Using the Sun to study the impact of stellar activity on exoplanet detectability
(Earth mass planets in the habitable zone around solar-like stars)

Nadège Meunier, Anne-Marie Lagrange
Institut de Planétologie et d’Astrophysique de Grenoble

IMI-2012, Grenoble, Octobre 9th

IPAG
Institut de Planétologie et d'Astrophysique de Grenoble

Outline of the talk

- Motivations
- Our approach
- Results: RV times series, periodograms and detection limits
- Comparison with solar and stellar observations
- Correction of the RV signal
- Conclusion

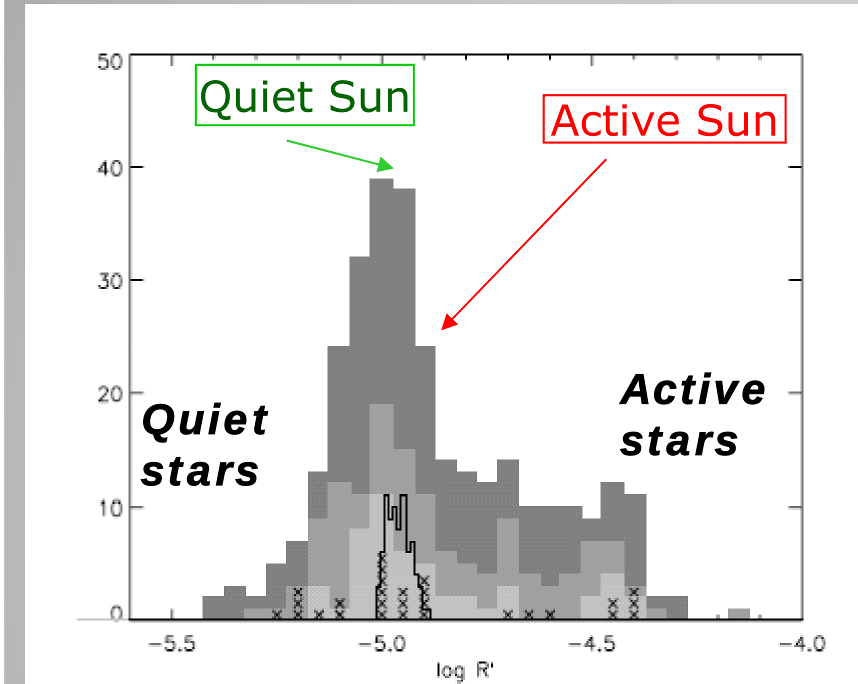
Stellar activity and exoplanet detectability

- Instruments with increased precision and stability
  - Allow search for very low mass planets
  - BUT more sensitive to stellar pertubations of these signals
  - → ***Impact exoplanet detectability***
- Stellar activity
  - *Magnetic activity* : time scale of days, months, years, decade …
  - *Oscillations / Pulsations* : time scales of minutes / hours
  - → ***Impact on photometry (transit), radial velocities (RV), astrometry***
- Two challenges
  - To be able to **detect a (exoplanet) signal** hidden behind the stellar contribution
  - To **determine** if a signal compatible with a keplerian orbit is **due to stellar activity**
  - → ***Need to study detectability***

Modelisation of the impact of activity

- Photometry and transit
  - Systematic approach Agrain et al 2004, Agrain & Irwin 2004
  - Case studies, e.g. Lanza et al. 2003 2009 2010, Mosser 2009 …
- Astrometry
  - 1 spot model Hatzes 2002, Makarov et al 2009
  - Complex activity pattern Makarov et al 2010, **Lagrange et al 2011**
- Radial velocity (RV)
  - Simulations from 1 spot (Saar & Donahue 1997, Desort et al 2007) to **complex activity pattern Lagrange et al 2010, Meunier et al 2010a, b → This talk**
  - Observed RV jitters and case studies (e.g. Boisse et al, Dumusque et al 2010, …)

The Sun as a moderately active star



Hall et al 2007

(See also Kepler results)

If we were observing the Sun in RV, would we be able to detect the Earth ?

