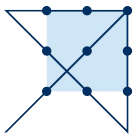
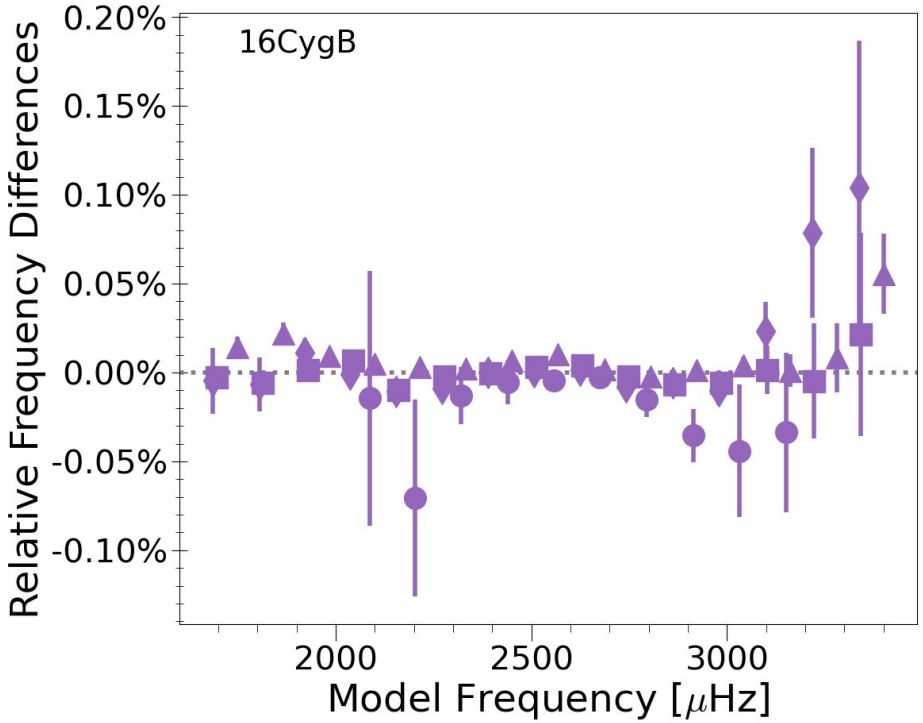


HITS
Heidelberg Institute for Theoretical Studies

Sound speed inversions of an ensemble of low-mass main-sequence stars

Lynn Buchele
Collaborators: Earl Bellinger, Saskia Hekker, Sarbani Basu

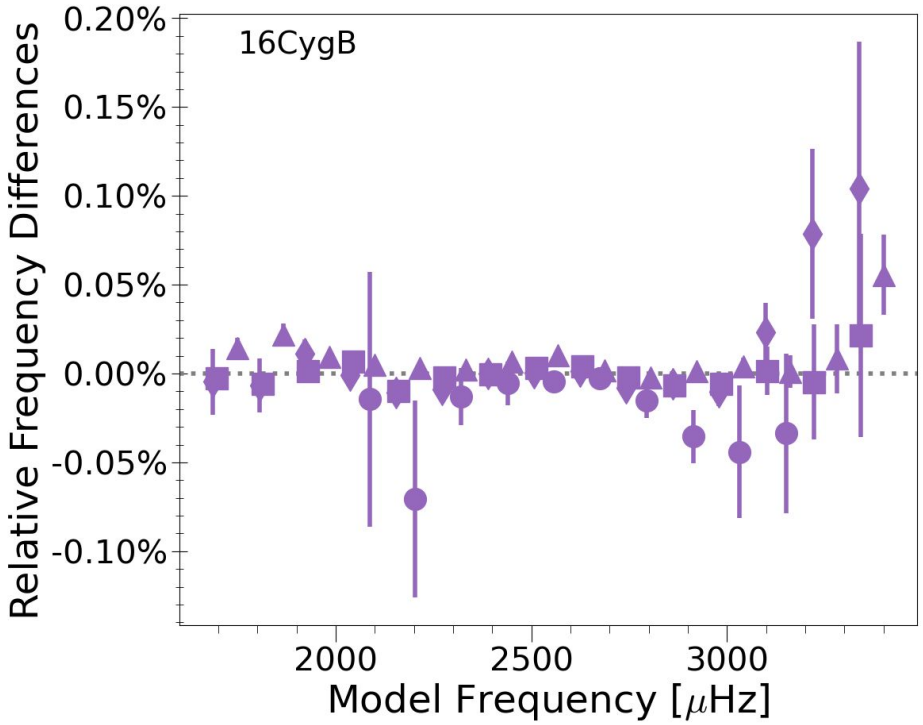
Asteroseismic Modeling and Structure Inversions



Asteroseismic Modeling and Structure Inversions

- Frequency Differences as a source of information

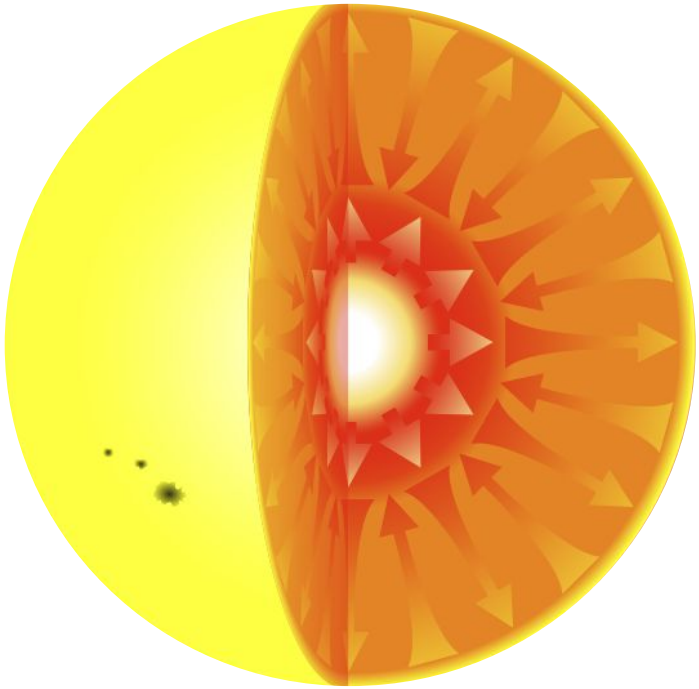
- Provide a way to test internal microphysics



12 Target Stars

Main-sequence Stars with Radiative Cores

$$M \lesssim 1.2 M_\odot$$



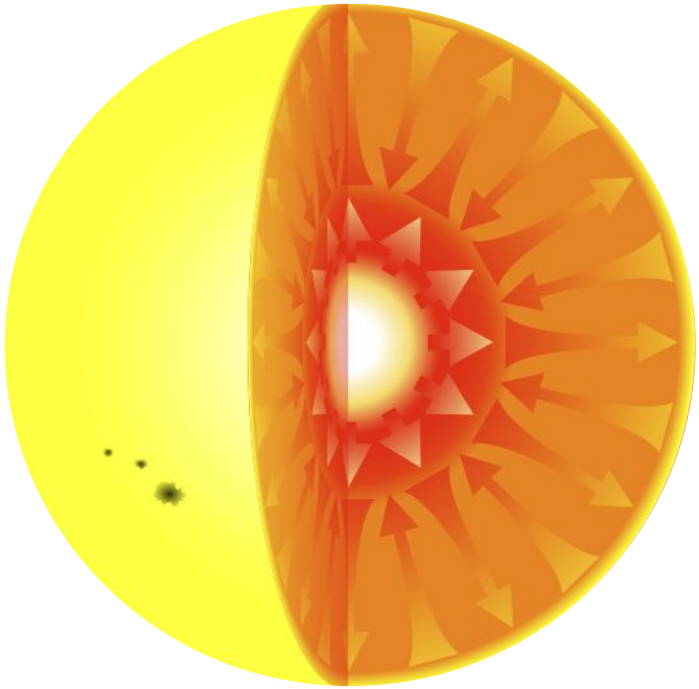
HeNRyKus, Public domain, via Wikimedia Commons

12 Target Stars

- Frequencies
  - Lund et al. 2017, Davies et . 2016, Roxburgh 2017
- Effective Temperature and Metallicity
  - Furlan et al. 2018
- Luminosity
  - Gaia DR3 Gaia Collaboration et al. 2016, 2022

Main-sequence Stars with Radiative Cores

$$M \lesssim 1.2 M_{\odot}$$



HeNRyKus, Public domain, via Wikimedia Commons

Reference Models

Free parameters

$$M, Y_{\rm initial}, Z_{\rm initial}, \alpha_{mlt}, {\rm Age}$$

MESA

Paxton et al. 2011,2013,2015,2018,2019
Jermyn et al. 2023

GYRE

Townsend & Teitler 2013

Reference Models

Free parameters

$$M, Y_{\rm initial}, Z_{\rm initial}, \alpha_{mlt}, {\rm Age}$$

MESA

Paxton et al. 2011,2013,2015,2018,2019
Jermyn et al. 2023

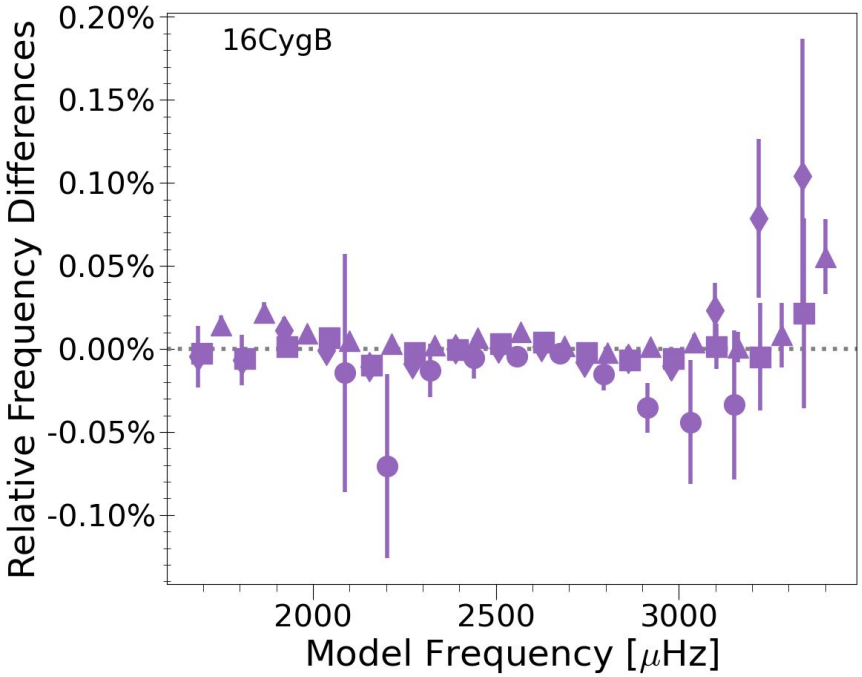
For models within 10σ of L find minimum of

$$\chi^2_{\rm fit} = \frac{\chi^2_\nu}{N_\nu} + \chi^2_{T_{\rm eff}} + \chi^2_{\rm [Fe/H]}$$

