# A fully parametrized model of the activity pattern of a Solar-like star

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# I. The Sun as a case study for exoEarths detectability

## Stellar activity and low-mass planet detectability

| Observable | Future instruments | Expected accuracy | Earth-mass planet @ 1 au | Solar activity amplitudes | |
|---|---|---|---|---|---|
| Radial velocity (RV) | Espresso/VLT Hires/E-ELT | 0.1 m/s | 0.09 m/s | 12 m/s (full cycle) | 0.5-1.5 m/s (Prot) |
| Astrometry | Neat | 0.05 µas | 0.33 µas | 0.05-0.1 µas | |
| Photometry | Tess, Cheops, Plato | $10^{-5}$ | $10^{-4}$ | $10^{-3}$ (full cycle) | A few $10^{-3}$ (Prot) |

- Increased accuracy : search for very low-mass planets allowed
- Major obstacle : **stellar 'magnetic' activity** : dark spots and bright features (plages+network)

  1-day to 1-decade timescale

  Impact on both **radial velocity (RV)**, astrometry, photometry
- For a given signal, two challenges :

  1. to distinguish between stellar noise and planetary signature
  2. if activity, how to correct it to find smaller planets

# I. The Sun as a case study for exoEarths detectability

## Current knowledge on stellar activity

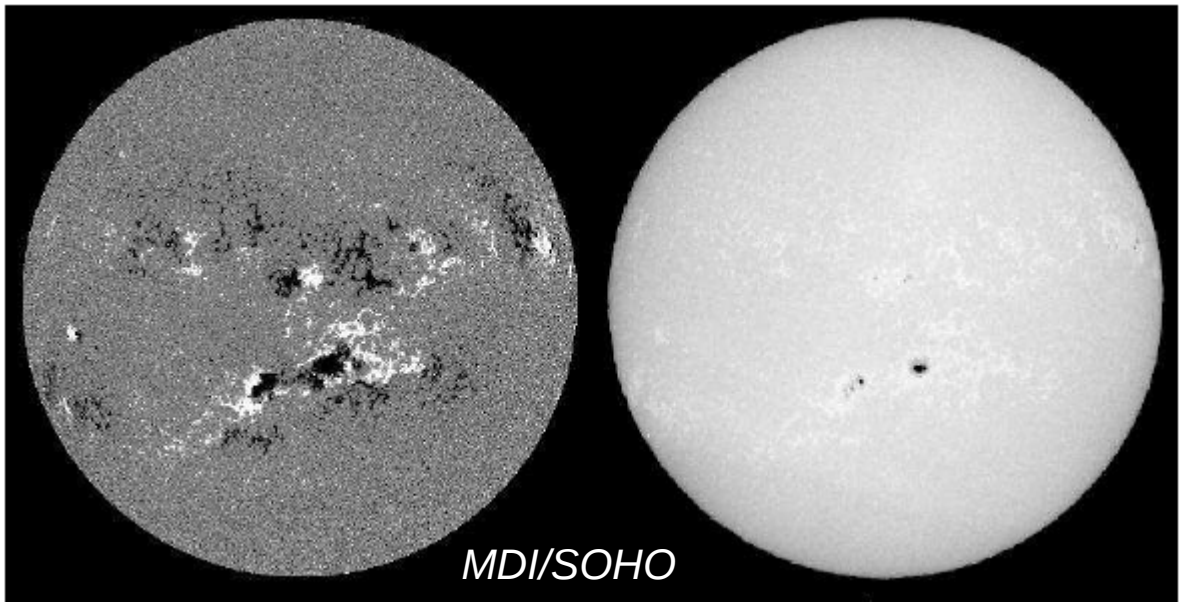
- **For most of stars** :
  - (+) indirect estimators : Ca index ; activity cycles
  - (-) active structures not directly observable, structure properties unknown
  - (-) convective inhibition level
- **Case of the Sun studied as a moderately active star :**
  - (++) observations of all structures (even the small ones)
  - (++) activity properties and active structures well described
- **An ideal prototype to study impact of activity on low-mass planets detectability**

