

# The search for planets around metal-poor stars

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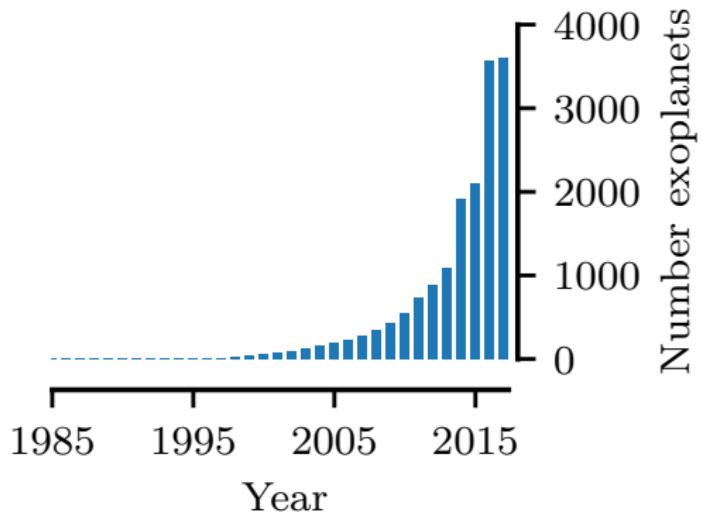


**FCT**

Fundação para a Ciéncia e a Tecnologia  
destinada ao ensino superior



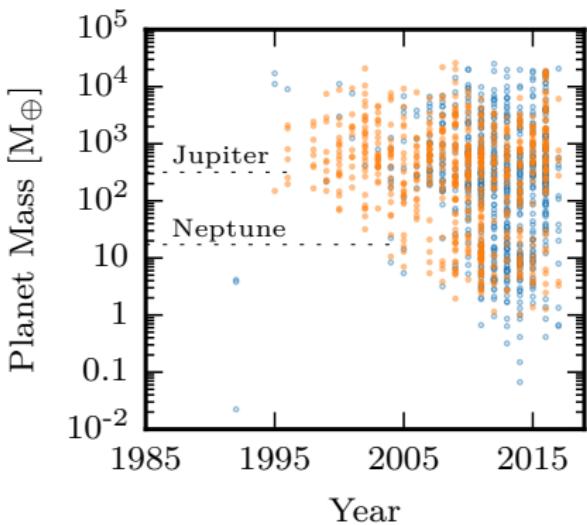
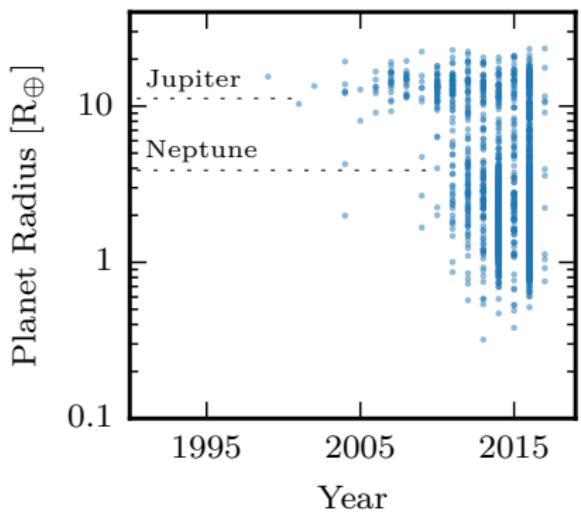
a quick overview



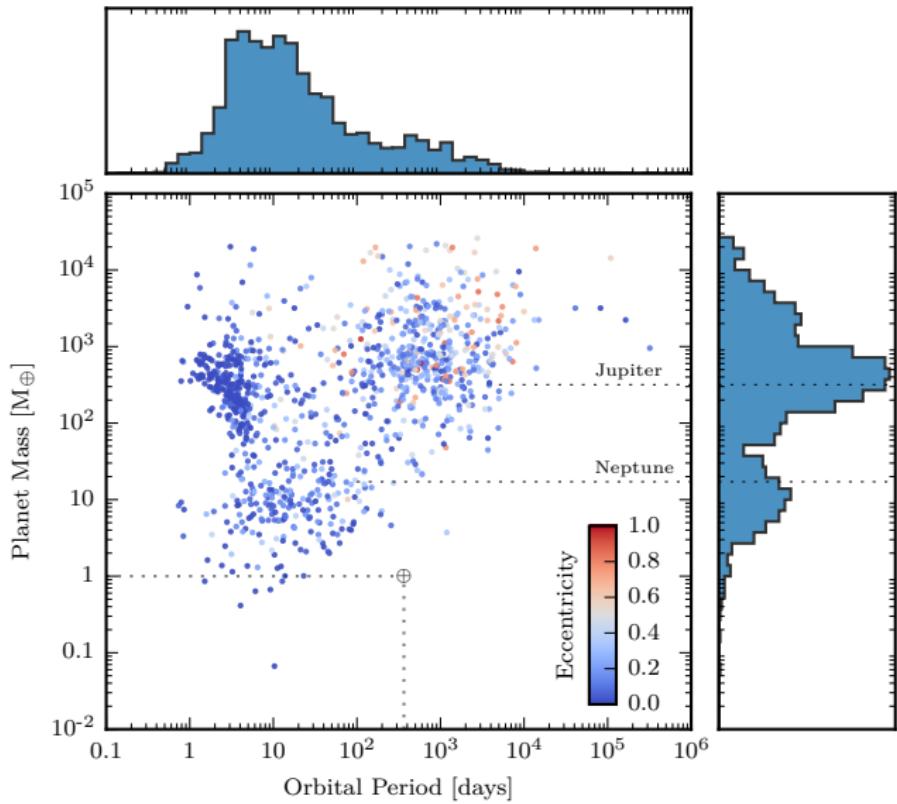
70% of all known exoplanets were discovered since 2014  
(source: [exoplanet.eu](http://exoplanet.eu))

- Kepler is the undisputed champion
- Many transiting planets require RV follow-up
- Microlensing and direct imaging probe different planet populations

# Transits and radial velocity



# The population(s) of exoplanets



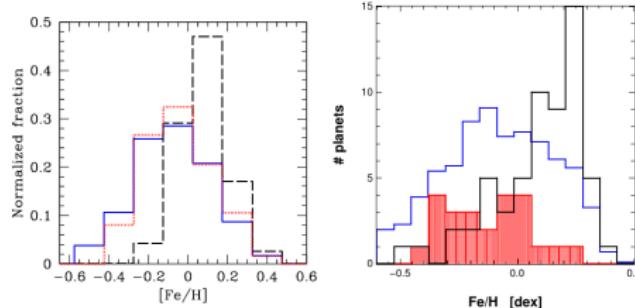
# Planet-metallicity correlation

From RV surveys

- more likely to find a giant planet orbiting a metal-rich star  
e.g. Gonzalez (1997); Santos et al. (2004); Mortier et al. (2013)
- for (super-)Earths, probably no metallicity effect  
Mayor et al. (2011); Sousa et al. (2011); Buchhave et al. (2012); Buchhave & Latham (2015)

but there's more to it...

