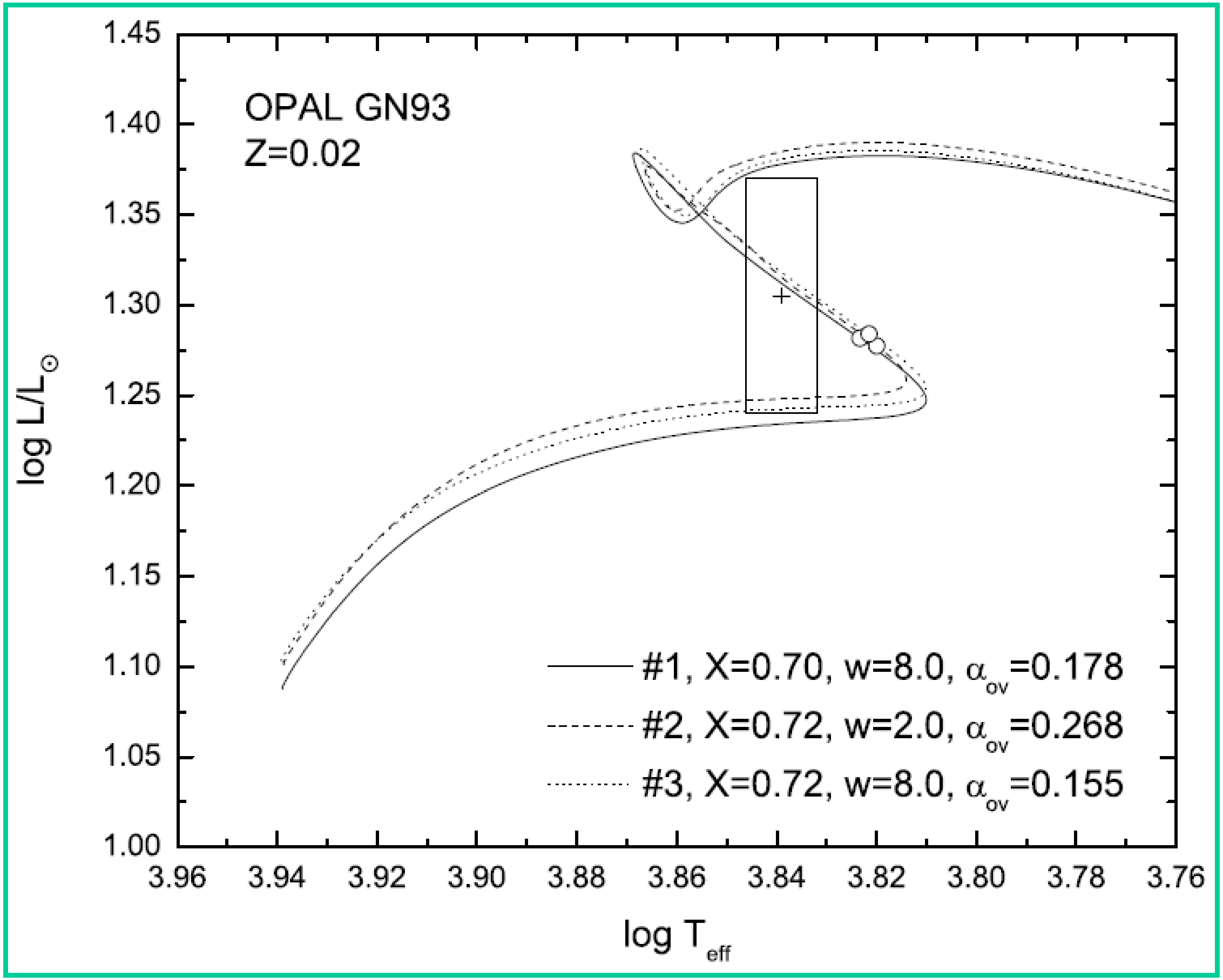
and

44 Tau (post-MS)

in the δ Scuti instability domain

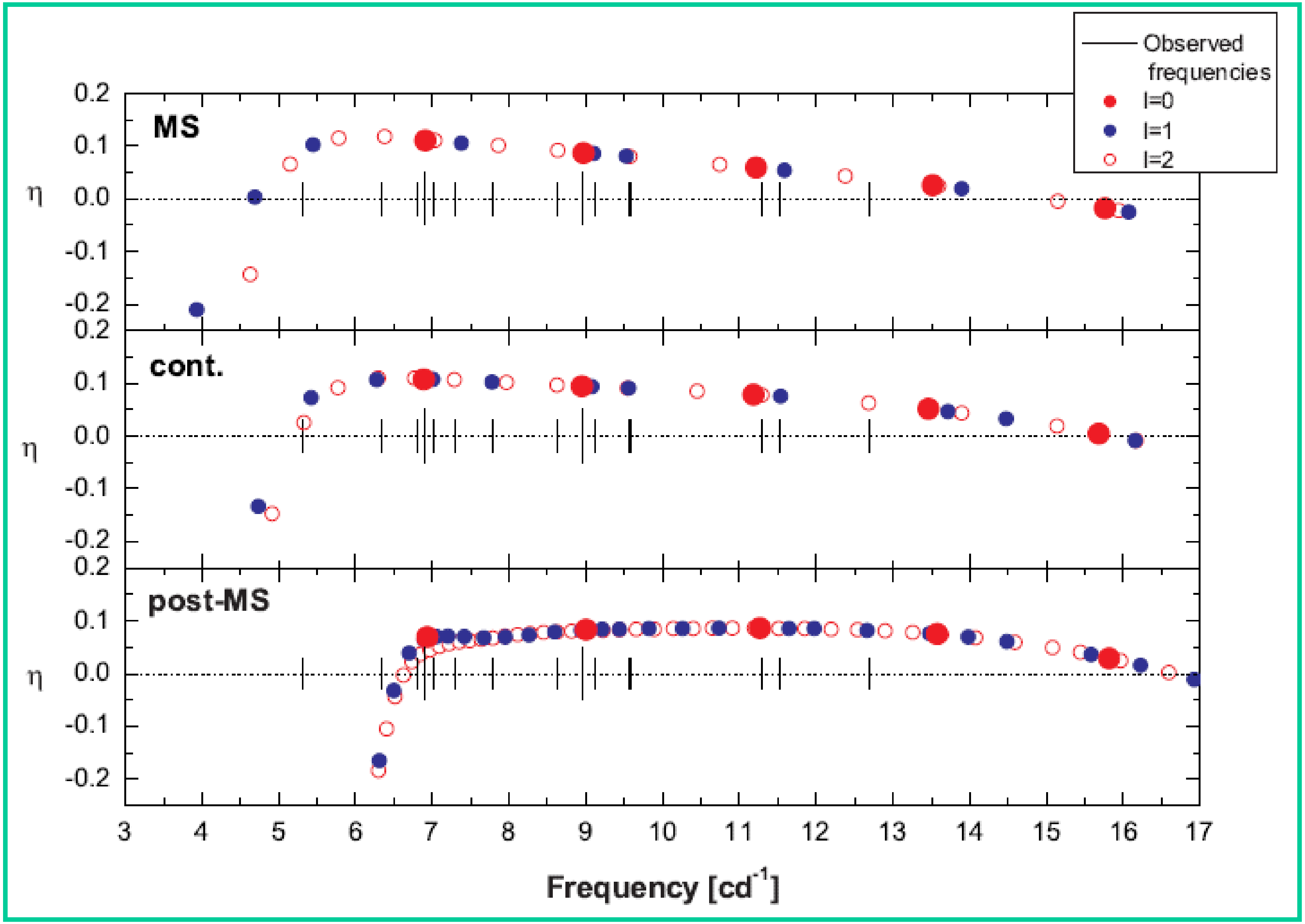


