Astrometric detection limits in the habitable zone of nearby stars due to stellar variability

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Outline

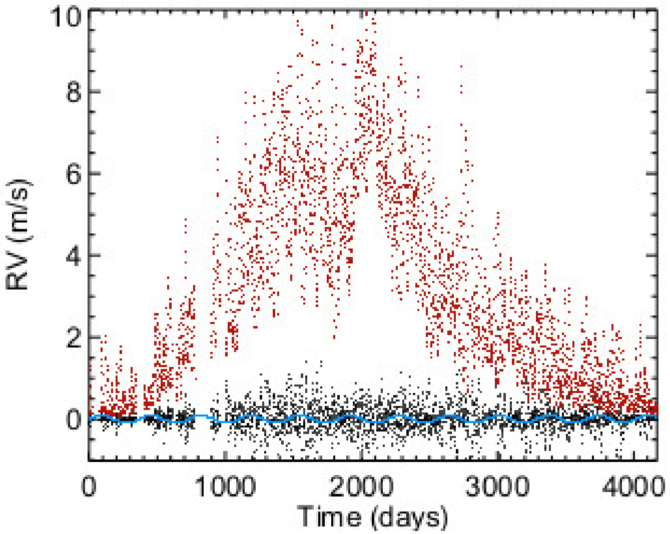
- Challenge with indirect methods, especially RVs
- Our general approach
  - Building realistic time series in RVs and astrometry
  - Blind tests
- Results
  - Blind tests RV vs astrometry
  - Detection limits for stars in the neighbourhood
  - Dedicated time series α Cen A and B

Facing a ~1m/s barrier with RVs…

Radial velocity
Astrometry
Photometric transit

Indirect methods

Impacted by stellar activity

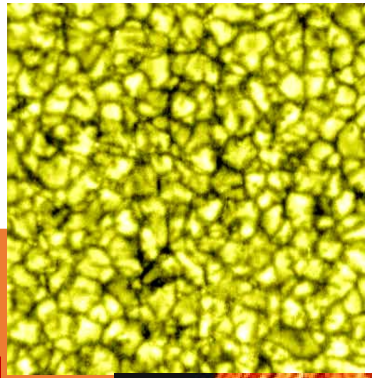


<10 cm/s

Meunier+ 10

The challenge: main processes impacting RVs for solar-type stars

Pic du Midi Obs.



