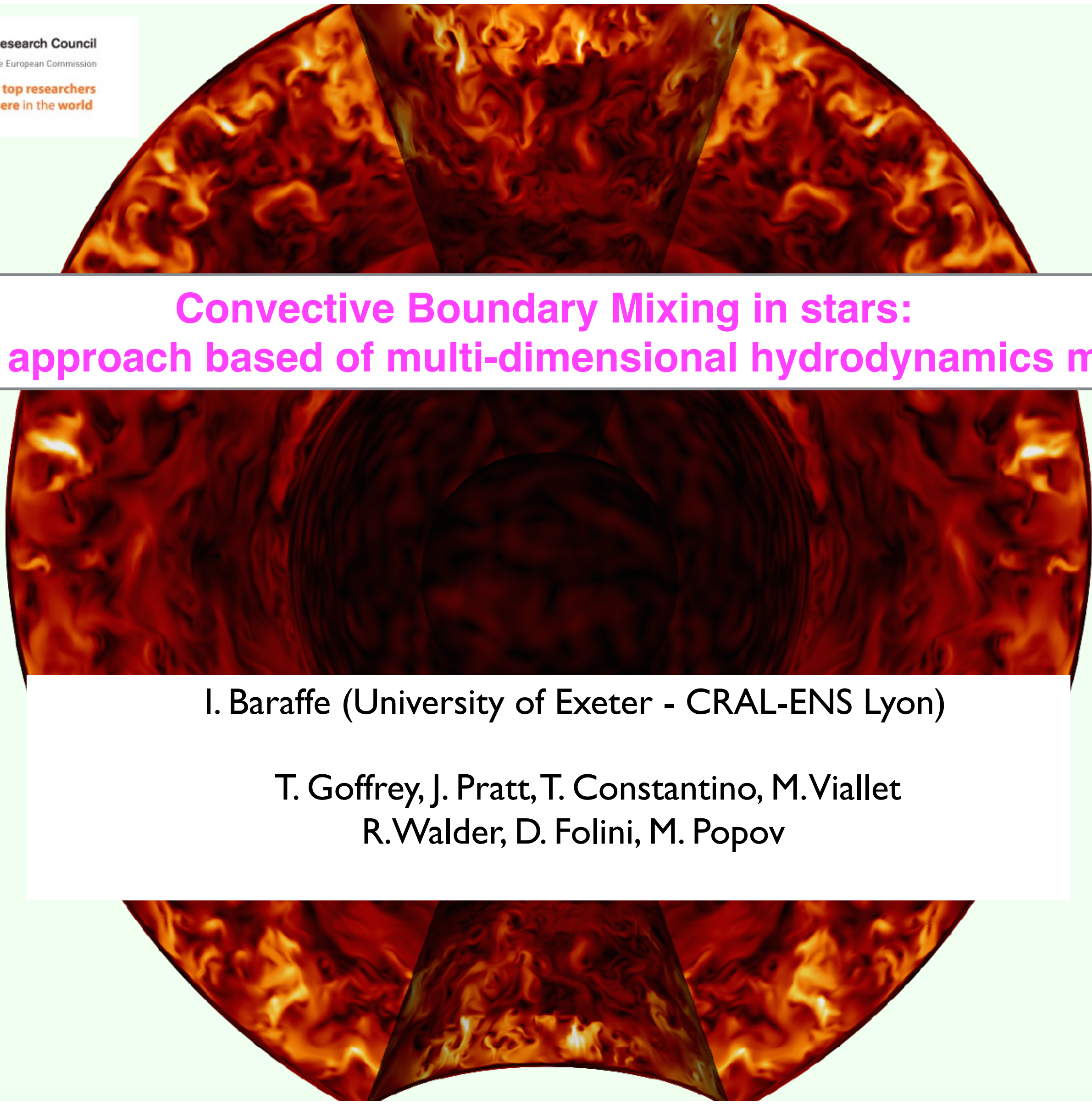


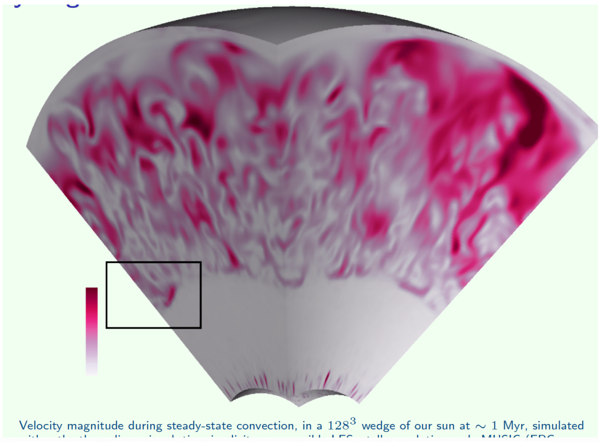
Convective Boundary Mixing in stars: A new approach based of multi-dimensional hydrodynamics models

I. Baraffe (University of Exeter - CRAL-ENS Lyon)

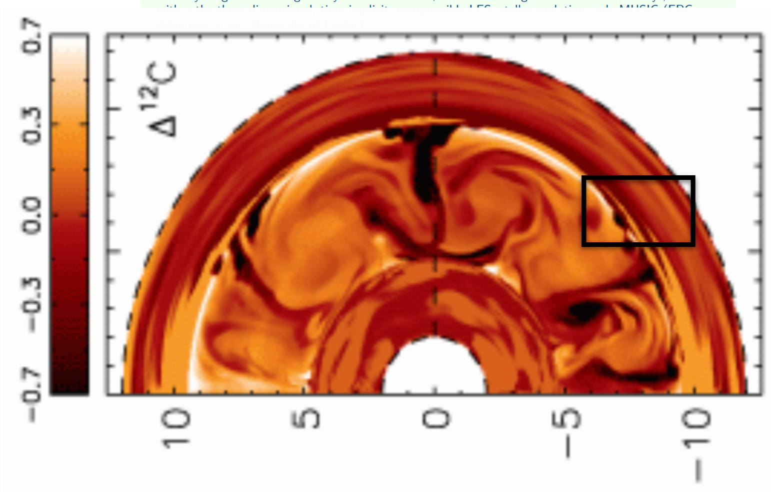
T. Goffrey, J. Pratt, T. Constantino, M. Viallet
R. Walder, D. Folini, M. Popov

The problem of convective boundary mixing (overshooting/ penetration) in stars

Long standing problem affecting chemical mixing, **age of stars**, transport of angular momentum and magnetic field, …