- Use of our extensive knowledge of solar activity
  - RV on full solar cycle
  - Consistent with photometric variability
- To reproduce
  - Amplitudes
  - **and** complex frequency distribution

Our approach 2/4

Principle

List of ***observed*** structures — *Spots and plages at each time step ~daily sampling*

Solar map

Spectrum — *Three components*

RV — *Computed from the spectra as stellar RV*

Noise & planet added — *Codex/E-ELT, Espresso/VLT : RV precision ~1-10 cm/s Detection of Earth mass planets in the habitable zone*

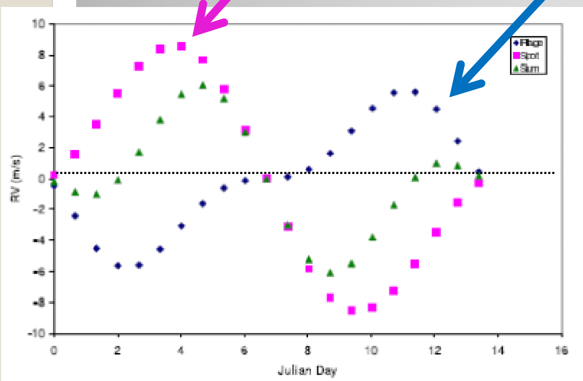
Periodograms & detection limits — *Two methods to take into account the frequency distribution of the power*

Our approach 3/4

Three RV components

1/ Spots *photometry*

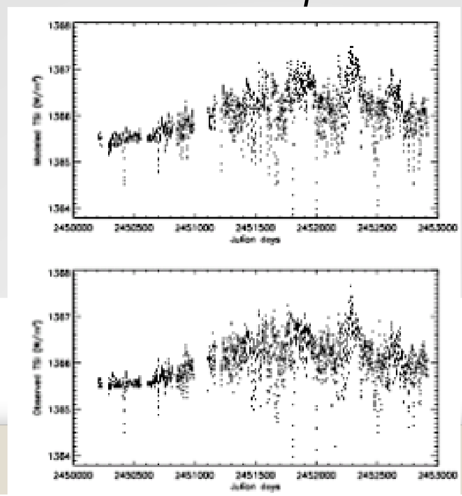
- Catalogues
- RV signal prop. to ΔT_{spot} contrast and size



2/ Plages & network *photometry*

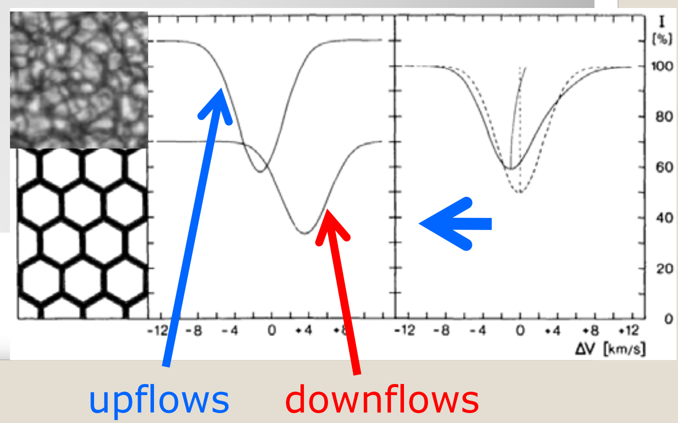
- MDI/SOHO magnetograms
- RV signal prop. to ΔT_{plage} contrast and size
- Opposite sign / spots, correlation between spots and plage positions

Check for coherent photometry



3/ Plages & network *convection*

- MDI/SOHO magnetograms
- Attenuation of the convective blueshift due to B
- Cumulative effect = net redshift
- Two parameters
  - Ampl. convective blueshift
  - Ampl. attenuation
- ΔV = 190 m/s



