Asteroseismology:

an irreplaceable tool to confront the great challenges of stellar physics

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Great achievements of helioseismology

Helped to solve the solar neutrinos problem
by assessing the central temperature of the Sun

Gave an estimate of the depth of the convection zone

Put some constraints on the extent of penetration

Estimate of the He content

Established the internal rotation profile:
helped discriminate between processes of angular momentum transport

Can we expect the same from asteroseismology ?

In principle yes, but

- only low degree modes are detectable
- mode identification is difficult when fast rotation

Asteroseismic H-R diagram

Based on asymptotic properties of acoustic modes

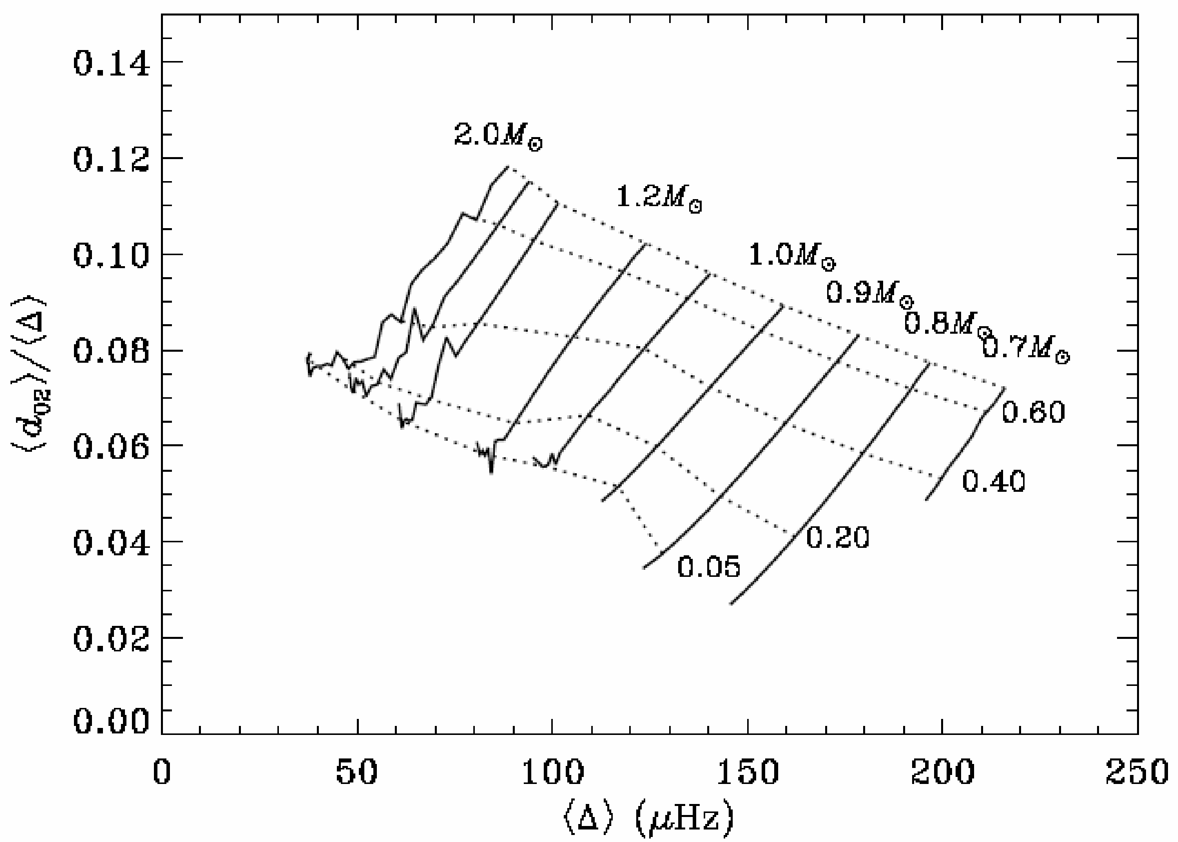
large difference :

$$\Delta_{L} = \nu_{n,L} - \nu_{n-1,L}$$

small difference :

