

ONDES INTERNES DE GRAVITE DANS LES ETOILES

Lucie Alvan

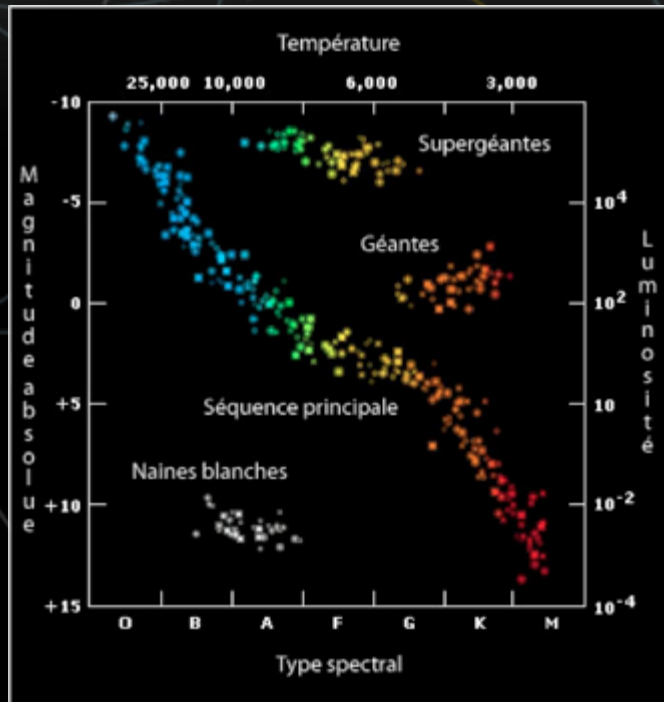
Directeurs de thèse :

Allan Sacha Brun

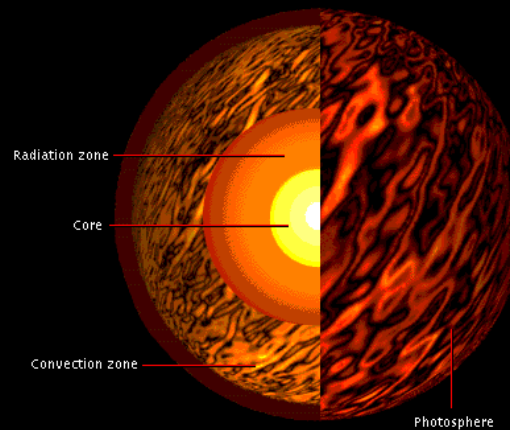
Stéphane Mathis

UN OBJECTIF GLOBAL :

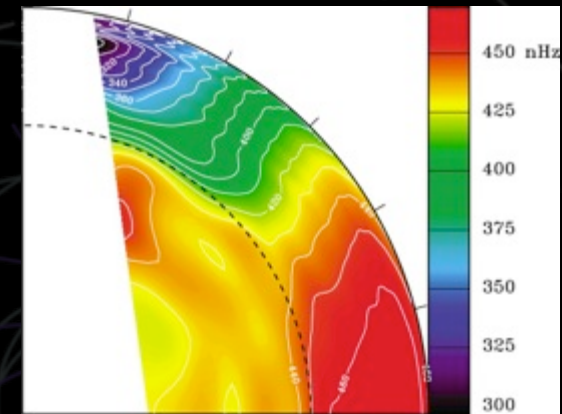
COMPRENDRE LA DYNAMIQUE INTERNE DES ETOILES



STRUCTURE INTERNE



ROTATION



ONDES ACOUSTIQUES
ONDES DE GRAVITE : pour aller plus loin

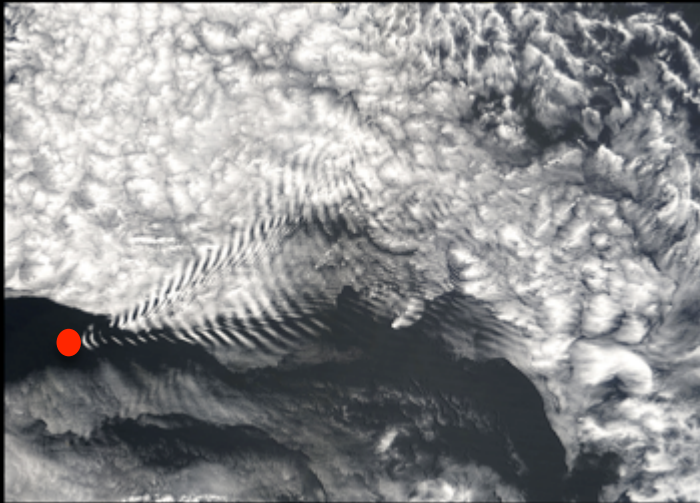
LES ONDES DE GRAVITE

Relation de dispersion

$$\omega^2 = N^2 \cos^2 \theta = N^2 \frac{k^2}{k^2 + m^2}$$

Fréquence de Brunt-Väisälä (stratification en densité)

Dans l'atmosphère terrestre



Île Amsterdam, océan indien (satellite Terra, NASA)

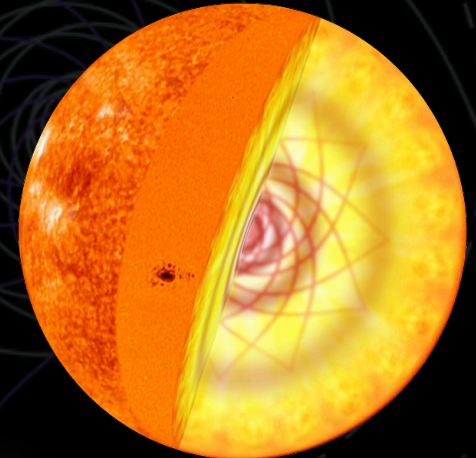
En laboratoire



<http://www.phys.ocean.dal.ca/>

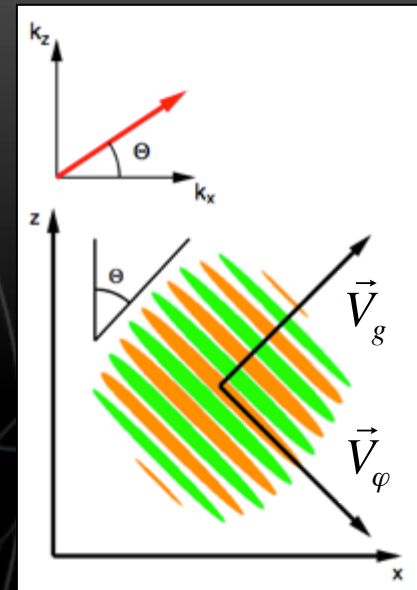
Croix de Saint André

Dans les étoiles...

