SEISMIC PROBING OF STELLAR INTERIORS:

PAST ACHIEVEMENTS AND FUTURE GOALS

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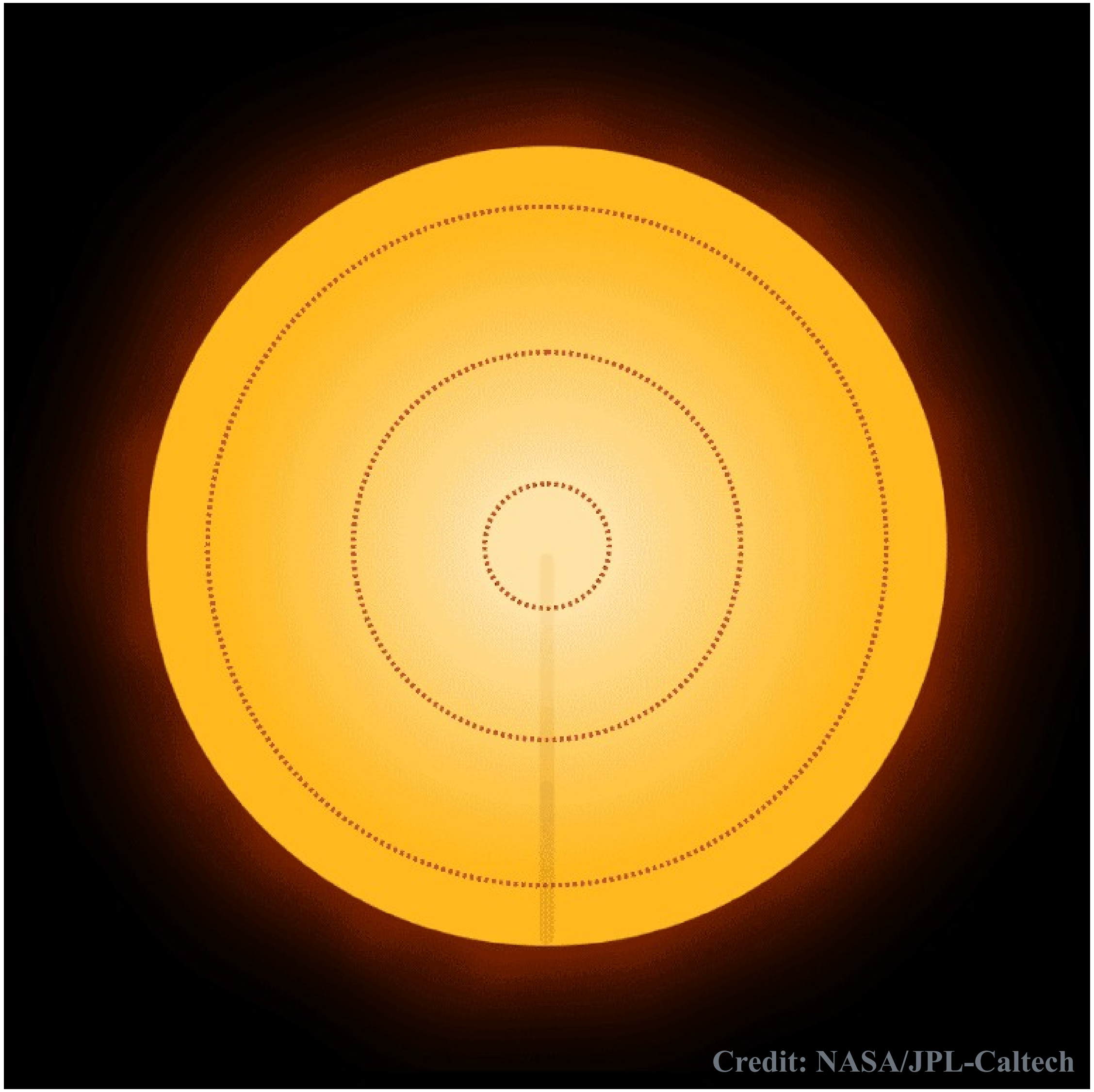
XLI Zjazd PTA, 2023

Credit: Gabriel Pérez

The stellar interior acts as a resonant cavity. Standing waves are generated (normal modes).

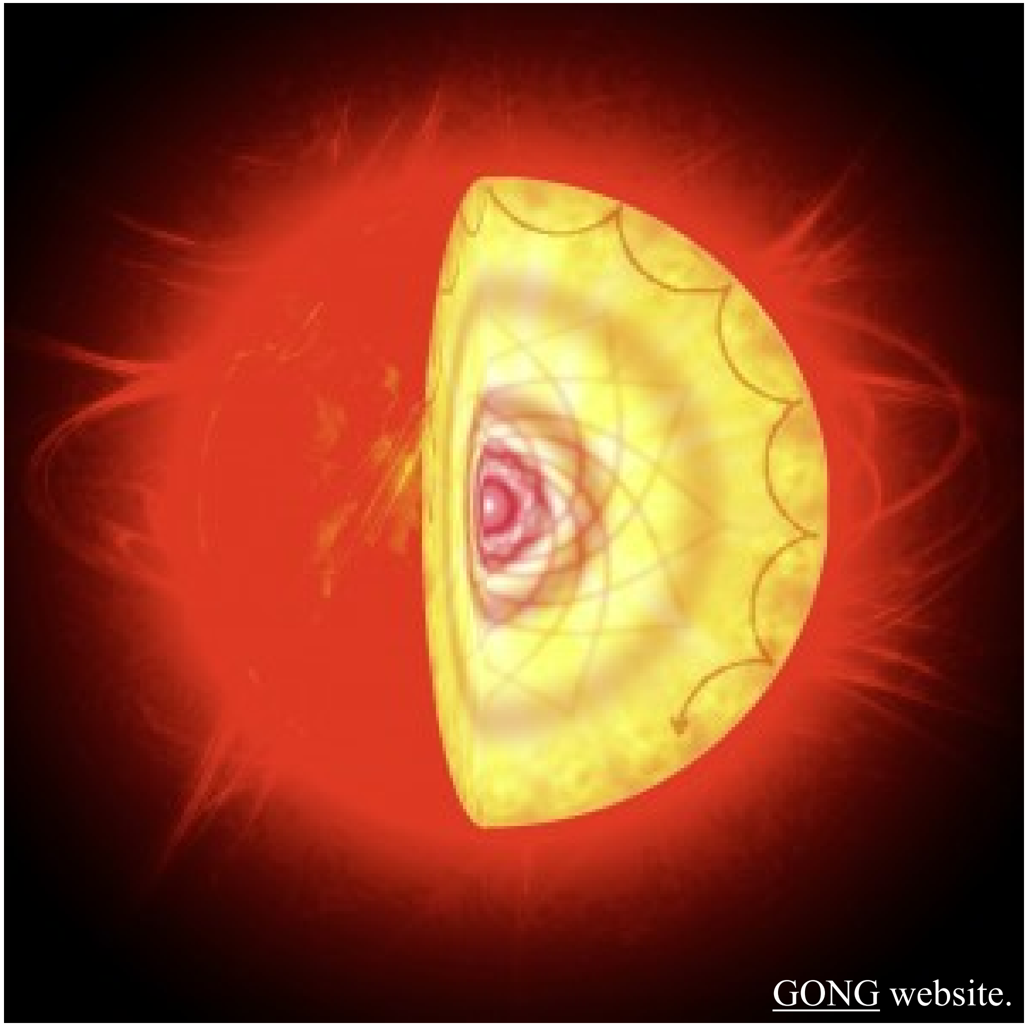


Credit: NASA/JPL-Caltech

ASTEROSEISMOLOGY

the inference about the internal structure of stars based on the study of the properties of **hydrodynamic waves** propagating in the interiors of stars

Stars can pulsate in many modes, which can penetrate different parts of a star and have different sensitivities to its structure.



GONG website.

asteroseismology allows us to look inside a star

Why do stars pulsate?

- **through self-excitation**

(heat-engine mechanism)

- **by an external force**

(turbulent convection, tidal forces)

TYPE OF MODES - RESTORING FORCE

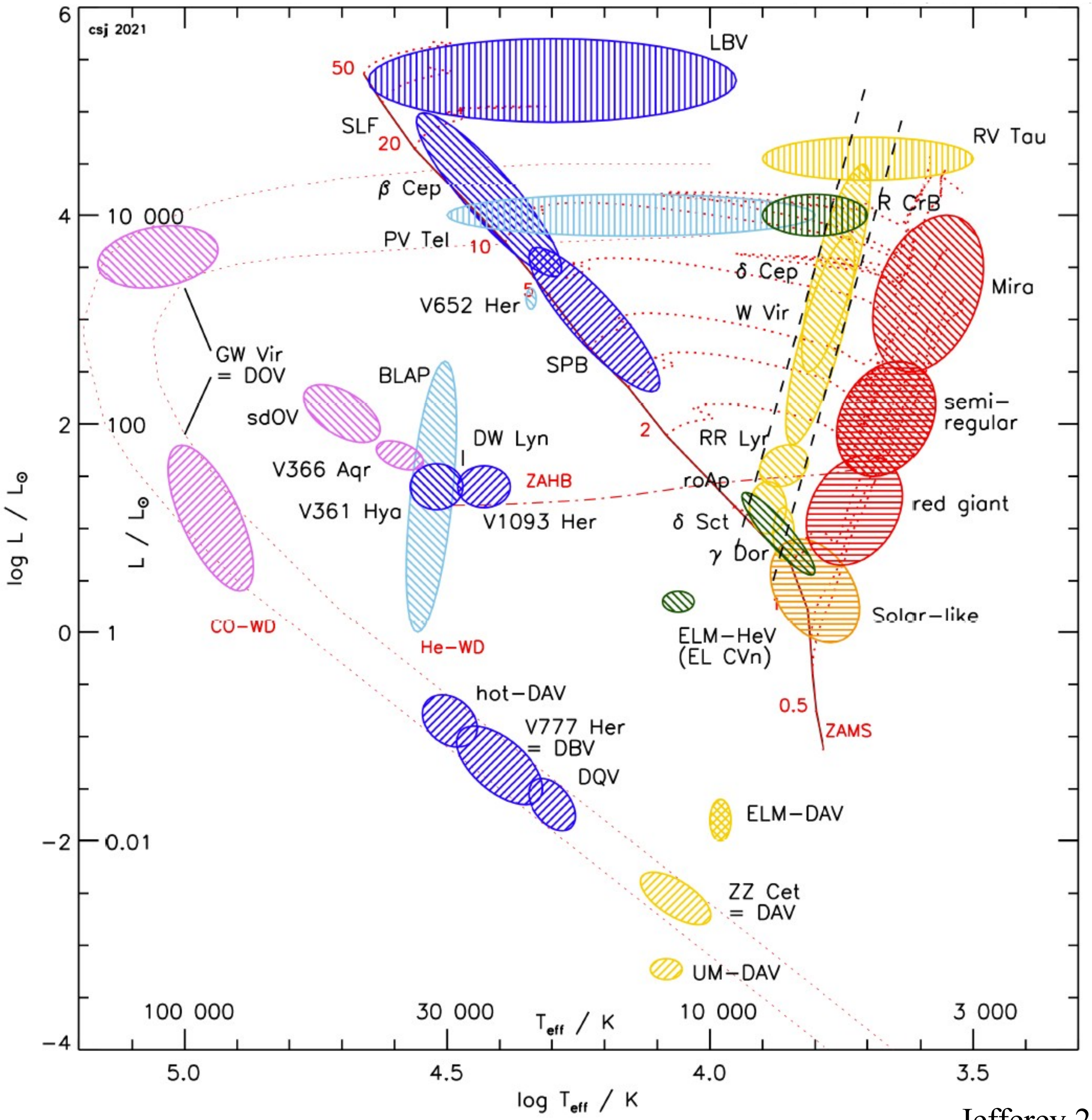
- **pressure (p) modes** - **pressure dominates**