- differences in the metallicity dependence between Neptune-like planets ( $10 - 40M_{\oplus}$ ) and super-Earths ( $< 10M_{\oplus}$ )  
Courcol et al. (2016)
- excess of hot ( $P < 10$  days), rocky ( $R < 1.7R_{\oplus}$ ) planets around metal-rich stars  
Mulders et al. (2016)



left, models: Benz+ (2014);

right, observed: Mayor+ (2011)



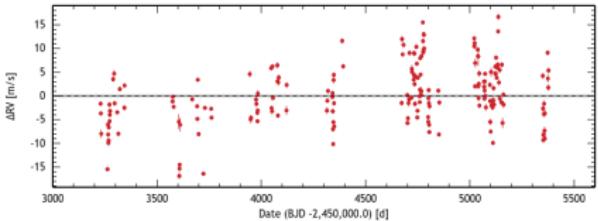
detecting exoplanets  
with radial velocities

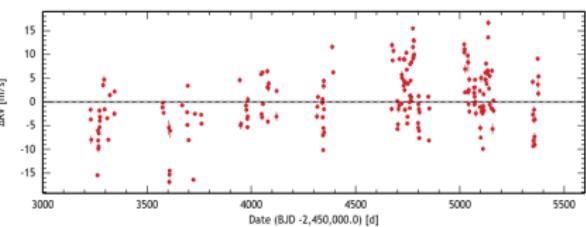
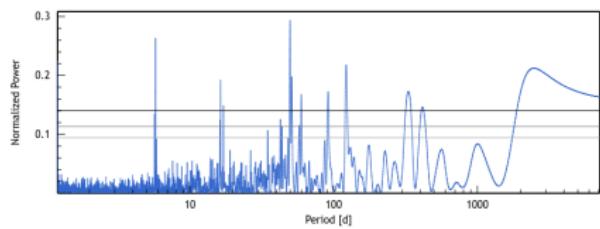
# Exoplanet detection in RVs

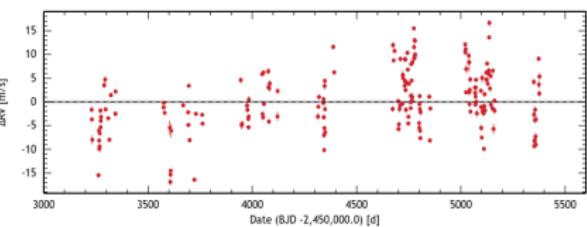
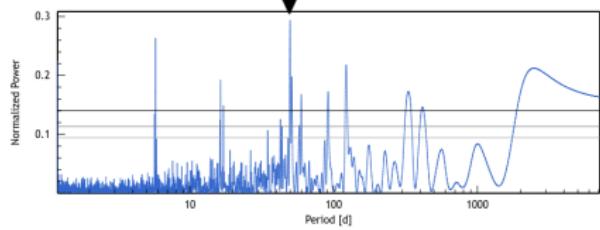
- RV method is more sensitive to massive, short-period planets

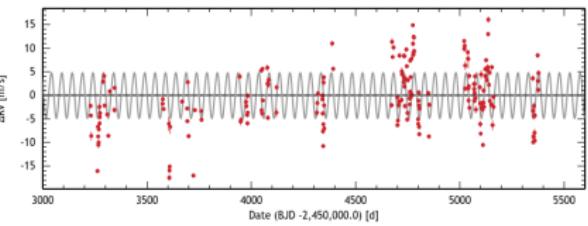
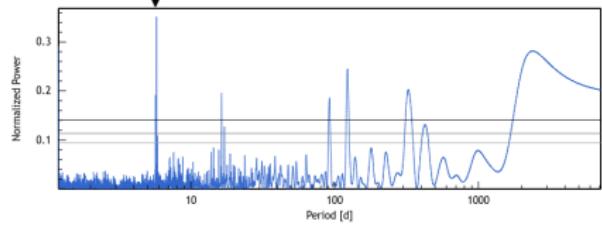
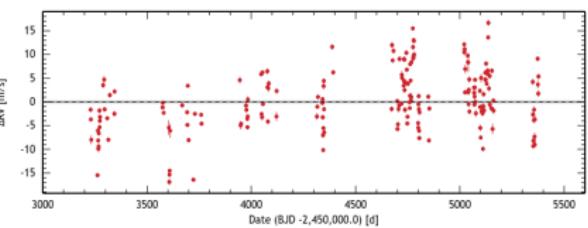
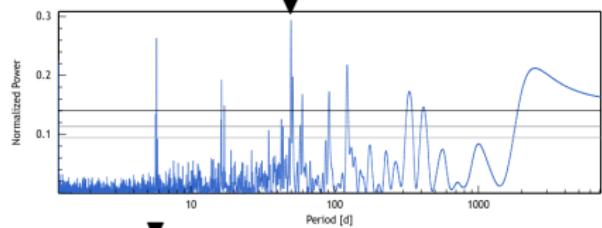
$$S/N \propto \sqrt{N} \frac{K}{\sigma_{\text{RV}}} \propto M_p P^{-1/3} M_*^{-2/3}$$

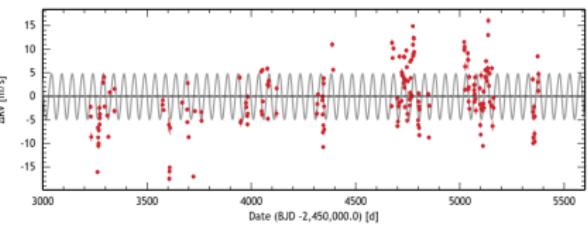
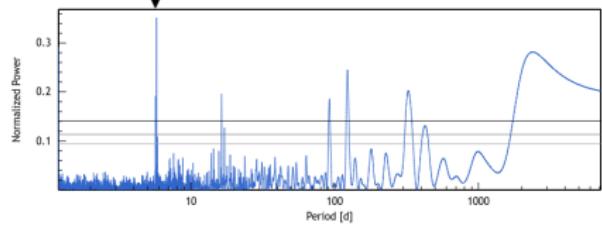
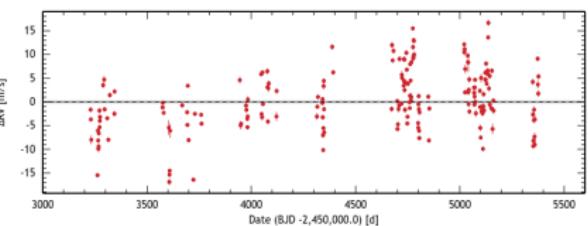
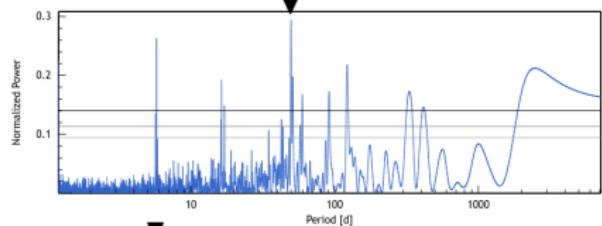
- Current instruments achieve  $\sigma_{\text{RV}} < 1 \text{ m/s}$   
RV effect of Earth on the Sun is 0.09 m/s
- Signals caused by planets well understood (Keplerian functions),  
even if multiple planets interacting gravitationally
- Measurements are often irregularly spaced  
big gaps, plus aliases at 1 yr, 1 month, 1 day
- Stellar activity contaminations at various timescales



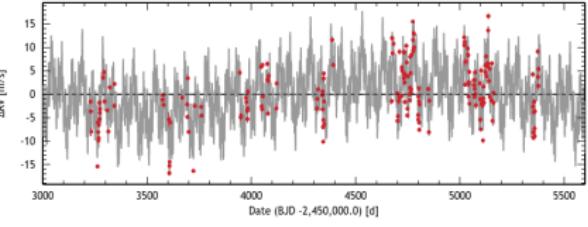
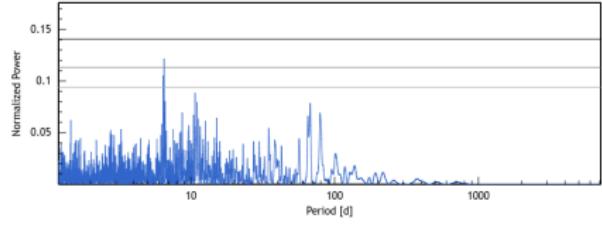








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## The HARPS search for southern extra-solar planets

### XXVIII. Up to seven planets orbiting HD 10180: probing the architecture of low-mass planetary systems<sup>★,★★</sup>

C. Lovis<sup>1</sup>, D. Ségransan<sup>1</sup>, M. Mayor<sup>1</sup>, S. Udry<sup>1</sup>, W. Benz<sup>2</sup>, J.-L. Bertaux<sup>3</sup>, F. Bouchy<sup>4,5</sup>, A. C. M. Correia<sup>6</sup>,  
J. Laskar<sup>7</sup>, G. Lo Curto<sup>8</sup>, C. Mordasini<sup>9,2</sup>, F. Pepe<sup>1</sup>, D. Queloz<sup>1</sup>, and N. C. Santos<sup>10,1</sup>

# Exoplanet detection in RVs

- This periodogram method is quite simple and fast.

