ASTEROSEISMOLOGY:
INSTRUMENTATION
&
OBSERVATIONS

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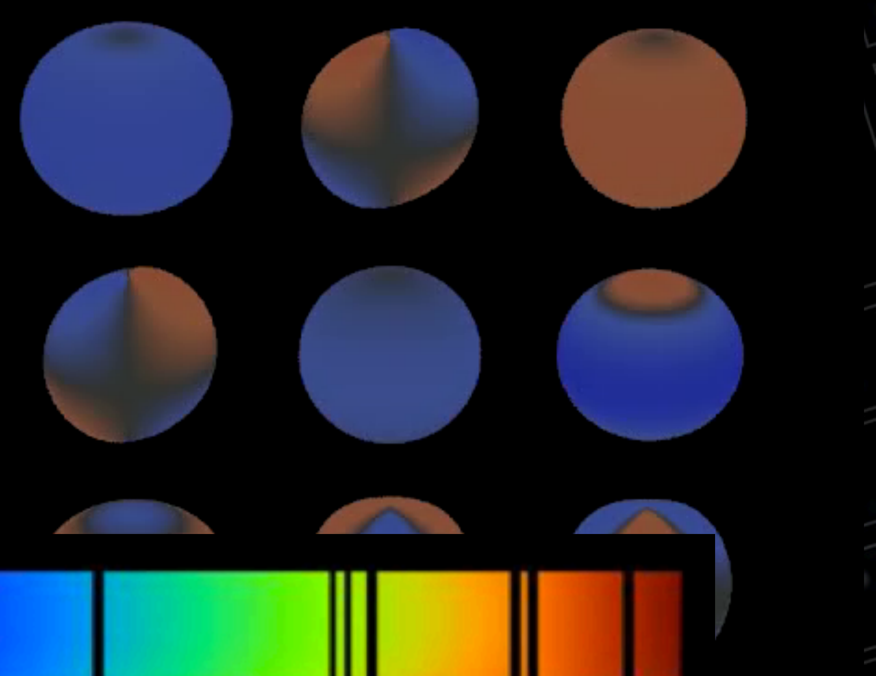
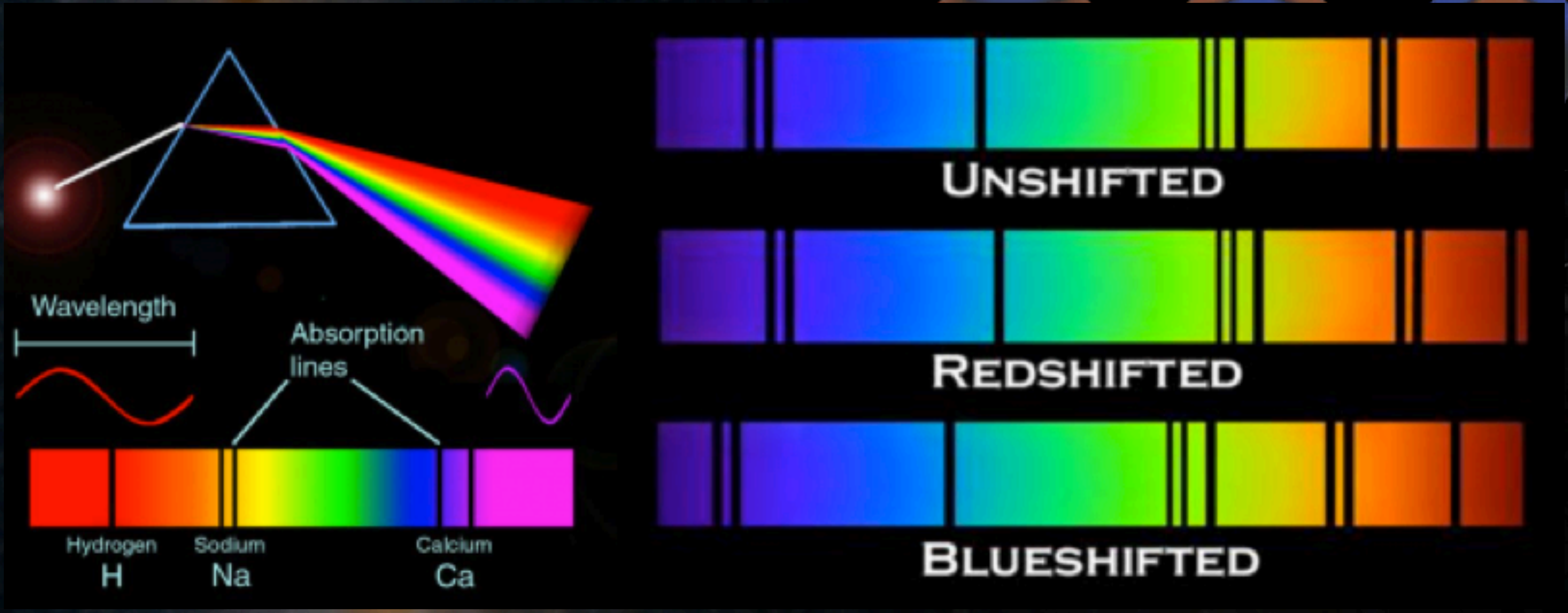
SUMMARY

- The seismic analyses can be summarized as follows:
  - I-Design and building appropriate instrumentation
    - Photometric observations of variability in the stellar flux
    - Doppler velocity displacement in spectroscopic observations
  - II-Data acquisition & preparation of the light curves for seismic analyses
    - Extracting the surface rotation & surface magnetism active
    - Gyrochronology and domain of applicability for field stars
  - III-Performing spectral analyses : Convection
  - IV-Performing spectral analyses : Seismic analysis & Scaling relations
  - V- Extract the main characteristics of the acoustic & Mixed modes
    - Directly from the spectrum
    - Defining proper models representative of the physical properties of our observables
      - Properly fitting the data
        - Frequentists vs Bayesian approaches (Dr. E. Corsaro)

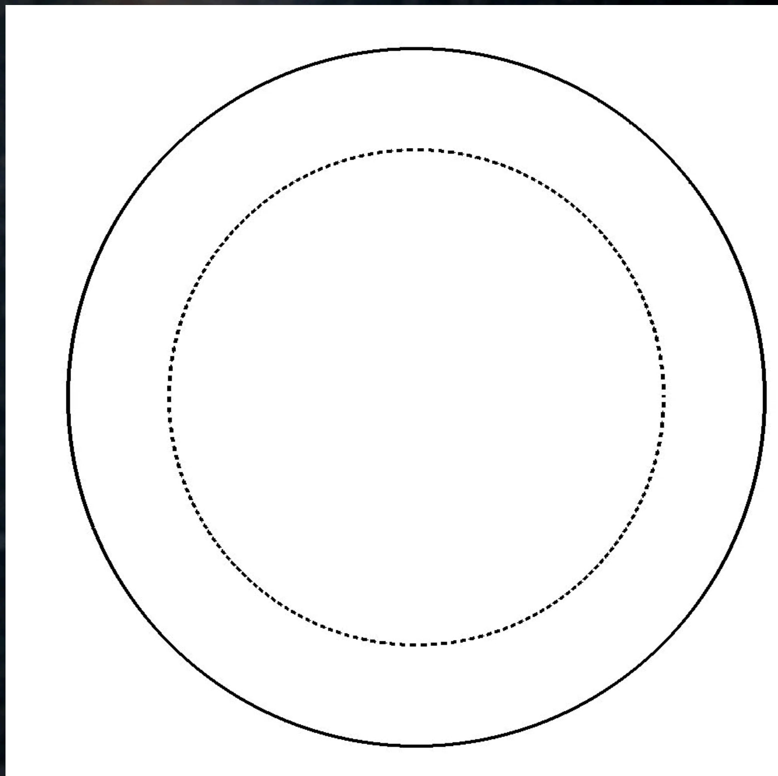
I -Instrumentation:

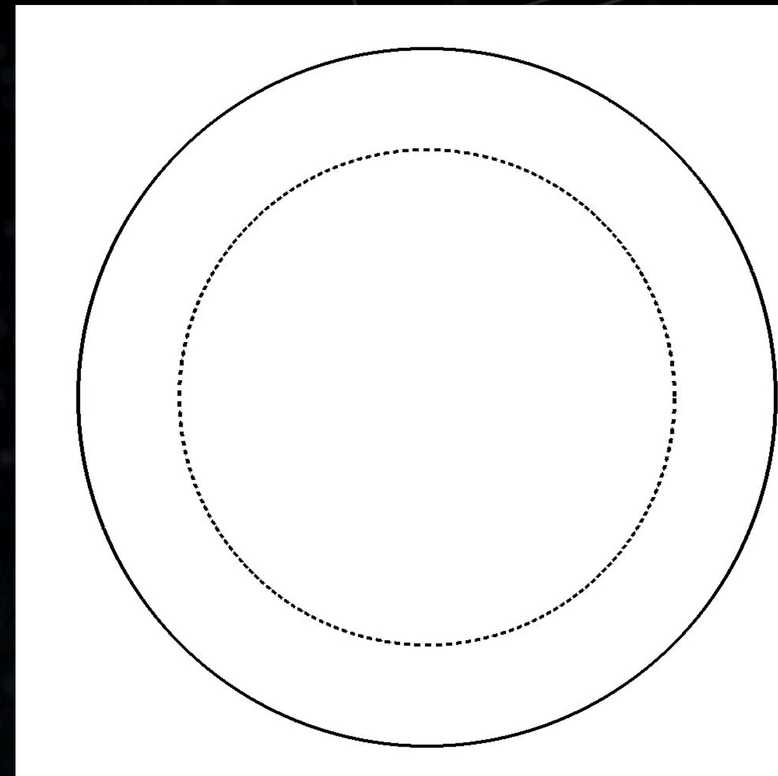
- Oscillations modifies the properties of the photosphere
  - Through variations of light
    - Directly
      - Intensity variations(temperature)
    - Doppler effect
      - Doppler velocity variations
    - Measurement of the Radius





I-GLOBAL SEISMIC PARAMETERS

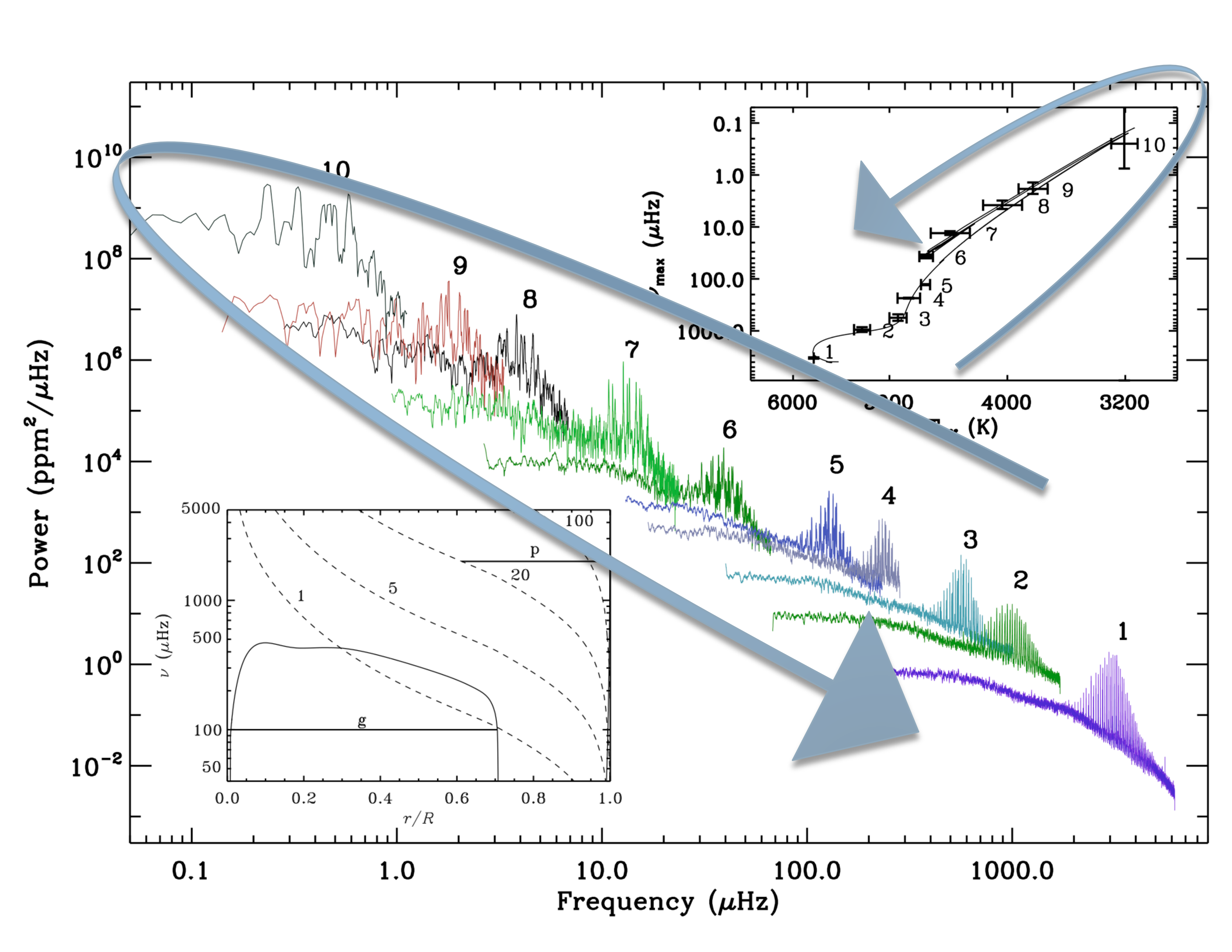




- Acoustic (p) modes:
  - Restoring force:
    - Pressure
    - High frequencies
    - Equidistant in frequency

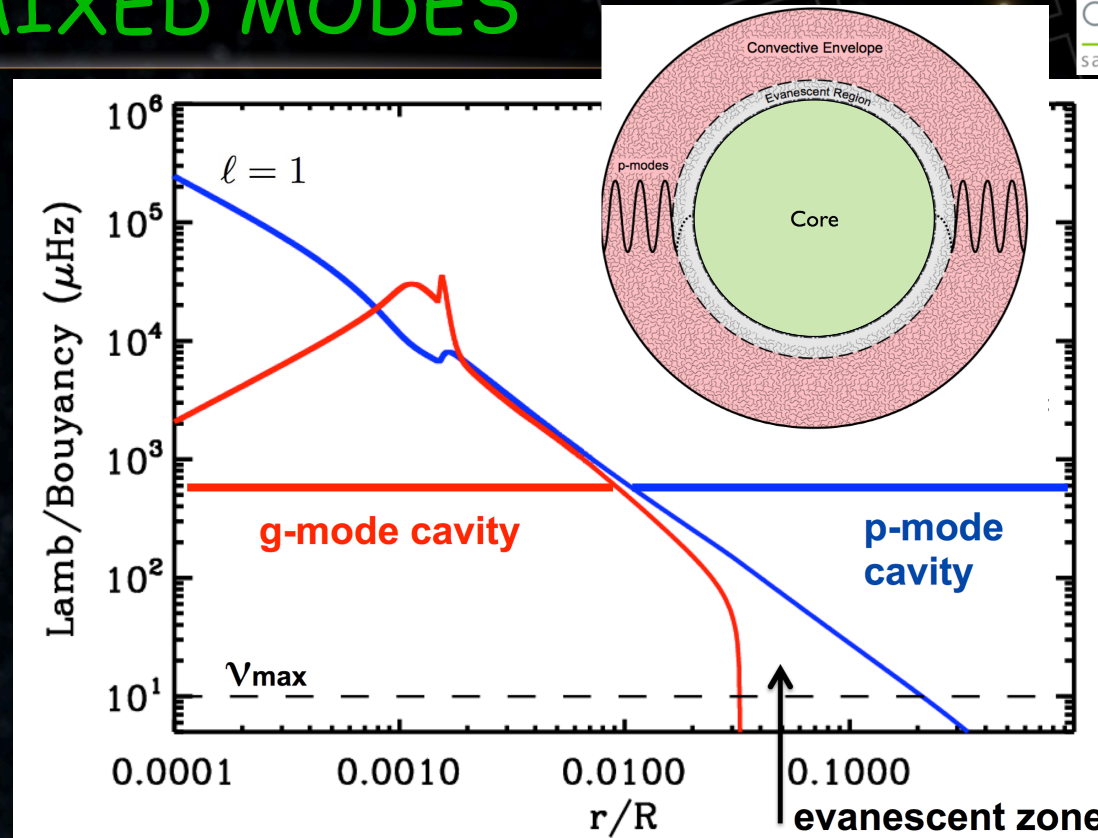
- Gravity (g) modes:
  - Restoring force:
    - Buoyancy
  - Low-freqeuncies
  - Evanescents in the convective zone
  - Equidistant in period

I- SEISMIC PARAMETERS & EVOLUTION

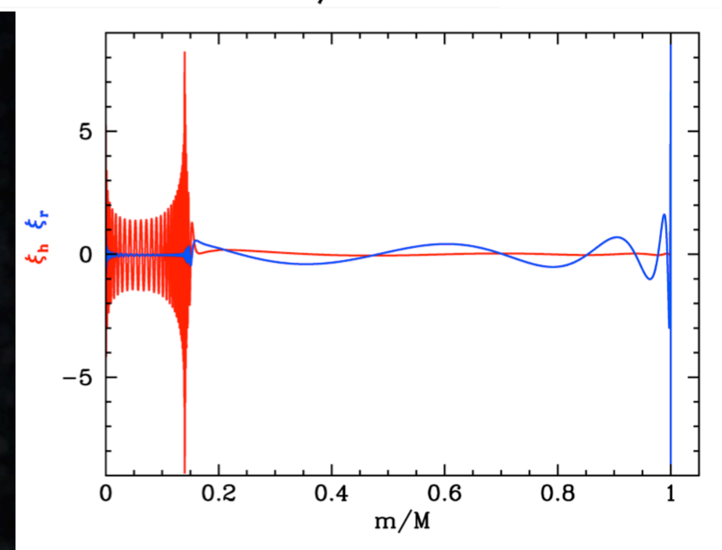


I-MIXED MODES

- Mixed modes:
  - At the surface they behave as a p mode
  - At the radiative internal region they behave as a g mode

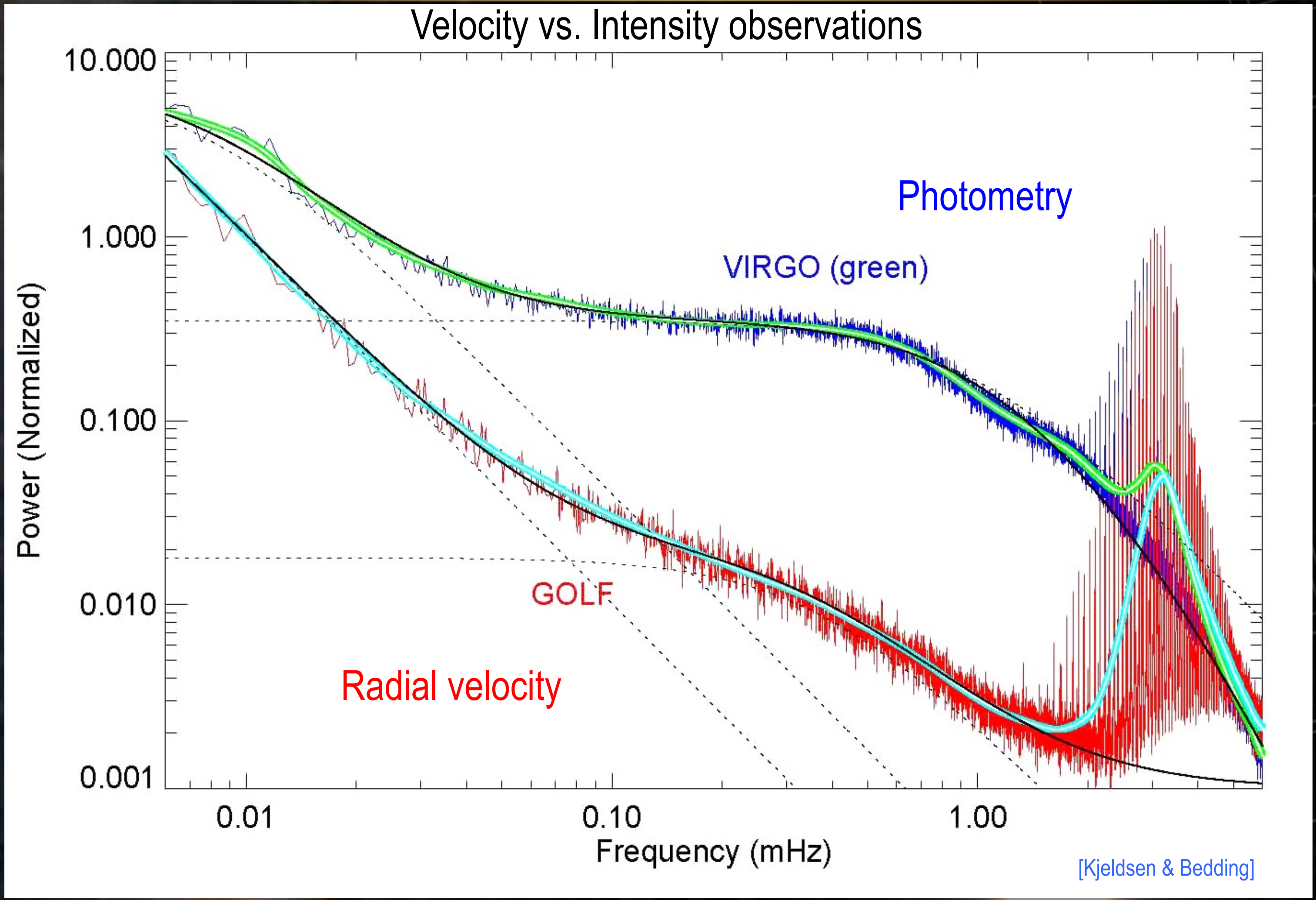


- Interest of mixed modes:
  - Sensitive to the core
  - Much higher amplitudes than pure g modes
- Strong constraints on the age of the stars



[e.g. Metcalfe et al. 2010; Deheuvels et al. 2010]

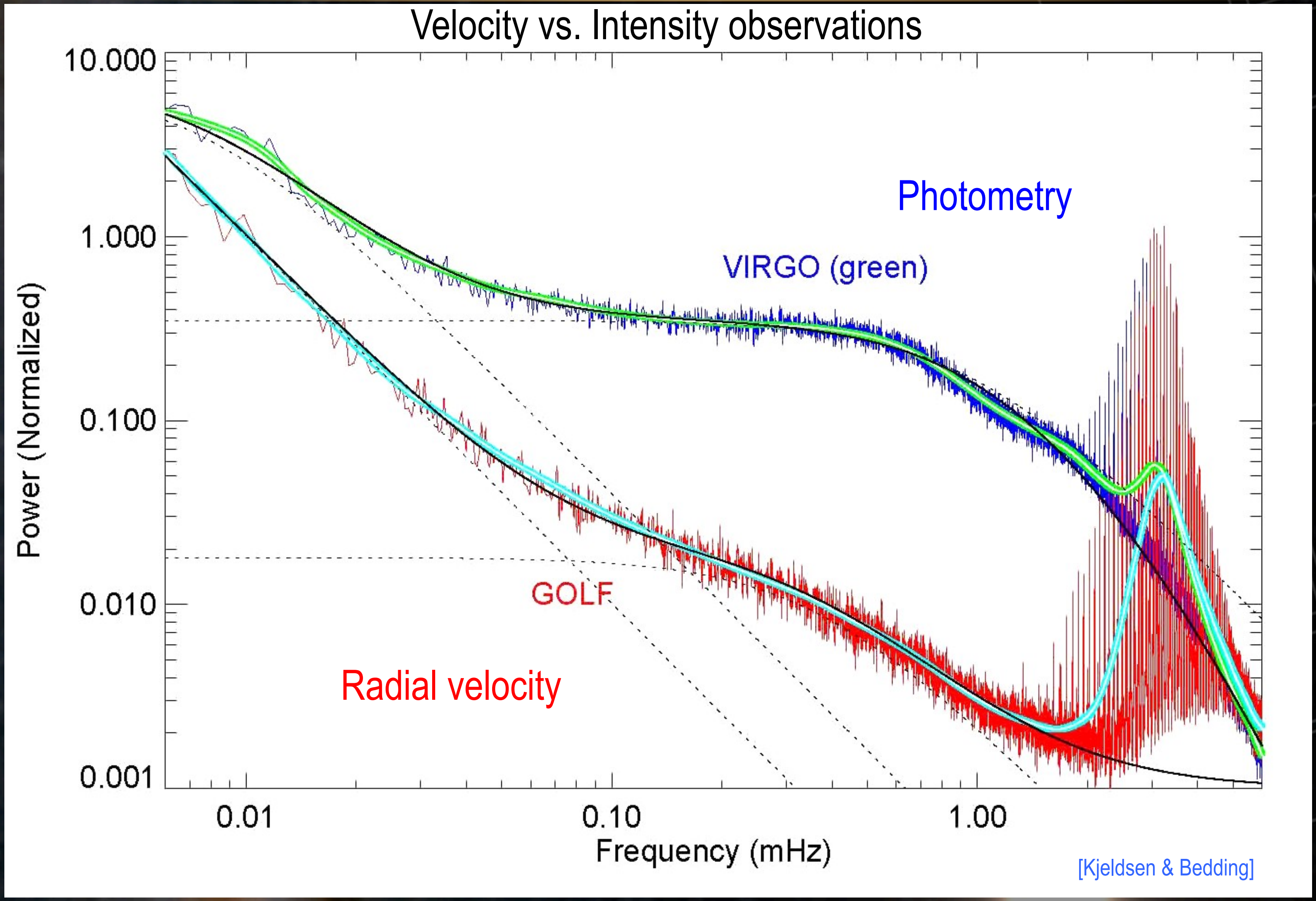
I- INSTRUMENTATION



- P-mode S/N ratio:
  - Intensity fluctuations <30
  - Velocity > 300

[e.g., Toutain et al., 1997]

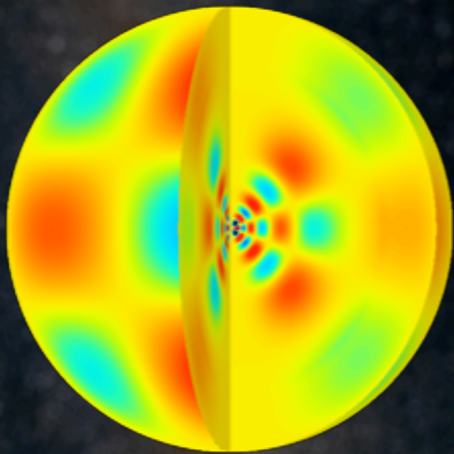
I- INSTRUMENTATION



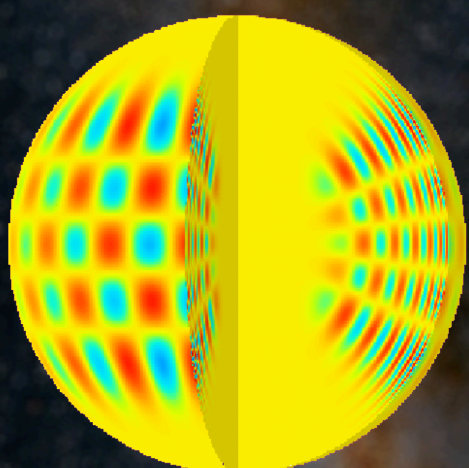
- Doppler velocity instruments
  - Requires a very high number of photons
  - Only a few stars at a time
  - High instrumental stability
- Photometric instruments
  - Less number of photons and stability
  - Many stars at a time (*Kepler* : 120,000)
  - Higher stellar background noise

I- INSTRUMENTATION

Helio- vs. astero-seismology:



- In asteroseismology we do not have spatial resolution:
  - Only low-degree modes can be measured
  - Classical pulsators
    - Higher degree modes than in S-L stars
- Poor internal resolution (with p modes only)
  - Mixed modes allow to probe the deep radiative interior
- Examples :
  - BiSON, SoHO, CoRoT, *Kepler*, MOST, SONG…

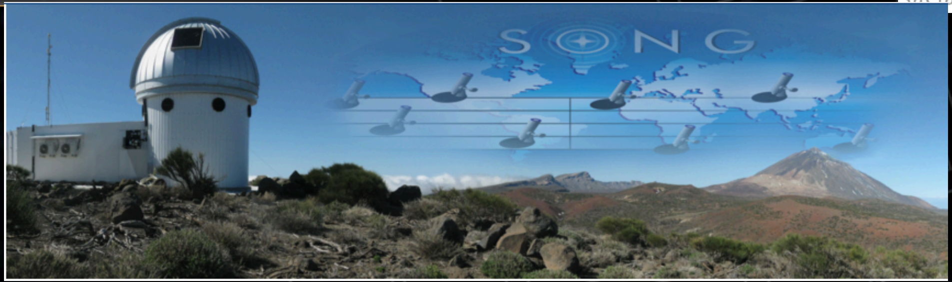


- In helioseismology we have spatial resolution:
  - Higher number of modes (several thousands)
  - Modes of different m covering different latitude ranges providing latitudinal resolution
- Examples :
  - GONG, SoHO/MDI, SDO

I- INSTRUMENTATION

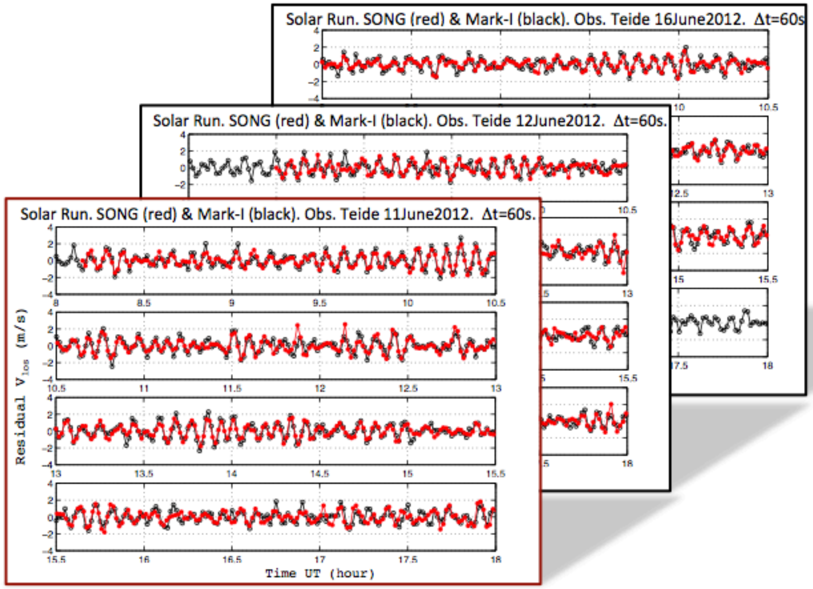
- Ground-based Observatories
  - Need to build a network
  - Problems of gaps and presence of the atmosphere
  - Easily reparation of any instrumental problem
  - Presence of the atmosphere
  - Unlimited telemetry
- Space
  - Reliability of the instruments
  - No atmosphere
  - Properties of the orbit & Telemetry
    - E.g. SAA
  - Limited telemetry

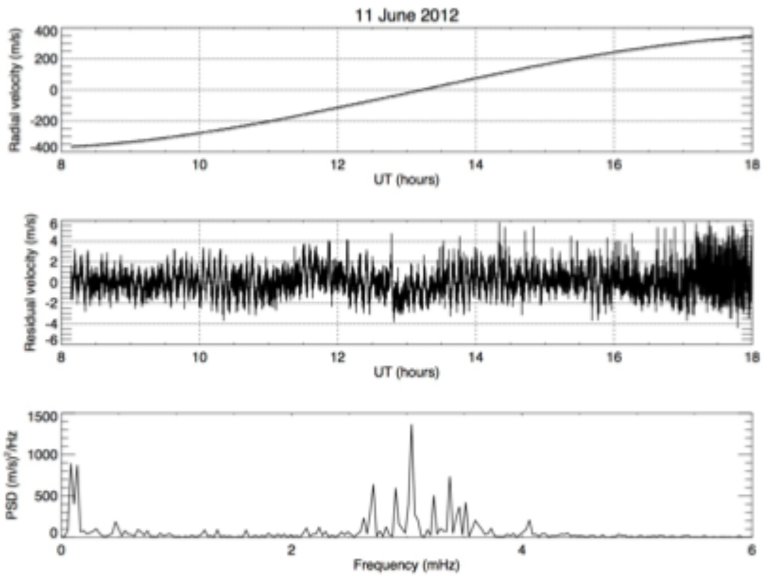
I-INSTRUMENTATION: SONG



- Ground-based network
  - Currently 1 in operations (OT)
  - 2 in construction (China)
- 1m alt-Az Cassegrain telescope
- High resolution èchelle spectrograph operating from 35.000 – 112.000 of resolution.
- Wavelength range: 4400 – 6900 A, 51 Orders
- 2k x 2k CCD detector
- Iodine cell and a Thorium-Argon lamp can be used for wavelength calibration

[Palle et al. 2013]

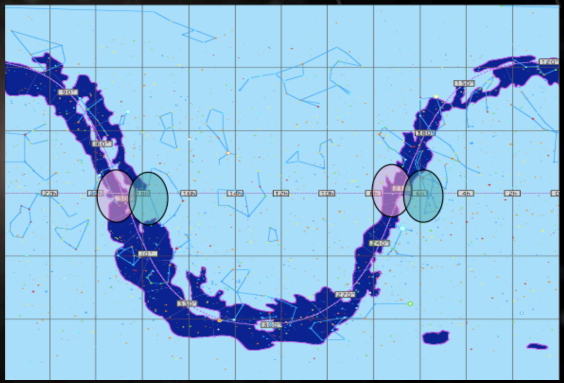




I-INSTRUMENTATION: COROT

- CoRoT (Convection Rotation & planetary Transits)
  - Launch: December 27, 2006
  - Stops: November 2012
  - 27 cm afocal telescope
  - 4 CCDs (2048x2048 pixels)
    - 2 exo; 2 sismo
  - Color information
    - Exo channel

