Asteroseismic inversions in the Kepler era: application to the Kepler legacy sample

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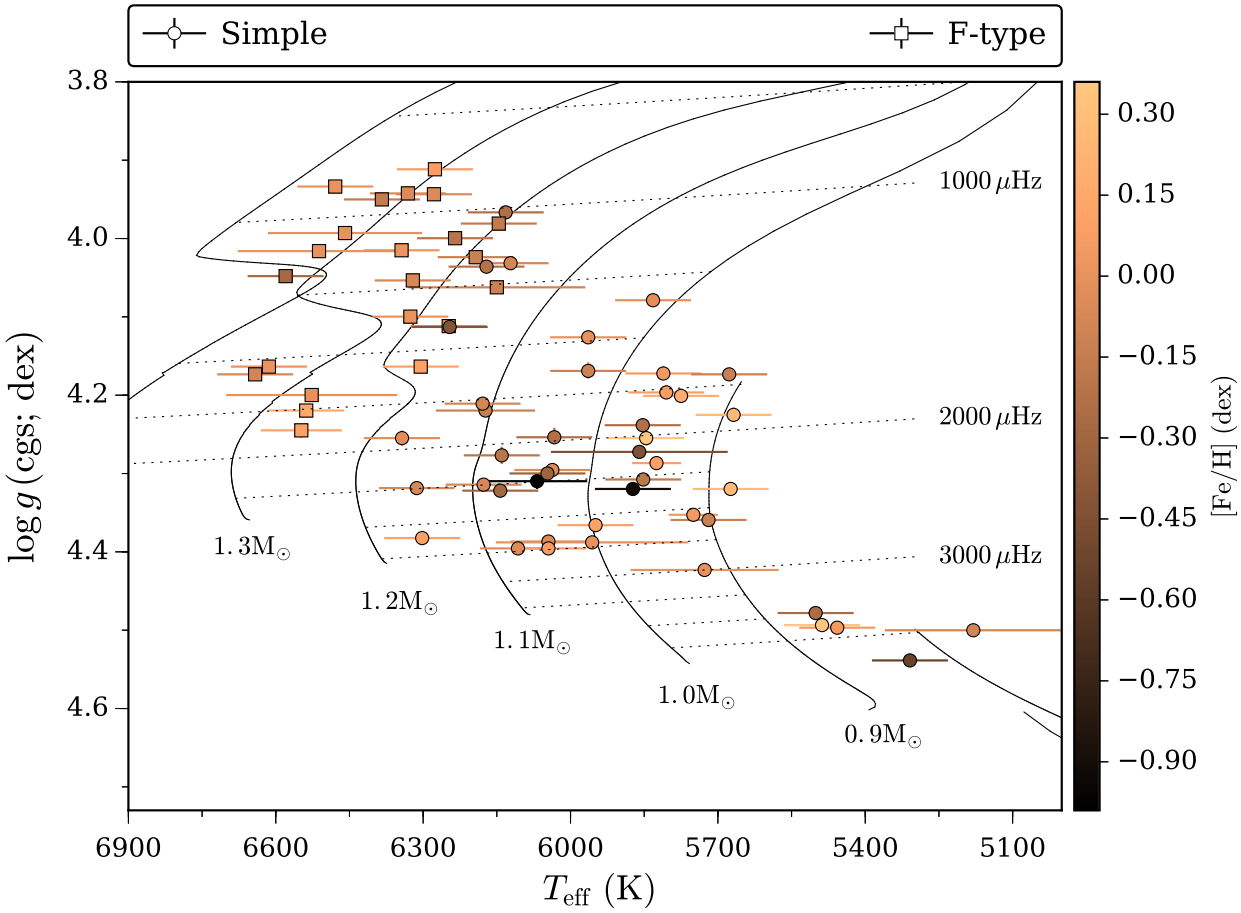
Structure of the presentation

INTRODUCTION - THE LEGACY SAMPLE

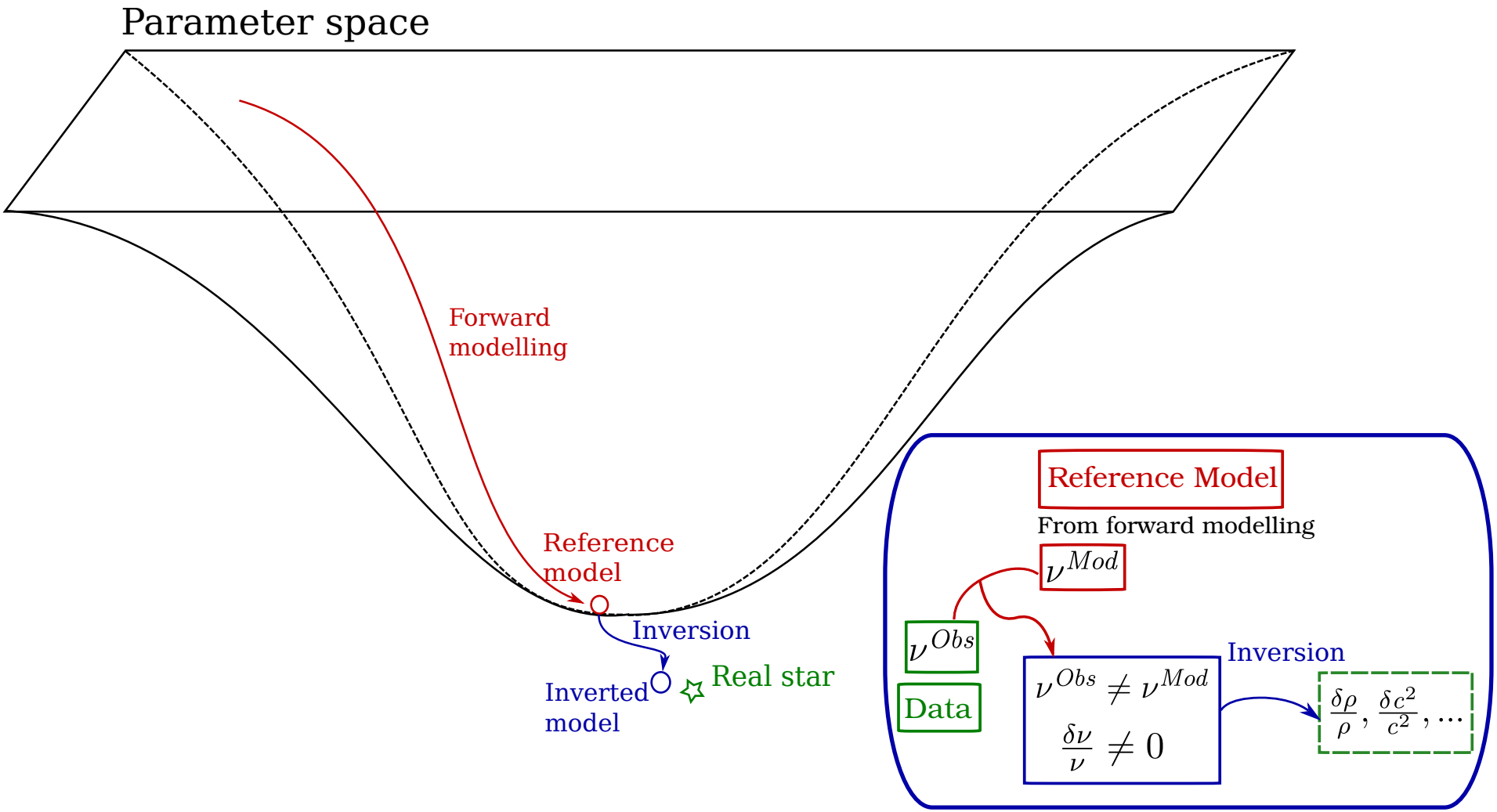
66 SOLAR-LIKE AND F TYPE STARS

- High quality data, benchmark stars.



(Lund et al. 2016, Silva Aguirre et al. 2016)

INTRODUCTION - INVERSION TECHNIQUES



INTRODUCTION - INVERSION TECHNIQUES

Inversion of integrated quantities (indicators)

Definition of an integrated quantity:

$$A = \int_0^R \mathcal{T}_A(r) s_A \, dr,$$

with s_A a function like ρ, c^2, $u = P/\rho$... Take the linear perturbation and obtain:

$$\delta A = \int_0^R \mathcal{T}_A(r) \delta s_A \, dr,$$

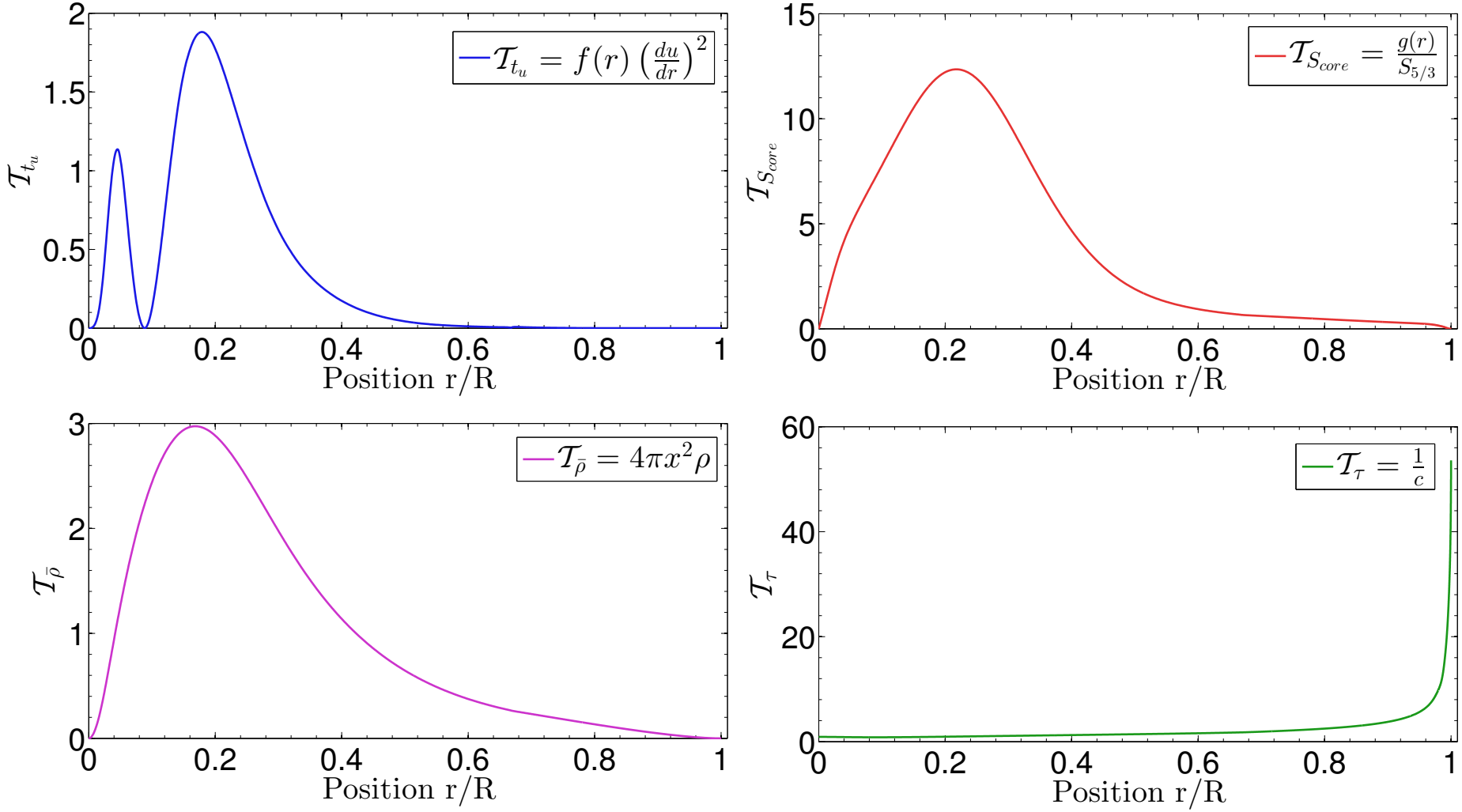
If enough data and model good enough, one can use (Gough & Thompson 1991, Dziembowski (1990)):

