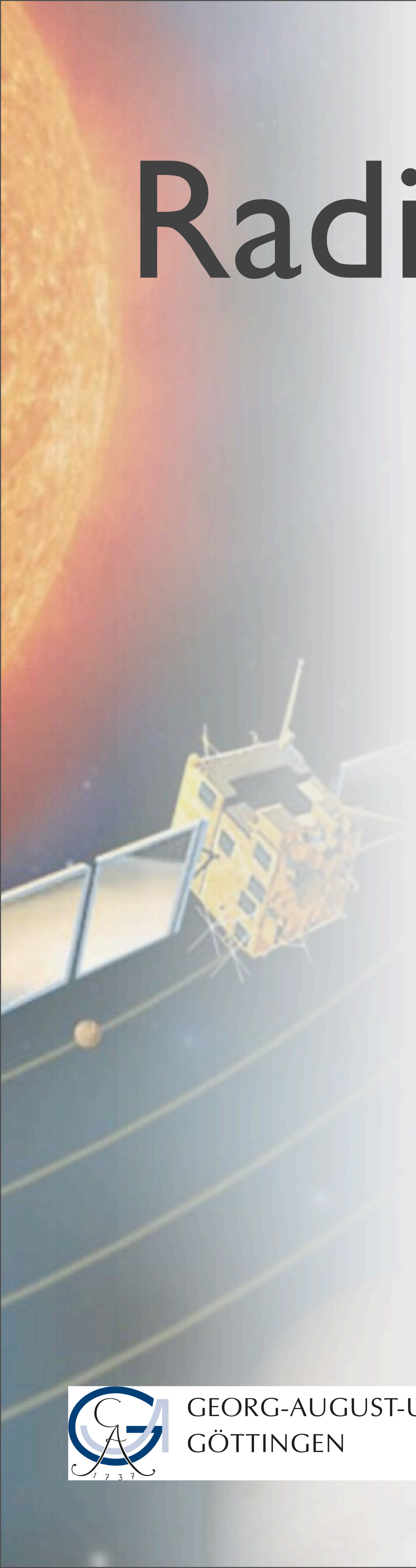


Radial Differential Rotation of Sun-like stars

Hannah Schunker

Jesper Schou & Warrick Ball

Martin Bo Nielsen

GEORG-AUGUST-UNIVERSITÄT GÖTTINGEN

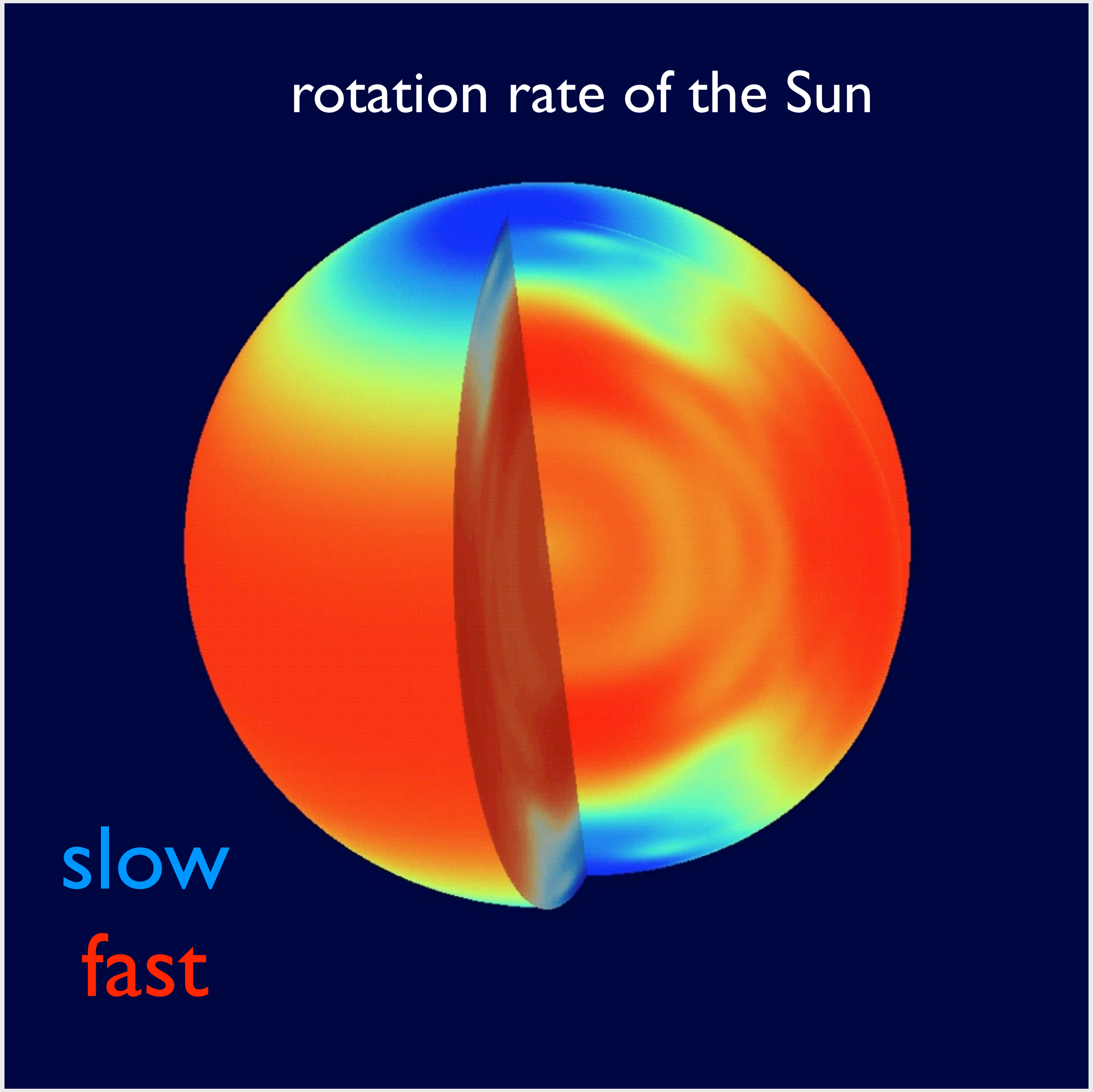
AstroFIT
Astrophysical Flow Instabilities and Turbulence

Max Planck Institute for Solar System Research

Rotation and Activity

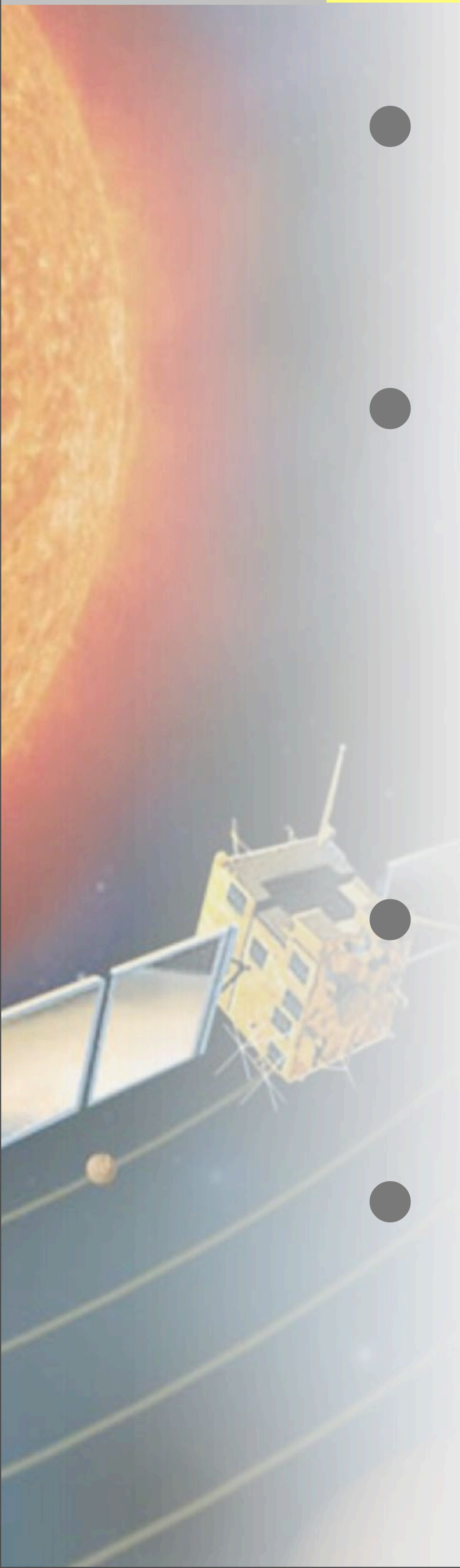
- Stars are magnetically active
- Magnetic field is generated in the interior (dynamo)
- Not well understood

$P_{\odot} \approx 27$ days

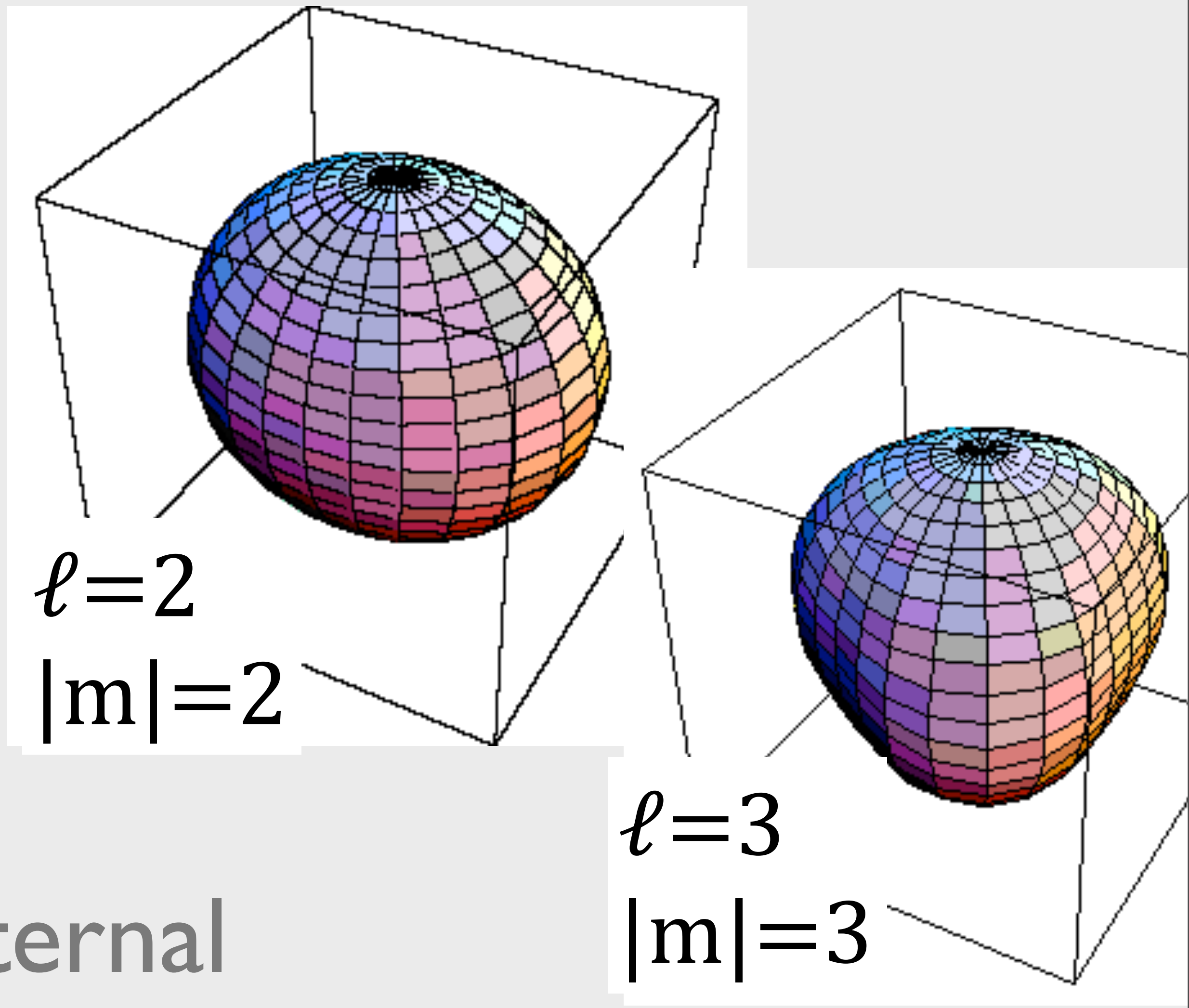


Schou et al 1998

Tool: Asteroseismology



- Solar-like oscillations are stochastically excited by turbulent convection
- Spherical harmonics
  ℓ, harmonic degree
  m, azimuthal order
  n, radial order

