Rotation and activity of solar-type and low-mass stars in the PLATO era

Sylvain N. Breton

INAF
ISTITUTO NAZIONALE DI ASTROFISICA
OSSERVATORIO ASTROFISICO DI CATANIA

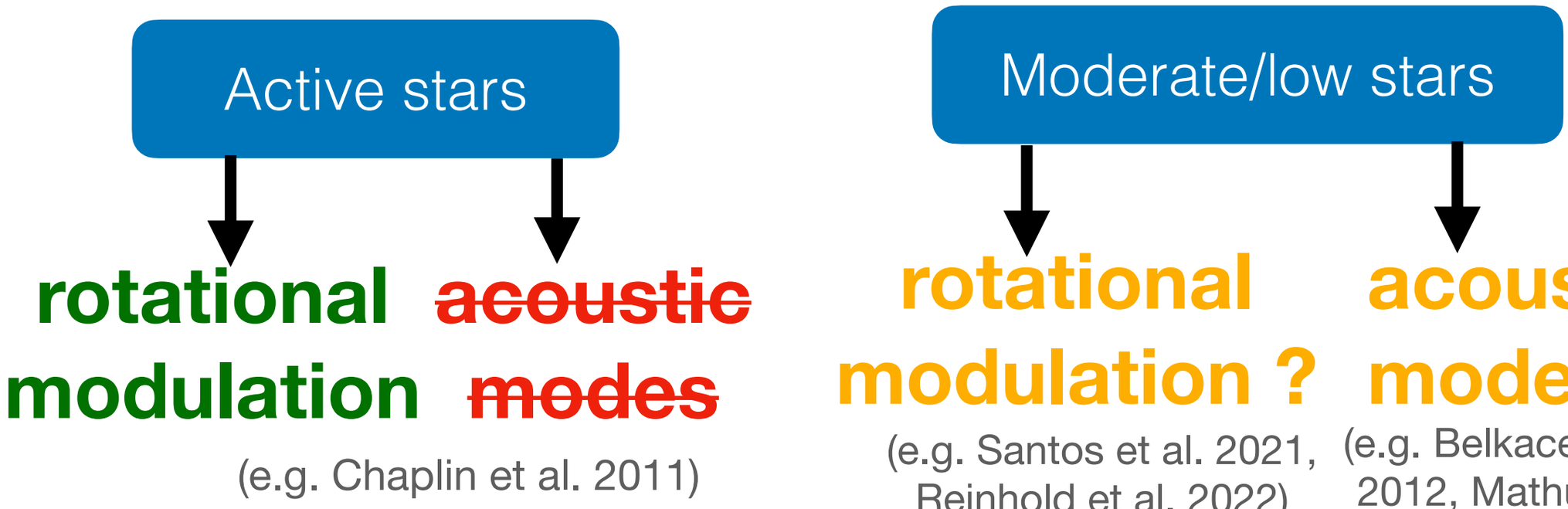
25/09/23 - PLATO in Italy

To access code resources presented in this talk:
`gitlab.com/sybreton`

In collaboration with
A.F. Lanza, S. Messina,
R.A. García, S. Mathur,
A.R.G. Santos, L. Bugnet,
E. Corsaro, S. Aigrain,
and I. Pagano.

Moderate and low-activity solar analogs

S.N. Breton
25/09/23
PLATO in Italy



The Sun is a « **moderate/low** » **activity star**

(e.g. Reinhold et al. 2020)

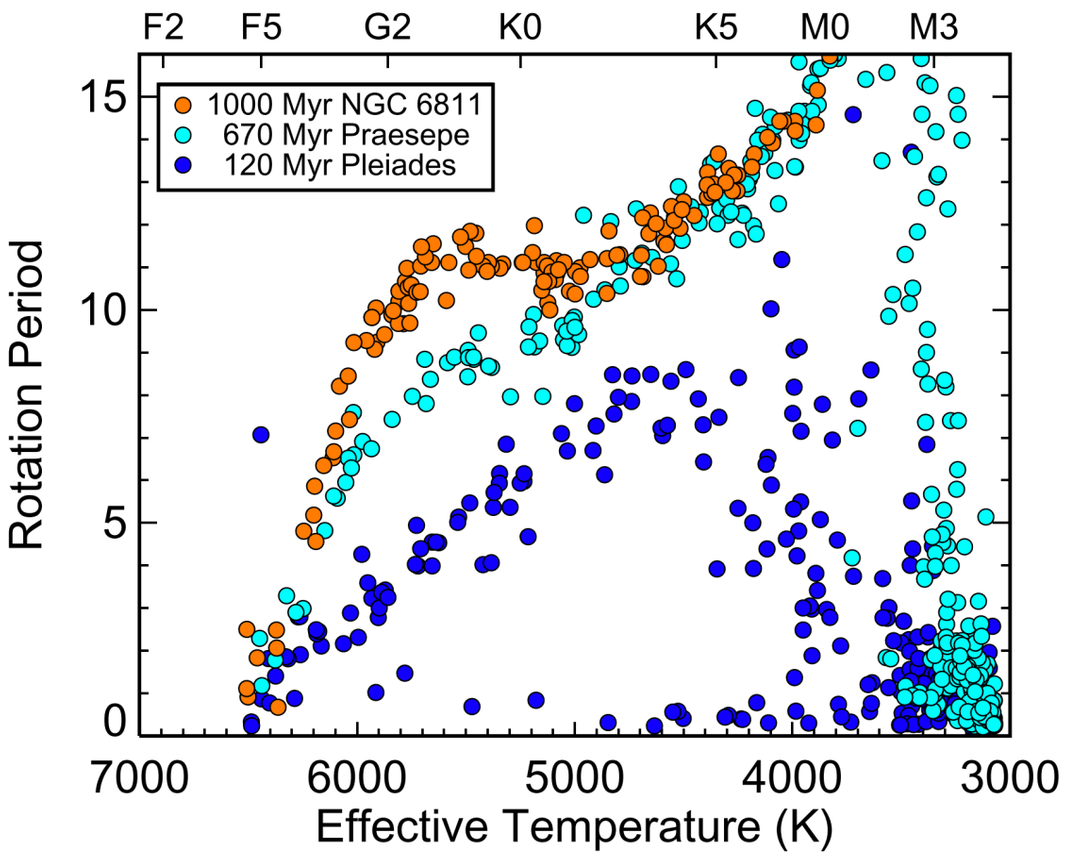
PLATO: we want **a gold sample of solar-type stars and analogs**

→ Necessity to measure **rotation** and **activity** in the **low-activity slow-rotating** stars with **oscillations**

Rotation and activity of solar-type stars

S.N. Breton
25/09/23
PLATO in Italy

Gyrochronology

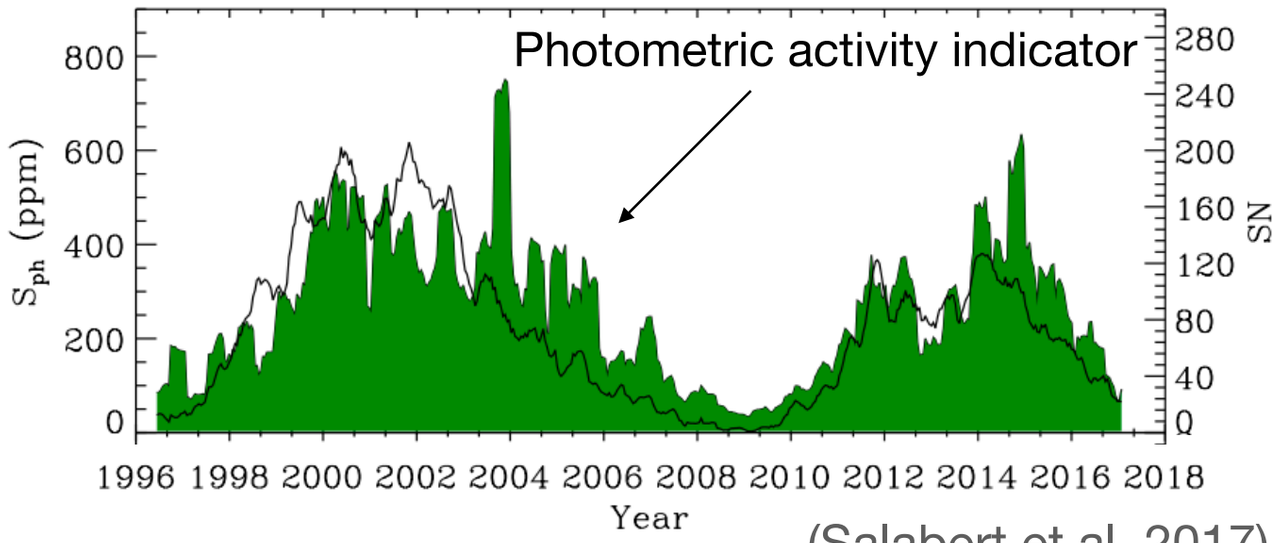


(Curtis et al. 2019)

+ star-planet interactions

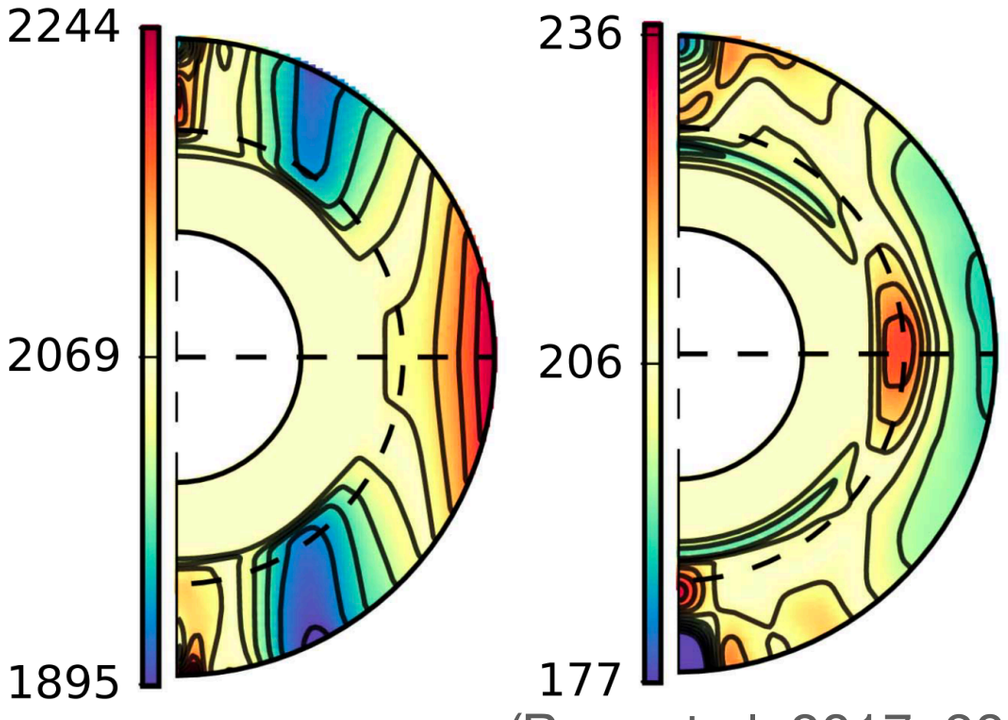
(e.g. Mathis 2018, Strugarek 2018)

Magnetic cycles



(Salabert et al. 2017)