Envelope

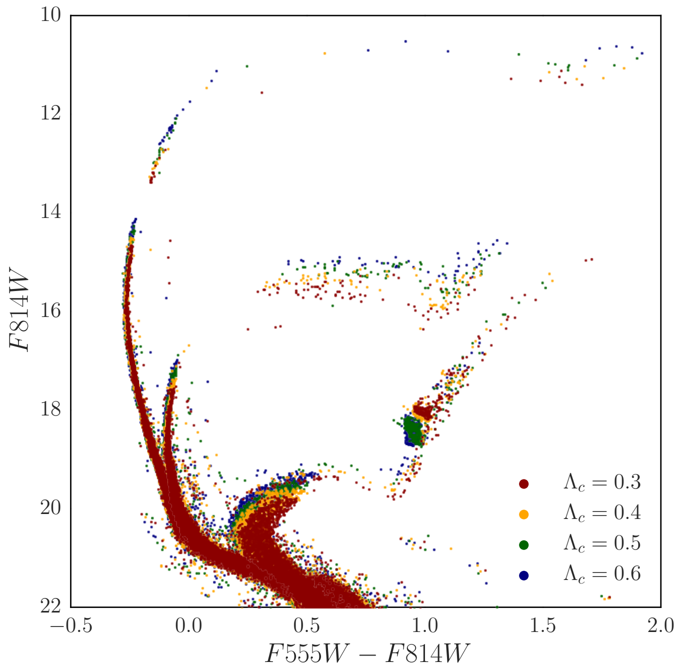


Core

Standard treatment in 1D codes: extra mixing over an arbitrary width $d_{ov} = \alpha H_P$ (α free parameter)

- Impact of core overshooting (free parameter Λ_c) on Color-Magnitude diagrams

Rosenfield et al. 2017



- Impact on size of convective core, age, surface abundances, etc…..

- Observational constraints from **helioseismology:** thermal/sound speed profile at the transition between convective envelope and radiative core in the Sun *(e.g Cristensen-Dalsgaard osenfield et al. 2011)*

- Constraints on convective core size from **asteroseismology** ⟹ constraints on overshooting efficiency and length *(e..g Silva Aguirre et al. 2013; Deheuvels et al. 2016; Bossini et al. 2017; etc…)*

- Constraints on convective core size from **eclipsing binaries**

☛ **"Model dependent"** methods based on comparisons between observational diagnostics *(frequency ratios, mode period spacing, mass/radius, Teff, L, etc…)* and predictions from stellar evolution models using different formalisms/recipes for overshooting.

Question: how reliable are these constraints?

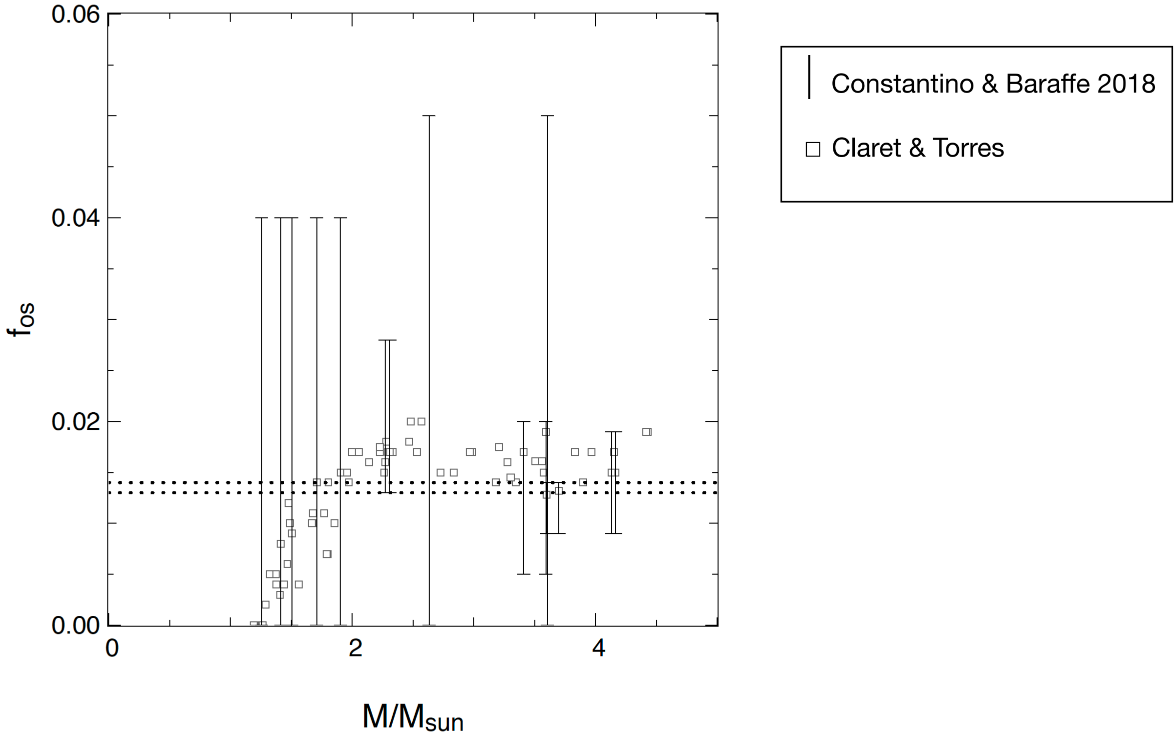
Not so good for eclipsing binaries…..

Suggestion of increasing overshooting length with stellar mass (Claret & Torres 2016, 2017, 2018)

Reanalysis of 5 eclipsing binary systems ~ 1.2 M⊙ - 4 M⊙ *(Constantino & Baraffe, 2018 submitted)*

☛ Large range of acceptable solutions for the overshooting parameter f_{os}

☛ No trend with mass



For EB to be really useful, one needs →

- **Very accurate determination of M, R, Teff and Z**
- **Combination with asteroseismology**
- **Better models because of degeneracy of solutions by varying (α_{MLT}, f_{os}, microscope diffusion)**

(conclusion also reached by Valle et al. 2016, 2017 by analysing synthetic binary systems)

☛ Motivation for better models

1D models based on phenomenological approaches—> ***Convection, rotation, dynamo, mixing, turbulence, etc…***

Calibration of free parameters from observations

- 👎 no predictive power
- 👎 degeneracy of solutions
- 😞 do we really understand the physics?