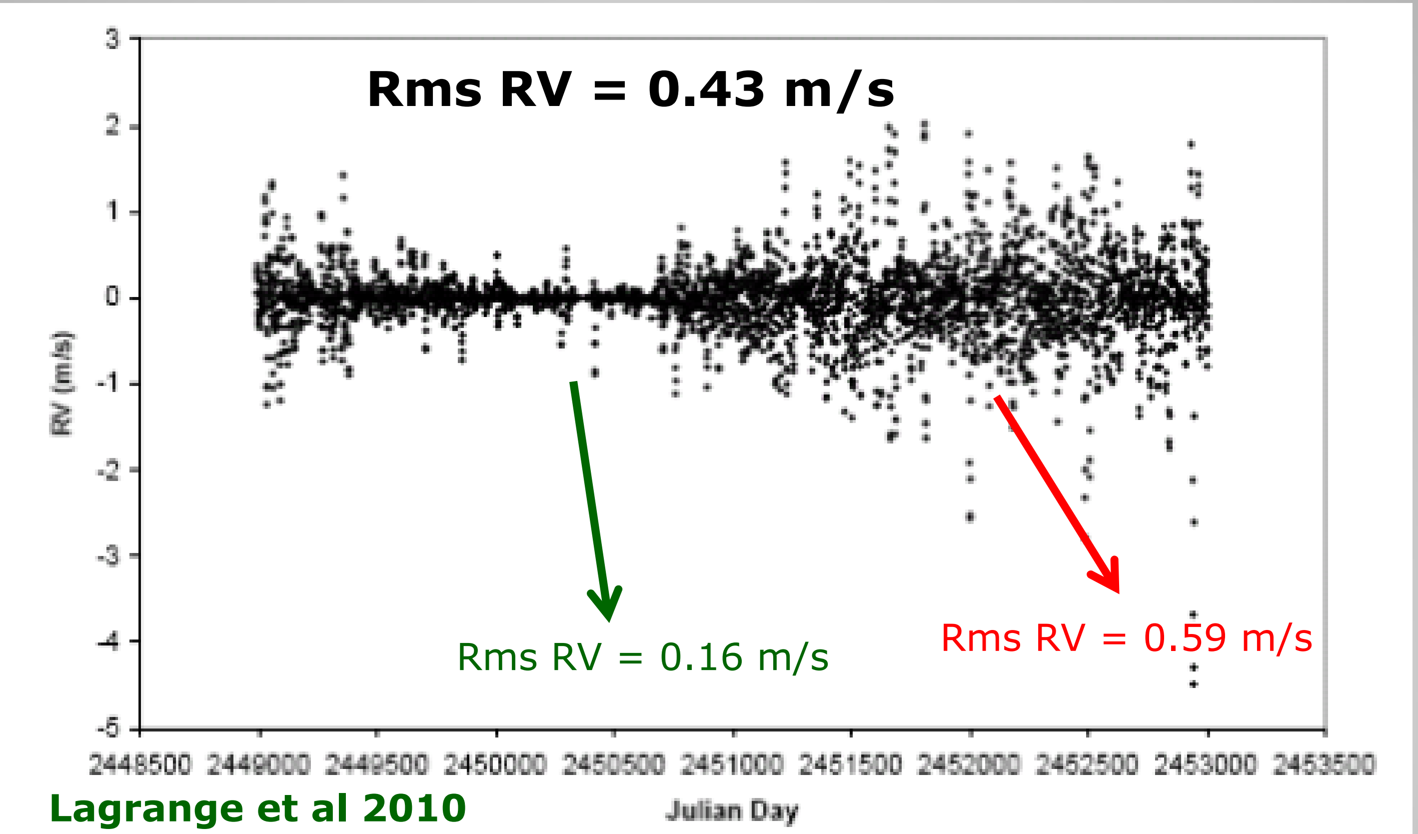
Detection limits

- Necessary to take into account the frequency distribution of the power
  - Several methods compared and tested on a sample of 10 stars
  - Based on 100 realizations
- Method 1 : correlation-based
  - Based on the comparison of
    - the correlation between the periodograms of: planet alone and planet+observed signal
    - With threshold obtained for very low planet masses
- Method 2 : local power analysis (LPA)
  - Based on the comparison of
    - the maximum power in the periodogram : determined locally
    - and the amplitude of the planet peak