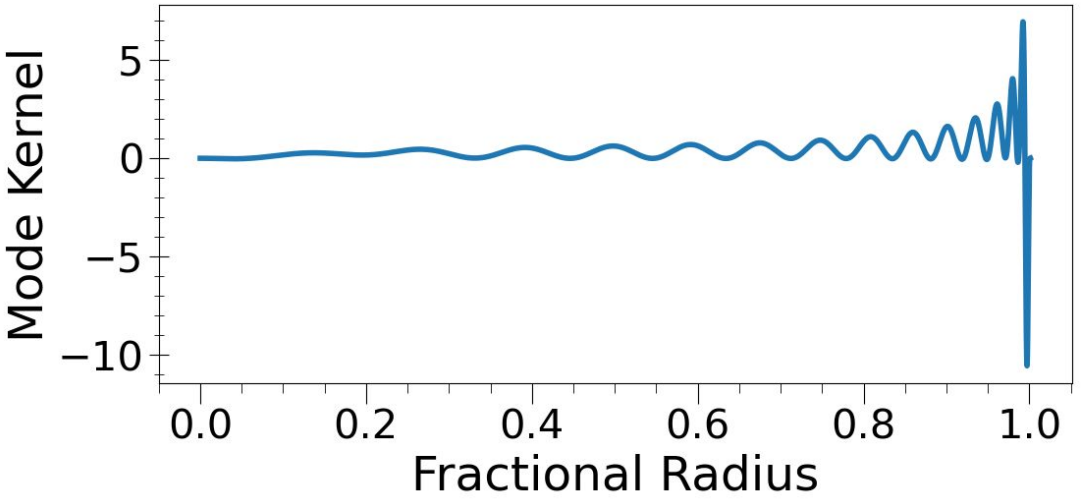
GYRE

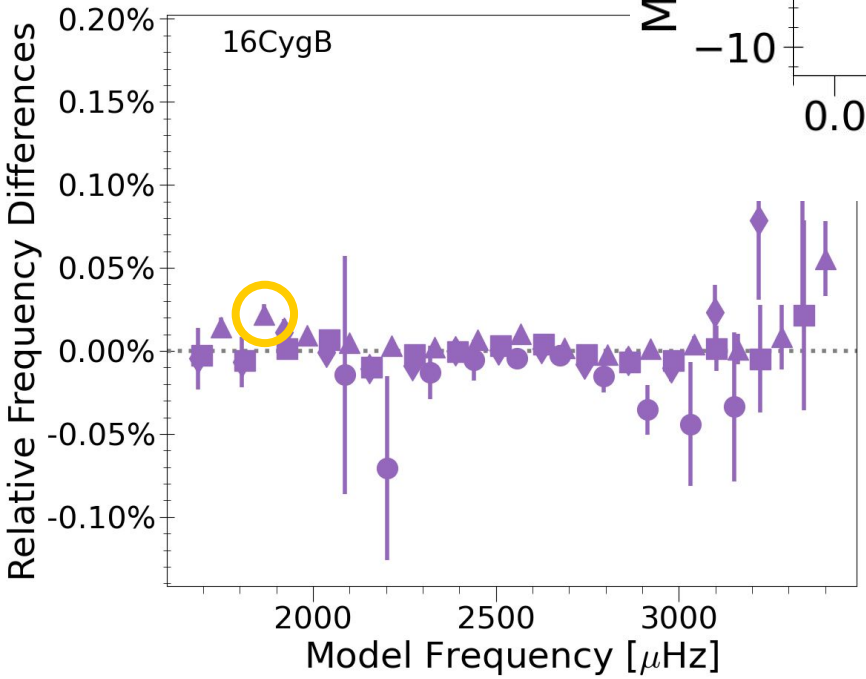
Townsend & Teitler 2013

Mode Kernels

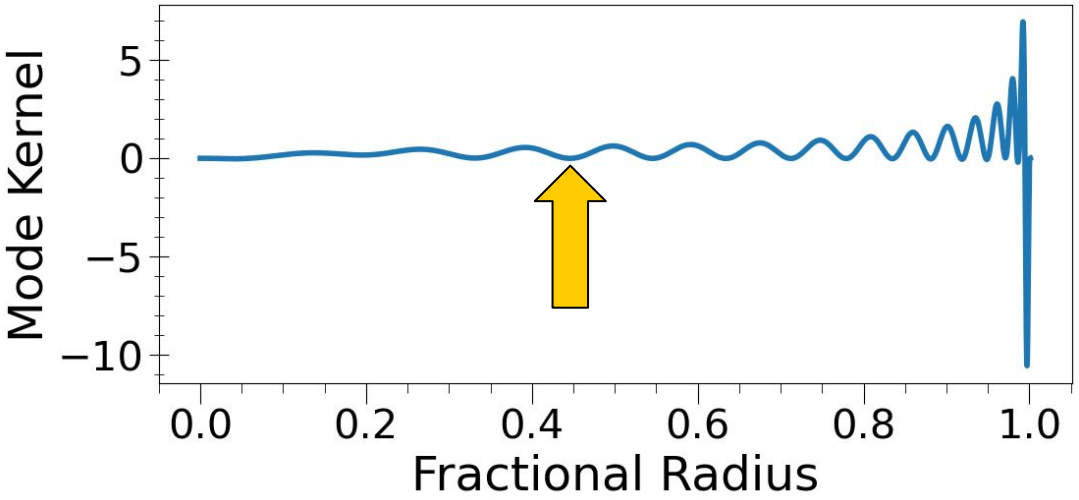


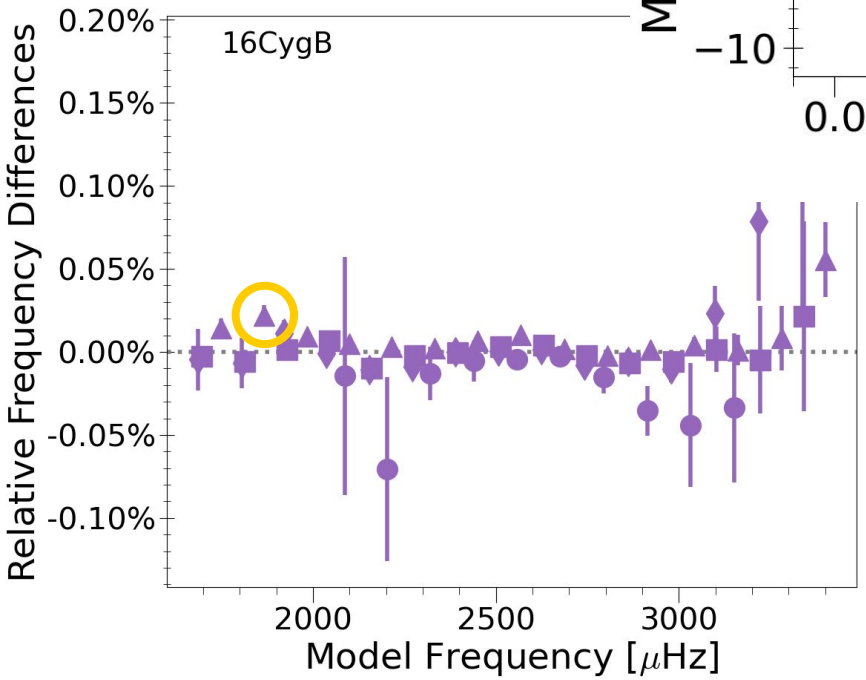
Mode Kernels



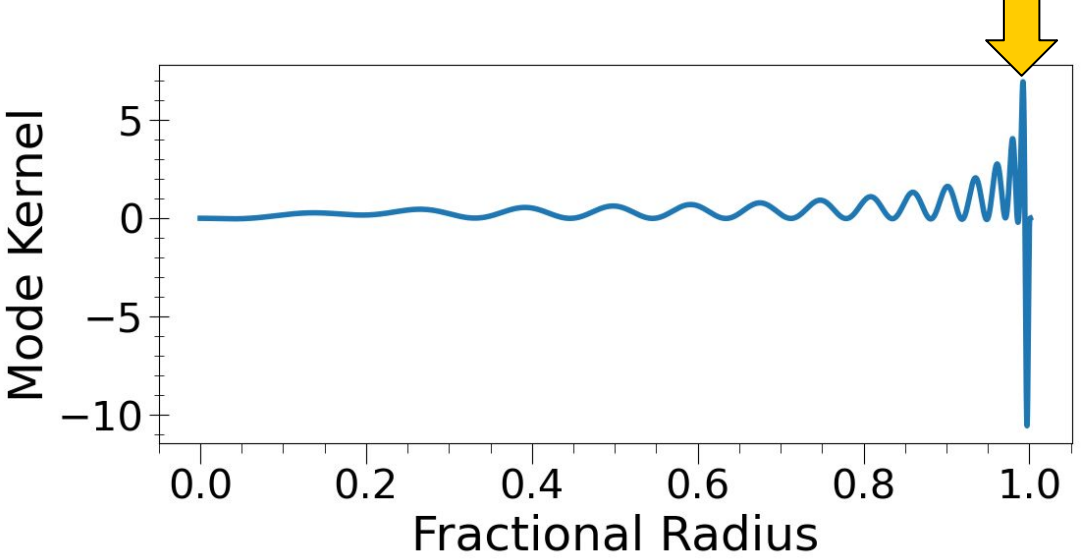


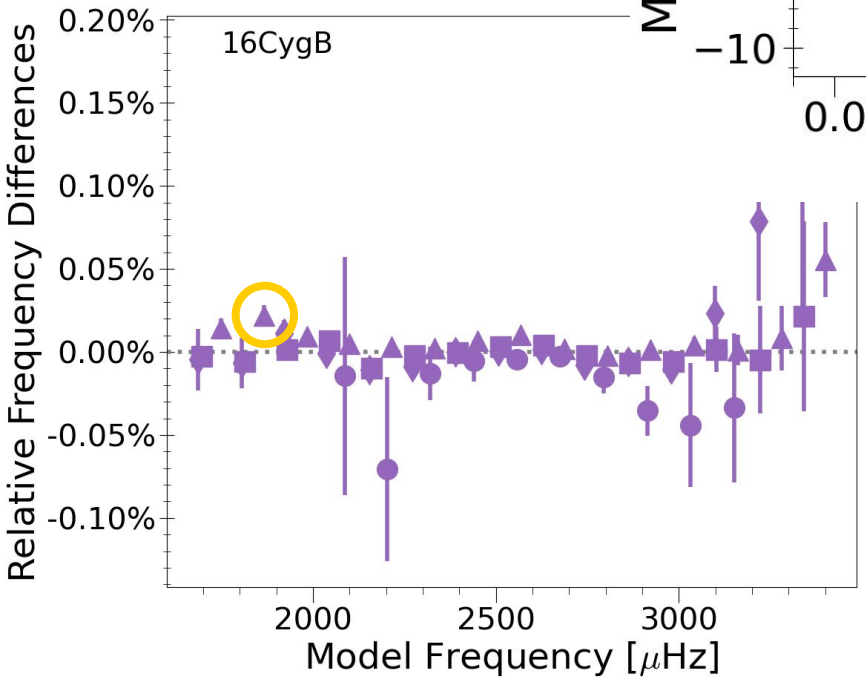
Mode Kernels



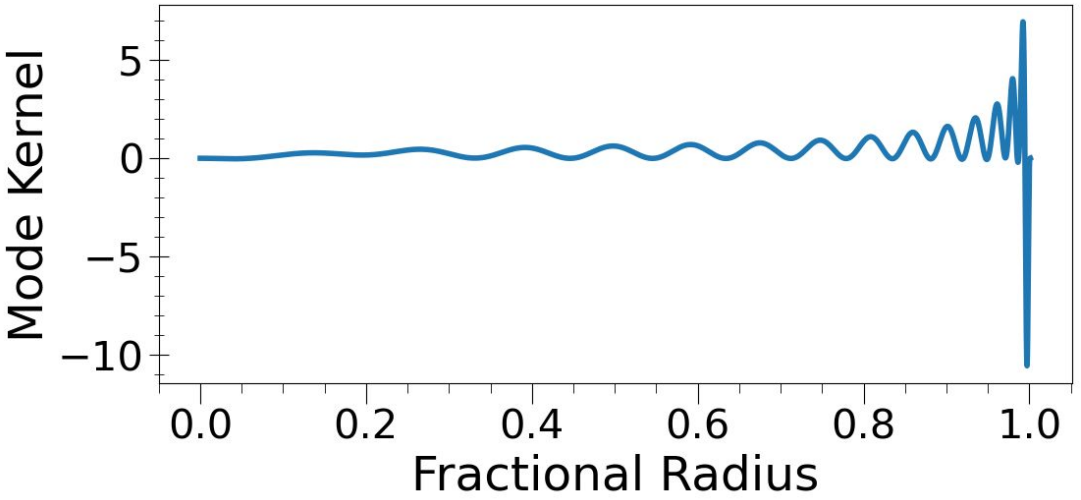