- **gravity modes (g)** – **buoyancy dominates**
  - **g modes (internal)**
  - **f modes (surface)**

- **mixed modes (p/g)** – **gravito-acoustic modes**
  both forces are important

- **Rossby (r) modes** - **Coriolis force dominates**

Instability domains in the Hertzsprung-Russell diagram



Jefferey 2015, Kurtz 2022

SEISMIC MODEL OF A STAR

$$\nu_{\mathrm{j,obs}} = \nu_{\mathrm{j,cal}}(n_j,\ \ell_j,\ m_j,\ \mathrm{P_M},\ \mathrm{P_T})$$

+

(T_{eff}, L) consistent with the observed values

$\mathrm{P_M}$ -- parameters of the model:

M_0, X_0, Z_0, age (or logT_{eff}), the angular momentum ($V_{\mathrm{rot,0}}$)

$\mathrm{P_T}$ -- free parameters of the theory:

convection, overshooting from convective regions, mass loss, angular momentum transfer, magnetic field, mixing processes

+

microphysics data

(opacity, EOS, reaction rates)

CONSTRAINTS ON OPACITY DATA

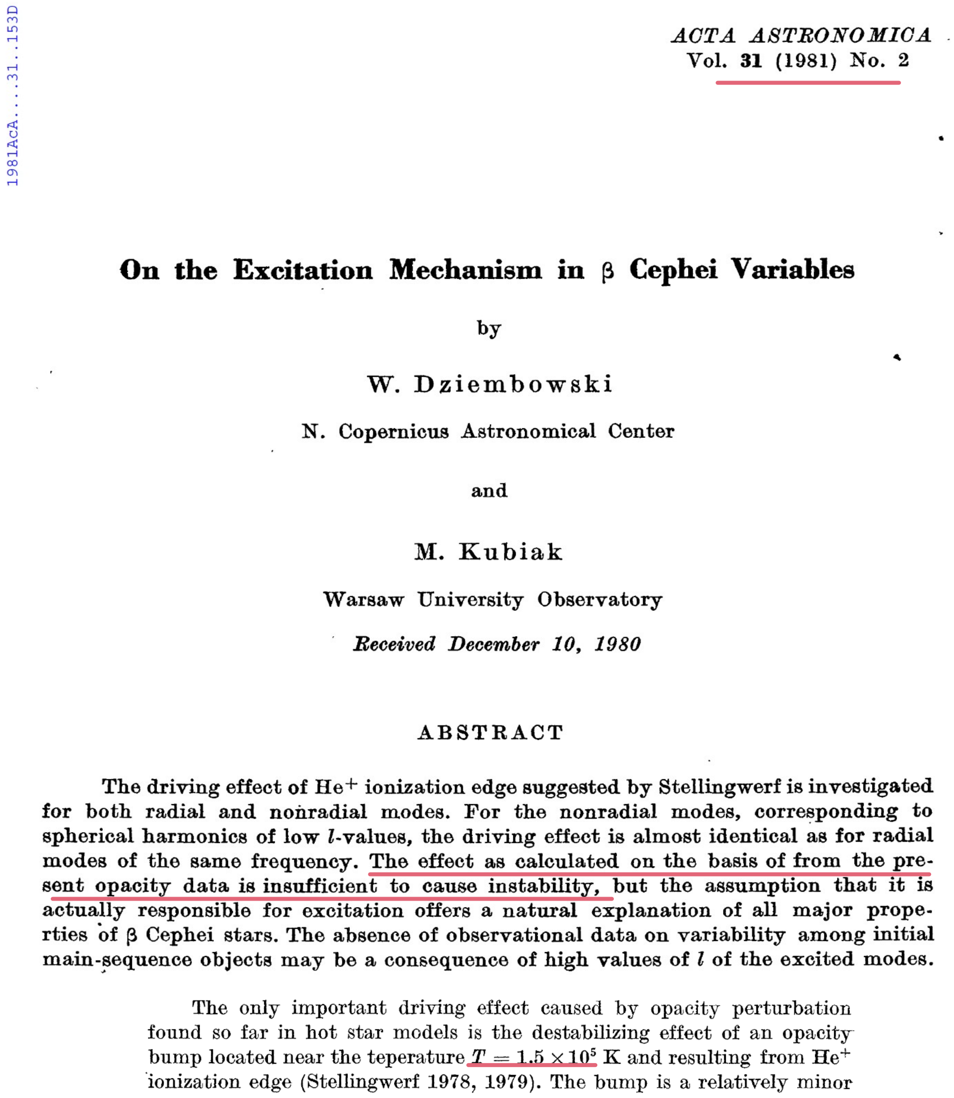
Eddington in 1926 pointed out that opacity is one of the most uncertain ingredients in stellar modelling

Opacity calculations that included for the first time bound-bound absorption - Los Alamos (Cox&Steward 1962, Cox 1965)

Los Alamos Opacity Library (LAOL) - Hübner, Merts, Magee (1977)

disagreements:

- ✶ **problems with the standard solar model**
- ✶ **too large period ratios in classical Cepheids models**
- ✶ **an unknown mechanism of pulsations in B-type MS stars**



ACTA ASTRONOMICA
Vol. **31** (1981) No. 2

On the Excitation Mechanism in β Cephei Variables

by

W. Dziembowski

N. Copernicus Astronomical Center

and

M. Kubiak

Warsaw University Observatory

Received December 10, 1980

ABSTRACT

The driving effect of He$^+$ ionization edge suggested by Stellingwerf is investigated for both radial and nonradial modes. For the nonradial modes, corresponding to spherical harmonics of low l-values, the driving effect is almost identical as for radial modes of the same frequency. The effect as calculated on the basis of from the present opacity data is insufficient to cause instability, but the assumption that it is actually responsible for excitation offers a natural explanation of all major properties of β Cephei stars. The absence of observational data on variability among initial main-sequence objects may be a consequence of high values of l of the excited modes.

The only important driving effect caused by opacity perturbation found so far in hot star models is the destabilizing effect of an opacity bump located near the teperature $T = 1.5 \times 10^5$ K and resulting from He$^+$ ionization edge (Stellingwerf 1978, 1979). The bump is a relatively minor

one of the first non-adiabatic pulsational codes - Dziembowski (1971-1977)

the evolutionary code of Bohdan Paczyński

Metal (Z) opacity bump

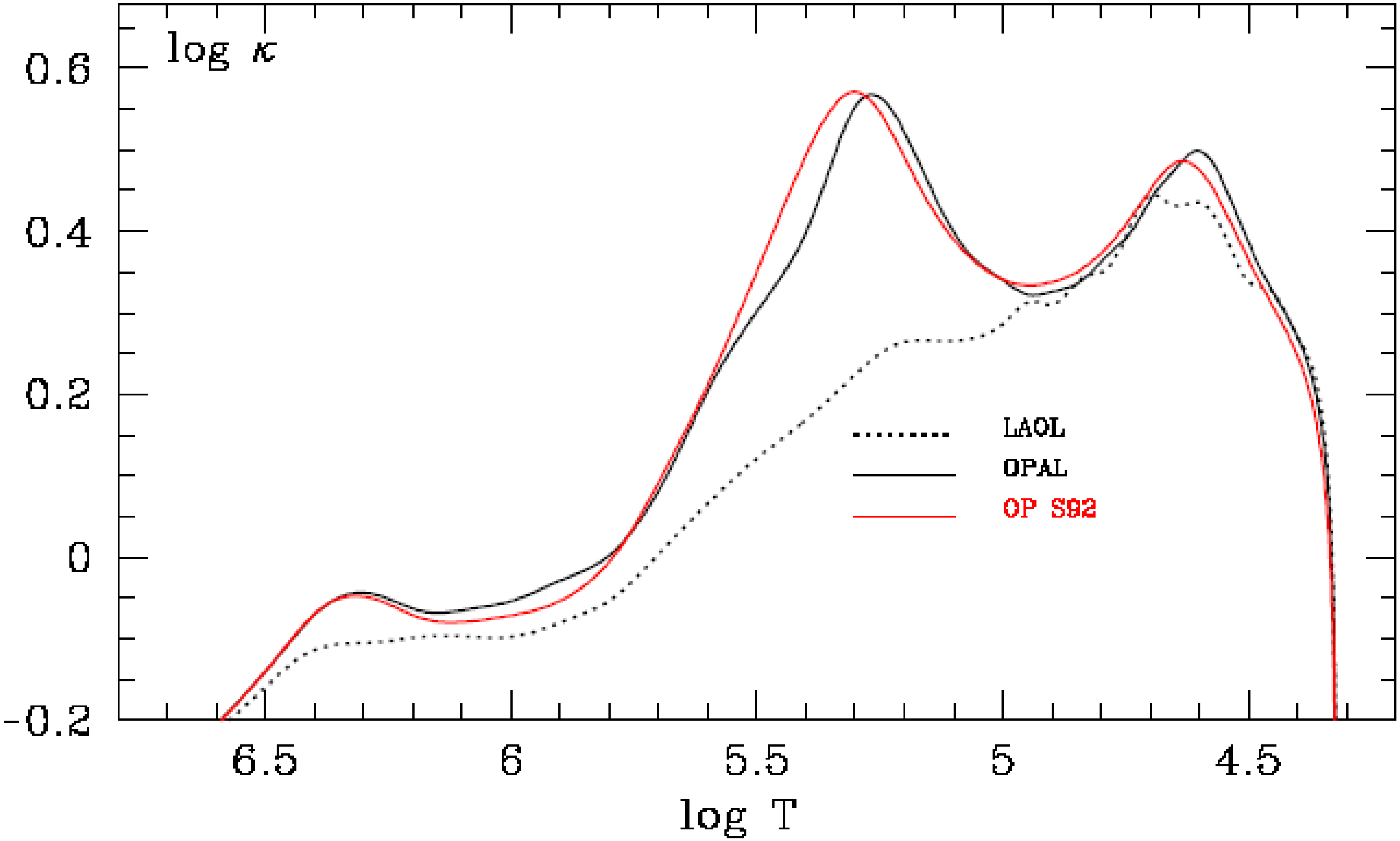
OPAL – physicists from Livermore: F. J. Rogers, C.A.Iglesias et al. .

