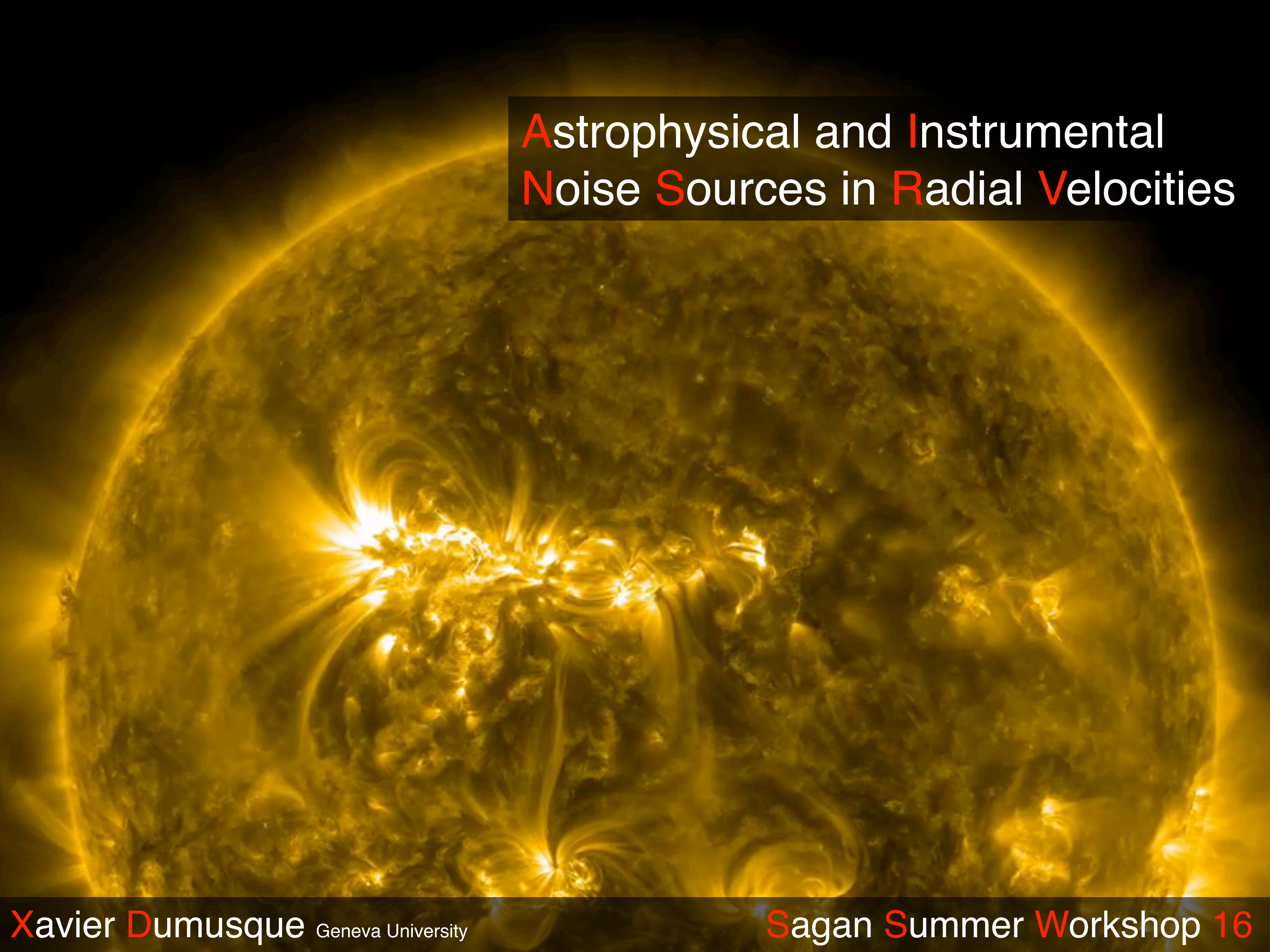