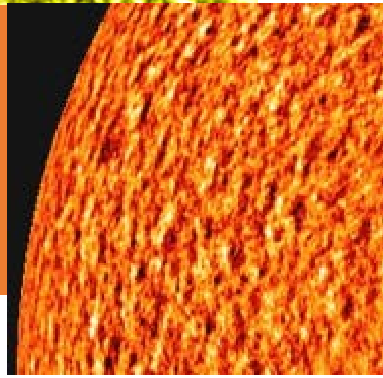
Photospheric flows

→ Oscillations

→ Granulation *0.4 m/s, minutes +*

→ Supergranulation *0.7 m/s, day +*

→ Meridional circulation *Ampl 1-2 m/s, cycle*



MDI/SOHO

Magnetic structures

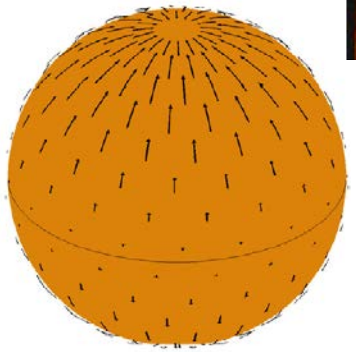
→ Spot and plage contrasts

0.3-0.4 m/s Prot+cycle modulation

Magnetism + flows

→Convective blueshift inhibition in plages

Ampl 8 m/s, Prot+cycle



Makarov+10

See review Meunier 2021, 2023 in press

Our approach

From the Sun to other stars

Characterisation of specific processes impacting RVs

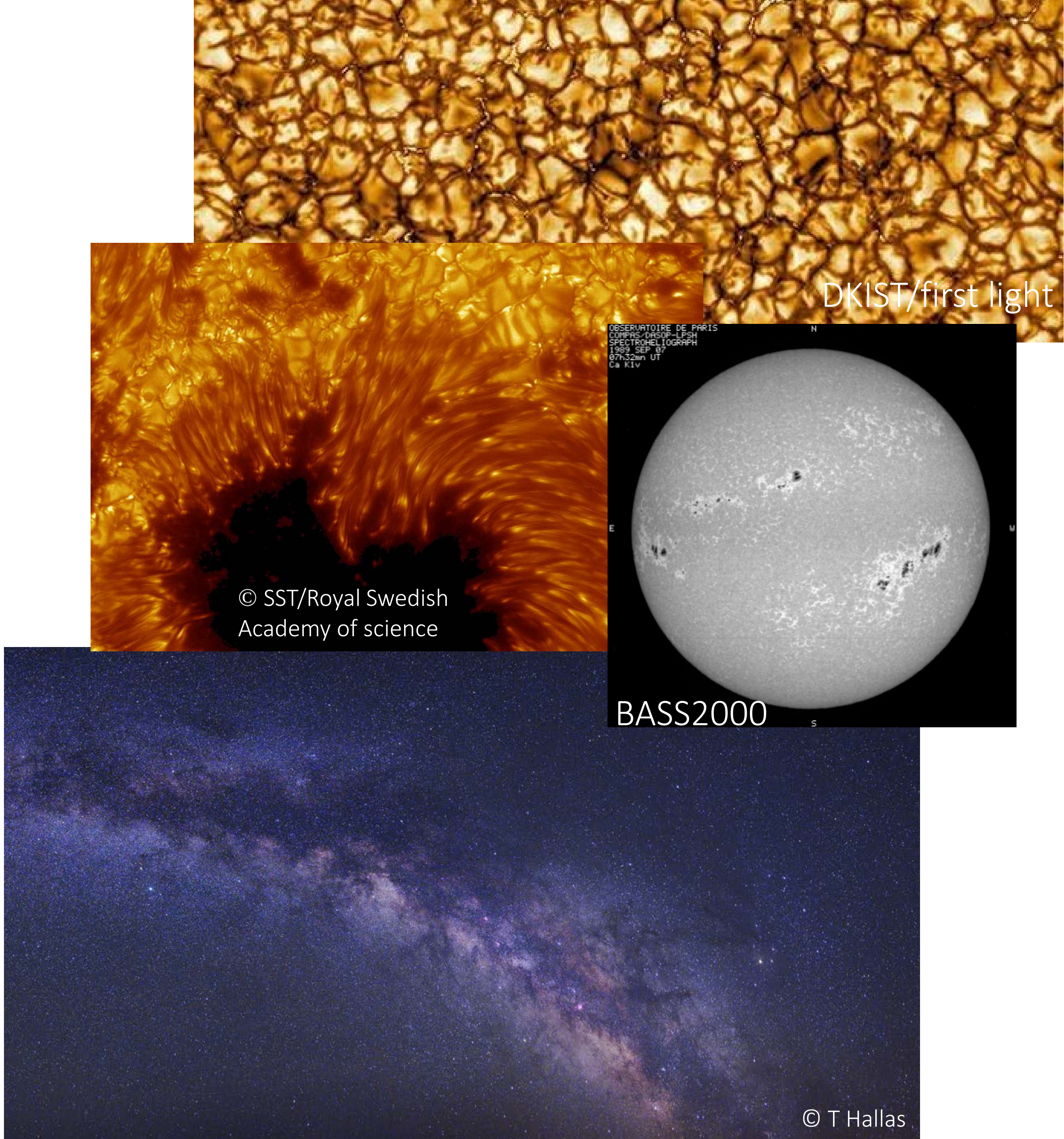
Building of synthetic time series

✓Complex magnetic activity patterns

✓Planet-free synthetic time series

✓Systematic approach (parameter space, performance estimation)

→ Blind tests on large set of time series

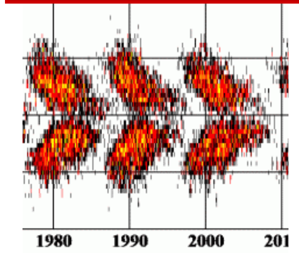


Simulation parameters from empirical laws

List of structures vs. t

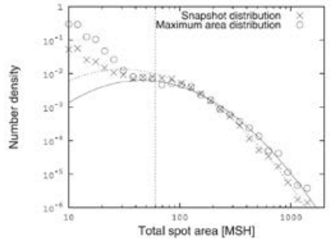
Consistent description *spots+plages+ network*

Spatio-temporal distribution



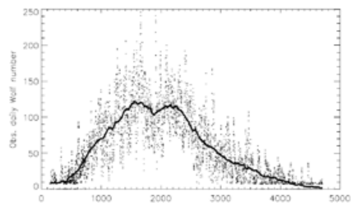
Butterfly diagram & maximum latitude, active longitudes

Size distributions ...



Size, decay, Spot/plage size ratio, Plage to network ratio

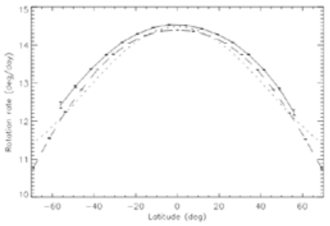
Long-term variability



Cycle length, Amplitude, shape

Dynamics

Prot, differential rotation, meridional circulation, diffusion



Time series *(analytical)*

RV, Photometry, Astrometry, LogR'$_{HK}$

Contrasts
(Photometry, RV, astrometry)
Spots, plages

Convective blueshift in plages (RV)
Amplitude, attenuation factor

Borgniet+ 15

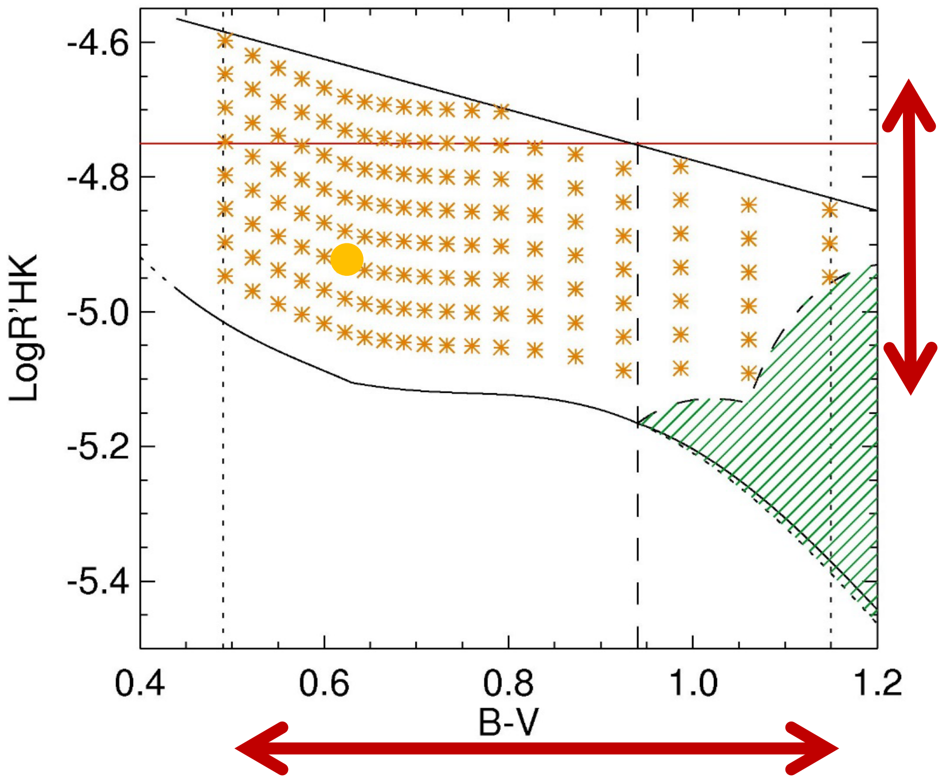
Extension to solar type stars

Coherent sets of parameters

- Parameters depending on B-V and/or $\log R'_{HK}$
- Range of parameters covered for each point

>11000 independent time series

X 10 inclinaisons



F6-K4

Based on published laws
Details in Meunier+ 19

Grid parameters : rotation period, cycle period, cycle amplitude, latitudinal coverage, spot contrasts + laws for plage contrast, convective blueshift vs. spectral type

Quantifying performance with blind tests

Large set of **realistic synthetic time-series**

- Planet-free
- Possible to choose temporal sampling and add noise + **planet**
- Model to correct for stellar activity (non-linear function of $\log R'_{HK}$ and cycle phase) → RV only

Follow-up of a transit detection (RV)