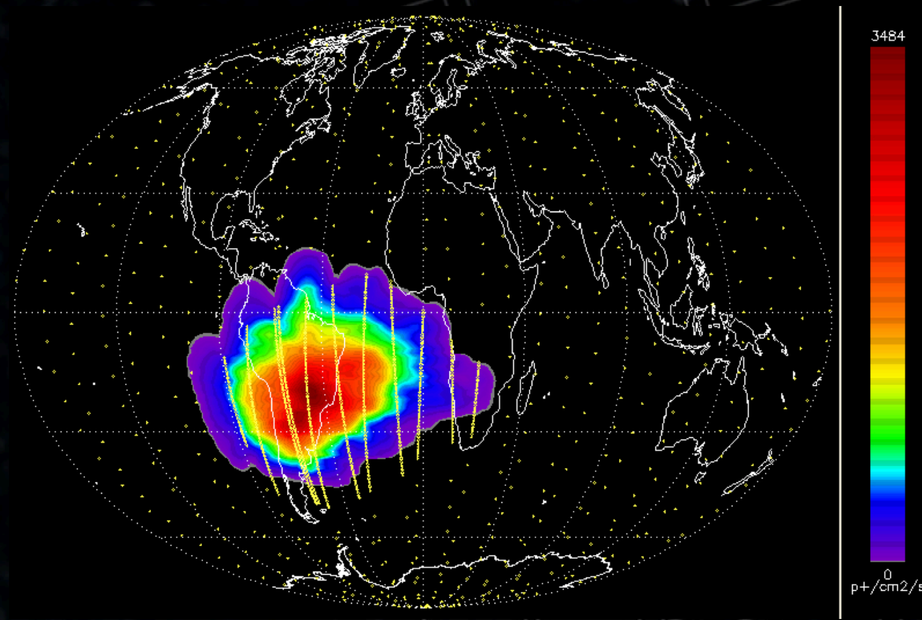
- Scientific objectives:
  - Astroseismology
    - ✓ ~100 pulsating stars
      - All HR diagram
  - Exoplanet research
    - ✓ >20000 stars



http://smsc.cnes.fr/COROT/

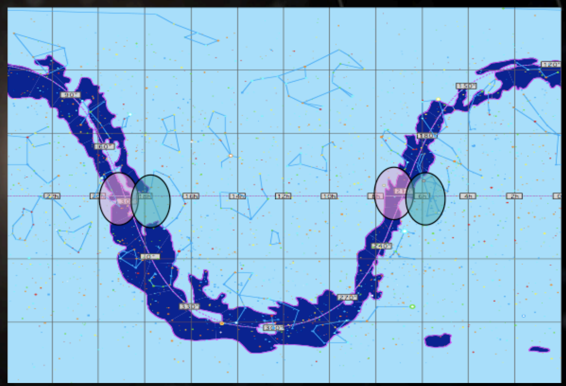
I-INSTRUMENTATION: COROT

- Low-altitude orbit
  - Increase telemetry rates
  - We cross the SAA
    - Several times per day
    - Perturbation in data acquisition
  - Harmonic of the orbit at
    - 161.7 μHz ± 11.57/2 μHz



- Data is delivered at two cadences
  - LC: ~8 minutes
  - SC: 32s

[Auvergne et al. 2009]

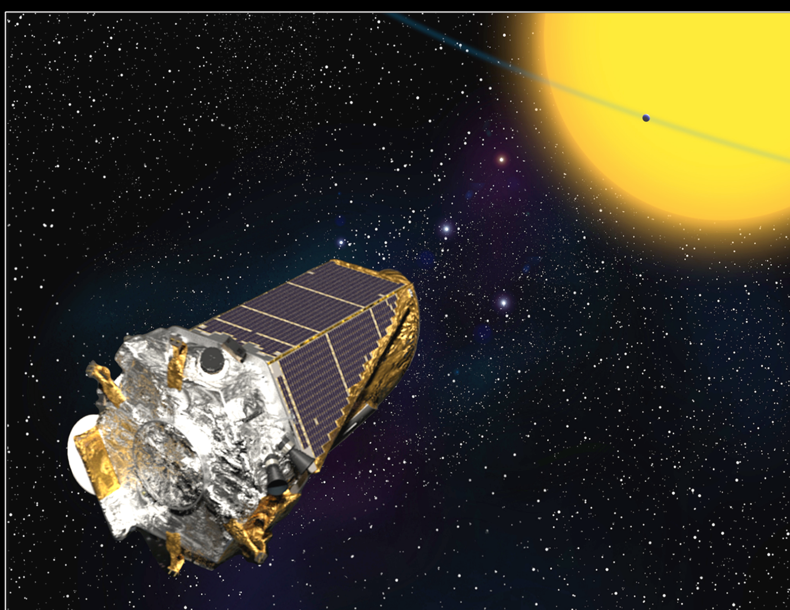


http://smsc.cnes.fr/COROT/

I-INSTRUMENTATION: *KEPLER & K2*

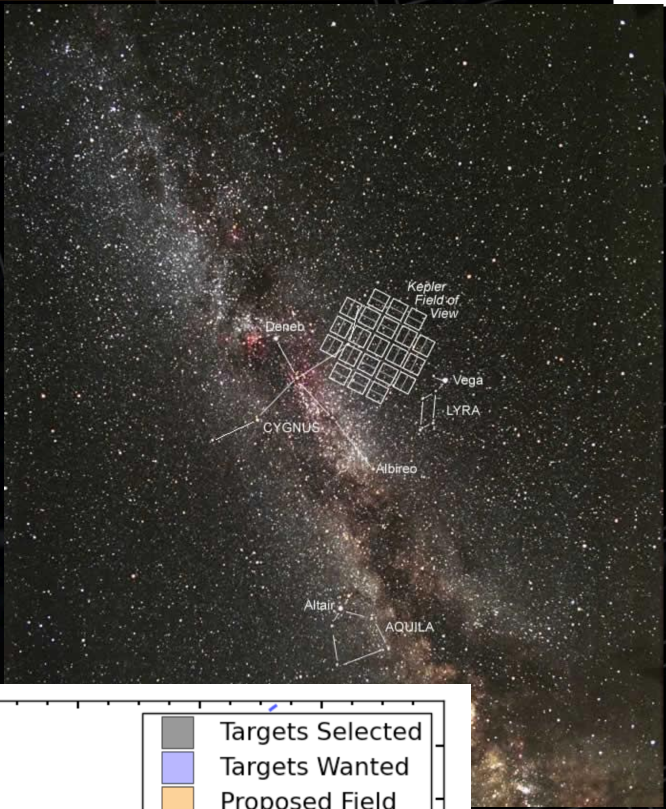
- 94 cm Telescope
- 195000 observed stars
  - ~540 S-L stars [Mathur et al. to be submitted]
  - >15000 Red giants
- 4 years mission
- K2 mission
  - Using 2 reaction wheels

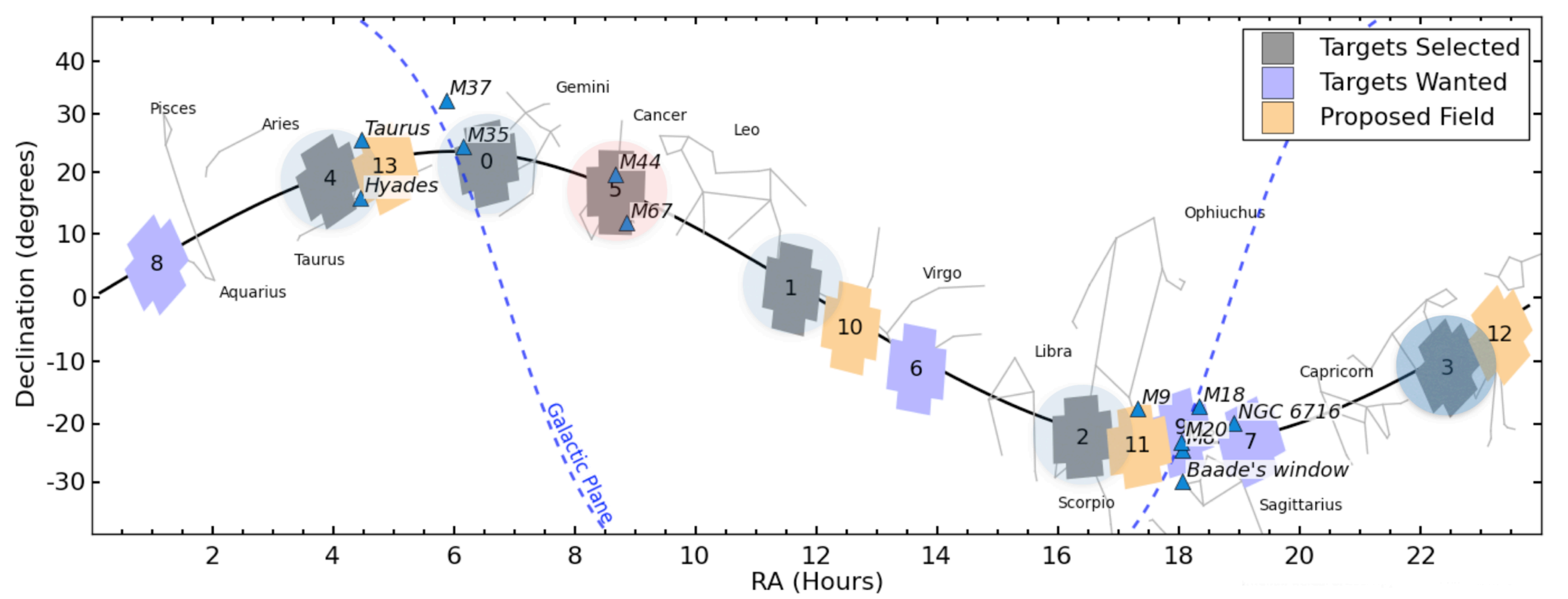
March 6, 2009



I-INSTRUMENTATION: *KEPLER*

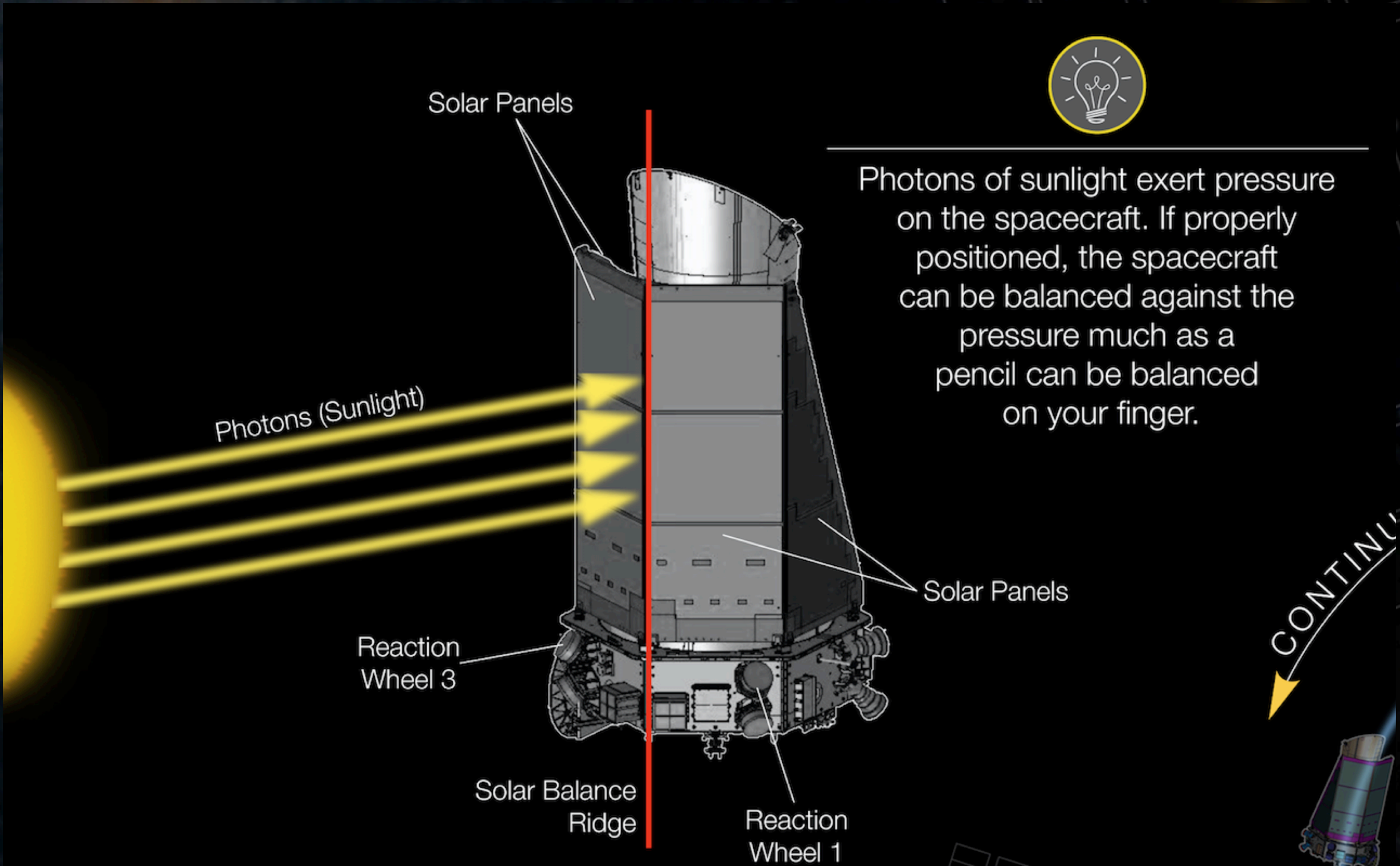
- Earth-trailing orbit (372.5 days)
- 1 single field Cygnus-Lyra (*Kepler*)
- 100 sq.deg. fields close to the ecliptic (K2)
- Every three months:
  - Roll of the satellite (*Kepler*)
    - Stars are observed in 4 different CCDs
  - Change of the field (K2)





I-INSTRUMENTATION: K2

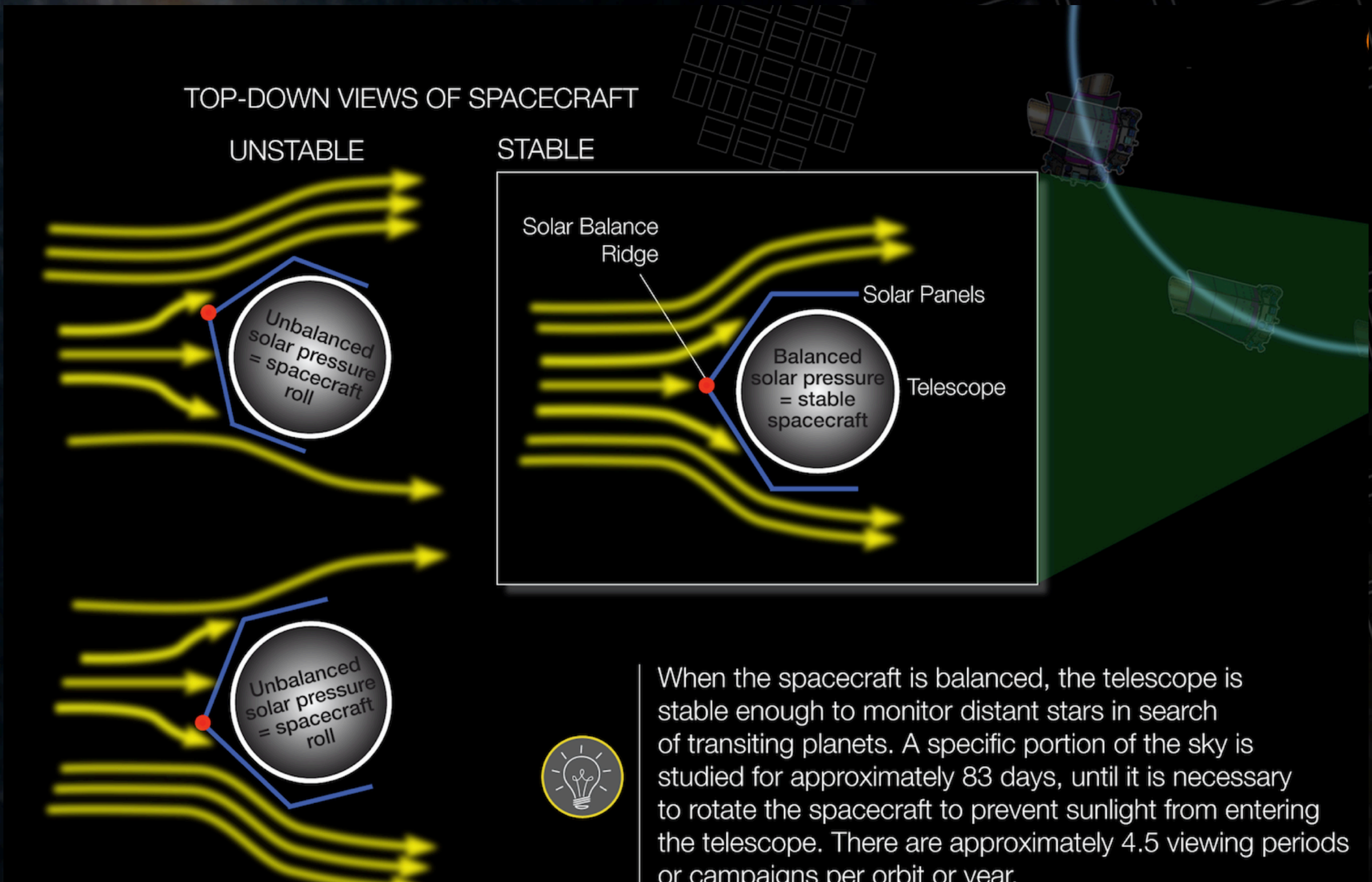
- Radiation pressure pushes the satellite
  - 3 reaction wheels needed to stabilize it



[Barclay, KASC8, 2015]

I-INSTRUMENTATION: K2

- Radiation pressure pushes the satellite
  - 2 reaction wheels function ⟶ Sun in the back

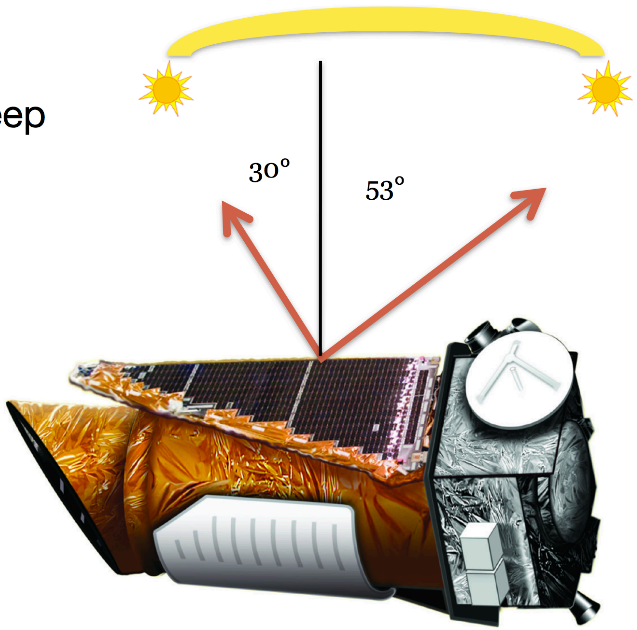


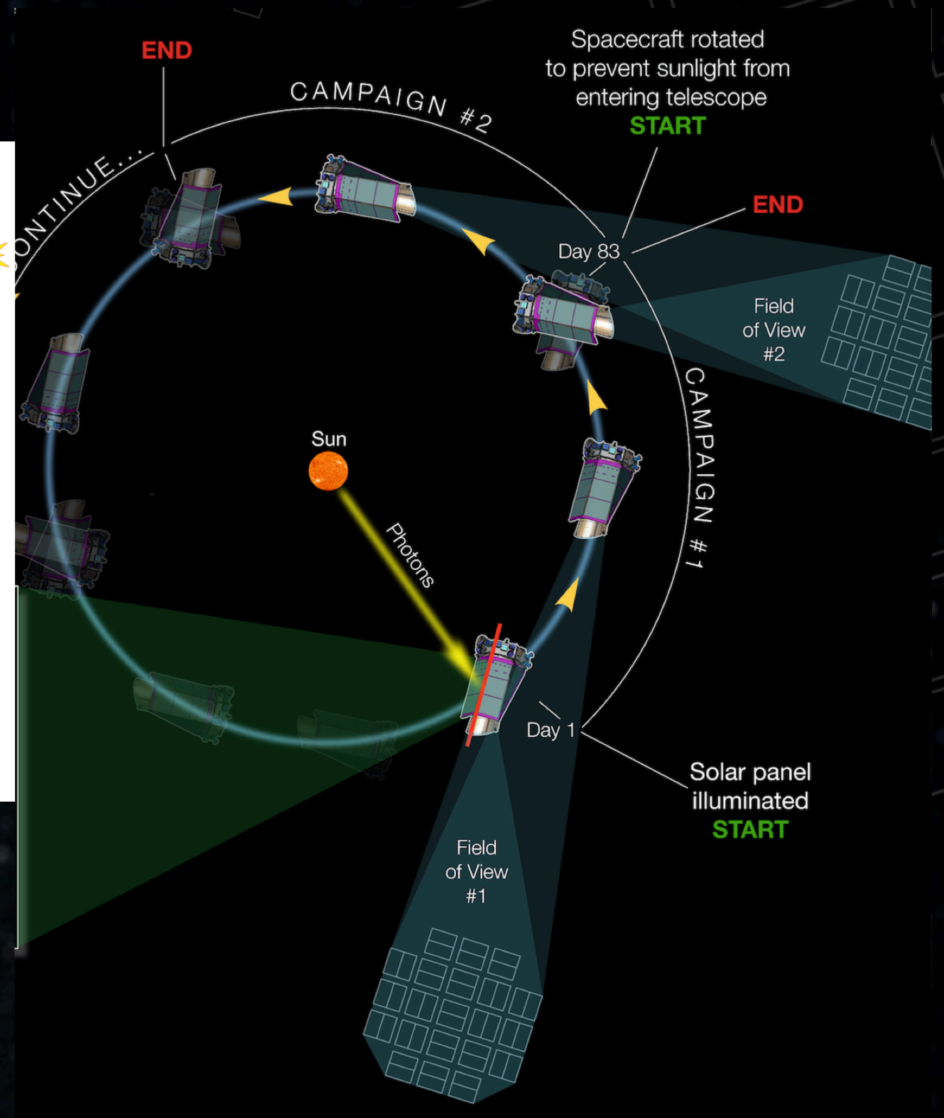
[Barclay, KASC8, 2015]

I-INSTRUMENTATION: K2

Spacecraft must keep solar panel pointed at the sun.

Limits time it can stare at a single field to 80-90 days (depending on the spacecraft orbital phase)





[Barclay, KASC8, 2015]

I-INSTRUMENTATION: *KEPLER*

- *Kepler* has two running modes

[Koch et al. 2010]

  - Short cadence
    - At any time 512 stars can be measured at a sample rate of 58.85s
  - Long cadence
    - All the rest of the stars (~170,000) are sampled at a rate of 29.4 minutes
  - Integration time is:
    - for a single cadence: 6.02s
    - with a readout time of 0.52s (=> ~91% integration time)

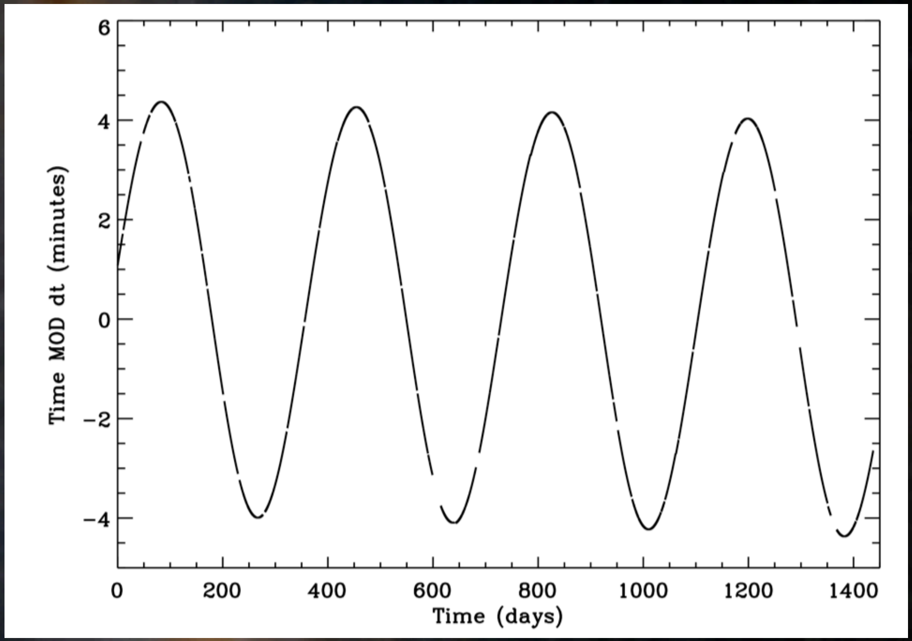
[Gilliland et al. 2010]

  - NASA provides 3 type of light curves:
    - Simple Aperture Photometry
      - Corrected from instrumental effects using a small aperture
    - PDC-msMAP
      - Light curves could by filtered from periods longer than 3 days
    - "Pixel-data" images
      - Personalized aperture photometry optimized for asteroseismology

[e.g. García et al. 2011; Handberg & Lund 2014]

I-INSTRUMENTATION: *KEPLER*

- About the *Kepler* timing (also applied to CoRoT):
  - 372.5- day heliocentric
- Pulsations will be phase modulated in the spacecraft frame of reference
  - because there is a component of the orbital motion of *Kepler* along the line-of-sight (target) direction, which delays or advances the arrival time of light from the star.
    - The magnitude of this effect will depend on the position of the star on FOV
    - To compensate for this effect the *Kepler*/CoRoT time stamps are corrected Barycentric Time
    - An important consequence is that the intervals between time stamps are no longer regular, but are modulated periodically on a ~ 1-yr timescale.



[García et al. 2014]

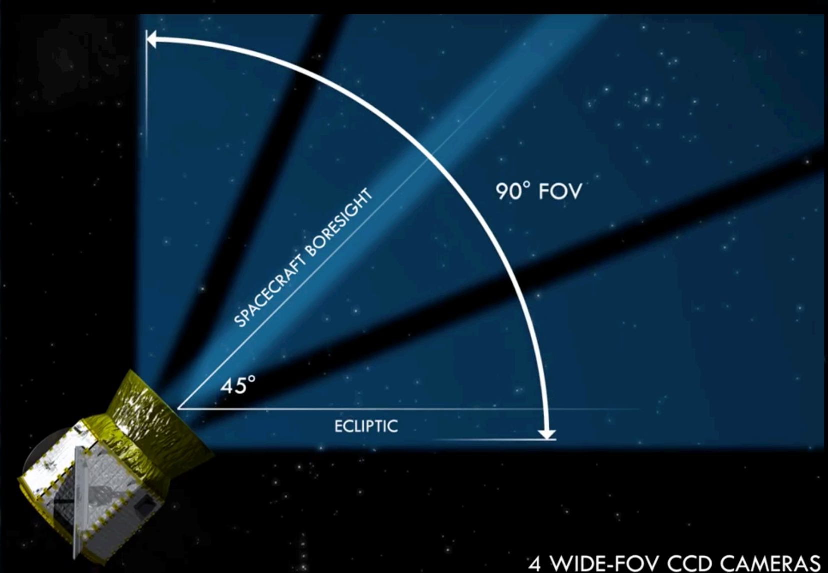
I-INSTRUMENTATION: TESS

Transiting Exoplanet Survey Satellite (TESS)

TESS HAS A SIMPLE "*STARE AND STEP*" OBSERVATION STRATEGY

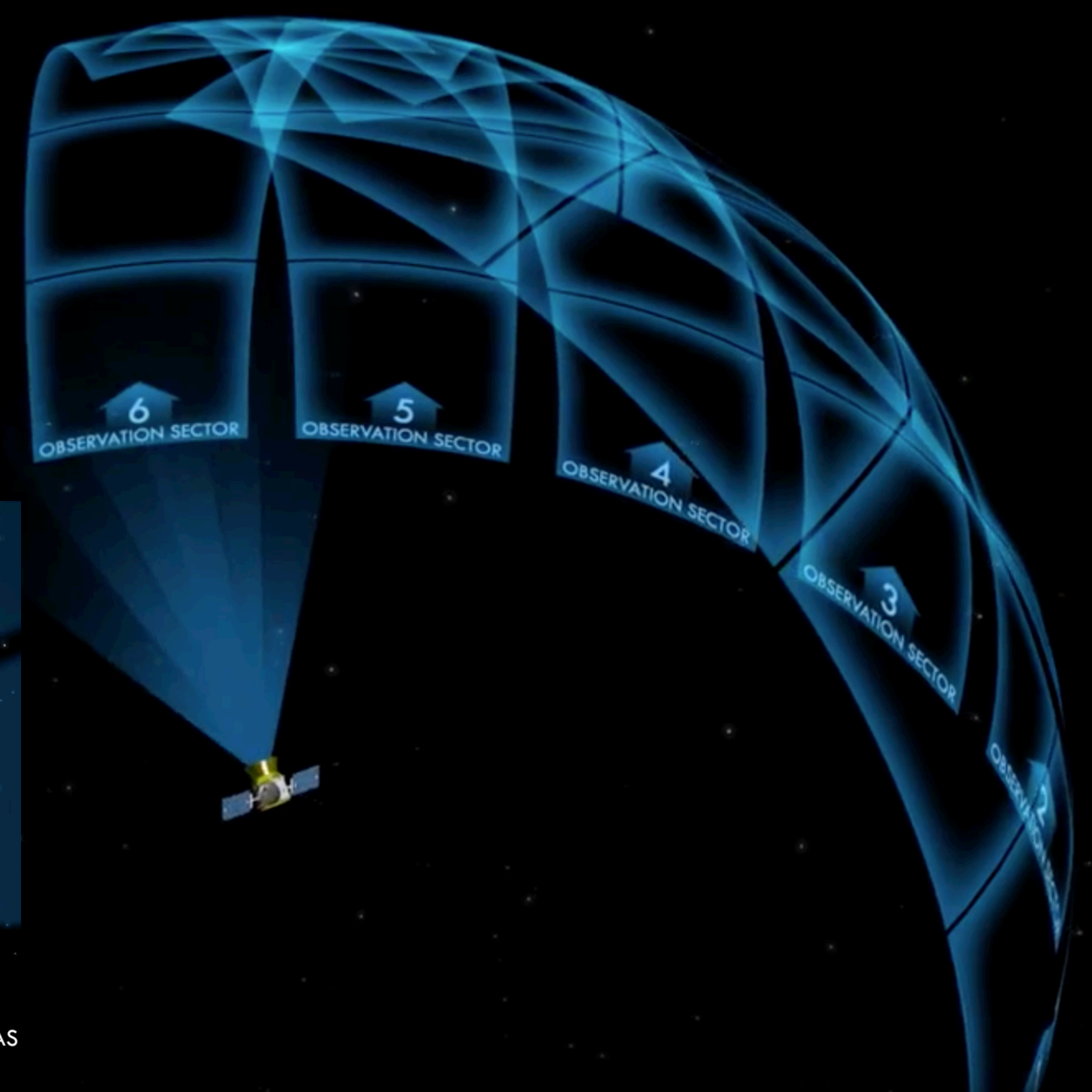
ANTISOLAR, FIXED IN INERTIAL SPACE FOR ~27 DAYS, OR 2 ORBITS

2-YEAR ALL-SKY SURVEY HAS 26 OBSERVATION SECTORS, 13 PER YEAR



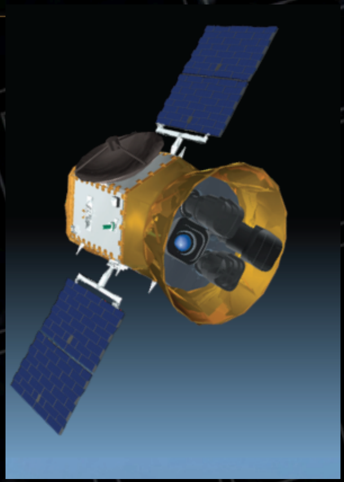
4 WIDE-FOV CCD CAMERAS

- All-sky survey
  - Bright targets (*Kepler*-TESS Δmag ≈ 5)

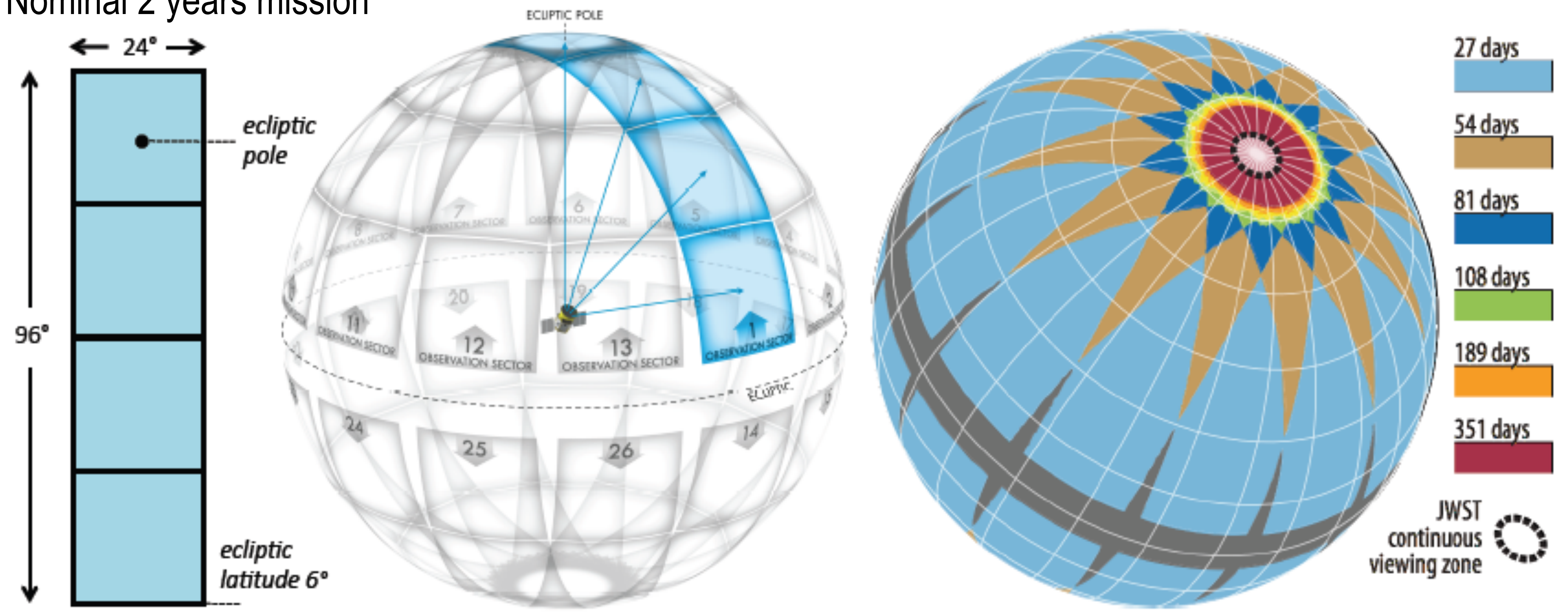


I-INSTRUMENTATION: TESS

- All sky time series data (27 d – 351 d)
- Bright targets (*Kepler*-TESS Δmag ≈ 5)
- At any given time:
  - 60 targets with 20 sec sampling
  - 750 targets with standard 2 min sampling
  - Full Frame Images (30 min sampling)



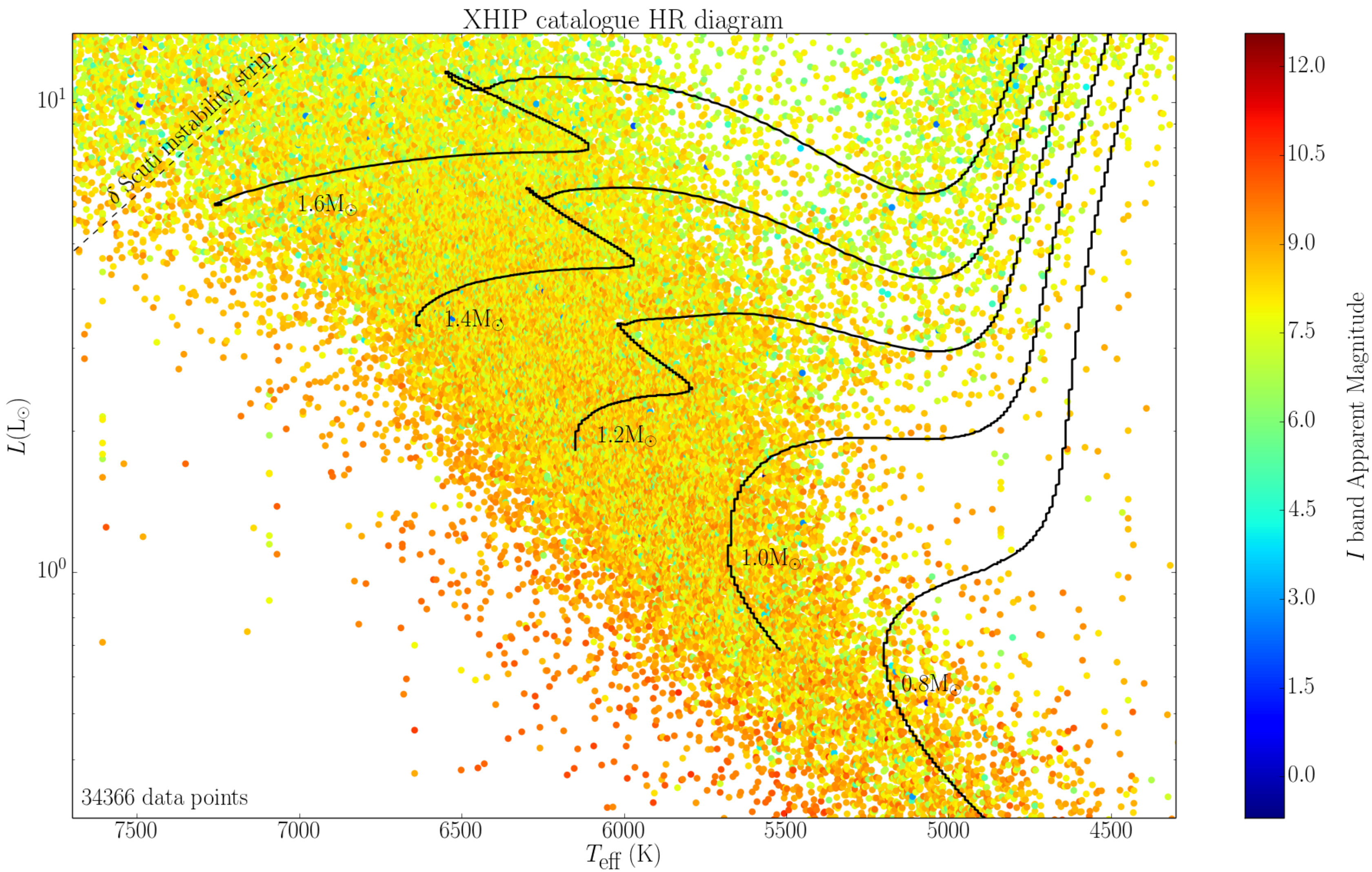
Nominal 2 years mission



[Ricker, Winna, Vanderspek and Latham et al.]

