The Solar/Stellar connection: Magnetic activity of seismic solar analogs

David Salabert
(collaborators: R.A. Garcia, P.G. Beck, et al.)

Motivation

Study effects in stars very similar to Sun due to differences in age

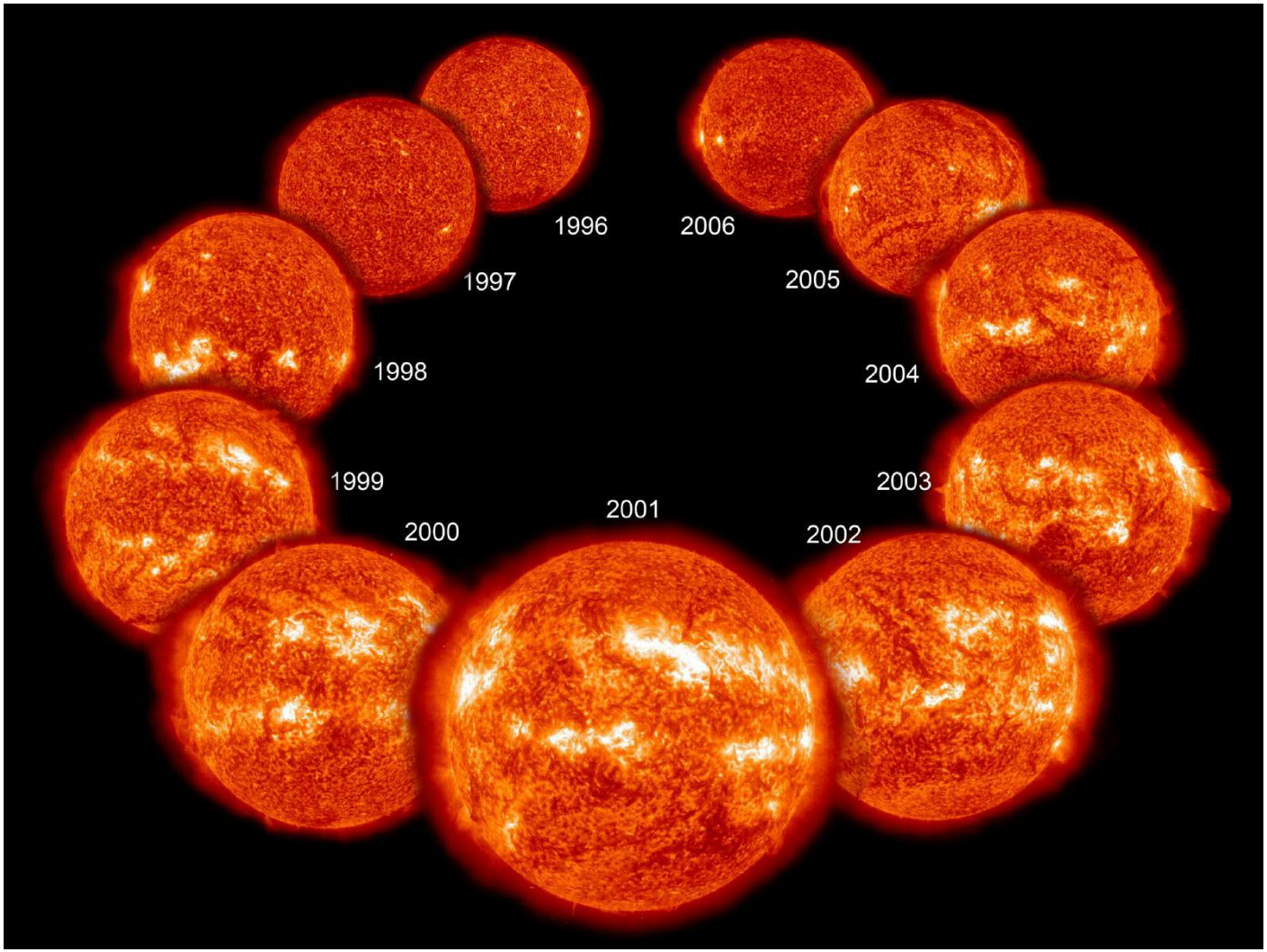
Sun In Context

- Solar activity with respect to other solar-like stars?
- Solar seismic parameters with respect to solar-like stars?
- Solar lithium with respect to solar-like stars?

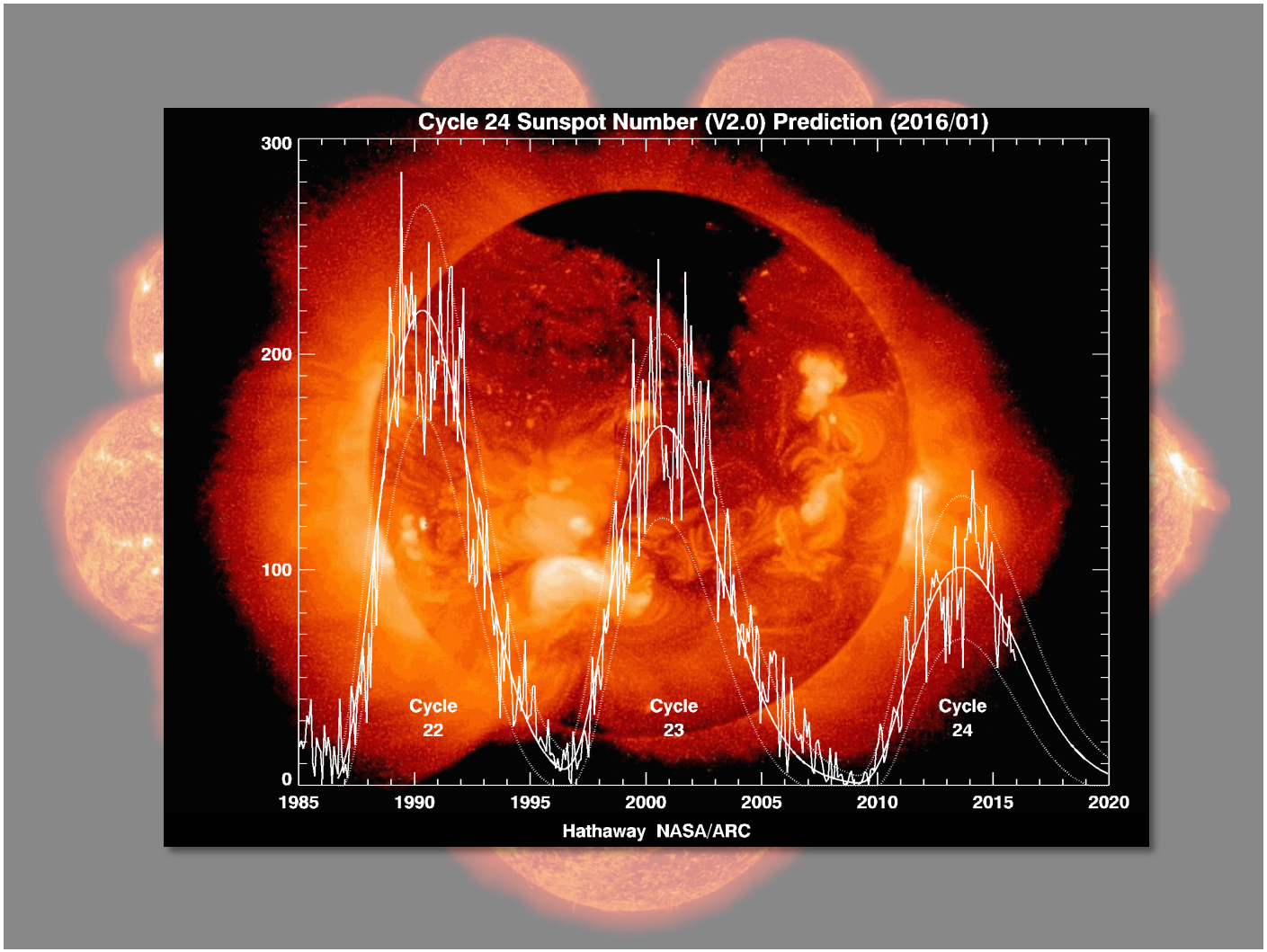
Motivation

- Study effects in stars very similar to Sun due to the differences in age
  - **Rotation rate**
    (Skumanich 1972, Garcia+ 2014, Van Sanders+ 2015, …)
  - **Stellar Activity**
    (Skumanich 1972, Garcia+ 2010, Chaplin+ 2011, Karoff+ 2013)
  - **Metallicity & Tracer elements**: Lithium, Beryllium, Potassium, …
    (Skumanich 1972, doNascimento+ 2009/10, Baumann+ 2010, Carlos+2016)