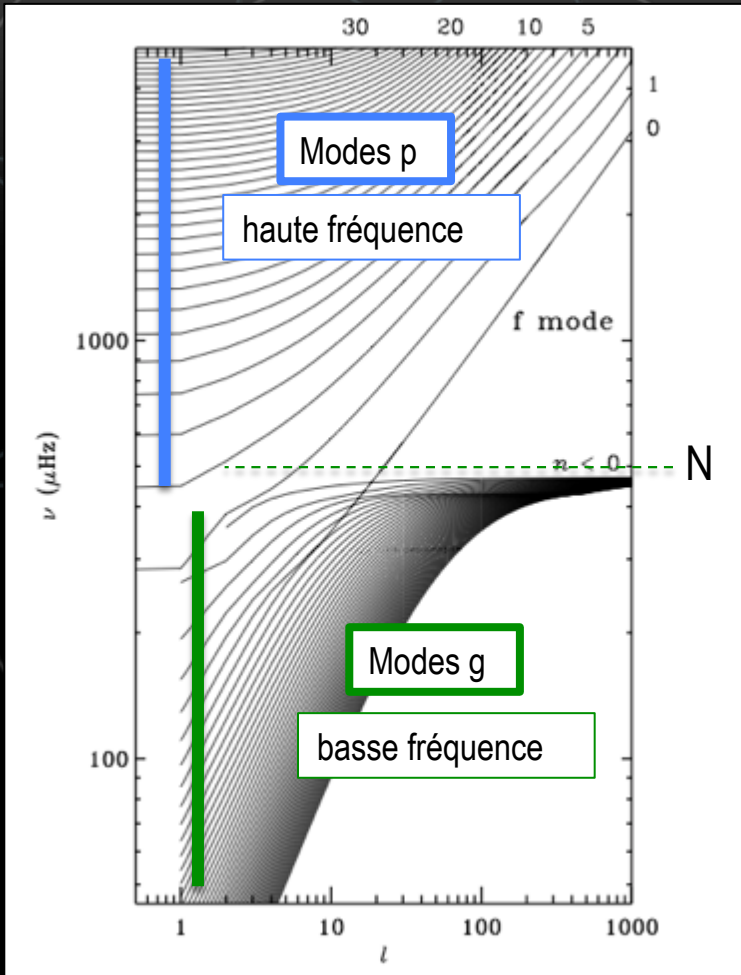


Ondes transverses

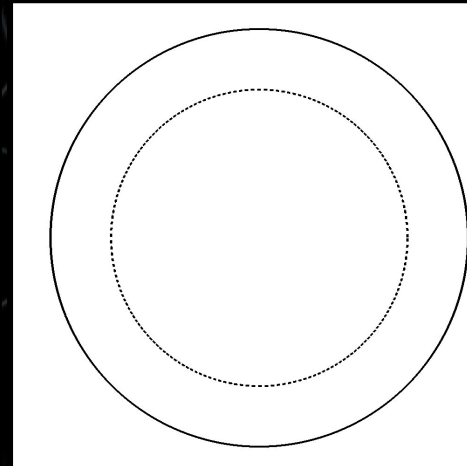
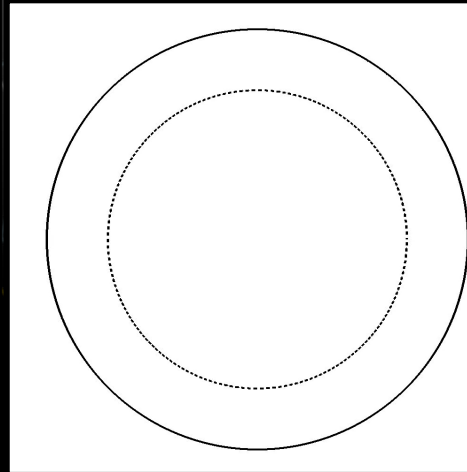
$$\vec{V}_\varphi \perp \vec{V}_g$$



LES MODES DE GRAVITE

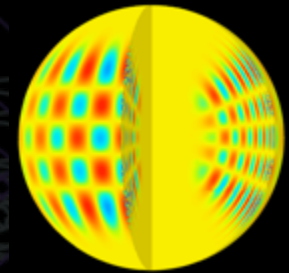


Lecture Notes on Stellar Oscillations, J. Christensen-Dalsgaard, 2003



3 nombres quantiques :

- degré l
- ordre azimuthal m
- ordre radial n



COMPRENDRE LE PROFIL DE ROTATION DES ETOILES

transport de moment cinétique

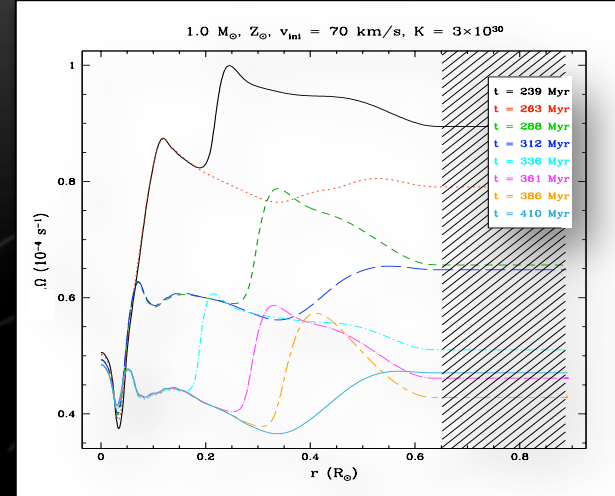
Amortissement radiatif :

Amplitude x

$$e^{-\tau/2}$$

$$\tau = (l(l+1))^{3/2} \int_r^{r_c} \frac{K}{\sigma^4} \left(\frac{N}{N^2 - \sigma^2} \right)^{-1/2} \frac{1}{r^3} dr$$

Coefficient de diffusivité thermique



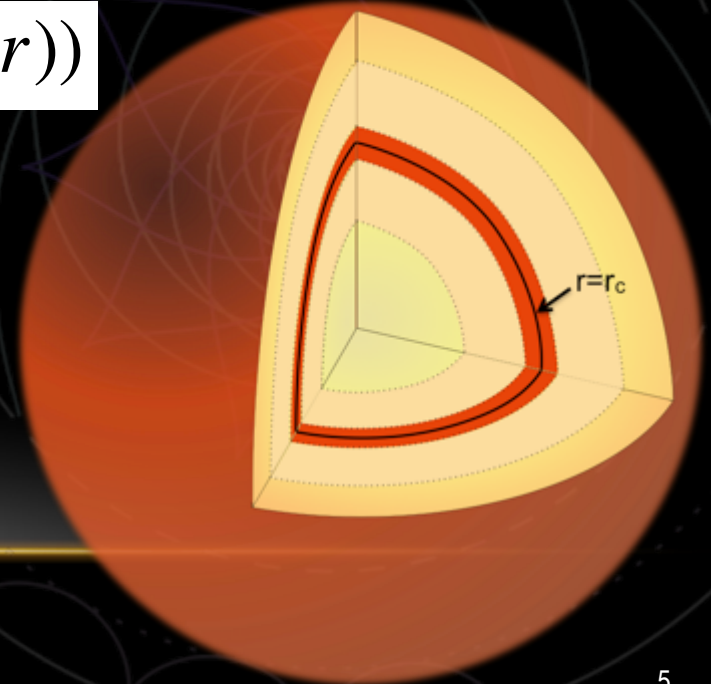
Alvan, Mathis, Decressin (2013)

Couches critiques :

$$\omega = m(\Omega_c - \Omega(r))$$

Nombre de Richardson :

