Constraining limb-darkening from young active solar analog stars

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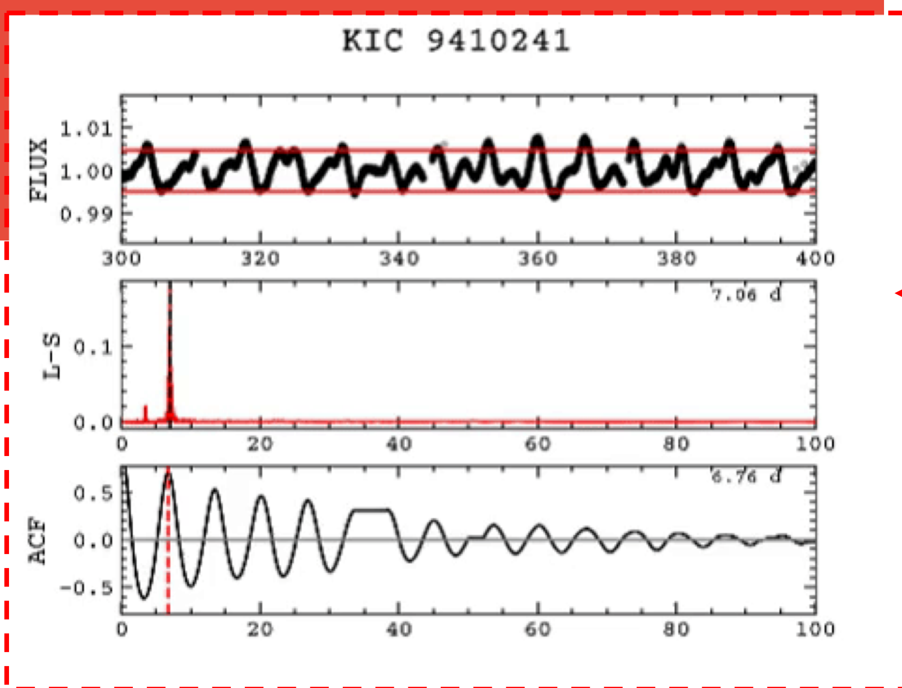
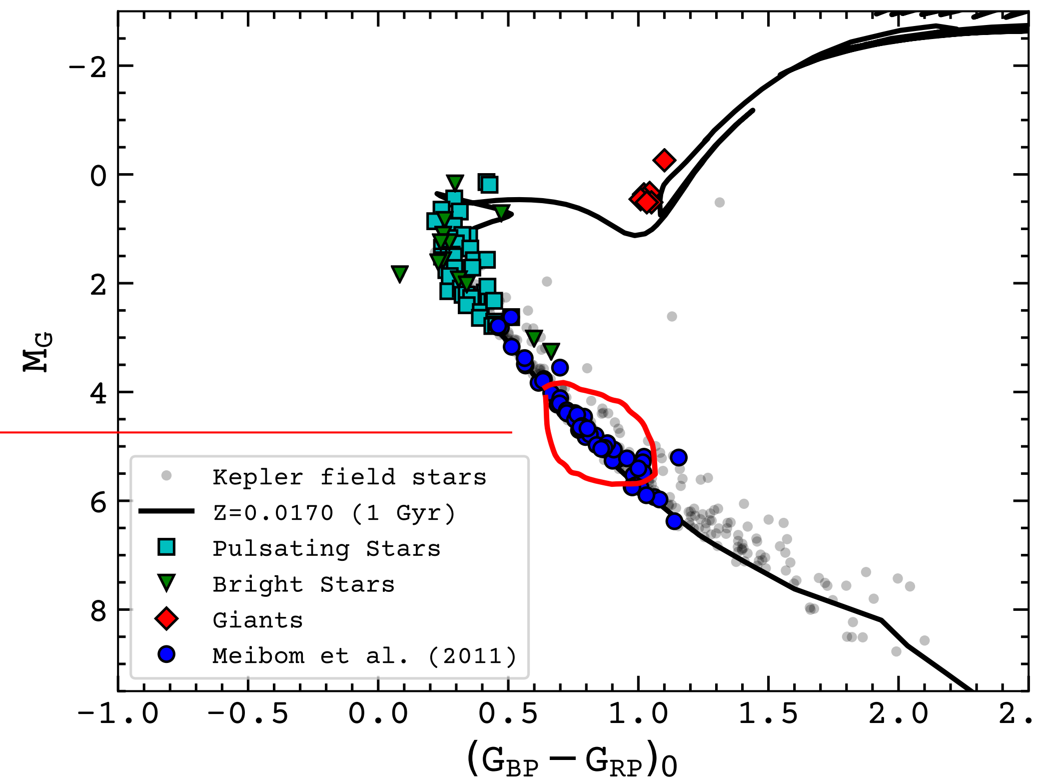
(*) PLATO 2.0 – WP122.400 PLATO Limb-Darkening meeting, Granada 2019

Introduction : "Fix or Fit Limb Darkening"

NGC 6811 and Kepler + GAIA DR2





(do Nascimento and Meibom 2018)

Introduction – Why young solar analogs?