$$\frac{\delta \nu^{n,l}}{\nu^{n,l}} = \int_0^R K^{n,l}_{s_A,s_B} \frac{\delta s_A}{s_A} dr + \int_0^R K^{n,l}_{s_B,s_A} \frac{\delta s_B}{s_B} dr.$$

- Requires enough frequencies,
- Provide additional constraints on stellar models.

SOME EXAMPLES OF INDICATORS

We use the SOLA technique (Pijpers & Thompson 1994) to compute corrections of these quantities.



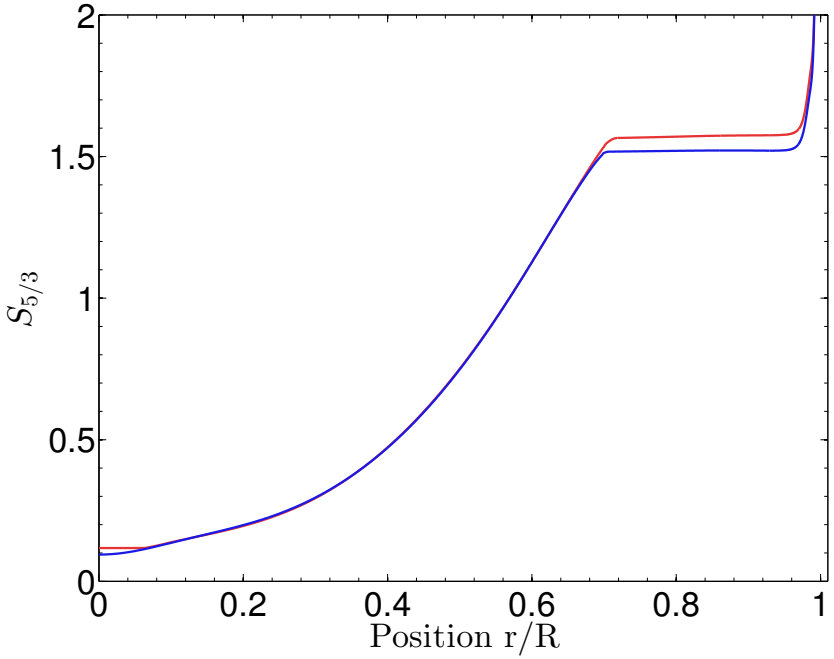
Indicators for convective regions

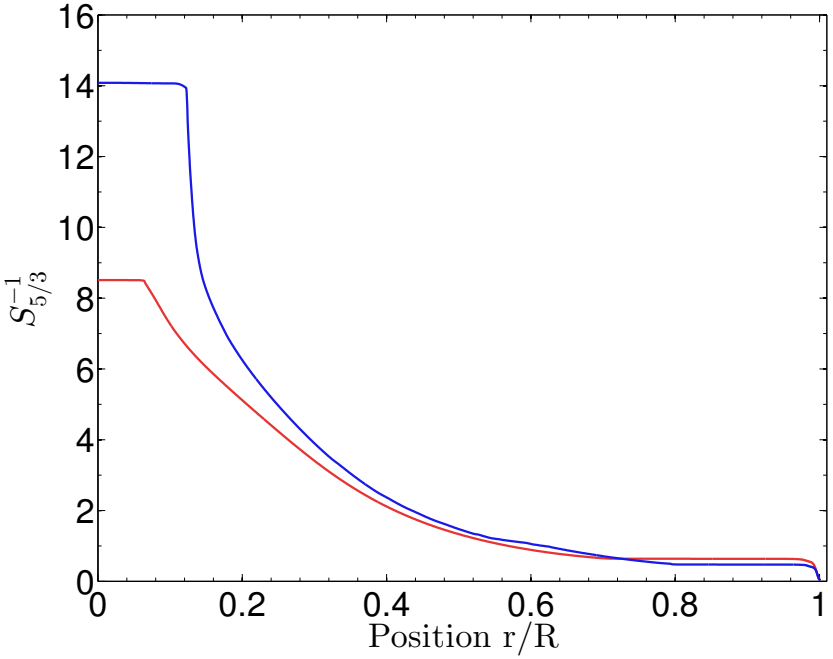
New indicator for stellar cores

We use an appropriated weight function along with the quantity $S_{5/3}^{-1}$ related to :

$$S_{5/3} = \frac{P}{\rho^{5/3}}$$

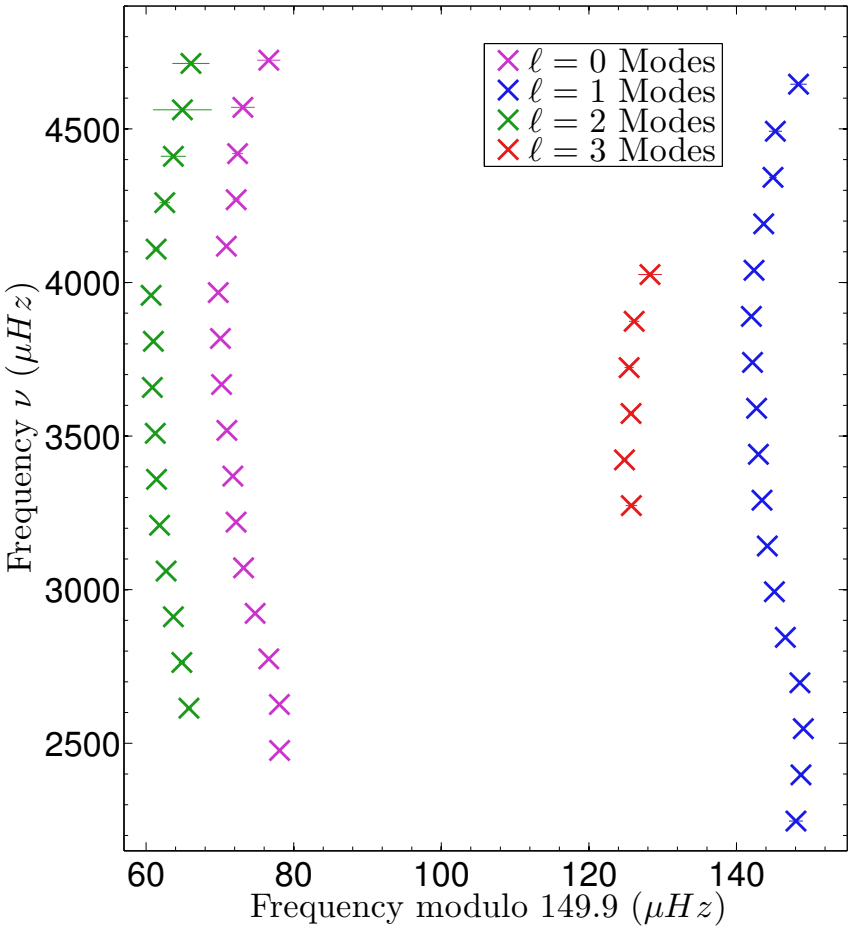
which reproduces the plateaus associated with convective envelopes and cores. We can probe both regions given the proper weight function.



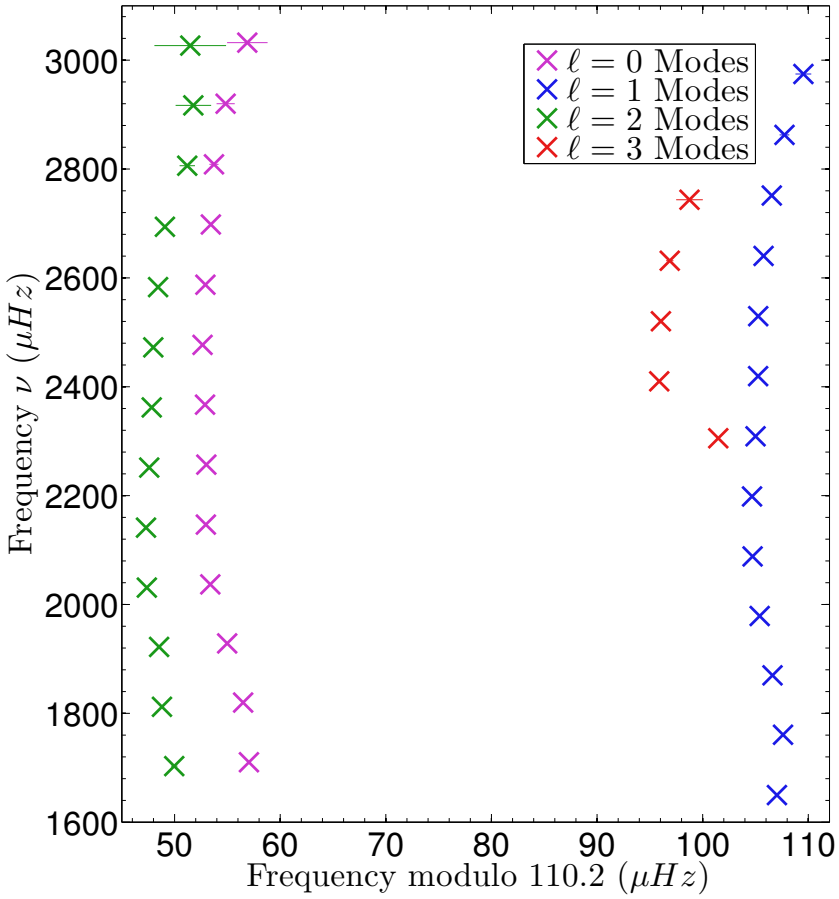


CHOOSING THE FIRST TARGETS

Only 2 stars: Doris (KIC8006161) and Saxo (KIC6603624).



$$T_{eff} = 5488 \pm 77$$
$$[Fe/H] = 0.34 \pm 0.10$$



$$T_{eff} = 5674 \pm 77$$
$$[Fe/H] = 0.28 \pm 0.10$$

(Courtesy of M. Lund and V. Silva Aguirre.)