44 Tau, evolutionary tracks for best models



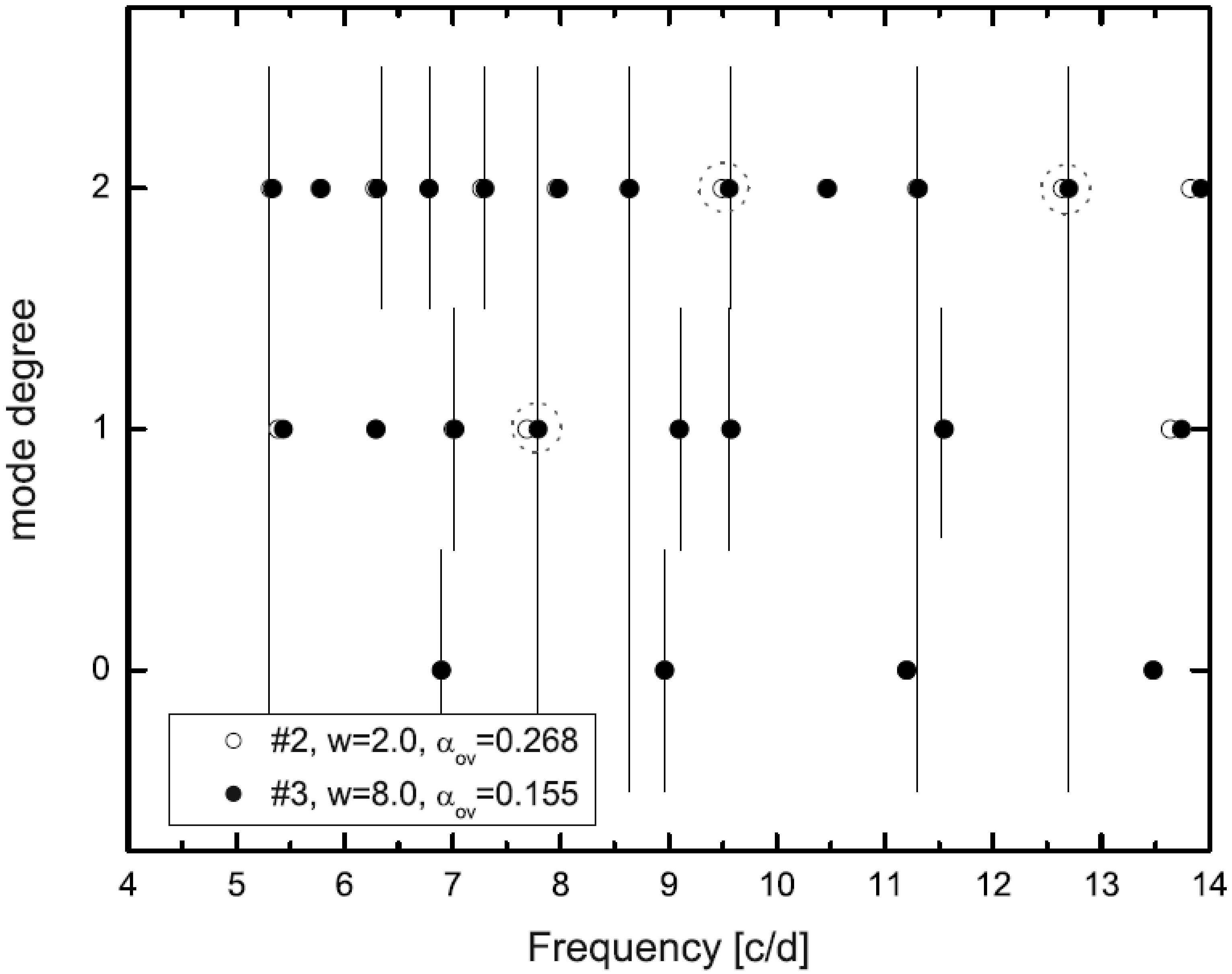
Lenz, Pamyatnykh, Zdravkov & Breger, 2010, A&A 509, A90