⇒ **Need for multi-dimensional models to improve the 1D formalisms**

Development of MUSIC "Multidimensionnal Stellar Implicit Code"

(Viallet et al. 2011, 2013, 2016; Geroux et al. 2016; Pratt et al. 2016; Goffrey et al. 2017; Pratt 2017)
ERC TOFU

- Spherical geometry (2D or 3D)
- Fully compressible hydrodynamics + rotation
- Realistic stellar physics (opacities and equation of state)
- **Time implicit solver** (no stability limit on the timestep)
- Initial models from 1D stellar evolution calculation

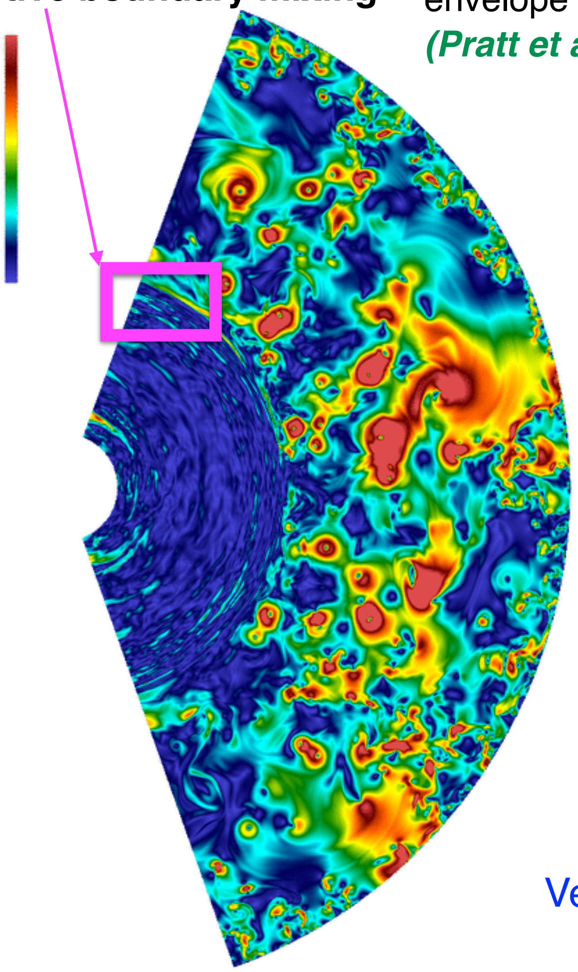
➤ *interface with Lyon code (Baraffe et al.) and MESA (Constantino et al, in prep)*

☛ Major motivation is to improve phenomenological approaches used in 1D stellar evolution codes

☛Application to convective boundary mixing in stellar envelopes

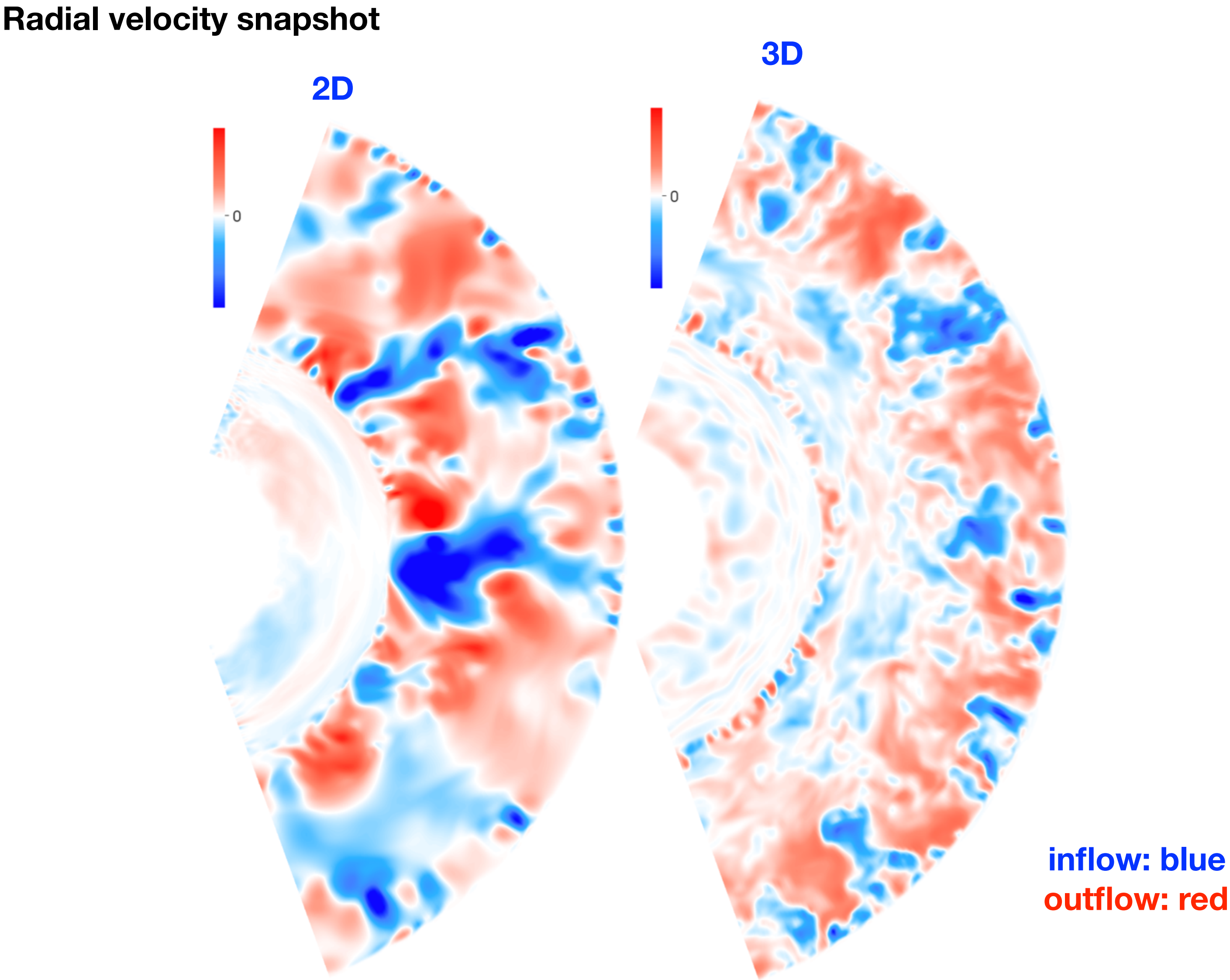
Penetration region
Convective boundary mixing

Analysis of 2D/3D simulations of a star with a large convective envelope and a radiative core (Pre-main sequence star) ***(Pratt et al. 2016, 2017)***