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but...

- Smaller amplitude signals are not always clear in the periodogram
- Classical statistical significance is known to have problems
- (very) Different numbers of planets for same data depending on method used to analyse it

e.g. Gl667C – from 2 to 7 planets Delfosse+(2013); Feroz & Hobson (2014); Gregory (2012);  
Anglada-Escudé+(2013)

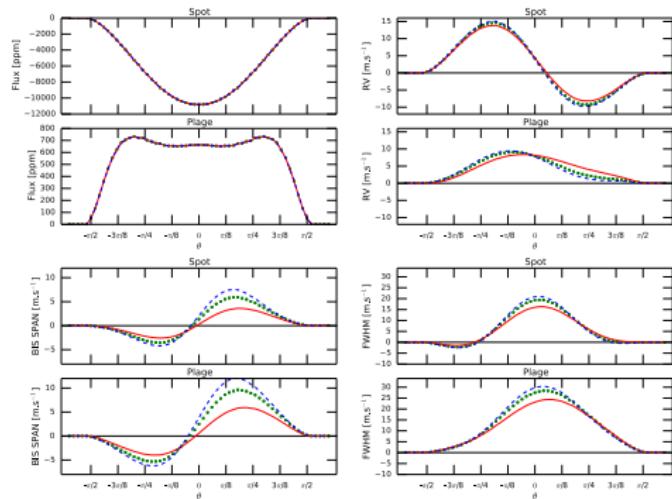
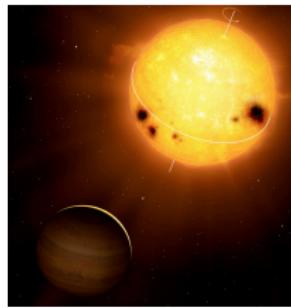
GJ581 – from 3 to 6 planets Hatzes (2016); Robertson+(2014); Baluev (2013);  
Vogt+(2012); Gregory (2011); Mayor+(2009)

HD41248 – 2 planets? Jenkins+(2013); Santos+(2014); Jenkins & Tuomi (2014); Feng+(2017)

$\alpha$ Cen b – planet? Dumusque+(2012); Rajpaul+(2016);

# Exoplanet detection in RVs the stellar activity problem

RV signals induced by the star are the main limitation  
for the detection of low-mass planets

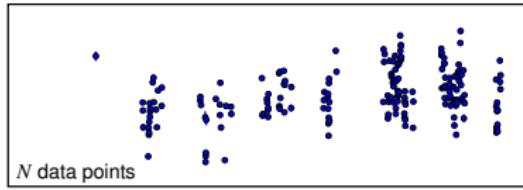


Dumusque et al. (2014)

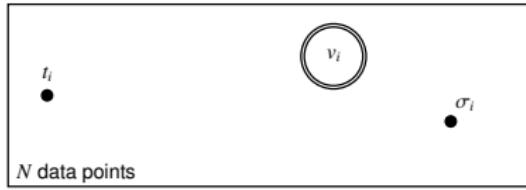


a new approach for  
planet detection in RVs

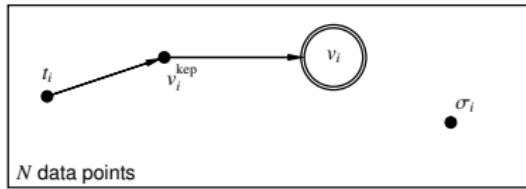
# A model for RV variations



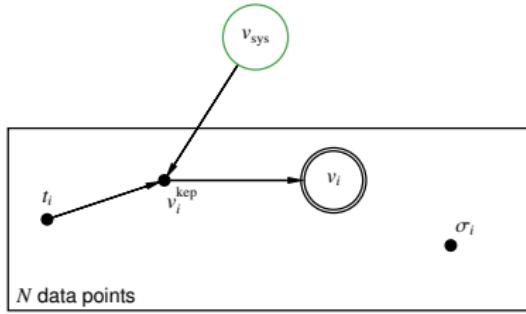
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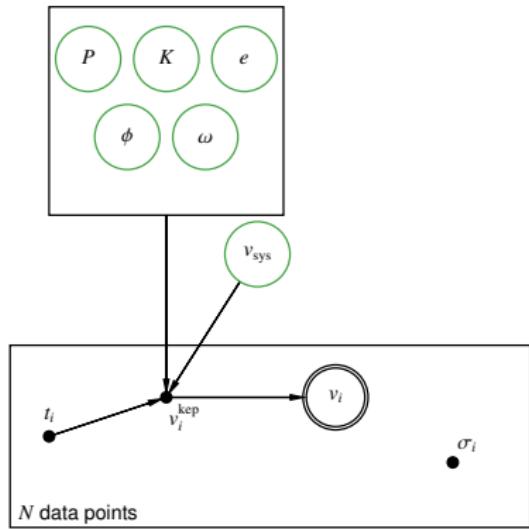
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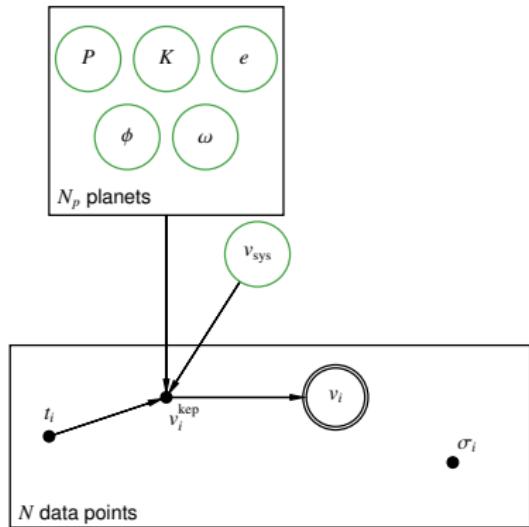
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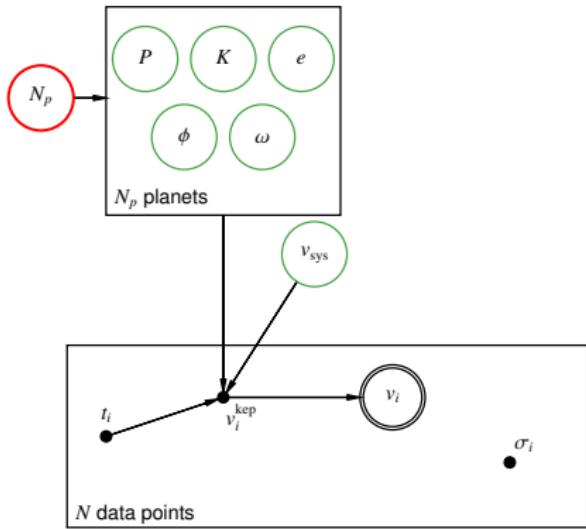
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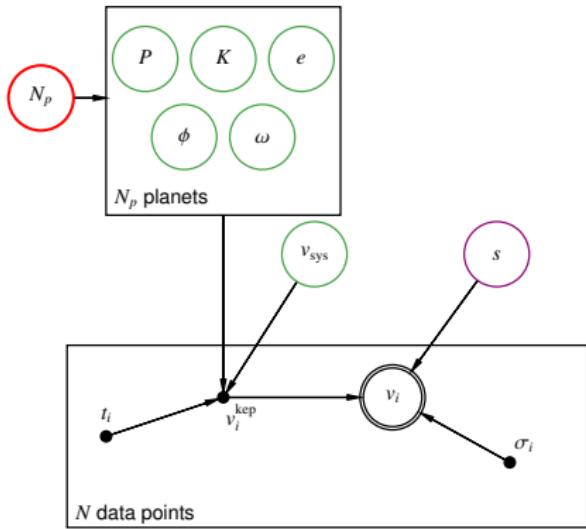
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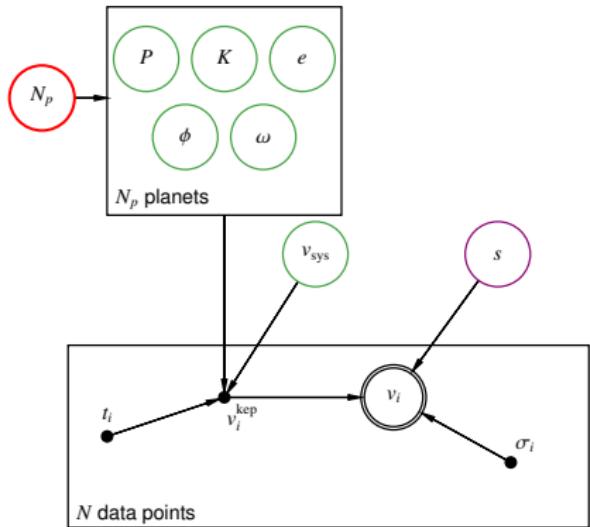
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sample the posterior distribution  
of all parameters with MCMC

