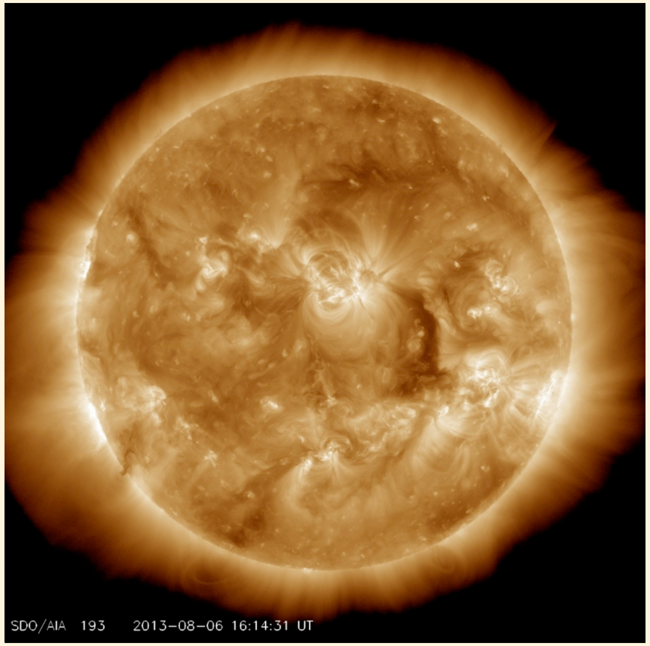
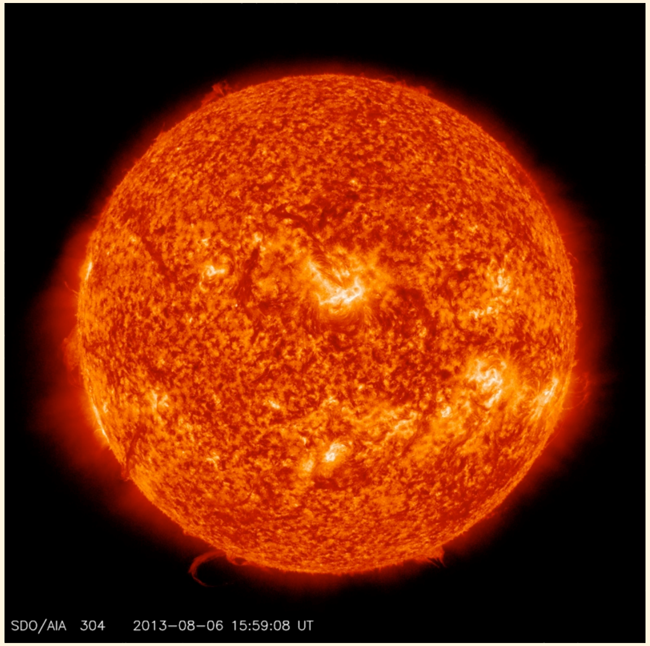
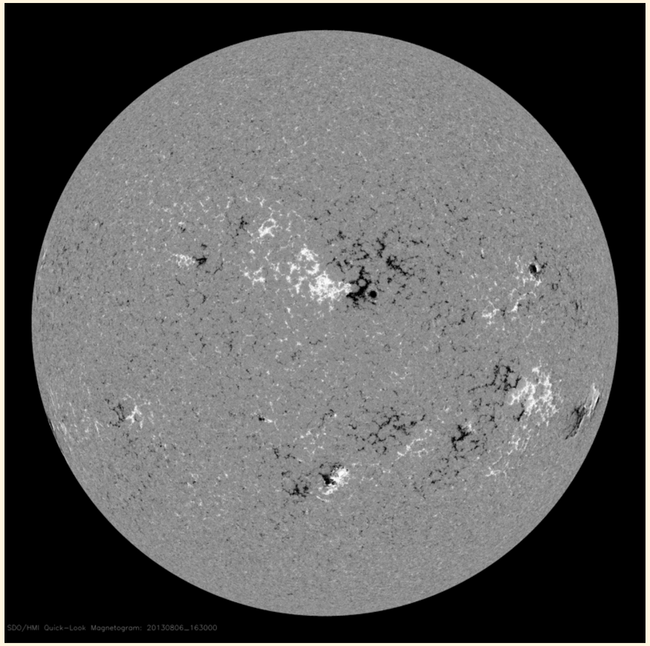
Measuring precise planetary masses in the presence of stellar activity in RV surveys







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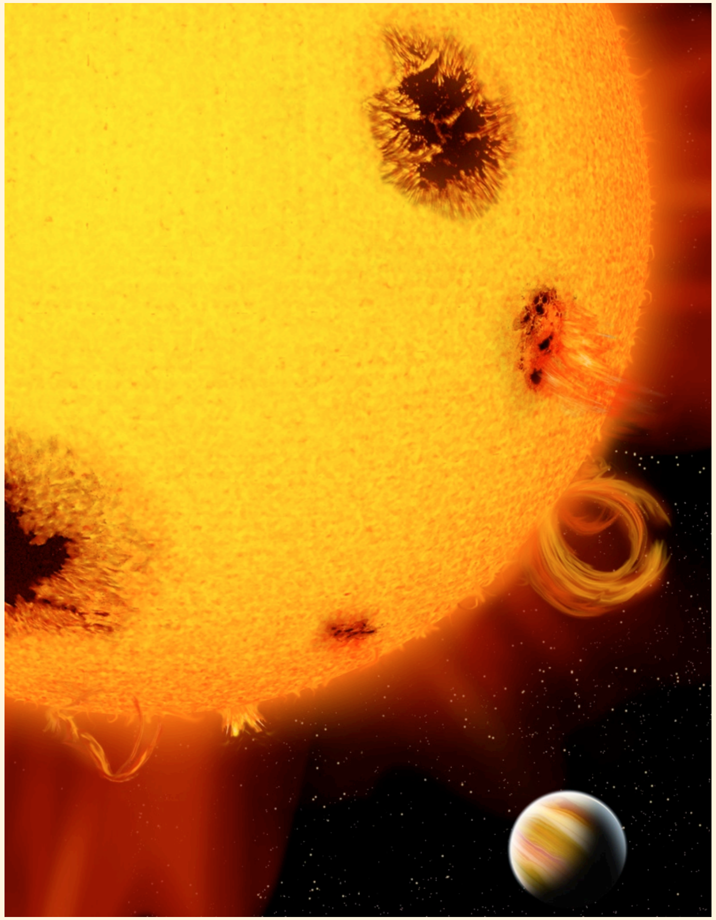
Context

For low mass planets:
Radial-velocity (RV) signal entangled with stellar activity RV signatures

