2D ROTATIONAL DYNAMICS OF STARS' RADIATIVE ZONE

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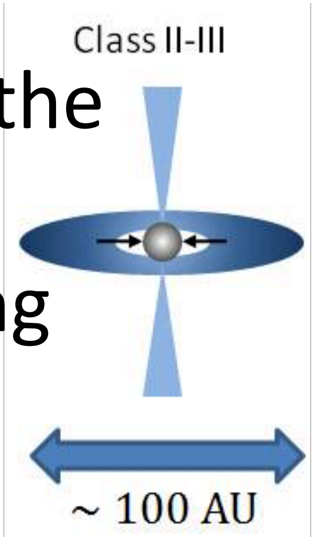
Post-doc seminar
25/10/16

ACADEMIC BACKGROUND



- 2012-2015 PhD with Michel Rieutord on the

"2D dynamics of the radiative zone of fast rotating intermediate mass stars undergoing gravitational contraction"

At IRAP, Toulouse.

- Since November 2015 Post-doc with Stéphane Mathis on "Mechanisms of angular momentum transport in stars" (ERC SPIRE, LDEE).

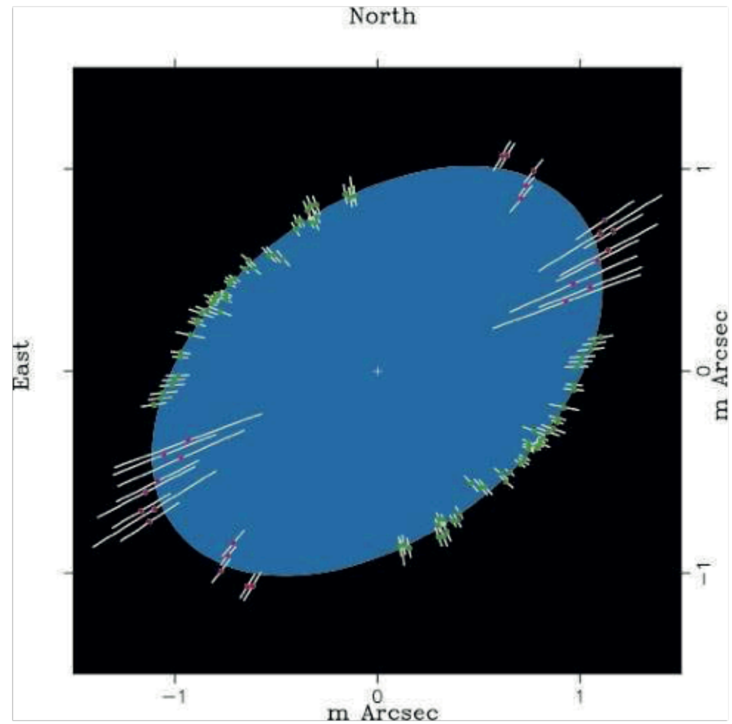
KEY WORDS OF WHAT I DO:

- Studied objects: **Stars**, their radiative zone (stable stratification)
- Tools: **2D numerical simulations**
  solving **hydrodynamics** equations
  analytical studies
- Codes: LSB, ESTER
- To characterize: the internal **rotation field** and angular momentum transports
- Resulting from: baroclinic state, gravitational contraction, dynamical boundary conditions
- Soon: magnetic field, internal gravity waves

0.5 - 1.5 solar masses

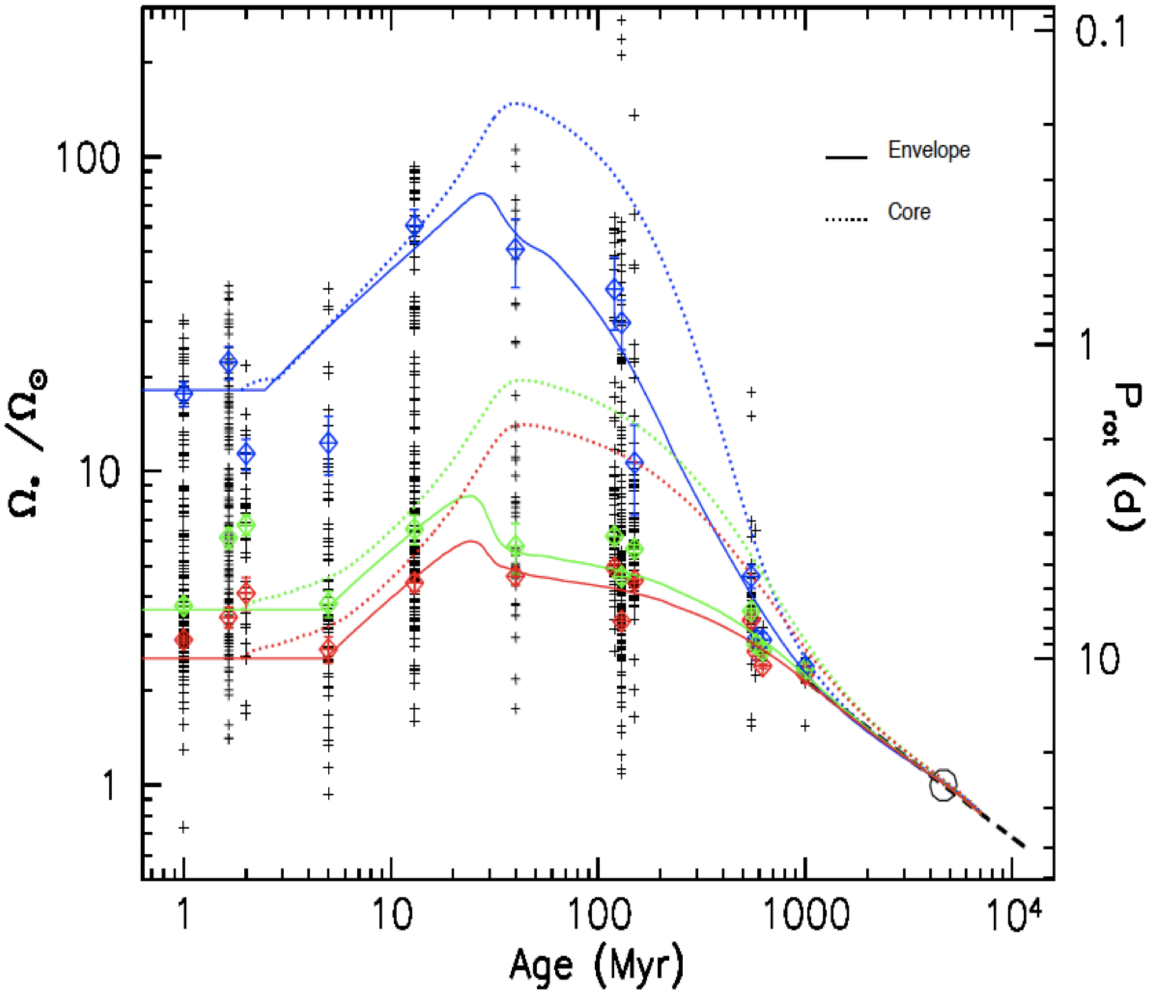
WHY 2D MODELS?

- Interested by the stellar rotation
- Intrinsically multidimensional
- 1D models good for slow rotation rate
- 3D models devoted to small timescales



