

The PLATO Solar-like Light-curve Simulator (PSLS)

<http://psls.lesia.obspm.fr>

PLATO- PSM - WP 126 100

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In short ...

- To simulate stochastically-excited oscillations
- Include stellar granulation background, activity, and white noise, planetary transit, rotational splitting, white and non-white instrumental components, and the time delays btw different group of camera.
- Applications (WP 120):
 - Stellar science performance study
 - Consolidation of the PLATO science case and preparation of the mission
 - Hare and Hounds exercises
 - PSM validation of the light-curve generation process (→ L1)
- Developed in Python
- Document: PLATO-LESIA-PSPM-TN-014, issue 1.1, sep. 2015
- Website: <https://psls.lesia.obspm.fr>

General principle

Model of the expected PSD : $\bar{P}(\nu) = W + I(\nu) + A(\nu) + G(\nu) + O(\nu)$

W : white noise ; I: non-white instrumental noise (systematic) ; A: activity ; G : granulation ; O : Oscillation spectrum

Simulation of the stochastic nature of the simulated phenomenon (Anderson et al, 1990's approach):

$$F(\nu) = \sqrt{\bar{P}(\nu)} (U + iV)$$

U and V : two Normal distribution ; Hypothesis : uncorrelated phenomenon

Simulated lighth-curve : inverse Fourier transform of F(ν)

Simulated PSD : $P(\nu) = |F(\nu)|^2 = \bar{P}(\nu) (U^2 + V^2)$

Granulation spectrum

Two components (pseudo-lorentzian):

$$G(\nu) = \sum_{i=1,2} \frac{h_i}{1 + (2\pi\tau_i\nu)^{\alpha_i}}$$

h_i : height(s)

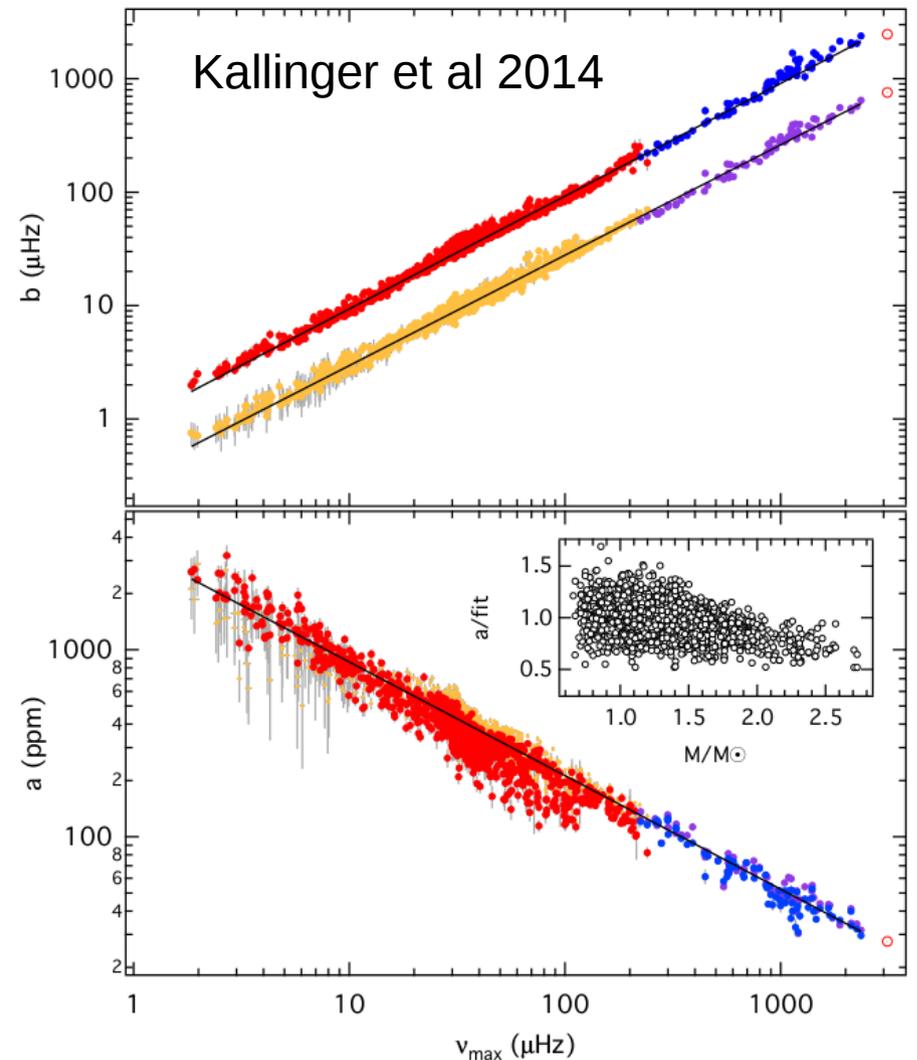
τ_i : characteristic time(s)

α_i : slope(s)

Origin of the two components not well established

Following Kallinger et al (2014) :

- Slopes fixed (=4)
- h_i and τ_i from scaling relations function of ν_{\max}



Oscillation spectrum

Two types of oscillation spectra:

- Universal Pattern (UP, Mosser et al 2010) with mixed-modes and splitting → for red-giant stars
- Set of theoretical oscillation frequencies derived from a pulsation code (ADIPLS) → for dwarf and sub-giant stars

$$O(\nu) = \sum_{i=1, N} L_i[\nu]$$

Resolved mode:

$$L_i(\nu) = \frac{H_i}{1 + (2(\nu - \nu_i)/\Gamma_i)^2}$$

h_i : mode height

ν_i : mode frequency

Γ_i : mode linewidth

Unresolved mode:

$$L_i(\nu) = \frac{\pi \Gamma_i H_i}{2 \delta \nu} \text{sinc}^2[\pi(\nu - \nu_i)]$$

Universal pattern

Following Mosser et al (2011)

$$\nu_{n,\ell} = n + \frac{\ell}{2} + \varepsilon(\Delta\nu) - d_{0\ell}(\Delta\nu) + \frac{\alpha_\ell}{2} \left(n - \frac{\nu_{\max}}{\Delta\nu} \right)^2 \Delta\nu + \delta_{n,\ell}$$

Additional term for dipole modes, asymptotic gravity-mode spacing (Mosser et al 2012)

$$\delta_{n,\ell} = \frac{\Delta\nu}{\pi} \arctan \left[q \tan \pi \left(\frac{1}{\Delta\Pi_1 \nu_{n,\ell}} - \epsilon_g \right) \right]$$

Mode amplitudes and line-widths:

Gaussian envelope

$$G(\nu) = H_{\max} \exp \left[\frac{-(\nu - \nu_{\max})^2}{\delta \nu_{\text{env}}^2 / 4 \ln 2} \right]$$

