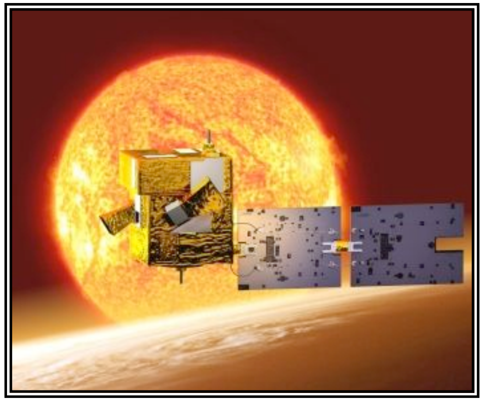
Internal Gravity Waves in the Sun



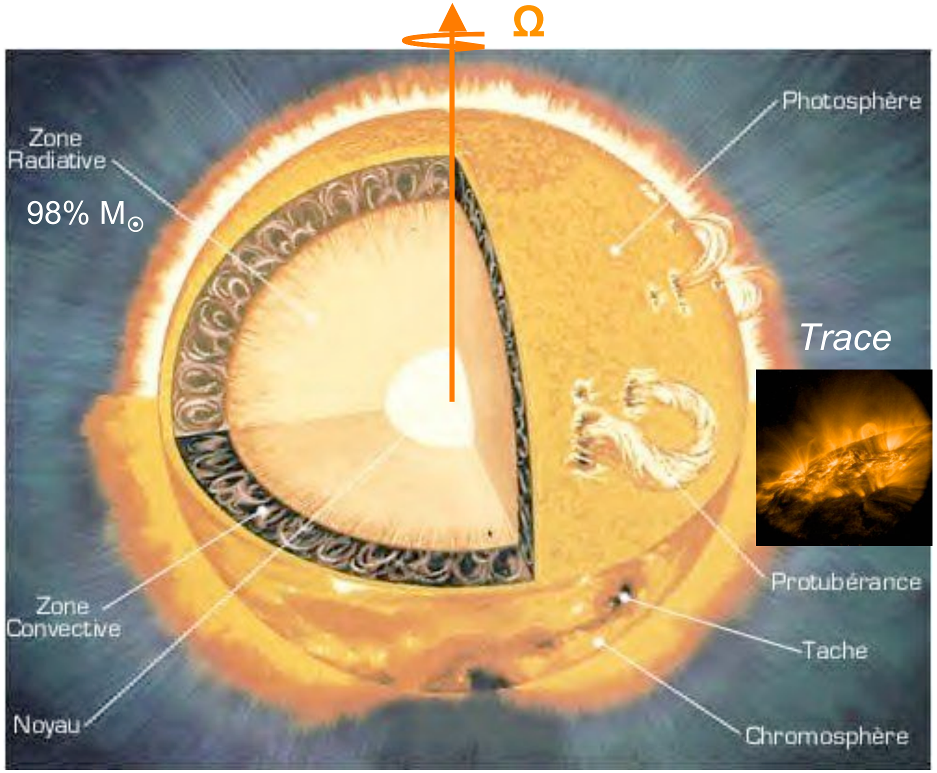
S. Mathis

CEA/DSM/IRFU/SAp; Laboratoire AIM, CEA/DSM - CNRS - Université Paris Diderot

First PICARD workshop;
8 – 9 March 2010, Paris, France

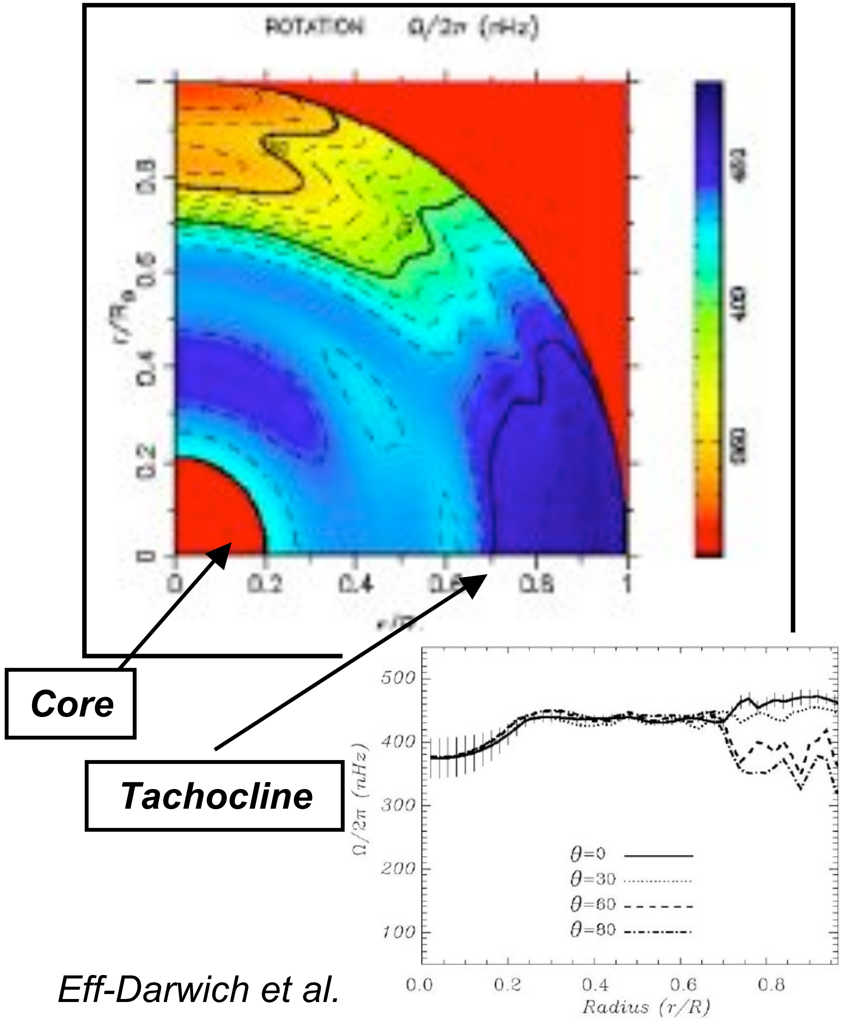
The dynamical Sun

Complex magnetism



Rotation profile not understood

(Corbard 1998, Turck-Chièze et al. 2004, Garcia et al. 2007-08, Leibacher et al. 2007, Mathur et al. 2008, Eff-Darwich et al. 2008)

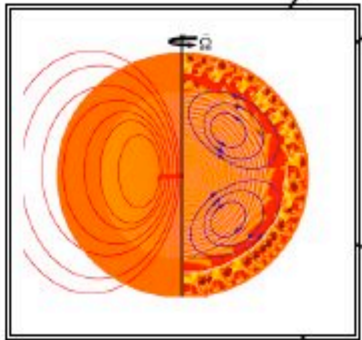


Eff-Darwich et al.

Internal mixing signatures

A coherent picture of the dynamical Sun and its evolution → need to understand the dynamical transport processes in RZ

Transport processes in radiation zone



Meridional circulation (diff. rot. and A. M. transport) (ADVECTION)

(Busse 1981; Zahn 1992; Maeder & Zahn 1998; Garaud 2002; Rieutord 2004; Mathis & Zahn 2004; Rieutord 2006; Espinosa Lara & Rieutord 2007; Mathis et al. 2007; Decressin et al. 2009)

Turbulence (shear of the diff. rot.) (DIFFUSION)

(Talon & Zahn 1997; Lignères et al. 1999; Garaud 2001; Maeder 2003; Mathis et al. 2004-2007)

Magnetic field

- **Secular torque**

  (Rüdiger & Kitchatinov 1997; Charbonneau & Mac Gregor 1993; Gough & McIntyre 1998; Garaud 2002; Mathis & Zahn 2005; Brun & Zahn 2006; Garaud & Garaud 2008)

- **Instabilities (and dynamo)**

  (Tayler; Spruit 1999-2002; Maeder & Meynet 2004; Braithwaite 2006-2007; Brun & Zahn 2006; Arlt et al. 2007; Kitchatinov & Rüdiger 2007; Gilman et al. 2007; Zahn, Brun, Mathis 2007)