I-INSTRUMENTATION: *KEPLER*

Simulations by Mathew Schofield, Tiago Campante and Bill Chaplin, Birmingham University



[Kjeldsen, KASC8, 2014]

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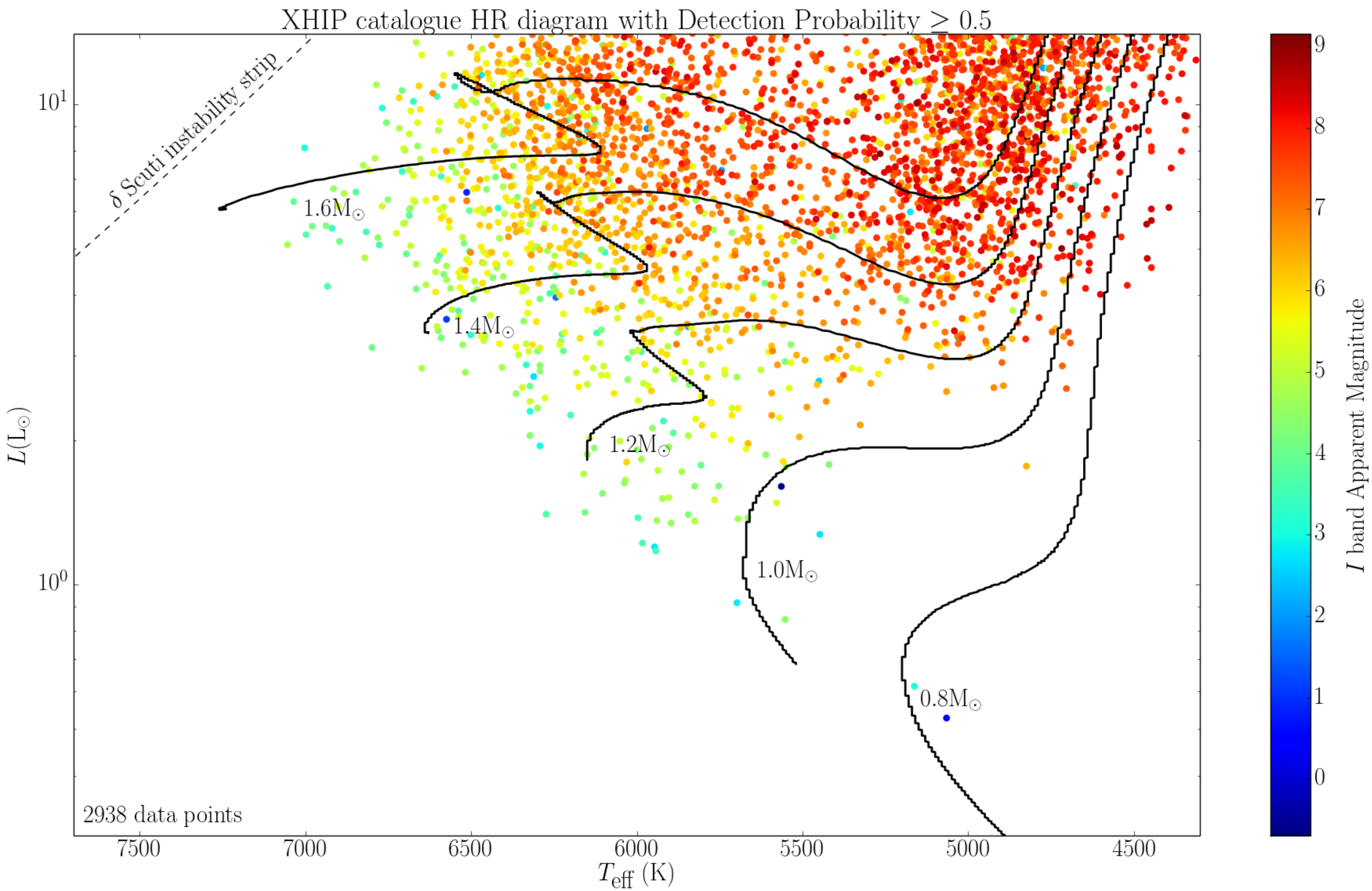

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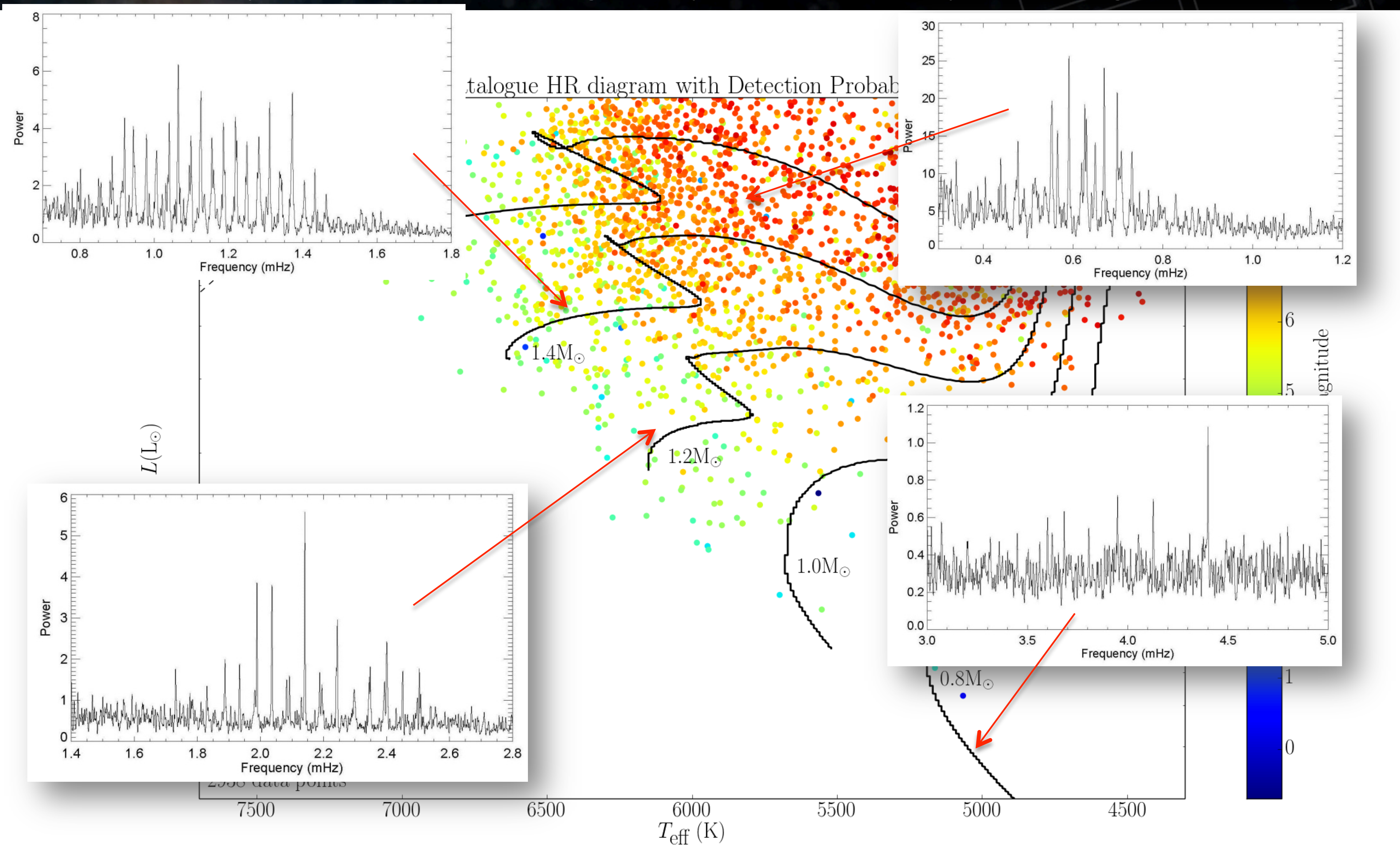

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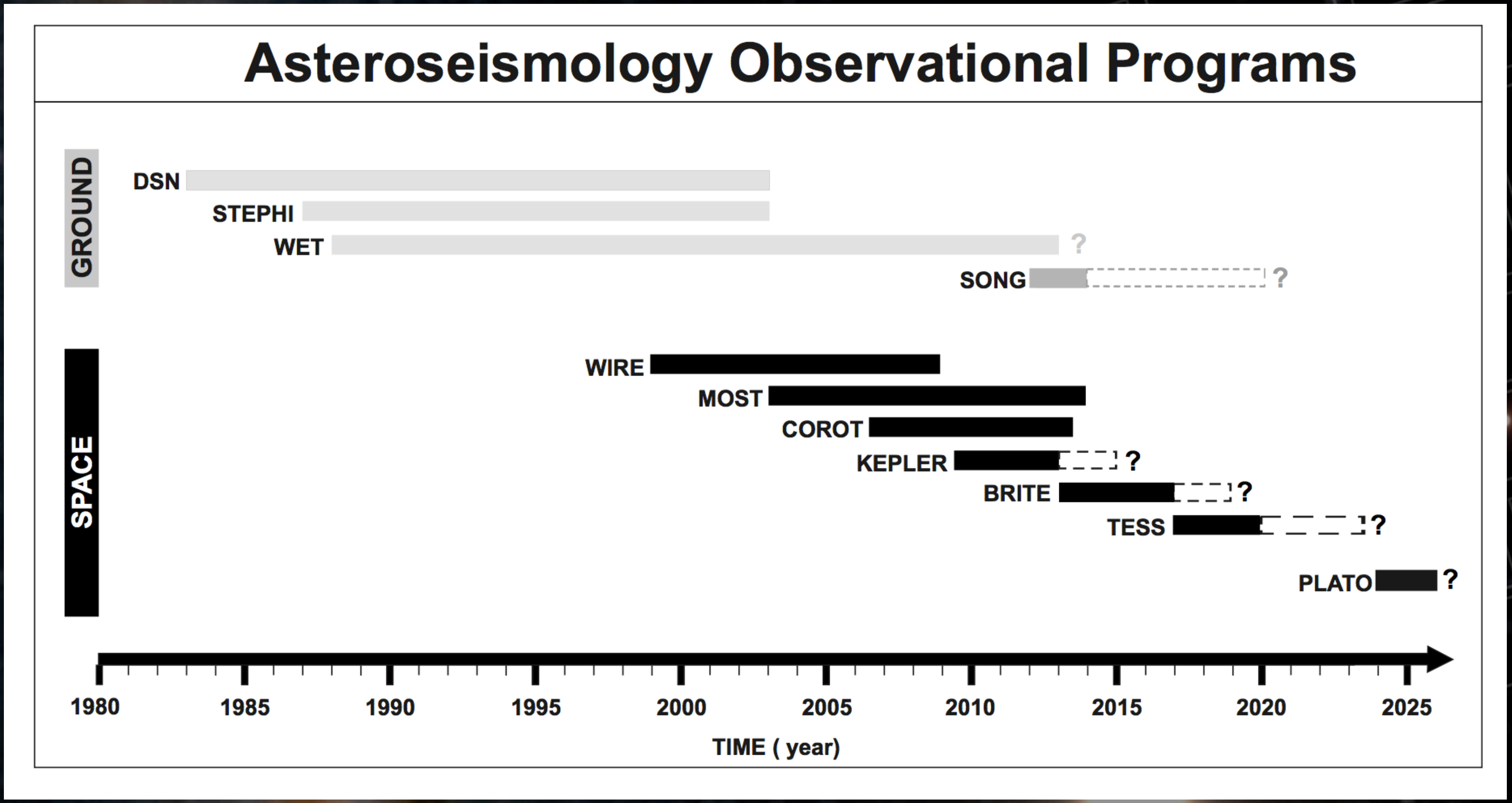
I- INSTRUMENTATION



- Continuous observational effort of the stellar community since 80's
  - Huge amount of archive data + new observations

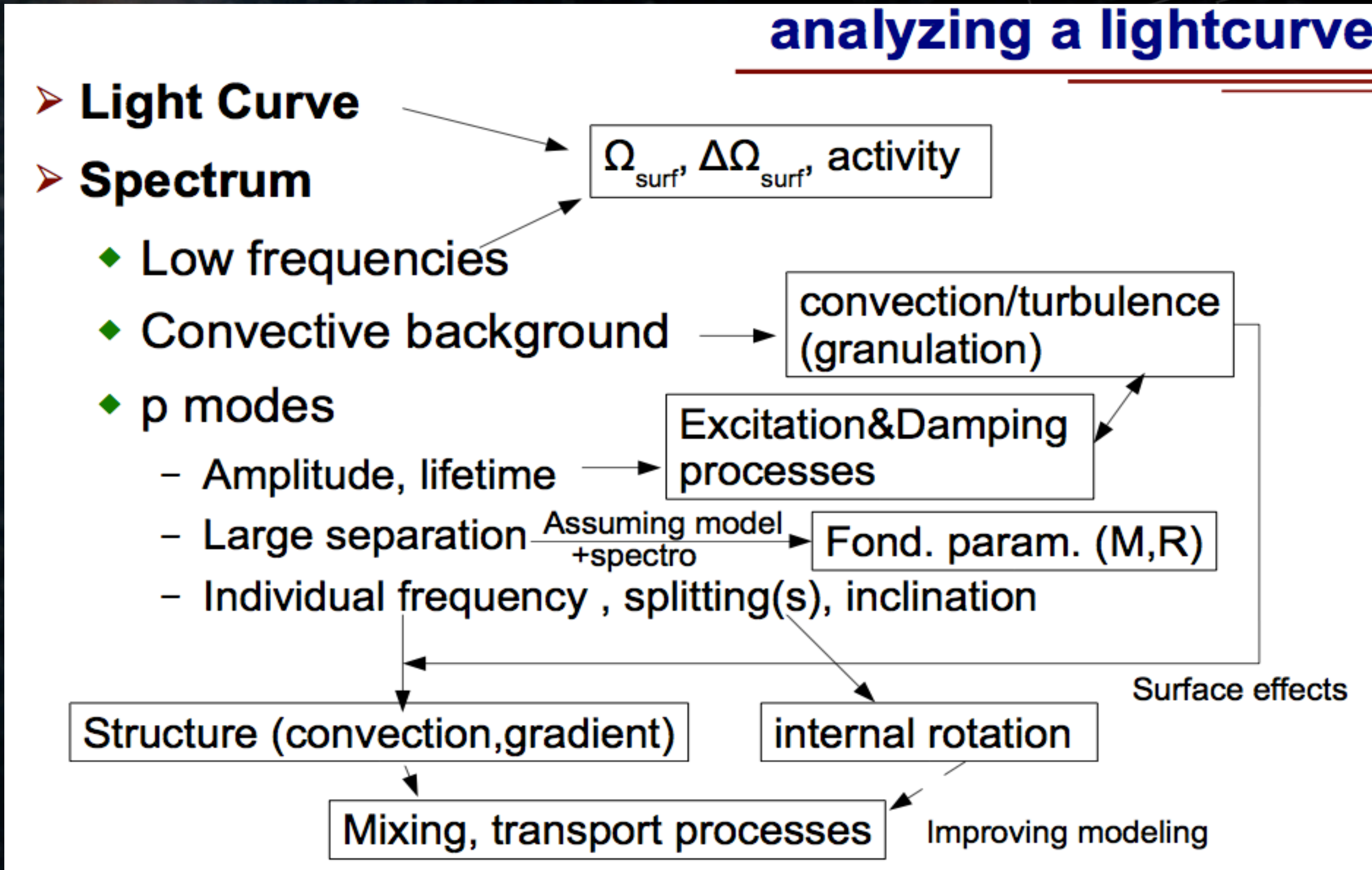
[Appourchaux & Grundhal, 2015]

I-INSTRUMENTATION: CONCLUSIONS

- Two main observables can be used:
  - Doppler velocity
    - A few stars at a time
  - Intensity
    - Less SNR, higher convective-noise background
    - Many stars at a time (thousands to hundred thousands)
- In asteroseismology
  - No spatial resolution
    - Low-degree modes (S-L stars)
- Ground-based Observatories
  - Need to build a network
  - Problems of gaps and presence of the atmosphere
- Space
  - Reliability of the instruments
  - Properties of the orbit & Telemetry

II -Analyzing the data

II-ANALYZING THE DATA

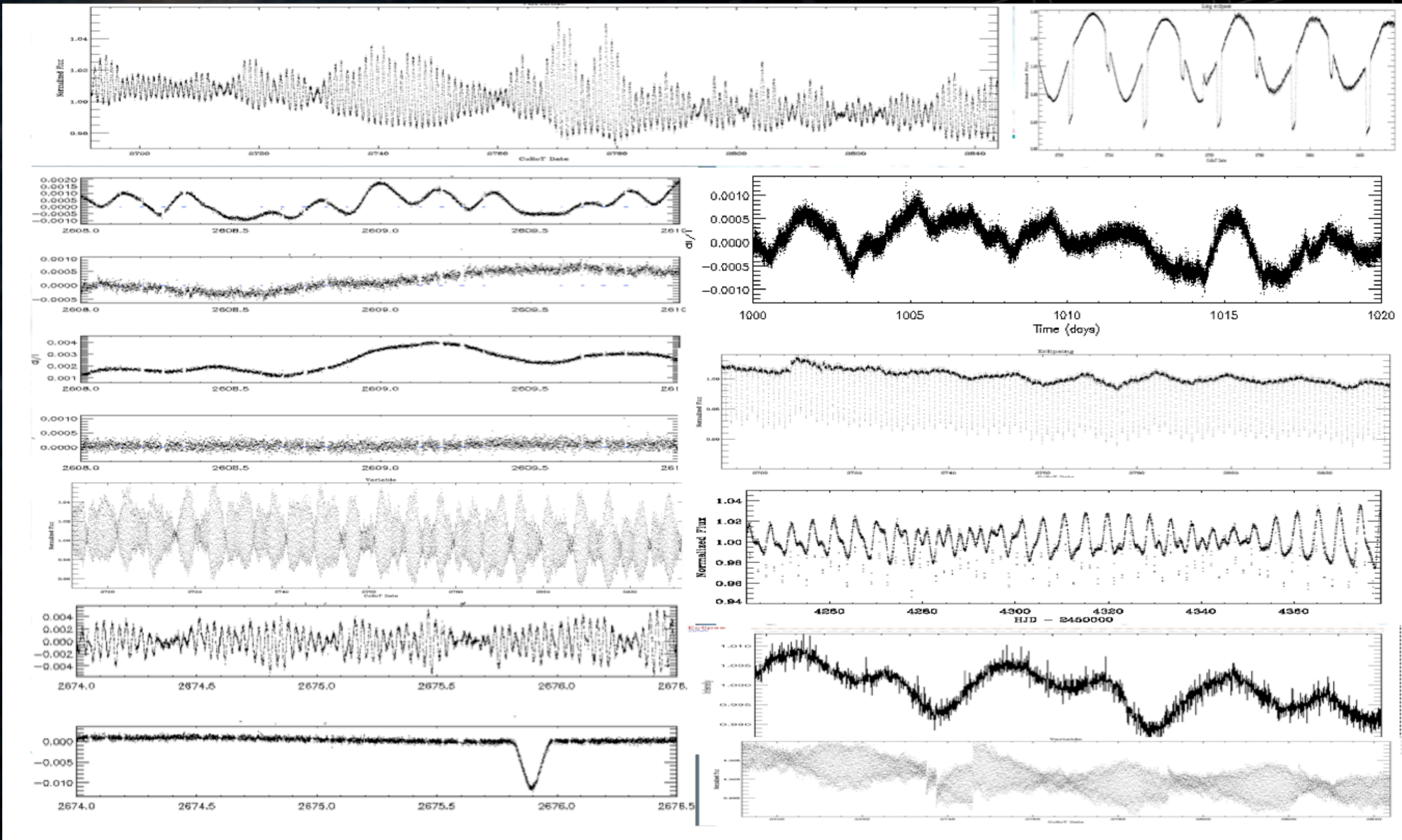


[extracted form Ballot et al. 2010]

II-Light Curves:

Surface rotation

II-LIGHT-CURVE ANALYSIS : SURFACE ROTATION

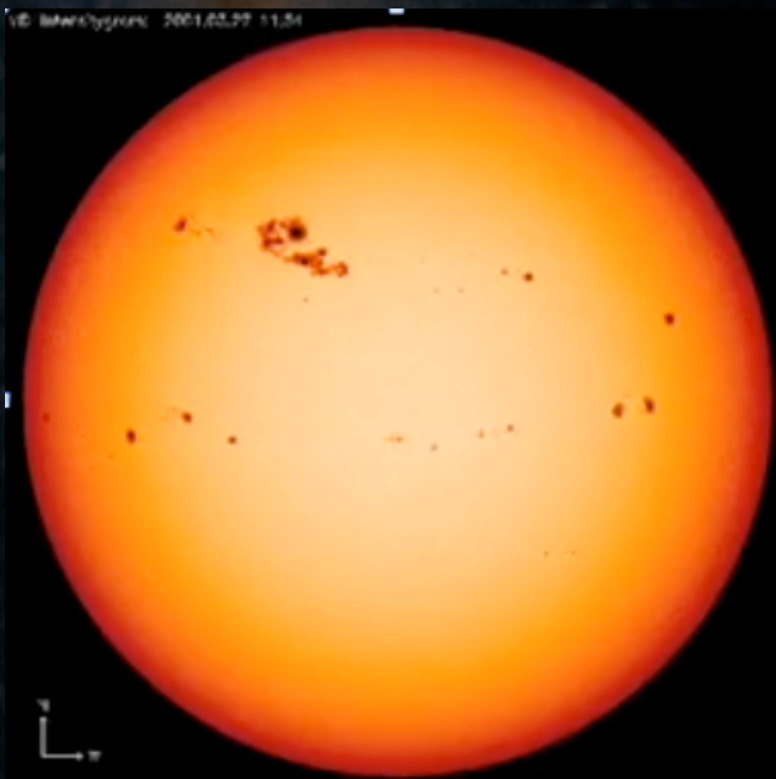


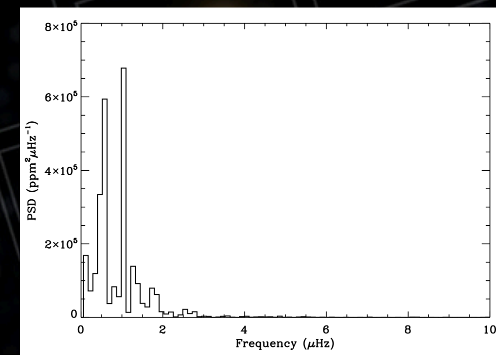
Courtesy A. Baglin

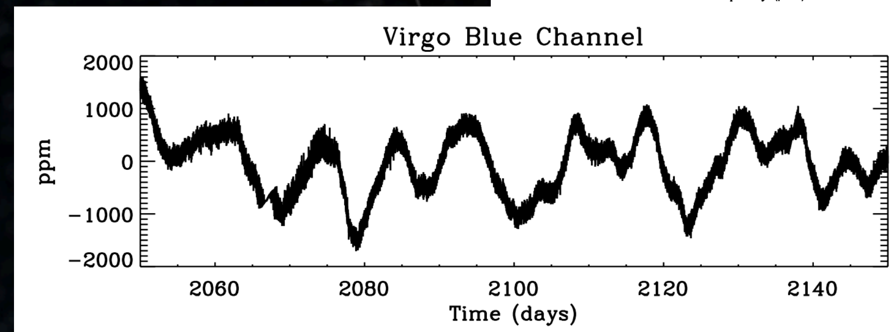
II-LIGHT-CURVE ANALYSIS : SURFACE ROTATION

- We study the signature in the light-curve of stellar spots crossing the visible disk of stars
  - Gives the surface rotation corresponding to the active latitudes
    - Allows to also determine the surface differential rotation

      [e.g. CoRoT targets: Mosser et al. 2009, Mathur et al. 2010, 2012…]







Solar Activity Maximum

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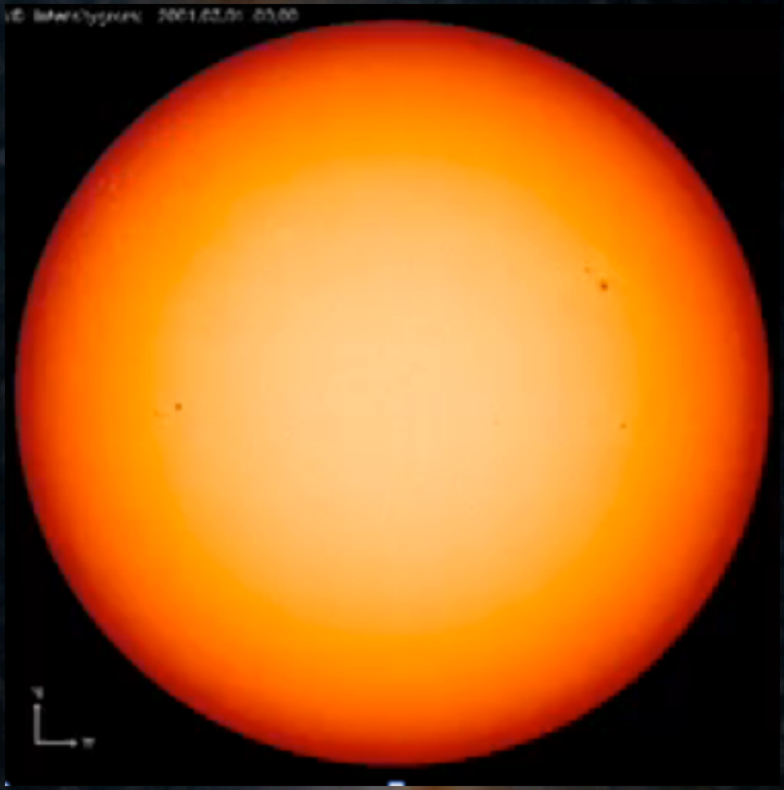
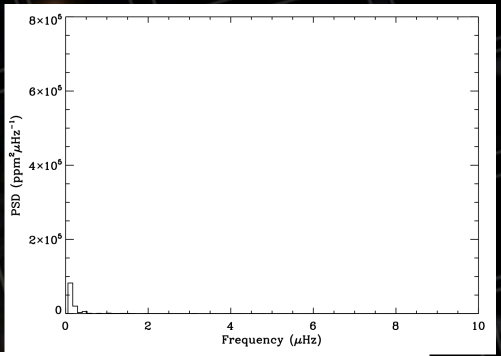
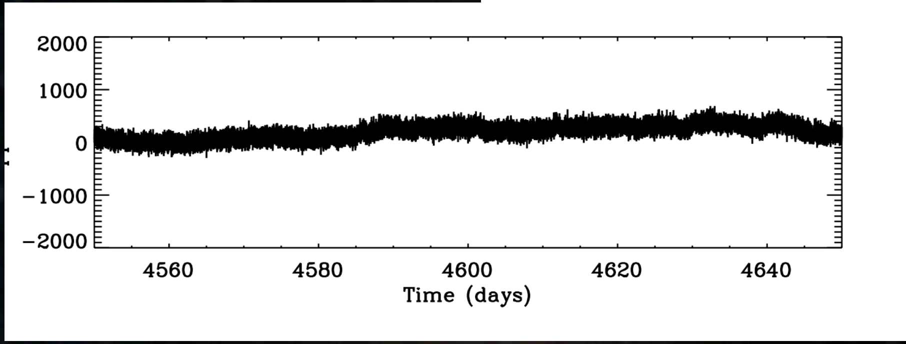


Solar Activity Minimum





II-LIGHT-CURVE ANALYSIS : SURFACE ROTATION

- Techniques based on the analysis of the autocorrelation of the light curve

- Spot modelling

- Techniques based on the analysis of the low-frequency part of the Periodogram

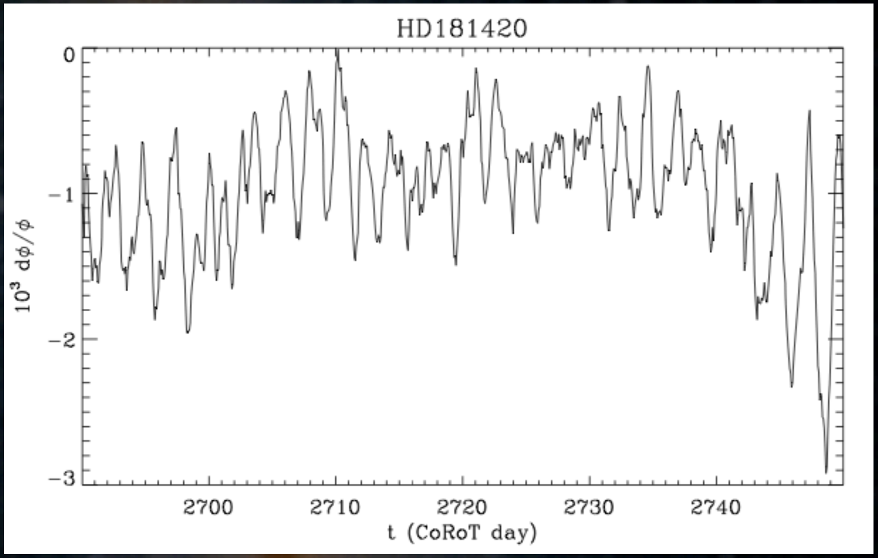
  - Highest peak (or peaks) in a given frequency range

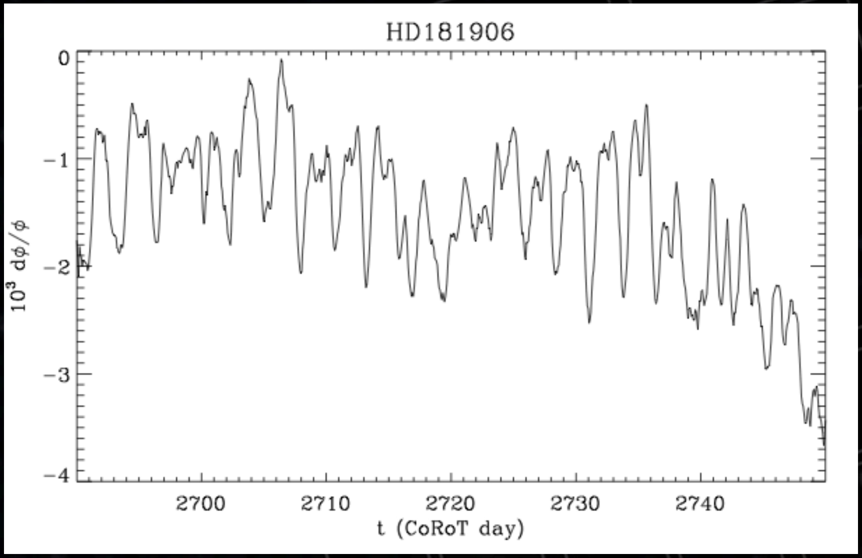
  - Wavelet power spectrum (& time frequency analyses)

Each analysis technique has its own pros and cons

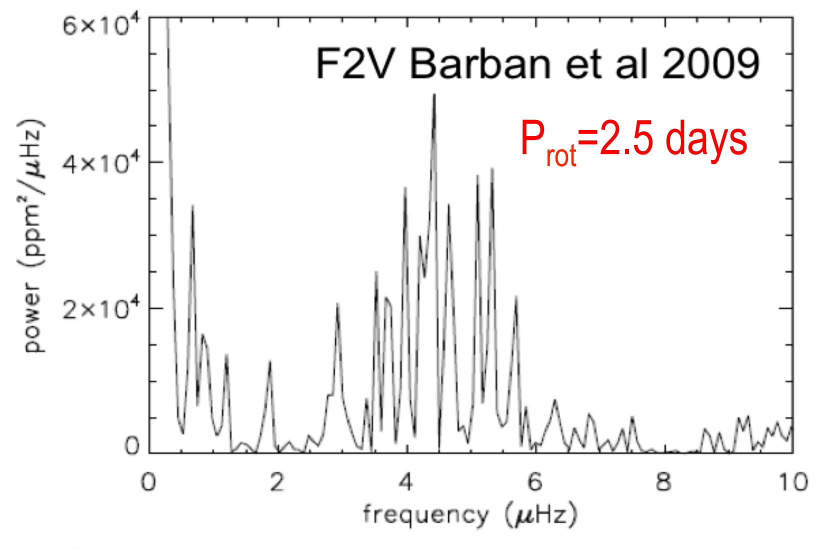
II-LIGHT-CURVE ANALYSIS : SURFACE ROTATION