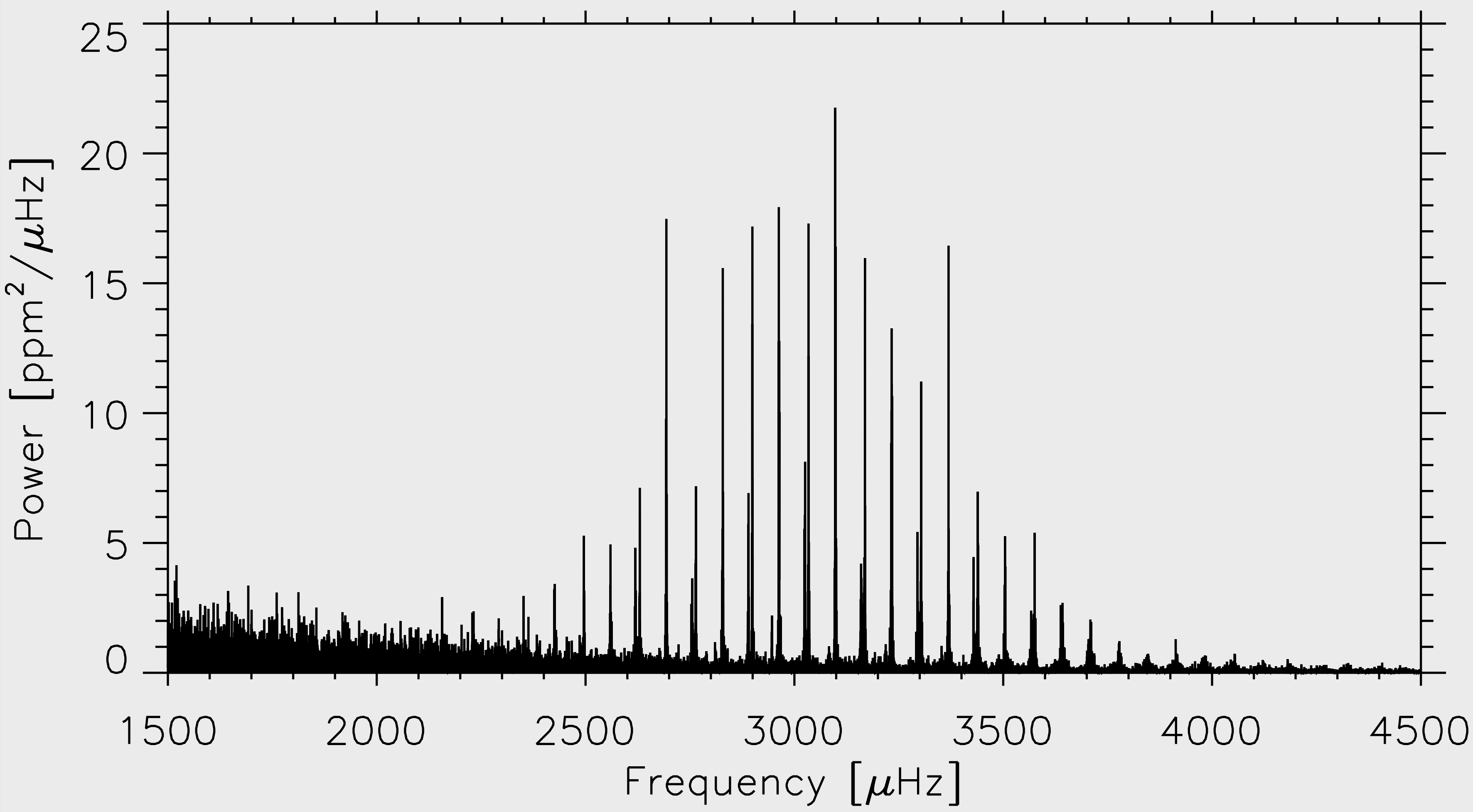


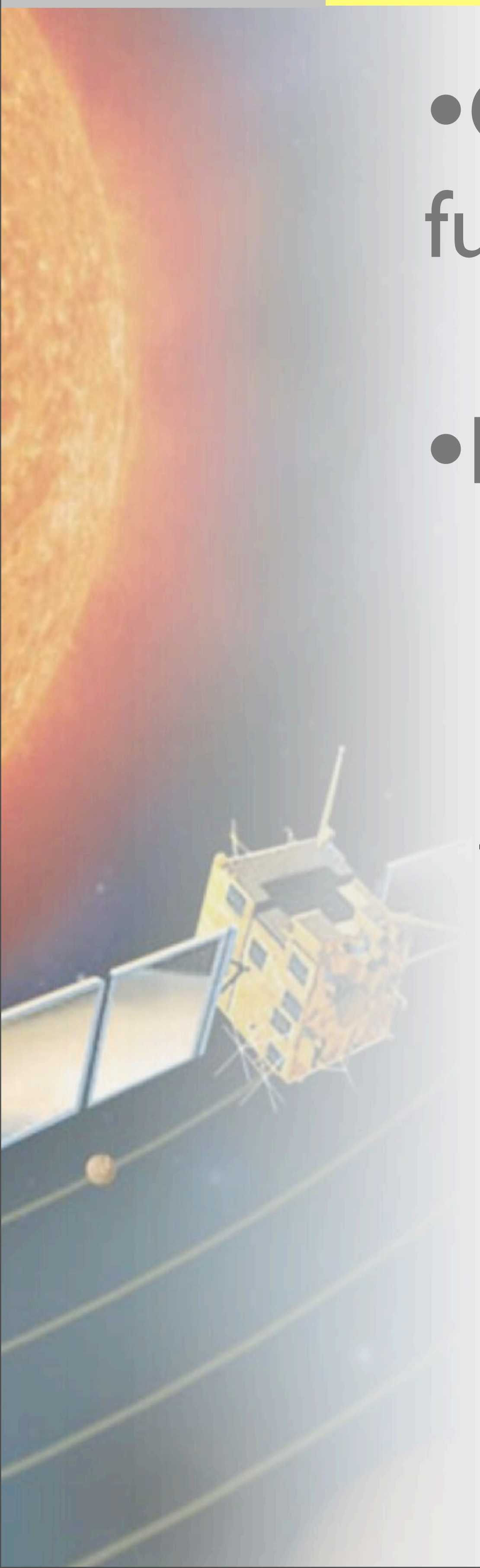
- Oscillations sensitive to interior
- Inversions to infer internal structure & rotation

Tool: Asteroseismology

- Observe light curve or Doppler velocity as a function of time

- Measure properties of the power spectrum

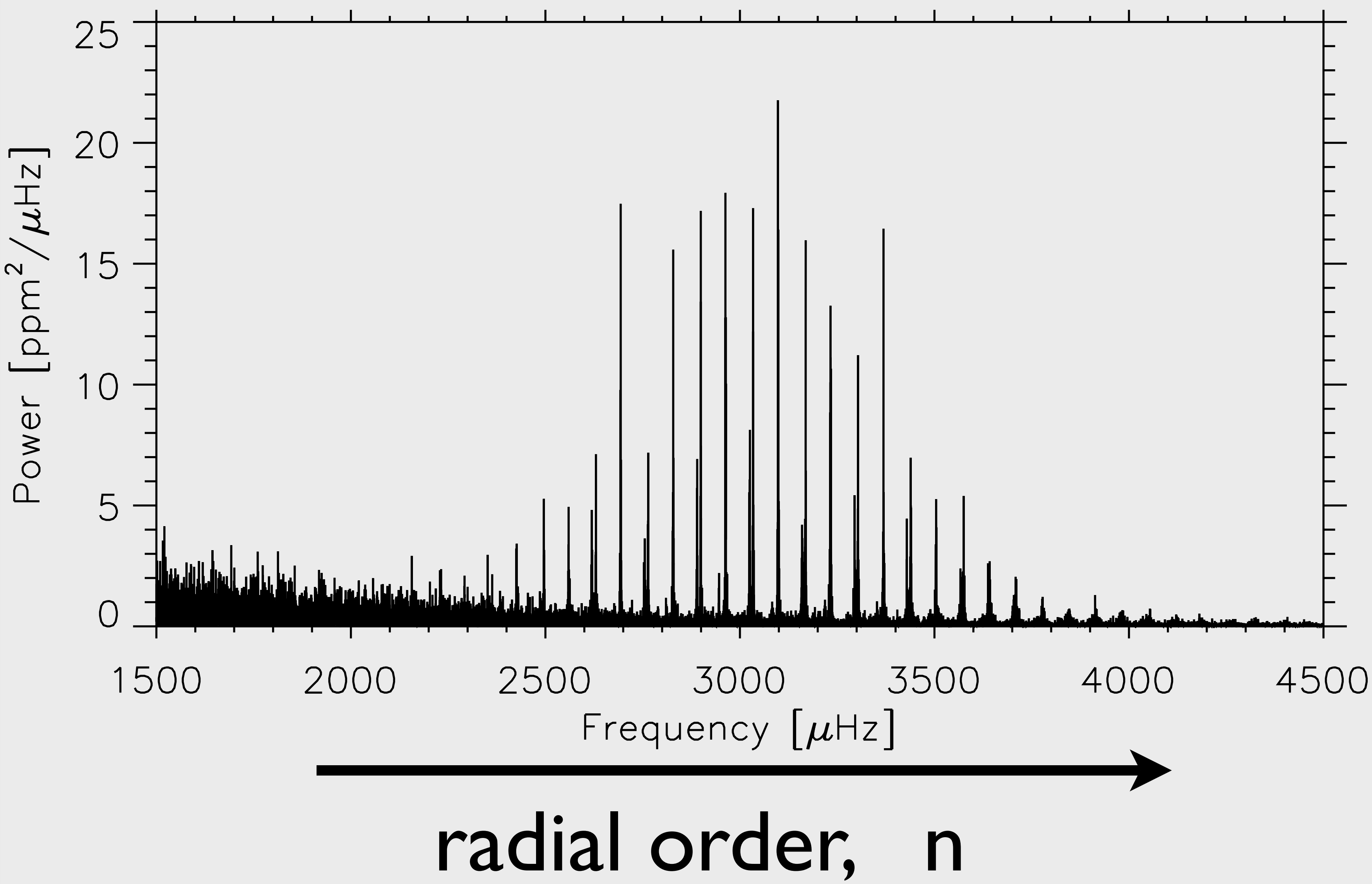




Tool: Asteroseismology

- Observe light curve or Doppler velocity as a function of time

- Measure properties of the power spectrum



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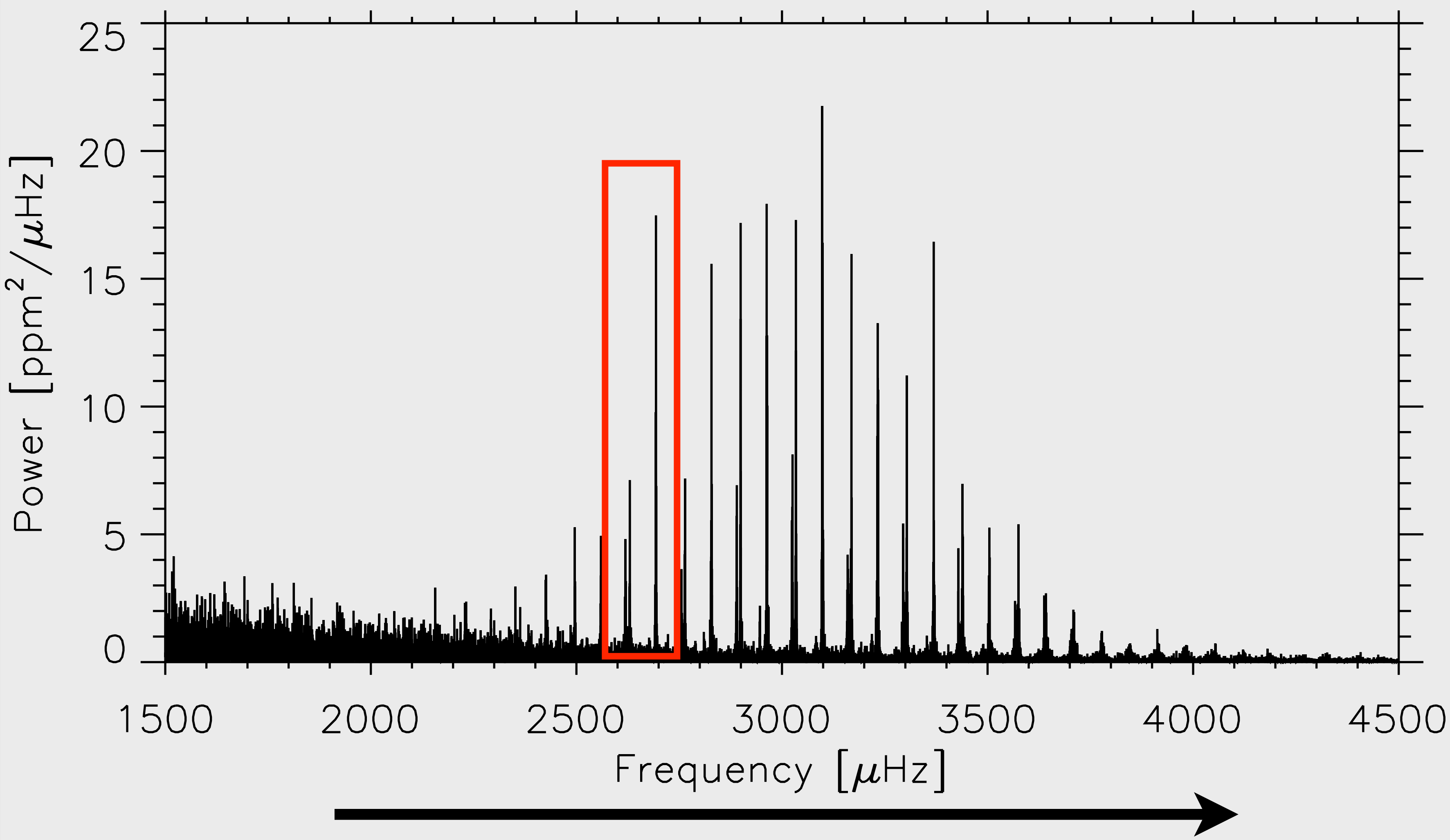
Tool: Asteroseismology