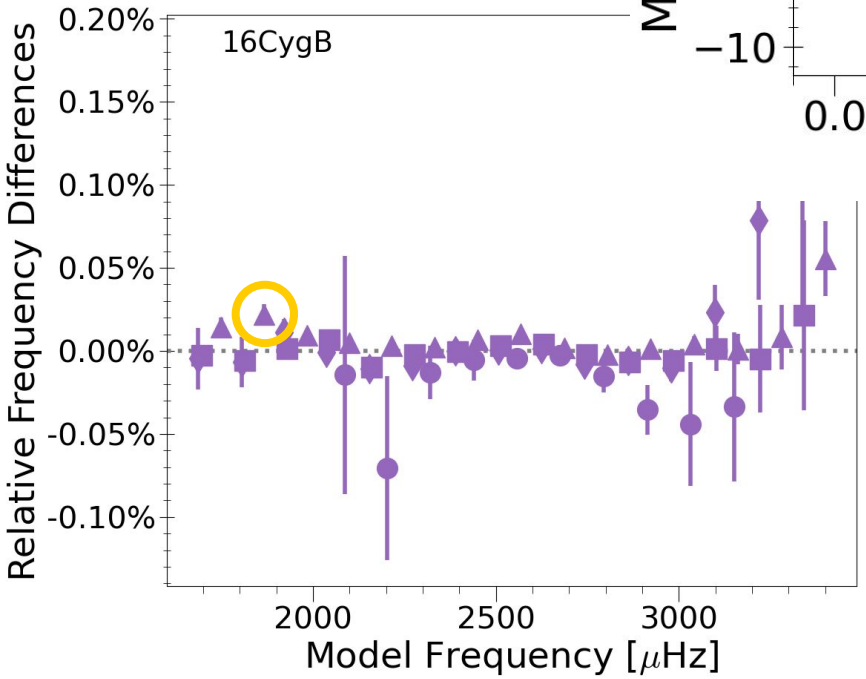
Mode Kernels





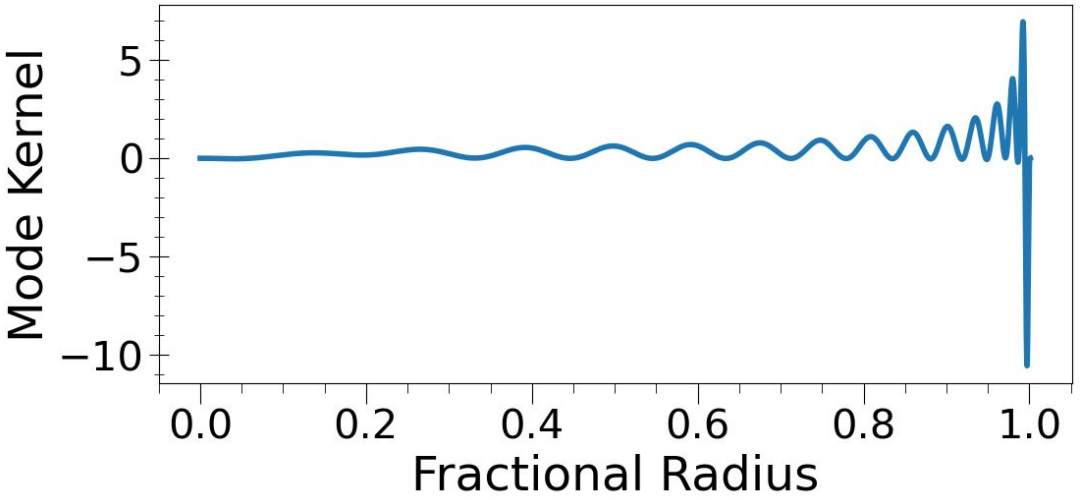
Mode Kernels

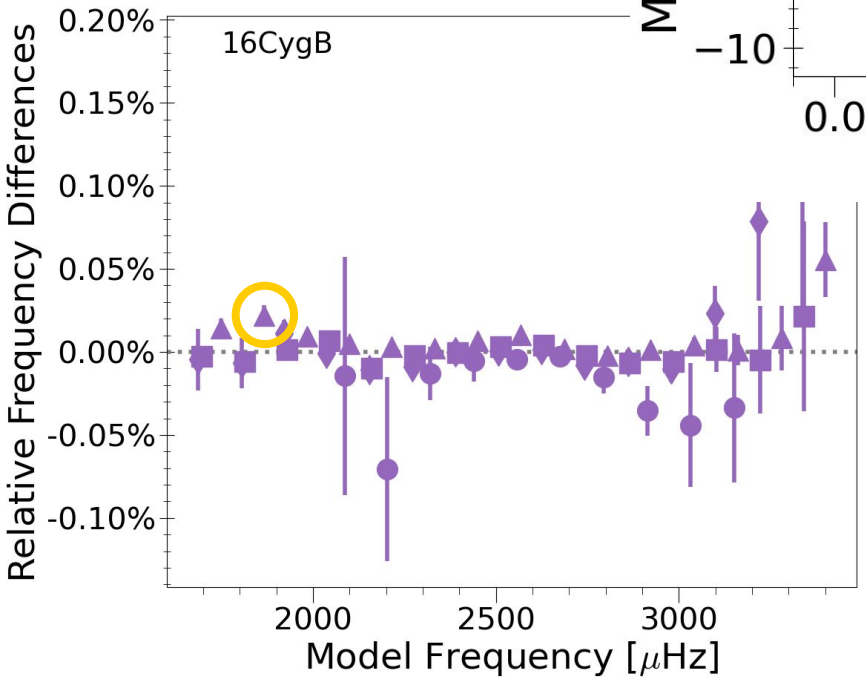




$$\frac{\delta\nu_i}{\nu_i} = \int_0^R K_i^{(u,Y)} \frac{\delta u}{u} dr$$ + Cross Term

Mode Kernels



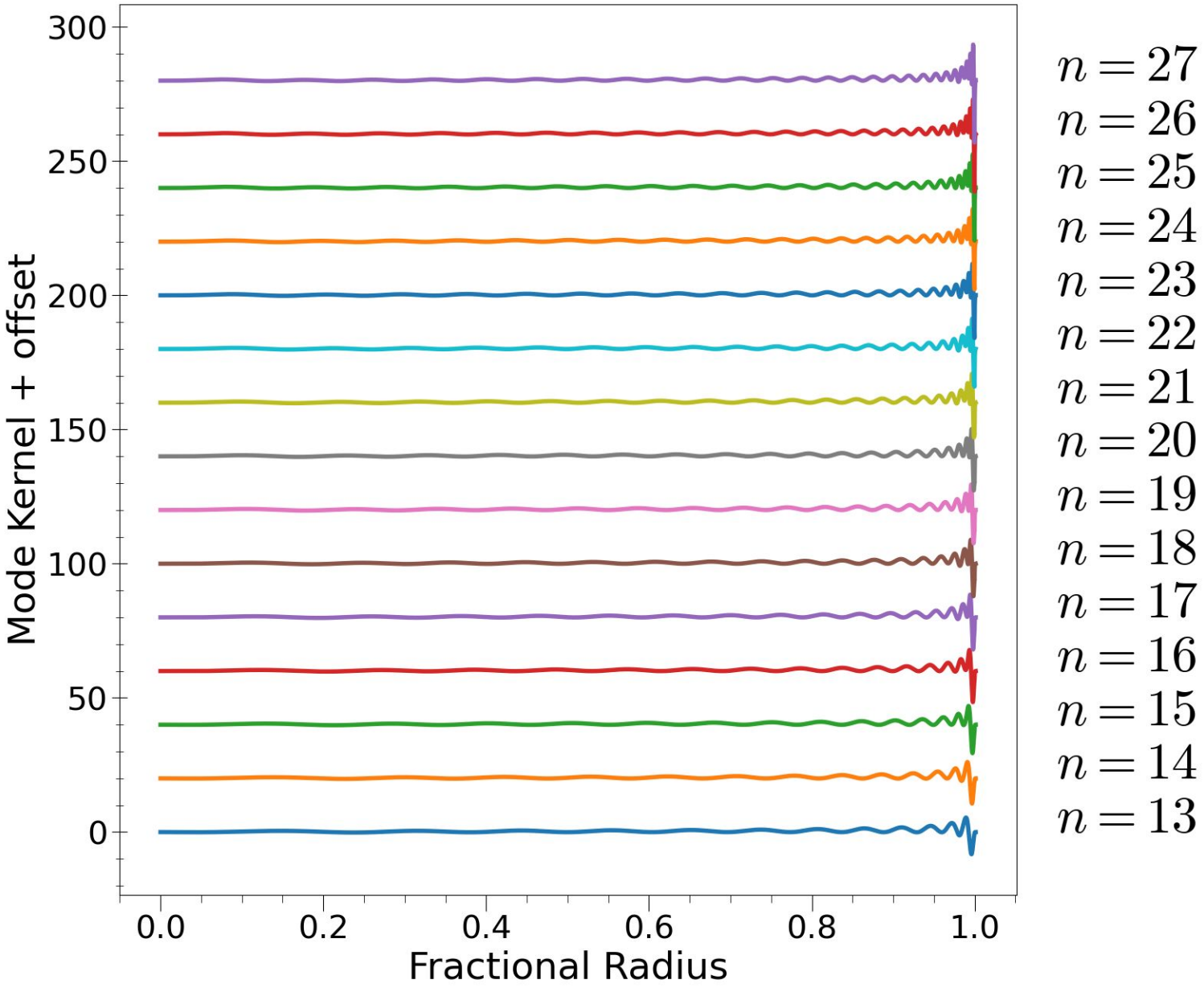


$$\frac{\delta\nu_i}{\nu_i} = \int_0^R K_i^{(u,Y)} \frac{\delta u}{u} dr \text{ + Cross Term}$$