44 Tau, pulsational instability range



due to Lenz 2009, PhD Thesis

44 Tau. Frequency fitting for best models



Lenz, Pamyatnykh, Zdravkov & Breger, 2010, A&A 509, A90

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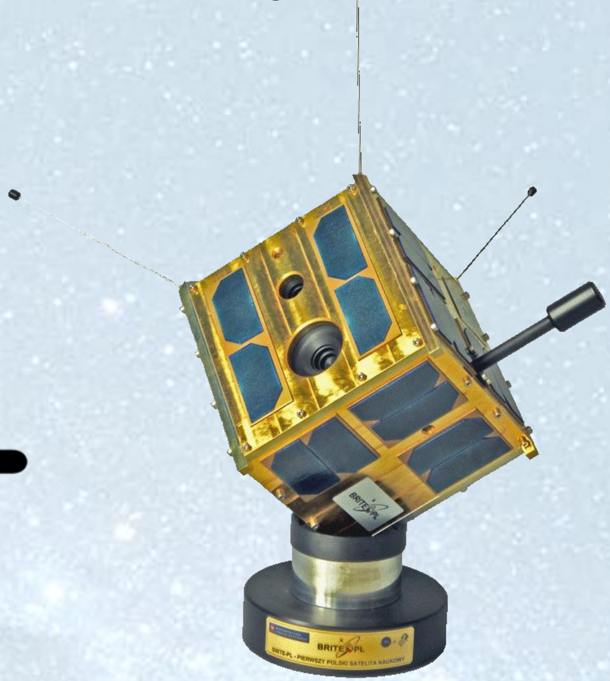
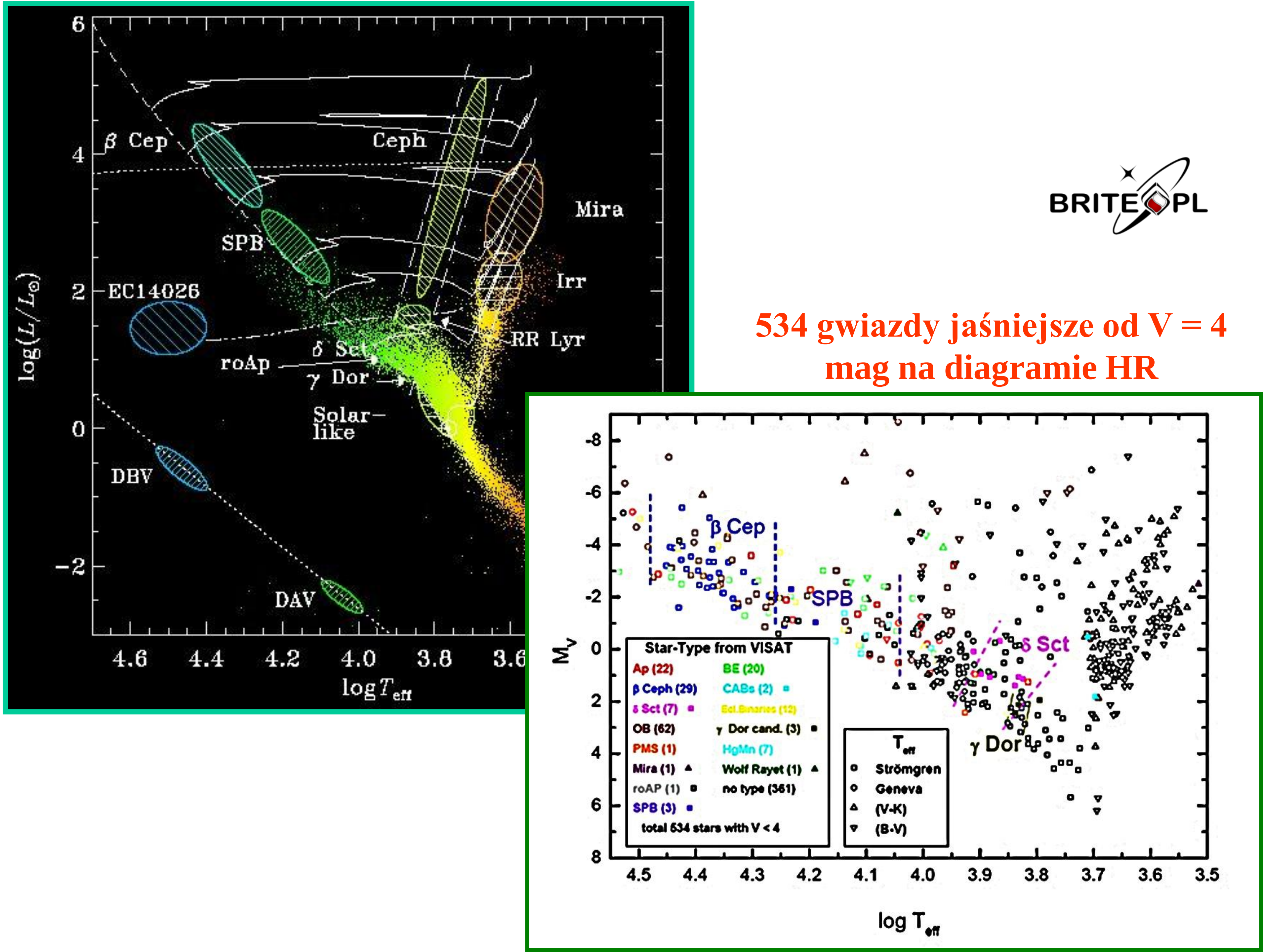
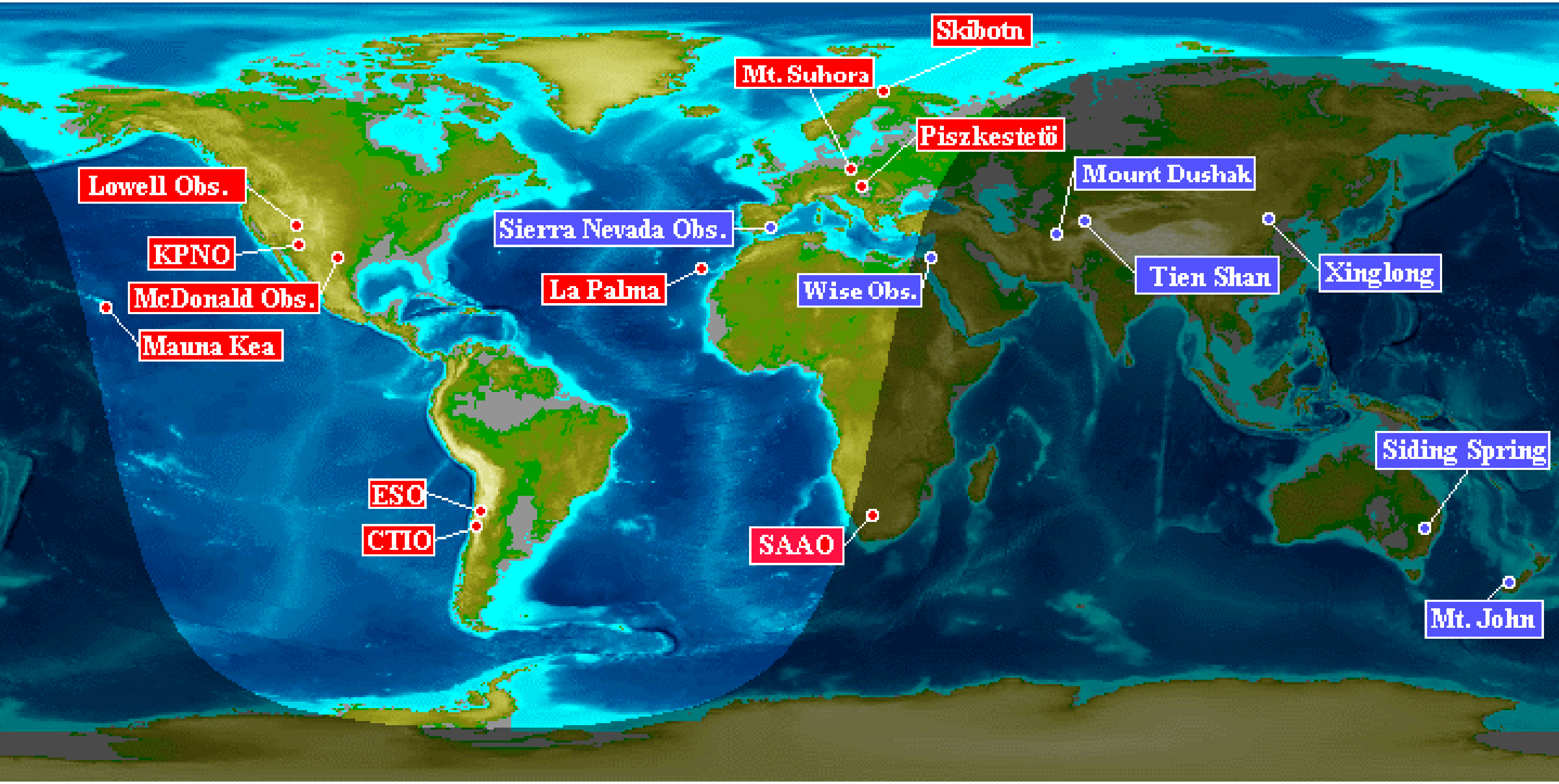