- Observe light curve or Doppler velocity as a function of time

- Measure properties of the power spectrum



radial order, n

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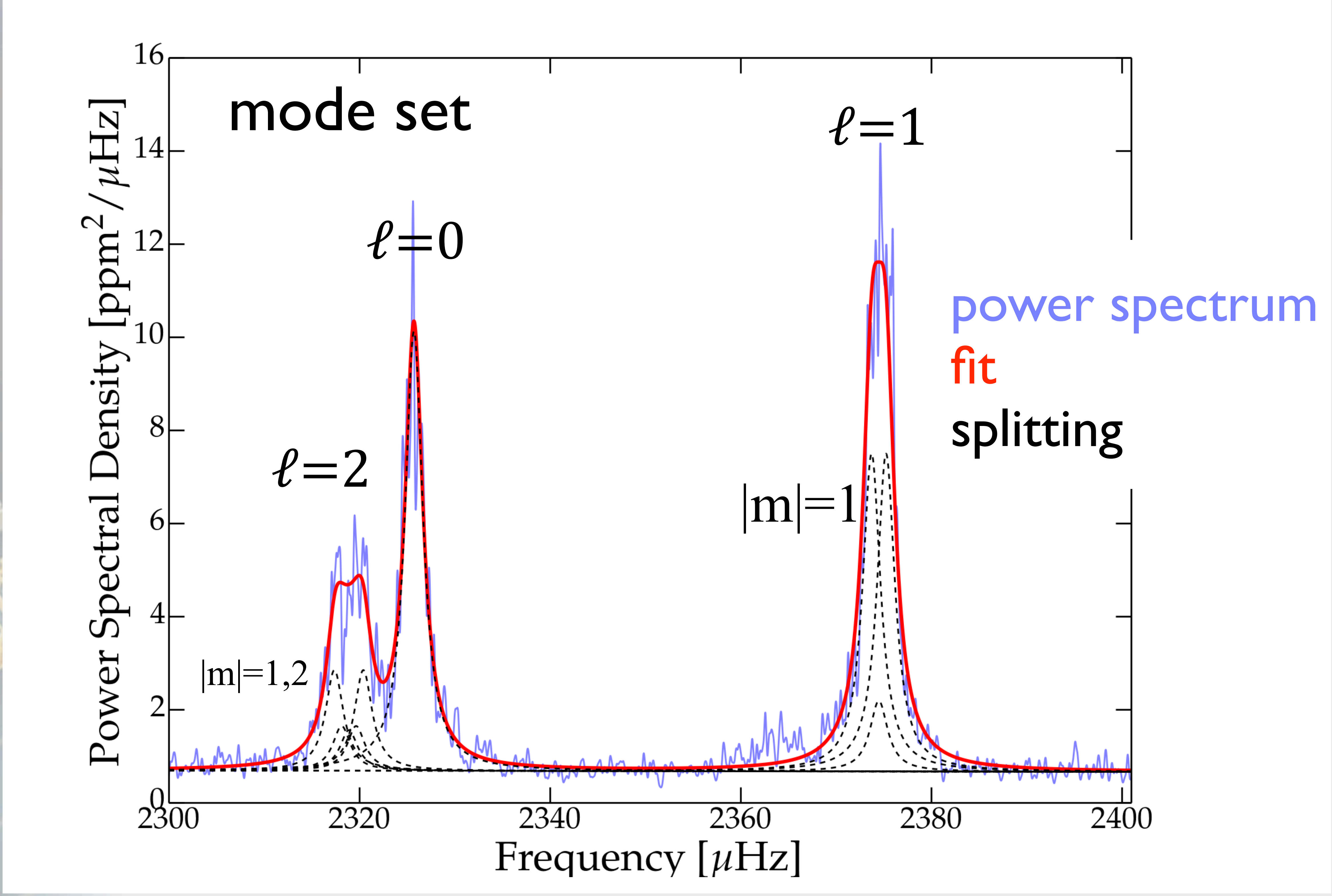
Tool: Asteroseismology



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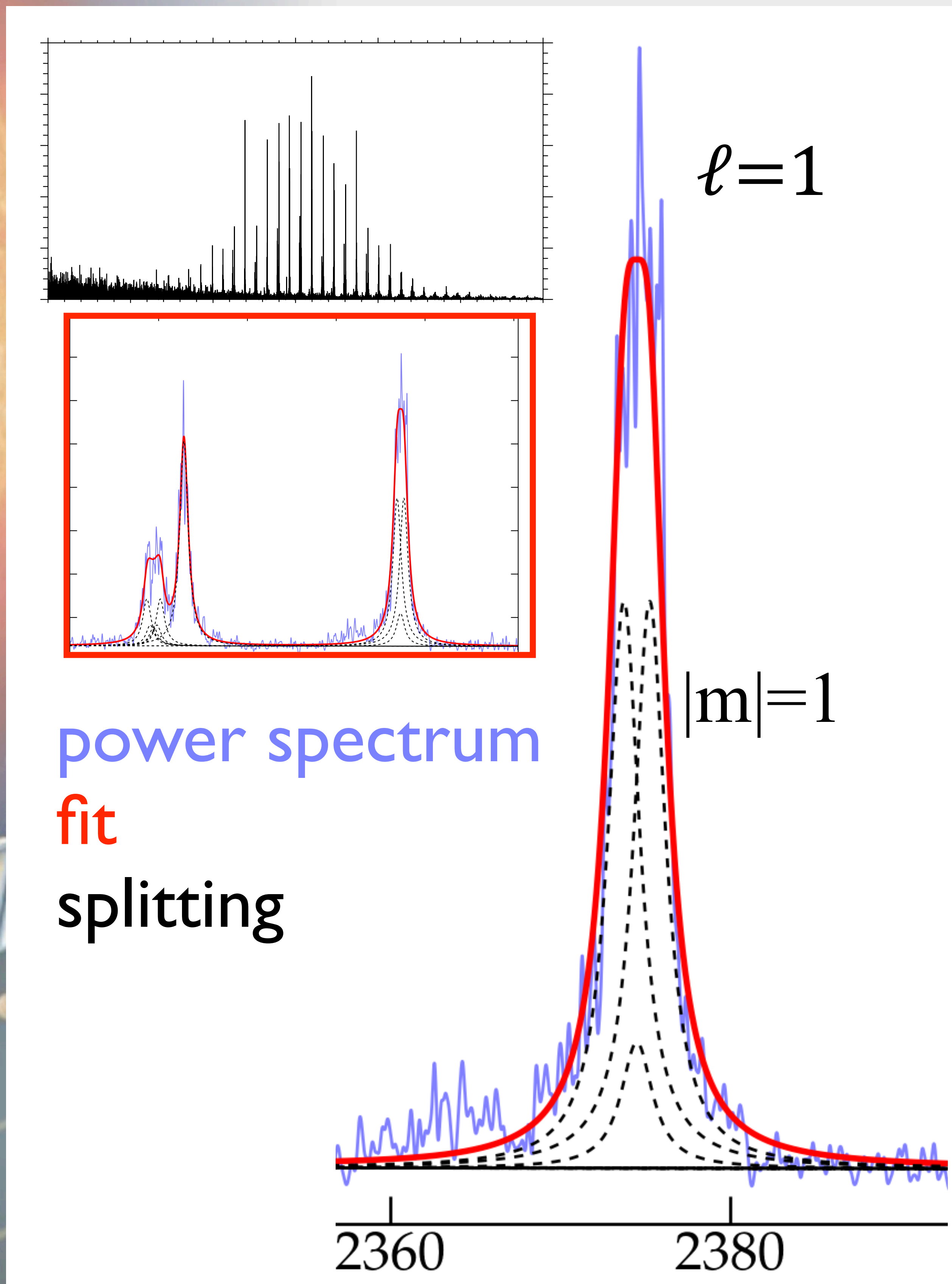
Tool: Asteroseismology



- Measure rotational splittings of the modes

  m, azimuthal order: splittings
  n, radial order: depth sensitivity

Inversions for Interior Rotation

observed

uncertainty in observations

?

$$\delta\omega_i = \int_0^R K_i(r)\Omega(r)\mathrm{d}r + \sigma(\delta\omega_i)$$

from stellar models

Inversions for Interior Rotation

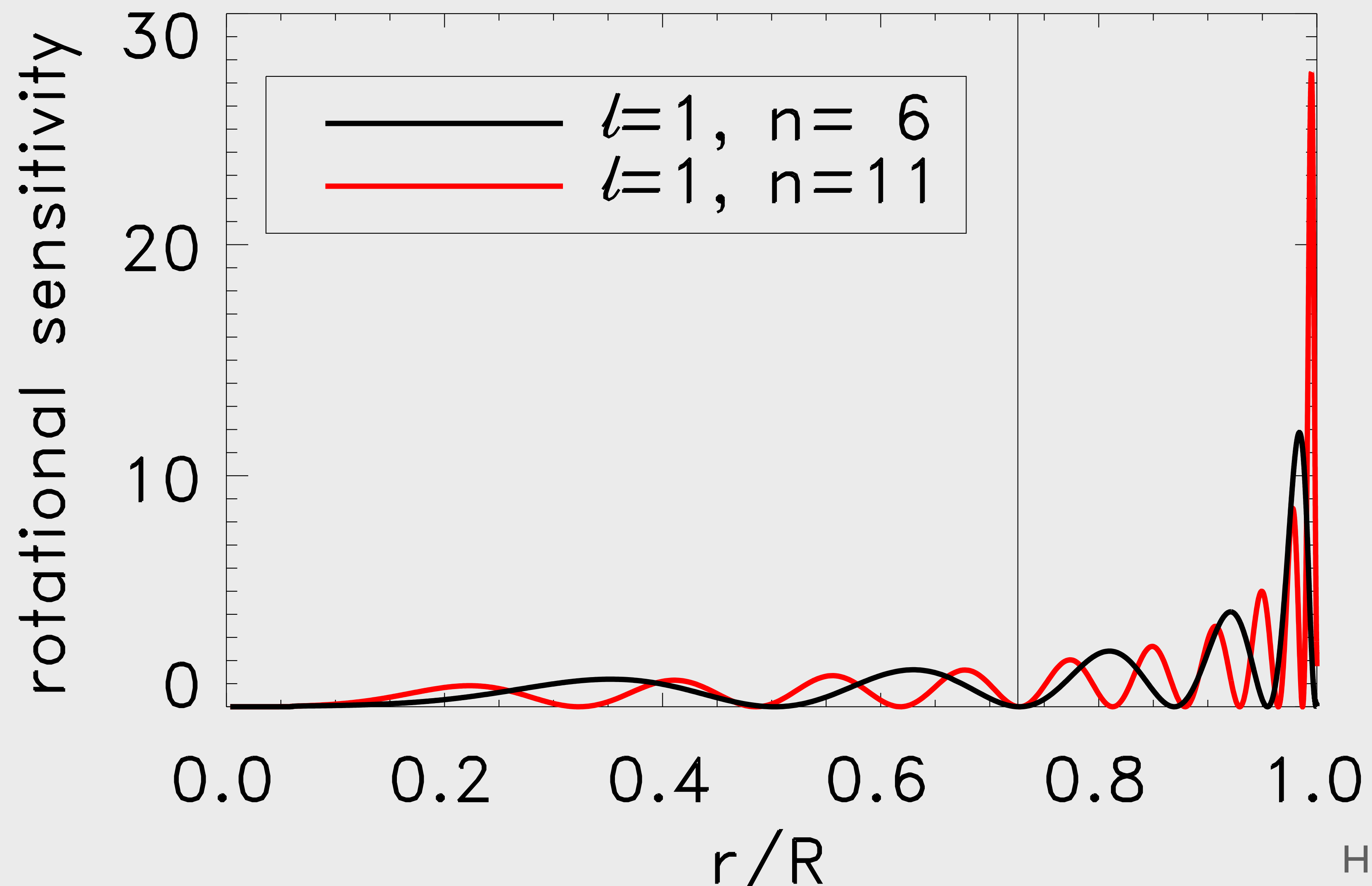
observed

uncertainty in observations

$$\delta\omega_i = \int_0^R K_i(r)\Omega(r)\mathrm{d}r + \sigma(\delta\omega_i)$$

?

from stellar models



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Inversions for Interior Rotation

observed

uncertainty in observations

$$\delta\omega_i = \int_0^R K_i(r)\Omega(r)\mathrm{d}r + \sigma(\delta\omega_i)$$

?

from stellar models

- To solve: Regularised Least Squares (RLS) inversions

Minimise

$$\sum_{i=1}^{M}\left[\delta\omega_i - \int_0^R \mathcal{K}_i(r)\overline{\Omega}(r)\mathrm{d}r\right]^2 + \text{smoothing}$$

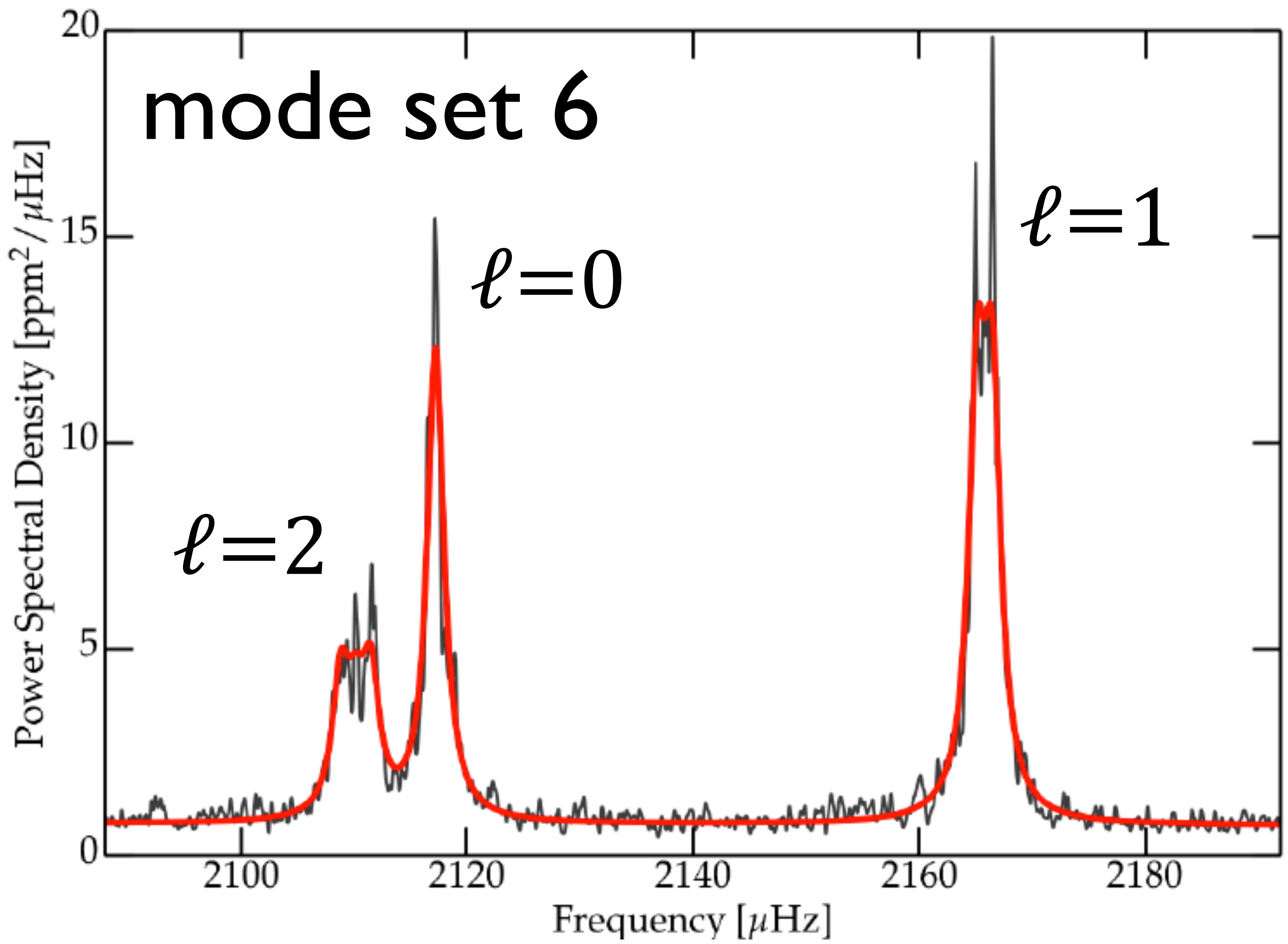
Rotation in Six Sun-like stars

- *Kepler* observed many stars suitable for asteroseismology over four years

- We identified six Sun-like stars with excellent power spectra and visible signs of rotation *Nielsen et al 2014*
  5600 K < T < 6100 K