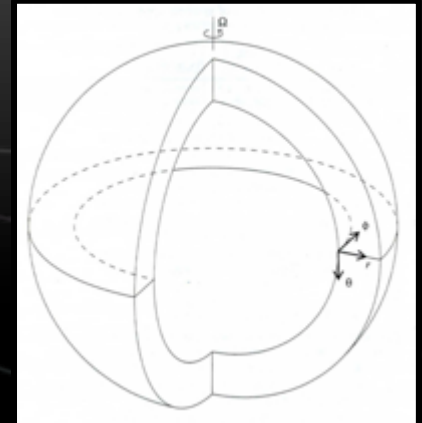
$$\text{Ri}_c = \left(\frac{N^2}{\left(r \frac{d\bar{\Omega}}{dr} \right)^2} \right)_{r=r_c}$$



SIMULATION 3D

Le code ASH (Anelastic Spherical Harmonic)

- Résout les équations de l'hydrodynamique sous l'hypothèse anélastique
- 3D – sphérique
- Non-linéaire



$$\nabla \cdot (\bar{\rho} \mathbf{v}) = 0,$$

$$\bar{\rho} \left(\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla) \mathbf{v} \right) = -\nabla P + \rho \mathbf{g} \\ - 2\bar{\rho} \mathbf{\Omega}_0 \times \mathbf{v} - \nabla \cdot \mathcal{D} - [\nabla \bar{P} - \bar{\rho} \mathbf{g}],$$

$$\bar{\rho} \bar{T} \frac{\partial S}{\partial t} + \bar{\rho} \bar{T} \mathbf{v} \cdot \nabla (\bar{S} + S) = \bar{\rho} \epsilon + \nabla \cdot [\kappa_r \bar{\rho} c_p \nabla (\bar{T} + T) \\ + \kappa \bar{\rho} \bar{T} \nabla S + \kappa_0 \bar{\rho} \bar{T} \nabla \bar{S}] + 2\bar{\rho} v [e_{ij} e_{ij} - 1/3 (\nabla \cdot \mathbf{v})^2]$$

- Modèle d'étoile de 0 à 0.97R
- type solaire

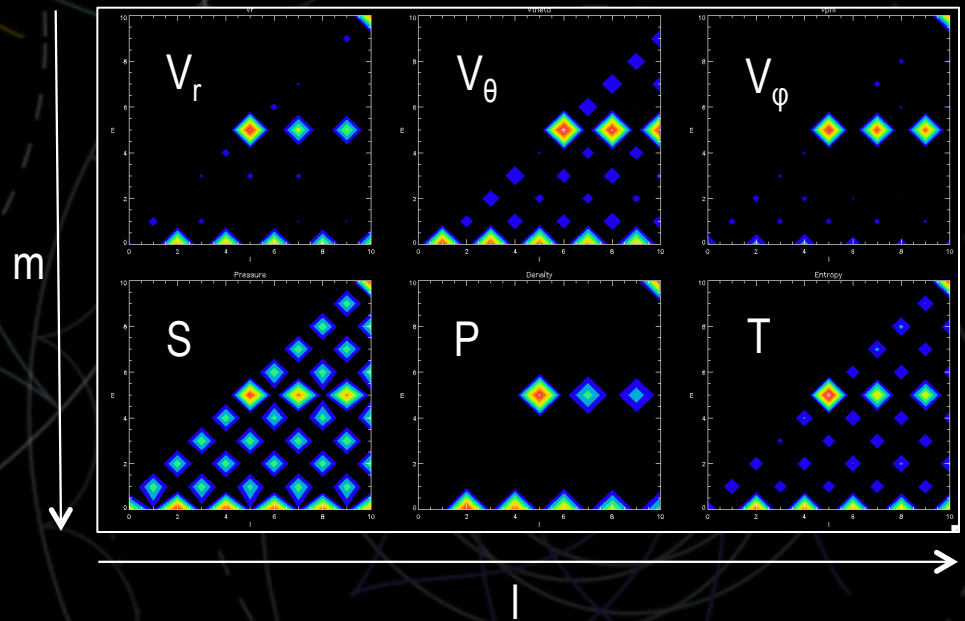
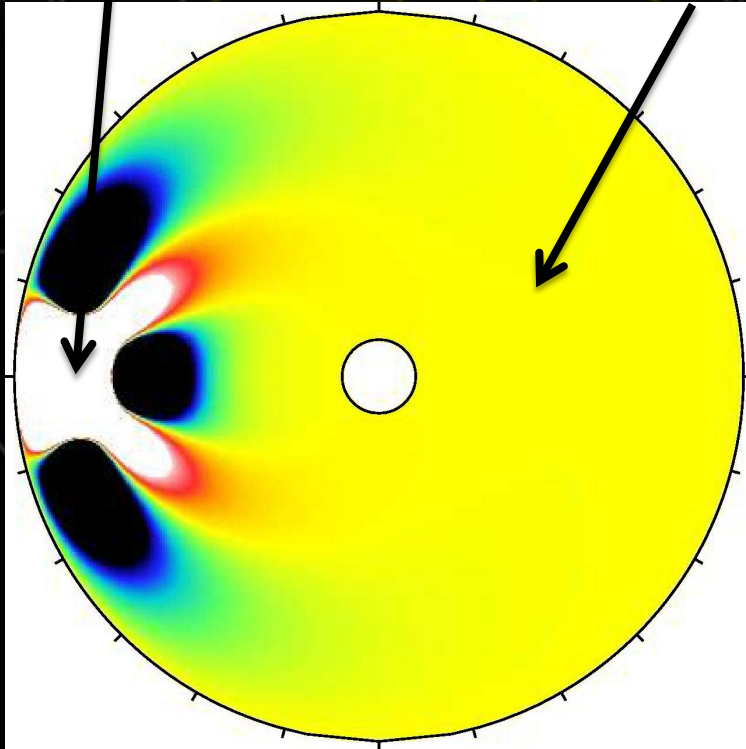
ASH code: Clune et al. 1999, Brun et al. 2004, Brun et al. 2011