Meunier et al, 2012

RV for spots only

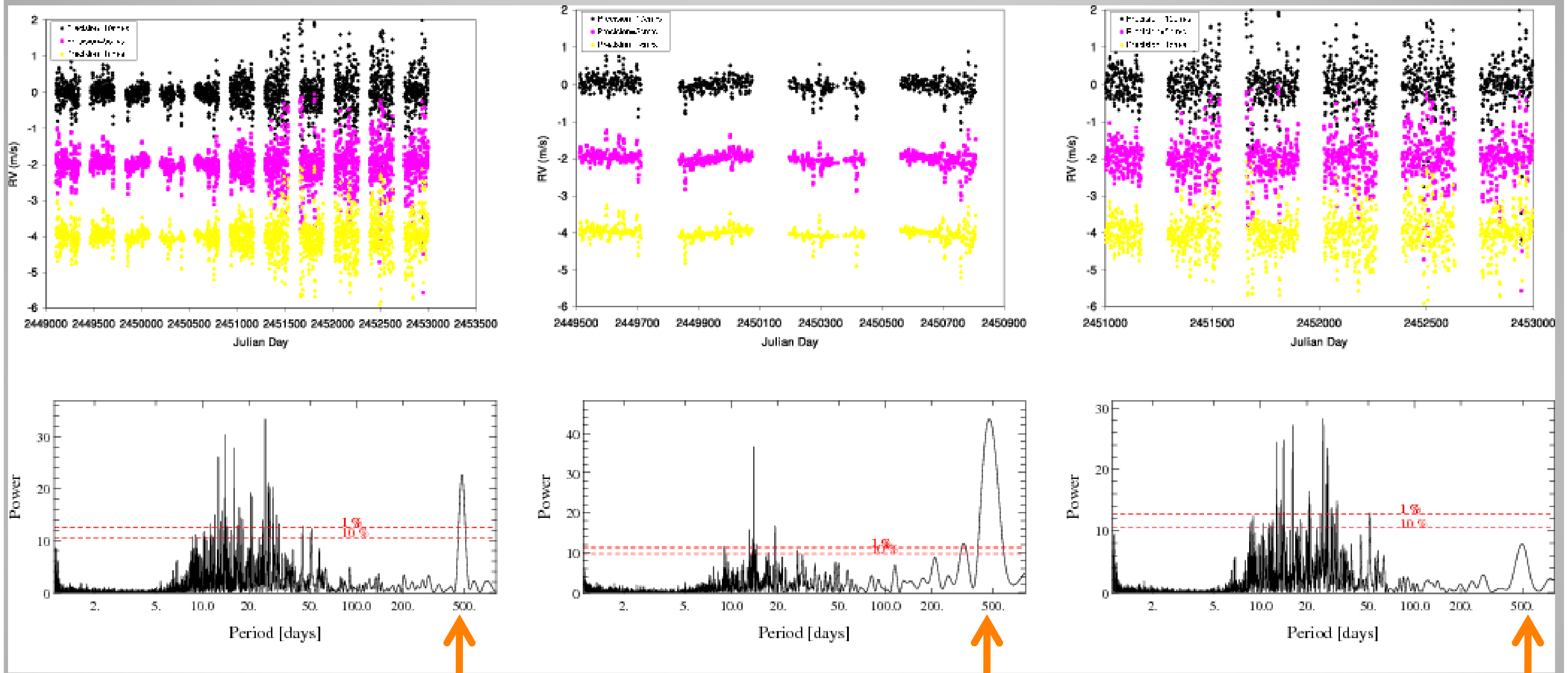
- *To compare with $1M_{Earth}$ at 1.2 AU → ~8 cm/s*