BRITE-PL – Pierwszy Polski Satelita Naukowy



534 gwiazdy jaśniejsze od V = 4 mag na diagramie HR

Delta Scuti Network



M. Breger et al.

Satelity obserwujące pulsacje gwiazd:

MOST (Microvariability and Oscillations of STars) (Kanada)
http://www.astro.ubc.ca/MOST/
start – 20.03.2003, rosyjska rakieta ROKOT, Plesieck

COROT (COnvection + ROtation + planetary Transits) (Francja)
http://smsc.cnes.fr/COROT/
start – 27.12.2006, rosyjska rakieta SOJUZ-2, Bajkonur

Kepler (USA, NASA)
http://www.nasa.gov/mission_pages/kepler/main/index.html
start – 06.03.2009, Delta II, Cape Canaveral

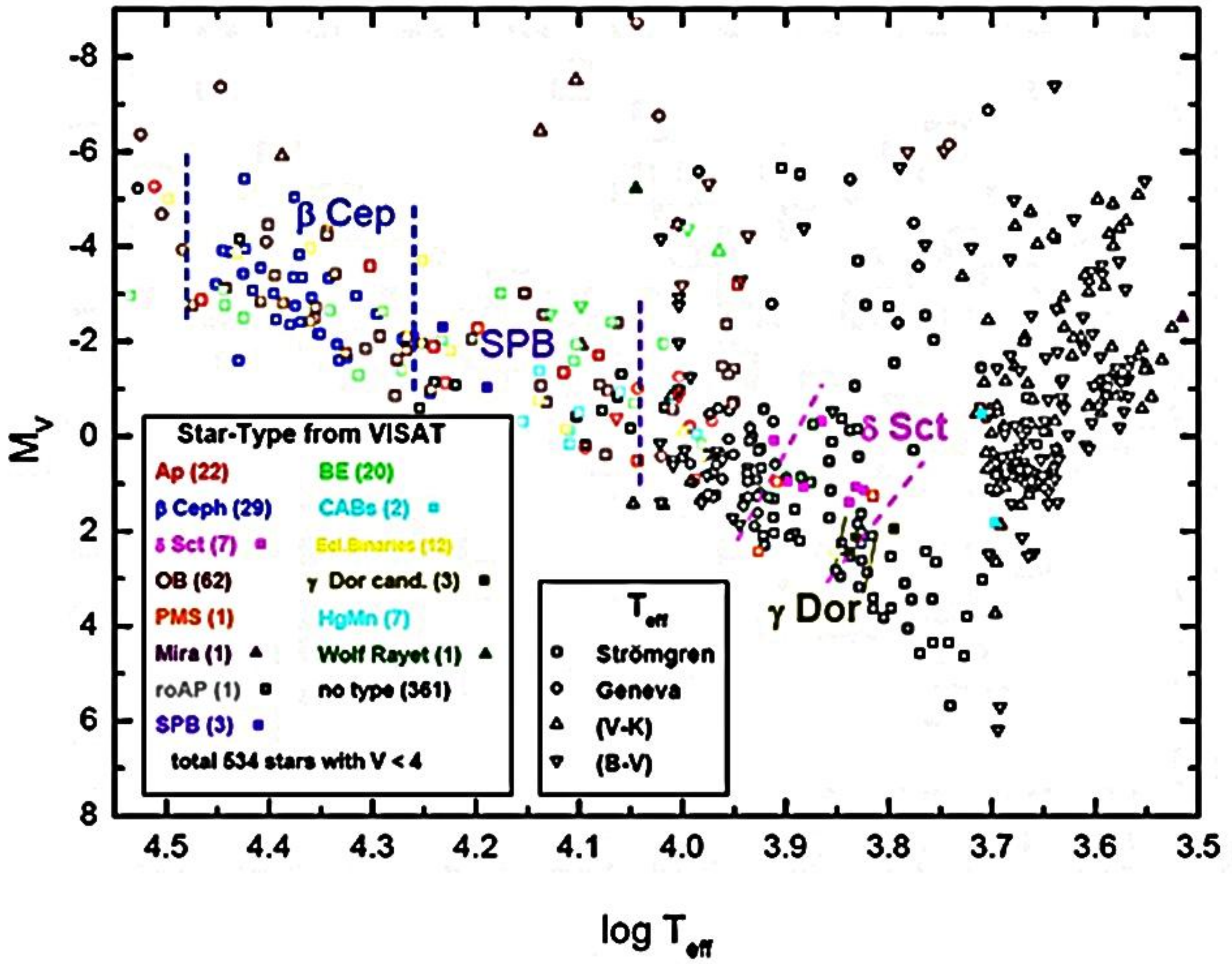
BRITE (BRight star Target Explorer) (Kanada, Austria, Polska)
http://www.brite-constellation.at/index.html
start – jesień 2012 (Austria, indyjska rakieta),
jesień 2012 (Polska, rosyjska rakieta)