$$d_{L,L+2} = \nu_{n,l} - \nu_{n-1,L+2}$$

Christensen-Dalsgaard 1984
Roxburgh & Vorontsov 2003
Floranes et al. 2005



Can test stellar models, if composition, mass and /or age are well known

Requires realistic models that depend only on very few parameters

Measuring the internal rotation profile

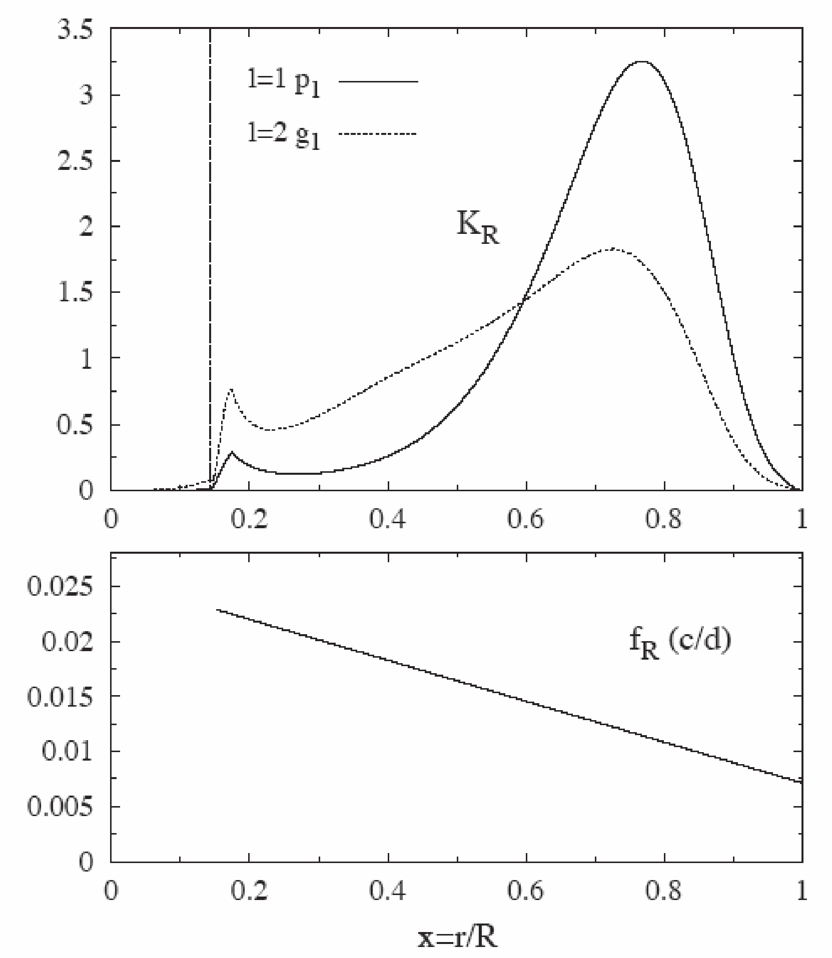
Feasibility discussed in Goupil et al. 1996, 2006

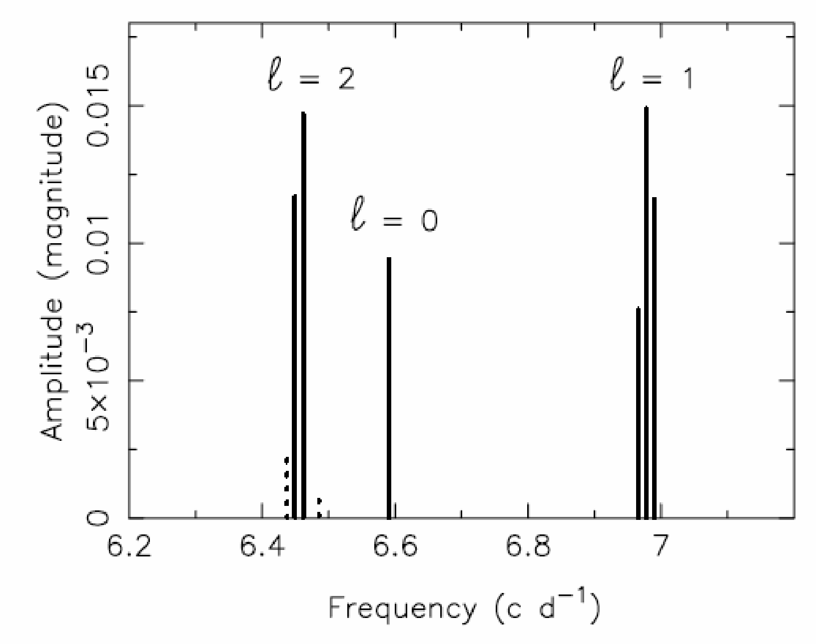
A recent case study:
β Cep star HD 129929 - a slow rotator
from rotational splittings of 2 eigenfrequencies

Analysis yields also amount of penetration

Aerts et al.; Dupret et al. 2004

Rotation kernels





The weakest points of present stellar structure theory

Convection:
- extent of convection zones
- penetration
- semi convection
- wave excitation

Mixing in radiation zones

Mass loss

Magnetism

Angular momentum loss

Treatment of convection

MLT : convective flux depends on local entropy gradient - no penetration

Reynolds stress models - capture non-local character

these 1D models are easy to implement
but they involve parameters that need to be calibrated,
and whose universality is not established