Results 2/4

Spots + planet ($1M_{Earth}$, 1.2 AU) + 10 cm/s noise, ~daily, 4 month gap

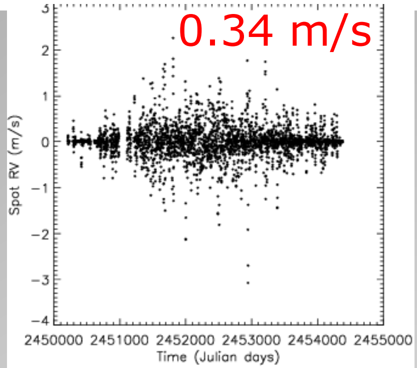
Full cycle | Low activity (1400j) | High activity (2000j)



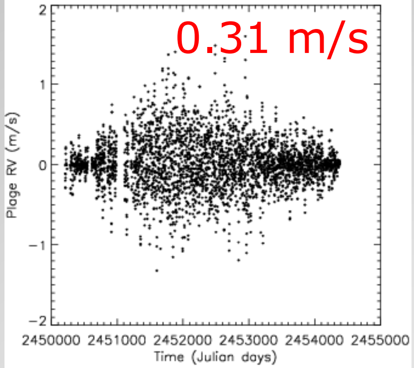
PLANET PLANET PLANET

Impact of the RV noise : can be neglected in the tested domain 1-10 cm/s

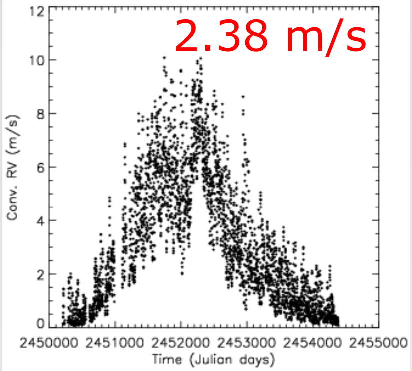
1/ Spots, ΔT



2/ Plages, ΔT



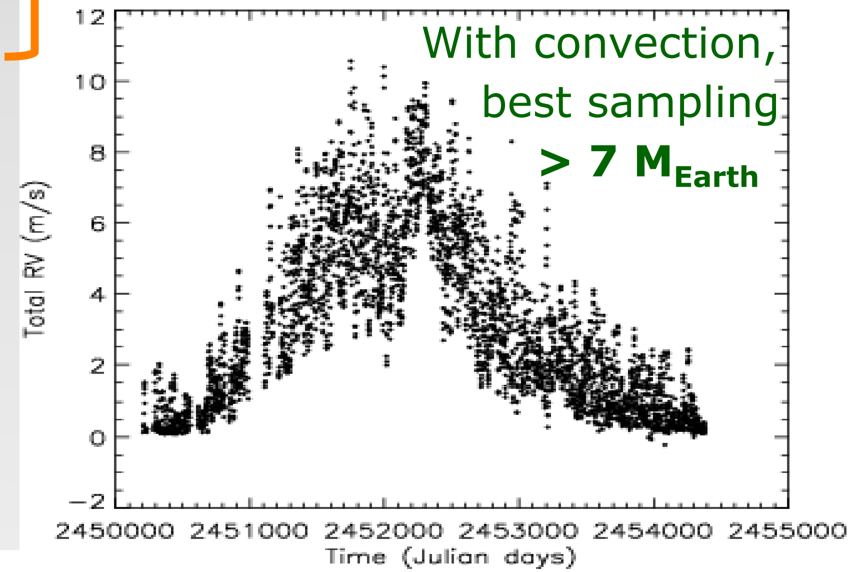
3/ Plages, ΔV
Ampl ~8 m/s



RV Spots+plages

Without convection