Satelita BRITE

zalety w porównaniu z innymi satelitami:

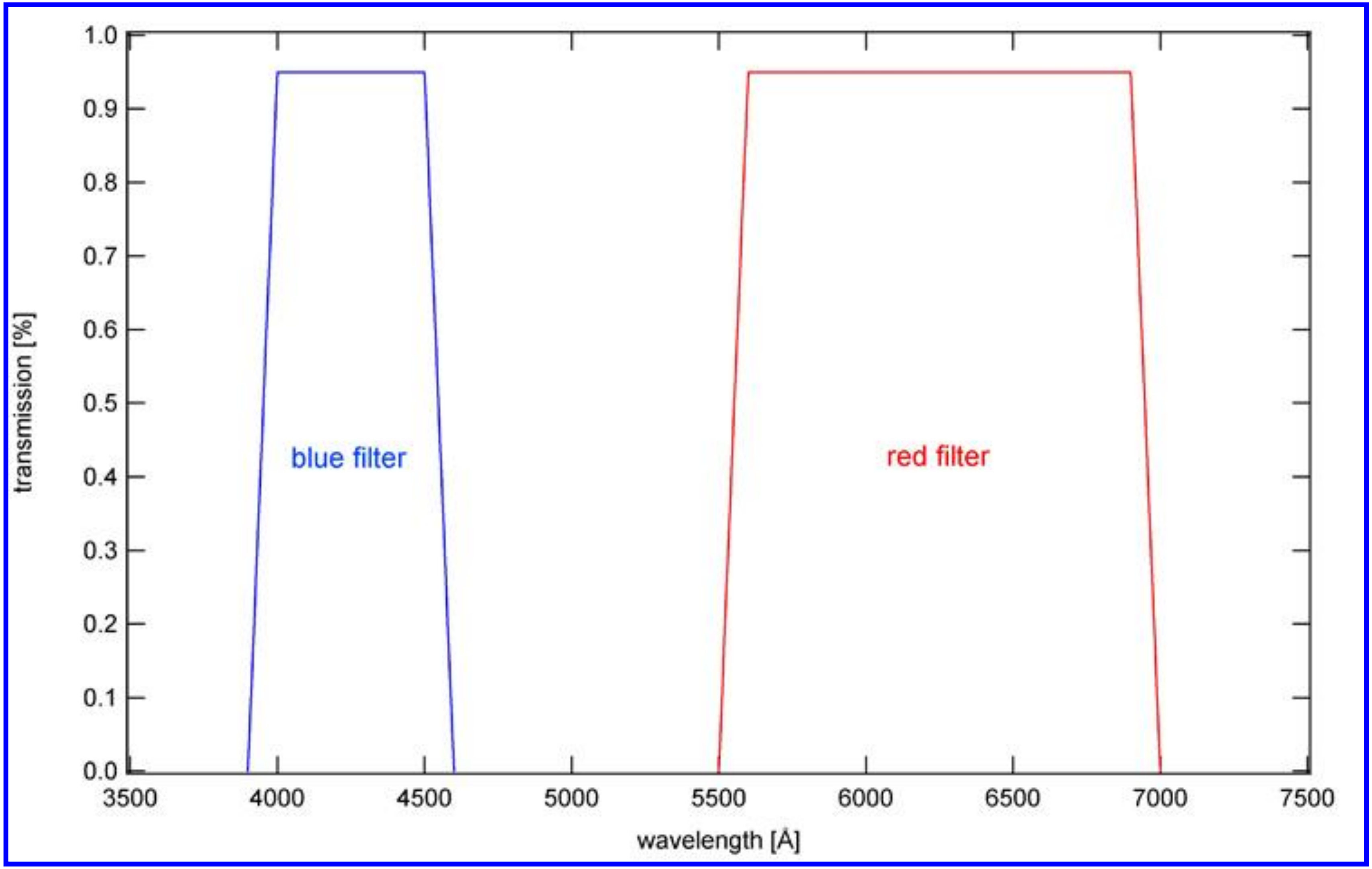
*** bardzo tani projekt,**
*** obiekty z całego nieba,**
*** obserwacje w dwóch kolorach,**
*** jednoczesne obserwacje z kilku teleskopów**

