Introduction to the session:

*Modelling frequencies: effects to consider*



# *Impact of some physical processes upon oscillation frequencies*

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→ Which physical processes do affect oscillation frequencies??

•p-mode frequencies depend on sound speed and its variation with radius

$$c_s^2 = \Gamma_1 P/\rho \sim T/\mu$$

•g-mode frequencies sensitive to Vaissala frequency and its variations

$N^2 \sim g^2$ (..(□$_{ad}$-□) +.. □$\mu$) (fully ionised medium)
evolution essentially =□$\mu$ (Christensen-Dalsgaard)

Criterium:

Physical processes must change sound speed or vaissala frequency.

They must be taken into account if associated *frequency changes* are large enough that they are detectable

either to study them or to put into light their pollution effects and make possible to remove them

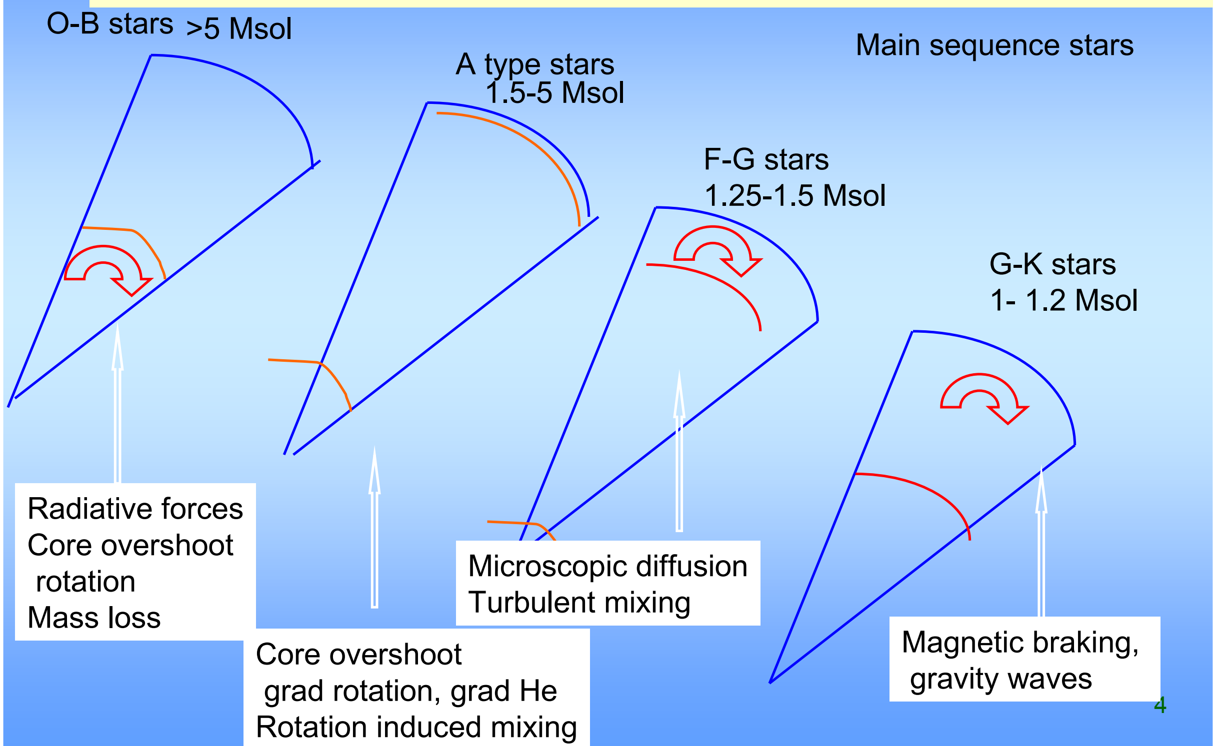
which means: detectable with the various seismic diagnostics which are availab

→ to what extent these effects are detectable? ($\Delta\nu$ > observational error; Corot)

→ Which seismic signature is most efficient ?



Physical processes acting on oscillaton frequencies and their magnitude are different depending on the type of star hence seismic diagnostics, and their efficienc are different as well



To assess effects of physical processes on oscillations frequencies, use of seismic diagnostics

→Direct comparisons between observed and theoretical frequencies

**Asymptotic modes**

→mean values of frequency (period) separations
→Seismic HR diagram (CD diagram)
and
→Oscillatory behavior due sharp variation of the sound speed (for p-modes) and Vaissala frequency for g-modes

→Echelle diagram for asymptotic p-modes
→ (equivalent for g modes in periods? )

**Other modes**

→Structure of power spectra and statistical studies for non asymptotic regime
→Depends on each specific case

SEISMIC SIGNATURES

Jargon des sismologues stellaires (seismic slung)

- Frequency differences :

$$\nu^{obs} - \nu^{model}$$

- Large (frequency) separations — mean large spacing

$$\Delta_{n,\ell} = \nu_{n,\ell} - \nu_{n-1,\ell} \qquad < \Delta_{n,\ell} >_n$$

sensitive to surface properties

- Small (frequency) separations

$$\delta_{n,02} = \nu_{n+1,\ell=0} - \nu_{n,\ell=2} \qquad < \delta_{n,\ell} >_n$$

probe inner regions but slightly sensitive to surface effects

- Scaled small (frequency) separations (Roxburgh, Vorontsov, 2001)

$$r_{n,02} = \frac{\delta_{n,02}}{\Delta_{n,1}} \qquad < r_{n,02} >_n$$

probe inner regions

- Small (frequency) spacing

$$d_{n,01} = 2\nu_{n,\ell} - (\nu_{n,\ell+1} + \nu_{n-1,\ell+1})$$

probe iiner regions

- Second (order) (frequency) differences (Gough, 1990; Monteiro et al 1994, 2000)

$$\delta_2 = \nu_{n+1,\ell} - 2\nu_{n,\ell} + \nu_{n-1,\ell}$$

detects local sharp variation of souns speed

- Higher orders (Mazumdar, Antia 2001)

Corot expected uncertainties for in dividual modes :

T= 150 days → 0.1 μHz for $\nu_{nl}$ → 0.5-1 μHz

•Large separation: 0.2 μHz → 1-2 μHz

•Small separation: 0.2 μHz → 1-2 μHz

•Second differences : 0.4 μHz → 1-4 μHz

•Small spacing : 0.4 μHz → 1-4 μHz

as widths of the modes add uncertainties

Better for mean values of course!

Asteroseismology: comparisons are made as differences between frequencies of
models with different input physics

→ for ***calibrated*** models ie at same location in the HR diagram (first level)

→for ***seismically calibrated*** models ie at same location in the HR diagram and same mean density
or mean large frequency separation
or mean (scaled) small spacing

One consequence: physical changes in outer layers translate into different evolutionary stages or mass
Hence changes in inner properties



Impact on oscillation frequencies due to

*Surface effects*

Frequencies are strongly dependent on surface effects
-- 1 Structure of the outer layers
-- 2 Nonadiabatic effects
-- 3 Turbulence in the outer layers

Inner properties : convective core and overshooting

Microscopic diffusion

Rotation

# *1.Structure of the outer layers*

Floranes et al 2005

Large separation for standard solar models and models with modified outer layers
For instance $\Gamma_1$ =5/3 kept constant
Strong change in ionisation regions in surface

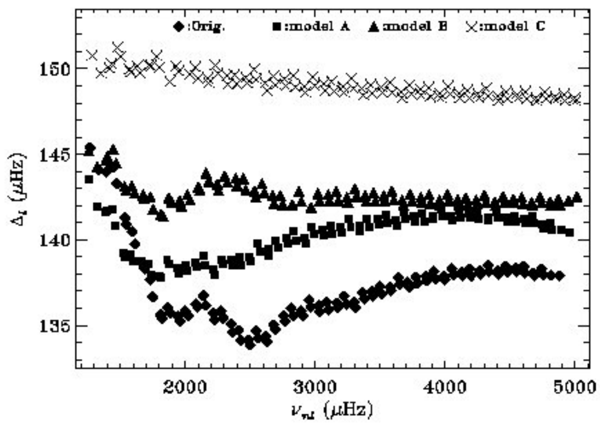


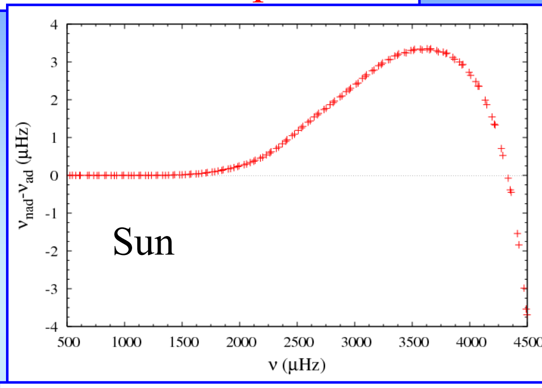

**Figure 2.** Large frequency separations $\Delta_l$, $l = 0, \ldots, 3$, as a function of mode frequency, for the standard solar model (Model S) and for the three modified models (A, B, C) as described in the text.

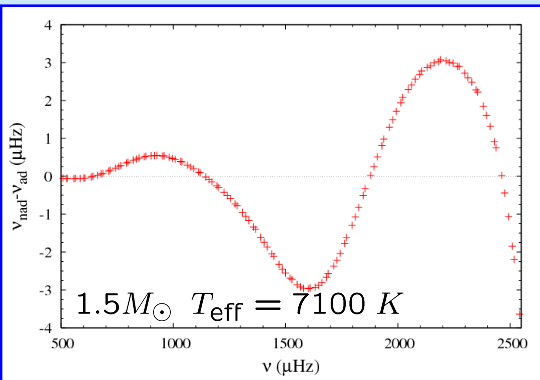


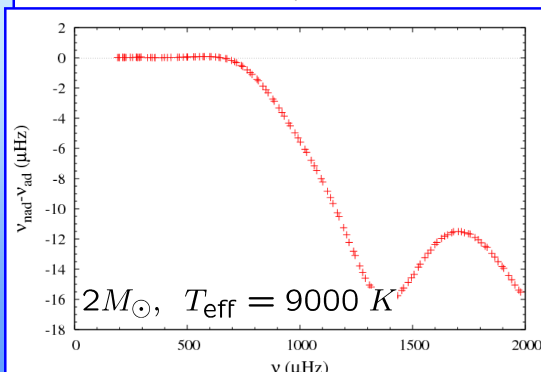
# *2.Non-adiabatic effects on the frequencies*