Mass estimation
Uncertainty

Search for planets (RV / astrometry)

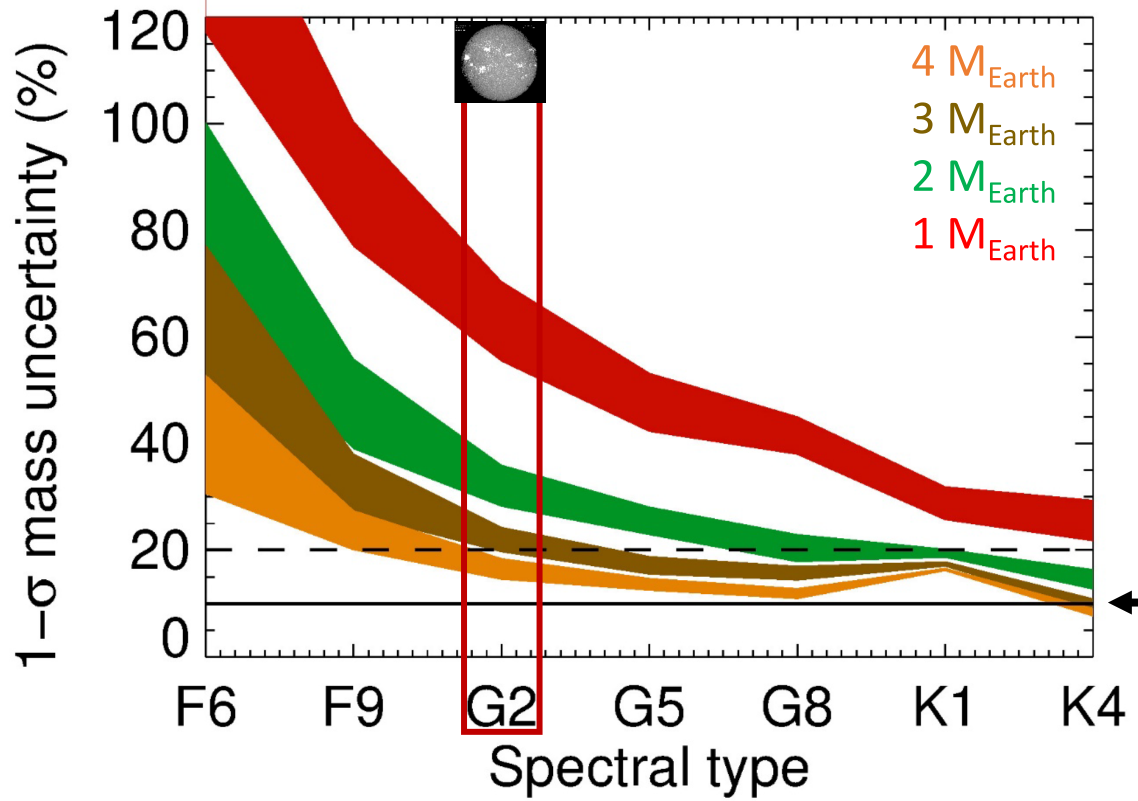
Good detection rates
Wrong detection rates
False positive rates

Recent RV results

1000 nights / 10 years

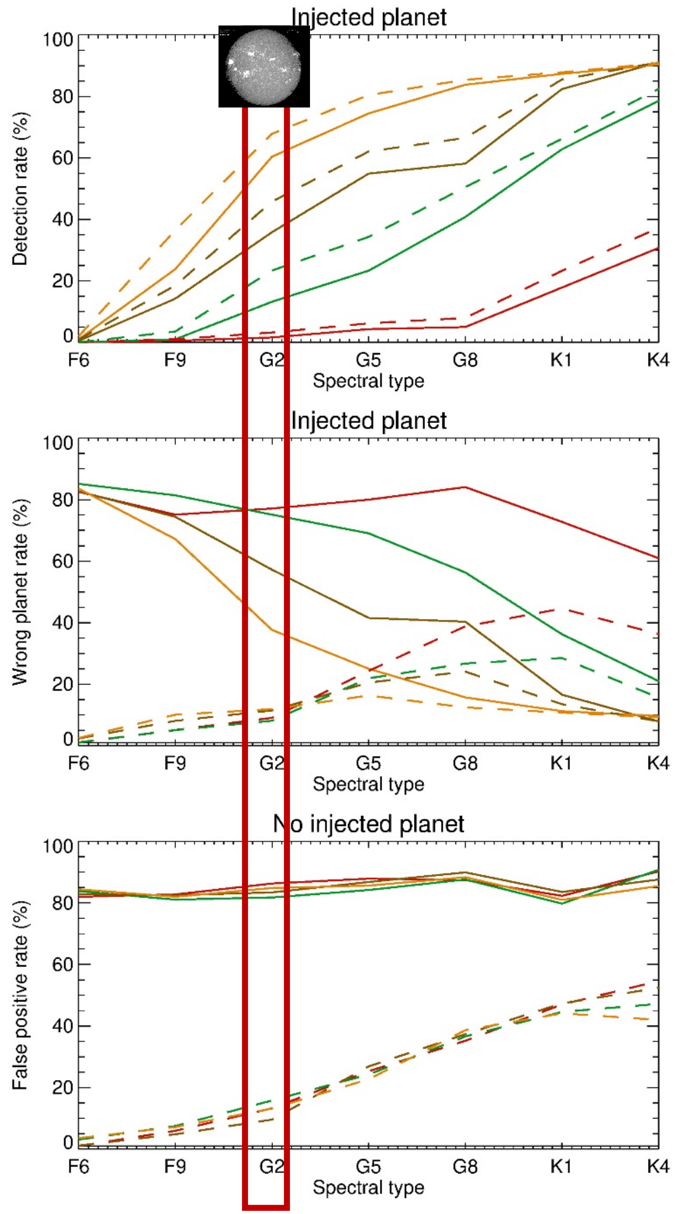
Very difficult to reach Earth analogues in the habitable zone around solar type stars

Middle of habitable zone



Meunier+23, accepted in A&A

PLATO Objective



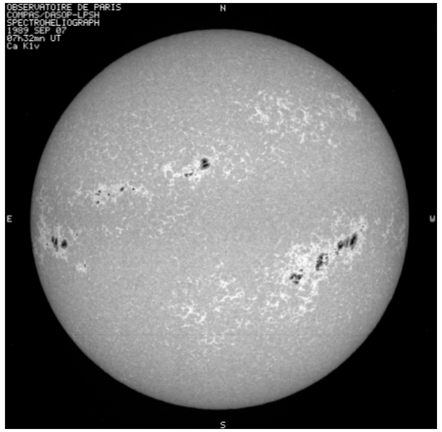
4 M_{Earth}
3 M_{Earth}
2 M_{Earth}
1 M_{Earth}

Our first for high precision astrometry

For a star @ 10pc 1 M_{Earth}, habitable zone

Solar jitter @10pc
- ✓ Makarov+ 10 0.052 ; 0.039 µas
- ✓ Lagrange+11 0.07 ; 0.05 µas

Compared to Earth signal 0.3 µas



Spot+plage intensity contrast contribution
No correction

Based on the observational strategy Theia coll., Boehm+17
→50 visits over 3.5 y, 0.2 µarcsec/meas.