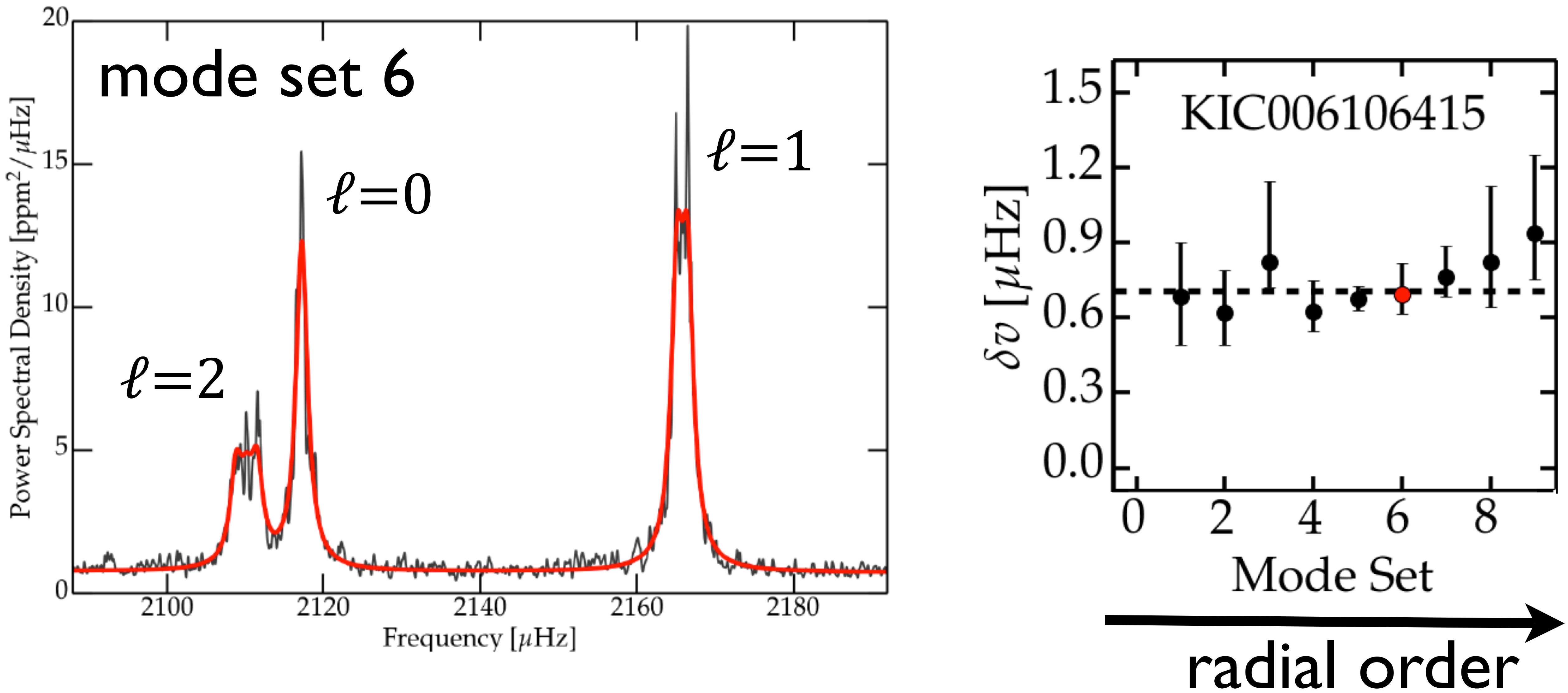
- Measured rotational splittings as a function of radial order, *n*

Rotation in Six Sun-like stars



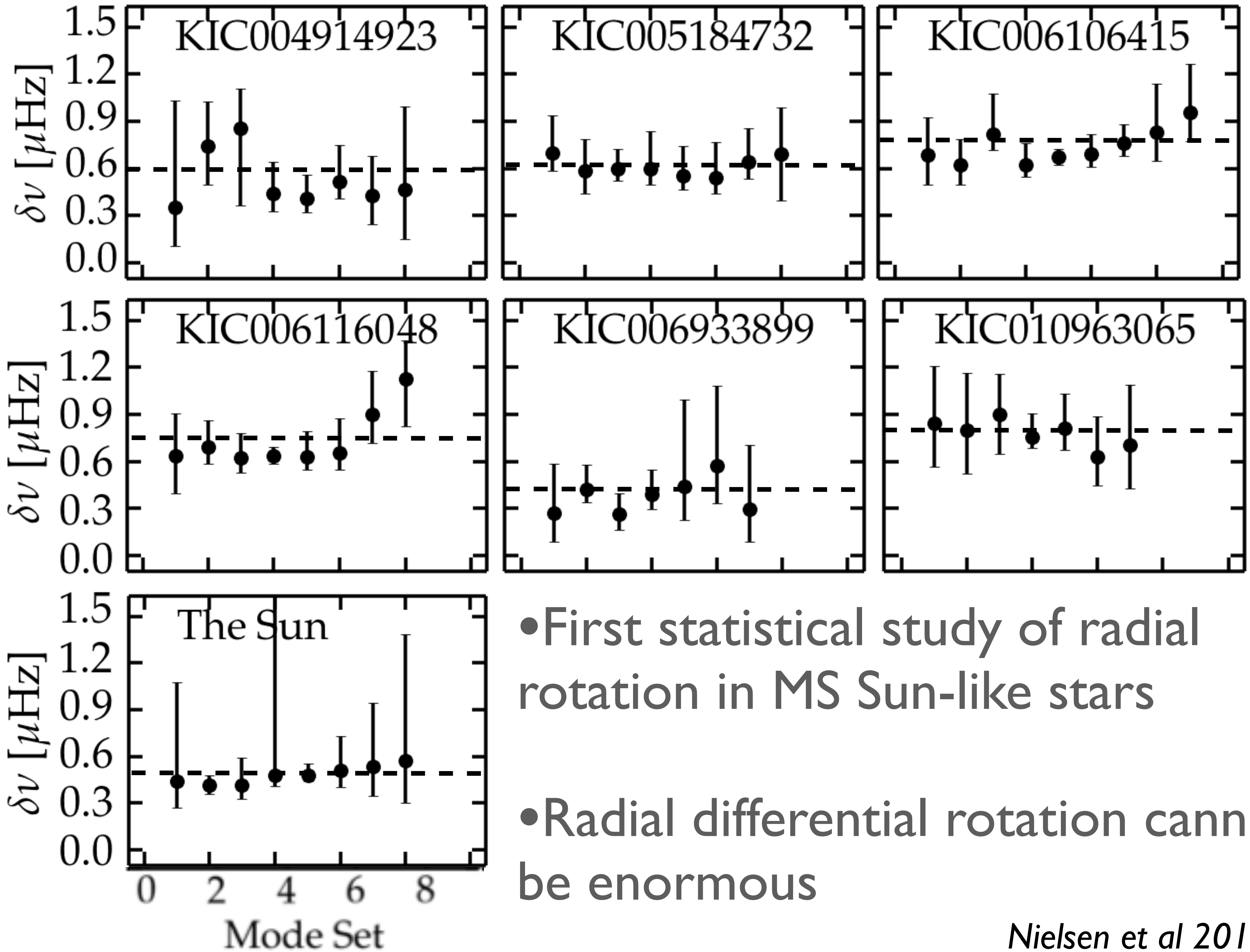
Nielsen et al 2014

Rotation in Six Sun-like stars



Nielsen et al 2014

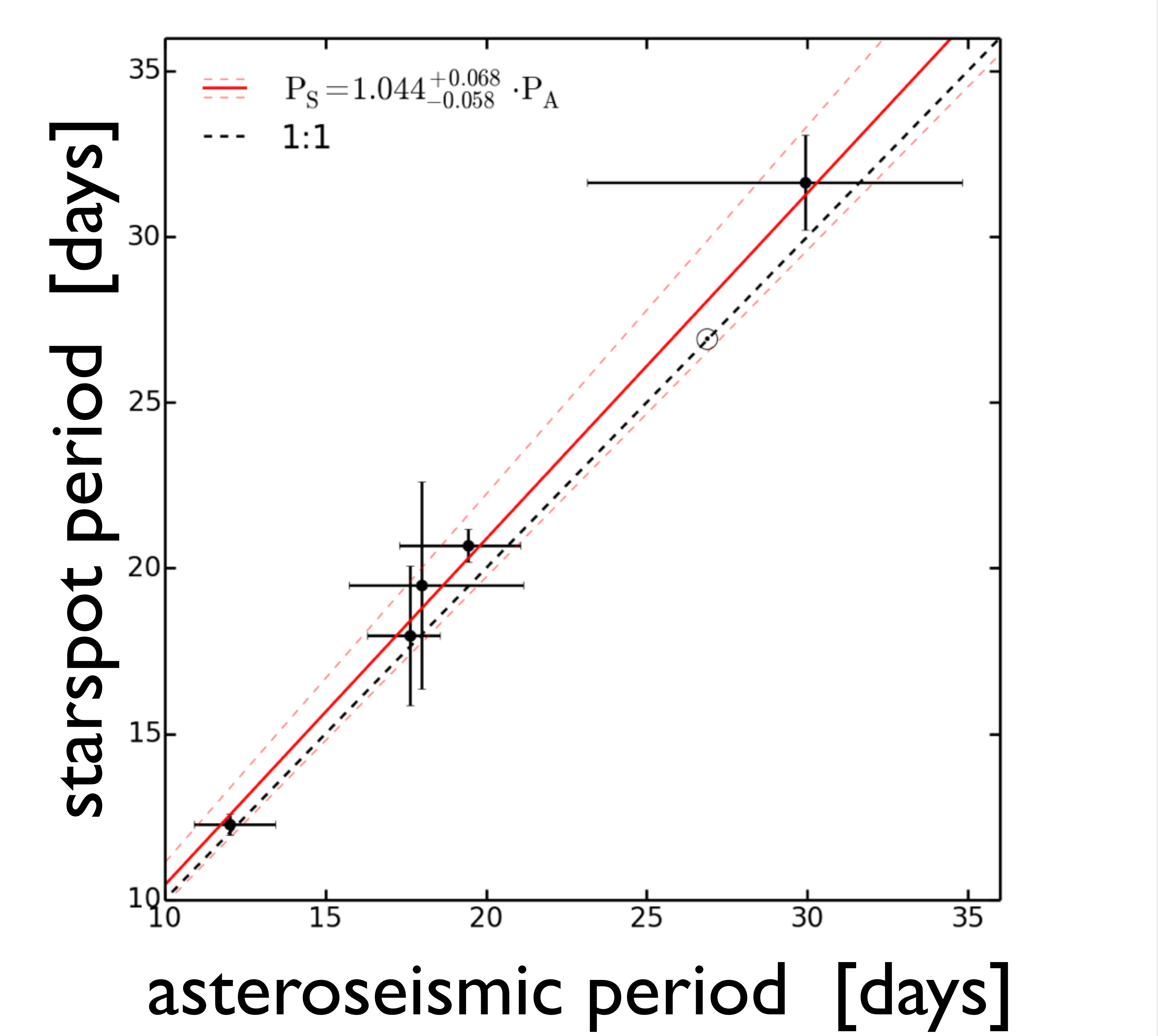
Rotation in Six Sun-like stars



- First statistical study of radial rotation in MS Sun-like stars
- Radial differential rotation cannot be enormous