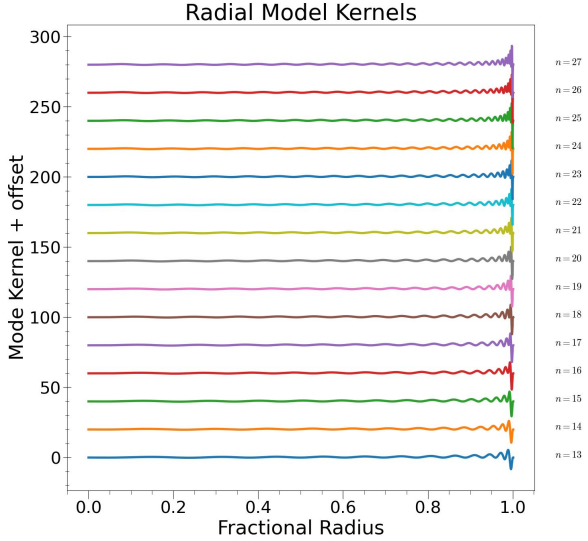
Structure difference

$$u = \frac{c^2}{\Gamma_1} = \frac{p}{\rho}$$

Radial Mode Kernels

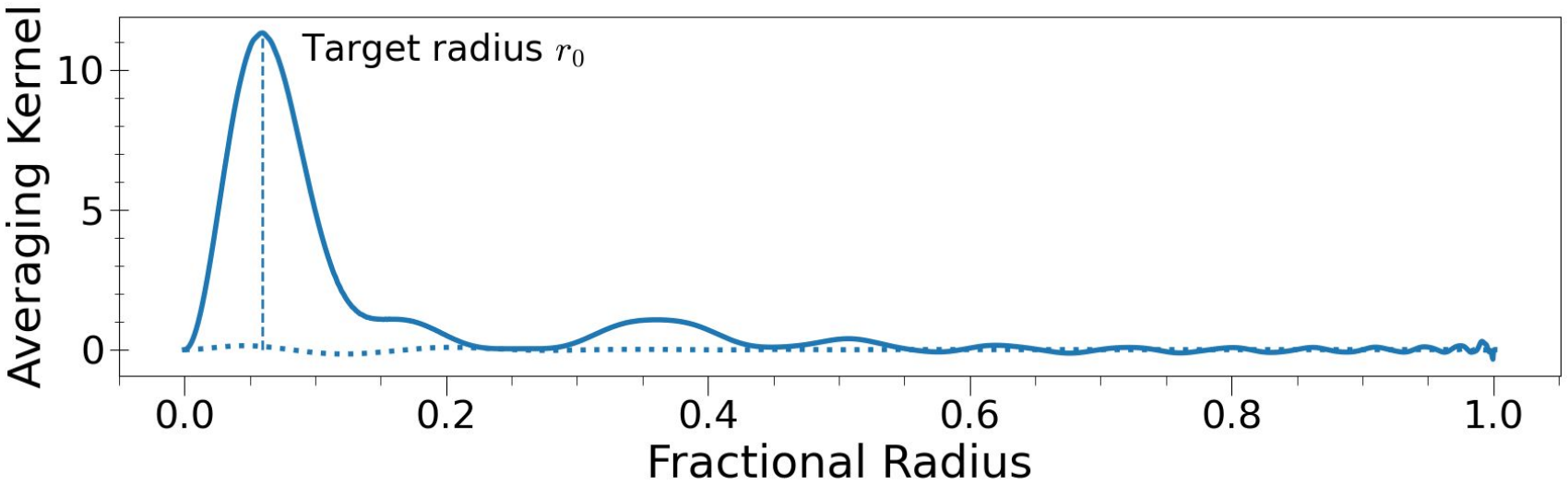


Averaging Kernel

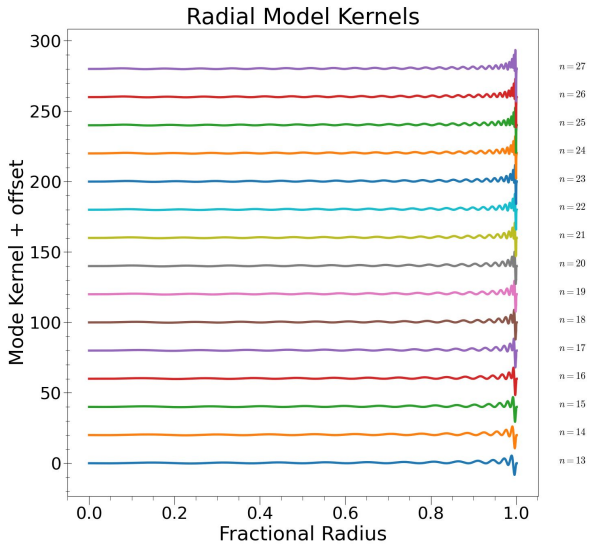


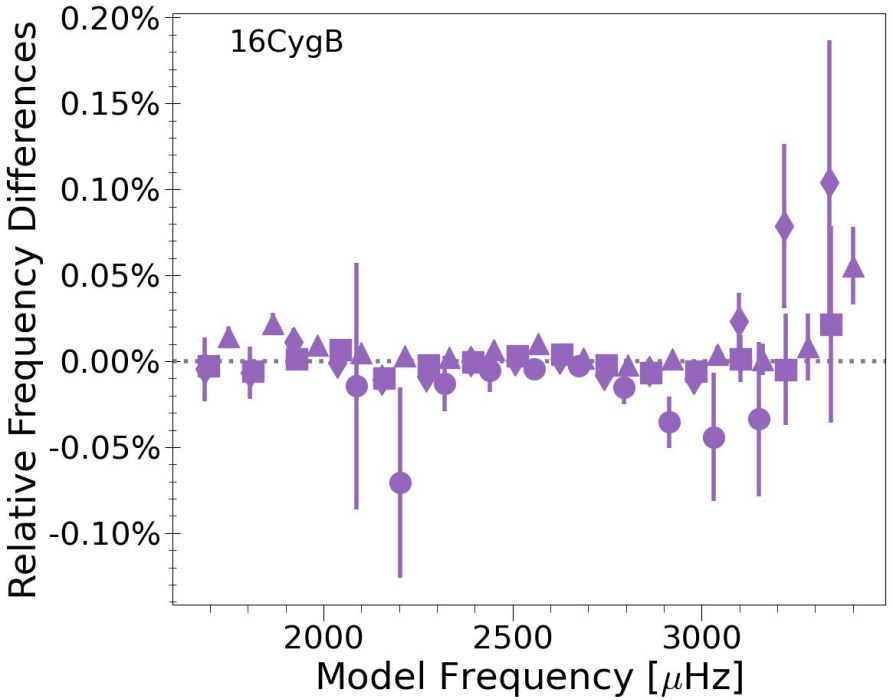
+dipole mode kernels + ...

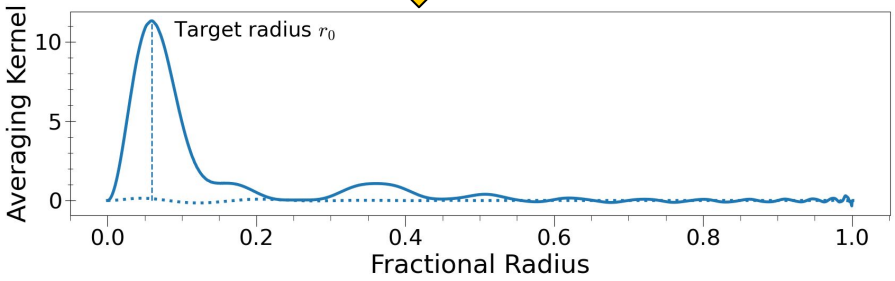
Linear combination to localize sensitivity