Blind tests, fap at 1%

σ < 20% on the mass

Very good dectection rates → only 10-20% missed planets

Extremely low false positive & wrong planet levels < 0.1% in the HZ

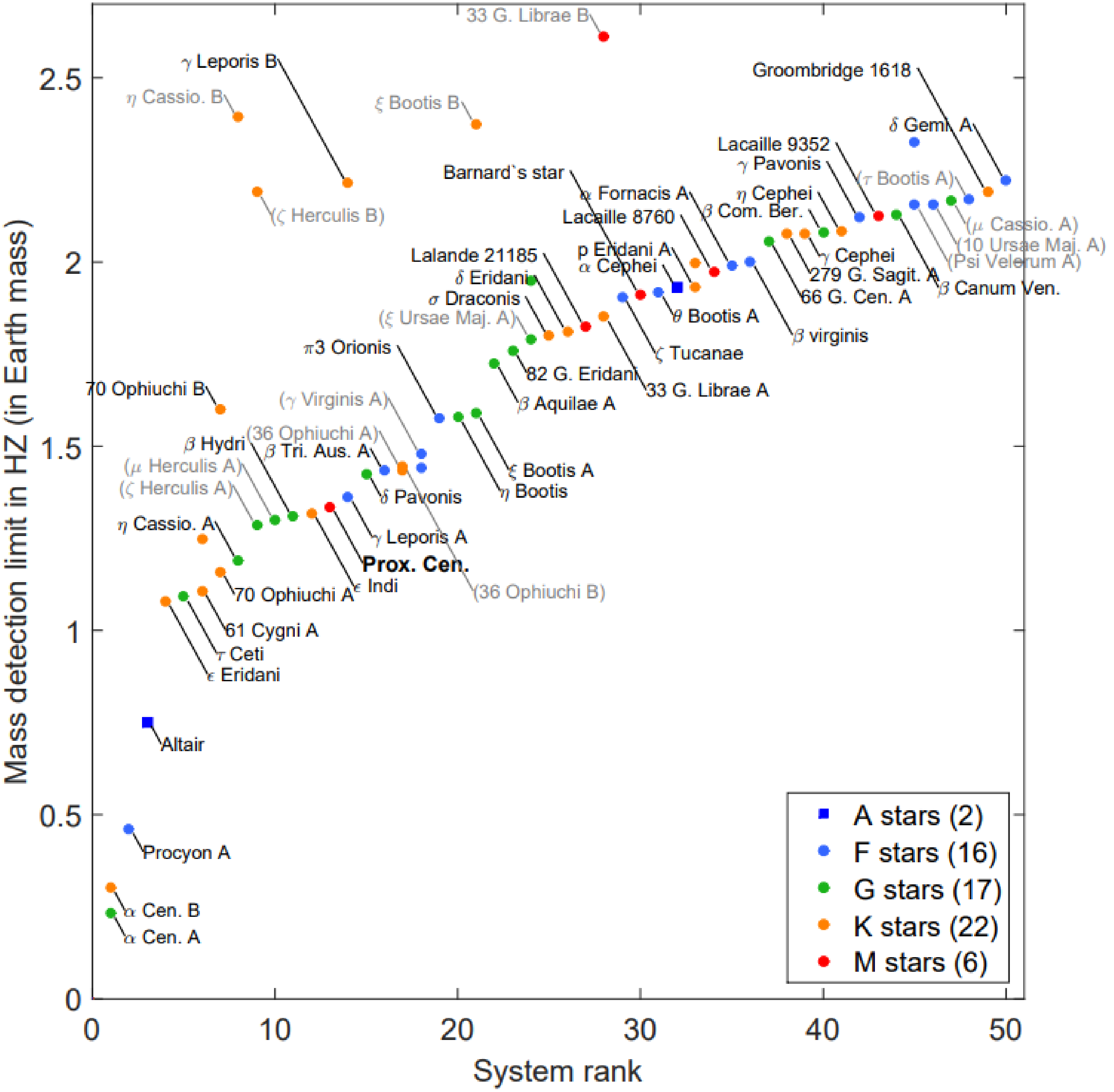
Meunier+20

Promising targets in the solar neighbourhood

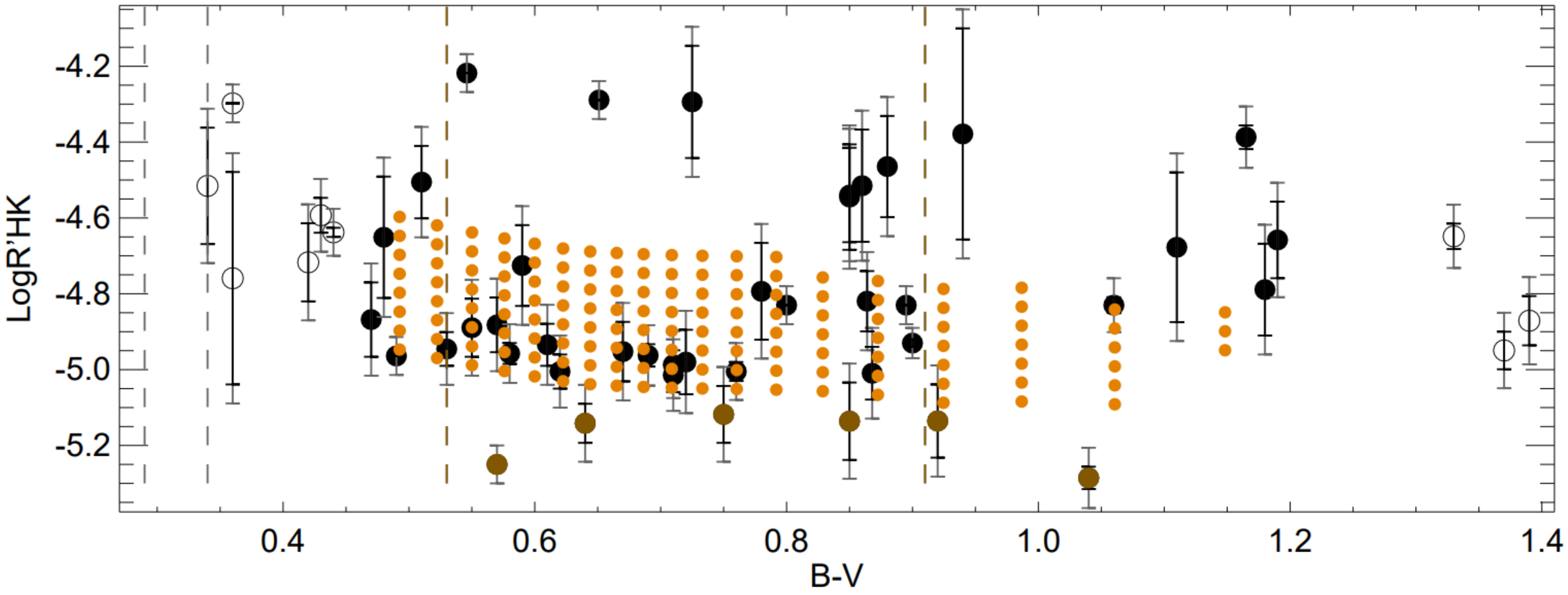
Theia Collaboration et al. 2017

Activity level based on a constant solar value from Lagrange et al 2011

- ✓ 55 F-G-K stars, including binaries and **α Cen A and B**
- ✓ 1.3-18.6 pc
- ✓ 45% are the A component of a binary system (22% = B component)



