LOW-DEGREE & LOW-ORDER GLOBAL SEISMOLOGY:

FOR THE SUN & STARS

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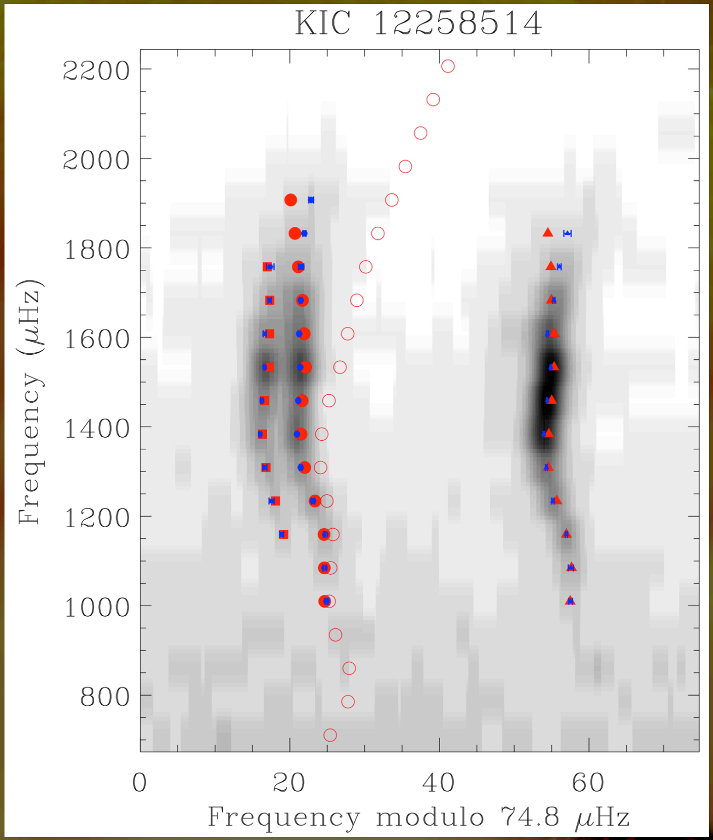
INTRODUCTION

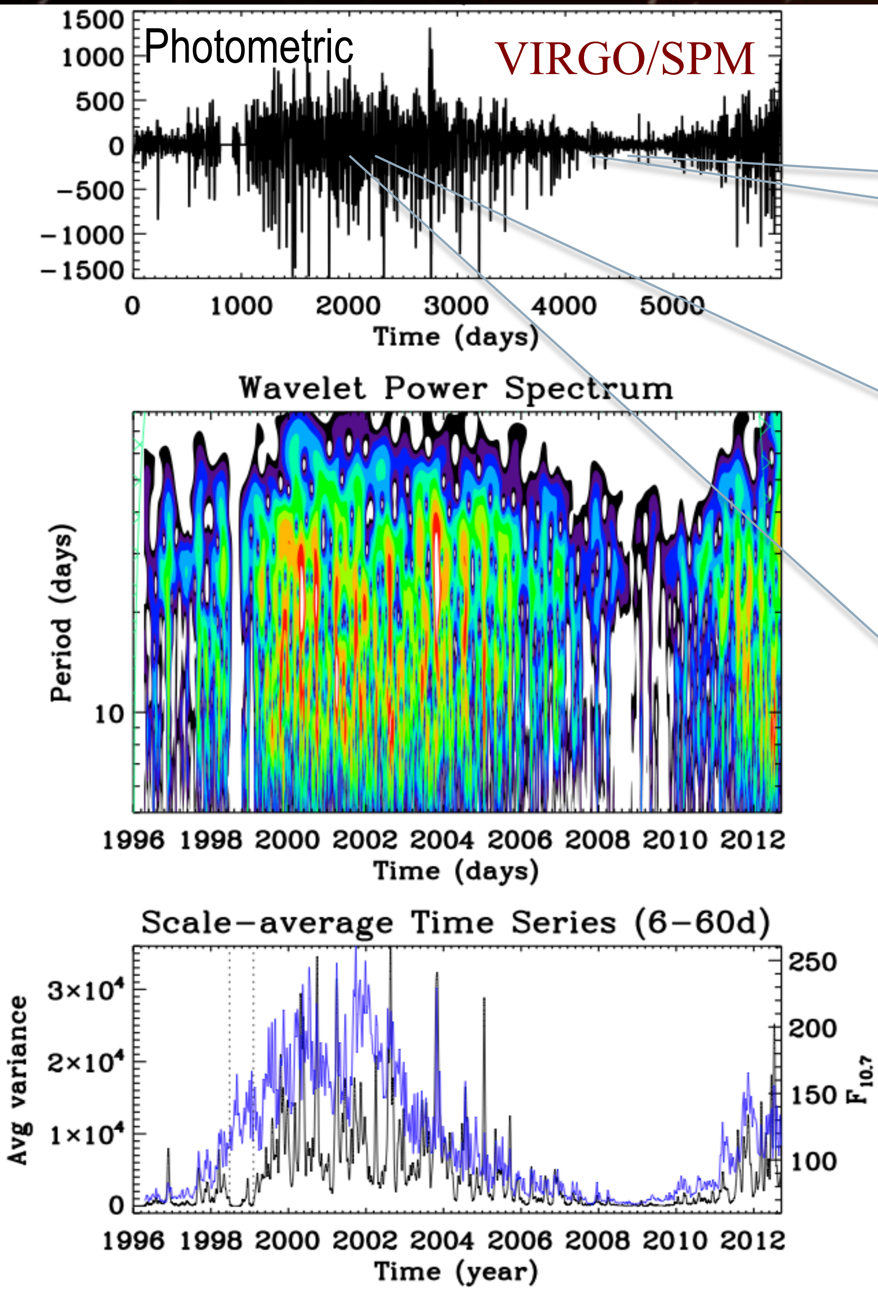
- Low-degree low-order p modes
  - Smaller line widths
    - Better precision
  - Deeper external turning points
    - Less affected by
      - surface magnetism
      - surface effects
  - In asteroseismology:
    - Help defining surface-effect corrections

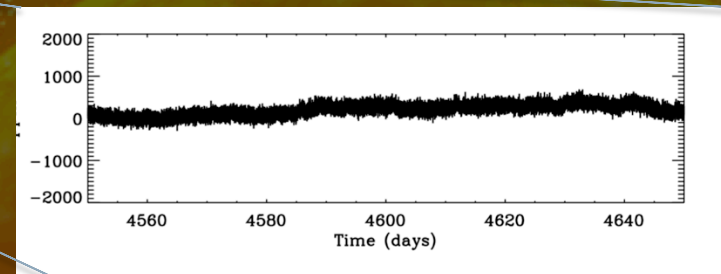


Metcalfe et al. 2014,
Freqs from Appourchaux et al. 2012

I.- Solar and Stellar Magnetism

I-PHOTOSPHERIC MAGNETIC ACTIVITY PROXY

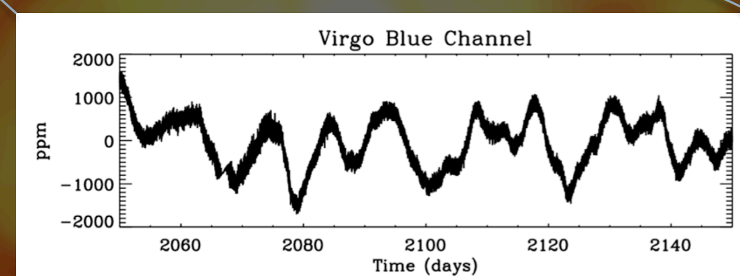




- The Scale Average time series

  and

- the variance of the light curve, $S_{ph}(t)$ are
  - Good proxies of the surface magnetic activity

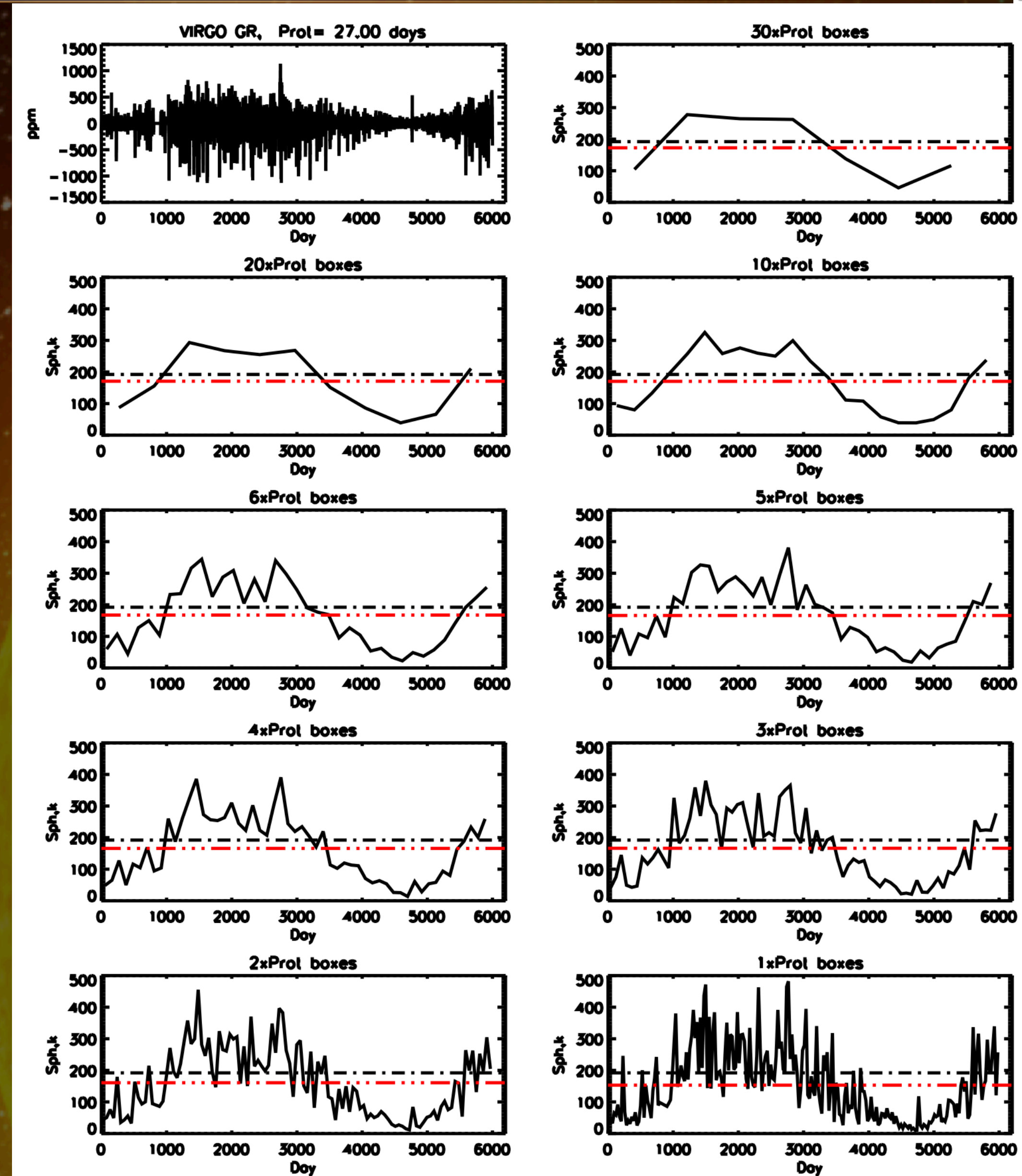


[García, Salabert, Mathur et al. 2013]

