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# A story about convection, penetration, rotation and waves in stars

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*Warwick:* T. Goffrey
*Atlanta:* J. Pratt

- Brief introduction to physical conditions in stars (solar-like)

- Observational constraints on rotation, convection and waves in the Sun

- The first step toward a systematic numerical analysis of convection $\longleftrightarrow$ penetration $\longleftrightarrow$ waves $\longleftrightarrow$ rotation

*(work in progress)*

# Characteristics of stellar interiors and stellar convection

## - Complex regime of parameters

- **Re = LU/$\nu$ >> $10^6$** *(intertial/viscous)*
  turbulent convection
- **Prandtl Pr << 1**

## - Characterised by very different timescales

**<u>Sun</u>** $\tau_{dyn} \sim (R^3/GM)^{1/2}$ $\sim$ 30 min

$\tau_{conv}$ $\sim$ 6 days

$\tau_{thermal} \sim GM^2/(RL) \sim 2\ 10^7$ yr

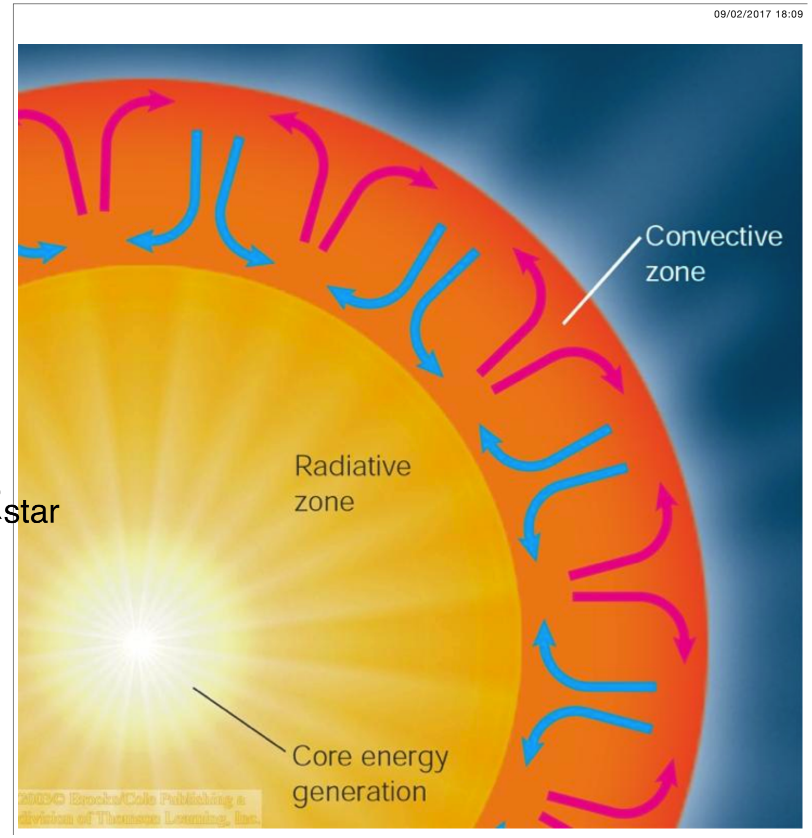
## - Very different lengthscales

Pressure scale height: $H_P = dr/d\ln P$

centre: $H_P \sim R_{star}$ Surface: $H_P \sim 10^{-3} - 10^{-2} \times R_{star}$

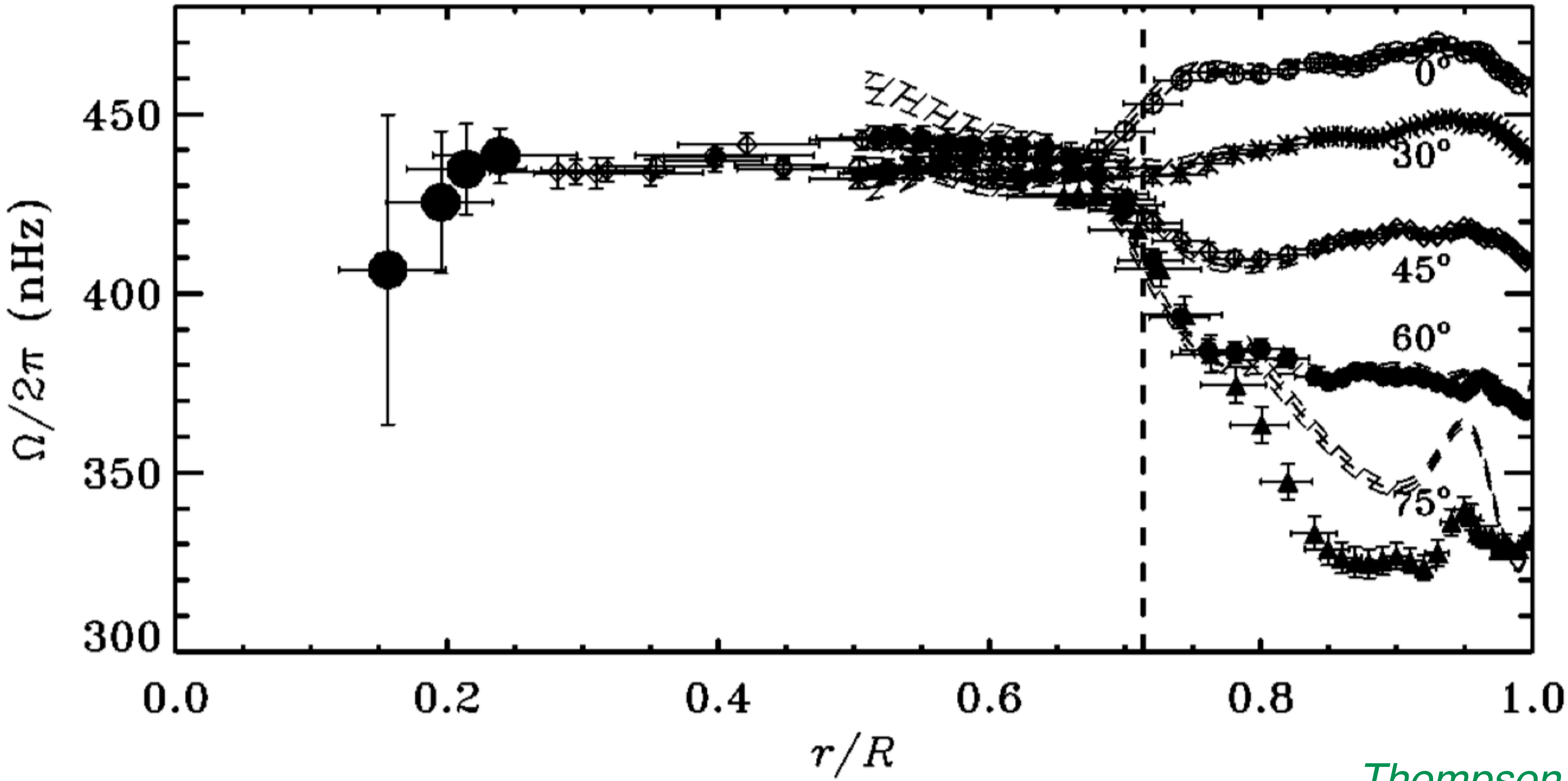
## - Range of Mach numbers (M ~ $10^{-6}$ - 1)