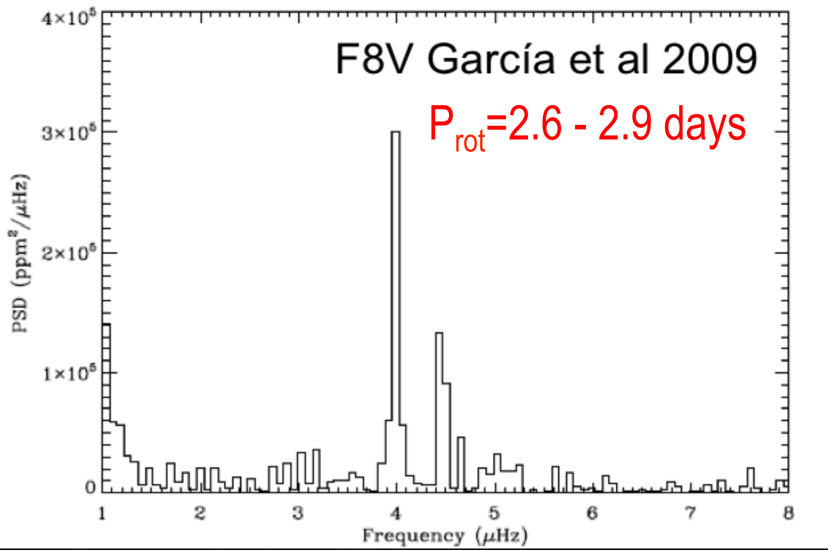
- Examples of two CoRoT F Stars





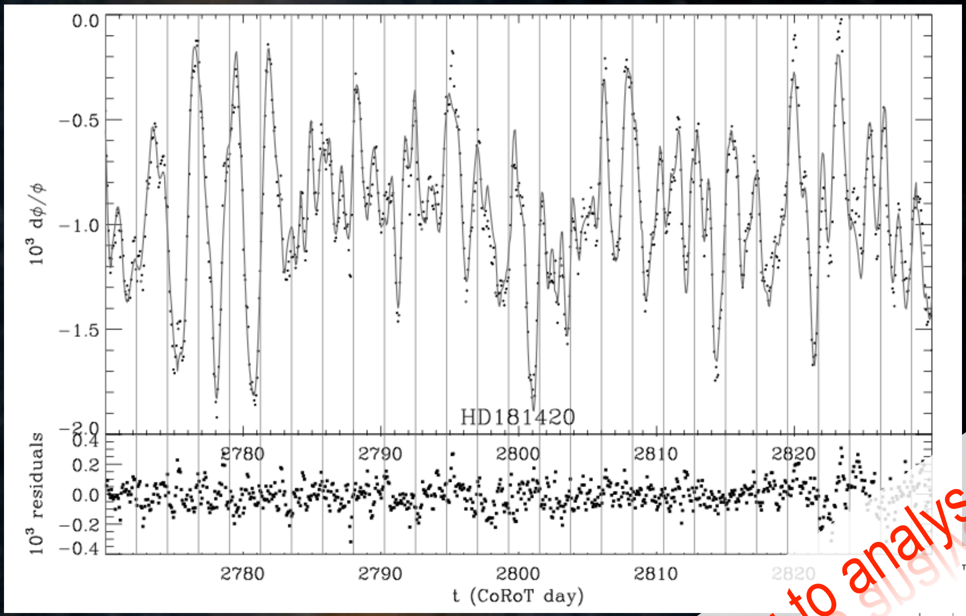
- Analysis of the low-frequency range of the periodogram





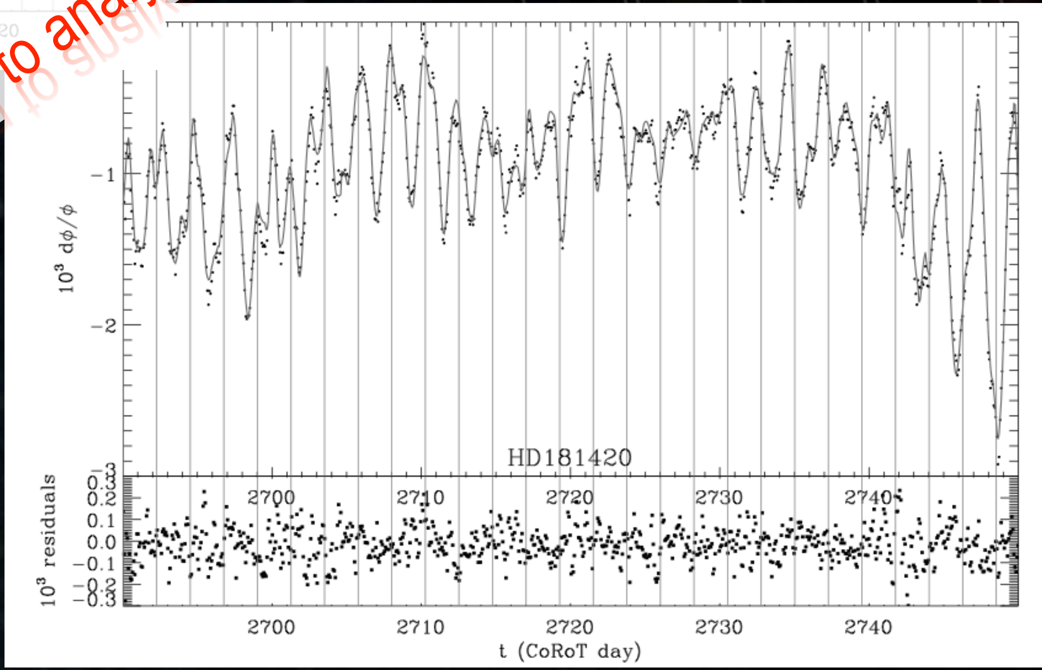
II-LIGHT-CURVE ANALYSIS : SURFACE ROTATION

- Spot modelling
  - Robust estimation of:
    - Average rotation
    - Spot lifetime
  - More uncertain estimation of:
    - Size and distribution of spots
    - Inclination of the star
    - Differential rotation



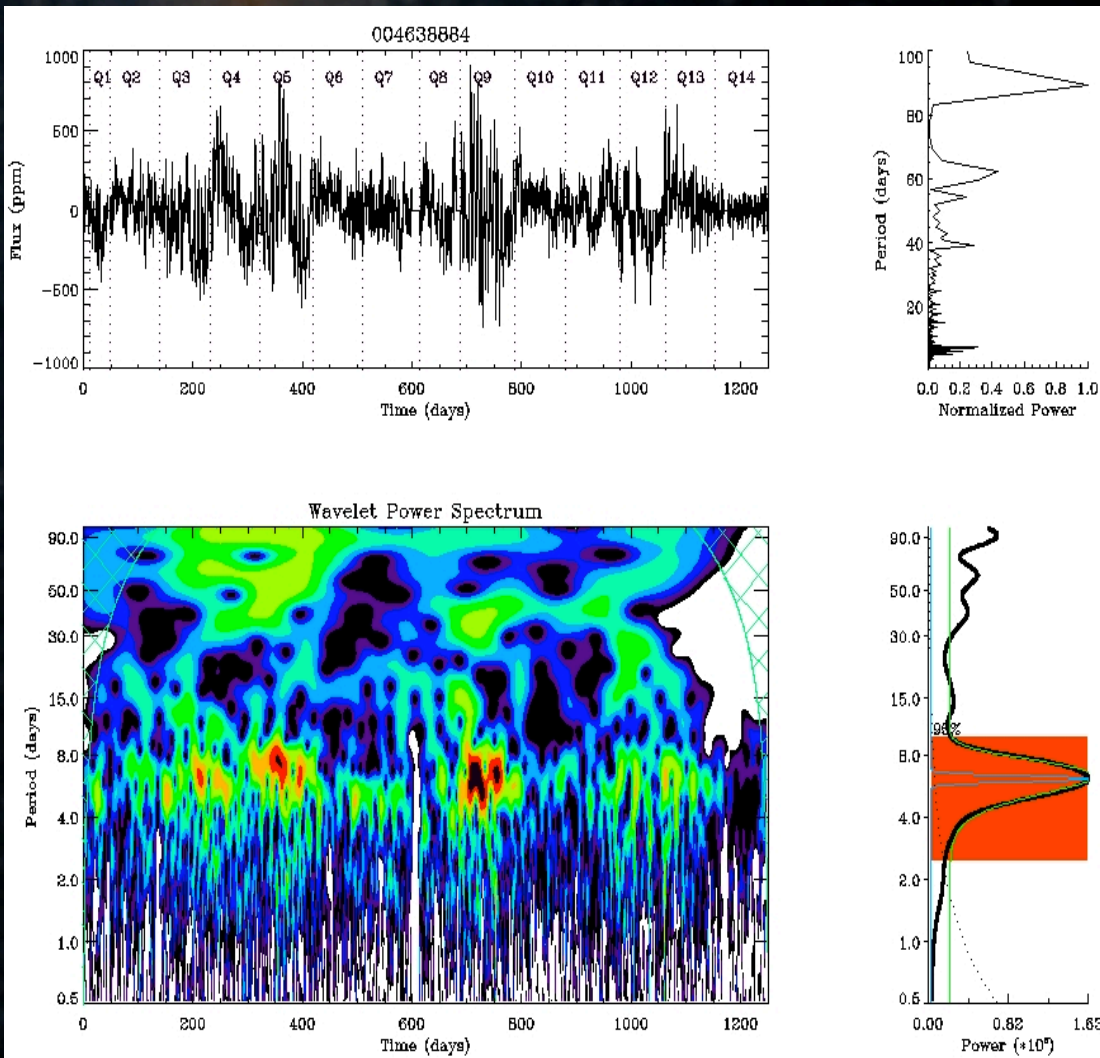
[Mosser et al. 2009]

Very time consuming to analyse hundred to thousand stars



- Techniques based on the analysis of the low-frequency part of the Periodogram
  - Wavelet power spectrum

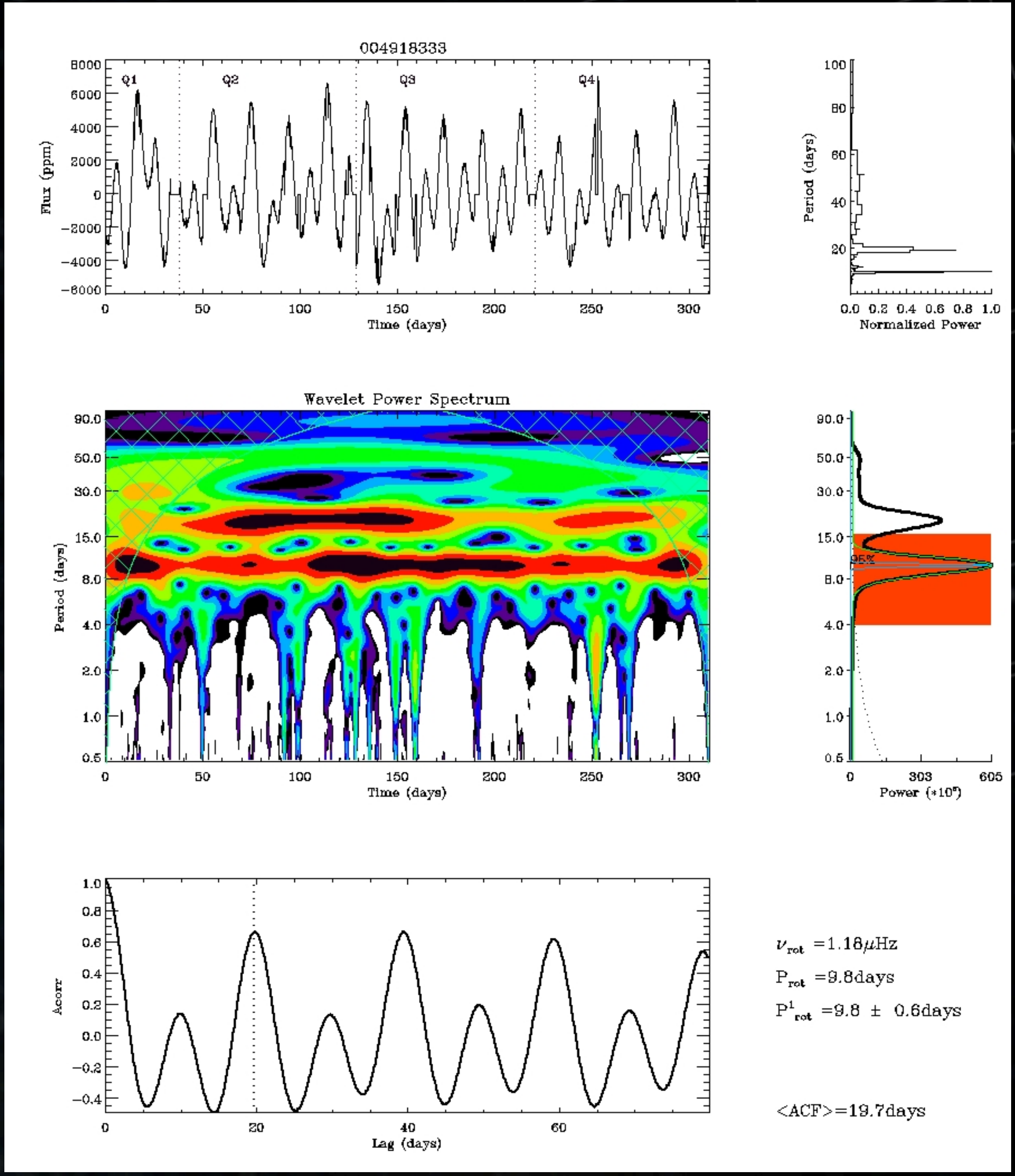
[Torrence & Compo 1998; Liu et al. 2007; Mathur et al. 2010]



- Takes into account:
  - Continuity of the signal
- Temporal evolution of the signal:
  - Easy to check
    - Correction problems

II-LIGHT-CURVE ANALYSIS : SURFACE ROTATION

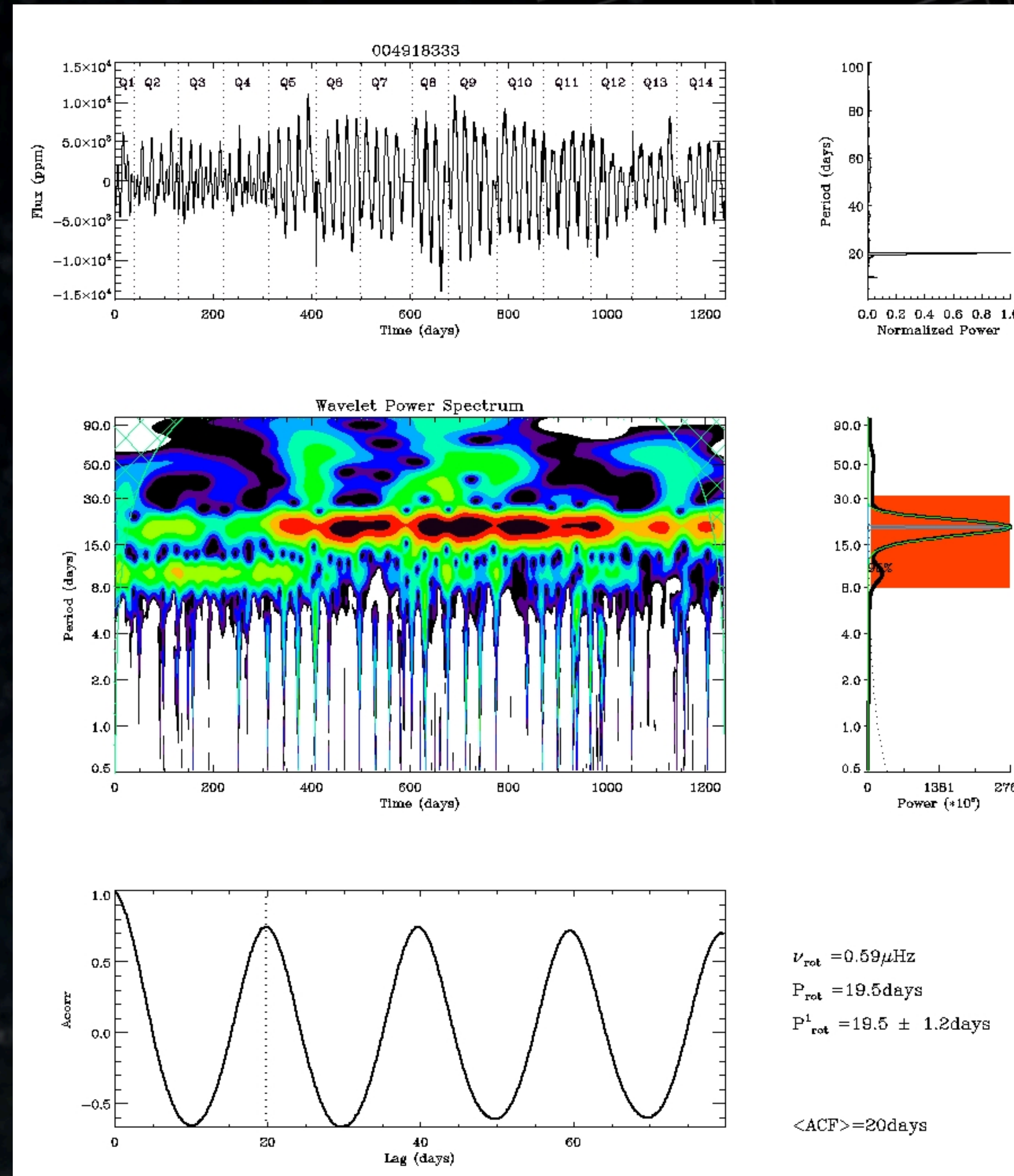
- Techniques based on the analysis of the low-frequency part of the Periodogram
  - Problem:
    - $2^{nd} > 1^{st}$ harmonic
    - Check half of P_{rot}
- Autocorrelation
  - Powerful for capturing the correct P_{rot}
    - When there are two well defined active longitudes



[KIC4918333 from McQuillan et al. 2013]

II-LIGHT-CURVE ANALYSIS : SURFACE ROTATION

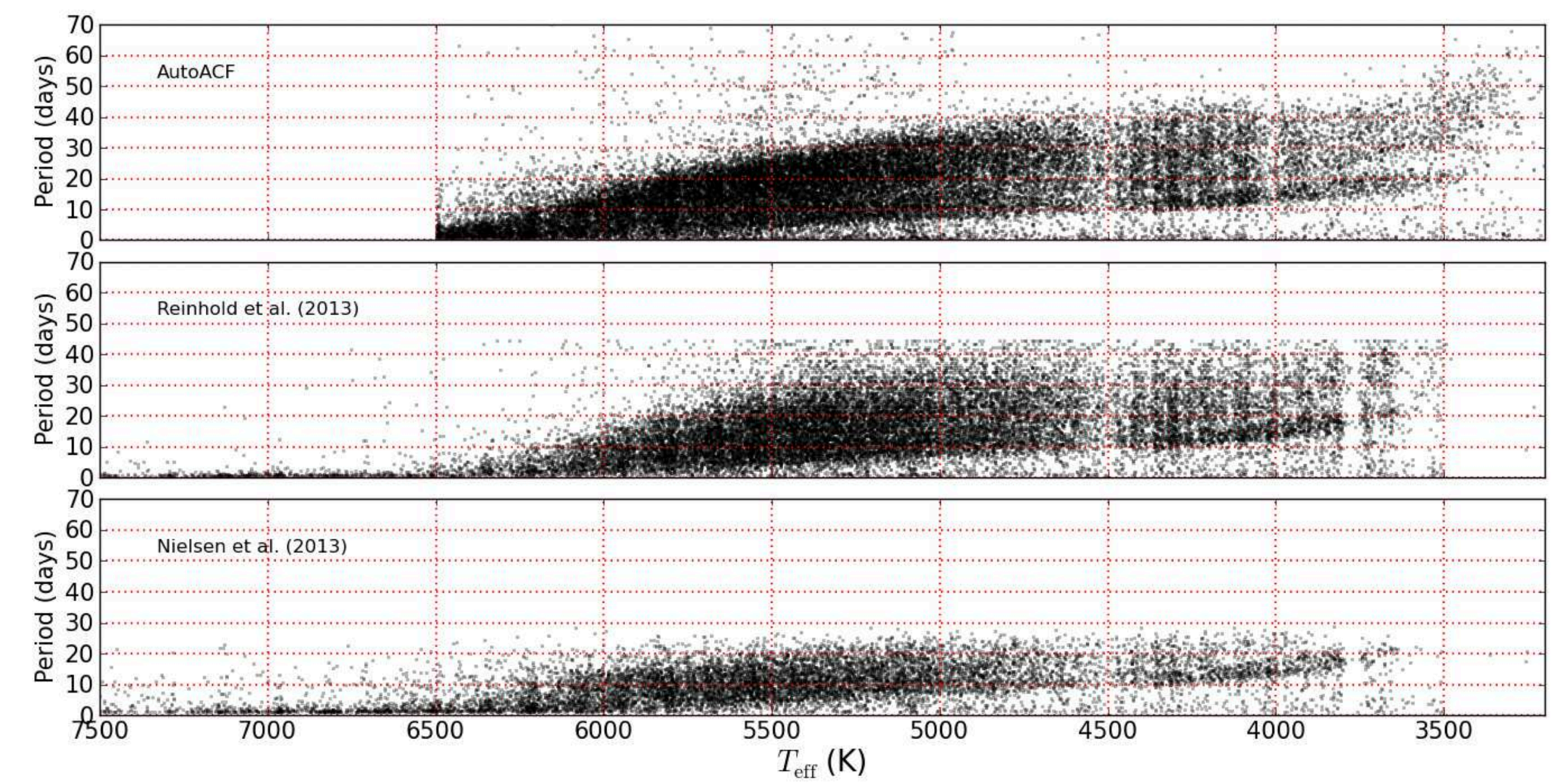
- Techniques based on the analysis of the low-frequency part of the Periodogram
  - Problem:
    - $2^{nd} > 1^{st}$ harmonic
    - Check half of P_{rot}
  - Using all the available data
    - Could solve it !!
- Autocorrelation
  - Powerful for capturing the correct P_{rot}
    - When there are two well defined active longitudes



[KIC4918333 from McQuillan et al. 2013]

II-LIGHT-CURVE ANALYSIS : SURFACE ROTATION

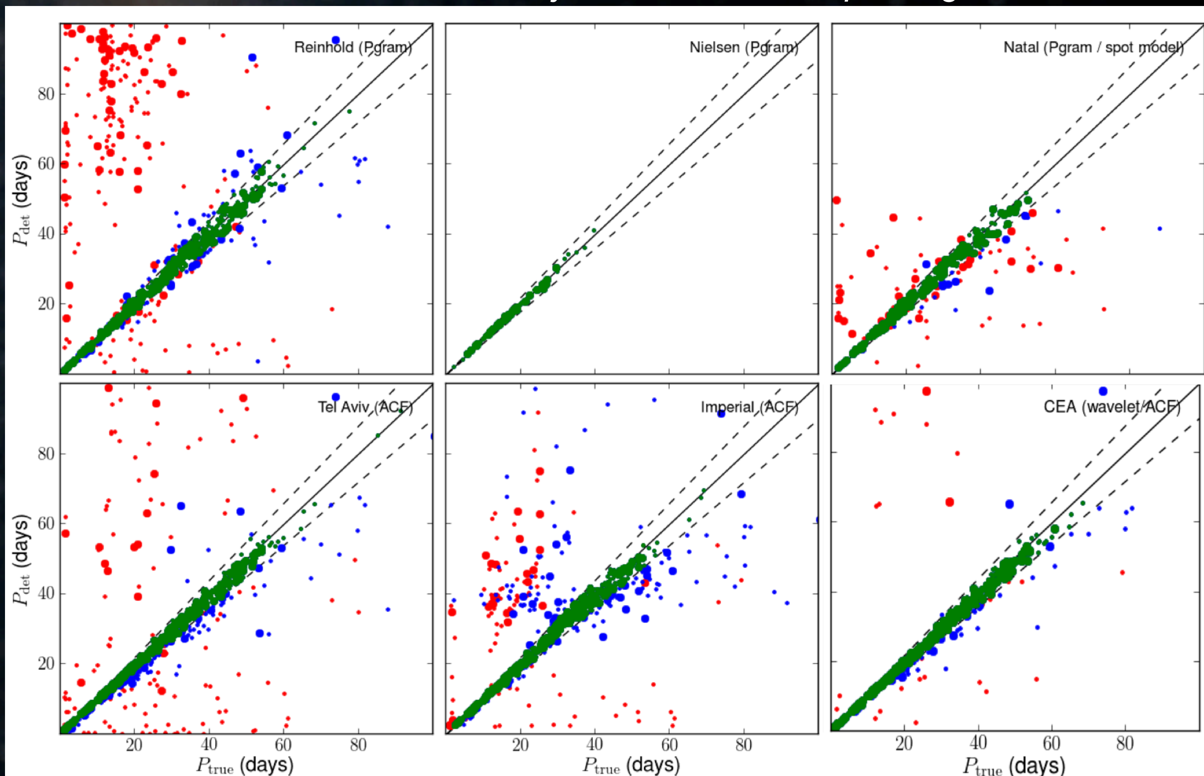
	AutoACF	Reinhold et al. (2013)	Nielsen et al. (2013)
Total Number	34,030	24,124	12,515
AND AutoACF	–	20,009	10,381
AND Reinhold et al. (2013)	20,009	–	9,292
AND Nielsen et al. (2013)	10,381	9,292	–

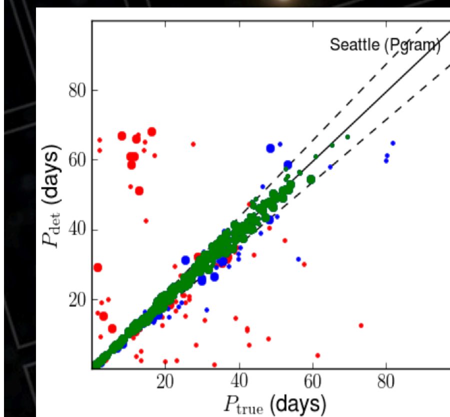


[McQuillan et al. 2014]

II-VALIDATING P_{ROT}

- Through Simulations:
  - 1000 simulated stars injected on real *Kepler* light curves

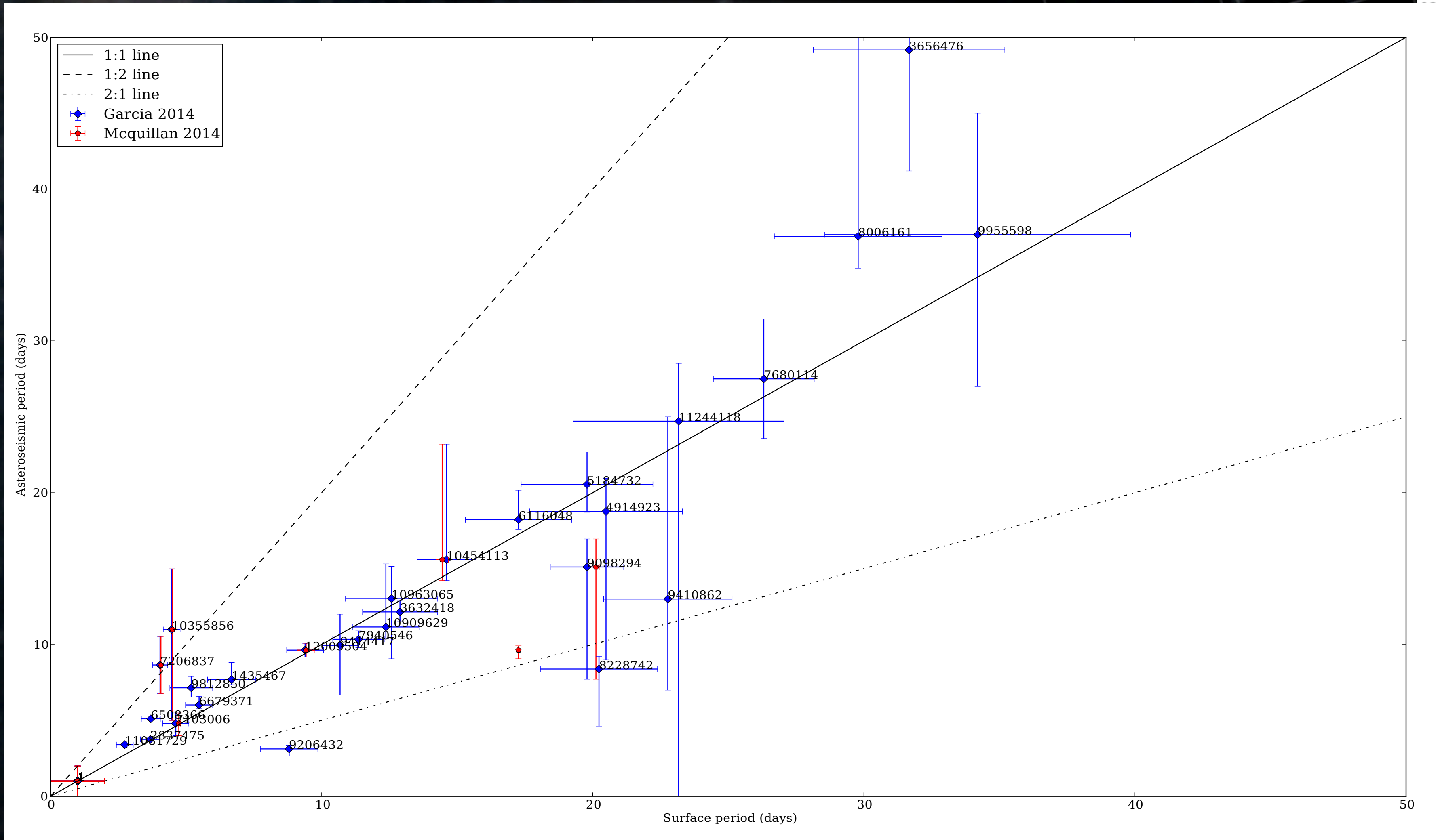




[Aigrain et al. 2015]

Method	Noisy % det	Noisy % good	Noisy % ok	Noise-free % det	Noise-free % good	Noise-free % ok	solar No. det	solar No. ok
Blind teams								
Reinhold (Periodogram)	82	67	76	87	65	77	4	2
Nielsen (Periodogram)	16	100	100	15	100	100	0	0
Natal (Periodogram / spot model)	27	69	76	72	80	85	5	2
Tel Aviv (ACF)	100	68	80	100	75	90	5	4
Imperial (ACF)	95	71	87	98	73	88	5	4
Non-blind teams								
Seattle (Periodogram)	68	81	88	75	84	90	0	0
CEA (Wavelets / ACF)	78	88	95	82	92	99	2	2

II-LIGHT-CURVE ANALYSIS : SURFACE ROTATION



- Inferred p-mode rotational splittings are a good proxy of surface rotation [Davies, García et al. in preparation]
  - Both inferences agree inside the error bars for most of the stars

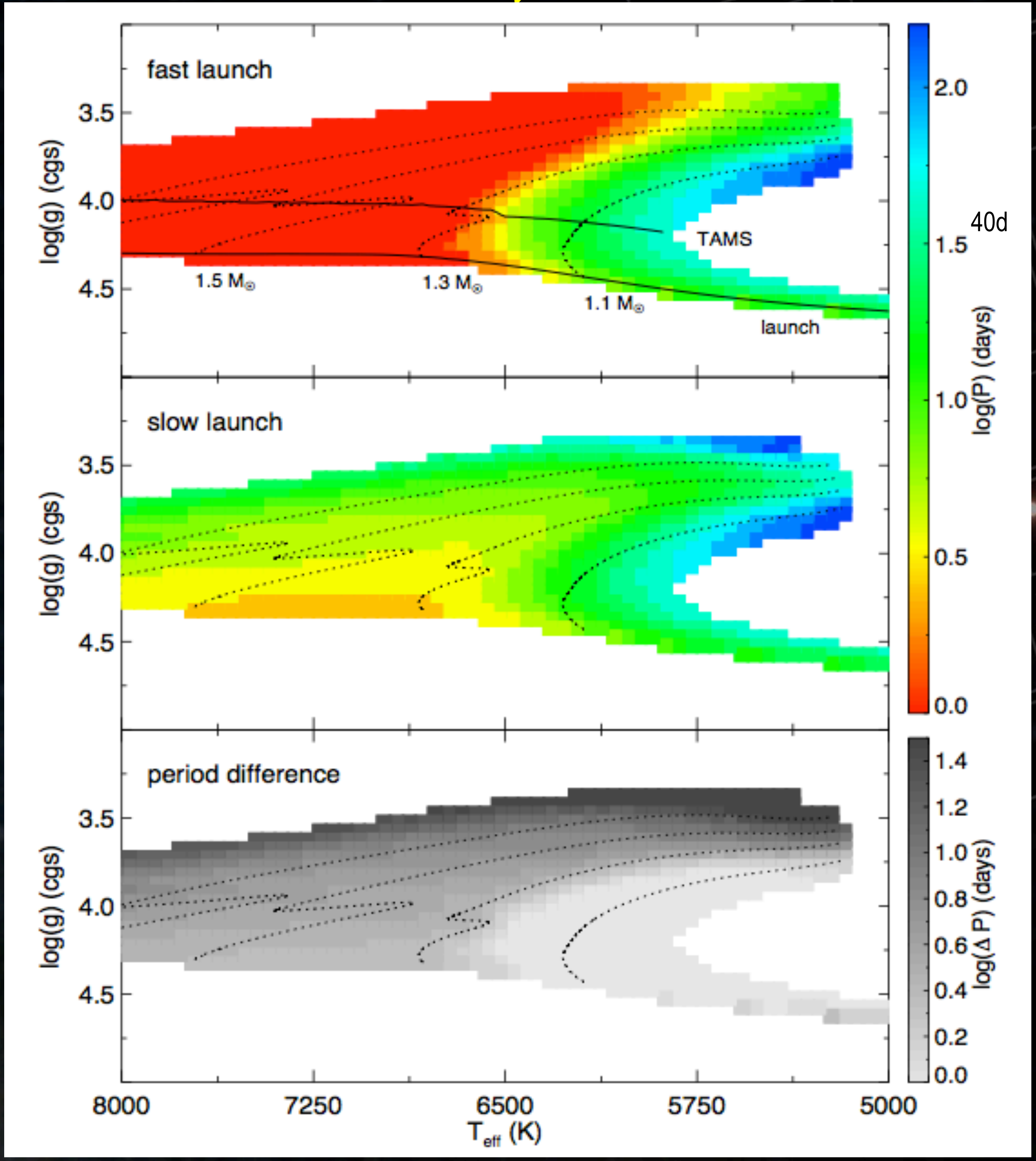
II-LIGHT-CURVE ANALYSIS : SURFACE ROTATION

- Stellar rotation is a strong function of both mass and evolutionary state.