1990 ApJ **360,** 221
1992 ApJ **397,** 717; ApJS **79,** 507
1994 Science **263,** 50
1996 ApJ **456,** 902

OP (Opacity Project) – international team led by M. J. Seatona

1993 MNRAS **265,** L25
1996 MNRAS **279,** 95
2005, MNRAS 362, L1

Mean opacity profile inside the model M=12 $M_\odot$, X_0=0.70, Z=0.02
OP (Seaton et al.) vs. OPAL (Livermore) vs. LAOL (Los Alamos)

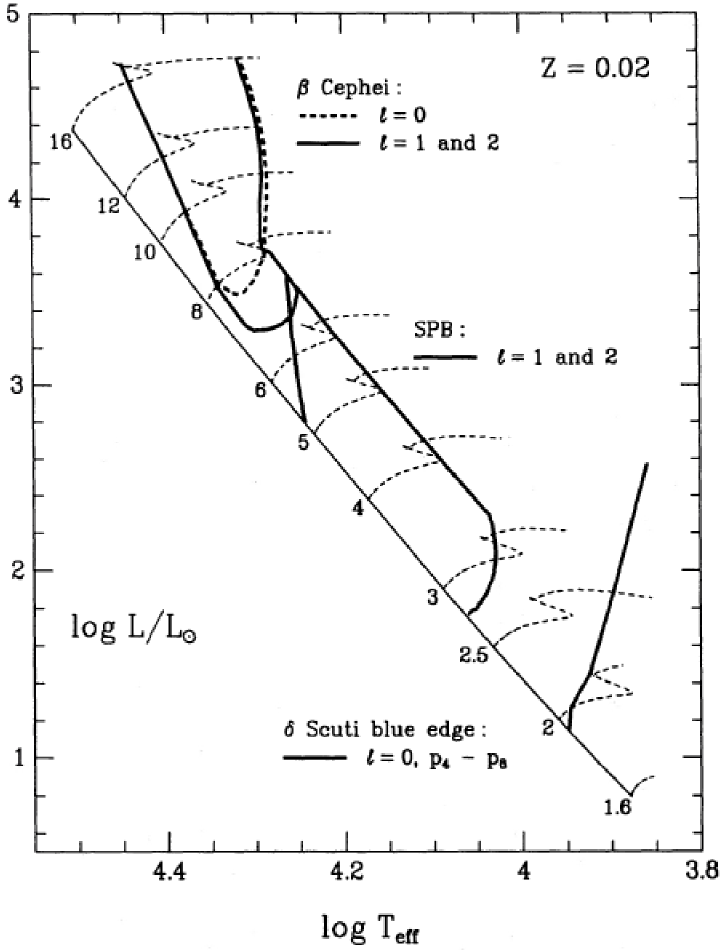


A. A. Pamyatnykh

First computations of pulsation of B-type stars with these new opacities:

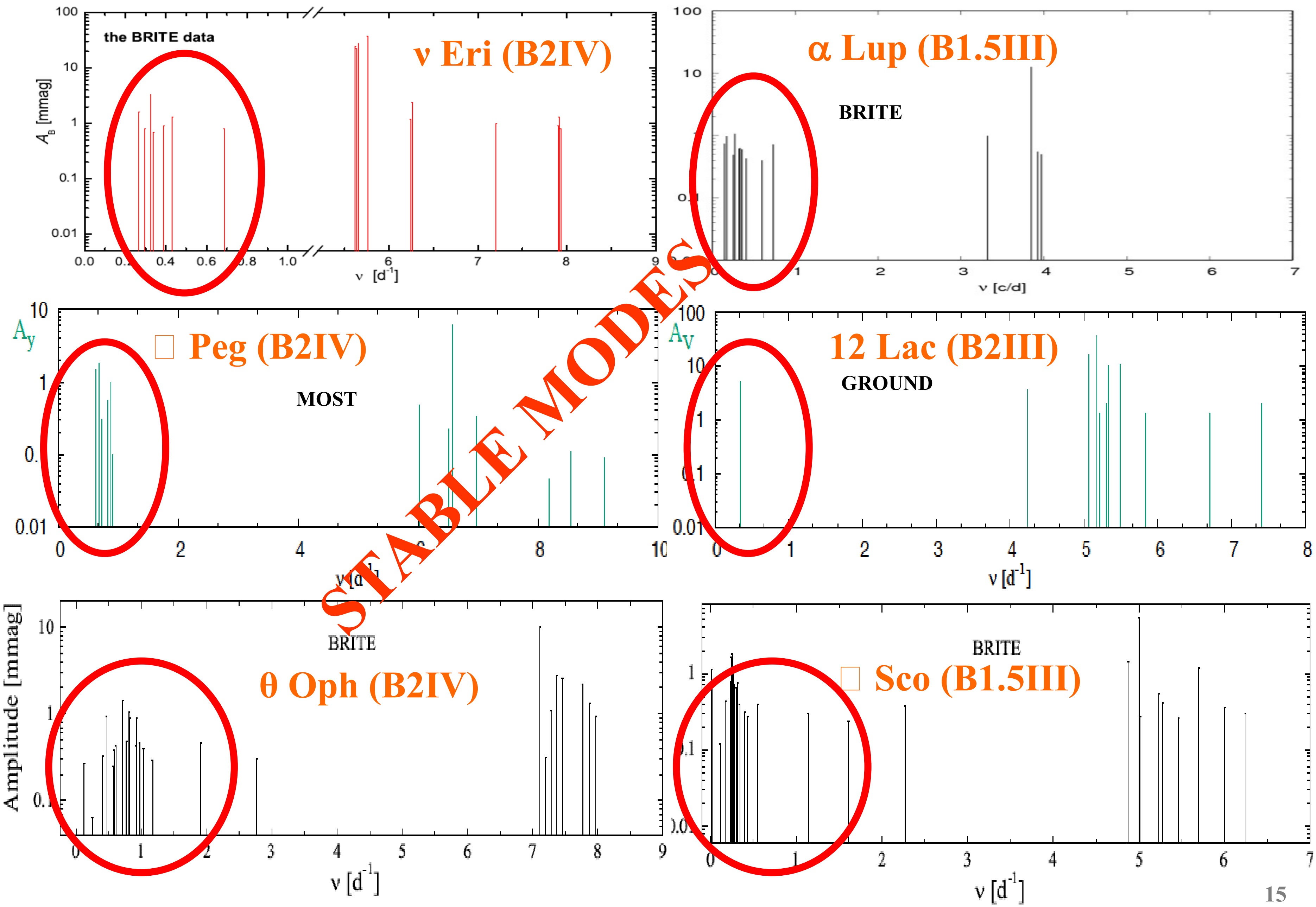
Moskalik & Dziembowski (1992)
Cox et al. (1992)
Kiriakidis et al. (1992)

Further improvements in opacities
(no need for higher metallicity):
Dziembowski & Pamyatnykh (1993)
Gautschy & Saio (1993)
Dziembowski, Moskalik, Pamyatnykh (1993)



pulsations in B-type MS stars (□ Cep, SPB)
the □ mechanism which operates thanks to an opacity bump due to the iron group elements (Fe, Ni, Mn, Cr) at T≈ 200 000 K.

oscillation spectra of early B-type stars



OPACITY TABLES WIDELY USED IN ASTROPHYSICS

OPAL
Iglesias & Rogers 1996

OP
Seaton et al. 2005

OPLIB **(new Los Alamos tables)**
Colgan et al. 2013, 2015

Low Temperature Rosseland Opacities
Ferguson et al. 2005

Hybrid pulsators are the rule rather than the exception. One of the main results of space missions.

MOST

BRITE

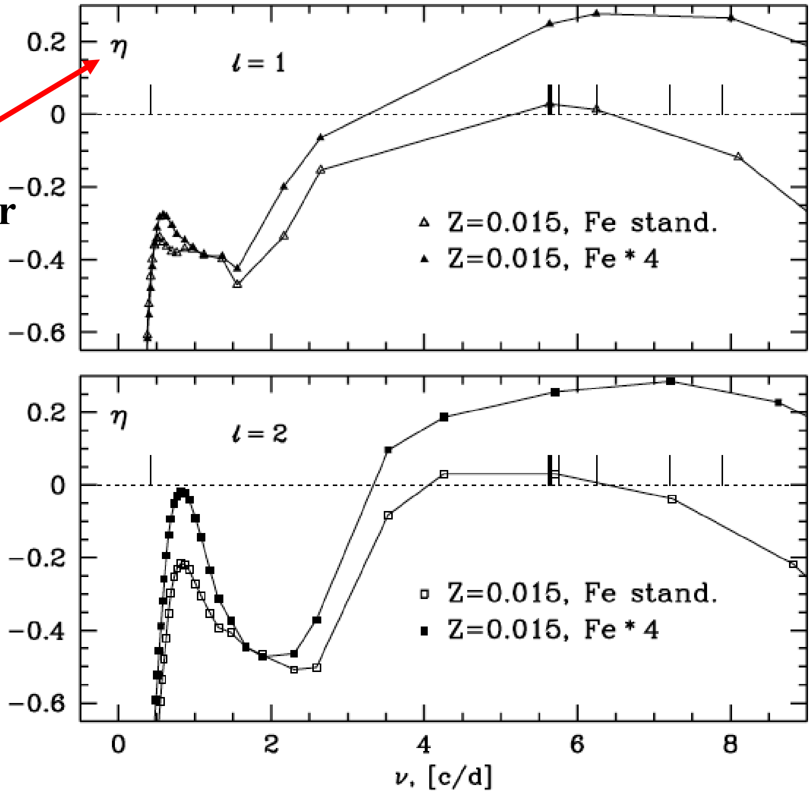
CoRoT

Kepler

TESS

Pamyatnykh, Handler, Dziembowski 2004

Asteroseismology of the β Cephei star ν Eridani: interpretation and applications of the oscillation spectrum



Instability parameter

□>0 unstable mode

□<0 stable mode

an ad hoc enhancement of iron in the driving zone

Modification of the mean opacity profile by adding Gaussians at depths (logT) critical for pulsation excitation

$$\kappa(T) = \kappa_0(T)\left[1 + \sum_{i=1}^{N} b_i \cdot \exp\left(-\frac{(\log T - \log T_{0,i})^2}{a_i^2}\right)\right]$$

κ_0 - the standard opacity profile
a_i – the width of the Gaussian
b_i – the height of the Gaussian
$\log T_{0,i}$ – the position of the Gaussian maximum

How to control opacity modifications?

How can we reduce the number of opacity modified models?