*surface: velocities ~ $c_{sound}$*



# Solar rotation rate

**From helioseismology:** Inferred rotation rate as a function of fractional radius r/R and latitude




*Thompson et al. 2003*

→Solid body rotation in the stable radiative core

→ Differential rotation in the convective envelope

☛ **Solar rotation: equator is faster than pole**

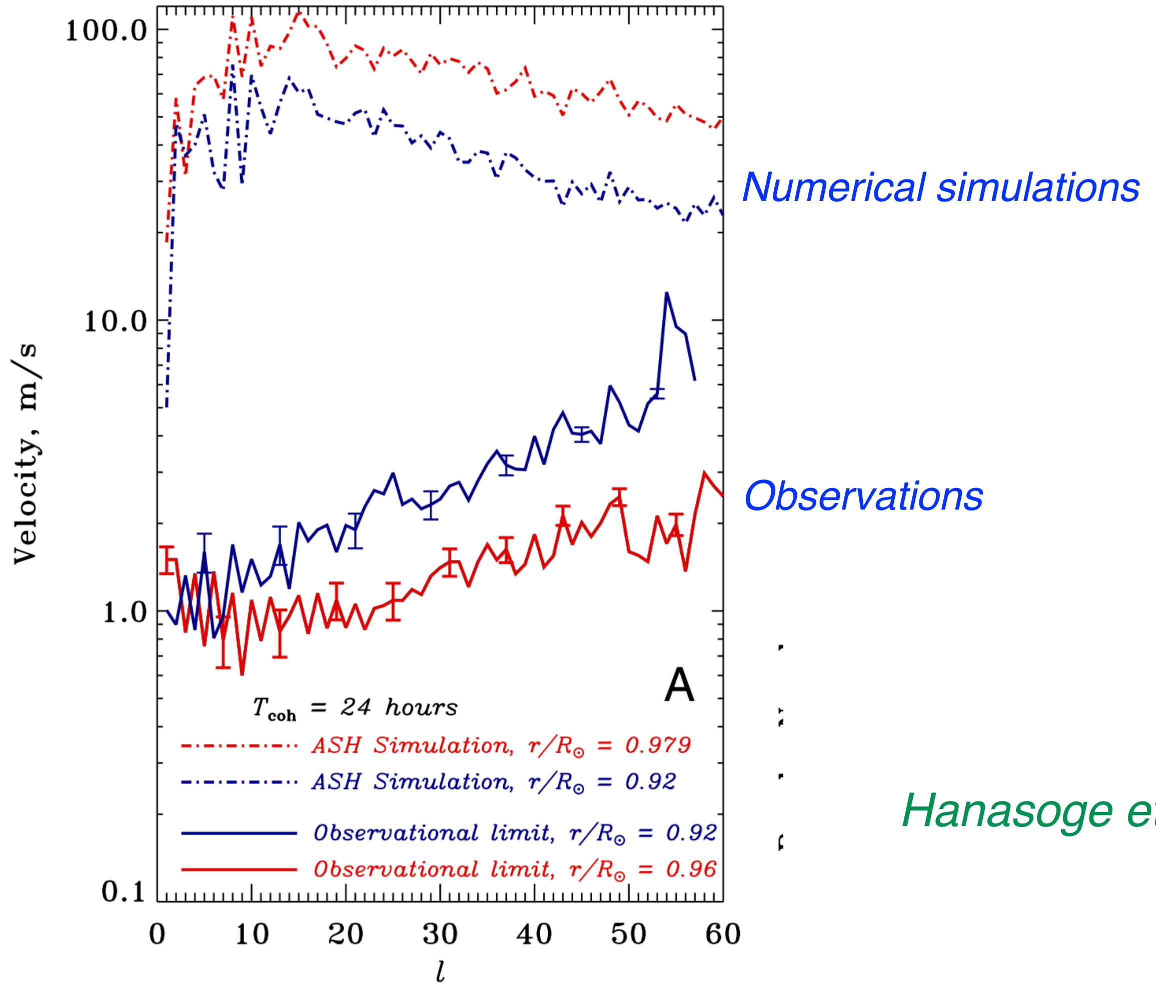
☛ The Sun's differential rotation is maintained by turbulent transport of angular momentum through the action of Reynolds stresses

☛ Spatial and temporal correlations between flow components that generate such stresses are thought to be imposed through Coriolis deflection of convective motions

$\Longrightarrow$ **Very strong connection between convection and rotation**

## Solar subsurface convective velocities: the “convective conundrum”

Convective velocities as a function of spherical harmonic degree l and depth inferred from helioseismic data




Hanasoge et al. 2012

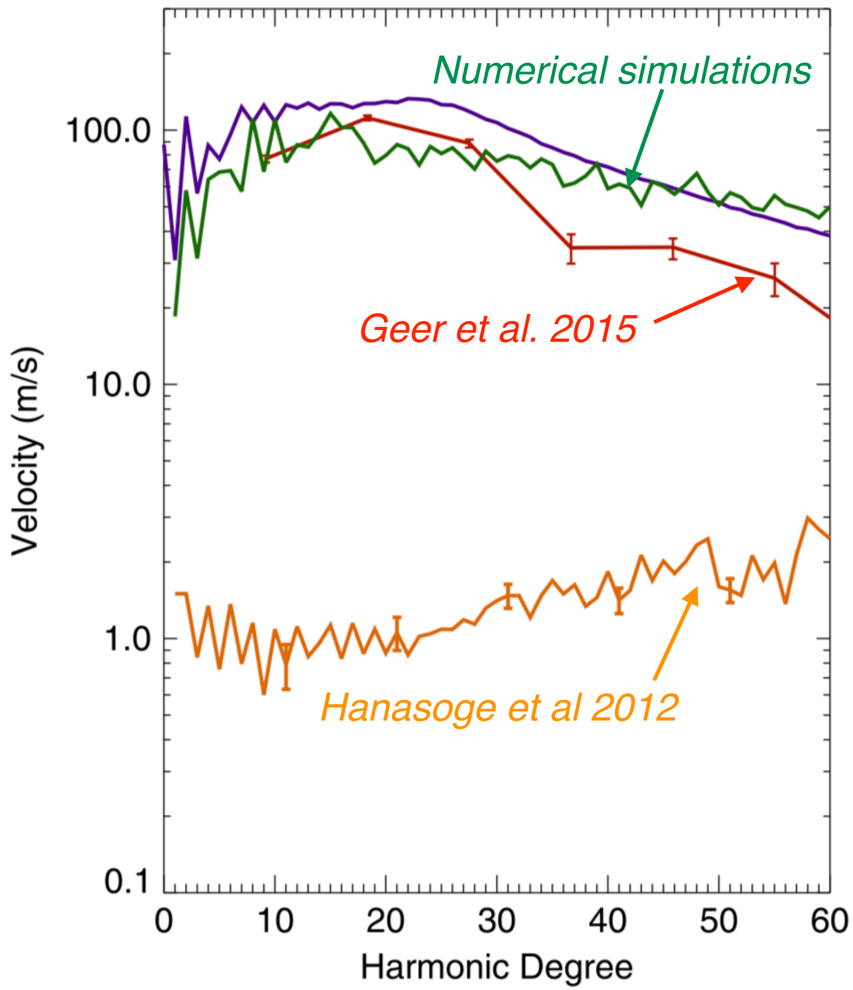
☛**Large scale flows deep (depth ~ 30 Mm $r/R_\odot \sim 0.957$) in the convective zone are significantly weaker than those predicted by most numerical simulations**

☛Dynamical balance in numerical simulations is far from solar conditions?

Or

☛ Problems with the method which underestimates velocities below few Mm?

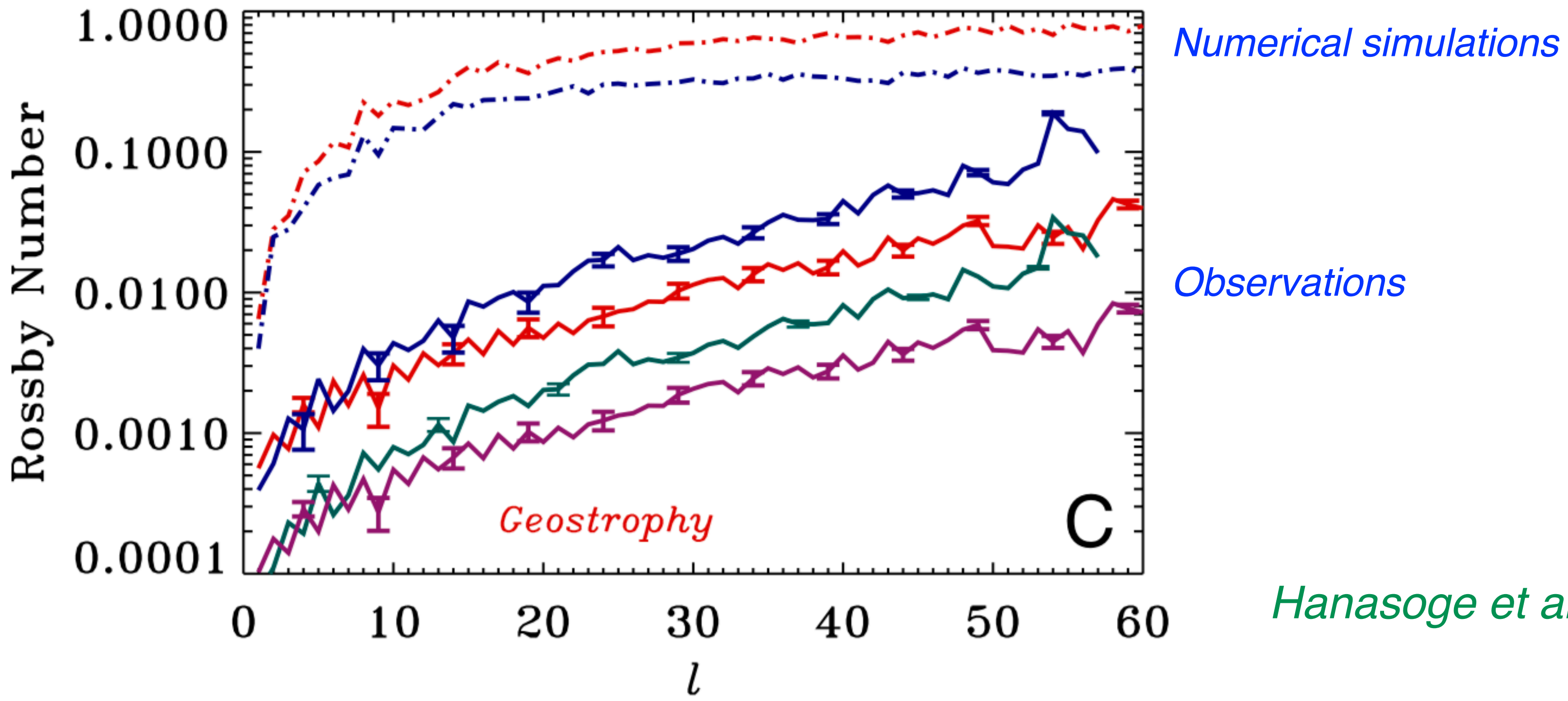
Reanalysis of the solar data by Greer et al. 2015:




Greer et al. 2015

**The jury is still out…..**

Observations suggest small Ro number at depth of ~ 30 Mm
and thus rotationally constrained convection

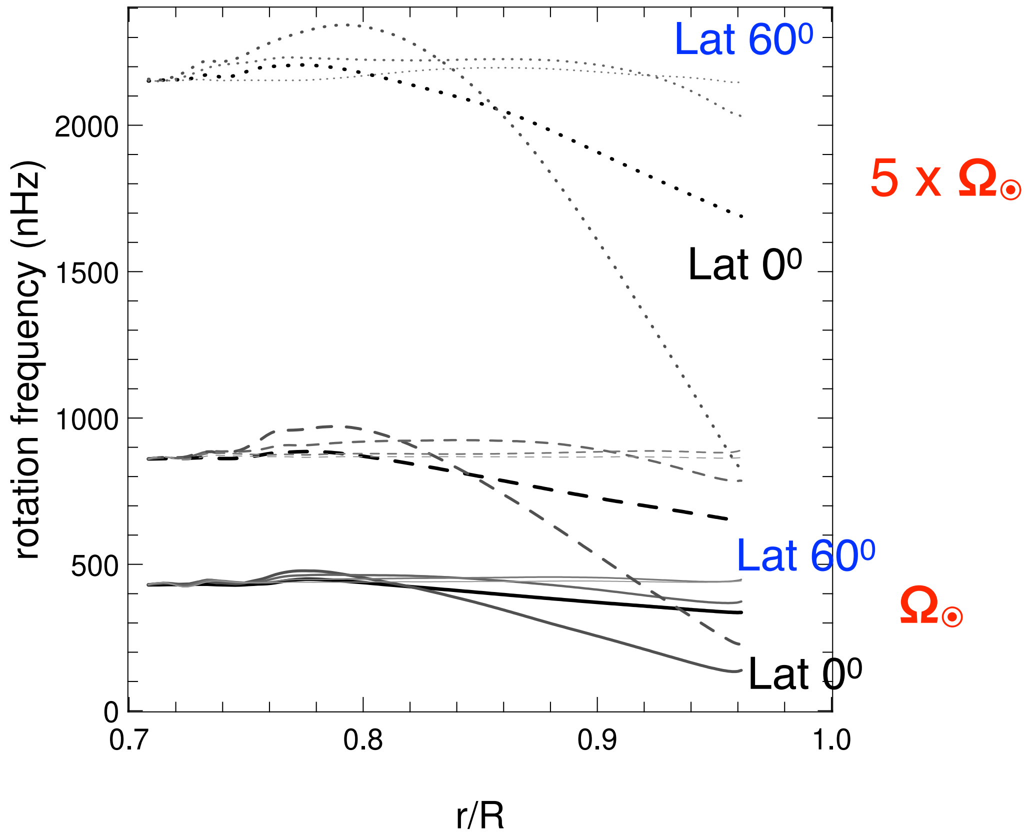


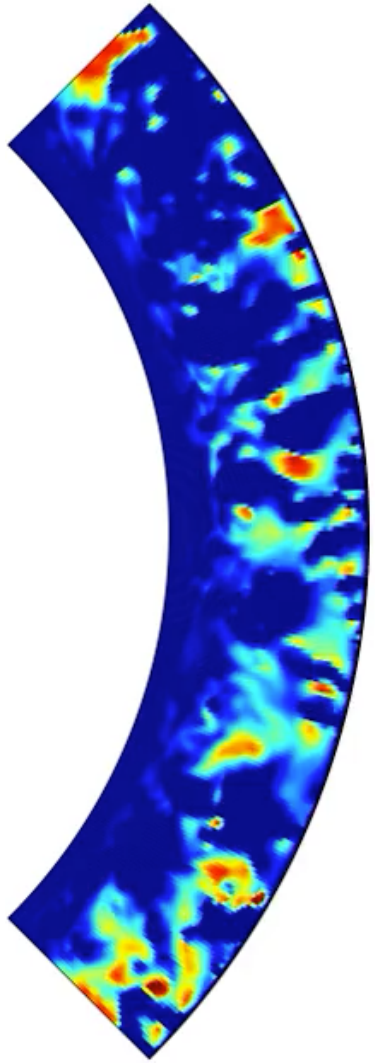

Hanasoge et al. 2012

☛ **According to Hanasoge et al. interior convection would be strongly geostrophically balanced (i.e., rotationally dominated) on these scales.**

# Many numerical simulations are in the wrong rotational regime for solar-like conditions

3D simulations of solar convective envelope with our compressible code MUSIC
($r/R_\odot = 0.7 - 0.96$ )



*Constantino, Baraffe et al. in prep*

☛Increased viscosity or lower diffusivity (**higher Pr**) or magnetic fields, can yield to solar-like rotation (and solve the solar convection conundrum)

☛**Interesting:** convective penetration (overshooting) and inclusion of stable layers beneath the convective zone have a profound impact on differential rotation profile *(Beaudoin et al 2018, ApJ)*

☛**Even more Interesting:** importance of taking into account non-local convection effects, i.e **surface cooling** leading to **downward plumes** that transport angular momentum radially inward

→ despite high Pr, this leads to antisolar-rotation *(Karak et al 2018, PhFl)*

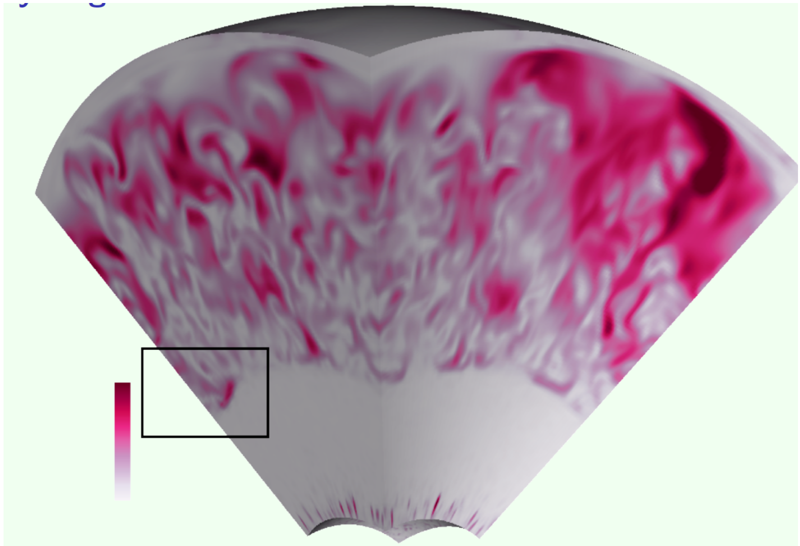
**☛ A consistent picture requires to account for surface cooling (near surface layers) and the interaction between convective zone/stable layers**

# Convective Penetration ("overshooting")

**Penetration/Overshooting:** Extension of convective motions beyond the convective boundary in stably stratified regions

Boundary: Schwarzschild criterion for instability $\frac{dlnT}{dlnP} > |\frac{dlnT}{dlnP}|_{\rm ad}$

☛ **Many observational evidences for presence of overshooting in stars of essentially all masses $\gtrsim 1\ M_\odot$**



Velocity magnitude during steady-state convection, in a $128^3$ wedge of our sun at $\sim 1$ Myr, simulated with a the three-dimensional, time-implicit, compressible LES, stellar evolution code MUSIC (ERC Advanced grant, University of Exeter).