Internal waves

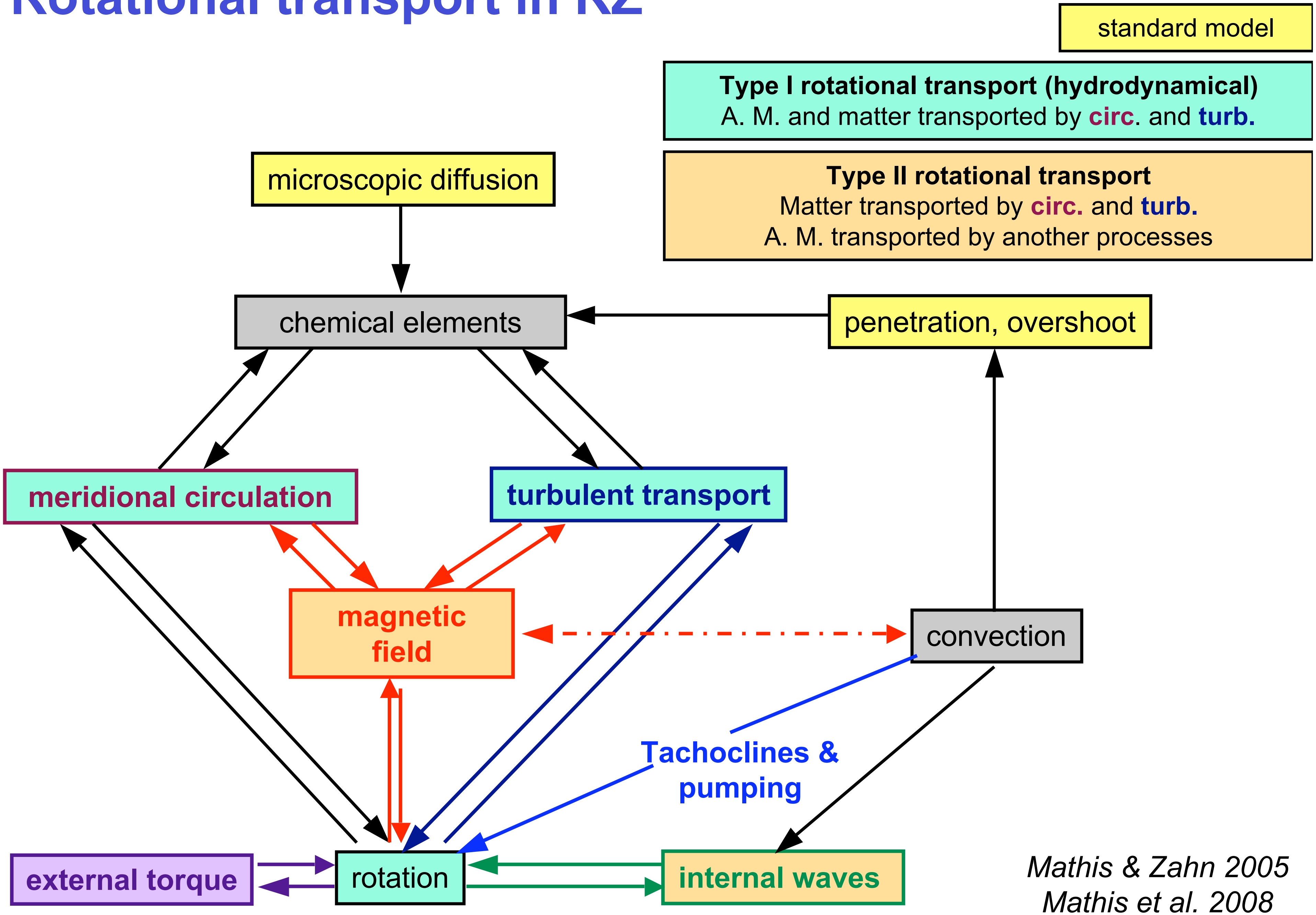
(Press 1981; Schatzman 1993; Montalban & S 1994-96-2000; Talon & Charbonnel 2005; Rogers et al. 2005-2006-2008; Mathis et al. 2008; Mathis 2009)

- excited at the borders with C. Z.
- propagating inside R. Z.
- A. M. settled where they are damped

(Goldreich & Nicholson 1989)

Transport angular momentum (and chemicals) ⟶ modify the dynamics and the evolution of the Sun

Rotational transport in RZ



Mathis & Zahn 2005
Mathis et al. 2008

Transport equations in stellar radiation zones

- Dynamics equation (Navier-Stockes equation)

$$\rho\,[\partial_t \boldsymbol{V} + (\boldsymbol{V}\cdot\boldsymbol{\nabla})\,\boldsymbol{V}] = -\boldsymbol{\nabla} P - \rho\boldsymbol{\nabla}\phi + \boldsymbol{\nabla}\cdot\|\tau\| + \left|\frac{1}{\mu_0}(\boldsymbol{\nabla}\wedge \boldsymbol{B})\right|\wedge \boldsymbol{B}$$

Advection

Turbulent diffusion

Waves

Lorentz torque

- Equation of continuity

$$\partial_t\rho + \boldsymbol{\nabla}\cdot(\rho \boldsymbol{V}) = 0$$

- Induction equation for magnetic field

$$\partial_t \boldsymbol{B} - \boldsymbol{\nabla}\wedge(\boldsymbol{V}\wedge \boldsymbol{B}) = -\boldsymbol{\nabla}\wedge(\|\eta\|\otimes\boldsymbol{\nabla}\wedge \boldsymbol{B})$$

- Equation for the transport of heat

$$\rho T\,[\partial_t S + \boldsymbol{V}\cdot\boldsymbol{\nabla} S] = \boldsymbol{\nabla}\cdot(\chi\boldsymbol{\nabla} T) + \rho\epsilon - \boldsymbol{\nabla}\cdot \boldsymbol{F} + \mathcal{J}(\boldsymbol{B})$$

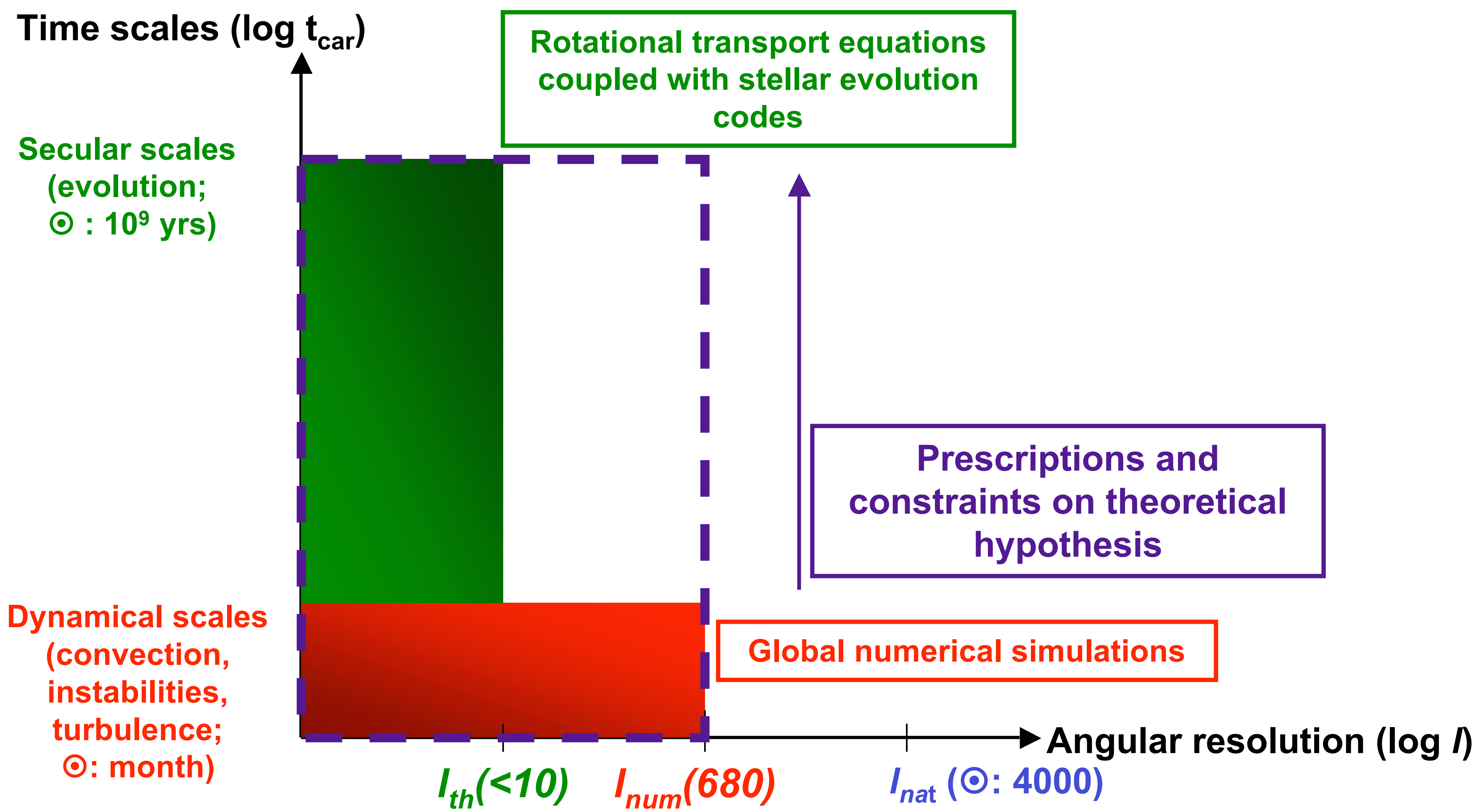
Thermal diffusion perturbing force

Spherical thermal diffusion

Nuclear energy production and heatings due to gravitational adjustments, turbulence and ohmic effects

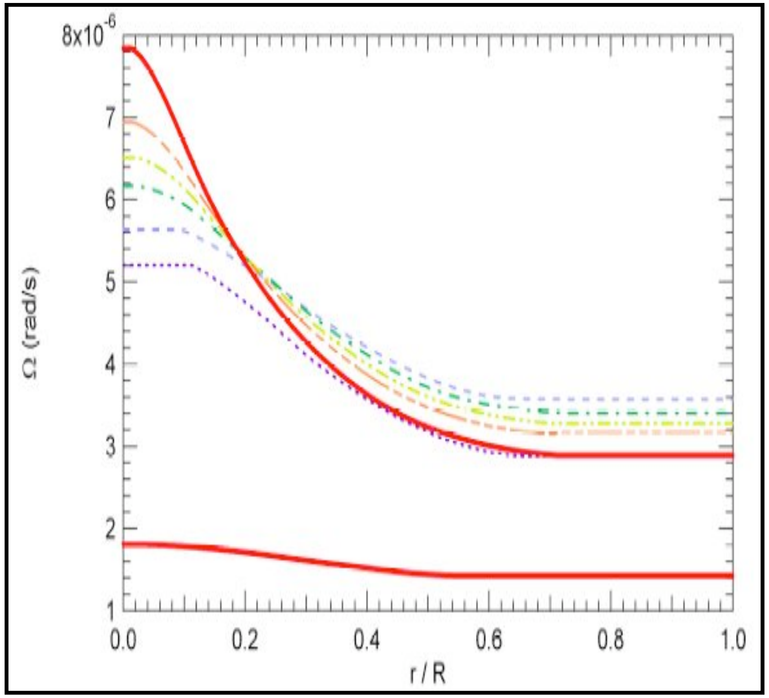
(+ Poisson equation and the transport equation for chemicals)

A multi-scale problem in time and space



Type I rotational transport

The same processes (circulation and turbulence) are responsible for the transport of angular momentum and the mixing of chemicals



Turck-Chièze et al. 2010

It does not reproduce the flat rotation profile of the solar radiative interior!