Beside oscillation frequencies, there is another seismic observable

The parameter *f* - a ratio of the flux perturbation to the radial displacement at the photosphere level

theoretical values of *f* -- linear, nonadiabatic computations

empirical values of *f* – from multi-colour photometry ($A_{\square}$ and $\square_{\square}$)

Daszyńska-Daszkiewicz, Dziembowski, Pamyatnykh 2003, 2005

the value of *f* depends on:

- pulsational frequency, ω
- stellar parameters, M, T_{eff} , L
- chemical abundance, (X, Z, mixture)
- Opacitiy data
- subphotospheric convection

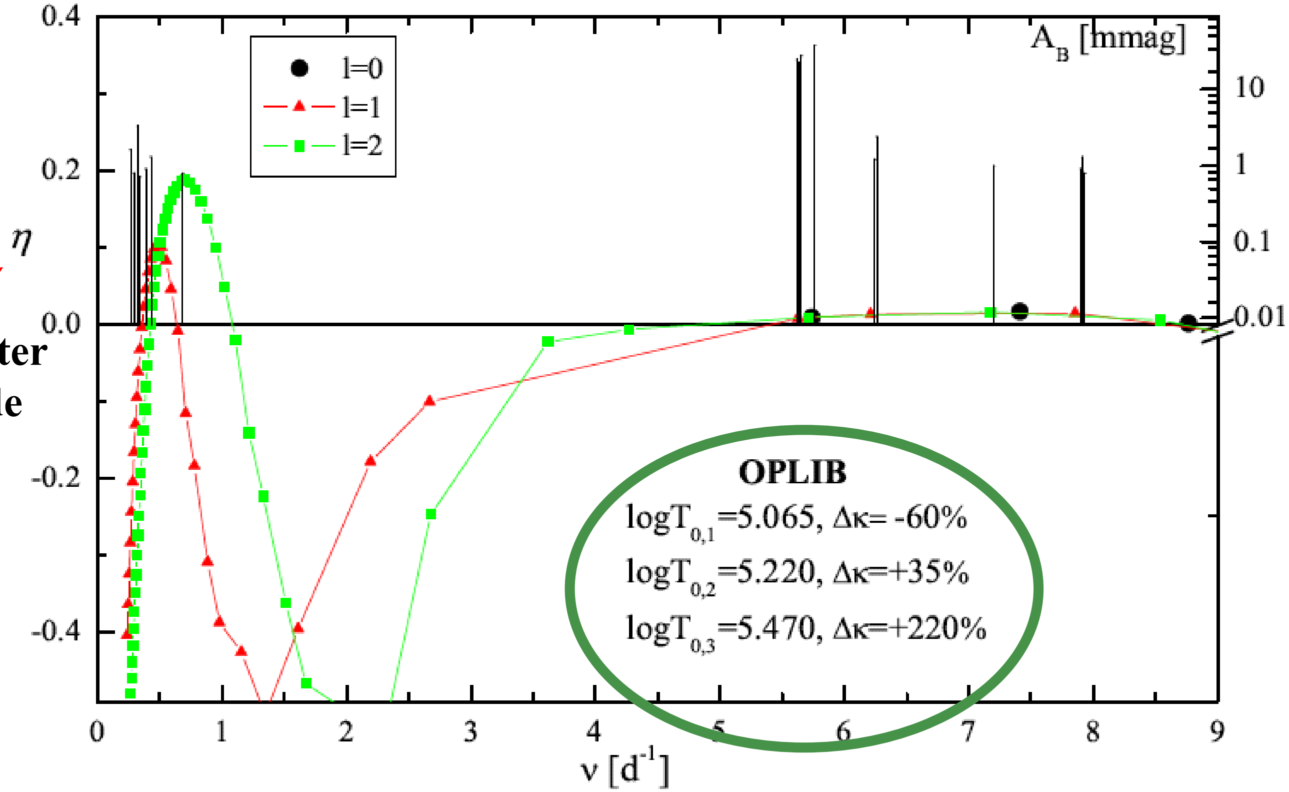
the parameter *f* -- the seismic probe complementary to oscillation frequencies

ν Eri

One radial mode and its *f* parameter, two dipole modes were fitted

the OPLIB seismic model

$M = 9.0M_{\odot}$, $\log T_{\mathrm{eff}} = 4.3314$, $Z = 0.015$, $X_0 = 0.7$, $\alpha_{\mathrm{ov}} = 0.163$



OPLIB

$\log T_{0,1}$=5.065, Δκ= -60%

$\log T_{0,2}$=5.220, Δκ=+35%

$\log T_{0,3}$=5.470, Δκ=+220%

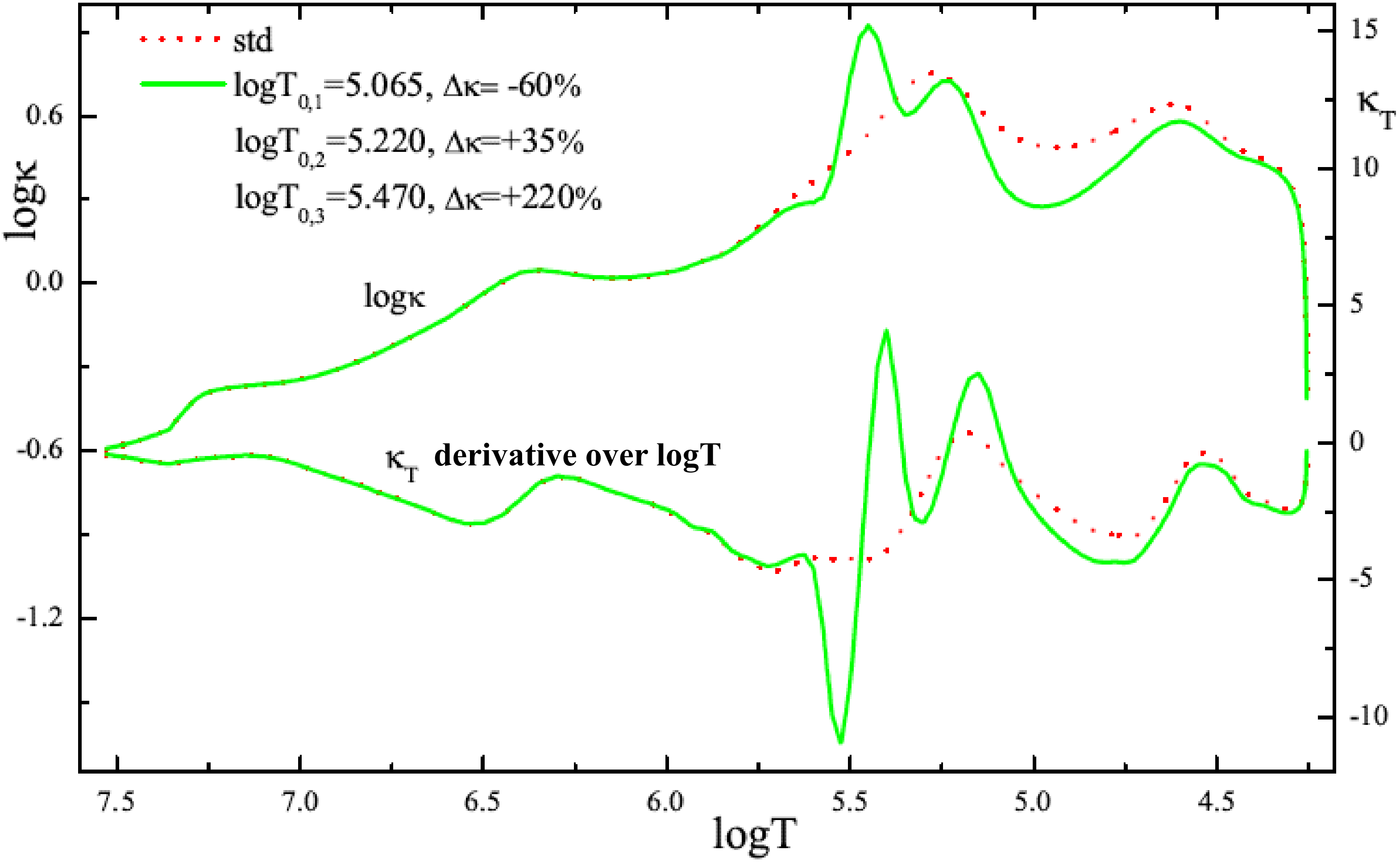
Instability parameter

□>0 unstable mode

□<0 stable mode

a good news: very difficult to find such model

the modified OPLIB opacity of the best complex seismic model of ν Eri *vs* the standard opacity



	$M/M_\odot$	$\log T_{eff}$	$\log T_{0,1}$	Δ□$_1$	$\log T_{0,2}$	Δ□$_2$	$\log T_{0,3}$	Δ□$_3$
ν Eri	9.0	4.331	5.06	-60%	5.22	+35%	5.46	+220%
12 Lac	11.2	4.376	5.06	-25%	5.22	+50%	5.46	+200%
γ Peg	8.1	4.324	5.06	-60%	5.22	+50%	5.46	+210%
θ Oph	8.4	4.343	5.06	+30%	5.30	+65%	5.46	+145%
κ Sco A	10.4	4.363	5.06	+30%	5.22	+30%	5.46	+100%
α Lup	12.0	4.351	-	-	-	-	5.46	+100%

log T = 5.46 -- Nickel has its maximum contribution to the Z bump

log T=5.22 - 5.30 -- Z-bump

log T=5.06 -- Kurucz-bump, Cugier 2012, 2014

The "nickel" opacity increase -->B-type pulsators Magellanic Clouds
Salmon et el . (2012)

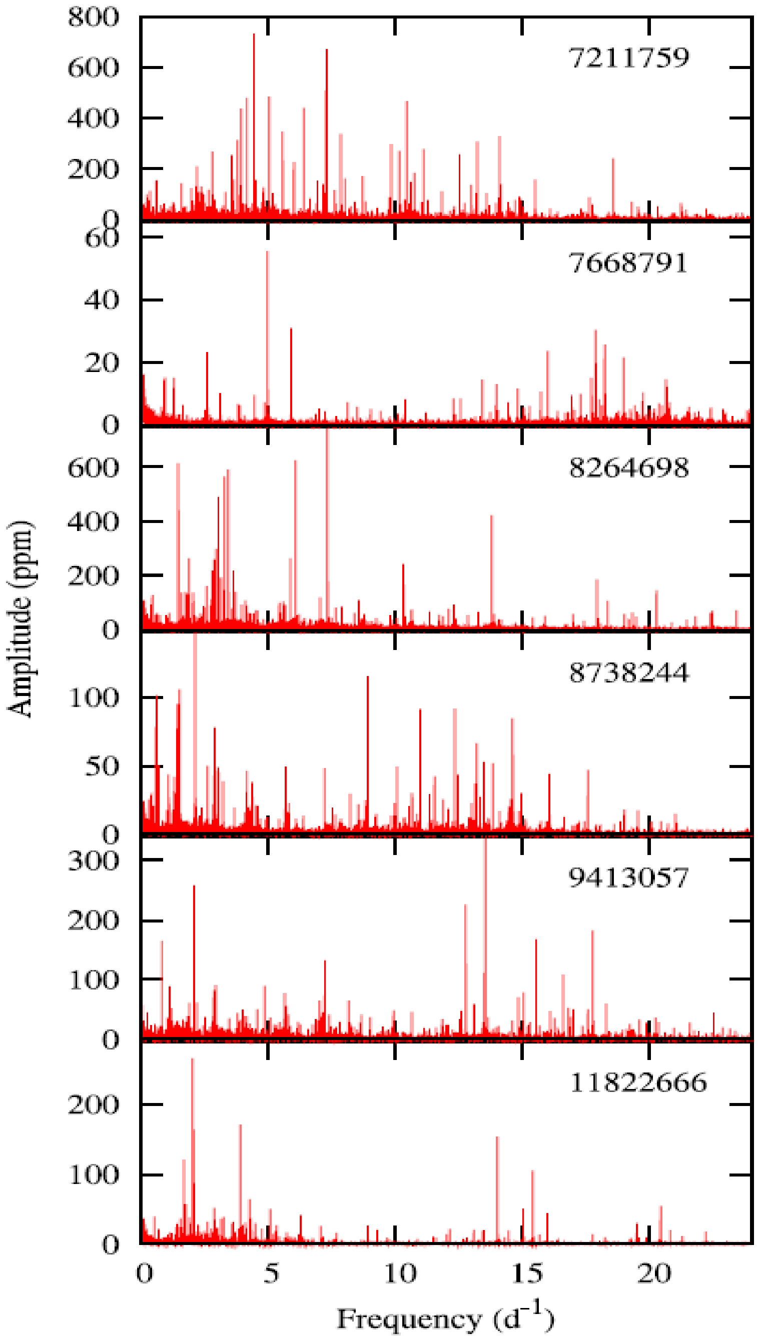
Similar problem occurs for cooler pulsating stars, δ Scuti pulsators