Comparison : adiabatic – nonadiabatic frequencies

$\nu_{\mathrm{non-ad}} - \nu_{\mathrm{ad}} \quad (\mu\mathrm{Hz})$



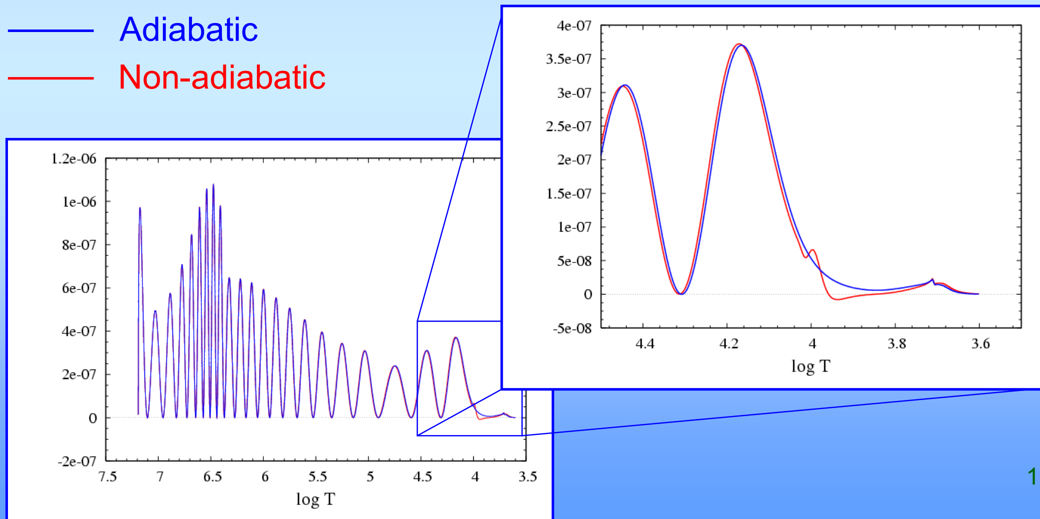
## Nonadiabatic effects : integral expression

$$\sigma^2 = \frac{\int \frac{\delta P}{\rho}\frac{\delta \rho^*}{\rho}\frac{dm}{d\log T}\, d\log T - \int \frac{4g}{r}|\delta r|^2 \frac{dm}{d\log T}\, d\log T}{\int |\delta r|^2 \frac{dm}{d\log T}\, d\log T}$$

Sun , $p_{22}$

Adiabatic

Non-adiabatic

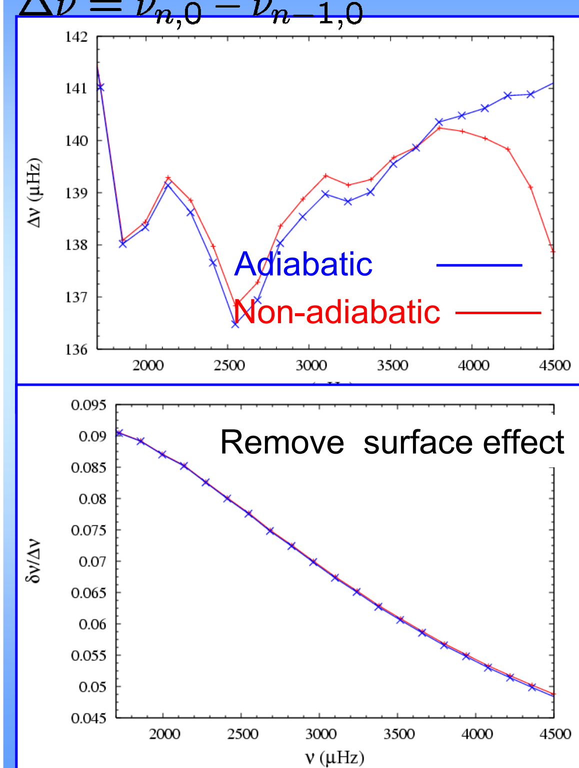





## Nonadiabatic effects : separations

Sun , $p_{22}$

$\Delta\nu = \nu_{n,0} - \nu_{n-1,0}$




Miglio, Montalban 2005

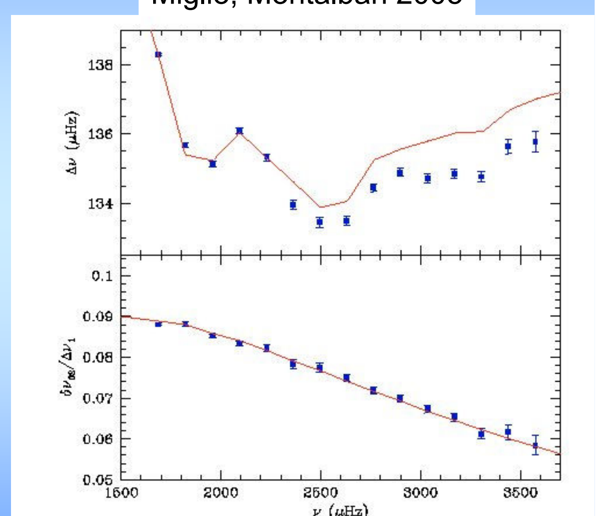
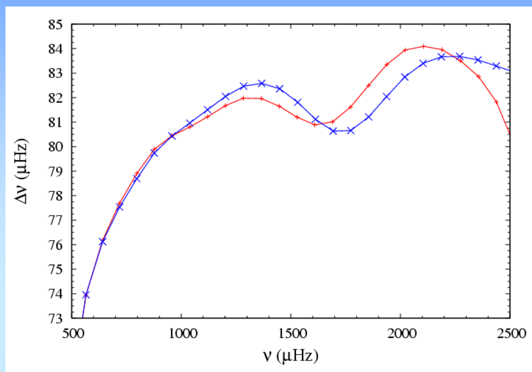
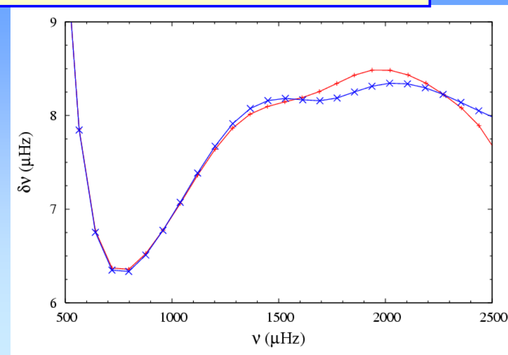
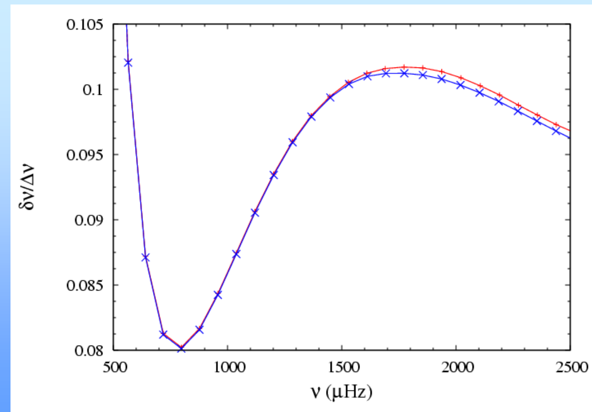


**Fig. 1.** Solar large frequency difference $\Delta\nu_{n,1}$ (*upper panel*) from standard seismic solar model S96 (Christensen-Dalsgaard et al. 1996) (solid line), compared to the observational solar large separation (dots) (Basu et al. 1997). *Lower panel*: as upper panel but for the ratio $r_{02}$.

# Nonadiabatic effects : separations



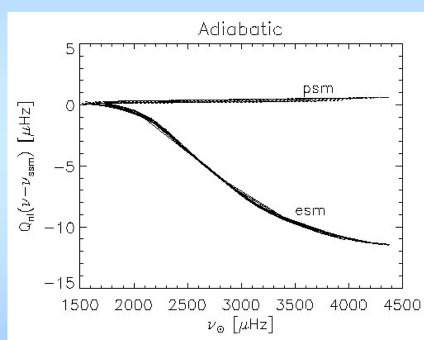




Nonadiabatic effects stronger for higher masses
 Exemple: 2Msol
Small nonadiabatic effects
Subsist  for r02

# 3. *Turbulence in the outer layers*

Inclusion of turbulence of outer layers  into 1 D models from 3D simulations : *patched* models

Sun → Rosenthal et al 1999
Li et al 2002




Scaled frequency differences between MLT models and patched models  Li et al 2002
Differences in scaled frequencies between models and solar observations ~ 5-10 muHz at 3mHz

Straka et al 2006

Sensitive to the turbulent kinetic energy

Red : models with turbulence
Green no turbulence

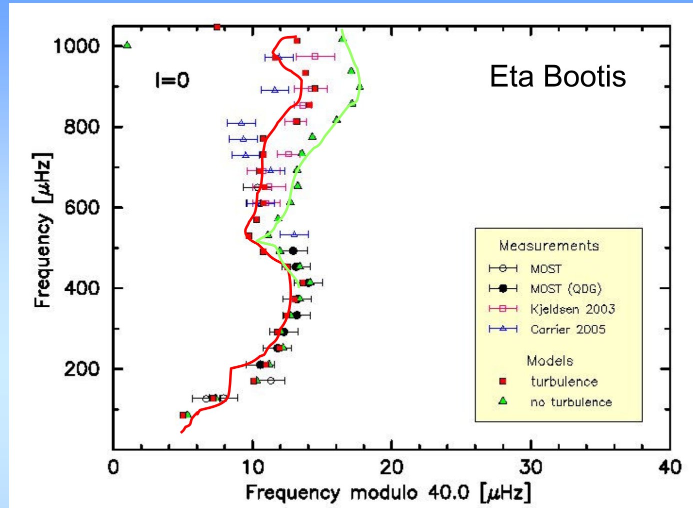



**Fig. 3.** Echelle diagram showing the non-adiabatic *p*-mode frequencies derived from a best-fit theoretical model without turbulence (triangles) in comparison to a model with turbulence (squares) on top of the ground and space based observational measure-



# Removing surface effect:

The scaled small separation r02 is rather insensitive to outer layers and sensitive to inner properties → convective core overshooting
(Roxburgh, Voronstov, 2003,2004; Roxburgh 2006)

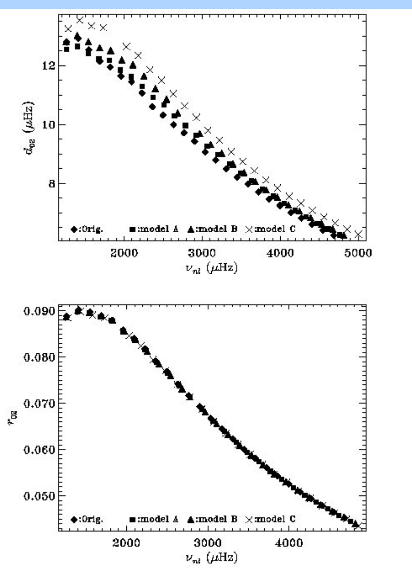



**Figure 4.** Upper panel: small frequency separation $d_{02}$ as a function of mode frequency for the same four 1-$M_{\odot}$ models illustrated in Fig. 2. Lower panel: as for upper panel, but showing the scaled small separation $r_{02}$.

Floranes et al 2004

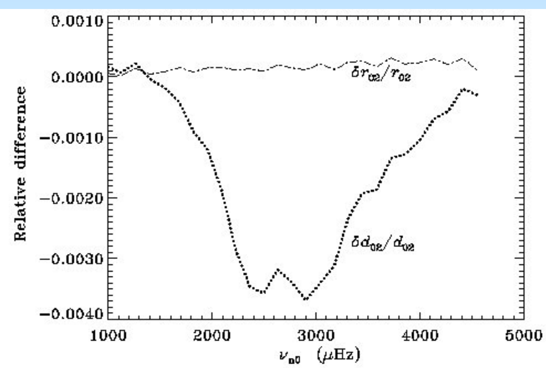
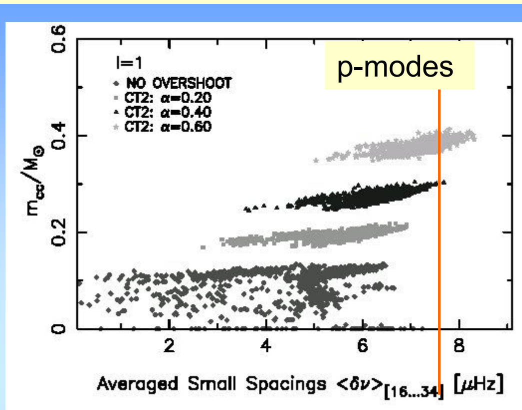



**Figure 10.** Upper panel: large frequency separations $\Delta_1$ in a standard solar model (solid curve) and a model constructed using the CM treatment of convection (dashed curve). Lower panel: the relative difference between the small separation $d_{02}$ in the sense of CM model minus standard model (dotted curve), and the corresponding relative difference between the separation ratio $r_{02}$ between the two models (dot–dashed curve).