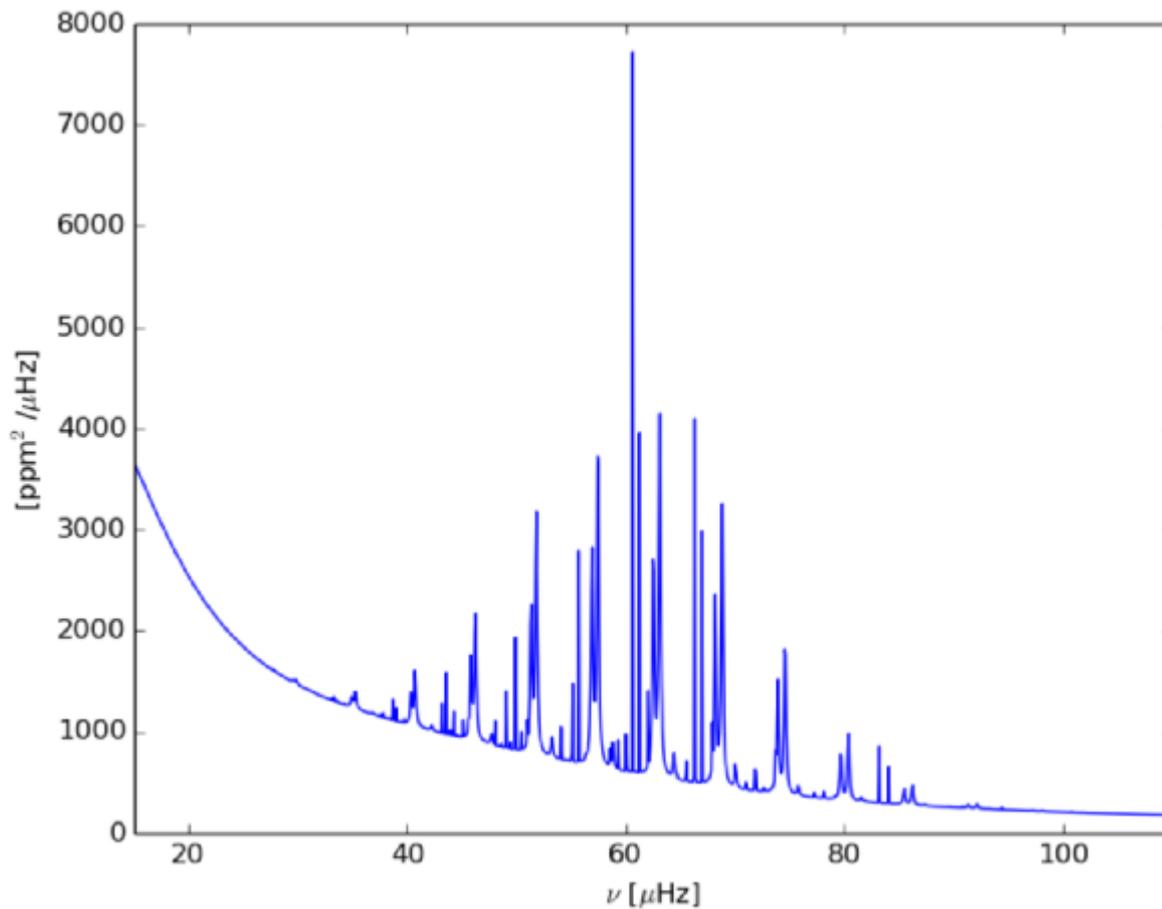
$$H_{\max} = \alpha \nu_{\max}^{-2.38}$$

(Mosser et al 2013,
SF2A)

$$\Gamma_{\max} = \Gamma_0 \left(\frac{T_{\text{eff}}}{4800 \text{ K}} \right)^{10.8}$$

(Belkacem 2012,
SF2A)

Universal pattern



Theoretical
spectrum
("expectation")

Input parameters:

- v_{\max}

- $\Delta\nu$

- T_{eff}

- q (coupling)

- $\Delta\Pi$ (asymptotic period
spacing)

Set of theoretical mode frequencies

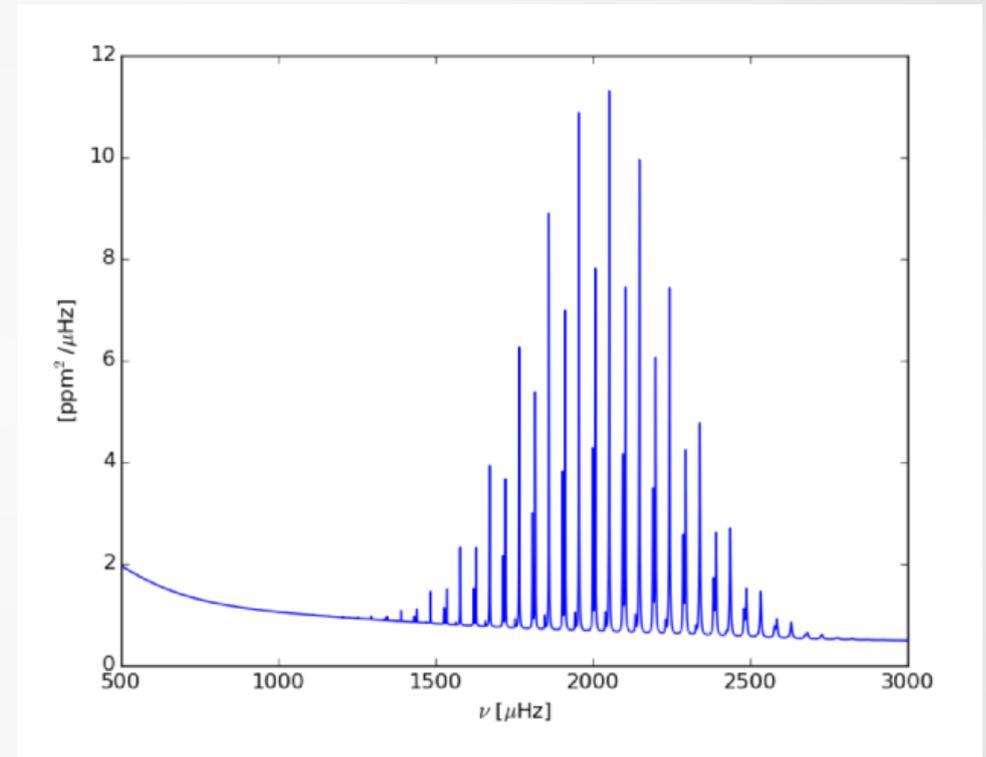
Theoretical adiabatic frequencies : as given by ADIPLS

Splitting : constant (Ledoux's constant from ADIPLS)

Surface effects :
Modified lorentzian component (Sonoi et al 2015), involved 2 free input parameters (a,b), derived as a function of T_{eff} and $\log g$ from corresponding scaling relation

Amplitudes : observationnal scaling relation from Corsaro et al (2013)

Line-widths : observationnal scaling relation from Appourchaux et al (2012)



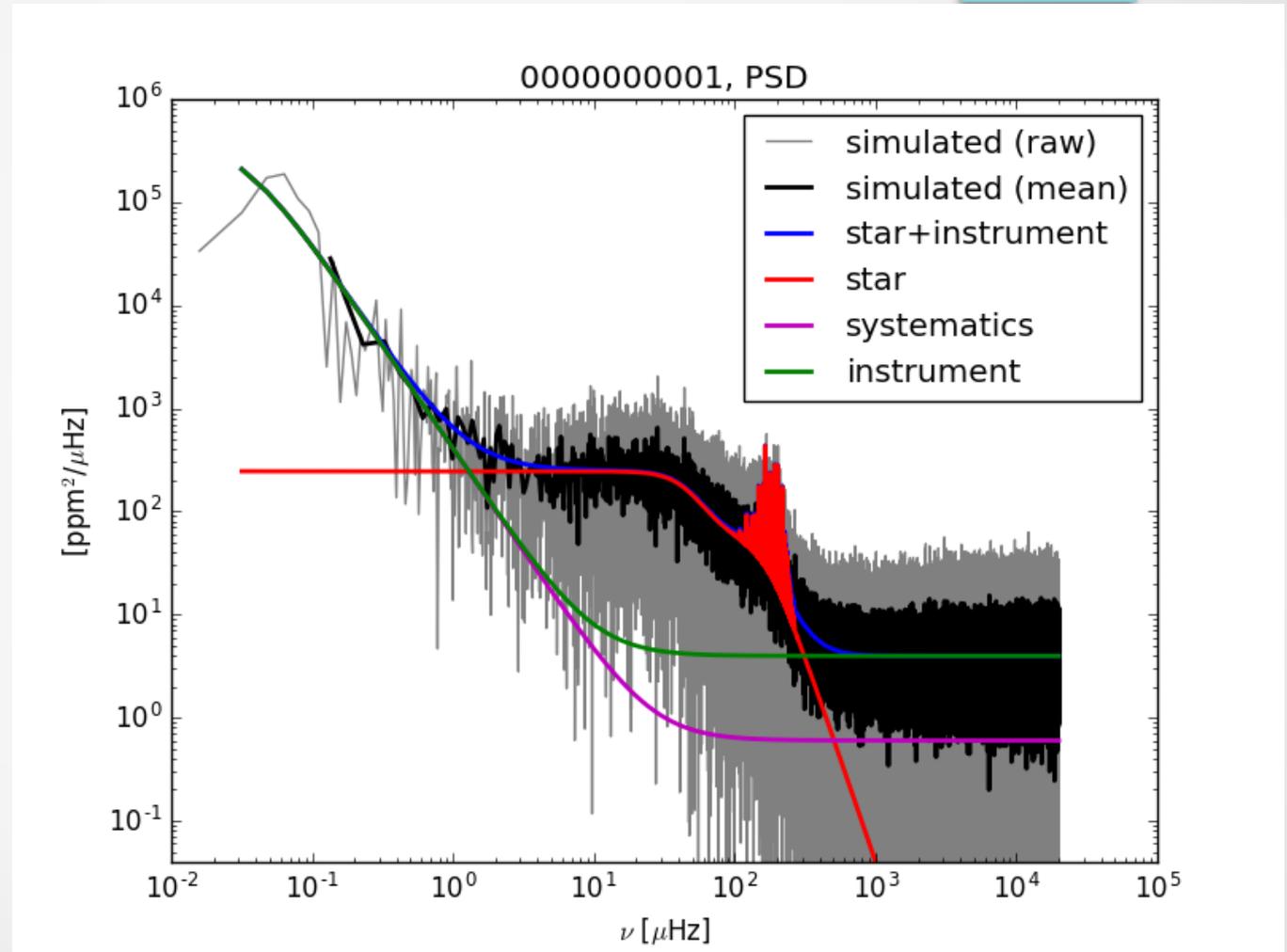
A typical PLATO target (here noise free...)