Interferometric observations of Achernar
Domiciano de Souza et al. 2003

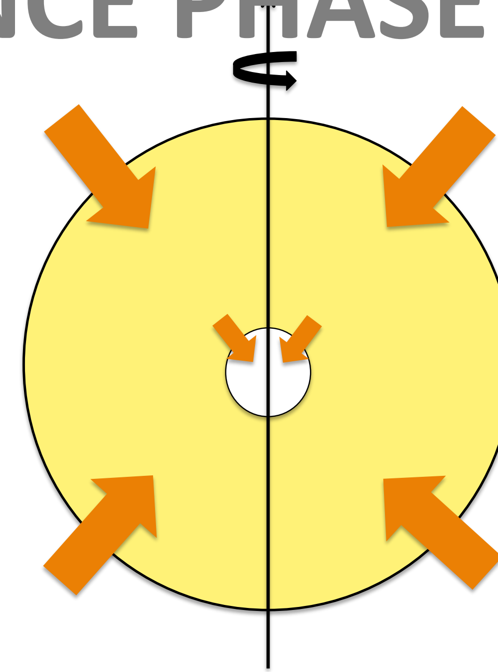
SCIENTIFIC CONTEXT OF THE PhD



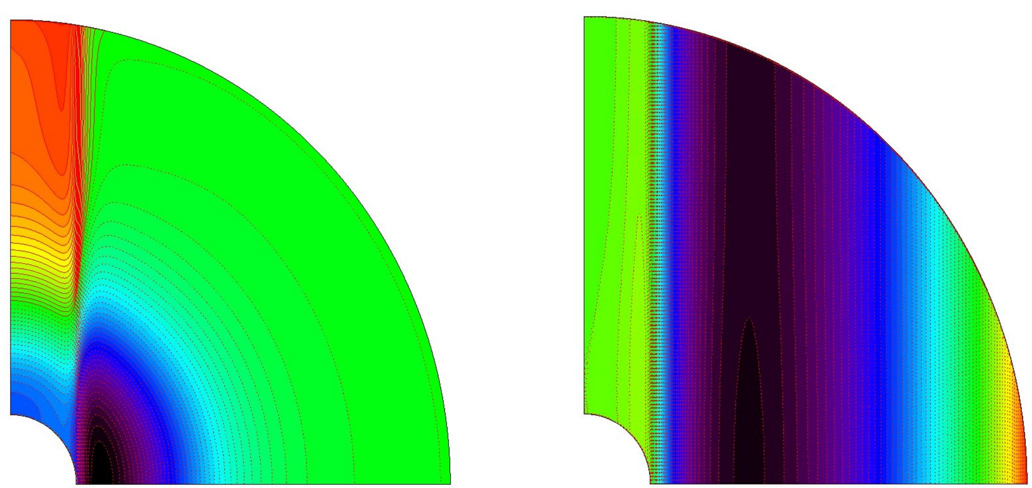
Gallet Bouvier 2013

- We do not know the **dynamical history** of stars
- Large spread of rotational velocity of stars on the main sequence
- Need for dynamical initial conditions: the **pre main sequence phase**

THE PRE MAIN SEQUENCE PHASE

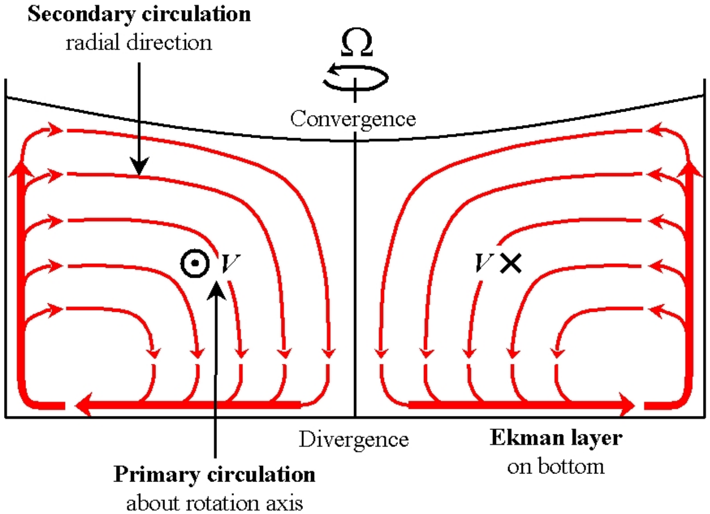


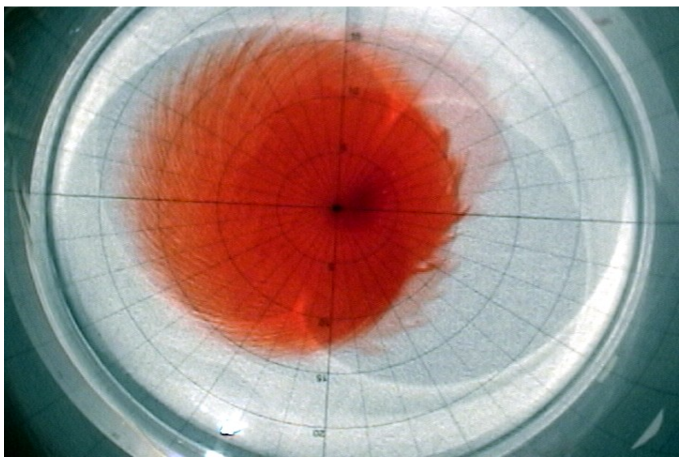
- Intermediate mass stars: large radiative core
- Phase of gravitational contraction: induces a **spin-up flow**
- Competition between the baroclinic solution and the spin up solution

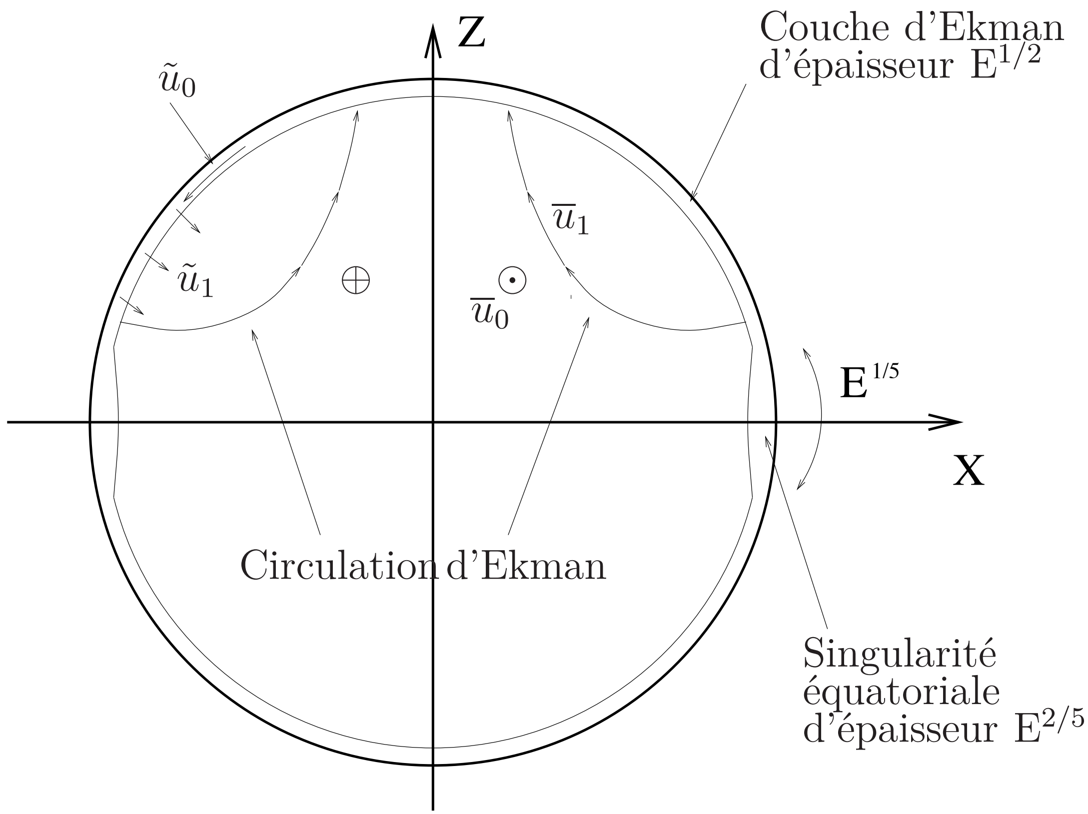


SPIN-UP FLOWS

Quasi steady flows arising when a fluid rotating at **Ω** is accelerated to **Ω+ΔΩ**







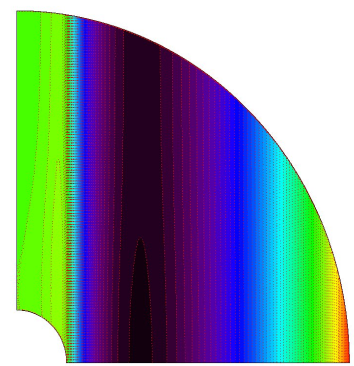
MAIN RESULTS

- The flow induced by the contraction has a higher amplitude at the end of the Pre Main Sequence phase:

Universal differential rotation at the ZAMS

Columnar structure

Needs a 2D description



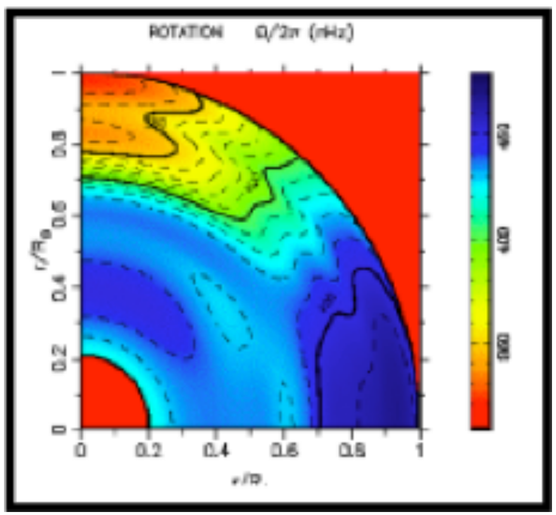
- Presence of a

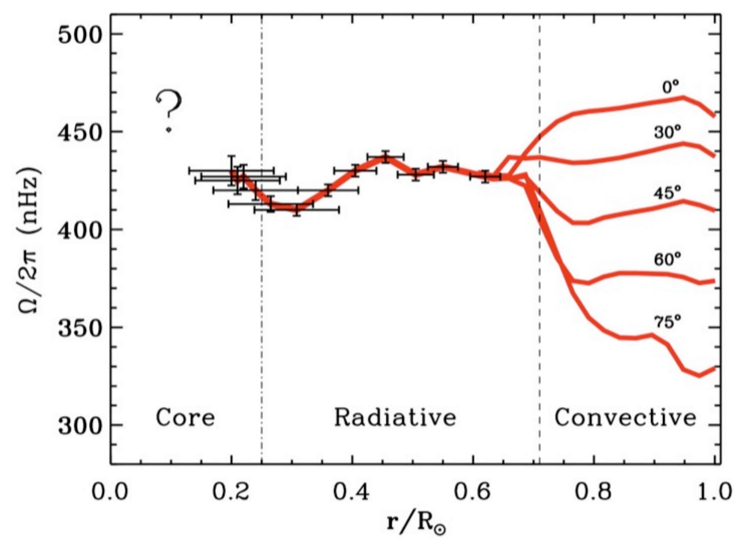
Stewartson layer: will be important for massive stars and evolved stars

POST-DOC: LOW MASS MAIN SEQUENCE STARS

Helioseismology: until 0.2Rsun the radiation zone rotates as a solid body.
Asteroseismology: Ω_c/Ω_s of numerous main-sequence, subgiant and giant stars (Benomar et al. 2015, Kurtz et al. 2014, Triana et al. 2014, Saio et al. 2015, Murphy et al. 2016, Deheuvels et al. 2012, Deheuvels et al. 2014, Deheuvels et al. 2016, Beck et al. 2012, Mosser et al. 2012) weaker than predicted: sign of a strong transport of angular momentum in stellar radiative zones

new constrains for stellar modelling

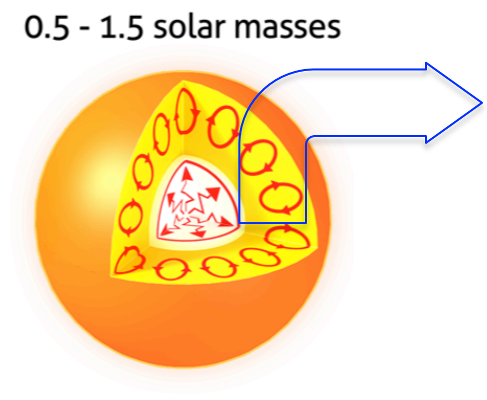


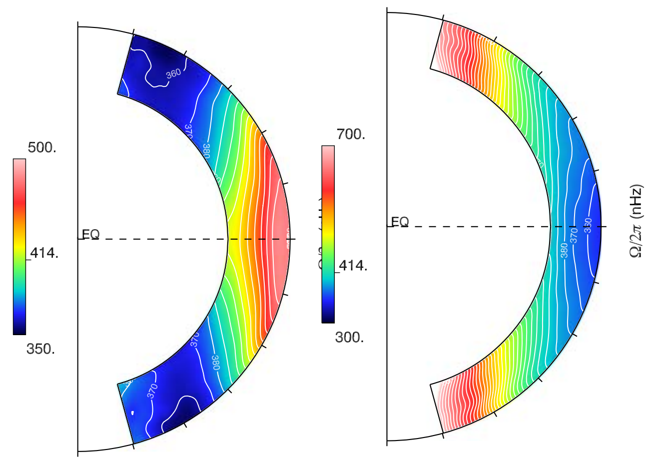


Garcia et al. 2007

Call for 2D hydrodynamical models on secular timescale

What 3D modelling tells



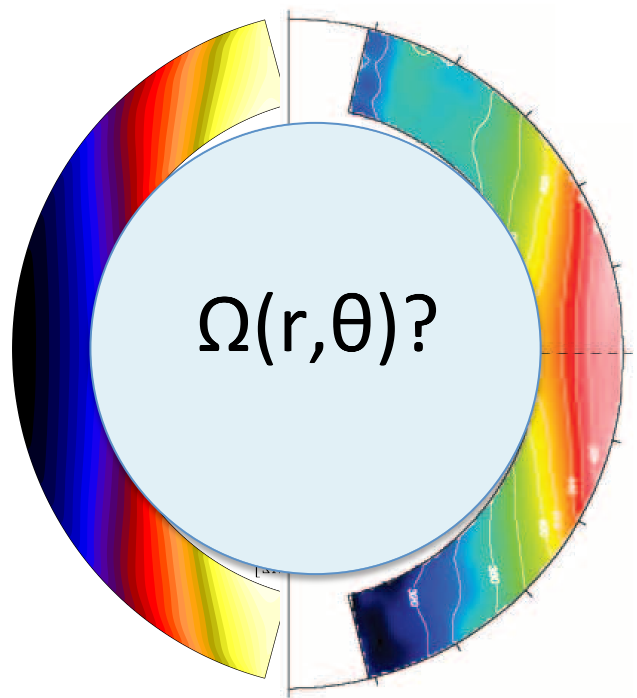


Matt et al. 2011

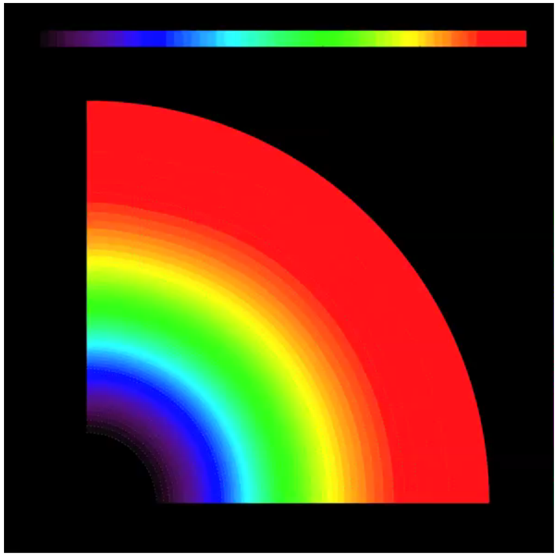
Different types of differential rotation in convective envelope

Need a general treatment:

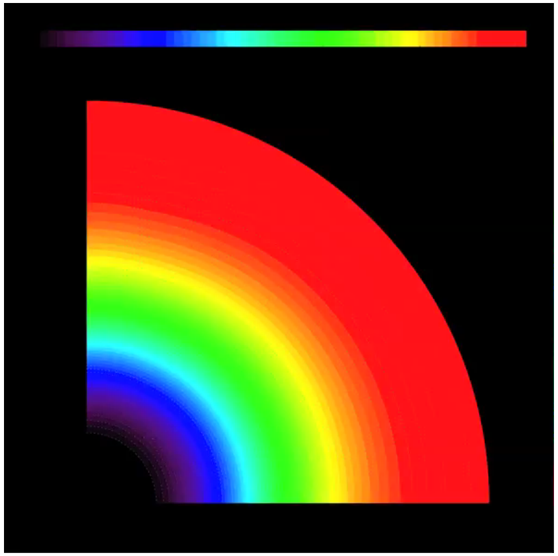
Parametrized dynamical boundary condition