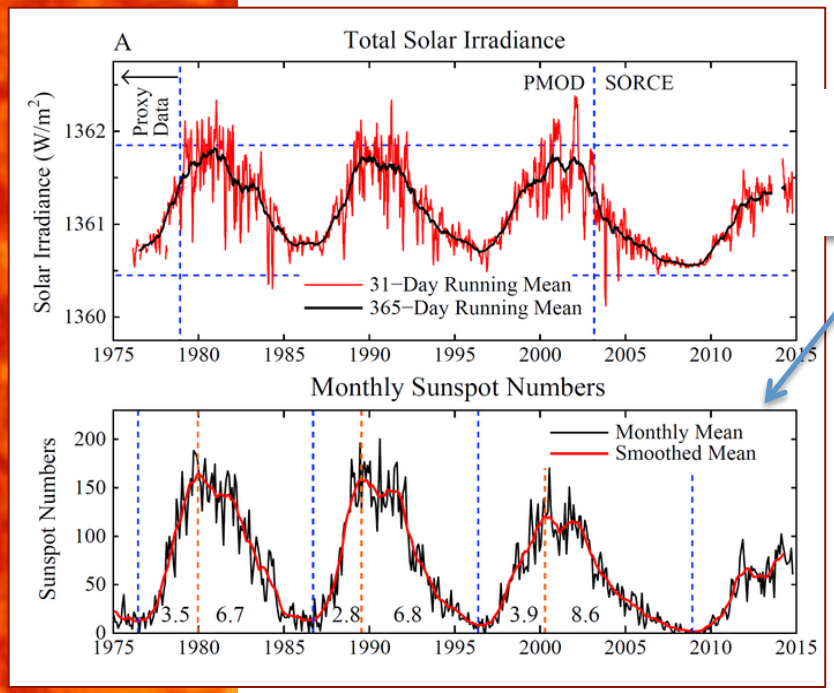
Solar activity



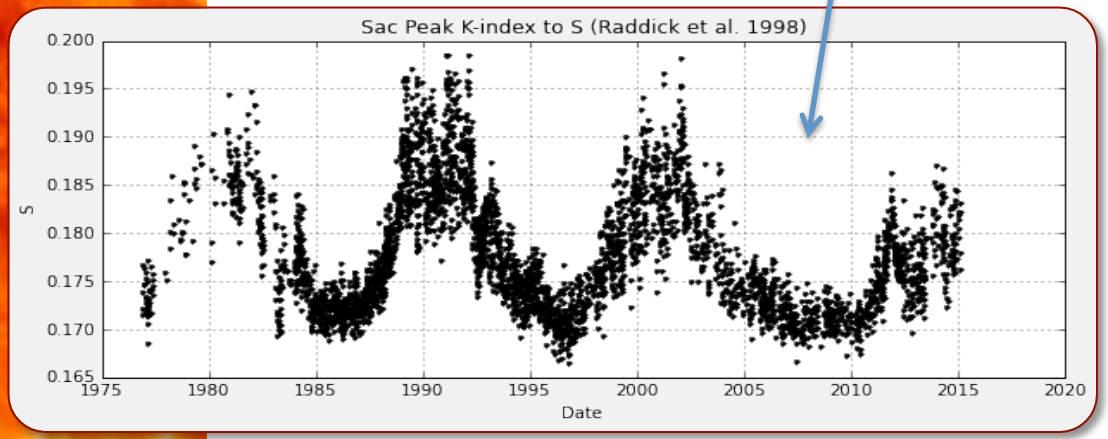
Solar activity

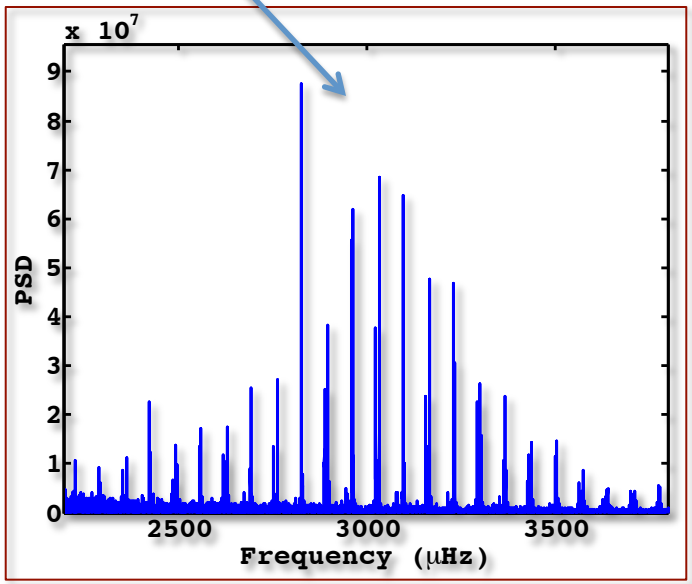


Proxies of solar activity

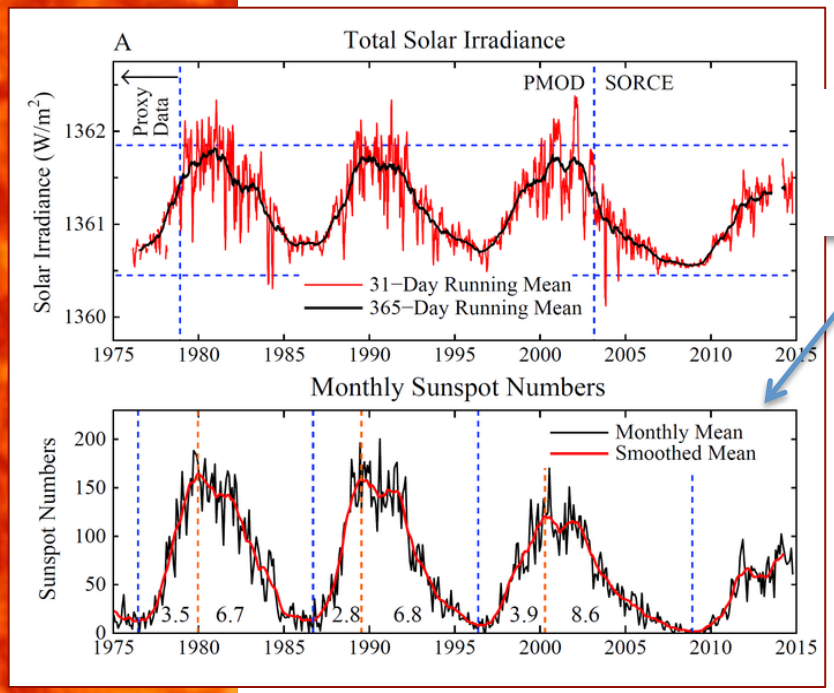


- Sun-as-a-star data show rotational modulation and long-term magnetic cycle
- Photometric data show integrated effect of dark spots and bright faculae
- Spectroscopic data track emission from faculae relative to the continuum
- Seismic data reveal inferences on subsurface changes with activity





Proxies of solar activity



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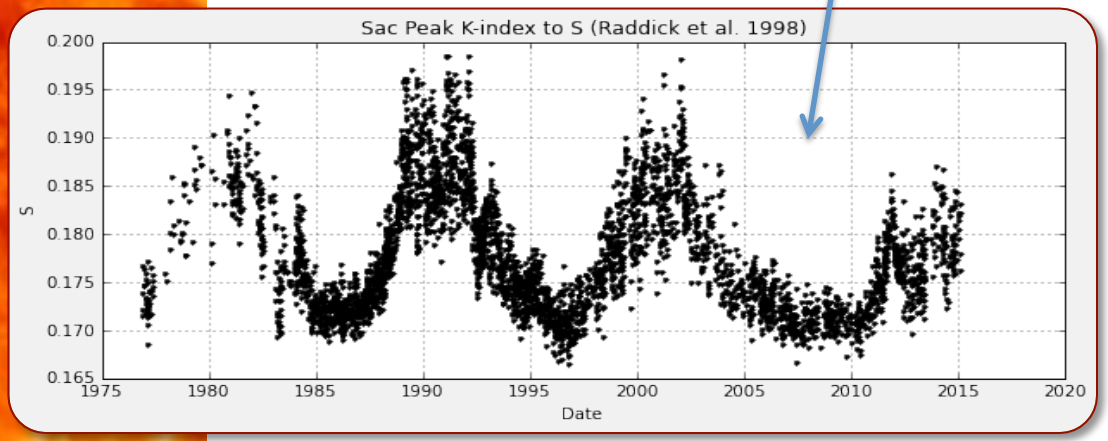
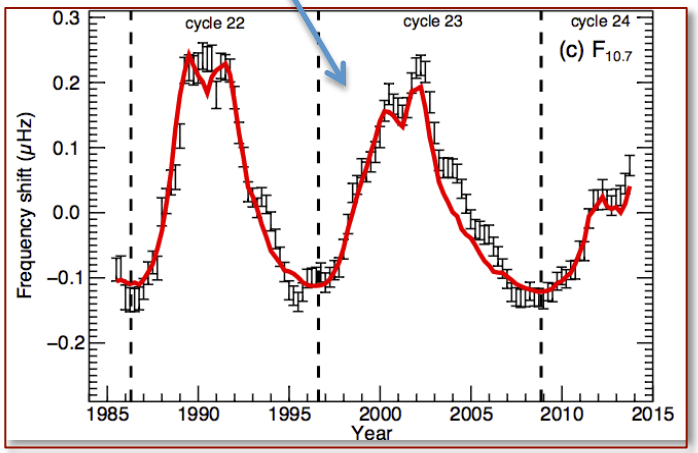
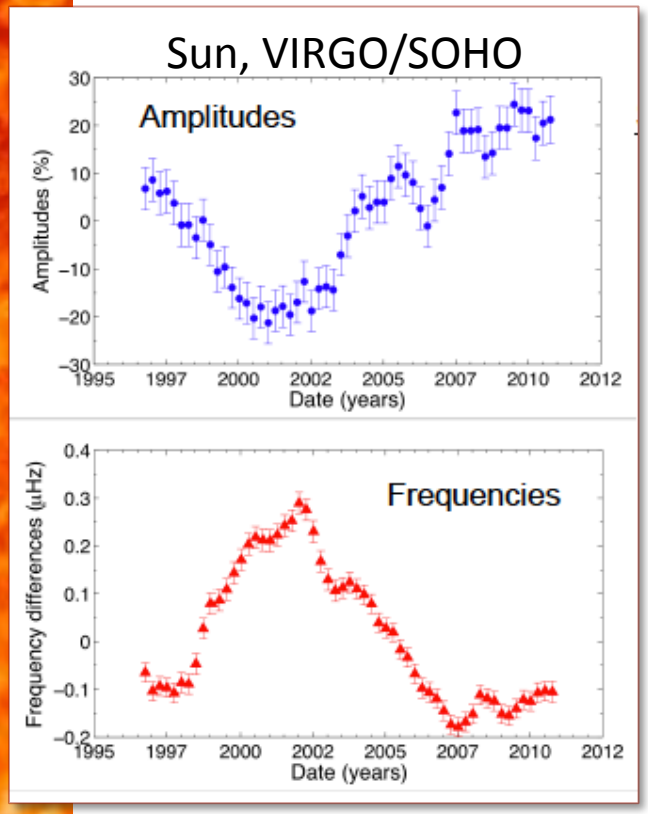




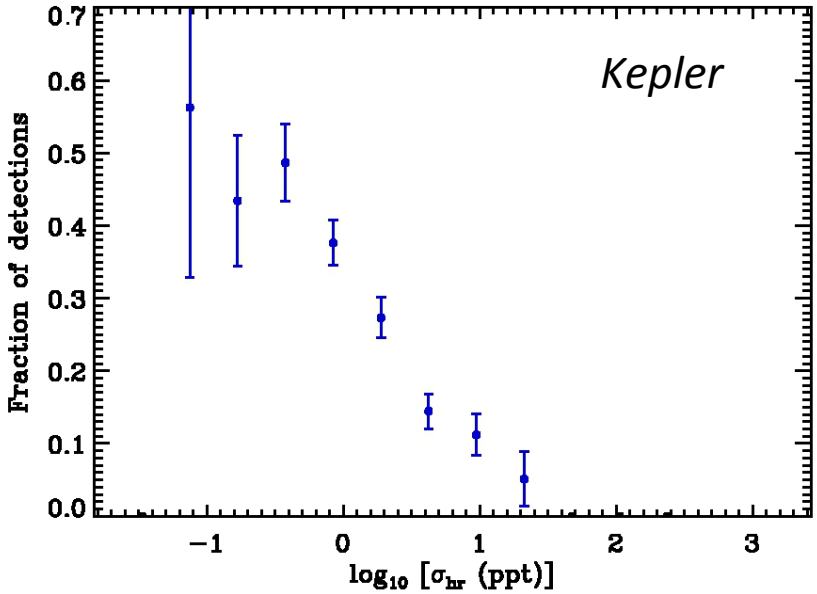
Influence on mode amplitudes

- Magnetism inhibits convection, reducing the oscillation amplitudes



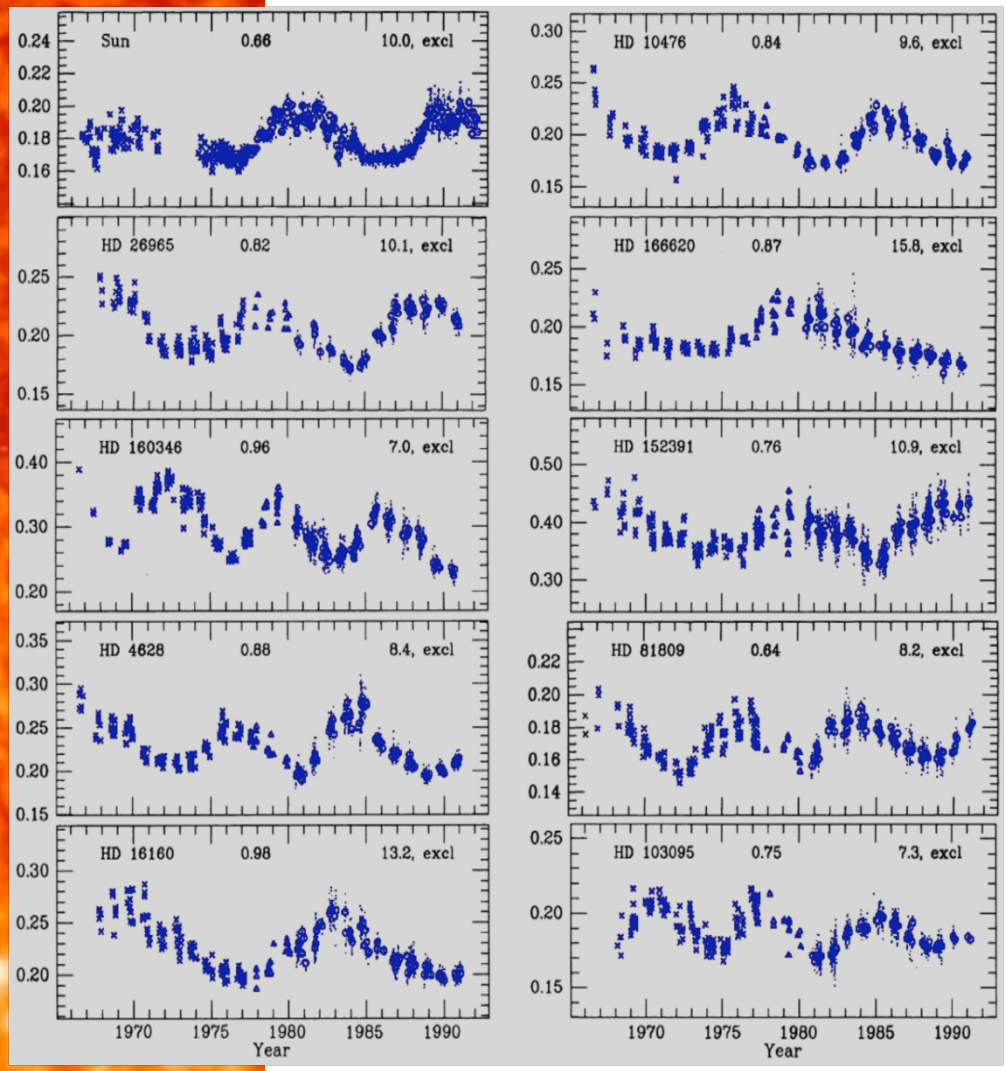
Salabert et al. (2011)