Brewer+ (2011), Brewer (2014), Brewer & Donovan (2015)

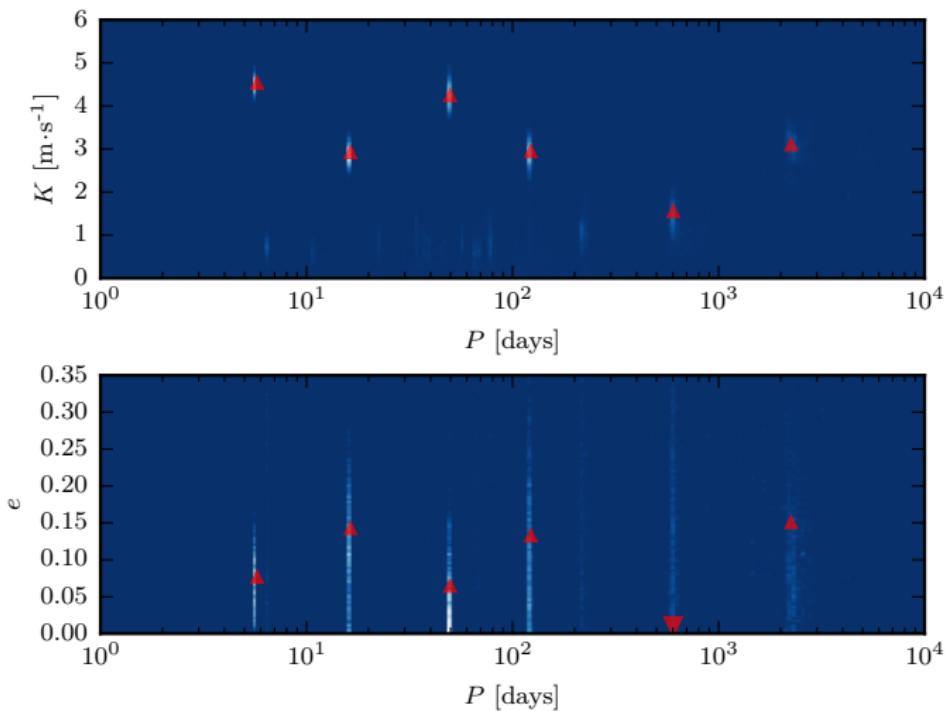
in total  $5 N_p + 3$  parameters

every parameter needs a prior  
every parameter has a posterior  
(likelihood is Gaussian)

$N_p$  is also a parameter!

# Posterior distributions

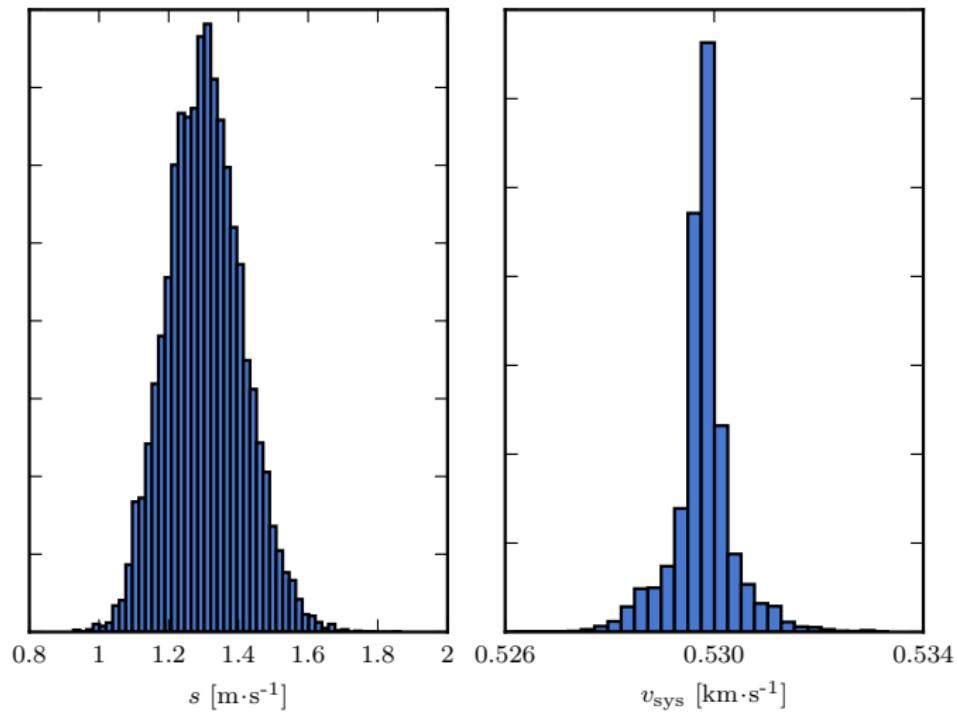
analysis of HD10180 as before



triangles are orbital parameters from Lovis et al. (2011)

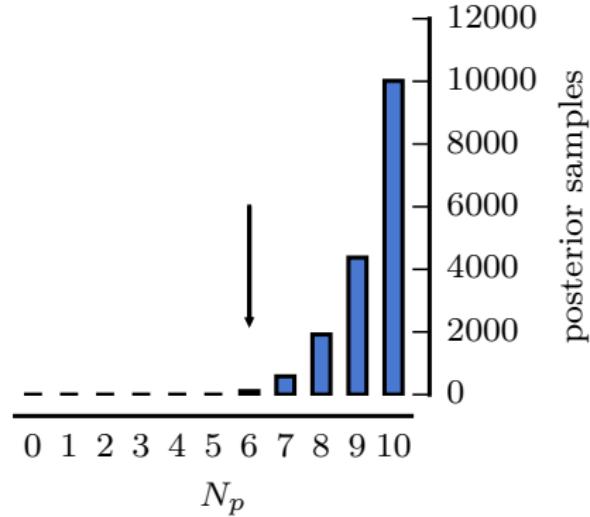
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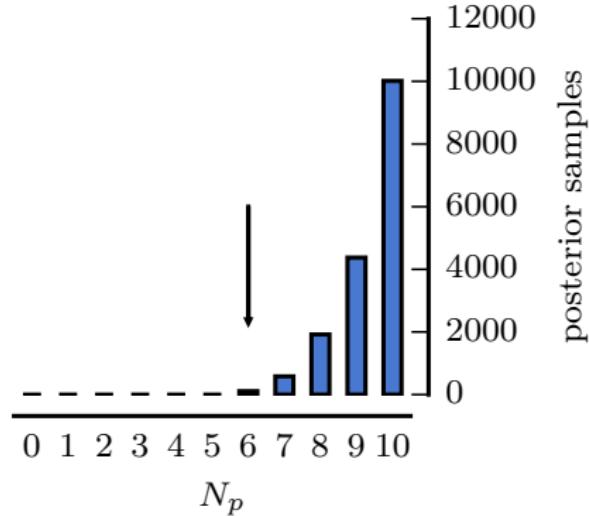