**Is the Earth detectable when observing the Sun as a star?** **(Part II)**

**Can we use the Sun as a template to study other stars ?** **(Part III)**

# II. The Sun seen as a star

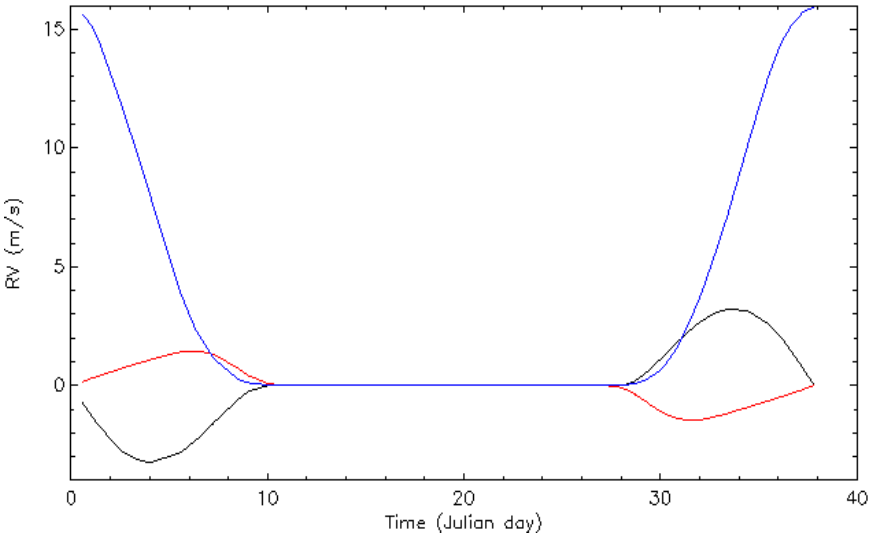
## 'Observational' Approach




- Instantaneous maps of solar activity pattern over full Cycle 23

  - dark spots from catalogs

  - bright features from MDI magnetograms (> 2M structures)




- Structure lists (daily time step, size, localization) : input to simulations
- Building spectra : solar spectrum +3 comp. (spots, bright features, attenuation of convective blueshift)
- Computing RV assuming an Espresso-like instrument
- Detection limits with noise and/or planets, periodograms