3D hydro simulations - a great leap forward

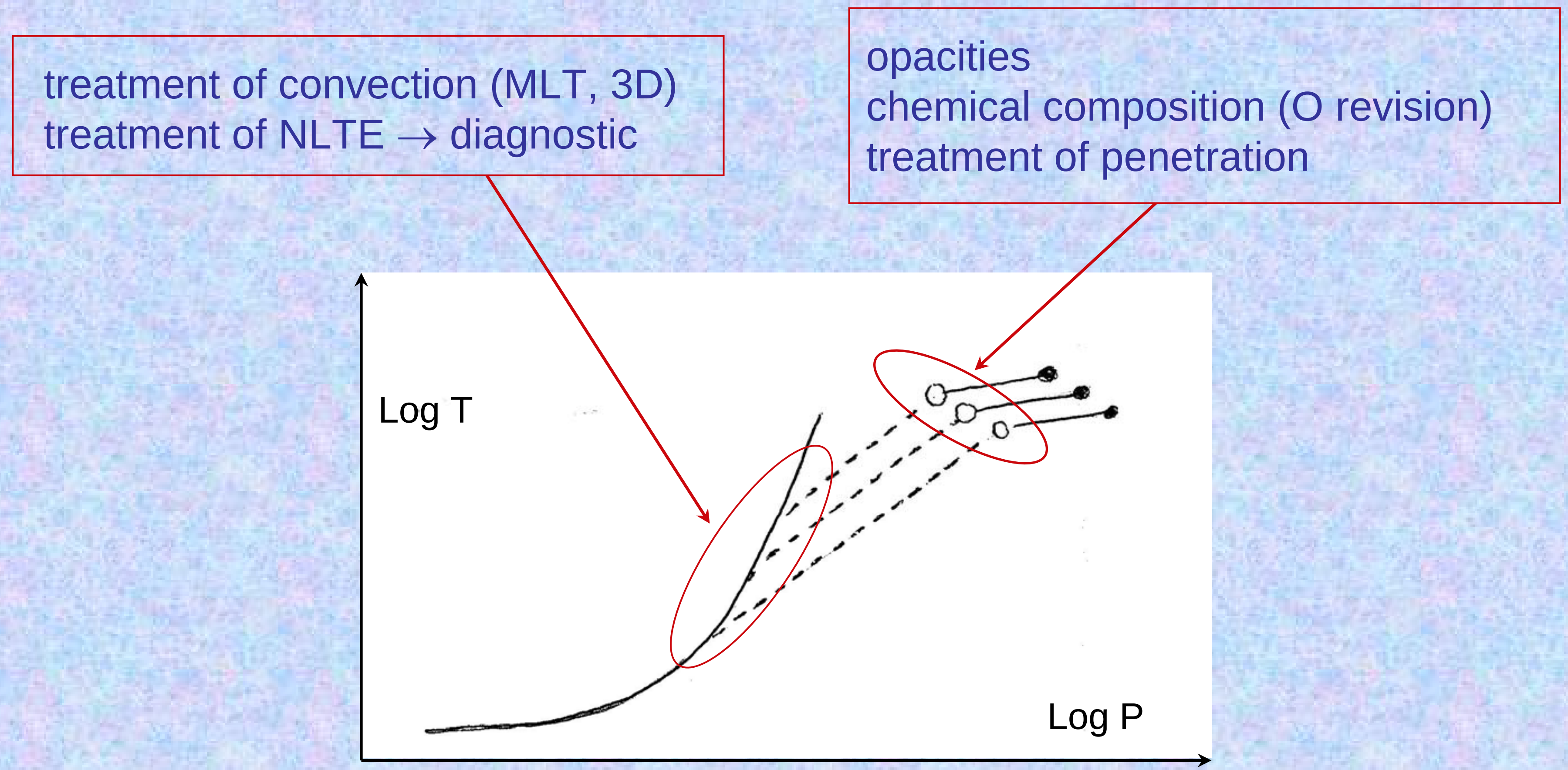
although Reynolds and Péclet numbers are still too low

difficult to implement as such in stellar evolution codes

but can be used to calibrate 1D prescriptions (cf. Ludwig et al. 1997)

Can predict spectrum of internal gravity waves excited by convection

Extent of the solar convection zone



treatment of convection (MLT, 3D)
treatment of NLTE → diagnostic

opacities
chemical composition (O revision)
treatment of penetration

Necessity of a precise calibration (R, L, surface composition, age)
and of seismic constraints

Present standard model

- Thoroughly mixed convection zones,
  delimited by Schwarzschild criterion, based on MLT
- Parametric description of convective penetration and overshoot
- Microscopic diffusion, gravitational settling and radiative levitation
- No mixing in radiation zones

Signs of extra mixing in radiation zones

Li depletion in solar-type stars

Seismic c^2 and ρ profiles below solar convection zone

Limited abundance anomalies at surface of `tepid' stars

Abundance anomalies at surface of red giants ($^{12}C/^{13}C$)

H and N excess at surface of massive stars and supergiants

Ratio of red and blue supergiants in stellar clusters

Consequences

Increases life-times of stars

Orients latest stages of evolution

Determines yields → chemical evolution of Galaxy

How to treat this extra mixing

Parametric approach:

introduce parametrized turbulent diffusivities,
for transport of chemicals and angular momentum

adjust parameters to fit observations

Physical approach:

strive to identify and to implement the physical processes that are likely to cause mixing in RZ :

- meridional circulation induced in rotating stars
  by applied torques (wind, accretion, etc.)
  and structural changes
- turbulence produced by instabilities
  (shear, magnetic, thermohaline,etc.)

→ ROTATIONAL MIXING

Rotational mixing in radiation zones

Meridional circulation

Classical picture: circulation is due to thermal imbalance
caused by perturbing force (centrifugal, magnetic field, etc.)

Eddington (1925), Vogt (1925), Sweet (1950), etc.

Eddington-Sweet time $t_{ES} = t_{KH} \frac{GM}{\Omega^2 R^3}$, with $t_{KH} = \frac{GM^2}{RL}$

Revised picture: after a transient phase of about t_{ES}
, circulation is driven by the loss (or gain) of angular momentum
and by structural changes due to evolution

Busse (1981), JPZ (1992), Maeder & JPZ (1998), Mathis & JPZ (2004)

- no AM loss: no need to transport AM to surface → weak circulation
- AM loss by wind: need to transport AM to surface → strong circulation

Tachocline circulation in vicinity of conv. zone Spiegel & JPZ (1992)

Rotational mixing in radiation zones

caused mainly by shear instabilities $\Omega(r,\theta)$

- vertical shear instability, due to $\Omega(r)$: well understood
  stabilizing effect of stratification limited by thermal diffusion

$$D_v = wl = Ri_c K \frac{\Omega^2}{N^2}\left(\frac{d\ln\Omega}{d\ln r}\right)^2 \qquad \text{(if } \mu = \text{cst)}$$