Identification of the closest simulations in our whole data set

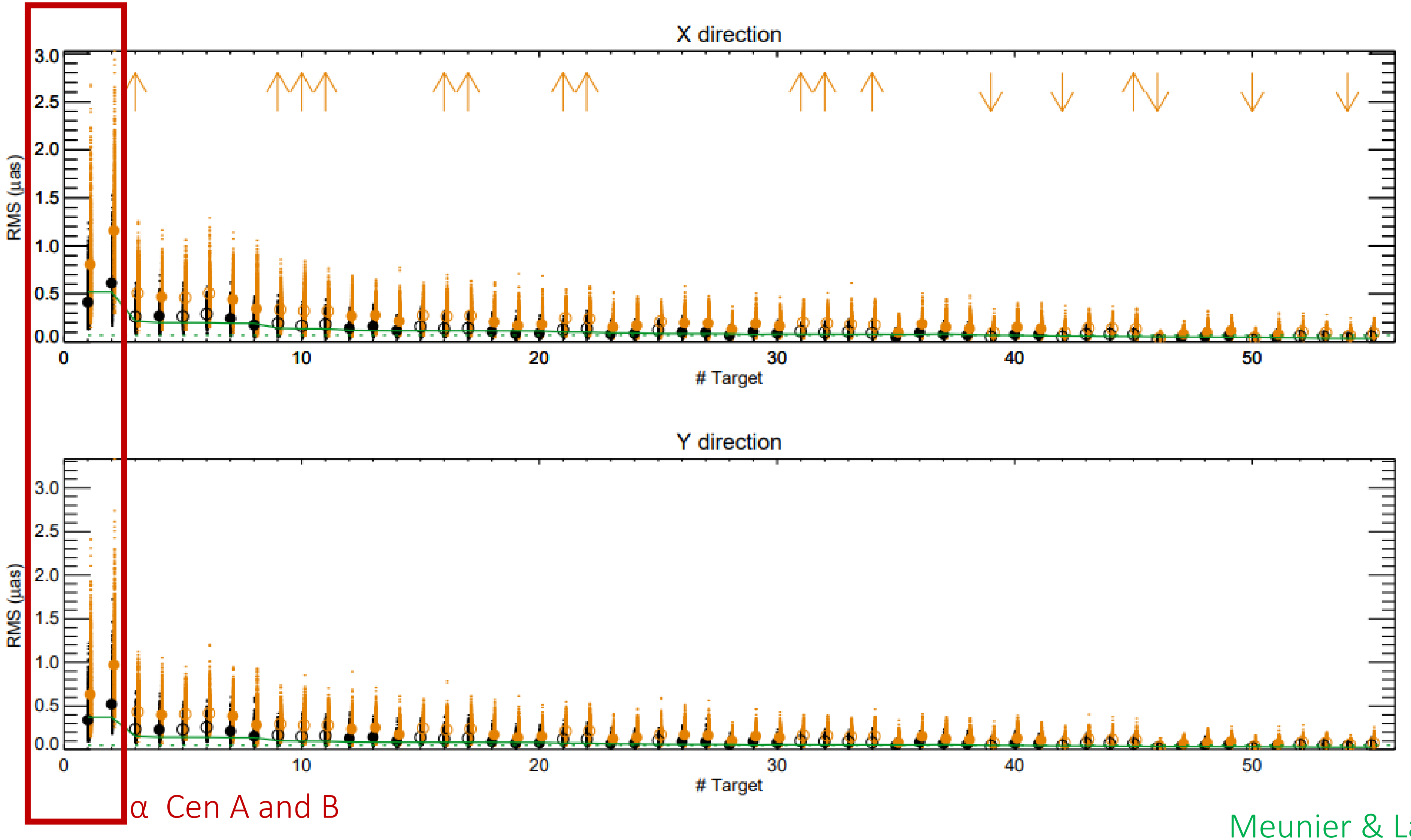


Based on **average LogR'HK** and **B-V** from the literature

Meunier & Lagrange 22

Rms of activity contribution in both directions

signal = mostly rotational modulation



In the direction of rotation

Along the rotation axis

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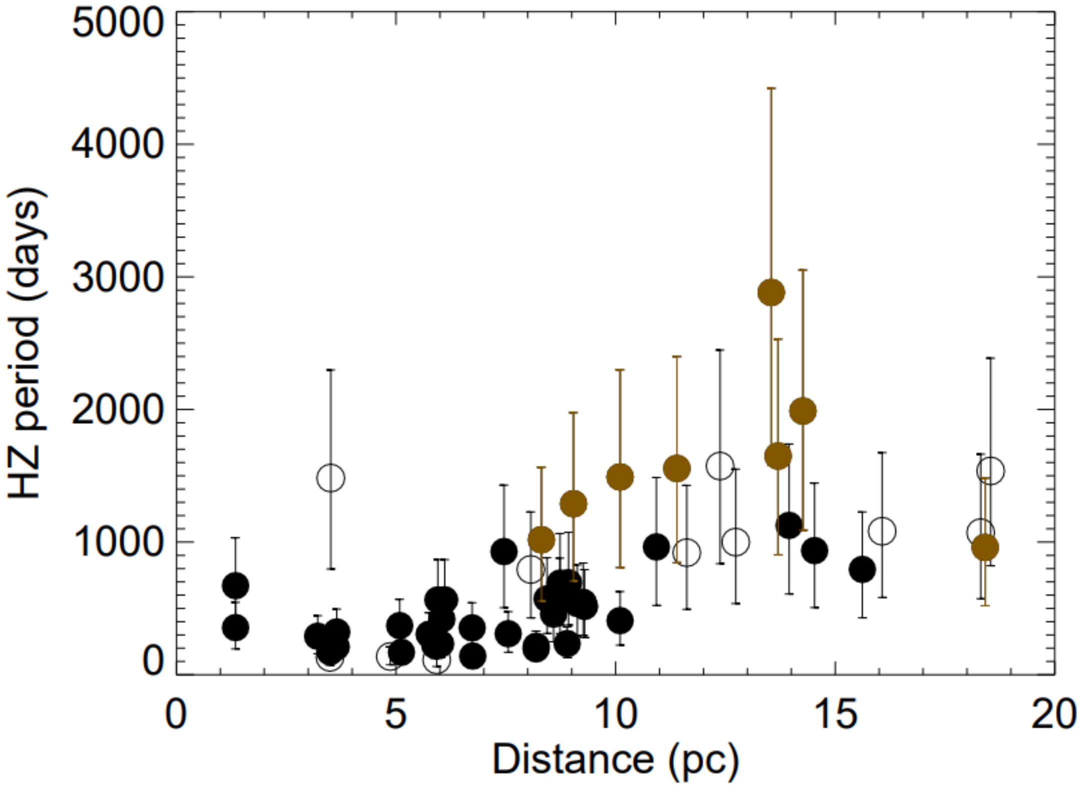
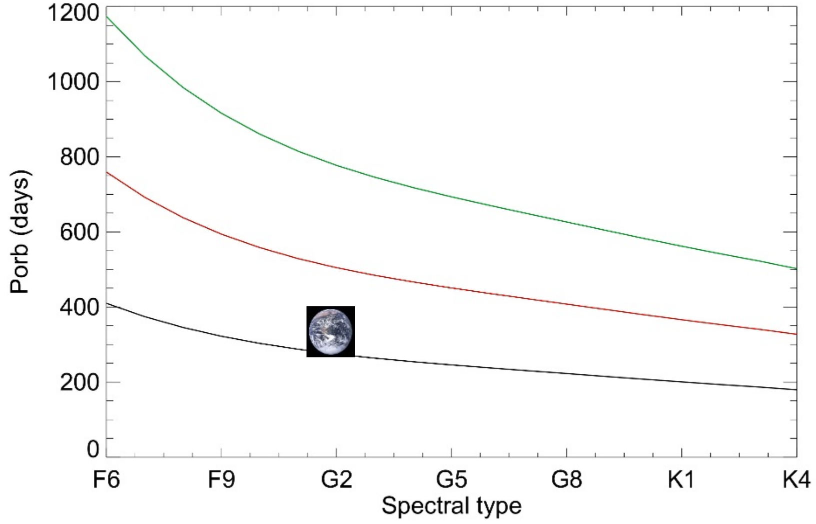
Focus on Earth analogues

- In the habitable zone around F6-K4 stars
  - → long periods 200-1200 d (>> Prot)