- Lower detection rate for stars with higher levels of magnetic activity



Chaplin et al. (2011)

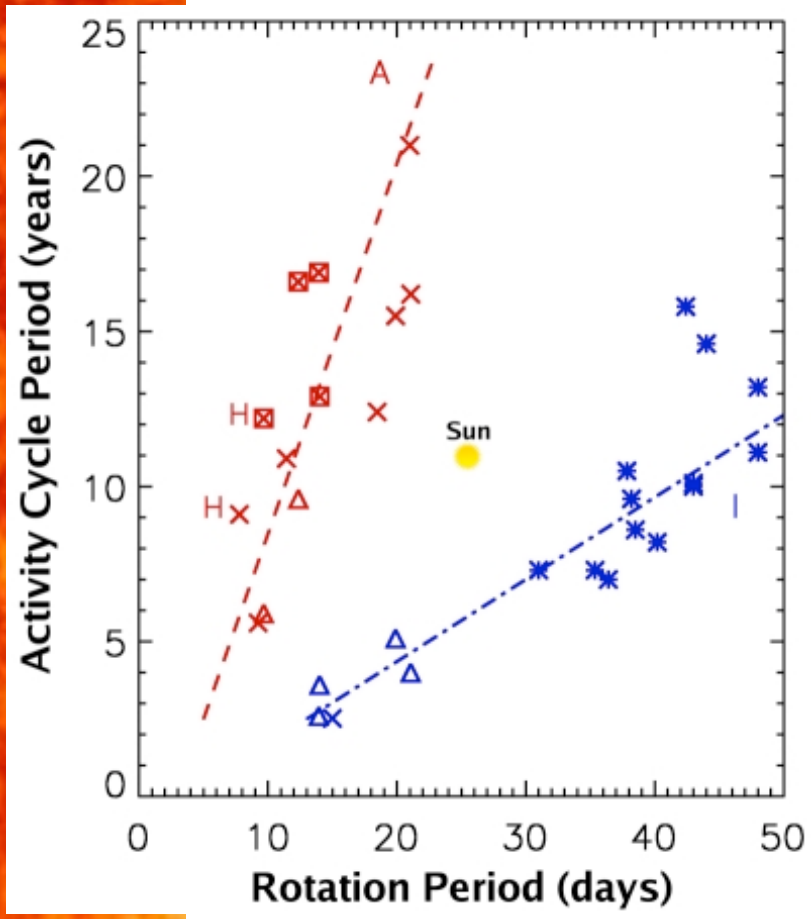
Mount Wilson survey



- Mount Wilson survey found magnetic activity cycles in many stars
- Mean activity level and cycle period scale with Rossby number (P_{rot} / τ_c)
- Survey ended in 2000's after more than 30 years of Ca HK observations

Wilson 1978; Baliunas et al. (1995)

Activity and rotation



- Saar & Brandenburg (99) sample of stars with clear rotation and cycle periods
- Two distinct relationships between cycle period and rotation (100 & 300/cycle)
- BV07: separate dynamo mechanisms
- Some stars on the Active branch show secondary cycles on Inactive branch

- The Sun appears as a peculiar outlier suggesting to be in transition from one dominant dynamo mechanism to another.

Saar & Brandenburg (1999), Bohm-Vitense 2007

Definition

- **Cayrel de Strobel (1996)**
  - **Solar-like:** dwarfs of 0.5< B-V < 0.80 (late F to late G/early K)
  - **Solar Analog:** within ±10% Mass (and Radius), T_{eff}: ±150K, and metallicity: ±0.3dex
  - **Solar Twin:** virtually equal (±10K, ±0.05 dex)

Age is not so much of a factor (Radius and T_{eff} less rigid)

Over last years, Seismology is a new tool/category:
18 Sco (Bazot+ 2012),
16 Cyg A&B (Metcalfe+ 2012, Davies+ 2015)
CoRoT 102684698 (do Nascimento+ 2013)

Ensemble analysis of more 500 solar-like oscillators:
Chaplin+ (2011,2014)

Our sample of seismic solar analogs

- Sample of 18 *Kepler* stars to study the **magnetic activity properties** (Salabert+, under revision A&A)
  - Extended Cayrel de Strobel (1996)'s definition to take into account the typical observational asteroseismic and spectroscopic uncertainties
  - Fundamental parameters derived from seismic analysis including ages (Chaplin+ 2014, Mathur+ 2012, Metcalfe+ 2014)
  - Large frequency separation > 85 µHz to avoid evolved stars
  - Measured surface rotation periods & gyrochronology (Garcia+ 2014) to insure active stars

- Complemented with **high-resolution spectroscopy** (Beck+ in prep.)

Project is a clear example of the advantage of

combining Seismology & high-resolution Spectroscopy

Properties of the 18 *Kepler* solar analogs

Table 2. Seismic solar analogs observed by *Kepler* and their derived stellar properties.

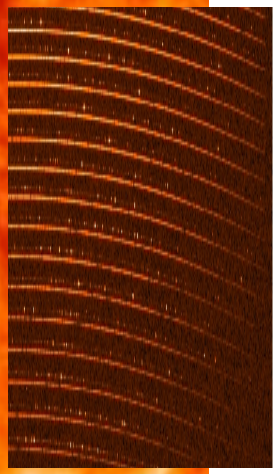
# star	KIC	M ($M_\odot$)	R ($R_\odot$)	Age (Gyr)	$T_{\rm eff}$ (K)	log g	$\Delta\nu$ (μHz)	Ref.	Flag
1	3241581	0.89 ± 0.12	1.03 ± 0.05	10.5 ± 5.0	5770 ± 81	4.36 ± 0.02	122.9 ± 1.6	1	1
2	3656476	1.09 ± 0.01	1.32 ± 0.03	7.7 ± 0.2	5710 ± 84	4.22 ± 0.01	93.3 ± 1.3	3	123
3	4914923	1.10 ± 0.01	1.37 ± 0.05	6.2 ± 0.2	5905 ± 84	4.21 ± 0.01	88.6 ± 0.3	3	3
4	5084157	1.06 ± 0.13	1.36 ± 0.08	7.8 ± 3.4	5803 ± 83	4.19 ± 0.02	87.3 ± 2.6	1	1
5	5774694	1.06 ± 0.05	1.00 ± 0.03	1.9 ± 1.8	5875 ± 84	4.46 ± 0.02	140.2 ± 4.0	2	2
6	6116048	1.01 ± 0.03	1.22 ± 0.01	6.2 ± 0.4	5935 ± 84	4.27 ± 0.01	100.9 ± 1.4	4	234
7	6593461	0.94 ± 0.16	1.29 ± 0.07	10.7 ± 4.4	5817 ± 101	4.19 ± 0.02	90.8 ± 2.0	1	1
8†	7296438	0.91 ± 0.15	1.30 ± 0.06	12.3 ± 4.3	5749 ± 56	4.17 ± 0.03	88.6 ± 2.1	1	1
9	7680114	1.12 ± 0.07	1.43 ± 0.04	6.5 ± 1.5	5855 ± 84	4.18 ± 0.01	85.1 ± 1.3	2	12
10	7700968	1.00 ± 0.12	1.21 ± 0.06	7.5 ± 3.1	5982 ± 75	4.27 ± 0.02	102.6 ± 2.9	1	1
11	9049593	1.13 ± 0.14	1.40 ± 0.06	6.4 ± 3.4	5788 ± 59	4.19 ± 0.02	86.3 ± 2.1	1	1
12	9098294	1.00 ± 0.03	1.15 ± 0.01	7.3 ± 0.5	5840 ± 84	4.30 ± 0.01	108.8 ± 1.7	4	124
13	10130724	0.85 ± 0.12	1.08 ± 0.05	13.8 ± 5.0	5648 ± 70	4.31 ± 0.02	112.9 ± 1.6	1	1
14	10215584	0.99 ± 0.13	1.12 ± 0.05	6.8 ± 3.5	5995 ± 57	4.34 ± 0.02	114.7 ± 3.1	1	1
15	10644253	1.13 ± 0.05	1.11 ± 0.02	1.1 ± 0.2	6030 ± 84	4.40 ± 0.01	123.6 ± 2.7	4	24
16	10971974	1.04 ± 0.12	1.19 ± 0.06	5.8 ± 3.0	6030 ± 58	4.30 ± 0.02	106.2 ± 3.5	1	1
17†	11127479	1.14 ± 0.12	1.36 ± 0.06	5.1 ± 2.2	5998 ± 57	4.22 ± 0.01	90.6 ± 2.5	1	1
18	11971746	1.11 ± 0.14	1.35 ± 0.06	6.0 ± 2.8	5952 ± 75	4.22 ± 0.02	90.8 ± 2.1	1	1


Observations

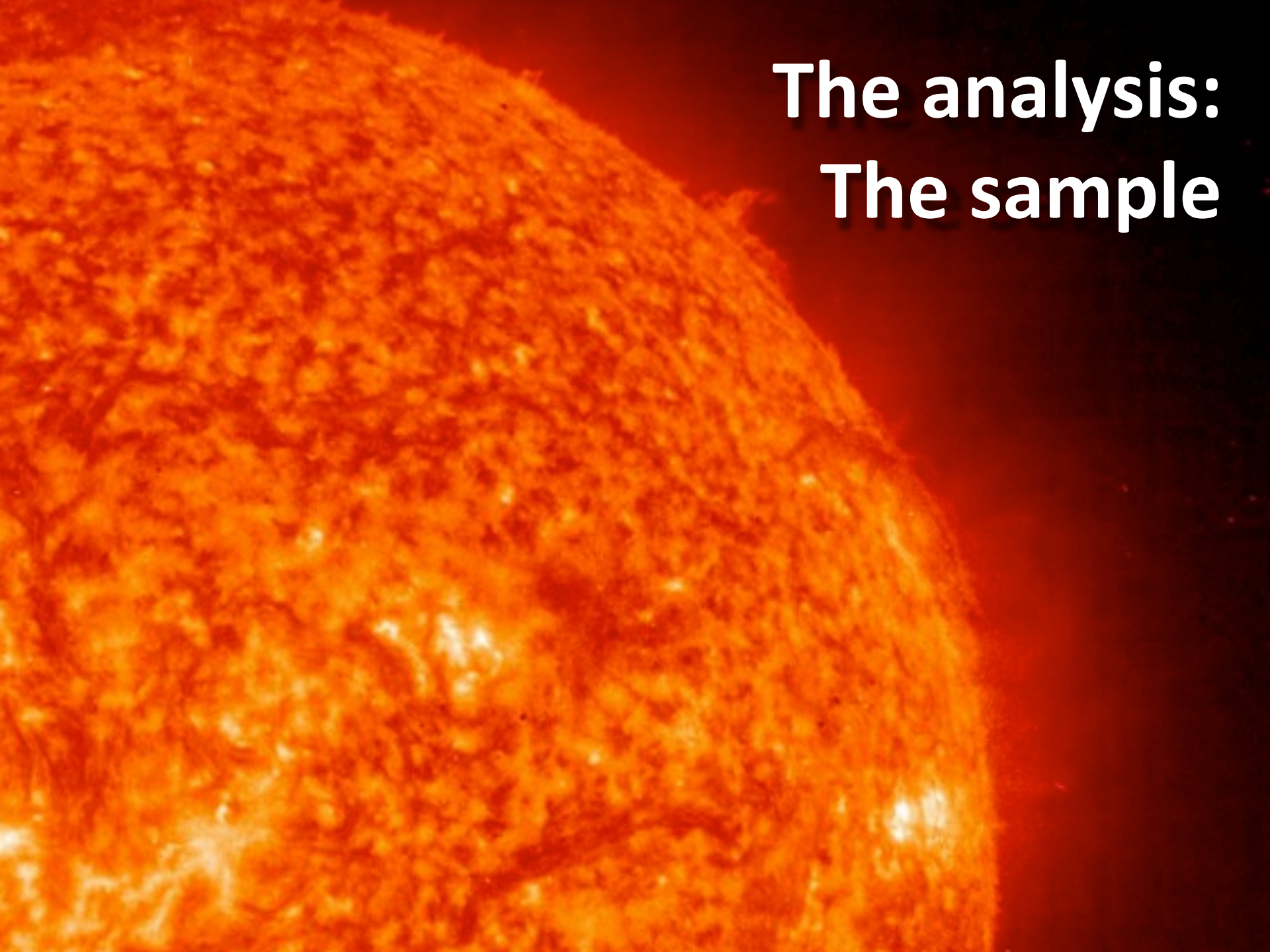
Observations

- **Photometry from *Kepler*/NASA satellite**
  - Long cadence data with a data point every 29.42 mins
  - Entire duration of the mission:

    Period covered: from 20/06/2009 to 11/05/2013, i.e. 1422 days
  - Light curves calibrated using KADACS (Garcia+ 2011) and in-painted (Garcia+2014, Pires+ 2015)



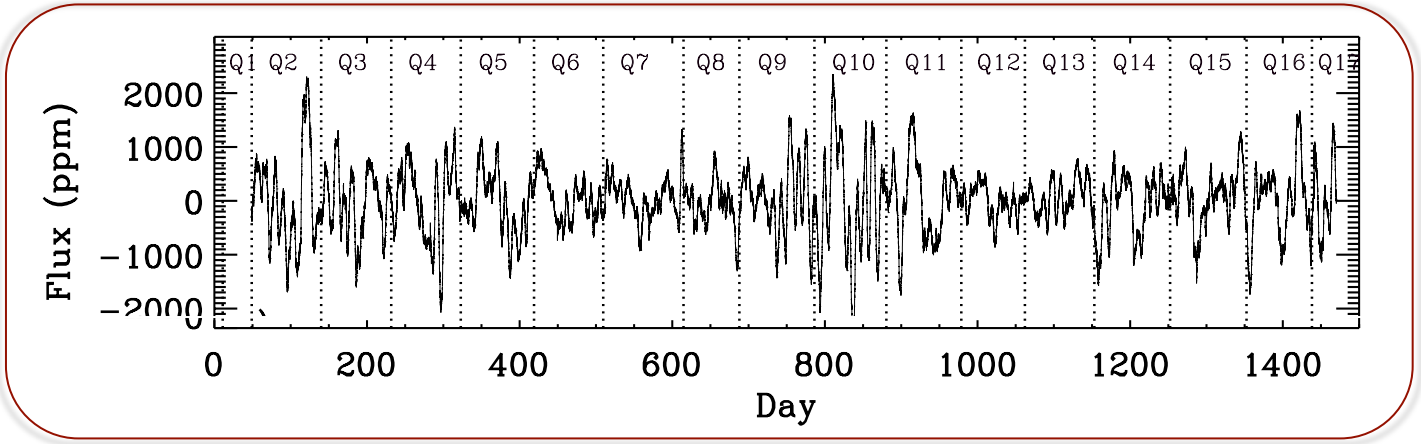
- **HERMES Spectroscopy**
  - High-resolution Echelle spectroscopy (Raskin+ 2011)
  - Mounted to the 1.2-m Mercator telescope (La Palma, Canary Islands)
  - Wavelength range: 370-900nm
  - Echelle: $R=\lambda/\Delta\lambda\approx85000$,
  - Stability: $\sigma=70$m/s



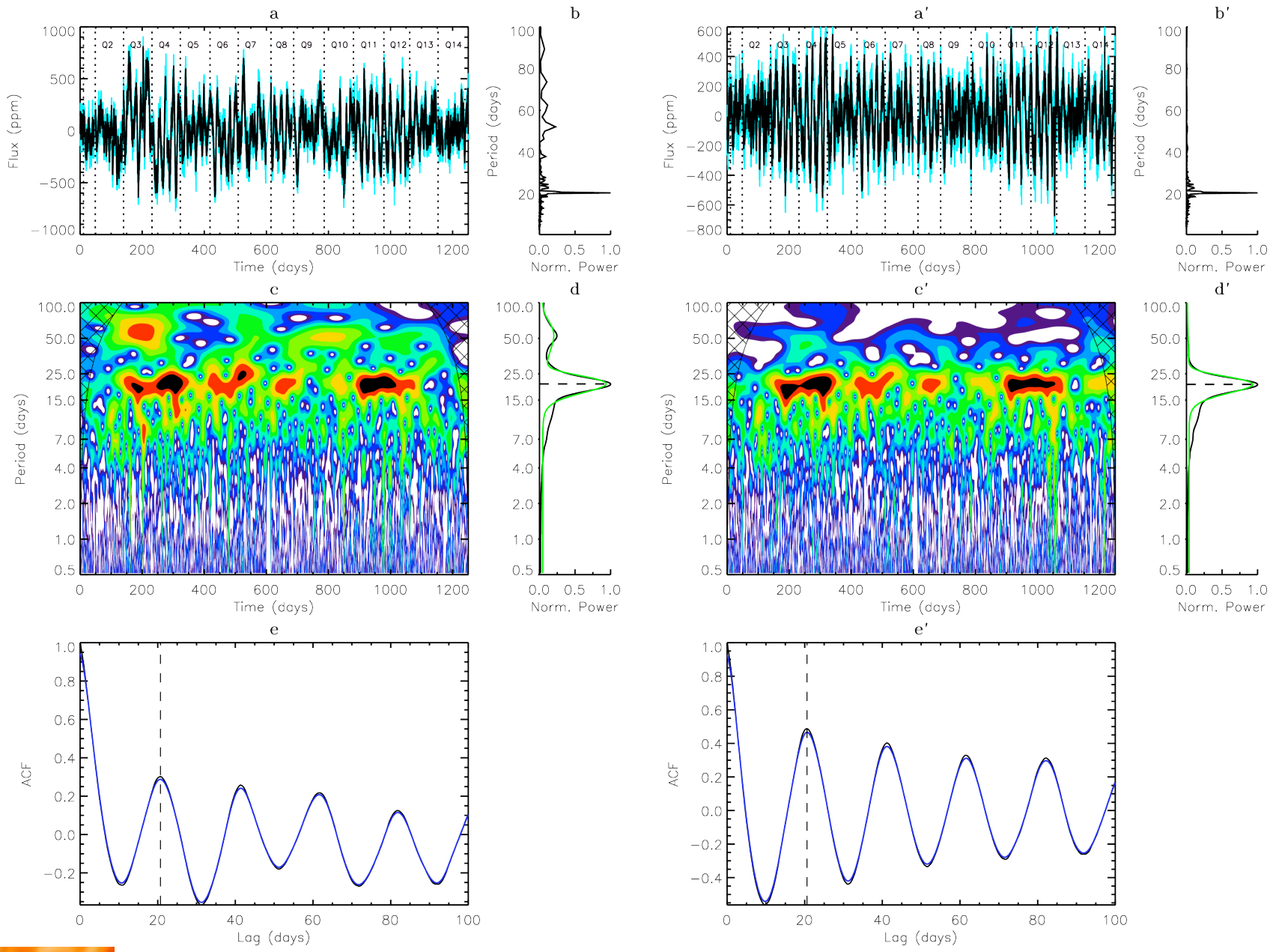
The analysis: The sample

Photospheric magnetic activity

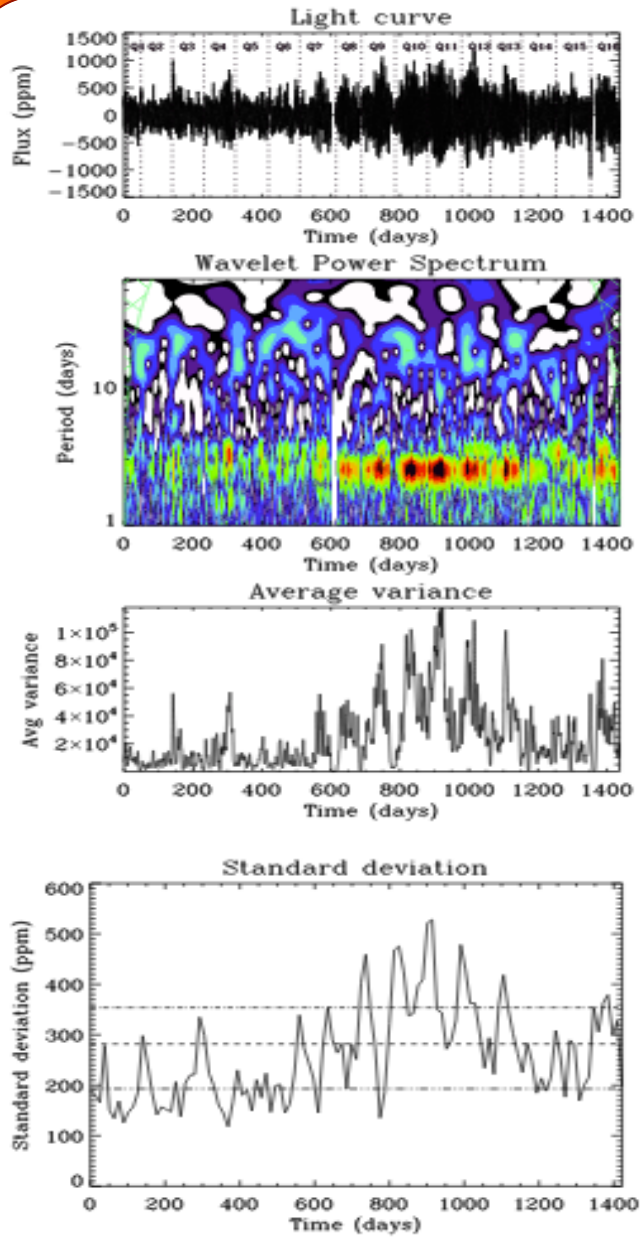
- Photospheric activity proxy, S_{ph} (Garcia+ 2010; Mathur+2014)
  - Measurement of global stellar magnetic variability derived by means of the surface rotation, P_{rot}
  - Rotation associated to the presence of spot or magnetic features
  - Mean value of the light curve fluctuations over sub series of $5xP_{rot}$
  - Most variability related to magnetism and not to other sources of variability at different timescales (convection, oscillations, companion, …)
  - Lower limit of stellar photospheric activity: depends on inclination angle



For example KIC 10644253: S_{ph} = 549.4 ppm for Prot = 10.9 days
(for comparison: Sun (VIRGO/SPM): S_{ph} = 172.6 ppm)

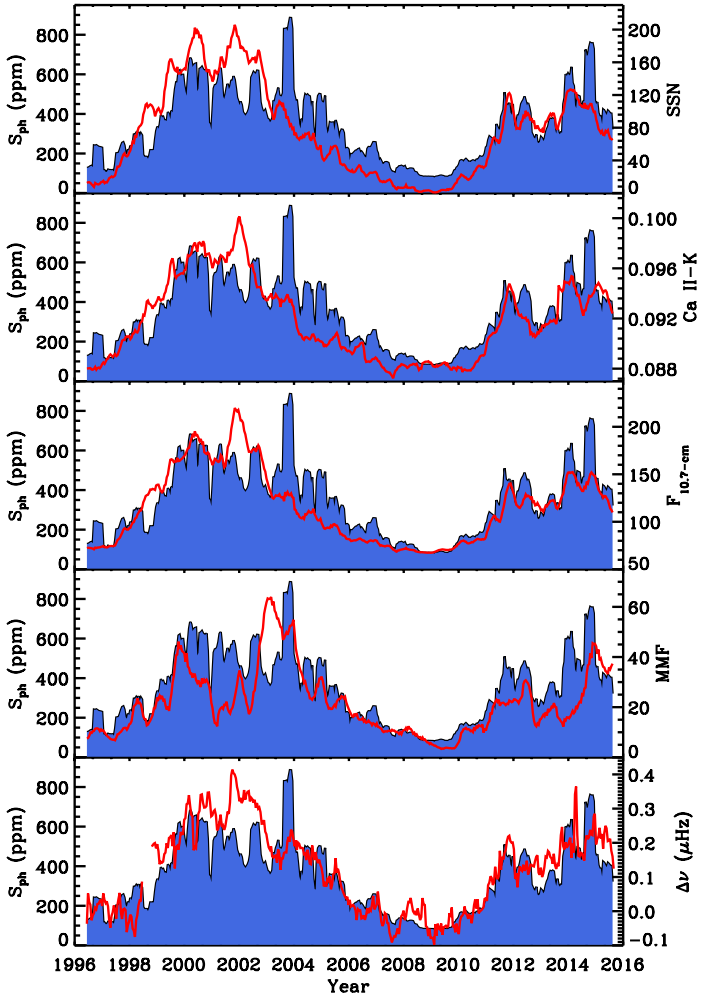

KIC 10147635
a
b
a′
b′
c
d
c′
d′
e
e′
Q2
Q3
Q4
Q5
Q6
Q7
Q8
Q9
Q10
Q11
Q12
Q13
Q14
Flux (ppm)
Time (days)
Period (days)
Norm. Power
ACF
Lag (days)