Obiekty dla BRITE



Główna zaleta satelitów BRITE – obserwacje w dwóch kolorach

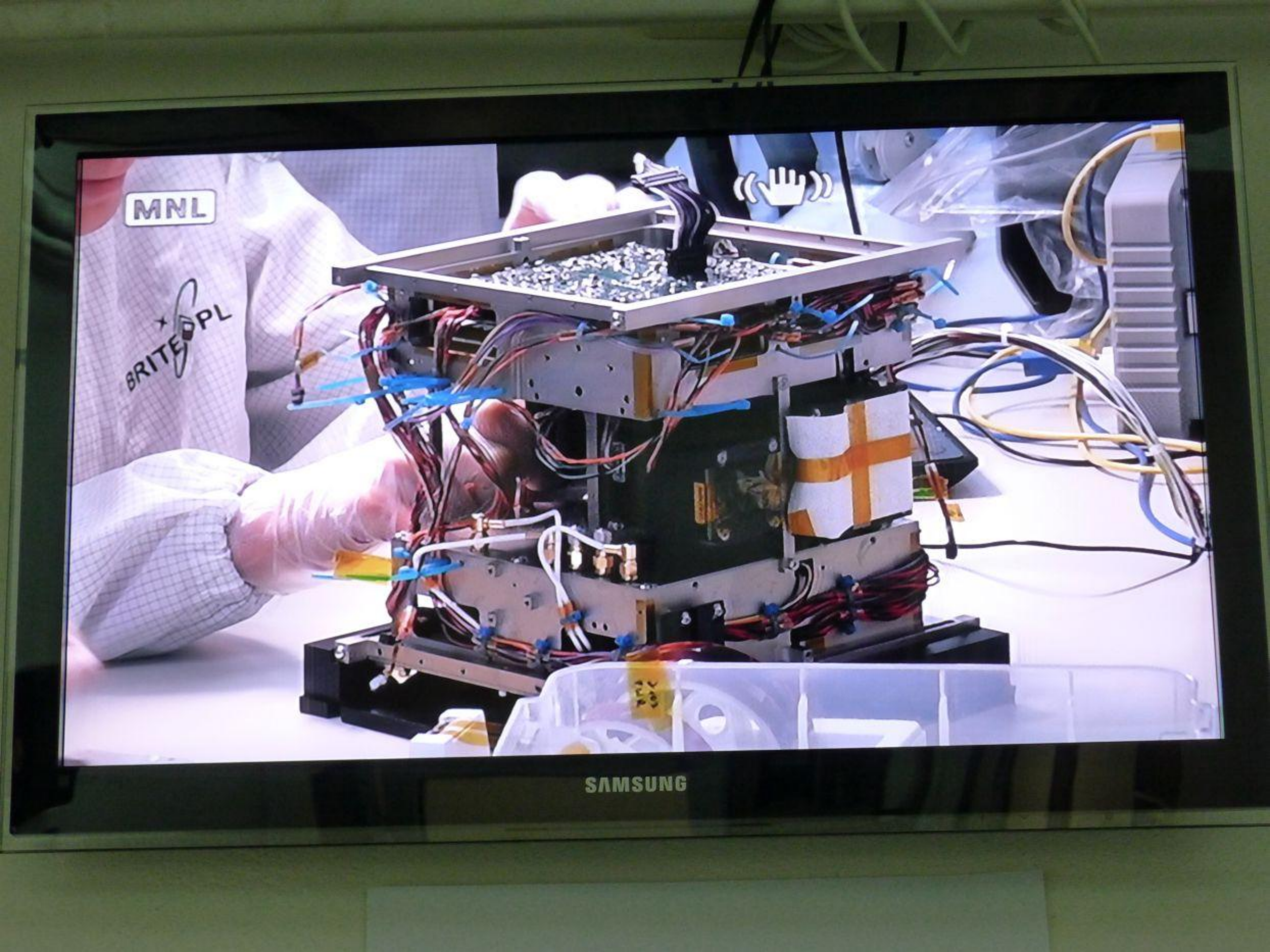
(trzy satelity obserwują w kolorze niebieskim, trzy – czerwonym)



Satelity BRITE (Austria, Kanada, Polska), główne charakterystyki techniczne:

Waga satelity - 6 kg !
Sześcian 20 x 20 x 20 cm
Moc elektryczna baterii – 5-10 W
Dokładność utrzymania obrazu – 1 min. luku
Obiektyw, średnica – 3 cm !
Pole widzenia – 24 stopni
Niska orbita nad Ziemią (600-800 km)
Detektory – CCD 4008 x 2672 (10.7 Megapiks.)
Trzy satelity – niebieski filtr (390-460 nm)
Trzy satelity - czerwony filtr (550-700 nm)
Okres misji kosmicznej – minimum 3 lata

Start – Jesień 2012 (Austria, indyjska rakieta),
Jesień 2012 (Polska, rosyjsko-ukraińska rakieta Dniepr
= SS-18 Szatan, baza wojskowa Jasny)


MNL
BRITE PL
SAMSUNG


Ясный
Байконур
РОССИЙСКАЯ
КАЗАХСТАН
УЗБЕКИСТАН
ТУРКМЕНИЯ
КИРГИЗИЯ
ТАДЖИКИСТАН
МОНГ
АСТАНА
ТАШКЕНТ
АШХАБАД
БИШКЕК
УЛАН-БА
Каспийское море
Оренбург
Орск
Новоказалинск
Кызылорда
Караганда
Семипалатинск
Павлодар
Омск
Новосибирск
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Челябинск
Уфа
Самара
Волгоград
Астрахань
Урумчи