Townsend 1959
Dudis 1974; JPZ 1974
Lignières et al. 1999

K thermal diffusion; *N* buoyancy frequency; $Ri_c = O(1)$

- horizontal shear instability, due to $\Omega(\theta)$
  leads probably to 'shellular' rotation $\Omega(r,\theta) \sim \Omega(\mathbf{r})$
  changes advection of chemicals by meridional circulation
  into vertical diffusion

$$D_{eff} = \frac{1}{30}\frac{(rU)^2}{D_h}$$

Chaboyer & JPZ 1992

but lack of firm prescription for D_h ($>> D_v$)

Rotational mixing - the observational test

Assumption: the same processes that cause the mixing of chemical elements
(i.e. circulation and turbulence)
are also responsible for the transport of angular momentum
JPZ 1992, Maeder & JPZ 1998

- quite successful with early-type stars (fast rotators)
  Talon et al. 1997; Maeder & Meynet 2000; Talon & Charbonnel 1999
- for late-type stars (which are spun down by wind) predicts
  - fast rotating core   not true: helioseismology
  - strong destruction of Be in Sun   not observed
  - mixing correlated with loss of angular momentum
    not true: Li in tidally locked binaries
    not true: little dispersion in the Spite plateau

⇒ Another, more powerful process is responsible
for the transport of angular momentum

· magnetic field ?   · internal gravity waves ?

Role of magnetic field

Dynamo field (solar-type stars, or from convective core)

- Likely to have reversals → will not penetrate into RZ

[Garaud 1999]

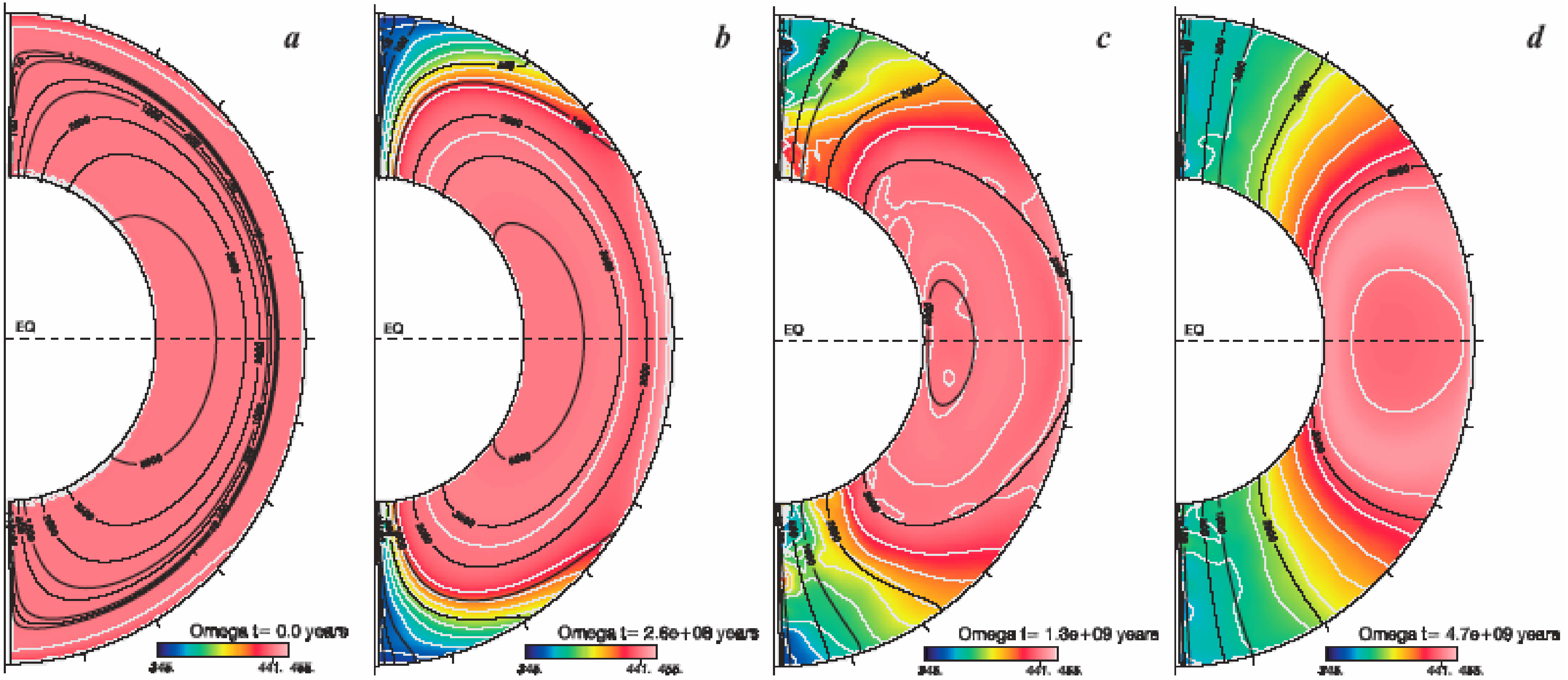
Fossil field (such as in Ap stars)

- renders the rotation uniform [Mestel and coll.]

  along field lines if axisymmetric (Ferraro law)
- imprints diff. rotation of CZ [Brun & JPZ 2006]