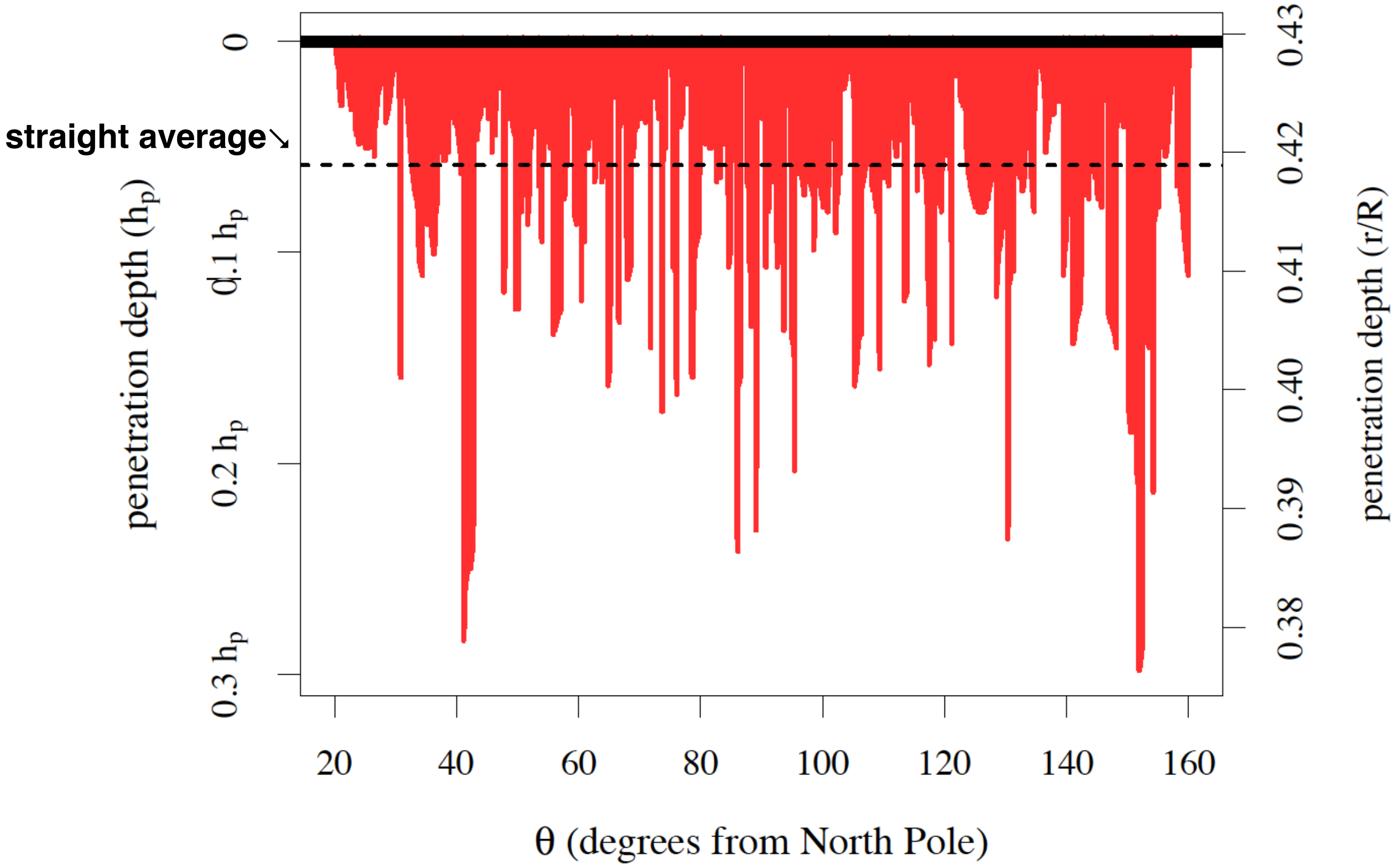


☛ Goal: Derivation of a **diffusion coefficient** D(r) characterising the mixing in the transition region

Velocity magnitude : very high res 2432x2048


Radial velocity snapshot
2D
0
3D
0
inflow: blue
outflow: red

Typical shape of the penetration depths (at a given time): extent of downflows beyond the convective boundary varies with colatitude θ



☛ **Straight average miss the larger penetration events**

Extreme penetrating plumes characterise the relevant penetration depth in stars

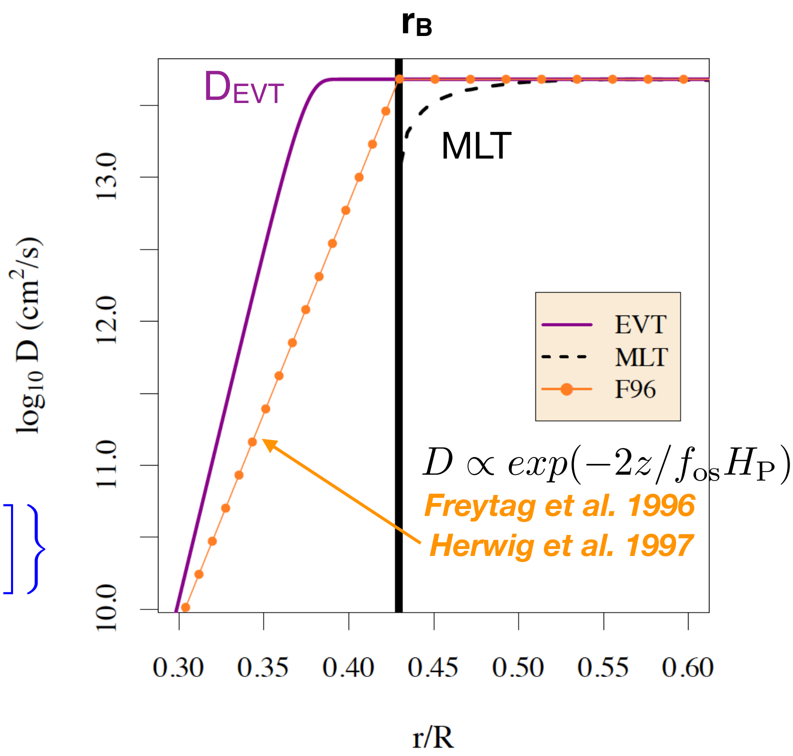
(Pratt et al. A&A, 2017)

Description of the statistical complexity of the data: **Extreme Value Theory**
Determine the probability of events that are more extreme than any previously observed (used in Earth science, traffic prediction, unusually large flooding event, finance…)