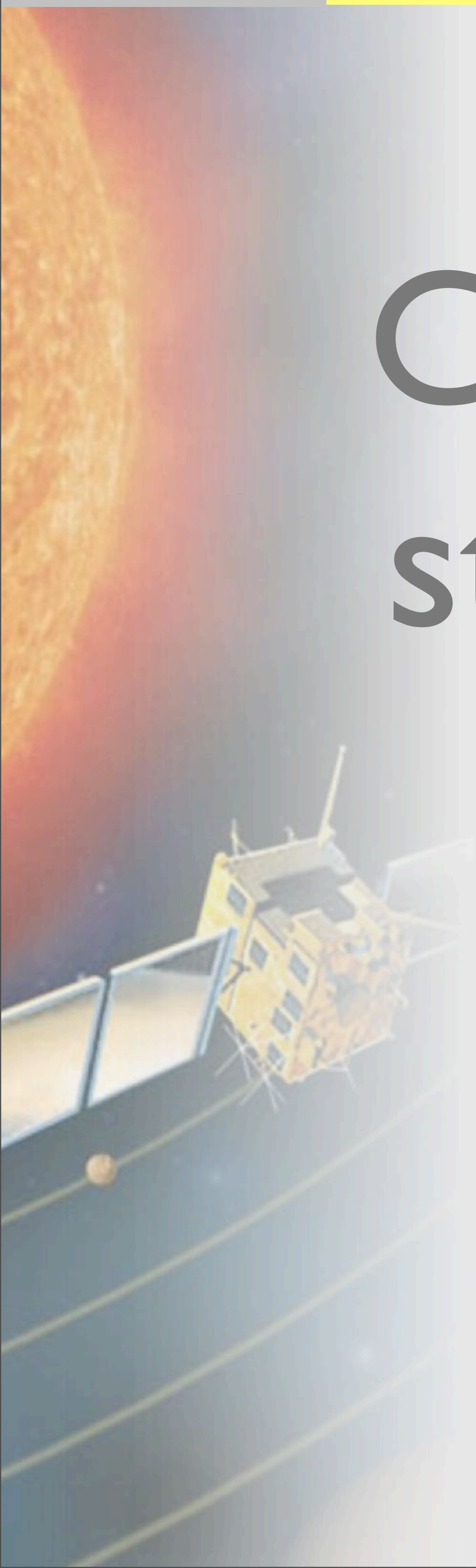
Nielsen et al 2014

Rotation in Six Sun-like stars



See Martin Bo Nielsen's poster

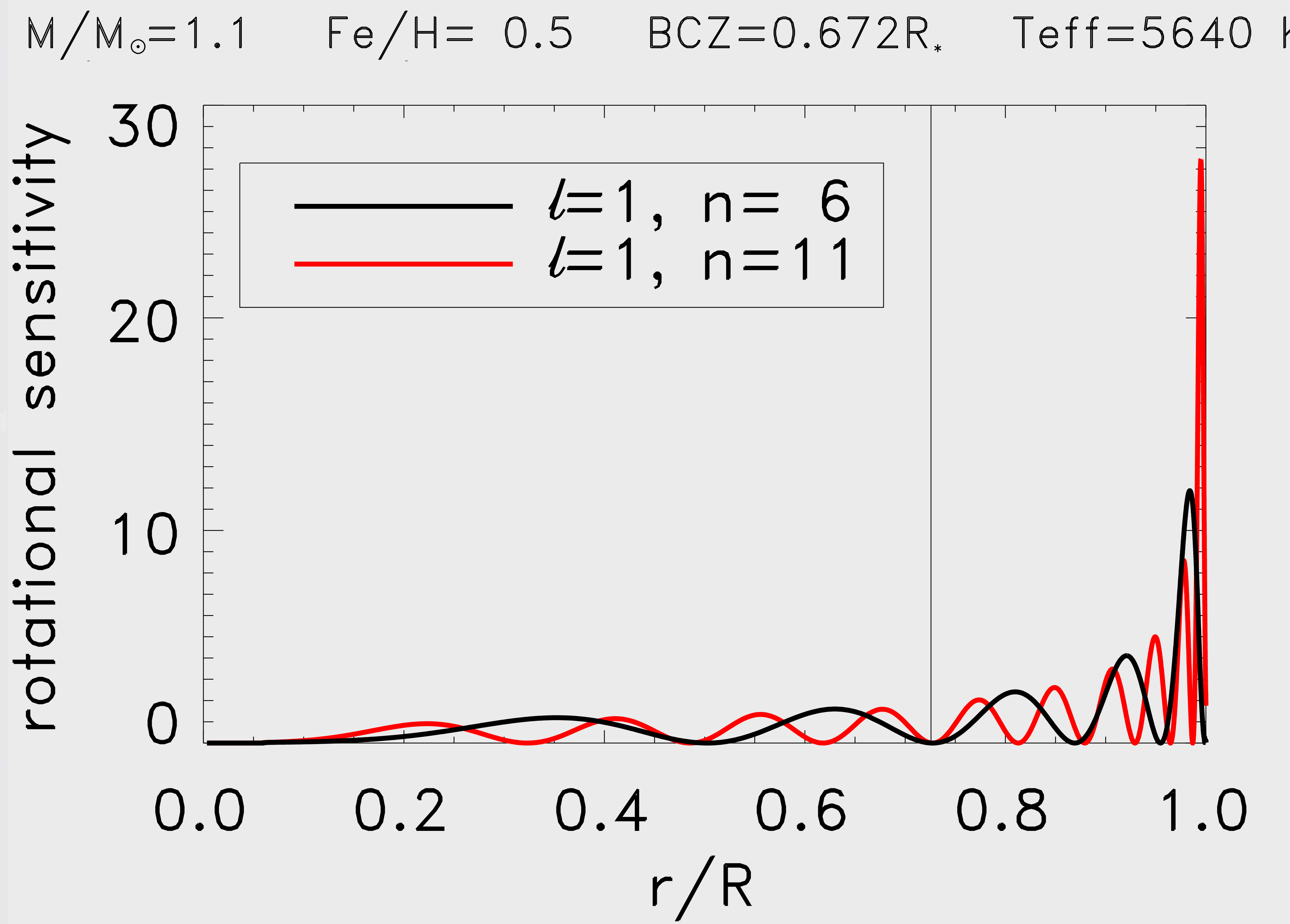
Nielsen et al, submitted



Can we invert for these stars and extract useful information?

Radial Differential Rotation of Sun-like Star

- Stellar model of main sequence Sun-like star



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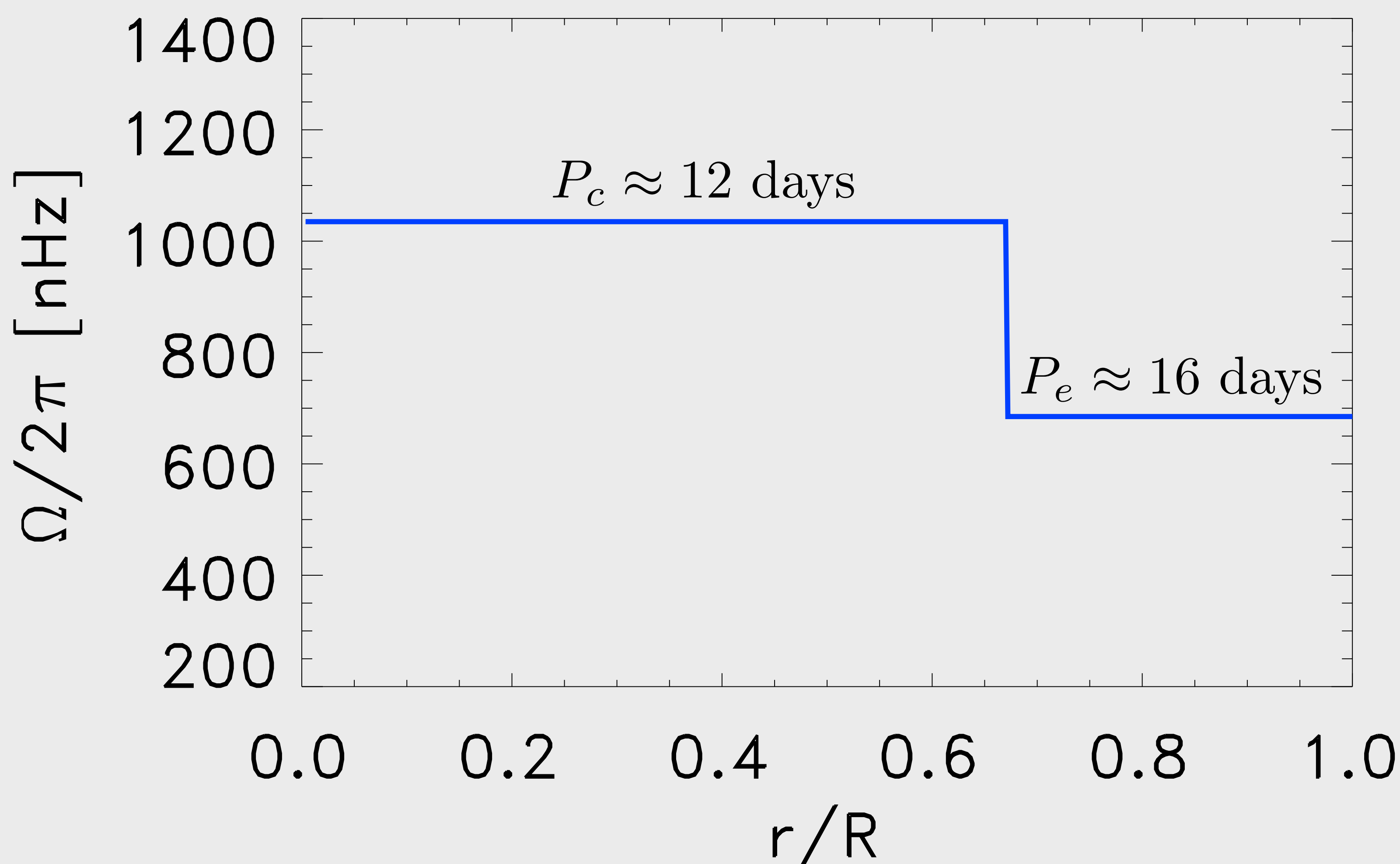
Radial Differential Rotation of Sun-like Star

- Synthetic rotation profile



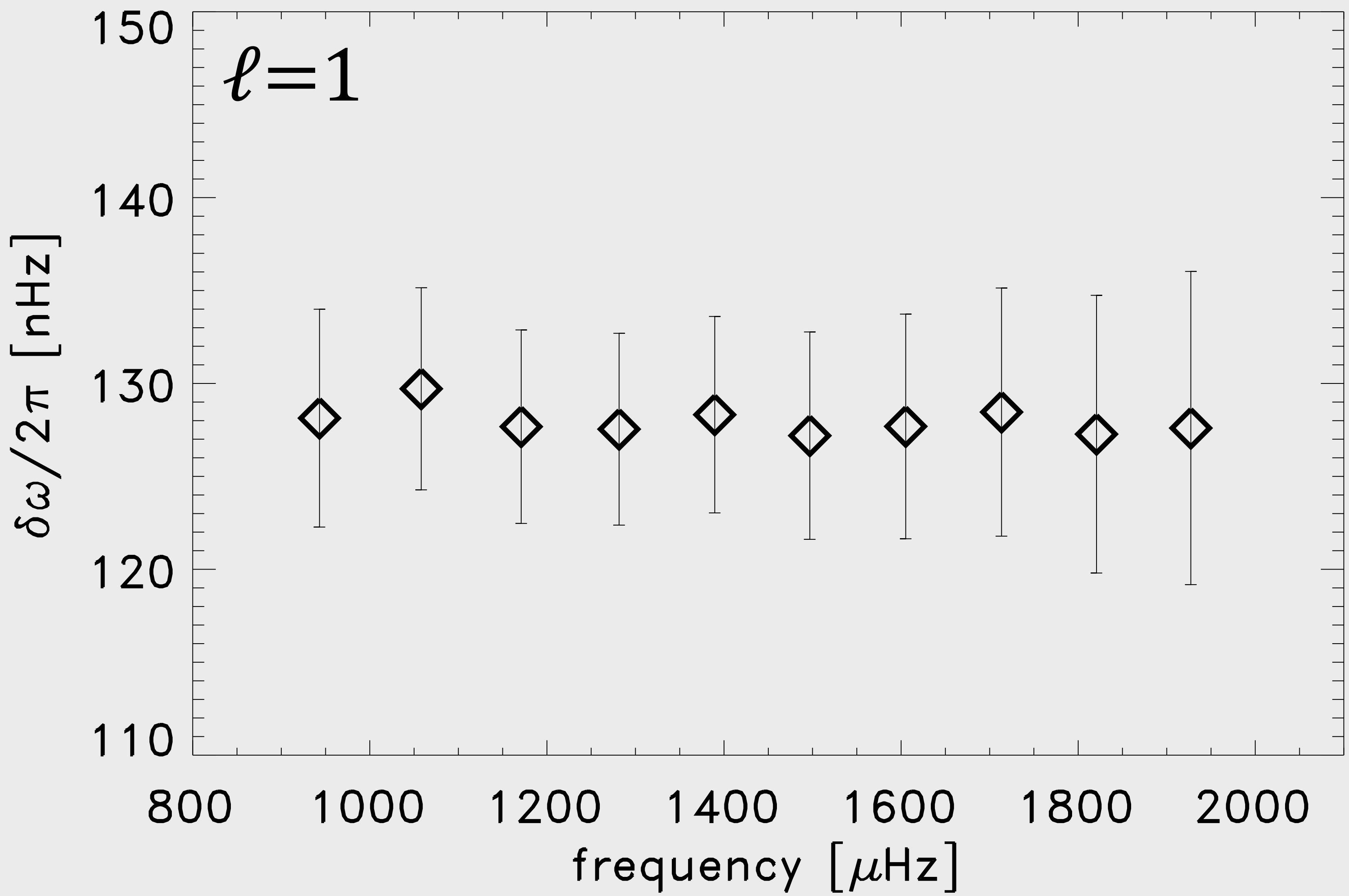
- Rotational splittings

$$\delta\omega_i = \int_0^R K_i(r)\Omega(r)\mathrm{d}r + \sigma(\delta\omega_i)$$

Radial Differential Rotation of Sun-like Star

- Uncertainties on the splittings based on scaling relations from Sun

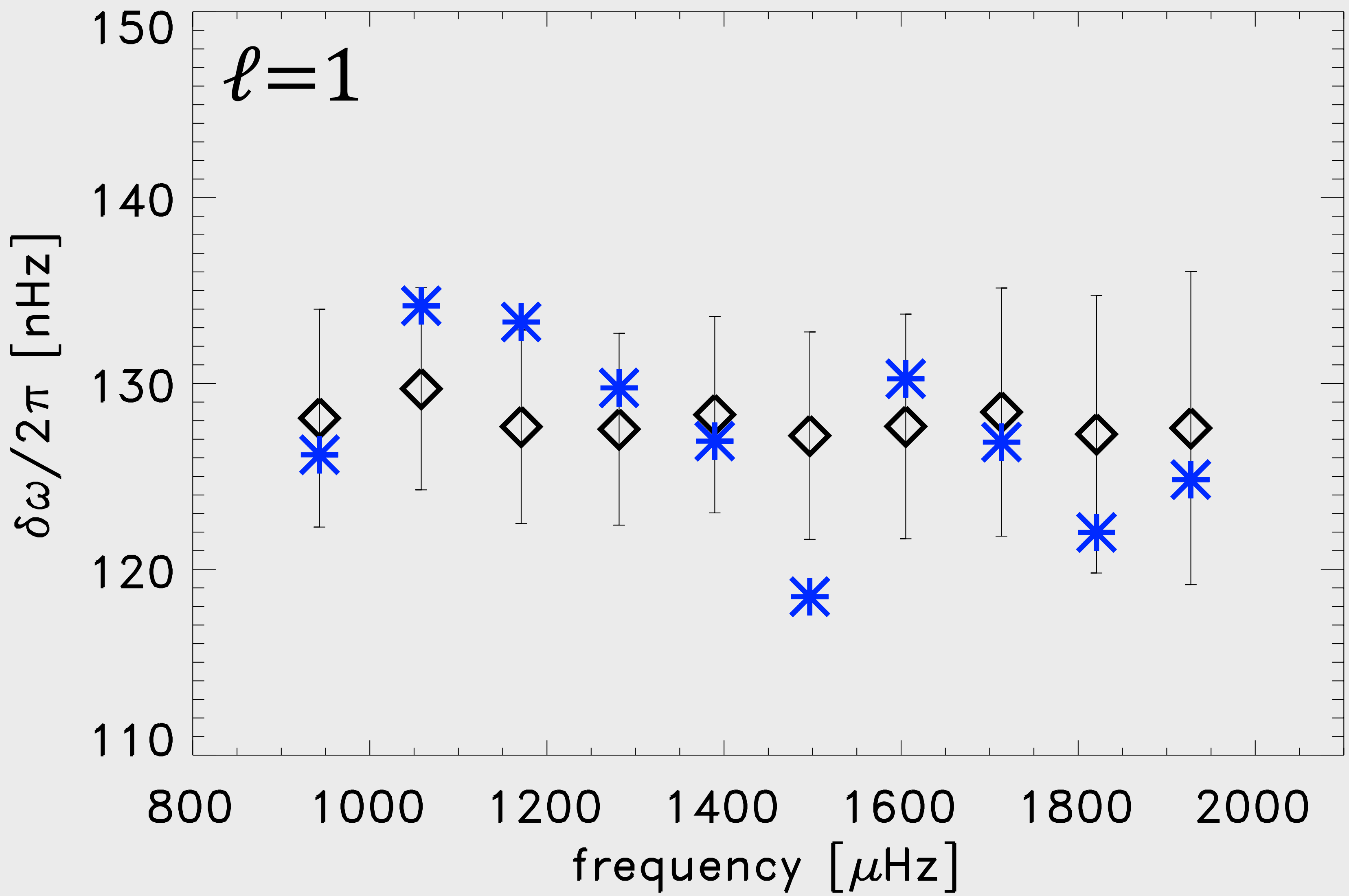
$$\sigma(\omega) = \sqrt{\frac{\Gamma}{4\pi T}} \longrightarrow \sigma(\delta\omega) = \frac{\sigma(\omega)}{\sqrt{1/3\ell(\ell+1)}}$$