- Younger stars are more active and consequently have a higher SNR in their light curve modulations;
- Possibility to constrain behavior of differential rotation and limb-darkening at a certain evolutionary stage;
- Narrow range of fundamental parameters (age, mass, metallicity) -- open clusters!
- NGC 6811 (1 Gyr, Z=0.0170): intermediate-age solar-type stars.
- Kappa 1 Ceti observed by MOST is a proxy of the young Sun

Introduction – Development of spot modeling

- Analytic models of Budding (1977), Dorren (1987) and Eker (1994) -- very similar!
- Softwares: SpotModeL (Ribárik et al. 2003) and StarSpotz (Croll 2006);
- Cheetah code and degeneracies (Walkowicz et al. 2013);

Limited to few long-lived spots with limb-darkening laws usually fixed a priori.

Introduction – The macula model

- Developed in Fortran by Kipping (2012);
- Non-linear limb-darkening with 4-parameter laws for both star and spot;
- 2-parameter differential rotation profile:

$$P(\Phi) = P_{\rm eq}/(1 - \kappa_2 \sin^2 \Phi - \kappa_4 \sin^4 \Phi)$$

- Spot area evolution with linear ingress and egress;
- Partial derivatives analytically computed with respect to each parameter.

The dwelf python module

CheetahModeler class

- Reformulated Cheetah code, with MCMC and the possibility to reduce degeneracies through estimates of v sin i and stellar radius;
- Allows to fit for a few (2 or 3) spots with infinite lifetimes and a fixed 2-parameter limb-darkening law;
- Values speed over precision.

MaculaModeler class

- Wrapped macula Fortran code;
- Many more free parameters --> higher dimensionality;
- Allows to use MCMC or MultiNest for posterior sampling;
- Includes sampling techniques for 2- and 3-parameter limb-darkening laws (Kipping 2013; Kipping 2016).

Inclination vs Period constraints

Main Idea:

$$\omega \sin i = \frac{v \sin i}{R_\star} \propto \frac{\sin i}{P_{\mathrm{eq}}}$$