DIFFERENTIAL ROTATION OF THE RADIATIVE CORE OF LOW MASS STARS



Solar-like shear

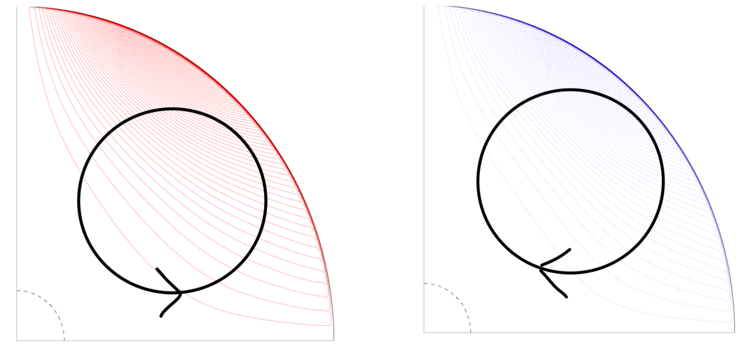


Anti-solar shear

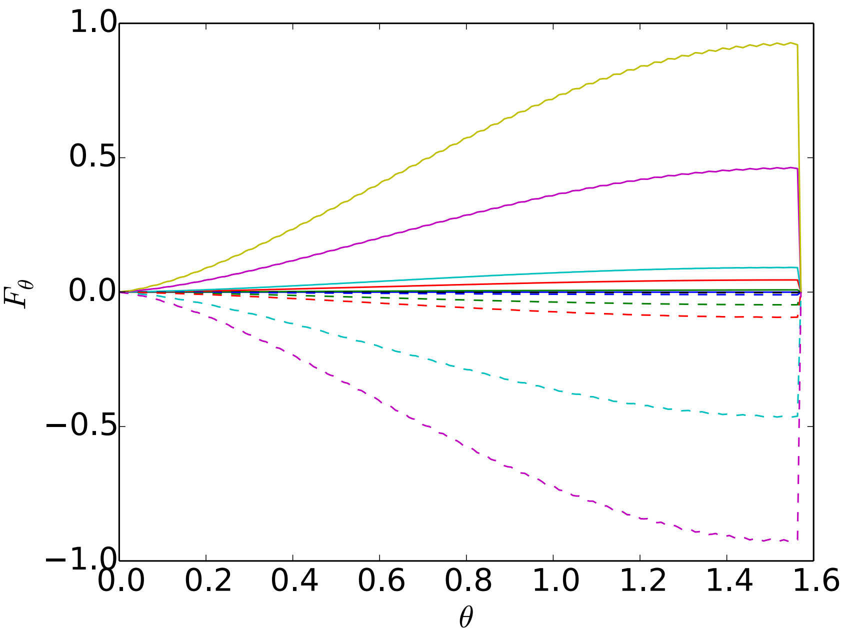
Increasing the shear leads to a quasi cylindrical differential rotation

FLUX OF ANGULAR MOMENTUM

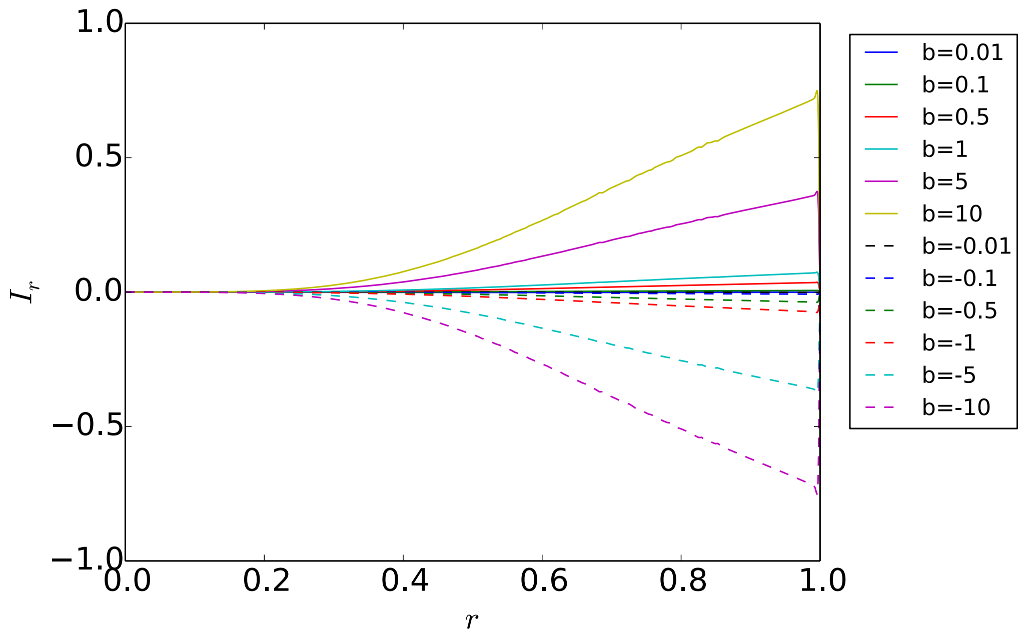
b > 0



b < 0

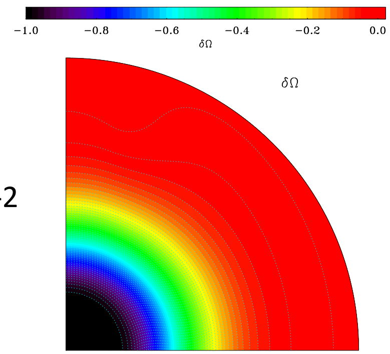


Latitudinal flux of angular momentum near surface α u_θ



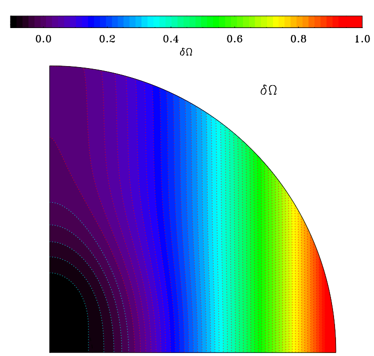
Averaged over latitude radial flux of angular momentum α $u^{l=2}$