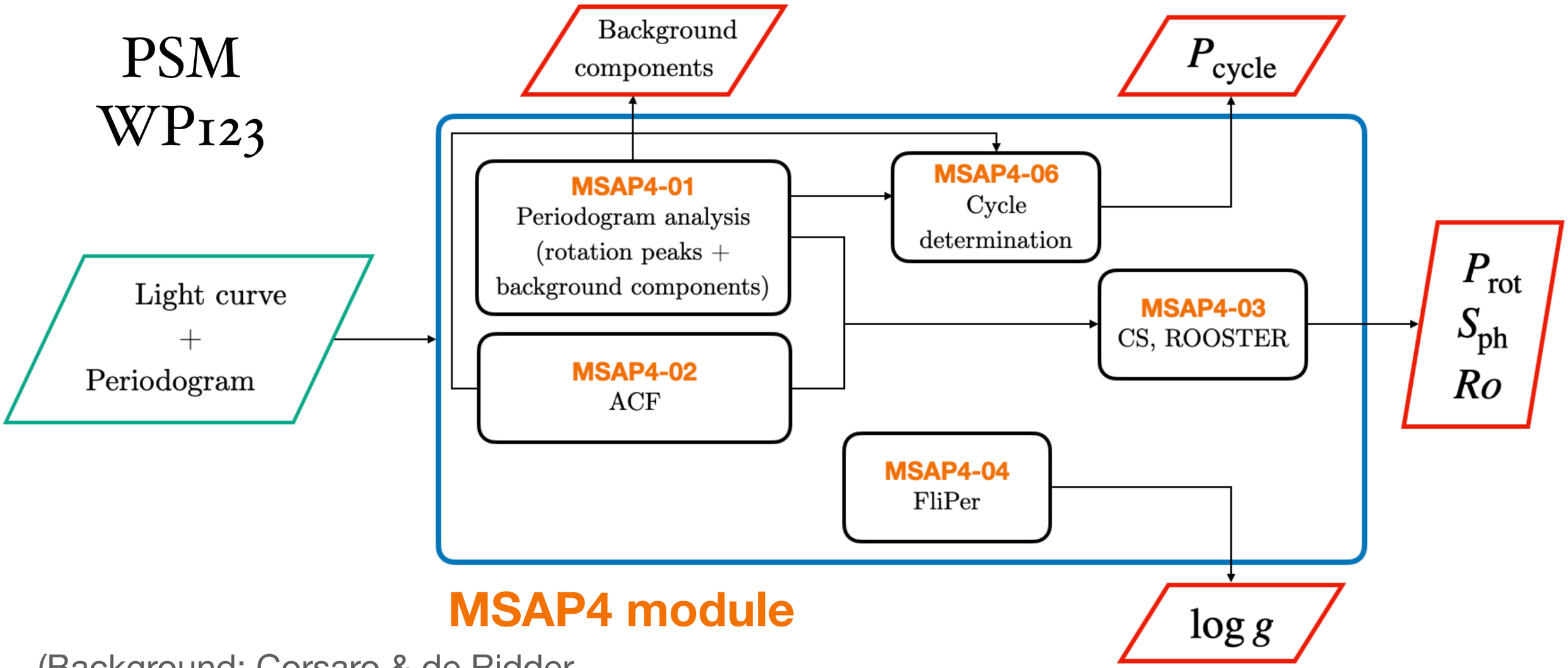
Differential rotation & dynamo



(Brun et al. 2017, 2022)

Rotation and activity in PLATO: current baseline

PSM
WP123



MSAP4 module

(Background: Corsaro & de Ridder 2013, Corsaro et al. 2015;
ACF: McQuillan et al. 2013, 2014;
CS: Ceillier et al. 2017;
FliPer: Bugnet al. 2018;
ROOSTER: Breton et al. 2021;
Ro prescription: Noraz et al. 2022;
S_{ph}: Mathur et al. 2014)

Publicly available data products, also used as inputs for the modelling step performed by the PLATO pipeline

The rotation & activity PLATO demonstrator

S.N. Breton
25/09/23
PLATO in Italy

The code is fully open-source and modular:
Source code: gitlab.com/sybreton/plato_rotation_pipeline
Documentation: plato-rotation-pipeline.readthedocs.io

PLATO MSAP4 demonstrator: Rotation and activity

Welcome to the documentation of the PLATO Module for Stellar AstroPhysics 4 (MSAP4) rotation and activity demonstrator module. The module provides functions and notebooks executing the tasks that will be implemented in the PLATO Stellar Analysis System.

The demonstrator is developed at the Osservatorio astrofisico di Catania (INAF-OACT).

Contact address: sylvain.breton@inaf.it

User guide

- Installation
- Fourier analysis (MSAP4-01A)
- Time series analysis (MSAP4-02)
- ROOSTER training framework (MSAP4-03)
- Analysis framework for rotation period extraction (MSAP4-03)
- Composite spectrum (CS), ROOSTER, and Sph index (MSAP4-03)
- Cycle determination (MSAP4-06)
- Wavelet analysis for rotation period extraction

Detailed API

- Analysis pipeline
  - Lomb-Scargle periodogram
  - Auto-correlation function (ACF)
  - Composite spectrum (CS)
  - Photometric index (Sph)
  - Wavelet analysis
- ROOSTER

Analysis pipeline

`plato_msap4_demonstrator.analysis_pipeline(t, s, periods_in=None, wavelet_analysis=True, plot=True, show=False, filename=None, figsize=(6, 12), show_light_curve=True, cmap='jet', normscale='log', ylogscale=False, vmin=None, vmax=None, lw=1, mother=None, xlim=None, dpi=200, smooth_acf=True, fit_lomb_scargle=True, show_kepler_quarters=False, tref=0, add_profile_parameters_to_features=False, smooth_period=True, show_contour_wps=False, levels_wps=None)`

Analysis pipeline combining Lomb-Scargle (or wavelet analysis), ACF and CS.

The pipeline compute Lomb-Scargle periodogram (or Wavelet Power Spectrum and Global Wavelet Power Spectrum), Auto-Correlation function, and Composite spectrum of the provided light curves, as well as a set of relevant features for each method of analysis.

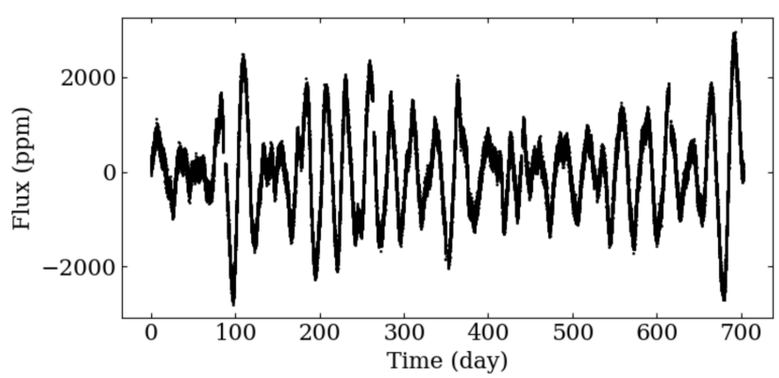
Parameters

- **t** (*ndarray*) – timestamps
- **s** (*ndarray*) – timeseries
- **period_in** (*ndarray*) – value which will be used as input to compute the ACF lags. A `periods` vector corresponding to the exact position of the lags will be returned by the function. If `None`, a `lags` vector (and corresponding period vector) from `0` to `s.size` will be generated. Optional, default `None`.
- **wavelet_analysis** (*bool*) – if set to `True` the timeseries will be analysed with a wavelet analysis. Otherwise the Lomb-Scargle periodogram will be computed and used to compute the composite spectrum

PLATO simulation: Rotation period analysis

This first part include preprocessing task that are not actually included in MSAP4-02 but are useful for the subsequent analysis.

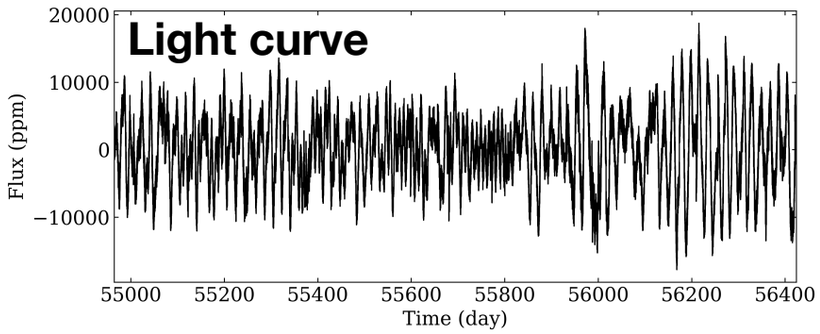
```
fig, ax = plt.subplots (1, 1, figsize=(8,4))

ax.scatter (t[s!=0]-t[0], s[s!=0], color='black',
            marker='o', s=1)

ax.set_xlabel ('Time (day)')
ax.set_ylabel ('Flux (ppm)')

fig.tight_layout ()

plt.savefig ('figures/plato_lc_filtered.png', dpi=300)
```

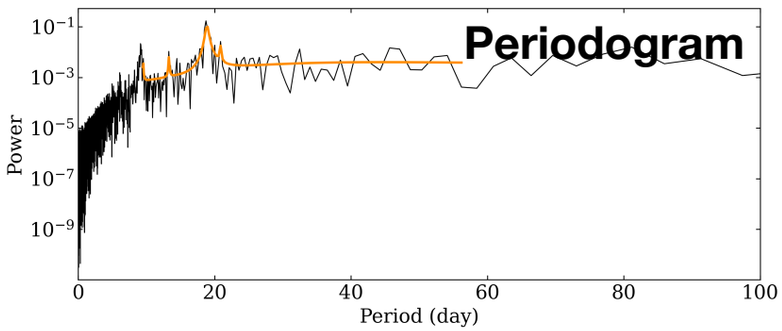


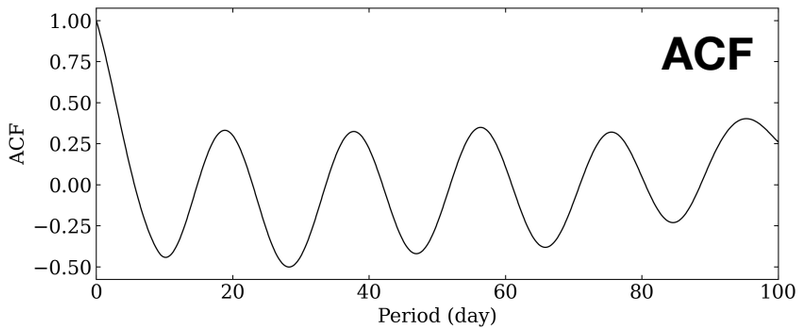
INAF
ISTITUTO NAZIONALE DI ASTROFISICA
OSSERVATORIO ASTROFISICO DI CATANIA

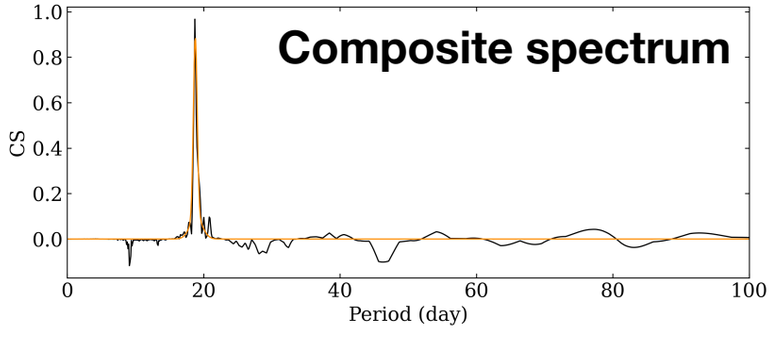
Measuring rotation: combining techniques

S.N. Breton
25/09/23
PLATO in Italy









$P_{\mathrm{rot,GLS}}$

$P_{\mathrm{rot,ACF}}$

$P_{\mathrm{rot,CS}}$

P_{rot}

P_{rot}
+
S_{ph}
(photometric **magnetic activity** proxy)
+
« **Rotation score** »
+
Rossby number Ro and differential rotation

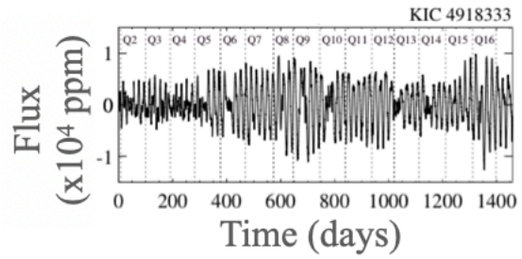
MSAP4-03
ROOSTER
Random fOrest Over STEllar Rotation

(Breton et al. 2021)