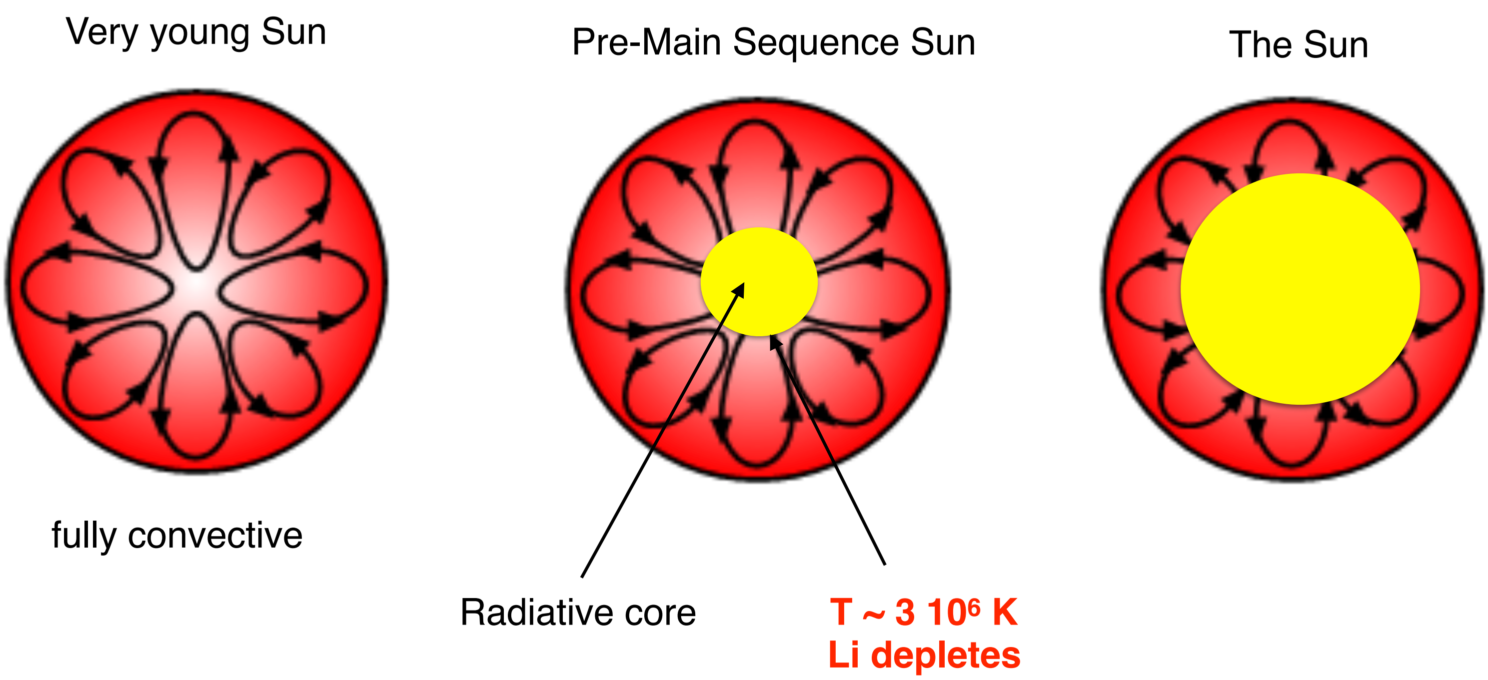
- Distribution of maximal penetration depths, linked to extreme events in the tail of the distribution → **contribute to mixing**
- Derivation of a diffusion coefficient D(r) characterising the mixing driven by penetrative plumes

$$D_{EVT} = D_0\left\{1 - \exp\left[-\exp\left(-\frac{(r_B - r) - \mu}{\lambda}\right)\right]\right\}$$

λ, μ are predicted by simulation



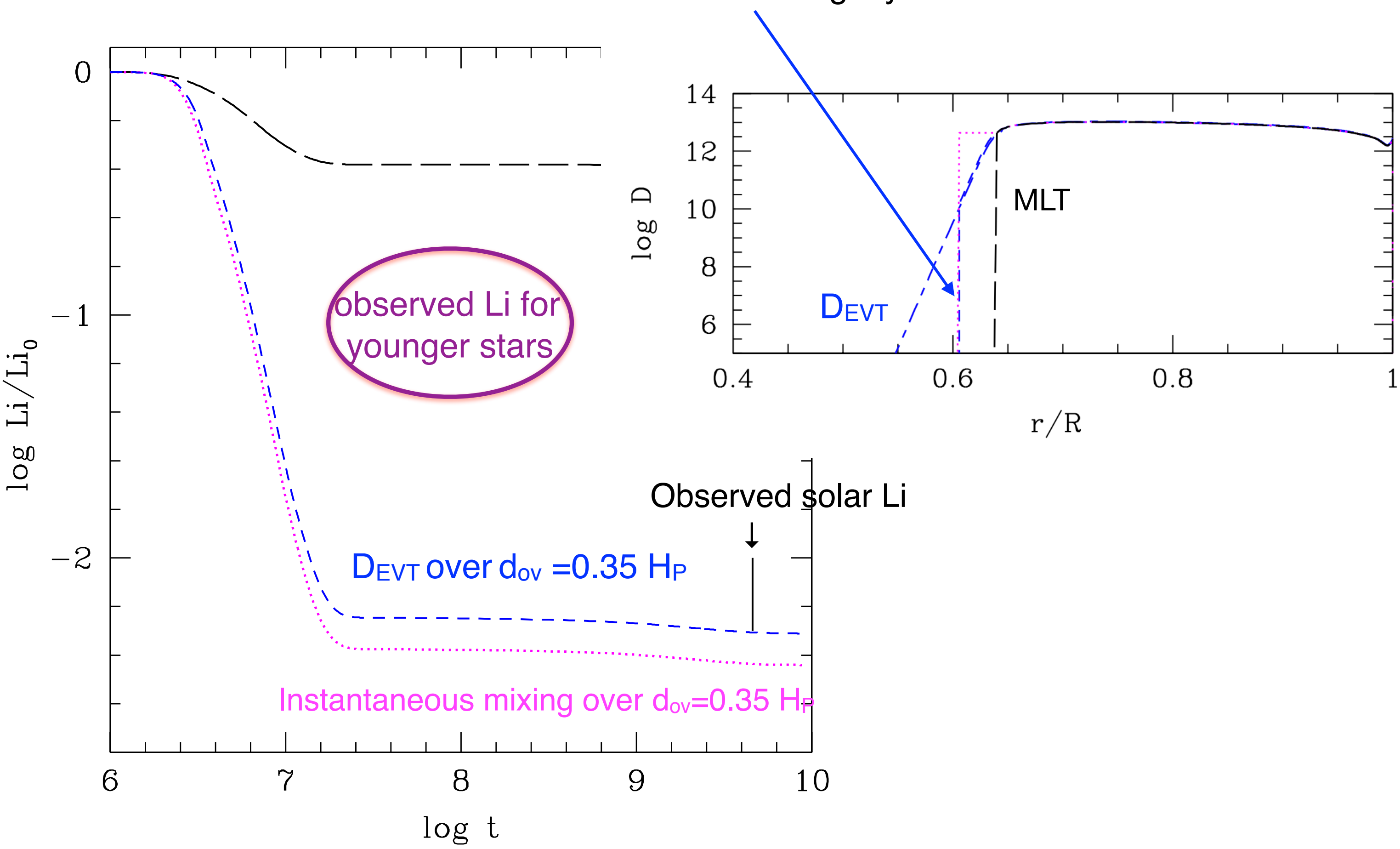
Application to the depletion of Li in the Sun's convective envelope