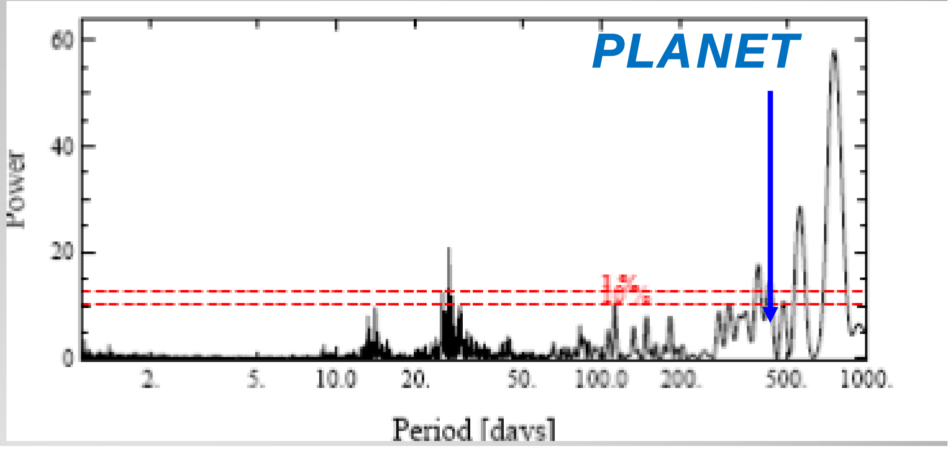
- With best sampling (~daily, 1 cycle): **0.2-0.3 M_{Earth}**
- With 1 point / 8 days or worse :**1-2 M_{Earth}**

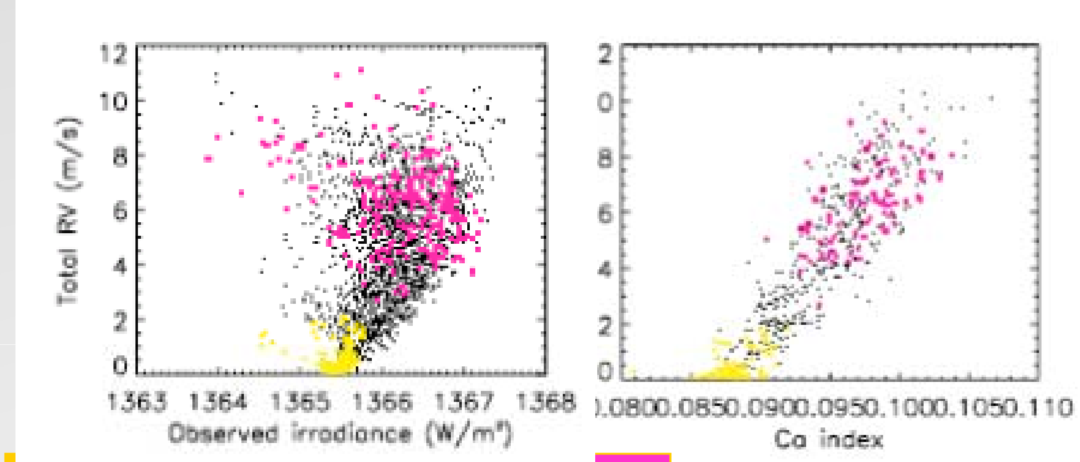


Meunier et al 2010, Meunier & Lagrange 2012 in revision

Periodograms and activity index

- Conditions
  - Planet 1 M_{Earth}, 1.2 AU
  - Full cycle, ~daily sampling
  - No RV noise
  - **= best situation !**
- No RV-photometry correlation
- RV-Ca correlation
  - RV dominated by convection
  - Large dispersion at small time-scales