FORWARD MODELLING RESULTS

STRATEGY (2 Steps Levenberg-Marquardt minimization):

- **Free parameters:** Mass, Age, X_0, Z_0, α_{MLT}.
- **Constraints:** $\bar{\rho}$ (or $< \Delta\nu >$ for the first step), $\tilde{\delta}\nu^{n,l}$, r_{01}, T_{eff} and $(Z/X)_S$.

PHYSICAL INGREDIENTS:

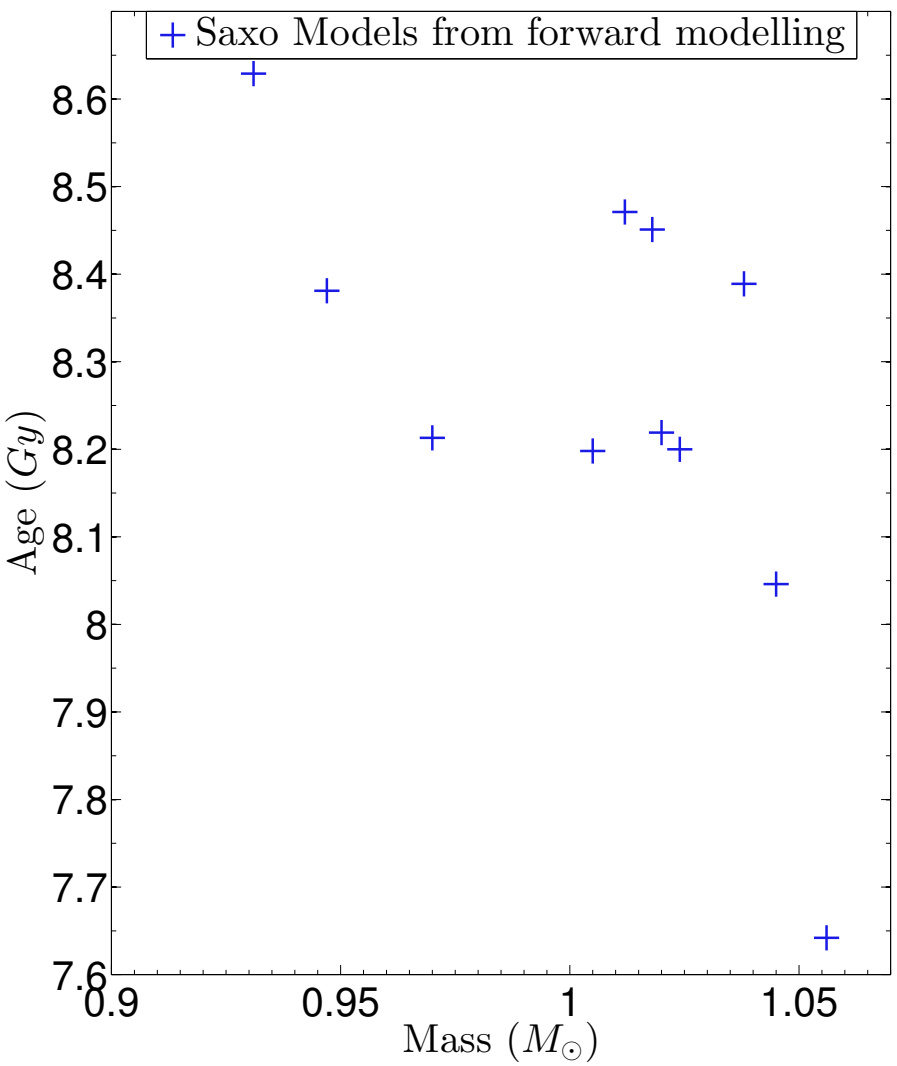
- Ceff e.o.s., OPAL opacities, microscopic diffusion, AGSS09 abundances but also tests with GN93.

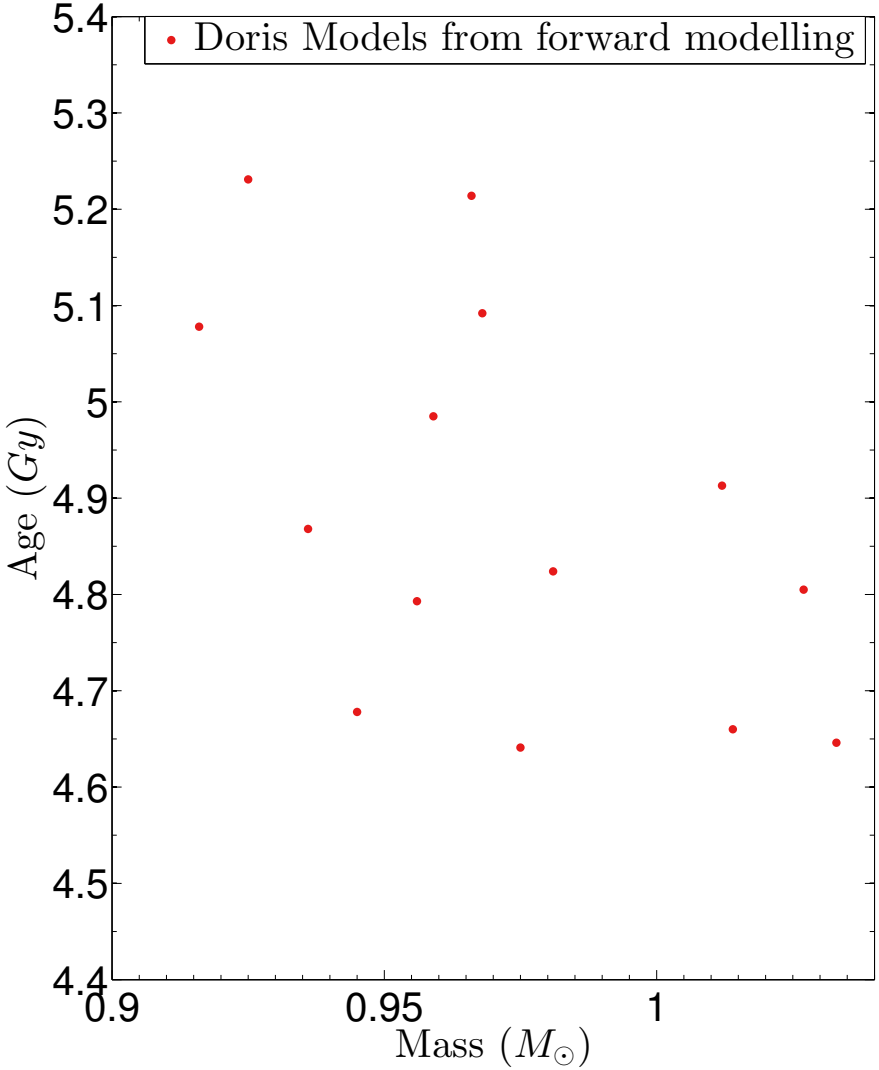
RESULTS: (Cles + Losc (Scuflaire et al. 2008a & b))

	Doris	**Saxo**
Mass ($M_\odot$)	$0.91 - 1.02$	$0.93 - 1.05$
Age (Gy)	$4.6 - 5.3$	$7.6 - 8.7$

Helium-mass degeneracy, diffusion, opacities?