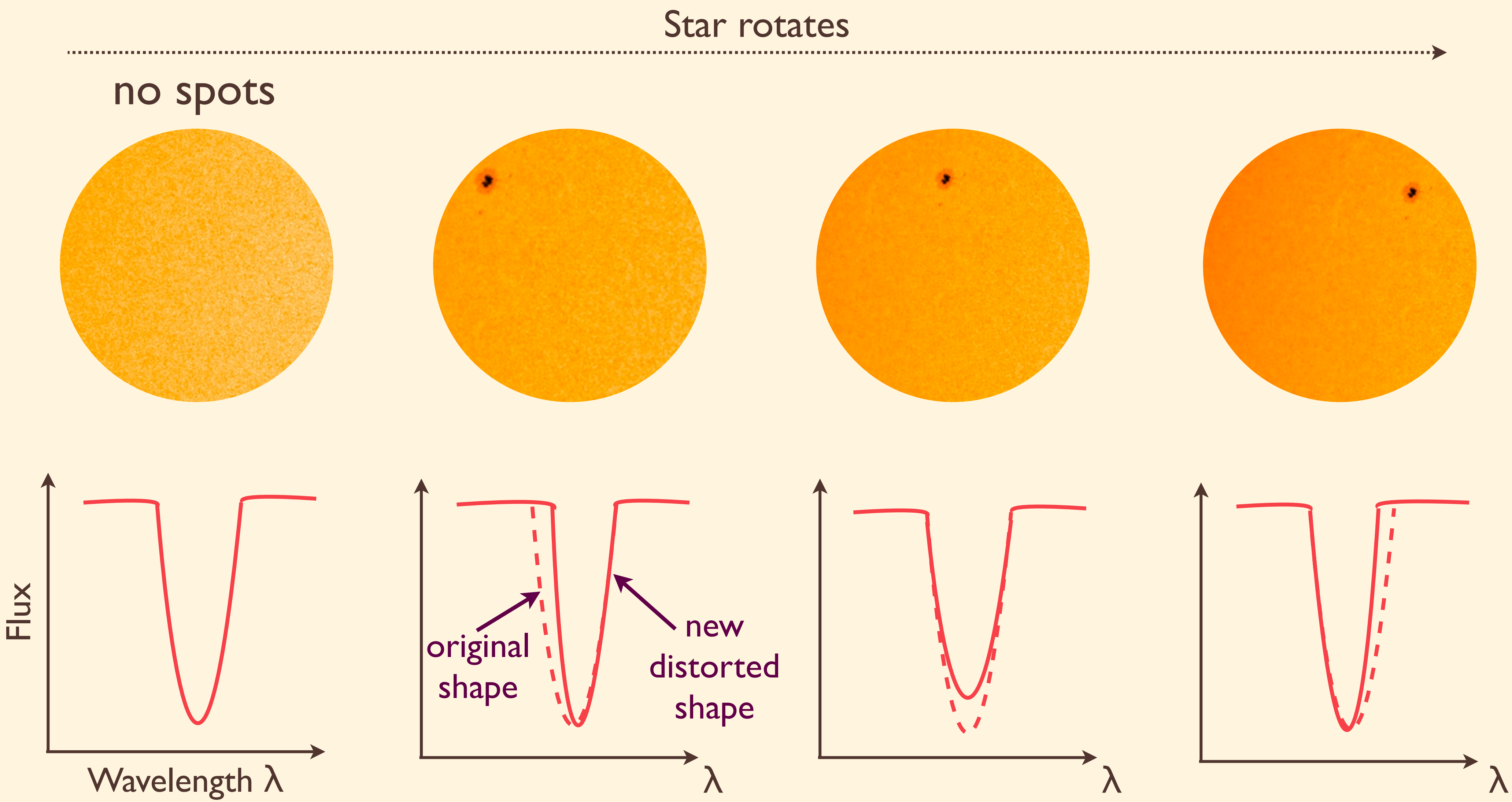
- Observations suggest that even "quiet" stars have $\Delta RV_{activity} \approx$ 1-2 m/s (Isaacson & Fischer 2010)

- Magnetic activity can lead to false detections (Queloz et al. 2001, Bonfils et al. 2007, Huélamo et al. 2008, Boisse et al. 2009, 2011)

- HARPS-N is looking for planets with 1-2 m/s amplitude, need to be able to trust results

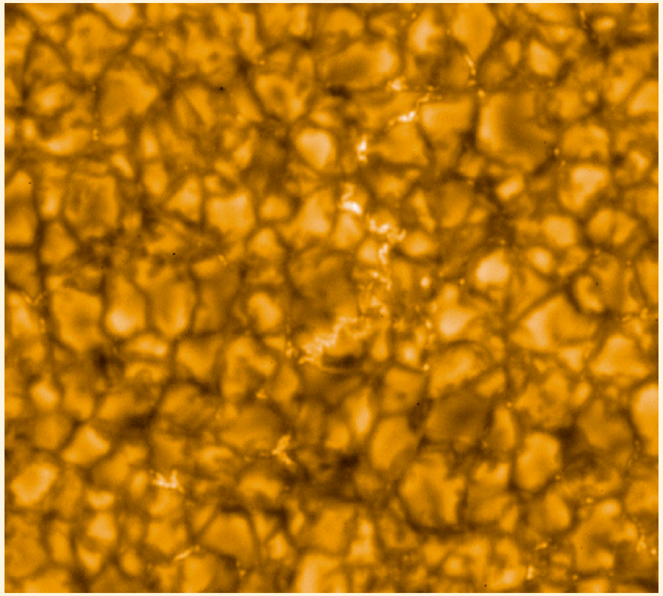


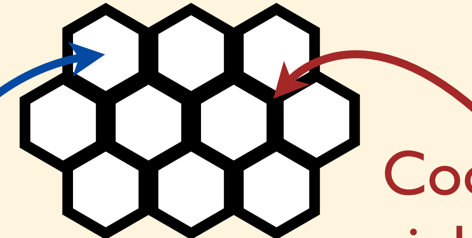
I. Flux blocked by starspots on a rotating star



Single spot on Sun-like star $\Delta RV \approx 0.38$ m/s (Makarov et al. 2009)