Fossil field and rotation

3D simulations - ASH code [Brun & JPZ 2006]



Fossil field expands into CZ, and prints its differential rotation on RZ

This does not occur in the Sun → no fossil field

Role of magnetic field

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  but are bd conditions realistic enough? [Garaud & Garaud 2008]

Field itself may be unstable [Tayler & coll.; Spruit 1998]

- yes - but instabilities are probably of Alvénic type → no mixing
- may these instabilities sustain a dynamo ? Probably not

[JPZ, Brun & Mathis 2007]

Angular momentum transport by IGW waves

Press 1981, Garcia-Lopez & Spruit 1991, Schatzman 1993, Zahn et al 1997

Internal gravity waves and gravito-inertial waves
are emitted at the edge of the convection zone

They transport angular momentum, which they deposit
where they are damped through thermal diffusion

damping rate $\propto \sigma^{-4}$

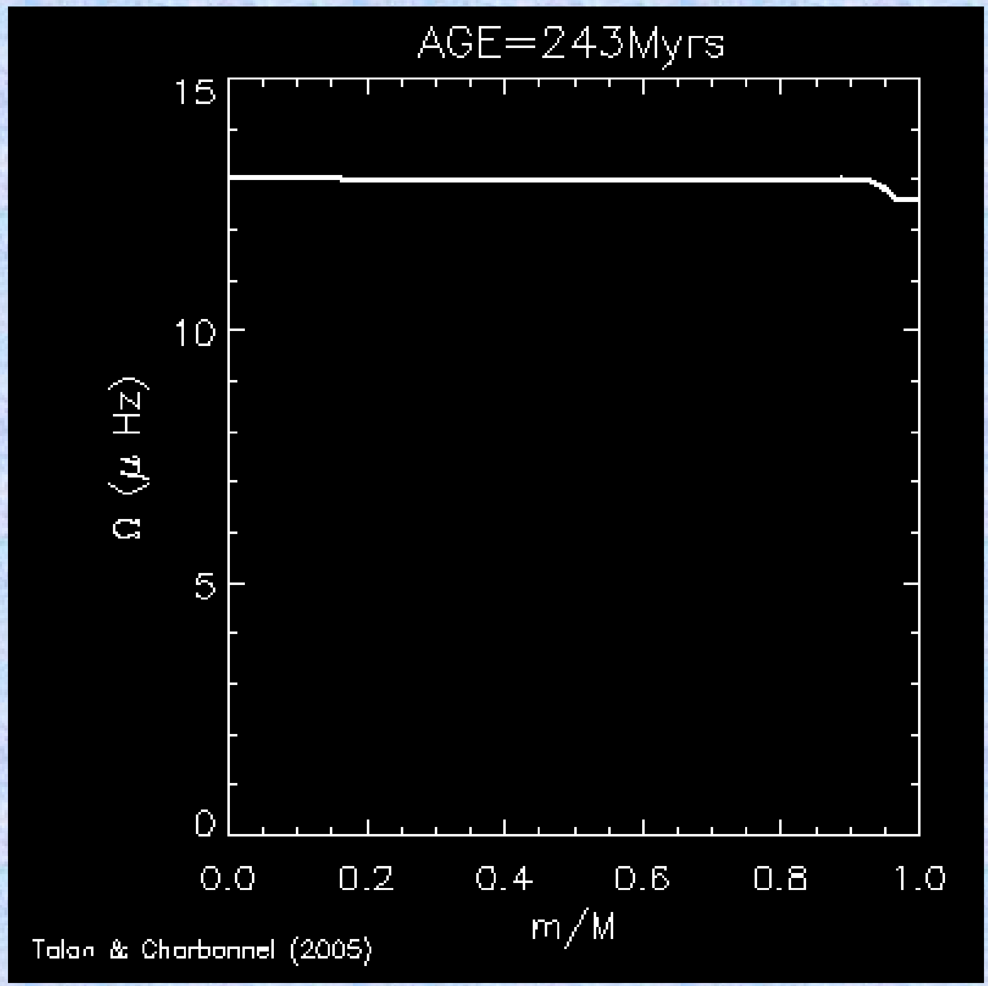
$$\sigma(r,m) = \sigma_c + m[\Omega(r) - \Omega_{zc}]$$

- if there is differential rotation,
  prograde and retrograde waves deposit their momentum
  (of opposite sign) at different locations

wave dissipation strengthens the local differential rotation,
until the shear becomes unstable $\Rightarrow$
turbulence