- Detection criteria:  $p(N_p + 1)/p(N_p) > 150$

Jeffreys (1961); Kass & Raftery (1995); Efron & Gous (2001); Feroz+ (2011); Tuomi (2012)

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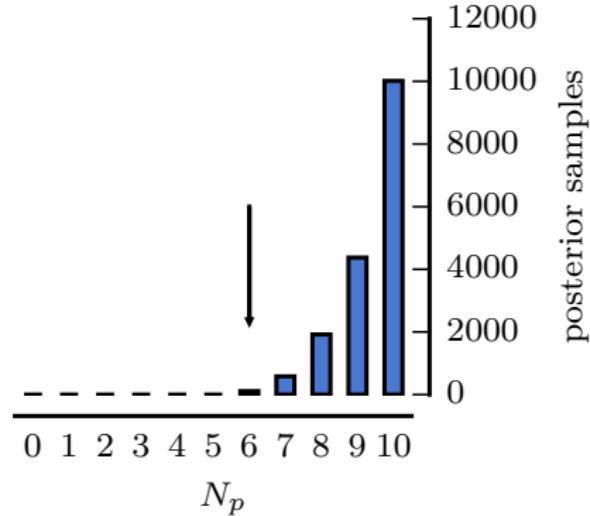
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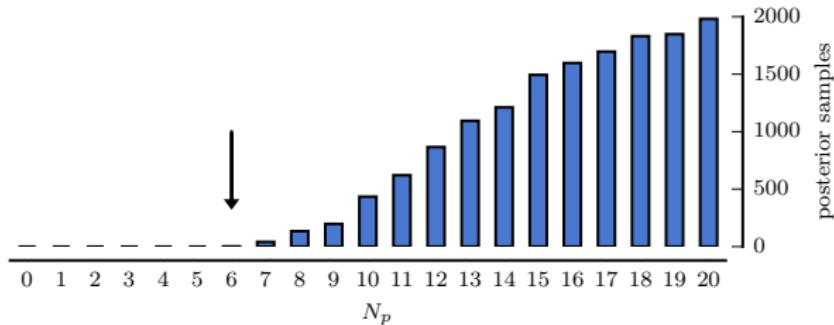
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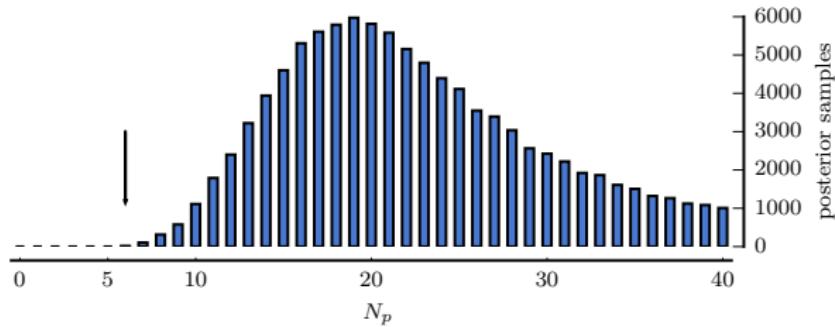
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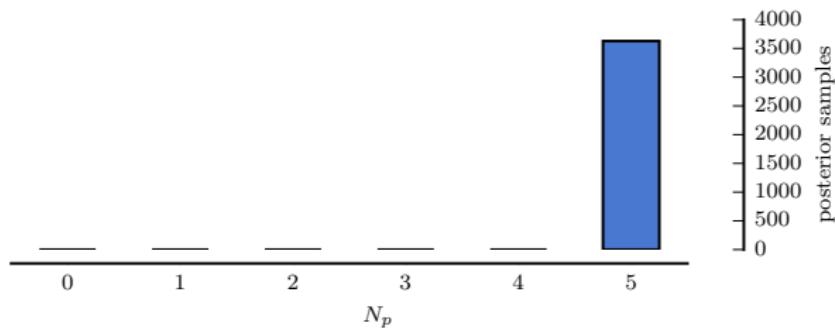
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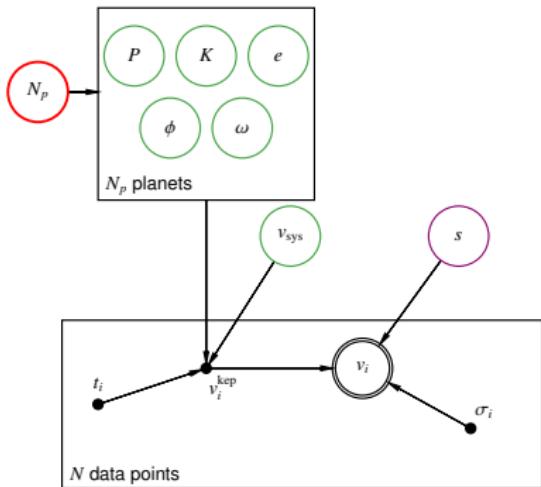
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# What about stellar activity?

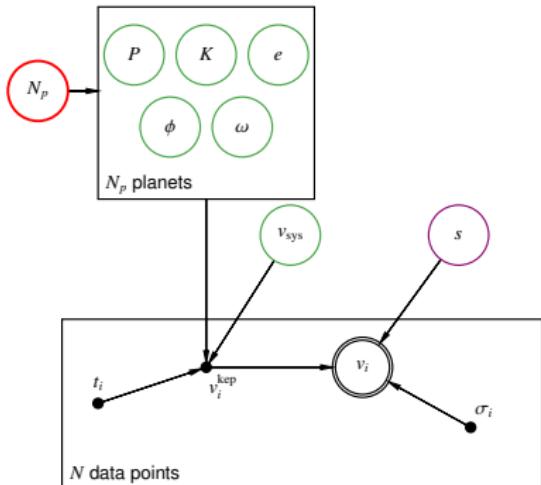
# What about stellar activity?



# What about stellar activity?

Activity signals are quasi-periodic:

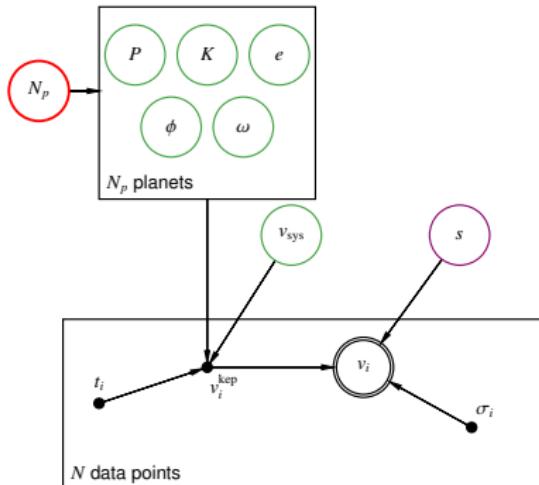
- stars rotate
- active regions evolve



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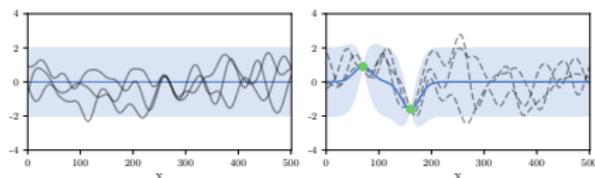
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Use Gaussian processes to model correlated activity “noise”