II. Suppression of convective blueshift

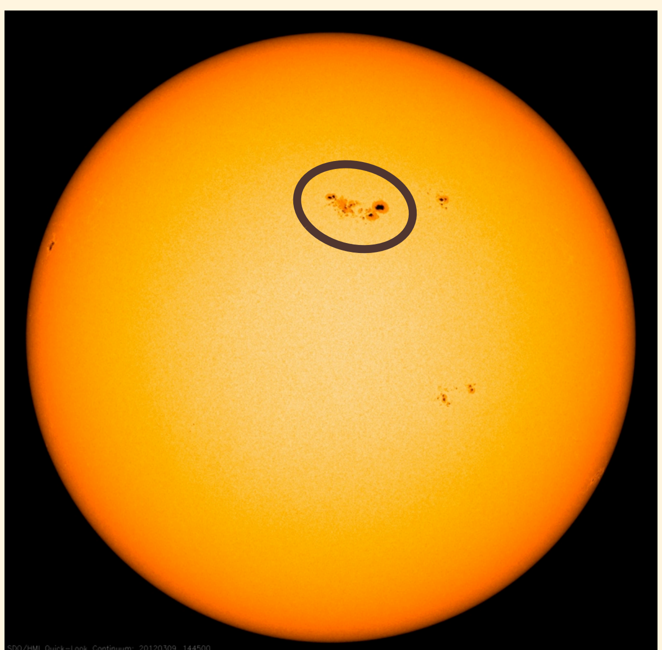




Hot & bright
outgoing flow
→ blueshift

Cool & dark
sinking flow
→ redshift

⇒ Net blueshift

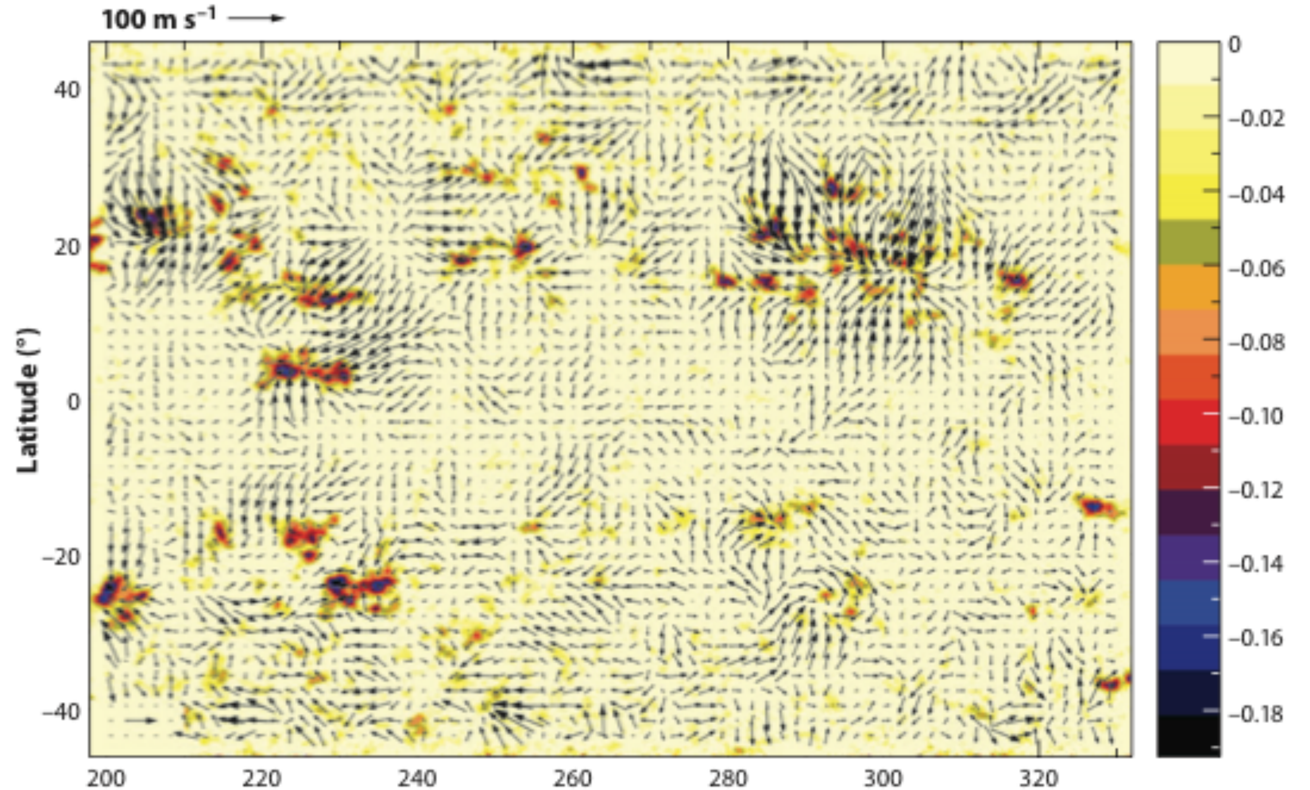


Active regions suppress
granulation blueshift
~ few m/s

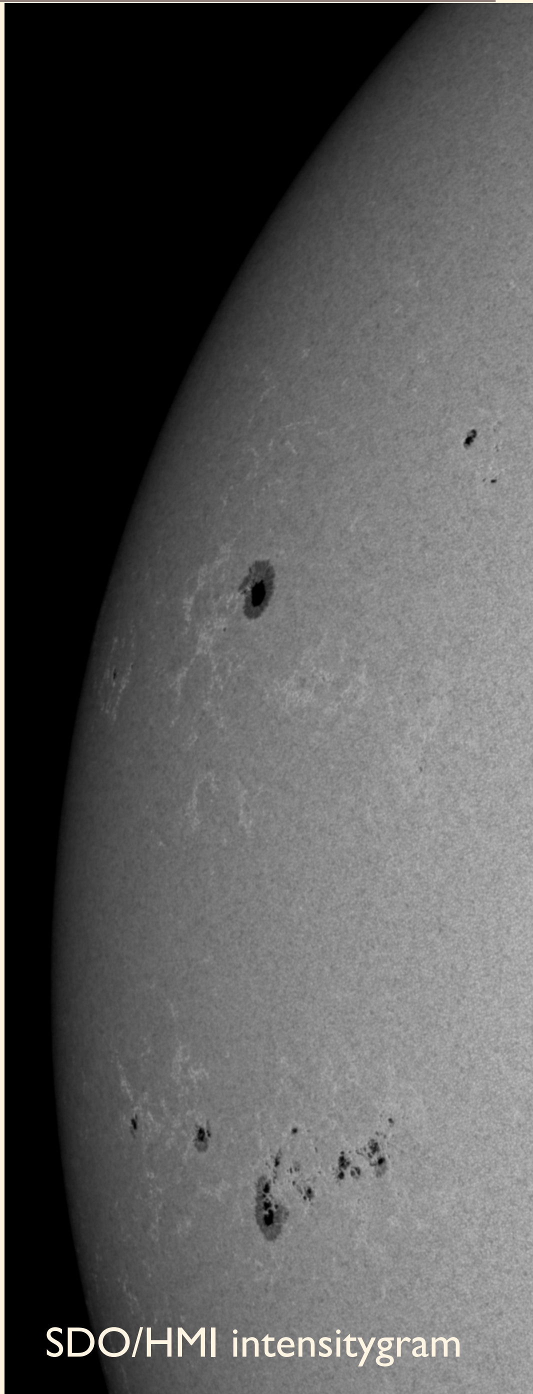
Found to be dominant contribution to $RV_{activity}$
(Meunier et al. 2010, Haywood et al. submitted)

III. Other potential stellar activity RV signals

- Faculae that are not associated with starspots
- ~ 50 m/s inflows towards active regions in the Sun (Gizon et al. 2001, 2010)
- Other... ?