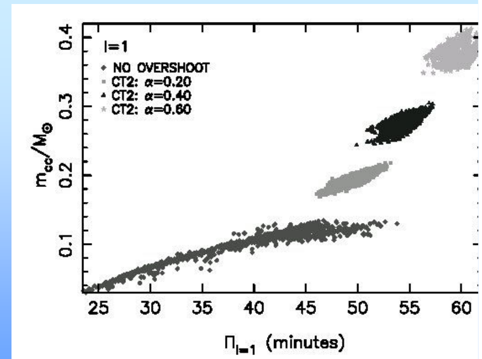
## 3 Existence of convective core and amount of overshooting

(Straka et al 2005)




Each dot = average small spacing for a possible model for Procyon A 1.4-1.5 Msol

Quasi one-to-one relation




g-modes

- $<\delta\nu>$ < 2 mHz: no overshoot, size of convective core between 0 and 0.1 Msol (r02, r01 ?)
- $<\delta\nu>$ > 7 mHz large overshoot, large convective core
- In between ?

Open issue : testing different descriptions?



## •Detection of a convective core : illustration alpha Cen A

(Miglio, Montalban 2005)

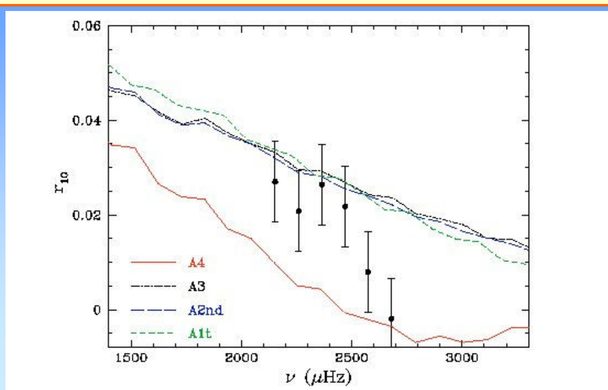



**Fig. 8.** $r_{10}(n)$ ratios for A component. Points represent the observational values with their error bars assuming an error in frequencies equal to $2\sigma$. Short-dashed line corresponds to the model calibrated

$r_{01}$ best seimic signature

A4 : with overshooting, with microscopic diffusion
A3 no overshooting, no microscopic diffusion
A1: no overshooting, microscopic diffusion

•Planet hosting stars : μ Arae : seismic signature to discriminate between Model with surface Z enrichmernt or or built from an enriched Z environment

Summary: efficiency of seismic signatures
for existence of convective core
for assessing size of mixed region
still not clear for p-modes
Need to learn how to disentangle overshooting from other effects in seismic signatures

Open issue:
More realistic prescriptions for core overshooting (plumes, 3D,…) to be implemented in models and tested with seismic signatures



# *Microscopic diffusion*

# Element diffusion in solar type stars

(Theado et al 2005)

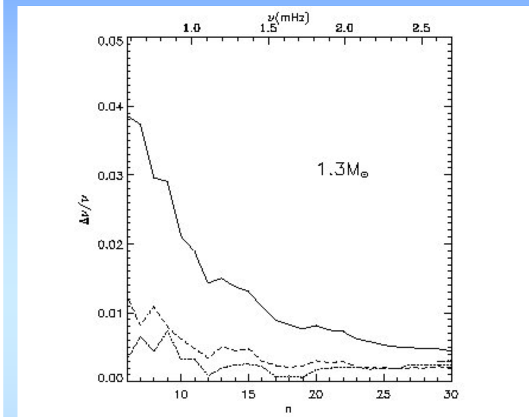
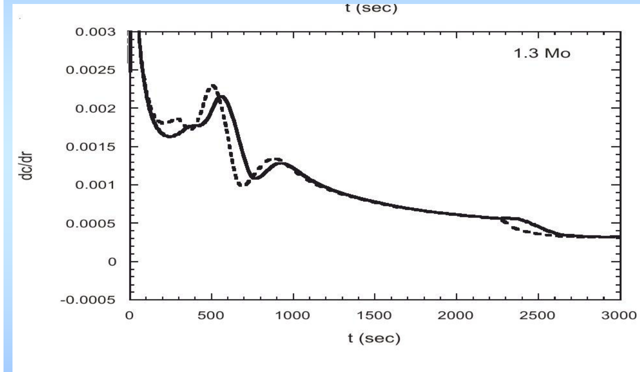



**Fig. 7.** Comparison between oscillation frequencies of 1.3 $M_\odot$ models with (M3-dif) and without microscopic diffusion (M3-hom) (at =2.320 Gyrs): $\Delta\nu/\nu = (\nu_{\rm diff} - \nu_{\rm hom})/\nu_{\rm hom}$. Solid curve: $l = 0$, dashed curve: $l = 1$, dotted curve: $l = 2$.

Difference in sound speed
between model with and without diffusion




As models are calibrated, the convective zone is deeper for the model with diffusion

1.3 Msol calibrated model
5-20 μHz
Less for lower masses



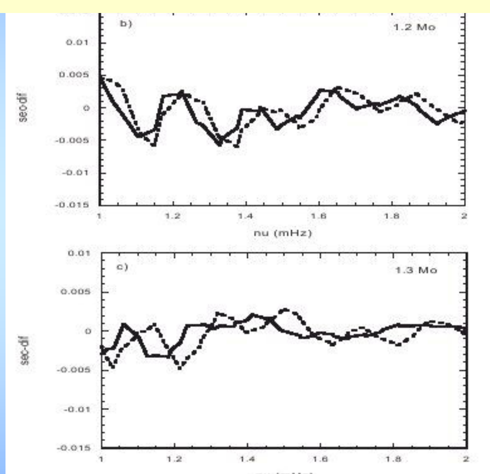
*Second differences*:

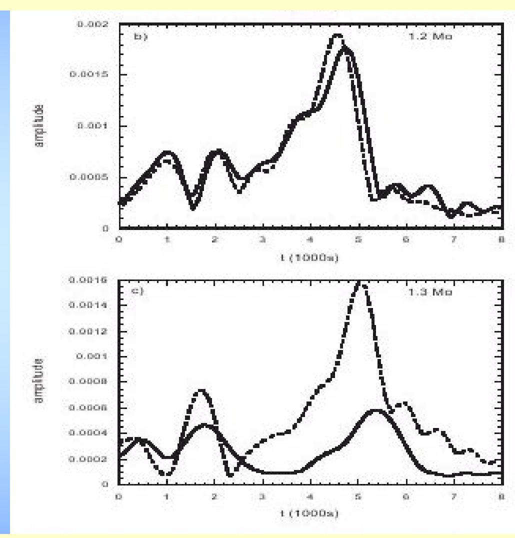
Solid line = with diffusion
Dashed line without diffusion

Signature of helium gradient
of the order of 1-4 muHz

Sharp variation of sound speed: oscillation in second differences (Monteiro et al 1994)

(Theado et al 2005)

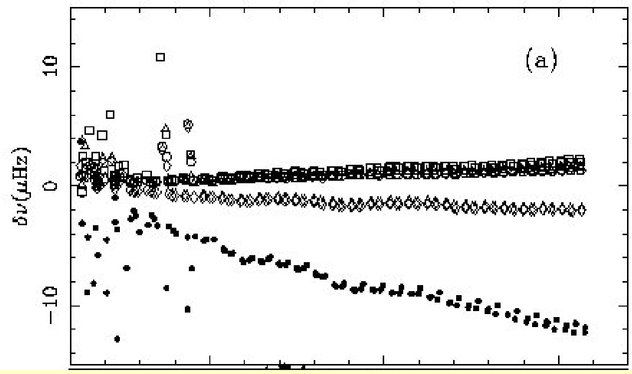



Effect is best seen with the Fourier transform of the second difference which also provides the location of the helium gradient

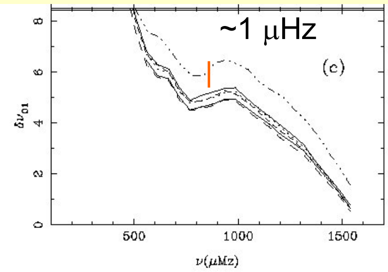
Effect of microscopic diffusion on asteroseismic properties of intermediate-mass stars

(Provost et al 2005)




$r_{01}$ best seismic signature
But affected by other effects
Outer convection: mixing length
Core overshoot, surface Z

$r_{01}$




Model without diffusion
Other models with different prescriptions for the microscopic diffusion from different authors (Michaud, Profitt or Burgers)

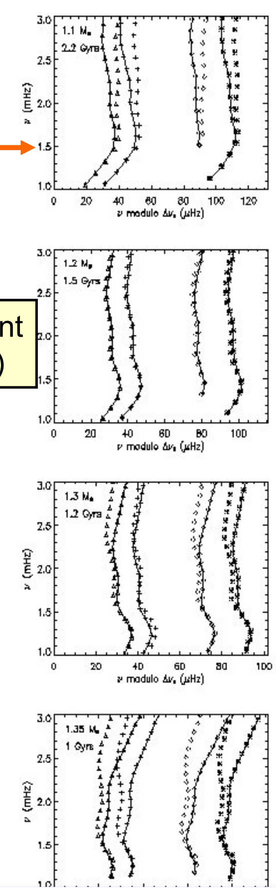
'*The effect of microscopic diffusion and core overshooting can be disantengled only at intermediate frequency*'

Dash dotted curves : without diffusion

~1.5 Msol



Signature of helium gradient in late F-type stars:
changes in the upper part of echelle diagram (Castro et al 2006)




Second differences as efficient seismic signatures of helium gradient below the convection zone of A type stars (Vauclair, Theado 2004)

Helium settling and mass loss in magnetic Ap stars:
Theado et al 2005

Pop II stars: Richard et al 2006

Summary: Detecting element stratification for solar-type stars with second differences will be possible, however marginally in practice due to pollution by noise
Seismic signatures expected to be larger in hotter stars ie with thiner outer convective zones (A-type stars).
Efficient seismic diagnostic is r01

For hotter stars, the radiative acceleration on metals can lead to metal accumulation in specific layers (Richard et al, Alecian et al) .

This can have an influence on excitation of the modes (Bourge et al 2006)
Whether it is possible to localize these inhomogeneiteies is an open issue ?

Open issue Detecting overshoot below convective envelopes of solar type stars (Monteiro et al 1994) using *second differences*
Possible if for stars other than the Sun, the overshoot region happens to be larger

Is it the case ?