Radial Differential Rotation of Sun-like Star

- Uncertainties on the splittings based on scaling from solar temperature

$$\sigma(\omega) = \sqrt{\frac{\Gamma}{4\pi T}} \longrightarrow \sigma(\delta\omega) = \frac{\sigma(\omega)}{\sqrt{1/3\ell(\ell+1)}}$$



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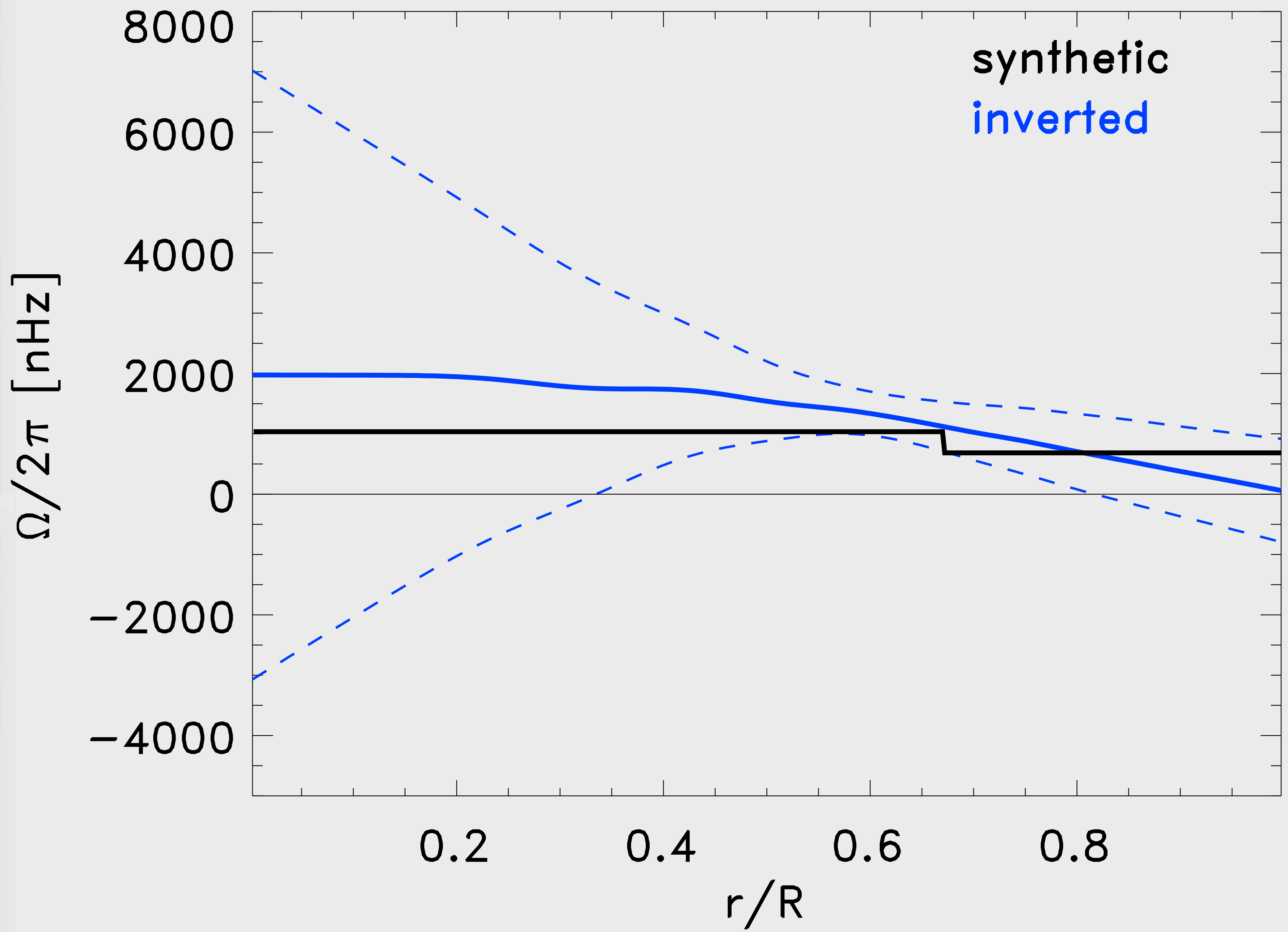
Radial Differential Rotation of Sun-like Star

- Stellar model of Sun-like star (kernels)
- Synthetic rotation profile
- Rotational splittings
  + uncertainties on the splittings
- Inversion

Radial Differential Rotation of Sun-like Star



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Ensemble Inversions

- PLATO will be launched in 2024
  PLAnetary Transits and Oscillations of stars
- Observe many more stars than *Kepler*
- Two long duration observations ~3 years long
- Assume that rotation is similar

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Ensemble Inversions

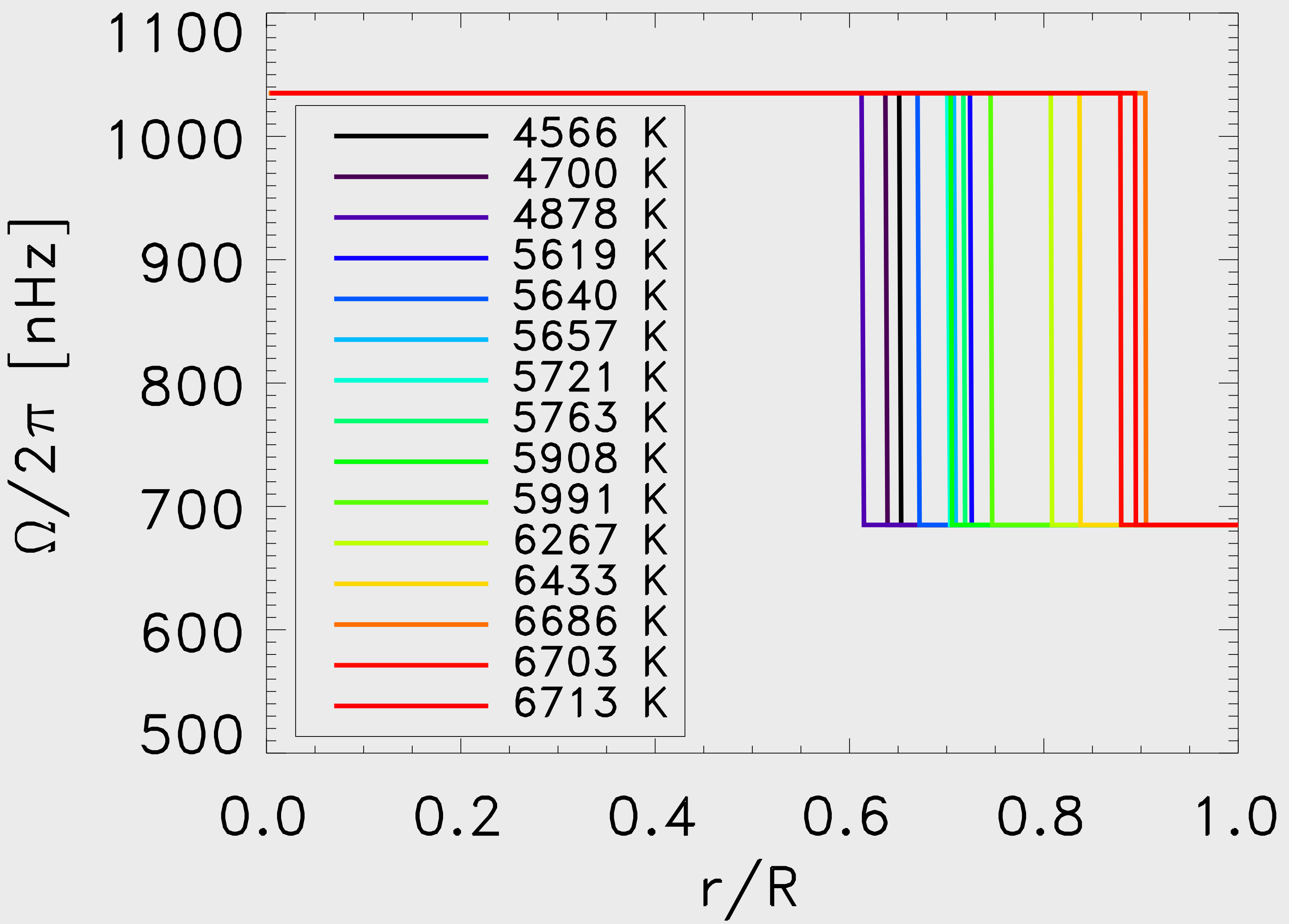
- Fifteen main sequence stellar models ranging from F to K type

$M/M_\odot=0.8$	$Fe/H=\ 0.5$	$BCZ=0.653R_*$	$T_{eff}=4566$ K	K
$M/M_\odot=0.8$	$Fe/H=\ 0.5$	$BCZ=0.639R_*$	$T_{eff}=4700$ K	
$M/M_\odot=0.8$	$Fe/H=\ 0.5$	$BCZ=0.615R_*$	$T_{eff}=4878$ K	
$M/M_\odot=0.8$	$Fe/H=-0.5$	$BCZ=0.726R_*$	$T_{eff}=5619$ K	G
$M/M_\odot=1.1$	$Fe/H=\ 0.5$	$BCZ=0.672R_*$	$T_{eff}=5640$ K	
$M/M_\odot=1.1$	$Fe/H=\ 0.5$	$BCZ=0.709R_*$	$T_{eff}=5657$ K	
$M/M_\odot=1.1$	$Fe/H=\ 0.5$	$BCZ=0.704R_*$	$T_{eff}=5721$ K	
$M/M_\odot=0.8$	$Fe/H=-0.5$	$BCZ=0.719R_*$	$T_{eff}=5763$ K	
$M/M_\odot=0.8$	$Fe/H=-0.5$	$BCZ=0.706R_*$	$T_{eff}=5908$ K	
$M/M_\odot=1.4$	$Fe/H=\ 0.5$	$BCZ=0.747R_*$	$T_{eff}=5991$ K	
$M/M_\odot=1.4$	$Fe/H=\ 0.5$	$BCZ=0.808R_*$	$T_{eff}=6267$ K	F
$M/M_\odot=1.4$	$Fe/H=\ 0.5$	$BCZ=0.838R_*$	$T_{eff}=6433$ K	
$M/M_\odot=1.1$	$Fe/H=-0.5$	$BCZ=0.905R_*$	$T_{eff}=6686$ K	
$M/M_\odot=1.1$	$Fe/H=-0.5$	$BCZ=0.880R_*$	$T_{eff}=6703$ K	
$M/M_\odot=1.1$	$Fe/H=-0.5$	$BCZ=0.895R_*$	$T_{eff}=6713$ K	

Ensemble Inversions

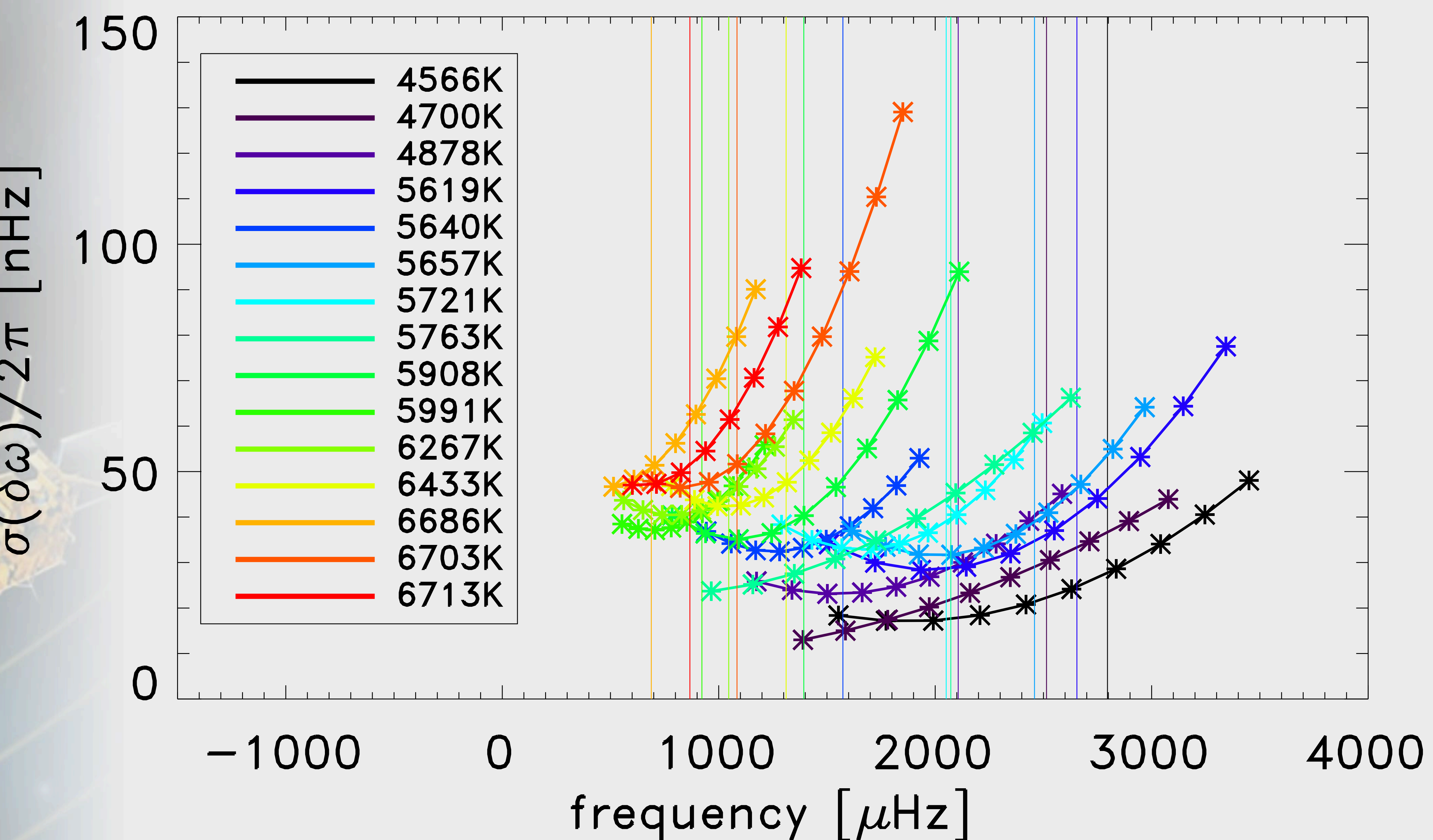
- Synthetic rotation rates
  - identical rotation rates
  - discontinuity at the BCZ