(Talon & Zahn 1998, Talon & Charbonnel 2005, Turck-Chièze et al. 2010)

Another process is responsible for the transport of angular momentum

Type II Rotational Transport

Circulation and turbulence are responsible for
the mixing of chemicals;

Another process operates for the transport of angular momentum;
has indirect impact on mixing, by shaping the rotation profile

Magnetic field ?

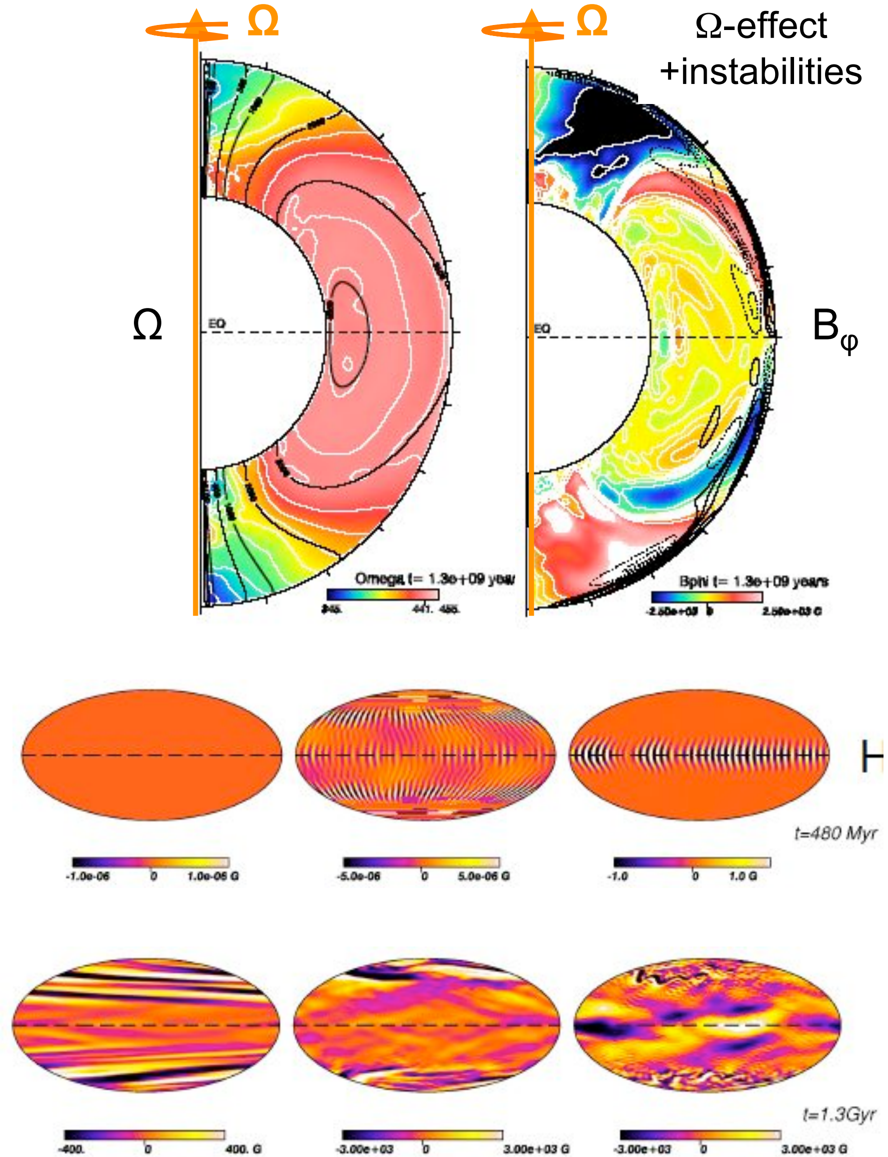
Internal Gravity Waves ?

Magnetic transport in radiation zones

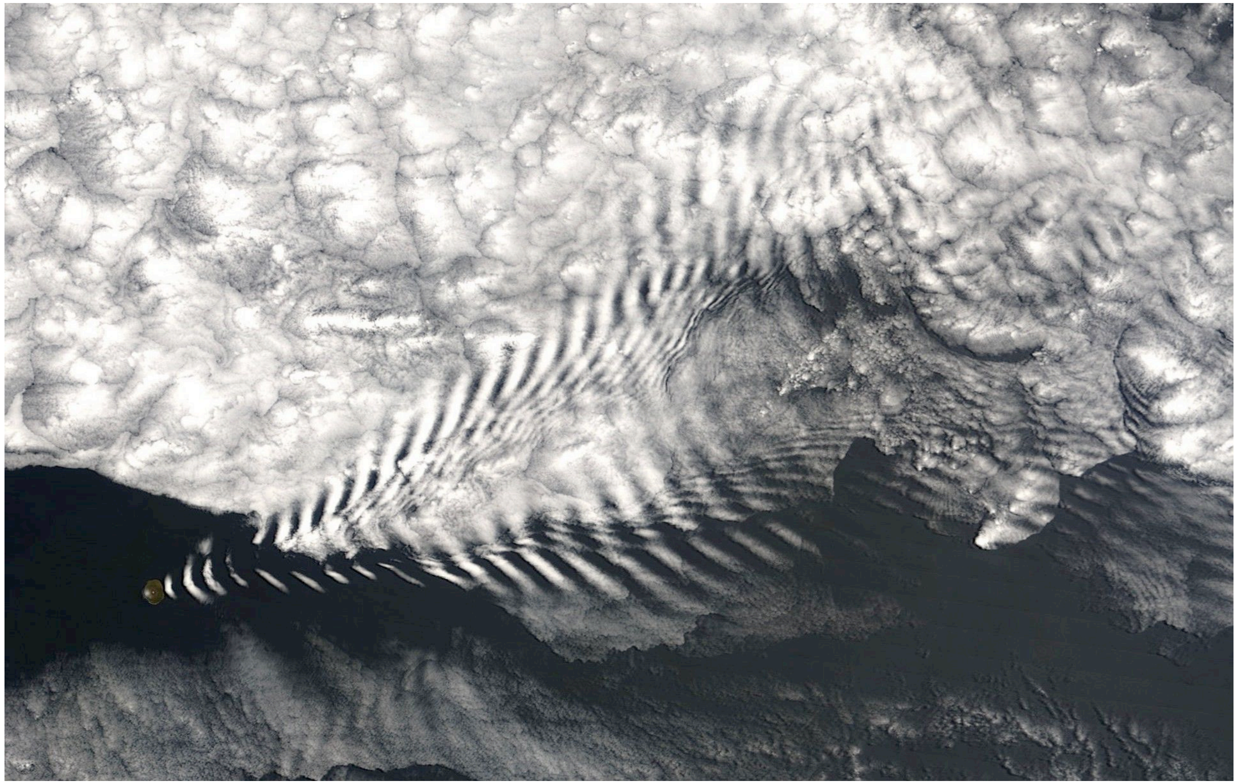
- Ferraro's law (even if penetrating flows)
- 3D non-axisymmetric MHD instabilities (wave-like);
- on the track of a potential dynamo