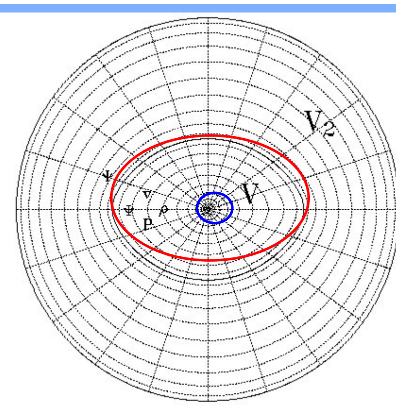
# ROTATION

(Lignieres et al 2006, Reese et al 2006)

Direct effect on the oscillations frequencies :

Centrifugal force : shape of the resonant mode cavity

Coriolis force : 'Doppler effect'




Indirect effect:

through the equilibrium model
Centrifugal distorsion induces thermal desequilibrium which drive meridional circulation
With anisotropic turbulence, the net effect is :
Rotation induced mixing and transport of angular momentum

through interaction convection-rotation : extension of convective core

## Rotation induced mixing:

(Zahn, 1992; Maeder, Zahn 1998; Mathis, Palacios,Zahn 2004)

βVirginis : 1.3 Msol main sequence
β star,  shows solar like oscillations
Modelling including rotationally induced mixing, (Eggenberger et al 2006) :

Effect on $\omega_0$ is small as rotation velocity for this star is small
Observed surface rotational velocity  v ~ 3-7 km/s

Processus not efficient enough to impose solid body rotation
$\Omega_c/\Omega_{surf}$ ~3.12
then Ω gradient ought to be detectable with rotational splitting
Mean value of splitting smaller than
 if  Ω uniform    (see also Suarez )

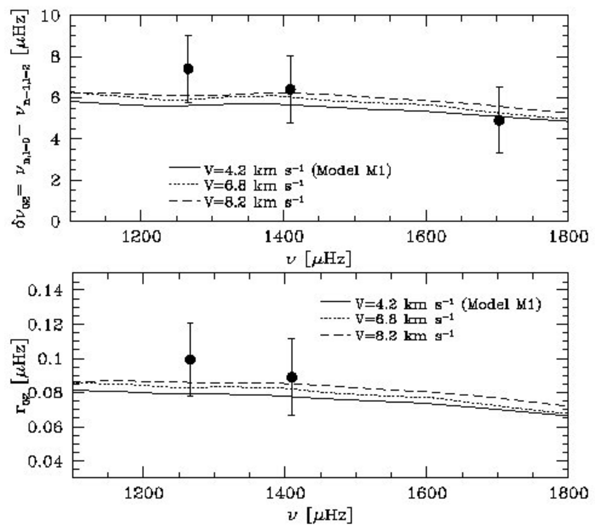



**Fig. 8.** Small spacing $\delta\nu_{02}$ and ratio of small to large separation $r_{02} \equiv \delta\nu_{02}/\Delta\nu_{n,\ell=1}$ as a function of frequency for models with the same value of the mean large spacing (72.1 μHz) but different surface velocities $V$. Apart from the initial value of the rotational velocity, the models have been computed with the same initial parameters as the M 1 model. Dots indicate the observed values.

Has a 1.3 Msol a solid body rotation a
hence an additional efficient mechanism is at work?

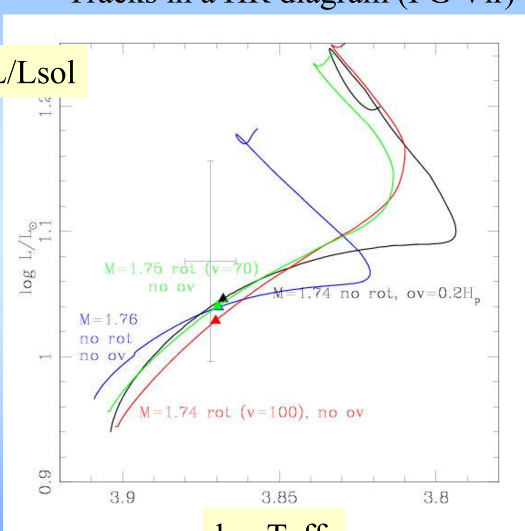


## Effects of rotationally induced mixing  on structure:1.7 Msol

From Zahn 92;  Talon, Zahn 97 and many other works  since then

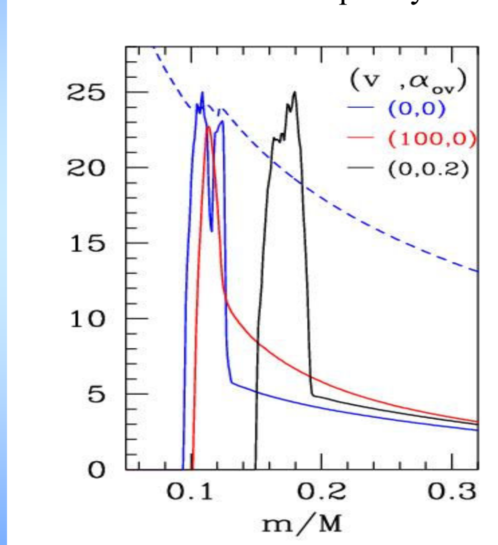
Tracks in a HR diagram (FG Vir)

log L/Lsol




log Teff

Vaissala frequency



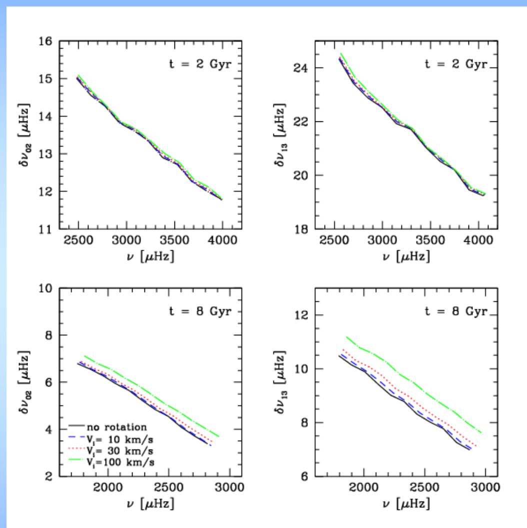

convective core

implemented in  ev. codes; comparison between STAREVOLV, CESAM going on

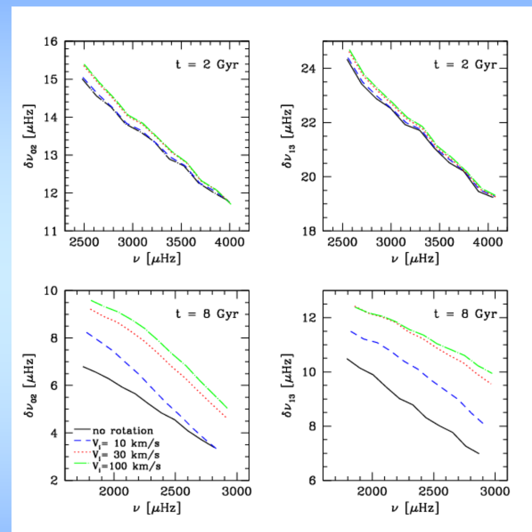
# Asteroseismic effect due to a dynamical processes: the case of the horizontal turbulence

**Eggenberger, PhD Thesis**

From Stephane Mathis 's talk




$D_h$ Zahn 1992




$D_h$ Maeder 2003

→ New prescriptions for the horizontal transport increase transport and mixing and thus the rotational effects on frequencies



Centrifugal distortion induces frequency shifts compared to Ω=0 values which are n, l dependent

For given $(n, \ell, m)$ mode:

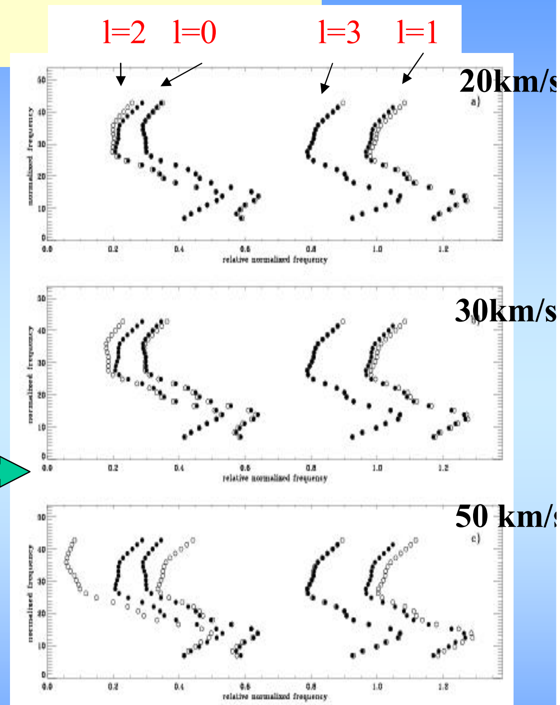
$$\nu = \nu_0 + \frac{\Omega}{2\pi} C + (\frac{\Omega}{2\pi})^2 (D_0 + m^2 D_1)....$$

Rotationally induded mixing

Splitting: slow rotators: Sun, beta Virginis
Coriolis effect

Moderation rotation: shifts of frequencies JC Suarez's talk
Centrifugal distortion

Moderate $\Omega$: frequencies of l=0 and l=2 are shifted depending on n,l
Consequences
on small separation and echelle diagram




FGK stars : slow rotators

but excited modes = high frequency modes

ie small inertia,

more sensitive to surface properties and rotation more efficient in surface

- small separation $\nu_a$-$\nu_b$ affected by $\Omega$ degeneracy

then echelle diagram affected

Black dots $\Omega$=0
Open dots $\Omega$ = 20, 30, 50 km/s

From Lochard et al 2006

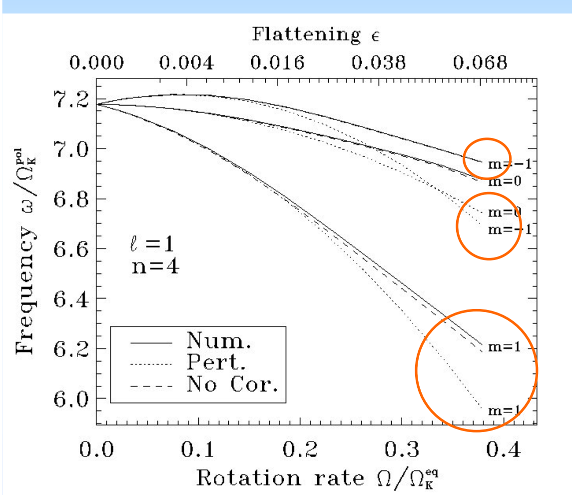
1

Rapid rotation (Lignieres et al 2006, Reese et al 2006)

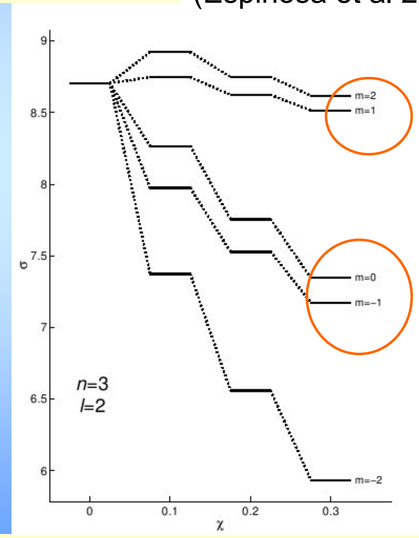
Sofar on 2 D polytrope models

Nonperturbative approach : expansion on spherical harmonics and Chebichev polynomials for the equilibrium and perturbed quantities

*Structure of a multiplet is quite modified for fast rotators*



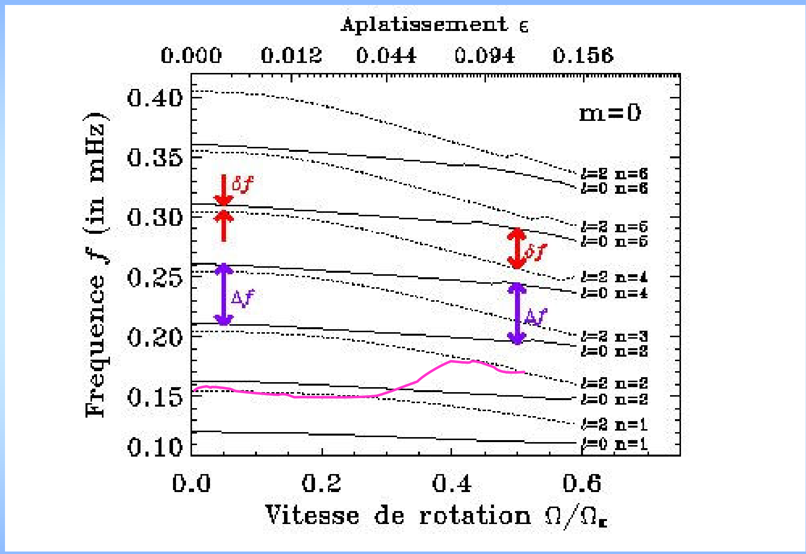

(Espinosa et al 2004)