*(Roxburgh 1965; Shaviv & Salpeter 1973; Schmitt et al 1984, etc…)*

## •Constraints from helioseismology

Frequencies of resonant acoustic waves depend on the adiabatic sound speed c

$$c^2 = \boldsymbol{\Gamma}_1\, p/\varrho \;\propto\; \boldsymbol{\Gamma}_1 T/\boldsymbol{\mu}$$

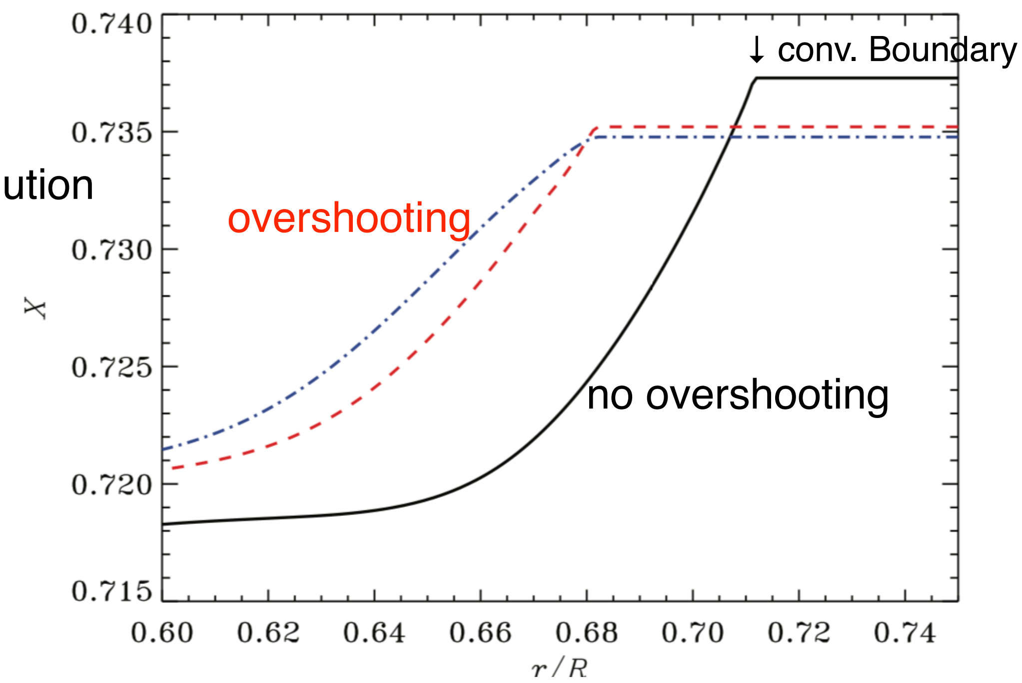
☛ helisoseismology provides information about the profile of $c^2$ in the Sun’s interior

$\Longrightarrow$ Indication of **extra mixing below the convective boundary**

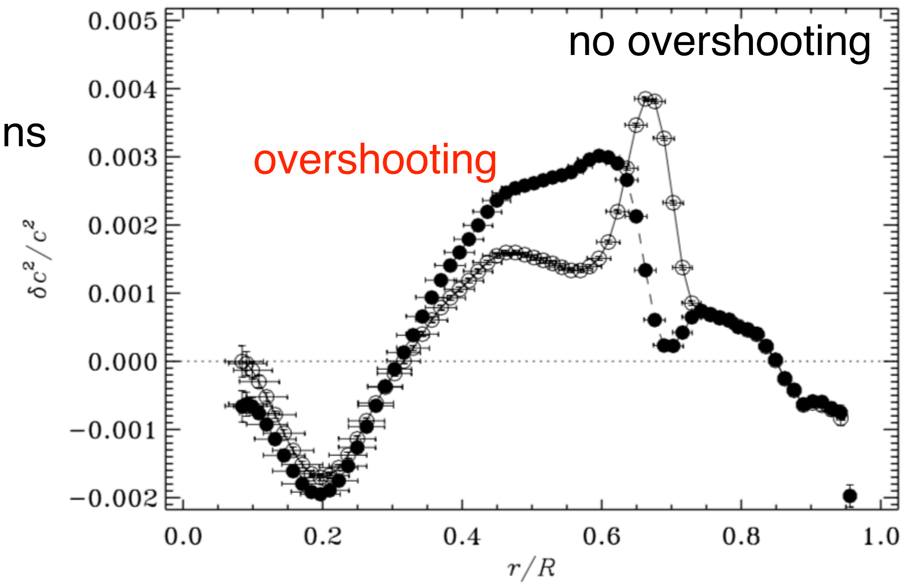
*Christensen-Dalsgard 1993*

## ☛ Convective penetration most likely the best process driving chemical mixing

Profile of hydrogen abundance close to the lower convective boundary from 1D stellar evolution models (phenomenological approach)

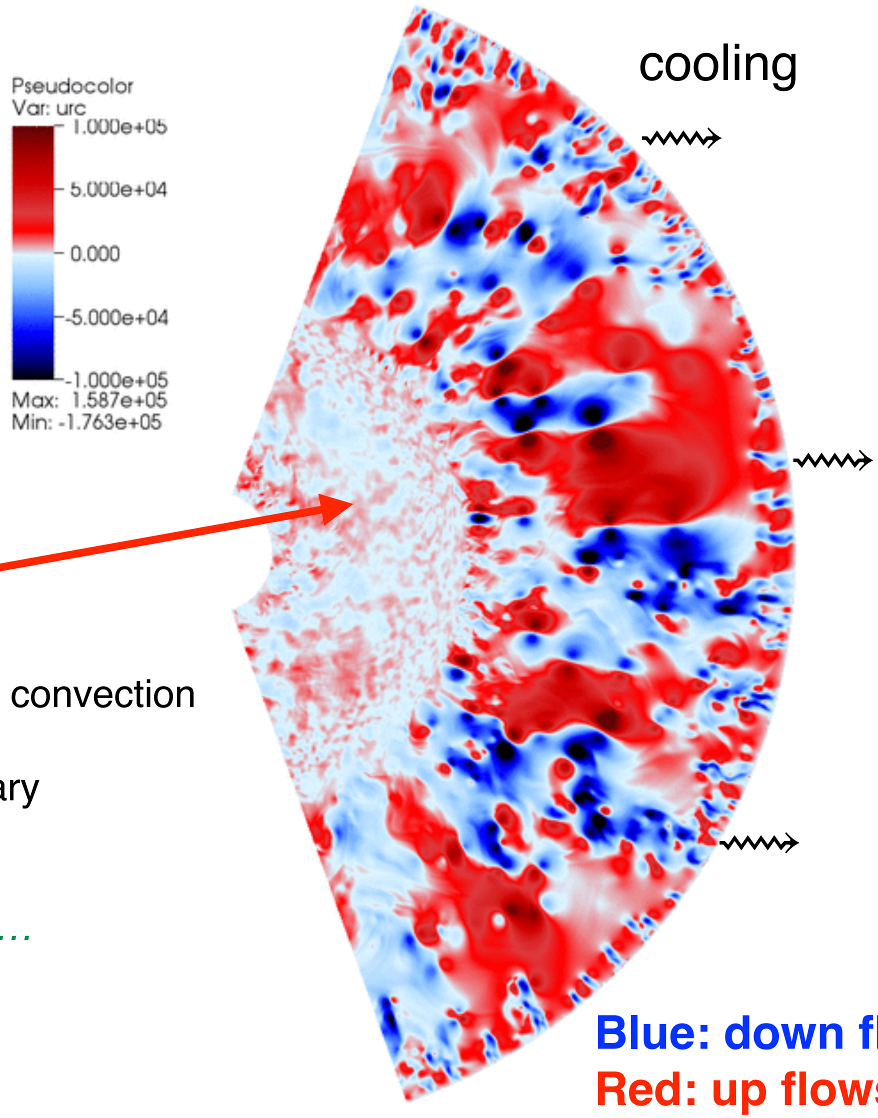



☛ Relative difference $\delta c^2/c$ between Sun observations and model




*Christensen-Dalsgard 2011*

# Internal Waves (gravity or gravito-inertial)




**Internal waves excited by**

- **Reynolds stresses** or **entropy fluctuation** due to convection near the bottom of the convective zone
- and/or **penetrative plumes** just below the boundary

*Press 1981; Schatzman 1993; Zahn et al. 1997;*
*Kumar & Quataert 1998; Goldreich et al. 1994, etc…*

**Blue: down flows**
**Red: up flows**

*Radial Velocity magnitude: characteristic patterns of convection with up-wards  and down-wards "plumes"*

☛**Transport of angular momentum** by convectively (and/or penetrating flows) excited internal waves

- Suggestion of a similar mechanism as the QBO in the Sun with shear-layer oscillations in the "tachocline" (Kumar et al. 1999)

Major mechanism for the wave damping in stellar interior is radiative damping:

Damping distance: $d \propto \frac{w^4}{l^3 K_T}$ Thermal diffusivity $K_T = \frac{16\sigma T^3}{3\rho^2 \kappa c_p}$