KIC 3733735



Sph for the Sun

- Comparison between S_{ph} and standard global activity proxies of solar magnetic activity
- Observations from the photometric VIRGO/SoHO



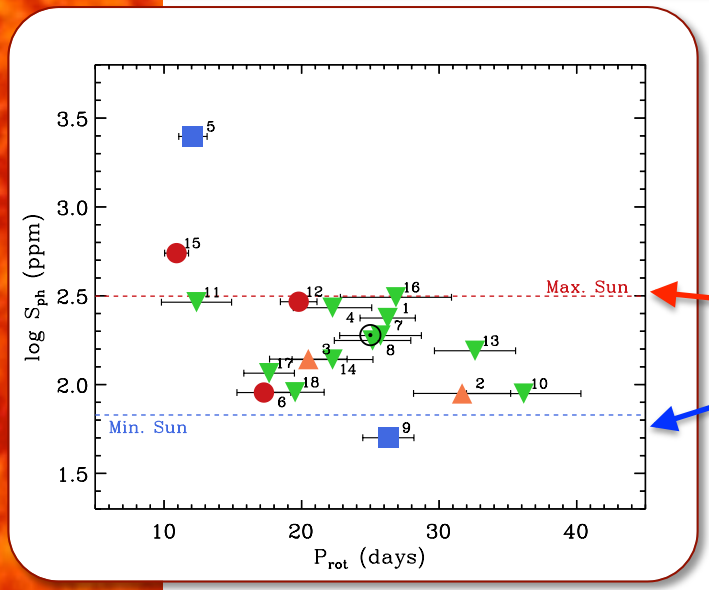
SpaceInn deliverables (Salabert+, in prep)

Activity of the 18 *Kepler* solar analogs

Table 4. Photospheric and chromospheric activity properties of the 18 seismic solar analogs derived from the photometric *Kepler* and spectroscopic HERMES observations.

# star	KIC	P_{rot} (days)	S_{ph} (ppm)	S index	log R'_{HK}	SNR(Ca)	ΔT (days)	N_{spec}
1	3241581	26.3 ± 2.0	236.9 ± 3.8	0.182 ± 0.024	−4.868	17.1	504	23
2	3656476	31.7 ± 3.5	89.1 ± 1.6	0.168 ± 0.000	−5.002	24.5	<1	1
3	4914923	20.5 ± 2.8	139.1 ± 2.5	0.168 ± 0.014	−4.927	26.6	34	6
4	5084157	22.2 ± 2.8	270.8 ± 4.8	0.217 ± 0.107	−4.840	11.0	33	9
5	5774694	12.1 ± 1.0	2492.3 ± 61.2	0.269 ± 0.021	−4.581	23.7	36	3
6	6116048	17.3 ± 2.0	90.2 ± 1.9	0.157 ± 0.001	−4.995	24.1	35	3
7	6593461	25.7 ± 3.0	188.8 ± 3.6	0.260 ± 0.119	−4.562	10.4	35	8
8	7296438	25.2 ± 2.8	177.1 ± 3.0	0.162	−4.994	20.4	35	3[a]
9	7680114	26.3 ± 1.9	50.2 ± 1.0	0.185 ± 0.019	−4.881	19.4	35	3
10	7700968	36.2 ± 4.2	88.9 ± 1.4	0.181 ± 0.010	−4.868	19.8	35	3
11	9049593	12.4 ± 2.5	290.8 ± 6.4	0.177 ± 0.016	−4.955	18.4	35	3
12	9098294	19.8 ± 1.3	292.7 ± 5.2	0.203 ± 0.031	−4.749	19.5	35	3
13	10130724	32.6 ± 3.0	155.0 ± 2.5	0.252 ± 0.067	−4.569	10.6	34	5
14	10215584	22.2 ± 2.9	138.3 ± 2.5	0.215 ± 0.049	−4.738	17.4	35	4
15	10644253	10.9 ± 0.9	549.4 ± 13.3	0.219 ± 0.014	−4.698	30.1	180	12
16	10971974	26.9 ± 4.0	309.9 ± 4.9	0.241 ± 0.066	−4.761	10.0	35	3
17	11127479	17.6 ± 1.8	115.9 ± 2.8	0.271 ± 0.169	−4.683	10.2	35	4
18	11971746	19.5 ± 2.1	90.5 ± 2.0	0.152 ± 0.028	−5.002	16.6	34	7

Photospheric activity of the 18 solar analogs

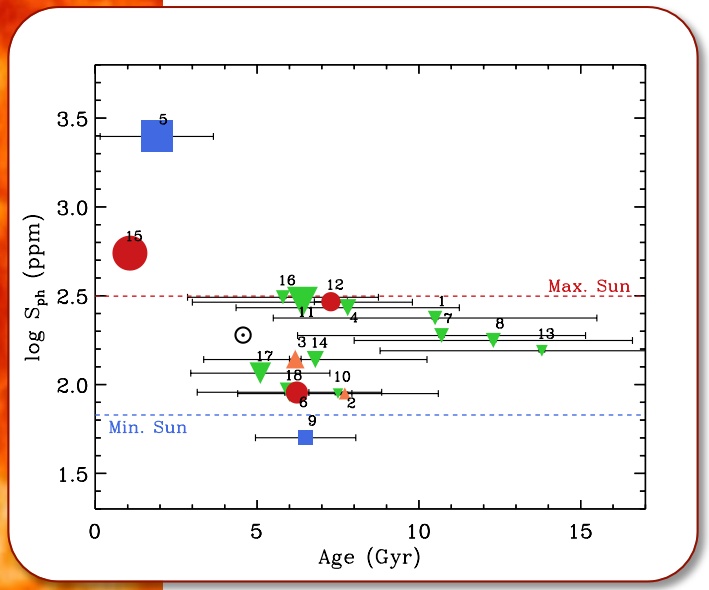


Salabert+ (under revision A&A)

- **Stellar Rotation** compared to activity S_{ph}
  - Falls within range of solar activity

Maximum Sun

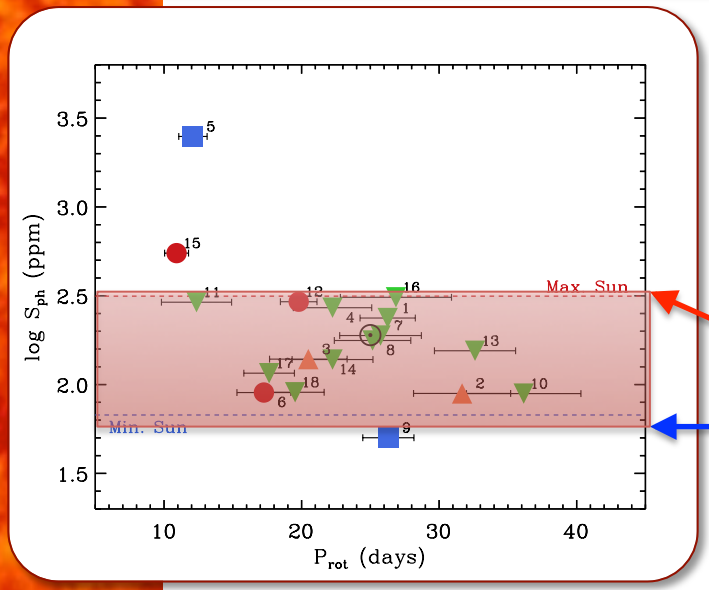
Minimum Sun



- **Seismic ages** compared to activity S_{ph}
  - Symbol size inversely proportional to rotation
  - The 2 youngest & fastest rotating stars of sample are the most active:
    $8xS_{ph,MAX\_SUN}$ and $2xS_{ph,MAX\_SUN}$
  - Lacking stars between younger than 5 Gyr-old in *Kepler* sample

Photospheric activity of the 18 solar analogs

Salabert+ (under revision A&A)



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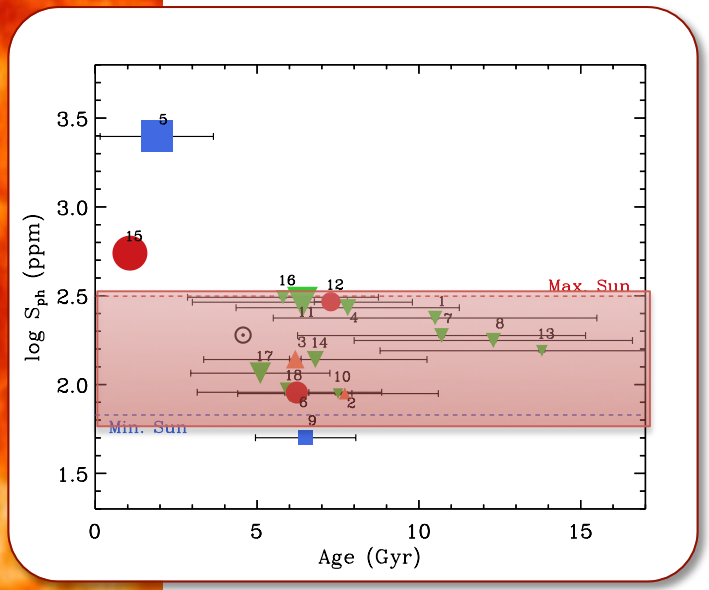