Gizon et al. 2010



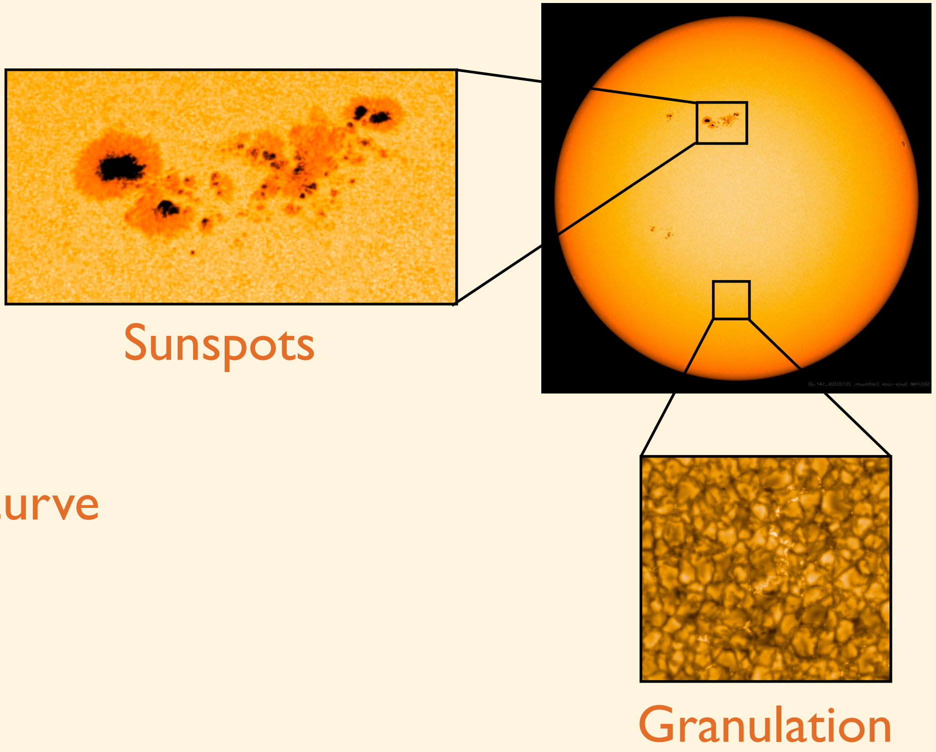
Outline of this work

- Monte Carlo Markov Chain (MCMC) code
- RV model:

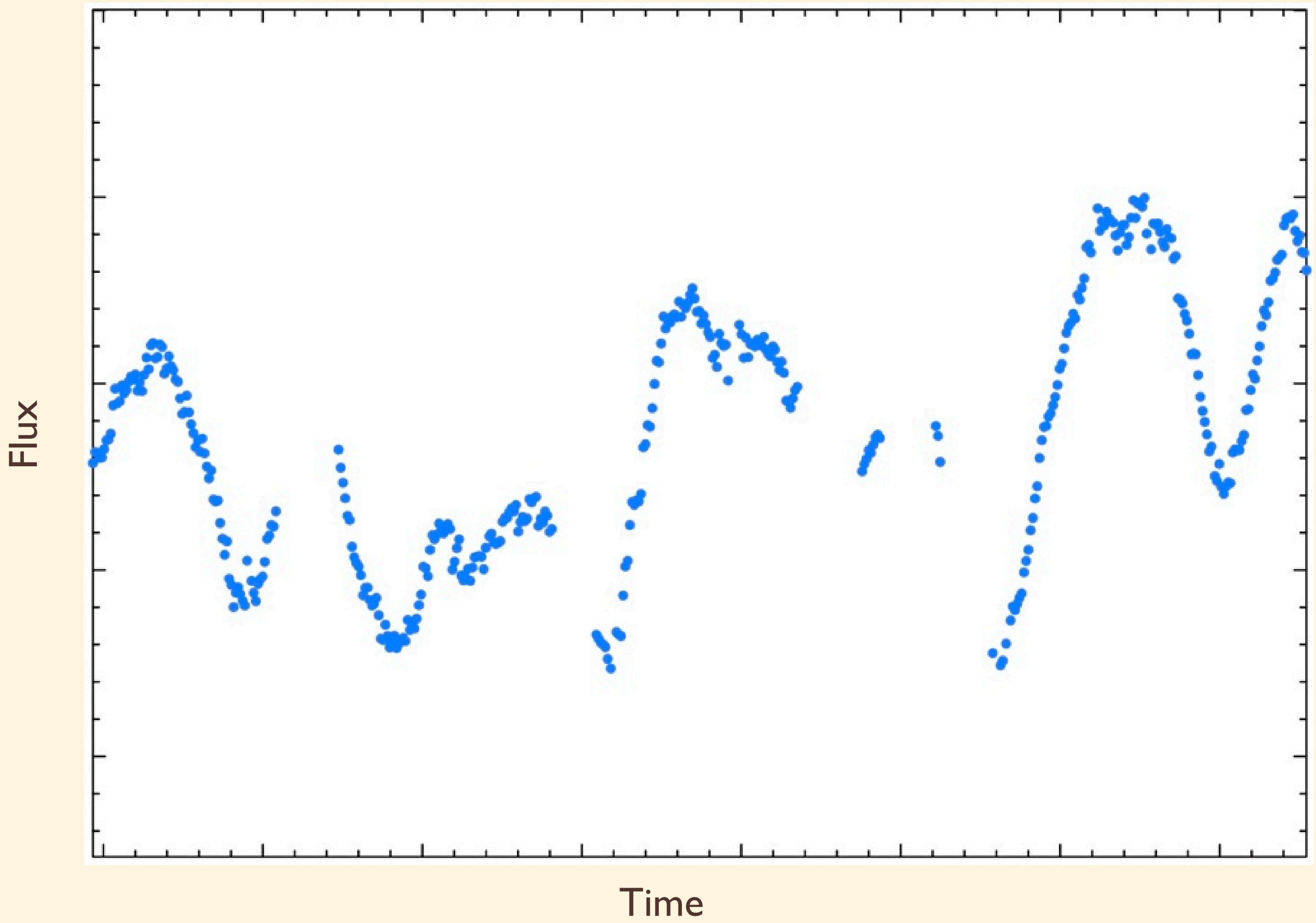
$$RV_{total} = RV_{planets} + RV_{activity}$$