The « original » ROOSTER: framework for *Kepler*

S.N. Breton
25/09/23
PLATO in Italy

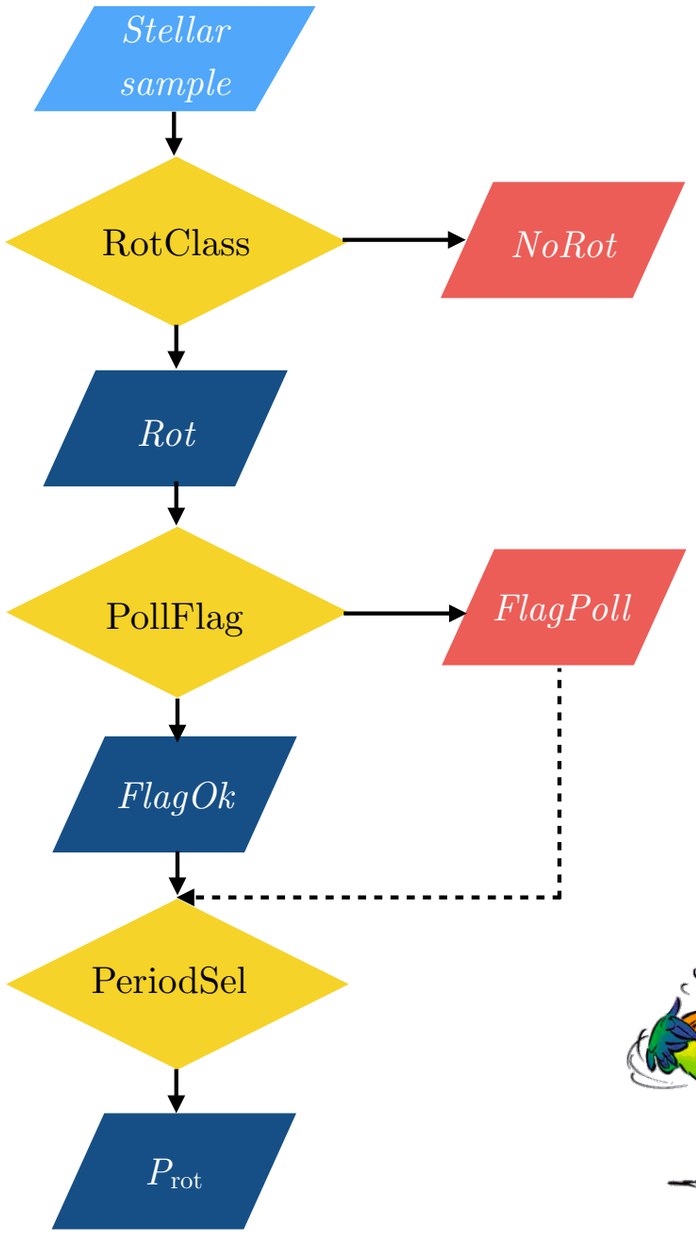
Let's say we have a light curve…



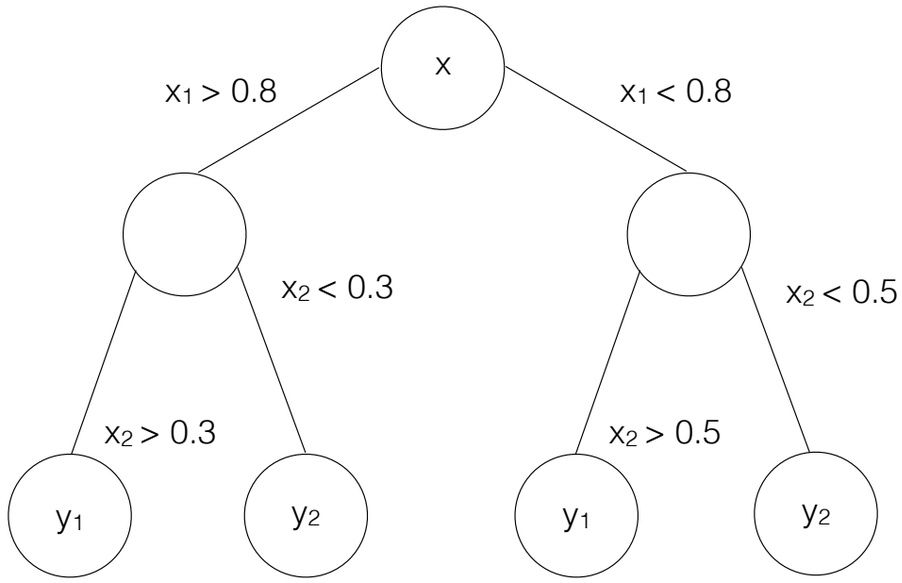
Light curve

ROOSTER: Method validation

S.N. Breton
25/09/23
PLATO in Italy



(Breton et al. 2021)



(Breiman et al. 1984, 2001, Pedregosa et al. 2011)

Training parameters
outputs from wavelet, ACF, CS methods + stellar parameters

159 input parameters

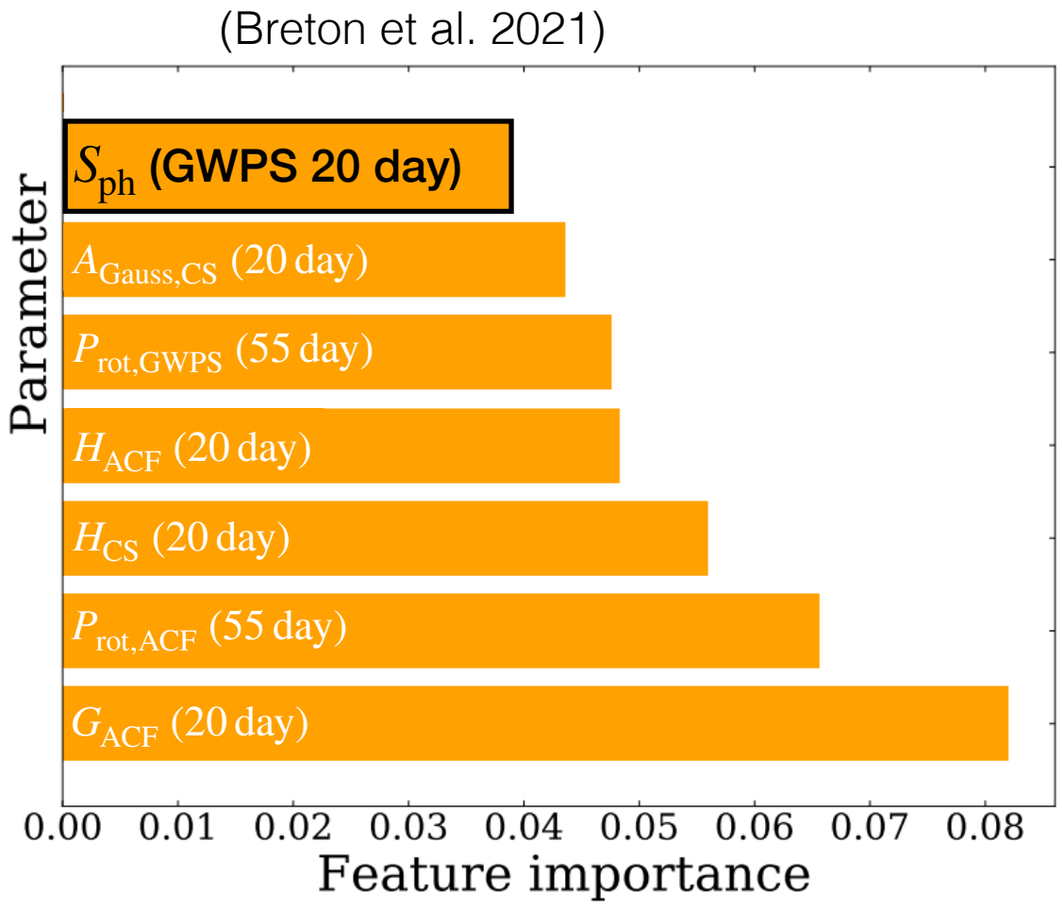
Working sample ~25,000 K and M-type stars from Santos et al. 2019.

Train & test
100 trainings with different training and test sets repartition

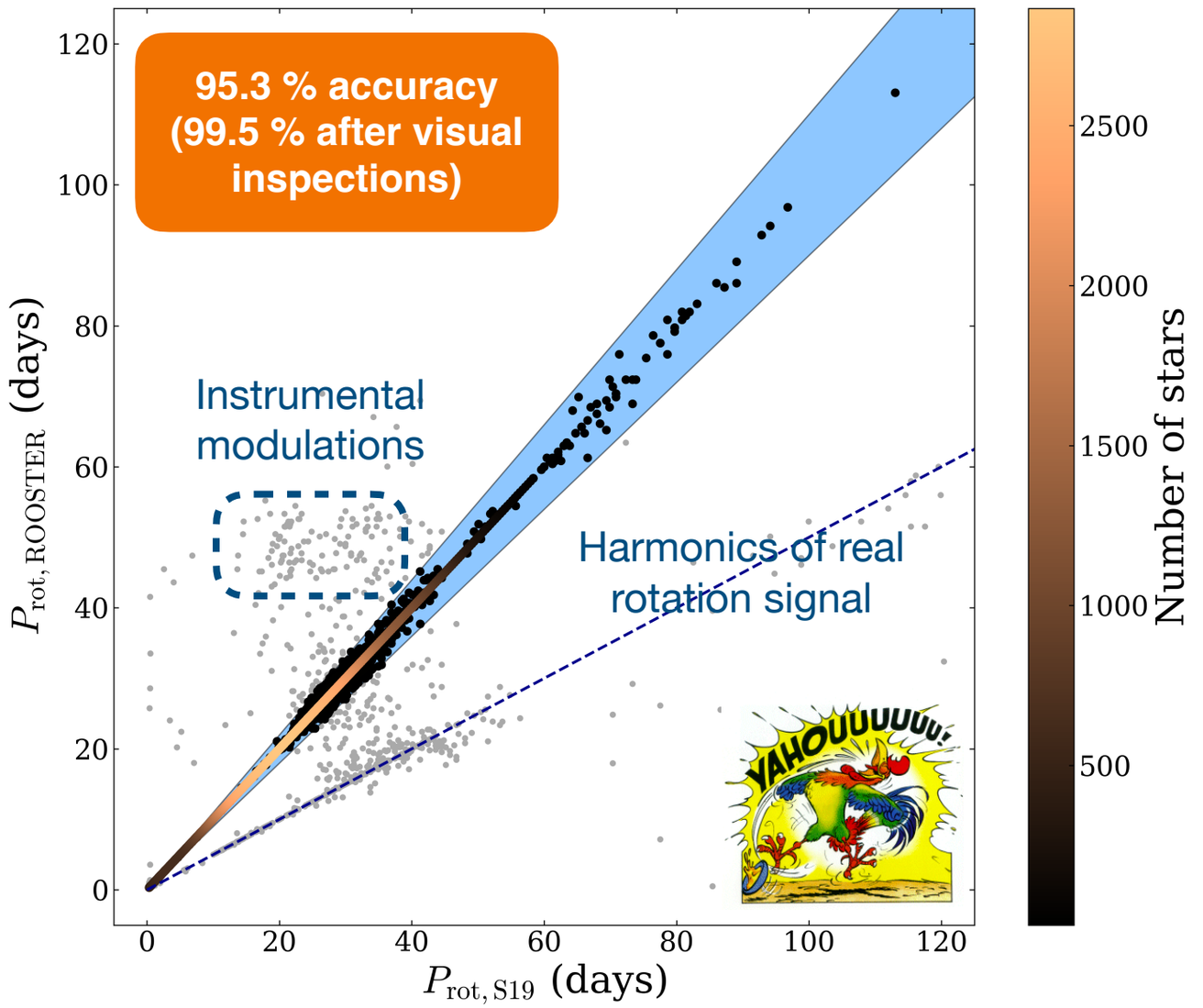
ROOSTER: Method validation

S.N. Breton
25/09/23
PLATO in Italy

(Breton et al. 2021)