*(Lagrange et al. 2010, Meunier et al. 2010)*

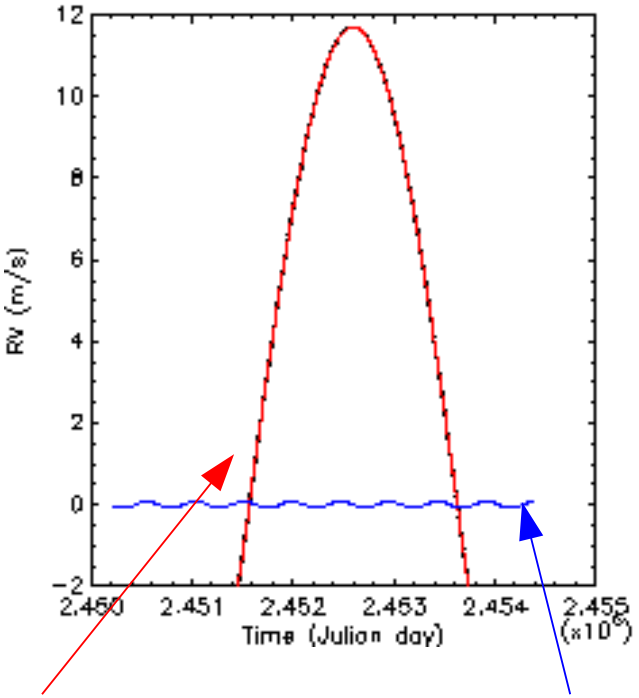
# II. The Sun seen as a star

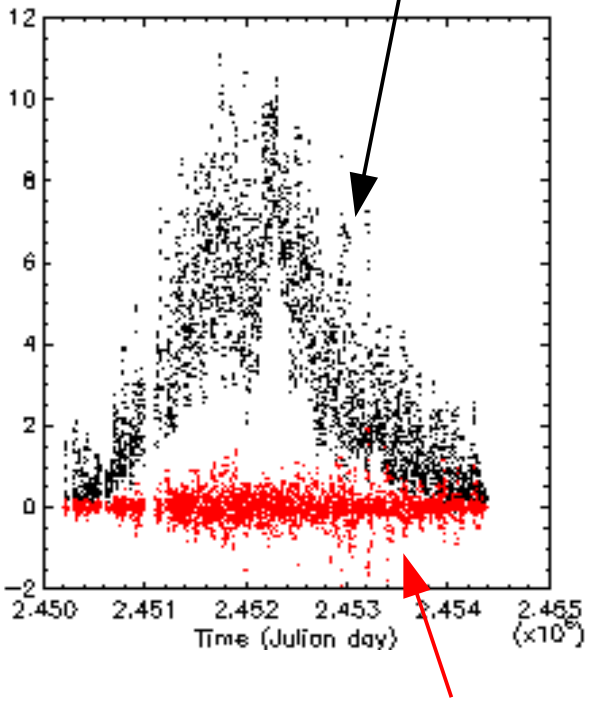
*Meunier et al. 2010*

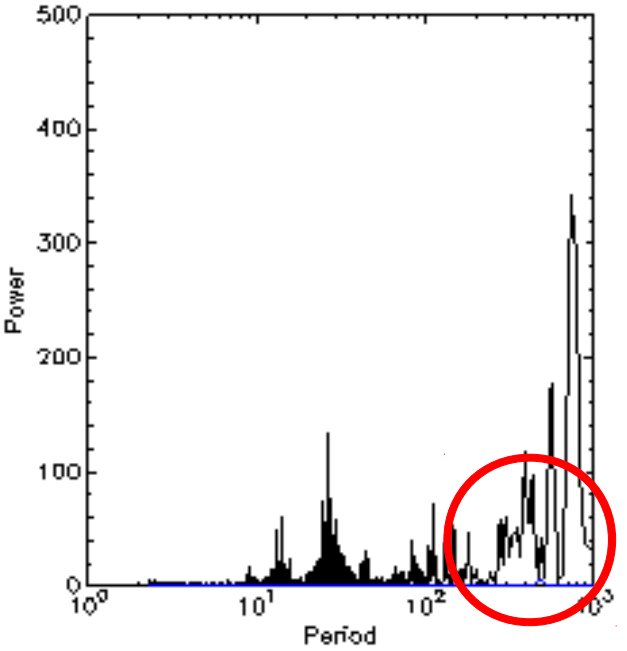
## Results : RV

- Attenuation of convective blueshift in active structures found dominant in case of RV

Spots, plages and convection
(rms 2.4 m/s)




1 Mjup planet
@ 5 au

1 Mearth planet
@ 1.2 au

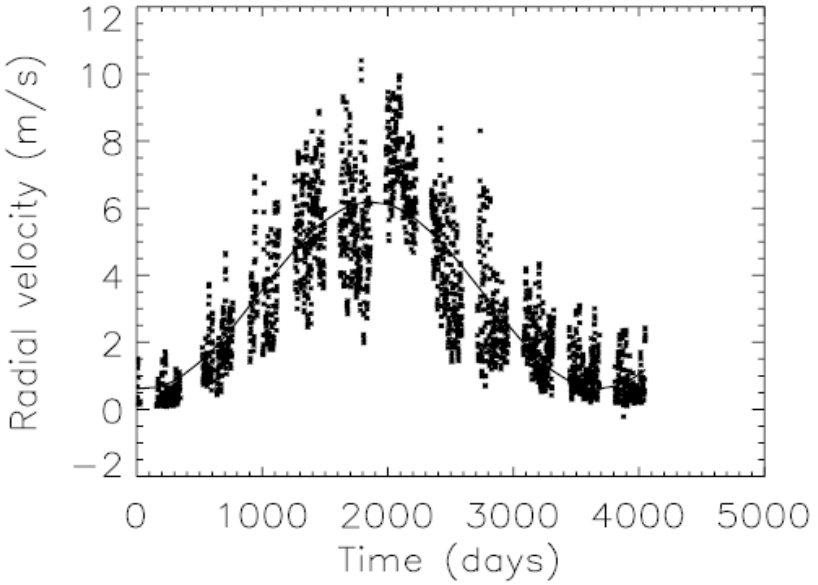
spots and plages
(rms 0.33 m/s)