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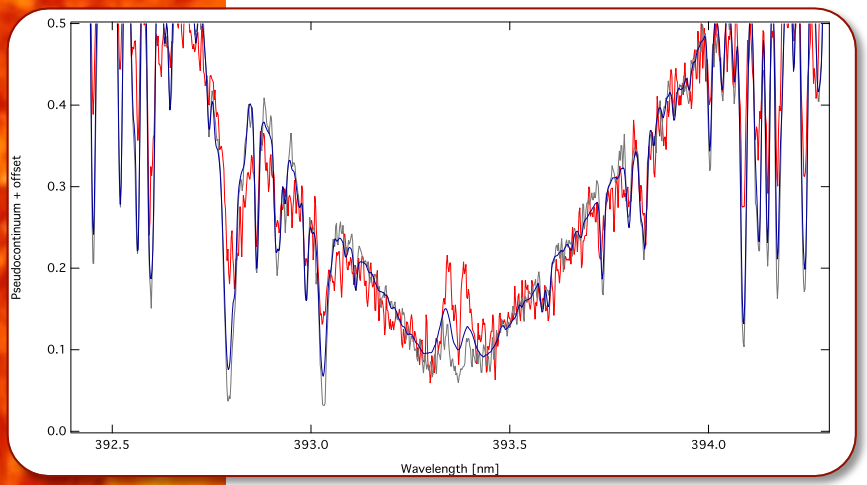
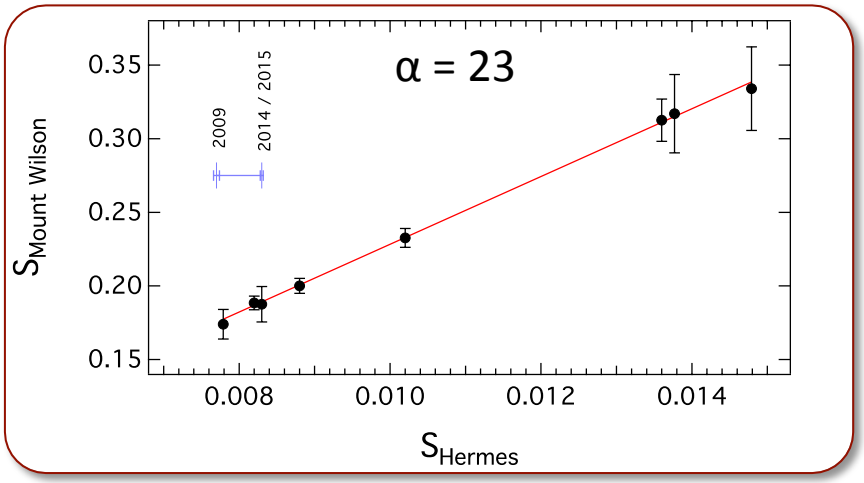
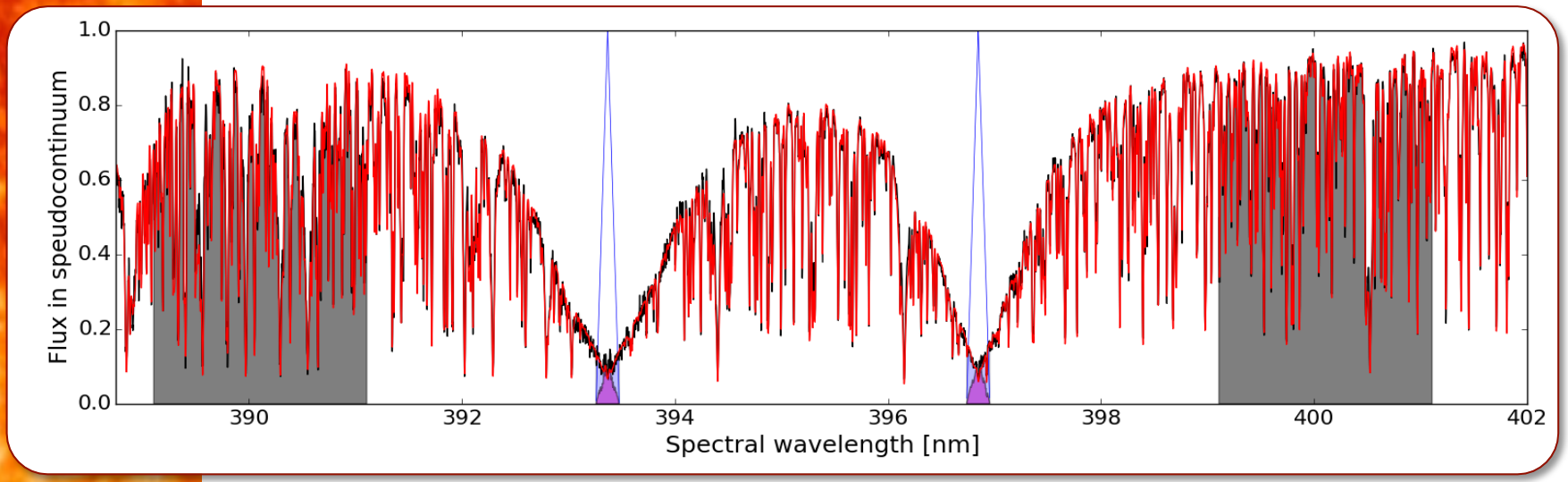
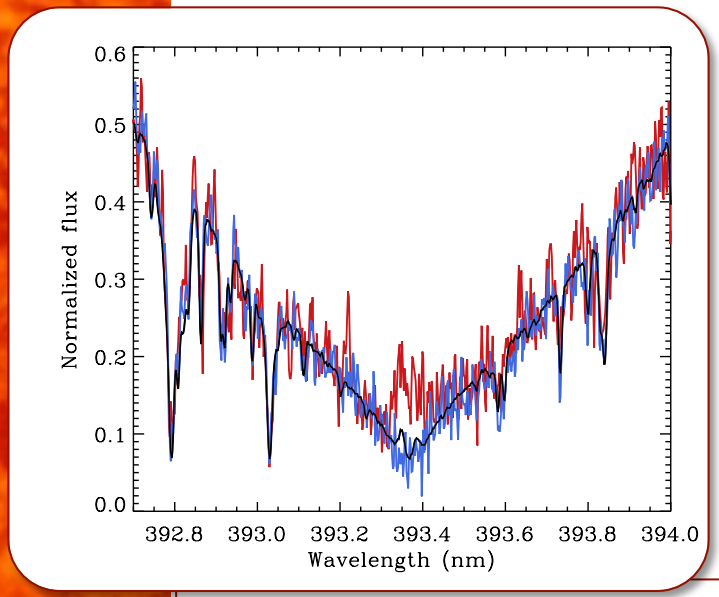
Chromospheric Activity







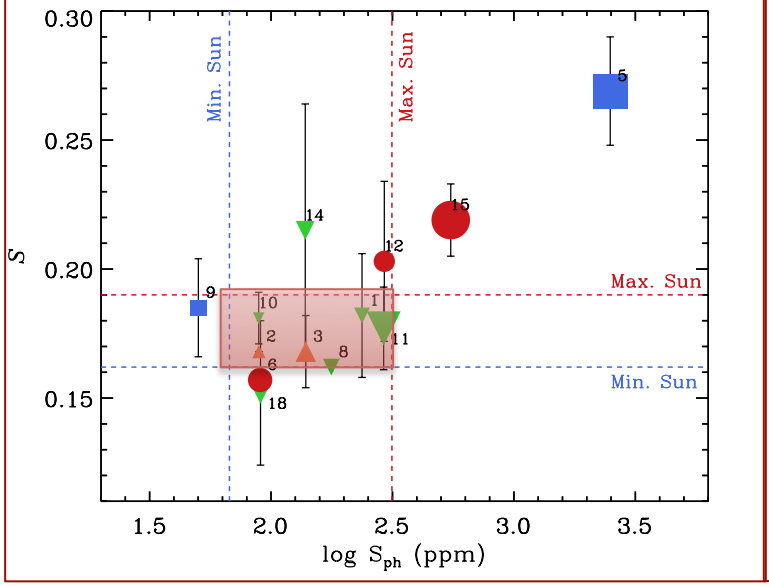
Chromospheric activity of the 18 solar analogs

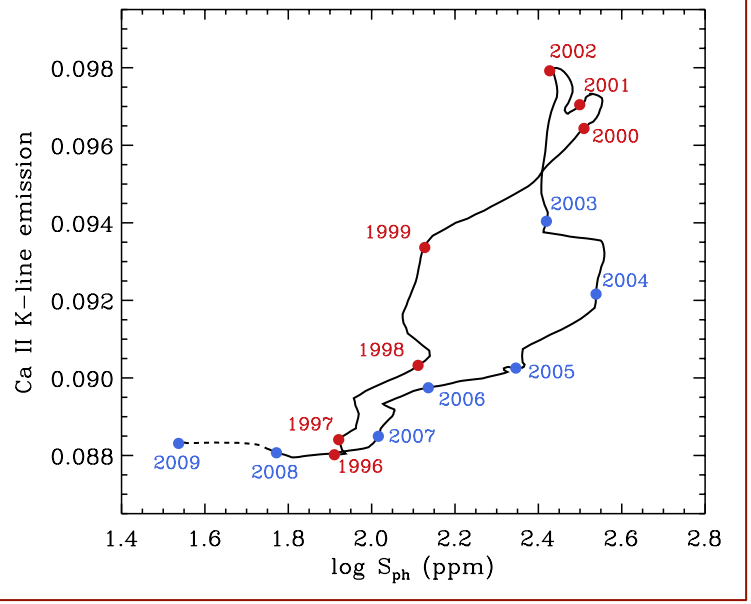


- ***S*-index**: Proxy of emission strength in Ca H&K (Duncan+ 1991)
- Calibration to **Mount Wilson** standard

- **New relation** between photospheric (S_{ph}) and chromospheric (*S*-index) activity proxies

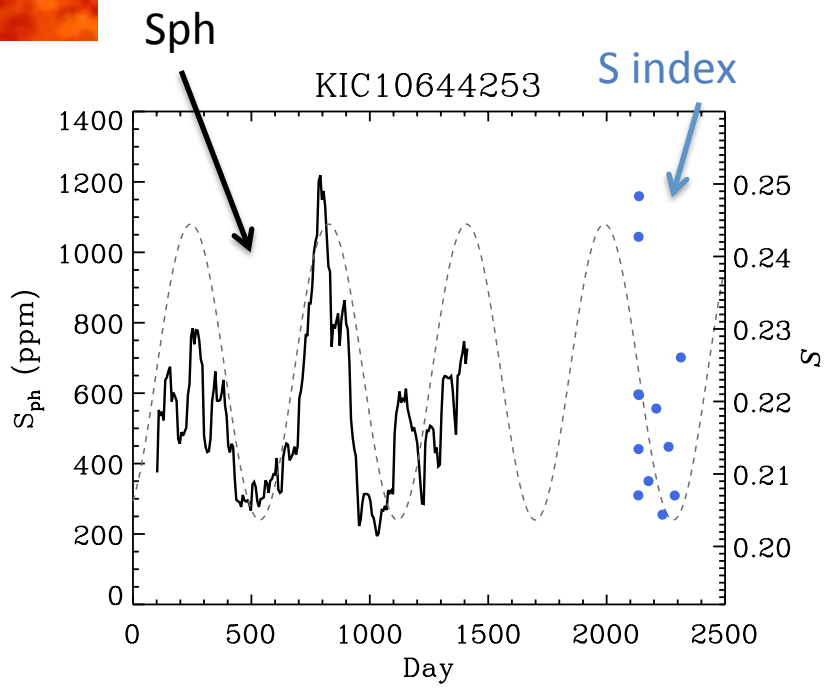
Ca K at 393nm of 2 solar analogs compared to the Sun