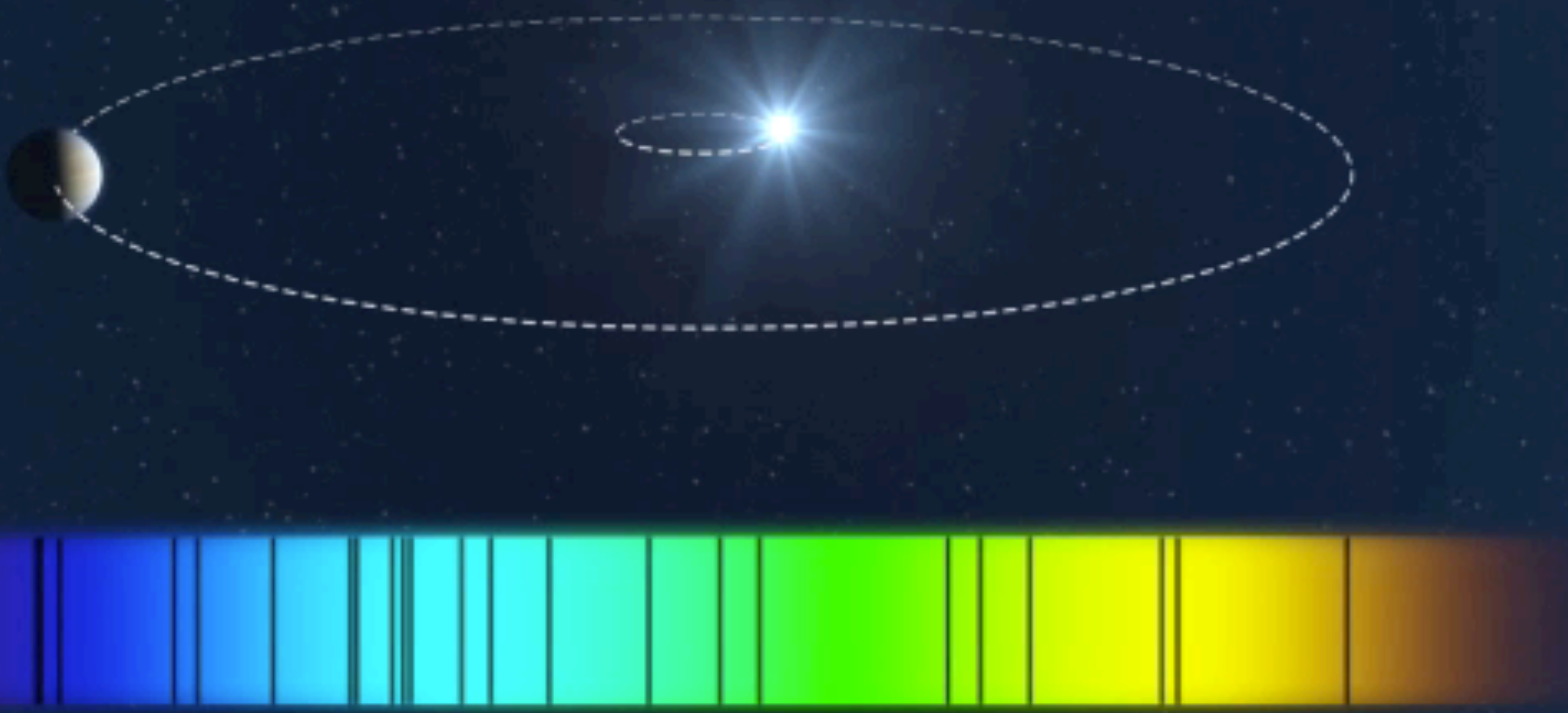