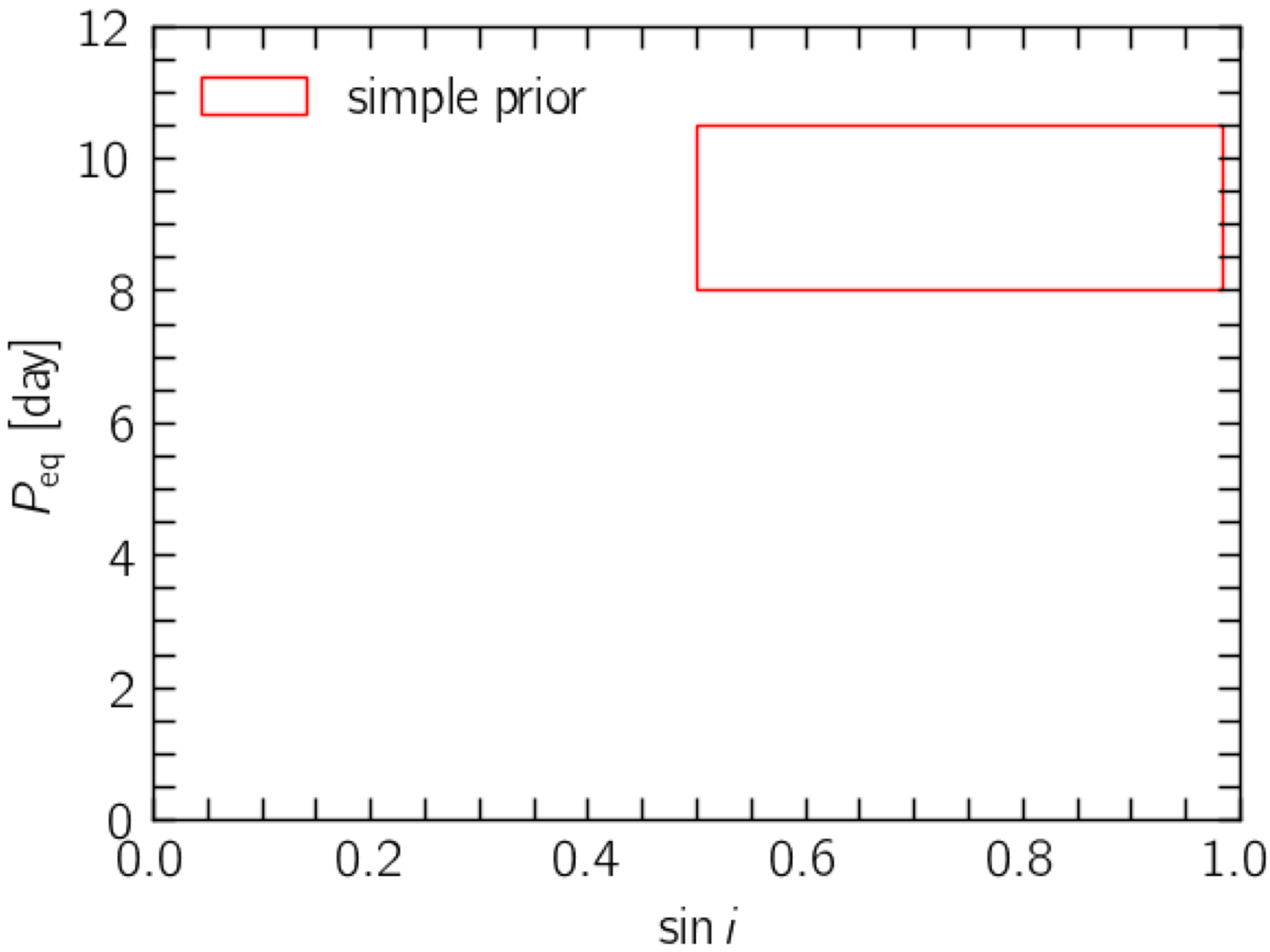
Sample scenario: *Kappa 1 Ceti*

Assuming $R_\star = 0.95 \pm 0.10 R_\odot$ and $4.5 \text{ km/s} < v \sin i < 5.5 \text{ km/s}$:

$$(\omega \sin i)_{min} = \frac{(v \sin i)_{min}}{R_{\star,max}} \simeq 6.16 \times 10^{-6} \text{ rad/s}$$

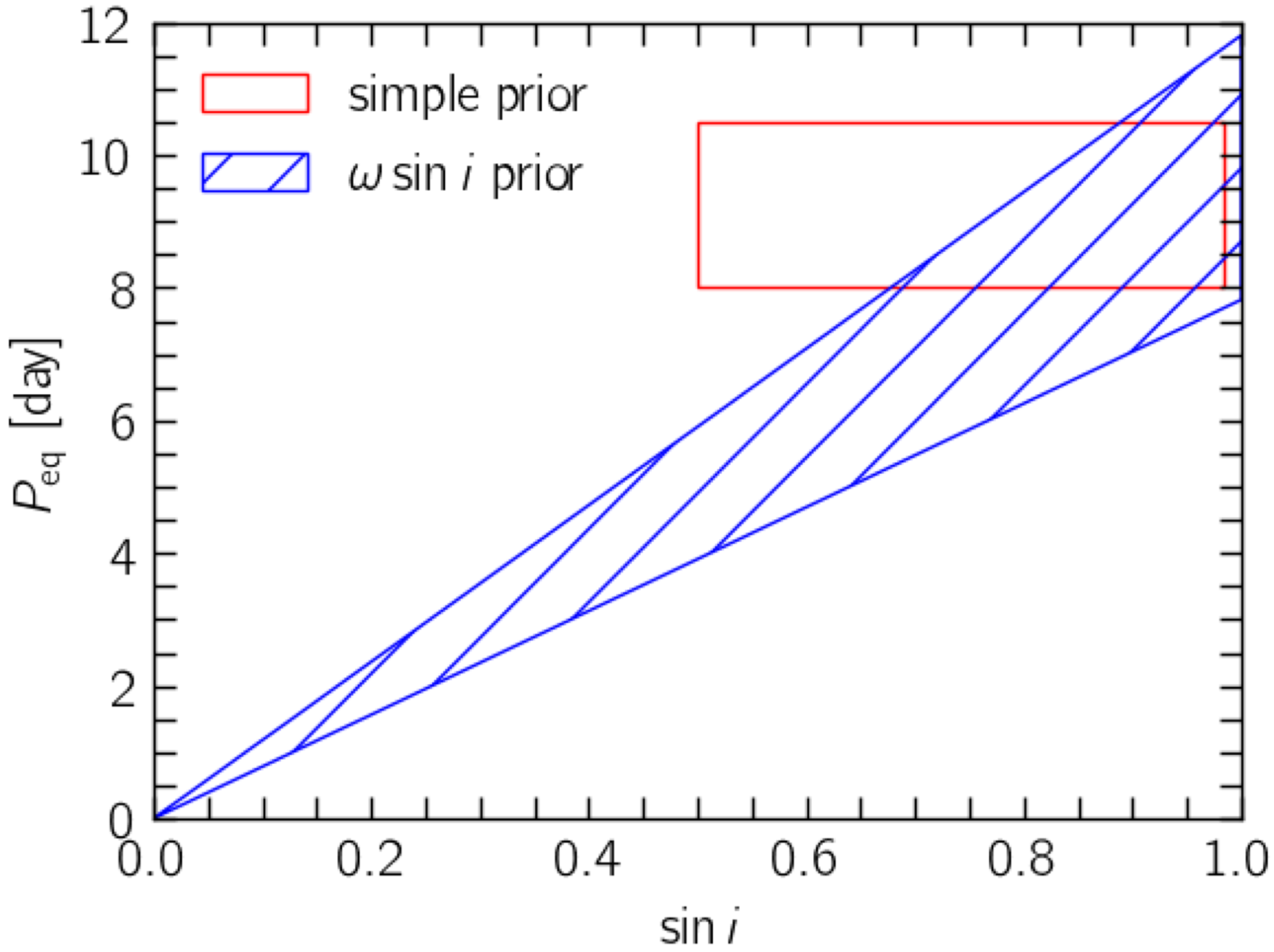
$$(\omega \sin i)_{max} = \frac{(v \sin i)_{max}}{R_{\star,min}} \simeq 9.30 \times 10^{-6} \text{ rad/s}$$