Talon et al 2002, Talon & Charbonnel 2005

Extraction of angular momentum through internal gravity waves



low-degree,
low-frequency waves
broad band spectrum

Angular momentum extracted by solar wind

Effect of high degree, high frequency waves filtered out

1 $M_\odot$ star

Talon & Charbonnel 2005

Extraction of angular momentum through internal gravity waves

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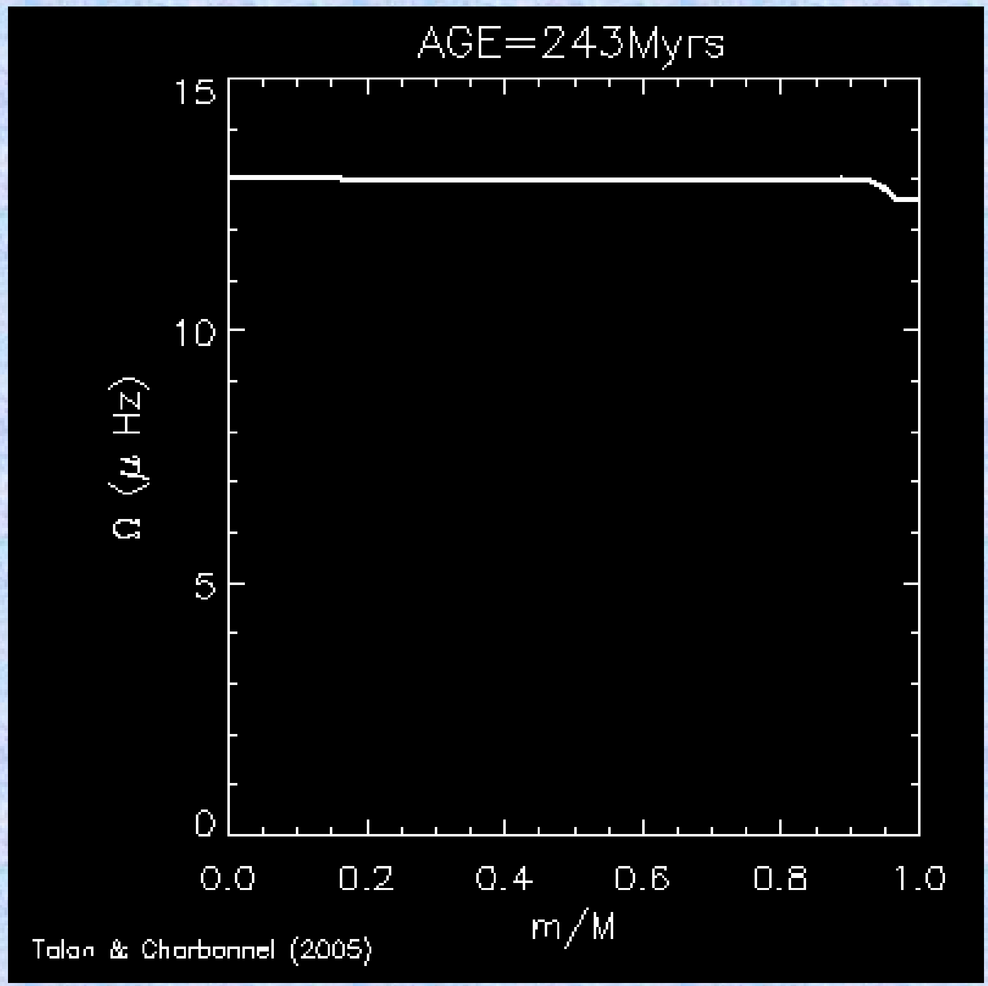

Angular momentum
extracted by solar wind

Effect of high degree,
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filtered out

1 $M_\odot$ star

Talon & Charbonnel 2005

Rotational mixing with IGW in solar type stars : the observational test

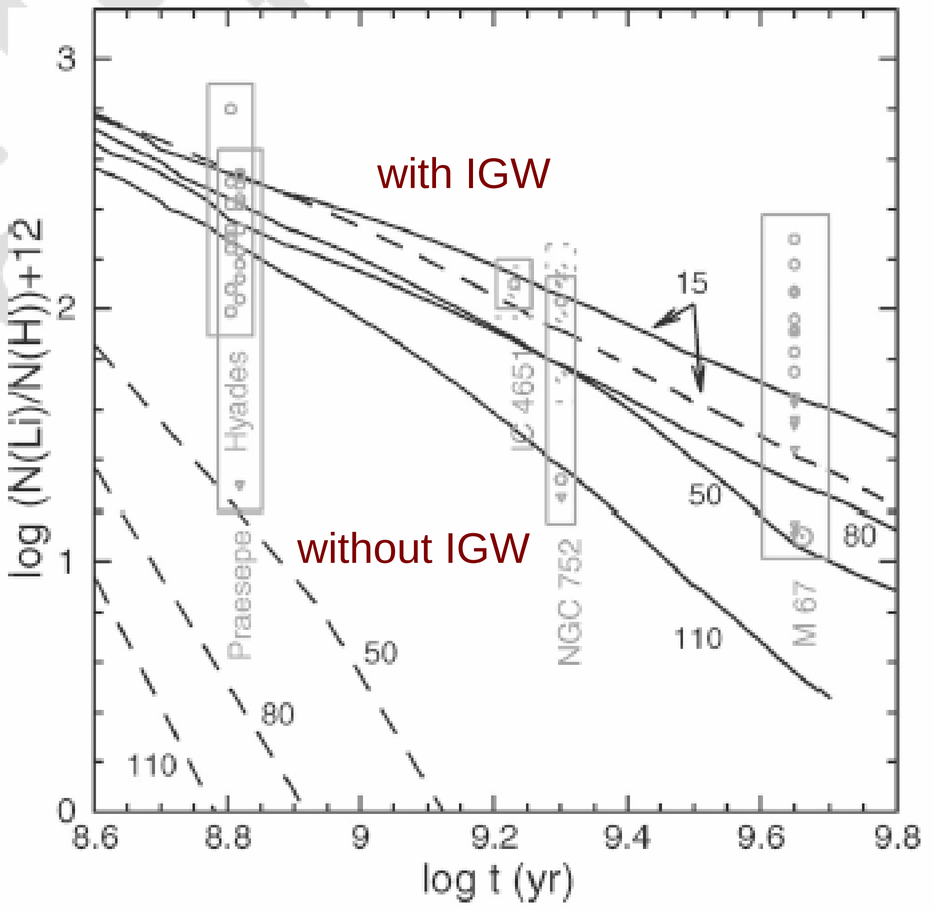
Assumption:

Circulation and turbulence are responsible
for the mixing of chemical elements

Angular momentum is transported
by internal gravity waves

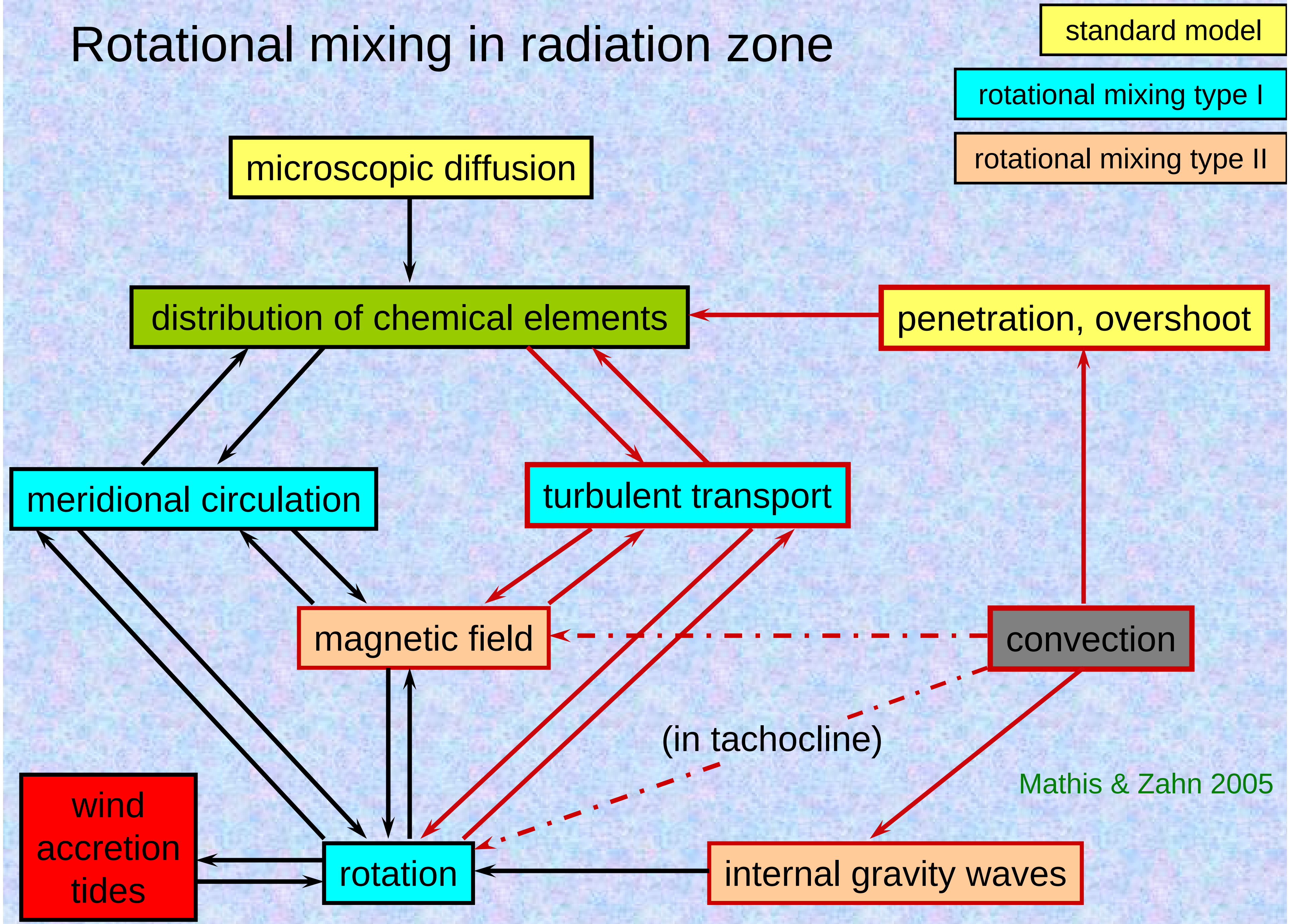
- IGW are able to extract AM
  from solar interior and
  to render the rotation uniform

- the right amount of Li is depleted
  in Pop I and Pop II stars



Charbonnel & Talon 2005

Rotational mixing in radiation zone



standard model

rotational mixing type I

rotational mixing type II

microscopic diffusion

distribution of chemical elements

penetration, overshoot

meridional circulation

turbulent transport

magnetic field

convection

(in tachocline)