Habitable zone

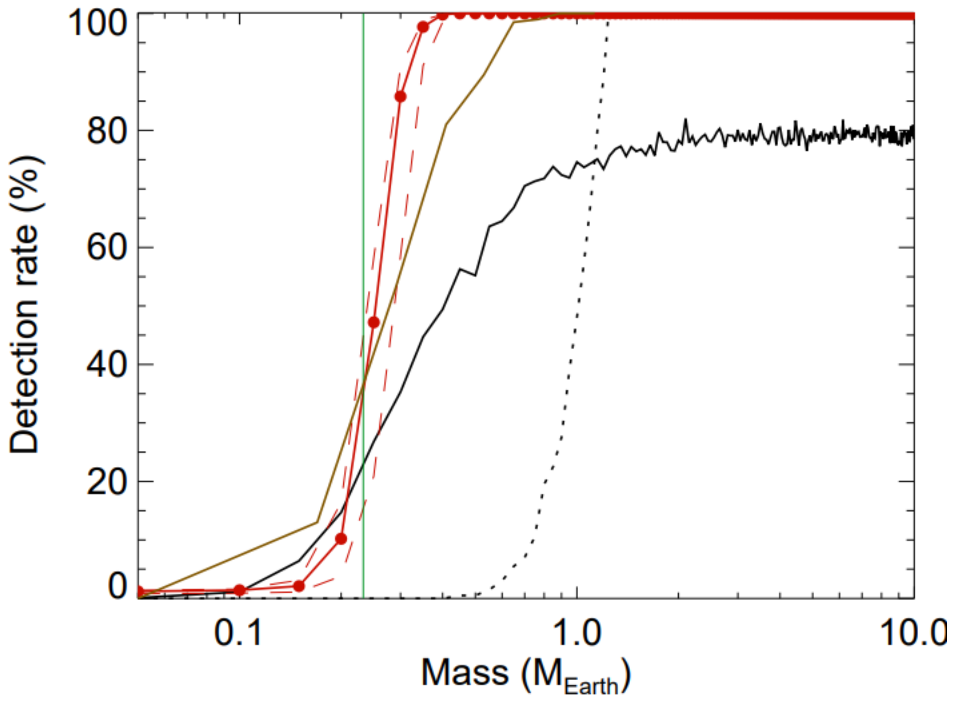


From laws in Kasting+93, Zaninetti08, Jones+06

Blind test and detection limits

- Blind test protocol
  - Computation of detection rate for a given planet mass (habitable zone)
  - Loop on mass → mass corresponding to a certain detection rate = detection limit
- 3 criteria
  - Fap threshold of 1%
  - Theoretical false positive of 1%
  - SNR_{peak} or $SNR_{global} > 6$
- Note: possible to reach low masses, but SNR low when computed from the rms of the signal →need to control noise sources