I-PHOTOSPHERIC MAGNETIC ACTIVITY PROXY

- To properly compute a magnetic proxy:
    - S_{ph} (t)
        - It is important to Take into account
            - P_{rot}

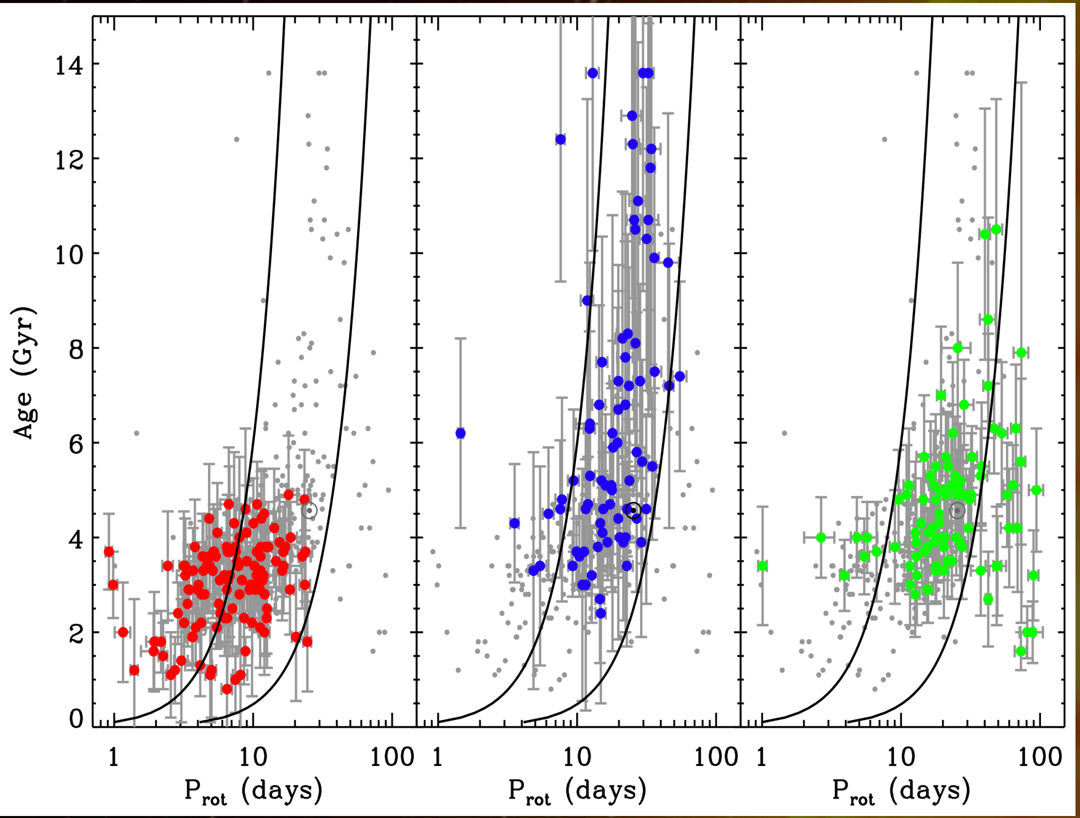
- GOLF & VIRGO/SPM Proxies
    - Will be available
    - Since the beginning of the mission
        - SPACEINN portal:
            - http://www.spaceinn.eu

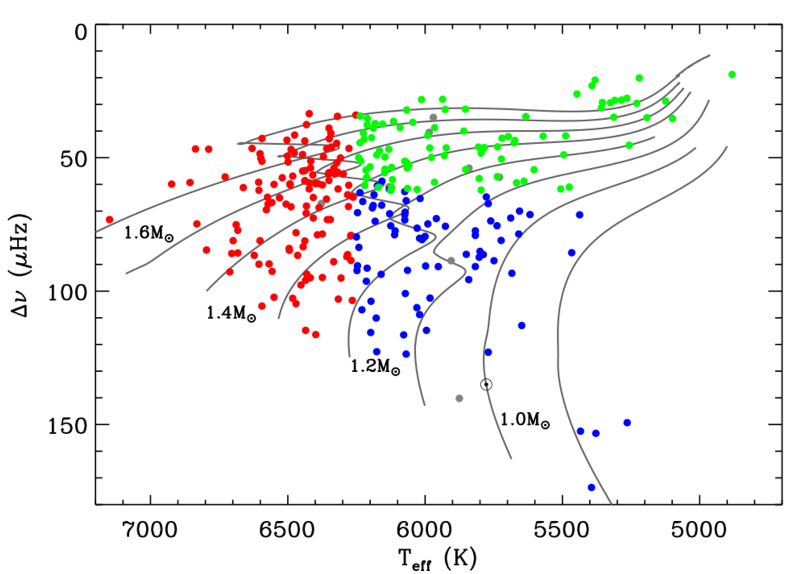


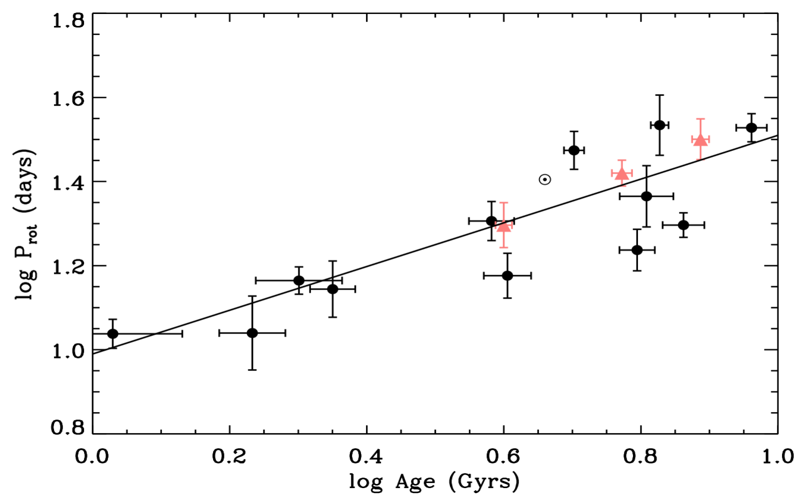
[Mathur , Salabert, García & Ceillier, JSW&SC, 2014]

I-P_{ROT} PULSATING *KEPLER* S-L STARS

- Sample of 540 pulsating *Kepler* S-L stars
  - P_{rot} measured in 310 stars [Chaplin et al. 2014]
- Towards asteroseismically calibrated age-rotation relations. Gyrochronology of field stars
  - Biased sample







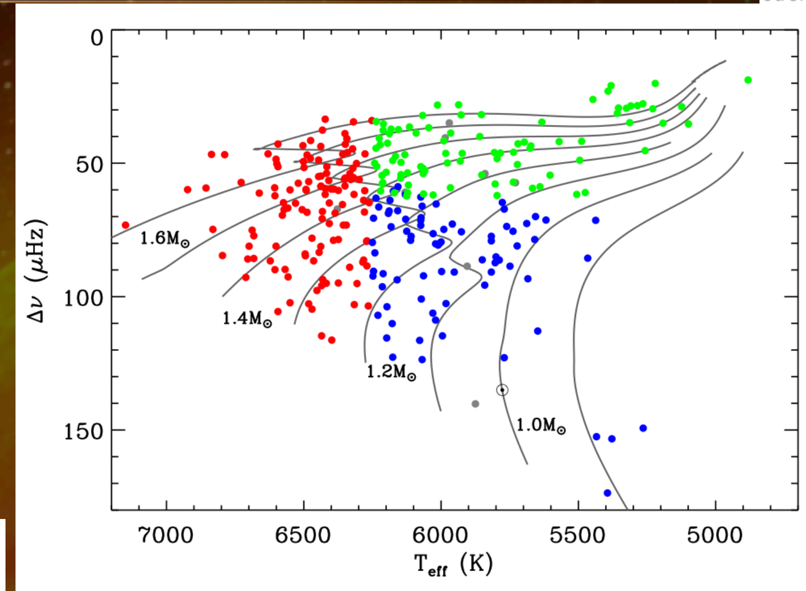
$$\log P_{\rm rot} = (0.52 \pm 0.06) \log(t) + (0.99 \pm 0.04).$$

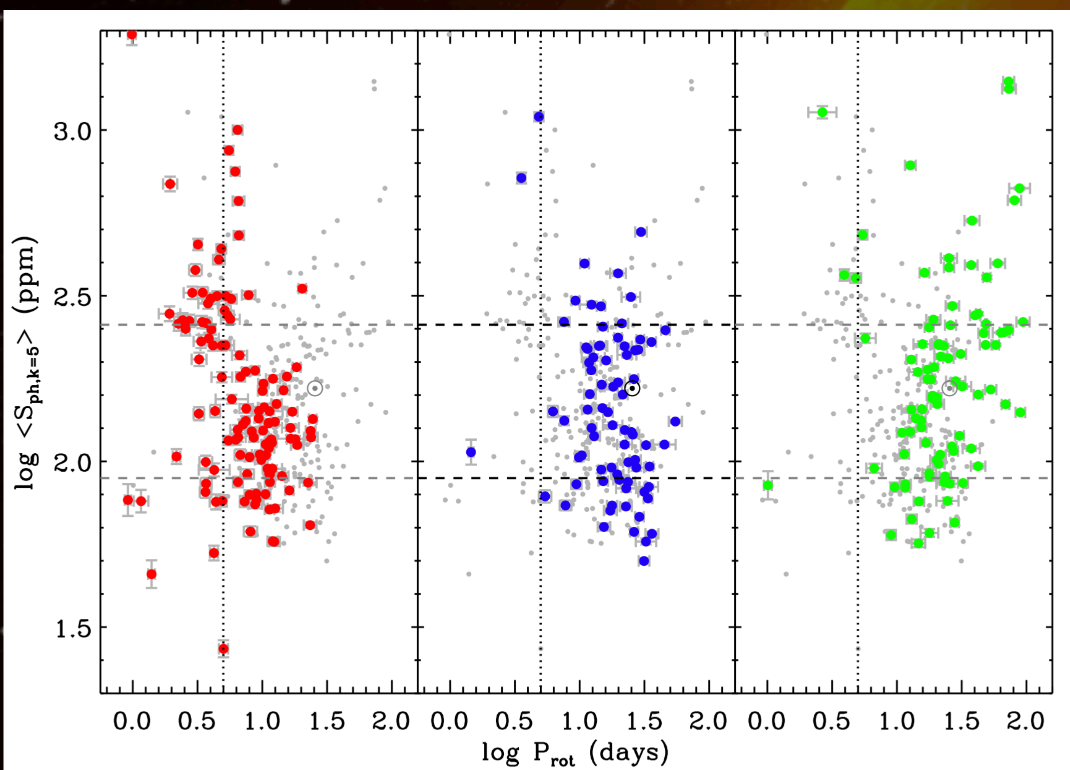
[Freqs from Appourchaux et al. 2012, models from Mathur et al. 2012 & Metcalfe et al. 2014
García et al. Submitted, ArXiv-1403.7155]