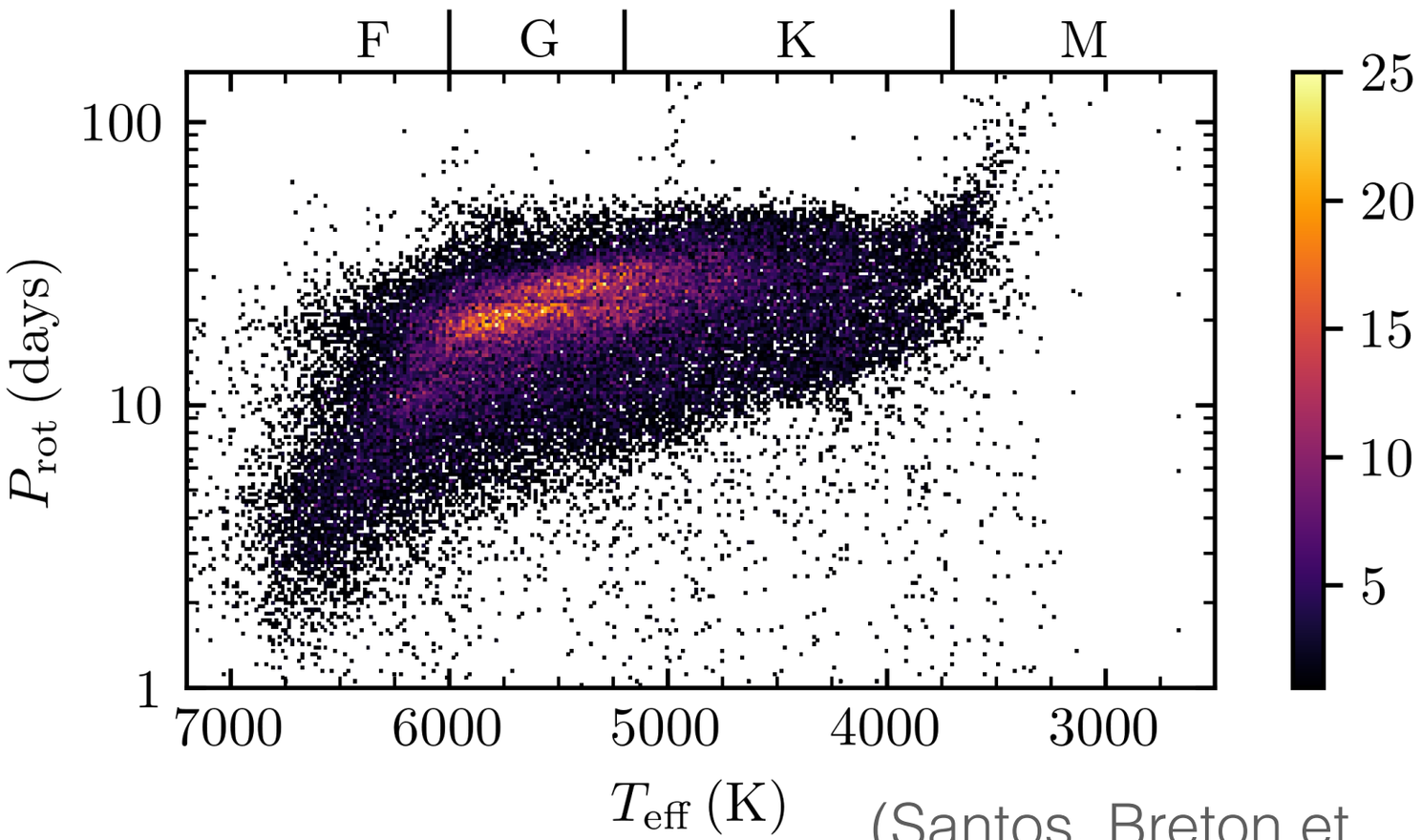
(Breton et al. 2021)



Application to the *Kepler* F and G sample (MS + subgiants)

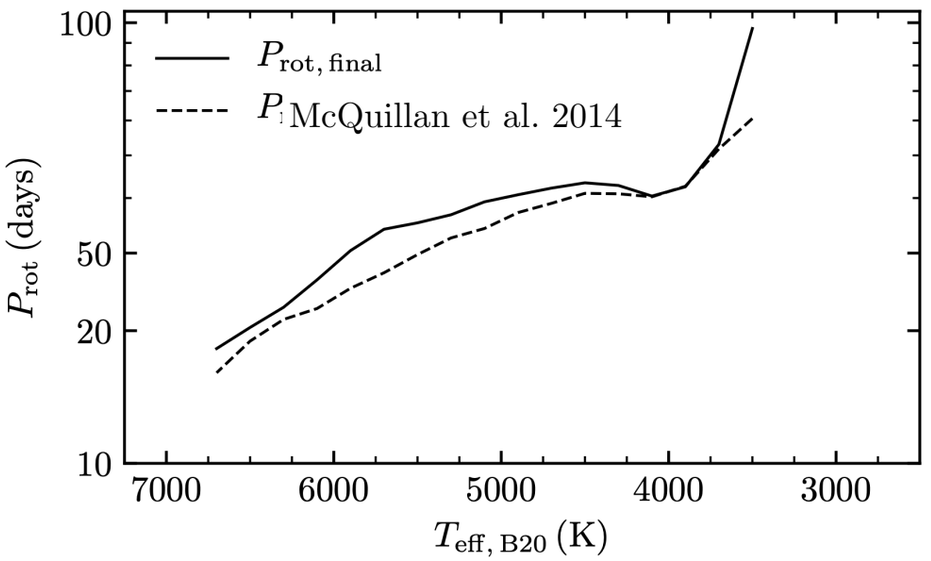
S.N. Breton
25/09/23
PLATO in Italy

55,232 stars with P_{rot}
(**62% more detections** in comparison with McQuillan et al. 2014)



(Santos, Breton et al. 2021)

(Santos, Breton et al. 2021)