UN MODELE SIMPLE : PERTURBATION PONCTUELLE

Perturbation ponctuelle

Zone radiative

Interaction non linéaires : ondes - fluide

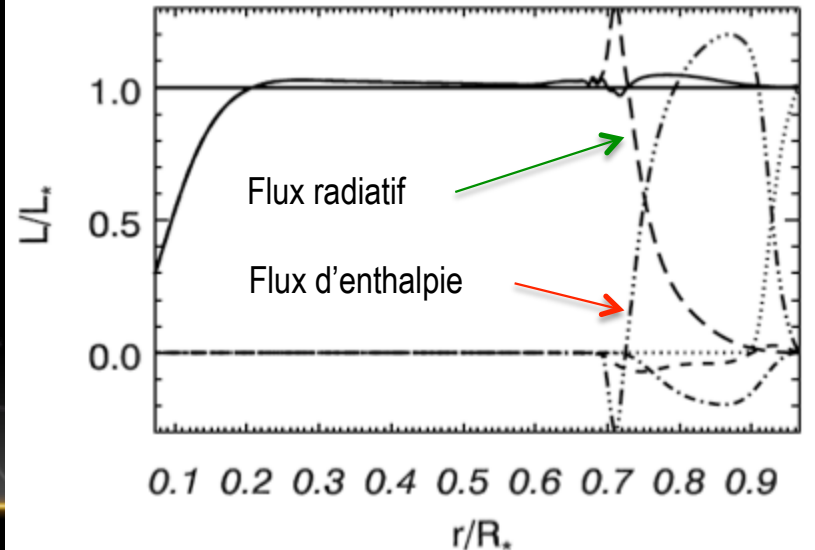
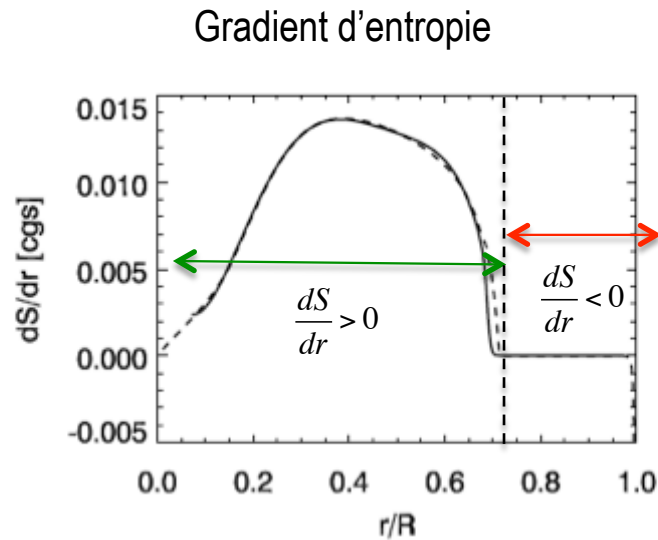
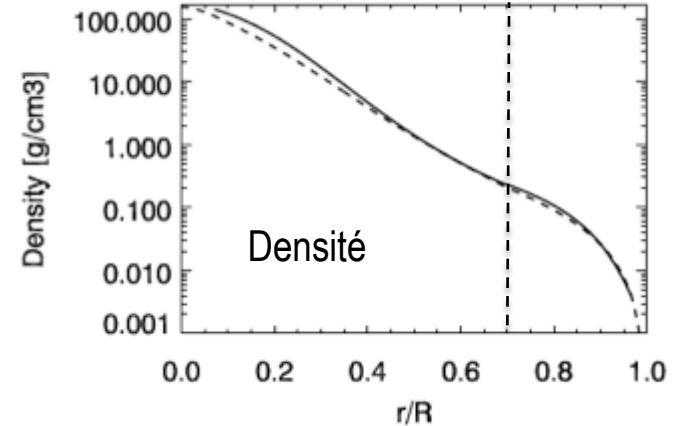
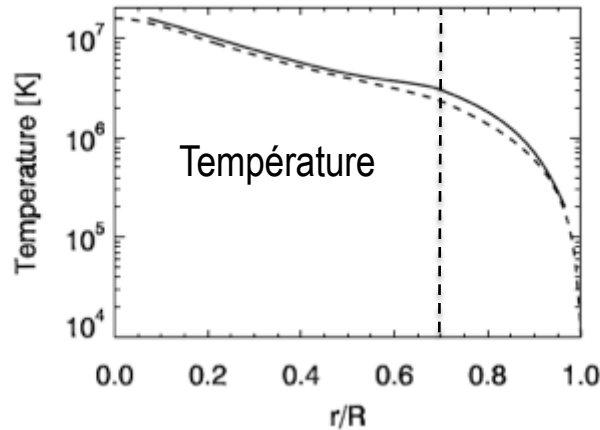


LE SOLEIL EN 3D : STRUCTURE RADIALE

Un état de référence réaliste

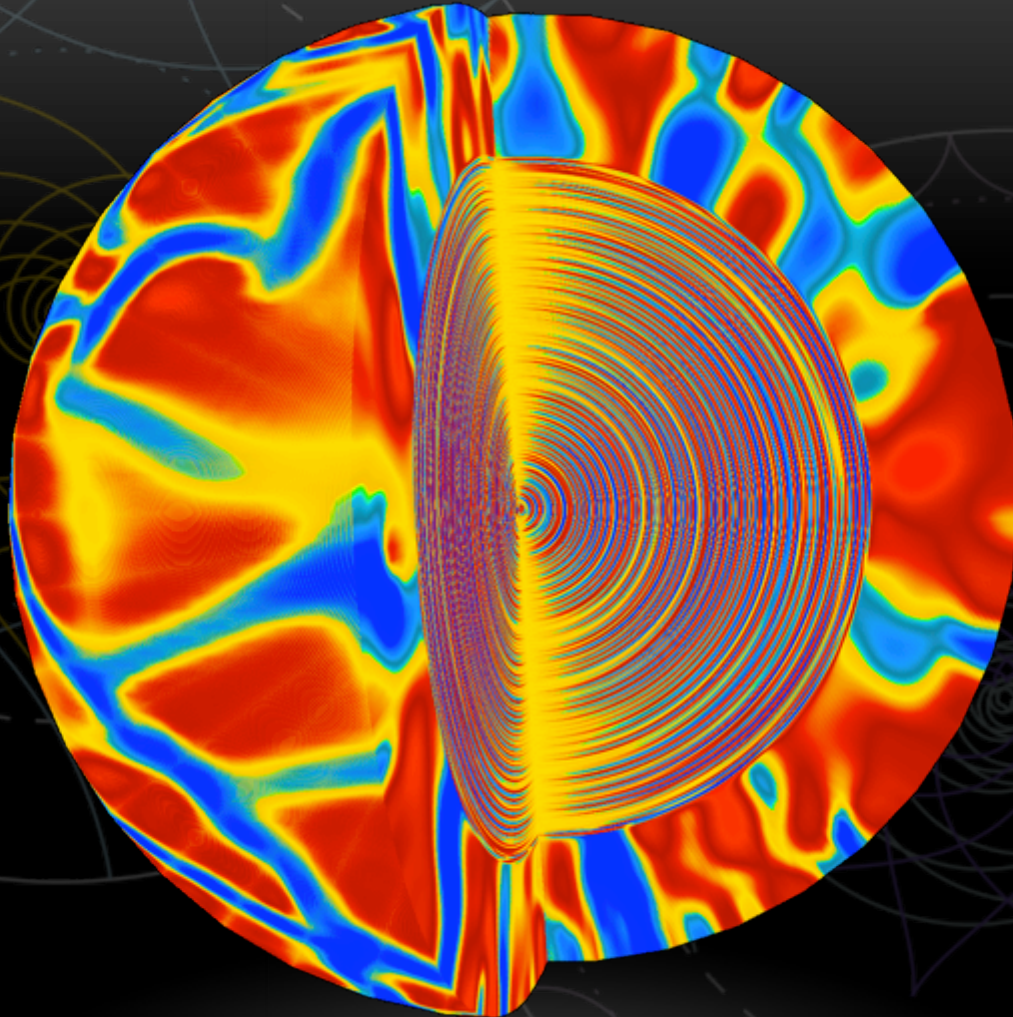
— ASH (3D)

----- CESAM (1D)