- Gyrochronology:
  - Strong magnetized winds
  - Spin down surface
  - Rotation as a clock

[Skumanich, 1972]

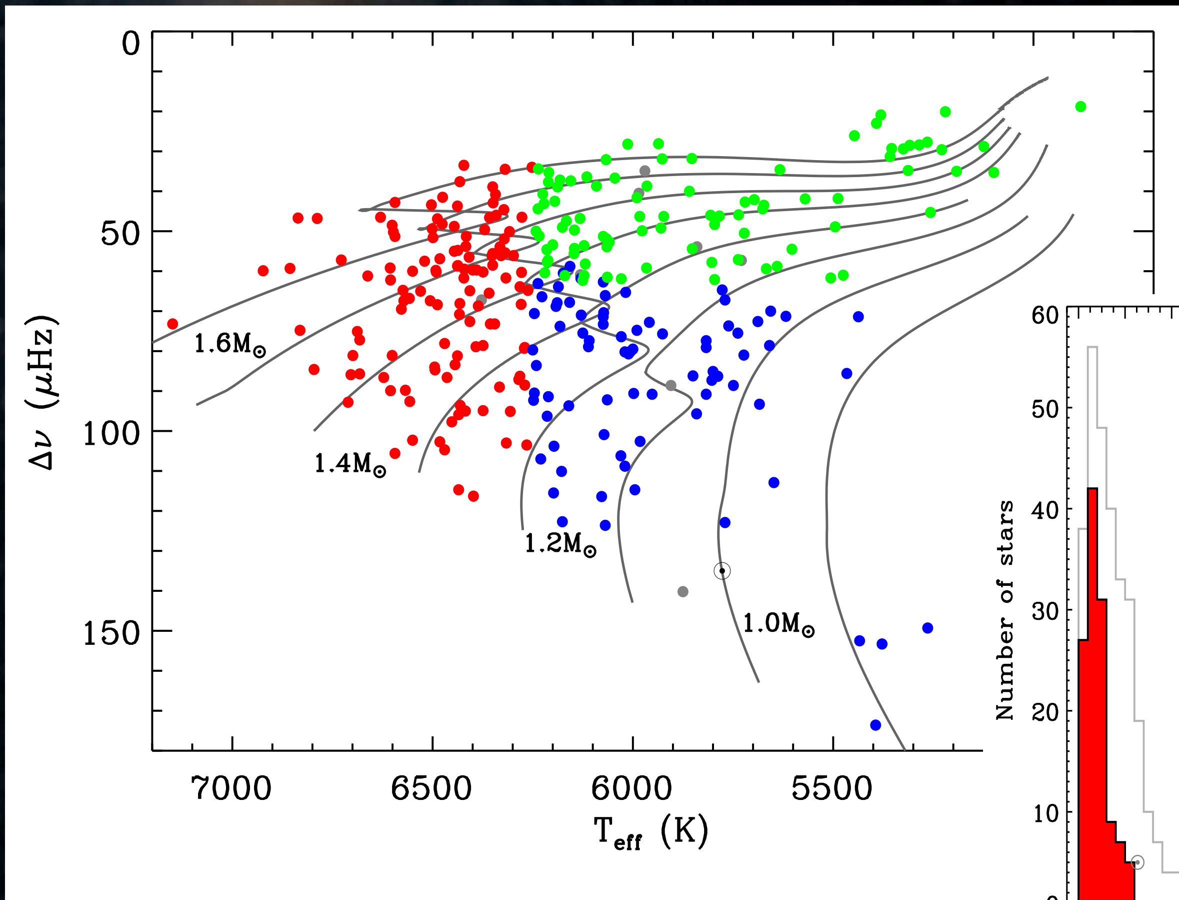
- Simple models (YREC).
  - No diffusion
  - No overshooting
  - Rigid internal rotation



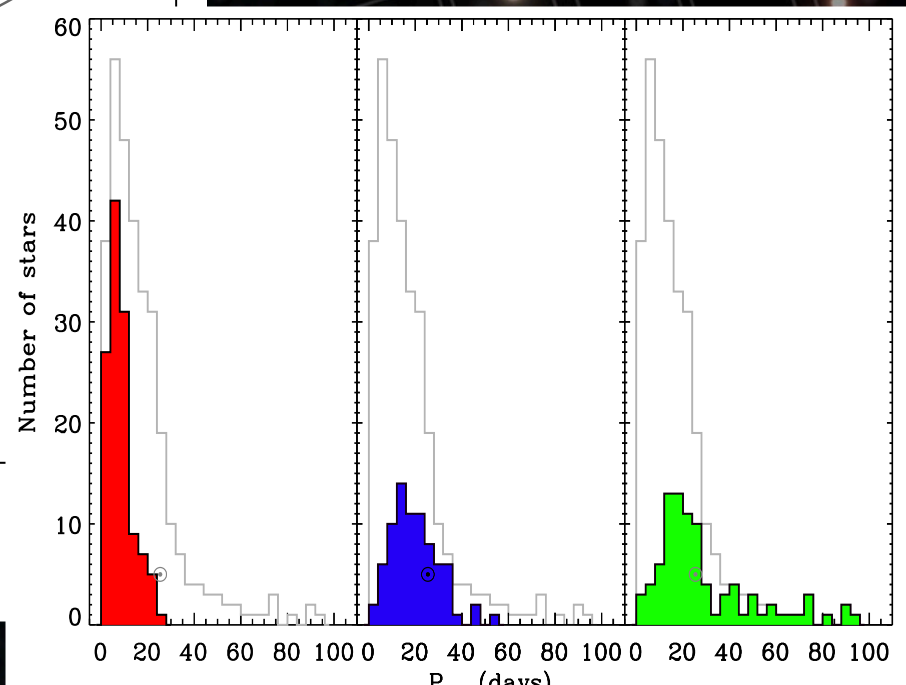
[van Saders & Pinsonneault 2012, 2013]

II-LIGHT-CURVE ANALYSIS : SURFACE ROTATION

- ~540 solar-like stars showing p-mode oscillations have been measured (1 month) [Chaplin et al. 2014]
  - Reliable surface rotation rates and photospheric magnetic index obtained for 310 stars
- Stars in which pulsations are measured
  - Low surface activity (biased sample) [Garcia et al. 2010; Chaplin et al. 2011]

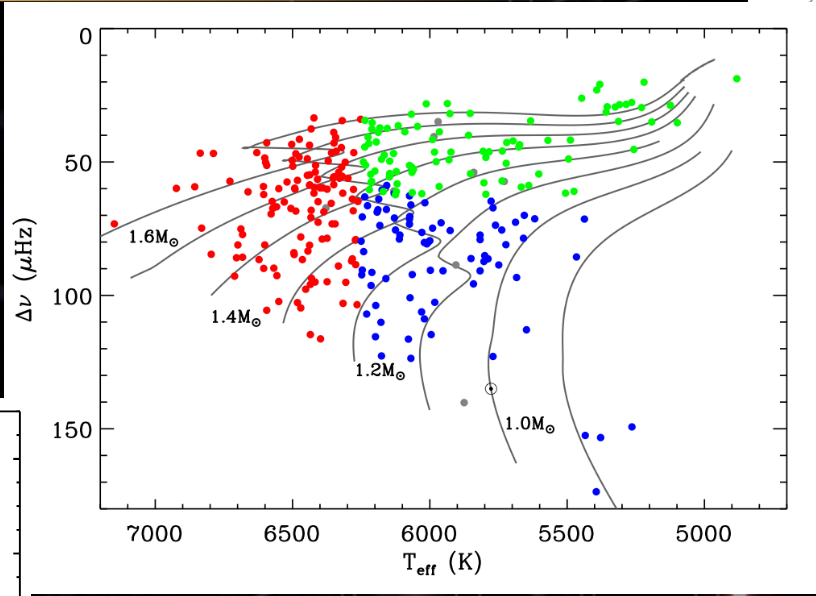


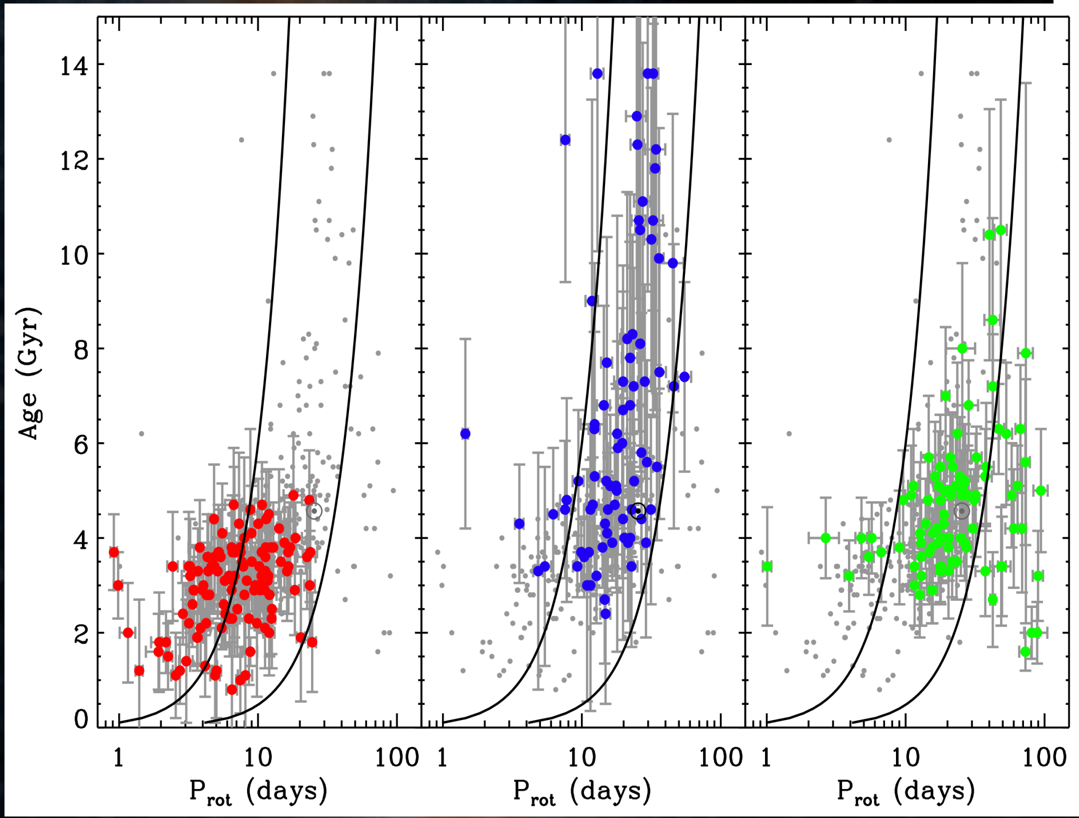
[García et al. in press]



II-LIGHT-CURVE ANALYSIS : SURFACE ROTATION

- Towards asteroseismically calibrated age-rotation relations. Biased sample

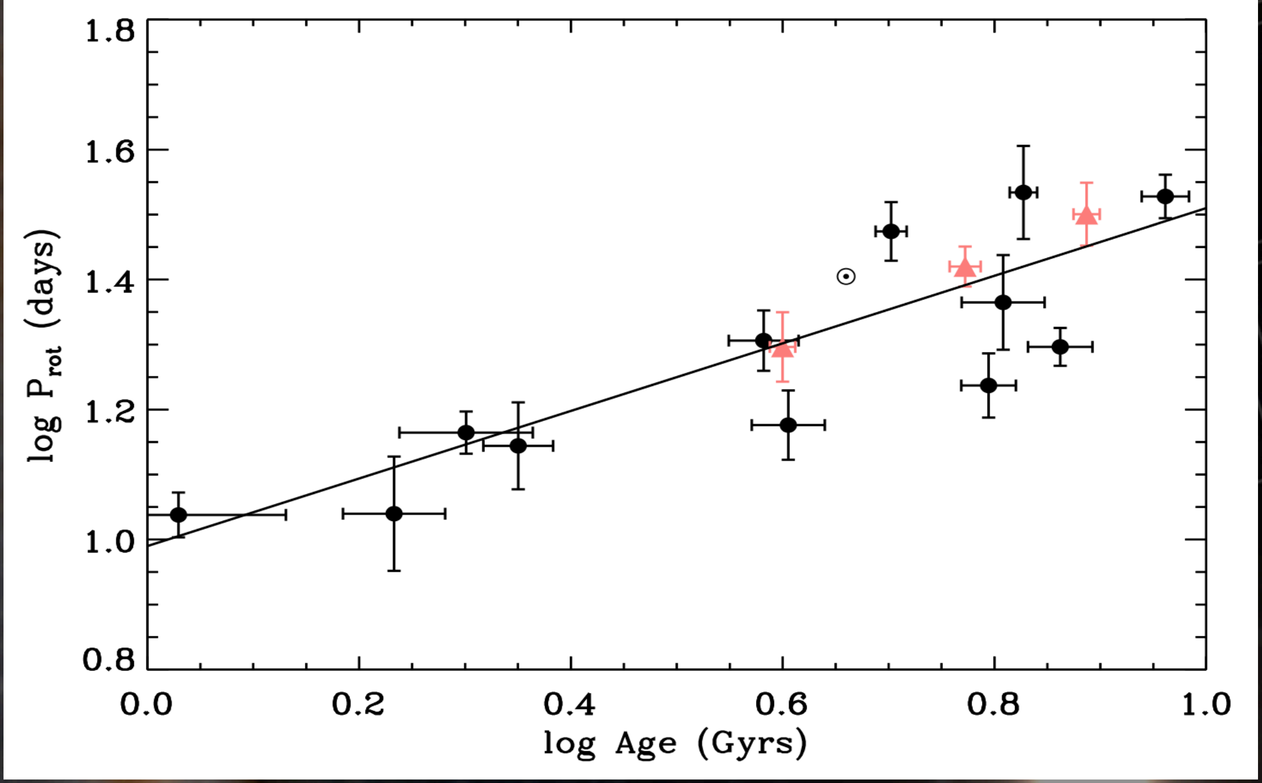




[García et al. 2014]

II-LIGHT-CURVE ANALYSIS : SURFACE ROTATION

- Towards asteroseismically calibrated age-rotation relations.
- Gyrochronology
  - Same law than Skumanich (1972) but for ~old field stars

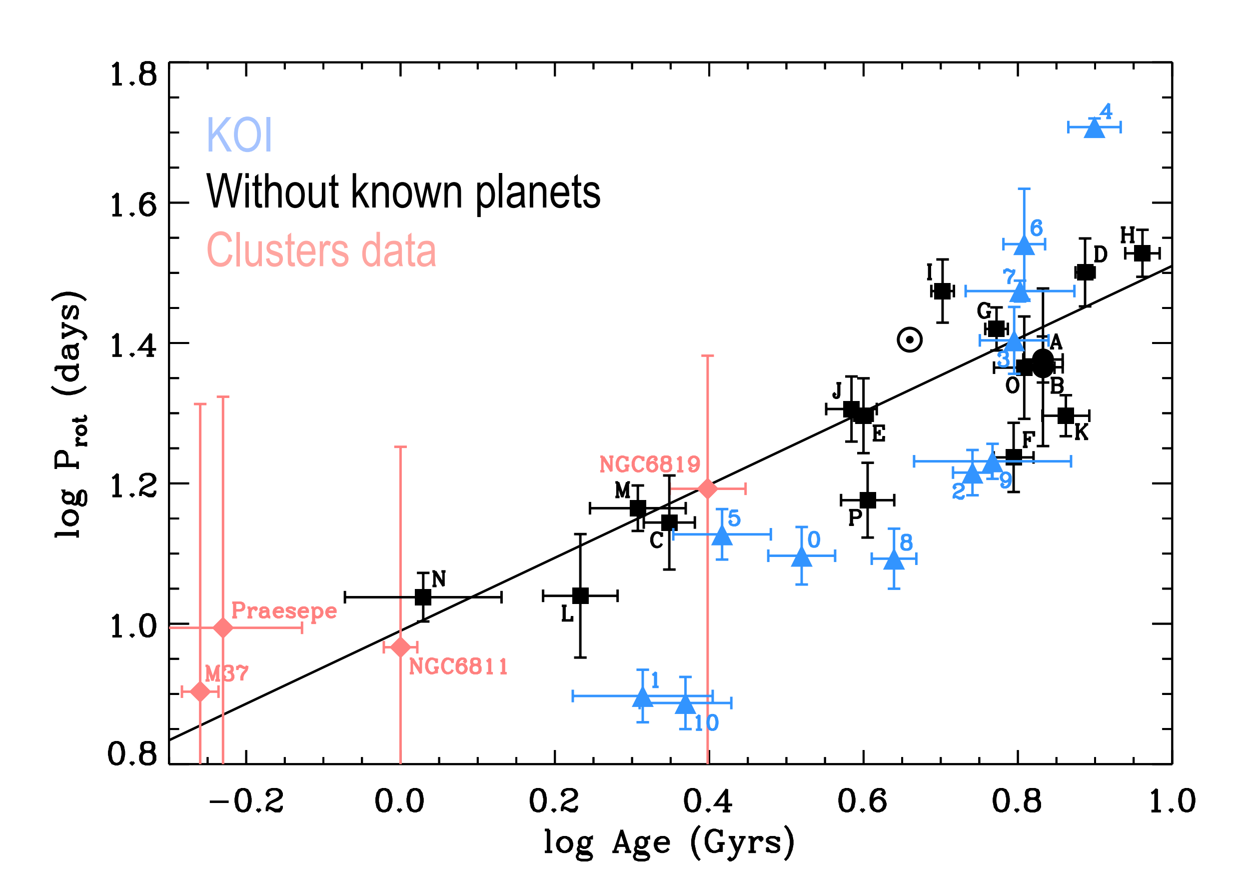


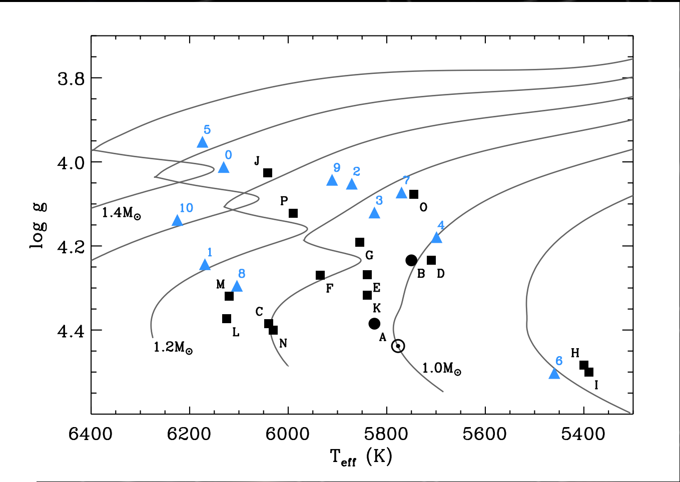
$$\log P_{\rm rot} = (0.52 \pm 0.06) \log(t) + (0.99 \pm 0.04).$$

[Freqs from Appourchaux et al. 2012, models from Mathur et al. 2012 & Metcalfe et al. 2014
García et al. 2015]

II-LIGHT-CURVE ANALYSIS : SURFACE ROTATION

- What happen with confirmed exoplanet systems with small planets ?.
- Gyrochronology

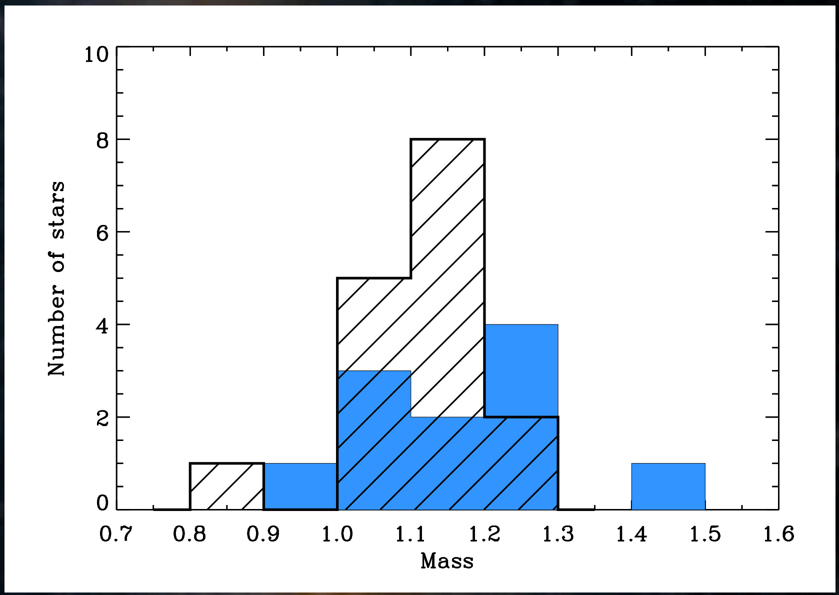


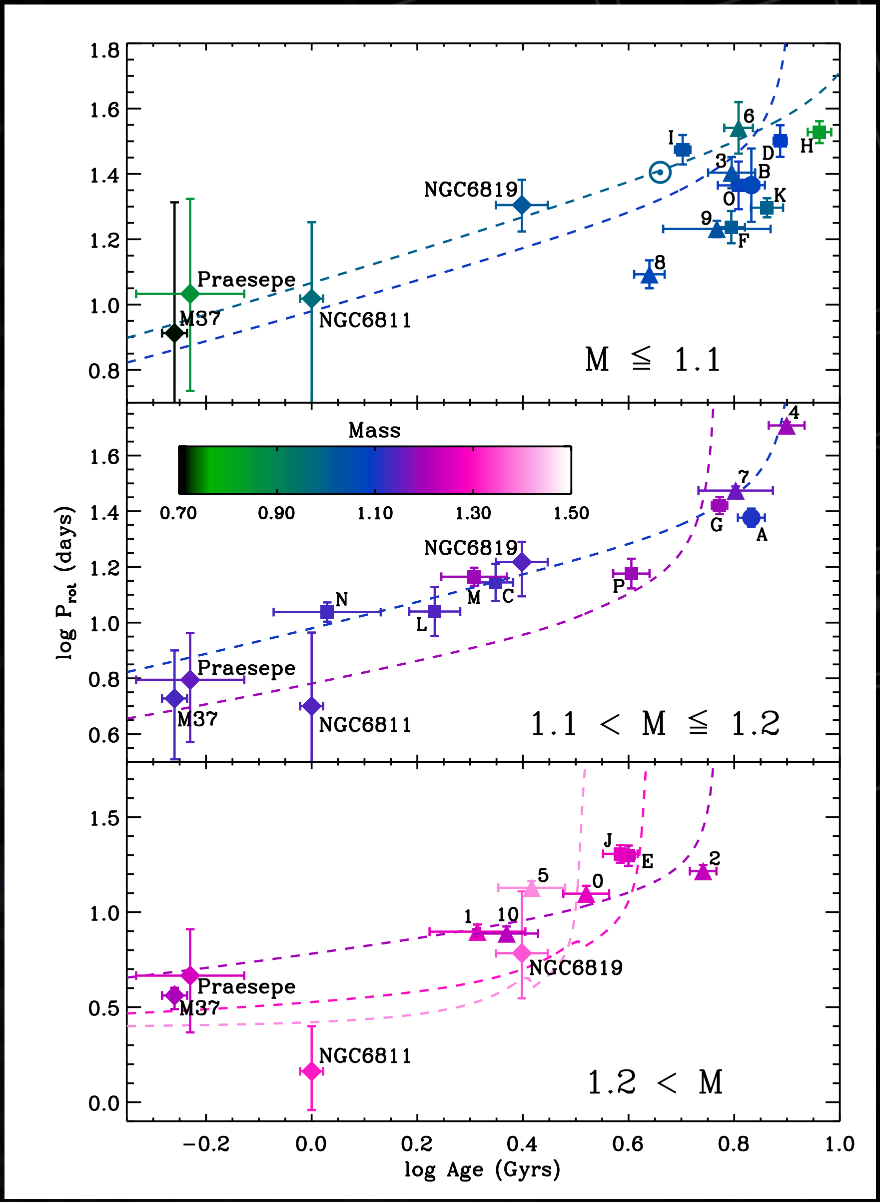


[Ceillier et al. In press]

II-LIGHT-CURVE ANALYSIS : SURFACE ROTATION

- What happen with confirmed exoplanet systems with small planets ?.
- Gyrochronology
  - Dependency between Rotation, Age, and Mass





Kolmogorov-Smirnov analysis

⇓

Same underlying distribution
(p = 0.97)

[Ceillier et al. In press]

- Stars with (short-period, low mass) planets
  - Tidal analysis: effects of planets on rotation
    - All planets are spiralling towards their host star
    - Characteristic time for angular momentum transfer longer than the lifetime of the star

No influence of these kind of planets on the rotation
(Bolmont et al. 2012)

Same rotational behaviour for KOIs and SL stars without detected planets

[Ceillier et al. In press]

II-LIGHT-CURVE ANALYSIS: SURFACE ROTATION

➢ Testing gyrochronology

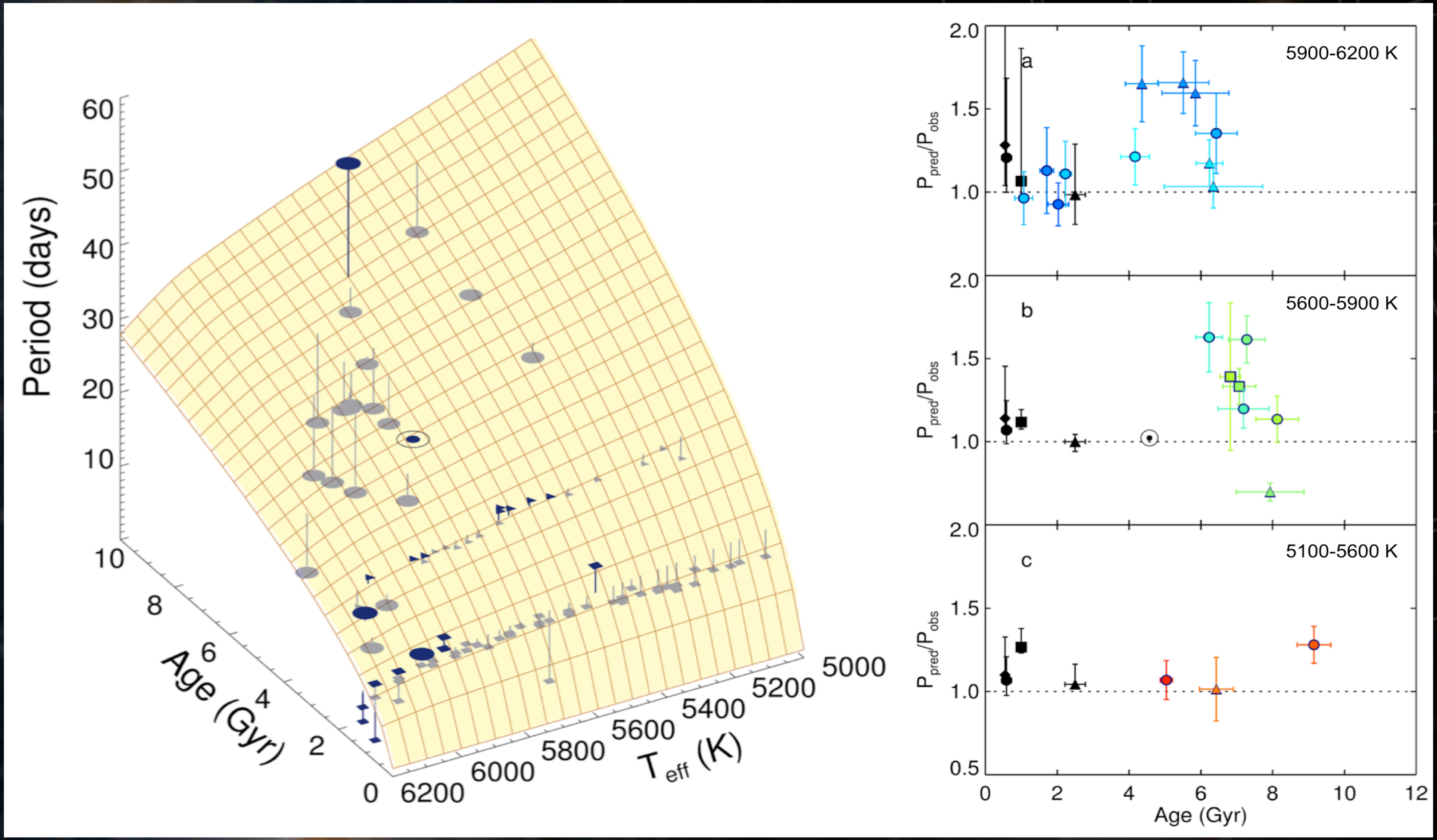
- Sample: 21 stars (14 SL + 7 KOIs)
- Best available sample:
  - Old field stars
  - Precise seismic ages
  - Reliable rotation periods

Constrain gyrochronology laws at old ages

[van Saders, Ceillier et al., Nature, In press]

II-LIGHT-CURVE ANALYSIS: SURFACE ROTATION

- Testing gyrochronology
  - Comparing with model predictions



[van Saders, Ceillier et al., Nature, In press]

- Testing gyrochronology
  - Modified braking: critical Rossby number

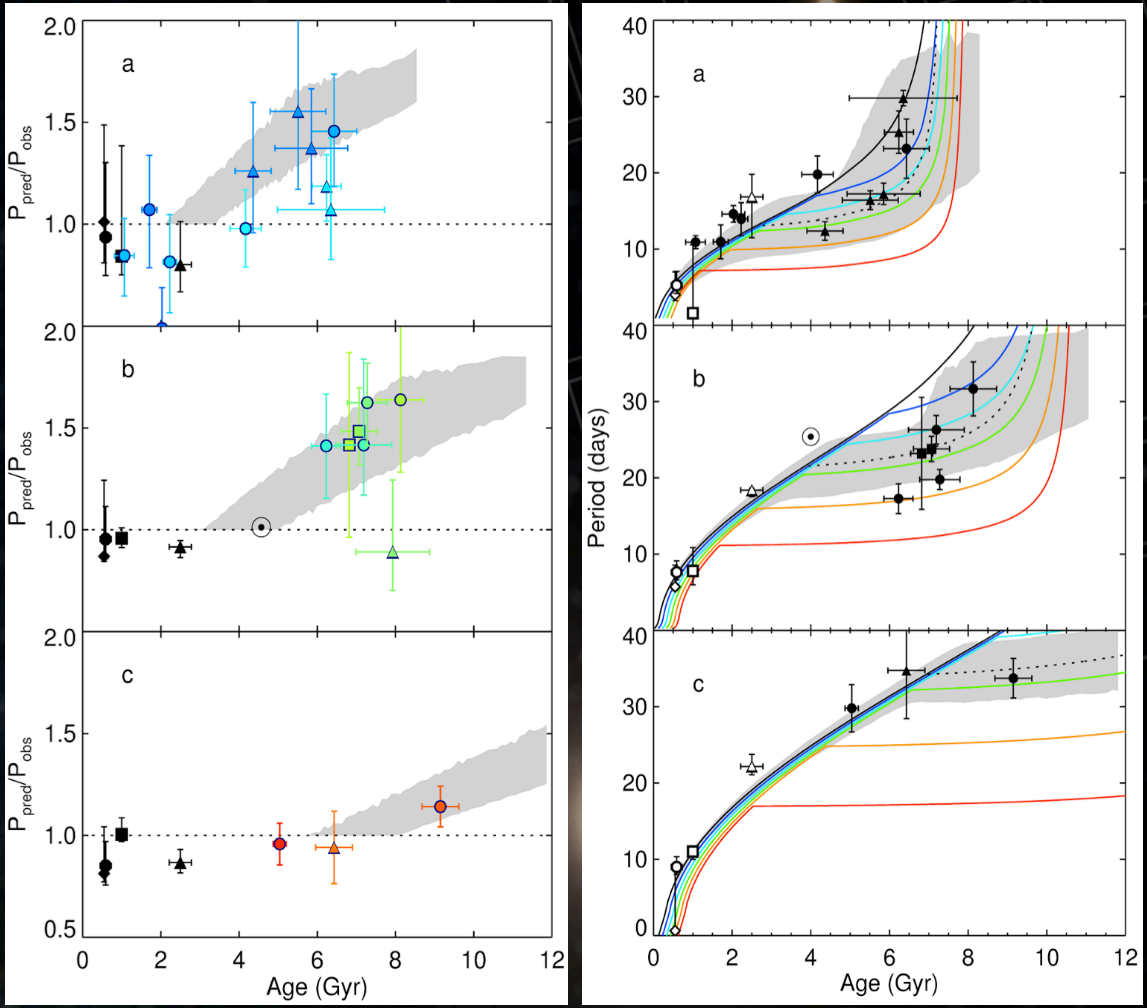
$$\mathrm{Ro} = \frac{P_{\mathrm{rot}}}{\tau_{\mathrm{CZ}}}$$

$$\mathrm{Ro} > \mathrm{Ro}_{\mathrm{crit}} = 2.16 \pm 0.09$$

⇩

No more braking

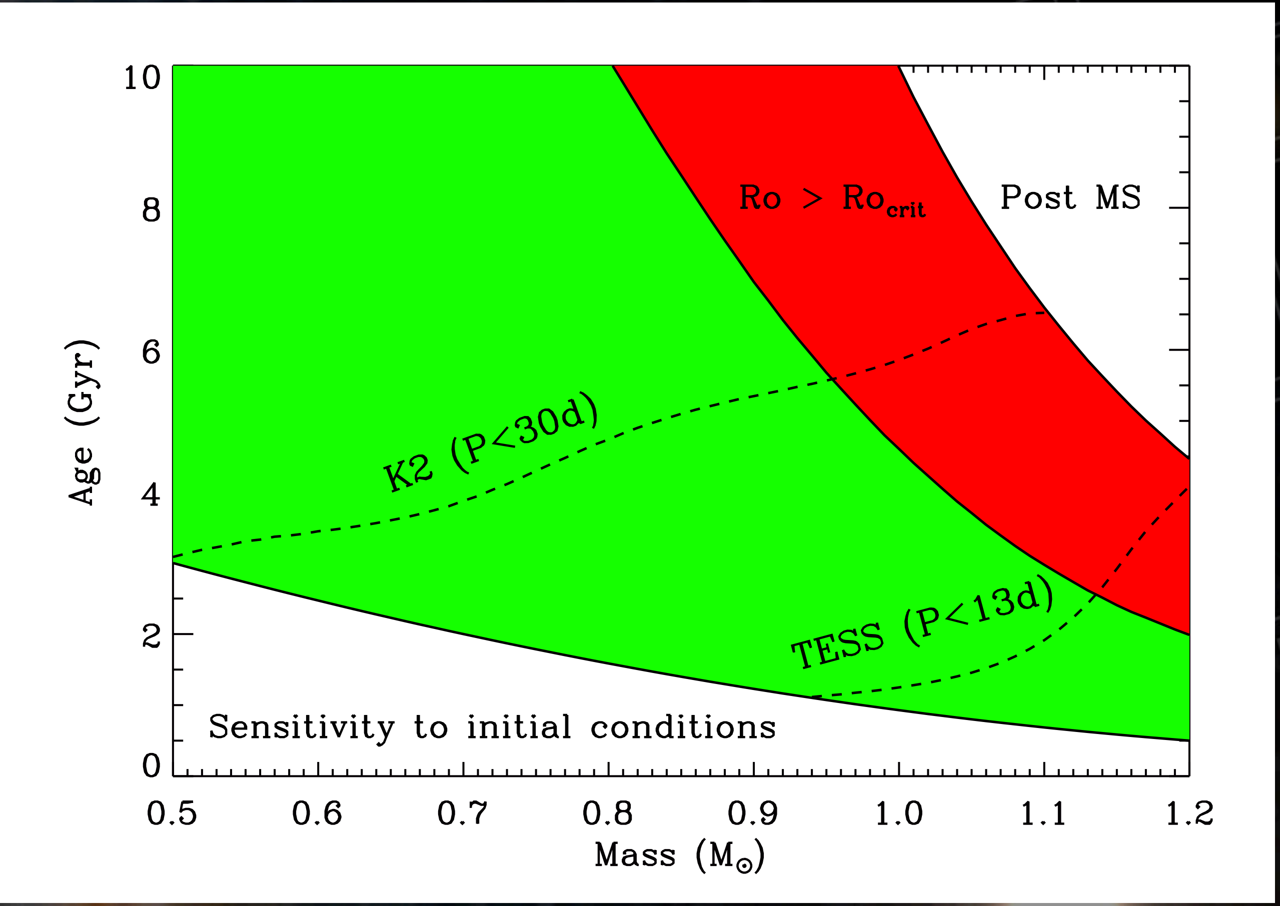
Reproduces very well the observed periods