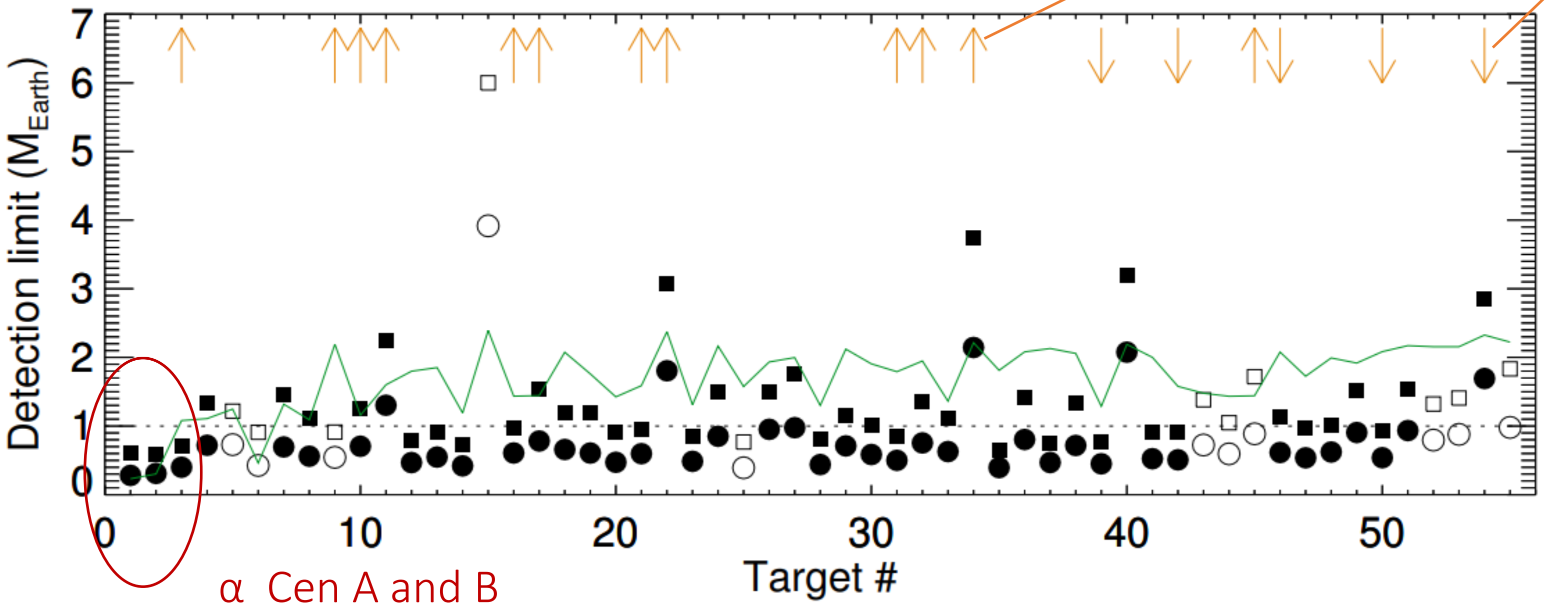
Example for α Cen A



New detection limits

Active stars →activity level underestimated, lower limits

Quiet stars →activity level overestimated, upper limits



50% detection rates

95% detection rates

Theia coll. + 2017

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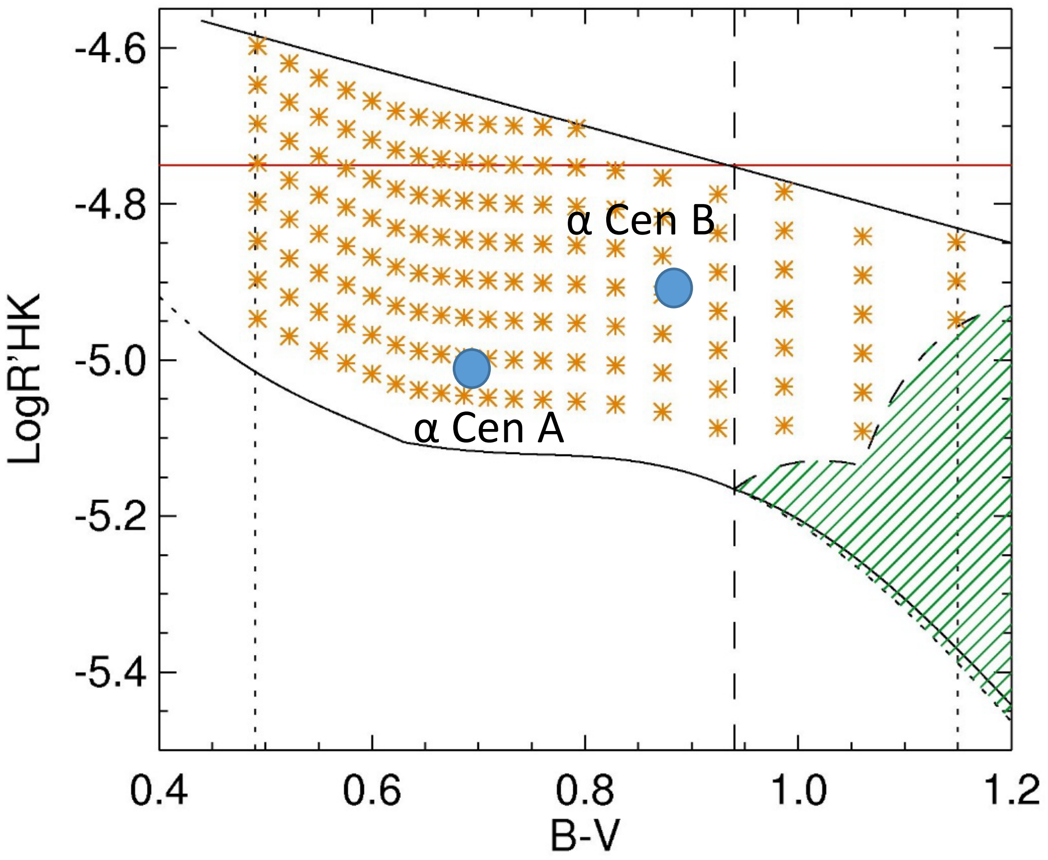
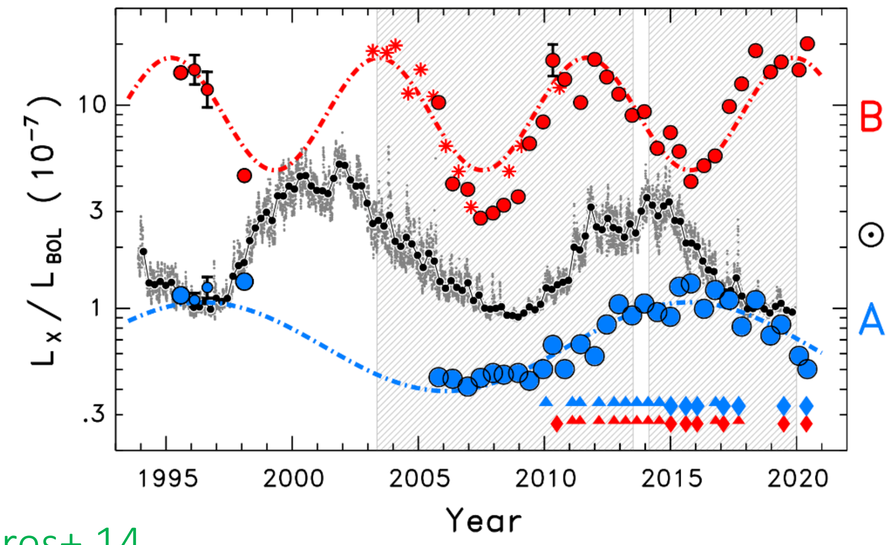
Dedicated time series for α Cen A & B