Averaging Kernel

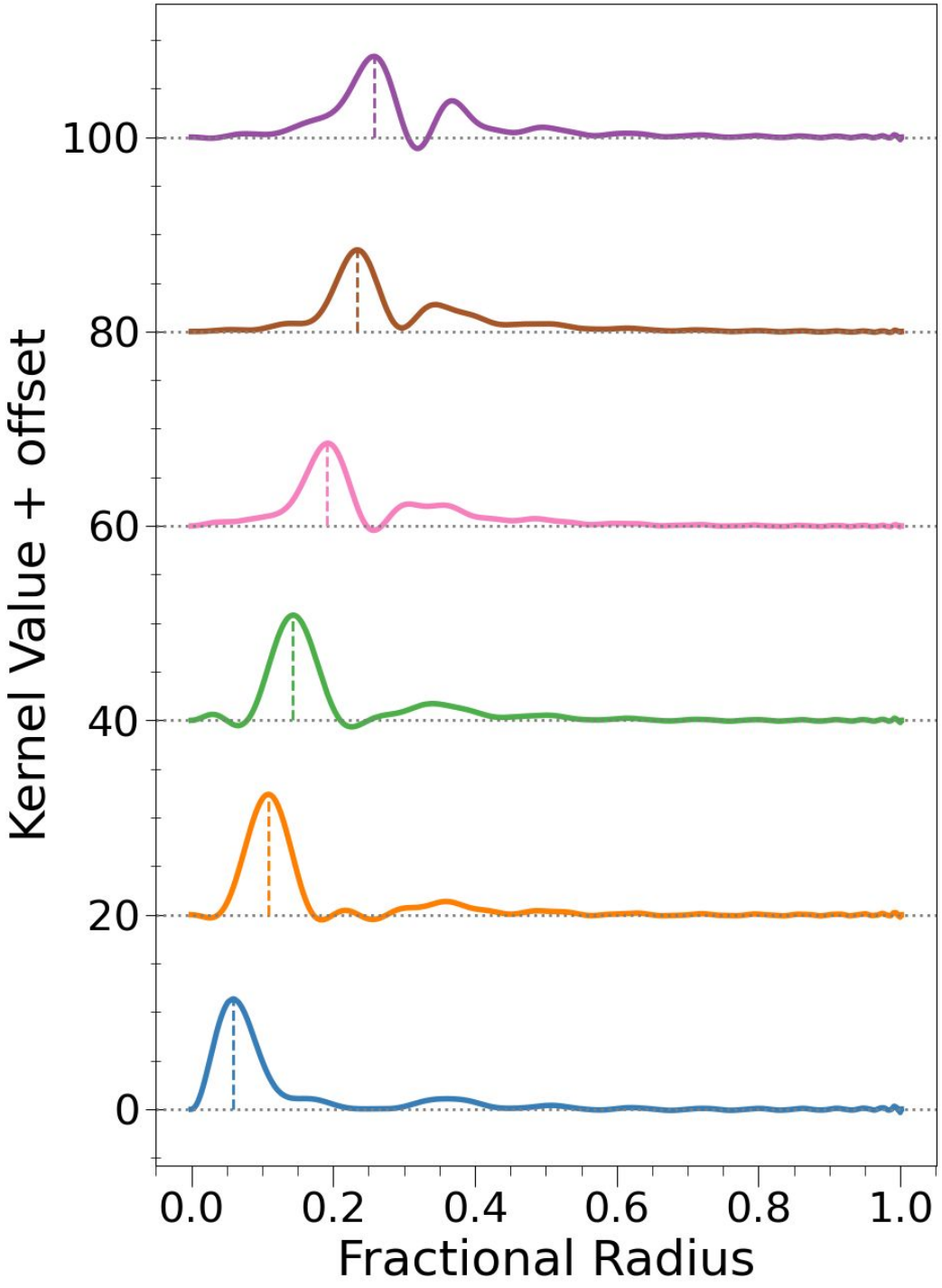




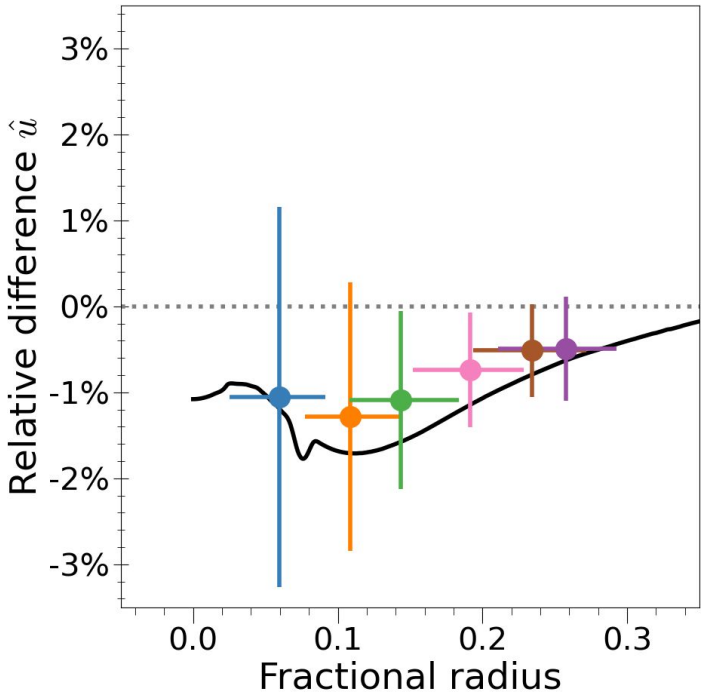


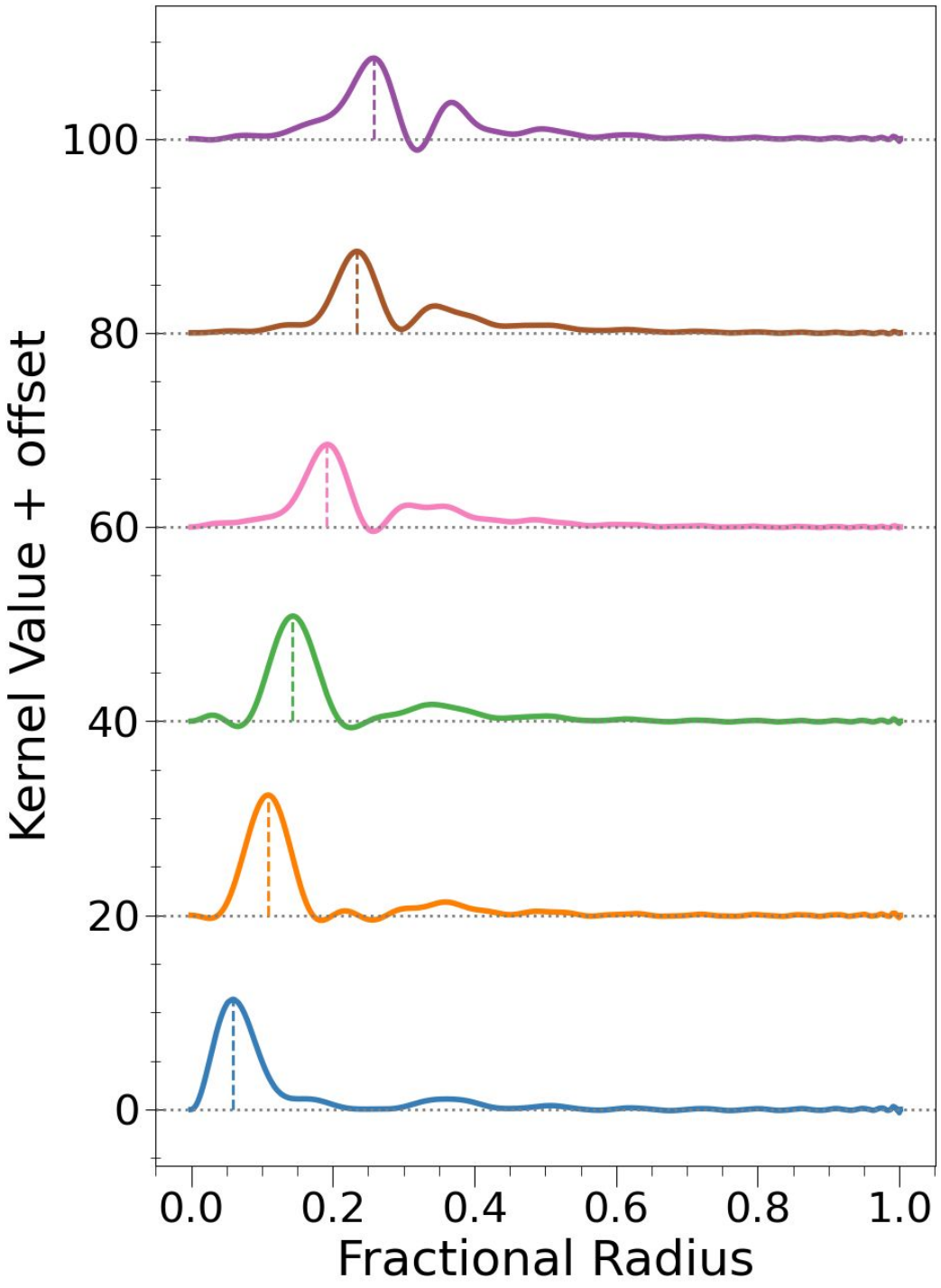
$$\left\langle \frac{\delta u}{u} \right\rangle_{r_0}$$

Averaging Kernels



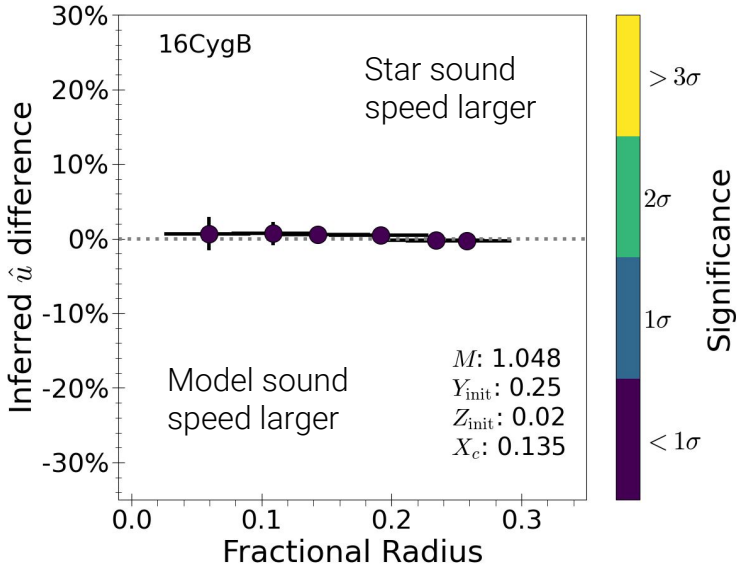
Model-Model Inversions





Results

Case 1: Agreement (3 stars)

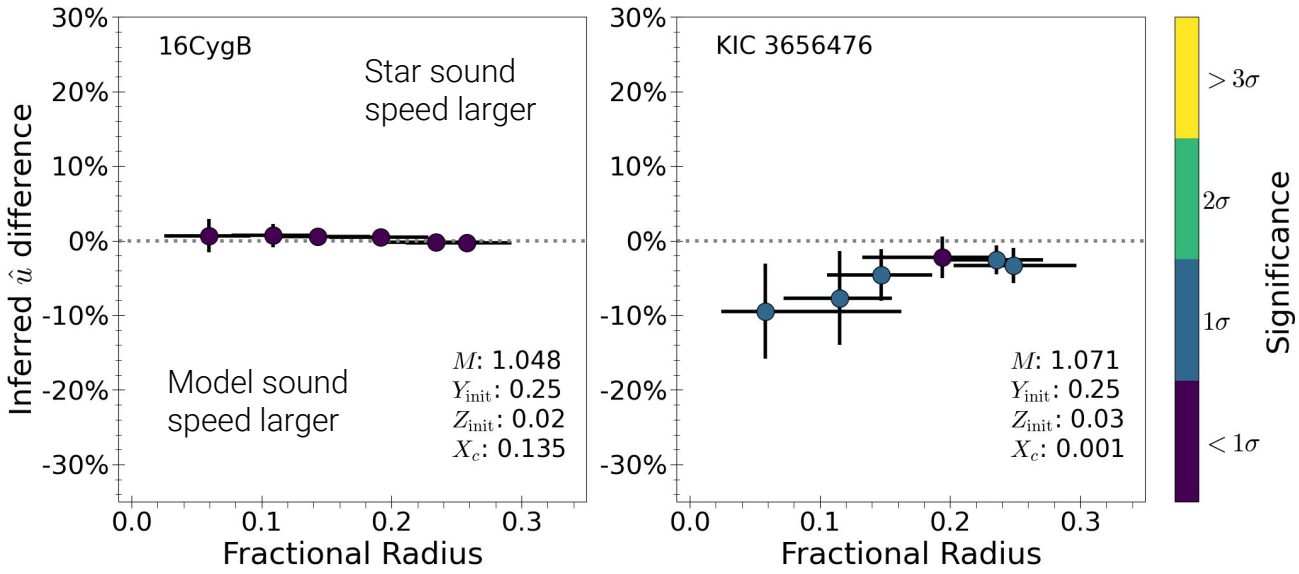


In agreement with Buldgen et al. 2022 and Bellinger et al. 2017

Results

Case 1: Agreement (3 stars)

Case 2: Ambiguity (5 stars)