Astrophysical and Instrumental Noise Sources in Radial Velocities

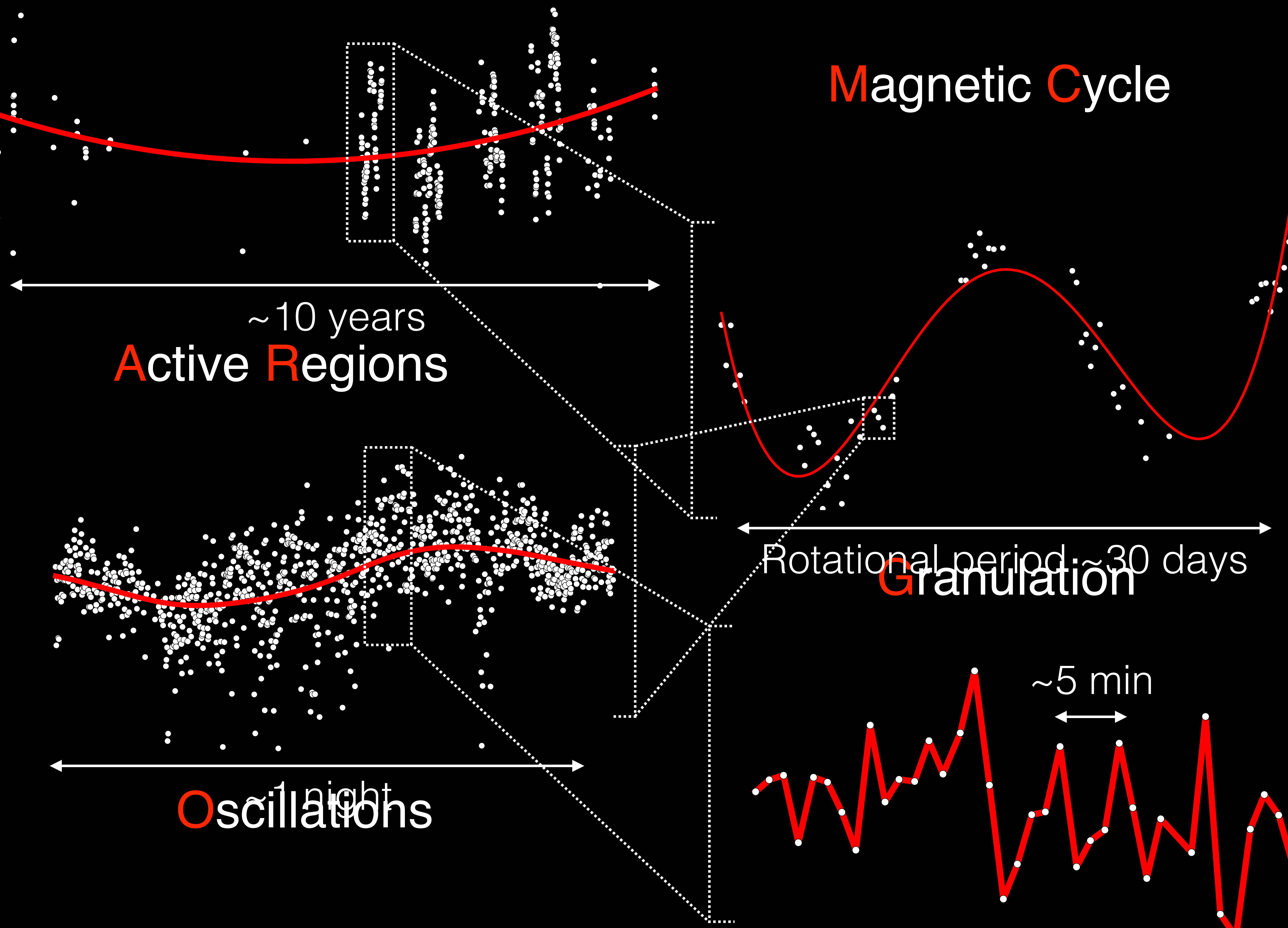
Xavier Dumusque Geneva University

Sagan Summer Workshop 16

The Radial Velocity Method



ESO


Magnetic Cycle
~10 years
Active Regions
Rotational period ~30 days
Granulation
~5 min
~1 night
Oscillations