[van Saders, Ceillier et al., Nature, In press]

II-LIGHT-CURVE ANALYSIS: SURFACE ROTATION

➢ Applicability of gyrochronology & Space missions



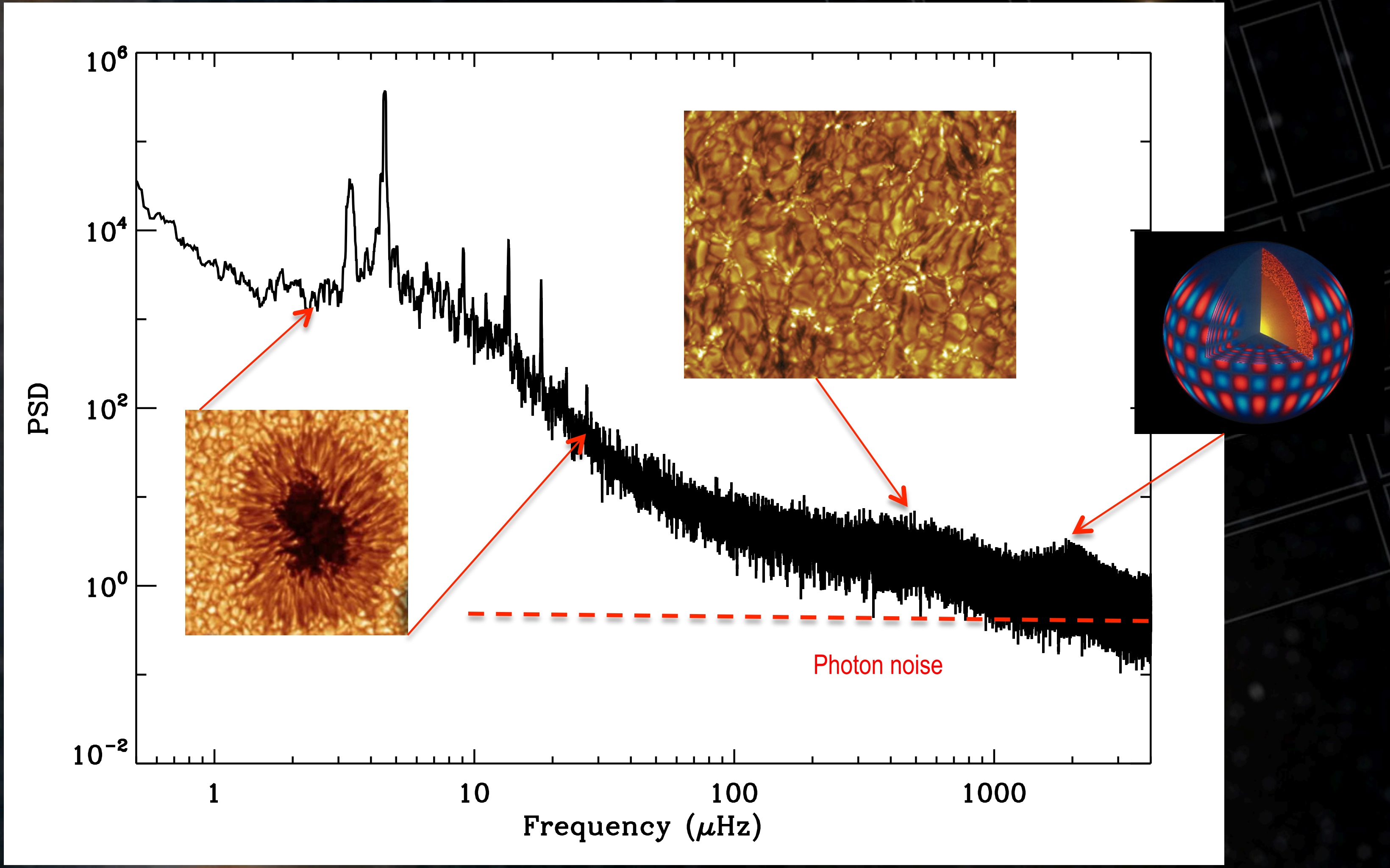
Reduces the range of applicability of gyrochronology

[van Saders, Ceillier et al., Nature, In press]

III-Spectral Analysis

III-SPECTRAL ANALYSIS

- Example of the PSD of a Solar-like stars

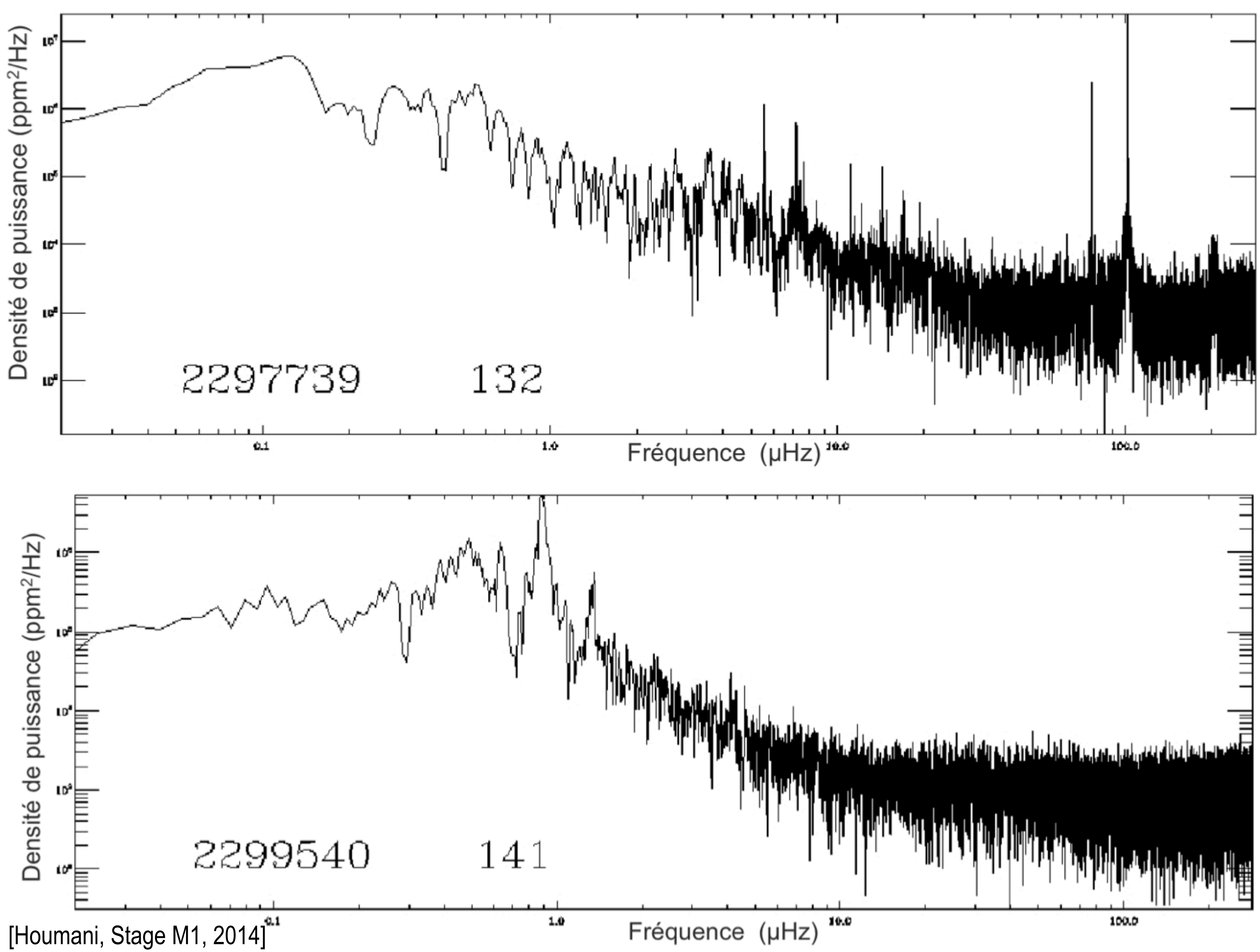


III-SPECTRAL ANALYSIS

- Different components:
  - *Rotation* of the order of several days to months: very low frequency
  - *Active regions* responsible for the shape of the power spectrum at low frequency
    - Can be modeled with a power law: a ν^{-b}
  - Convection time scales: order of a day to a few minutes depending on the scale of granulation and the type of star
    - Supergranulation
    - Mesogranulation (still questioned but observed in the Sun)
    - Granulation
    - Faculae or bright points (still questioned…)
      - Or faster granulation component
  - P-mode spectrum

III-SPECTRAL ANALYSIS

- Example of other type of pulsators

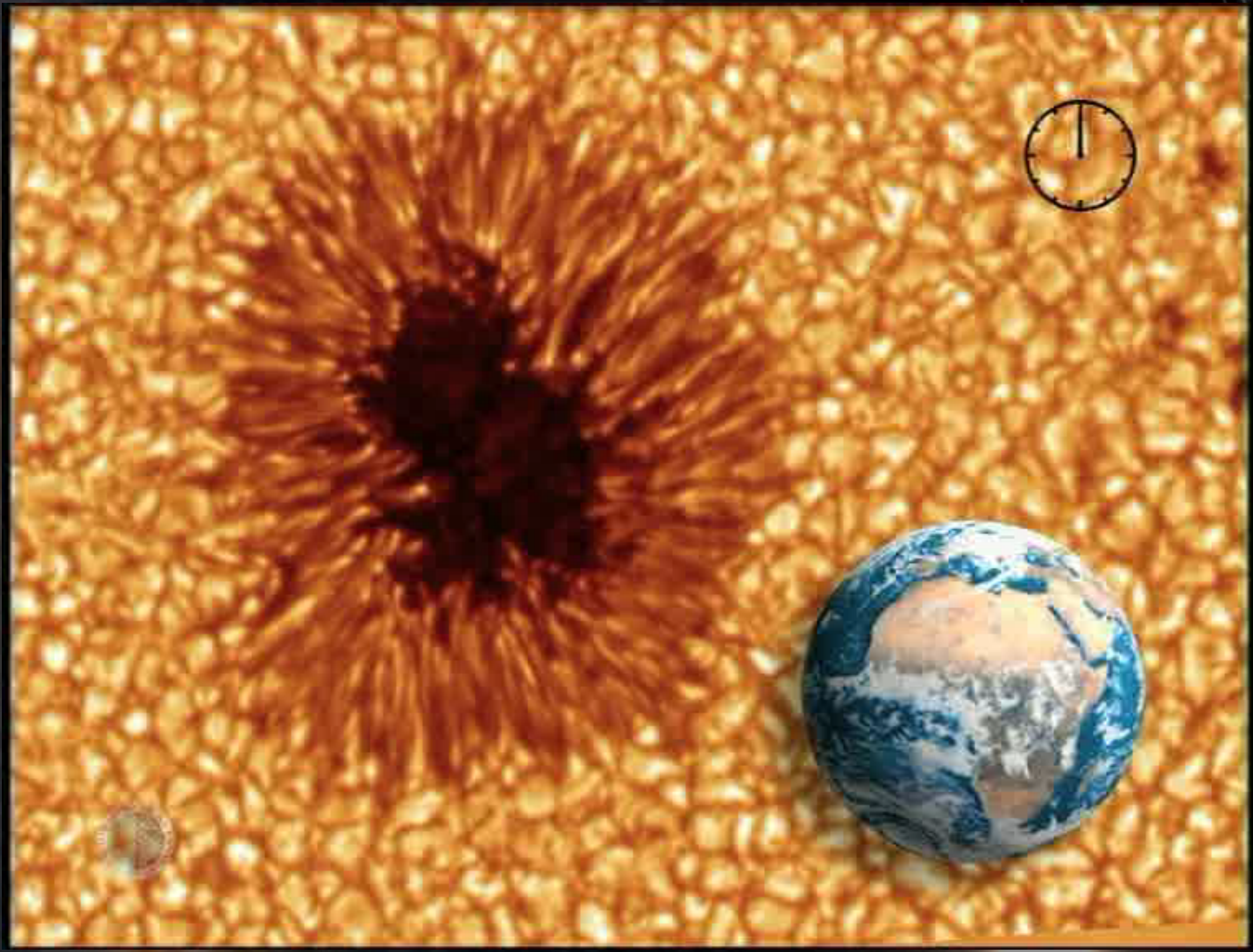


[Houmani, Stage M1, 2014]

III'-Spectral Analysis:

Convection

III'-SPECTRAL ANALYSIS: CONVECTION



- In particular, solar-like stars have an external convective zone
  - With different scales: granulation, supergranulation…
- The convection excites the waves

III'-SPECTRAL ANALYSIS: CONVECTION

- Granules evolve with time and produce a quasi-periodic brightness fluctuations on a wide range of time scales and amplitudes
- Harvey (1985) approximated the autocovariance of the time evolution of the granulation by an exponential decay function with a characteristic time τ_{gran}.

$$\frac{4\sigma^2\tau_{gran}}{1+(2\pi\nu\tau_{gran})^{\alpha}}$$

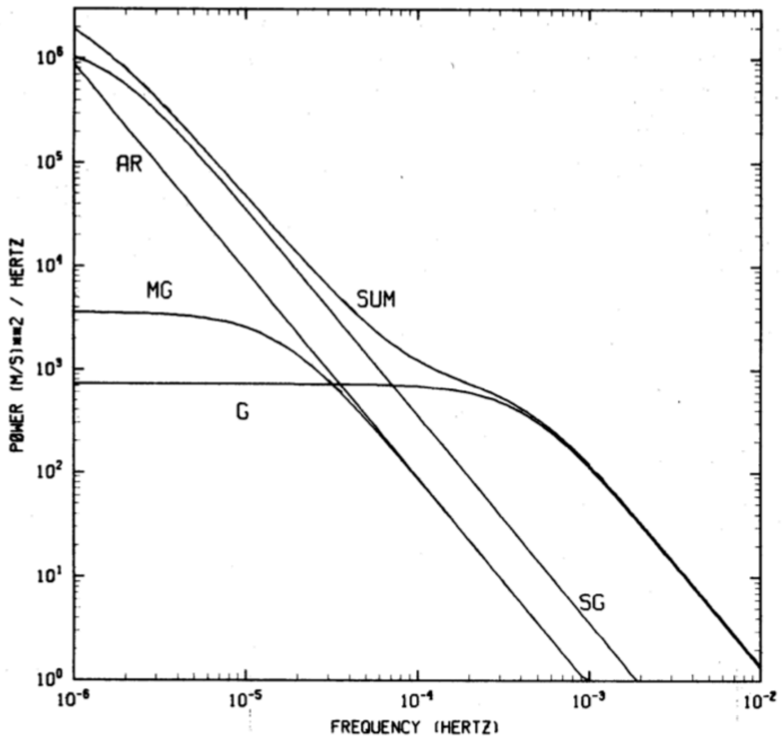


Figure 4. Estimated solar background noise for an observation of Doppler shifts of a moderately strong photospheric spectrum line averaged over the solar disk (G=granulation, MG=mesogranulation, SG=supergranulation, AR=active regions).

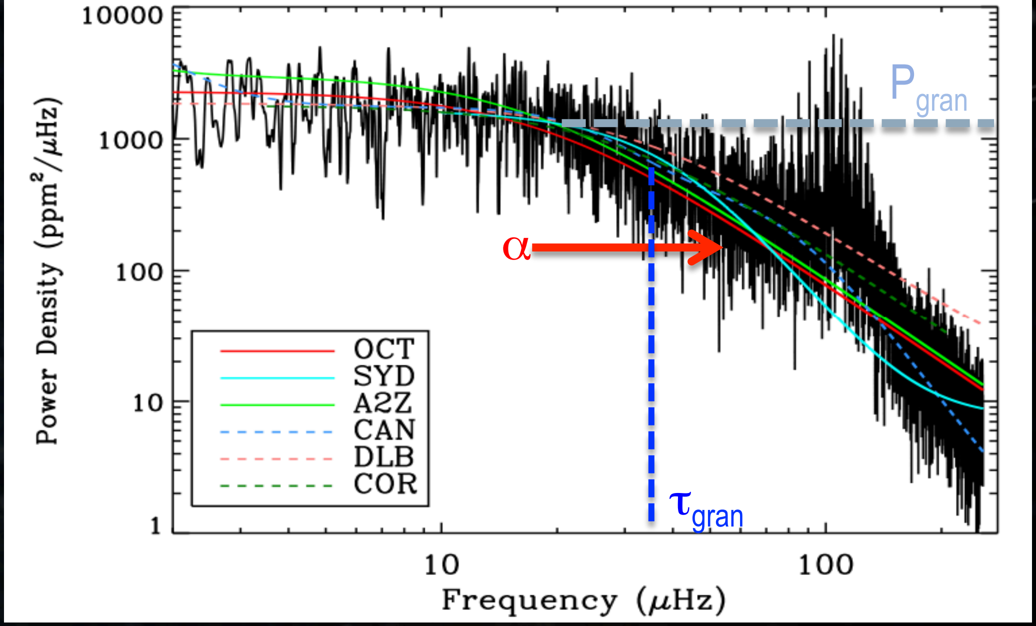
Table 1. Basis for solar noise spectrum estimate

Feature	τ (s)	σ_{vert} (m/s)	σ_{horiz} (m/s)	$\sigma_{fulldisk}$ (m/s)
Granulation	372	890	460	0.7
Mesogranulation	10^4	60	0?	0.3
Supergranulation	10^5	30?	150	1.9
Active regions	10^6	200?	100?	3.0

[Harvey 1985]

III'-SPECTRAL ANALYSIS: CONVECTION

- Harvey-like function: $$\frac{4\sigma^2 \tau_{gran}}{1+(2\pi \nu \tau_{gran})^{\alpha}}$$
- Characteristic amplitude of the granulation σ
- Granulation power: $P_{gran}=4\sigma^2 \tau_{gran}$
- Slope α: how fast the power decays with frequency
  - α=2: Lorentzian function. Used in the case of the Sun.
    - Difficult to measure but different values are being used.
  - -> 0: flatter and tends to white noise
  - -> infinite: sinc function
- Timescale τ_{gran}



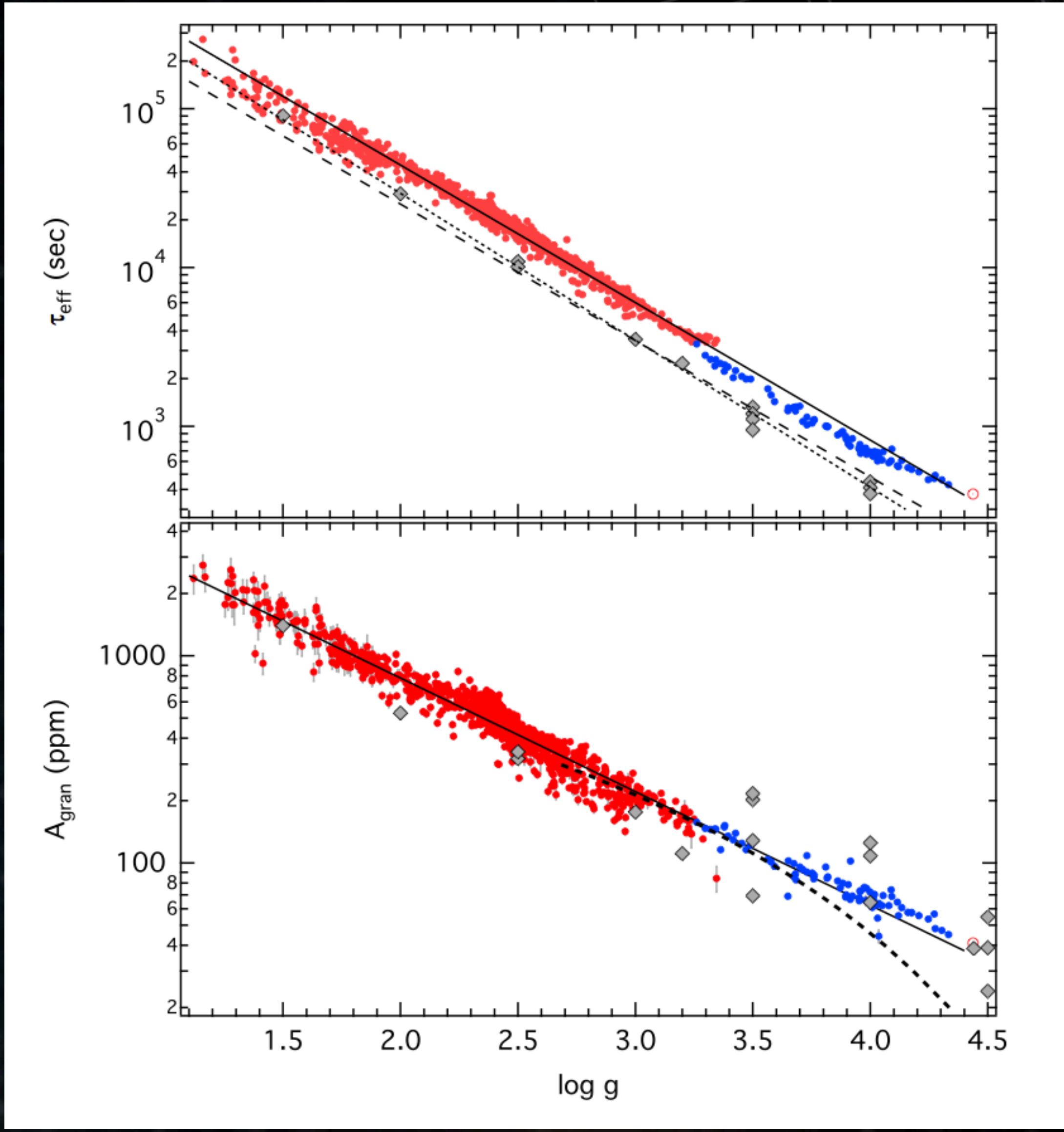
[Mathur et al. 2011]

III'-CONVECTION: RELATION WITH LOG G

- Granulation parameters:
  - 3 years of data for red giants
  - 1 year of data for solar-like stars
    - Need high enough Nyquist frequency

$$\tau_{\text{eff}} \propto g^{-0.85}\, T^{-0.4}$$

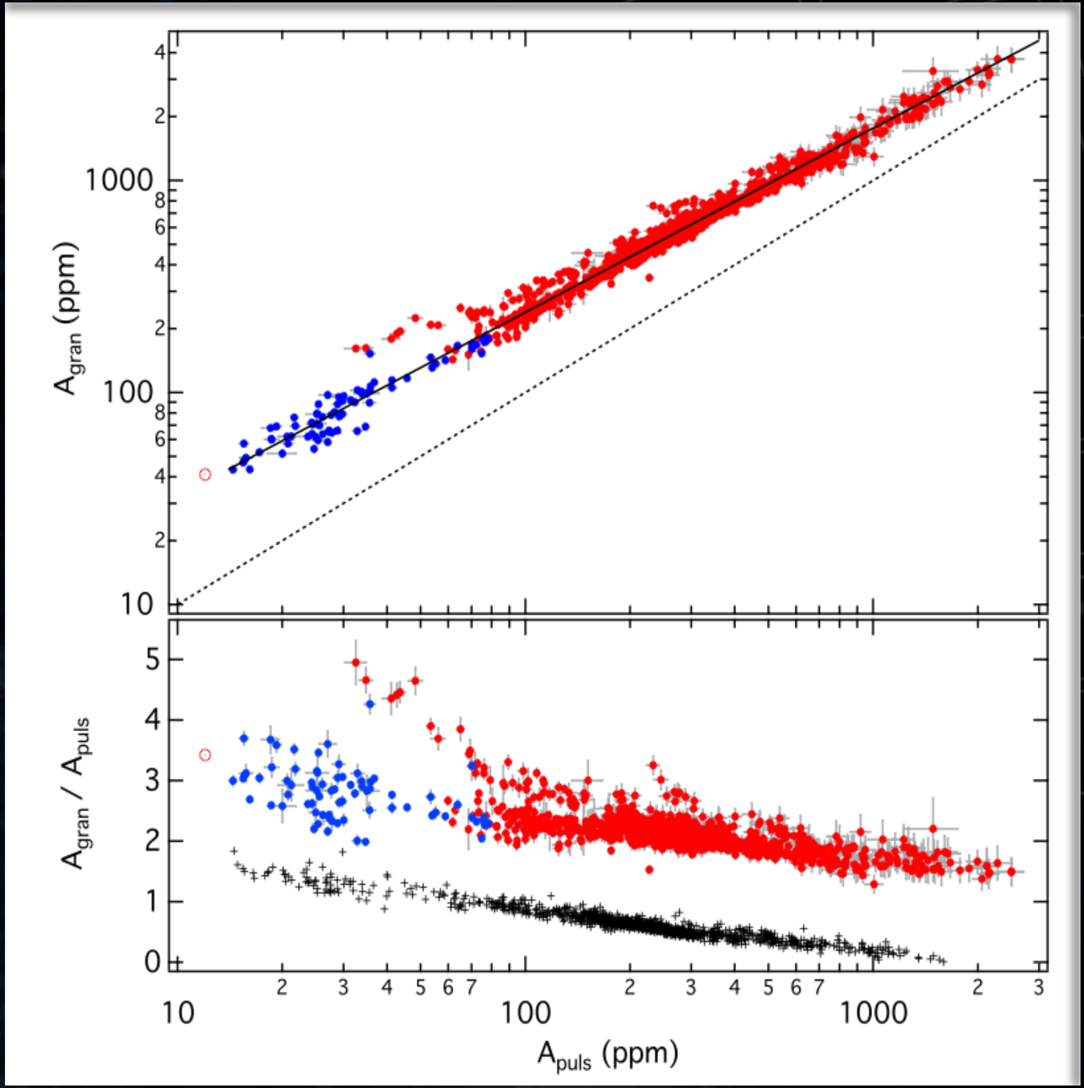
With $T=T_{eff}/5777$



[Kallinger et al. 2014]

III'-GRANULATION AND MODES

- Solar-like oscillations are excited by convection
- Tight link between granulation power and mode amplitude (A_{puls}).
- Ratio changes with evolutionary state
  - for MS stars
    - A_{gran} ~3 times larger than A_{puls}
  - for RG
    - A_{gran} ~1.5 times larger than A_{puls}



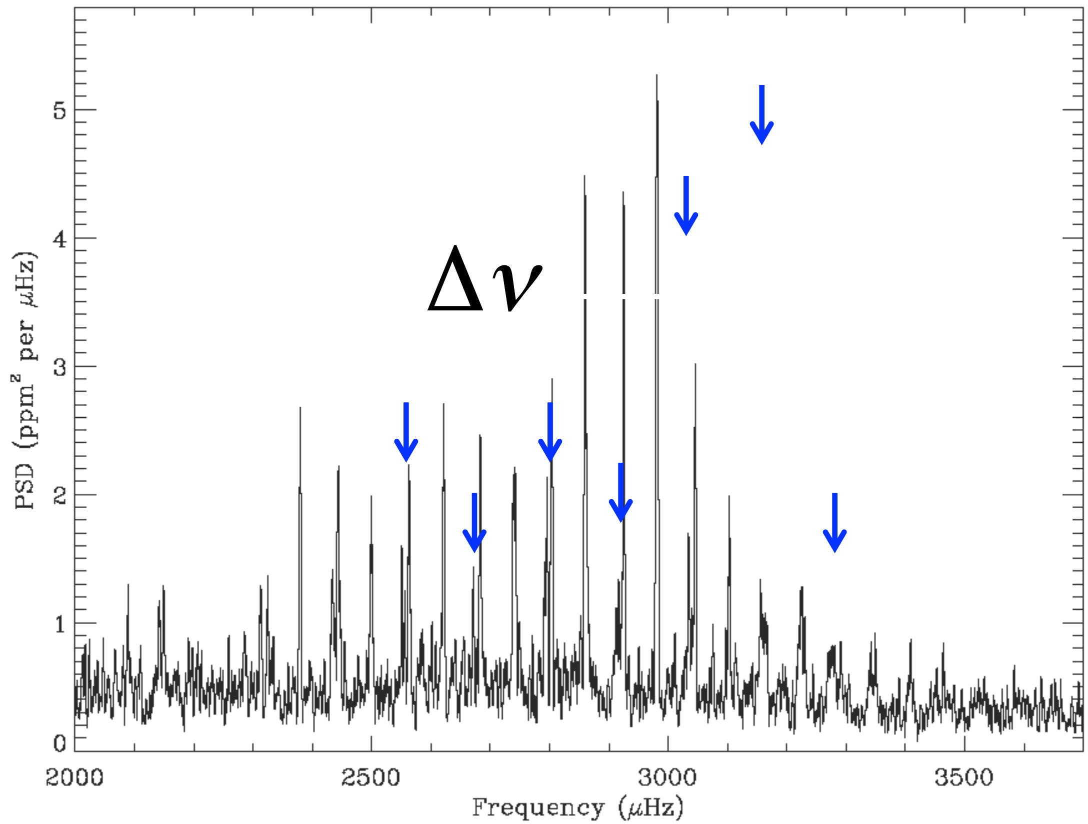
[Kallinger et al. 2014]

IV-Global seismic parameters

IV-GLOBAL P-MODES PARAMETERS

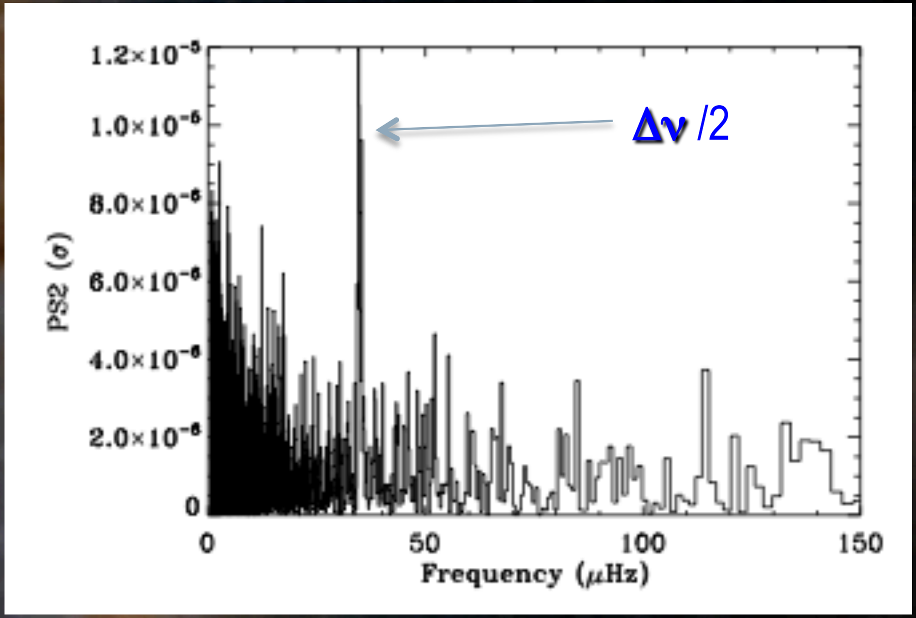
- ***Large separation:***
  - $\Delta\nu = \nu_{n,\ell} - \nu_{n-1,\ell}$
    - Average properties of the star

$$\langle \Delta\nu \rangle \propto \langle \rho \rangle^{1/2} \propto M^{1/2} R^{-3/2}$$



IV-DETERMINATION OF $\Delta\nu$

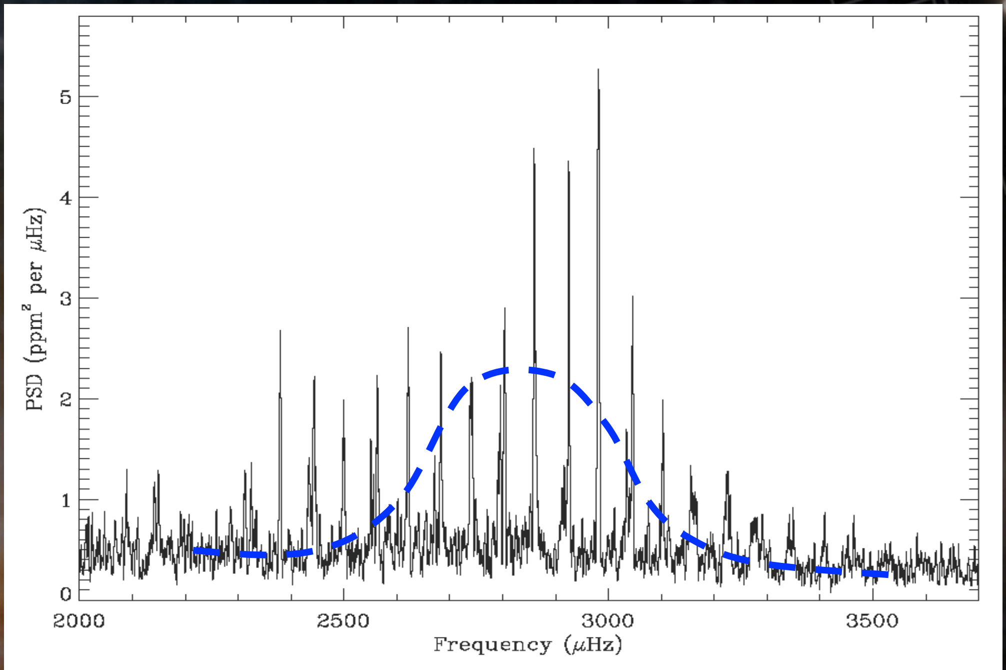
- Periodicity in frequency in the power spectrum (PS)
- Different methods exist
  - PS of PS [e.g. Hekker et al. 2009, Mathur et al. 2010]
  - Auto-correlation of the light curve [Roxburgh & Vorontsov, 2006, Mosser & Appourchaux 2009]
- Example: PS of PS (or PS2)
  - Look for the highest peak and assume it is half the mean large separation



[Mathur et al. 2010]