3D solutions ASH code

Brun & Zahn 2006; Zahn, Brun & Mathis 2007



Internal Gravity Waves



Transport of angular momentum by internal waves

Basis

Cause of transport: **thermal and viscous diffusions**

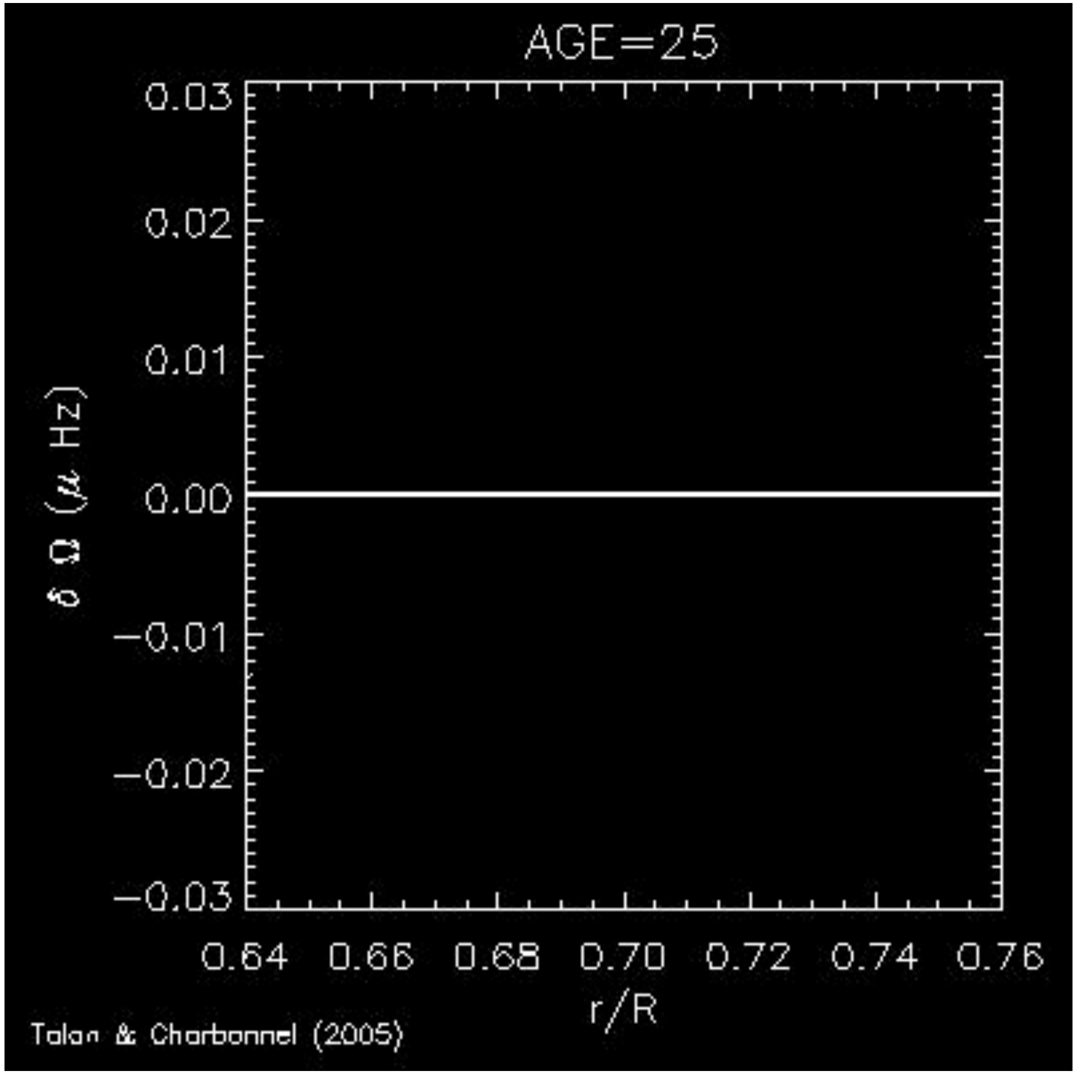
- Retrograde waves (m>0) → extract angular momentum (-δΩ)
- Prograde waves (m<0) → deposit angular momentum (+δΩ)

→ High horizontal degree waves damped before low-degree ones

If prograde and retrograde waves are equally excited:

- No differential rotation → no net deposition of A. M.
- Differential rotation → Doppler shift → net deposition of A. M.

Transport by high degree waves below the convection zone: the Shear Layer Oscillation



Talon & Charbonnel 2005

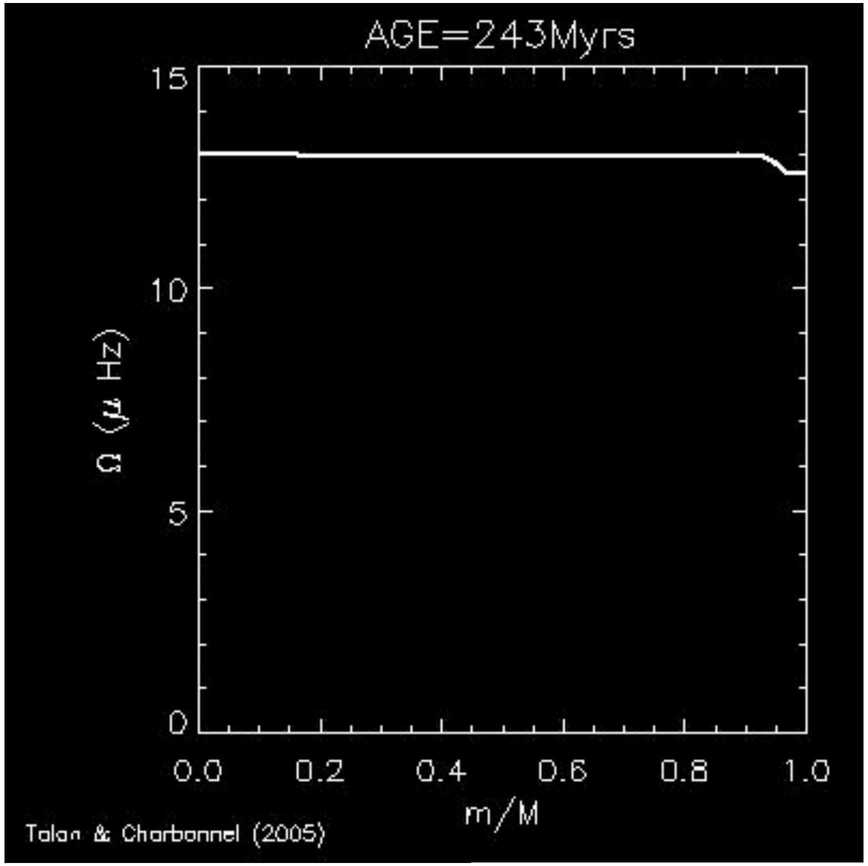
Dynamical vision of a $1M_{\odot}$ star with magnetic braking (V_i=50 $Km.s^{-1}$) and the advection

1D simulation:
Ω averaged over latitude

Strong dissipation region; oscillating differential rotation

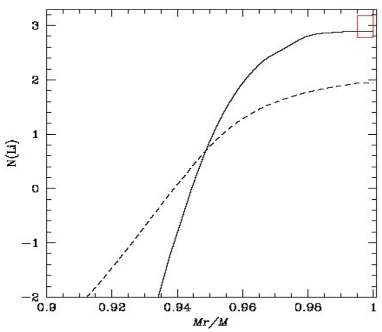
Internal waves cycle?

Transport by low degree (l≈10), low frequency waves (ν<5μHz): the secular extraction



Talon & Charbonnel 2005

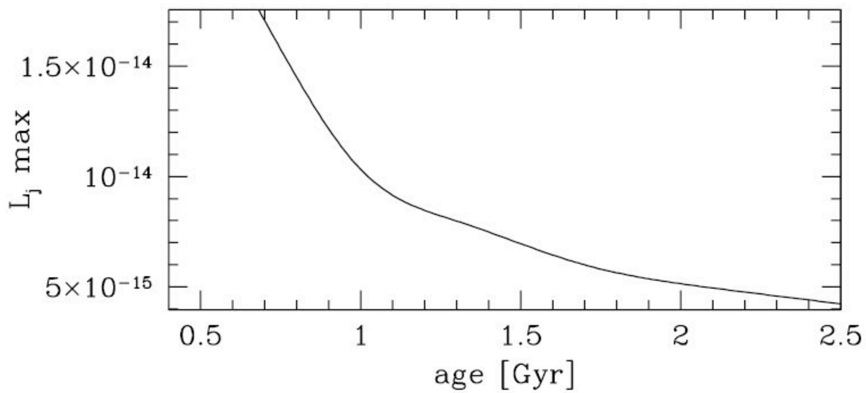
Li (0.7 Gyr)



Hyades

Effects of the SLO filtered out

Low degree retrograde waves propagate in the interior → A. M. extraction driven by the wind



Could provide the rotation profile of the solar radiative interior

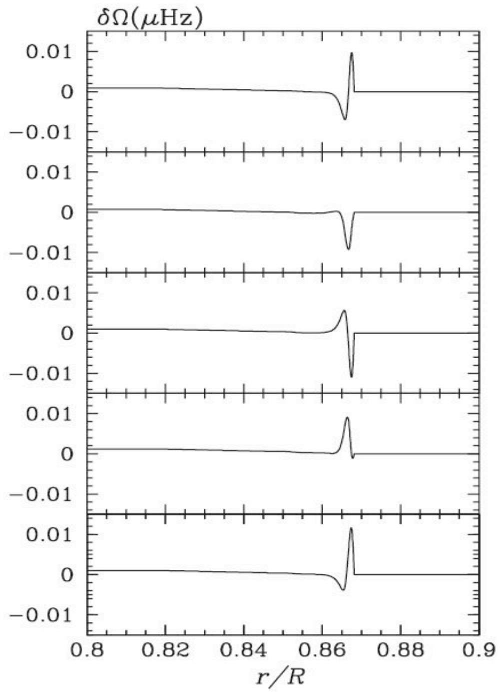
Transport of Angular Momentum by internal waves

If prograde and retrograde waves are equally excited:

- No differential rotation → no net deposition of A. M.
- Differential rotation → Doppler shift → net deposition of A. M.