- Detection limits : 1 Earth-mass planet @ 1.2 au ***not detectable*** when convection not corrected for

# Results : correcting for the convective signal

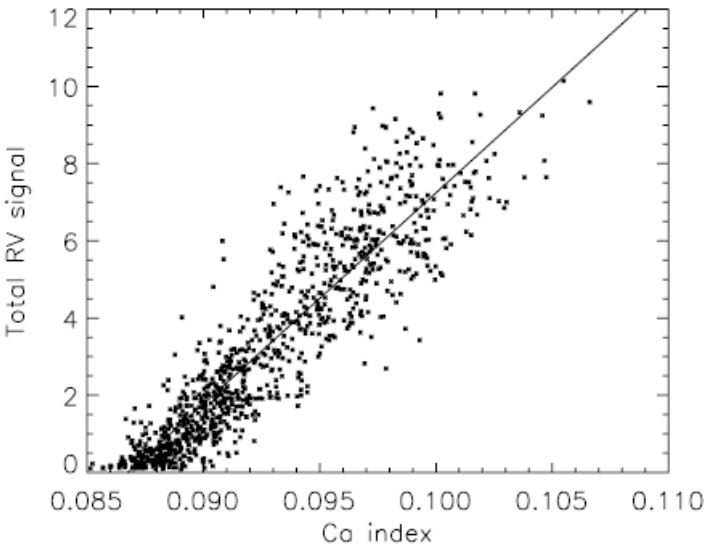
Strong correlation between convective RV and bright features filling factor
Correction using Ca index

1. Sinusoidal fit of Ca variations




RV rms before correction : 2.4 m/s
rms (o-c) : 1.3 – 1.5 m/s

2. Correlation of RV with Ca index




RV rms before correction : 2.4 m/s
rms (o-c) : 1.05 – 1.2 m/s

Impact on detection limits : 1 Mearth planet @ 1.2 au only reachable if excellent snr on Ca and excellent data sampling (typ. 1000 observations)