Problem: Models predict less depletion of Li than observed ☛ **still an open issue!**

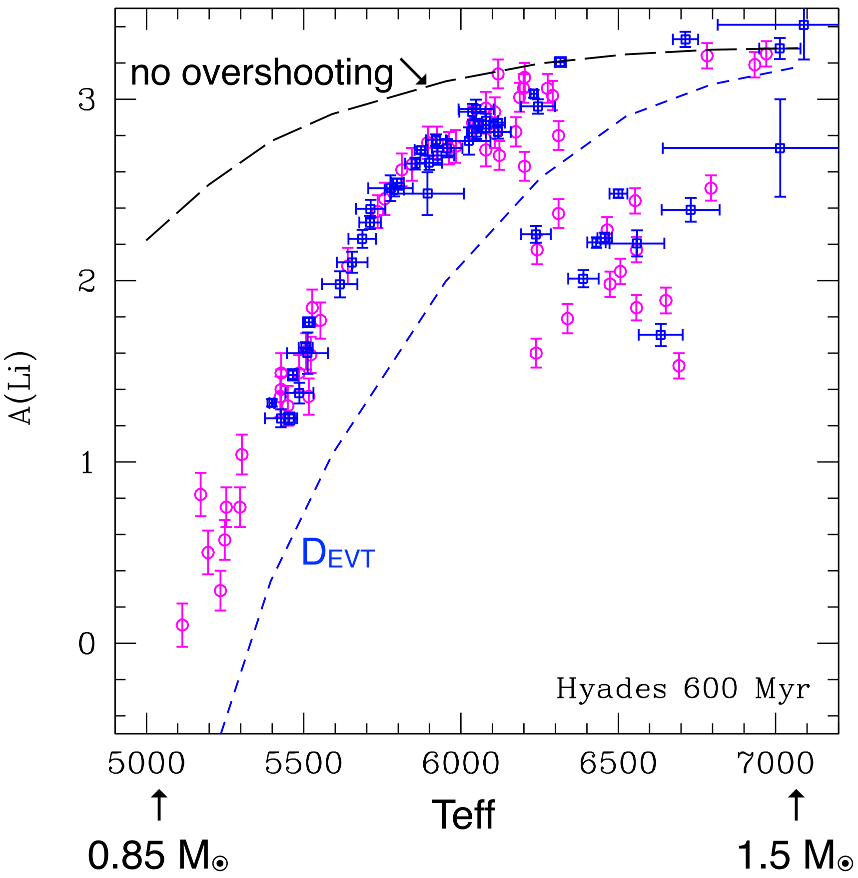
Evolution of Li in a 1 $M_\odot$ with 1D code and our statistical diffusion coefficient

☛ need to limit the extension of the overshooting layer to $d_{ov} \sim 0.35\ H_P$



Baraffe et al. 2017

Application to the depletion of Li in **younger clusters** (50Myr - 4 Gyr) for a range of masses 0.85 - 1.5 $M_\odot$

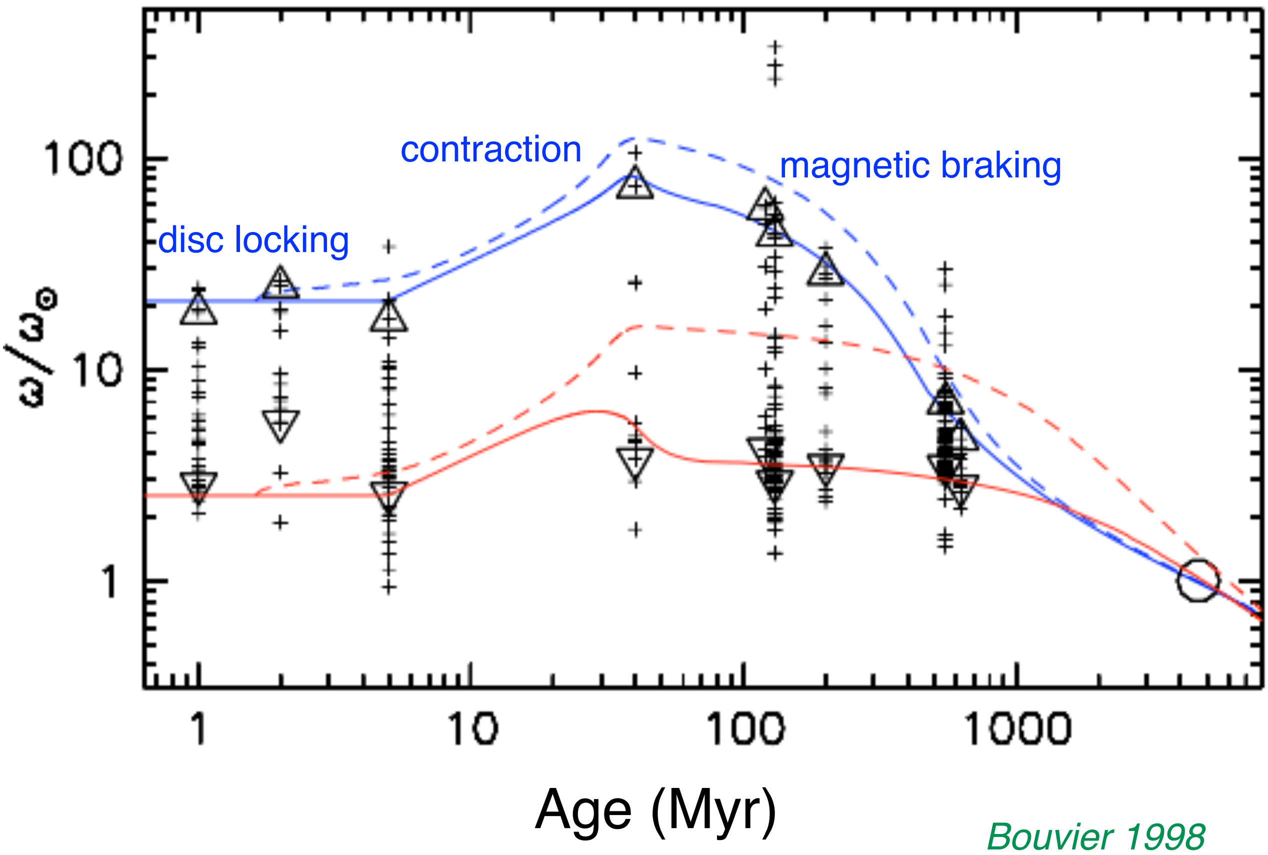


Hyades 600 Myr

Problem: Li is depleted too rapidly!