High degree waves below the convective zone:

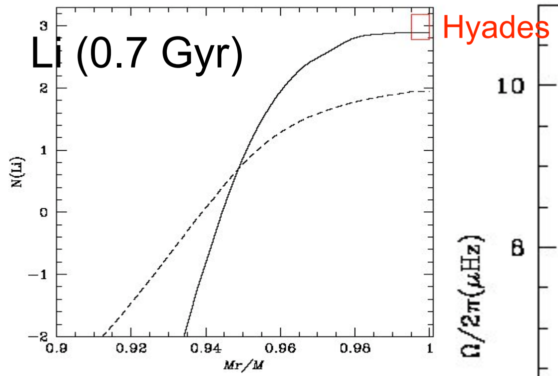
Shear Layer Oscillation



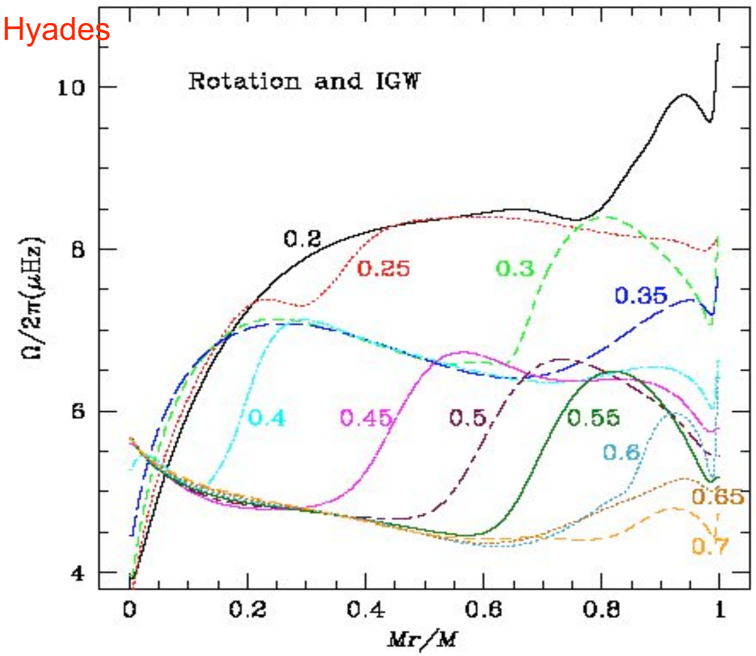
Transport by low degree (l≈10), low frequency waves (ν<5μHz)

Secular A. M. extraction driven by the wind (S.L.O. filtered out)

→ **nearly uniform rotation profile (cf. solar R. Z.)**



Talon & Charbonnel 2005



Dynamical vision of a 1.2 $M_\odot$ star with the magnetic braking (V_i=50 $Km.s^{-1}$);
1D simulation: Ω averaged over latitudes

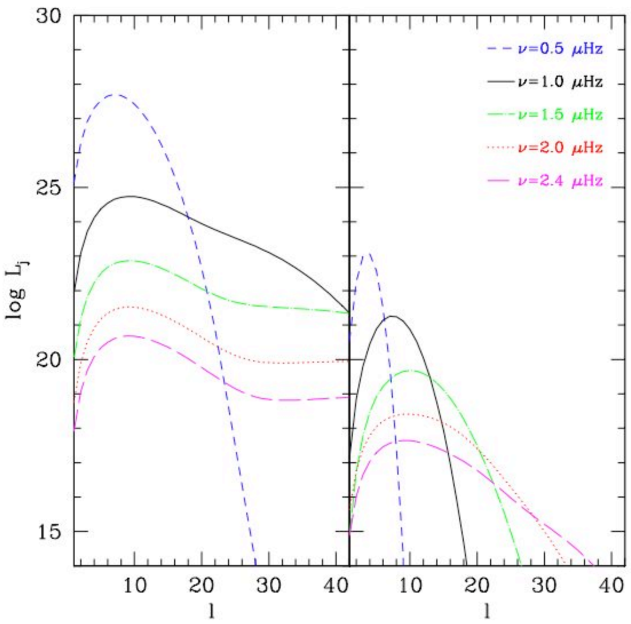
Diagnosis and identification

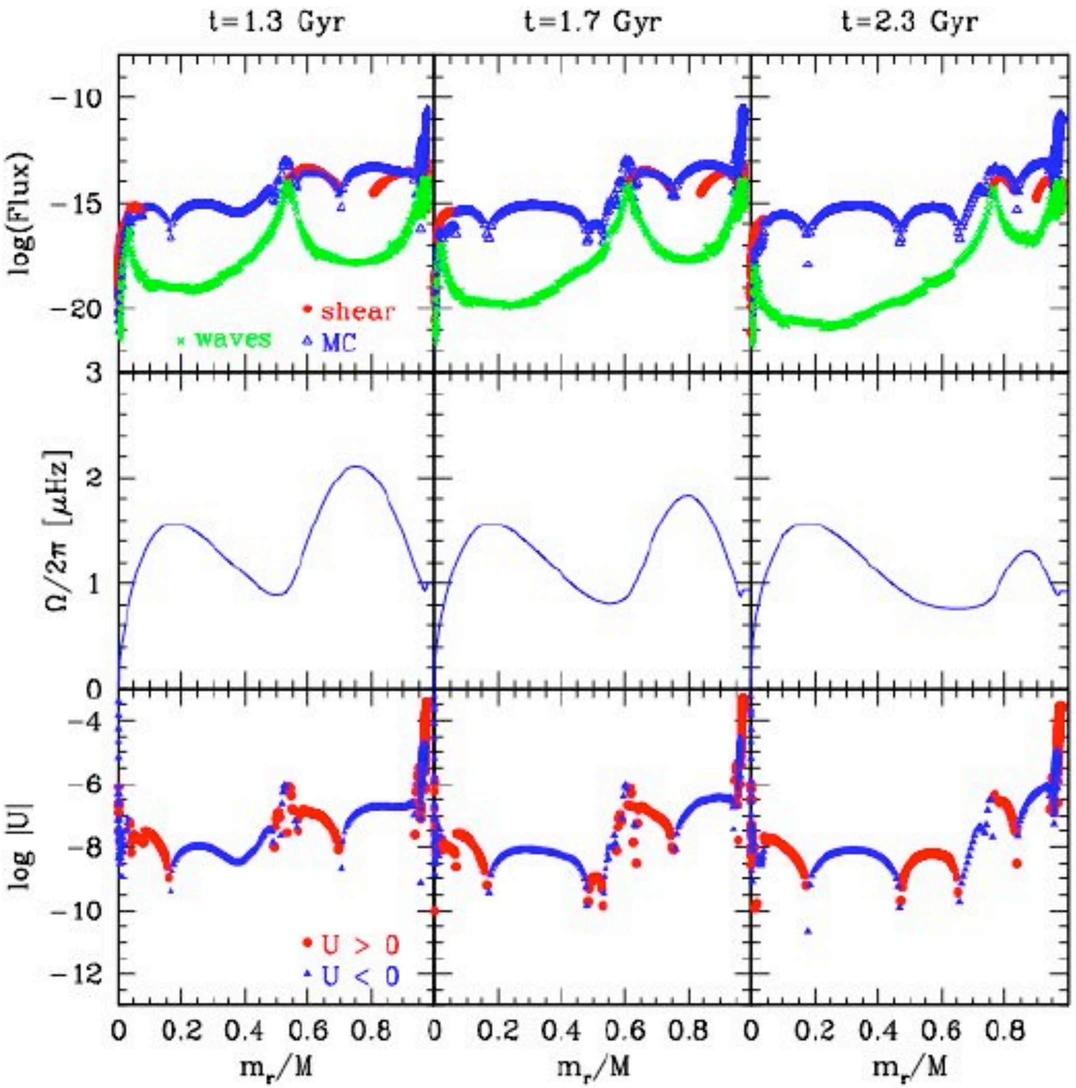
Dynamical vision of the evolution of a $1M_{\odot}$ star with magnetic braking (V_i=50 km.s^{-1})

Secular extraction of angular momentum with an associated **highly multi-cellular** meridional circulation

→ **Transport driven by the braking** at the surface and the **associated extraction fronts**

Spectrum of the Action of A. M. at r_c & r_{max}



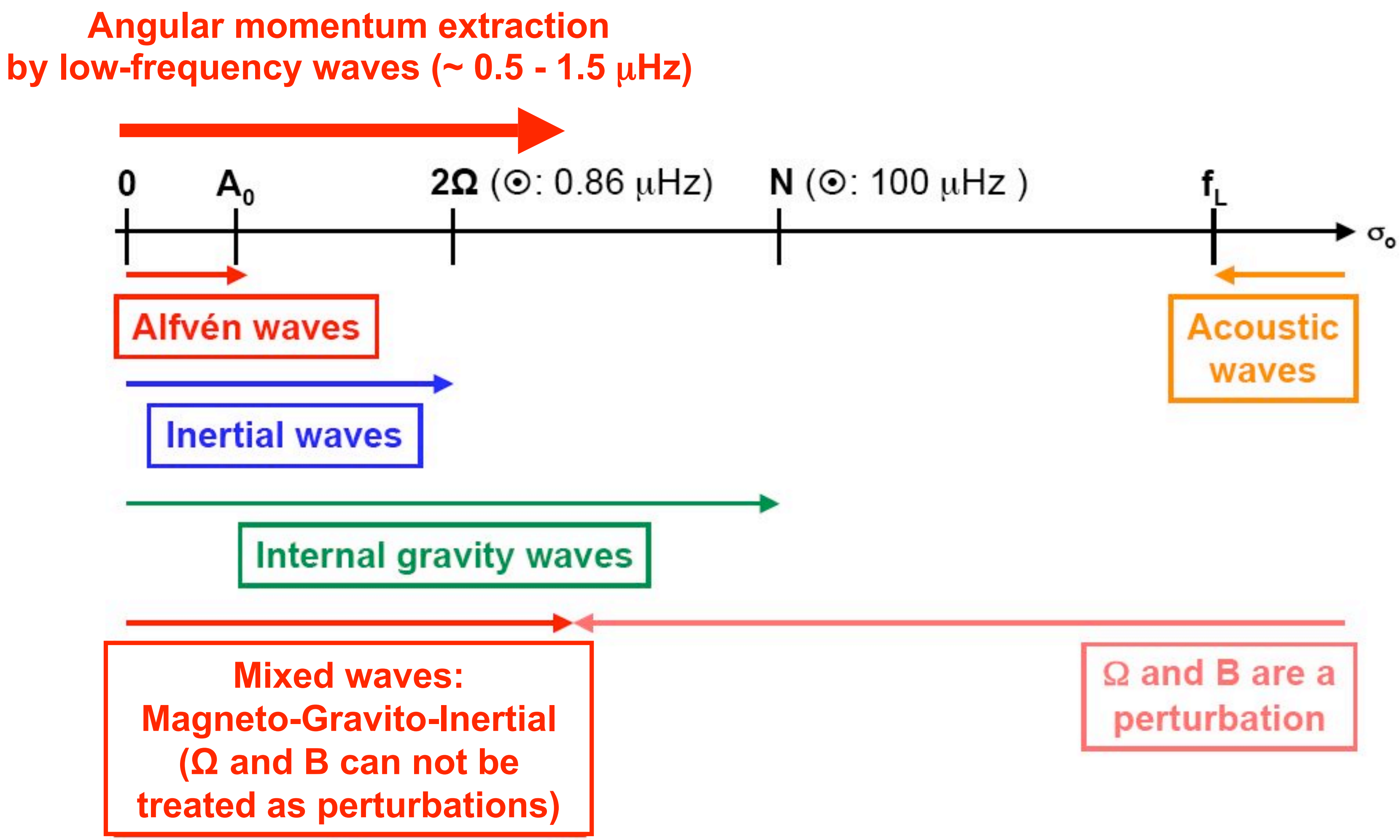


Mathis, Eggenberger, Talon, Charbonnel; in prep.