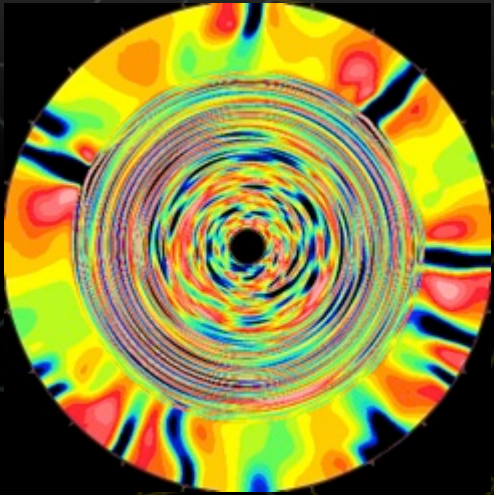
Brun, Miesch, Toomre, 2011, ApJ, 742 & Alvan, Brun, Mathis 2013

LE SOLEIL EN 3D

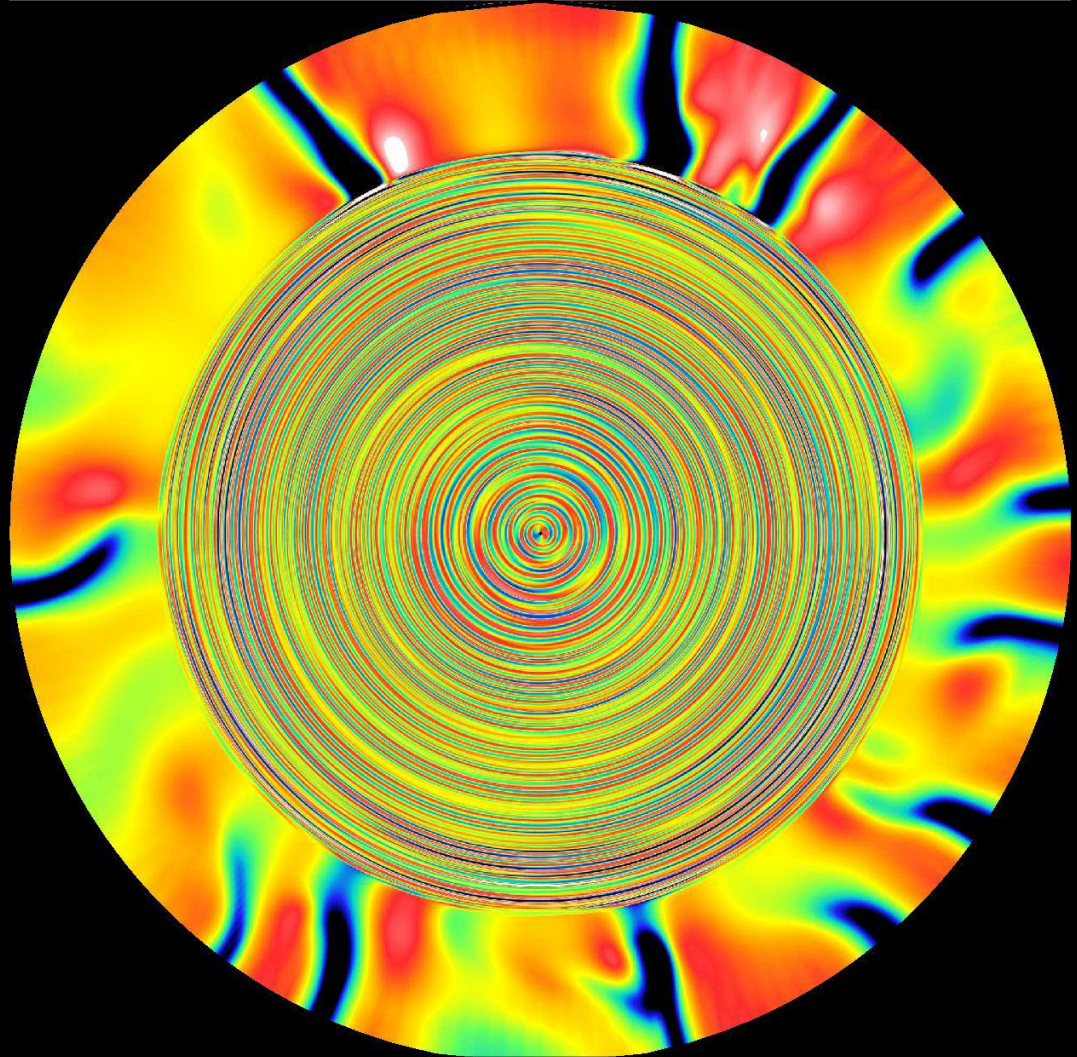


DES ONDES DANS LA ZONE RADIATIVE

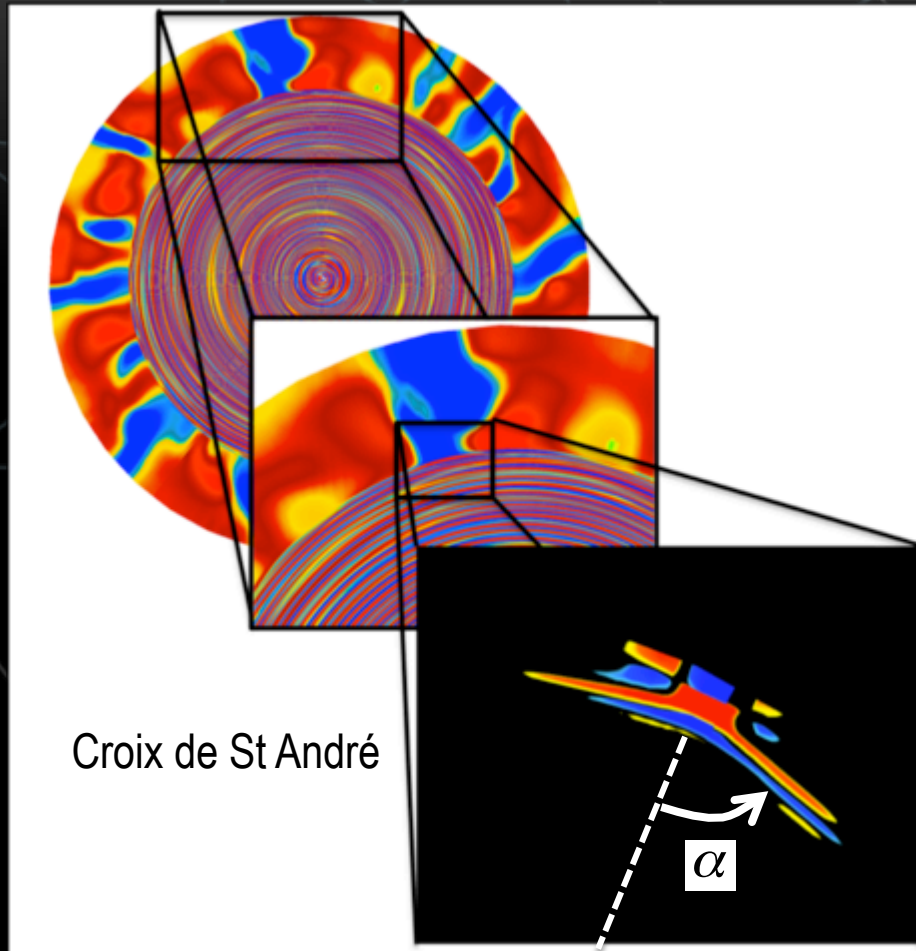
Bille centrale



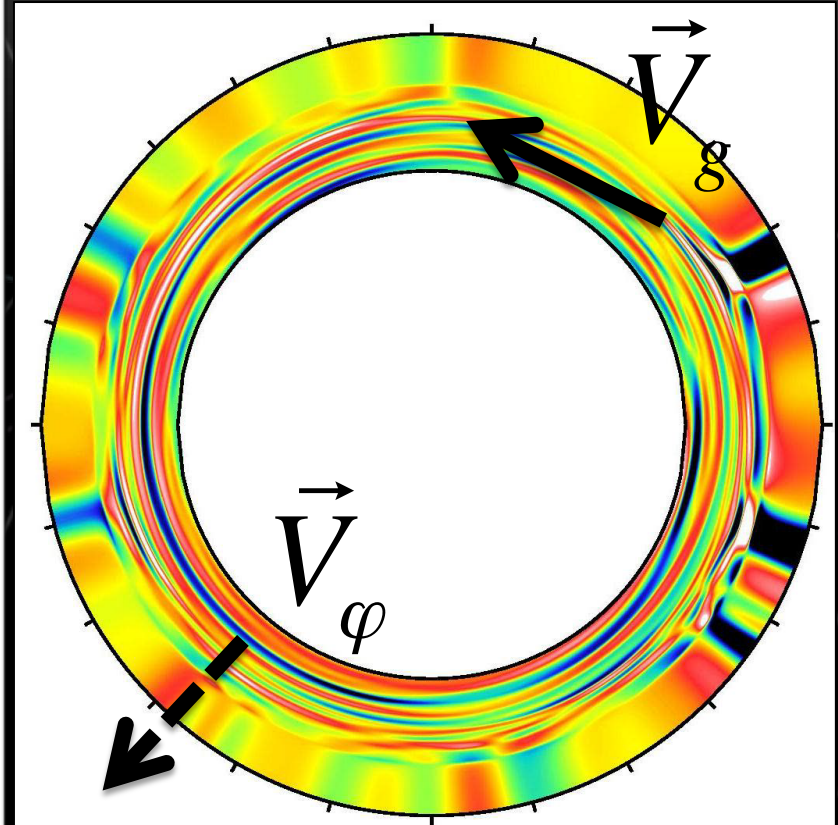