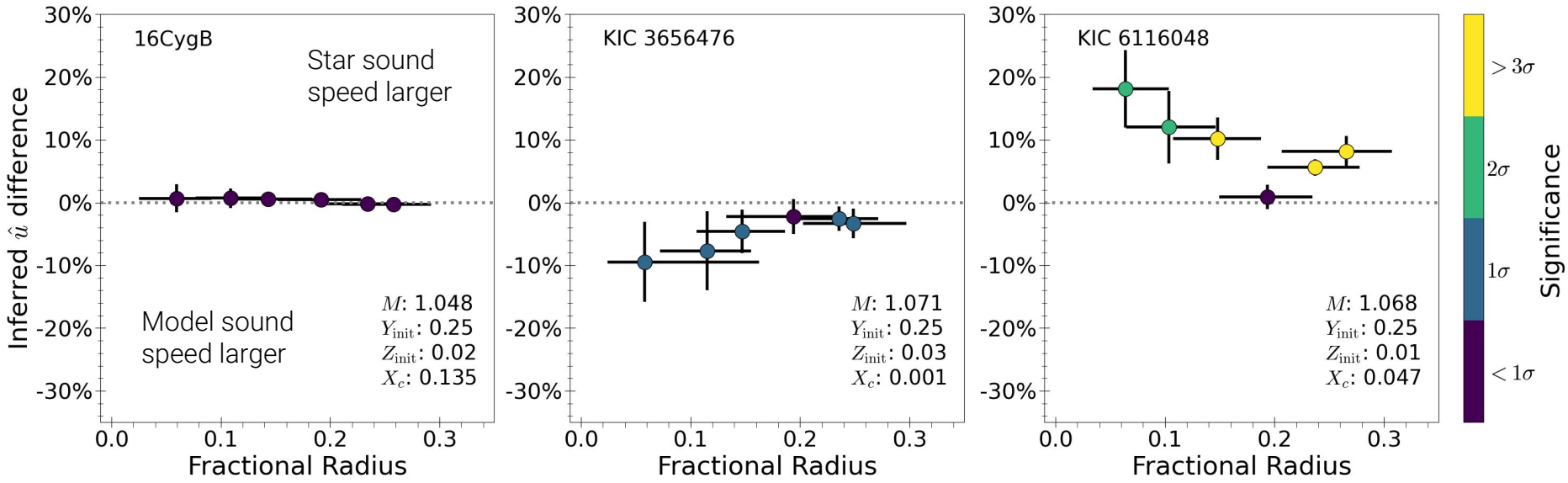
In agreement with Buldgen et al. 2022 and Bellinger et al. 2017

Results

Case 1: Agreement (3 stars)

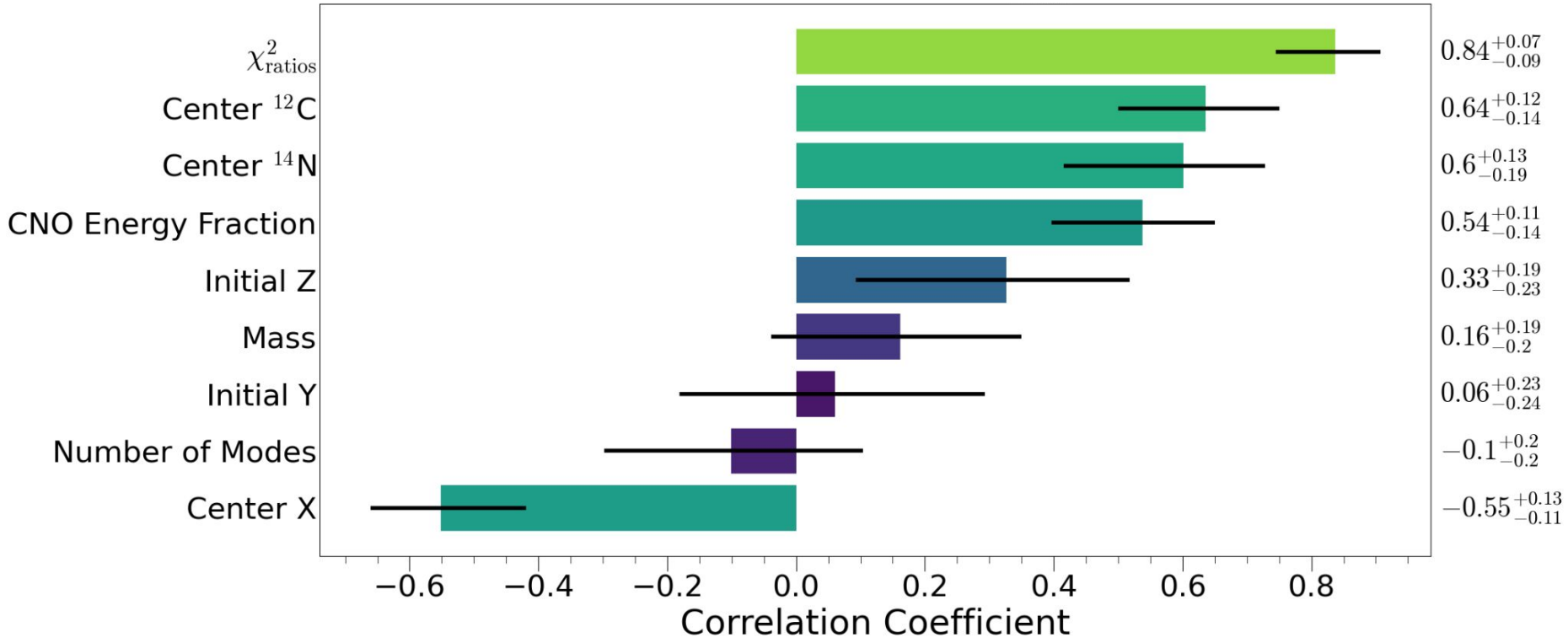
Case 2: Ambiguity (5 stars)

Case 3: Disagreement (4 stars)



In agreement with Buldgen et al. 2022 and Bellinger et al. 2017

Correlation with $\chi^2_{\text{Inversion}}$

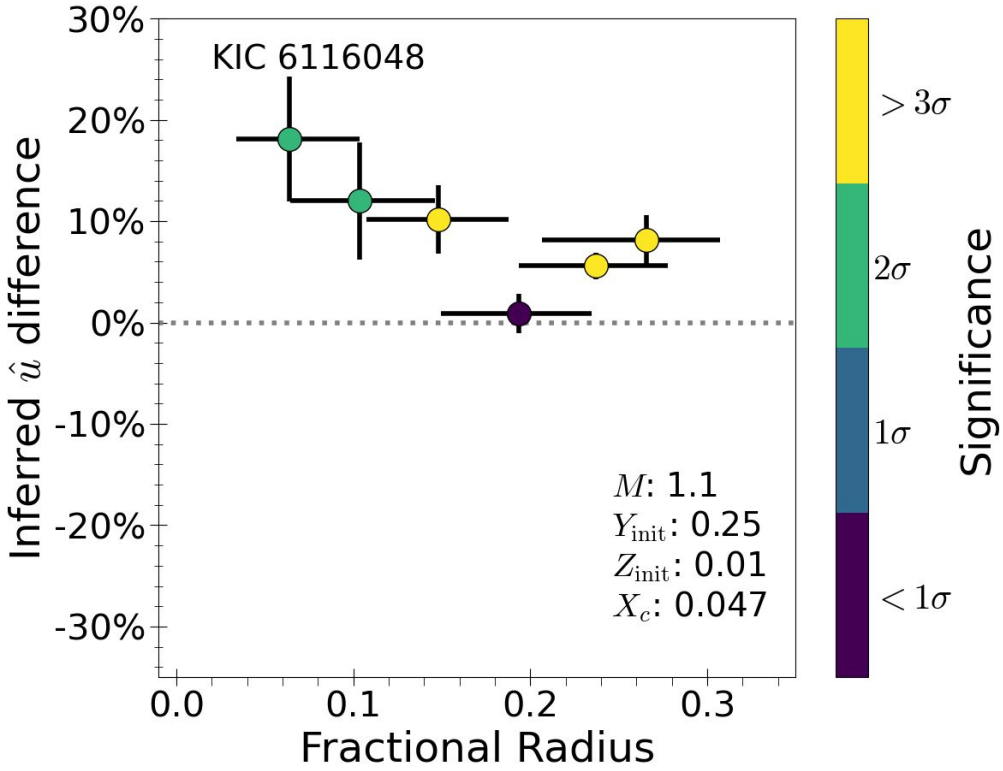


Can the models be improved?