Modes appearing by pairs as observed (E. Michel, 1996; Breger et al 2004)

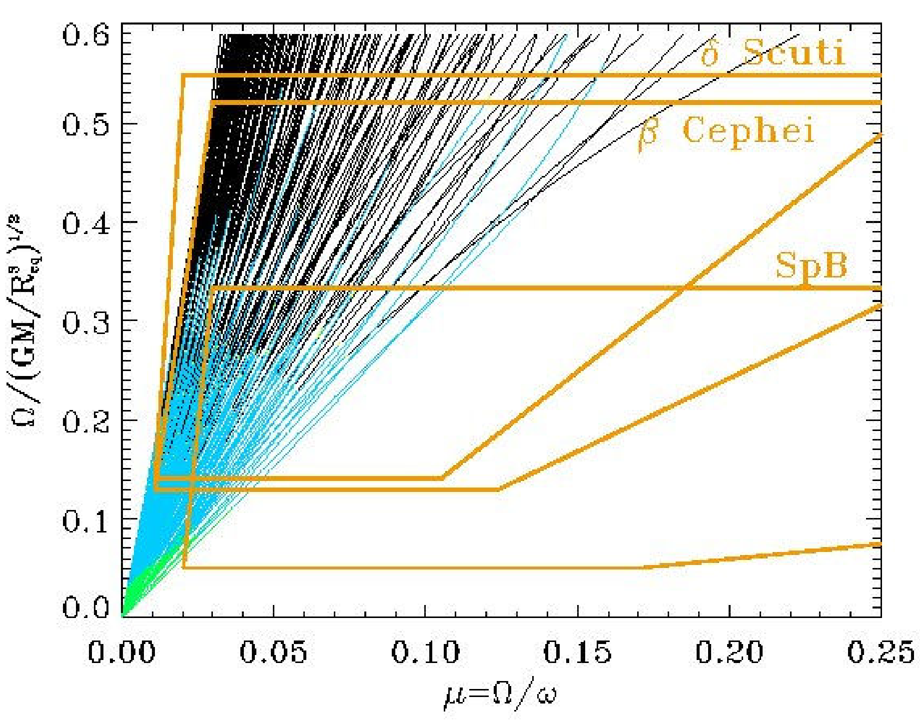
Evolution of the frequency pattern with the rotation rate

Some equidistance are conserved : Large and 'small' separation subsist






Validity domains : green = first order
bleu = second order ; black perturbation no longer valid



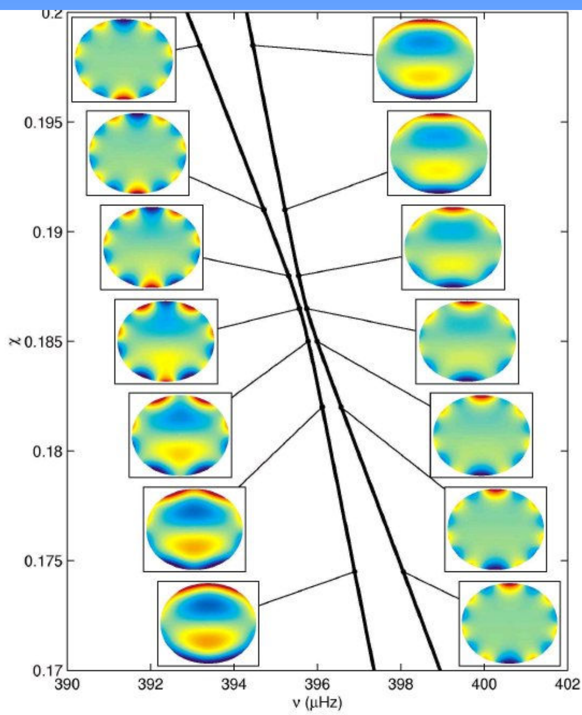



*Figure 3. Avoided crossing between the modes n = 0, l = 7, m = 0 and n = 1, l = 1, m = 0. Both modes are seriously affected by coupling, interchanging their properties after the crossing.*

Avoided crossing: Espinosa et al 2004



# Open issues

## 1. Initial conditions and PMS

Marques et al 2004 : Just before arriving onto the ZAMS, loop in a HR diagram for a 2Msol in presence of a significant convective core

Marques et al 2006 implementation of mass accretion 'a la Palla, Stahler' into Cesam code : differences in structure near the birthline for masses > 3.5 Msol. This is particularly important for masses > 6-7 Msol

Talon et al 2006 : for intermediate mass stars, Eddington-Sweet time scale (asymptotic rotation profile) is smaller than MS lifetime for fast rotators (100 km/s , 1.7 Msol; He decrease of 10% over 0.1 Gyr)

For slower rotators, 30 km/s, tau_ED ~ tau_MS and *'rotation evolution on PMS can have an impact on the magnitude of turbulent diffusion on MS'*

## 2. Rotation

In outer convection zones, differential rotation 0.04 μHz (Bonnanno et al 2006)
Rotating Convective core : disentangling rotation and overshoot (Browning et al 2004) ?

## 3. Gravity waves

Angular momentum transport by internal gravity waves :
Is β Virginis (1.3 Msol) and star-like rotating uniformly in their radiative zone?
Transport of chemicals by waves, seismic consequences?

## 4. Magnetic field

seismic consequences of multipole magnetic structure ? (Mathis, Zahn 2006)
Daniel Reese's talk

… and mass loss and accretion….

….and even more …. as one must remember :

frequencies are sensitive to stellar input physics but eigenfunctions are even more (variational principle)

important for Amplitudes and linewidths

and

2D rotating models ESTER (Rieutord); Roxburgh 2005, 2006



# Fin

## To built a seimic model, fit the small separation

from Lochard et al 2006

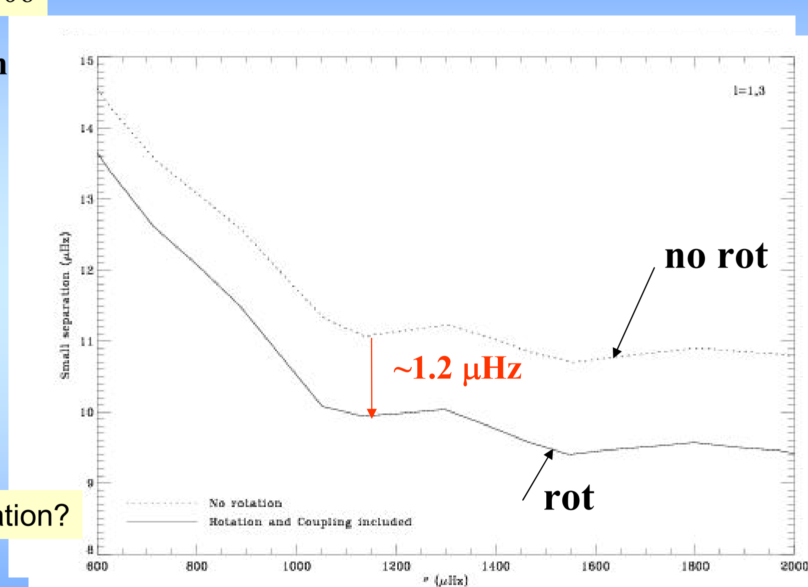
**Small separation**

$\nu_{la,n}-\nu_{lb,n-1}$

$l_a=3, l_b=1$ modes

**1μHz ~> 1Gy**

Scaling by large separation?




ν (μHz)

Magnetic field : asphericity

'Zeeman effect' (Ap stars, oblique rotators)
and shift in frequencies (DG97)

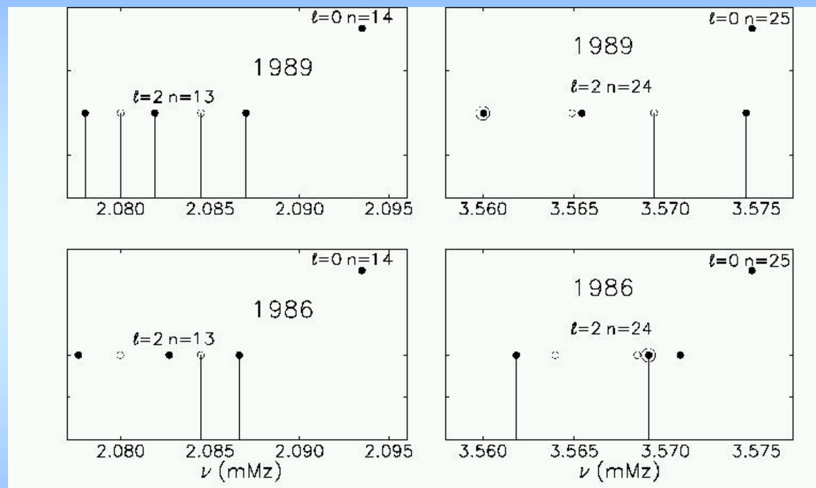
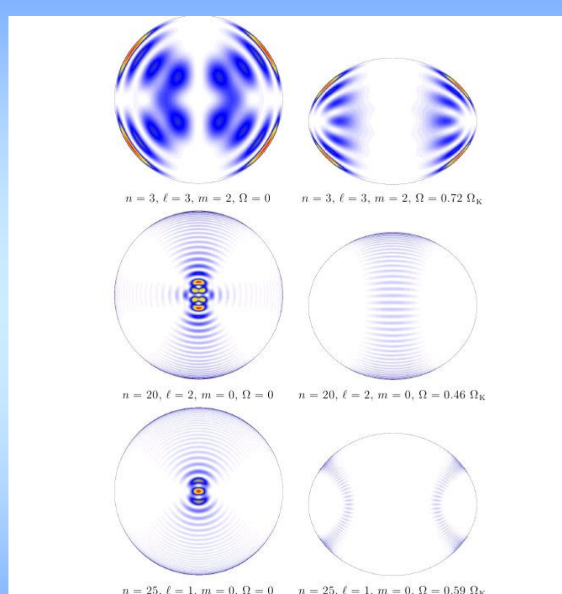



Fig. 4.— Structure of selected multiplets in the solar oscillation spectrum with the rotation rate and the magnetic activity effects artificially increased by factors 5 and 25, respectively. The activity effects were inferred from the high-ℓ multiplet structures as determined from BBSO observations in 1986 (activity minimum) and in 1989 (activity maximum) The amplitudes are arbitrarily set to $4 - \ell$. Modes with even

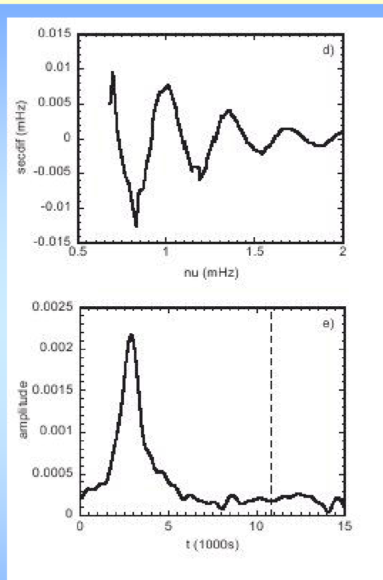


Geometry of the modes : concentration of amplitude about the equator or the poles