Other components

- Activity component: Lorentzian function ($\alpha=2$) ; users specify its characteristic time (τ) and amplitude (σ)
- Non-white instrumental noise component (corresponding to systematics): Lorentzian function ($\alpha=2$) ; users specify its characteristic time (τ) and amplitude (σ)
- Planetary transit: based on Mandel & Agol (2002) equations ; users specify typical transit parameters (radius, period, distance, and orbital angle)

Illustration

Power spectrum of a light-curve simulated for a red-giant star on the basis of the Universal Pattern



Inputs/outputs

The configuration file

```
1 # PLATO Solar-like Light-curve Simulator (PSLS) configuration file
2
3 # Observations conditions
4 Duration : 100. # 730. # [days]
5 Sampling : 25. # Sampling cadence of each camera [seconds]
6 IntegrationTime : 22. # Integration time [s]
7 NGroup : 4 # Number of camera groups (1 -> 4)
8 NCamera : 6 # Number of camera per group (1->6)
9 MasterSeed : 1704040900 # Master seed of the pseudo-random number
10
11 # Instrument parameters
12 NSR : 150. # Noise to signal ratio [ppm/hr], for one single camera
13 SystematicsSigma : 1000. # Amplitude of the non-white systematics
14 SystematicsTau : 60. # Time-scale of the non-white systematics noise
15 SystematicsWhite : 63.3 # White level of the systematic noise, for
16 TimeShift : 6.25 # Time shift between camera groups [s]
17
18 # Stellar parameters
19 StarMag : 10.5 # Magnitude
20 StarID : 2 # star ID
21 StarModelDir : '/home/reza/seism/python/sls/models/m+0y27l' # Directory
22 StarModelType: 'grid' # Type of input model: 'grid' or 'single'
23 StarModelName: '' # Name of the input model, to be specified when
24 StarES : 'ms' # Evolutionary status: 'ms' for the main-sequence phase
25 StarTeff : 5777. # Effective temperature [K]
26 StarLogg : 4.438 # Surface gravity, ignored for redgiants
27 numax : 179.3 # frequency of the maximum power [muHZ], used only for
28 delta_nu : 13.68 # Mean large separation [muHz], used only for redgiants
29 DPI : 80.58 # Asymptotic values of the gravity mode period spacing
30 q : 0.15 # Mixed modes coupling factor
31 Activity : 1
32 ActivitySigma : 1000. # Amplitude of the activity component [ppm]
```

Input files:

- ADIPLS output: <...>.gsm file
- Or
- A grid of <...>.gsm files

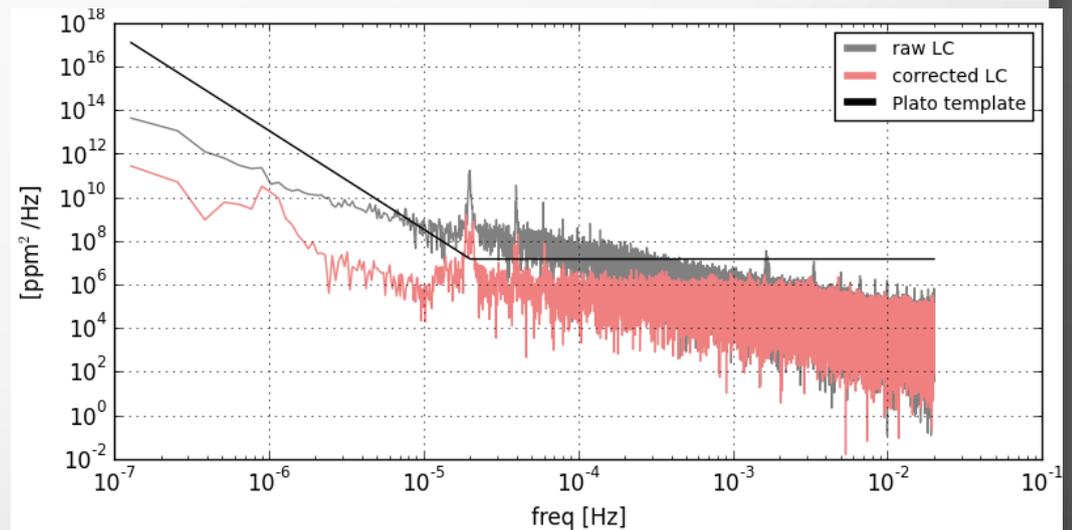
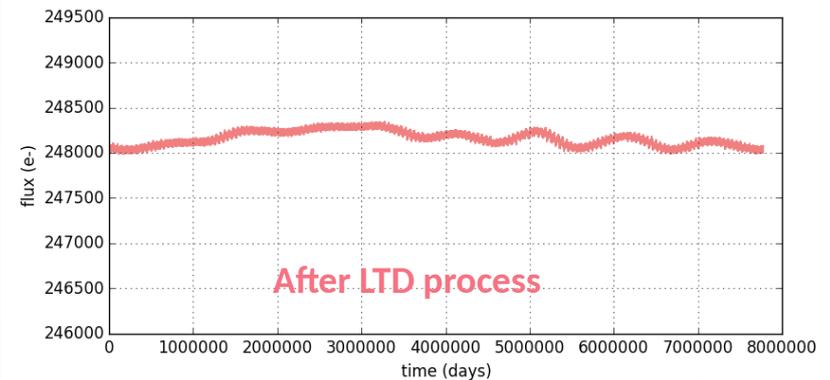
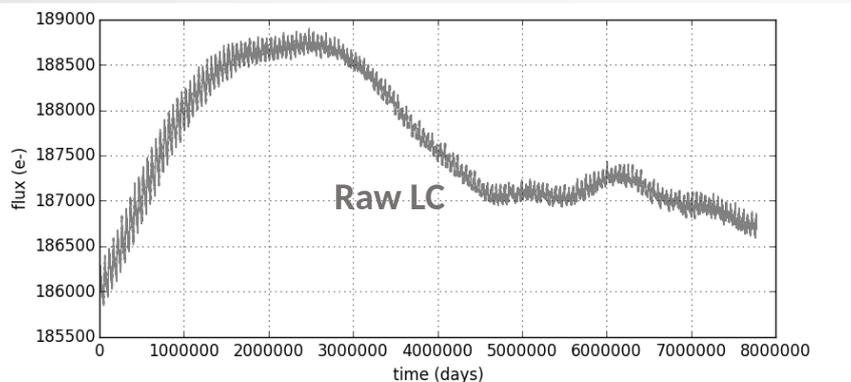
Outputs:

- A light-curve corresponding to the intensity measurements averaged over the total all the camera ;
- [Option:] A light-curve obtained by merging the intensity measurements averaged over each group of camera
- [Option:] some illustrative plots

Instrumental systematic modeling

Residual errors expected after correction (systematic) at different FoV position and magnitude

- **CCD images**
 - simulated with the PLATO Image Simulator (PIS) using state-of-the art instrument model
- **Micro-scanning:**
 - Compute inverted PSF for each star simulated.
 - Continuous micro scanning
 - Inverted PSF with a sub-resolution of 1/128 pixel
- **Long Term Drift correction:**
 - With the inverted PSF
 - Perfect knowledge of PRNU
 - Perfect knowledge of displacement



Instrumental systematic modeling

Generate a template model composed by:

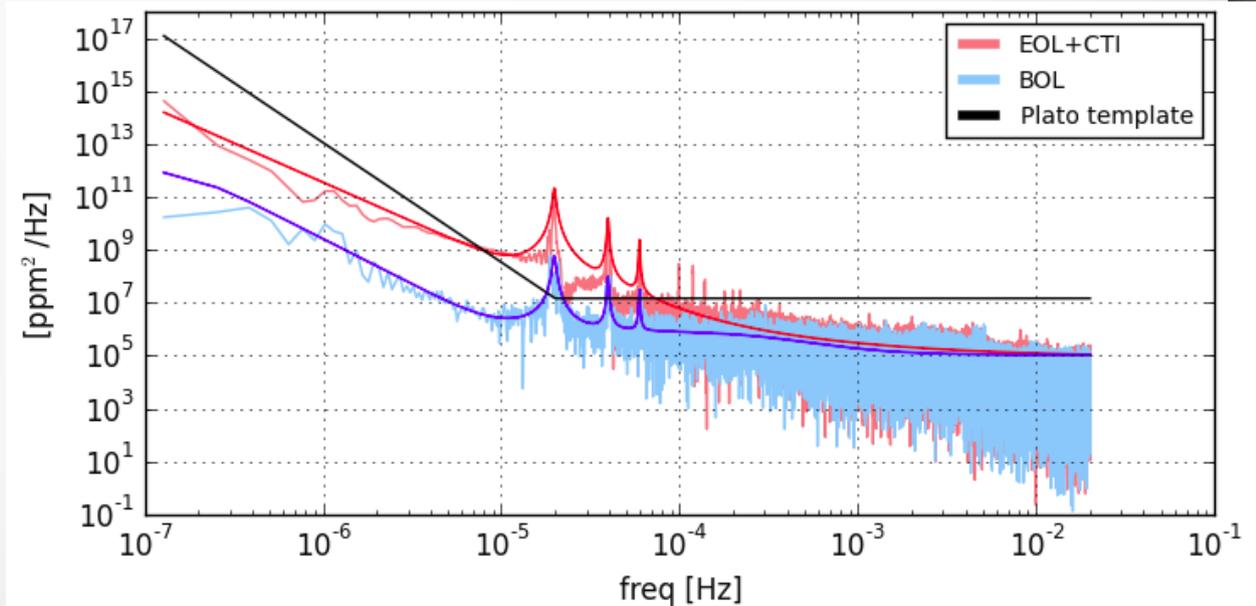
- A first pseudo-Lorentzian function for low frequency.
- A second pseudo-Lorentzian function for the high frequency pattern.
- 3 peaks for the periodic perturbation.
- (each peak is modelled by a lorentzian function too)

$$L(f, h, \tau, \alpha) = \frac{h}{1 + (2\pi \cdot \tau \cdot f)^\alpha}$$

The model fitted on the corrected PSD using Powell's method

These models/prescriptions can easily be implemented into light-curve simulators, such as PSLs

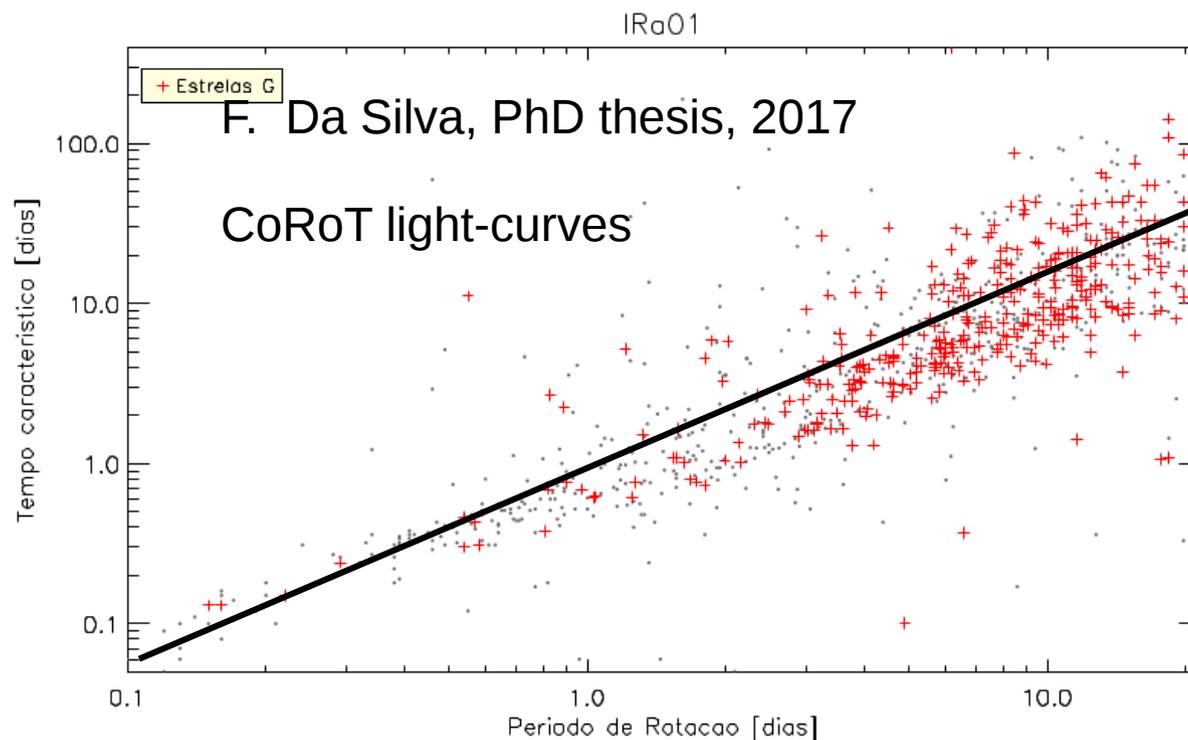
Various simulations for various magnitudes and FoV positions were built and systematics characterized using this method.
→ derivation of some prescriptions for the model parameters