CORE-TO-SURFACE ROTATION RATIO

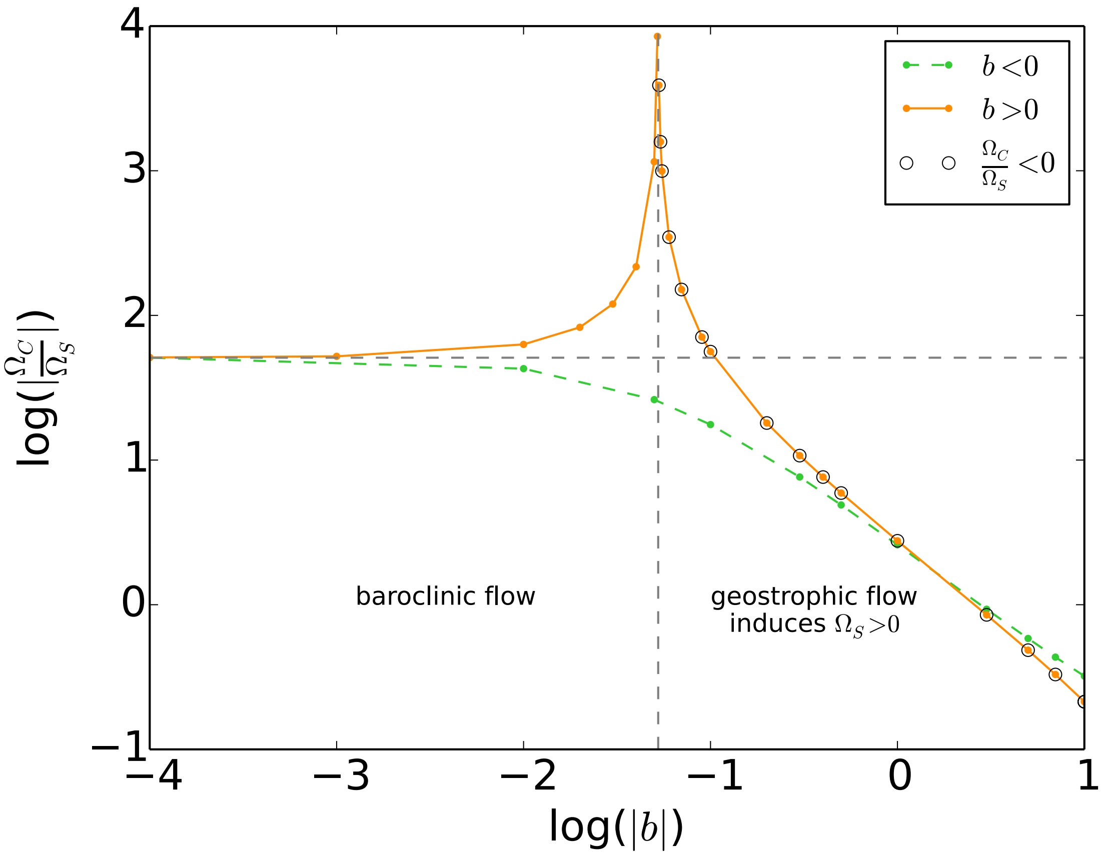


b=10^{-2}

Transition shellular-like
Cylindrical differential rotation
= weakest Ω_c/Ω_s

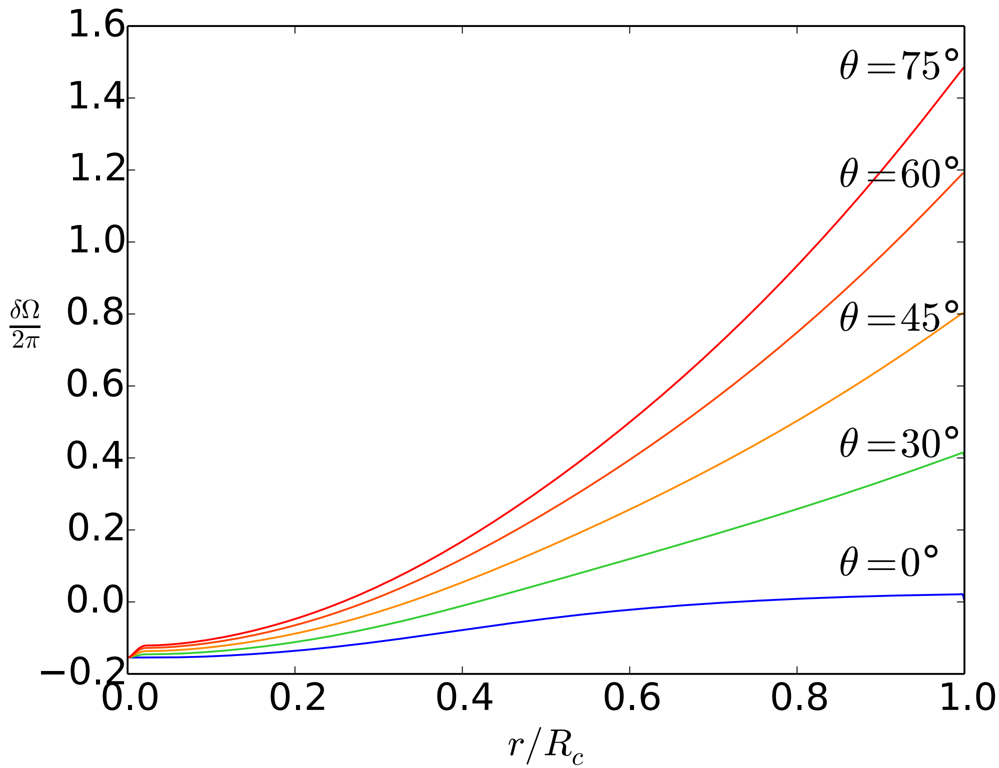


b=10



Importance of 2D transport of angular momentum

Internal rotation profile in a « solar-like » case

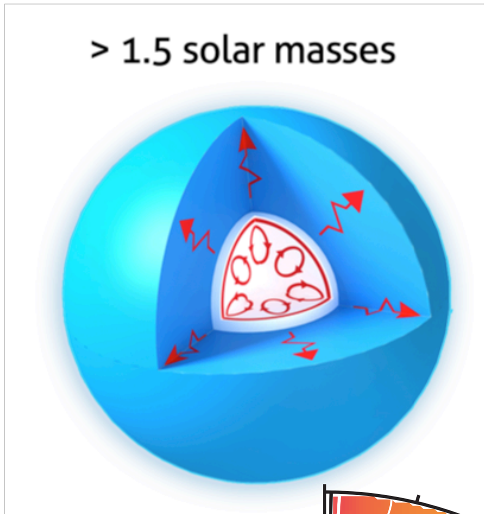


Need for another processus of transport of angular momentum both in the radial and in the latitudinal directions

CONCLUSION

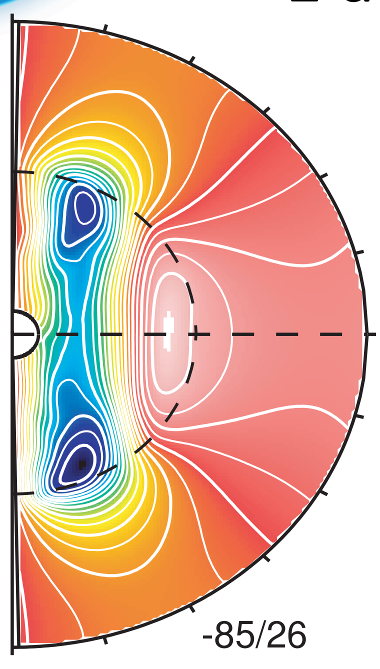
- Flux of angular momentum both in the radial and latitudinal directions are **proportional** to the shear parameter **b**.
- The core to the surface rotation ratio decreases as the shear increases.
- In the solar case, we find a roughly cylindrical differential rotation throughout the radiative zone with a small core to the surface rotation ratio.
- This is not compatible with the observations showing that the solar internal rotation profile is flat at least until 0.2 solar radius**. This calls for additional processes responsible for extra transport of angular momentum in the radial and latitudinal directions** (magnetic fields, internal gravity waves, turbulence…).

MAIN SEQUENCE MASSIVE STARS



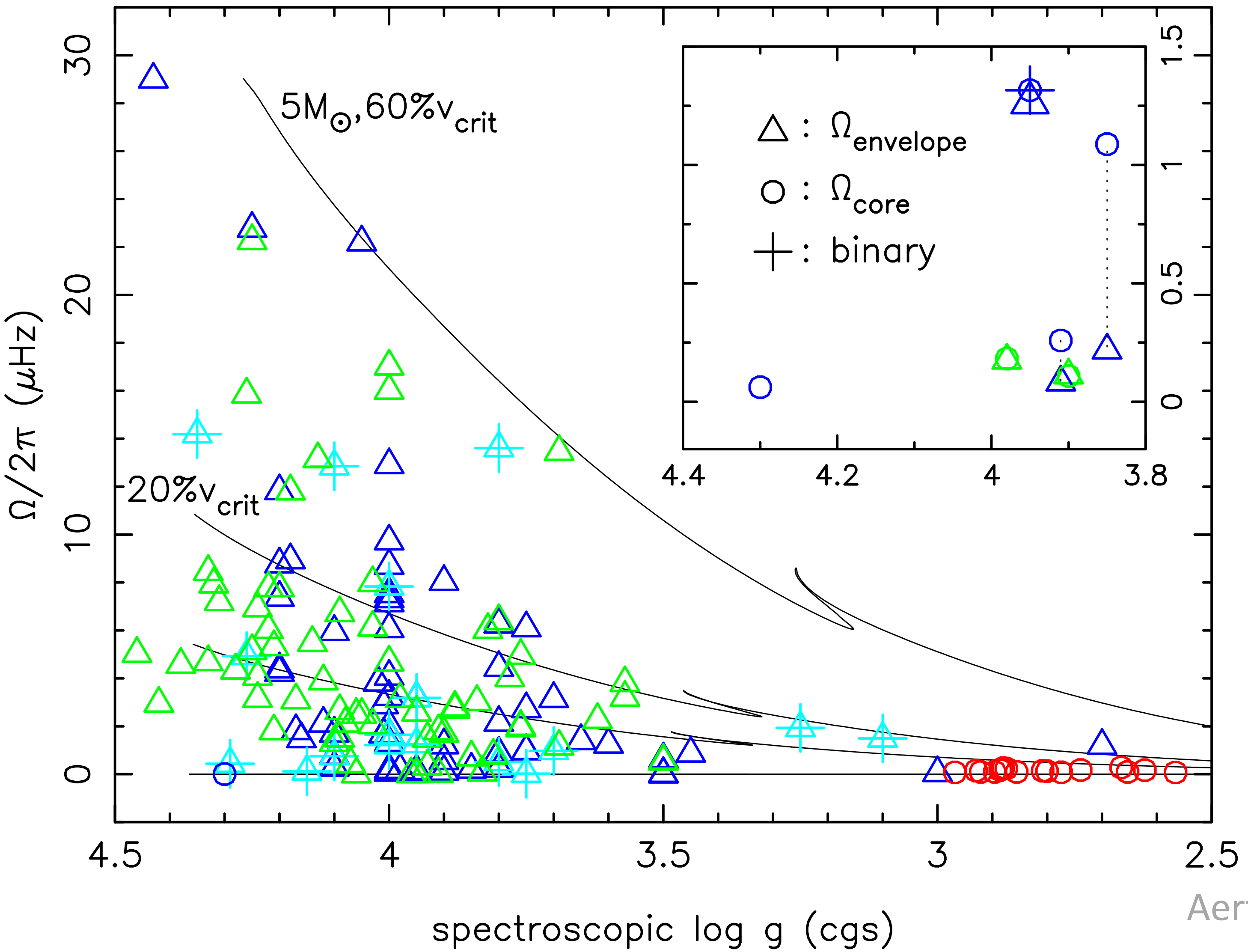
- Evolution of massive stars not fully understood
- Asteroseismology: Ω_c/Ω_s of numerous main-sequence massive stars between 1 and 4 (Kurtz & al 2014, Triana & al 2015, Aerts 2015)