Consequences important for the apparent oscillation amplitudes and visibility of the mo

2Msol 63 Myr with helium diffusion



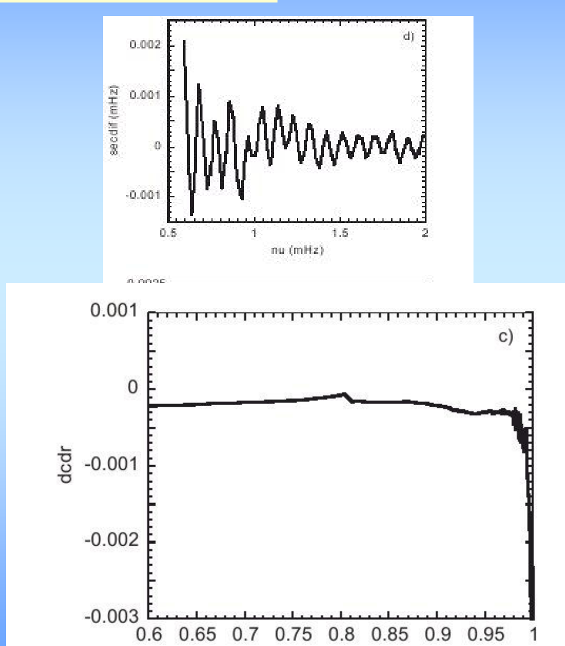

Vauclair et al 2004 A-type stars
1.6 Msol

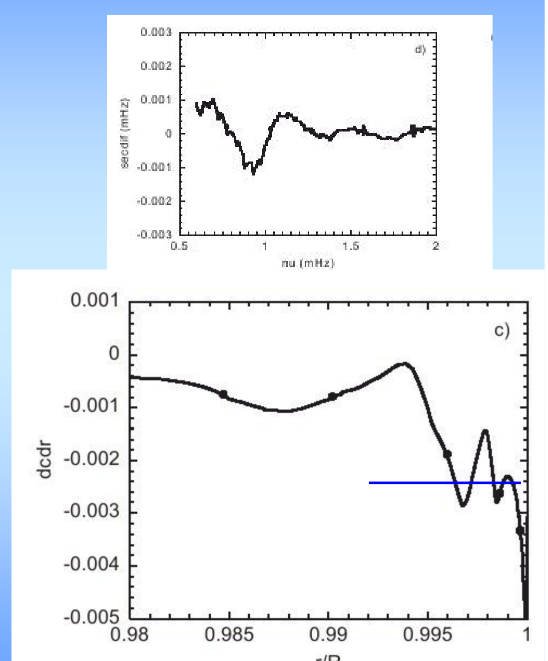


Vauclair et al 2004 A-type stars : 1.6 Msol

Influence of ionisation regions

*Second differences*




1.6 Gyr with helium diffusion

1.6 Gyr no diffusion

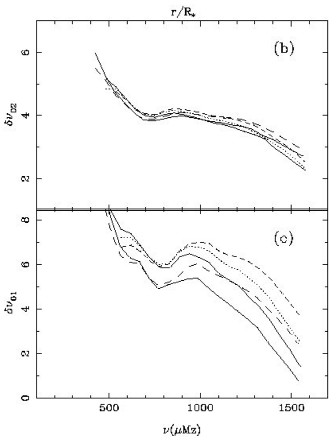



**Fig. 7.** Effect of changing the core overshoot parameter ζ. **a)** Relative difference of sound speed between model $D_0$ and models with different values of ζ core, respectively $S_0$ (ζ = 0.2, full), $S_4$ (ζ = 0.1, dashed) and $S_3$ (ζ = 0.15, dotted), as a function of the stellar radius. **b)** and **c)** Small spacings $\delta\nu_{01}$ and $\delta\nu_{02}$ for $D_0$ (ζ = 0.2 heavy full), $D_5$ (ζ = 0.1 heavy dashed) and the models $S_0$ (ζ = 0.2, full), $S_4$ (ζ = 0.1, dashed) and $S_3$ (ζ = 0.15, dotted).

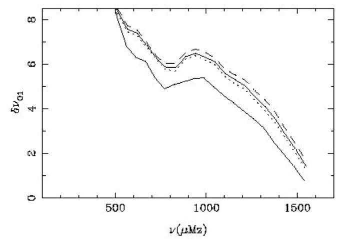



**Fig. 8.** Effect of changing the surface metallicity. Small spacing $\delta\nu_0$ for $D_0$ (heavy full line) and the models of $S_0$ (Z/X = 0.0245, full line) $S_5$ (Z/X = 0.0217, dashed) and $S_6$ (Z/X = 0.0270, dotted).

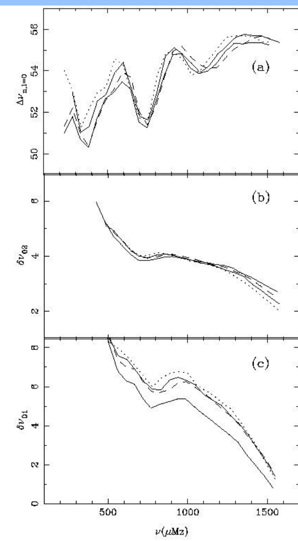



**Fig. 6.** Effect of changing the mixing-length parameter λ: variation of the large and small spacings, respectively **a)–c)**, as a function of the frequency, for model $D_0$ (heavy full line) and models $S_1$ (λ=1.05, dotted), $S_0$ (λ = 1.0, full), $S_2$ (λ = 0.95, dashed).



Rotation modifies convection hence criterium of instability hence size of the convective cor
Overshoot from the convective core still occurs but is also modified by rotation

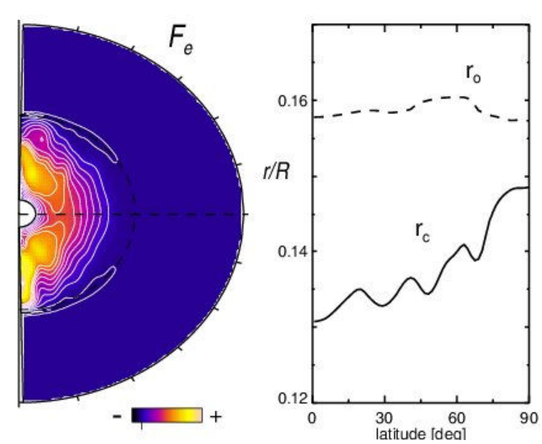
→ *size of the convective core depends on the star*
(its mass and age and its rotation rate)

3D simulations:

Extension of overshoot modified by rotation

Rotation increases --> larger mixed region

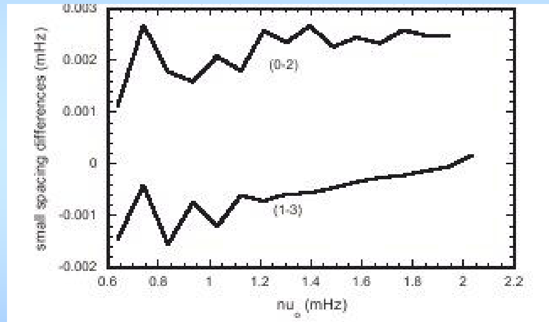
2 $M_{sol}$ ; rotation 1/10 to 4 times $\Omega_{sol}$




Heat (enthalpy) flux

Between model with and without microscopic diffusion (Theado et al 2005)

Models are calibrated, hence their inner properties differ.
These differences can be measured with the small spacing
Differences are fo the order of 1-2 μHz
But
→ Noisy data
→ Pollution by surface effects






Beta Vir with rotation and diffusion
Two possible model : M1 main sequence
M2 post mainsequence

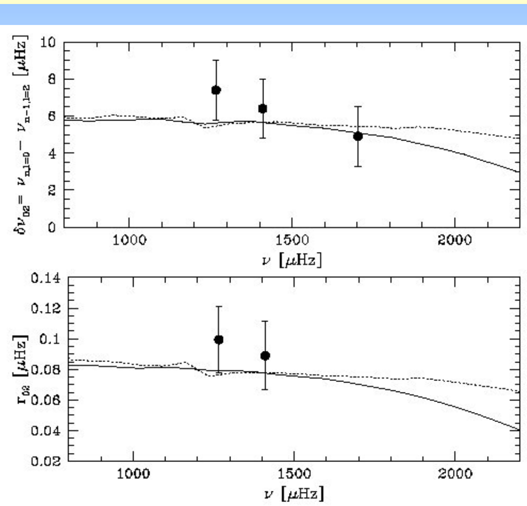
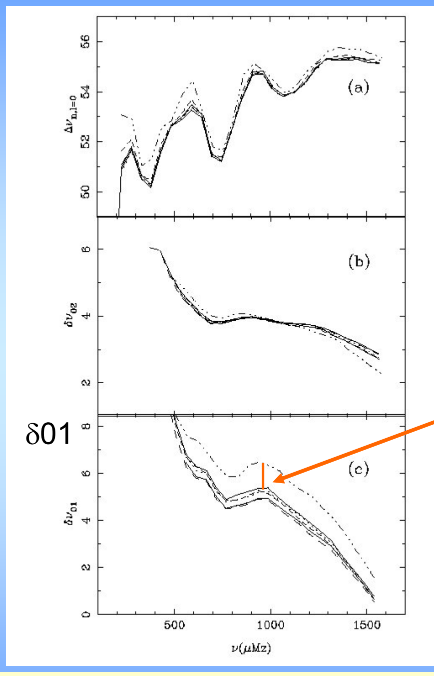



**Fig. 5.** Small spacing $\delta\nu_{02}$ and ratio of small to large separation $r_{02} \equiv \delta\nu_{02}/\Delta\nu_{n,\ell=1}$ as a function of frequency. The continuous line corresponds to the M 1 model, while the dotted line corresponds to the M 2 model. Dots indicate the observed values.