Basis functions derived from lightcurve
(*FF'* method of Aigrain 2012)

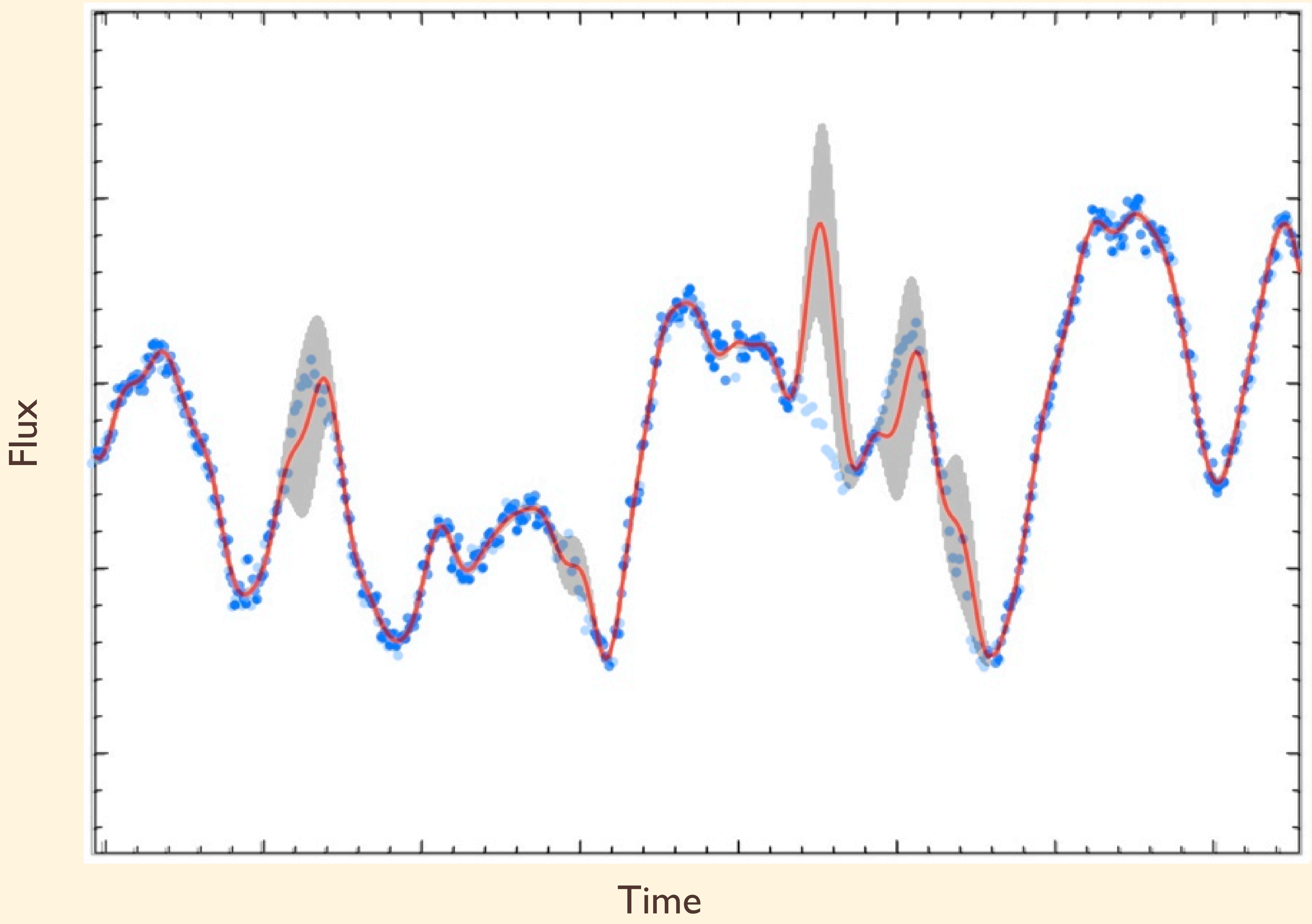
Gaussian process with covariance
properties of lightcurve
(Haywood et al., submitted)



Gaussian processes



Gaussian processes



A Gaussian process is encoded by a **covariance function**

Quasi-periodic form:

$$k(t,t') = \theta_1^2 \,.\, exp\Big(-\frac{(t-t')^2}{2\theta_2^2} - \frac{2\sin^2(\frac{\pi(t-t')}{\theta_3})}{\theta_4^2}\Big)$$