Stellar Signals

Lindegren & Dravins 03

Flares

~ 1 h

<1 m/s (only active M)

Saar 09

Granulation

15 min - 2 d

a few m/s (Dumusque+ 11)

Del-Moro+ 04, Del-Moro 04
Cegla+ 12, Cegla+ 14

Active regions

10 - 50 d

a few m/s (Meunier+ 10)

Saar & Donahue 97, Queloz+ 01
Hatzes 02, Meunier+ 10,
Boisse+ 11, Dumusque+ 11,
Lanza+ 11, Aigrain+12,
Boisse+ 12, Reiners+ 13,
Dumusque+ 14, Haywood+ 14,
Rajpaul+ 15, Haywood+ 16

Gravitational Redshift

10 d - 10 yrs

< 10 cm/s (Cegla+12)

Magnetic Cycles

~ 10 yrs

1-20 m/s (Lovis+ 11)

Makarov 10, Dumusque+ 11
Dumusque+ 12 , Meunier+ 13

Oscillations

< 15 min

a few m/s (Dumusque+ 11)

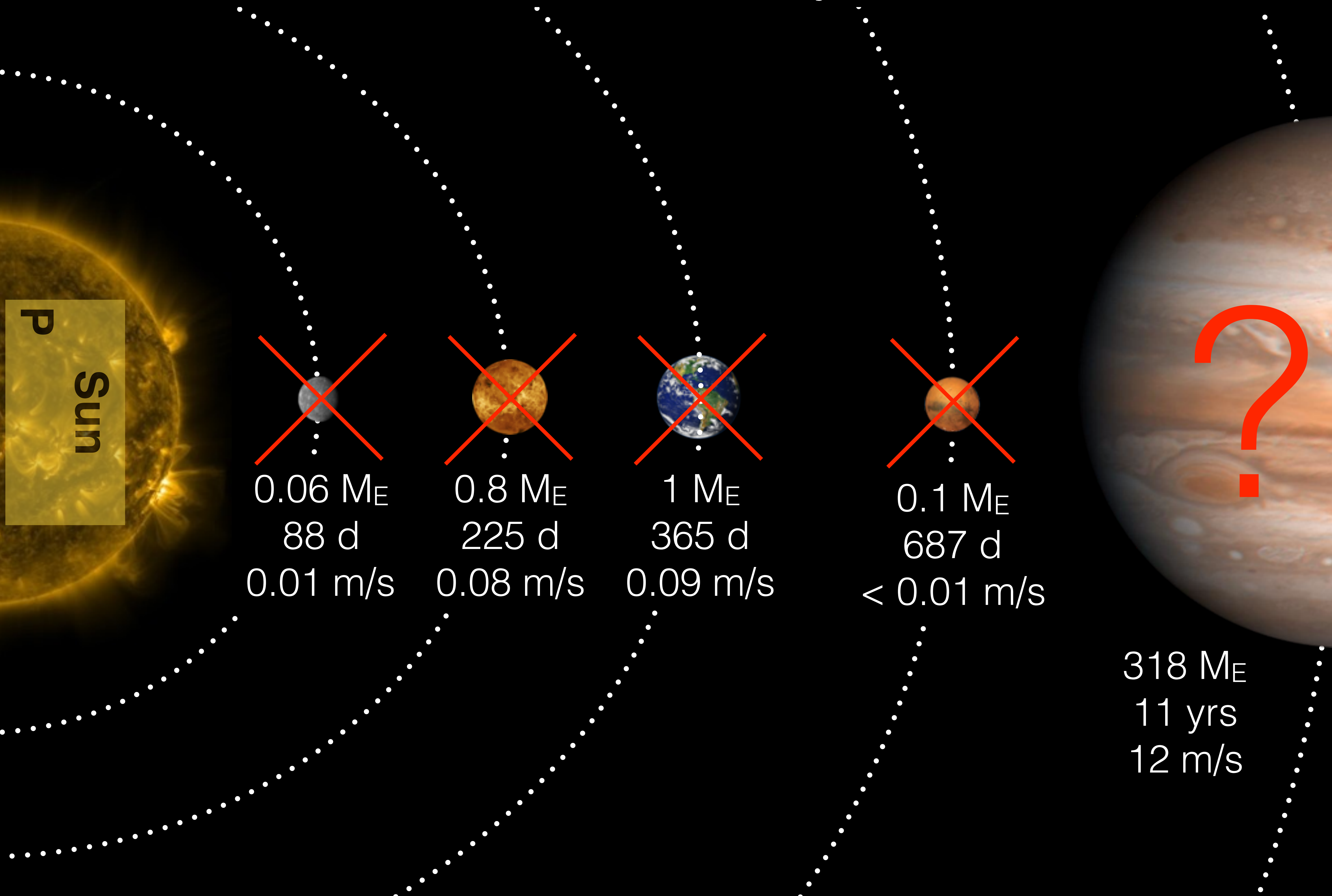
Kjeldsen+ 95, Bouchy & Carrier 01,
Butler+ 04, Bedding & Kjeldsen 07