Microscopic diffusion on seismic properties intermediate mass stars

(Provost et al 2005)

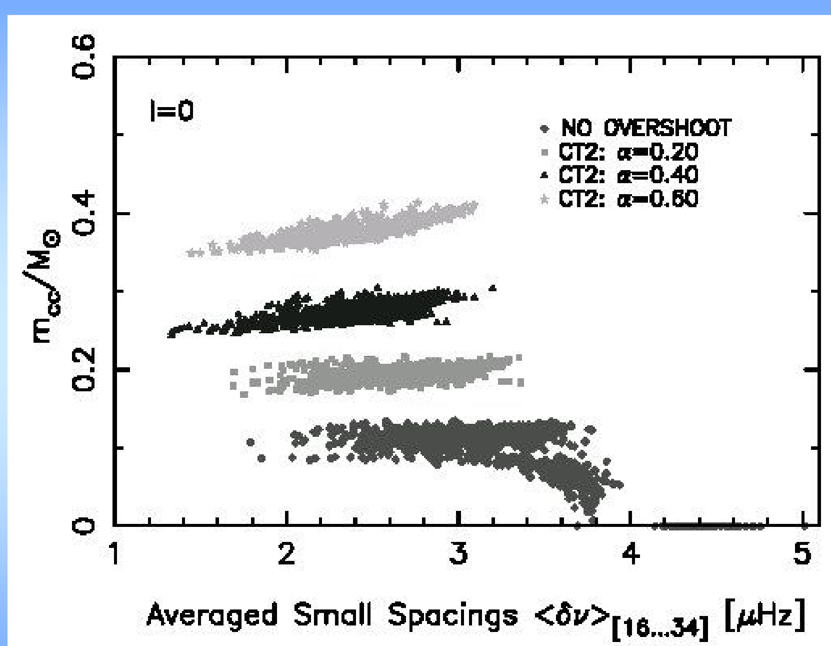



~1 μHz

$\delta_{01}$ best seismic signature
But affected by other effects
Outer convection: mixing length
Core overshoot, surface Z

Dash dotted curves : without diffusion

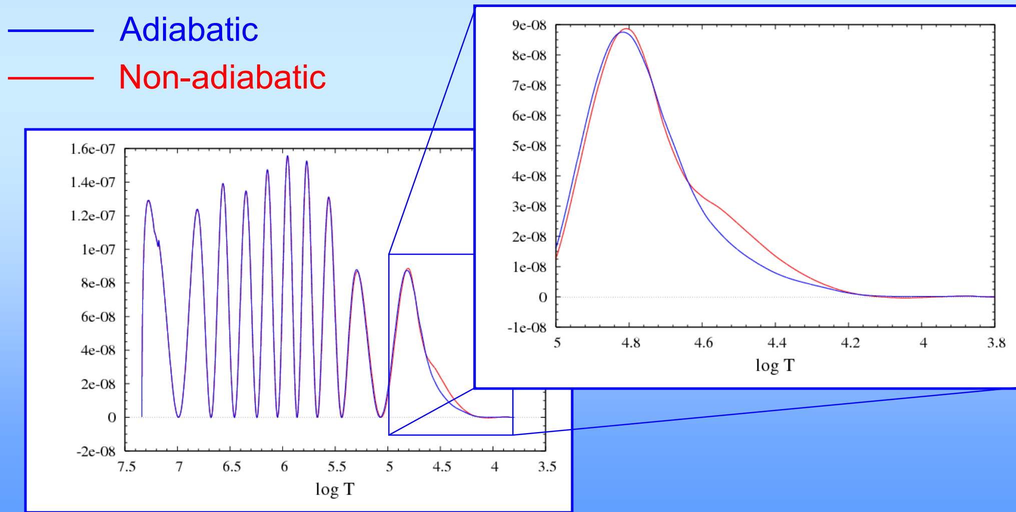
Other curves : computed with slightly different prescriptions for the microscopic diffusion

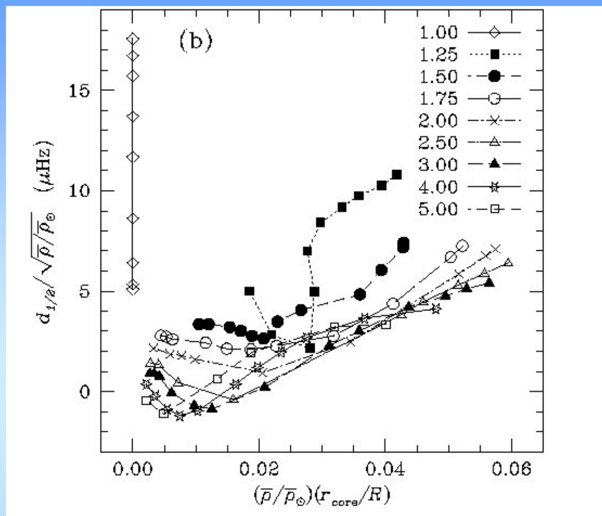


# Nonadiabatic effects : integral expression

$$\sigma^2 = \frac{\int \frac{\delta P}{\rho}\frac{\delta\rho^*}{\rho}\frac{dm}{d\log T}\, d\log T - \int \frac{4g}{r}|\delta r|^2 \frac{dm}{d\log T}\, d\log T}{\int |\delta r|^2 \frac{dm}{d\log T}\, d\log T}$$

$2M_\odot,\ \ T_{\rm eff} = 9000\ K\ ,\ \ p_{10}$





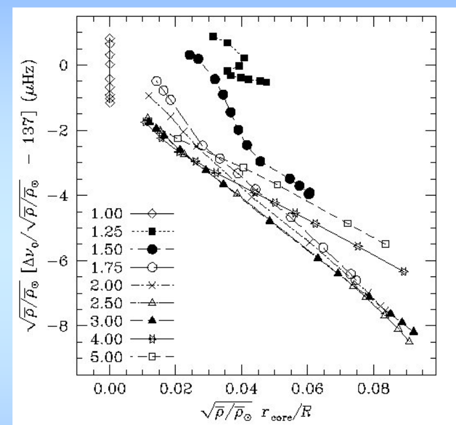




**Fig. 10.** Large frequency separation, $\Delta\nu_0$, as a function of convective core radius. Both the axes have been scaled by $\sqrt{\bar\rho/\bar\rho_\odot}$.

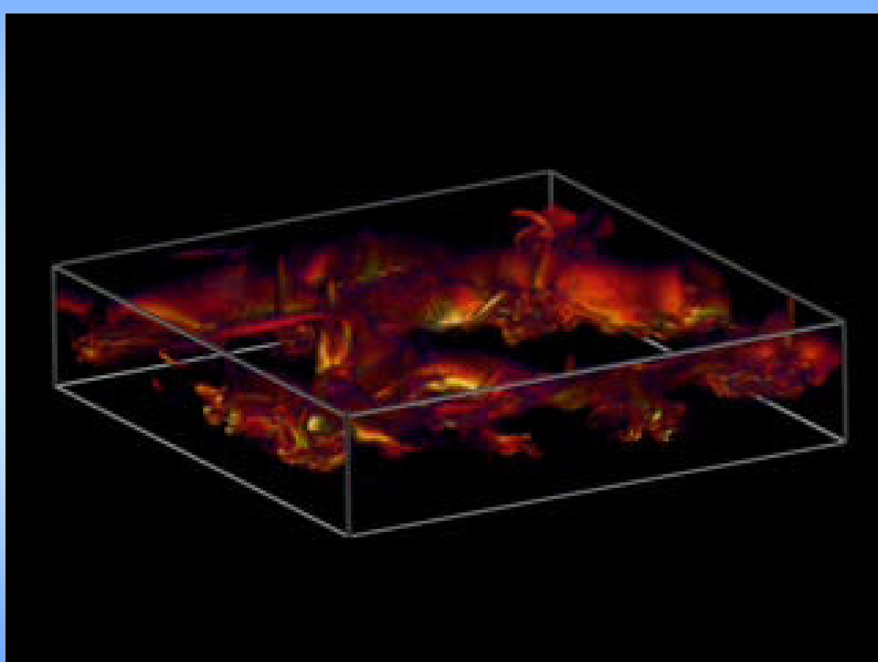
Mazumdar, Antia 2001

## Nonadiabatic effects : integral expression

$$\sigma^2 = \frac{\int \frac{\delta P}{\rho}\frac{\delta\rho^*}{\rho}\,dm - \int \frac{4g}{r}|\delta r|^2\,dm}{\int |\delta r|^2\,dm}$$

$$= \frac{\int \boxed{\frac{\delta P}{\rho}\frac{\delta\rho^*}{\rho}\frac{dm}{d\log T}}\,d\log T - \int \boxed{\frac{4g}{r}|\delta r|^2\frac{dm}{d\log T}}\,d\log T}{\int \boxed{|\delta r|^2\frac{dm}{d\log T}}\,d\log T}$$





Binary system alpha Cen A, B

Effet d'equation d;etat
Effet de microscopic diffusion

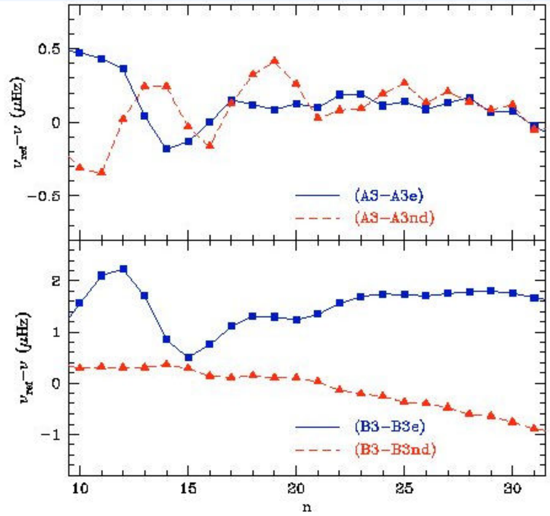



**Fig. 7.** Difference of frequencies between a reference calibration (A3, B3), and both, that with a different EoS (A3e, B3e) (solid lines), and without microscopic diffusion (A3nd, B3nd) (dahsed lines). Upper panel corresponds to component A, and lower panel to component B.

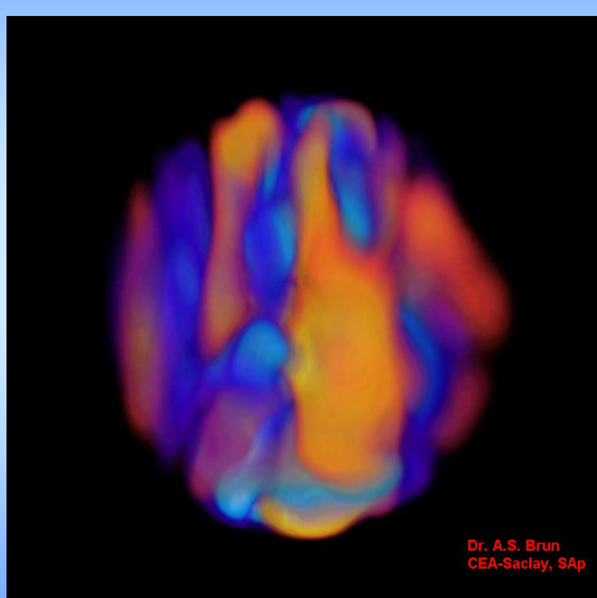
(Straka et al 2005)



# Rotating convective core of A stars
# 3 D simulations (Browning et al 2004)

2 Msol

$\Omega = 1\Omega$sol




Velocity field
Blue = ascending flows

$r_c$ = 0.1 Hp (prolate)
$r_{mix}$ = 0.15 Hp

$\Omega$ enhances overshoot

overshoot $\Omega$ dependent
ie star dependent

Rotating convective is nonhomogeneous

Rotating convective core is prolate

Effects of frequencies can be classified as

-Near surface effects
Frequencies are strongly dependent on near-surface effects:

- Envelope effects : microscopic diffusion
Below an upper convective zone (solar like stars) or in the radiative outer layers (etoiles A and hotter)

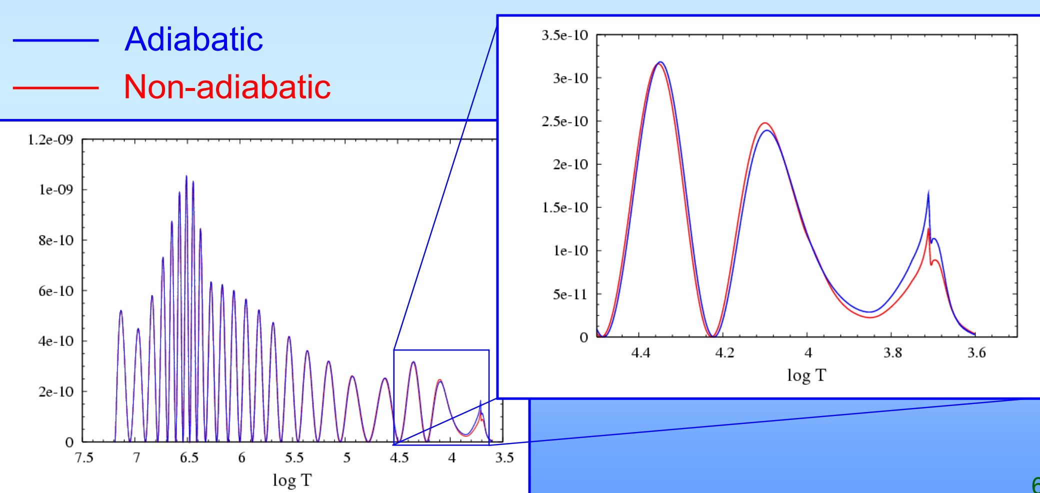
-Inner properties : existence and size of a convective core
extension of the mixed central region (overshooting, rotation)