Prescription for the magnetic activity parameters

$$L(\nu) = \frac{4 \sigma^2 \tau}{1 + (2\pi \nu \tau)^2}$$

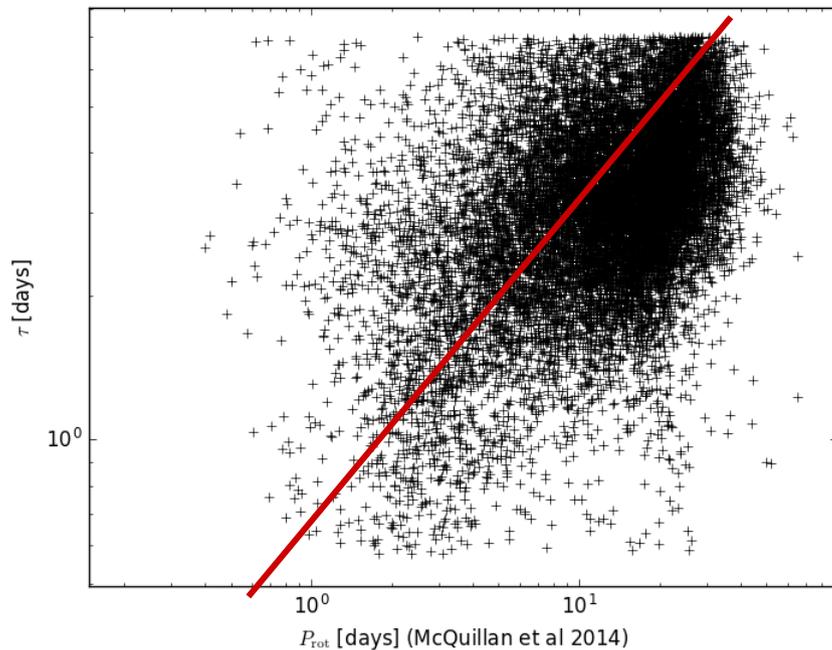
The magnetic activity component is specified by its **amplitude** σ [ppm] and **characteristic time** τ [days]



Fit of a pseudo-lorentzian function on CoRoT ligh-curves and derivation of orbital period using ACF method → derivation of τ and P_{rot}

→ Clear correlation between τ and P_{rot}

Prescription for the magnetic activity parameters



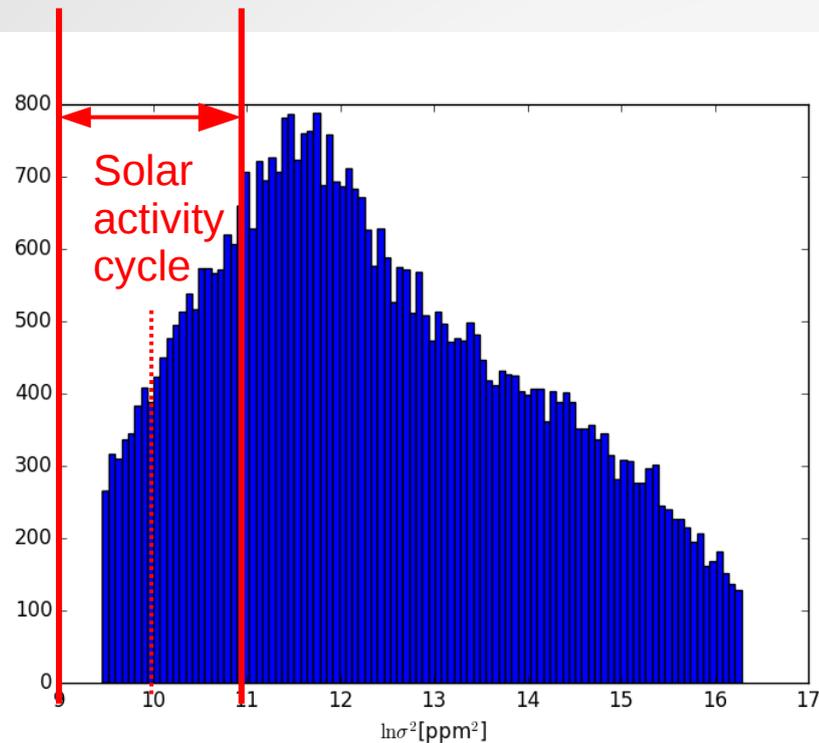
Analysis Kepler long cadence light-curve

Cross match with P_{rot} measurements by Mc Quillan+ 2014: $\sim 18,000$ dwarf stars in common

→ The correlation between τ and P_{rot} is confirmed

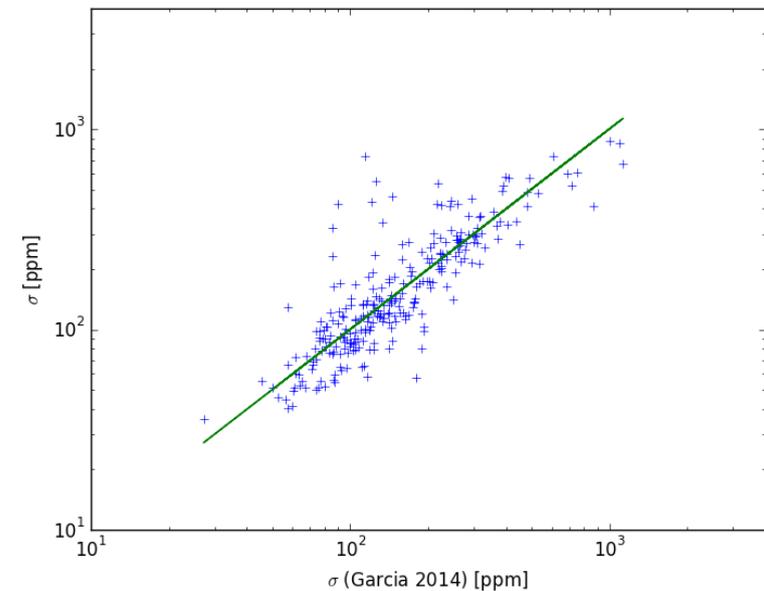
→ Possible use of a scaling relation between τ and P_{rot}

Prescription for the magnetic activity parameters



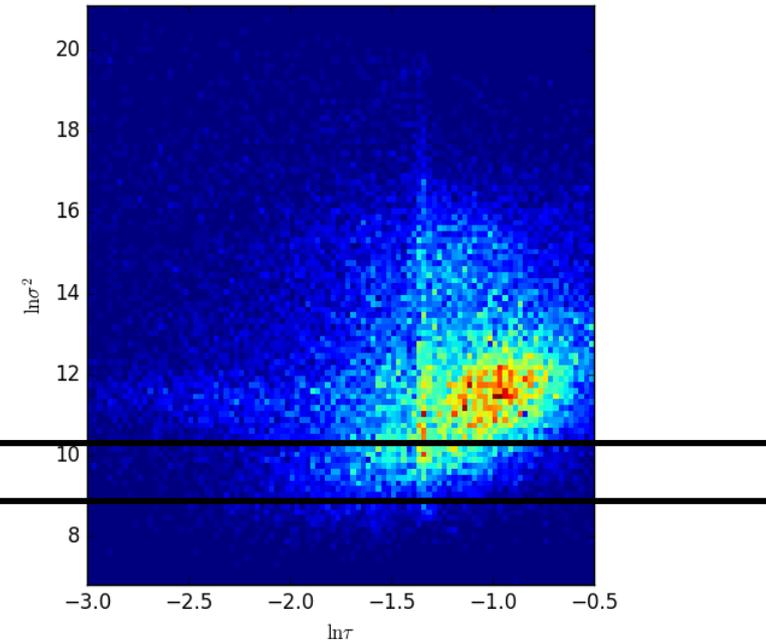
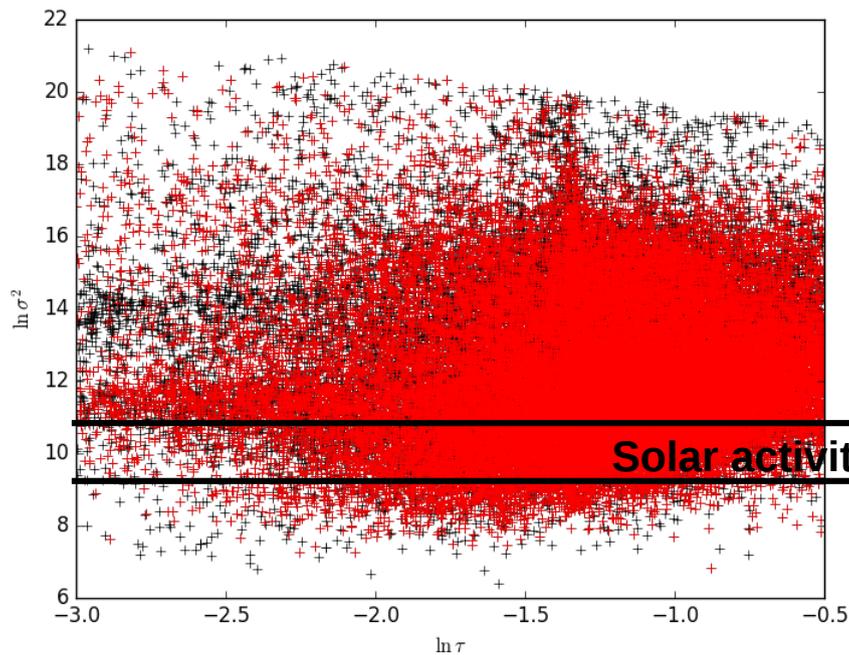
Histogram of the magnetic activity amplitude ($\ln \sigma^2$)