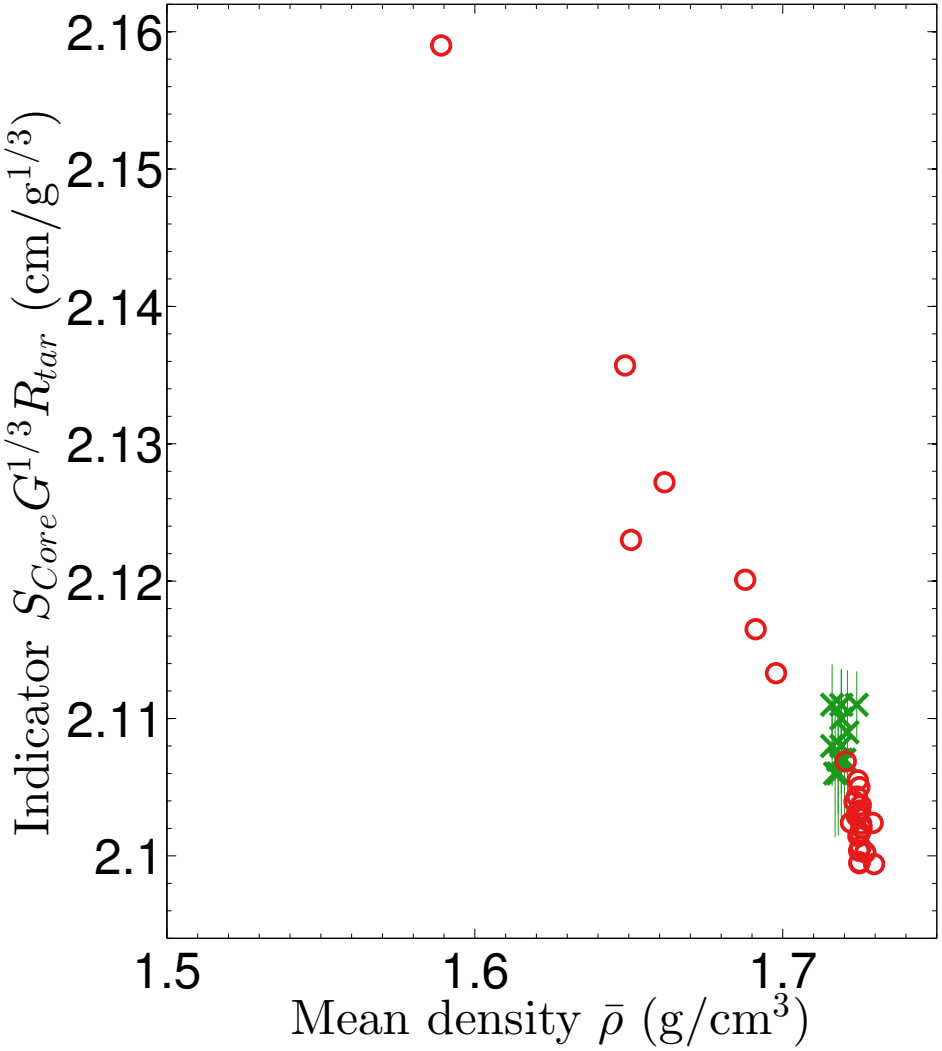
FORWARD MODELLING RESULTS

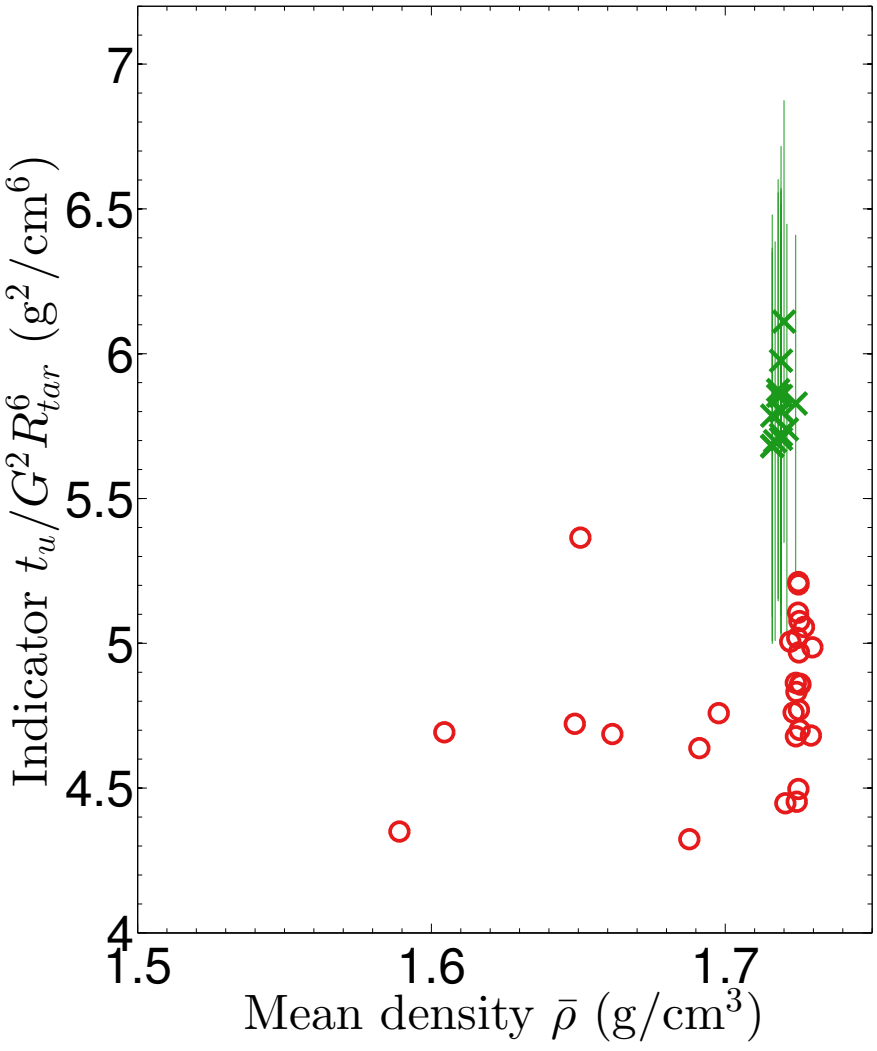




$\Rightarrow$ **try the additional indicators like for 16Cyg.**

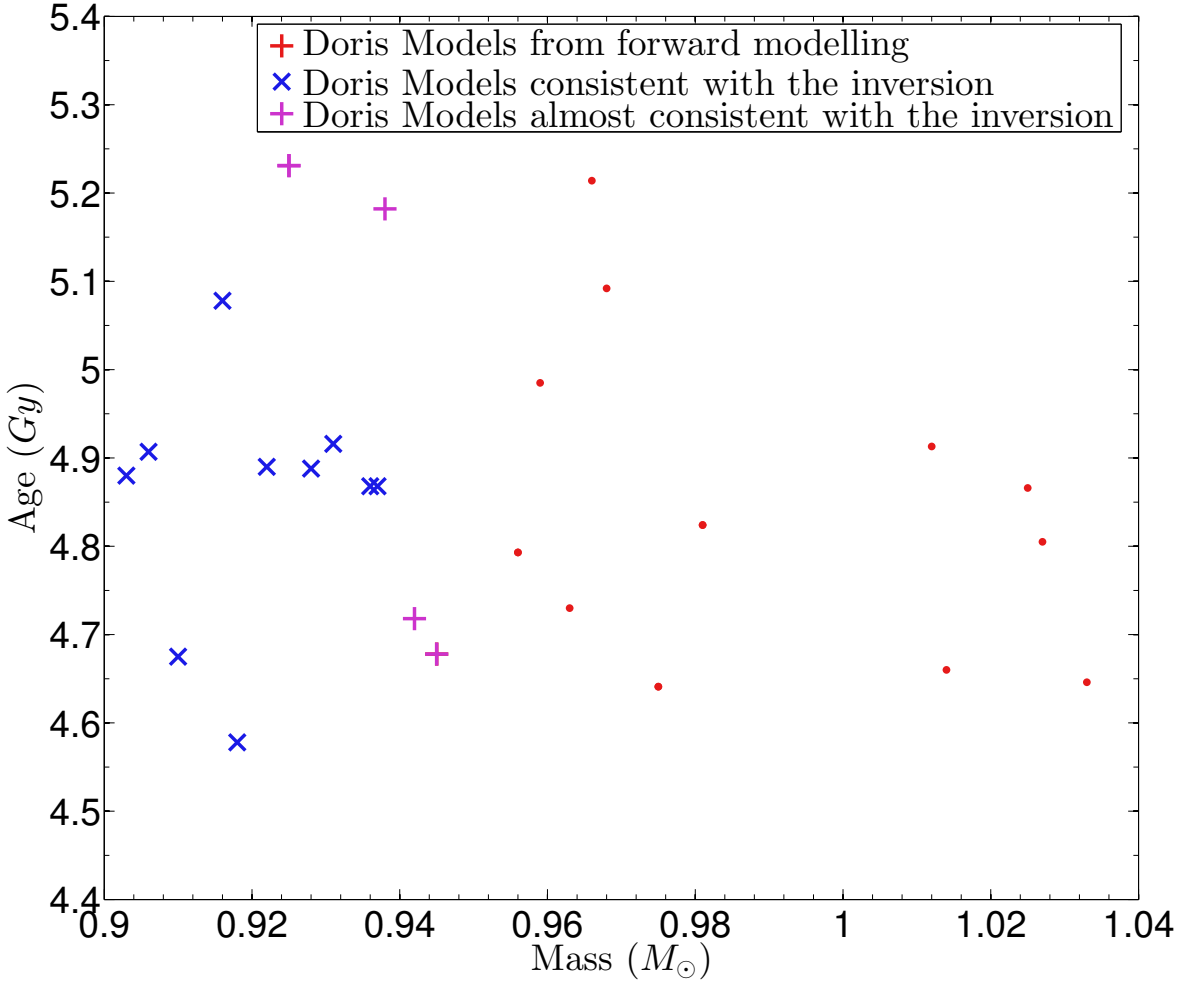
INVERSIONS RESULTS - DORIS





Behaviour of both indicators? Different sensitivity?

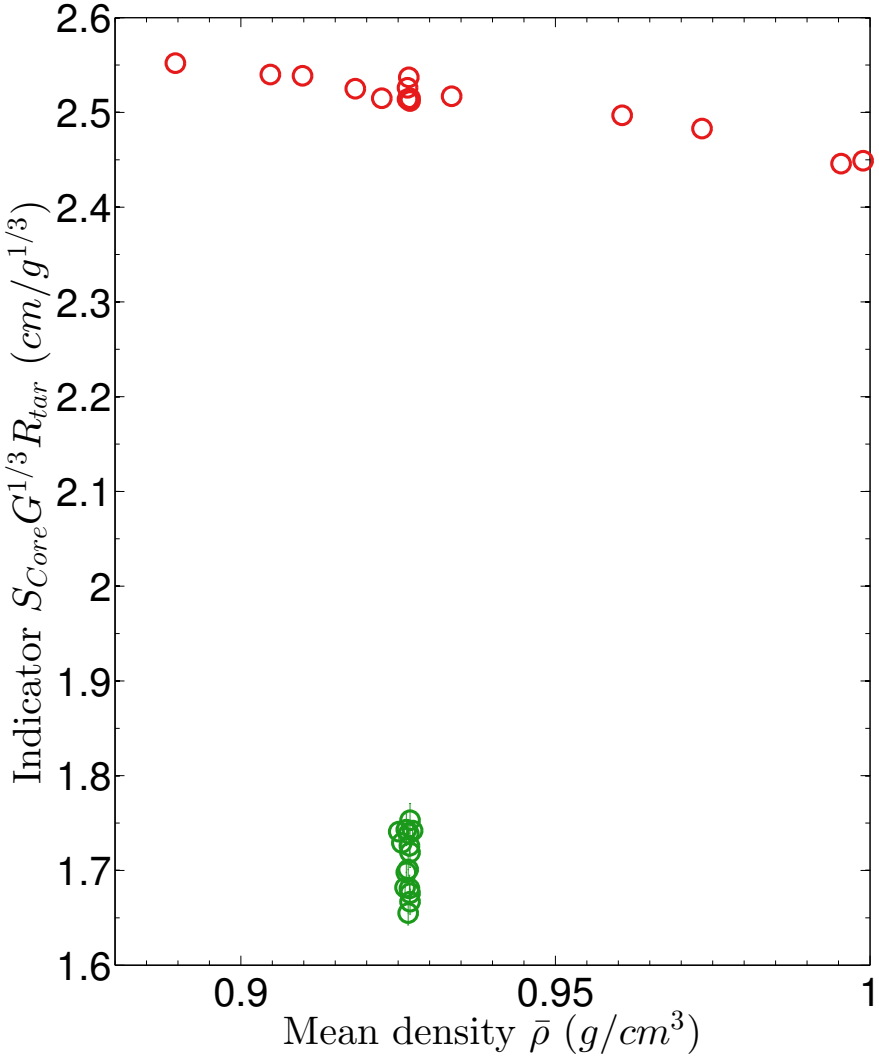
Constraints on mass and age (preliminary) - Doris