  --> rotational splittings



Ensemble Inversions

- Uncertainties for 3 year long observations



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Ensemble Inversions

all observed splittings

average rotation

all uncertanties

$$\delta\omega_i = \int_0^R K_i(r)\Omega(r)\mathrm{d}r + \sigma(\delta\omega_i)$$

all the stellar models

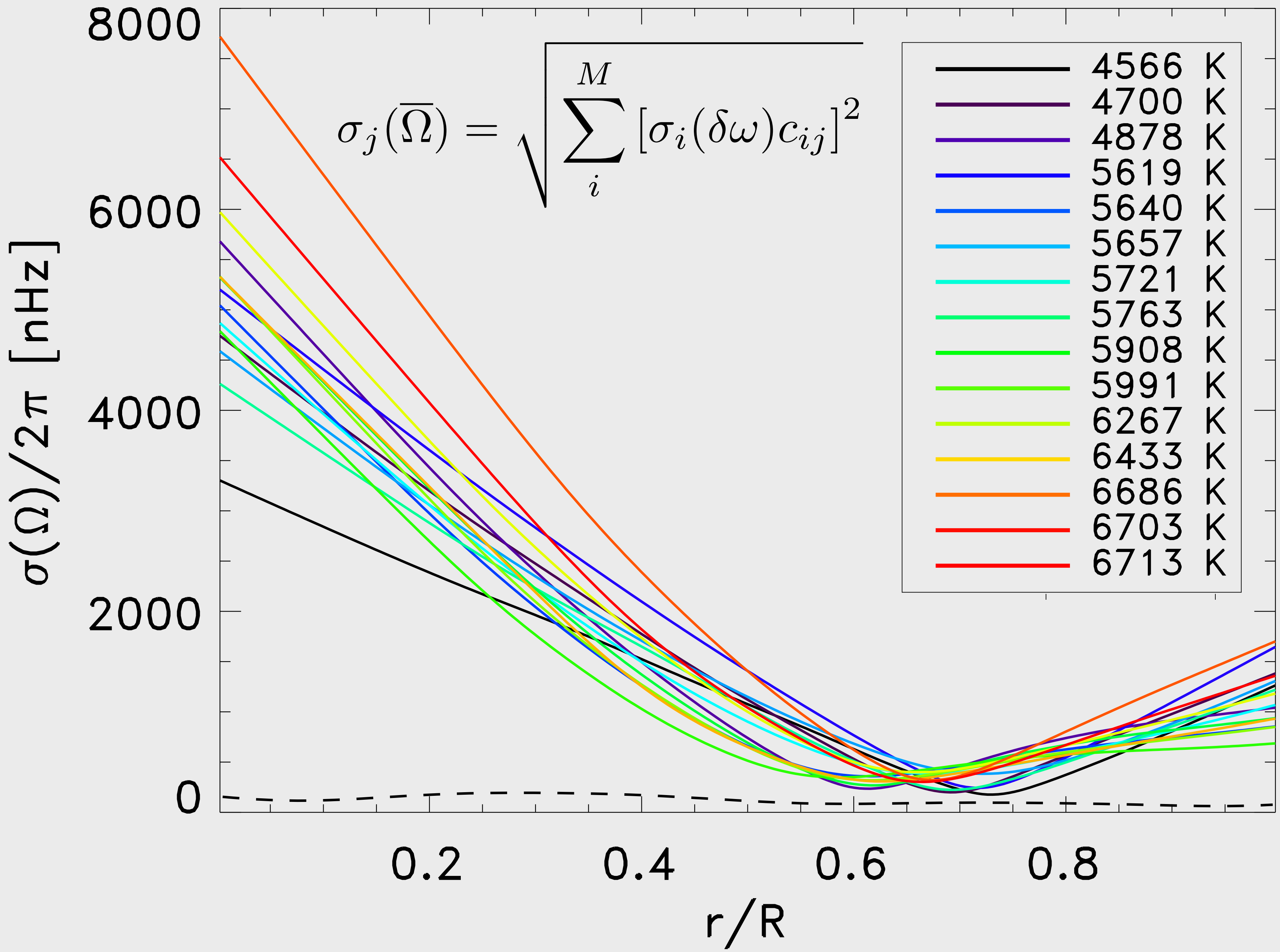
RLS Inversion

$$\sum_{i=1}^{M}\left[\delta\omega_i - \int_0^R \mathcal{K}_i(r)\overline{\Omega}(r)\mathrm{d}r\right]^2 + \mathrm{smoothing}$$

Ensemble Inversions

- Fifteen stellar models ranging from F to K type
- Synthetic rotation rates
  - identical rotation rates
  - discontinuity at the BCZ
- Rotational splittings
- Uncertainties for 3 year long observations
- Inversion for the average rotation profile
  -- do the uncertainties decrease?

Ensemble Inversions



Uncertainties

-- similar for all stars regardless of type

-- decrease with √N

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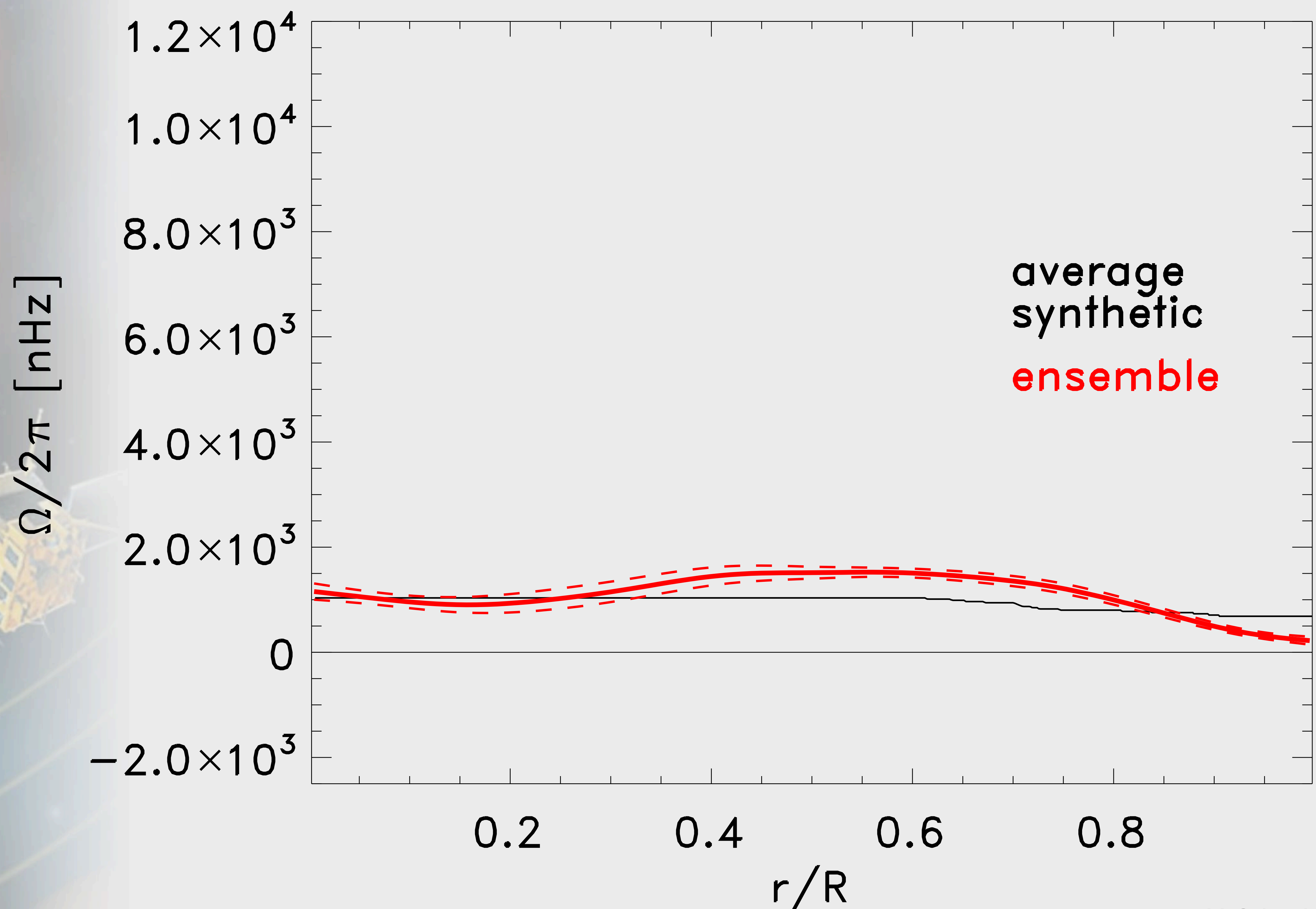
Ensemble Inversions



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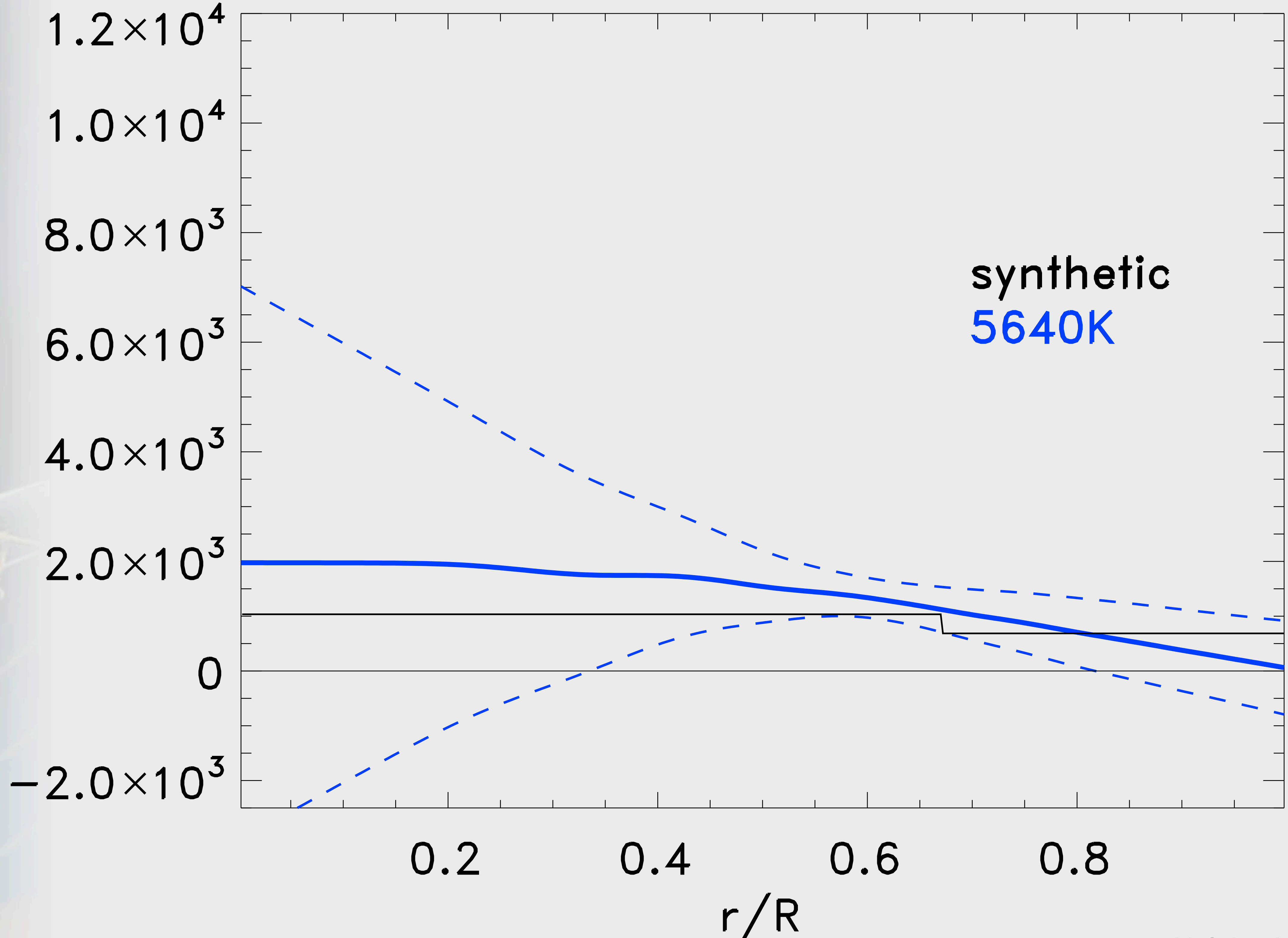
Ensemble Inversions