For ~ 51,000 Kepler targets



Comparison with the standard deviation of the light-curves, S_{ph} as measured by Garcia+ 2014 on 310 Kepler targets

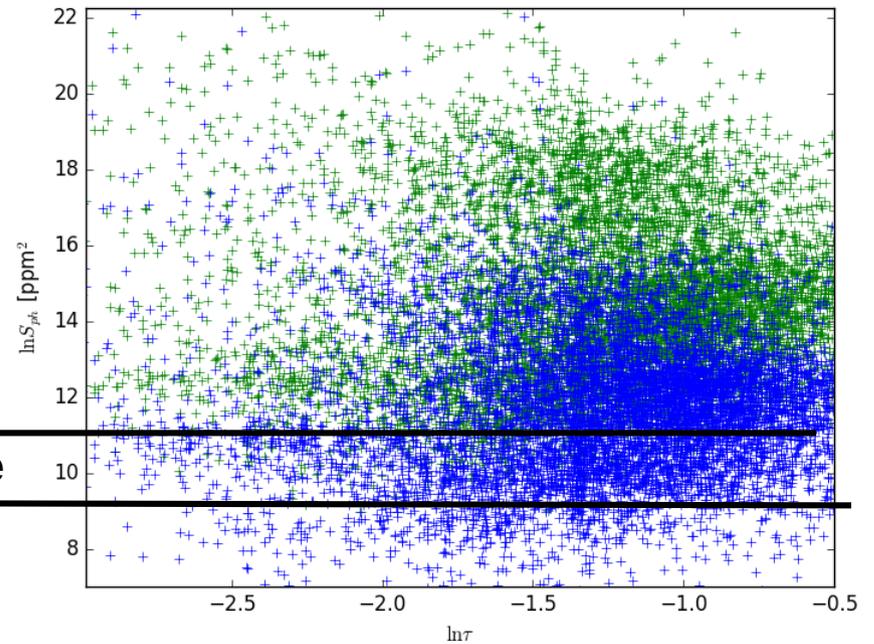
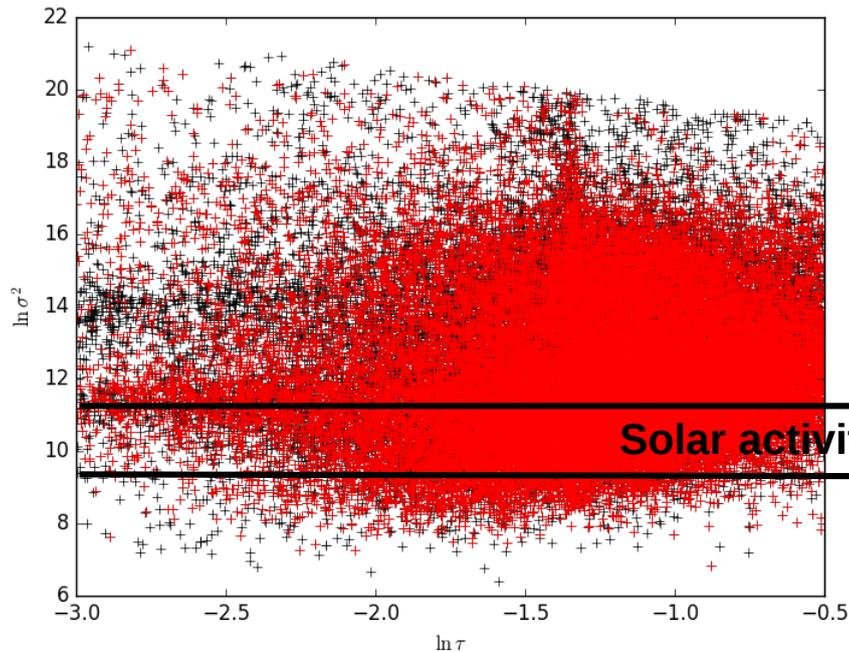
Prescription for the magnetic activity parameters



In **red**: FGK dwarf and sub-giant stars identified with GAIA DR2

Median value of σ almost constant with τ but dispersion increases with τ .

Prescription for the magnetic activity parameters



Blue: minimum values of S_{ph} **Green:** maximum values of S_{ph}

→ Dispersion can very likely be explained by activity cycles

Two prescriptions: one for the minimum, the second for the maximum of activity

Conclusion and perspectives

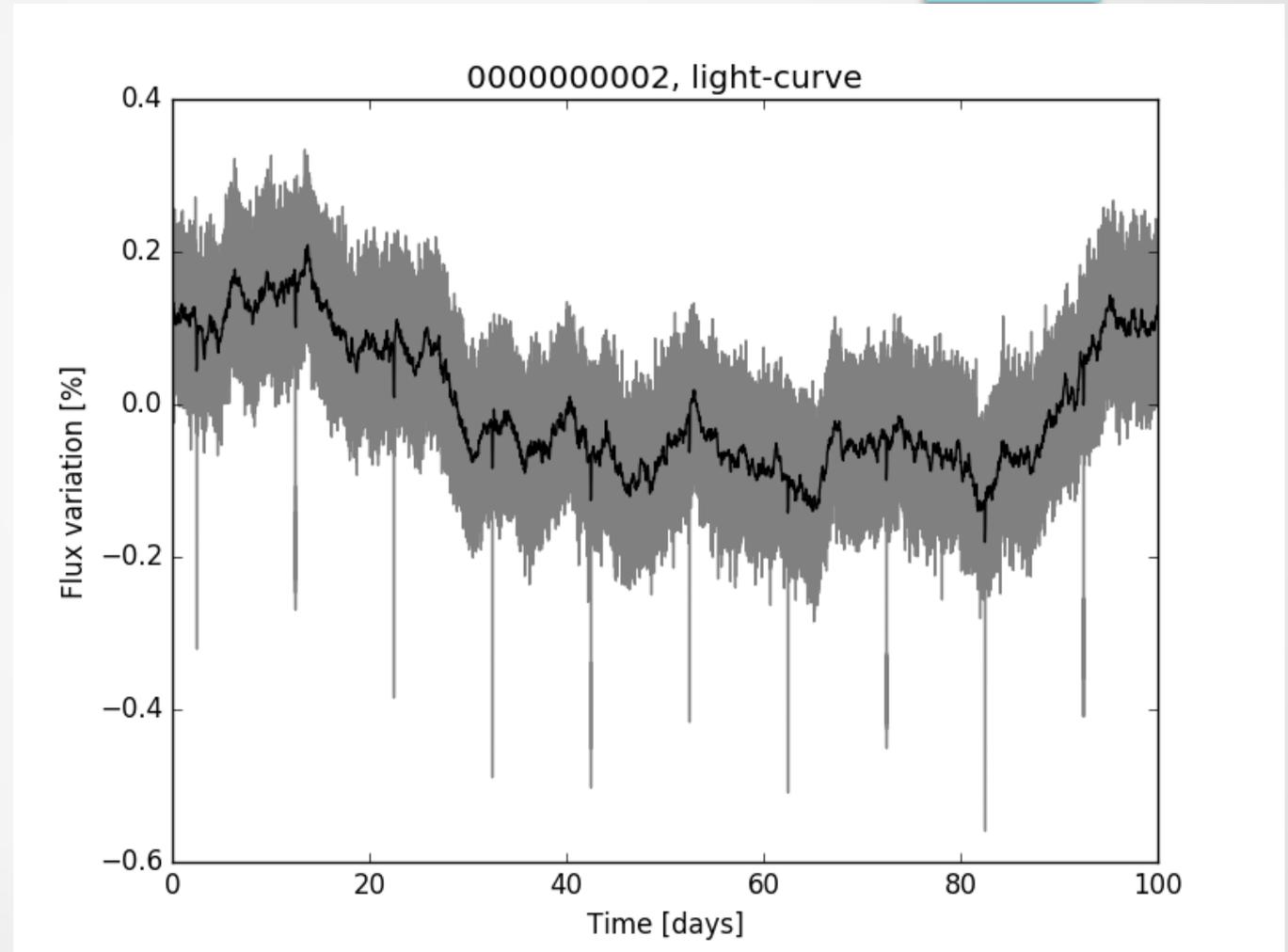
- Easy to install and use, fast
- Free access (<https://psls.lesia.obspm.fr/>)
- A paper in preparation: Samadi et al