amplitude

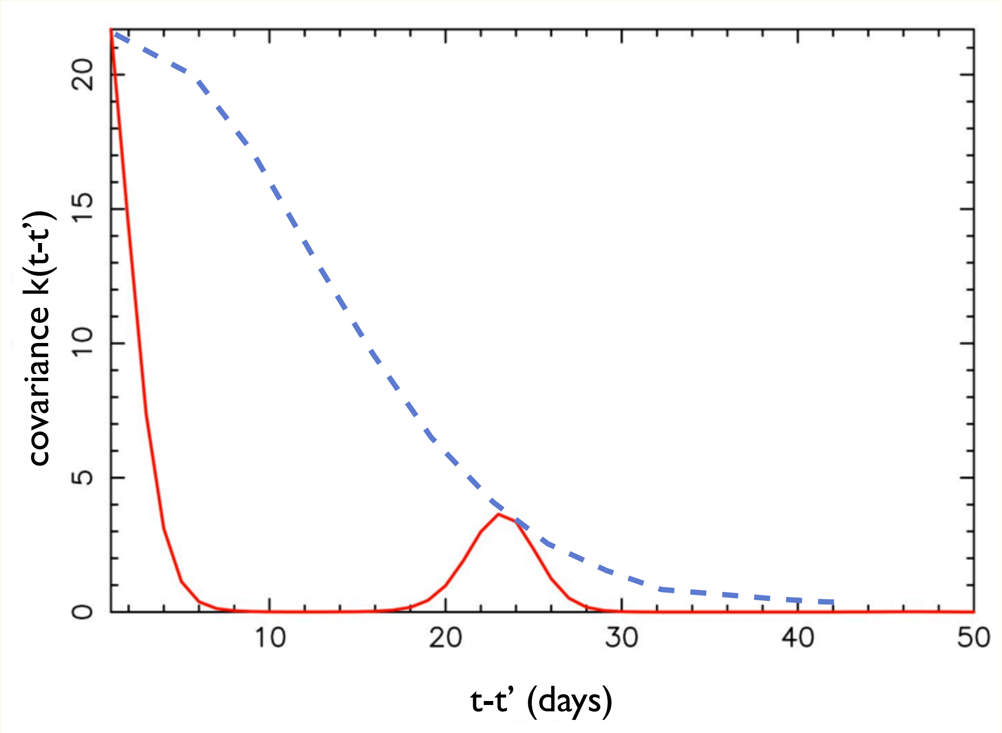
decay timescale

smoothing factor

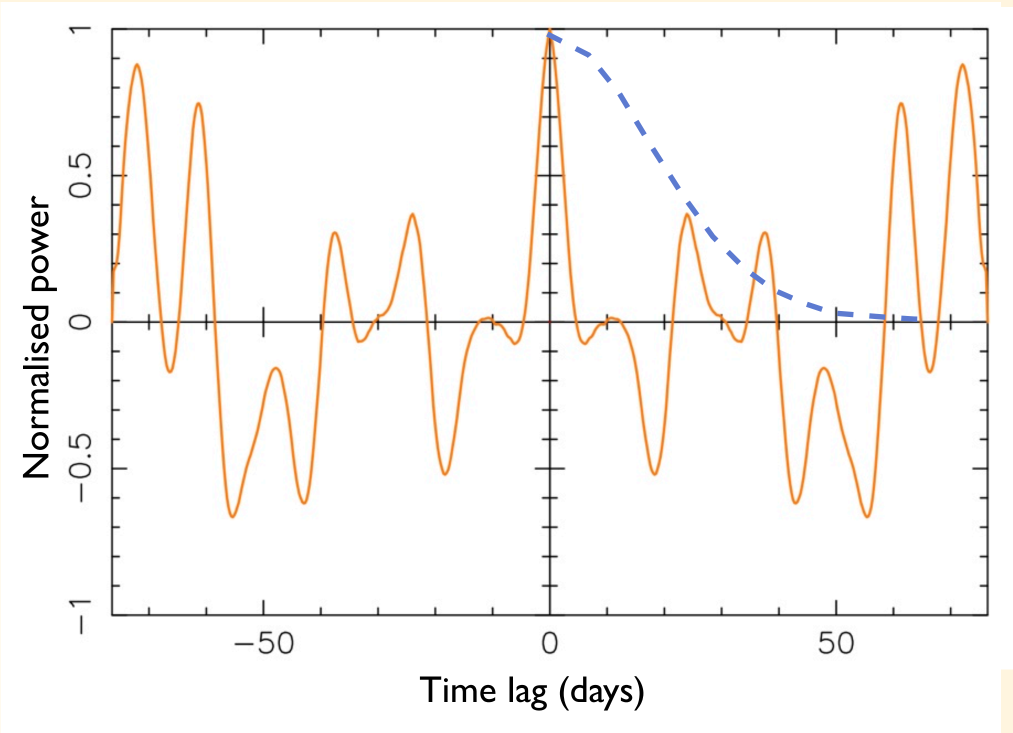
reccurence timescale

See Rassmussen & Williams (2006), Gibson et al. (2011)

Covariance function

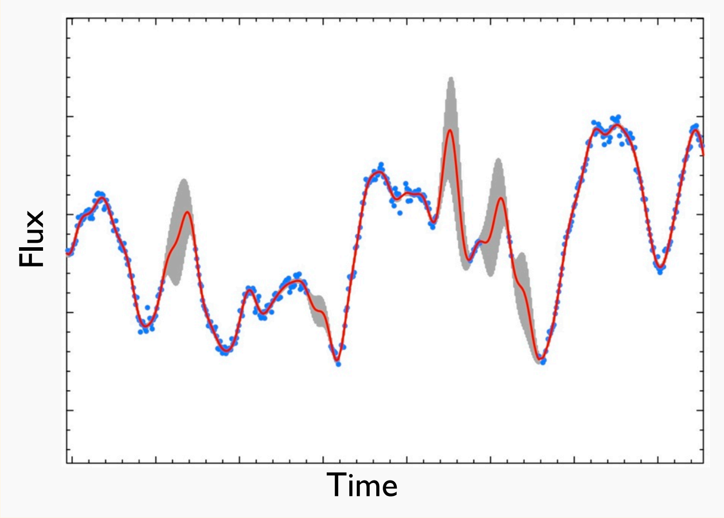


Autocorrelation function



Using a Gaussian process to fit data

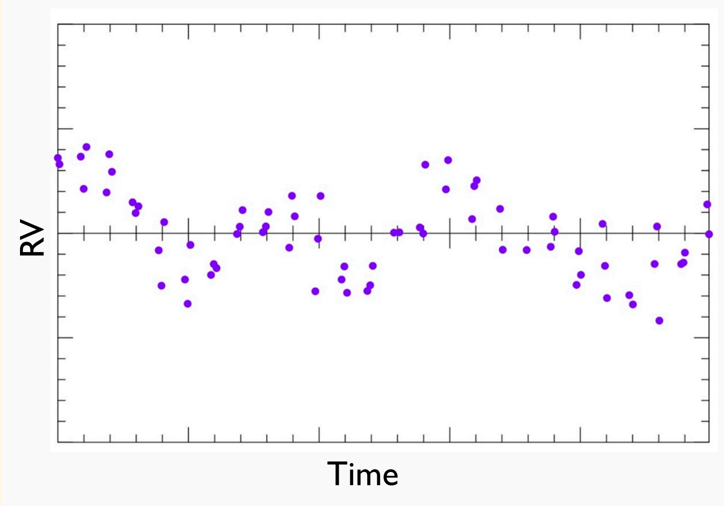
Lightcurve:
naturally has covariance properties of star's magnetic activity



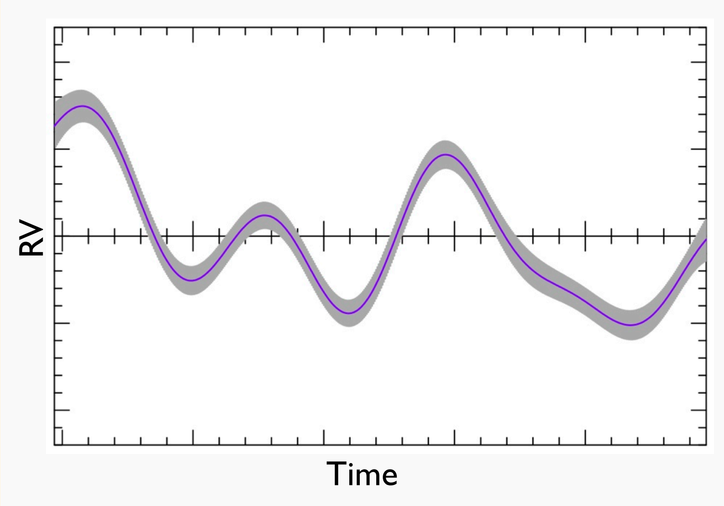
train GP: determine $\theta_1, \theta_2, \theta_3, \theta_4$ of covariance function through MCMC simulation