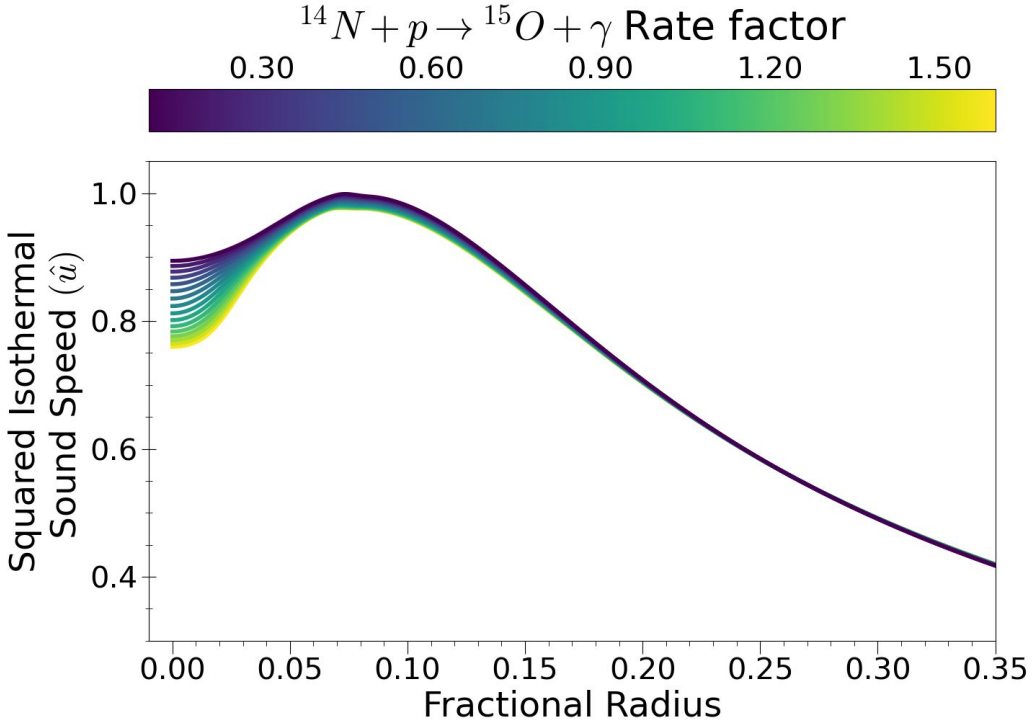
CNO Reaction Rate

pp II Reaction Rate

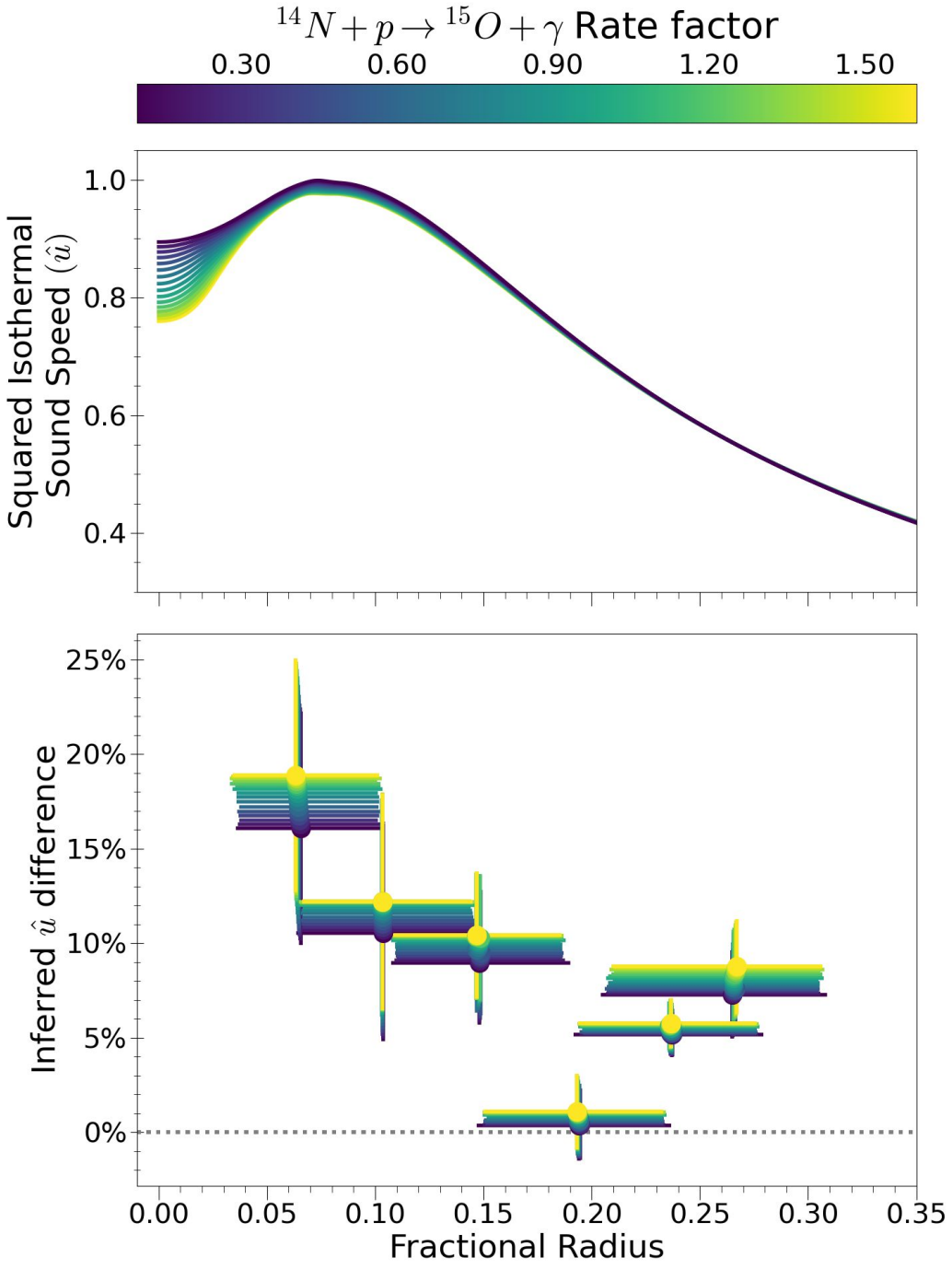
Core Opacity



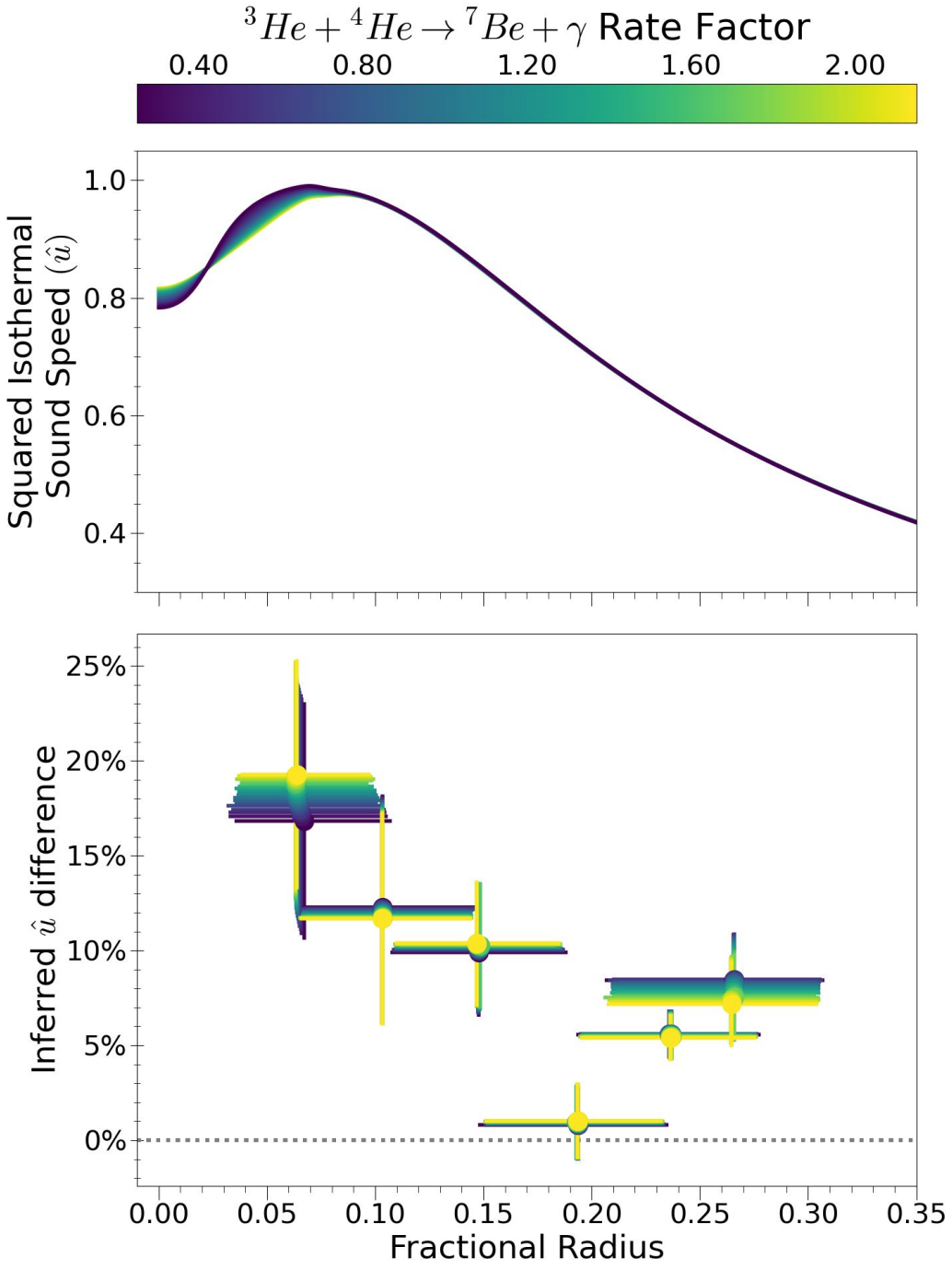
Microphysics Changes: CNO Cycle



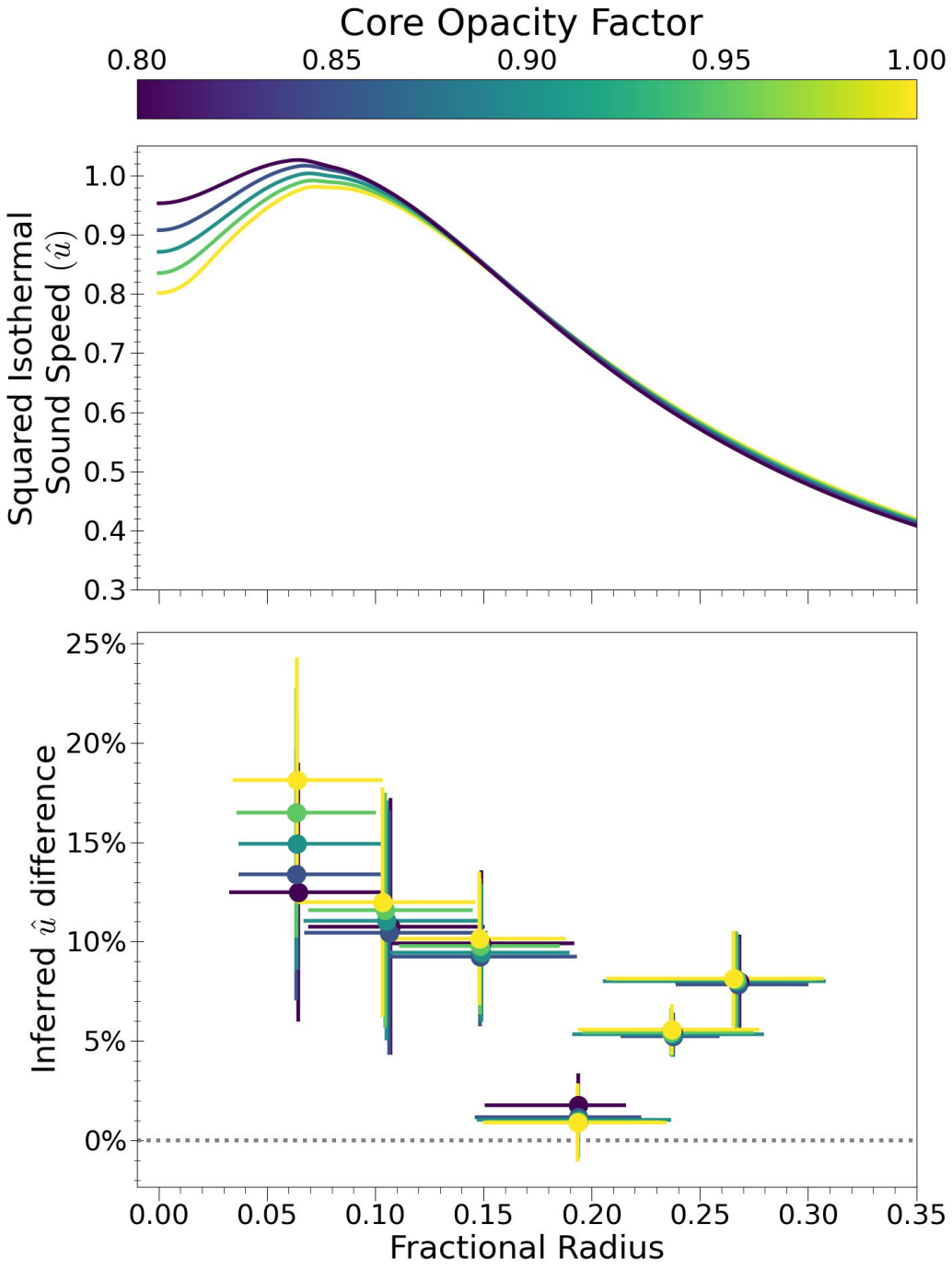
Microphysics Changes: CNO Cycle



Microphysics Changes: p-p II & III

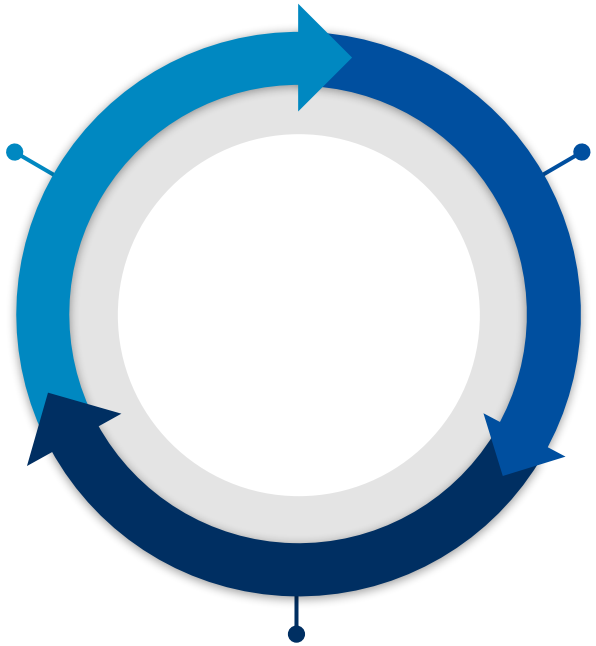


Microphysics Changes: Core Opacity



Stellar Modeling

Obtained reference models for 12 Kepler main-sequence stars with radiative cores



Structure Inversions

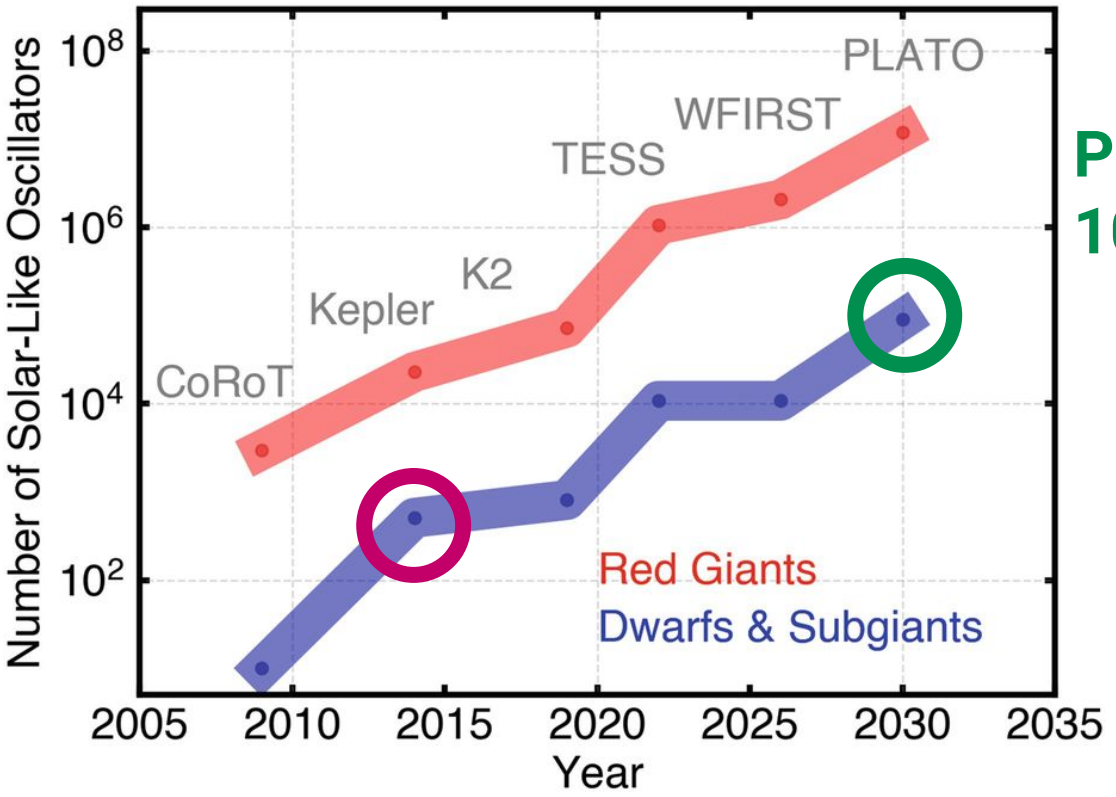
Results show

- 3 stars with full agreement
- 5 stars with slight disagreement
- 4 stars with large disagreement

Improved Physics