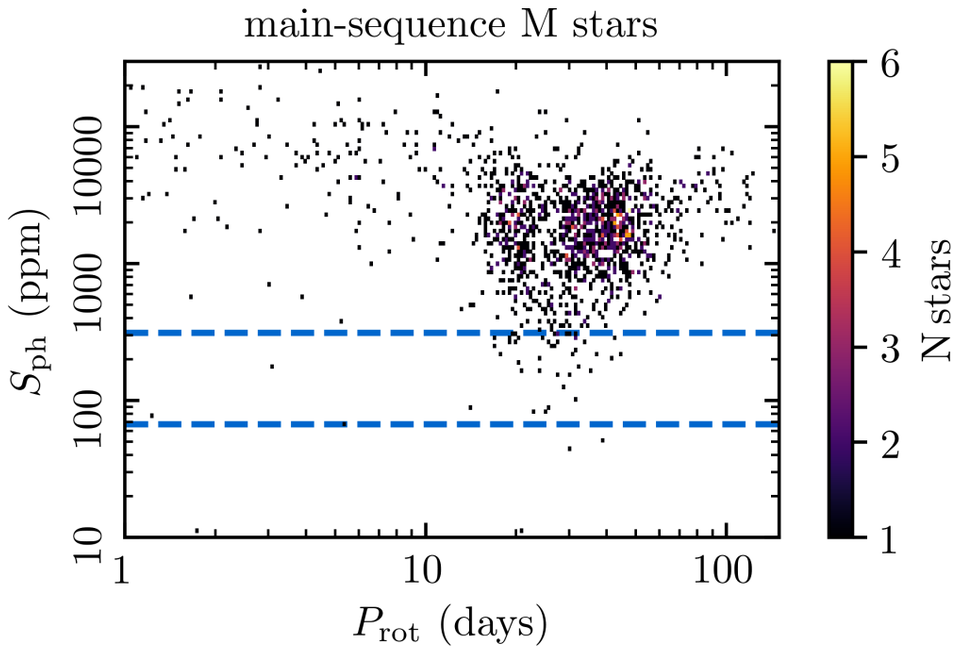


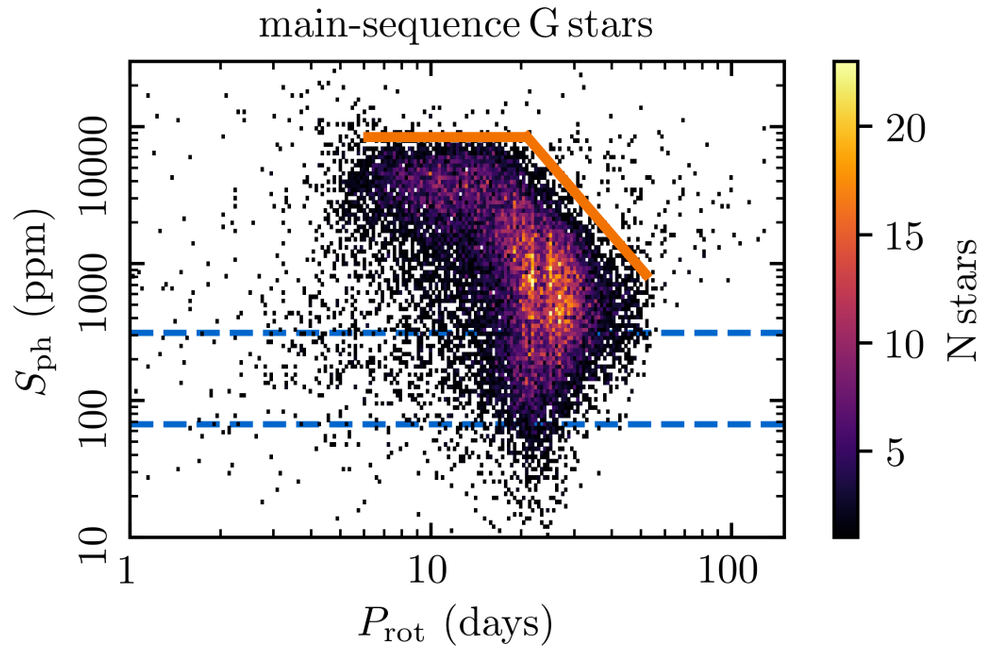
A view of what we will get with PLATO

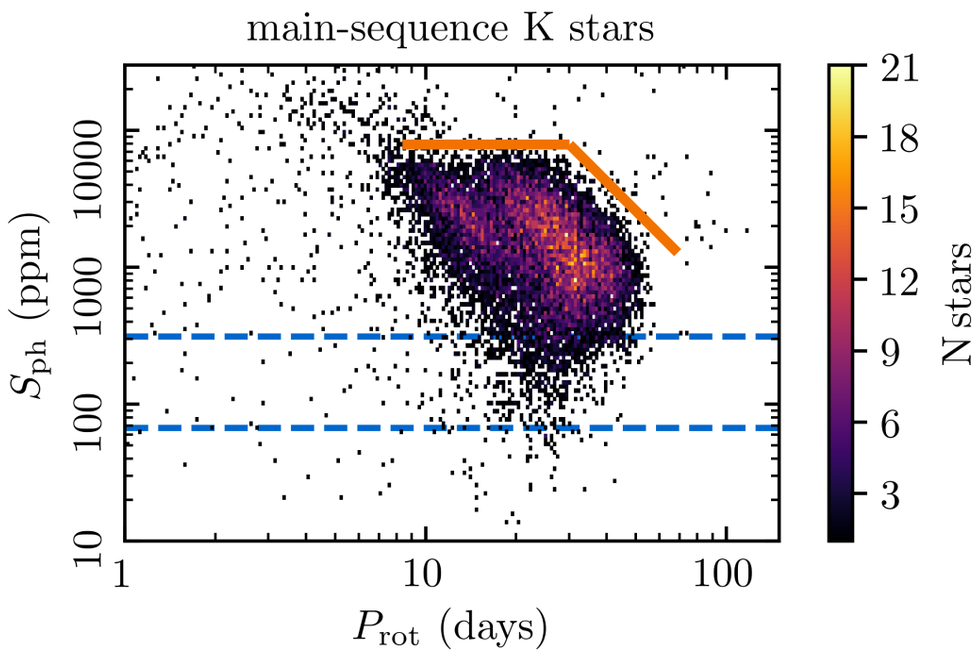
Photometric activity in *Kepler*

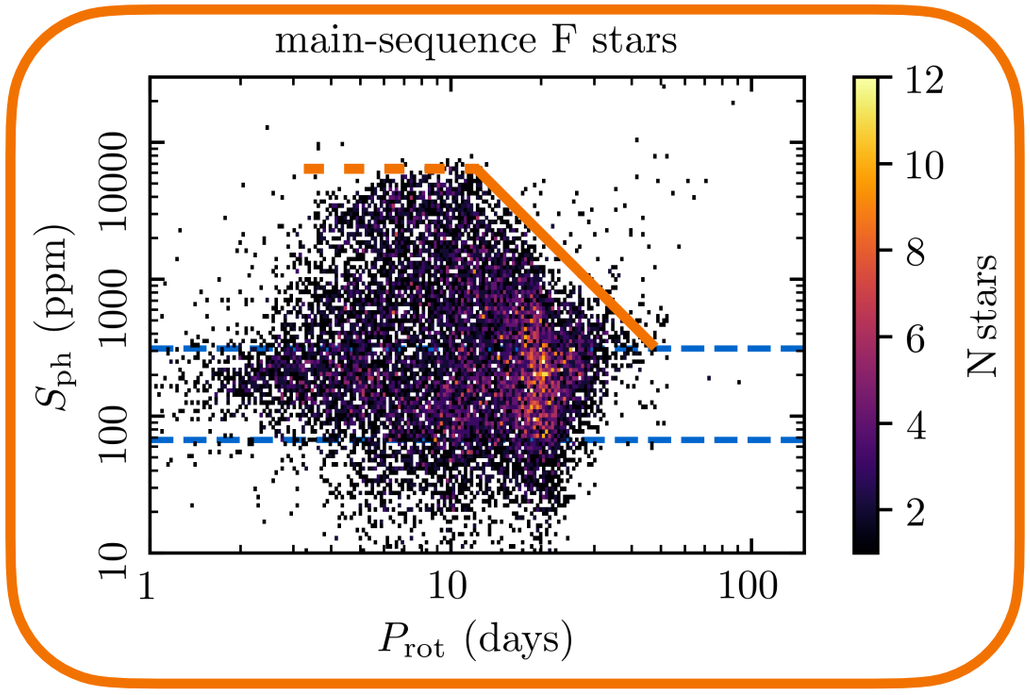
S.N. Breton
25/09/23
PLATO in Italy

S_{ph} indicator for FGKM stars









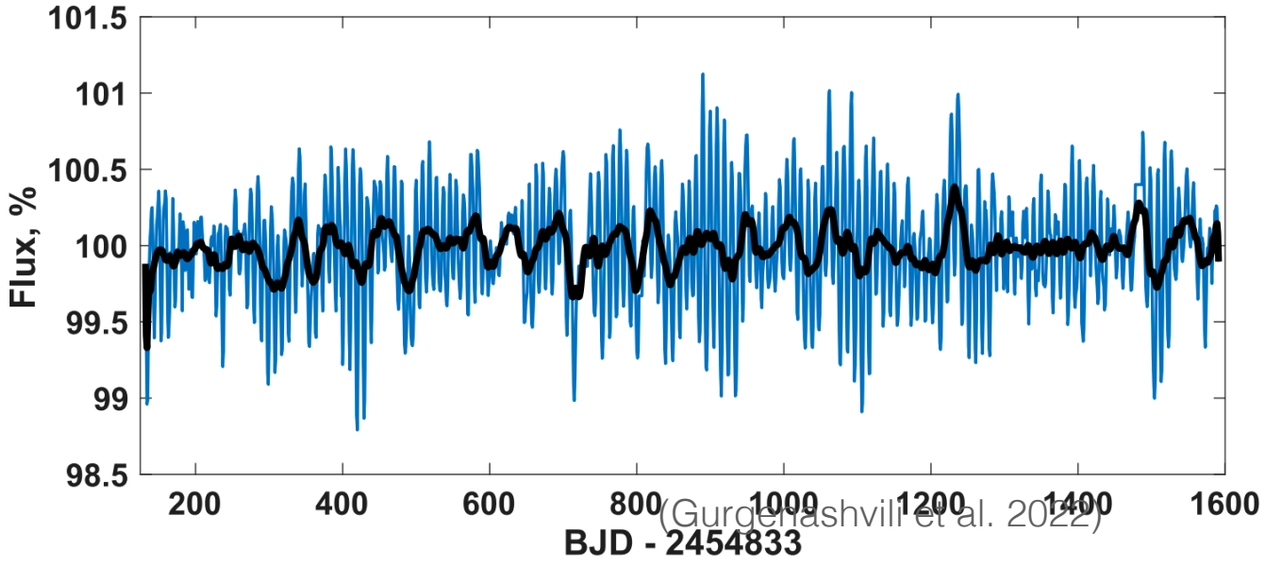
(Santos et al. 2019; Santos, Breton et al. 2021)

Activity and cycles in PLATO

S.N. Breton
25/09/23
PLATO in Italy

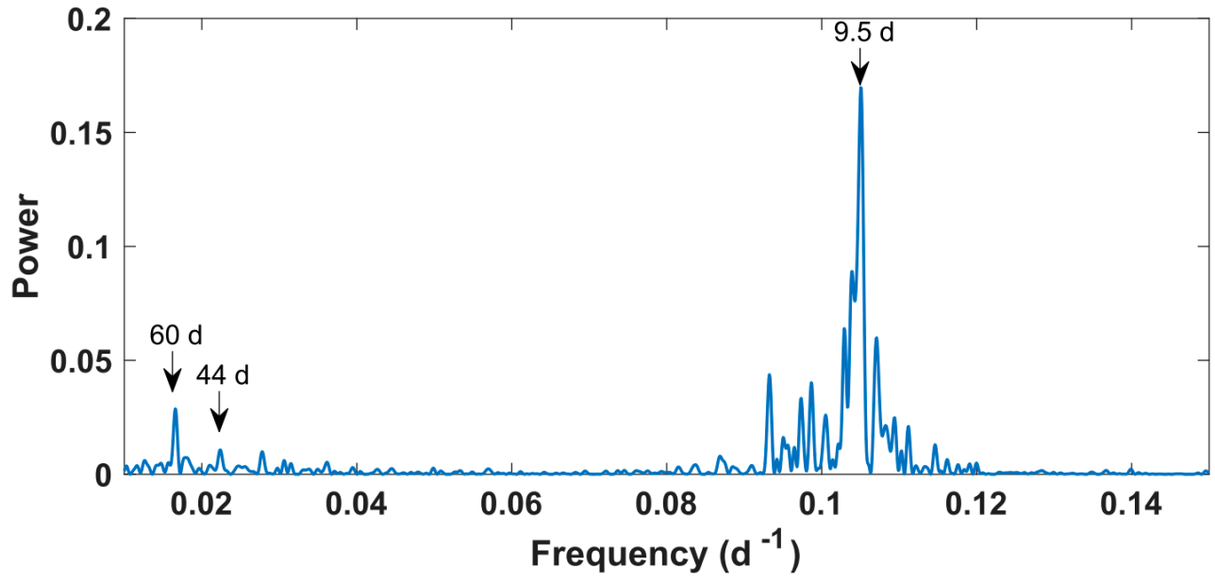
Short cycles such as Rieger-like periodicities (~150 days)

(Rieger 1984, Gurgenashvili et al. 2021, 2022)



(Gurgenashvili et al. 2022)

MSAP4 will combine:
- Fourier low-frequency analysis
- ACF long-periodicity
- S_{ph} time series modulations

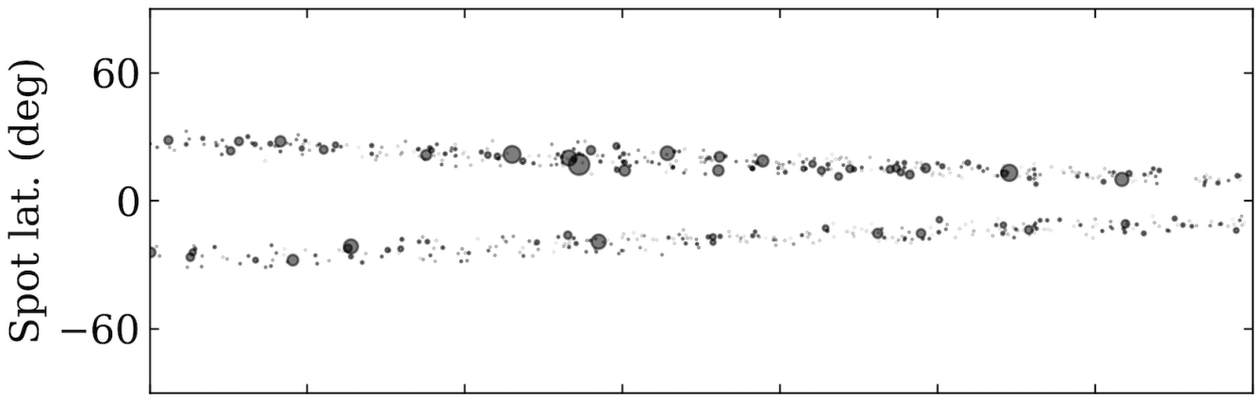


Key importance of low-frequency instrumental stability

Exploration of the possibility to use astrophysical calibrators

Rotation and activity simulations

«P1-like» target parameters selected from the PLATO input catalog
(PIC, Montalto et al. 2021)



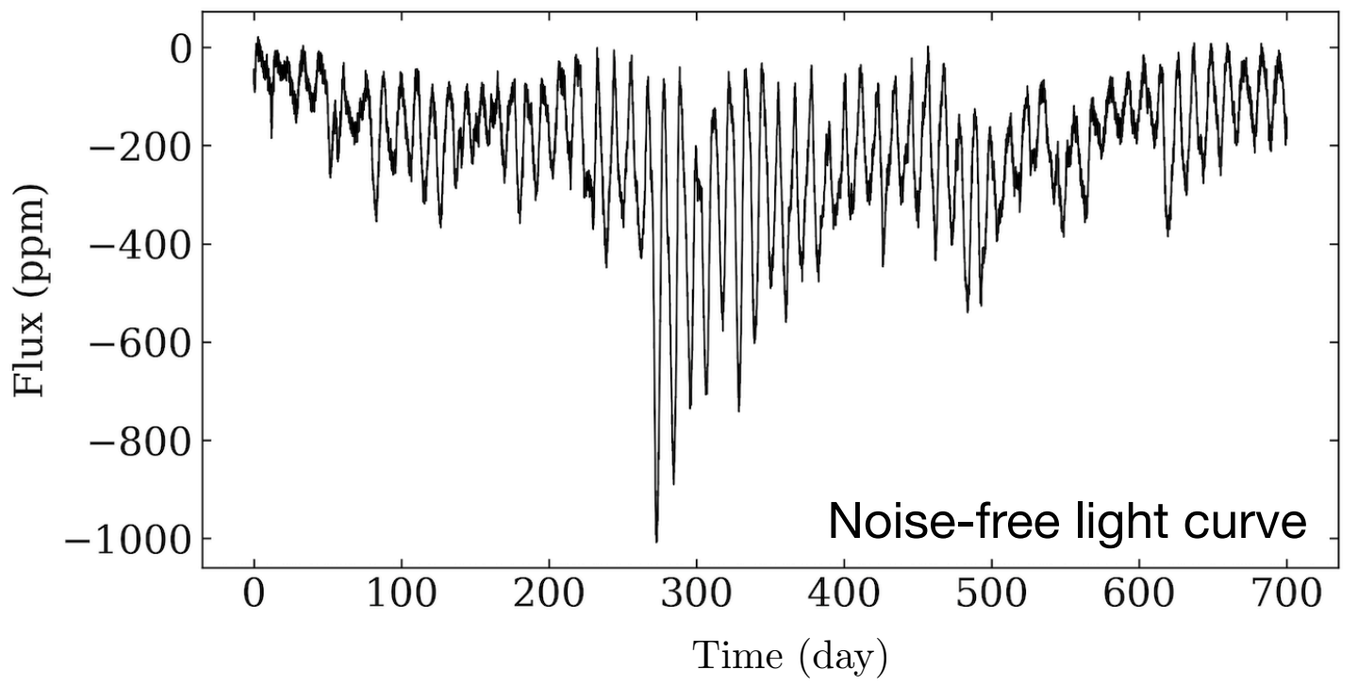
	P1
Stars	≥15 000 (goal 20 000)
Spectral Type	Dwarf and subgiants F5-K7
Limit *V*	11
Random noise (ppm in 1 hr)	<50
Wavelength (nm)	500–1000

(Montalto et al. 2021)

Spot modulations (includes activity cycle) computed with the pyspot code
(Aigrain et al. 2015, Meunier et al. 2019)

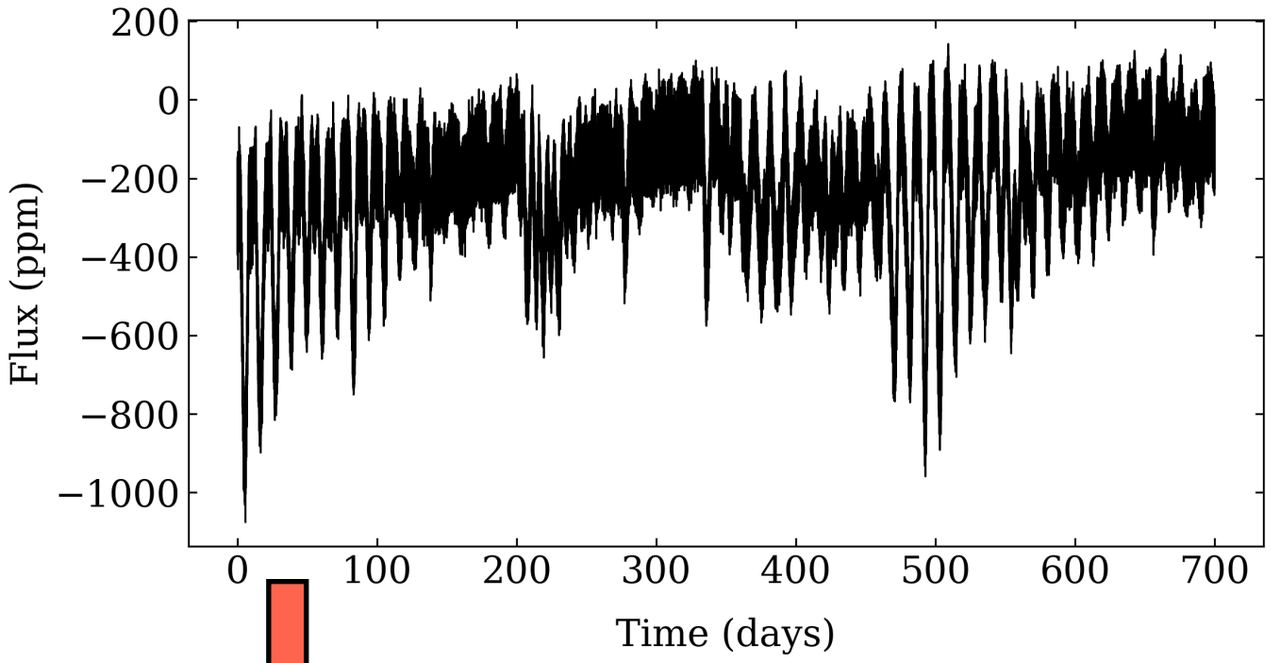
+

Convective granulation
(prescription from Kallinger et al. 2014)