*Meunier et al. 2013*

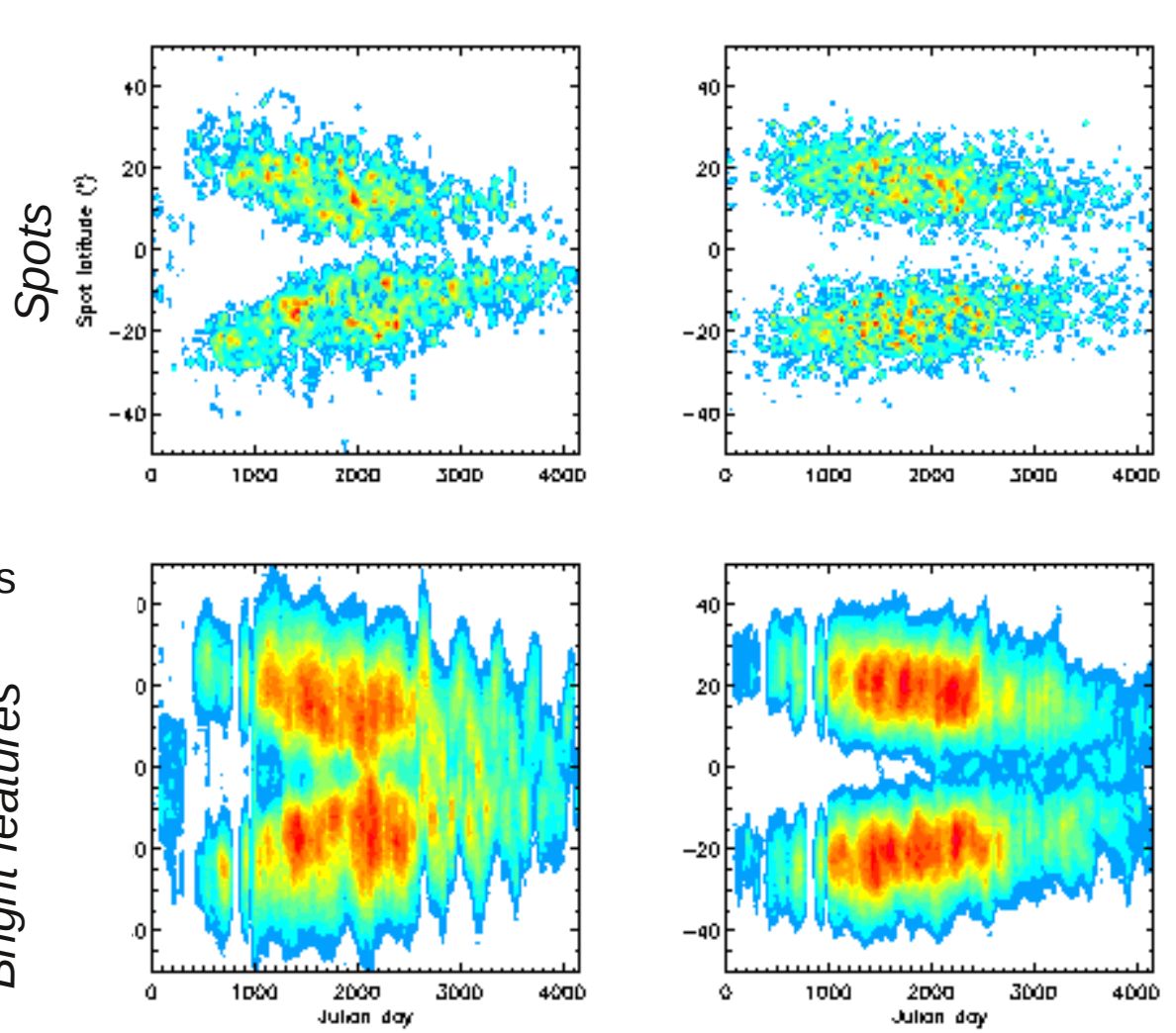
# III. The Sun as a template

## Parametric approach

- Activity pattern over a full solar cycle :

  need **~30 parameters**

  - **-** Global activity distribution
  - **-** Large scale dynamics
  - **-** Spatial/temporal structure distributions
  - - Individual structure behavior
  - - ~2M structures




- Parameters constrained with literature

  (from various solar obs.)

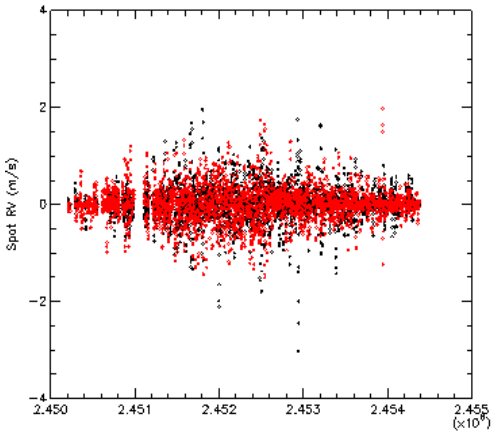
- Outputs : spot and bright feature lists (time step, size, localization)
- **Advantage : active structures over 360°** : study of stellar inclination impact