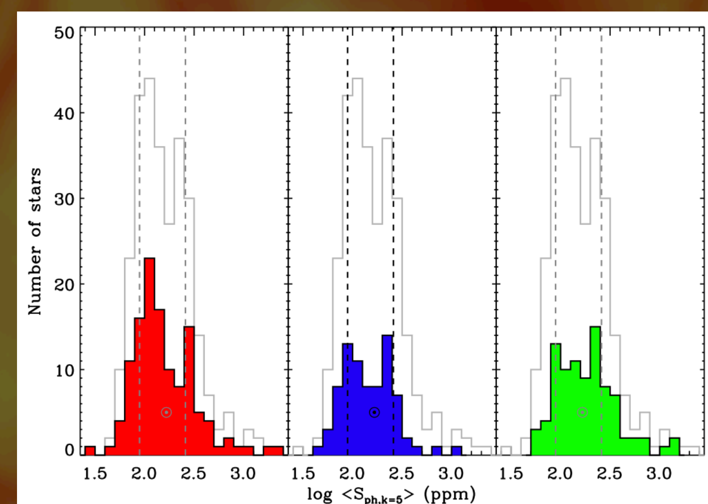
I-S_{PH} PULSATING *KEPLER* S-L STARS

- Sample of 540 pulsating *Kepler* S-L stars
  - P_{rot} measured in 310 stars [Chaplin et al. 2014]
  - $S_{ph,k=5}$ close to solar values
    - Biased sample
    - Activity reduces p-mode amplitudes

[García et al. 2010, Chaplin et al. 2011]







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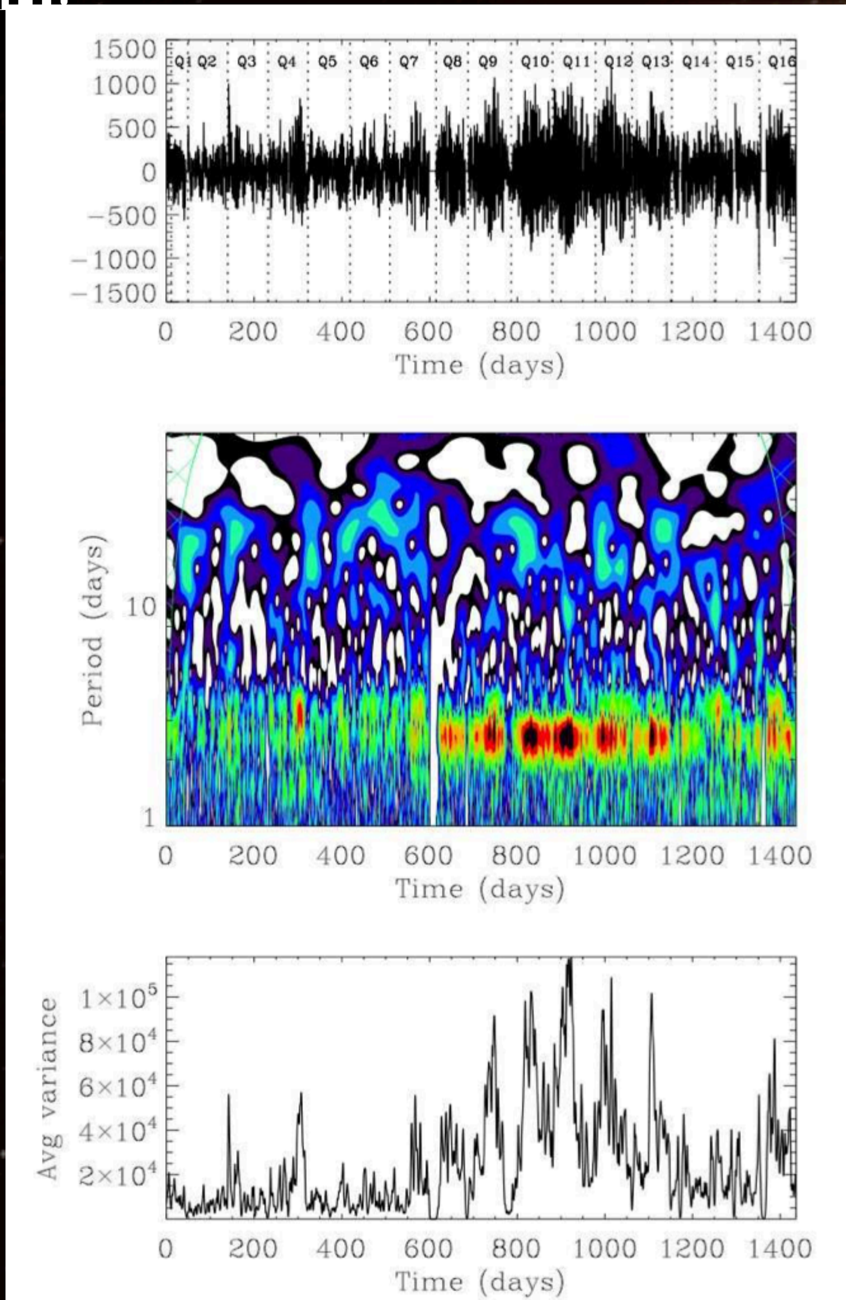
I- PHOTOSPHERIC MAGNETIC ACTIVITY



KIC 3733735

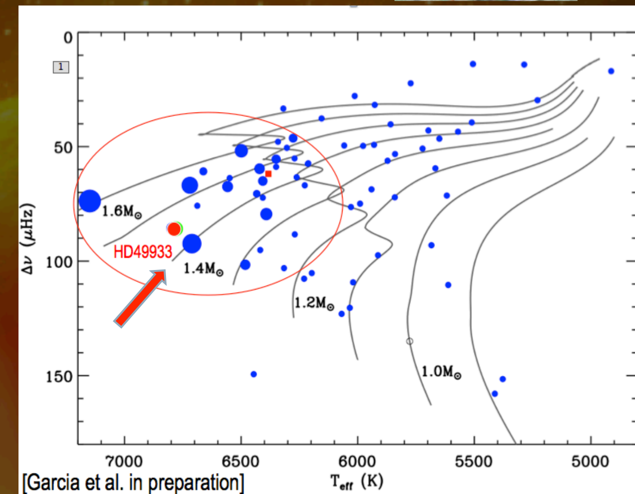
P_{rot}=2.5d

$<S_{ph}>$ = 250 ppm

Asteroseismology:

M~1.4$M_{\odot}$

DCZ~1%



We observe:

- Magnetic Cycle like behaviour

- Differential rotation

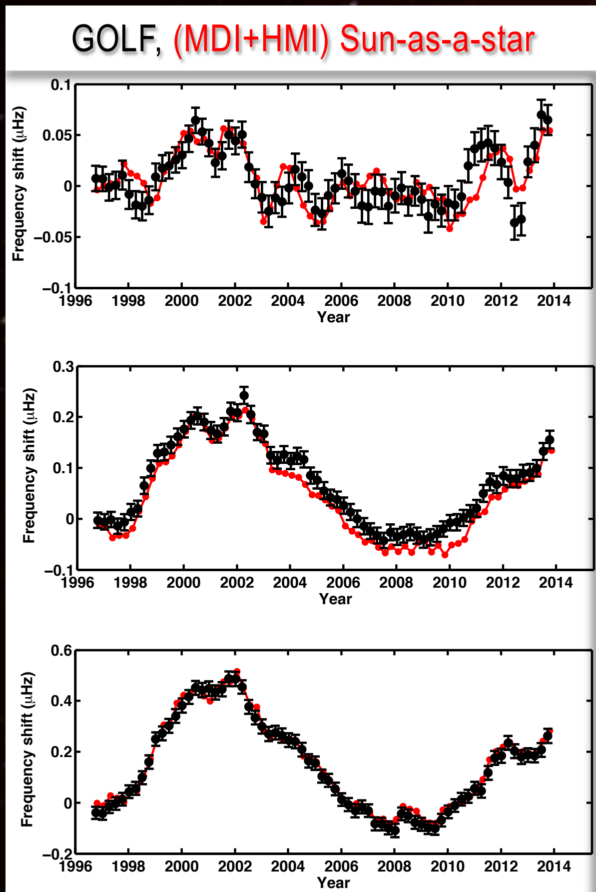
  Changing with cycle (Butterlfly-like diagram)

- Presence of Active longitudes during maximum activity

[Mathur, Garcia, Ballot et al., ApJ, 2014]