$\Longrightarrow$ **larger damping (i.e small d) for decreasing frequency** $w$

## Basic picture:

Frequency of waves excited at convective boundary $r_c$ in the rest frame at radius r:

$$w_{rf}^m(r) = w_c + m\,[\Omega_c - \Omega(r)]$$

If $\Omega(r)$ increases with depth below the convective zone ($\Omega(r) > \Omega_c$)

→ **Prograde** ($m > 0$) are shifted to **lower** $w$

→ **Retrograde** ($m < 0$) are shifted to **higher** $w$

⟹ **Damping of prograde waves is enhanced (shorter damping length) relative to retrograde waves (d $\alpha$ $w^4$)**

⟹ positive angular momentum deposited just below $r_c$ while retrograde waves deposit their negative angular momentum further away

☛ **double-peaked shear layer**

⟹ prograde shear layer propagates toward $r_c$ to eventually merge with shear layer just below convective zone

☛ process repeats leading to oscillatory behaviour i.e QBO-like process

Attempts to find evidence of this process in hydrodynamical simulations of the Sun

- No QBO-like oscillations at the convective boundary (tachocline)
  Suggestion of a low-amplitude QBO-like oscillation well below the convective boundary *(Rogers et al. 2006)*

- Simplified numerical experiments can produce oscillating shear flows *(Rogers et al. 2008)*

☛ Importance of critical layers where waves are attenuated and which could dominate the mean flow dynamics

☛ **Importance of the spectrum and amplitudes** of waves driven (i.e excitation mechanism of the waves → convection/turbulence/plumes?)

Press 1981: *“Convective overshoot and sub scale turbulent instability of a highly nonlinear internal wave are two aspects of a single, but **messy**, physical process”*

To understand/describe waves and transport of angular momentum in stellar radiative cores

☛ **one needs to understand the full connection(s) between convection-penetration-rotation-waves**

**A very long journey!**

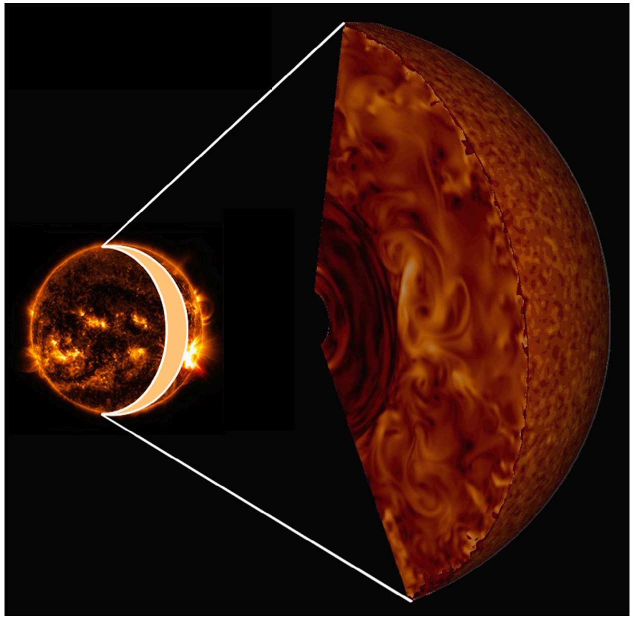
Our first step of this thousand miles journey is to **understand convection and penetration** and their close inter-connection *(which impact convective velocities,* differential *rotation, waves and vice-versa….*)

## Our approach of the problem: a systematic survey of convection/penetration based on 2D and 3D fully compressible time implicit simulations

*In progress*

☛ Explore the impact of radial extension of the numerical domain:
Near-surface layers + stable radiative layers

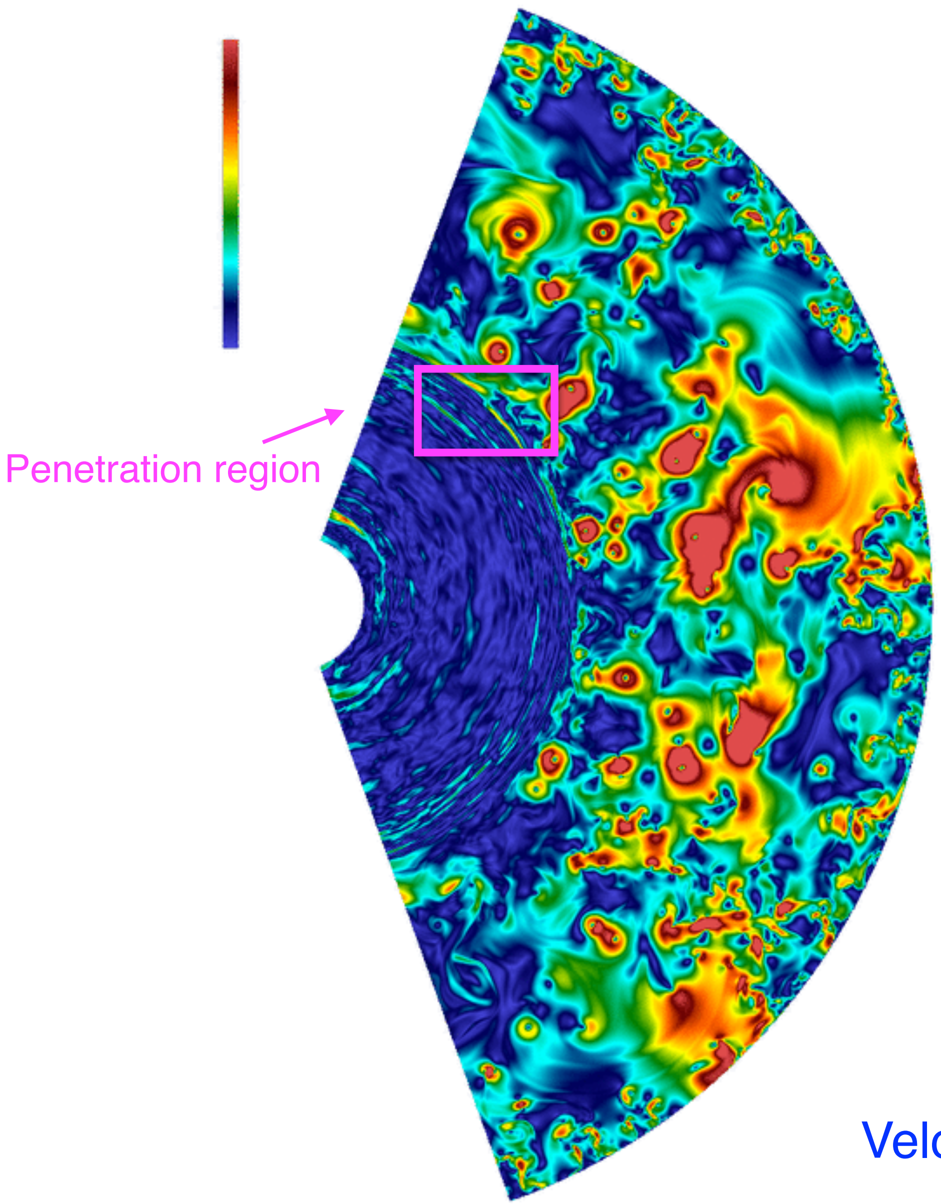
☛ Analyse the excitation of waves



*Next steps:*

- Explore the impact of rotation and transport of angular momentum
- Explore the impact of magnetic fields

☛ **Primary goal:** understand the connection between the dynamics in the convective zone and plumes in the penetration region (characterise the mixing, wave excitation, etc..)