SpT: ~A0 – F5

$T_{eff} \approx 6500 - 9500$ K

$M \approx 1.7 - 2.7\ M_{\odot}$

the κ mechanism operating in He II zone

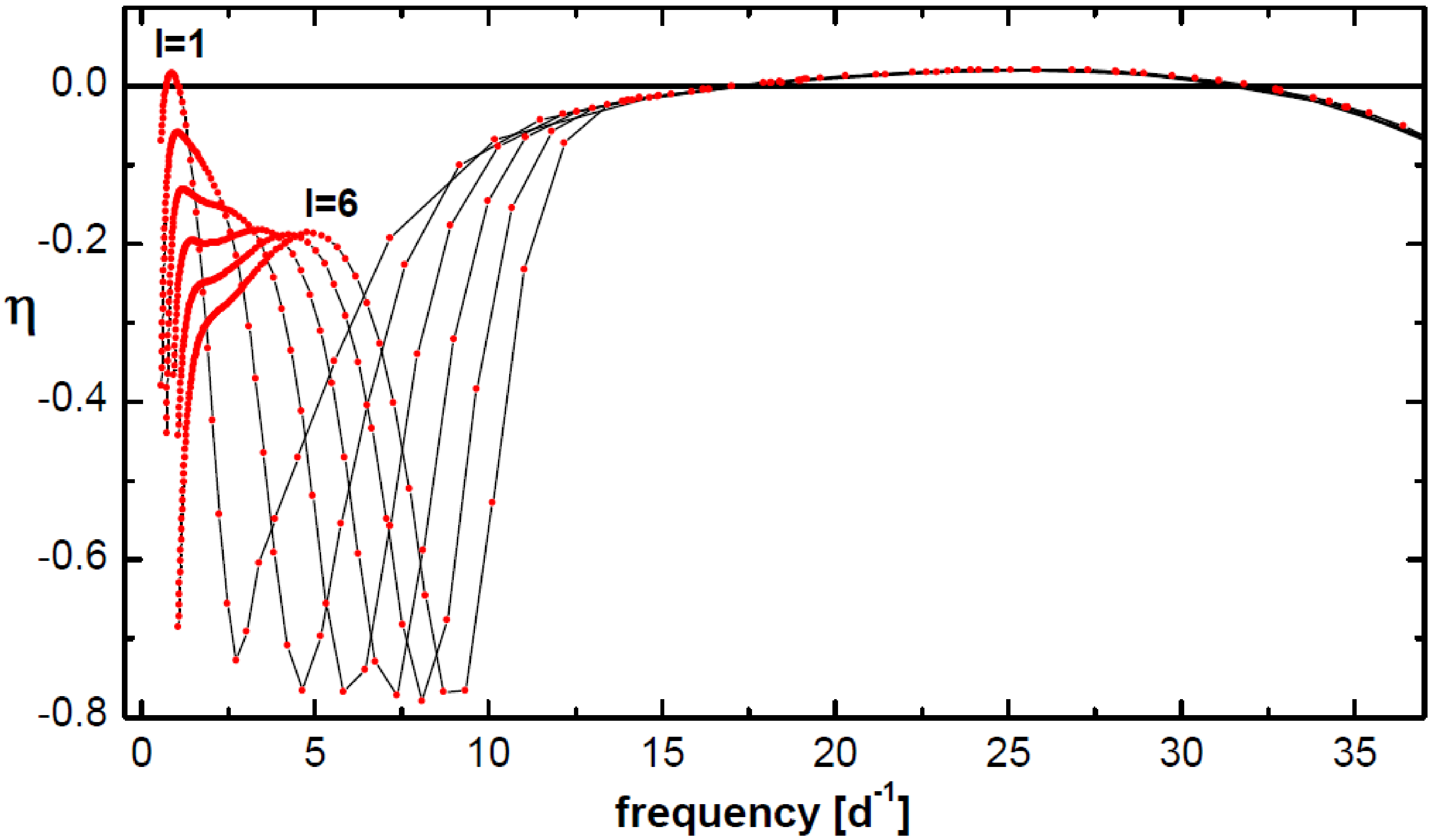


Result from Kepler photometry: all δ Scuti stars have low frequencies less than 5 d^{-1} of unknown origin.

Such low-frequency modes are stable in pulsational models

L. Balona (2014)

M =1.76, log $T_{\rm eff}$ =3.8855, log L= 1.093, Z=0.015
2*κ at log$T$=5.06 (T ≈ 115 000 K)



Seismic modelling of high-amplitude δ Sct (HADS) stars pulsating in two radial modes:

*BP Pegasi, AE Ursa Majoris, and RV Arietis (Population I)

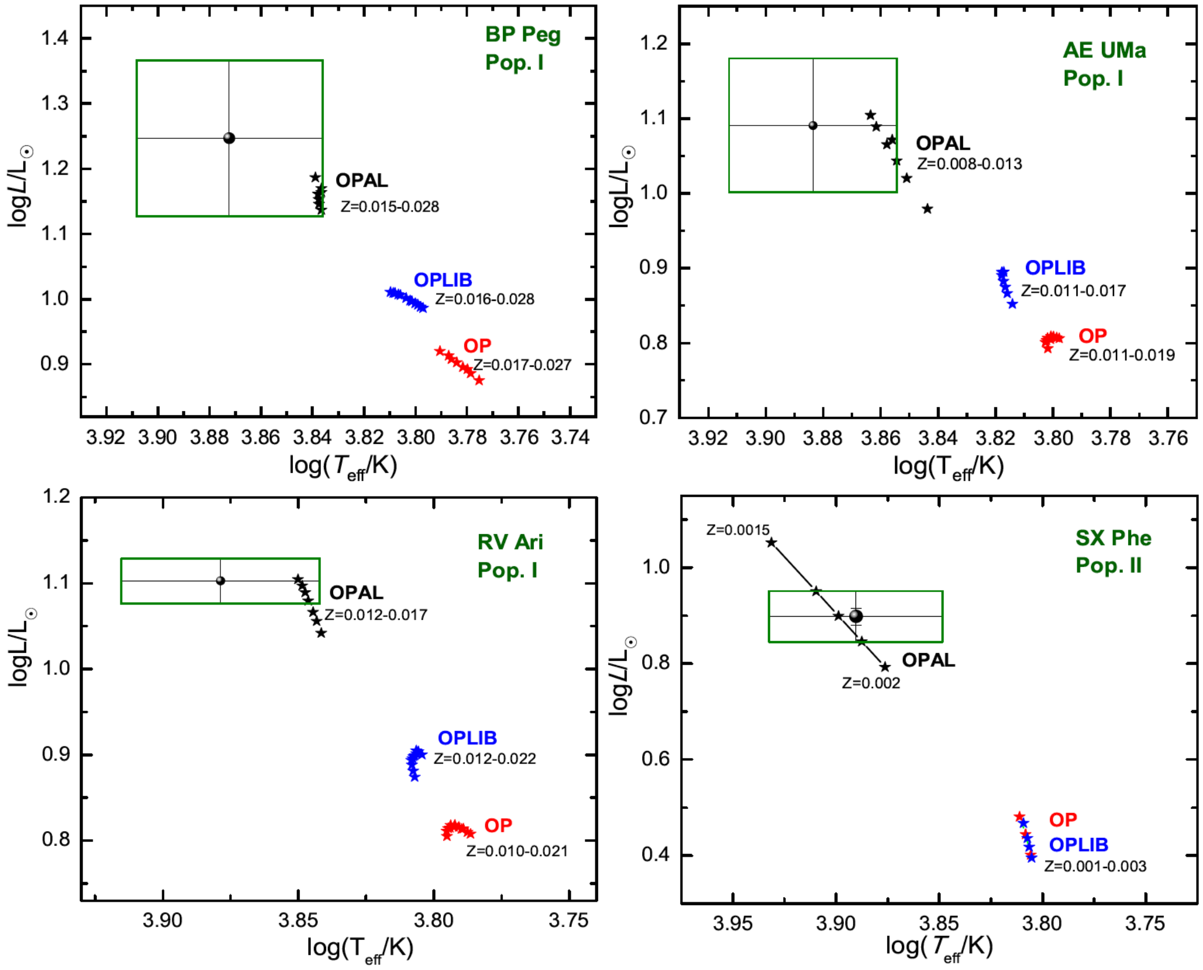
*SX Phoenicis (Population II)

All have multi-colour photometry (UVBY) → the parameter *f*

the Bayesian analysis based on Monte Carlo simulations

- mass M
- initial hydrogen abundance X_0
- metallicity Z,
- rotational velocity $V_{\mathrm{rot},0}$
- overshooting from the convective core, α_{ov}
- efficiency of envelope convection, α_{MLT}

Seismic models on HRD computed with three opacity tables: OPAL, OP and OPLIB



ONLY OPAL SEISMIC MODELS HAVE ($T_{\rm eff}$, L) WITHIN THE OBSERVED ERROR BOX

?

Such a huge effect of opacity also can occur for classical Cepheids or RR Lyr stars that are used as standard candles to measure distances.

ROTATION

- deforms the star from spherical symmetry
- causes a higher polar than equatorial flux (gravity darkening)
- induces various instabilities and mixing in the stellar interior

- affects pulsations:
  - p modes -- the centrifugal force
  - g modes -- the Coriolis force

Stellar rotation – rotational splitting of modes

$\omega_{n\ell m} = \omega_{n\ell 0} + m\Omega$, if $\Omega = \mathrm{const}$

$\Omega(r)$ – patterns in high-order g modes

$\Omega(r, \square)$

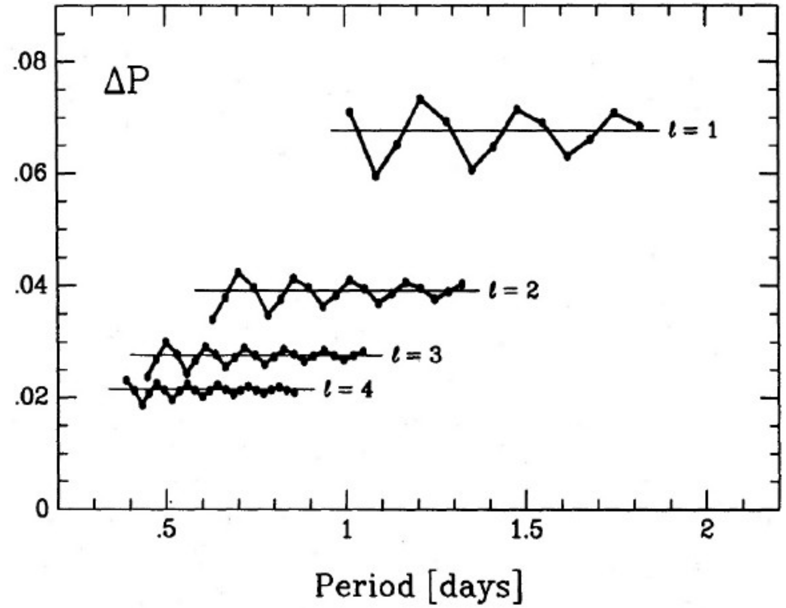
For high order gravity modes, asymptotic theory predicts some patterns in period spacing (quasi-equal period spacing if slow and solid rotation)