We want to discover small-mass planets

However……

Stars create larger signals

The Inner Solar System

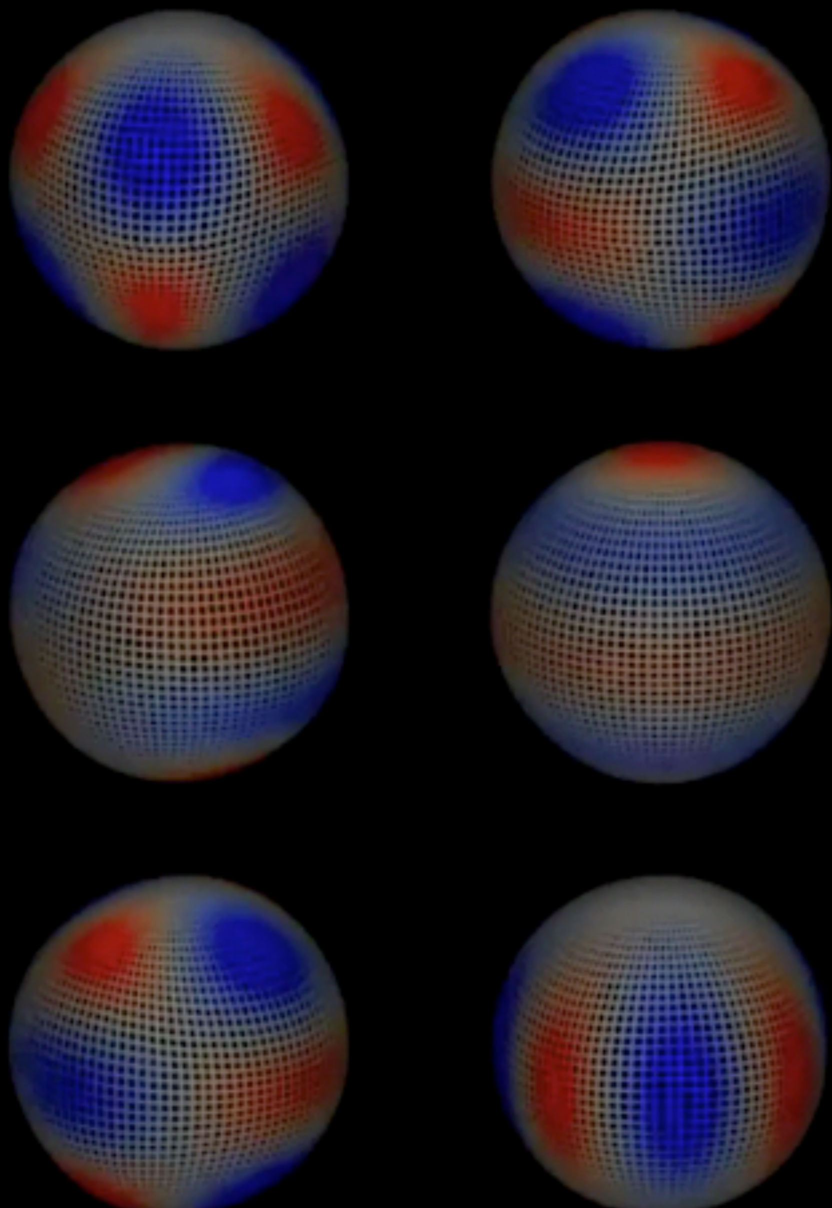


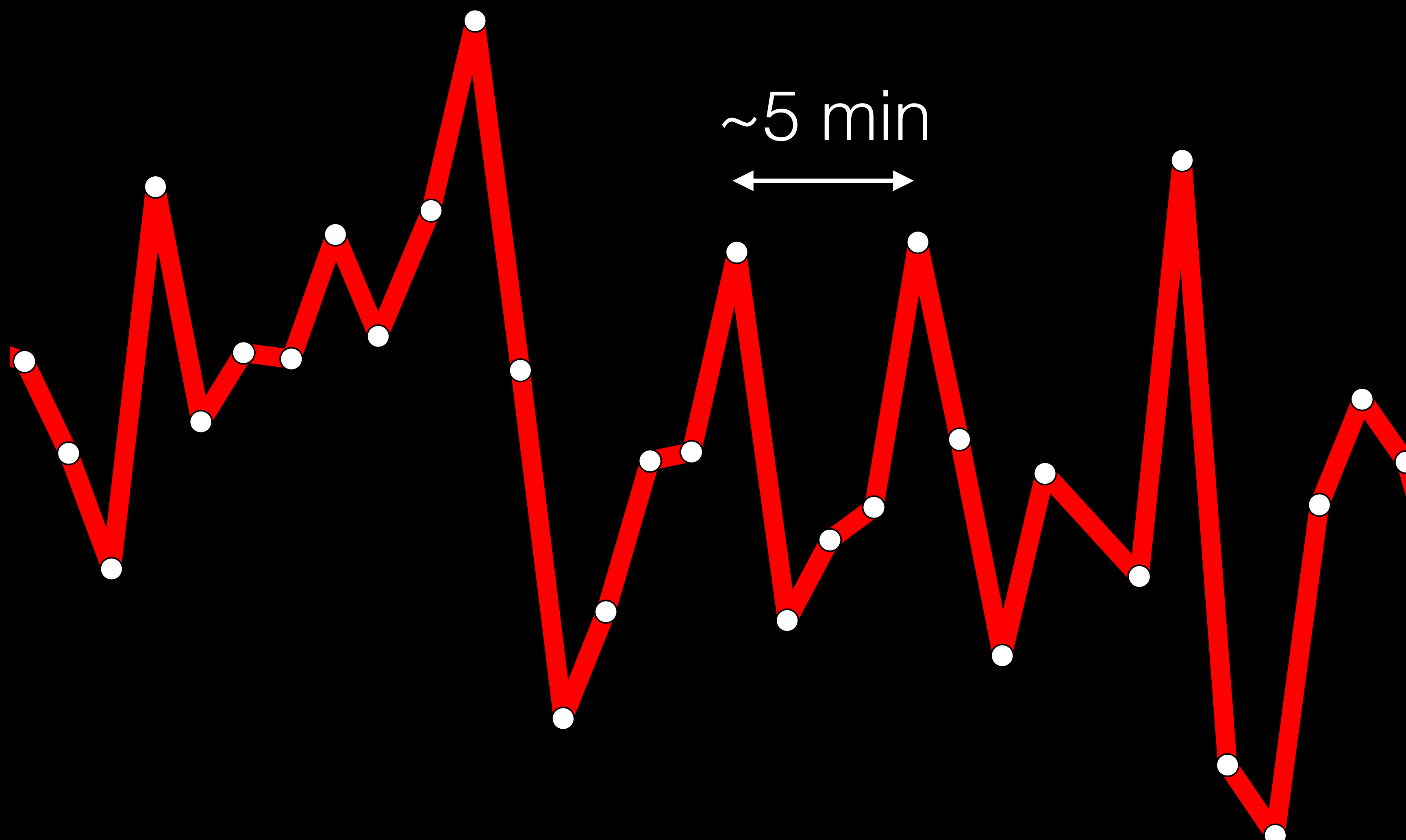
Oscillations