I-SOLAR ACTIVITY CYCLE 23 & 24

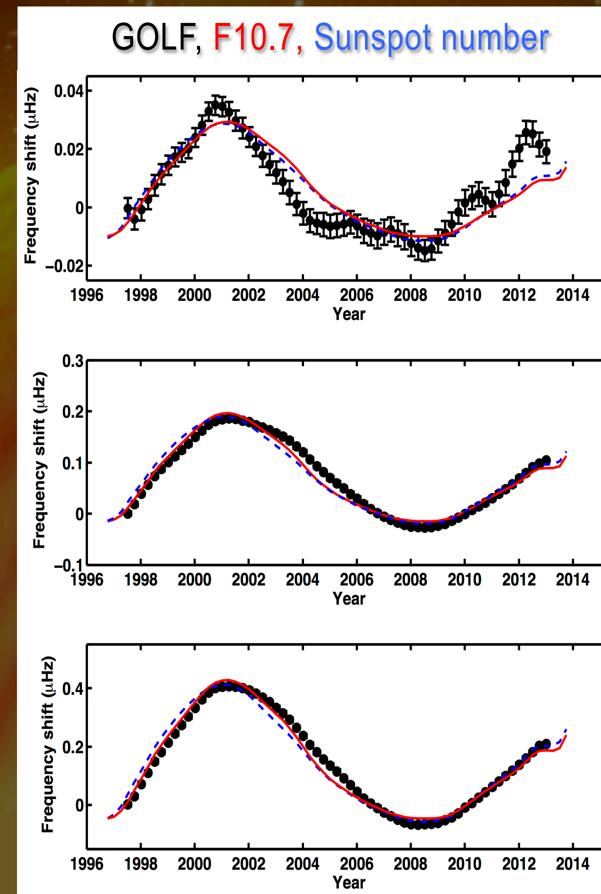
2-yr moving average



Low-freq
1800-2450μHz

Mid-freq
2450-3110μHz

High-freq
3110-3790μHz



<L=0,1,2> FREQUENCY SHIFTS 1995-2014

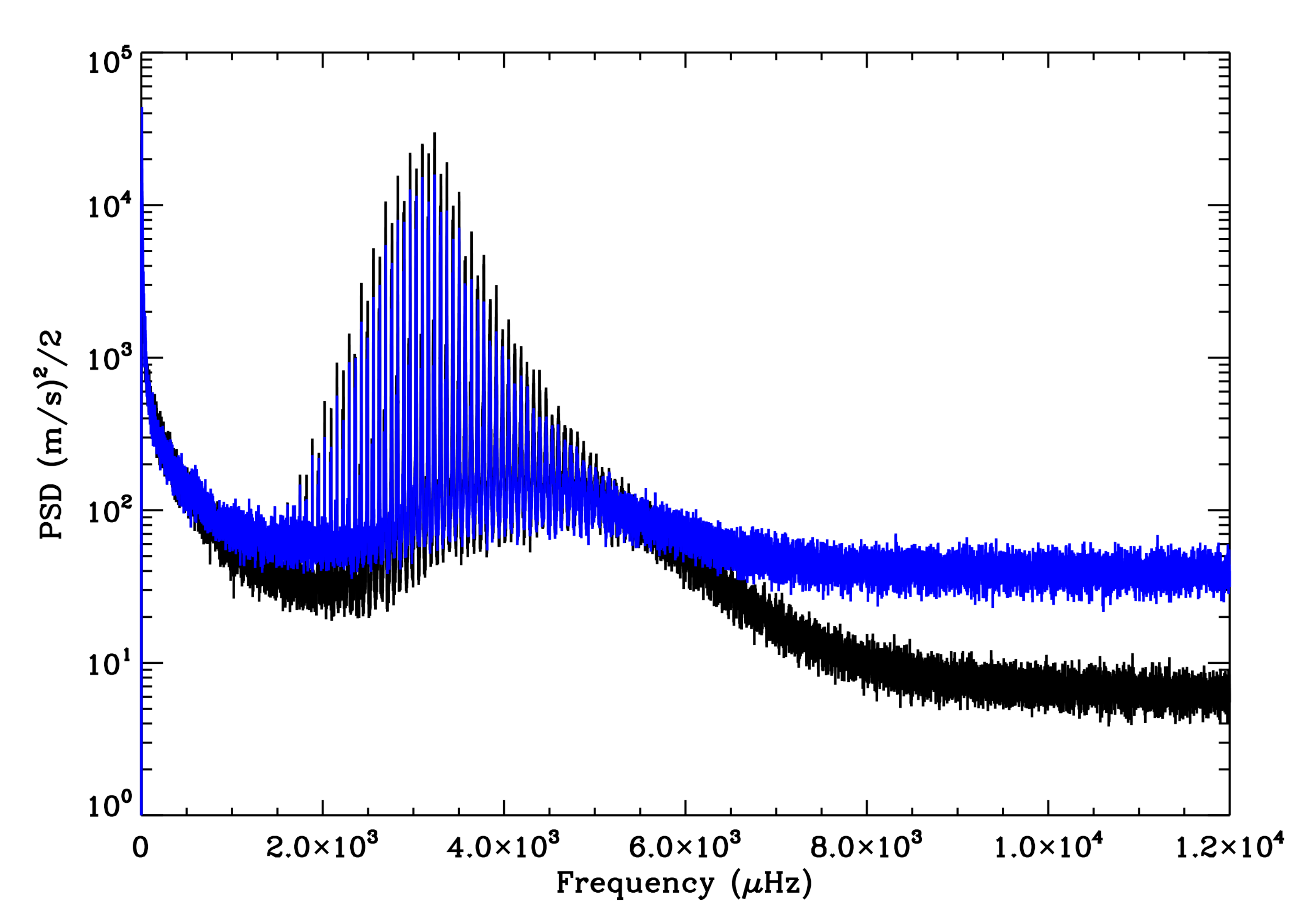
[Salabert, García, Turck-Chièze, et al. in preparation]

II.- Low-degree low-order p modes

18 years of GOLF

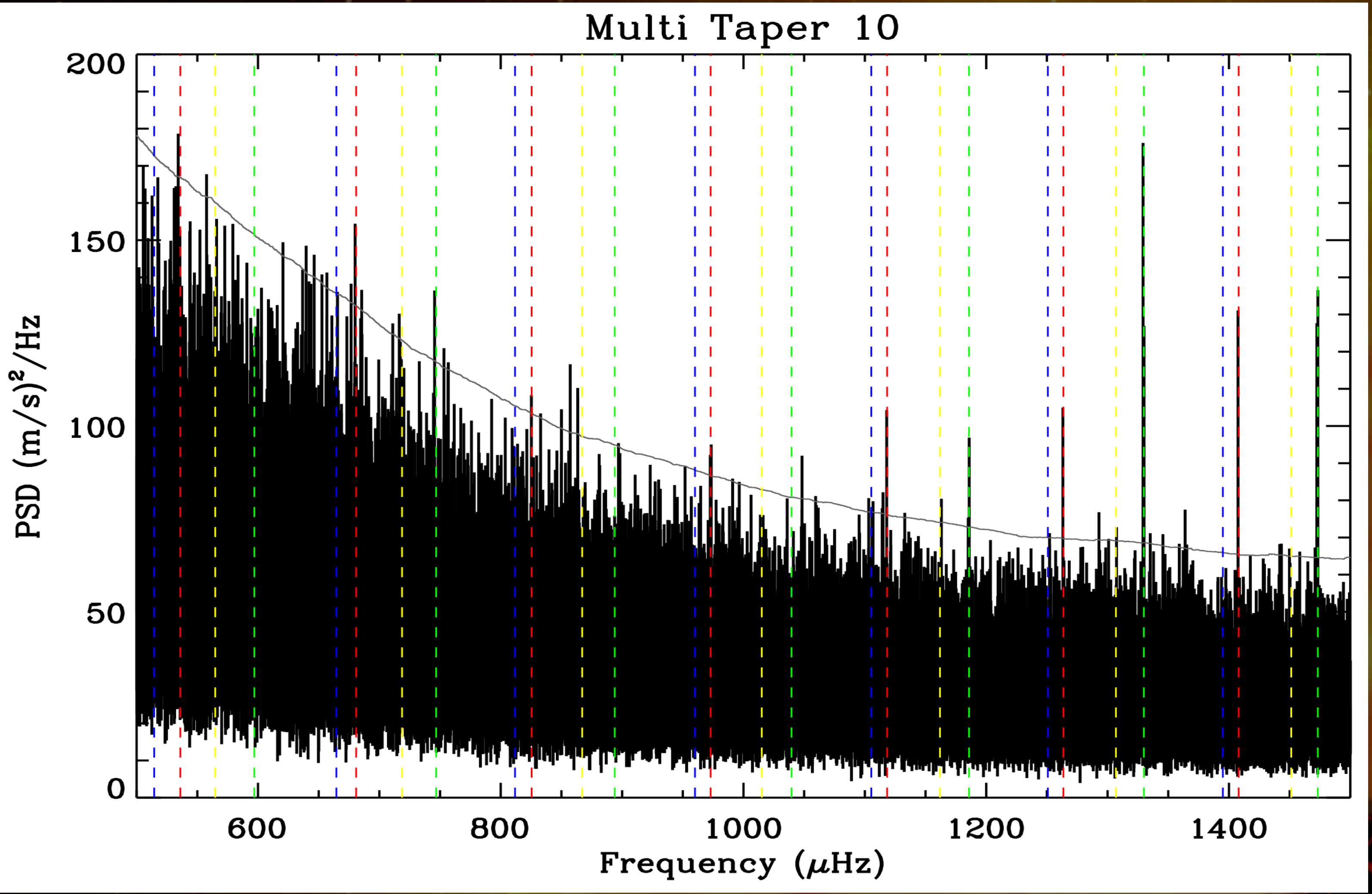
II-LOW-DEGREE LOW-ORDER P MODES

- Temporal evolution of the GOLF instrument
  - Lost a factor ~5 on the noise level



II-LOW-DEGREE LOW-ORDER P MODES

- Low-frequency part of the GOLF PSD (MT-10)