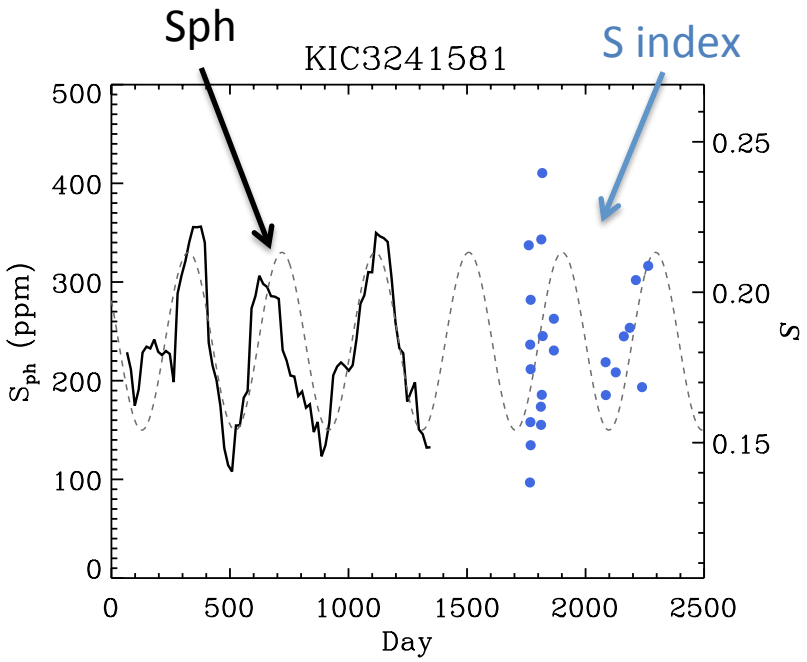




Salabert+ (submitted); K-index from Sac. Peak

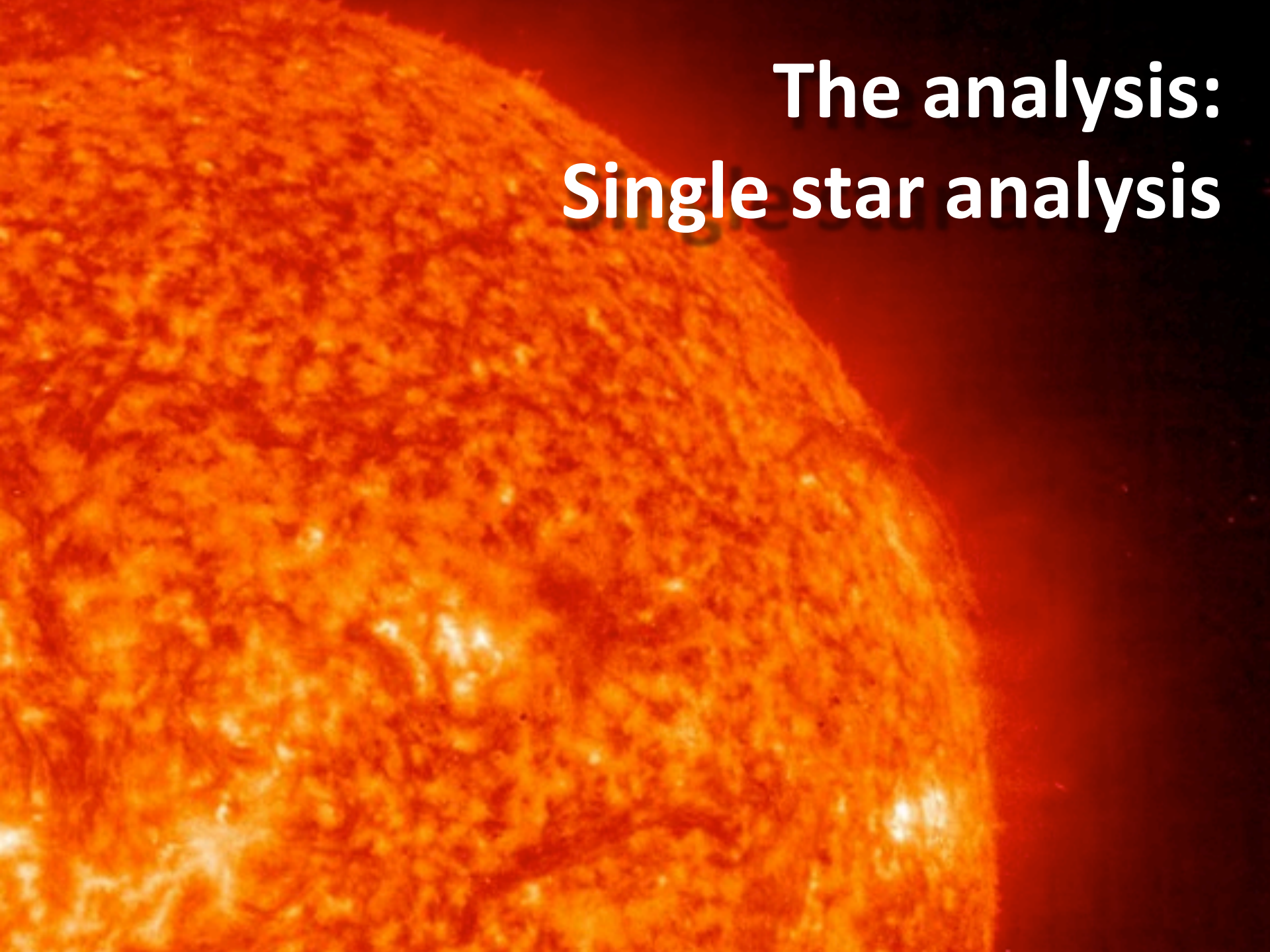
Photospheric & chromospheric activity: Temporal variability





Comparison with previous measurements

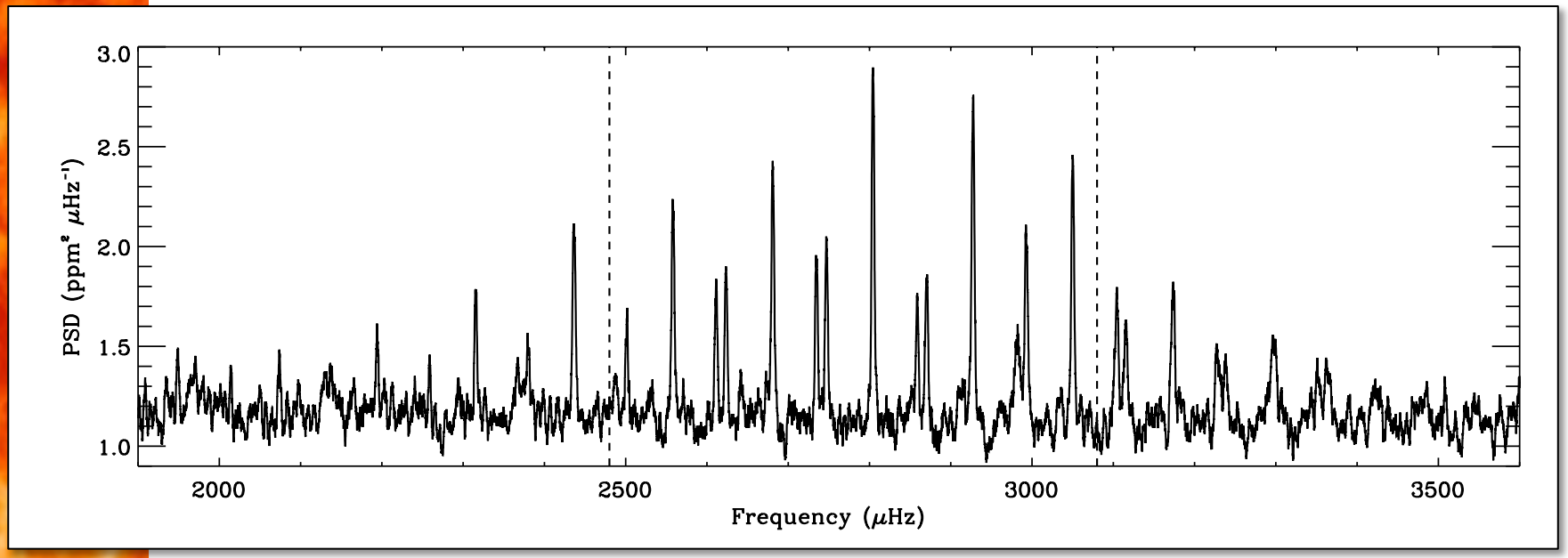
KIC	Karoff+ 2013	Issacson & Fischer 2010	This work
4914923	0.137+/-0.005	-	0.168+/-0.014
6116048	0.152+/-0.001	0.157	0.157+/-0.001
9098294	0.150+/-0.003	-	0.203+/-0.031


The analysis:
Single star analysis

The young solar analog KIC 10644253

(Salabert+ 2016, A&A, 589, A118)

- Youngest solar-like pulsating star observed by *Kepler*
- G0 spectral type
- $\Delta\nu$ = 123.6 µHz, ν_{max} = 2819 µHz (Chaplin+ 2014)
- M = 1.13, R=1.11, Age = 1.1Gyr, R_{bcz}/R = 0.77 (Metcalfe+ 2014)
- Prot = 10.9 days (Garcia+2014)



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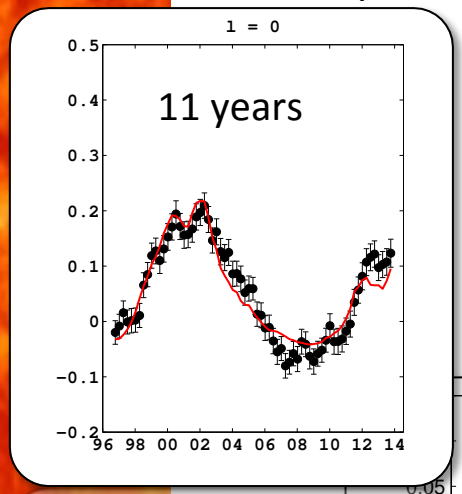
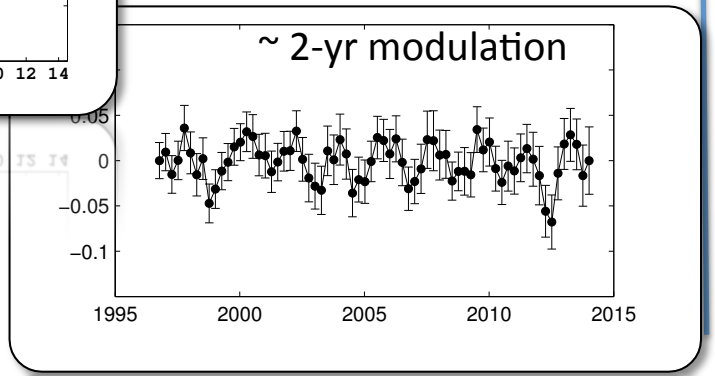
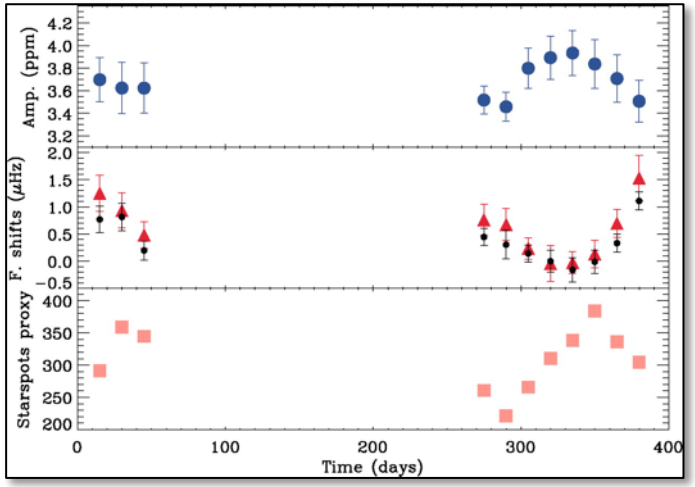
(Salabert+ 2016, A&A, 589, A118)

- ~1000 days of SC *Kepler* data (~59 sec) split in subseries of 180 days
- Analysis of temporal variations of the low-degree p-mode oscillation frequencies to study magnetic variability: 3 independent methods
- Acoustic frequencies sensitive to change in surface activity (Sun: e.g. Salabert+ 2015, F-type HD49933: Garcia+2010)
- Frequencies: only proxy revealing inferences on sub-surface changes



Sun, GOLF/SoHO





HD49933, CoROT

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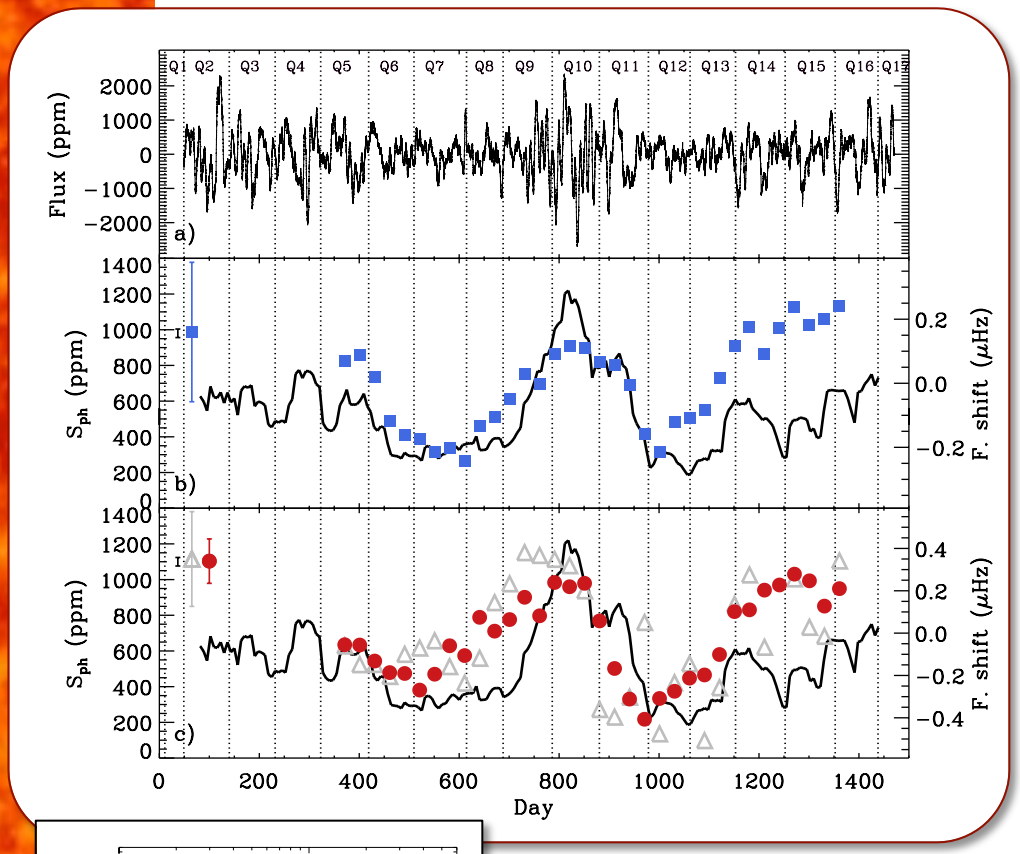
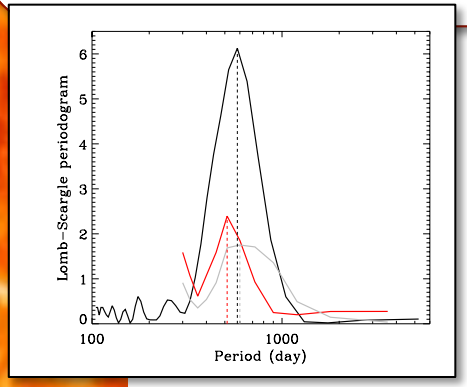