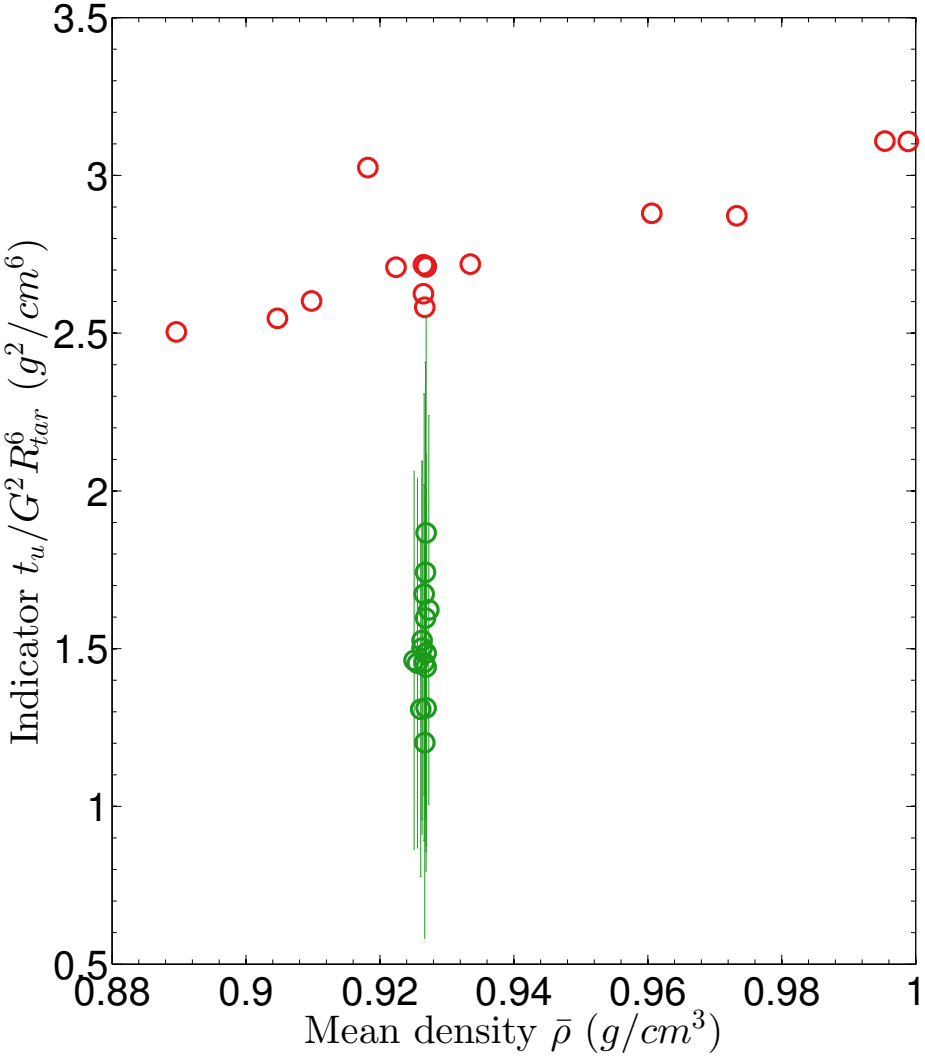


Results:

- all models include diffusion (models without diffusion are rejected),
- final dispersion with t_u ($\pm 2.5\%$ in mass and $\pm 4.5\%$ in age),
- model-dependent results!
- Unlike 16Cyg, no fit of Y.

INVERSIONS RESULTS - SAXO





Clear diagnostic, but solution needs to be studied carefully.

SOME LAST WORDS

To conclude:

- Inversions can be used for the Kepler legacy targets. Currently: Perky, Kitty, Arthur, Nunny, Doris and Saxo are done,
- New indicators for upper regions can be used for the best of the Legacy targets,
- 16Cyg is being re-studied (Collaboration with M. Deal et al.).
- S_{Core} applicable to convective cores.

A question remains:

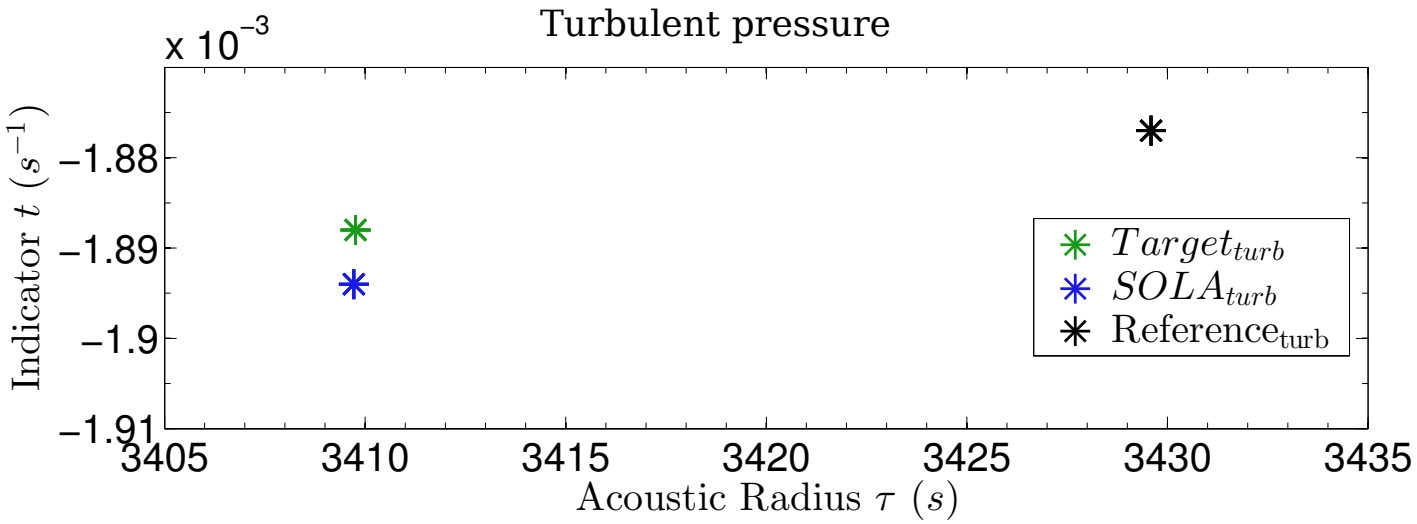
- Coupling with forward modelling? (What constraints?)

Thank you for your attention!

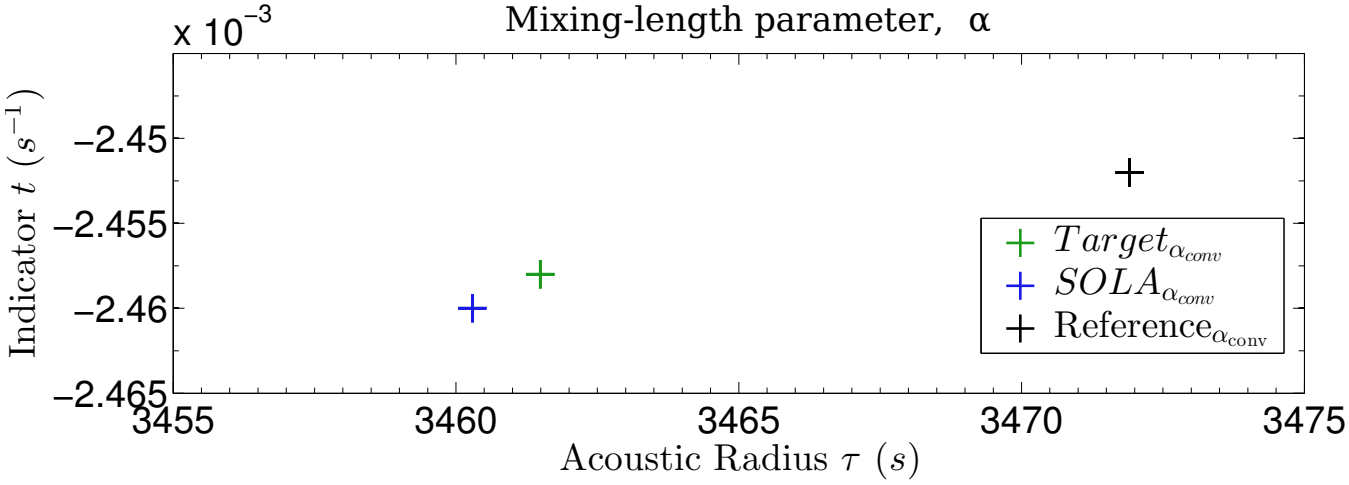
APPENDICES - STRATEGY HARE AND HOUNDS 0

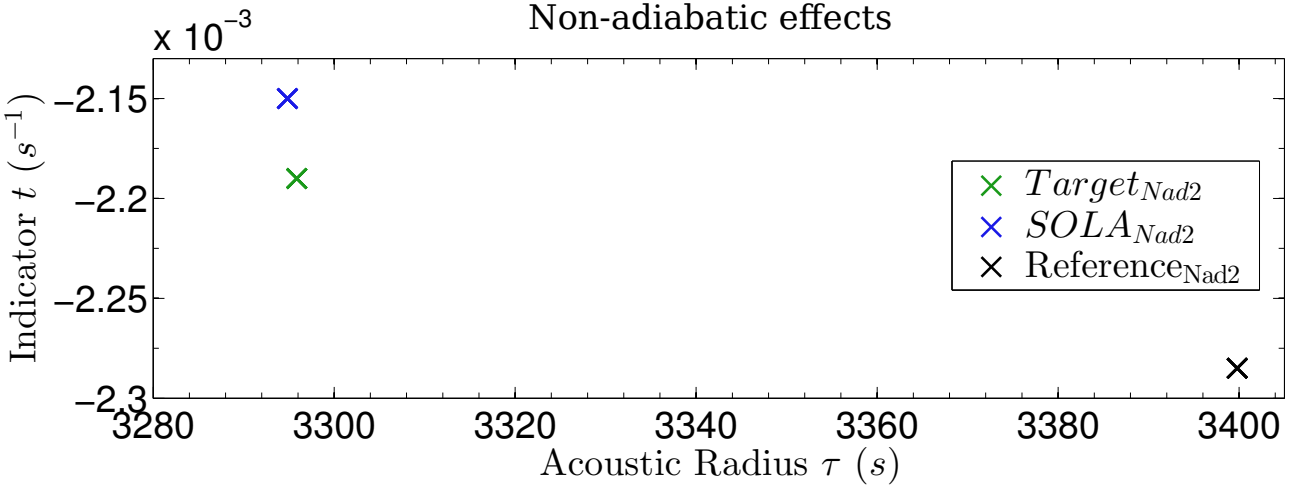
Test strategy

- Build target including complex physics
- Seismic modelling using simple physics
- Carry out **inversions for indicators**