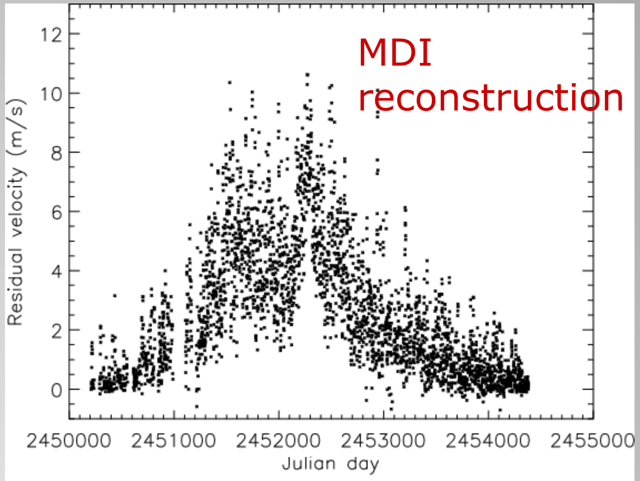


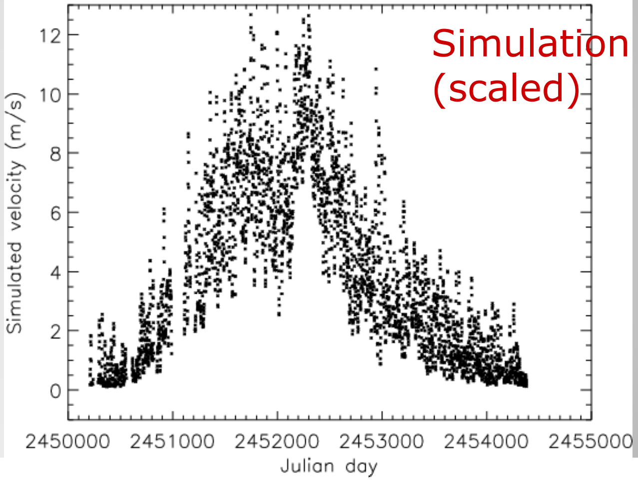
Low activity *High activity*

Solar observations

- Lack of reliable long-term RV time series
  - Jimenez et al (1986) : K 7699 Å, 30m/s (long- term), 20 m/s (short-term)
  - Deming & Plymate (1994) 2.3 μm, peak-to-peak 30 m/s (long-term)
  - Mc Millan et al (1993) : deep lines at short λ, amplitude < 4m/s
- RV reconstruction from MDI/SOHO Doppler maps
  - Only one line (Ni 6768 Å), expected ΔV larger than average
  - Objective = to check the amplitude of the convective contribution
  - **→Observation ≈ 70% simulation, with very good correlation**
- 2nd result: detailed study of ΔV versus B

Meunier et al 2010

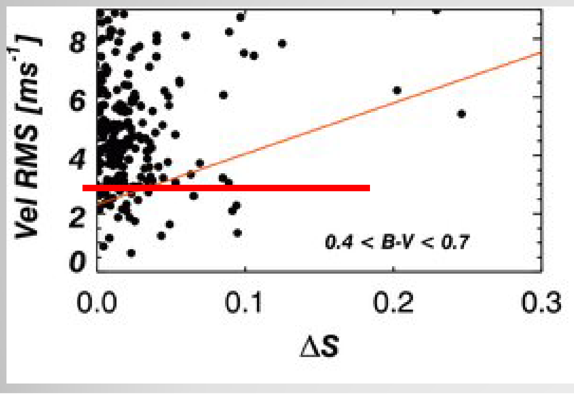




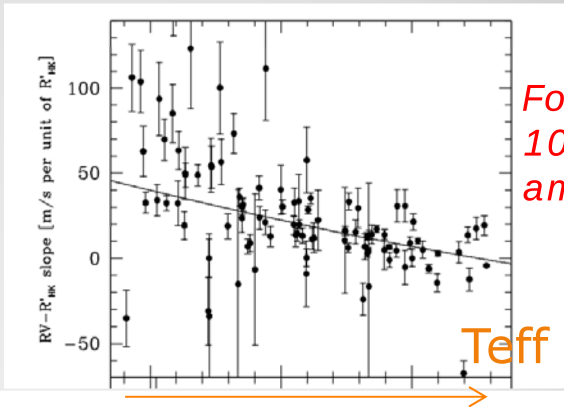
Comparison with RV stellar jitter

- Surveys
  - Young and old stars, F – M, e.g. : Saar et al 1998, Santos et al 2000, Paulson et al 2002, 2004 , Wright 2005, Santos et al 2010, Isaacson & Fischer 2010, Lovis et al 2011
- Typical results
  - G stars: 5-40 m/s
  - Correlation between RV-Ca time series, but
    - Correlation expected when dominated by the convection contribution
    - Young stars dominated by spots, correlation not expected if complex pattern