Modelling weaknesses

- Need for prescriptions for wave excitation by turbulent convection
- Effects of rotation and magnetic field are not taken into account
- Non-linear effects (critical layers and breaking) are not treated

Ω & B effects in the treatment of internal waves: a necessity

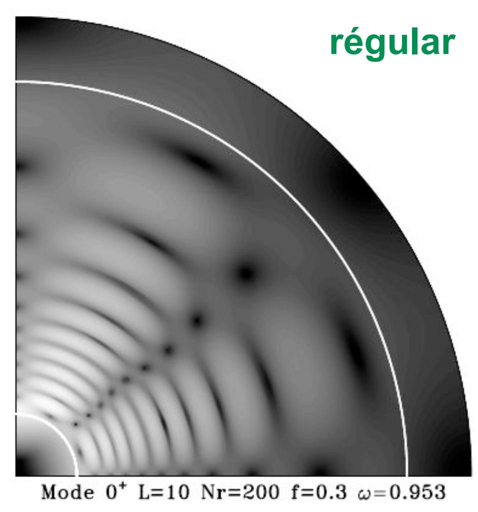


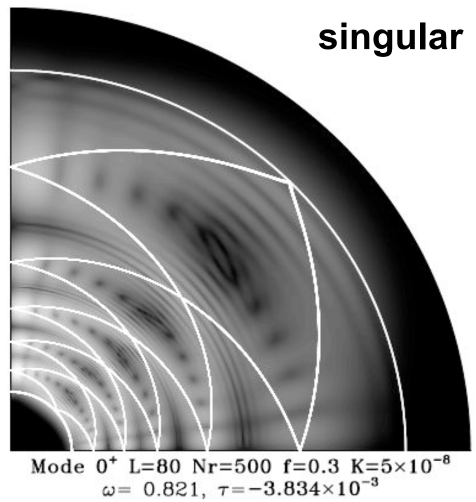
Mathis 2009-2010

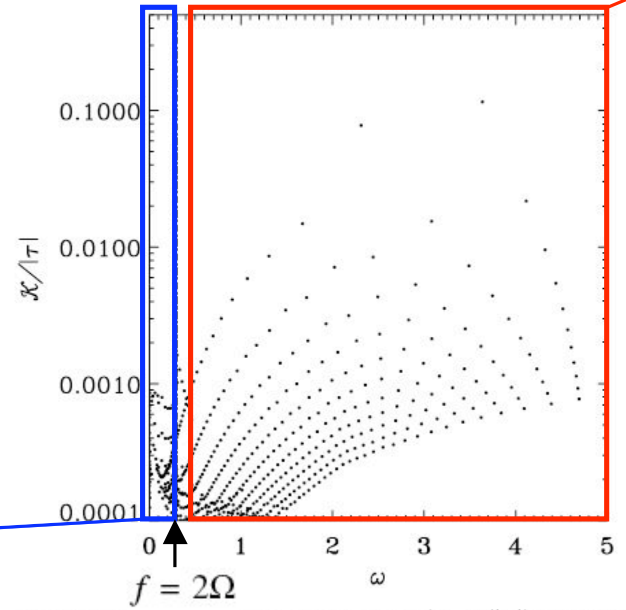
The G.-I. waves: different families

Elliptic waves

$\widetilde{E}_1 : \quad 2\Omega < \omega < N$





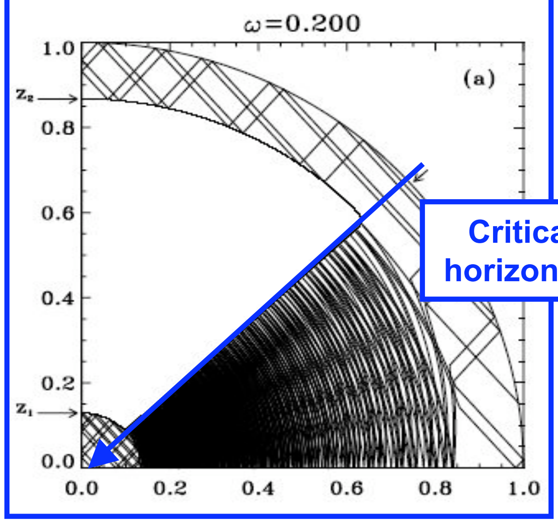


Hyperbolic waves

Fig. 9. Distribution in the complex plane $(\omega, \mathcal{K}/|\tau|)$ of the eigenvalues with $f = 0.3$, $m = 0^+$ and $\mathcal{K} = 5 \times 10^{-5}$. The resolution is $L = 22$ and $Nr = 100$.

Dintrans & Rieutord 2000
(1.5 $M_\odot$; solid-body rotation)

$\widetilde{H}_2 : 0 < \omega < \min(2\Omega, N)$

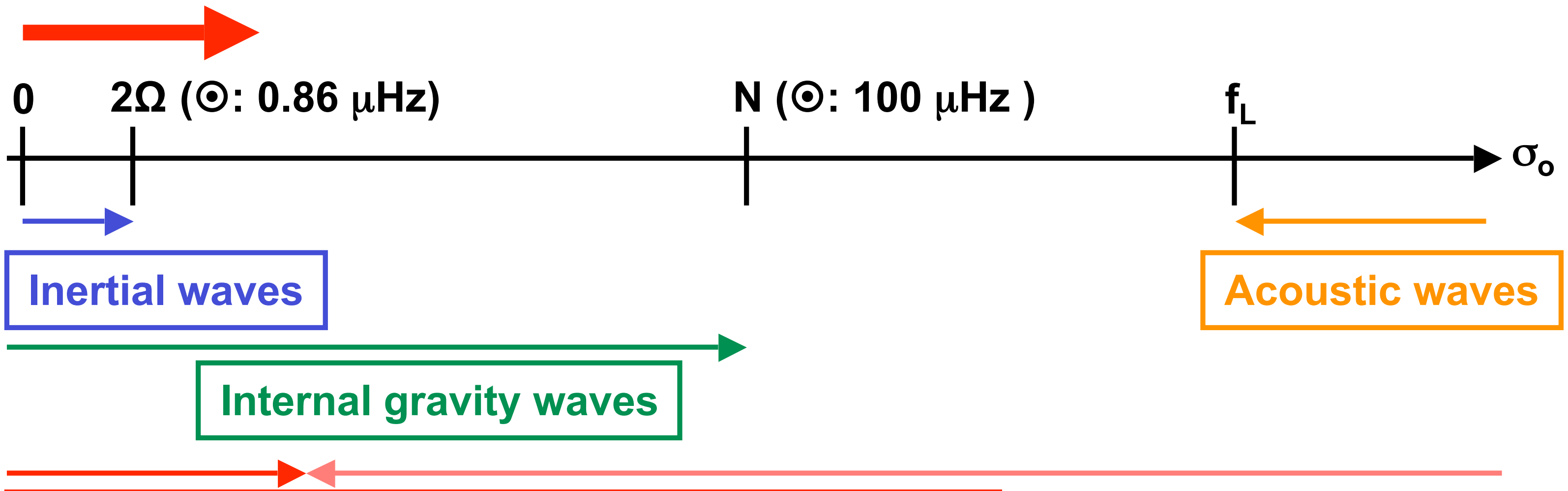


Critical latitude:
horizontal trapping

$$\Lambda = \omega + i\tau$$

Transport of angular momentum by regular G.-I. waves

Angular momentum extraction by low frequency waves

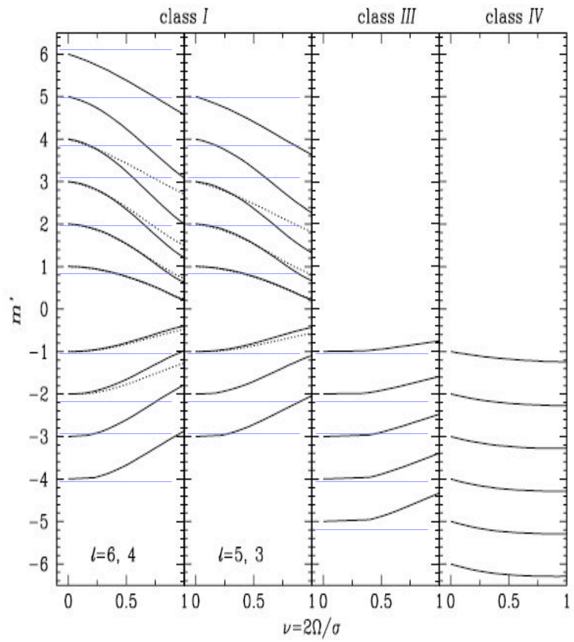


Rotation can not be treated as a perturbation
Gravito-Inertial waves

Regular *Mathis et al. 2008, Mathis 2009*

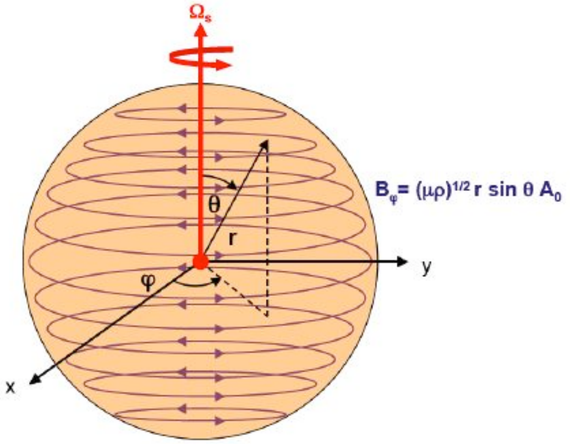
- **Class I** (gravity waves + Coriolis) **reduction**
- **Class II** (conservation of specific vorticity+curvature, retrograde waves; Rossby waves) **not excited in this regime**
- **Class III** (mixed class I & class II; Yanai waves) **reduction**
- **Class IV** (conservation of specific vorticity+stratification, prograde waves; Kelvin waves) **positive A. M. transport**