- Inpout for the end-to-end TOLIMAN simulations
- Position in our grid of parameter → B-V, average $LogR'_{HK}$
- But also
  - Rotation period: 28.3±05d (α Cen A, Huber 20), 36.7±0.3d (α Cen B, Dumusque+14)
  - Cycle period: 19.2±0.7 (α Cen A) and 8.1±0.2 (α Cen B), Ayres+14
  - Amplitude of the logR'HK variation: 0.07 (α Cen A) and 0.13 (α Cen B)
  - Inclination: 50° - 80°
- Distance, radius, T_{eff}





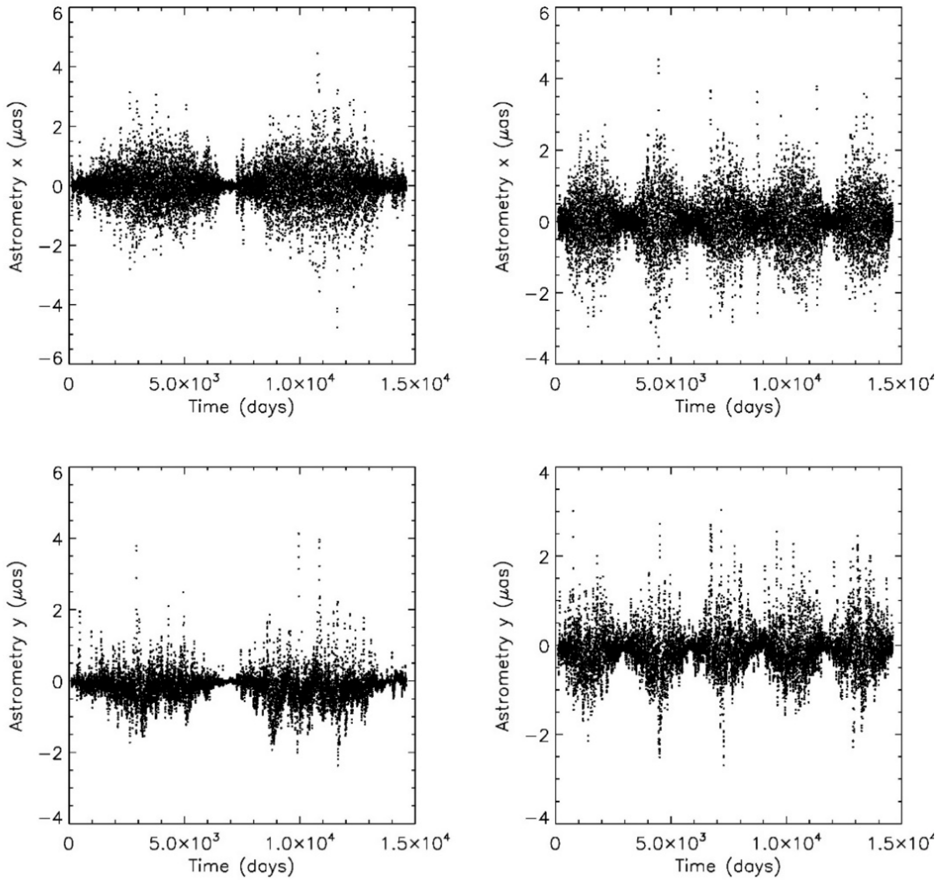
Ayres+ 14

α Cen A & B activity cycles

α Cen A & B typical jitter

Example for the low spot contrast (solar) and i=80°

α Cen A α Cen B



Assumption	X-direction	Y-direction
$\Delta T_{\odot}$, 50°	0.59	0.69
$\Delta T_{\odot}$, 50°	1.14	1.07
ΔT_{high}, 80°	0.60	0.40
ΔT_{high}, 80°	1.22	0.86

Assumption	X-direction	Y-direction
$\Delta T_{\odot}$, 50°	0.69	0.71
$\Delta T_{\odot}$, 50°	1.34	1.17
ΔT_{high}, 80°	0.67	0.47
ΔT_{high}, 80°	1.34	0.96

Conclusion and perspectives

A very fruitful approach

Systematic approaches and realistic simulations necessary to understand limitations

Many processes in RV, similar orders of magnitudes, all timescales →very difficult to reach Earth analogues

→ Stellar astrometric jitter > theia noise only for very close stars such as α Cen A & B

→ Search for Earth analogue with high-precision astrometry not limited by stellar activity

Perspectives

Need space mission with high astrometric precision !