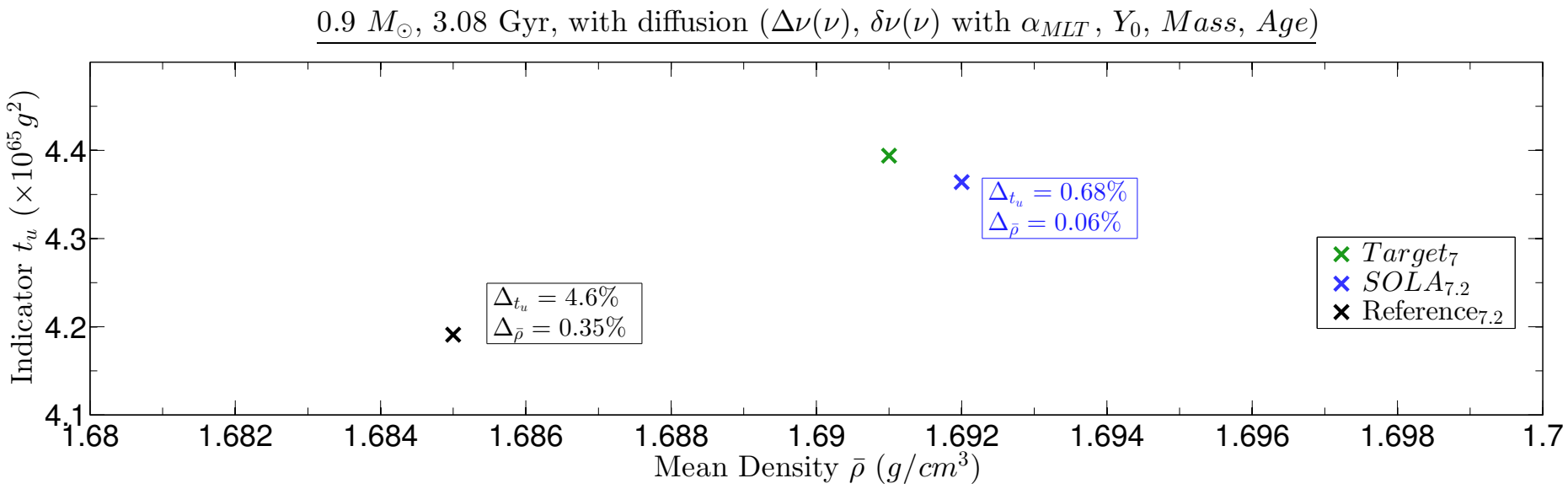


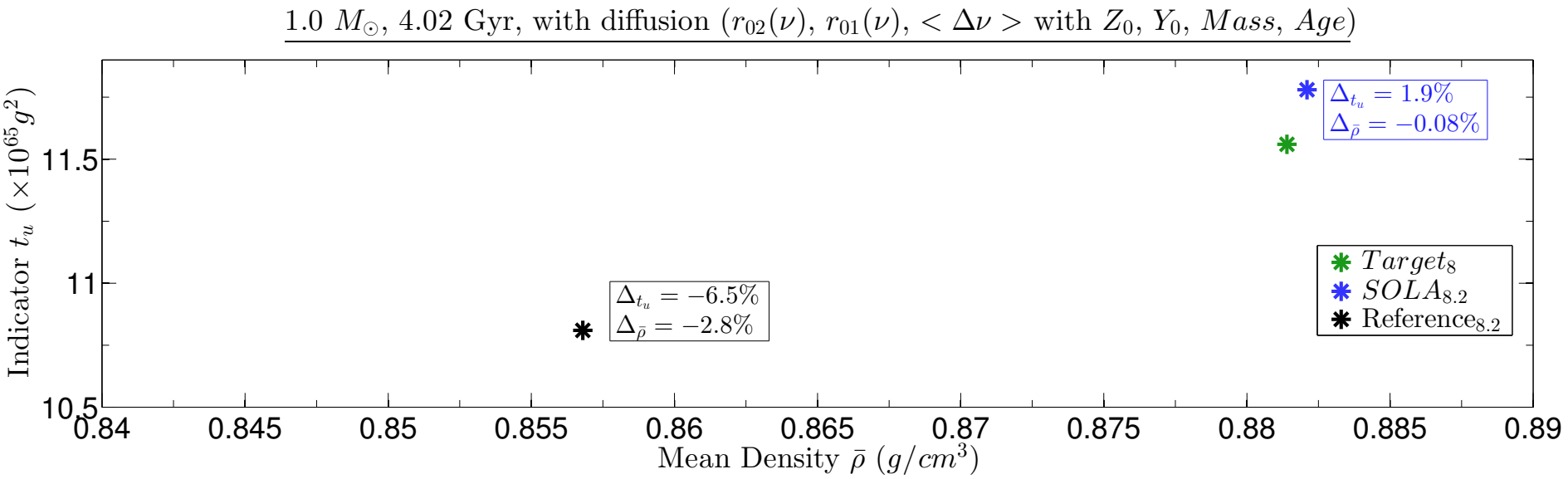
APPENDICES - HARES AND HOUNDS 1



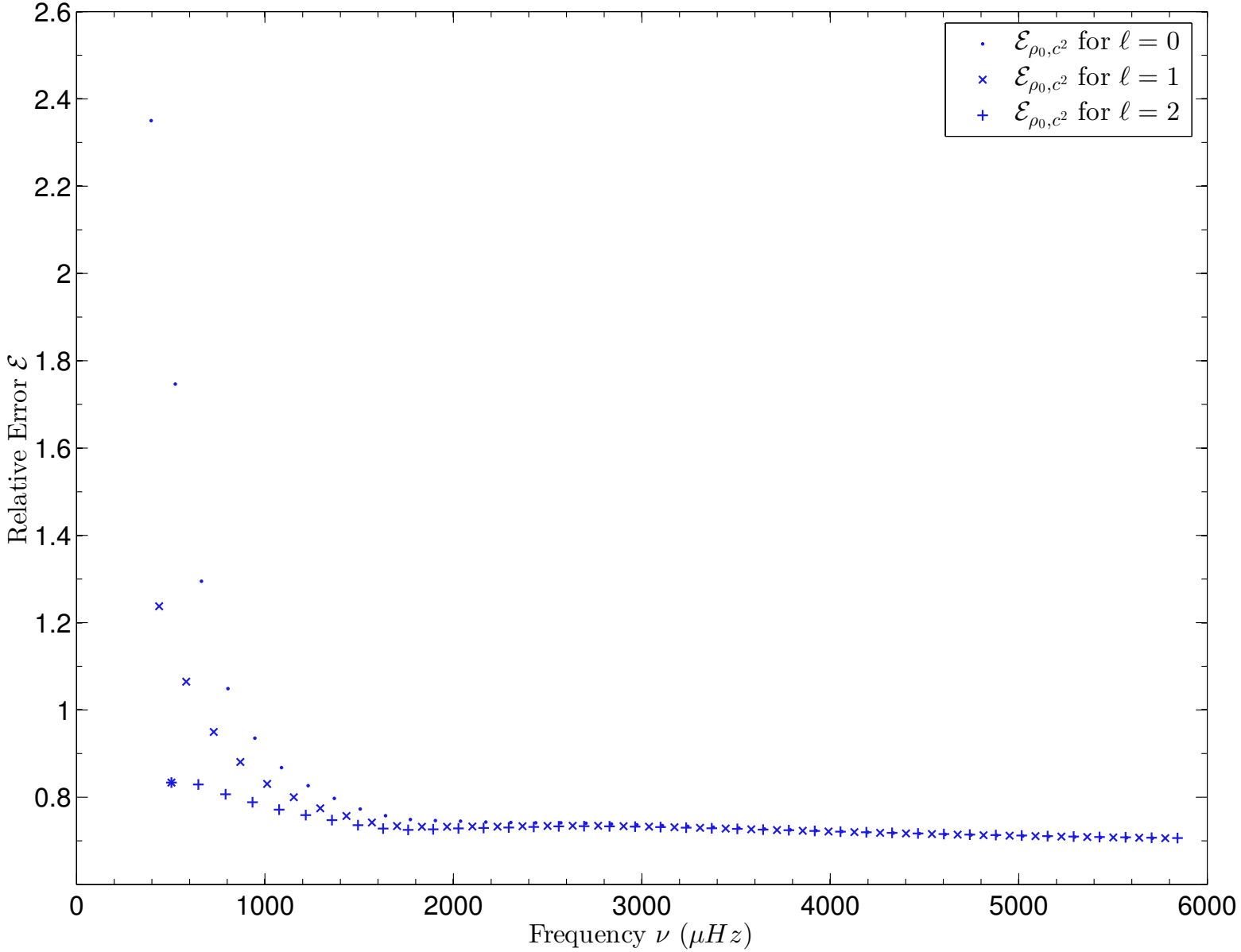


APPENDICES - HARES AND HOUNDS 2