Changes to reaction rates and core opacity reduce, but don't fully resolve, differences

What can be expected with PLATO data?



PLATO: 1000+ Stars

Kepler: 12 Stars

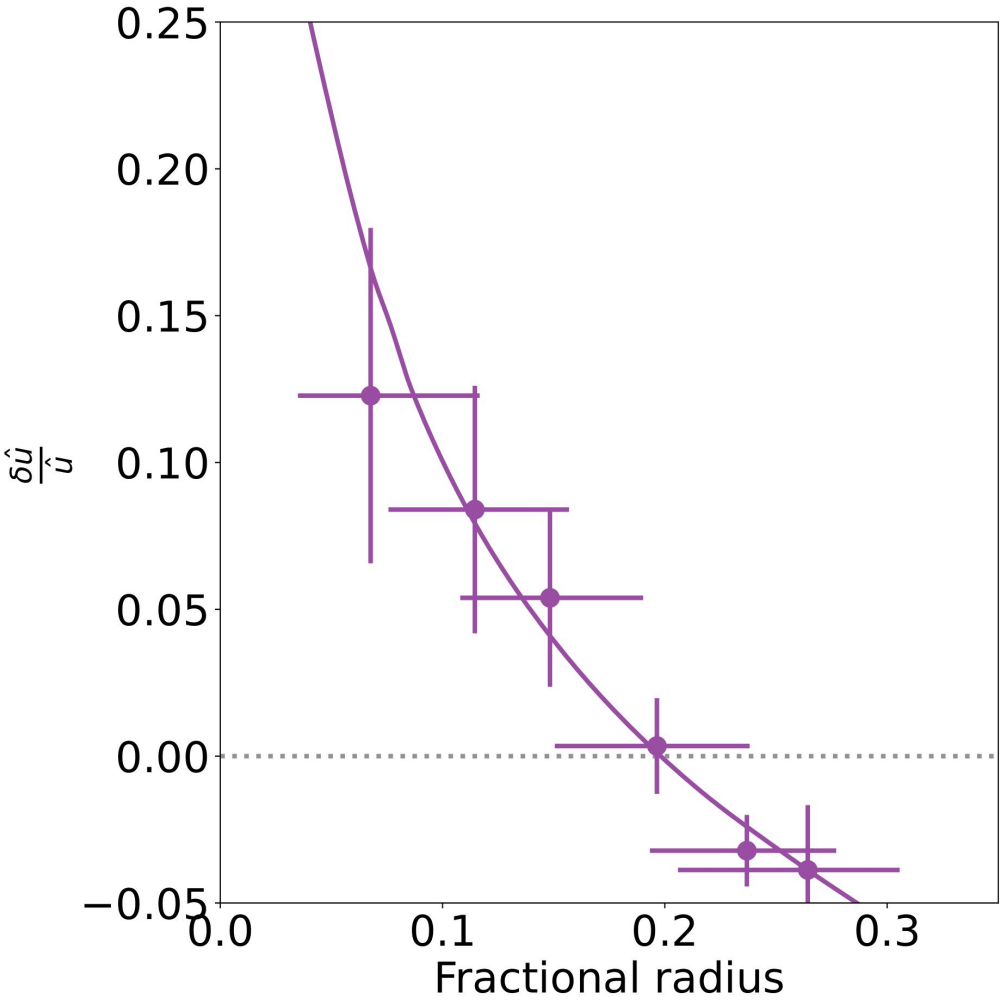
Huber et al. 2020, Fig 1

Is 15% difference linear?

Model with opacity factor of 0.5 for entire star

Really bad fit to the frequencies

Inversions recover the large difference well

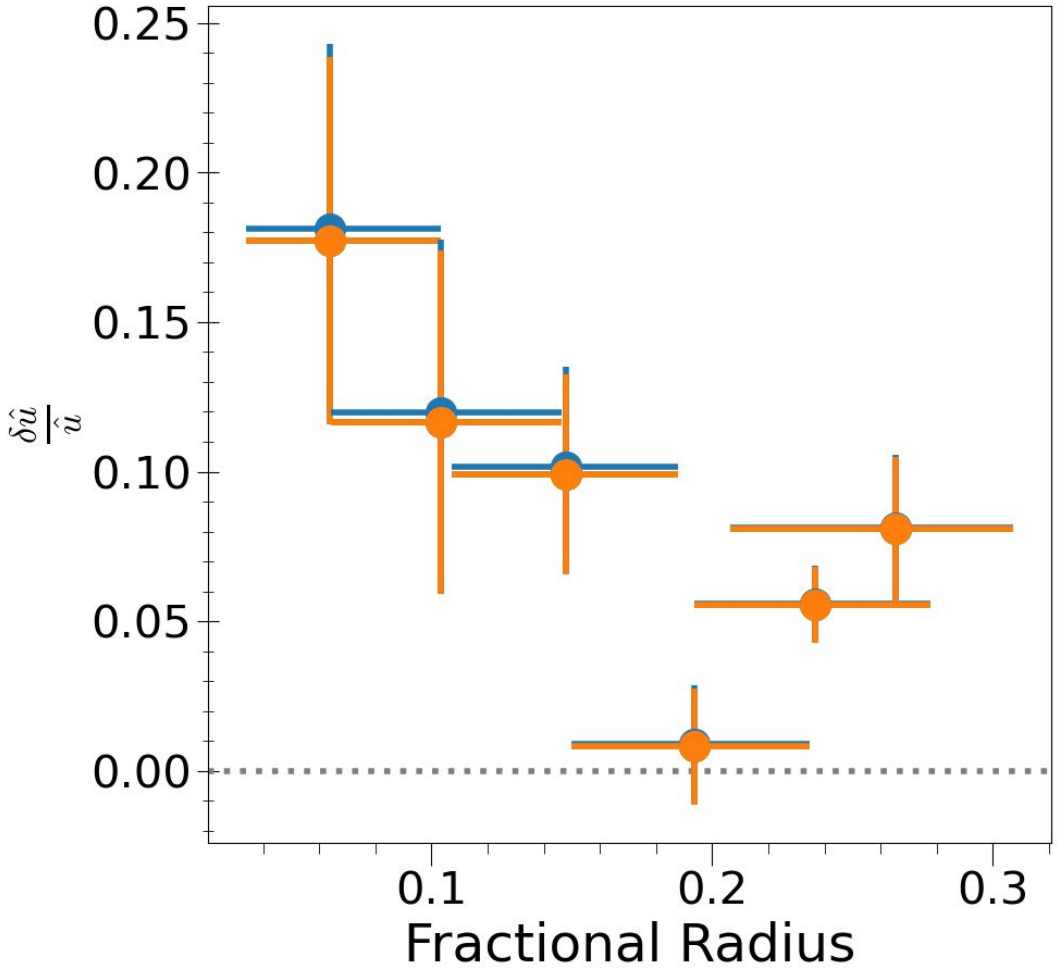


Mean Density Considerations 1

Test two methods of non-dimensionalization

- Delta nu scaling
- Weighted mean

Inversion results are unaffected



Mean Density Considerations 2

Using alternative reference models (with different M and R values) yields consistent results