Browning & al 2004



- Parametrized boundary condition at the bottom of the radiative envelope

NEW OBSERVATIONAL CONSTRAINS

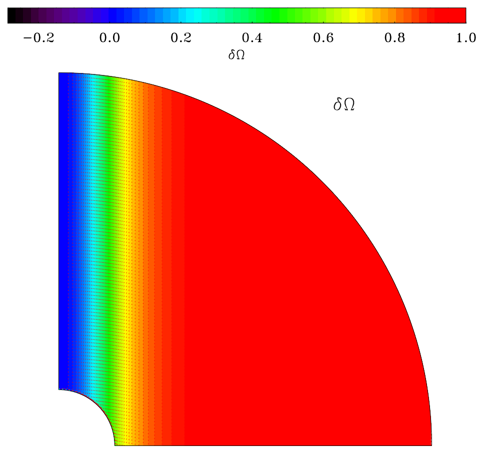


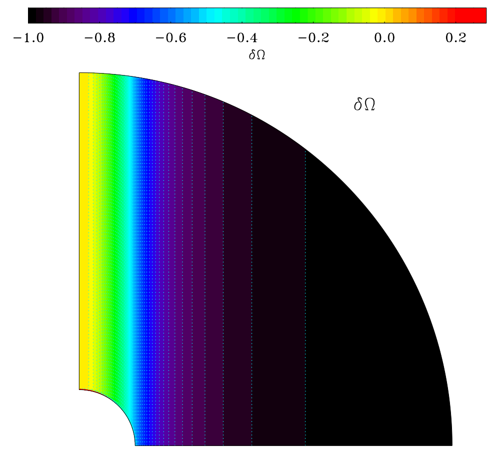
Aerts 2015

STEWARTSON LAYER

b=10

Columnar structure

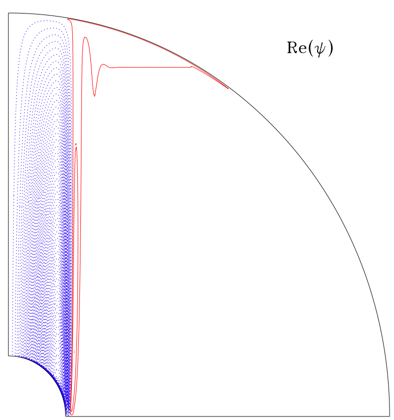


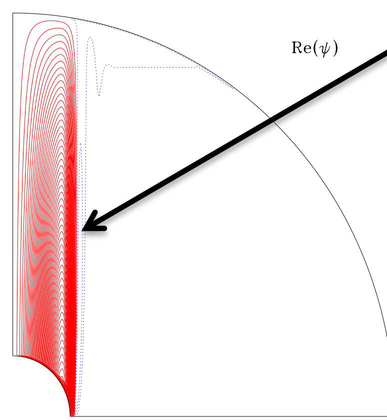


b=-10

The envelope rotates quasi uniformely

Not a classical spin-up meridional circulation



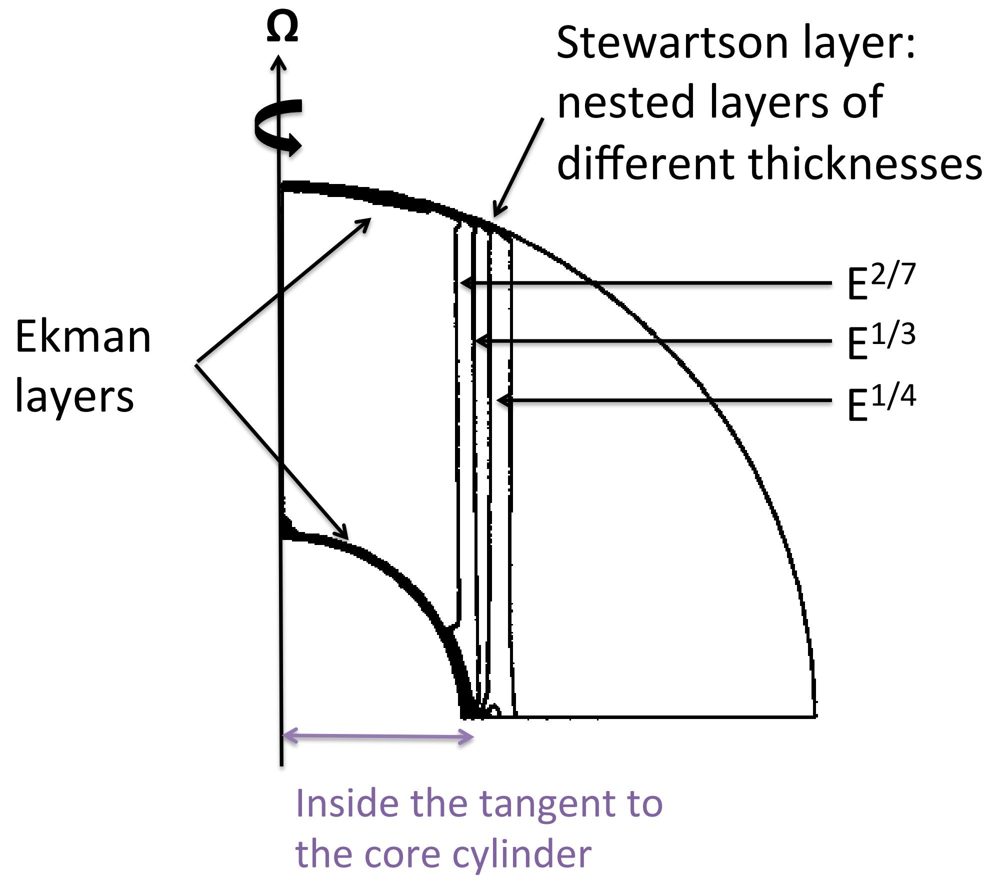


A **Stewartson layer** at $s=\eta$

STEWARTSON LAYER: ASTROPHYSICAL VIEW

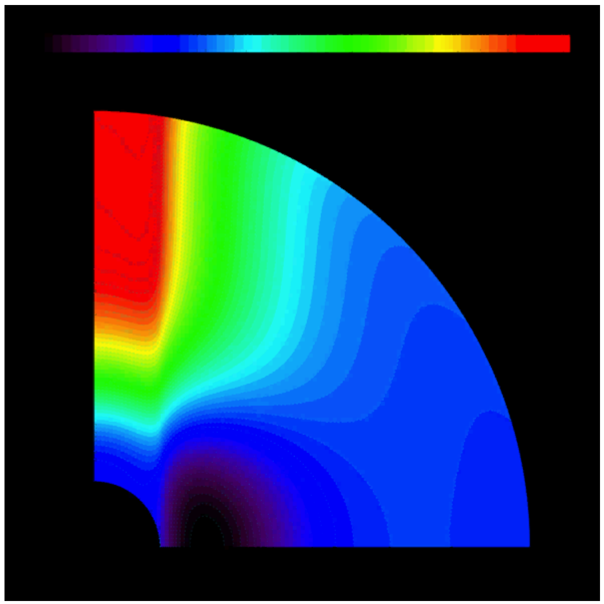
- Layer of cylindrical shear: **mixing**
- Generated by a small differential rotation in Couette flows: boundary conditions of radiative zones
- Regularize the continuity (of **v**, ρ or ν) between the 2 zones:

Transport of angular momentum

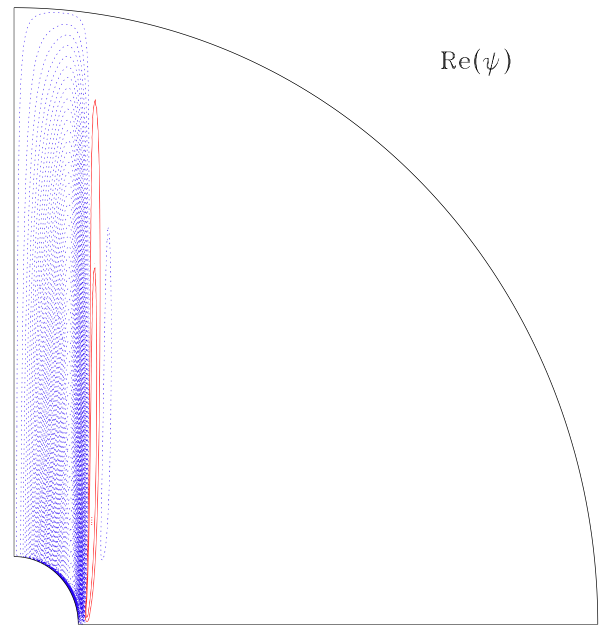


Stewartson 1966, Hollerbach 2003

FORCING BY BOUNDARY CONDITIONS + STABLE STRATIFICATION

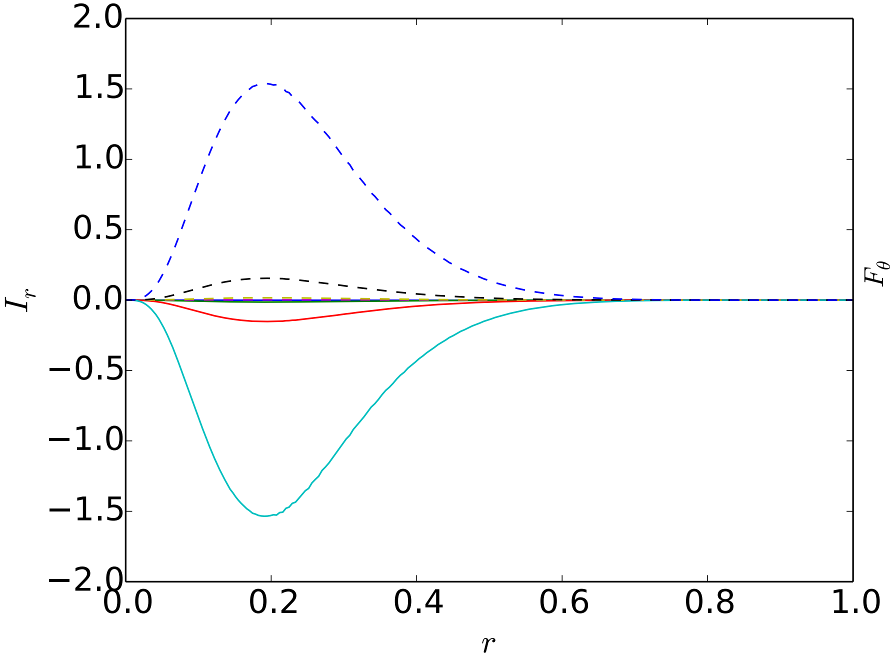


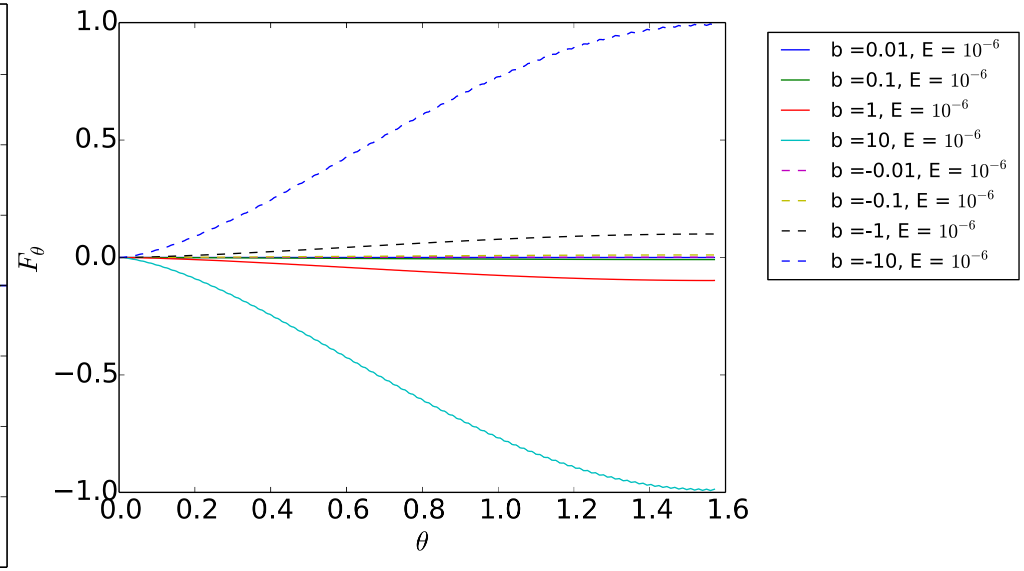
b > 0



Increasing the shear leads to a cylindrical differential rotation

FLUX OF ANGULAR MOMENTUM





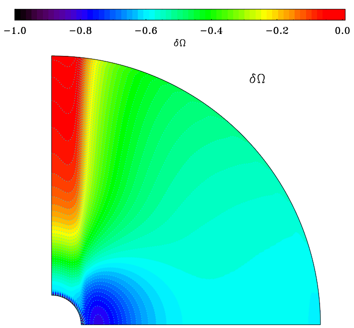
Averaged over latitude radial flux of angular momentum