Baraffe et al. 2017

Typical rotational evolution of stars



Bouvier 1998

☛ Inspired by our preliminary results for plume penetration, we suggest the following scenario:

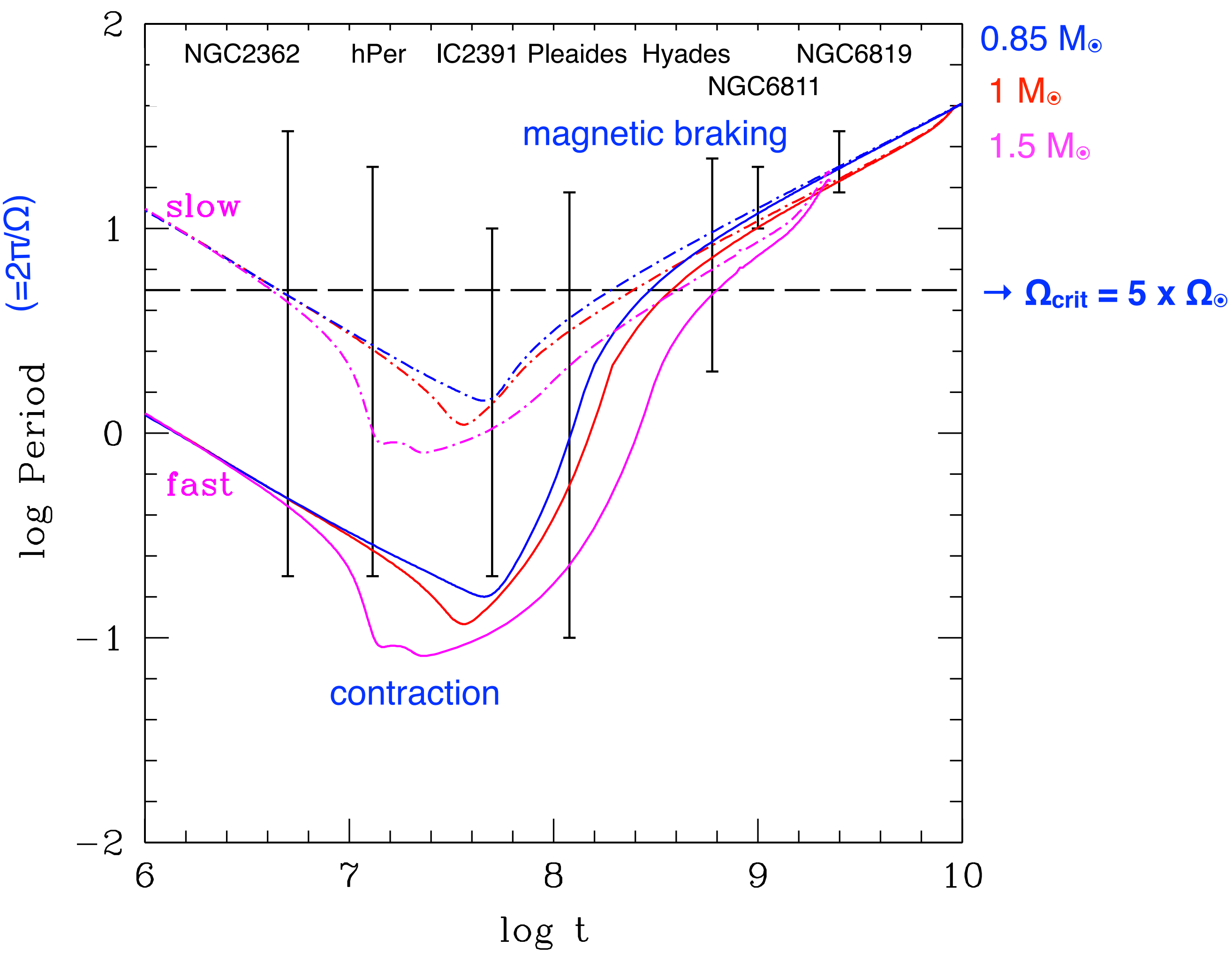
One major hypothesis (***that now needs to be checked by further numerical simulations***)

The depth of penetrating plumes depends on rotation: fast rotation prevents vertical penetration of plumes
(Brummell 2007; Fabregat et al. 2016)

☛ Below a **critical Ω** (slow rotators), plumes can penetrate deeply (according to the probability distribution of Pratt et al. 2017) down to a depth $d_{ov} \sim 1\ H_P$

☛ Above a **critical Ω** (fast rotators), the plume penetration depth is limited to a given depth $d_{ov} \sim 0.1\ H_P$