Numerical simulations with MUSIC

*(Viallet et al. 2011, 2013, 2016; Goffrey et al. 2017)*

- Spherical geometry (2D or 3D)
- Finite volume scheme
- **Time implicit solver**
- **Fully compressible** hydrodynamics
- Thermal diffusion $\nabla \cdot (\chi \nabla T)$

*Radiative conductivity* $\chi = 16\sigma T^3 / 3\kappa\rho$

- Realistic stellar stratification

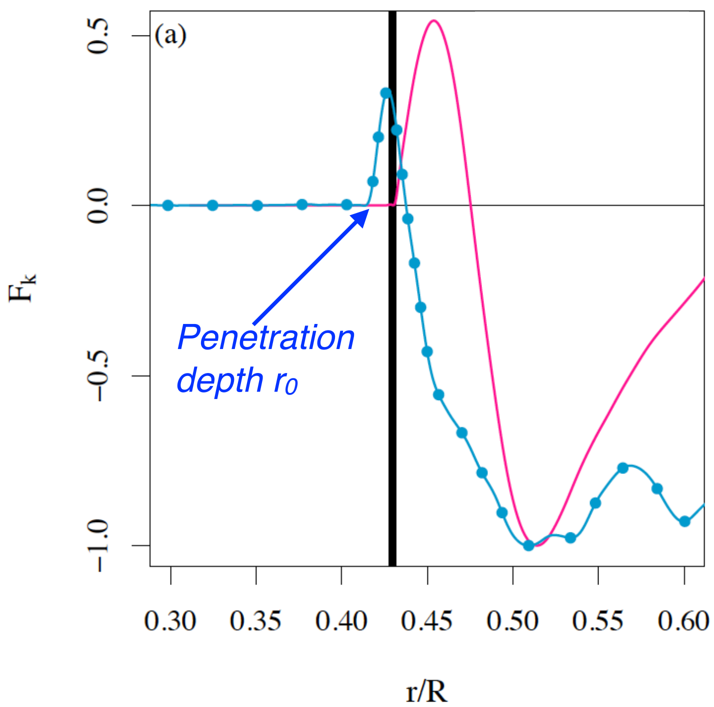
*Realistic equation of state (ionisation, partial degeneracy, mixture of composition, etc*

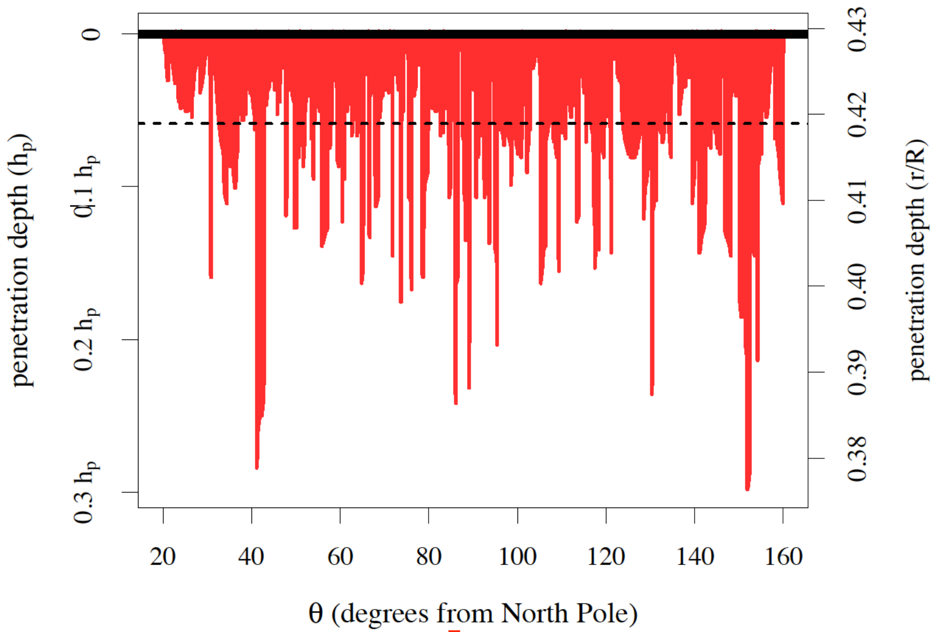
Velocity magnitude : very high res 2432x2048

## ☛ A new approach to describe convective penetration: Extreme value statistics
*(Pratt et al. 2017, 2019)*

Typical shape of the penetration depths (at a given time): extent of downflows (defined by vertical flux of kinetic energy —> 0) beyond the convective boundary varies with colatitude θ

$F_k = 1/2\ v_r\ \rho\ v^2$



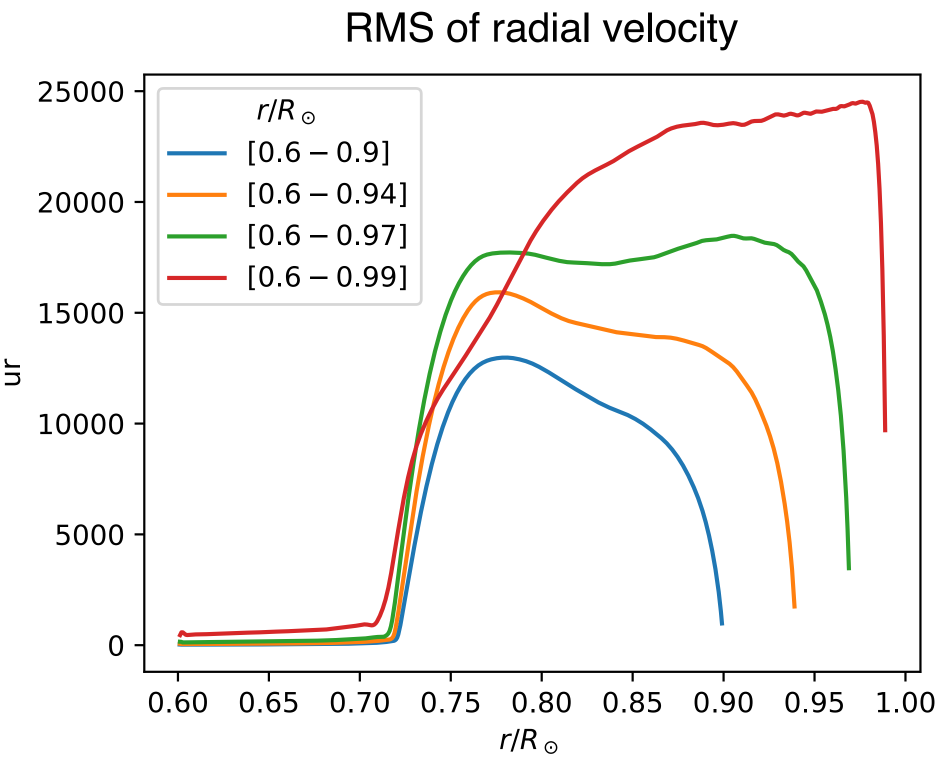

PDF of penetration depths $r_0$ for all downflows (over the whole simulation time) and the PDF of maximal penetration depths $r_{max}$

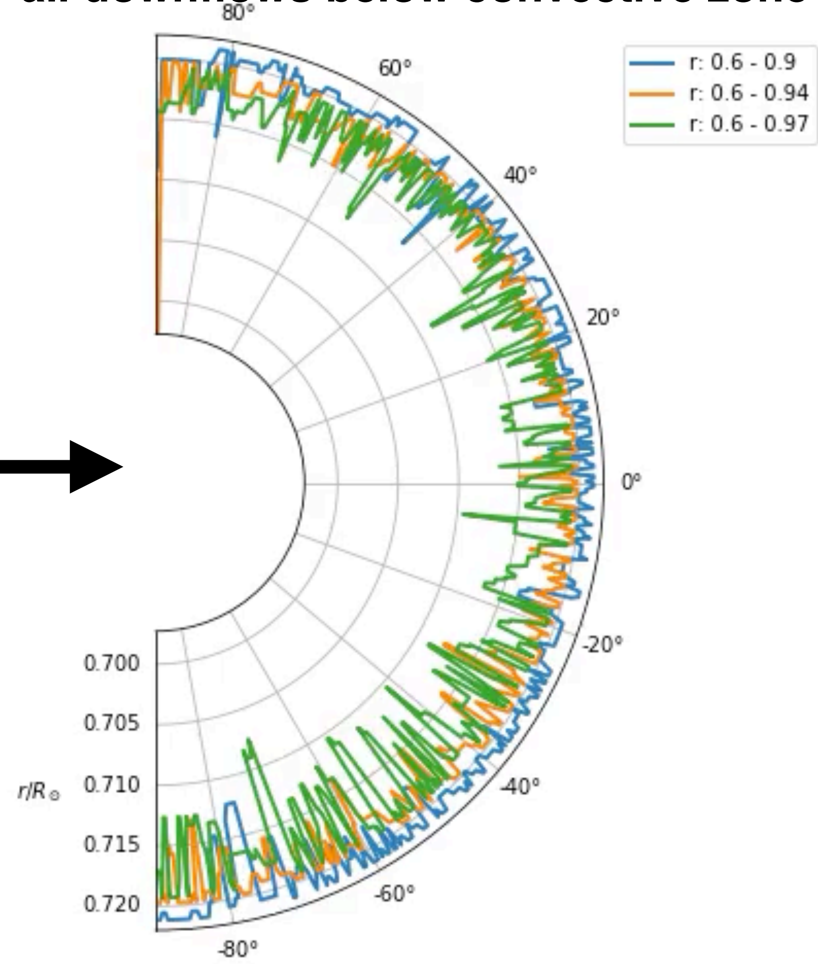
**Impact of radial extension of the numerical domain:**

(*In progress)* wide survey (2D/3D) of a solar-like model with variable radial extensions in the range r/R = 0.1 - 1

- General **increase** of radial velocities when including more near-surface layers (effect of **surface cooling** on the **strength of convective plumes**)