Sampling region



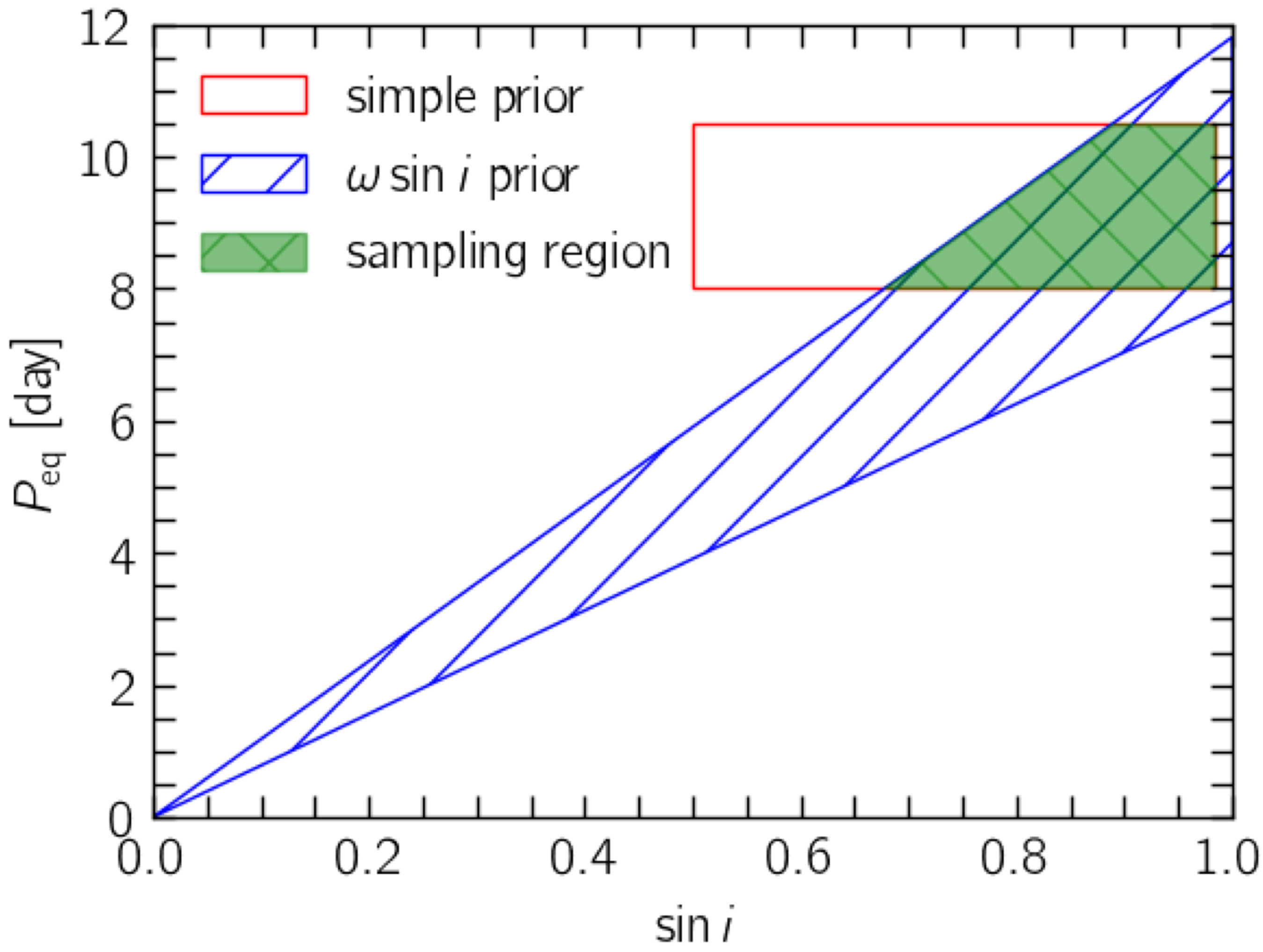
- A simple prior consists on a uniform distribution over some range of valid rotation periods and sin i
  (--> rectangle)
- In this example, we are restricting kappa Ceti's period to between 8.0 and 10.5 days, and its inclination from 30 to 80 degrees.