“Full sphere”



EXCITATION PAR LES PLUMES CONVECTIVES



$$\alpha = \arccos\left(\frac{\omega_0}{N}\right)$$



$$\vec{V}_\varphi \perp \vec{V}_g$$

DOMAINE SPECTRAL :

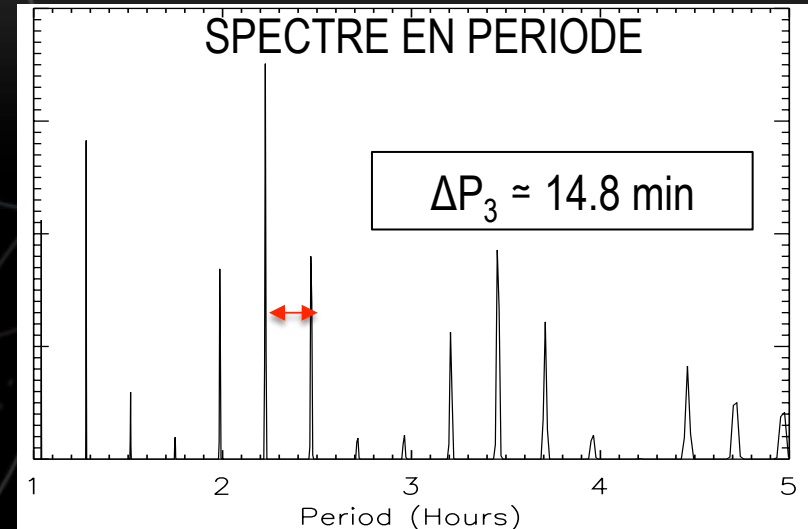
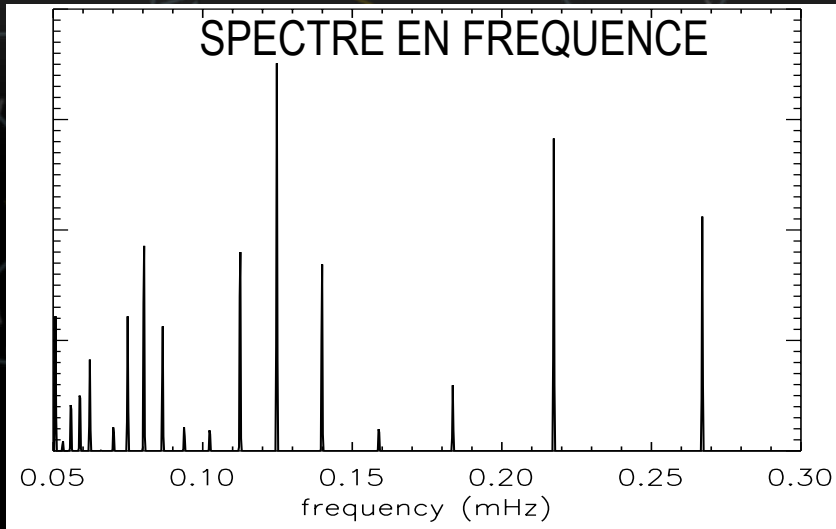
$$V_r(r, \theta, \varphi, t)$$