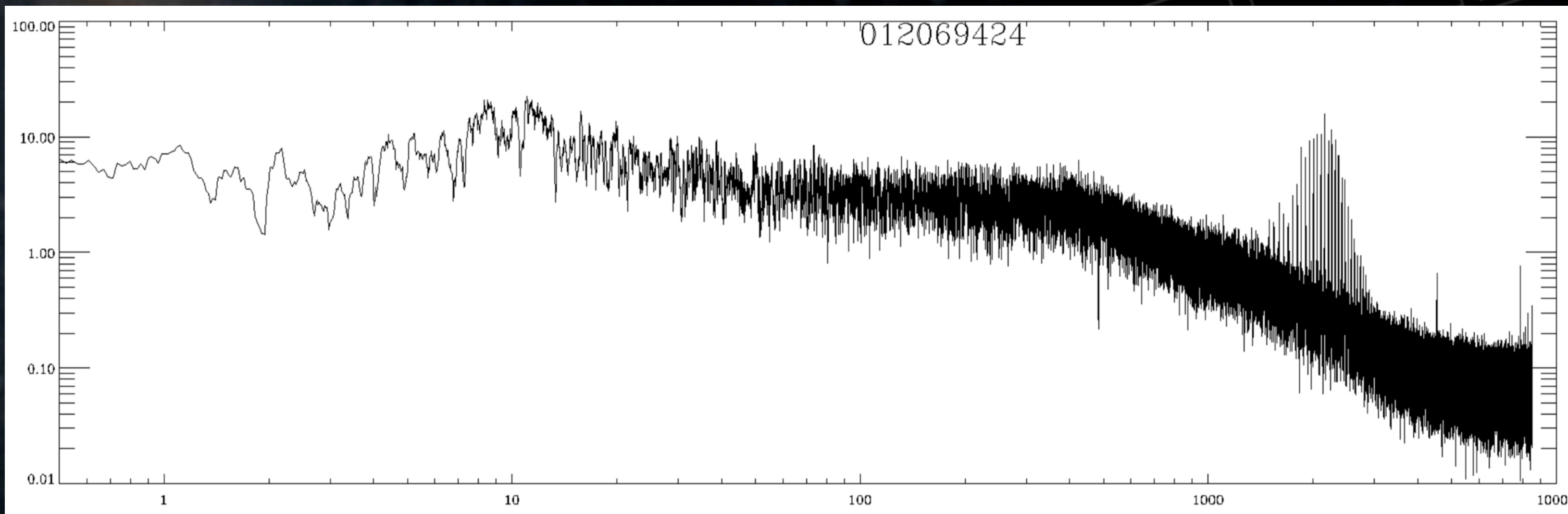
IV-GLOBAL DETERMINATION OF ν_{max}

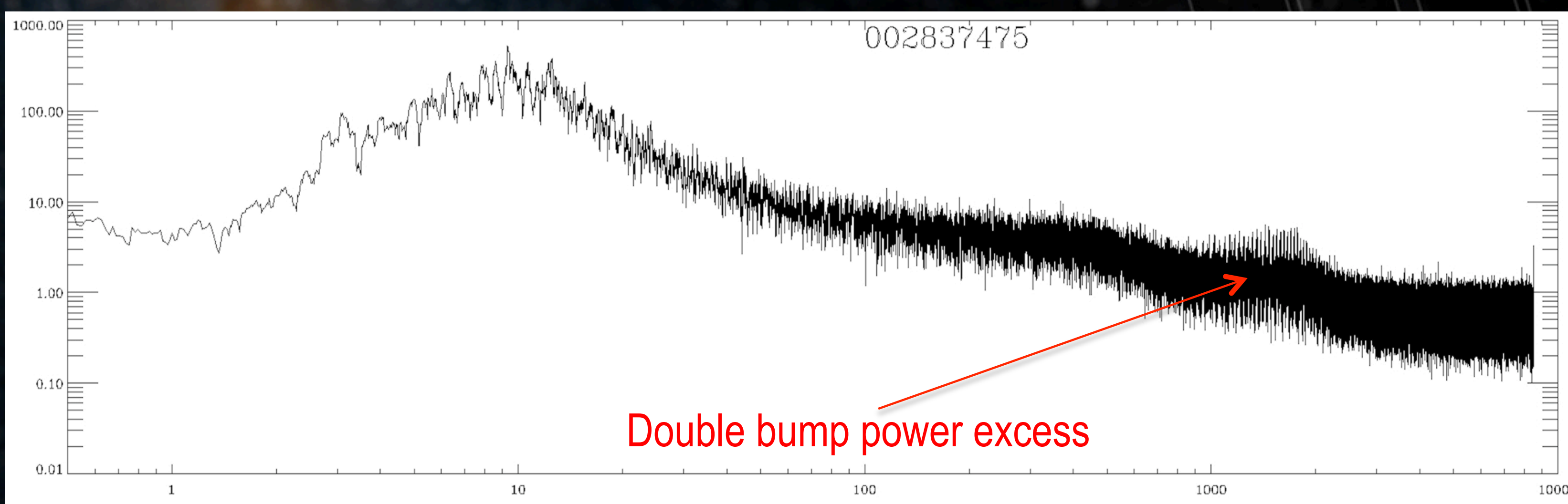
- Fit the background and subtract it
- Fit a Gaussian between fmin and fmax of detection of modes
  - Over a smoothed PS
    - In general 4 times $\Delta\nu$
- Also gives
  - A_{max}
  - FWHM



IV-GLOBAL DETERMINATION OF ν_{max}

- Example of S-L pulsators

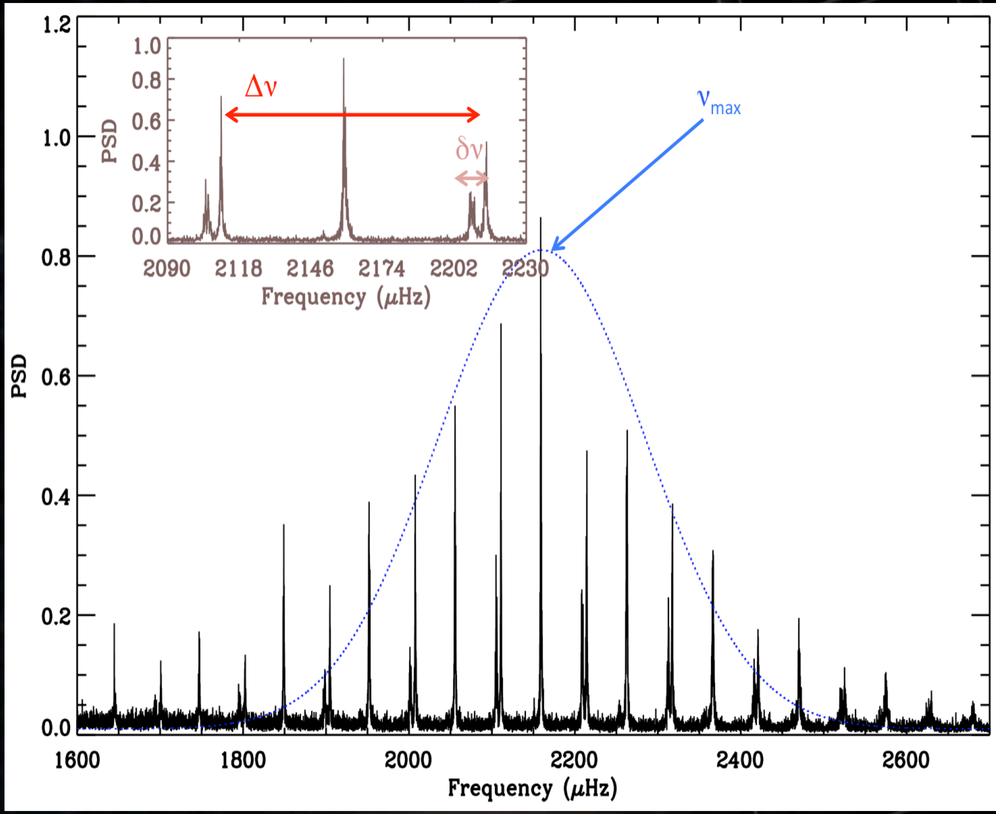




IV-SEISMIC SCALING RELATIONS

- Mean large frequency separation $\Delta\nu$

$$\Delta\nu = \left(\frac{M}{M_\odot}\right)^{1/2} \cdot \left(\frac{R}{R_\odot}\right)^{-3/2} \cdot 135\,\mu\text{Hz}.$$



- Frequency at maximum power ν_{max}

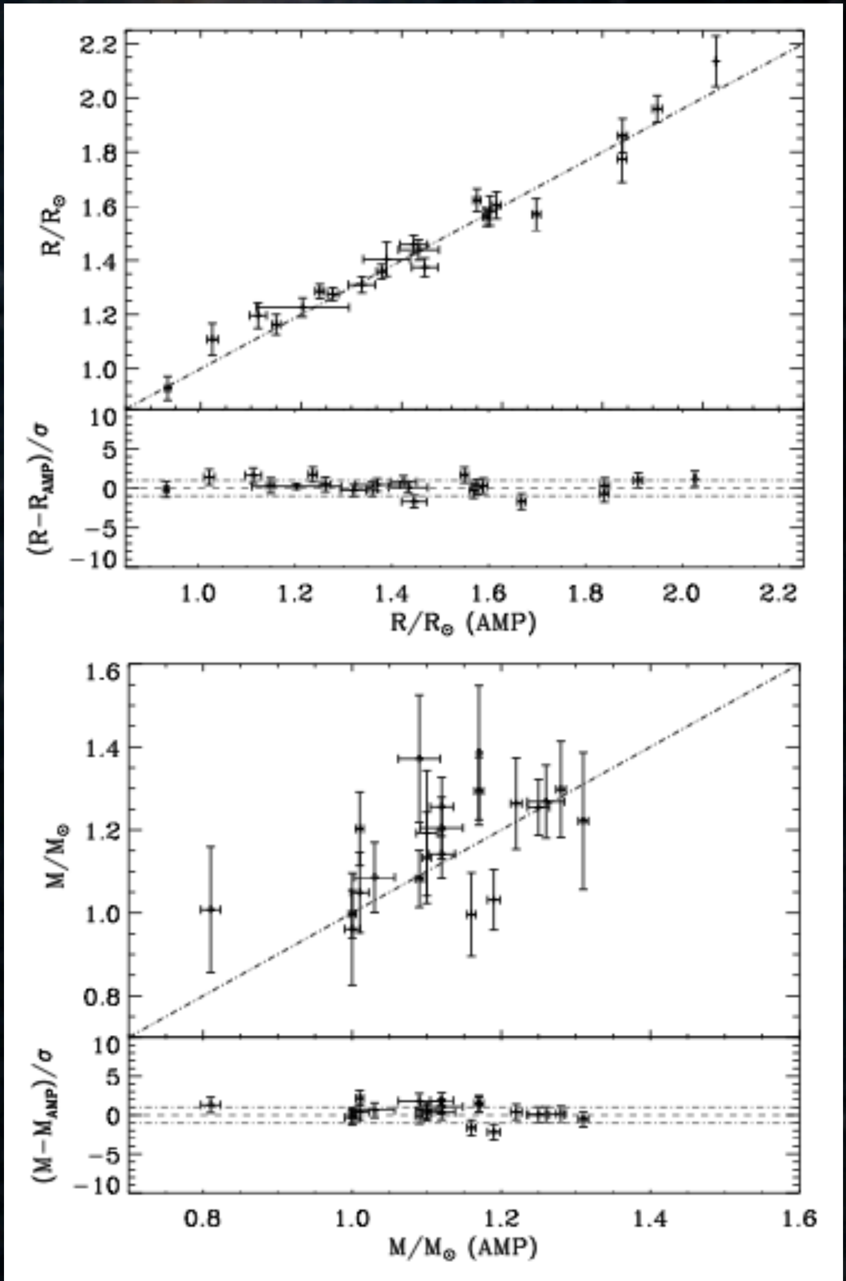
$$\nu_{\text{max}} = \frac{M/M_\odot}{(R/R_\odot)^2 \cdot \sqrt{\frac{T_{\text{eff}}}{5777}}} \cdot 3050\,\mu\text{Hz}.$$

- Maximum amplitude A_{max}

$$A_{\text{max}} = \left(\frac{\text{d}L}{L}\right)_{\text{max}} = \left(\frac{L/L_\odot}{M/M_\odot}\right)^{0.7} \cdot \sqrt{\frac{5777}{T_{\text{eff}}}} \cdot A_{\odot\,\text{max}},$$

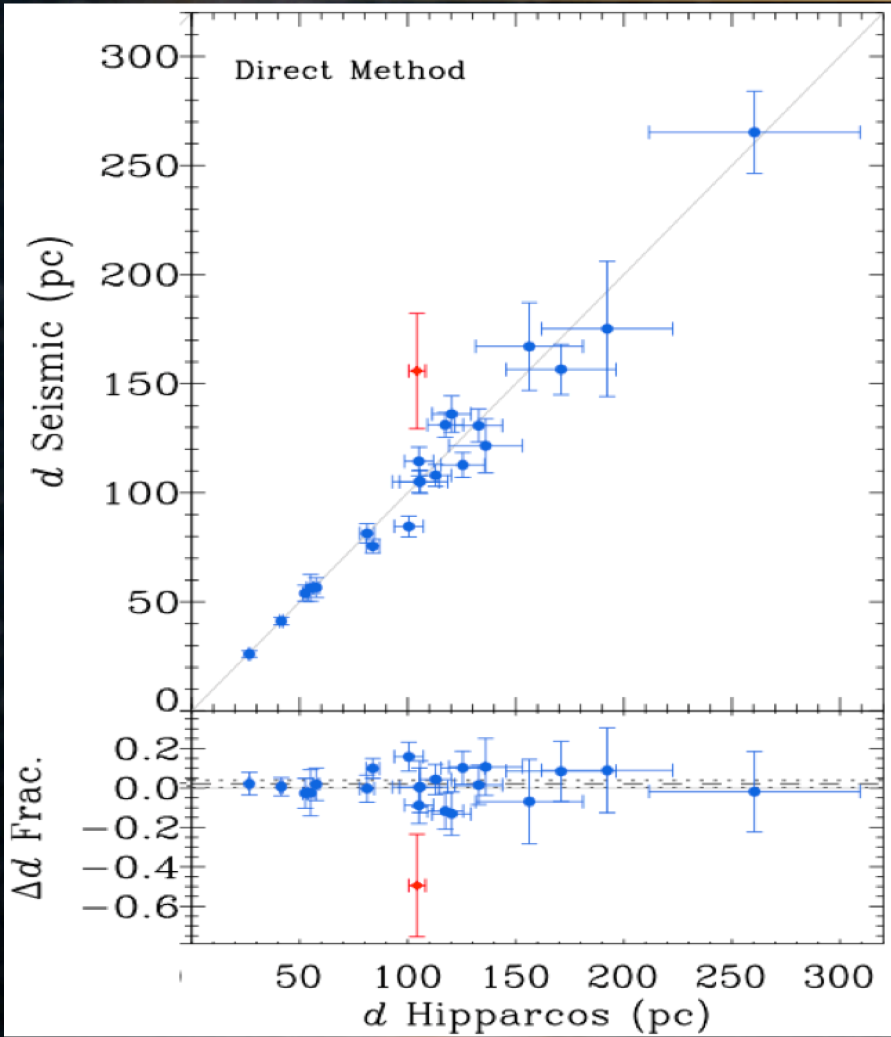
- Combination of T_{eff}, $\Delta\nu$, and ν_{max}: 1st determination of R and M

IV-VALIDATING SCALING RELATIONS



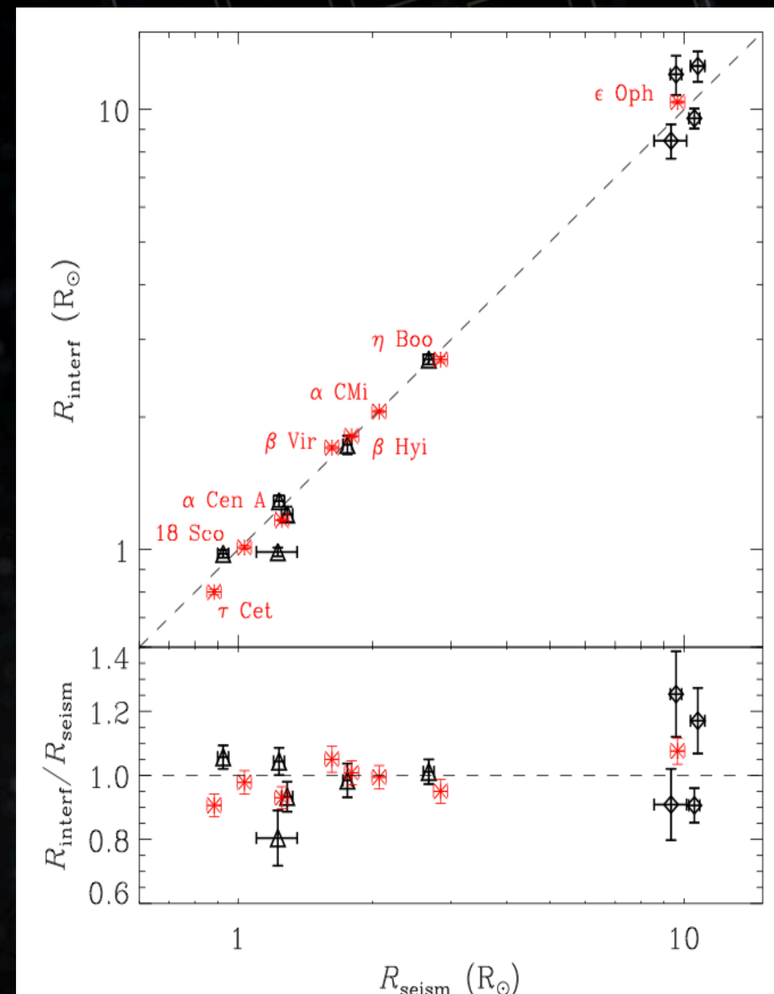
- ~60 S-L Stars
  - already models in an homogeneous way
    - by AMP
- General agreement
- Internal error
  - AMP
    - 0.7% in R,
    - 1.2% in M
  - Scaling relations
    - 3% in R
    - 9% in M
  - Error increase towards subgiant regime

IV-VALIDATING SCALING RELATIONS



- Combining seismic measurements with with Infra red (Teff) using Hipparcos distances
  - CoRoT and *Kepler* stars

[Silva Aguirre et al. 2012]

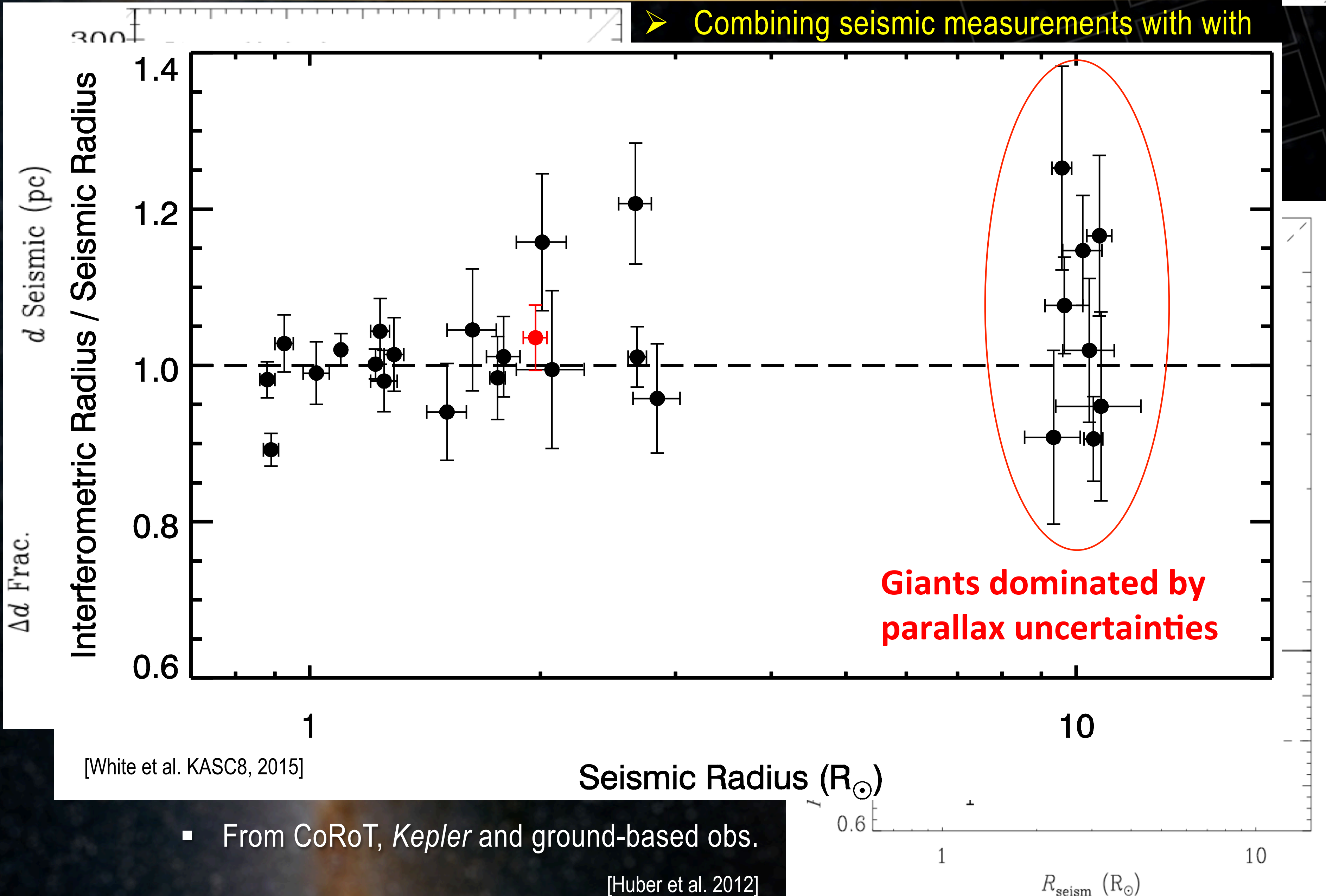


- From interferometric measurements
  - From CoRoT, *Kepler* and ground-based obs.

[Huber et al. 2012]

IV-VALIDATING SCALING RELATIONS

➢ Combining seismic measurements with with



- From CoRoT, *Kepler* and ground-based obs.

[Huber et al. 2012]

V-Characterizing

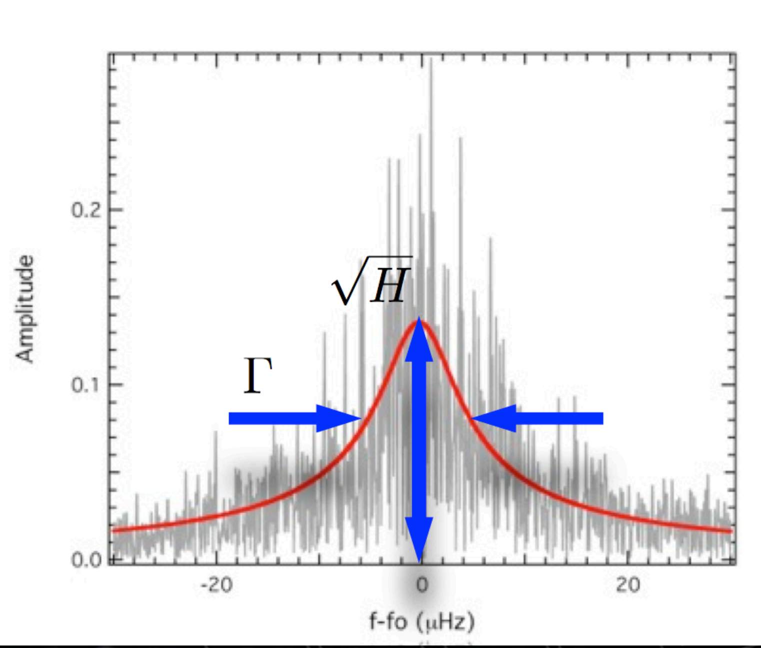
P & mixed modes

V-FITTING P MODES

- For resolved modes
  - Lorentzian profile is used
    - Stochastically excited modes

$$P(f) = \frac{H}{1 + 4\left(\frac{f - f_o}{\Gamma}\right)^2}$$

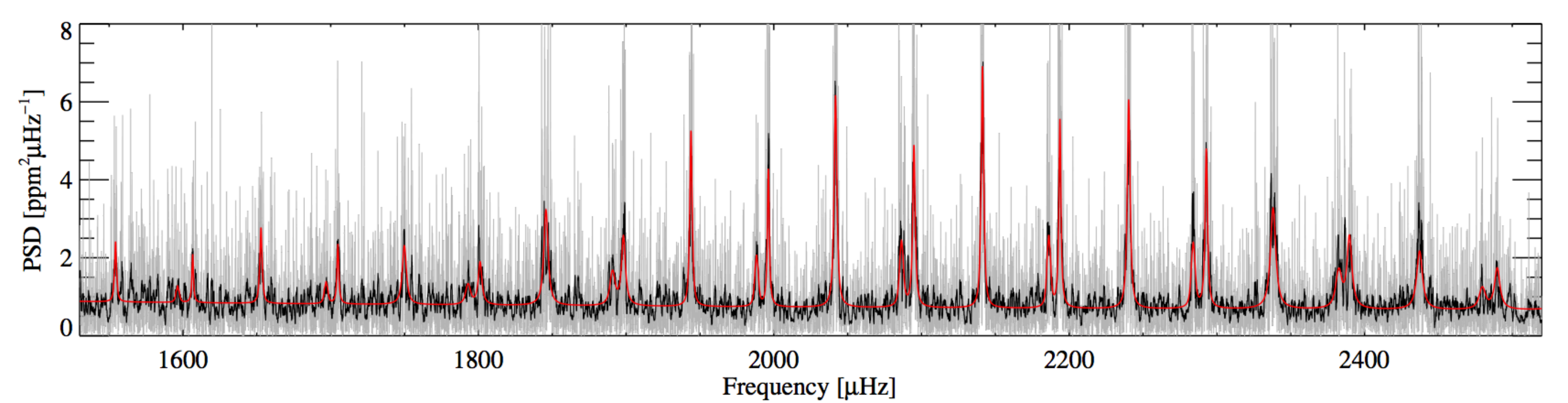
  - In helioseismology
    - Asymmetrical profile
    - Adds a degree of complexity
    - Not yet needed in current asteroseismic data



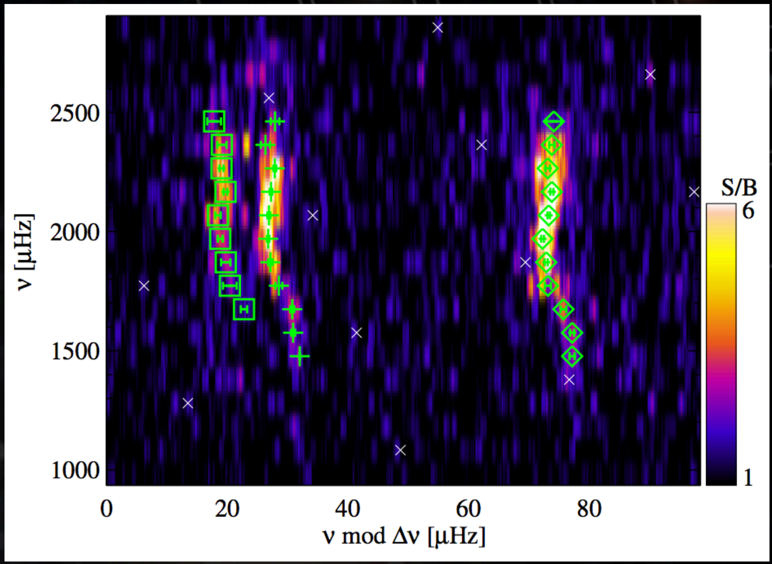
[Kallinger et al. 2014]

V-FITTING P MODES

- Example: HD52265



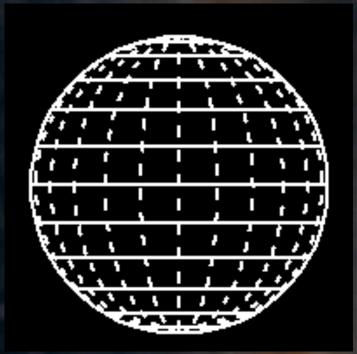
- To reduce the parameter space:
  - Global fitting approach
    - All modes fitted at once
  - Common hypothesis
    - Amplitudes and linewidths are linked
      - In sequences of l=0-4



[Ballot et al. 2011]

V-FITTING P MODES

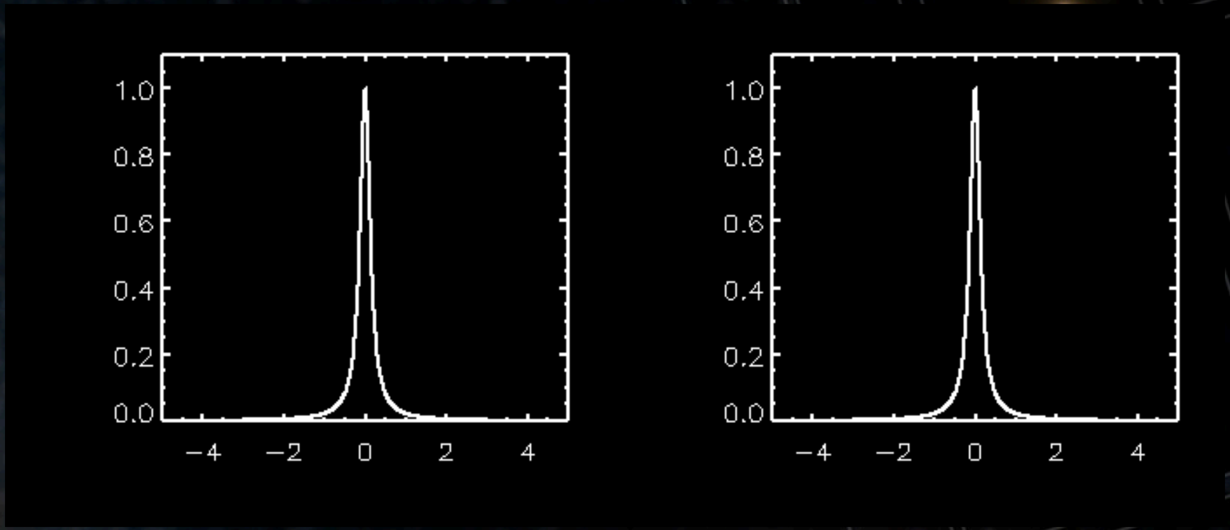
Ω = 0,0



i = 90°

ℓ=1 mode

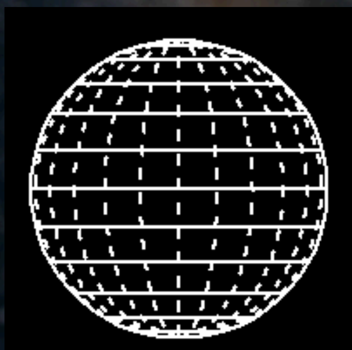
ℓ=2 mode



[Adapted from J. Ballot 2010]

V-FITTING P MODES

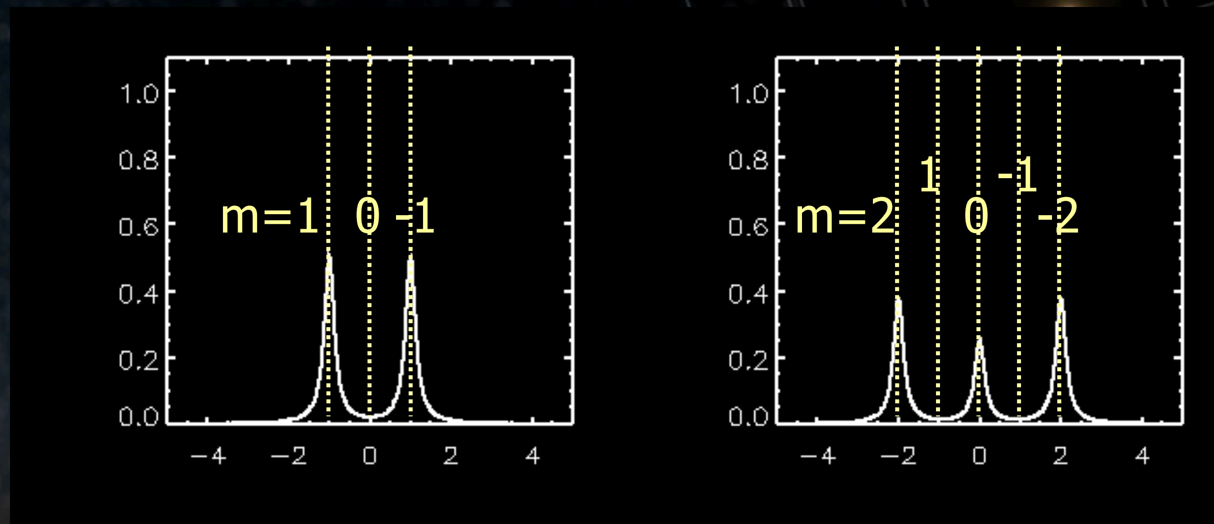
$\Omega = 1{,}0$



$i = 90°$

$\ell=1$ mode

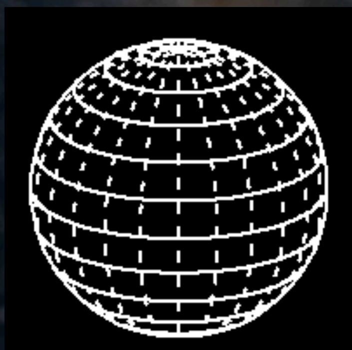
$\ell=2$ mode



[Adapted from J. Ballot 2010]

V-FITTING P MODES

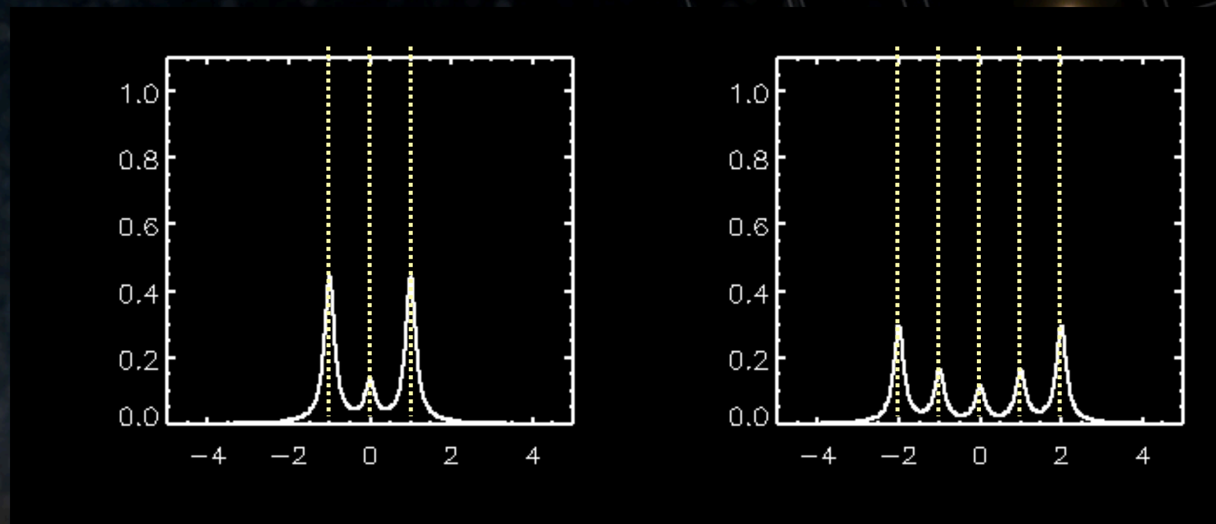
Ω = 1,0



i = 70°

ℓ=1 mode

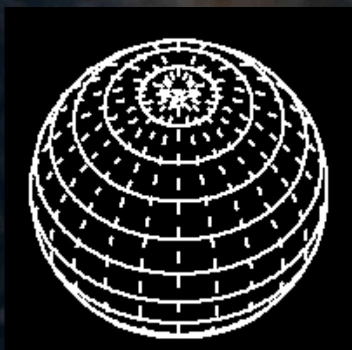
ℓ=2 mode



[Adapted from J. Ballot 2010]