ДНЕПР
КОС

The END

MODY

$$\frac{\delta T}{T} = y_{T,n}(r) Y_\ell^m(\theta,\phi)\exp(-\mathrm{i}\omega_{n\ell m}t)$$

$y_{T,n}(r)$ radialna funkcja własna

n radialny rząd modu

$n < 0$ mody **g** $(\ell > 0)$

$n = 0$ mody **f**

$n > 0$ mody **p** $(\ell > 1)$

$Y_\ell^m(\theta,\phi)$ sferyczna harmonika

$$\nabla_H^2 Y = -\ell(\ell+1)Y$$

ℓ stopień modu

$m = -\ell, \ldots 0, \ldots \ell$ rząd azymutalny

$$Y_\ell^m(\theta,\phi) = (-1)^m \mathcal{N}_\ell^{|m|} P_\ell^{|m|}(\mu)\exp(\mathrm{i}m\phi)$$

$$\mathcal{N}_\ell^{|m|} = \sqrt{\frac{(2\ell+1)(\ell-|m|)!}{4\pi(\ell+|m|)!}}$$

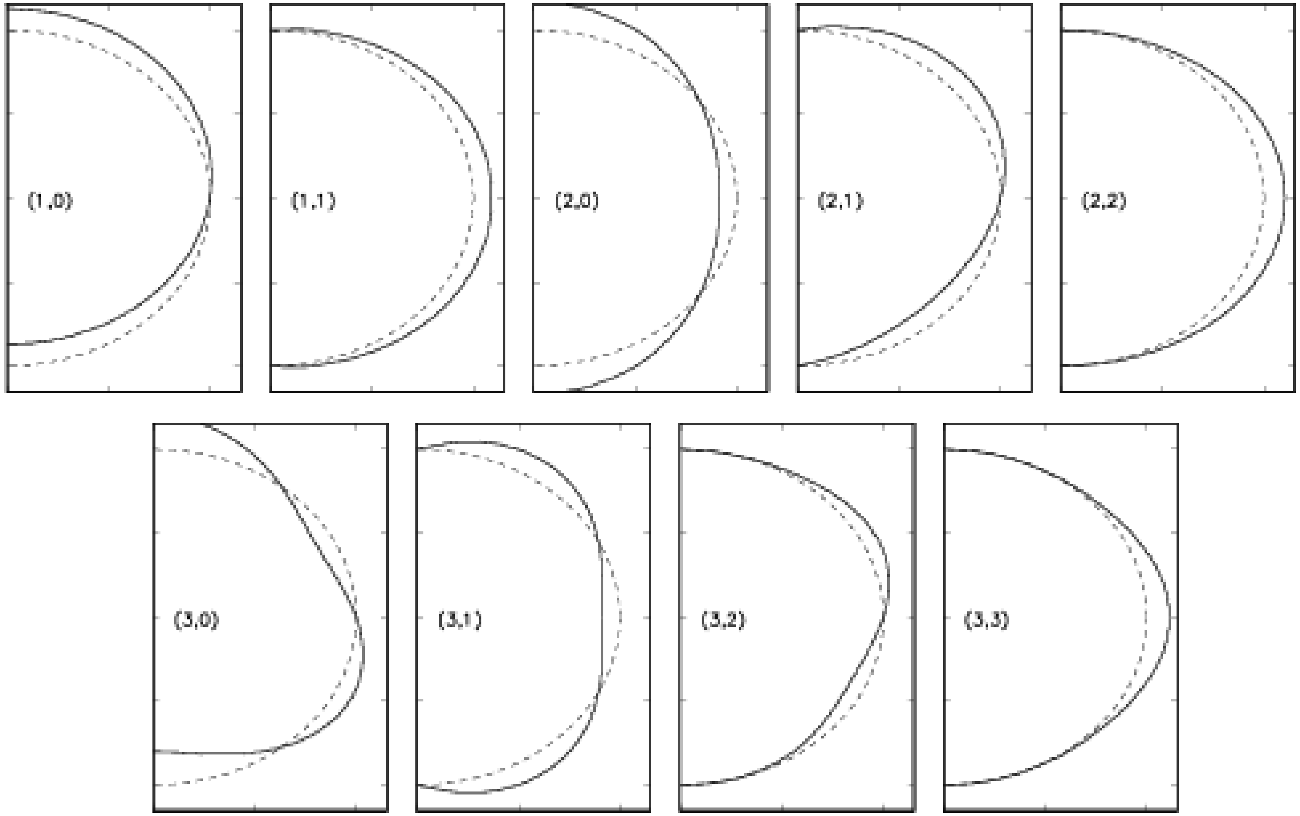
$$\mu = \cos\theta$$

$$P_\ell^{|m|}(\mu) = (1-\mu^2)^{\frac{|m|}{2}}\frac{d^{|m|}P_\ell}{d\mu^{|m|}}$$ - stowarzyszone funkcje Legendra

P_ℓ - wielomiany Legendra

W. A. Dziembowski

Harmoniki sferyczne Y_l^m



czynnik uśredniania amplitudy <0.1 @ $l > 2$ i <0.01 @ $l > 4$

W. A. Dziembowski