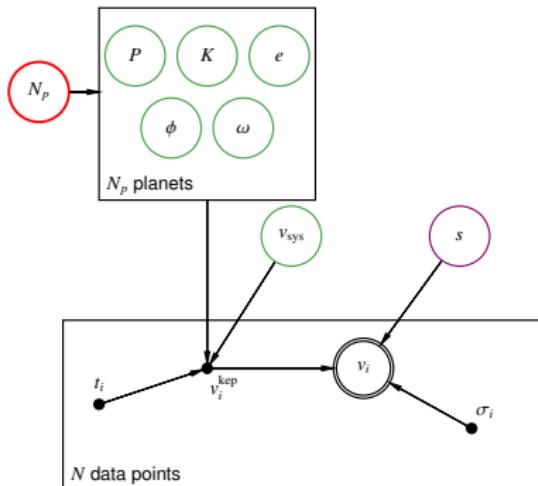
Haywood+ (2014), Grunblatt+ (2015), Faria+ (2016)



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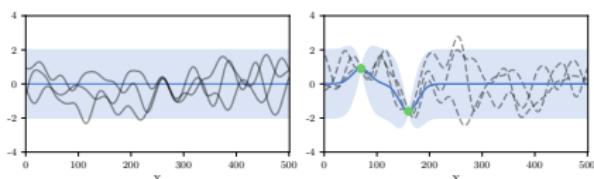
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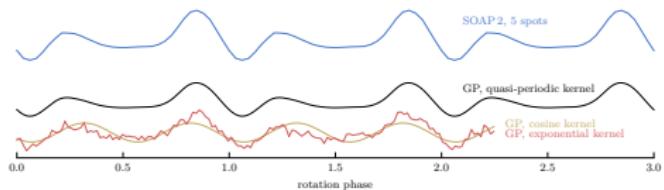


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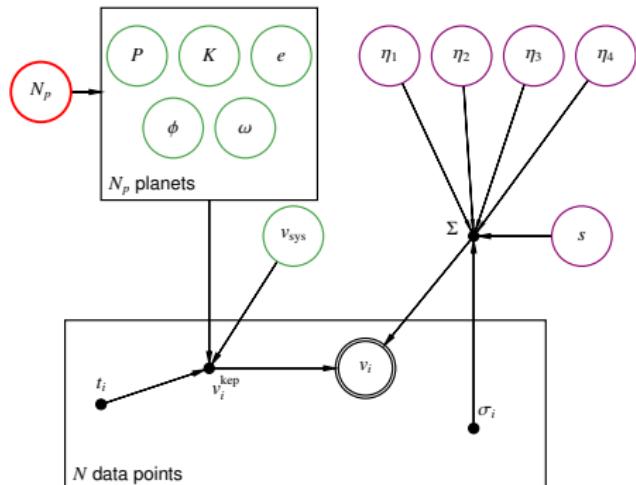
Choose a kernel that can match RV activity signals see also João Camacho's work



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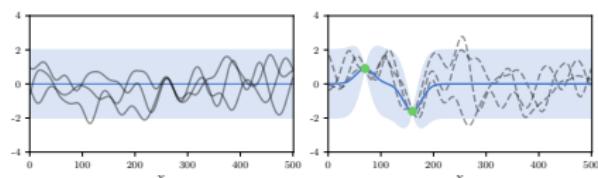
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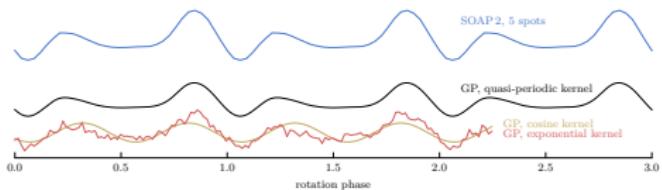


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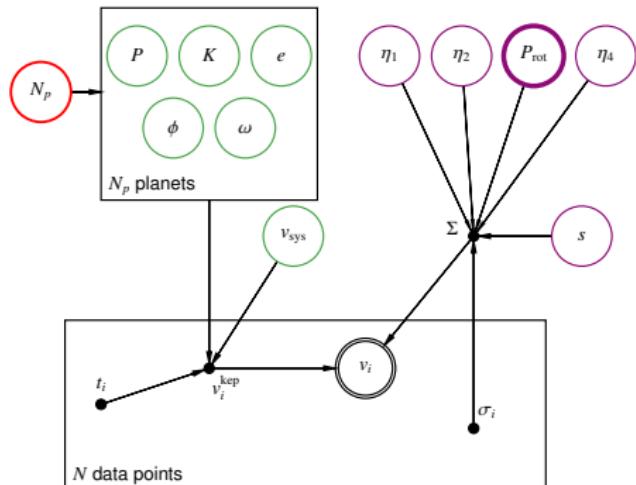
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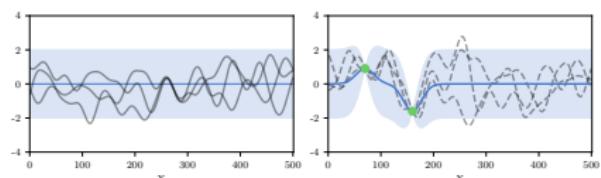
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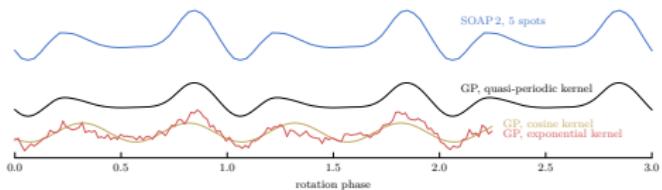


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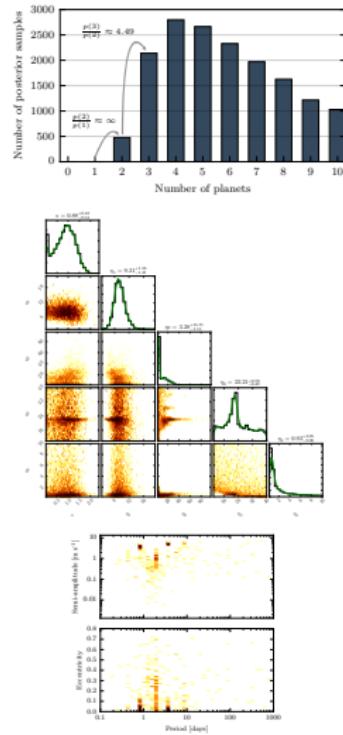


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## CoRoT-7

Faria+ (2016), Haywood+ (2014)



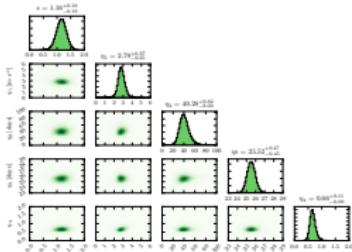
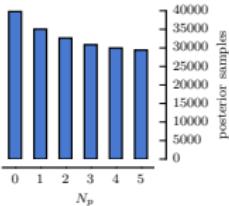
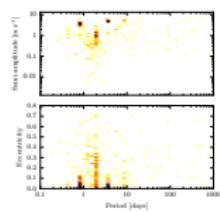
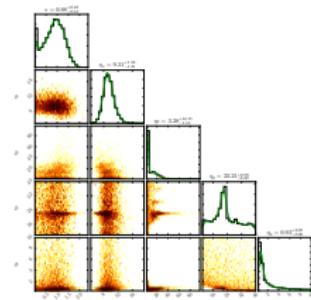
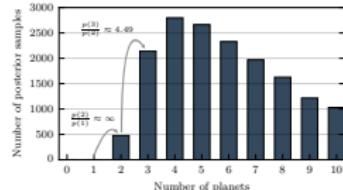
# What about stellar activity?