Sampling region



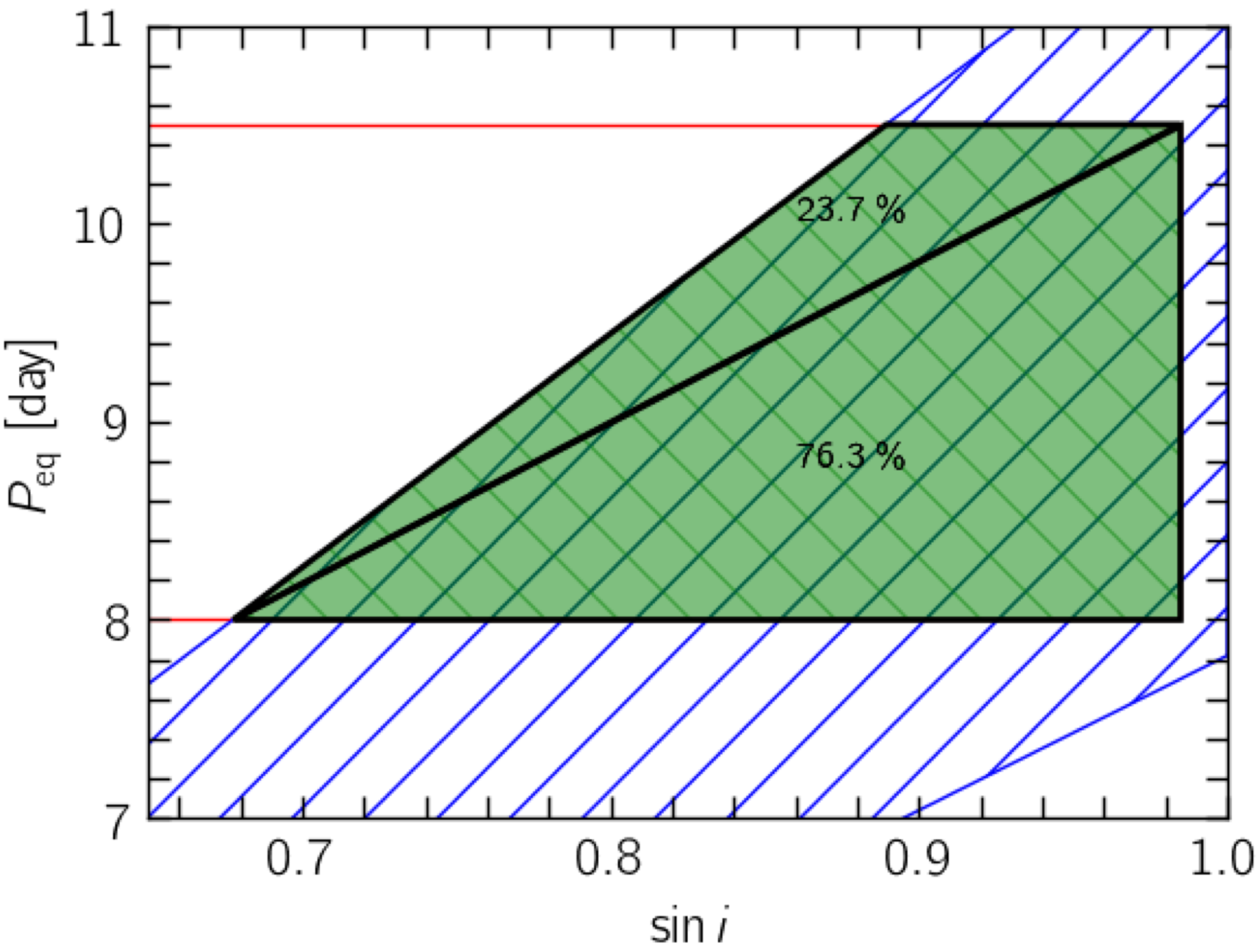
- Now the spectroscopic constraint comes in, only allowing the region between two straight lines.
  (--> triangle)

Sampling region



- The physically meaningful region of parameter space is hence the intersection of the two previous polygons.