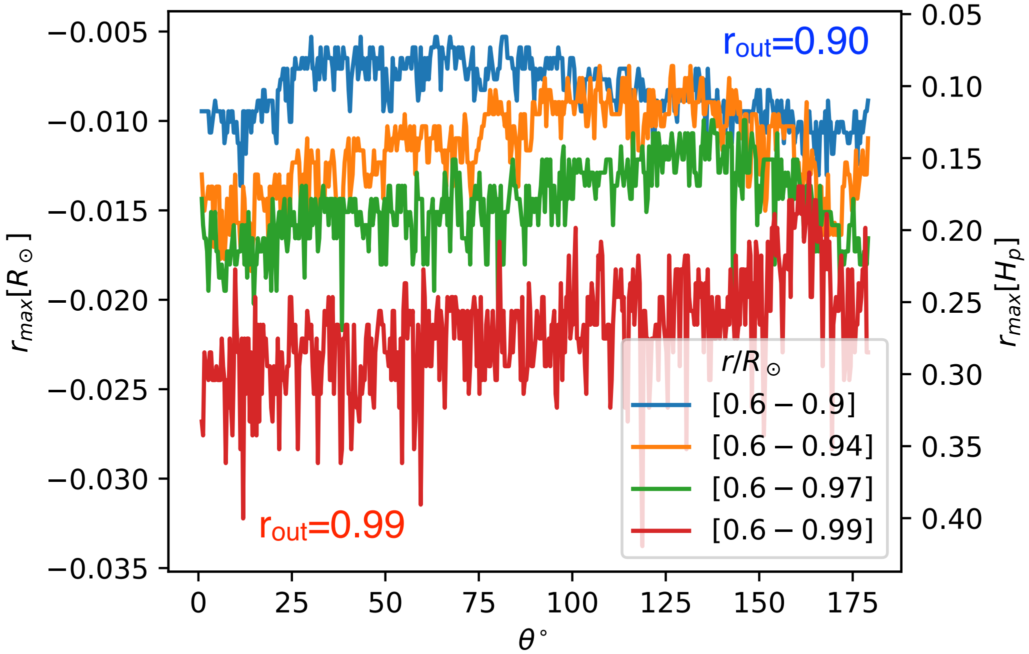
**Determination of the Penetration depths $r_0$ for all downflows below convective zone**



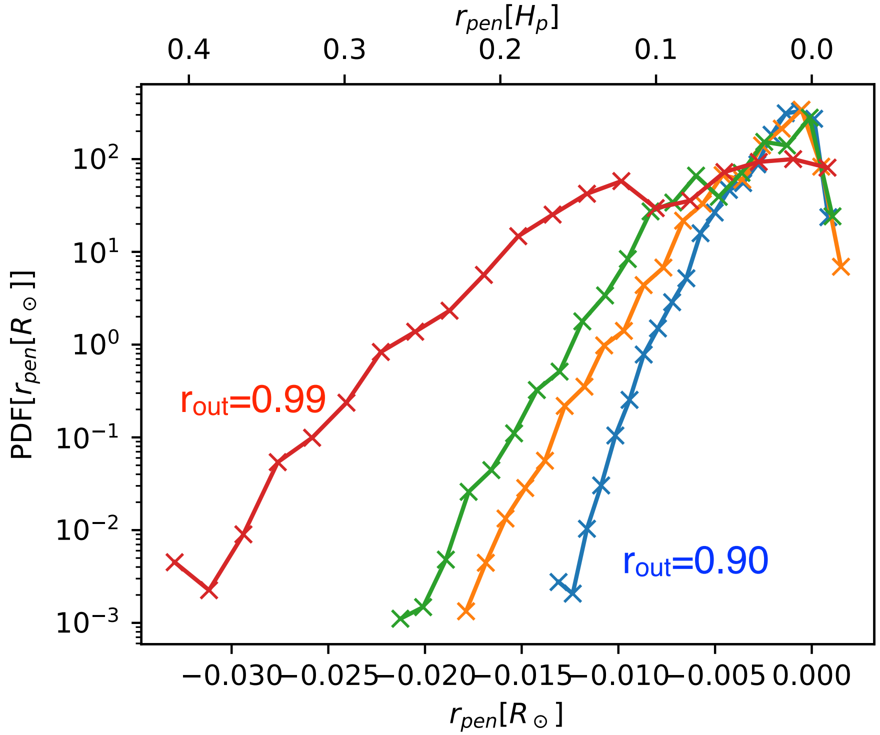




*Vlaykov et al., in prep*

**Maximum penetration depths $r_{max}$ below convective zone**



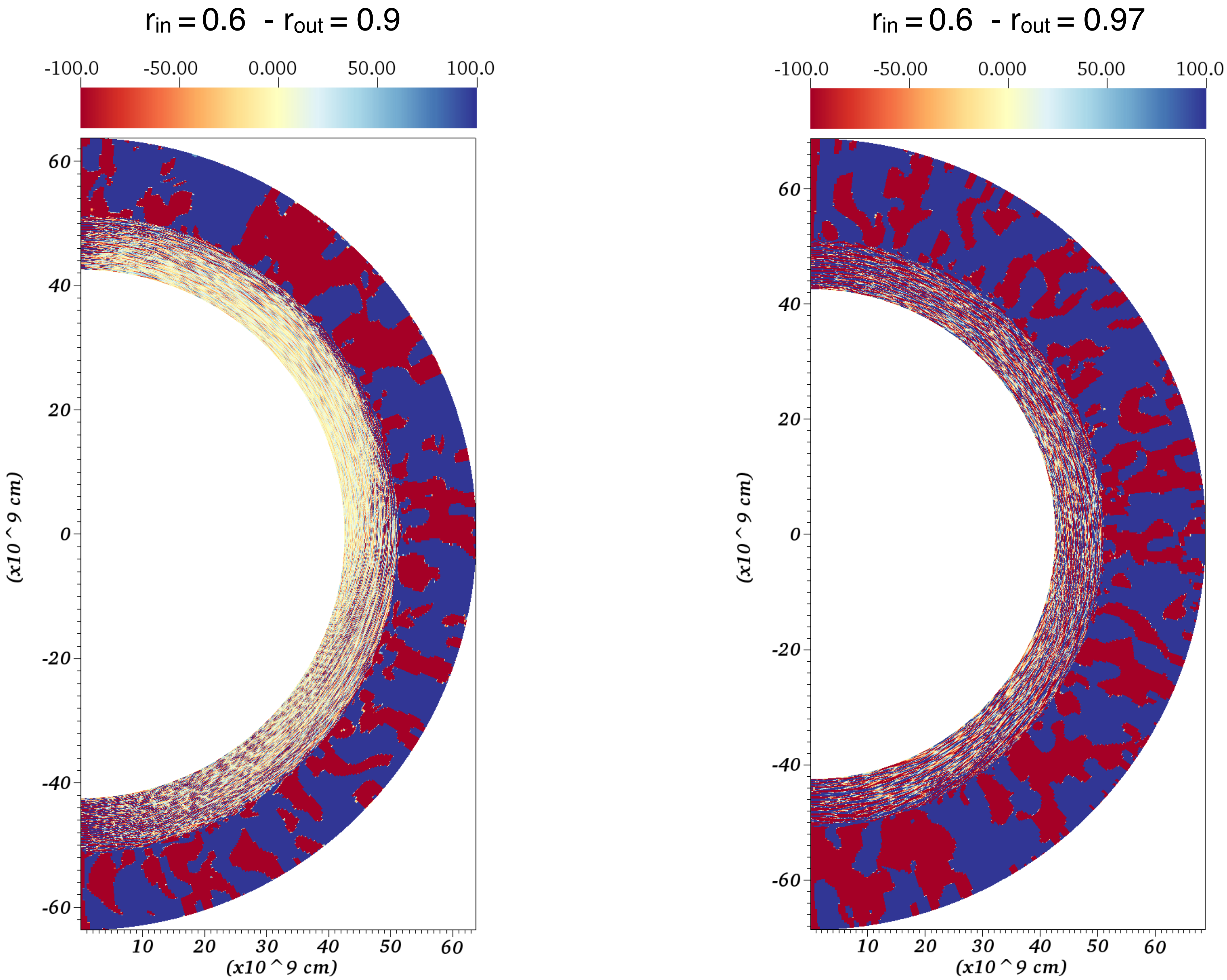

**PDF of penetration depths $r_0$**




☛ The **closer** the upper domain to the **near-surface layers** where **cooling** takes place, the **stronger the downwards plumes** and the **deeper the penetration plumes**

☛ Ongoing analysis of the impact of including a larger inner domain (stably stratified region extending down to rin=0.1)

# Radial velocity snapshot for two different outer extensions



☛ **Next step: Quantitative analysis of internal waves**

Radial velocity fields are used to characterise internal gravity waves that propagate in the stable zone