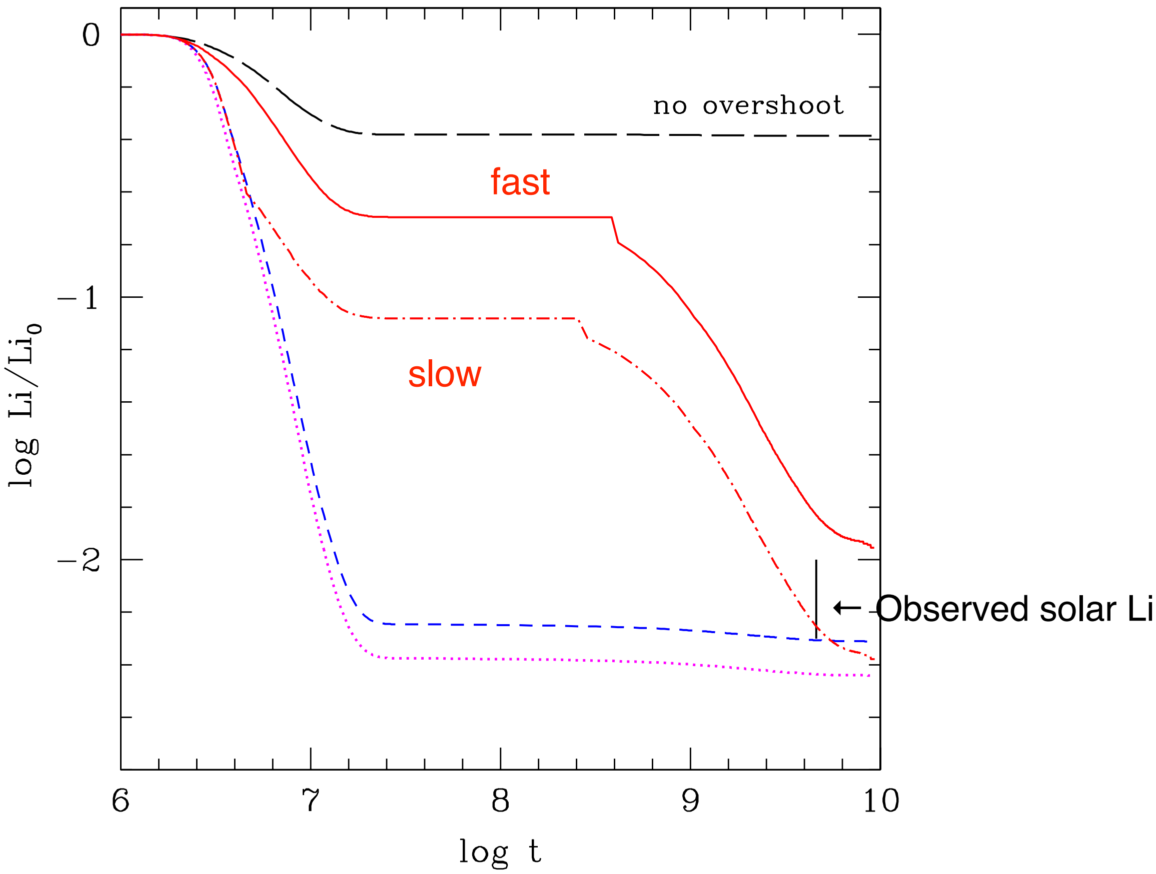
Assuming a simple model for rotation evolution with initially slow and fast rotators for 0.85 - 1.5 $M_\odot$ *(as observed in young clusters, see Gallet & Bouvier 2015)*



Results for depletion of Li in a 1 $M_\odot$ star adopting mixing according to our statistical diffusion coefficient and assuming that rotation limits the plume penetration depth

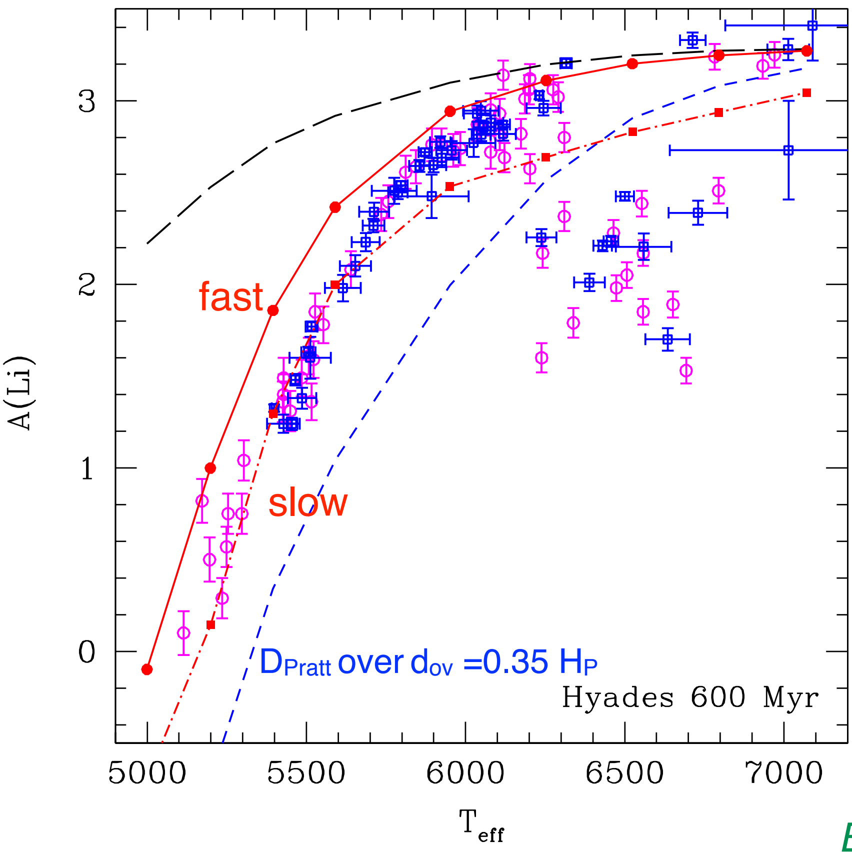
Working hypothesis in the overshooting layer:

- **$\Omega < \Omega_{crit}$** —> depth not limited
- **$\Omega > \Omega_{crit}$** —> depth limited to ~ 0.1 H_P



☛ Interesting results: trend of Li depletion as a function of age can be reproduced (IC2391 50 Myr to M67 4 Gyr)

☛ Can reproduce the observed correlation between rotation and Li abundance: fast rotators are less depleted



Baraffe et al. 2017

Conclusion ☛ Next steps

- **More work to confirm our main assumption which can explain within the same scenario Li depletion in young clusters and in the Sun**

  Main assumption: Depth of penetrating plumes depends on rotation with fast rotation preventing vertical penetration of plumes and existence of a threshold in Ω

  - Extension of multi-D simulations to **different masses/ages and rotation rates**
  - Longer term: explore **MHD effects**
  - Analyse the **heat transport** in the overshooting region

- Test new convective boundary mixing formalisms against observational constraints:
  - Li as a function of age and rotation in solar type stars
  - Speed of sound profile in the transition region of the Sun

- **Extend our 2D/3D simulations to convective core overshooting:**
  - Can we apply the same statistical approach i.e presence of extreme penetrating plumes responsible for the mixing?

  - Test new transport coefficients (chemical species, heat) against asteroseismology
    Search for signatures on mode properties that can be diagnosed by asteroseimology

☛ **new ERC COBOM**

Conclusion: Some advantages of the MUSIC approach for stellar physics

- **Spherical coordinates** natural for stellar interiors

- **Realistic input physics**

- Solve **fully compressible** hydrodynamical equations

- **Time implicit solver**
  —> large timesteps (CFL ~ 10-1000)
  —> Cover a range of Mach numbers: from centre ($M \ll 1$) to surface $M \sim 1$
  (no need for truncating the surface as e.g anelastic codes)
  —> speed up the relaxation phase starting from 1D initial model
  (large time steps + stability)
  *(**key** to explore a range of parameters)*

Main conclusion: time implicit fully compressible hydrodynamic code has formidable potentials to provide improvement to phenomenological approaches used in 1D stellar evolution codes.