Rotation and activity simulations

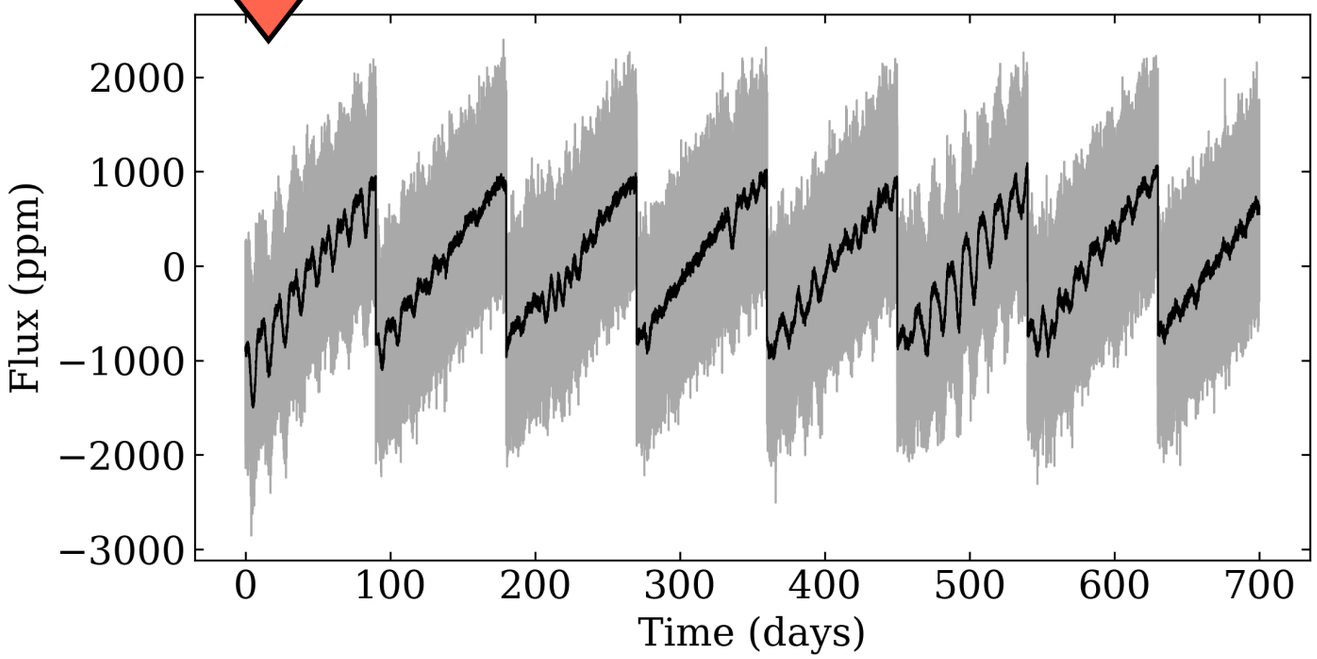
S.N. Breton
25/09/23
PLATO in Italy



Noise free

Analyse it and get the « ground truth » of the algorithms

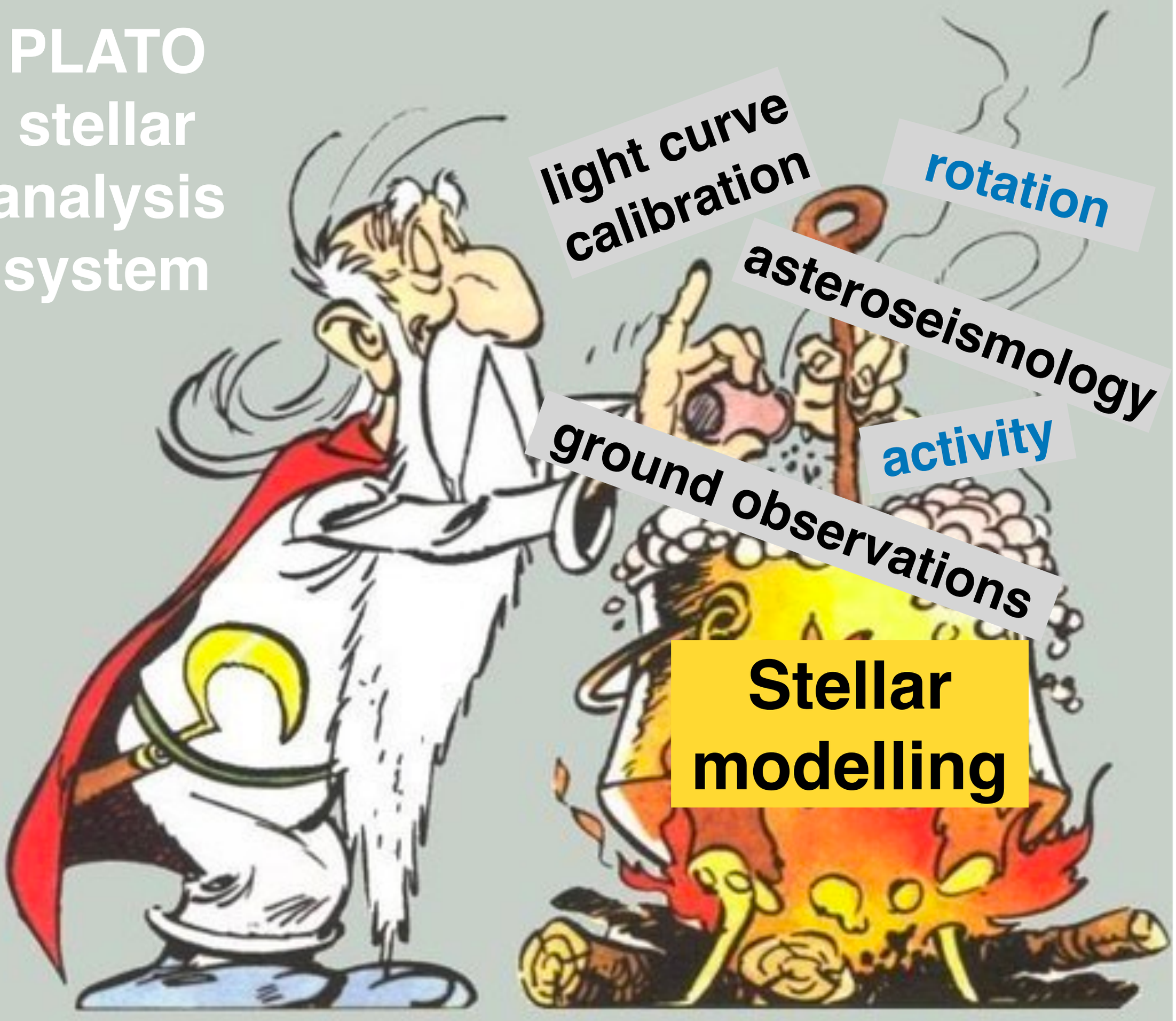
Interfacing with the PLATO Solar-Like Simulator (PSLS, Samadi et al. 2019)



Noisy

Well suited to test the algorithms inside an end-to-end PLATO pipeline trial

PLATO stellar analysis system

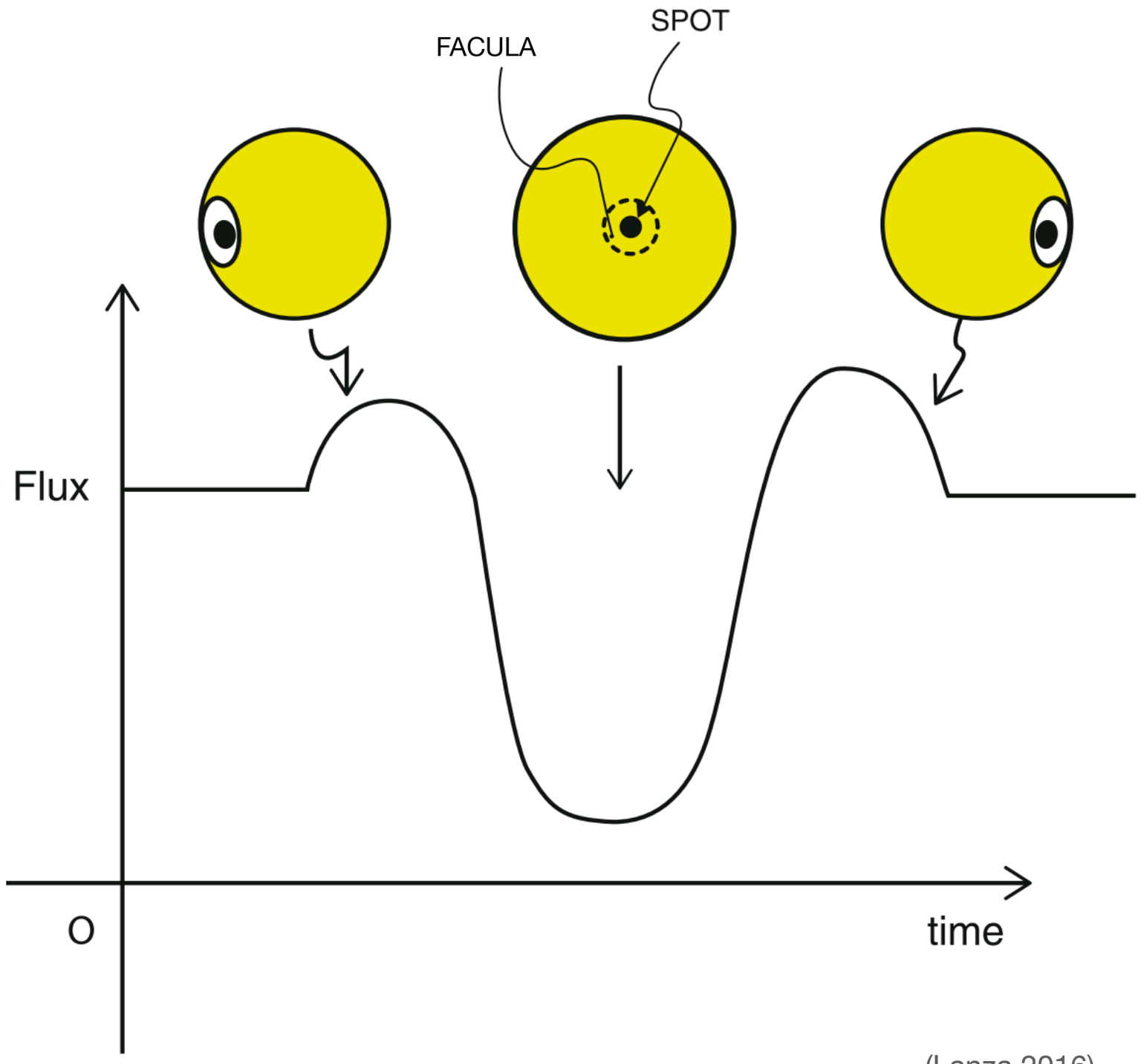


Beyond the PLATO pipeline: starspot modelling

S.N. Breton
25/09/23
PLATO in Italy

Physically-motivated modelling of the stellar surface activity-induced brightness variation