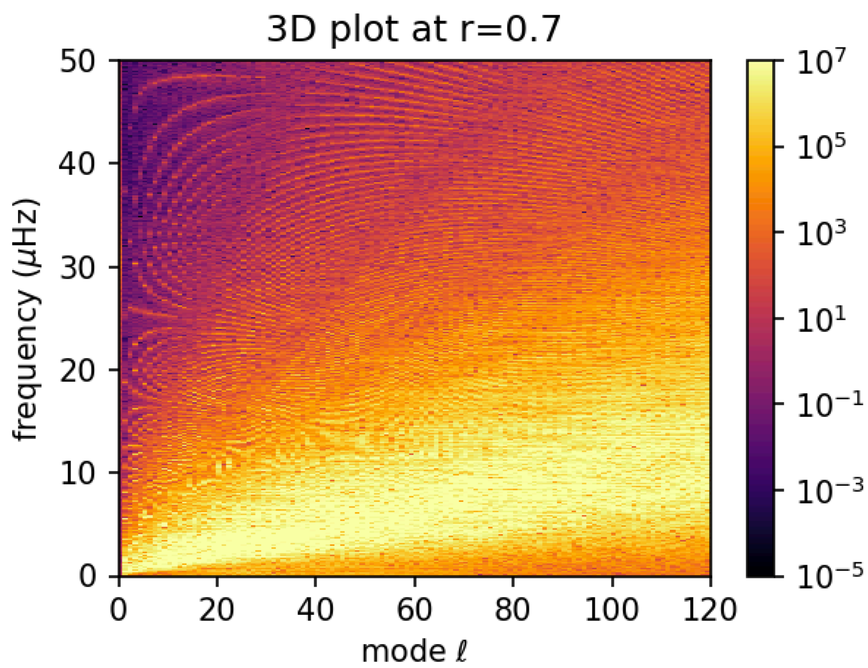
From the radial velocity fields: $v_r\ (r,\theta,\varphi,t)$

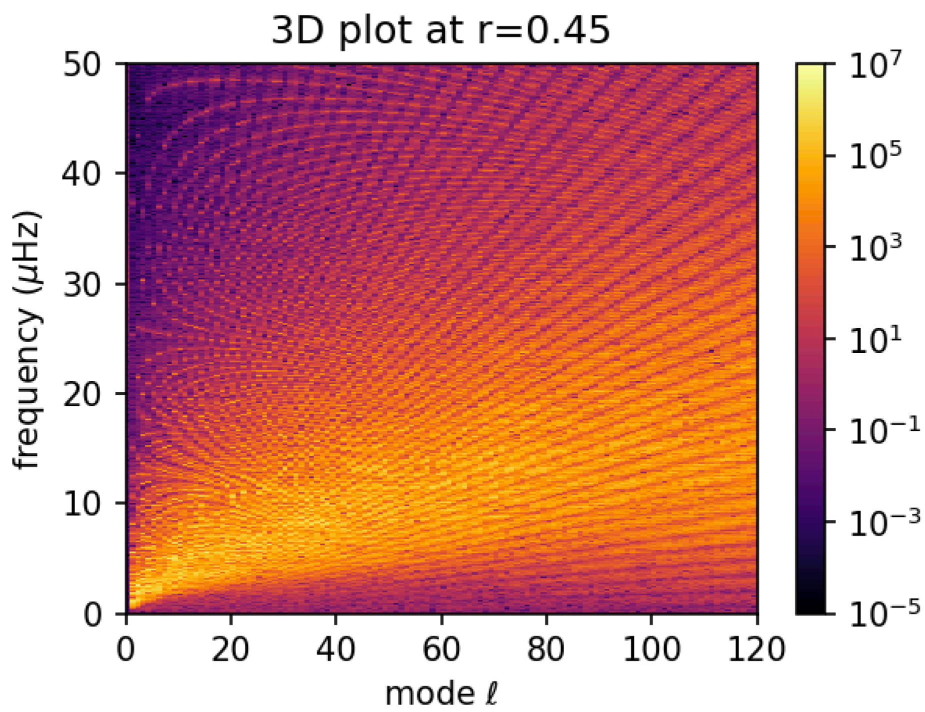
—> projection on spherical harmonic basis $Y_l^m.\ \mathbf{e}_r$ —> $v_r'(r,l,m,t)$

—> Fourrier transform —> $v_r''(r,l,m,\omega)$ *($\omega$ is the mode frequency)*

## Illustration for a Solar model $r_{in}$=0.4 - $r_{out}$=0.9

### Spectrum of waves at different depths: $(v_r'')^2$

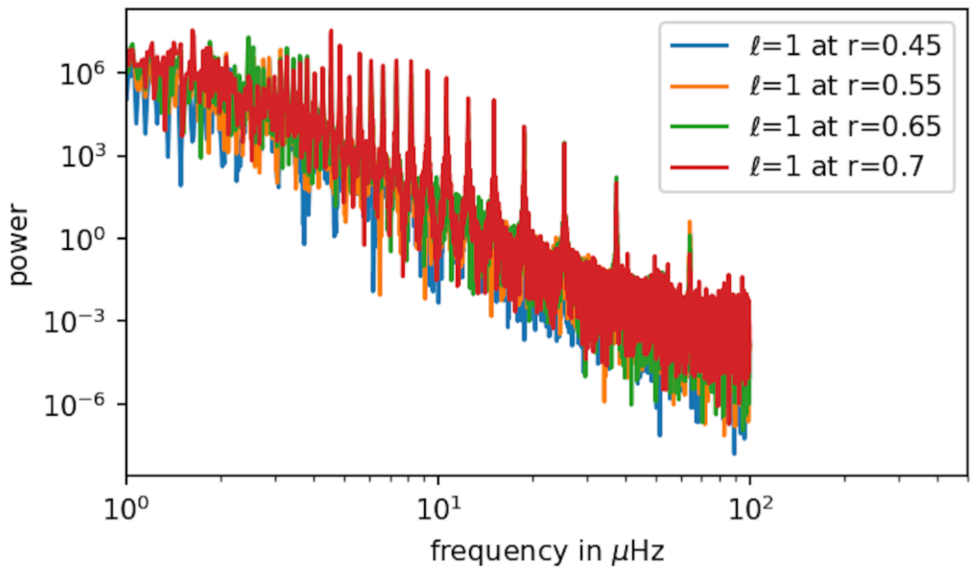


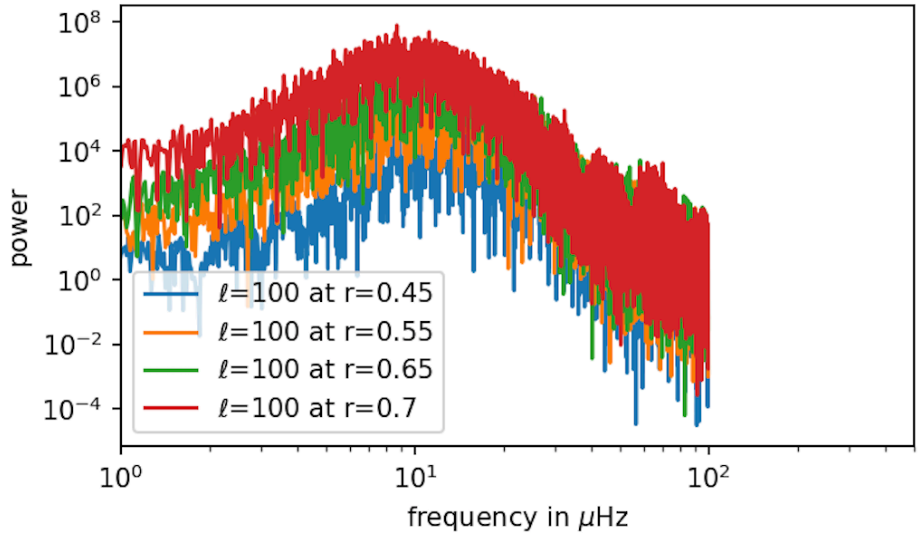

*Lesaux et al.*

# Spectrum for different l at different depths

l=1




l=100




☛ Powerful tool to analyse the excitation spectrum of waves (stresses due to convective eddies at the boundary and/or **penetrating plumes**)
*Rogers & MacGregor 2011; Alvan et al. 2015*

☛ A motivation: Impact of extreme penetration events?

**Story to be continued….**

# Conclusion (or thoughts…)

☛ Solar rotation, convective velocities, waves and convective penetration are linked
$\Longrightarrow$ **Need for a global framework**

☛ **Surface cooling and plumes dynamics play an important role**

☛ **What is the role of extreme penetrating plume events on wave excitation mechanism and properties?**