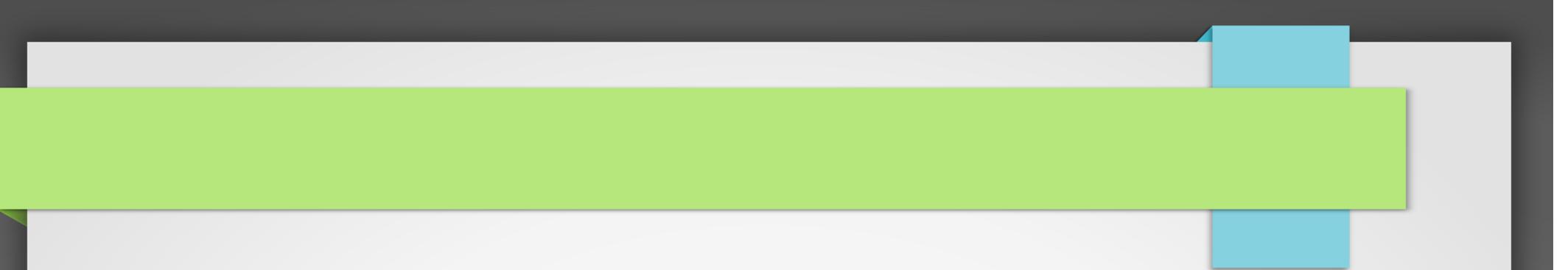
TODO list:

- More realistic mode line-widths variation with frequency (e.g. results from non-adiabatic calculations) ;
- Prescription for the parameters of the activity and instrumental components ;
- Inclusion of spot modelling (collaboration with Cilia Damani and co)
- Inclusion of possible instrumental periodic perturbations ;
- Account for mask photometry as generated on-board (as function of the star position and intensity) ;
- Simulation of independent camera (different PSF/FoV).

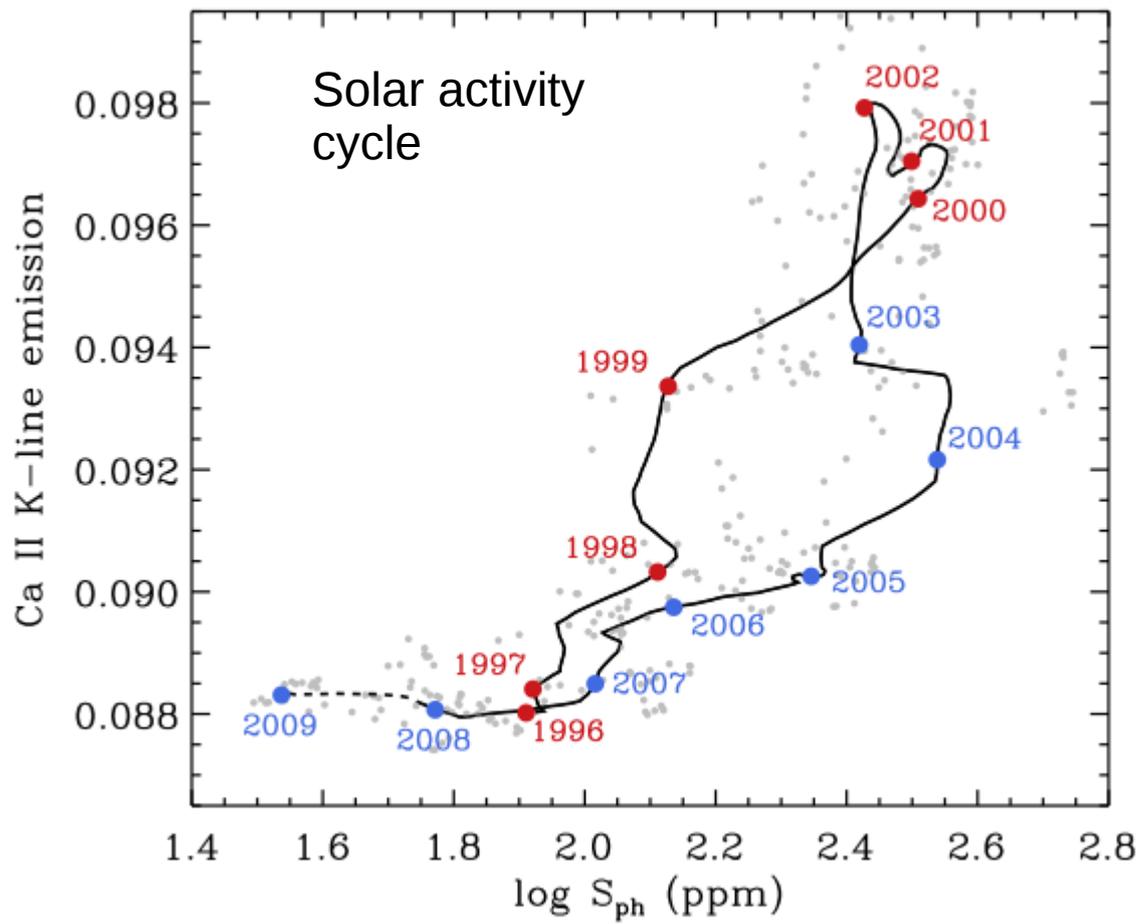
Illustration

Simulated light-curve with the presence of a planetary transit, following Mandel & Agol (2002) equations