Triangulating the sampling polygon

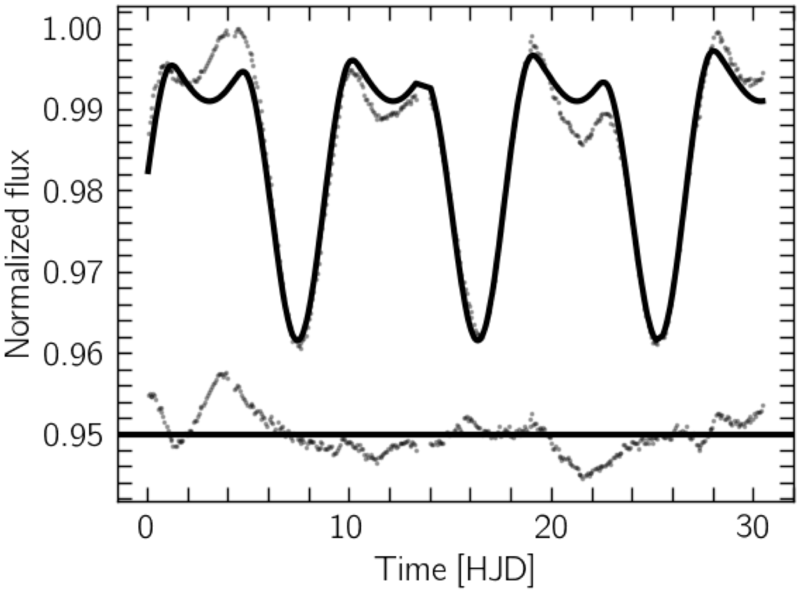


1. In order to uniformly sample this irregular convex polygon we first cut it into triangles;
2. Then we random-pick one of the triangles based on their relative areas;
3. And finally we pick a point in the chosen triangle using standard algorithms of uniform triangle sampling.

First results

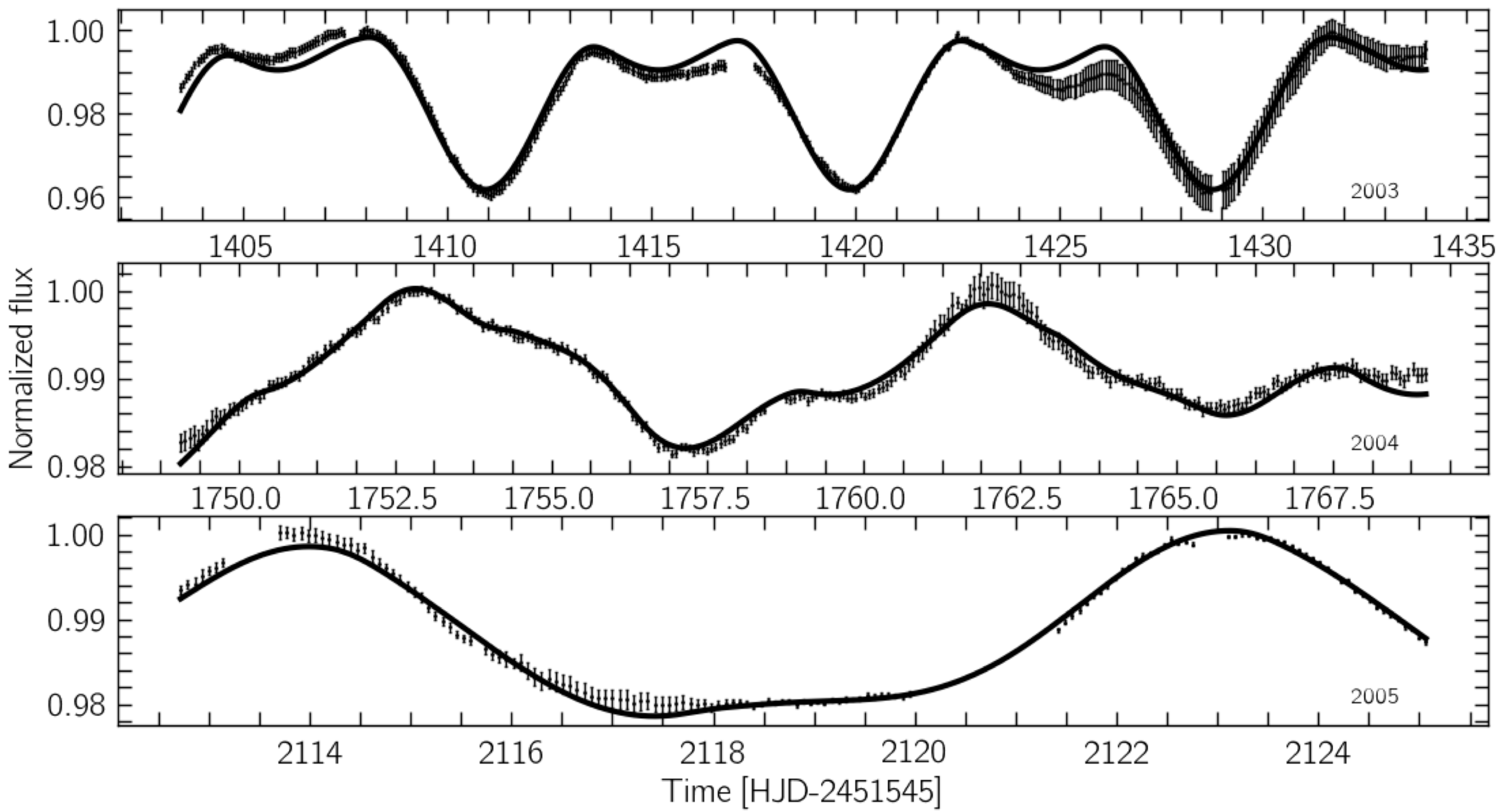
Validating CheetahModeler

Parameter	CheetahModeler	Walker et al. 2007
i (deg)	$61.79^{+11.02}_{-8.78}$	57.8 – 63.5
P_{eq} (day)	$8.82^{+0.37}_{-0.40}$	8.74 – 8.81
κ	$0.118^{+0.211}_{-0.260}$	0.085 – 0.096