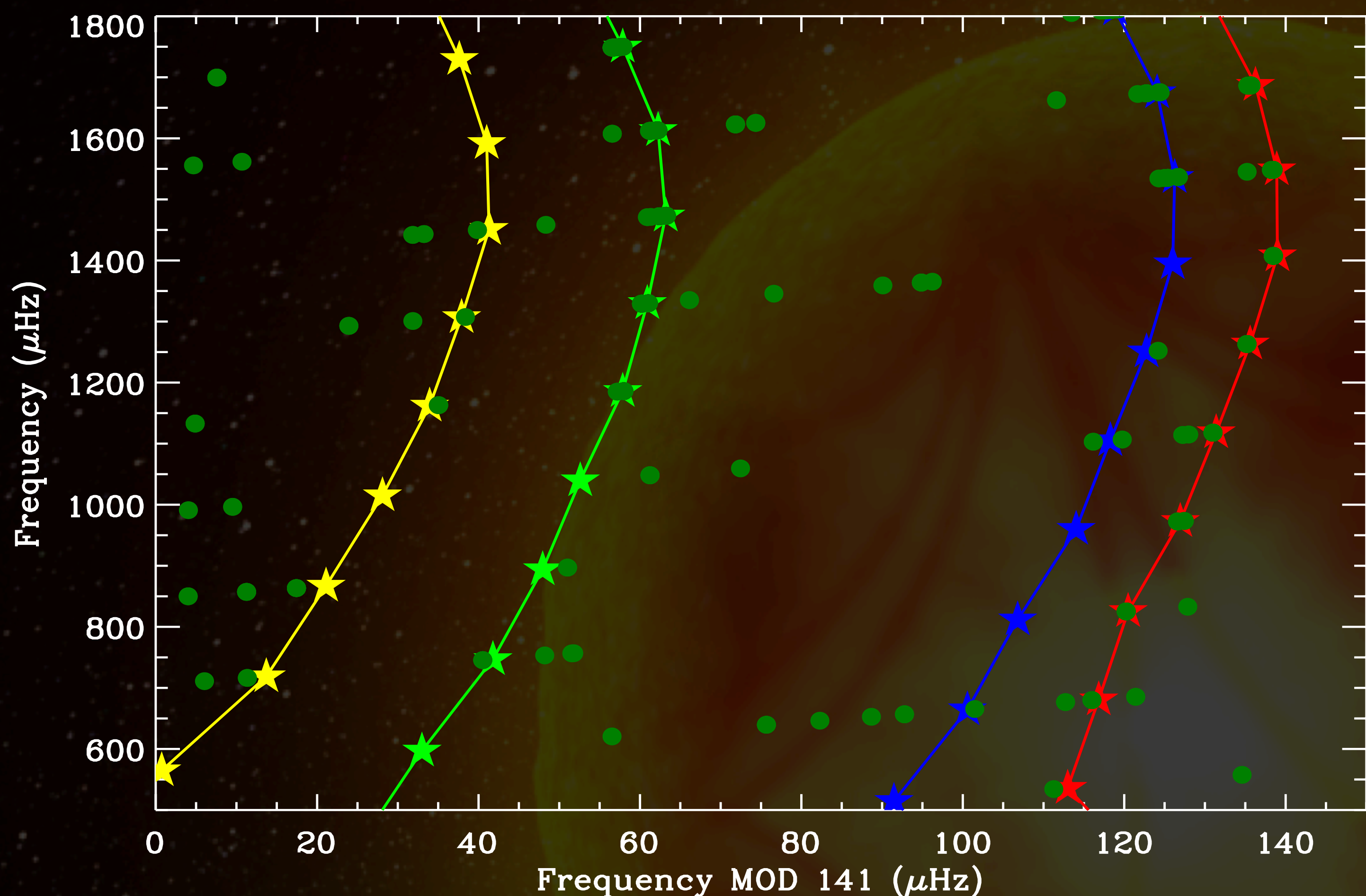


Theoretical Frequencies from the seismic model by Mathur et al. 2007

[García et al. in preparation]

II-LOW-DEGREE LOW-ORDER P MODES

- Échelle diagram



Theoretical Frequencies from the seismic model by Mathur et al. 2007

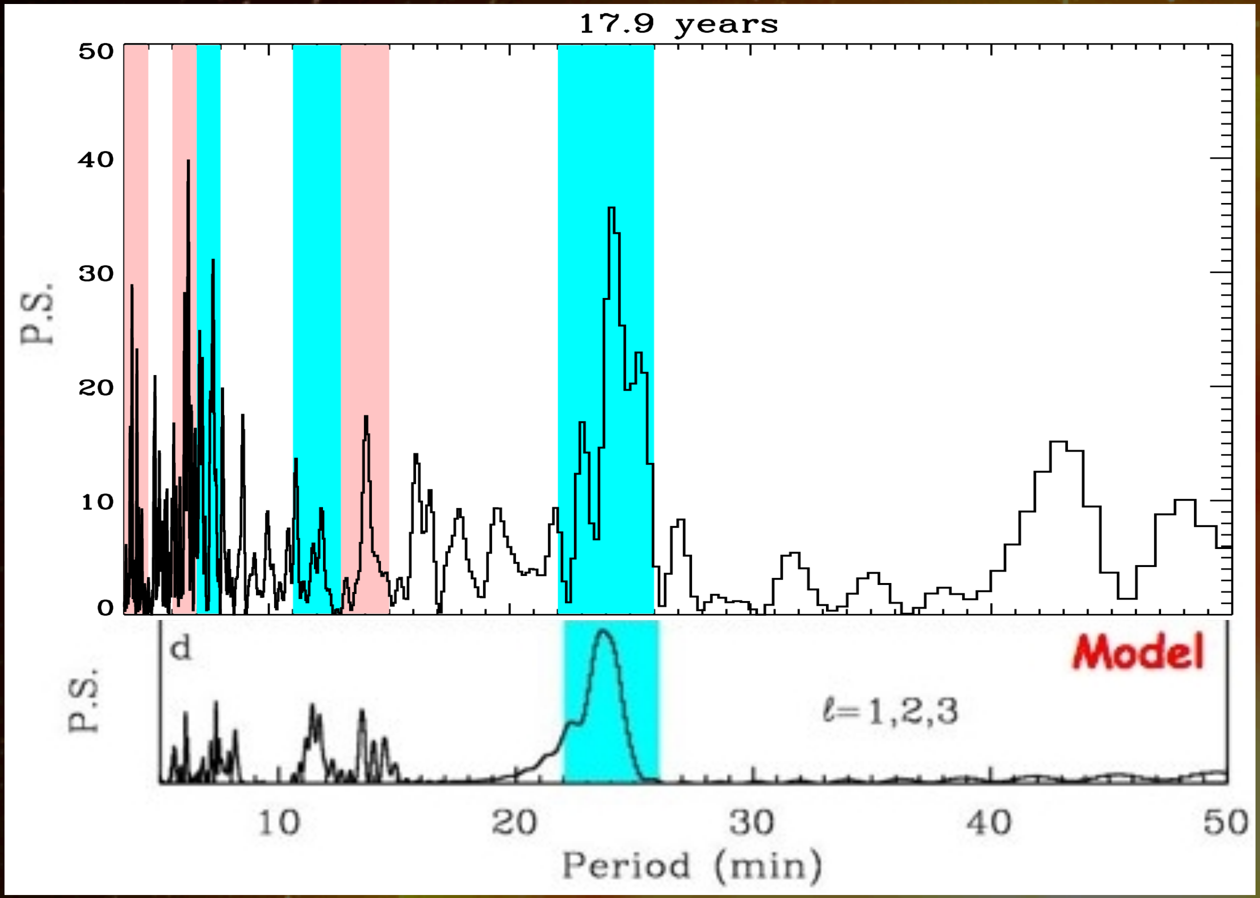
[García et al. in preparation]

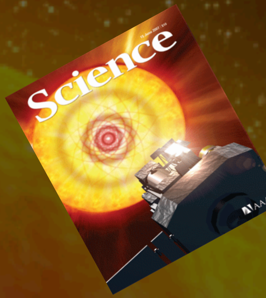
III.- Studying g-modes region

3D models and GOLF

III-GOLF G-MODE ANALYSIS

- In 2007, using ~10 years of GOLF data



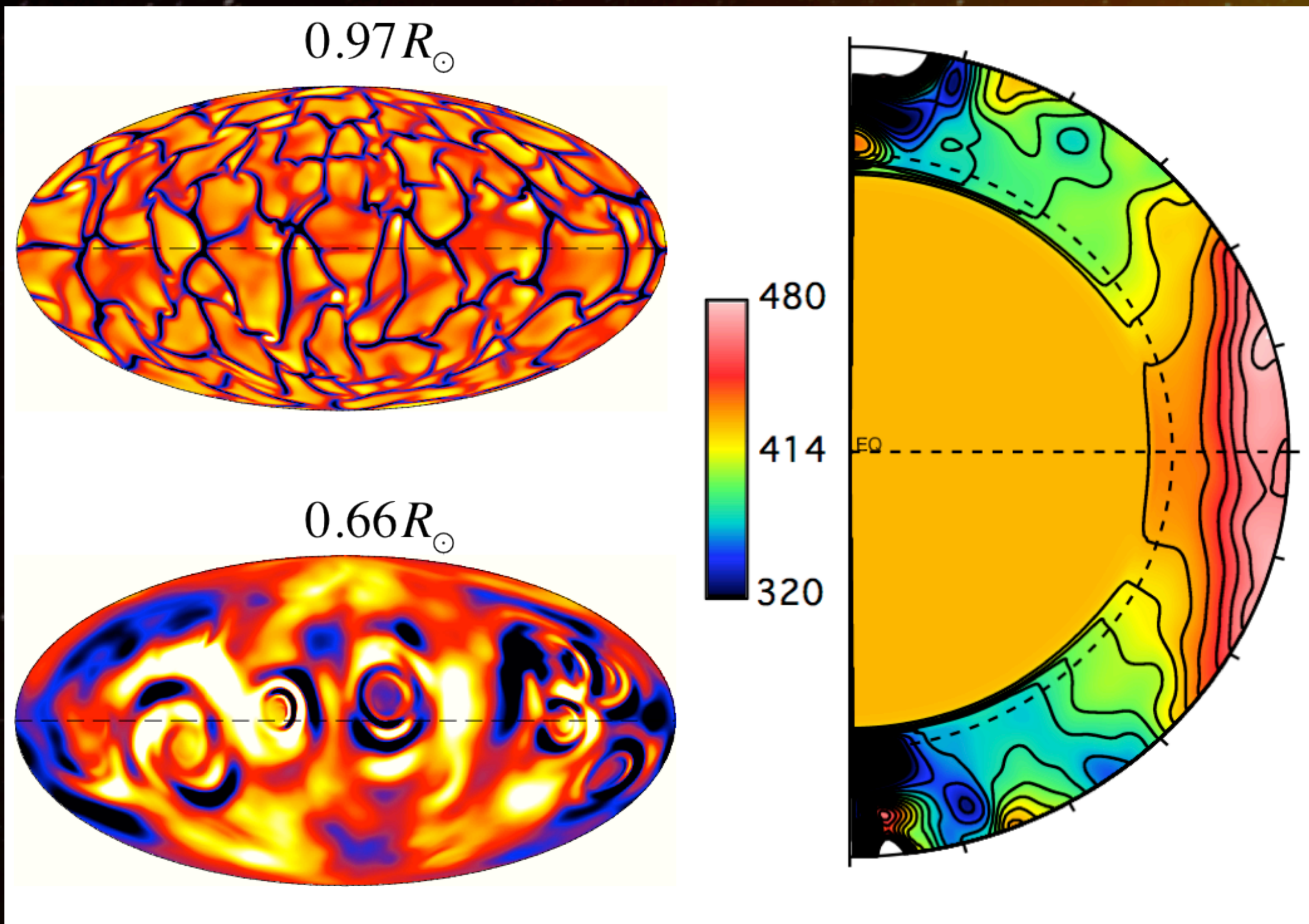


- Measurement of the ΔP_1 with a confidence level > 99.9%
- Results suggested:
  - Modes are wide (re-excited during the observation time)
  - Core of the Sun spins in average 3-5 time Ω_{rad}

[García et al. 2007, 2008]

III.- 3D MODELLING

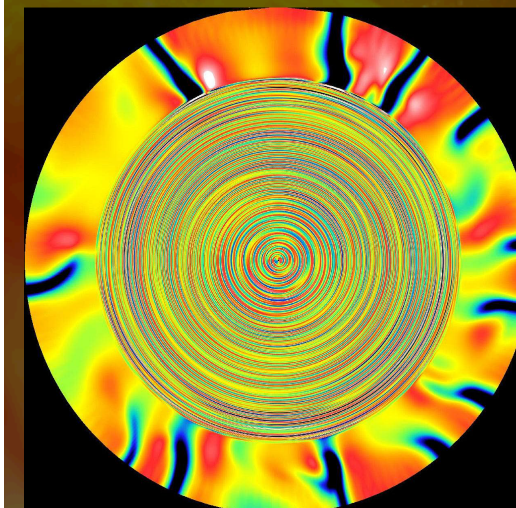
Convective pattern | Differential rotation