V-FITTING P MODES

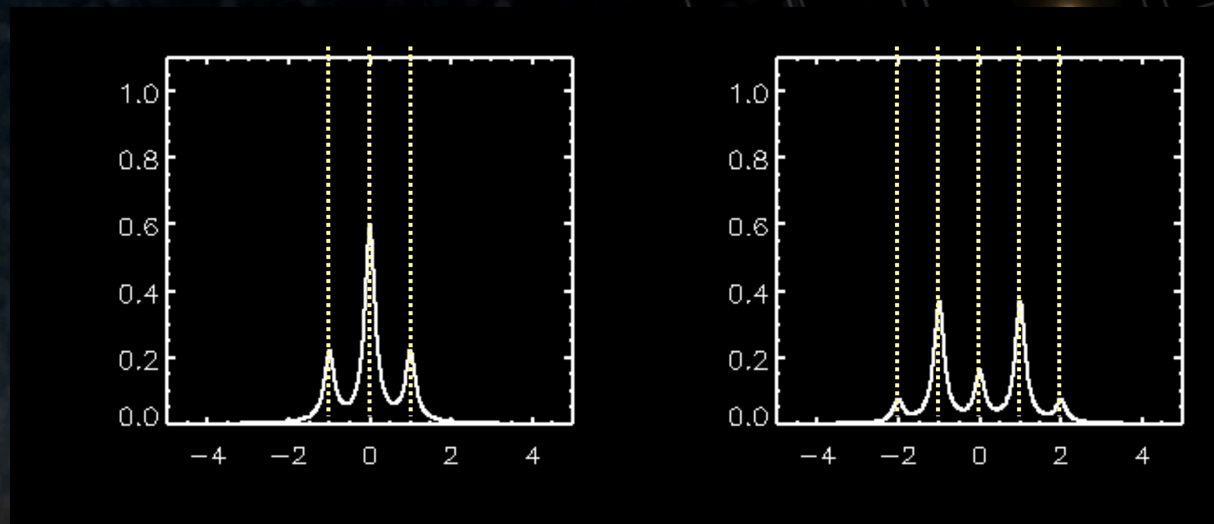
Ω = 1,0



i = 40°

ℓ=1 mode

ℓ=2 mode



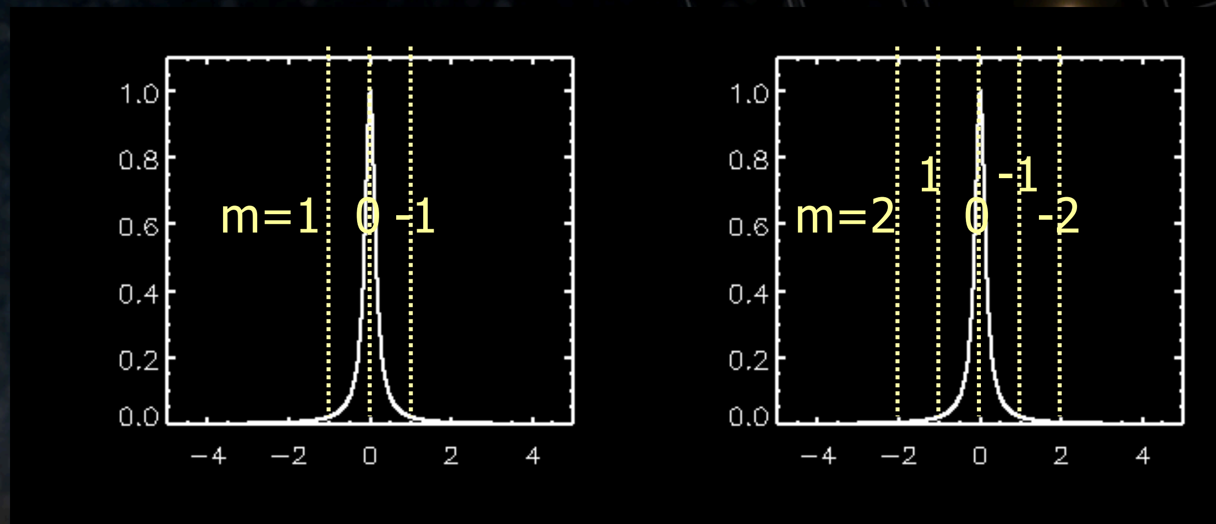
[Adapted from J. Ballot 2010]

V-FITTING P MODES

Ω = 1,0

i = 0°

ℓ=1 mode   ℓ=2 mode

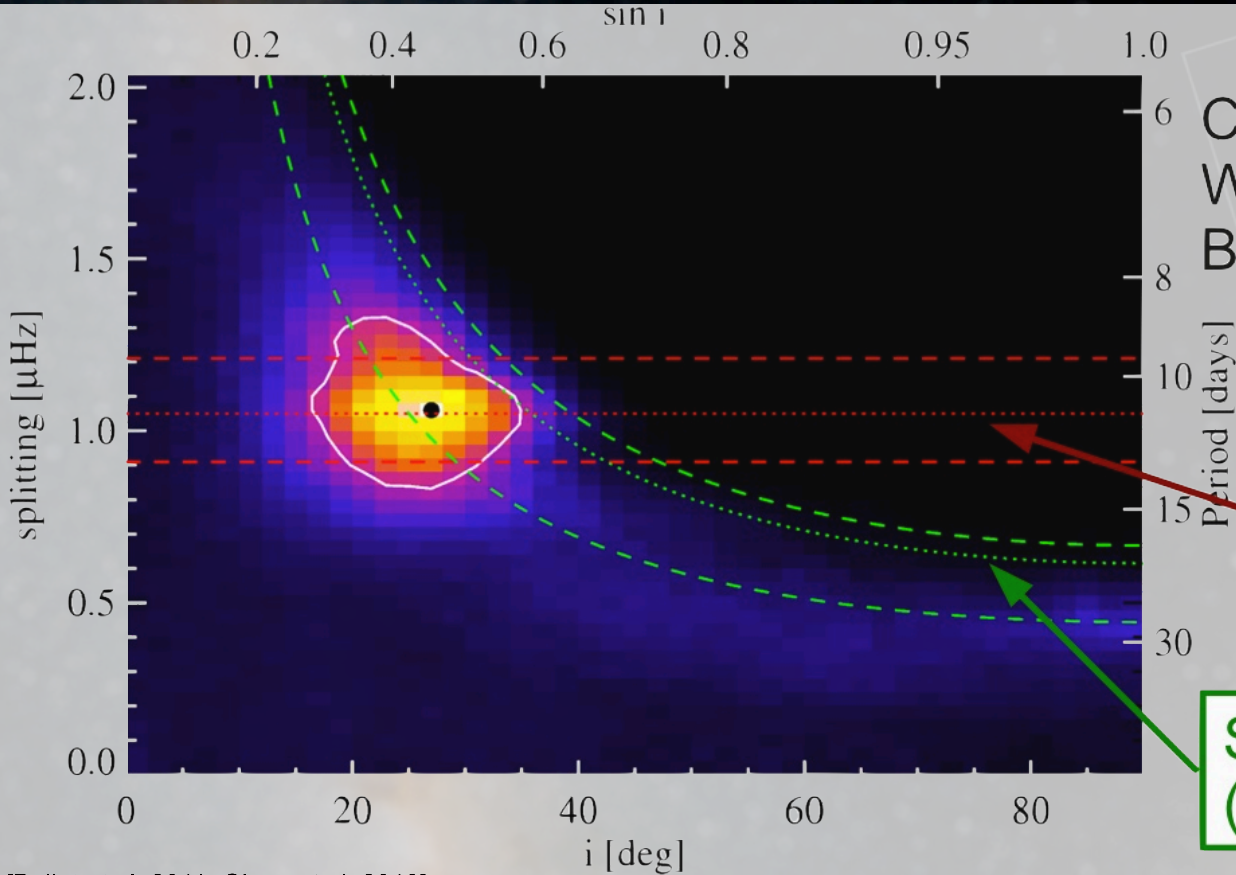


- Strong correlation between angle and splitting
  - We need to fit the stellar inclination angle and the rotational splitting together

[Ballot et al. 2006]

[Adapted from J. Ballot 2010]

V-FITTING P MODES: INTERNAL ROTATION



HD52265

Colored map: mode fitting
White: high probability
Black: low probability

spots

Spectro. Constraints (vsini) + R from seismo.

[Ballot et al. 2011; Gizon et al. 2013]

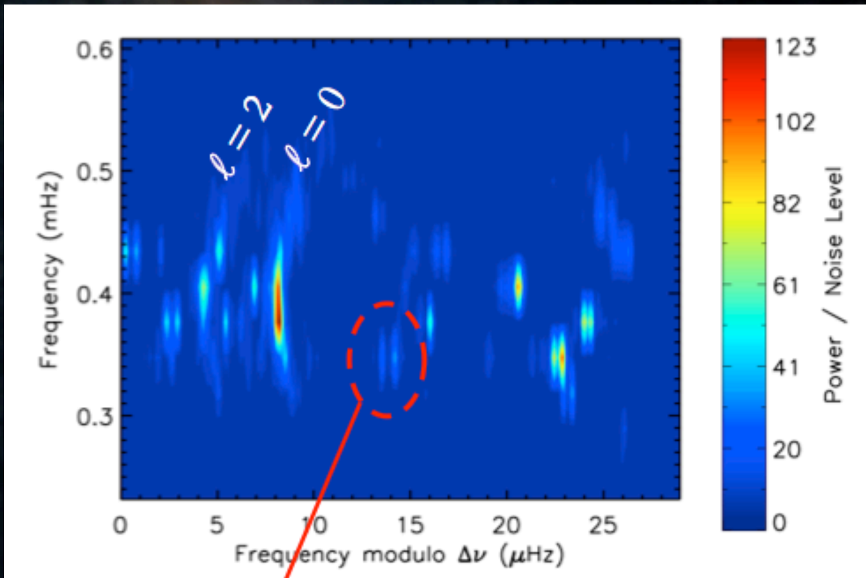
Asteroseismic inclinations put constraints on star-planet systems dynamics

[c.f. Laskar talk]

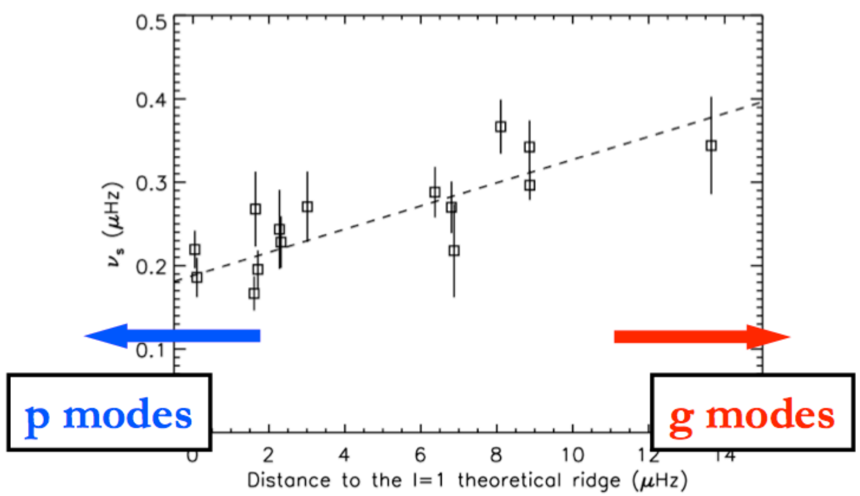
[Chaplin et al. 2013 for some Kepler results on Kepler-50 and Kepler-65
Huber et al. 2013 for Kepler-56]

V-FITTING MODES: INTERNAL ROTATION

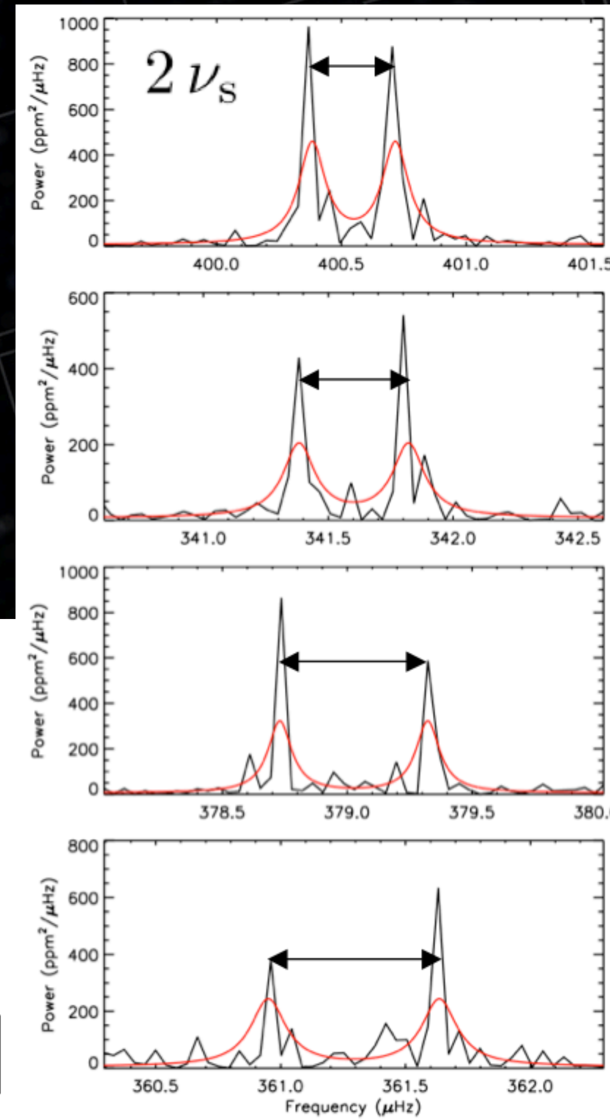
➢ Mixed modes allow us to study the internal dynamics



Modes rotationally split



suggests that $\Omega_{core} > \Omega_{surface}$

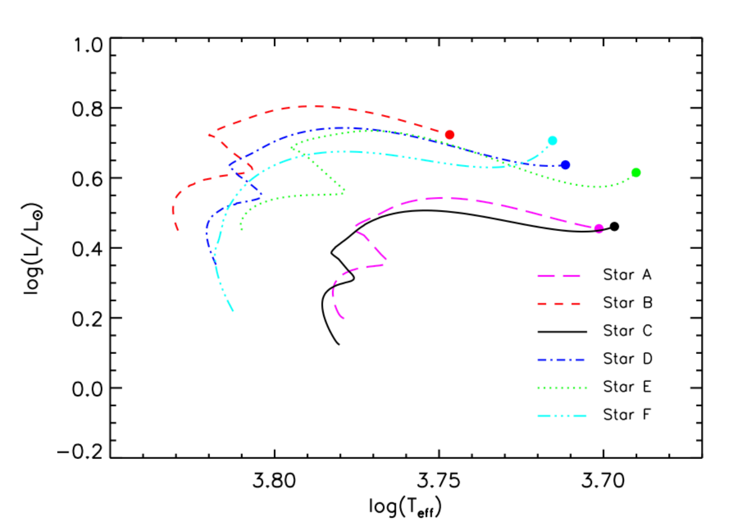


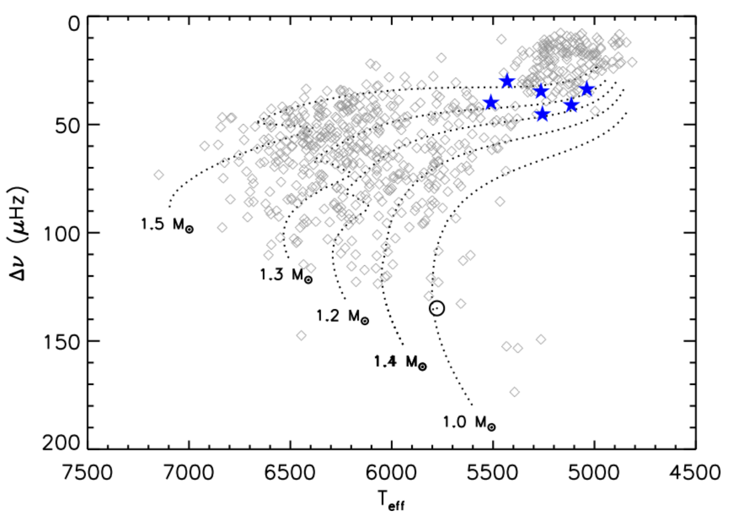
[Deheuvels, Garcia, et al. 2012, 2014]

V-FITTING MODES: INTERNAL ROTATION

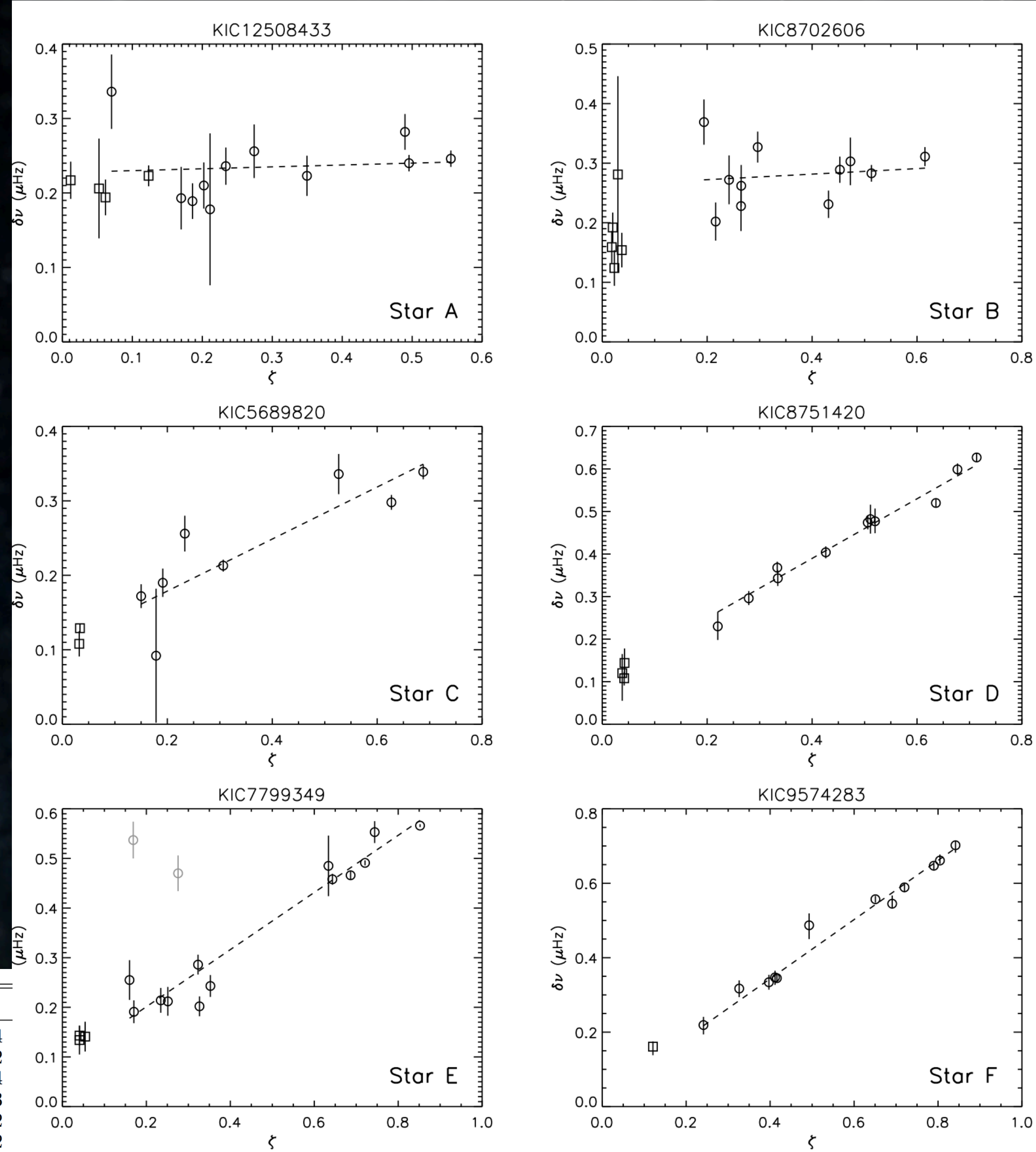
- 6 Subgiant/early RGBs

[Deheuvels et al. 2014]





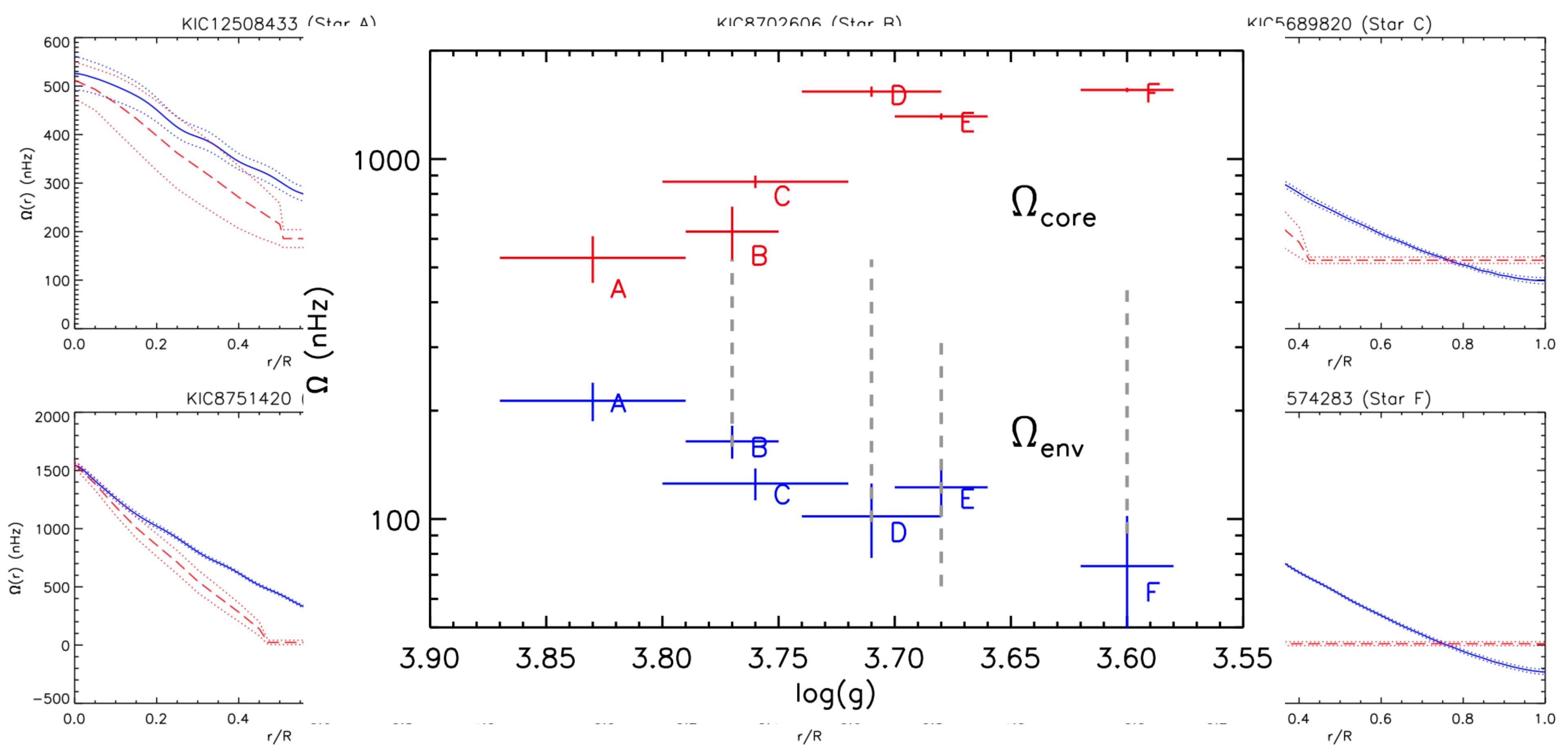
Star	Ref. letter	$\Delta\nu$ (μHz)	ν_{max} (μHz)	M	R	$\log g$
KIC12508433	A	45.3 ± 0.2	793 ± 21	1.20 ± 0.16	2.20 ± 0.10	3.83 ± 0.04
KIC8702606	B	39.9 ± 0.4	664 ± 14	1.27 ± 0.15	2.44 ± 0.11	3.77 ± 0.02
KIC5689820	C	41.0 ± 0.3	695 ± 15	1.11 ± 0.16	2.29 ± 0.12	3.76 ± 0.04
KIC8751420	D	34.7 ± 0.4	598 ± 14	1.50 ± 0.20	2.83 ± 0.15	3.71 ± 0.03
KIC7799349	E	33.7 ± 0.4	561 ± 8	1.33 ± 0.14	2.77 ± 0.12	3.68 ± 0.02
KIC9574283	F	30.0 ± 0.5	455 ± 8	1.24 ± 0.17	2.92 ± 0.17	3.60 ± 0.02



V-FITTING MODES: INTERNAL ROTATION

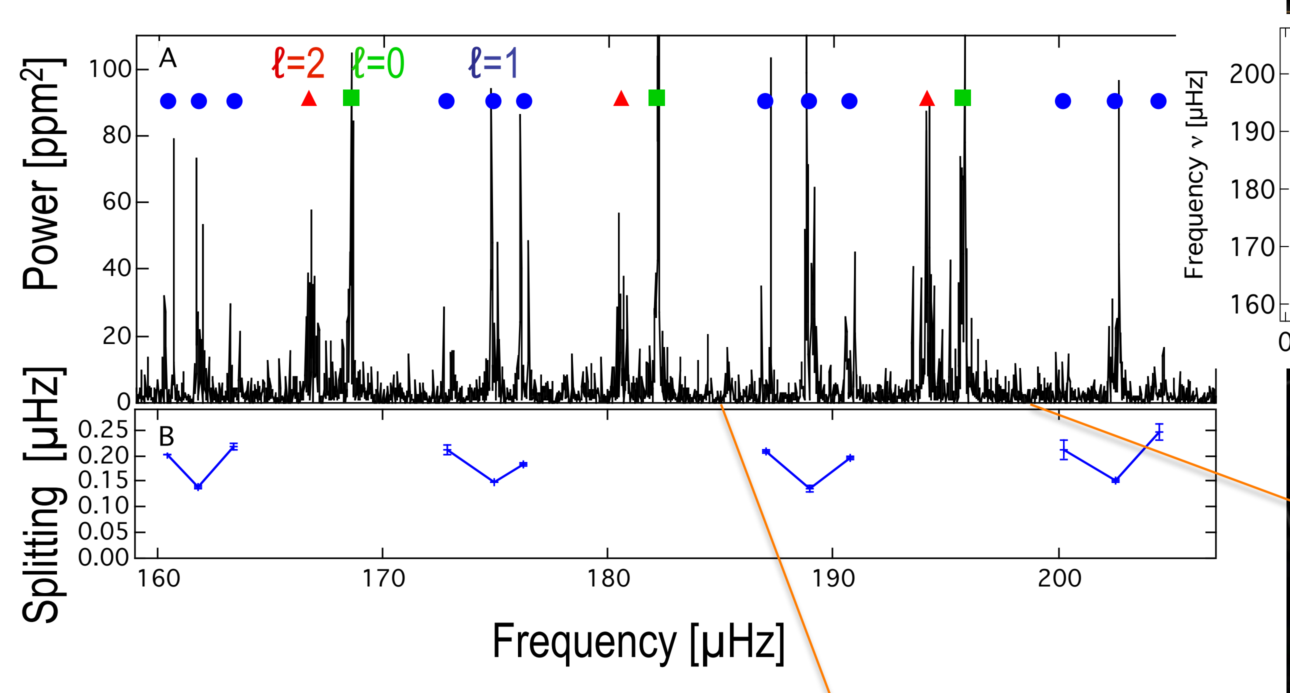
- 6 Subgiant/early RGBs

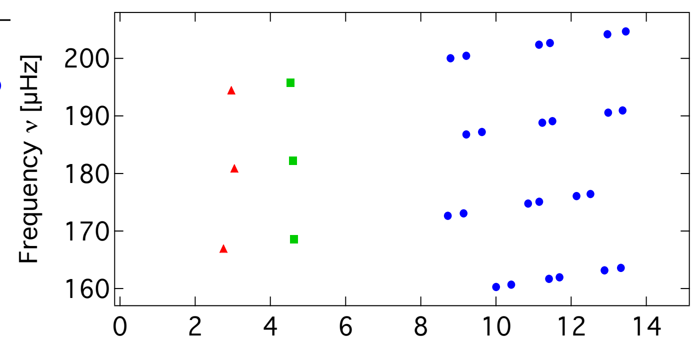
[Deheuvels et al. 2014]



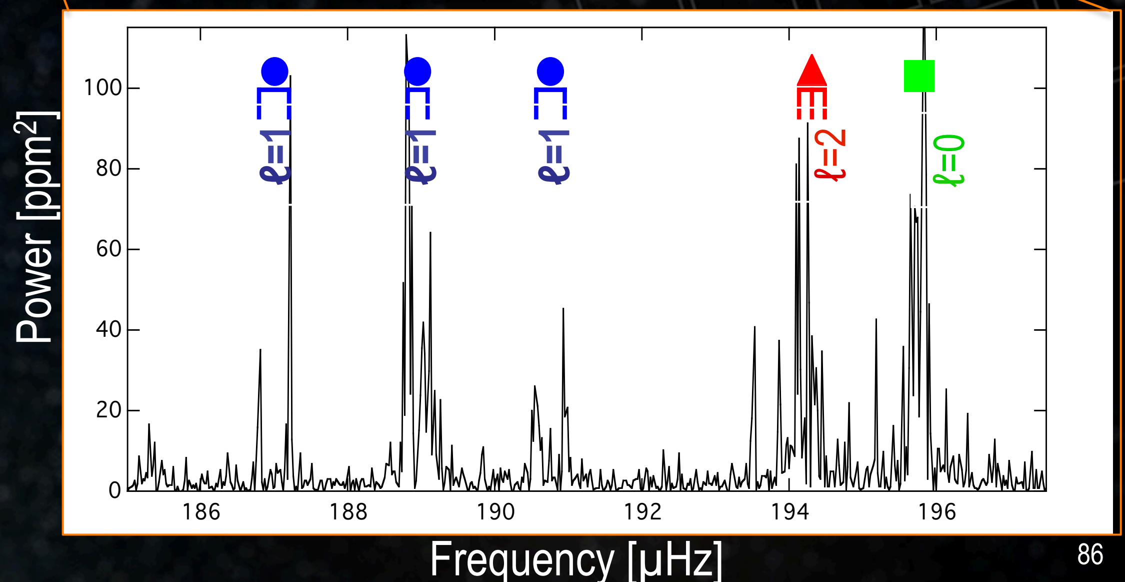
The trend with the seismic logg suggests that the core spins in the subgiant phase

V-FITTING MODES: INTERNAL ROTATION



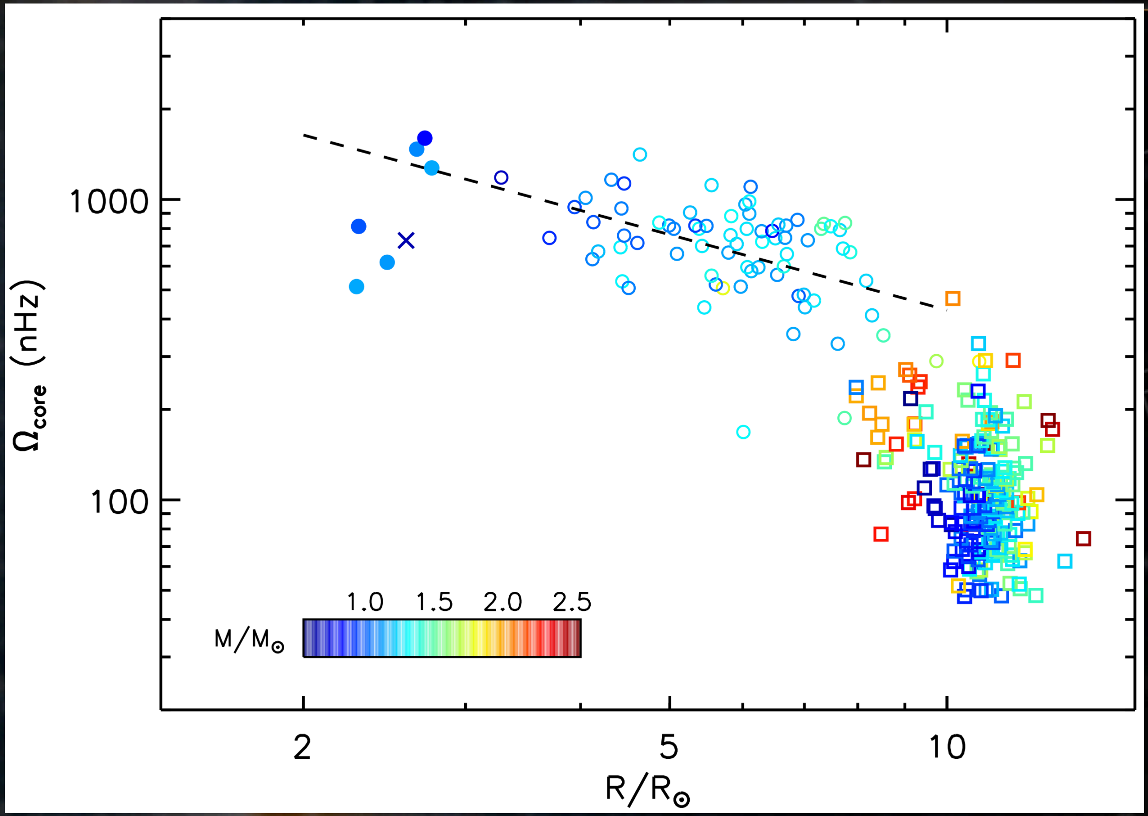


- By measuring the splittings
  - In more evolved stars
  - Core rotates 10 times faster
    - Radiative region
    - In 3 RG stars



[Beck et al. 2012]

V-FITTING MODES: INTERNAL ROTATION



[Mosser et al. 2012
Filled circles from Deheuvels et al. 2014]

- Ensemble analysis used to obtain a proxy of the rotation rate of the deep radiative interior
- During RGB (circles):
  - The core of the stars during RGB spins down!
  - Efficient AM transport to counterbalance the core contraction and not efficient during subgiant phase
- Change from RGB to the clump (squares) can be related to the expansion of the non-degenerate helium burning core.
  - It can not explain all the reduction [Iben 1971; Sills & Pinsonneault 2000]
    - significant transfer of internal angular momentum from the inner to the outer layers.

V-FITTING P MODES

- The Fitting can be done:
  - Frequentist approach
    - In an statistical way:
      - A model is fitted using a Maximum-likelihood minimization
      - A likelihood of the result is obtained
  - “Bayesian” approach
    - For each parameter of a model
      - A prior probability is provided
    - The “bayesian” fit
      - Returns the posterioir probability of each parameter

[Bayes 1793, Appourchaux 2008, Benomar et al. 2008]

VI-Magnetic fields

VI-MAGNETICS FIELDS IN STARS

- Magnetic fields play a role in almost all stages of stellar evolution
- Most low-mass stars, including the Sun, show surface fields that are generated by dynamo processes in their convective envelopes
- Intermediate-mass stars do not have deep convective envelopes, although 10% exhibit strong surface fields that are presumed to be residuals from the stellar formation process.
- These stars do have convective cores that might produce internal magnetic fields, and these might even survive into later stages of stellar evolution

But information has been limited to the surface because of our inability to measure the fields below the stellar surface