APPENDICES - SCALING EFFECTS



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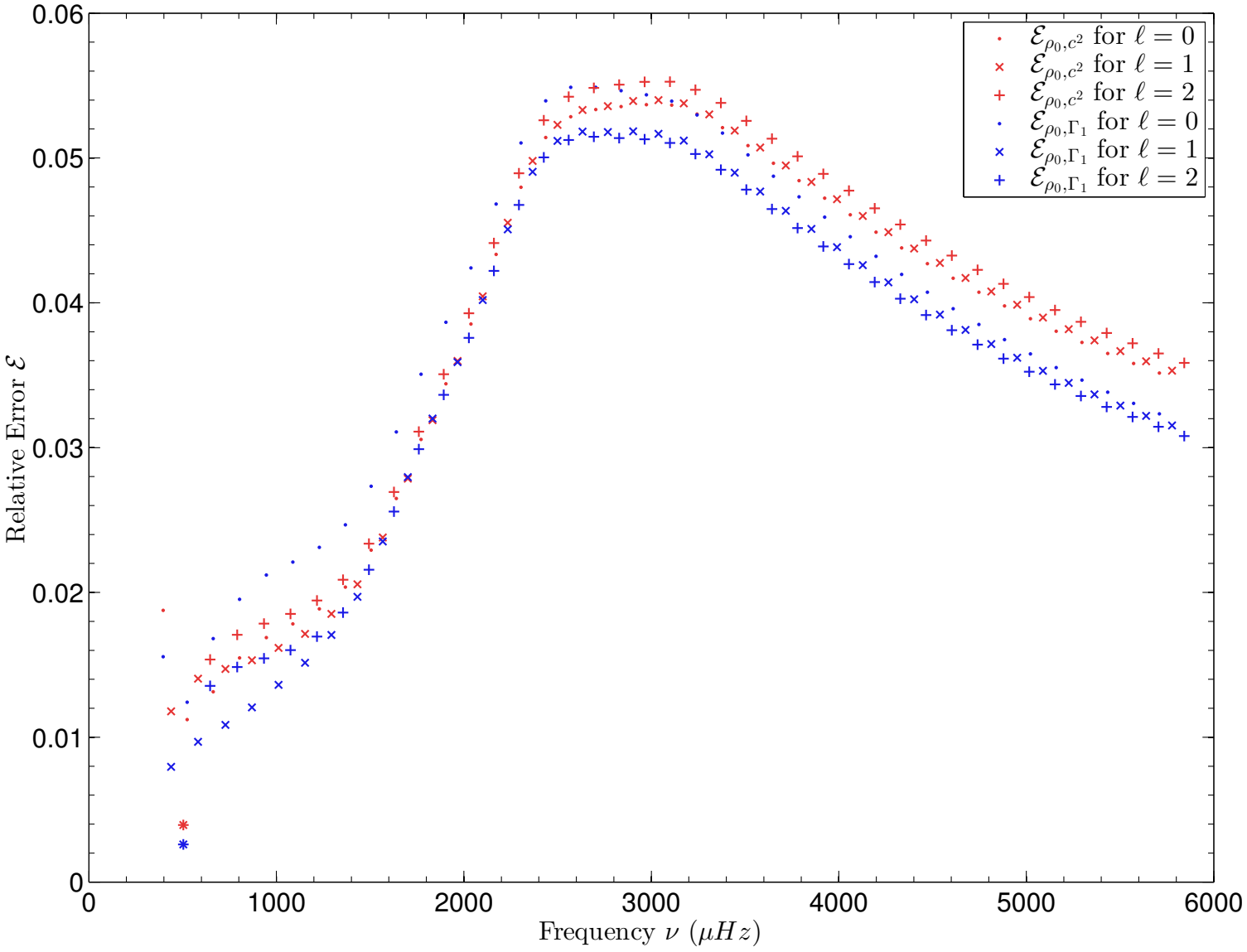
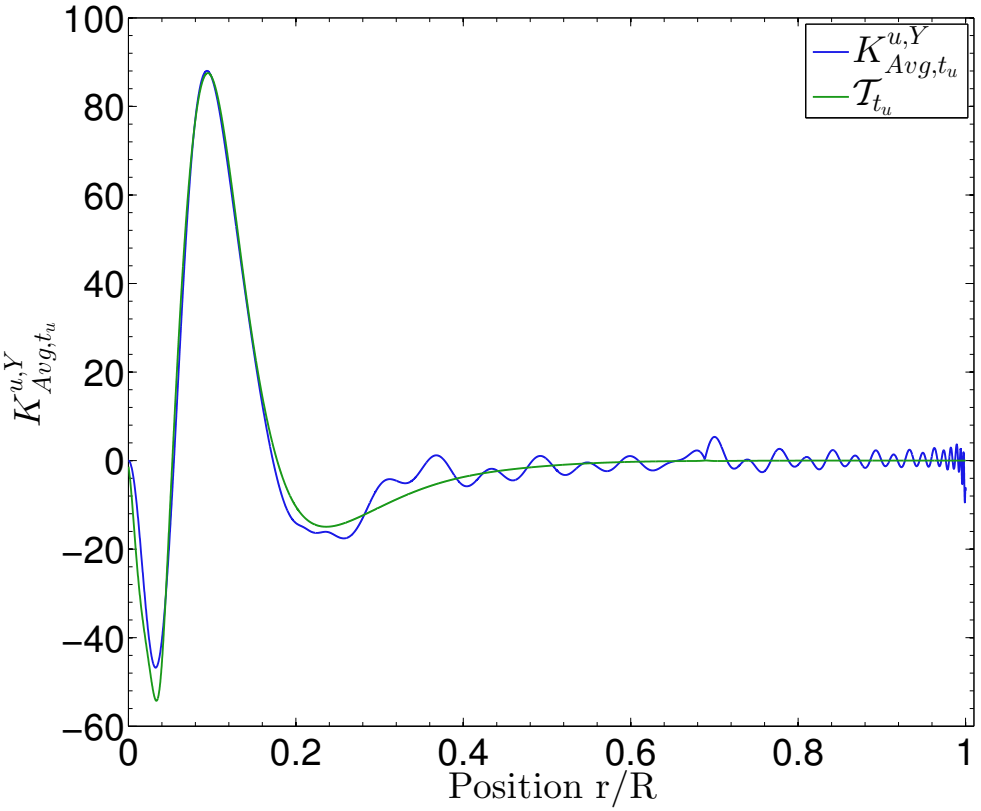
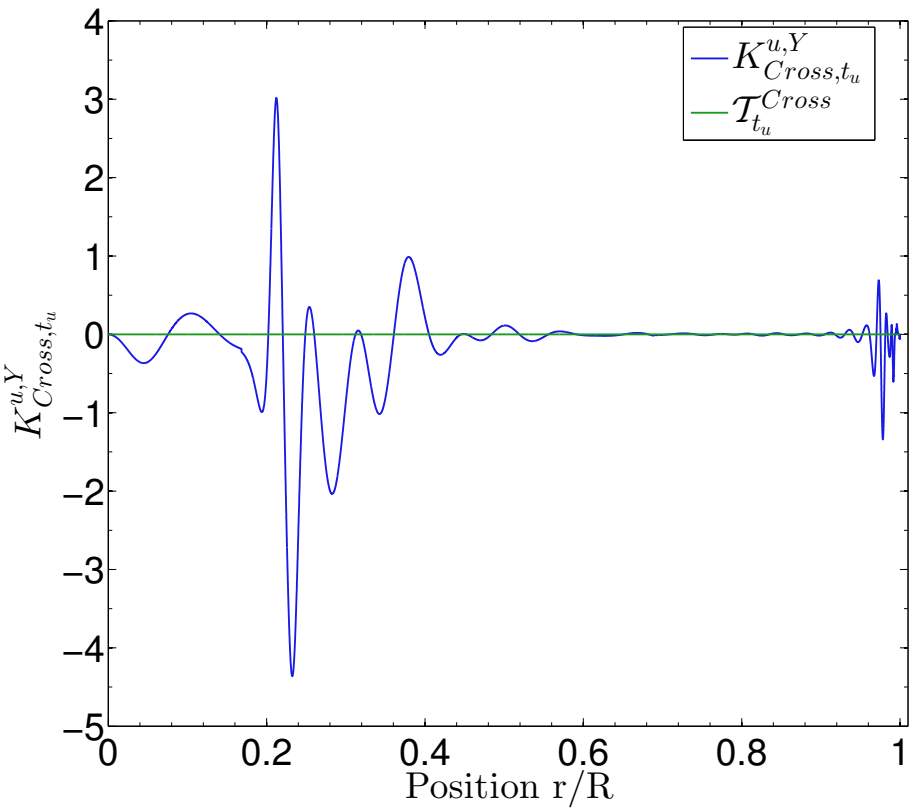