(shell slices)

(polar slice)

Internal waves



(equatorial slice)

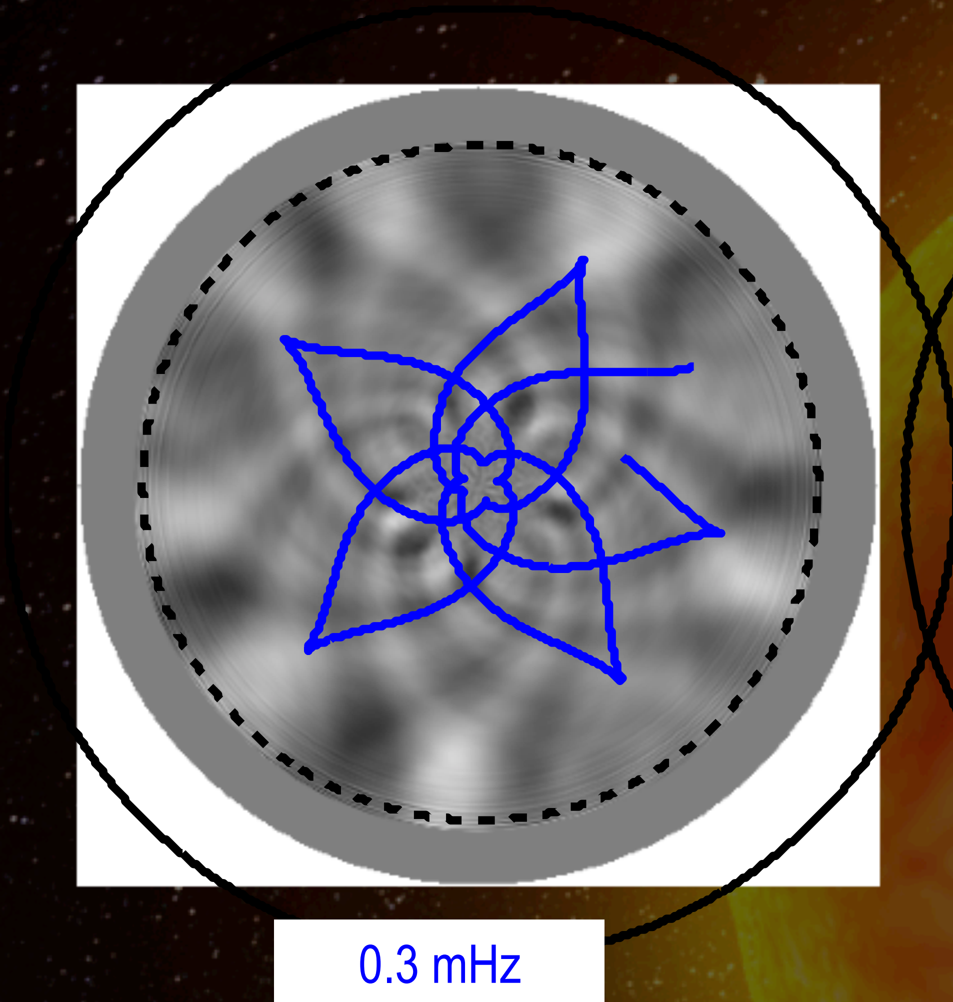
Time of calculation for (550 simulated days):

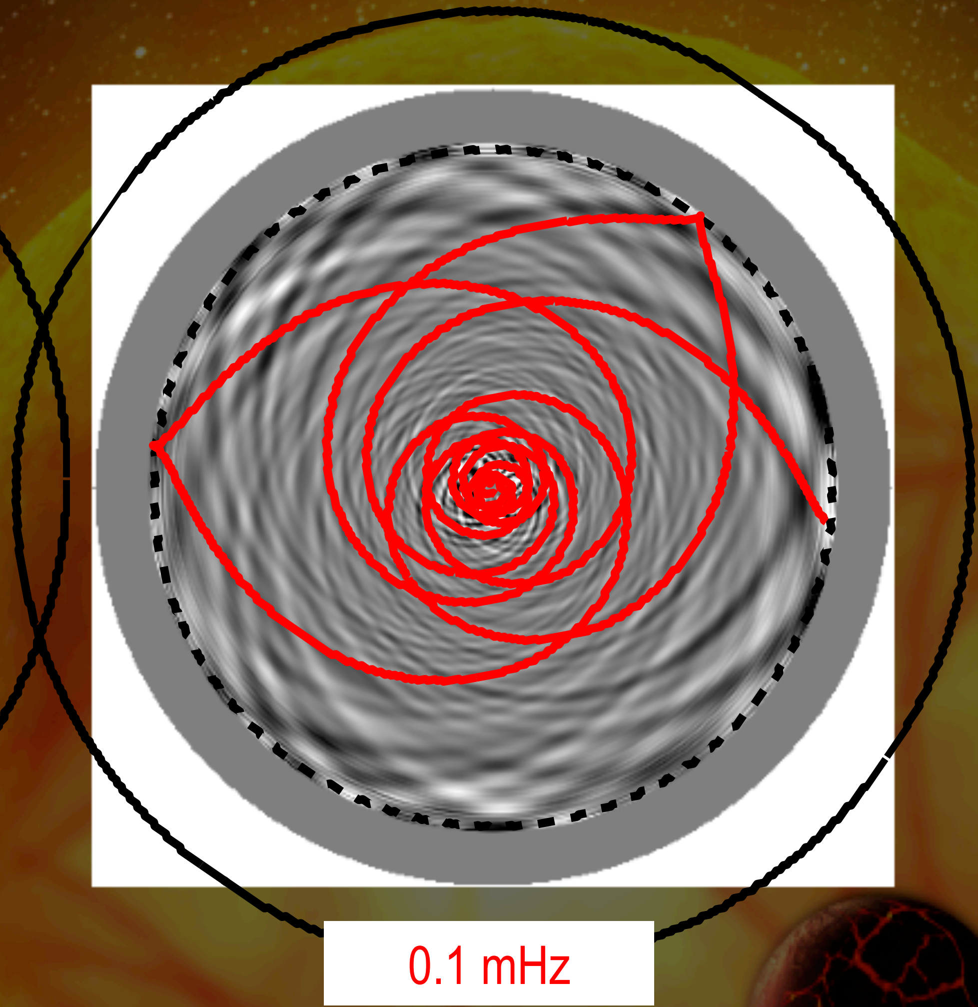
- 20 days using 2048 cores
- 1 000 000 hours (100 years) on a single computer

Reference state based on a 1D standard solar model (CESAM)

[Alvan, Brun & Mathis 2014]

III.- 3D MODELLING





[Alvan, Brun, Mathis & García in preparation]

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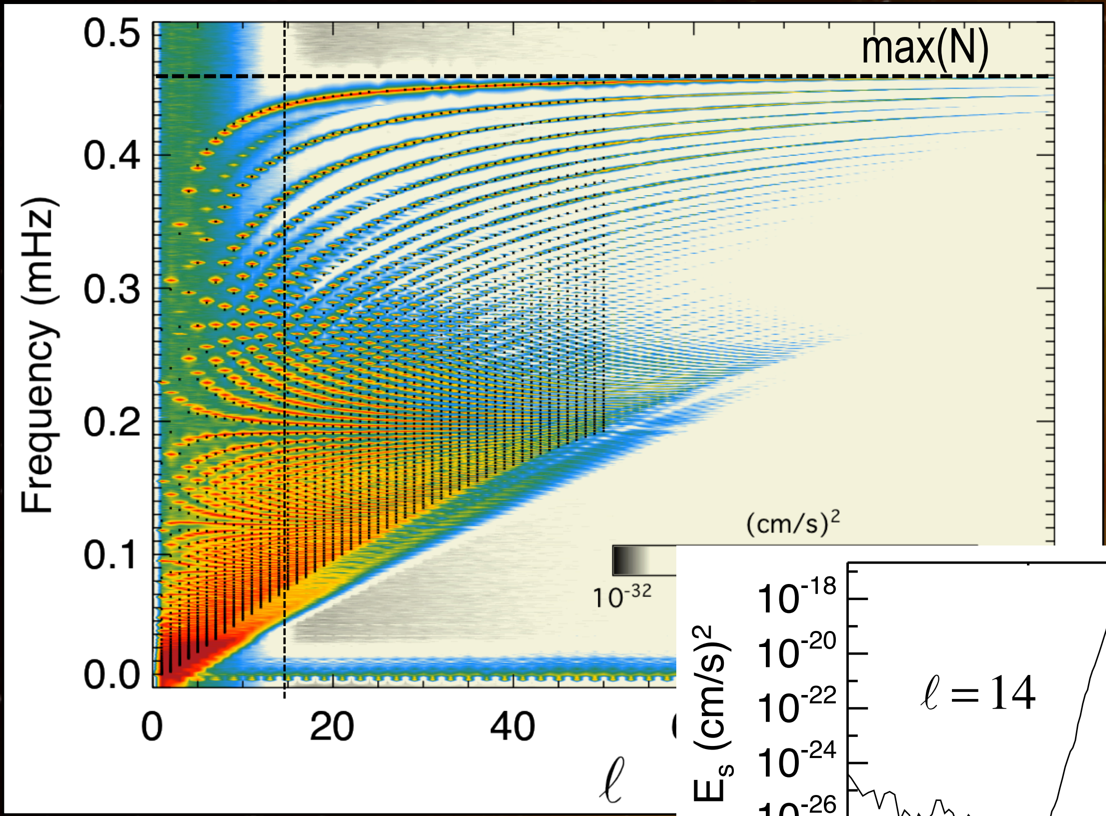
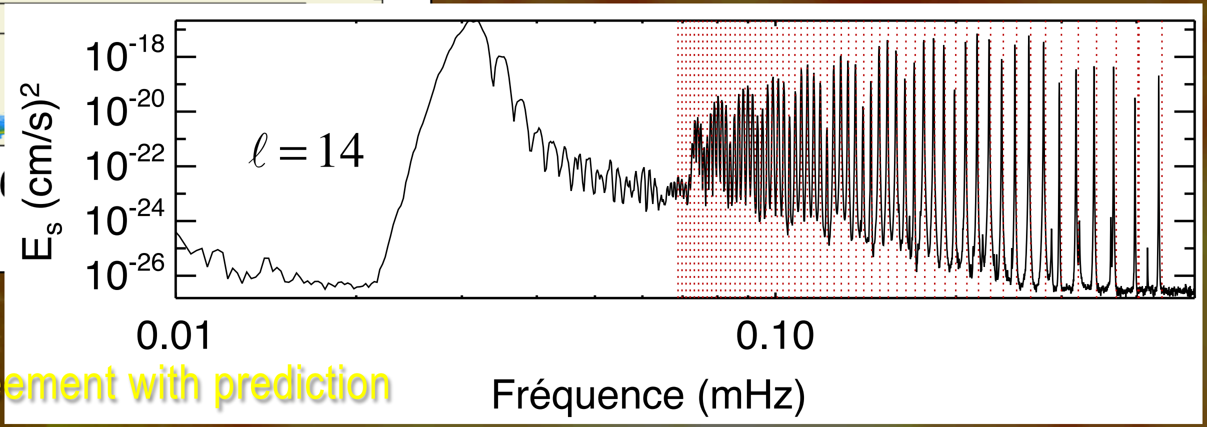