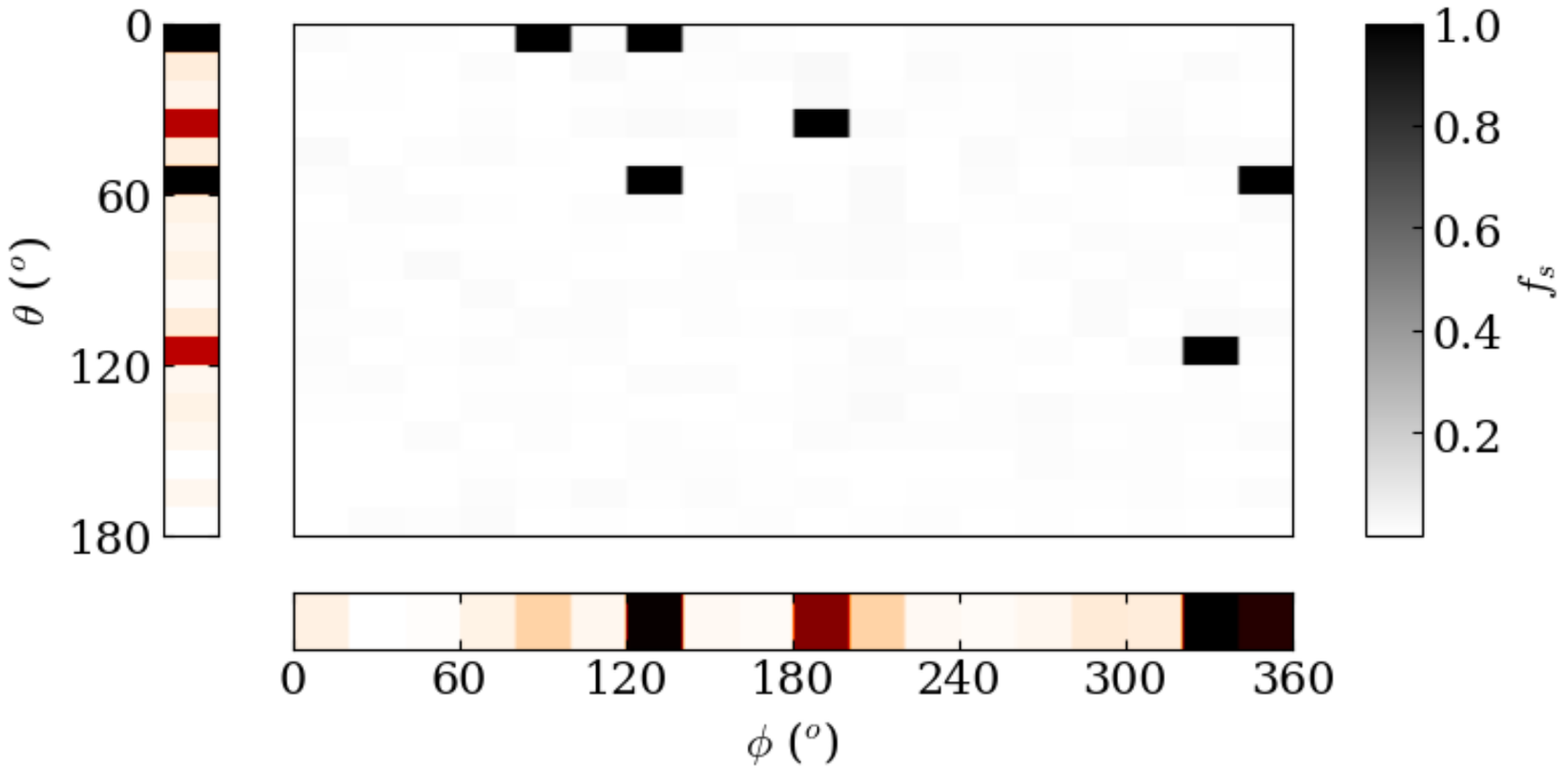
(Starspot modelling has been considered for the PLATO pipeline baseline but is currently not included it.)



(Lanza 2016)

A Bayesian continuous starspot model

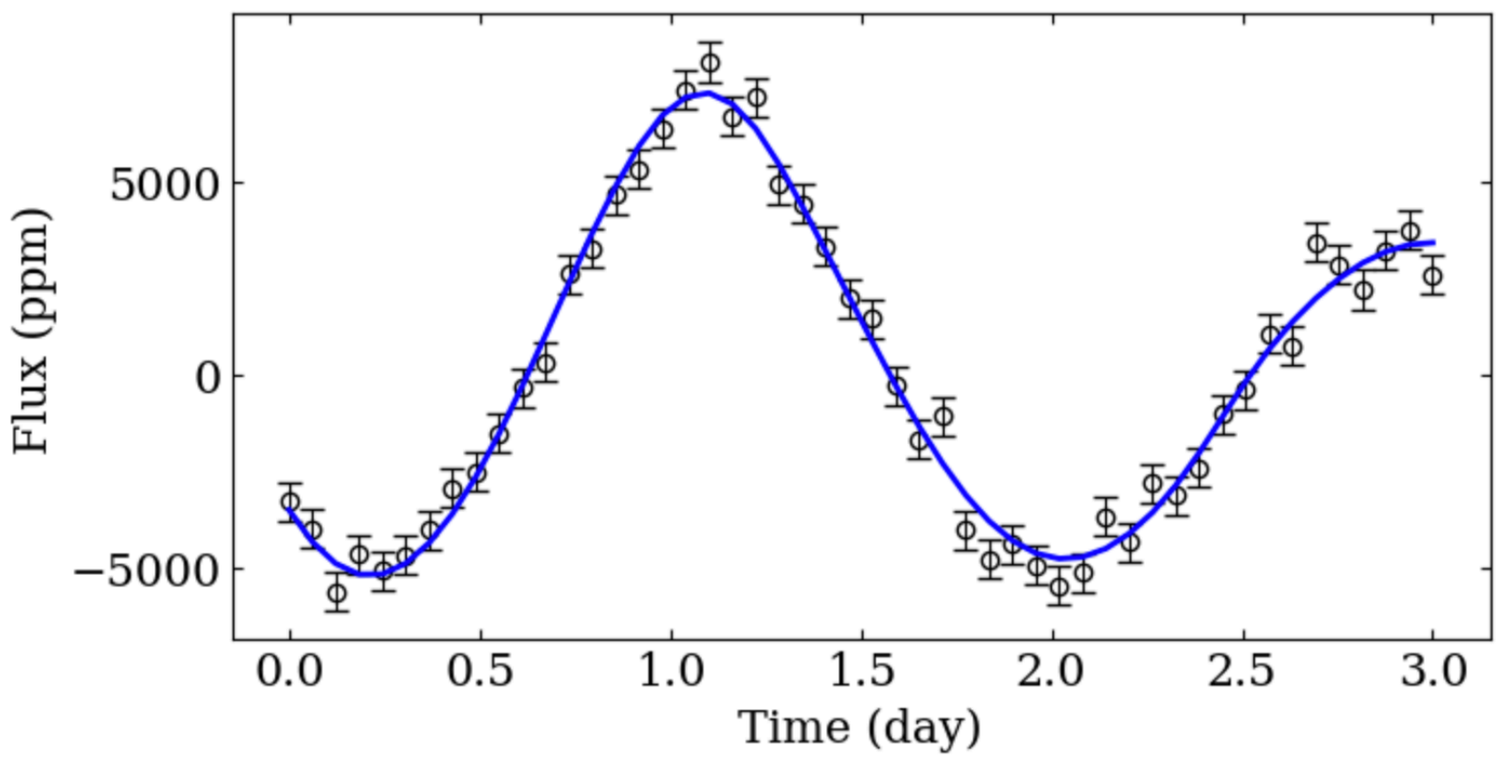
S.N. Breton
25/09/23
PLATO in Italy



loupiotes

(Breton et al. in prep.)

gitlab.com/sybreton/loupiotes
loupiotes.readthedocs.io/en/latest



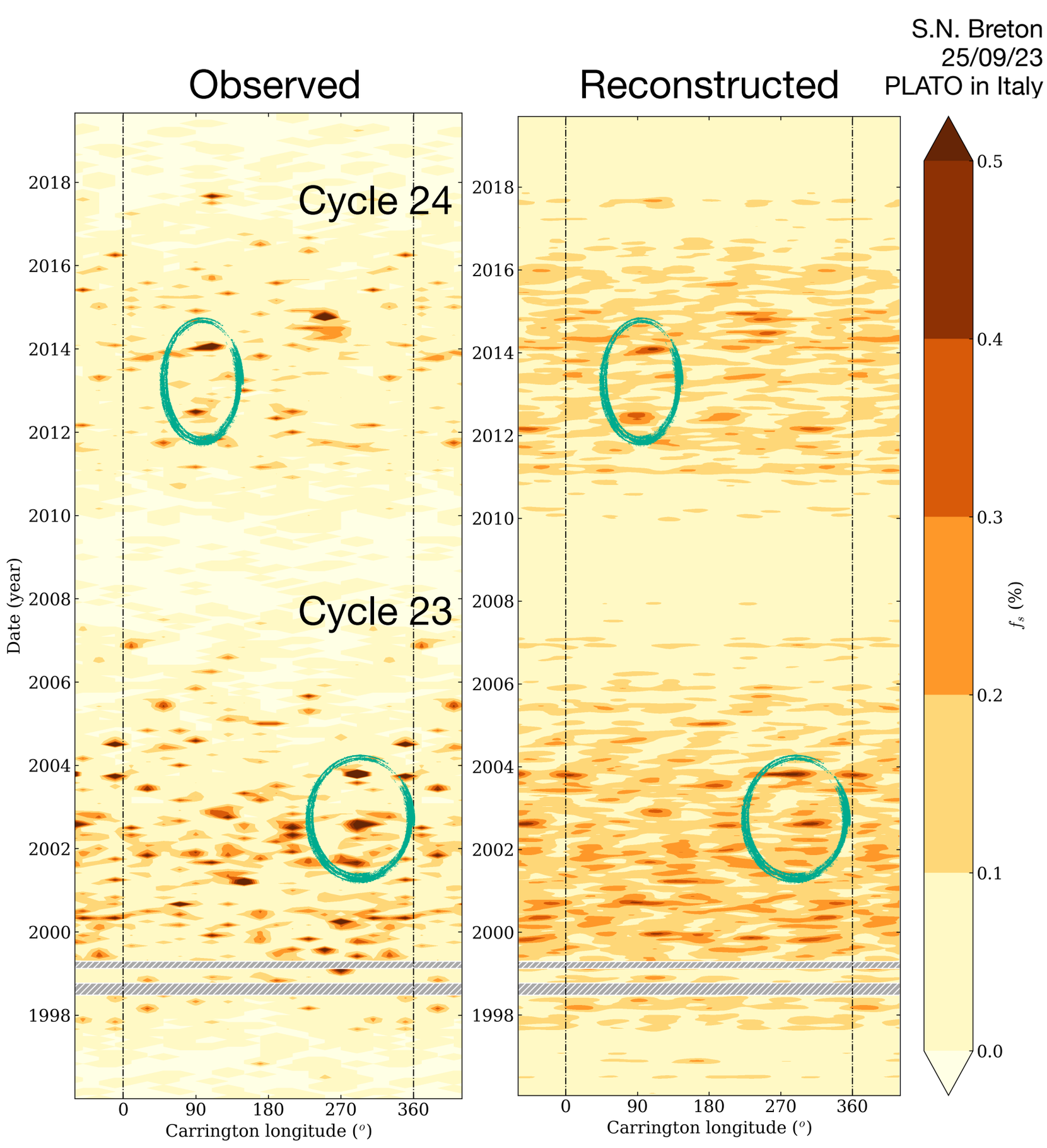
INAF
ISTITUTO NAZIONALE DI ASTROFISICA
OSSERVATORIO ASTROFISICO DI CATANIA

The solar case

Actual sunspot coverage compared to the spot model computed with the VIRGO/SPM time series.