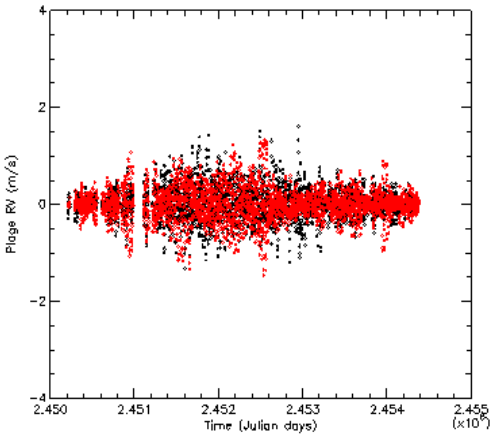
# III. The Sun as a template

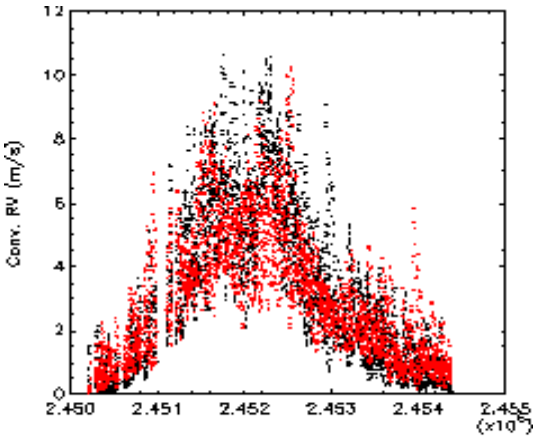
## Preliminary results : Validation of the approach

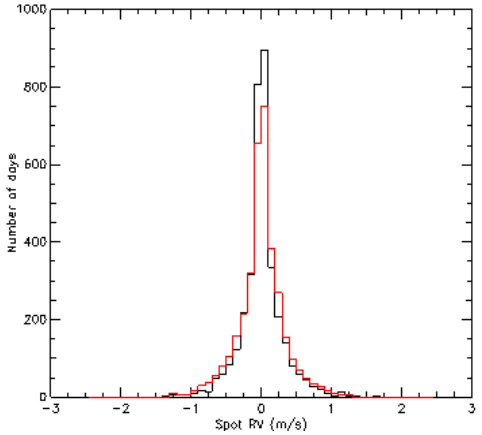
Structures : observed / simulated

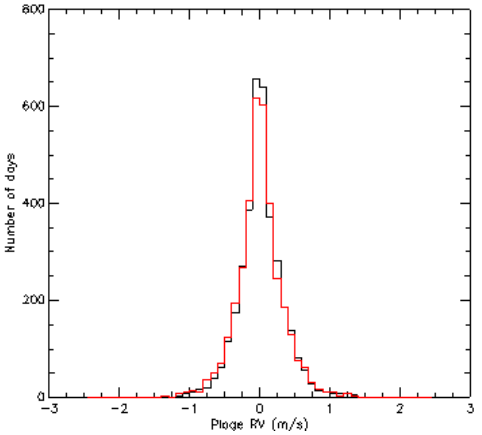
| | Spots : | Bright features : | Spots+bright features+conv. : |
|---|---|---|---|
| RV rms (m/s) | 0.34 – 0.34 | 0.31 – 0.32 | 2.40 – 2.00 |