$$V_r(r, l, m, \omega)$$

ESPACEMENT REGULIER EN PERIODE

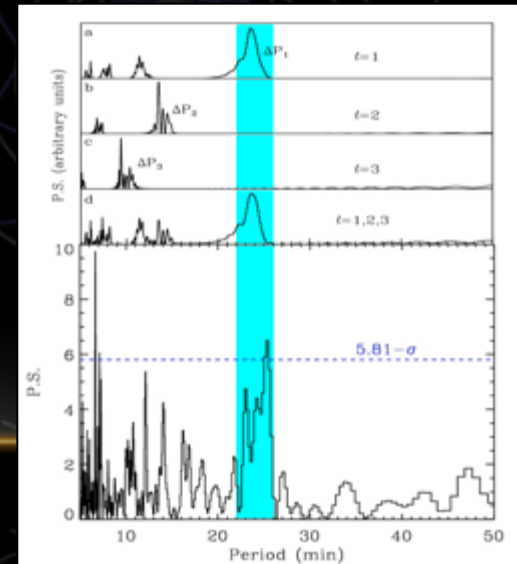
Vers la detection des modes g



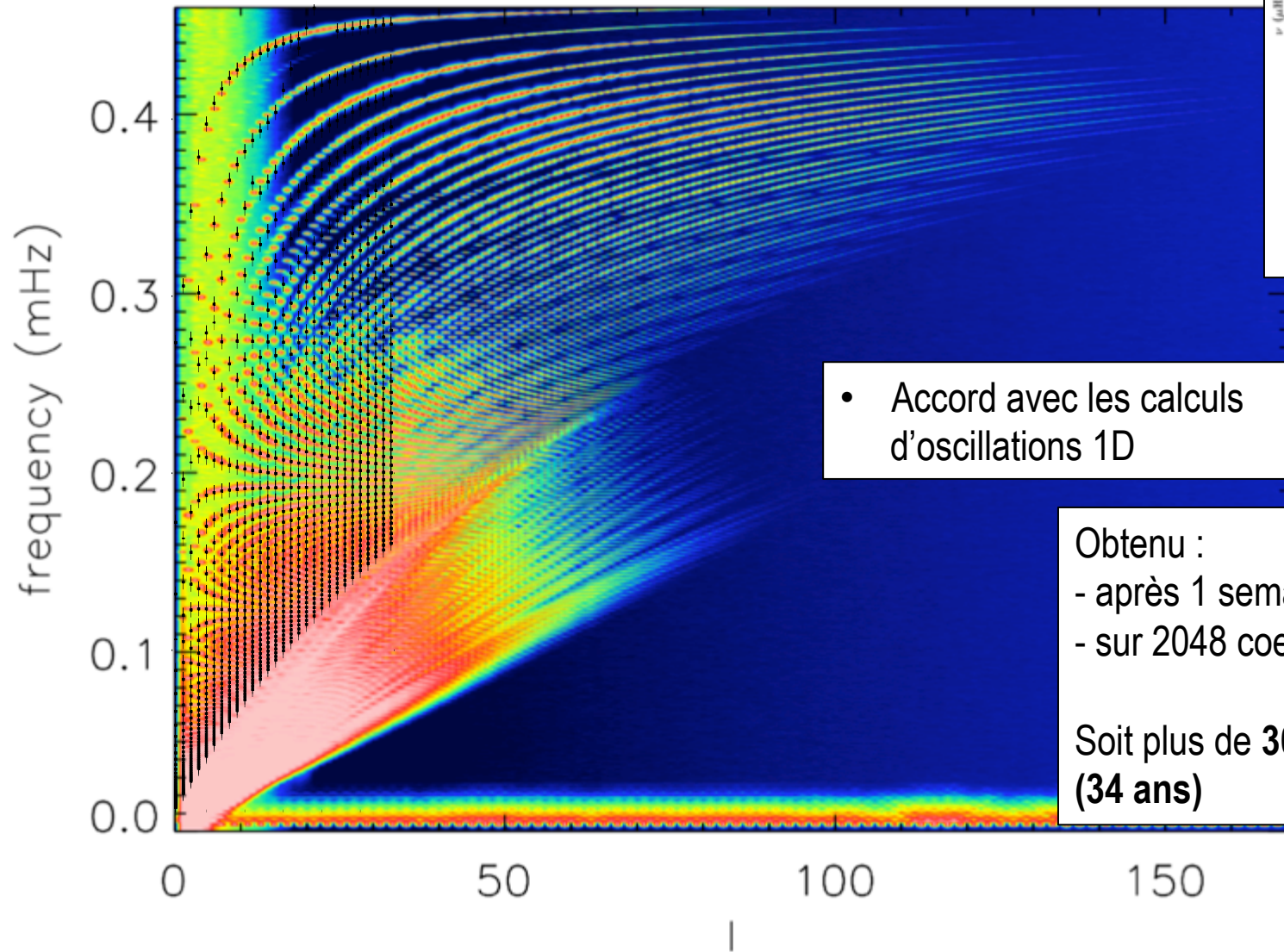
$$P_{n,l} = \frac{\pi}{2\sqrt{l(l+1)}} \int_0^{r_1} \frac{N}{r} dr (2n+l-\delta)$$

$$\delta \approx 5/6$$

$r_1(\omega)$ turning point



UN SPECTRE RICHE EN INFORMATIONS



- Accord avec les calculs d'oscillations 1D

Obtenu :

- après 1 semaine de calcul
- sur 2048 coeurs

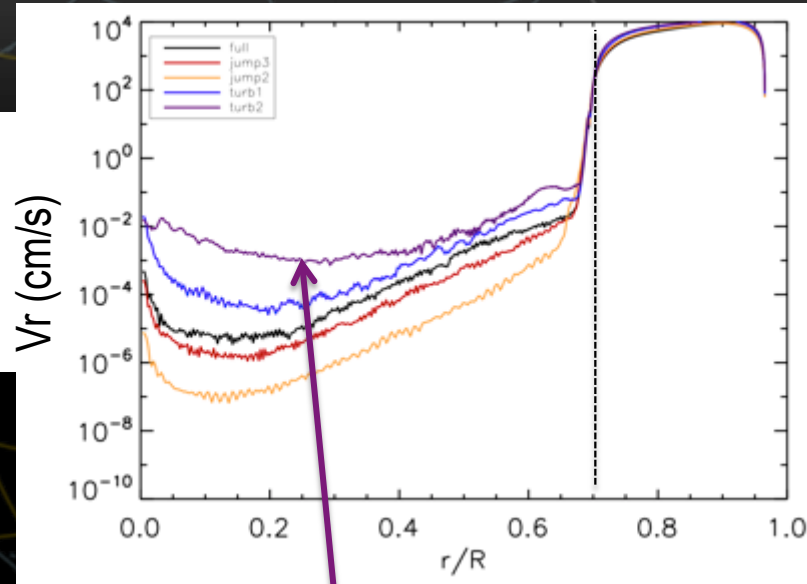
Soit plus de **300 000 heures**
(34 ans)

Alvan et al. 2013

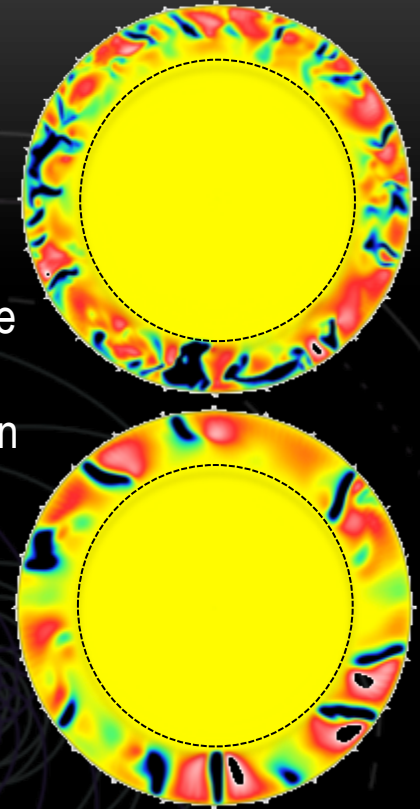
AMPLITUDE DES MODES

Quel pourcentage de la luminosité totale est transformé en ondes ?