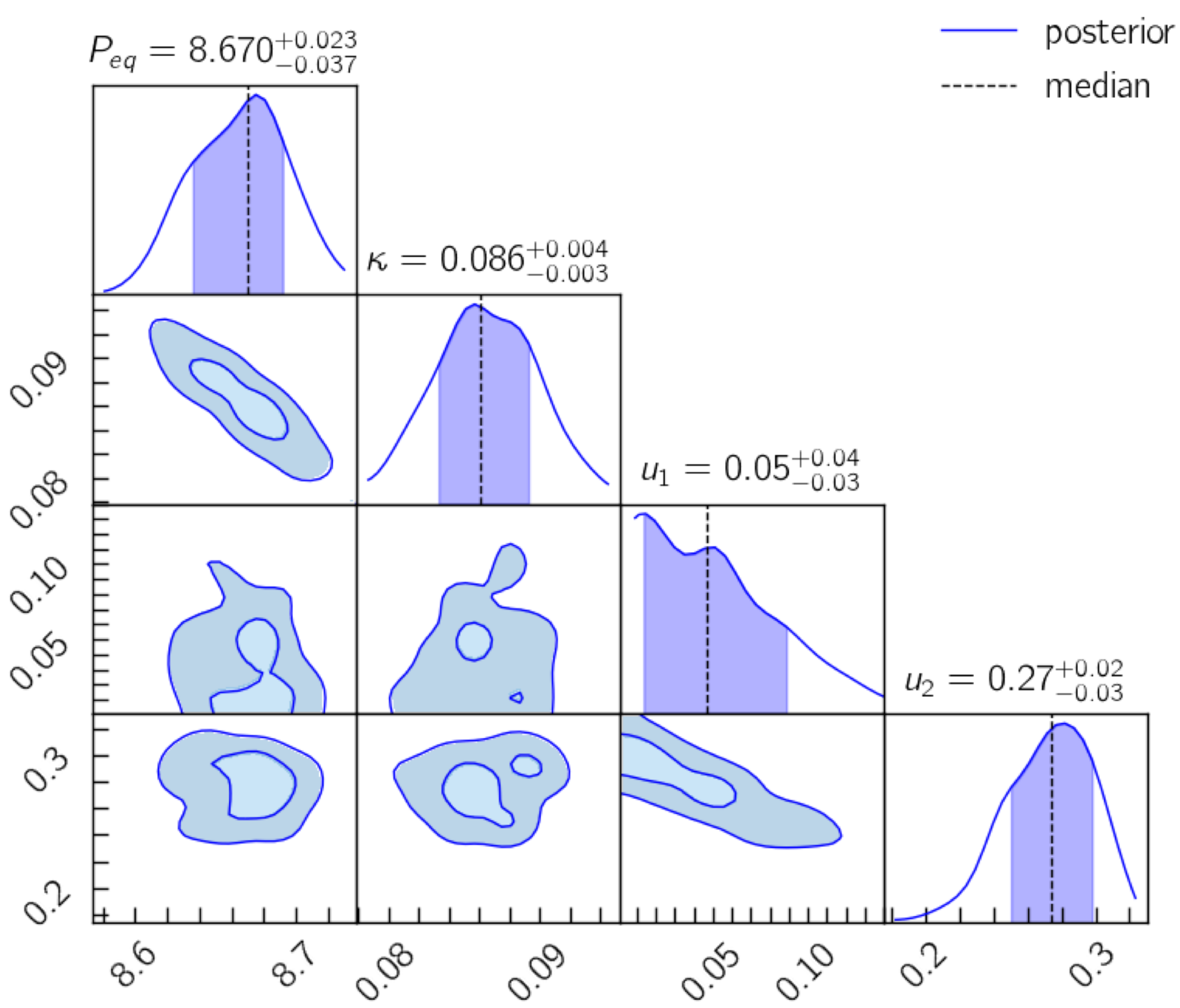


A meaningful result is obtained with large uncertainties but little computational work (~30 mins)