$$\Delta =$$

$$P_0 = 2\square^2$$

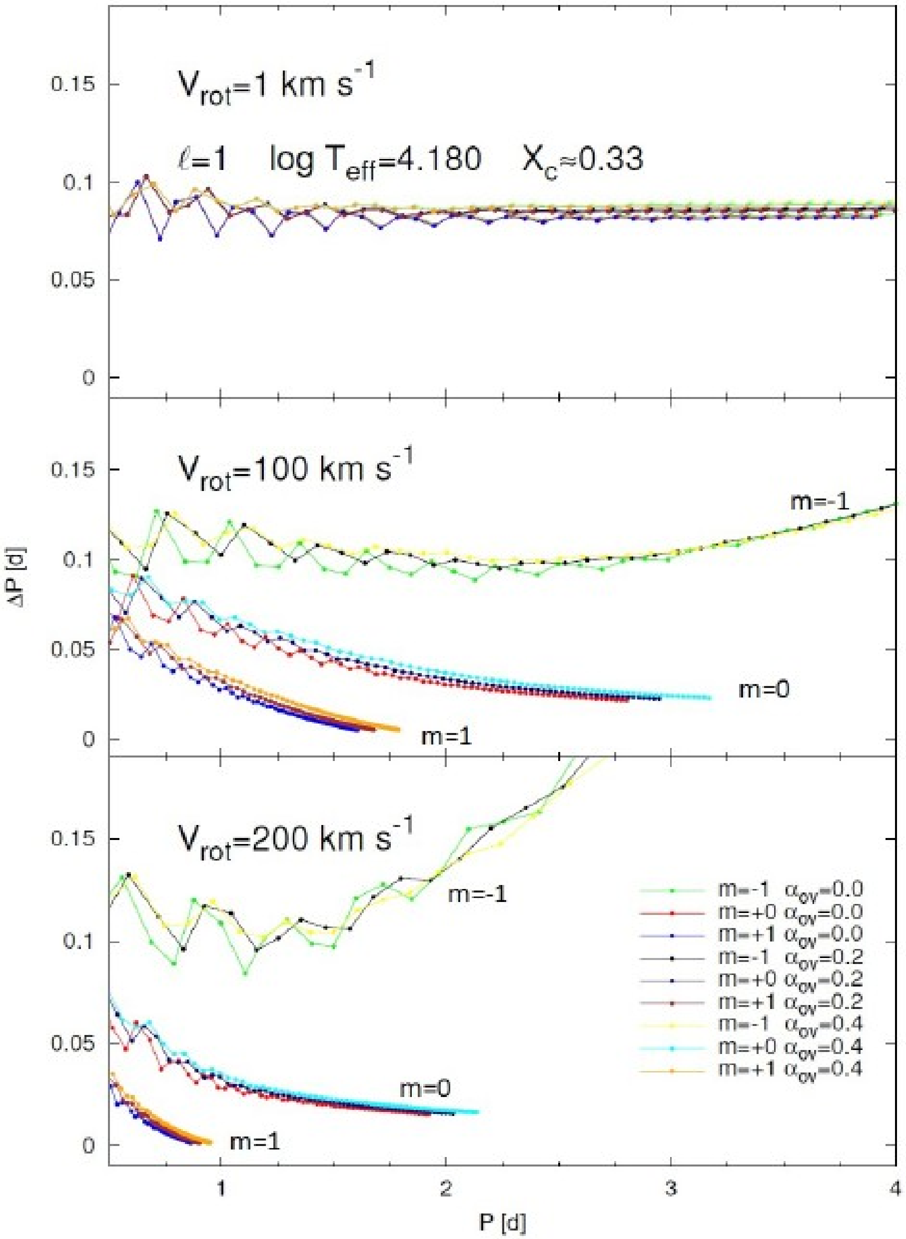
P_0 – the characteristic period

(the buoyancy travel time across the star)



- $M = 4\,M_\odot$
- $\log L/L_\odot = 2.51$
- $\log T_{\rm eff} = 4.142$
- $X_c = 0.37$

Dziembowski, Moskalik & Pamyatnykh, 1993

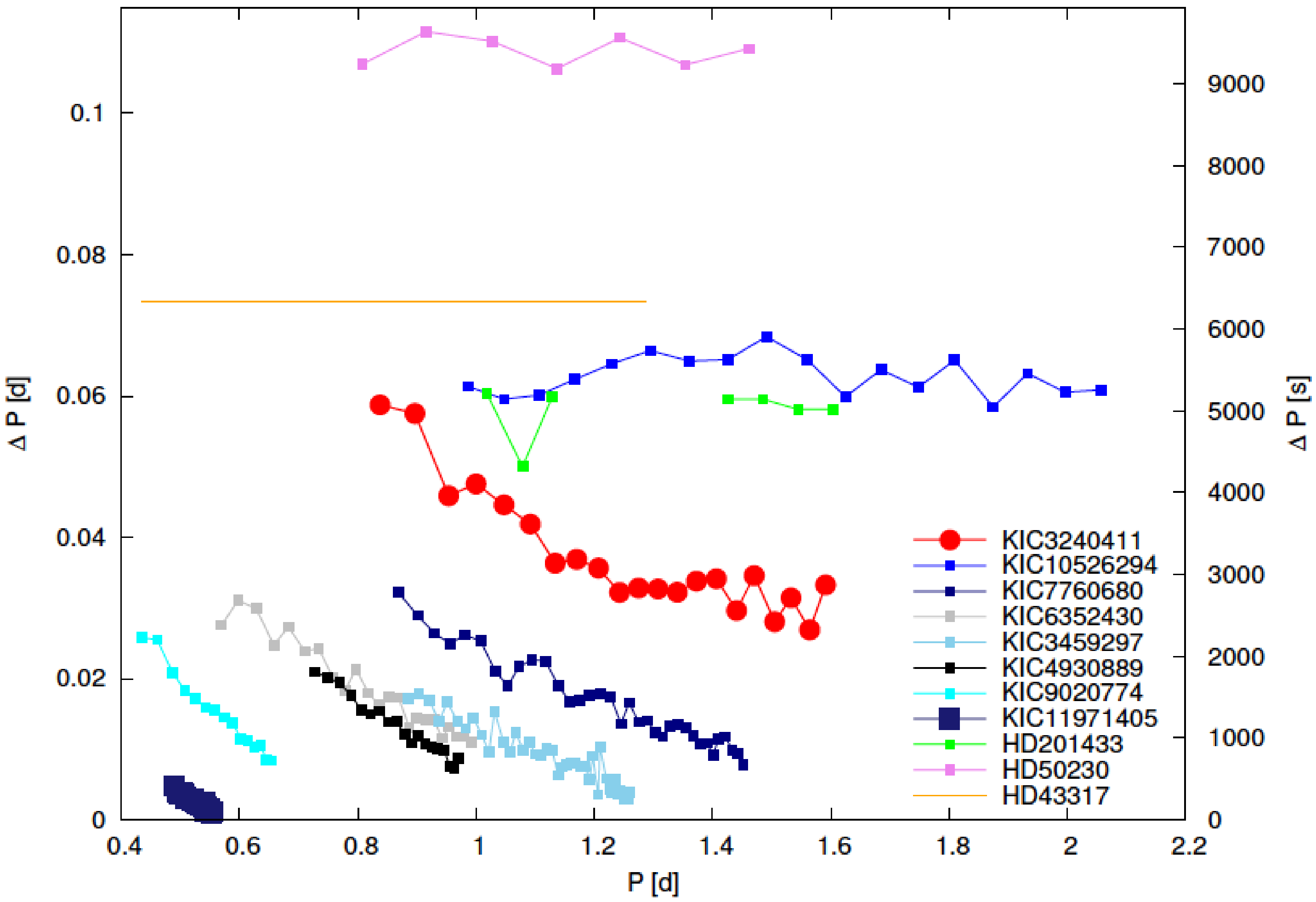


The effects of rotation included

- $M = 5\mathrm{M}_{\odot}$
- $\log T_{\mathrm{eff}} = 4.18$
- $X_{\mathrm{c}} = 0.33$

W. Szewczuk, PhD 2015

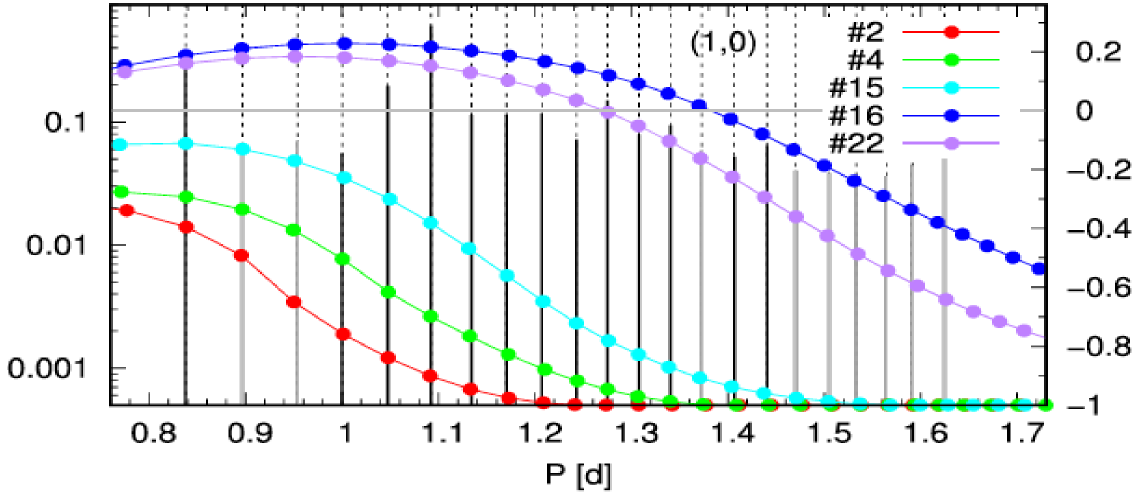
Period spacing for B-type stars obtained from Kepler data



Courtesy of W. Szewczuk

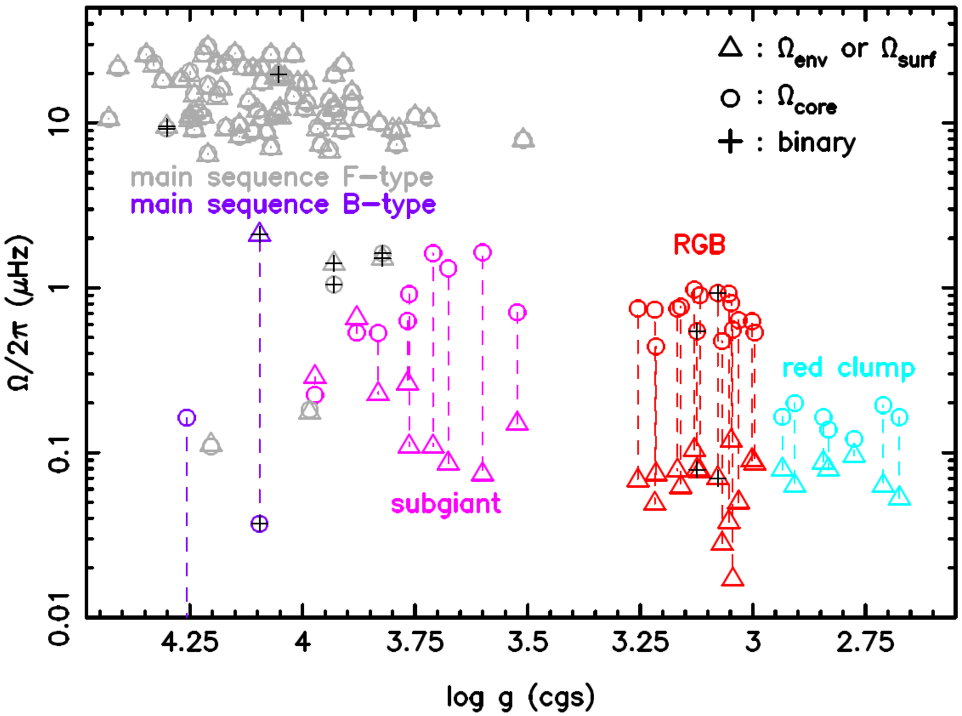
KIC 3240411 – the SPB star

High-order g-modes with ℓ=1, m=0



the rotation from fitting ΔP of g-modes: 160–180 km s^{-1}

the projected velocity from spectroscopy: V$_{rot}$ sini = 43(5) km s^{-1}
If the inclination angle is not far from 90° then the near-core rotation is about 4 times faster than the outer layers