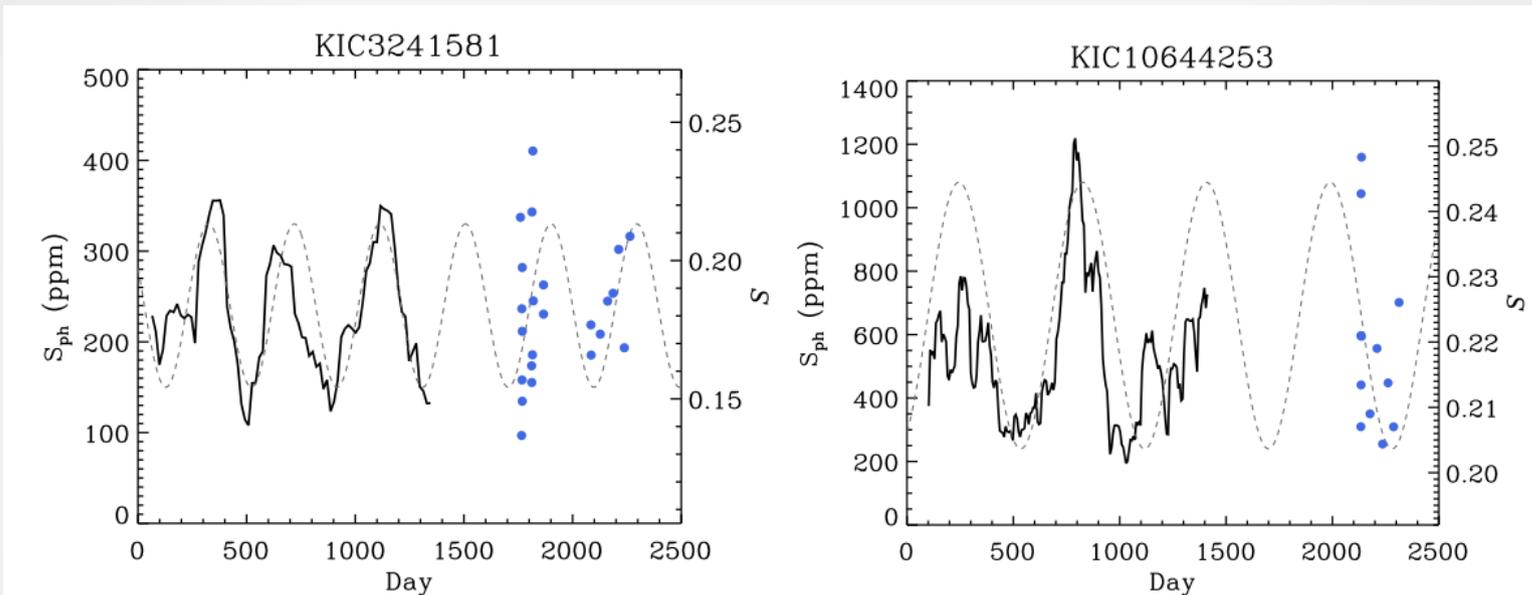


Additional slides



Salabert et al (2016)

R. Samadi, The PLATO Solar-Like Light Curve Simulator, STESCI Workshop Milazzo, 22-25 May 2018



Salabert et al (2016)

Variation of the Sph index can be high (here a factor ~ 4)

Some references, similar simulators

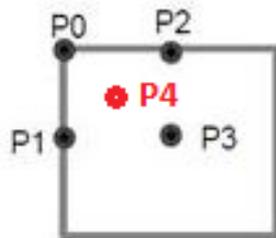
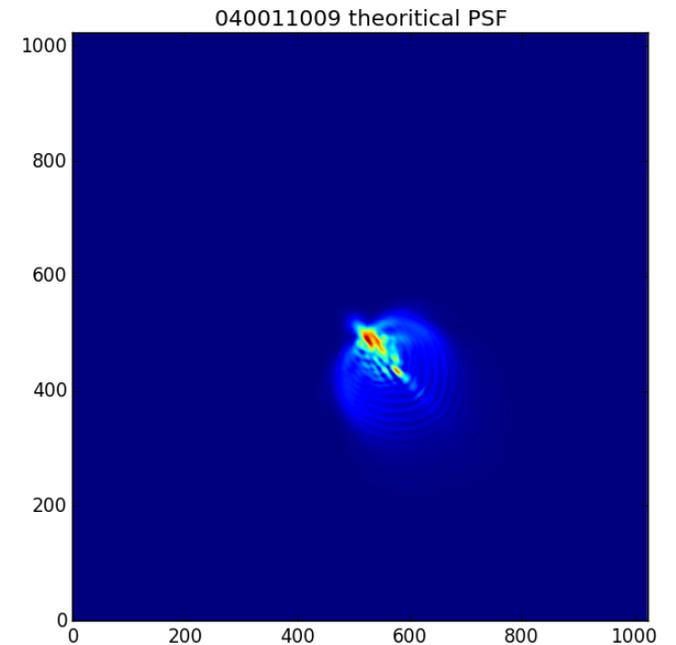
- “Simu-LC : a Light-Curve simulator for CoRoT”, Baudin et al, 2006, The Corot book, ESA SP 1306
- “Modelling space-based high-precision photometry for asteroseismic applications”, de Ridder et al, 2006, MNRAS

Systematic analysis, by A. Deru, LESIA, France

To evaluate the systematics residues for different position/magnitude

Light curve simulations performed with the PLATO Image Simulator (PIS) :

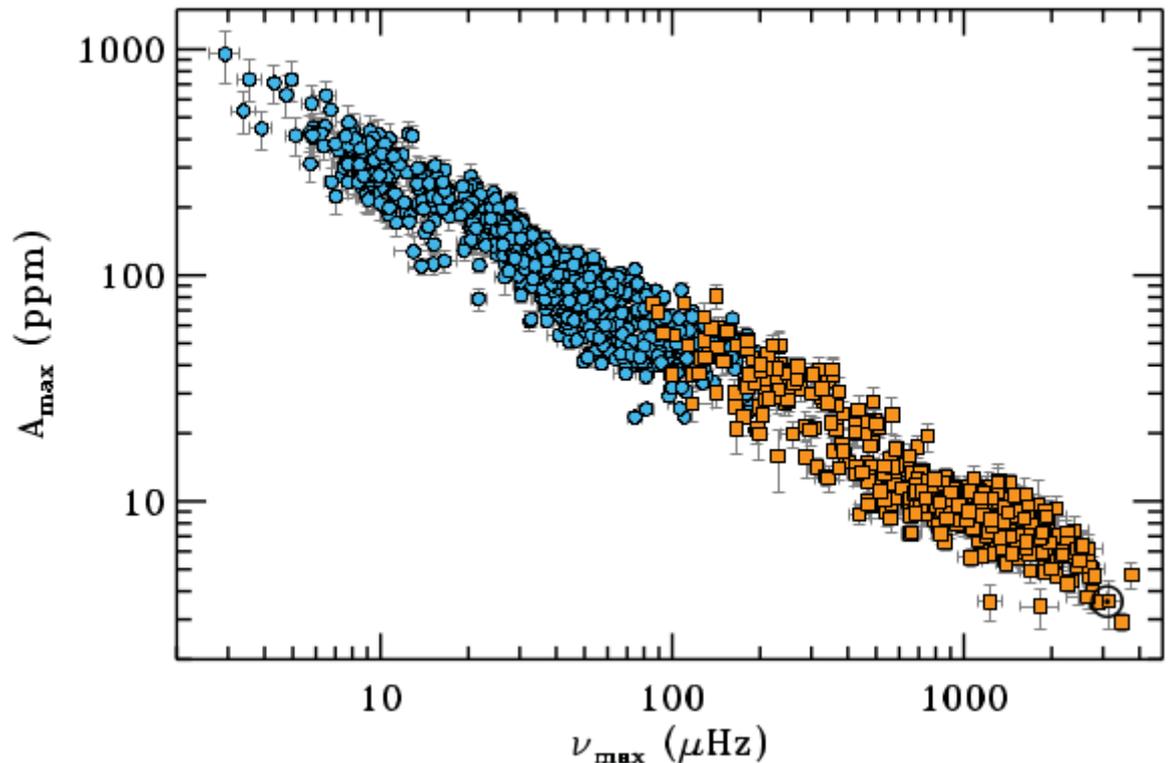
- 9 magnitudes, from 9 to 13 by step of 0.5
- 14 angular positions from 1.41° to 18.9°
- 5 intra pixel positions
- 90 days simulation
- Without random noises (readout and photon noises)
- PRNU and IPRNU 1%
- Linear long term drift + DKA 0,5 pixel in 3 months
- Medium periodic perturbation: triangular 14h
- Mask updated every 0,015 pixel
- PSF September 2017 "real" with alignment error
- No CTI effect
- No BFE effect
- 3 MHz electronics
- 21 sec of exposure time.



Positions on a CCD pixel

Observational scaling relation of mode amplitudes

Corsaro et al (2013)



$$\ln \left(\frac{A_{\text{bol}}^{(3)}}{A_{\text{bol},\odot}} \right) = (2s - 3t) \ln \left(\frac{\nu_{\text{max}}}{\nu_{\text{max},\odot}} \right) + (4t - 4s) \ln \left(\frac{\Delta\nu}{\Delta\nu_{\odot}} \right) \\ + (5s - 1.5t - r + 0.2) \ln \left(\frac{T_{\text{eff}}}{T_{\text{eff},\odot}} \right), \quad (43)$$

zoo, 22-25 May 2018