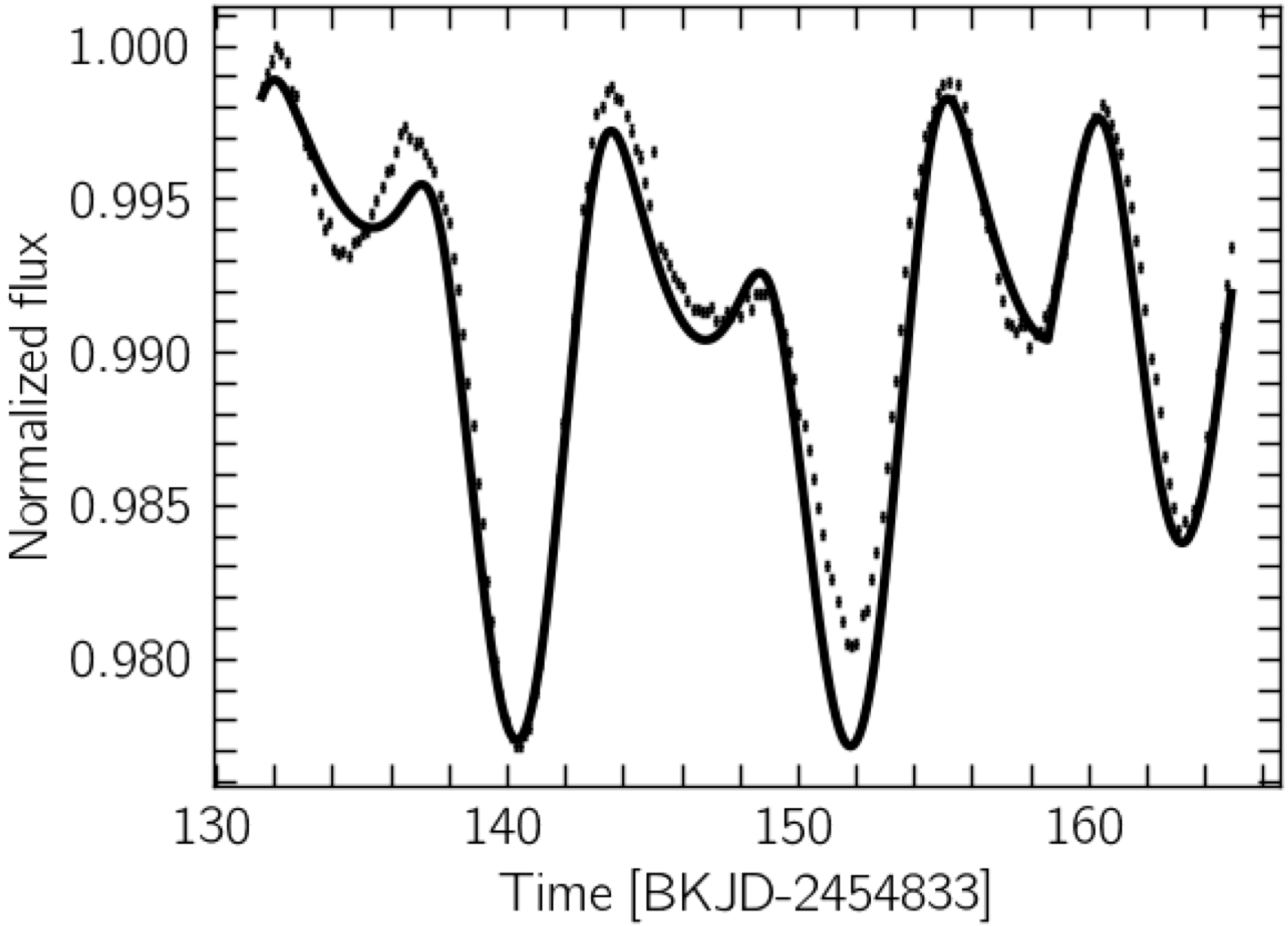
MaculaModeler test case 0 – recover results for kappa Ceti



MaculaModeler test case 1 – revisit kappa Ceti (fitted quadratic law)



MaculaModeler test case 2 – KIC 9655172 (NGC 6811)



Conclusions & Perspectives

- Apply the MultiNest + macula method to Kepler light curves from active solar analogs of NGC 6811 and determine differential rotation parameters;
- Fit limb-darkening coefficients for stars with spot configurations already determined by non-photometric techniques;
- Use these results as benchmarks until PLATO flies.

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Astronomy & Astrophysics manuscript no. output
February 15, 2019

Spot-induced modulations of active solar analog stars

I. Constraints to limb-darkening

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Received September 15, 1996; accepted March 16, 1997

ABSTRACT

Context. Light curve modulations of cool stars are the result of spots crossing the visible stellar disc. Due to differential rotation, spots at different latitudes have different rotation periods. In order to accurately model a star's rotation profile, it is necessary to consider the effects of limb-darkening on the stellar surface.
Aims. Constrain parameters of limb-darkening and differential rotation using spot modelling.
Methods. We use the macula starspot model together with MultiNest sampling algorithm to sample the posterior probability distribution of the parameter space.
Results. We are able to reproduce the known results for κ^1 Ceti, a young solar analog observed by MOST, and we extend the method to active solar analog stars in the intermediate-age open cluster NGC 6811. We choose time windows from the 4 year long Kepler light curves in order to reduce the computational complexity.
Conclusions. This method could be useful for identifying trends in differential rotation and limb-darkening as a function of mass and age for solar-type dwarfs observed by PLATO.

Key words. methods: miscellaneous – stars: solar-type – starspots

THANK YOU!

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