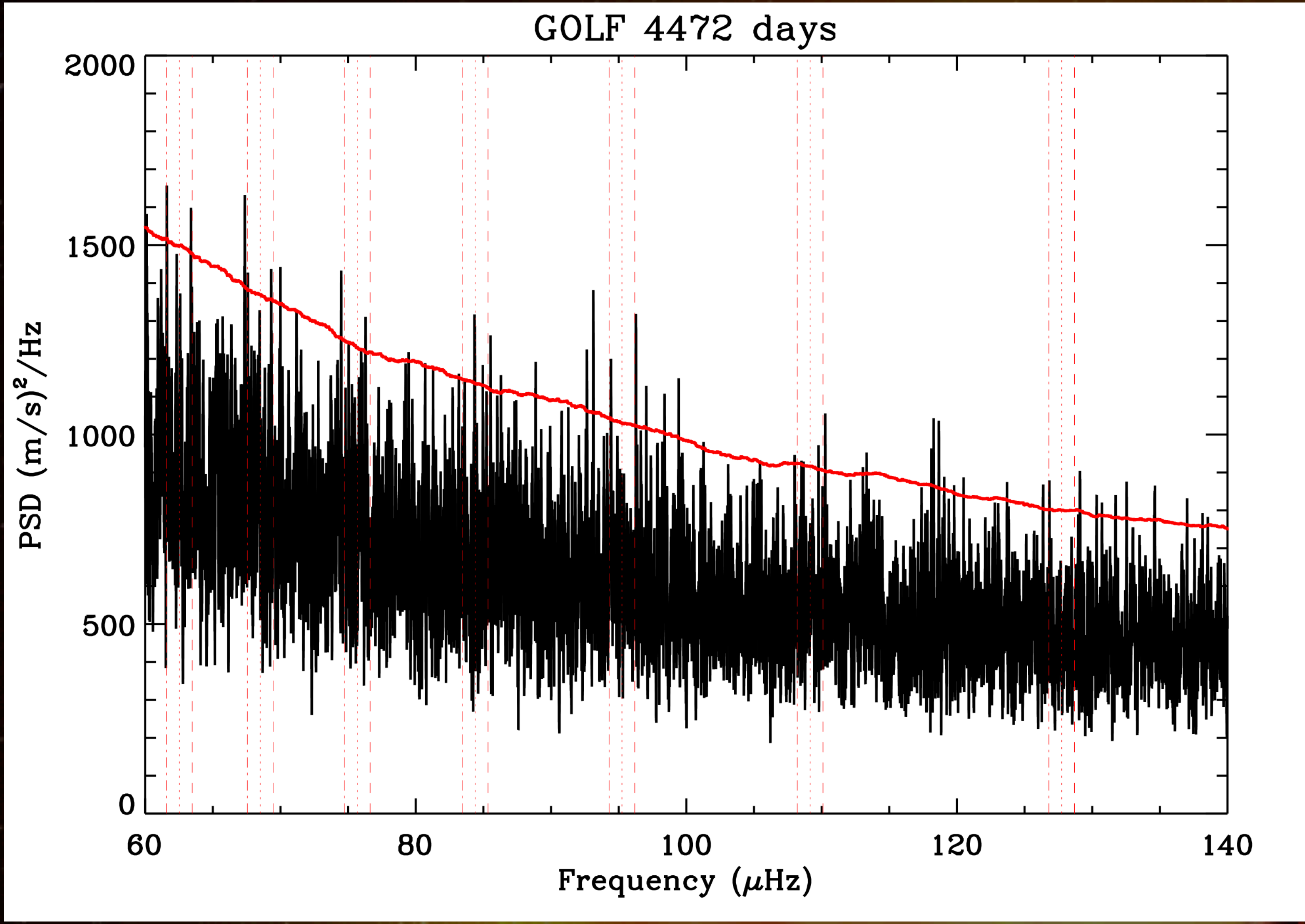
Comparison with an oscillation code
1D adiabatical frequencies
(model-S, Christensen-Dalsgaard)



- g-mode frequencies are in agreement with prediction
- A comparison shows a disagreement between the temporal damping and linear theoretical predictions.
  - g modes are excited and damped due to the convection
  - Preliminary results show g modes have finite lifetimes

[Alvan, Brun & Mathis 2014]

III-GOLF G-MODE ANALYSIS 12-YR



Theoretical Frequencies from the seismic model by Mathur et al. 2007
Splitting = 4.75 Ω_{rad}

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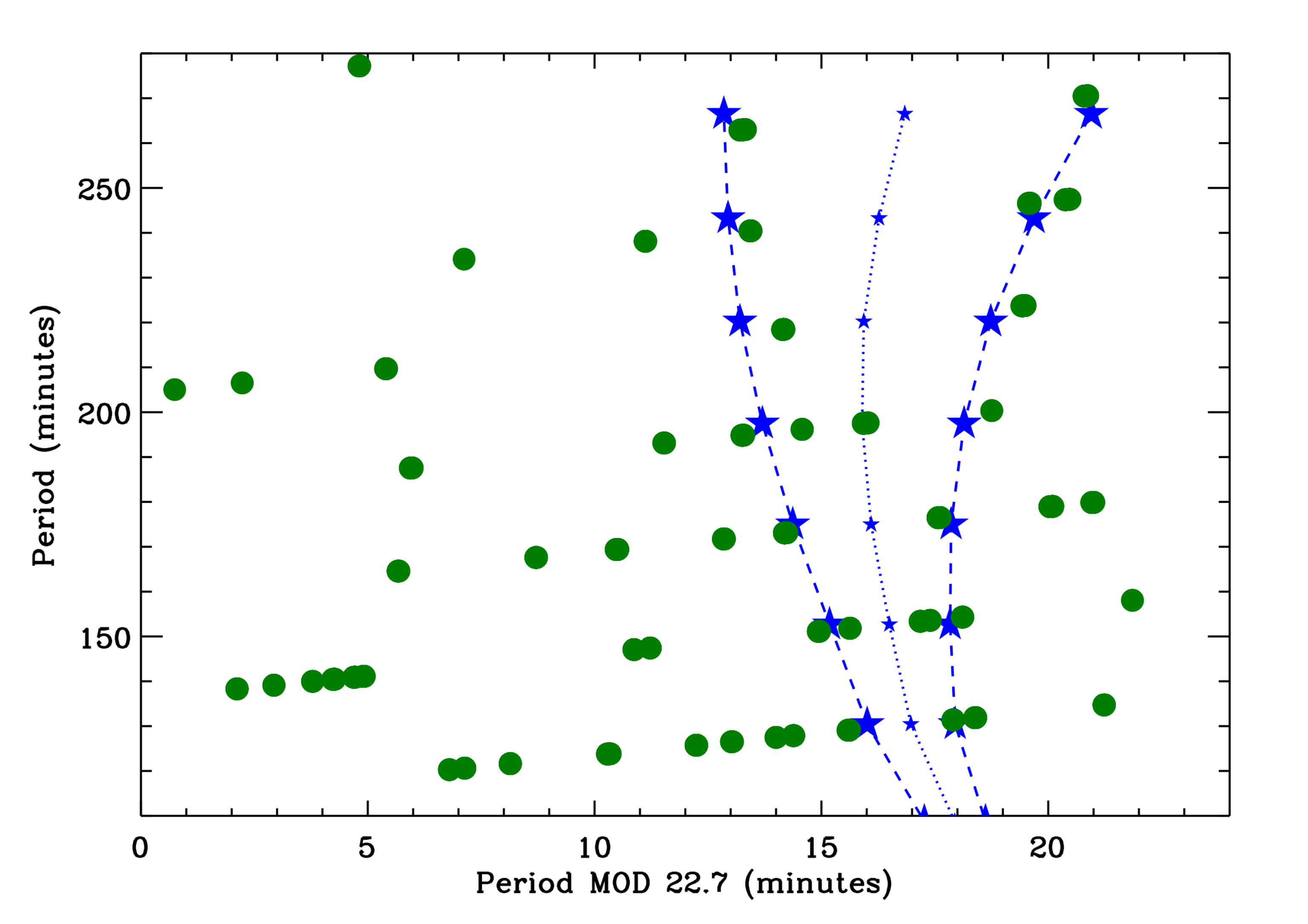