Kernel fits - SAXO





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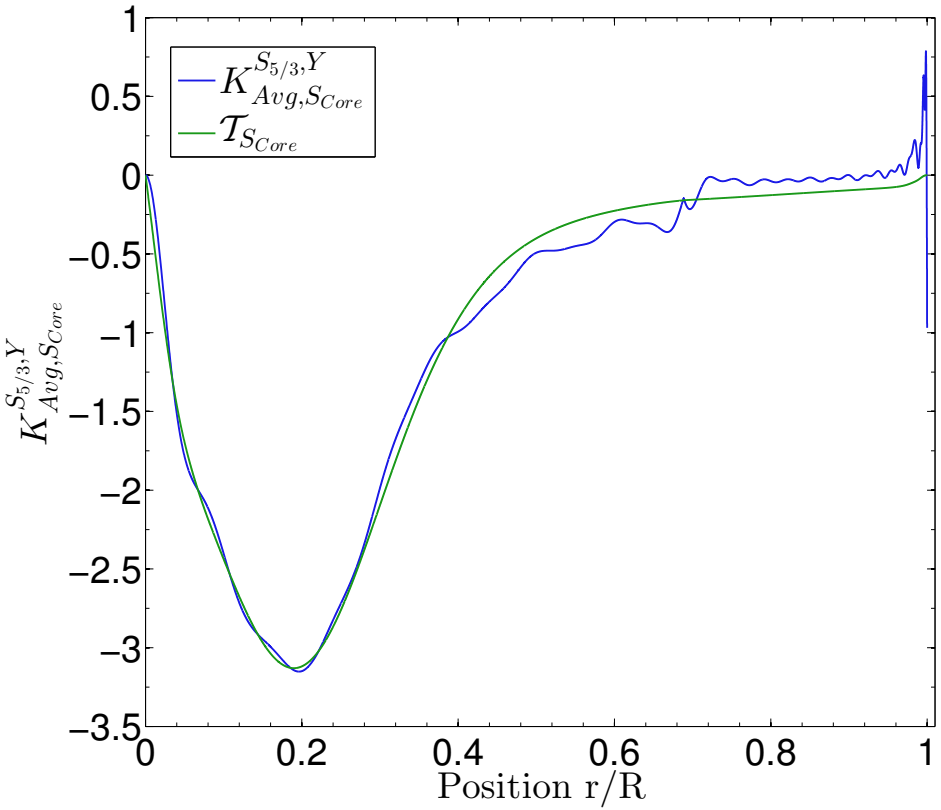
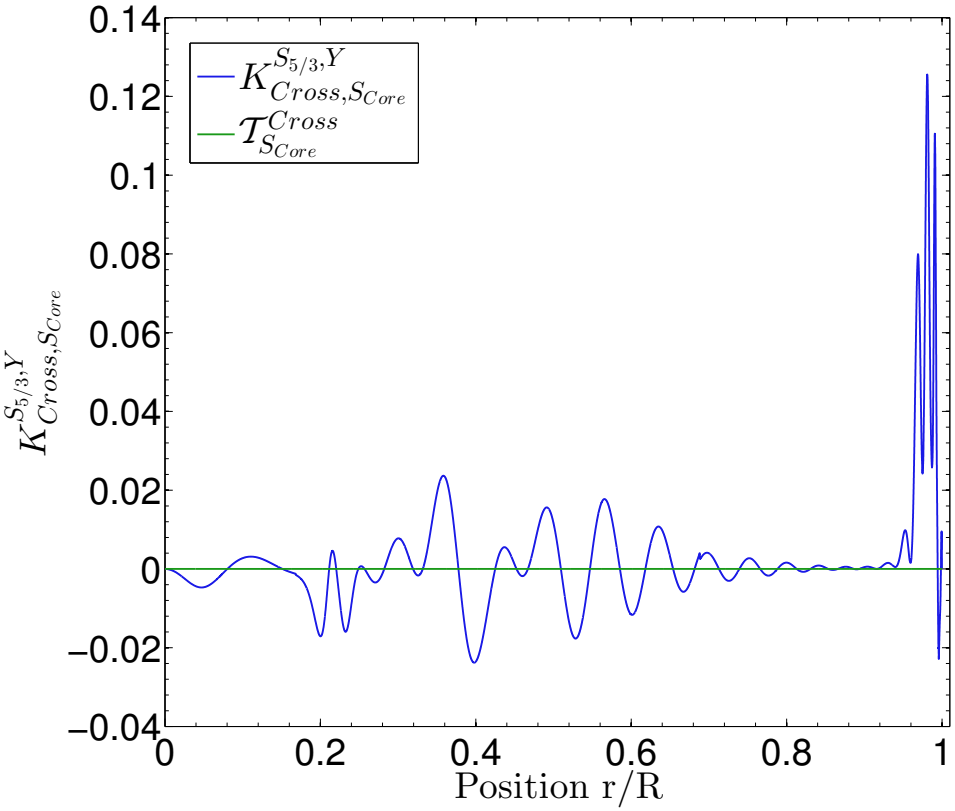
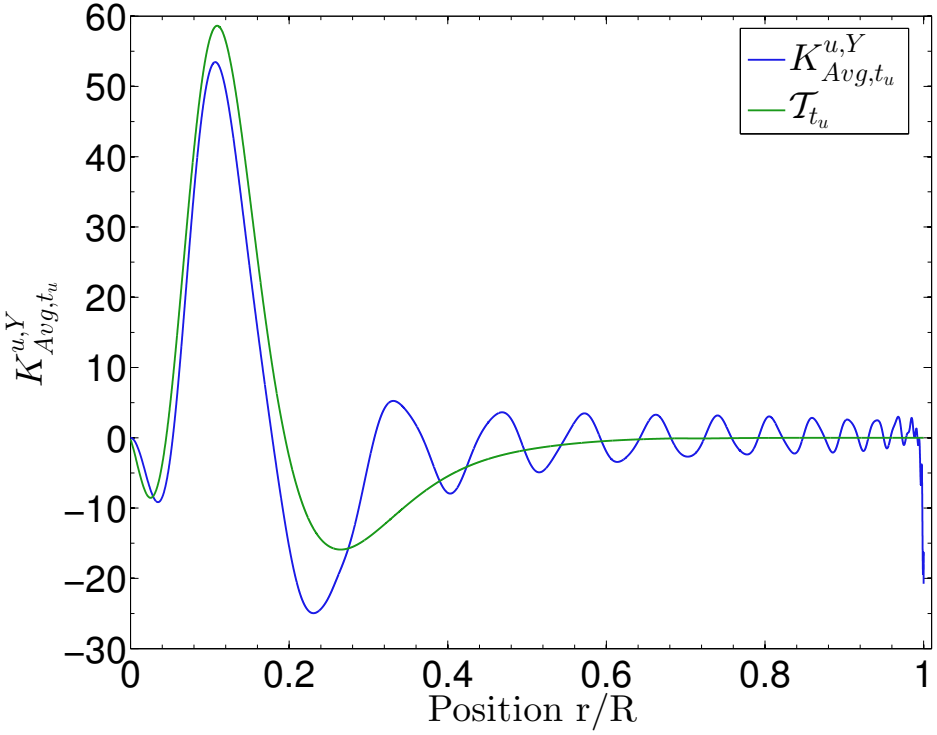
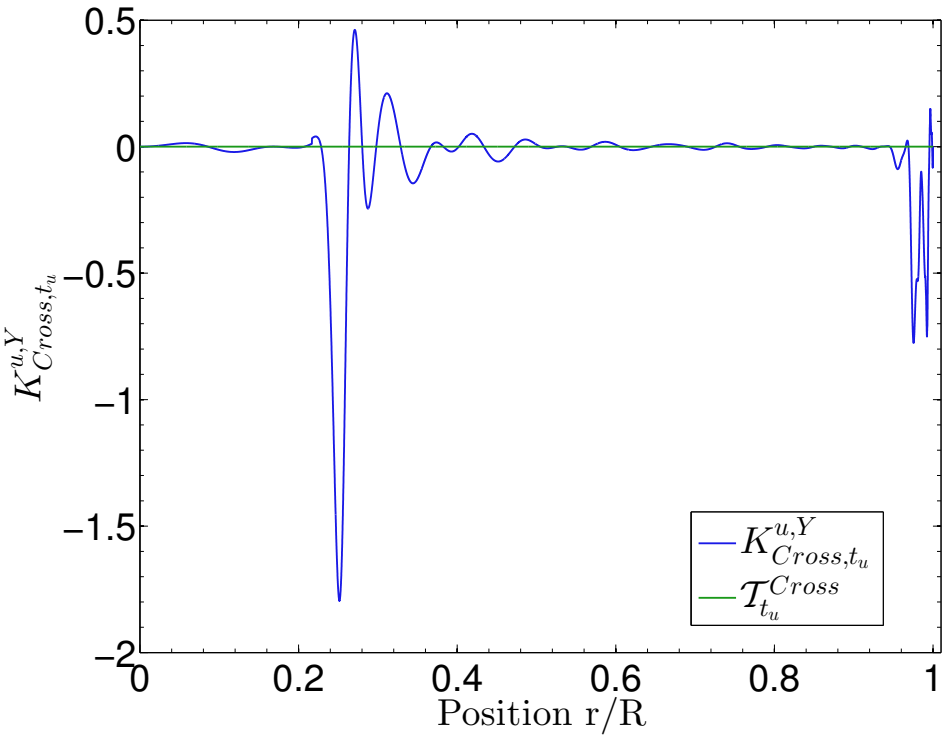




KERNEL FITS - DORIS





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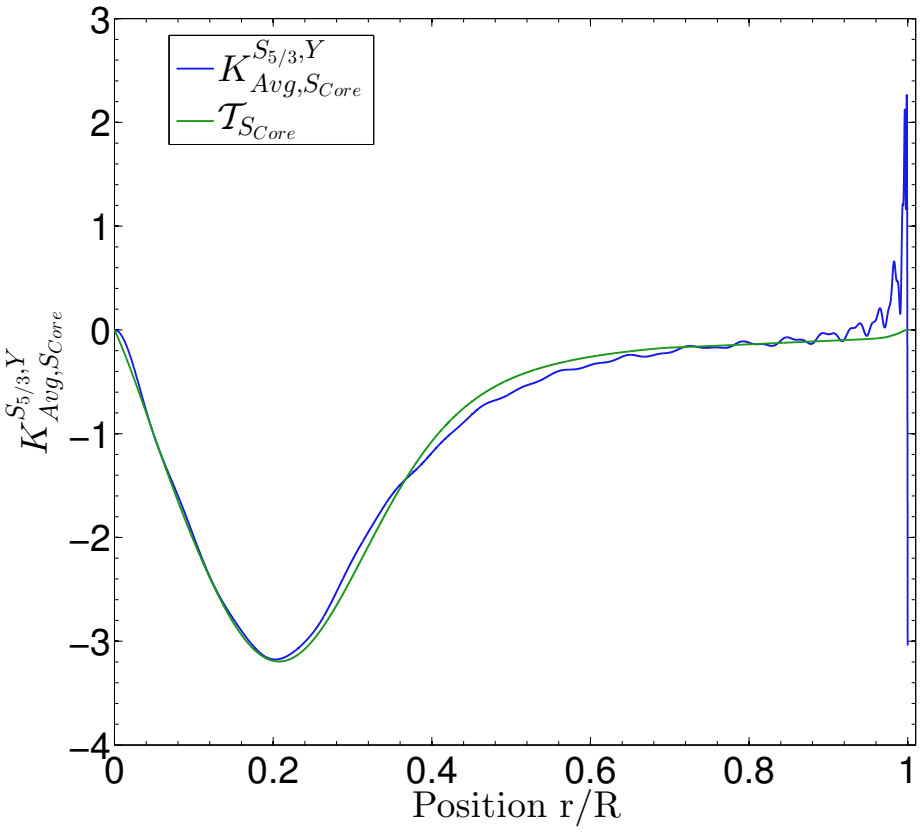

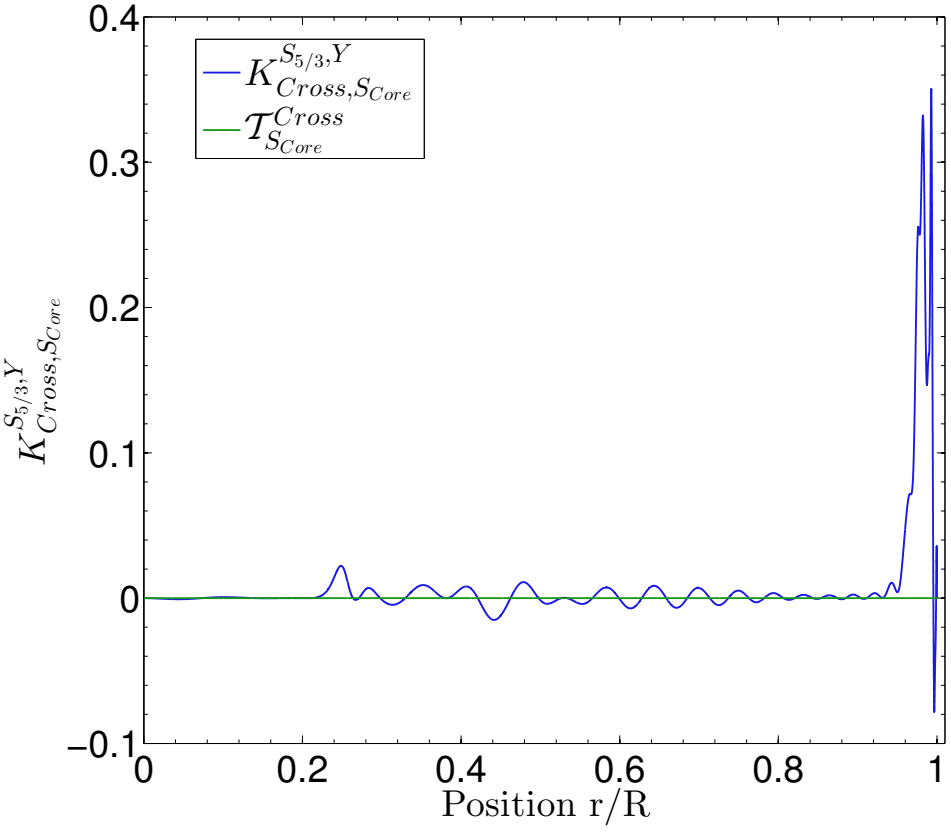

KERNEL FITS - SAXO