amortissement
radiatif



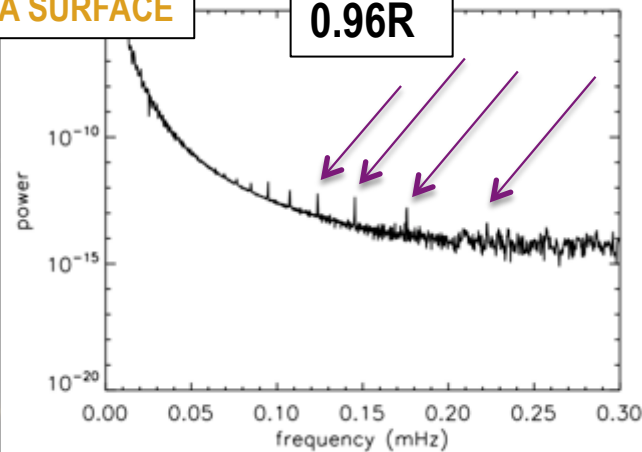
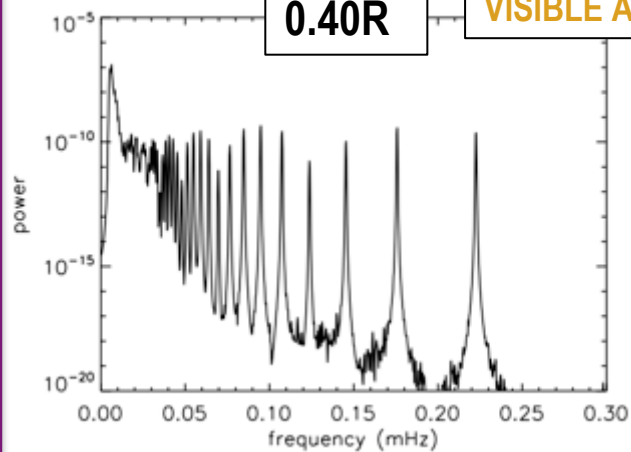
turbulence
de la
convection



0.40R

VISIBLE À LA SURFACE

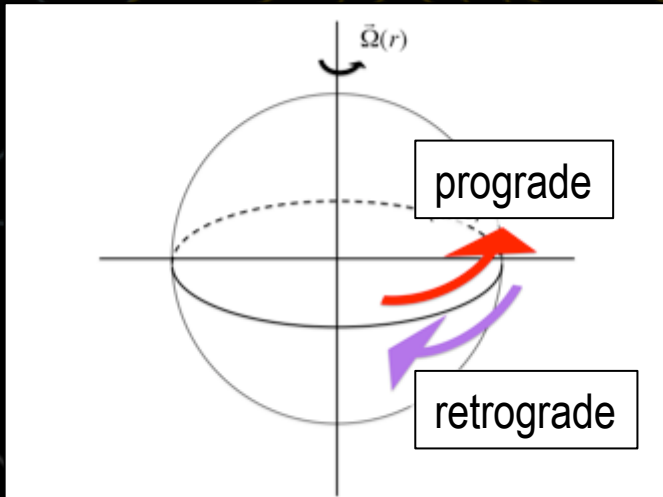
0.96R



EFFETS DE LA ROTATION

$$F(V(r, l, m, t)) = \text{Onde prograde } (m > 0)$$

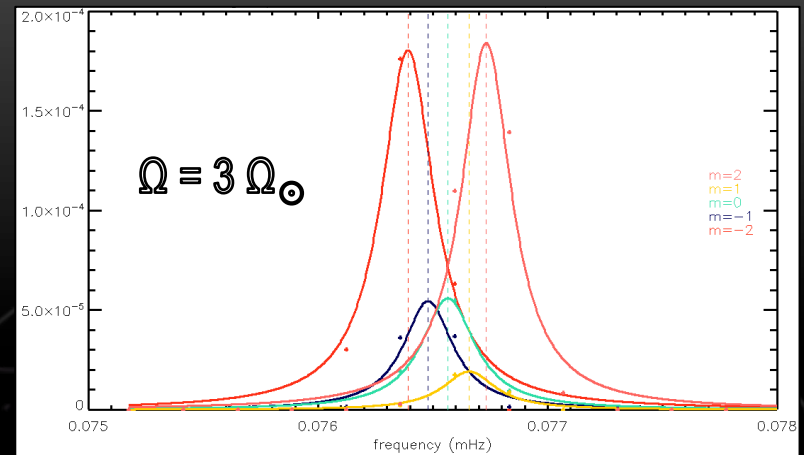
$$F(\overline{V(r, l, m, t)}) = \text{Onde retrograde } (m < 0)$$



Loi asymptotique

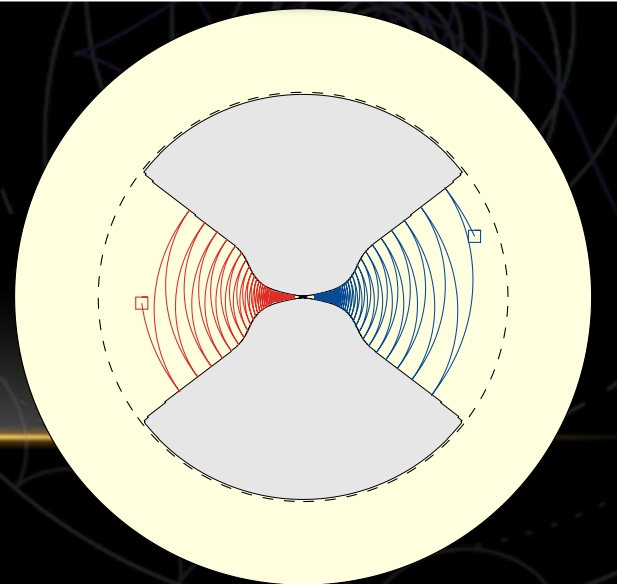
$$\nu_{n,l,m} = \nu_{n,l,0} + m \frac{\Omega}{2\pi} \left(1 - \frac{1}{l(l+1)} \right)$$

“Splitting”

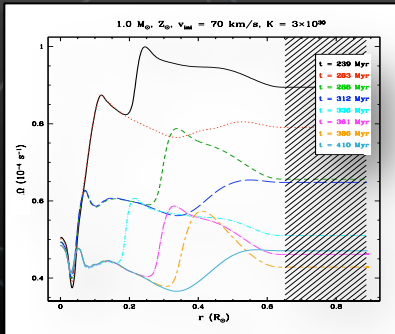


“Trapping”

si $\omega < 2\Omega$



CONCLUSION



COMPRENDRE LE TRANSPORT DE MOMENT CINETIQUE DANS LES ETOILES

Couches critiques :
Alvan, Mathis, Decressin 2013, A&A

ONDES INTERNES DE GRAVITÉ

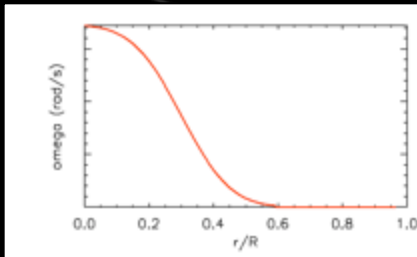
AMELIORER LA COMPREHENSION DES MODES G POUR AIDER À LEUR DETECTION

Brun, Alvan, Strugarek et al. 2013

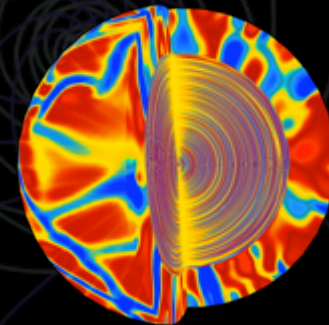
COMPRENDRE LES INTERACTIONS ENTRE LES ONDES ET LE MILIEU

(interactions non-linéaires, rotation, champ magnétique....)

Mathis, Alvan, Brun 2013 (en préparation)



Simulation 3D



Alvan, Brun, Mathis 2013 (soumis)