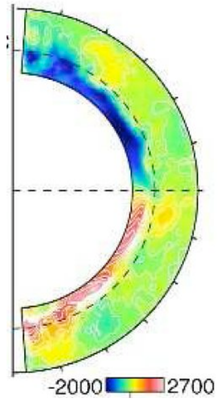
Singular (shear layers) *Dintrans & Rieutord 2000*



Magnetic field effects on internal waves

The set-up:





(cf. Browning et al. 2006)

Rogers et al. 2010, Mathis 2010

Control parameter:

$$\nu_{\rm M} = \nu_s \frac{(1 - m\Lambda_{\rm E})}{\left(1 - \frac{m^2}{2}\nu_s \Lambda_{\rm E}\right)}$$

$$\nu_s = \frac{2\Omega_s}{\sigma_s} = R_o^{-1}$$

Rossby number

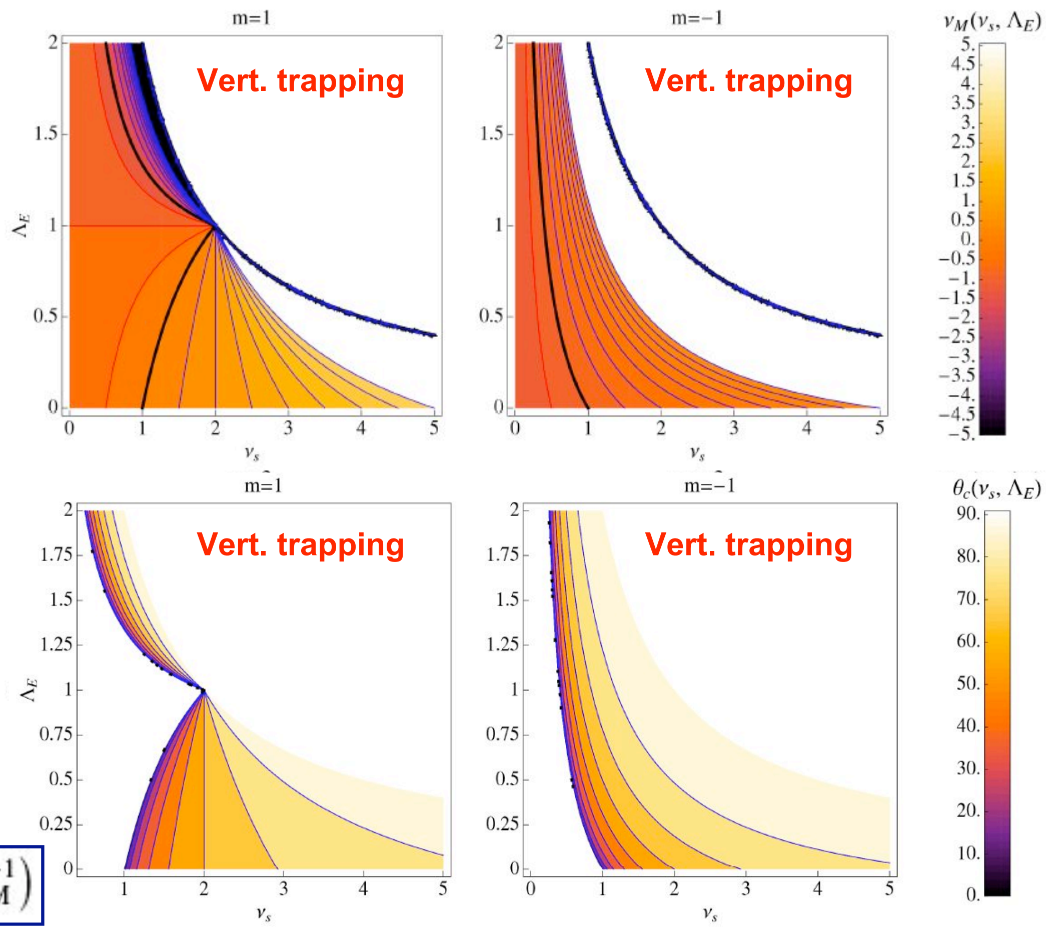
$$\Lambda_{\rm E} = \frac{A_0^2}{\Omega_s \sigma_s}$$

Elsasser number

Allowed region (regular waves)

Forbidden region (singular waves)

m>0 - retrograde
m<0 - prograde



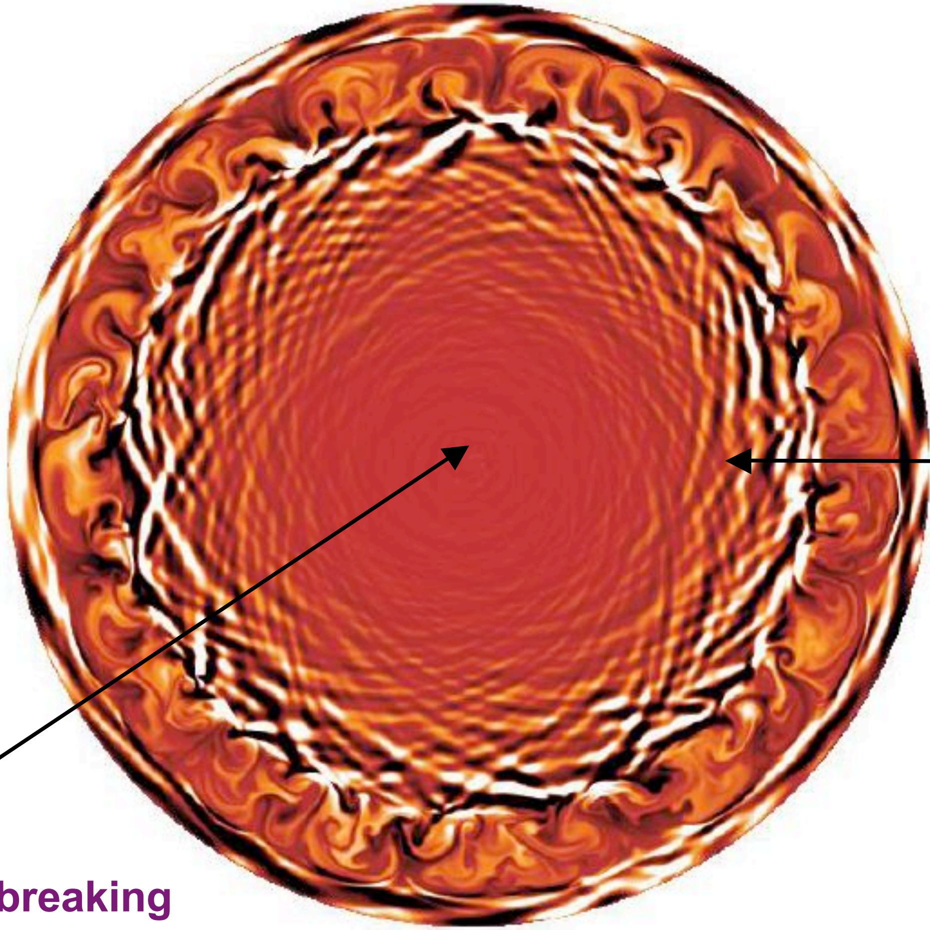
Waves regular in spherical shell(s) where:

→ $|\nu_{\rm M}| < 1$

$$\theta_c = \cos^{-1}\left(\nu_{\rm M}^{-1}\right)$$

Non-linear effects

Corotation when
$-m\Omega=\omega$



Non-linear excitation

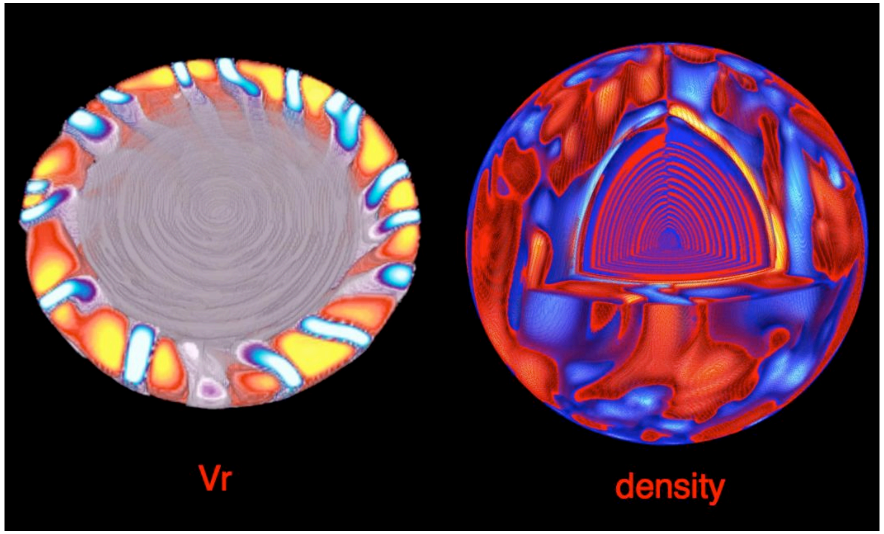
Central focussing and breaking

Booker & Bretherton 1957,
Rogers et al. 2008,
Barker & Ogilvie 2010,
Mathis & Belkacem (WIP)