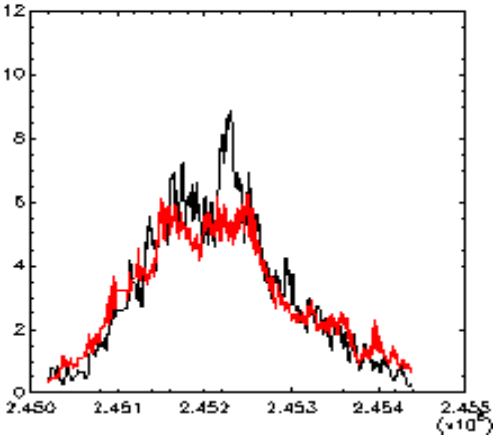


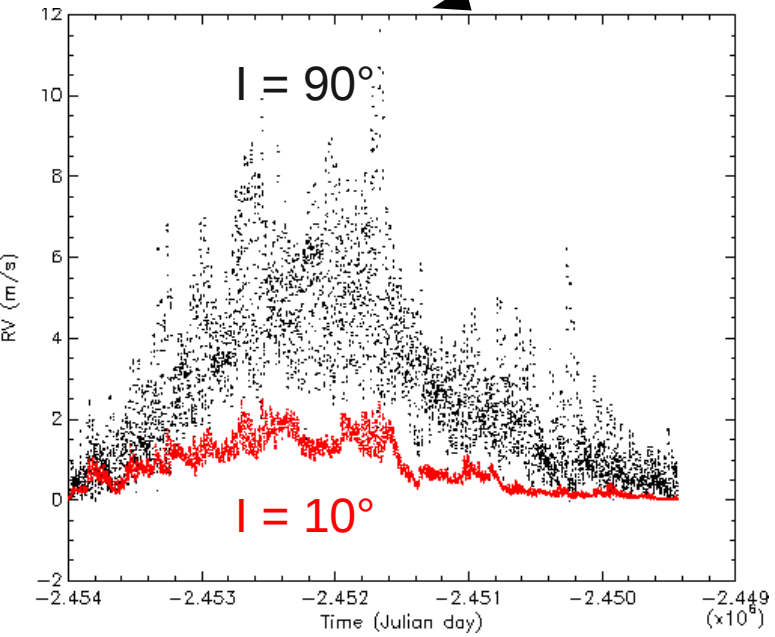



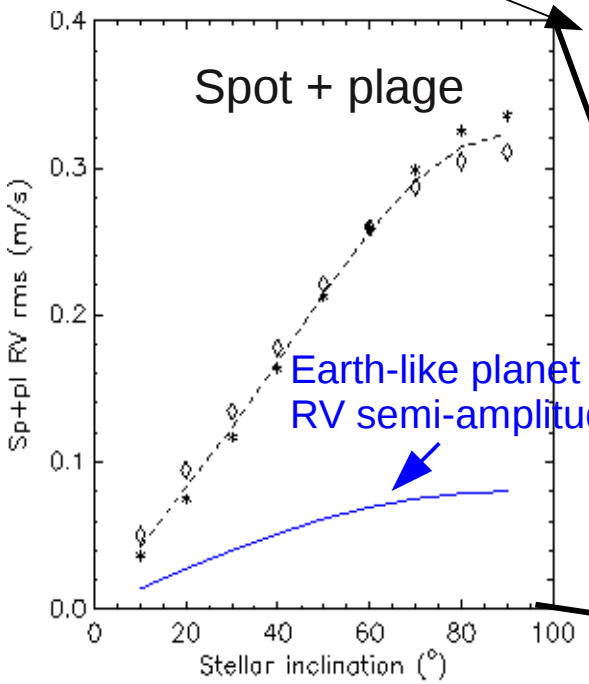



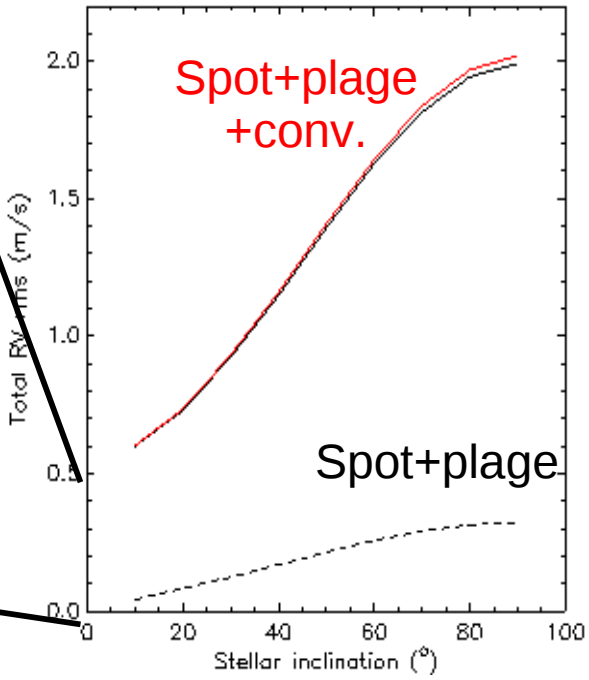
# III. The Sun as a template

## Preliminary results

- Impact of **stellar inclination** for a star with an 'activity belt' centered on the equator, assuming a convection inhibition level
- Decrease of both activity amplitude and dispersion with I.