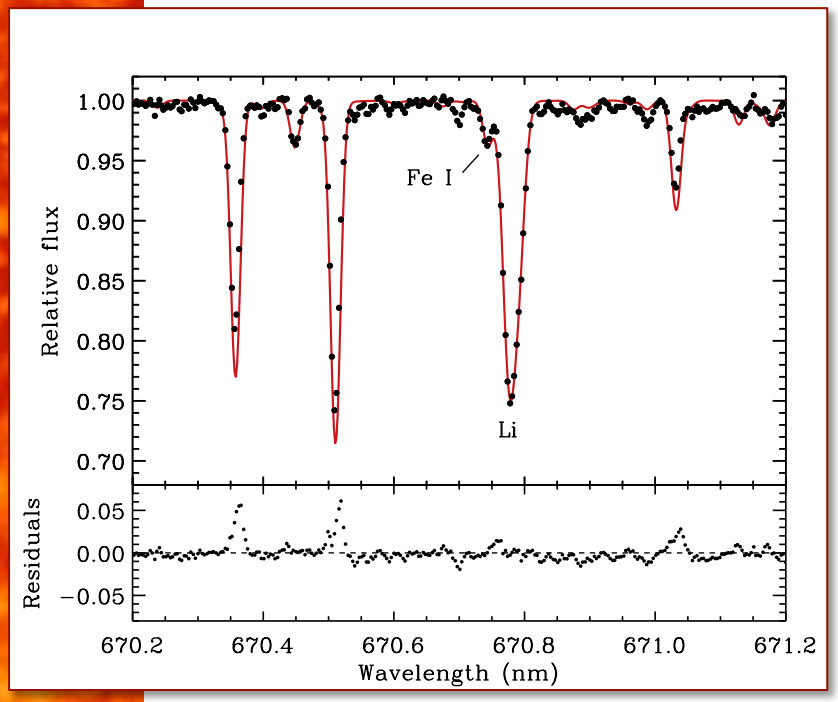


Lomb-Scargle periodograms

- Magnetic activity modulation of ~1.5 years measured in both
  Sph: ~900ppm
  frequency shifts: ~0.5 μHz
- Could be signature of short-period modulation (QBO) as in Sun (e.g. Fletcher+2010) and the 1Gyr-old analog HD 30495 (Egeland+ 2015)
- Frequency dependence indicates same physical mechanisms involved

The young solar analog KIC 10644253

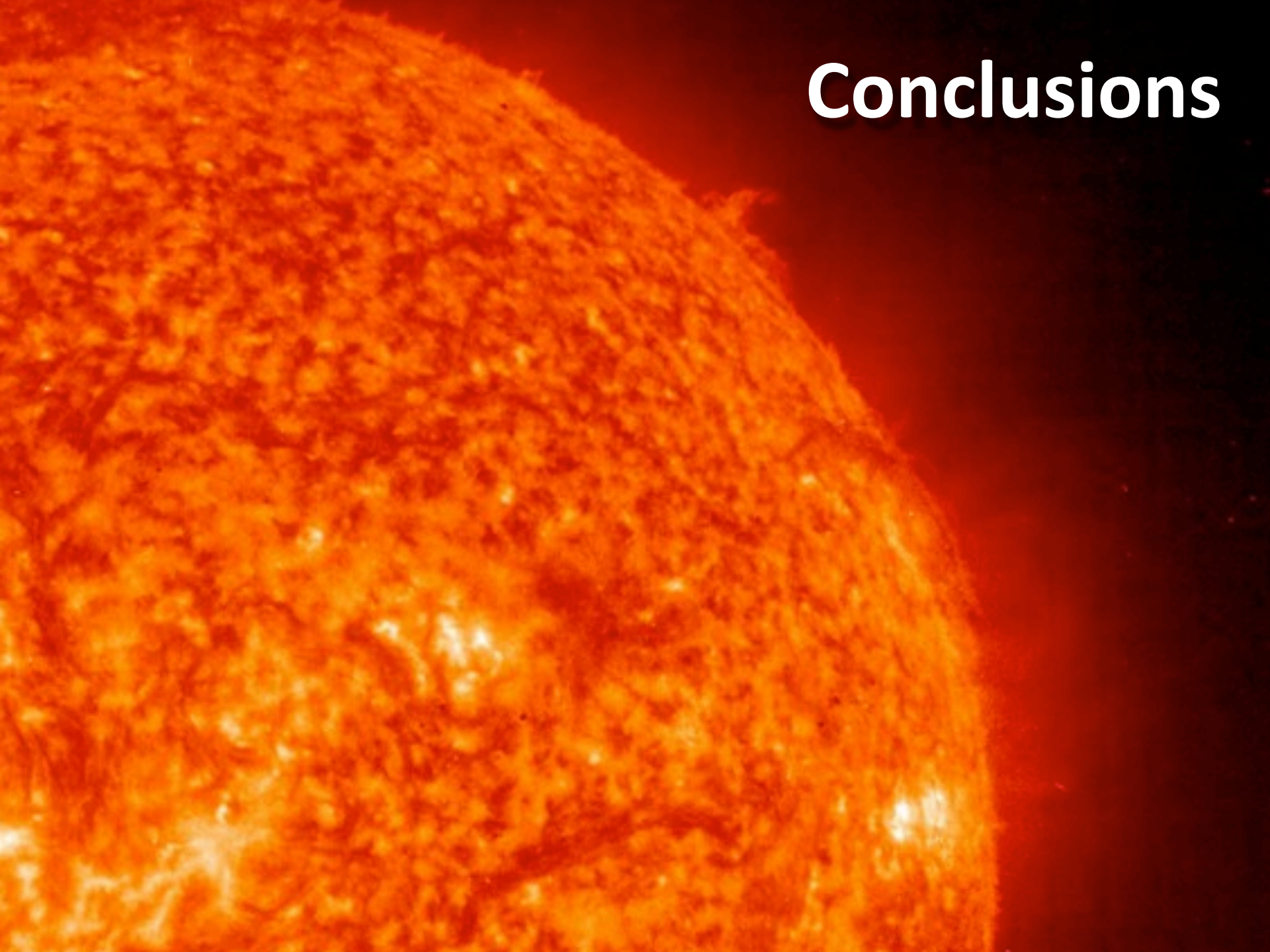
(Salabert+ 2016, A&A, 589, A118)



Lithium doublet of KIC 10644253 with Hermes

Time base	180 days
Teff	6006 +/- 100 K
Log g	4.3 +/- 0.1
[M/H]	0.2 +/- 0.1
A(Li)	2.74 +/- 0.03
S	0.219 +/- 0.014

- Lithium abundance and rotation period consistent with a young star
- Validate young age (~1Gyr-old) estimated from seismology
- Consistent with rotation from gyrochronology

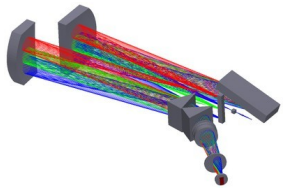


Conclusions

Observational inputs on the solar/stellar connection

- **Study of 18 solar analogs identified among the *Kepler* seismic sample**

- Measurements of their magnetic activity properties compared to the Sun
- Photospheric and chromospheric activity of the seismic solar analogs is comparable to the activity of the Sun
- Youngest and fastest rotating stars are the most active
- Older, slower stars have entered a stable stage of activity
- Relation between photospheric Sph and chromospheric S-index
- Validate Sph as a suitable activity indicator

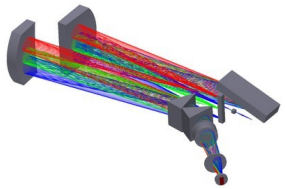


Observational inputs on the solar/stellar connection

- **Magnetic variability in the young solar analog KIC 10644253**

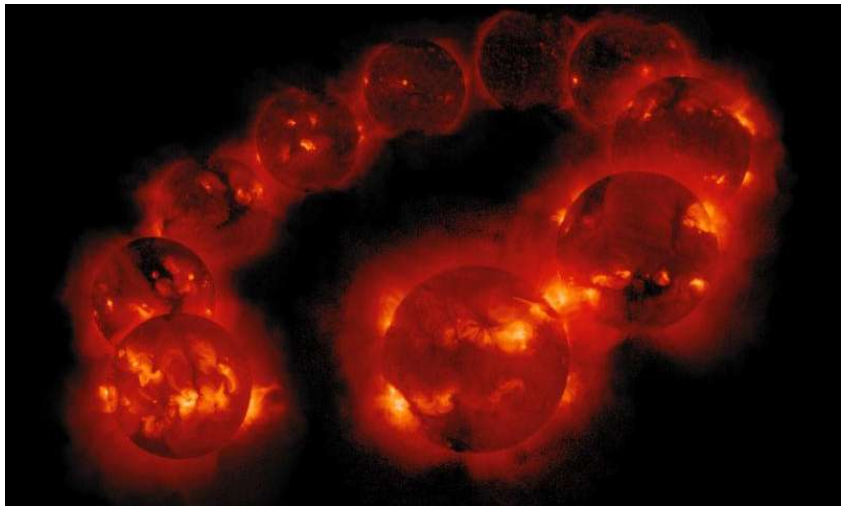
- Magnetic activity variations of ~1.5 years in the 1-Gyr-old star
- Observed in acoustic frequencies and photospheric activity
- Could be the signature of the quasi-biennal oscillation as in Sun and HD30495
- Dual cycles: Sun, ε Eridani, HD30495, ...
- Lithium abundance and chromospheric activity confirm younger age and higher activity level than the Sun

Kepler



Observational inputs on the solar/stellar connection

- **The magnetic activity and the variability of the Sun is NOT peculiar in comparison to analogs with measured oscillations.**



- Long-term monitoring program with Hermes
- New photometric observations with TESS in the near future
- *Kepler* was recovered and returned to the K2 Mission

Project's Publication Record

- **"The HERMES Solar Atlas and the spectroscopic analysis of the seismic solar analog KIC3241581",** 2016, A&A, 589, 27, by *Beck, Allende Prieto, Van Reeth, Tkachenko, Raskin, van Winckel, do Nascimento, Salabert, Corsaro, & Garcia*

- ***"Magnetic variability in the young solar analog KIC 10644253",*** 2016, A&A, 589, A118, by *Salabert, Regulo, Garcia, Beck, Ballot, Creevey, Perez Hernandez, do Nascimento, Corsaro, Egeland, Mathur, Metcalfe, Bigot, Ceillier, & Pallé*

- ***"Photospheric and chromospheric magnetic activity of seismic solar analogs",*** Under revision for A&A, by *Salabert, Garcia, Beck, Egeland, Pallé, Mathur, Metcalfe, do Nascimento, Ceillier, Andersen, & Trivino Hage*

- ***"Rotation and Lithium abundance of seismic Solar Analogues"*** in preparation for A&A, by *Beck, do Nascimento, Salabert, Tkachenko, Mathur, Egeland, Garcia, Metcalfe, Montes, Mathis, Andersen, Palle, Trivino Hage, Kamath, & Raskin*

- ***"Seismic study of KIC 3241581, a solar younger sibling observed by Kepler and Hermes" ,*** in preparation for A&A, by *Garcia, Perez Hernandez, Salabert, Allende Prieto, Beck, Benomar, Ceillier, Mathur, do Nascimento, Regulo*