CoRoT-7

Faria+ (2016), Haywood+ (2014)

HD 41248

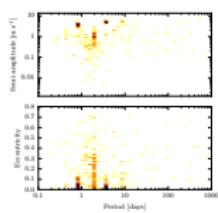
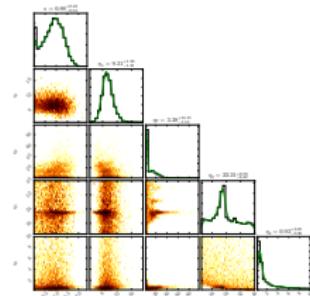
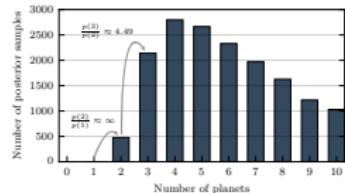
see also Santos+ (2014)



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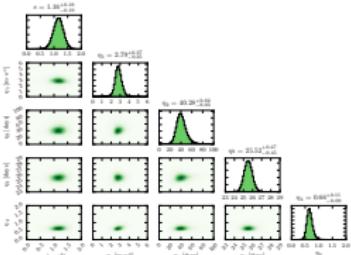
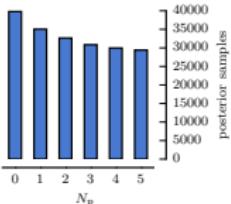
CoRoT-7

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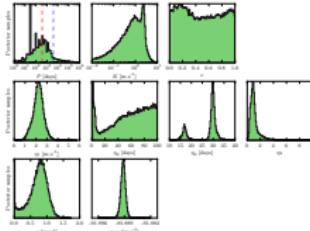
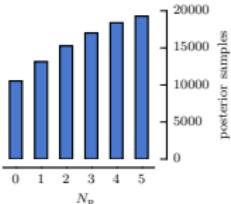
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HD 175607

see also Mortier+ (2016)

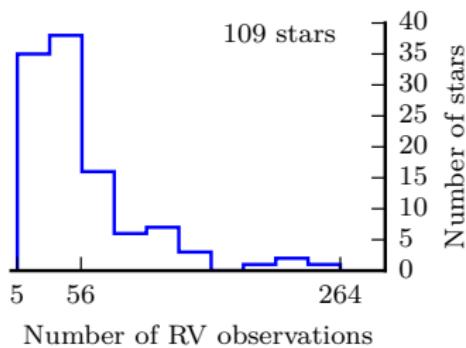
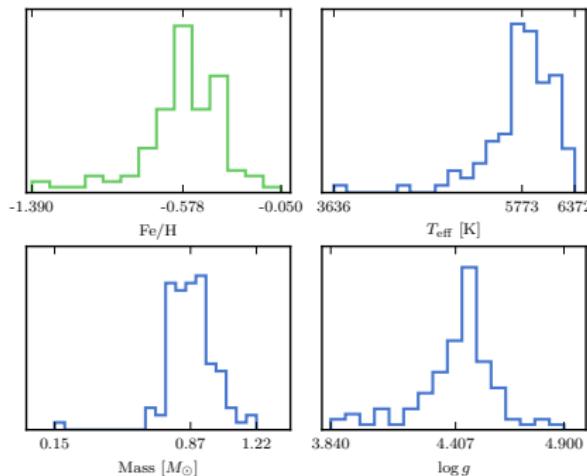