Mode and internal wave excitation

Numerical simulations of penetrative convection

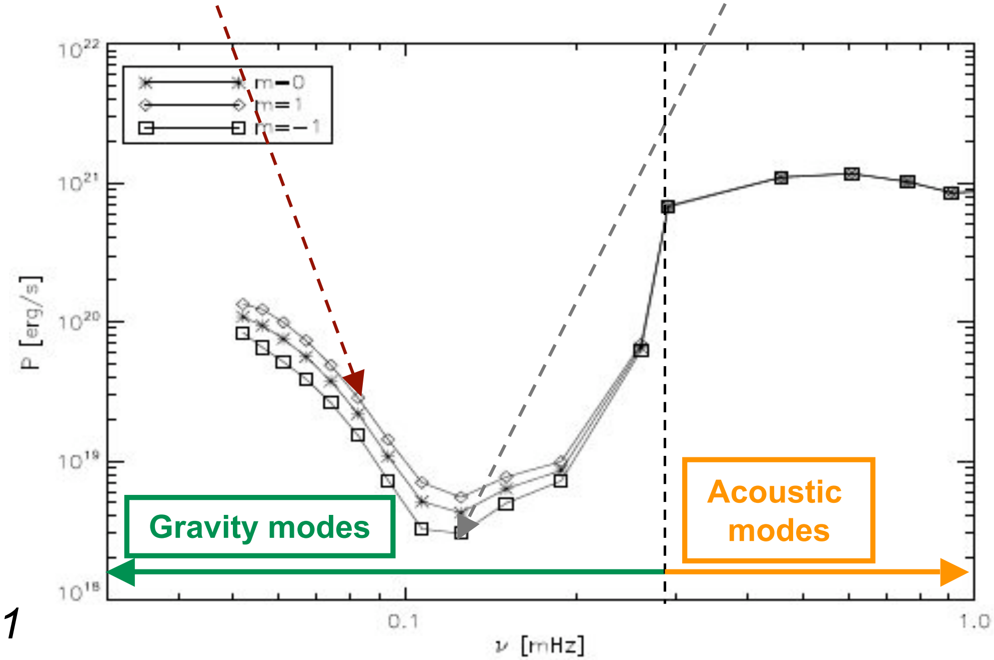
Spectrum and flux of the excited waves
Kiraga et al. 2003-2005, Dintrans 2005,
Rogers et al. 2005-2006-2008,
work in progress ***Brun et al.***



Analytical treatment of volumic excitation

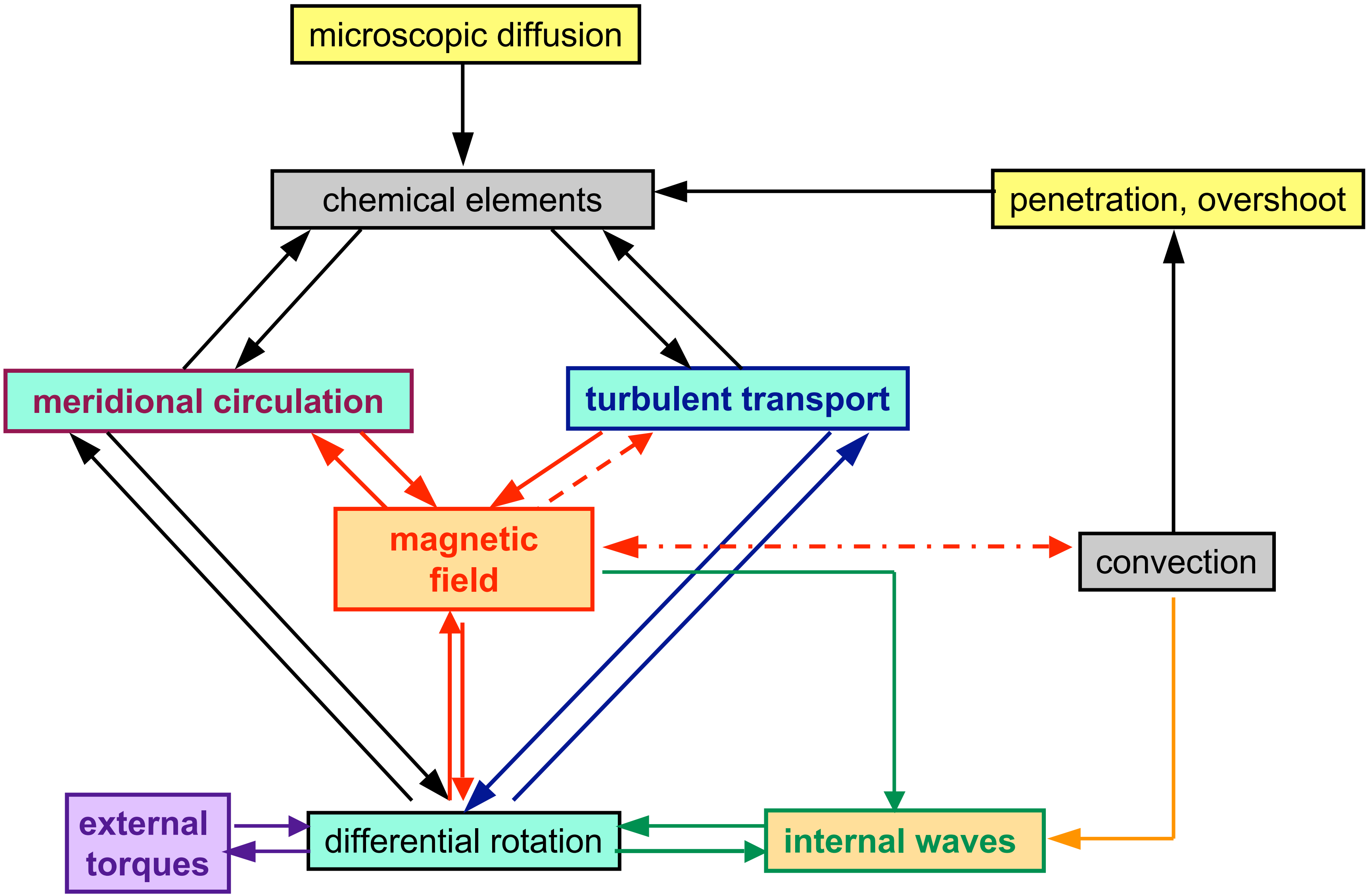
Goldreich, Murray & Kumar 1994 used
by Talon & Charbonnel 2003-2004-2005,
Samadi et al. 2001, Belkacem et al. 2008-09,
Belkacem, Mathis, Goupil, Samadi 2009

Asymmetry in
retrograde (m>0) and prograde (m<0)
wave excitation



l=1

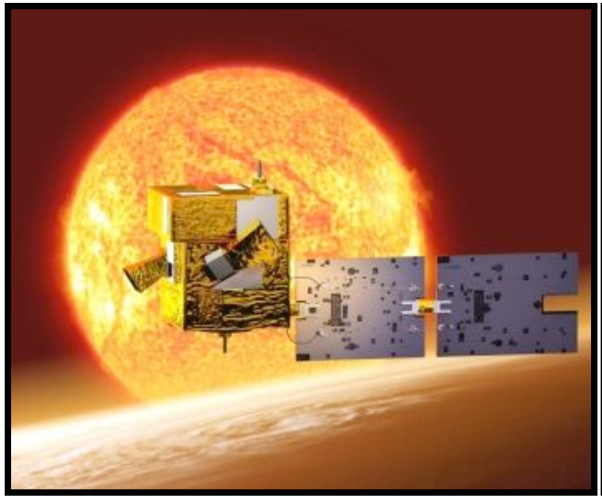
Towards a complete picture

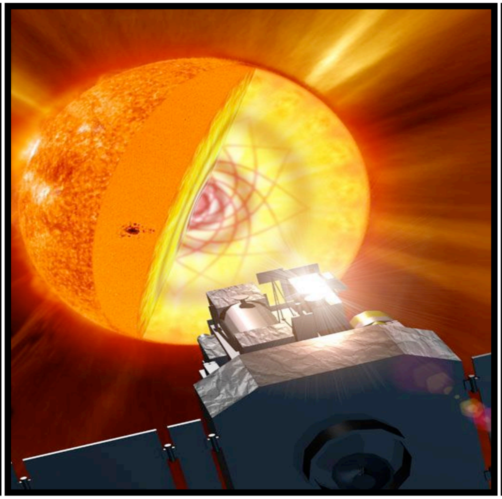


Context

- Helio and asteroseismology spatial missions
(SOHO, SDO, **PICARD**, Golf-NG, Solar Orbiter;
MOST, COROT, KEPLER, PLATO)

- Powerful ground-based instruments
(BiSON, GONG; EsPaDonS,
HARPS, SONG)





- Numerical simulation of stellar
(magneto-)hydrodynamics (ASH, ESTER)

- Laboratory experiments relevant for
astrophysical plasmas (ITER, LIL)

→ **Dynamical vision of the Sun (and stars)**