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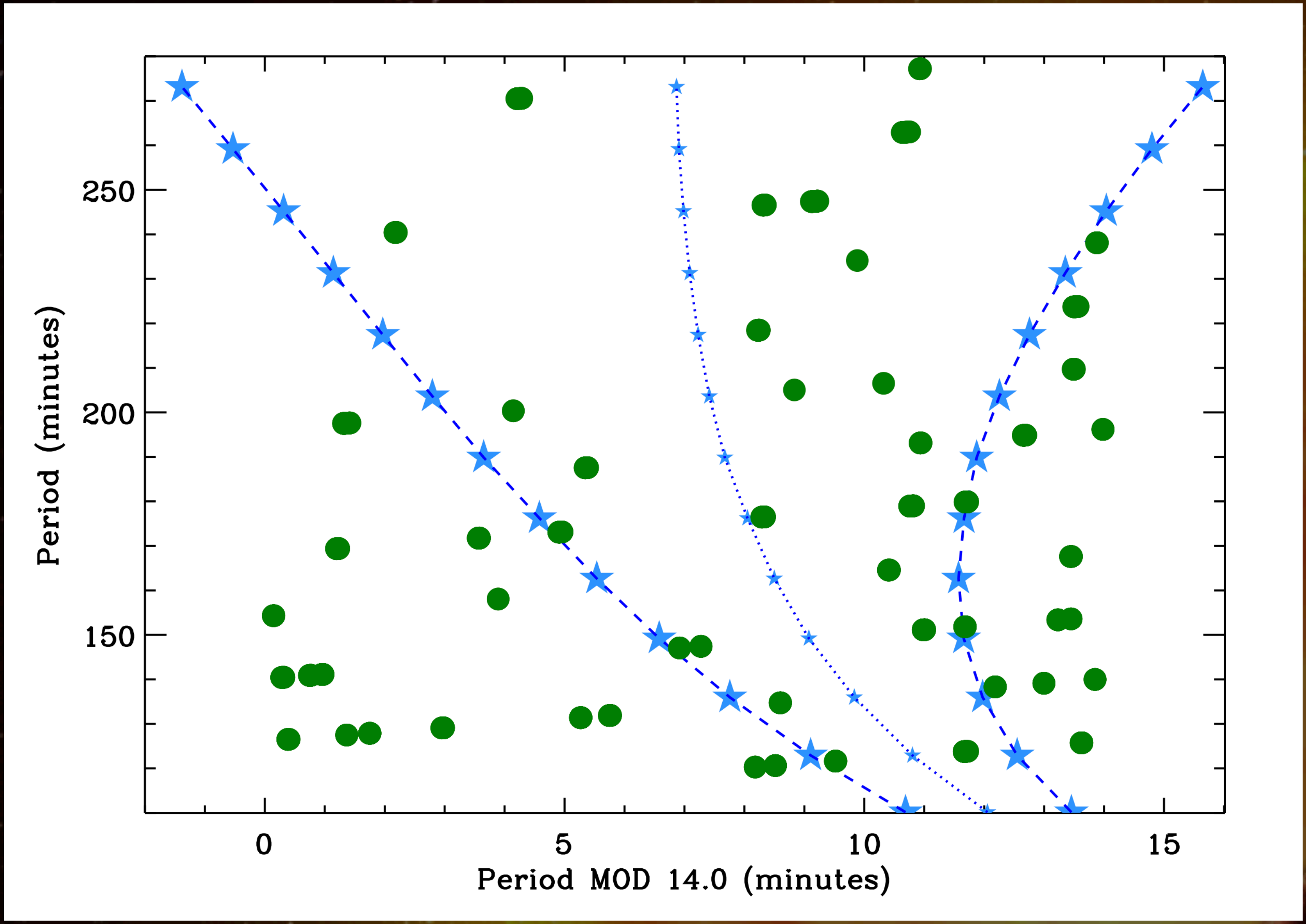

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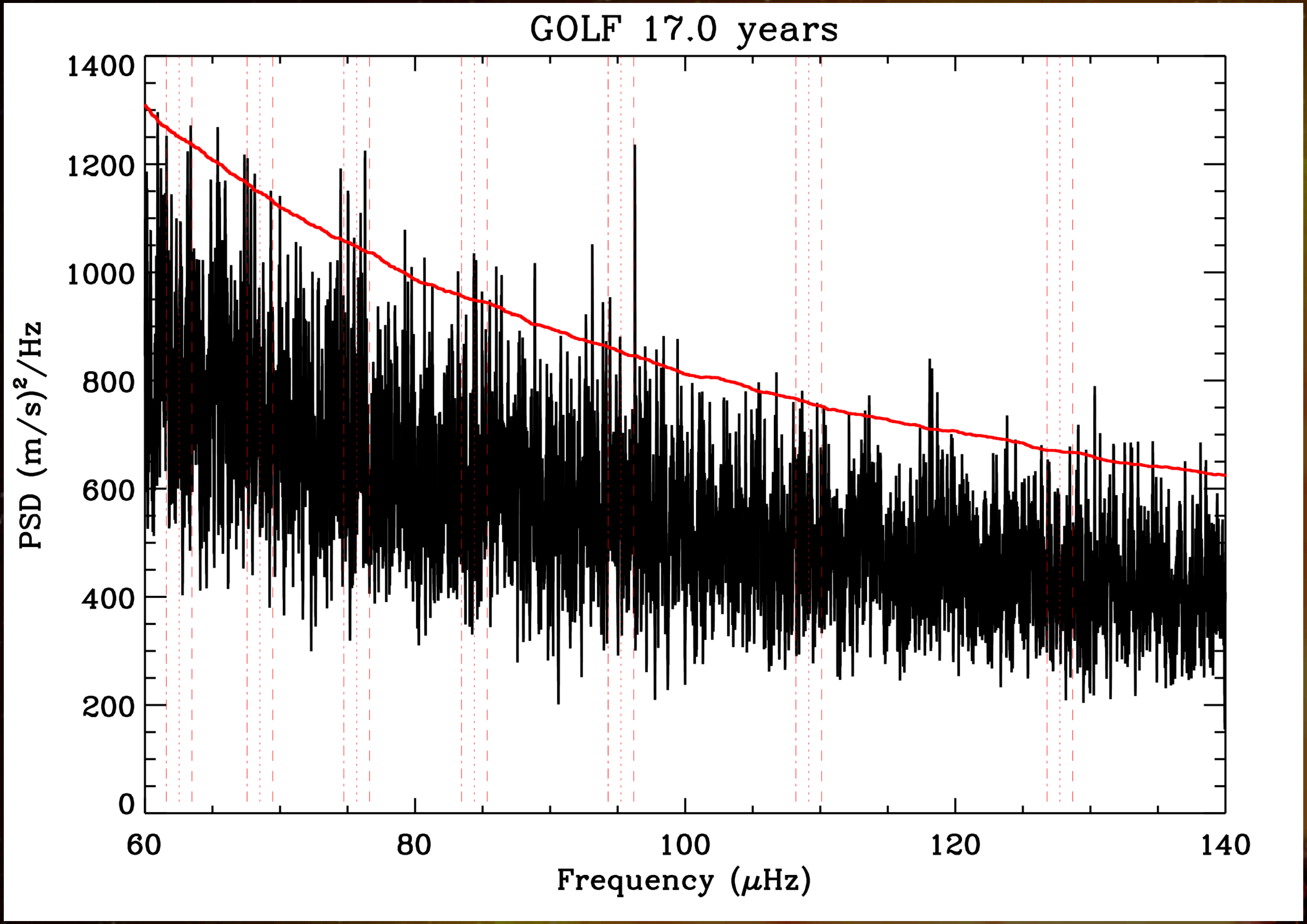
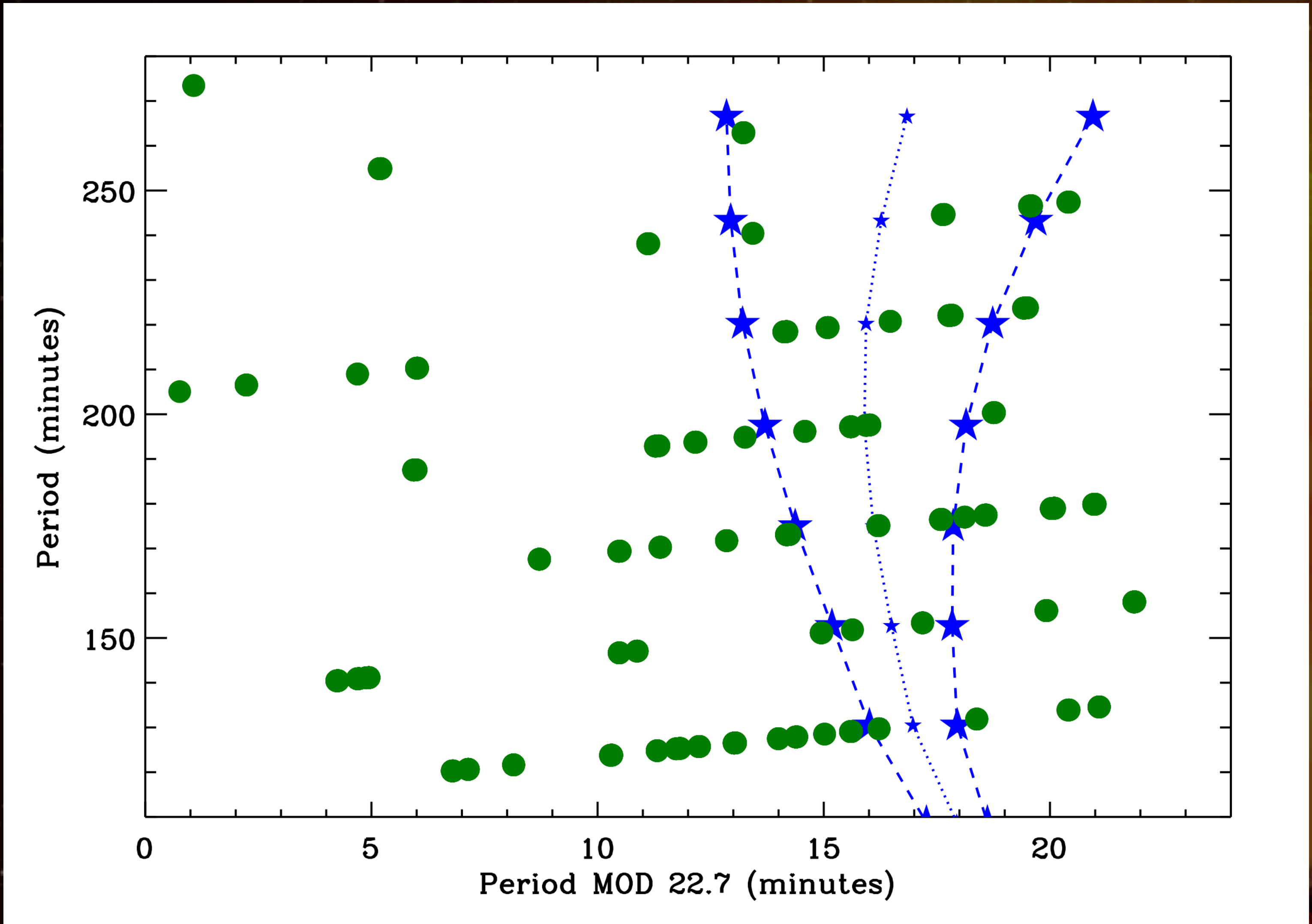
III-GOLF G-MODE ANALYSIS 17-YR



Theoretical Frequencies from the seismic model by Mathur et al. 2007

Splitting = 4.75 Ω_{rad}

III-GOLF G-MODE ANALYSIS 17-YR



Theoretical Frequencies from the seismic model by Mathur et al. 2007

Splitting = 4.75 Ω_{rad}

CONCLUSIONS

- Low-frequency low-order modes are very important
- GOLF has lost factor ~5 in high frequency noise
  - Affecting region at 1mHz
- Preliminary analysis of 18 years of GOLF data show modes l=0 down to n=3
- Magnetic activity cycle proxies (S_{ph}(t) will be available soon
  - For VIRGO/SPM and GOLF
- Cycle #14 shows a different behaviour in the low-frequency region [1800-2450 μHz]
  - 2-yr modulation seems to be longer
  - As a consequence:
    - For the same activity level the frequency shifts are larger.
- In the region of high-frequency g modes [60-140 μHz]
  - Individual l=1 g modes are now identified in the GOLF PSD
    - For l=1 modes, the splitting is ~4.75 Ω_{rad} (850-1000 nHz)
  - Increase of the average noise since 2012 currently under study

Thanks