- **Single stars with $M \in [0.8, 3.3]M_{\odot}$ rotate nearly uniformly during the H and He core burning**

- **cores rotate up to 10 faster than the envelope during the red giant phase Beck et al. 2012**

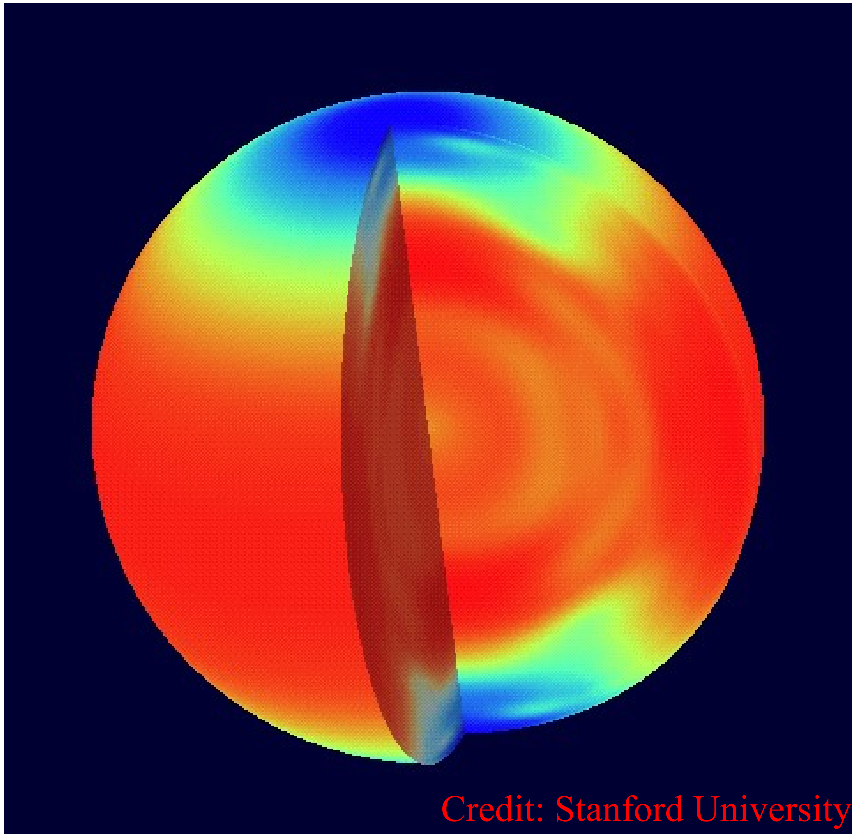
- **the angular momentum of the He-burning core of stars is in agreement with the angular momentum of white dwarfs Aerts, Mathis, Rogers, ARA&A, 2019**

Data of G. Li and J. Tayar
Figure by Aerts 2021

1) core rotation rates drop significantly between H to He core burning

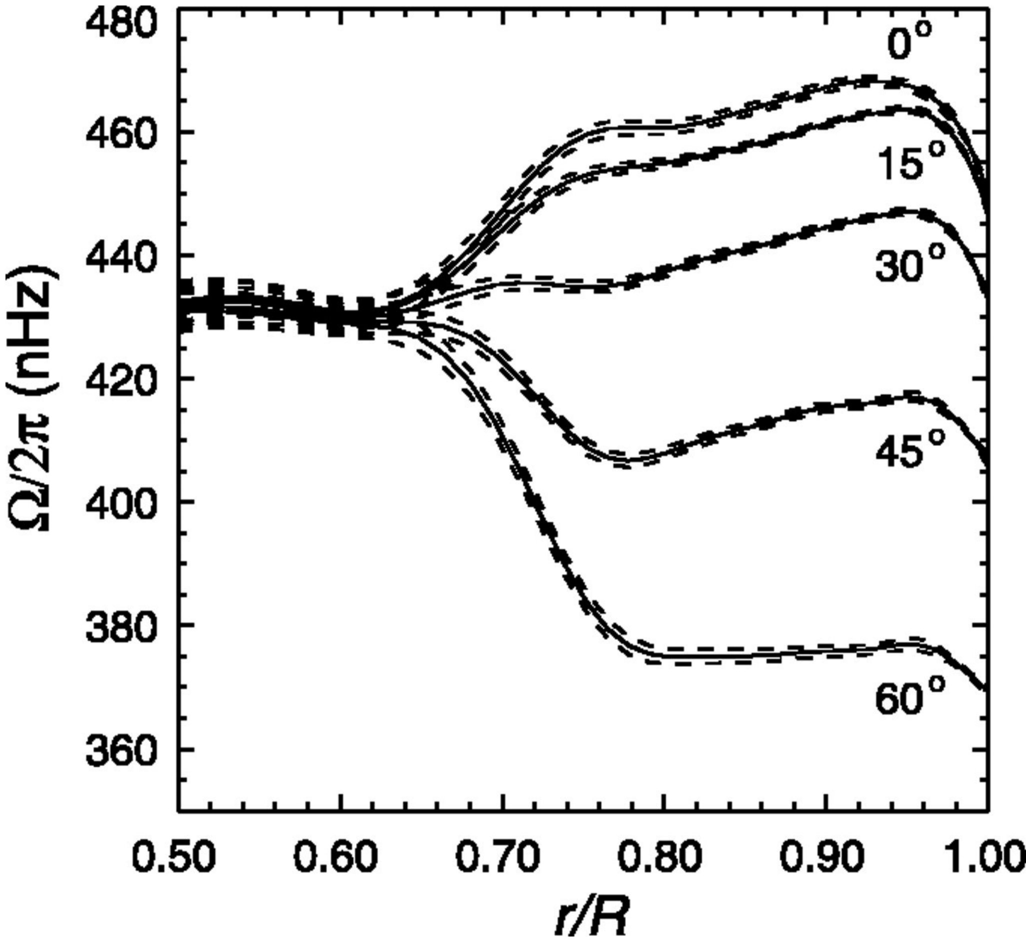
2) efficient mechanisms for the transport of interior angular momentum

The solar rotation from the splitting of the global oscillation frequencies (GONG, Global Oscillation Network Group)



Credit: Stanford University

red - the fastest rotation
dark blue - the slowest rotation



Howe et al. 2000

Nothing in asteroseismology yet competes with that results

CONVECTION

One of the largest sources of uncertainty in stellar models.

Mixing Length Theory (MLT): $l_m = \alpha_{MLT} \cdot H_p$

α_{MLT} **– free parameter**

H_p **- the local pressure scale height**

The usual practice is to assume that the solar mixing length applies to all stars.

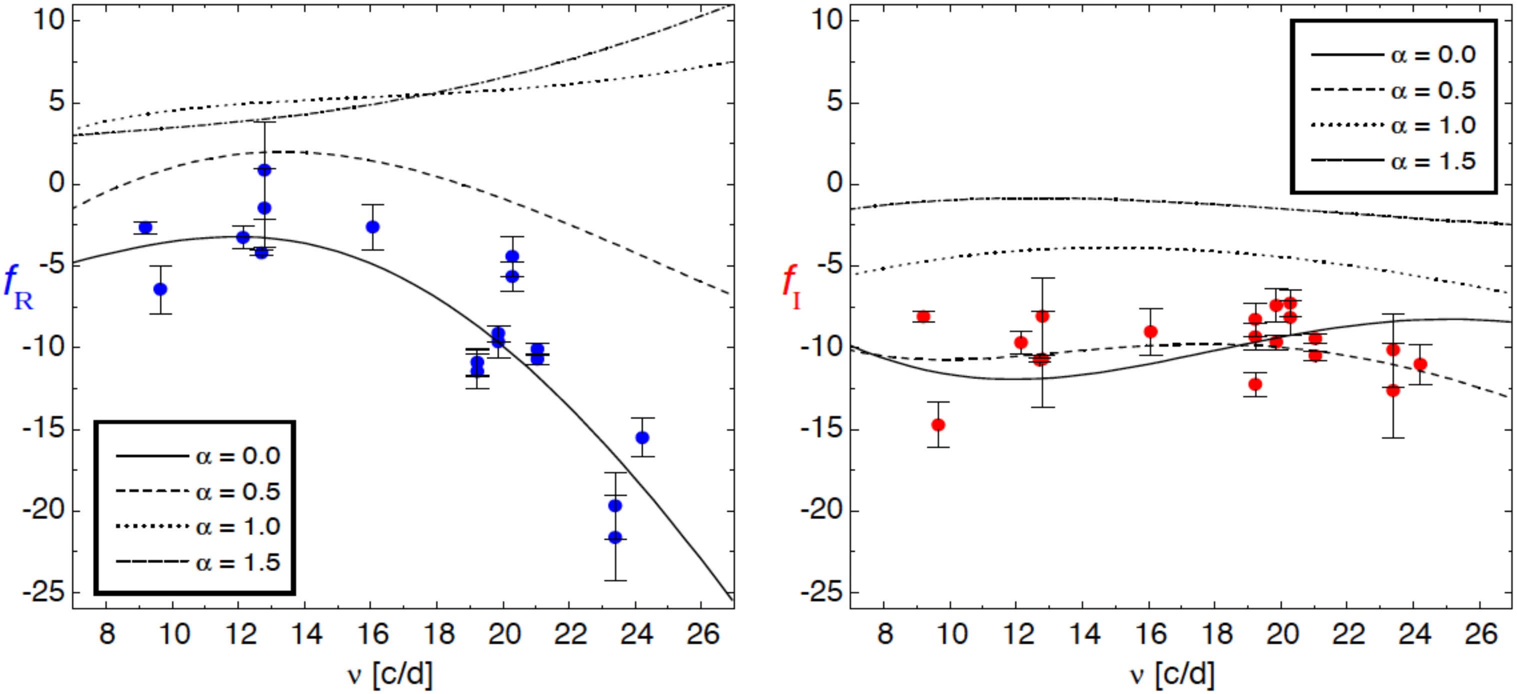
Constraints on convective energy transport in the envelopes of δ Scuti stars (AF-type)

The theoretical values of the parameter *f* are very sensitive to the efficiency of subphotospheric convection

FG Vir (A8/9V)