Isaacson & Fischer 2010



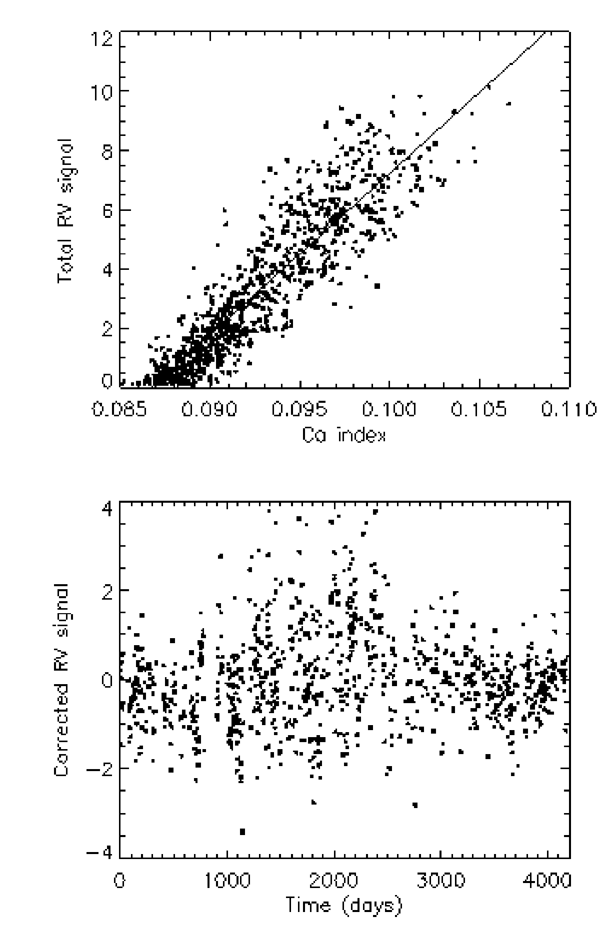
Lovis et al 2011 submitted



For the Sun : 10 m/s amplitude

Correction of the RV signal

- Principle: Ca emission and RV (convection) strongly correlated with plage filling factor
  - Ca time series: measured (Sac Peak) and reconstructed
  - Test: impact sampling, Ca noise …
- Two methods
  - 1/ Sinusoidal fit of Ca variations, used to fit RV(t)
  - 2/ Linear relation RV-Ca, used to derive correction
- *Issue: performances of these methods ?*
- A few results
  - *Low S/N Ca noise*: similar performances, 2-15 M_{Earth}
  - *High S/N Ca noise*: method 2 is the best
  - Ideal case + excellent Ca S/N + excellent sampling: <1 M_{Earth}, otherwise > 1 M_{earth}
  - But above 1 M_{earth} if such a planet is present in the original RV



Meunier & Lagrange 2012, in revision

Conclusion

- Summary
  - Reconstructed RV time series for the Sun seen edge-on
    - Consistent with observed stellar jitters in recent stellar surveys
  - Exoplanet detectability
    - Limitation = solar activity pattern and level, seen edge-on
    - *Without convection*: 1 M_{Earth} could be detected with excellent sampling
    - *With convection*: impossible to detect 1 M_{Earth} in the habitable zone directly (detection limits>7M_{Earth} at best)
    - *Correction for the convective contribution using the RV-Ca relation:*
      - Significant improvment of the detection limits
      - But not good enough to reach the 1 M_{Earth} regime
- Future work → *Simon Borgniet (PhD thesis, starting oct 2012)*
  - Impact of inclination (solar case)
  - Exploration of stellar cases
    - Stellar activity not as well known as for the Sun, large diversity
    - Need to know the convective blueshift (& attenuation)