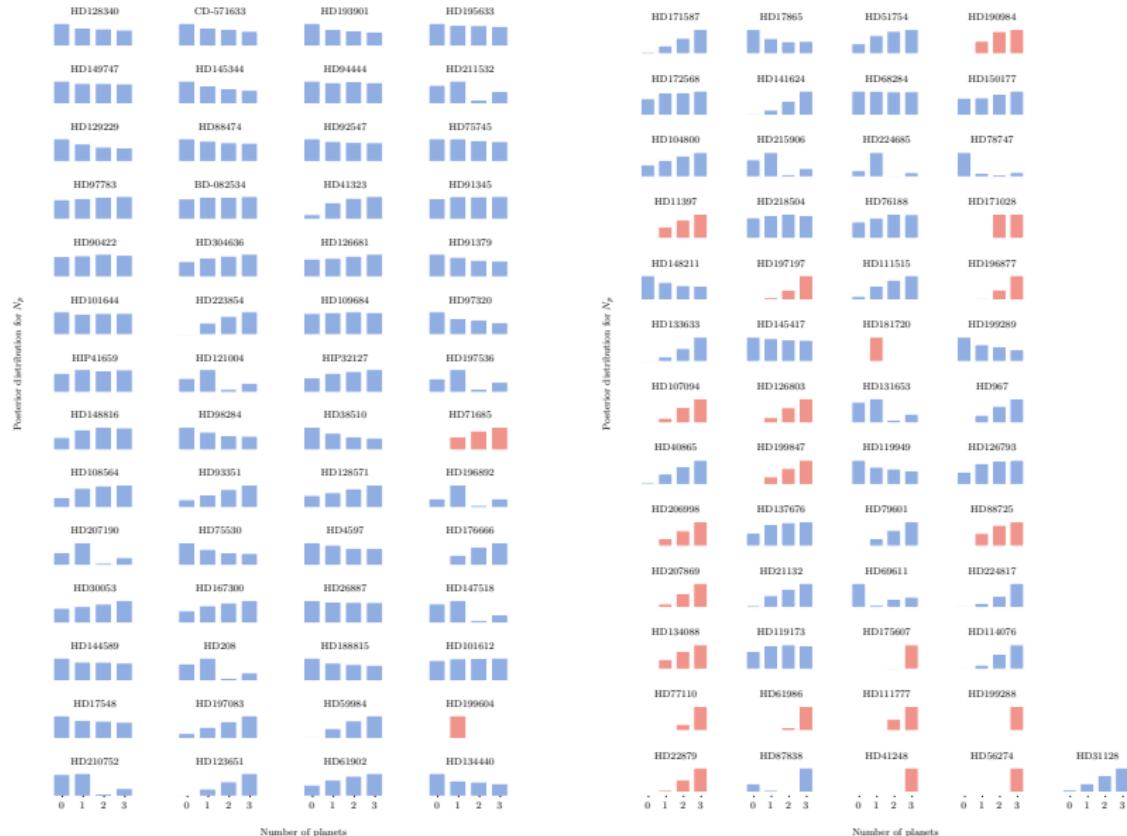
the metal-poor survey

# The metal-poor survey

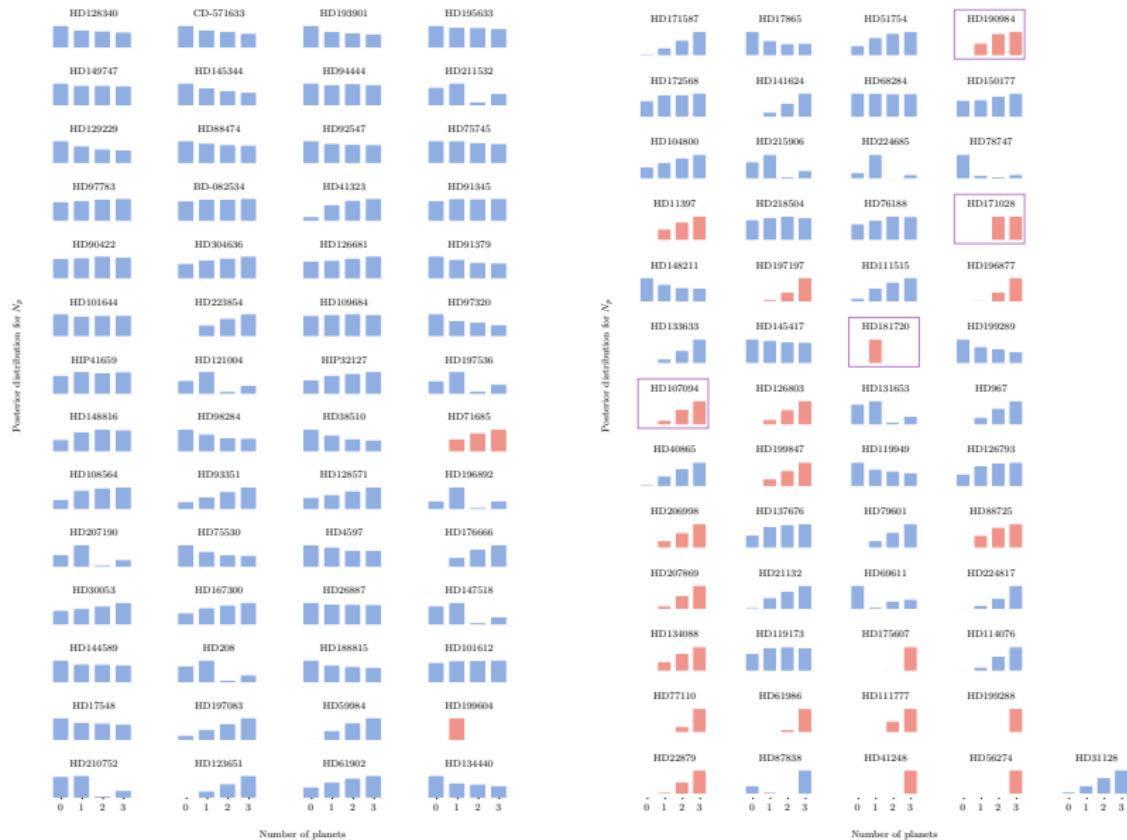
- A sample of 109 metal-poor stars followed extensively with the HARPS spectrograph
- Main goal 1: detect low-mass planets
- Main goal 2: calculate occurrence rate in metal-poor regime



# The metal-poor survey - planet detection



# The metal-poor survey - planet detection



# The metal-poor survey - planet detection

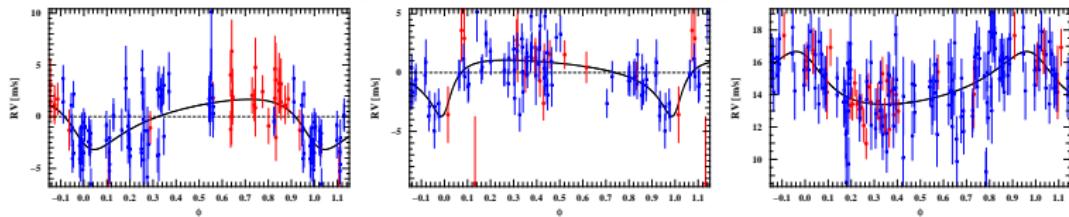


# The metal-poor survey - planet detection



# The metal-poor survey - planet detection

a few candidate planets



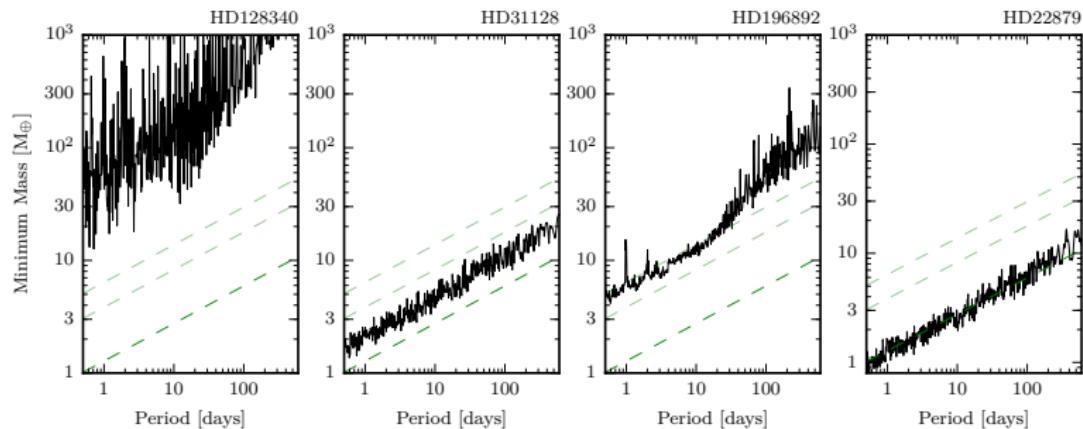
but not very convincing...

## The metal-poor survey - detection limits

- Each star's RV timeseries provides upper limits on which planets can be detected

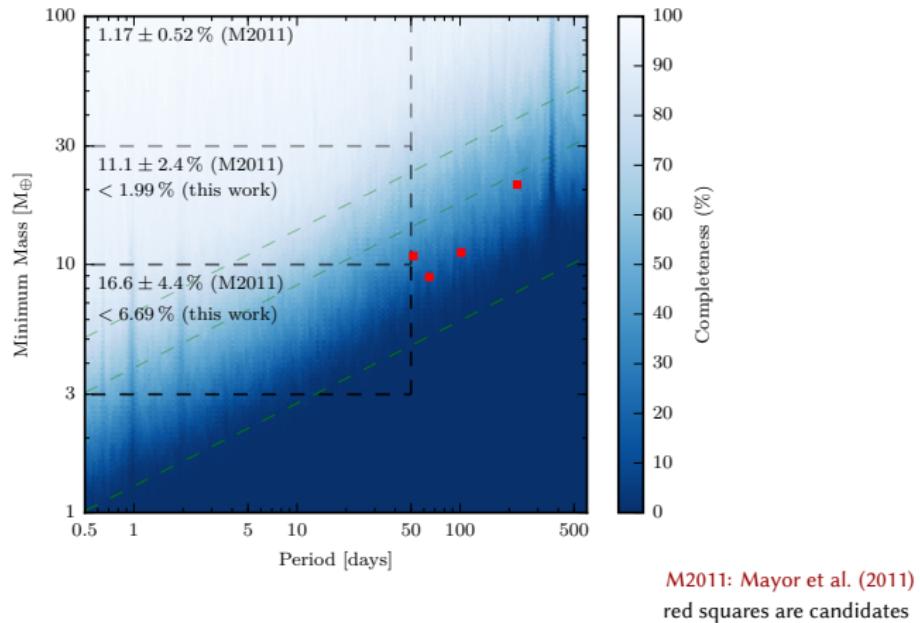
# The metal-poor survey - detection limits

- Each star's RV timeseries provides upper limits on which planets can be detected
- Upper limits depend on number of observations, sampling, etc.



# The metal-poor survey - detection limits

- Combining all stars we obtain the survey completeness



Significantly lower occurrence rates than in solar-metallicity stars

# Take-home messages

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- RV planet detection can be approached with a general model where all planets' parameters and the number of planets are **inferred simultaneously**

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- RV planet detection can be approached with a general model where all planets' parameters and the number of planets are **inferred simultaneously**
- Extended this model to **account for stellar activity** using GPs to model the stellar quasi-periodic signals
  - CoRoT-7: 2 planets, consistent orbital parameters details in Faria+ (2016)

## Take-home messages

- RV planet detection can be approached with a general model where all planets' parameters and the number of planets are **inferred simultaneously**
- Extended this model to **account for stellar activity** using GPs to model the stellar quasi-periodic signals
  - CoRoT-7: 2 planets, consistent orbital parameters details in Faria+ (2016)
- Application to the metal-poor survey reveals a few interesting candidates but **lower occurrence rates** when compared to solar-metallicity stars

# The search for planets around metal-poor stars

Question time

João Faria, IA, Porto



**FCT**

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