$k\ (t, t')$

+

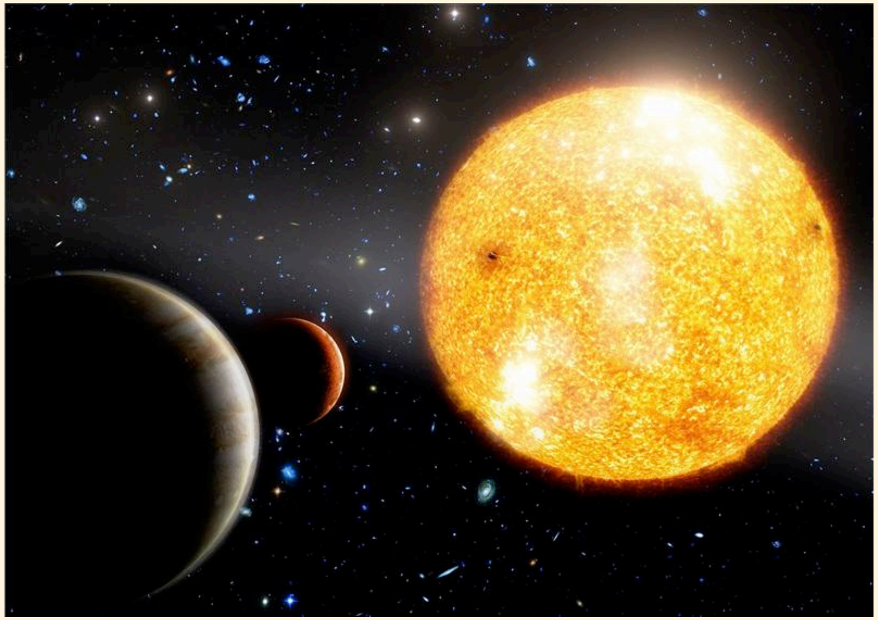


predict GP: compute covariance matrix using $k\ (t, t')$



RV basis function with covariance properties of lightcurve

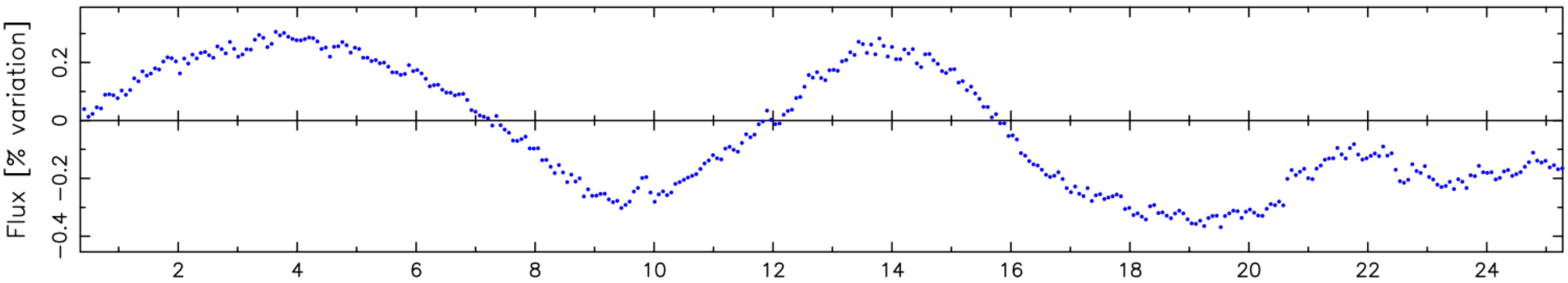
Application to CoRoT-7



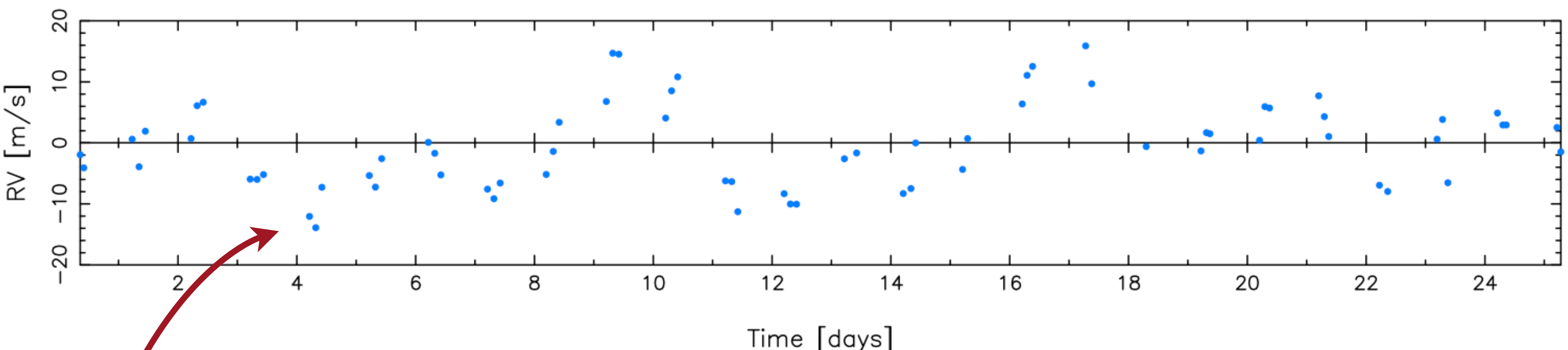
- G9, V=11.7
- CoRoT transit observations in 2009
  ➡ super-Earth CoRoT-7b (Léger et al. 2009)
- HARPS radial-velocity campaign (2009)
  ➡ another super-Earth CoRoT-7c (Queloz et al. 2009)
  ➡ sub-Neptune mass planet CoRoT-7d at 9 days (Hatzes et al. 2010)
- Many analyses, no agreement
  Bruntt et al. 2010, Lanza et al. 2010, Pont et al. 2010, Boisse et al. 2010, Ferraz-Mello et al. 2011, Hatzes et al. 2011
- Jan. 2012: New observations: simultaneous CoRoT photometry & HARPS RV