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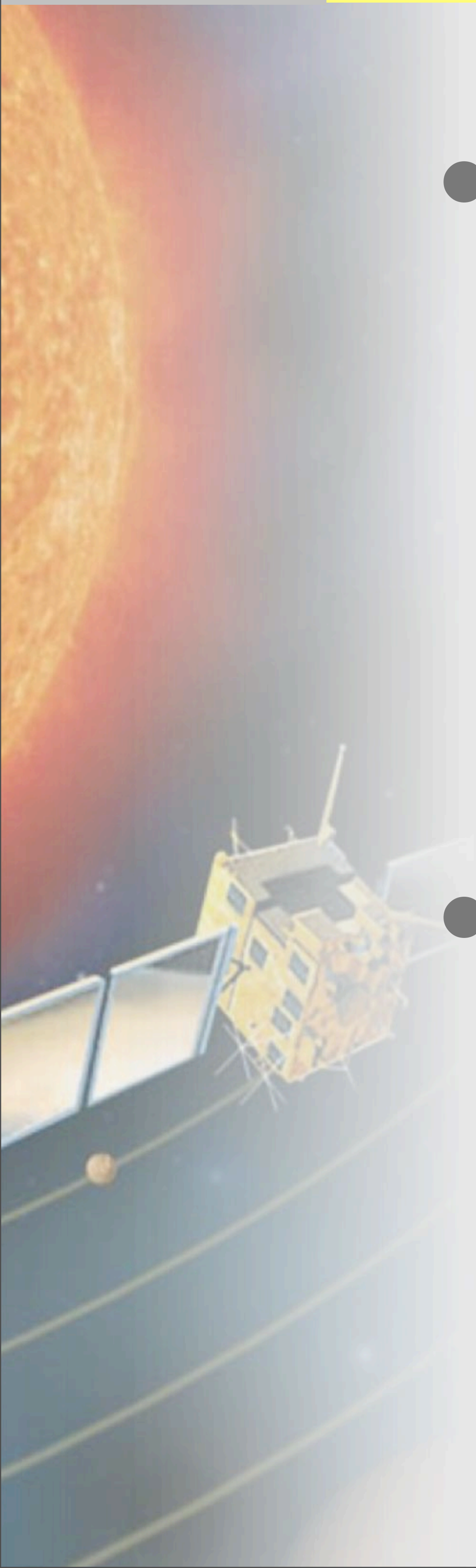
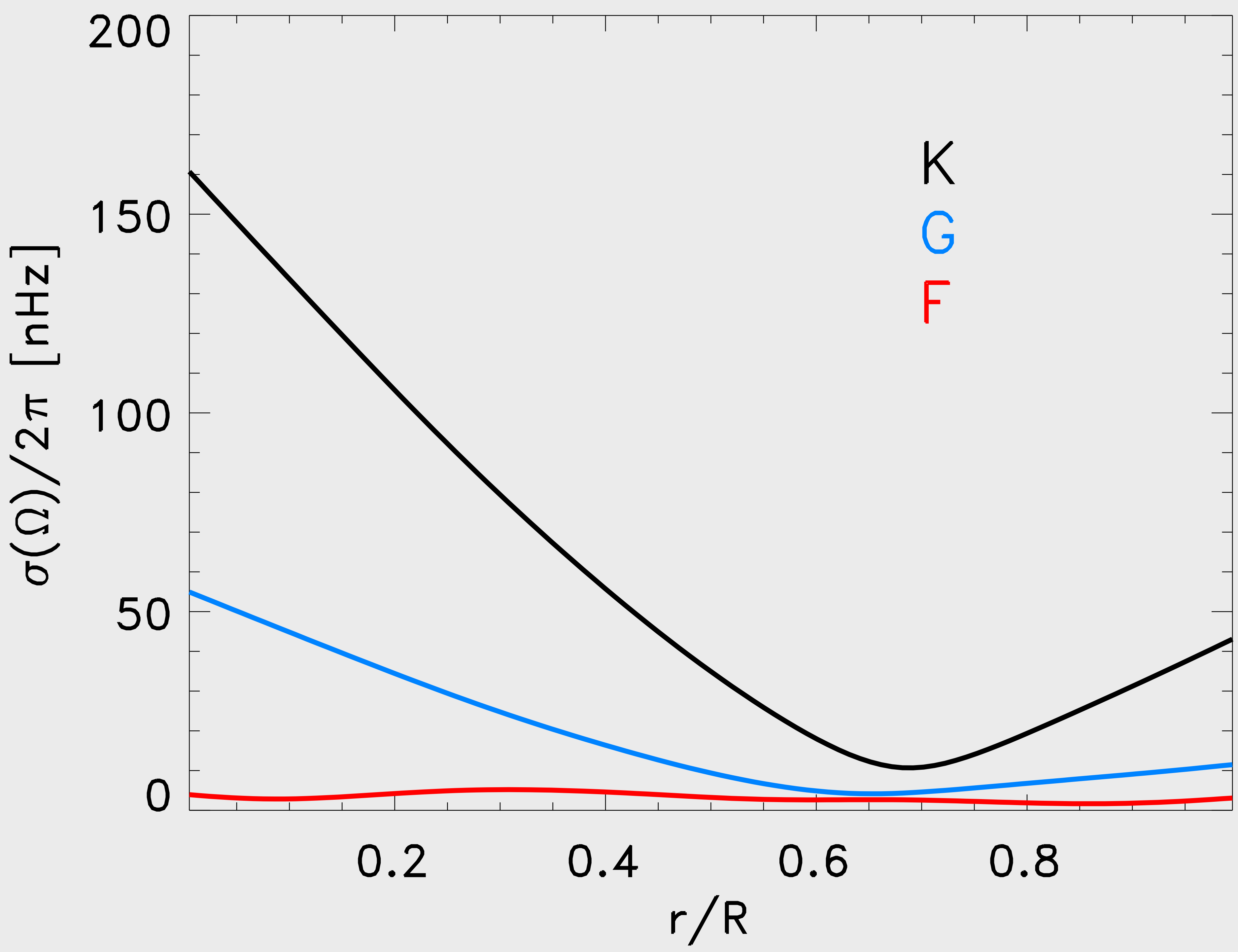


PLATO

- Long Observation Fields: 2-3 years
  2,700 stars F5 to K7 type
  mv < 8
  50 sec cadence
  34 ppm/h

- 65% (1800) F dwarfs,
  30% (800) G dwarfs,
  5% (100) K dwarfs
  logg > 3.5 and Teff < 6510 K

Rotation vs Stellar Type



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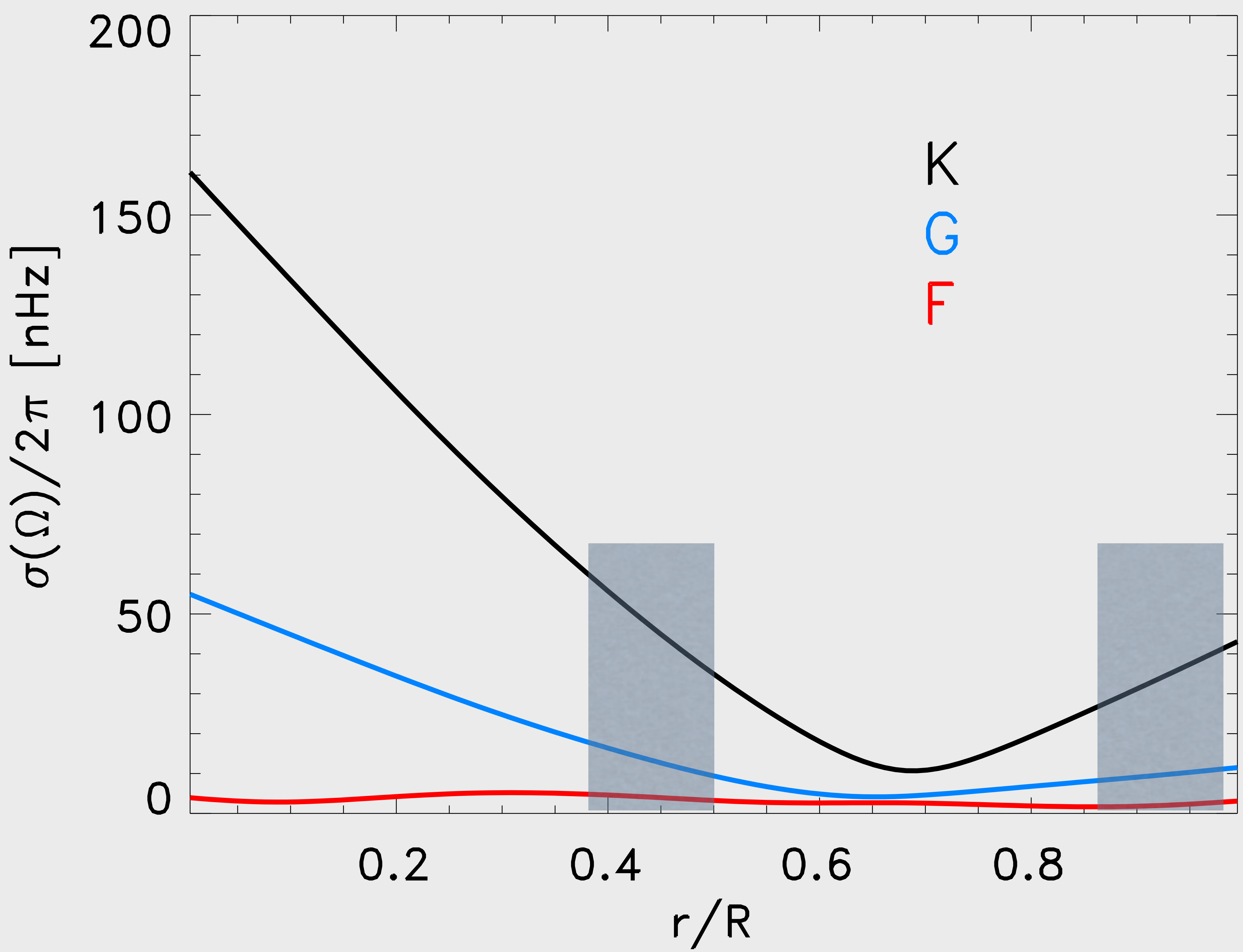
Rotation vs Stellar Type



Detect a minimum rotational difference of ~100 nHz

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Outlook

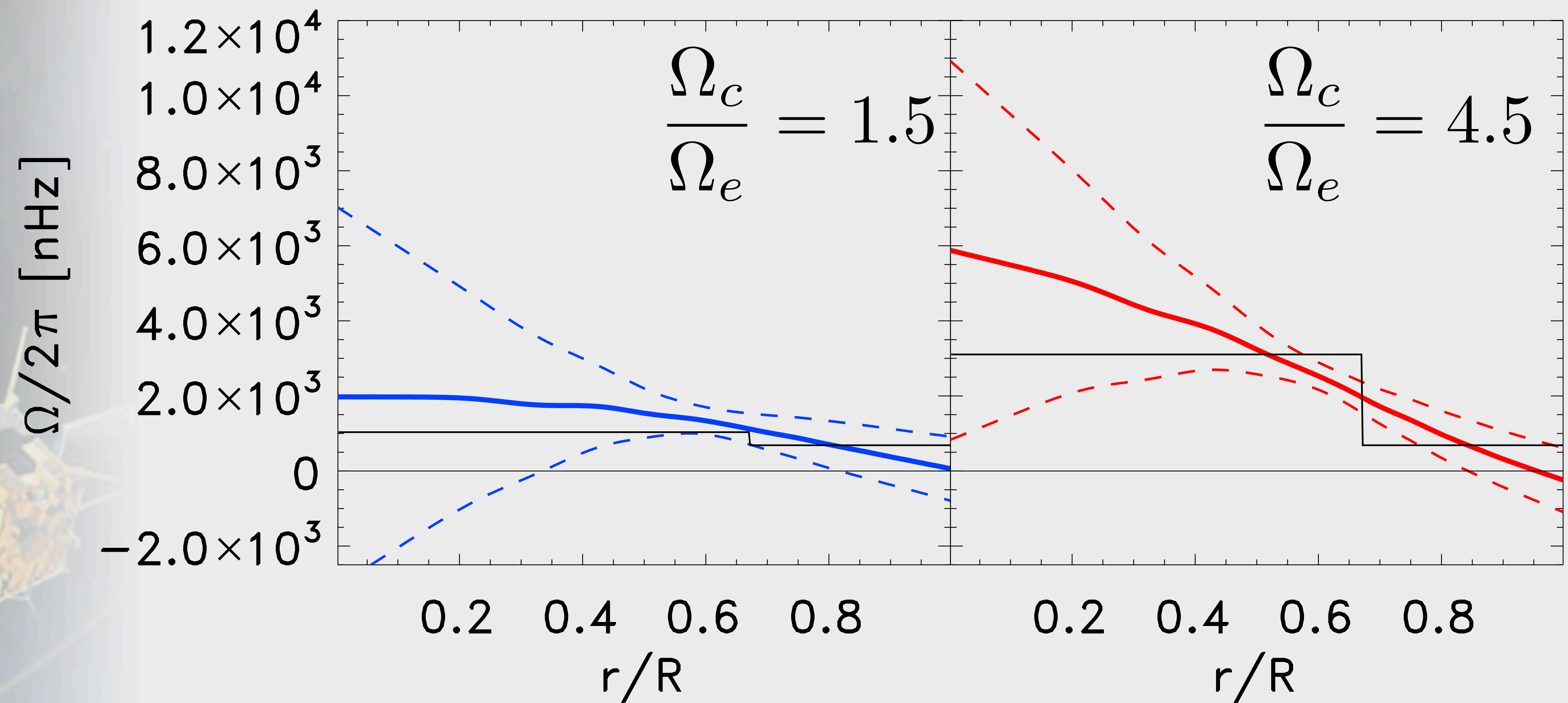
- PLATO will observe 1000s of bright Sun-like stars
- Ensemble inversions: reduced uncertainties
- Differentiate between rotation of F, G, K type of stars
- Different inversion method?
- Comparison between starspot and seismic rotation periods may reveal more about
  - the depth sensitivity of starspots
  - latitudinal differential rotation

Radial Differential Rotation of Sun-like Star

- Increase the core rotation rate x3

$$\Omega_c \approx 6\Omega_\odot$$

$$P_c \approx 4 \text{ days}$$



- Detect a rotational difference of ~2000 nHz