**RMS still > 0.6 m/s for a nearly pole-on star**

- Impact of rotational velocity on RV: linear in the range 1.5-12 km/s
- Impact of convection inhibition level on RV: linear in the range 50-300 m/s

# IV. Summary and Prospects

**Using the Sun to study the detectability of low-mass planets**

- **Is the Earth detectable when observing the Sun ?**

  - Inhibition of convective blueshift dominant in stellar noise for the Sun

  - Earth-mass planets detectable with RV only under very good (exceptional?) circumstances : dedicated telescope very valuable

- **Can we use the Sun as a template ?** (*work in progress)*

  - RV rms decreased by 1/3 from 90° to 10° inclination

  - Impact of rotational velocity on RV : linear in the range 1.5-12 km/s

  - Impact of convective inhibition level on RV : linear in the range 50-300 m/s

- **Perspectives**

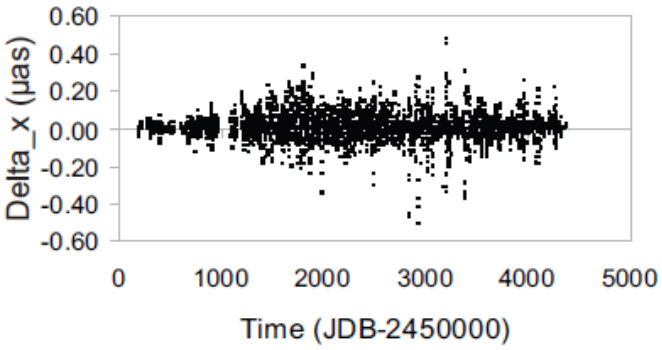
  - Application to other stars, other activity levels and other activity properties

  - Combination of different observables (RV, astrometry, photometry) essential

  - Application to astrometry (participation to the NEAT double blind-test)

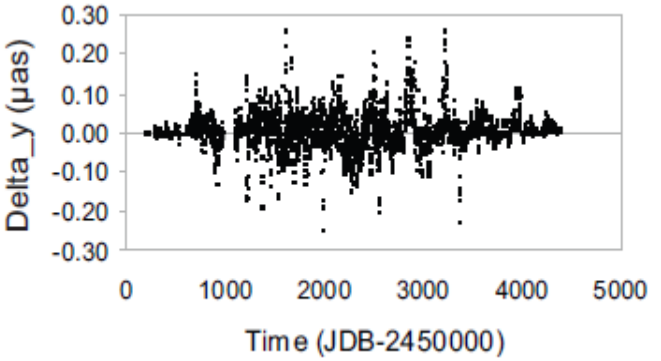
Thank you !

# Astrometry




Astrometric shifts along (Δx) and ⊥ (Δy) to the equatorial plane :

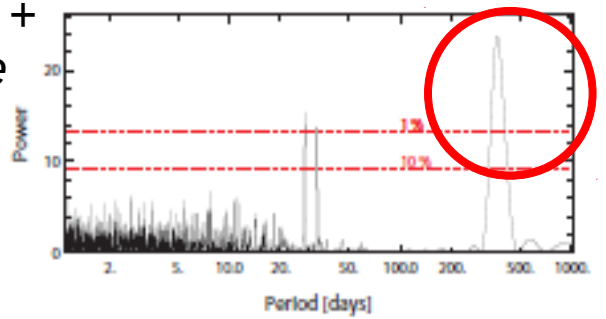
- **0.07 µas** average dispersion (over full cycle)



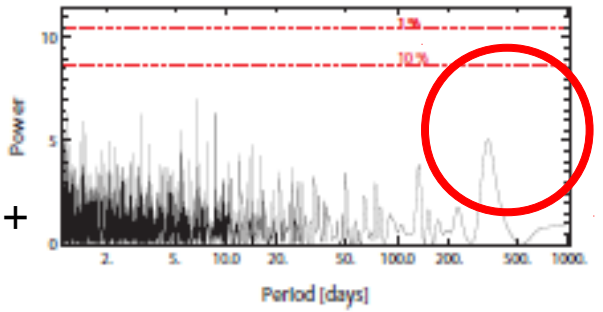

Detection limits:

Earth-mass planet @ 1.2 au (edge-on)
- **0.33 µas** shift on Δx
- detectable in most of the cases

*Low activity + added noise*




*High activity + added noise*




Interest of combining astrometry and RV

*Lagrange et al. 2011*