CoRoT-7 2012 simultaneous RV and photometry

CoRoT lightcurve (transits of CoRoT-7b removed)



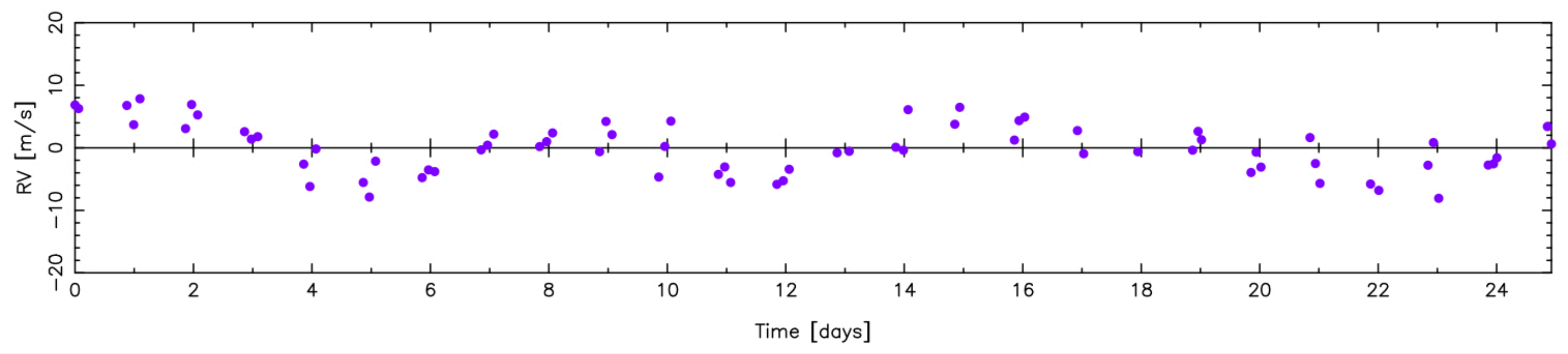
HARPS RV data



$RV_{total} = RV_{activity} + RV_{planets}$

Why the Gaussian process is needed

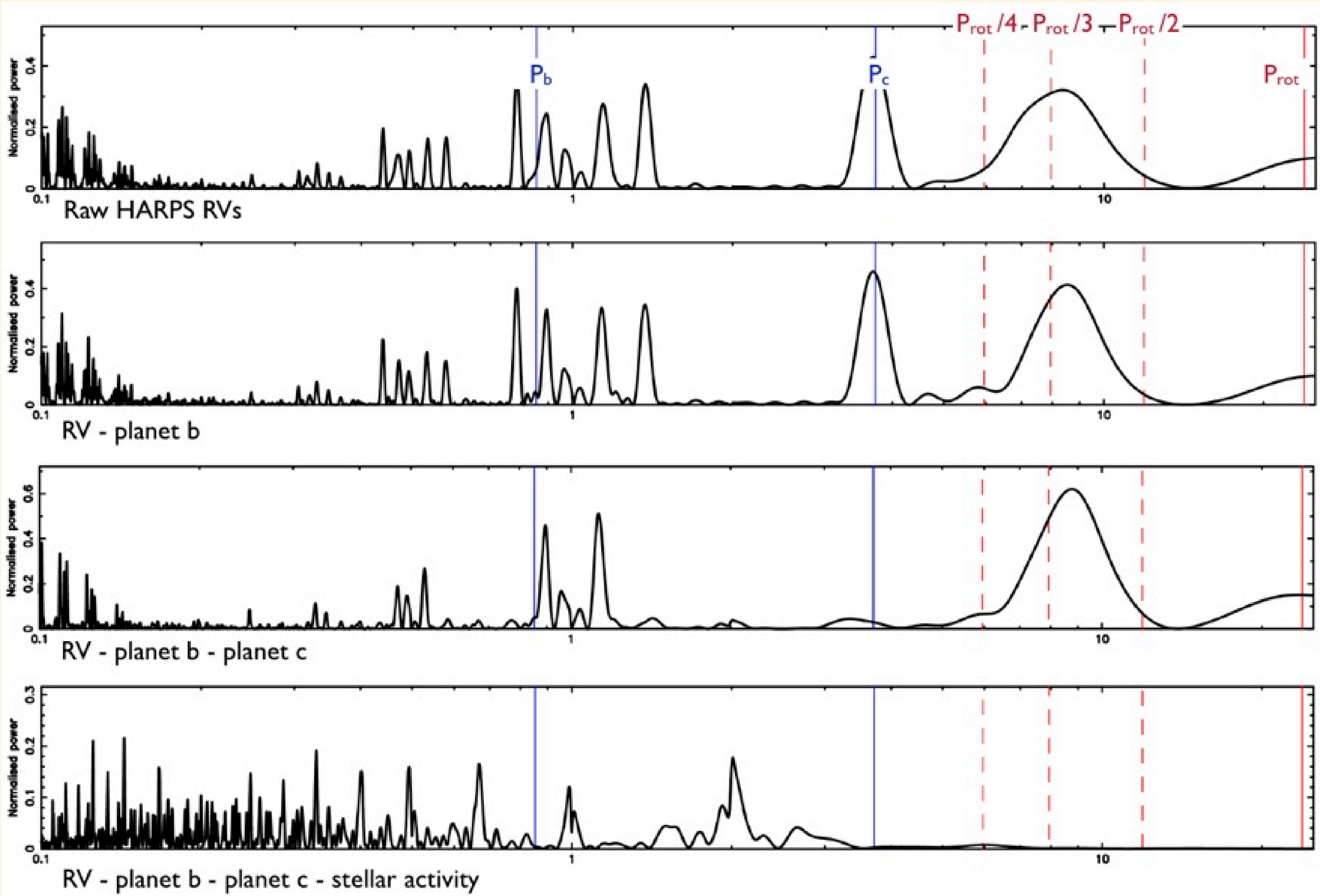
If model RVs with only method of Aigrain (2012) and 2 planets, get correlated residuals:



Fit Gaussian process to residuals

Outcome of MCMC for CoRoT-7

Haywood et al., submitted



Summary

- In case of CoRoT-7:
  - m_b = 4.62 ± 0.89 $M_\oplus$ and m_c = 13.62±1.06 $M_\oplus$
  - signal at 9 days best explained as activity rather than a planet

- Accounting for stellar activity RV signals is key to detecting low-mass planets and determining their masses

- Can account for activity using method of Aigrain et al. (2012) + Gaussian process trained on lightcurve (Haywood et al., submitted)

- Apply to Kepler systems observed with HARPS-N