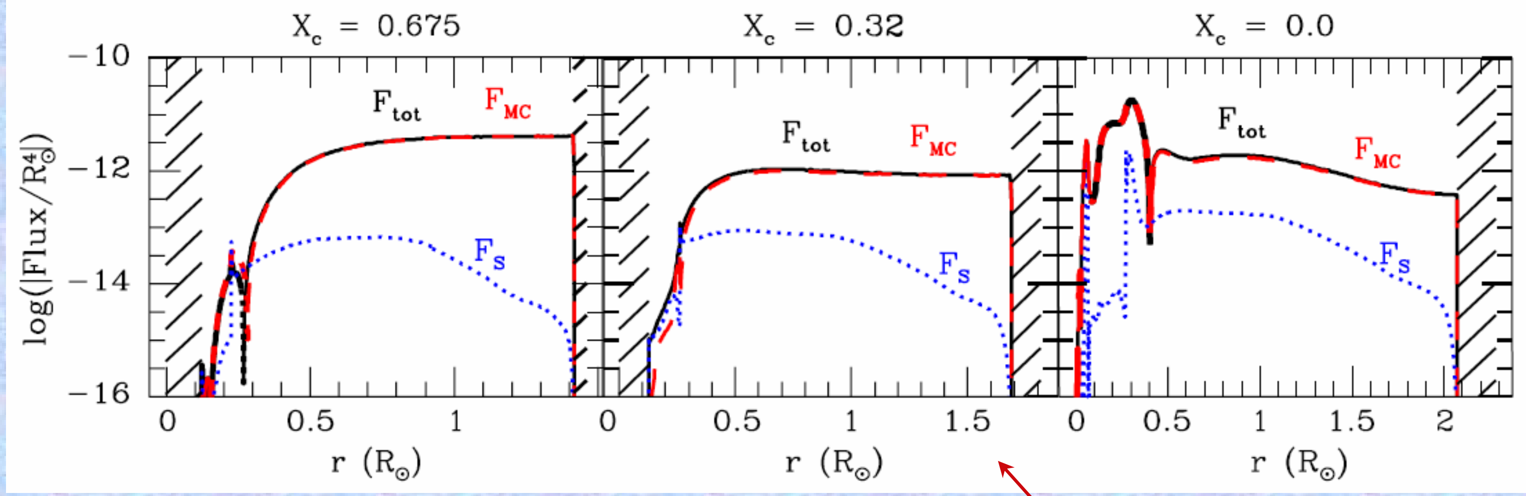
wind
accretion
tides

rotation

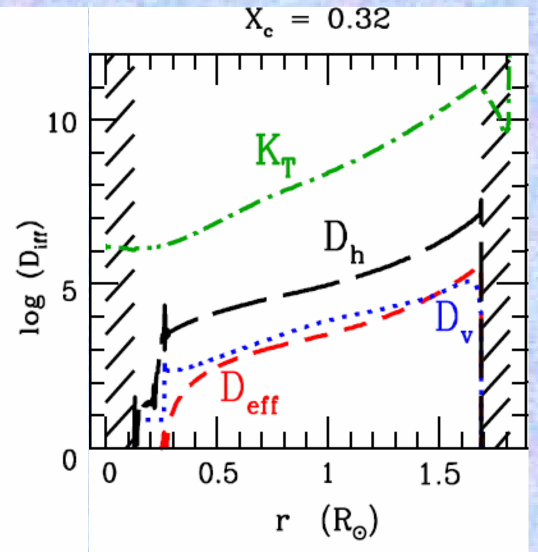
internal gravity waves

Mathis & Zahn 2005

Implementation of rotational mixing in stellar evolution codes



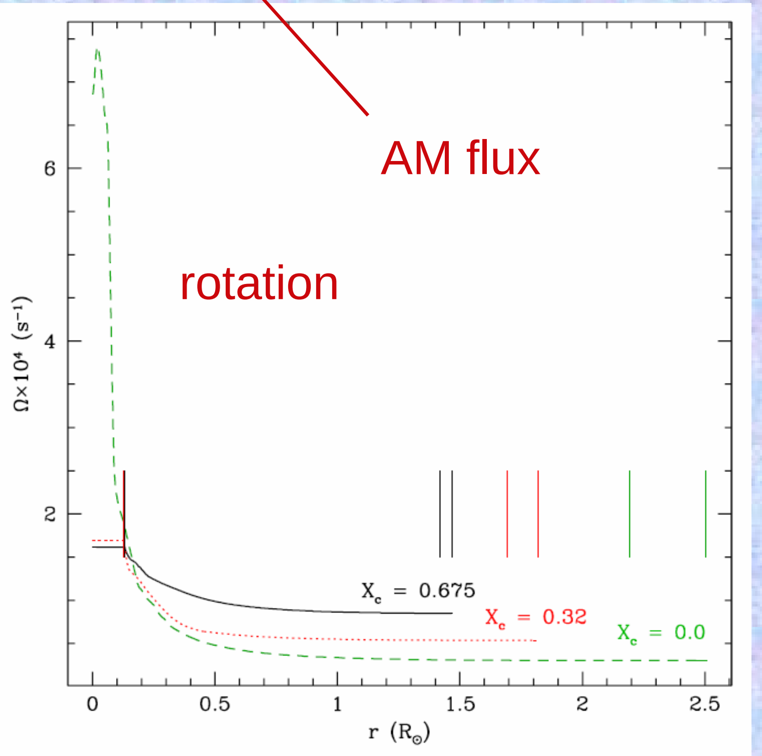
Talon et al. 1997
Maeder & Meynet 2000
STAREVOL (Forestini, Siess & co)
CESAM (Morel & co)



$M=1.5\ M_\odot$
wind driven circulation

no magnetic field
no IGW

Decressin, et al.



AM flux

rotation

Weak points of present models with mixing in radiation zones

- Parametrization of the turbulence caused by differential rotation
- Power spectrum for IGW emitted at base of convection zone
- Impact of rotation on IGW - inertial waves
- Particle transport by IGW ?
- Role of instabilities due to magnetic field ?
- Prescription for thermohaline mixing

modelling stellar interiors
will benefit greatly from asteroseismology