12 frequencies with mode identification and the empirical *f's*

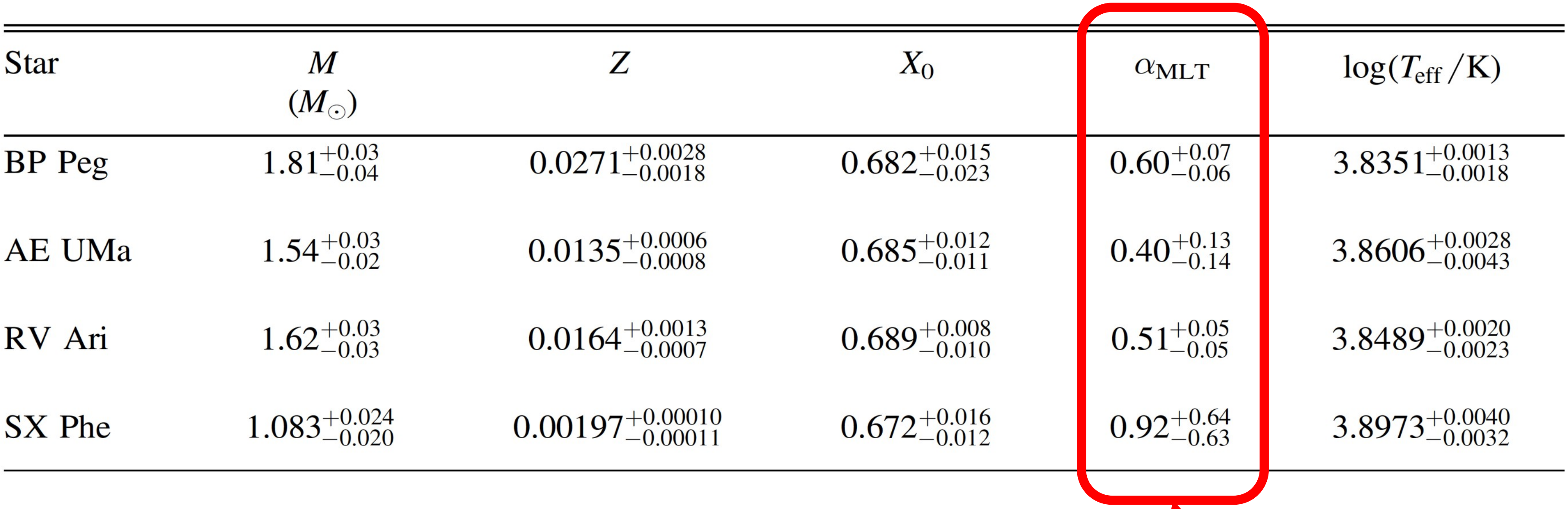
Comparison of the theoretical and empirical values of *f*



$\square_{\mathrm{MLT}} < 0.5$

HADS stars

The median values of the parameters from seismic modelling using the Bayesian analysis based on Monte Carlo simulations



Star	M $(M_\odot)$	Z	X_0	$\alpha_{\rm MLT}$	$\log(T_{\rm eff}/{\rm K})$
BP Peg	$1.81^{+0.03}_{-0.04}$	$0.0271^{+0.0028}_{-0.0018}$	$0.682^{+0.015}_{-0.023}$	$0.60^{+0.07}_{-0.06}$	$3.8351^{+0.0013}_{-0.0018}$
AE UMa	$1.54^{+0.03}_{-0.02}$	$0.0135^{+0.0006}_{-0.0008}$	$0.685^{+0.012}_{-0.011}$	$0.40^{+0.13}_{-0.14}$	$3.8606^{+0.0028}_{-0.0043}$
RV Ari	$1.62^{+0.03}_{-0.03}$	$0.0164^{+0.0013}_{-0.0007}$	$0.689^{+0.008}_{-0.010}$	$0.51^{+0.05}_{-0.05}$	$3.8489^{+0.0020}_{-0.0023}$
SX Phe	$1.083^{+0.024}_{-0.020}$	$0.00197^{+0.00010}_{-0.00011}$	$0.672^{+0.016}_{-0.012}$	$0.92^{+0.64}_{-0.63}$	$3.8973^{+0.0040}_{-0.0032}$

much below the solar value
=1.8

MIXING PROCESSES

- ✷ **Overshooting from the convective core (regions)**

- ✷ **atomic diffusion**

- ✷ **rotationally induced mixing**
  - **Dynamical Shear Instability**
  - **Solberg-Høiland Instability**
  - **Secular Shear Instability**
  - **Eddington-Sweet Circulation (meridional circulation)**
  - **Goldreich-Schubert-Fricke Instability**

CONVECTIVE OVERSHOOTING

convective elements pass the classical convective boundary because of their momentum,

Increases the main-sequence lifetime and alters the star's evolution

a size of the layer affected by overshooting from the convective core

$$d_{ov} = \alpha_{ov} \cdot H_p$$

α_{ov} - a free parameter that can be calibrated against observations

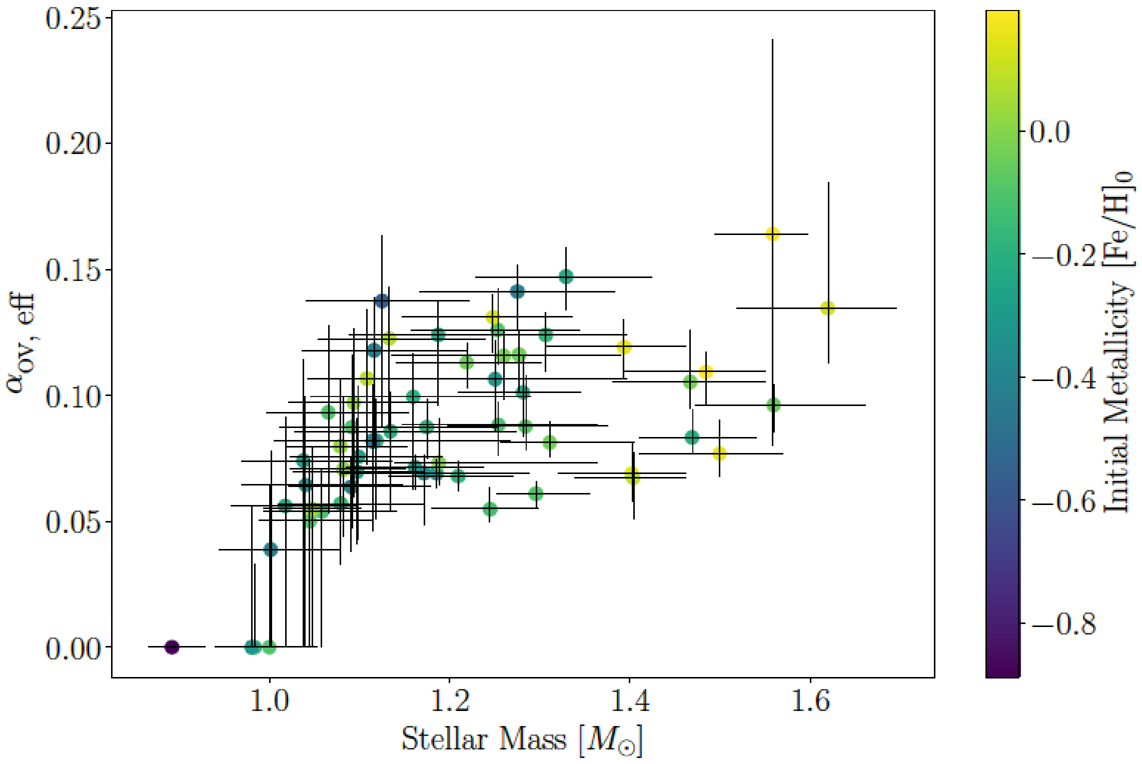
CONSTRAINTS ON OVERSHOOTING

□ Cep stars

ν Eri	$\alpha_{ov} \in (0.07, 0.16)$
12 Lac	$\alpha_{ov} \in (0.2, 0.5)$
γ Peg	$\alpha_{ov} \in (0.2, 0.3)$
θ Oph	$\alpha_{ov} \in (0.2, 0.3)$
κ Sco A	$\alpha_{ov} \approx 0.2$

SPB stars $\alpha_{ov} \in (0.05, 0.3)$

4 HADS stars $\alpha_{ov} < 0.1$ **(close to zero)**



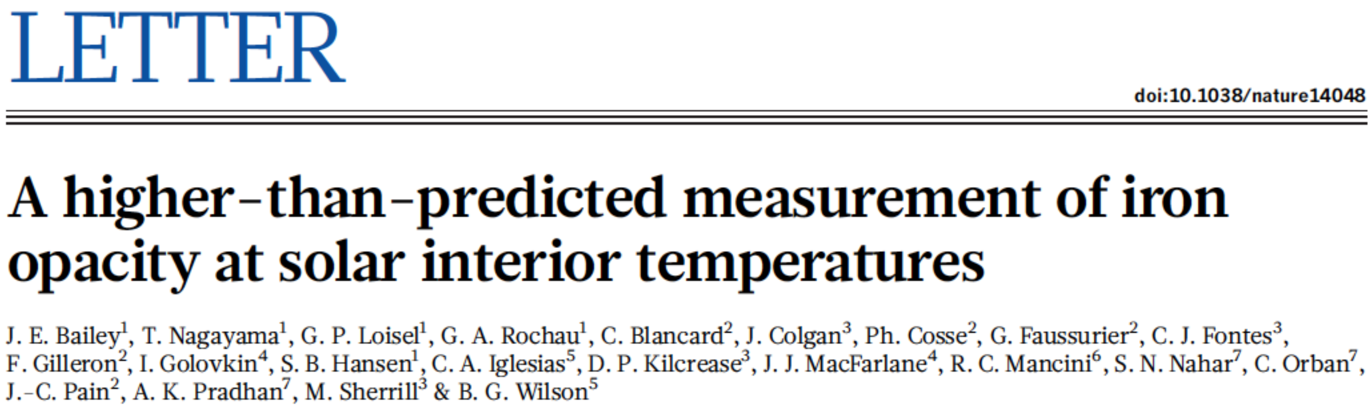
based on the seismic analysis
of solar-like oscillations
in subgiant stars
(Kepler, K2, TESS)
From frequency separations.

Lindsay, Ong, & Basu 2023

FUTURE GOALS

- ✶ mechanisms for the transport of interior angular momentum
- ✶ constraints on mixing processes
- ✶ a puzzling effect of opacity on seismic models
- ✶ asteroseismology with 2D rotating models
- ✶ constraints on binary evolution, mass transfer etc.
- ✶ tidal asteroseismology
- ✶ asteroseismology of exoplanet host stars
- ✶ asteroseismology with non-standard evolution, non-standard formation,
  (e.g., collision product, merger of stars in a binary system)
  Oscillating blue stragglers, Blue Large Amplitude Pulsators

Thank you !



LETTER

doi:10.1038/nature14048

A higher-than-predicted measurement of iron opacity at solar interior temperatures

J. E. Bailey[1], T. Nagayama[1], G. P. Loisel[1], G. A. Rochau[1], C. Blancard[2], J. Colgan[3], Ph. Cosse[2], G. Faussurier[2], C. J. Fontes[3], F. Gilleron[2], I. Golovkin[4], S. B. Hansen[1], C. A. Iglesias[5], D. P. Kilcrease[3], J. J. MacFarlane[4], R. C. Mancini[6], S. N. Nahar[7], C. Orban[7], J.-C. Pain[2], A. K. Pradhan[7], M. Sherrill[3] & B. G. Wilson[5]

Measurements of wavelength-resolved iron opacity at conditions very close to the radiation/convection zone boundary in the Sun.

The opacity is 30–400% higher than predicted by all codes.

Bailey et al. 2015
Pradhan & Nahar 2018
Zhao et al. 2018
Nagayama et al. 2019