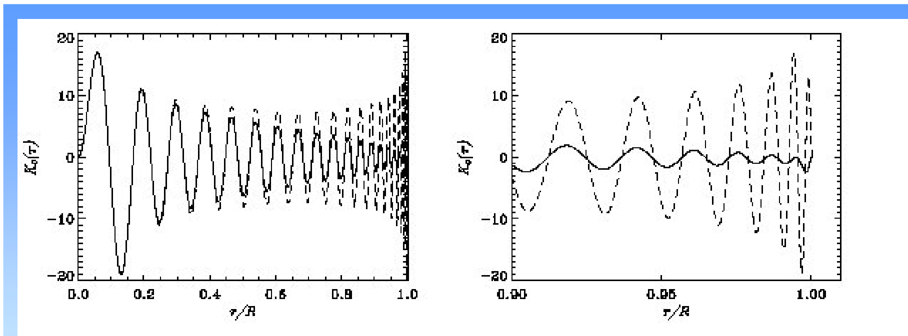


# Nonadiabatic effects : integral expression

$$\sigma^2 = \frac{\int \frac{\delta P}{\rho}\frac{\delta \rho^*}{\rho}\frac{dm}{d\log T}\, d\log T - \int \frac{4g}{r}|\delta r|^2 \frac{dm}{d\log T}\, d\log T}{\int \boxed{|\delta r|^2 \frac{dm}{d\log T}}\, d\log T}$$

Sun , $p_{22}$








Comparison between solar observations and different modes including turbulence from 3D simulations Li et al 2002

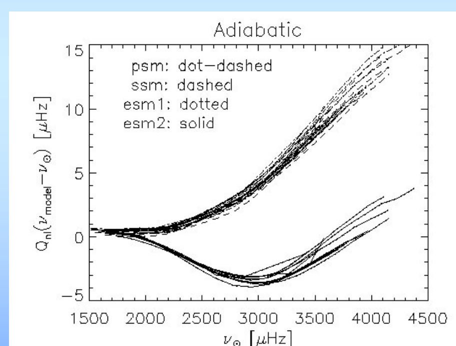



FIG. 12.—*p*-mode frequency difference diagrams: observation minus model, scaled by the mode mass $Q_{nl}$, for the SSM, the turbulent PSM, the solar model with fixed turbulent pressure and kinetic energy (ESM1), and the solar model with evolutionary turbulent pressure and kinetic energy (ESM2, almost overlapping ESM1). Plotted are the $l = 0, 1, 2, 3, 4, 10, 20, \ldots, 100$ *p*-modes.

## Microscopic diffusion

Helium and heavy element settling

Radiative forces : on strongly ionized element → iron peak elements → hot stars

sofar localised accumulation of iron effects studied for instability (Bourge et al..)

must be conteract somewhat by turbulent mixing (Richard et al)



Hence frequencies are sensitive to the state of the medium →EOS
radiative transport → Opacity
Tc, rhoc, muc energy generation → nuclear reaction rates
and gradients due to transport processes

Main transport processes which affect frequencies:

Standard (already included in models)
- CONVECTION
- OVERSHOOT
- MICROSCOPIC DIFFUSION

Start to be included in models and impacts on frequencies inferred:
TURBULENT MIXING in radiative zones,
ROTATION
INTERNAL GRAVITY WAVES
MAGNETIC FIELD

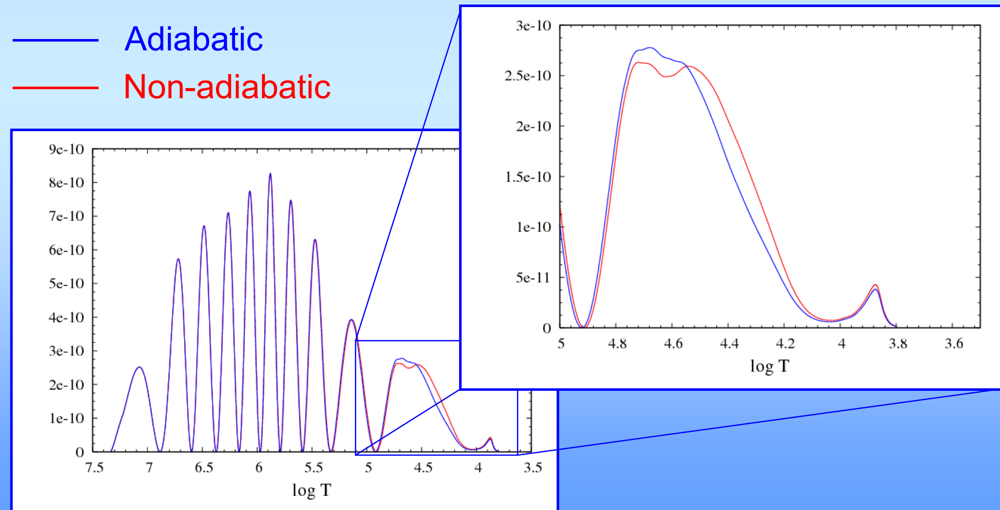
Initial conditions and PMS evolution

Effect of mass loss and accretion on frequencies : impact on frequencies to be inferred

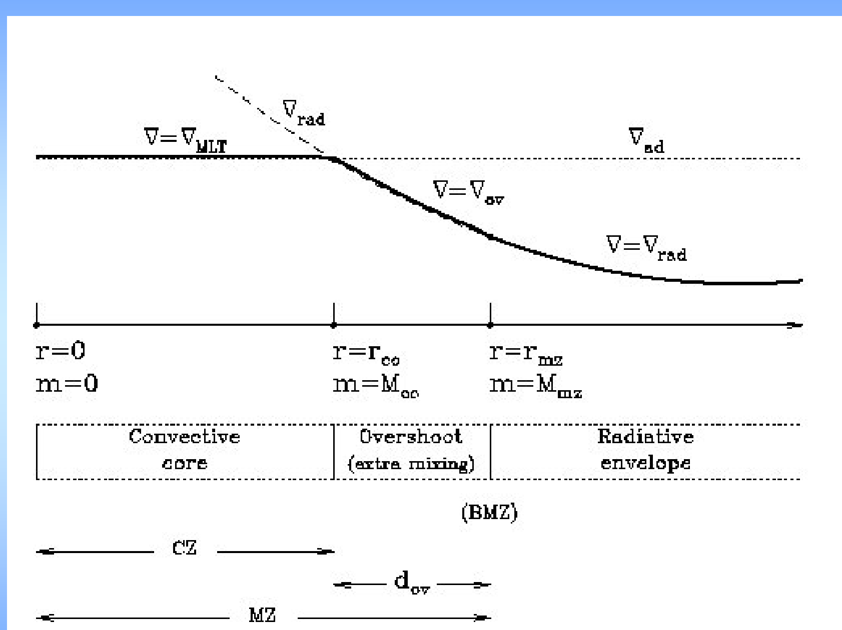
# Nonadiabatic effects : integral expression

$$\sigma^2 = \frac{\int \frac{\delta P}{\rho}\frac{\delta \rho^*}{\rho}\frac{dm}{d\log T}\, d\log T - \int \frac{4g}{r}|\delta r|^2 \frac{dm}{d\log T}\, d\log T}{\int |\delta r|^2 \frac{dm}{d\log T}\, d\log T}$$

$2M_\odot,\ \ T_{\rm eff} = 9000\ K\ ,\ \ p_{10}$





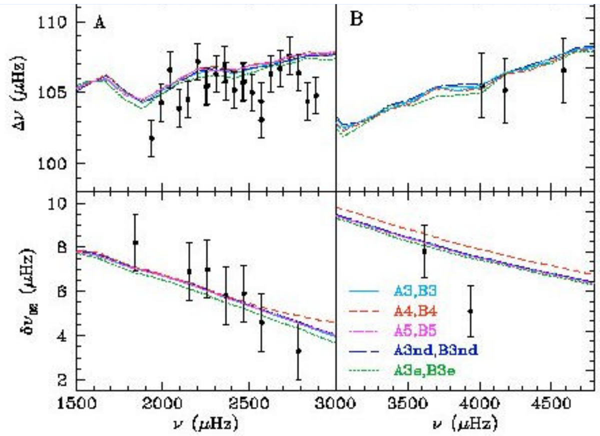



**Fig. 5.** As Fig. 4 but with different curves corresponding to different physics included in the stellar computation: convective overshooting (dashed lines); solar mixture from Asplund et al. (2004) instead of Grevesse & Noels (1993)(dash-dotted lines); no gravitational settling (solid lines); CEFF equation of state instead of OPAL01 (dotted lines).

Straka et al 2005 Alpha cen A, B



Beta Virginis Eggenberger et al 2006

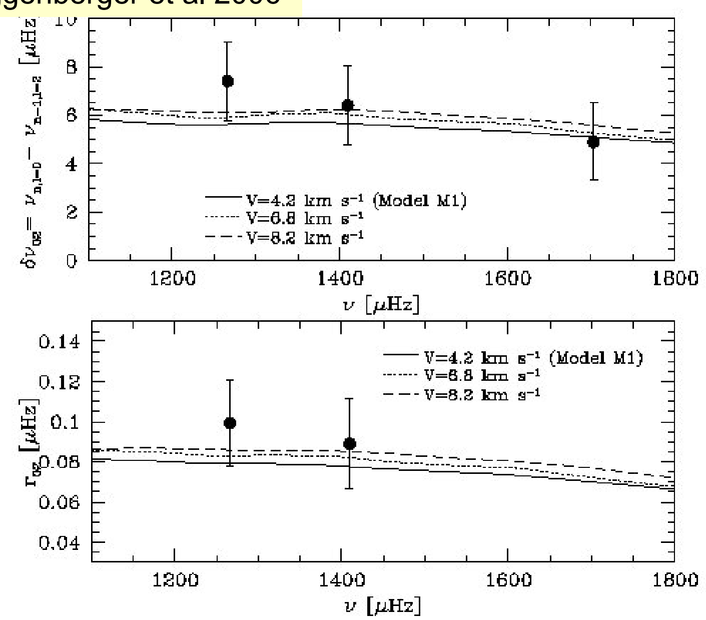



**Fig. 8.** Small spacing $\delta\nu_{02}$ and ratio of small to large separation $r_{02} \equiv \delta\nu_{02}/\Delta\nu_{n,\ell=1}$ as a function of frequency for models with the same value of the mean large spacing (72.1 $\mu$Hz) but different surface velocities $V$. Apart from the initial value of the rotational velocity, the models have been computed with the same initial parameters as the M 1 model. Dots indicate the observed values.

## Internal gravity waves

Talon et al 2006 AmFm stars
Talon, Charbonnel …. Li
Talon, Charbonnel solid body rotation for the Sun
what about Beta Virginis (Eggenberger et al ..)

Transport of angular momentum
Efficient mean of forcing solid body rotation in radiative zone
In modifying differential rotation profile has an indirect effect on mixing
conteract microscopic diffusion