Latitudinal flux of angular momentum near core

Could be used in 1D models

CORE-TO-SURFACE ROTATION RATIO

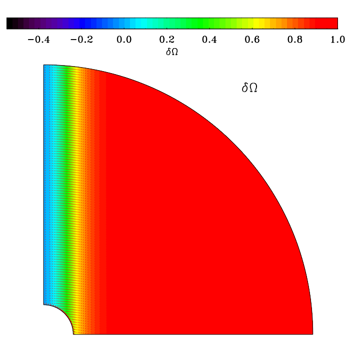
b=10^{-2}

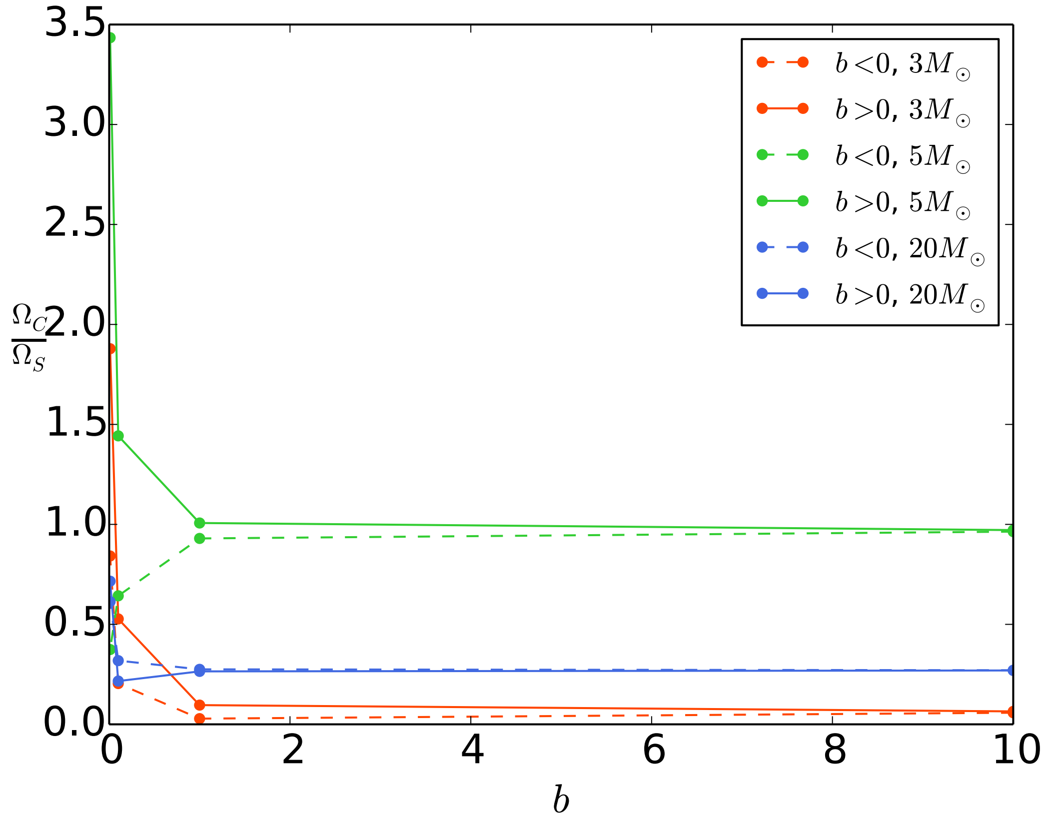


Transition towards cylindrical differential rotation

~ constant and small Ω_c/Ω_s

b=10

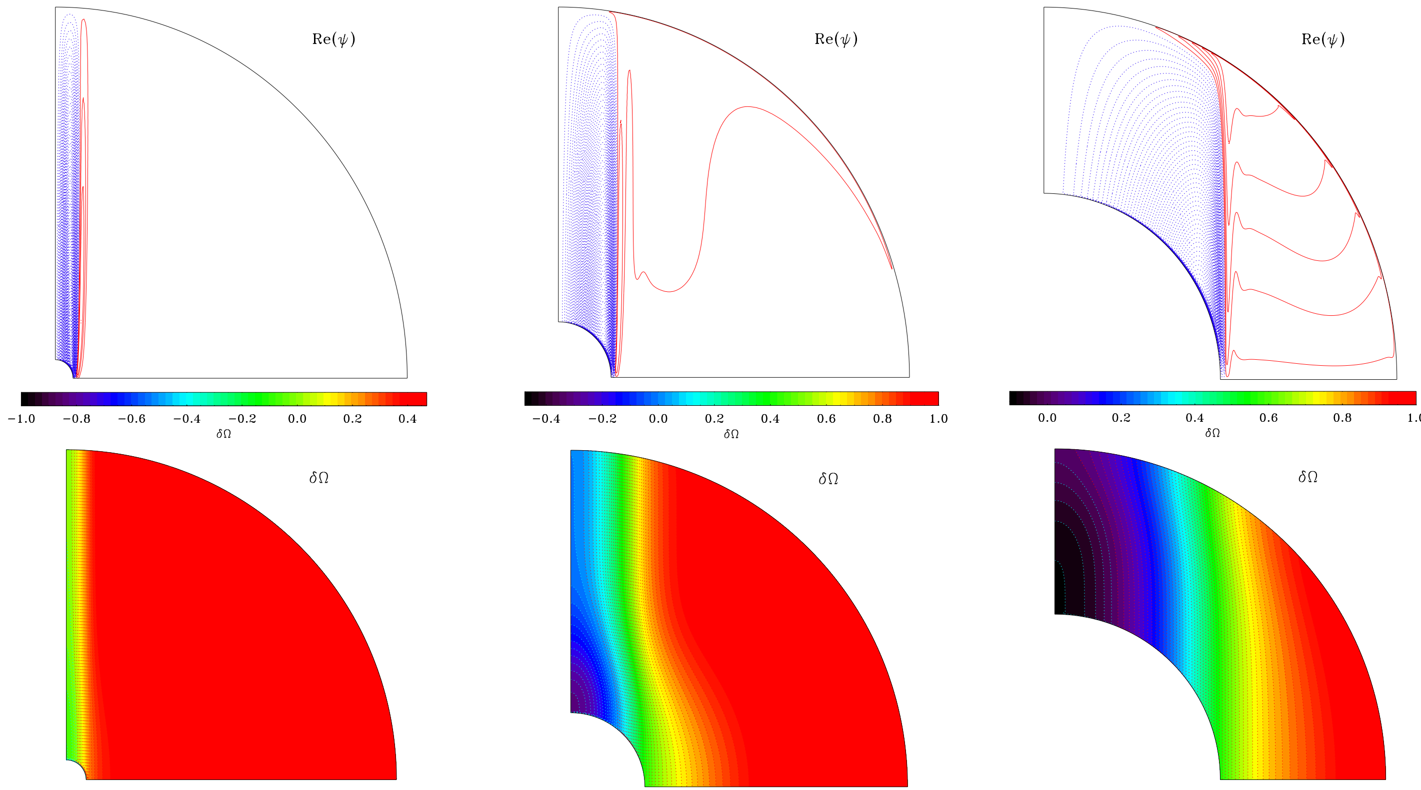




Importance of 2D transport of angular momentum

But these are **radial**-like diagnosis

INFLUENCE OF THE SIZE OF THE CORE



Bigger cores lead to higher differential rotation within the envelope.
On the MS, higher mass stars have bigger cores.
Small cores (lower mass stars): a quasi solid rotation in the envelope.
Big cores (higher mass stars): a spin-up meridional circulation in the envelope.

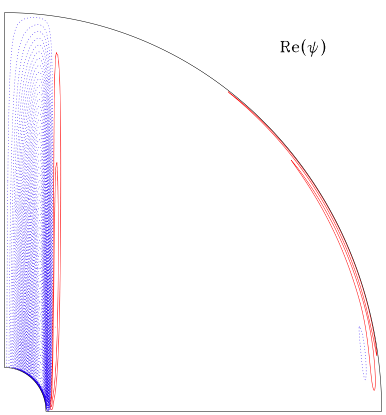
THE IMPACT OF THE THERMAL DIFFUSIVITY

$$\mathcal{P} = \frac{\nu}{\kappa}$$

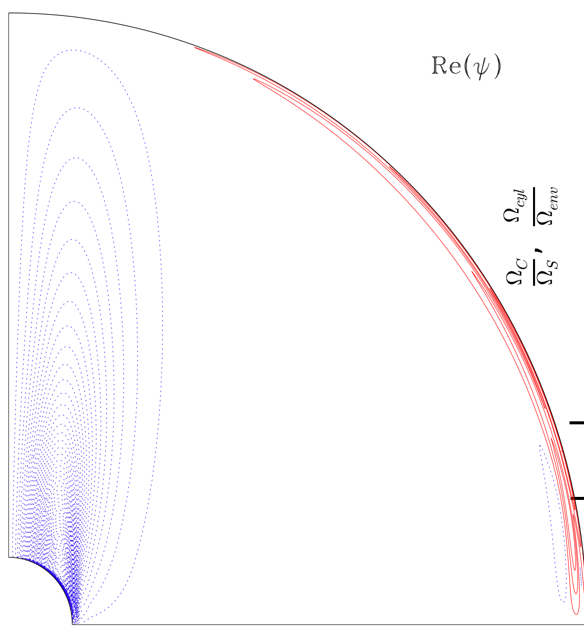
In 3D ASH simulations with Pr=1, they do not observe Stewartson layers.

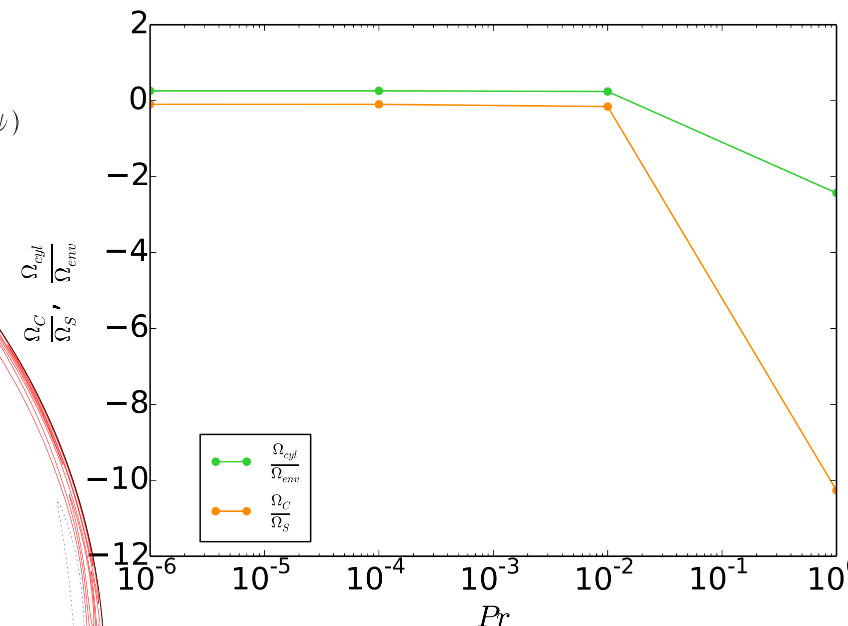
In our simulations, the Stewartson layers appear when $Pr<10^{-2}$.

$Pr=10^{-4}$



$Pr=1$





CONCLUSION

- The convective core generates a **Stewartson layer.**
- This calls for a better description of viscous effects.
- Look for **asteroseismic signatures of the Stewartson layer.**

ON GOING PROJECTS

- Additional angular momentum transport processes: Magnetized cartesian box with gravito inertial waves
- 3D simulation of massive stars' interior at low Prandtl number: seeking Stewartson layers

Thank you