(Fröhlich et al. 1995, Basri et al. 2010)

See also Lanza et al. (2003, 2007)

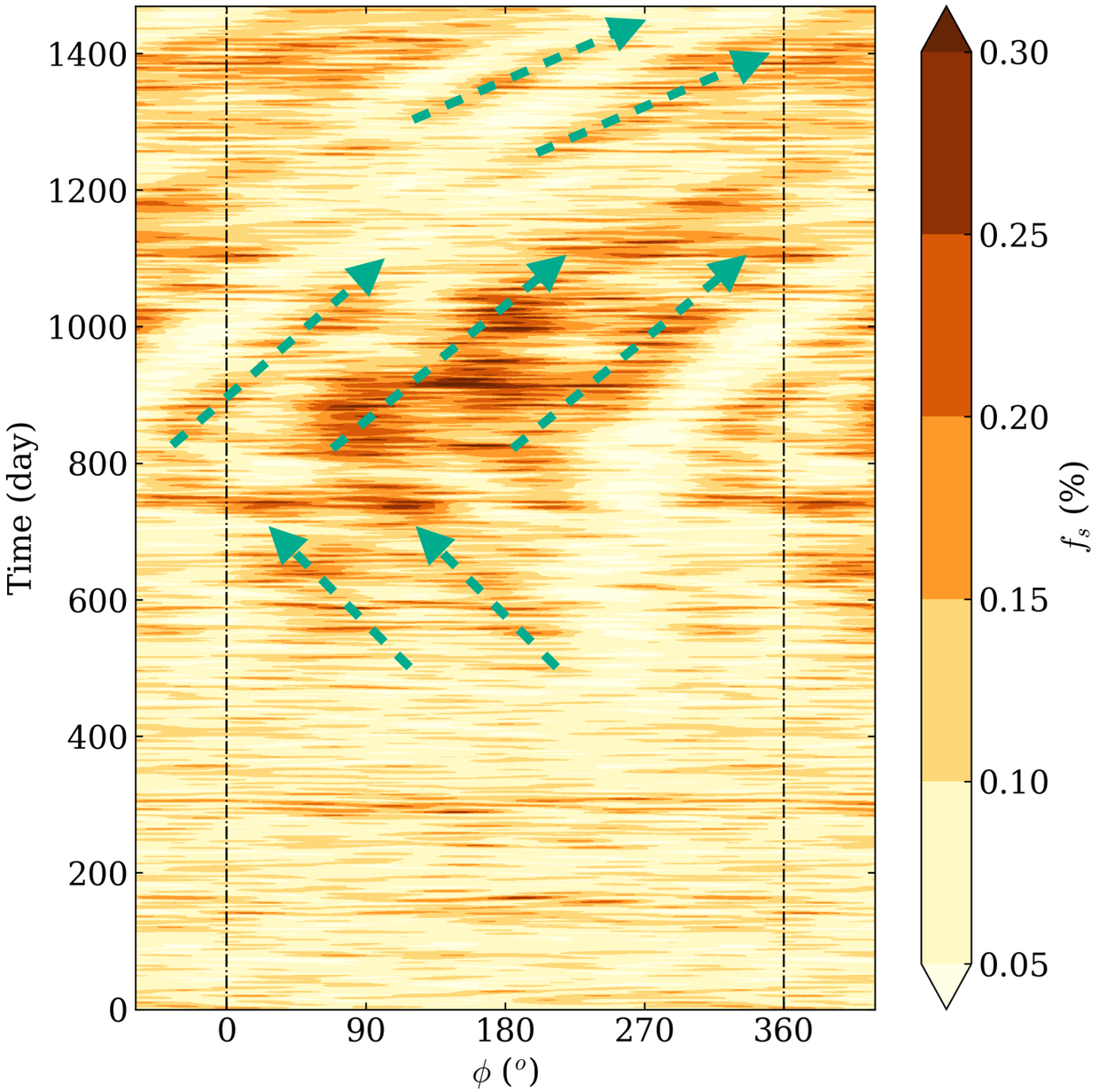


(Breton et al. in prep.)

Longitudinal active nests in solar-type pulsators

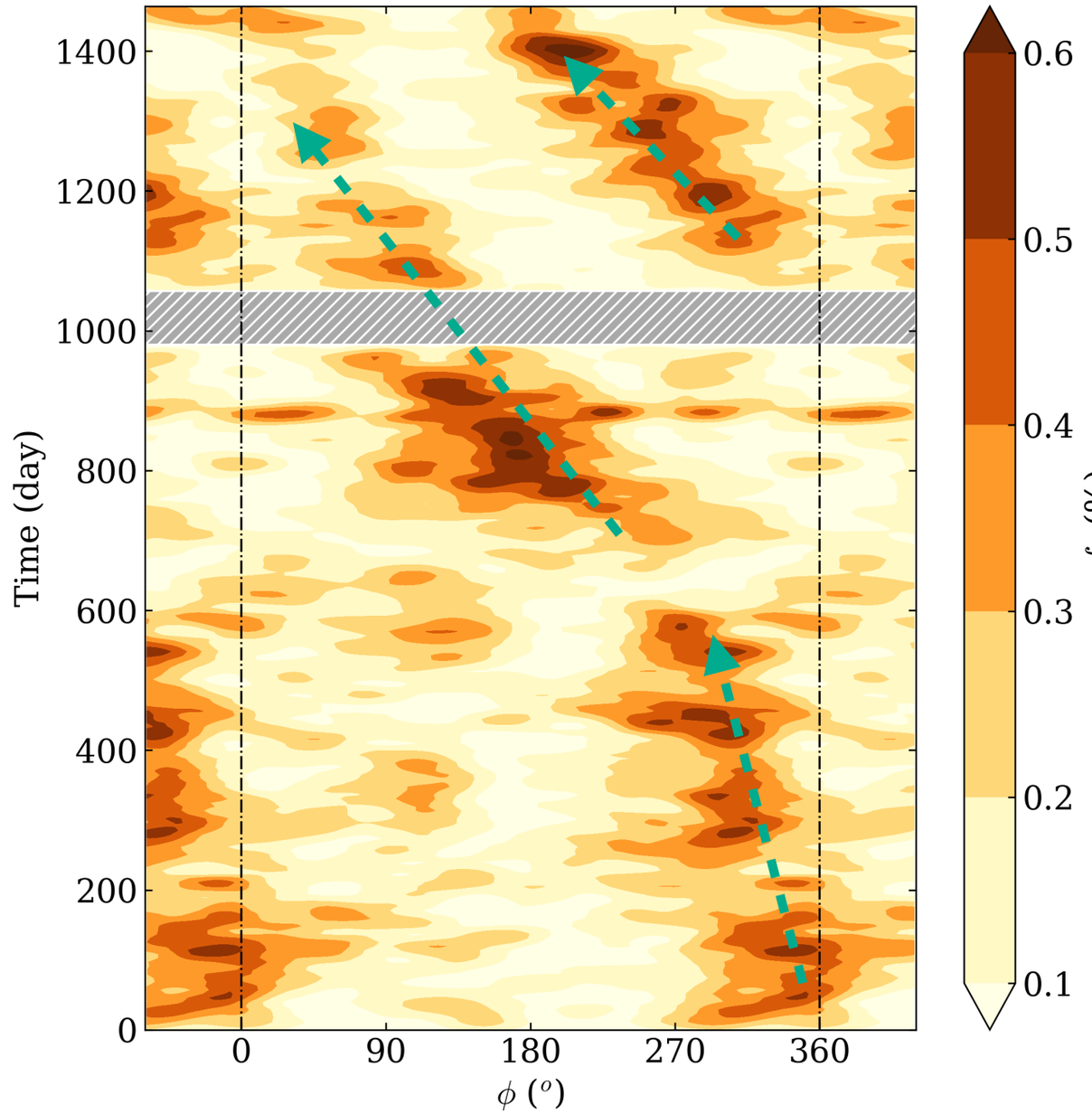
S.N. Breton
25/09/23
PLATO in Italy

(Breton et al. in prep.)



$T_{\rm eff} = 6676\,{\rm K}$ $P_{\rm rot} = 2.57\,{\rm days}$

$M_\star = 1.26\,{\rm M}_\odot$ $Ro/{\rm Ro}_\odot = 0.52$



$T_{\rm eff} = 6067\,{\rm K}$ $P_{\rm rot} = 17.09\,{\rm days}$

$M_\star = 1.12\,{\rm M}_\odot$ $Ro/{\rm Ro}_\odot = 0.84$

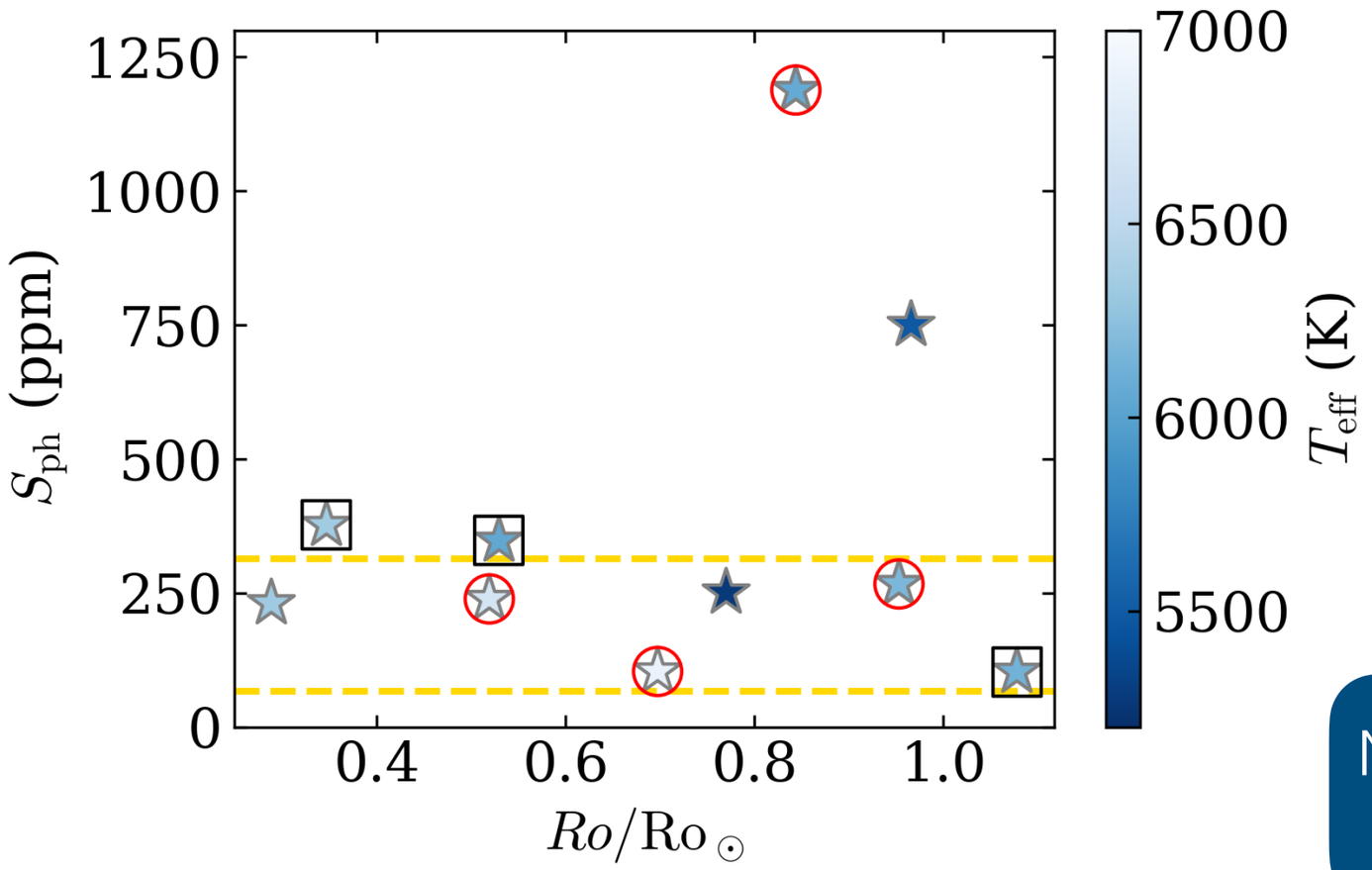
Solar-type pulsators observed by the *Kepler* mission

(Borucki et al. 2010, Chaplin et al. 2011)

The core targets for PLATO stellar science

INAF
ISTITUTO NAZIONALE DI ASTROFISICA
OSSERVATORIO ASTROFISICO DI CATANIA

Diverse activity levels and convection/rotation regime



(Breton et al. in prep.)

Clear detection of stable active nests

Possible detection of stable active nests

No clear dependence on Rossby number or activity index

The mechanisms enabling active longitudes to emerge needs to be clarified

PLATO will allow perform this type of analysis on a large scale

Wrapping it up

S.N. Breton
25/09/23
PLATO in Italy

PLATO baseline (Stellar analysis system)

Following our PSM deliveries, module is currently integrated into the PLATO Stellar Analysis System at CEA Saclay and IAS Orsay (France)

A set of **rotation and activity data products (DP4)** will be made **publicly available** during data releases.

The current stage is testing and validation for the ESA review in 2024.

Beyond the baseline

Opportunities to draw an **unprecedented landscape** of the **magneto-hydrodynamics** of solar-type stars

There remains a lot to explore in starspot modelling of solar-type pulsators

Connection to **asteroseismology** and **internal processes** at stake in the convective envelope

S.N. Breton
25/09/23
PLATO in Italy

If you have any question about stellar rotation and activity in PLATO, get in touch with us !

sylvain.breton@inaf.it
antonino.lanza@inaf.it
sergio.messina@inaf.it