Oscillations

Oscillations

a few m/s (Dumusque+ 11)



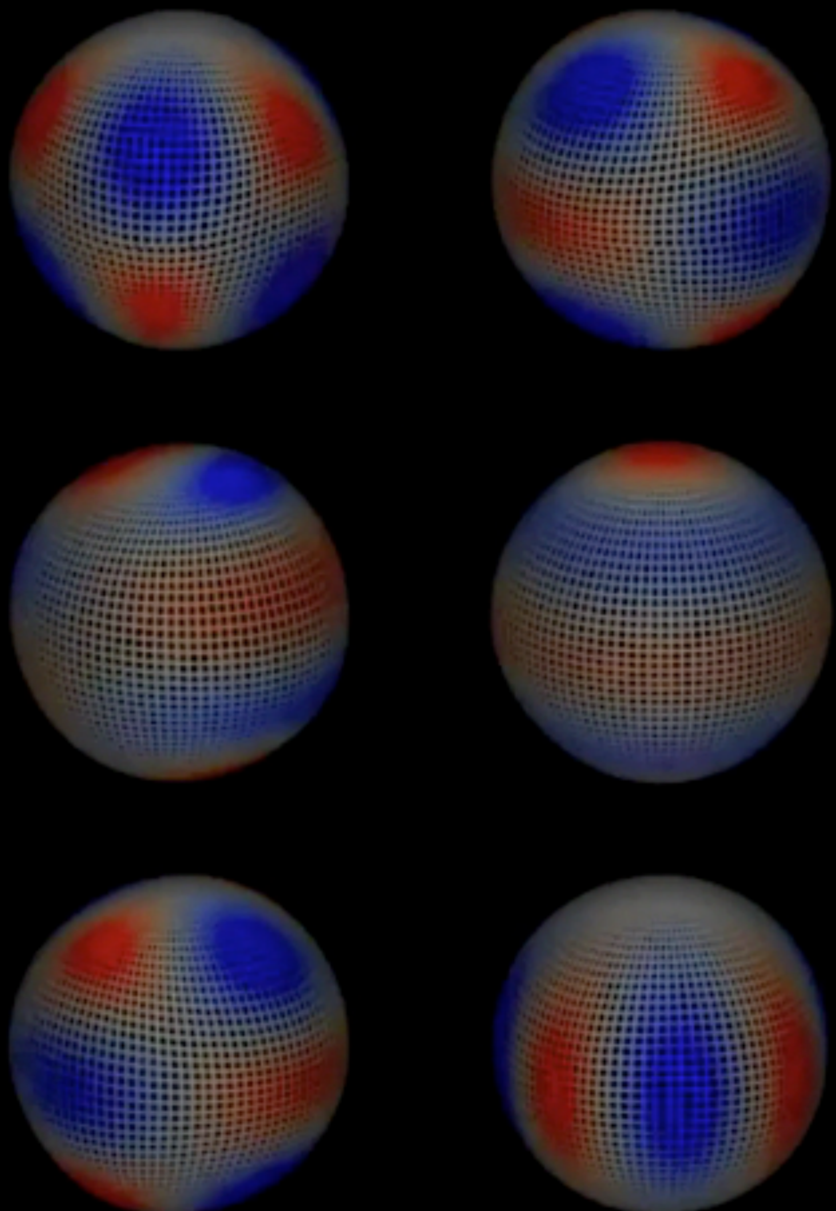


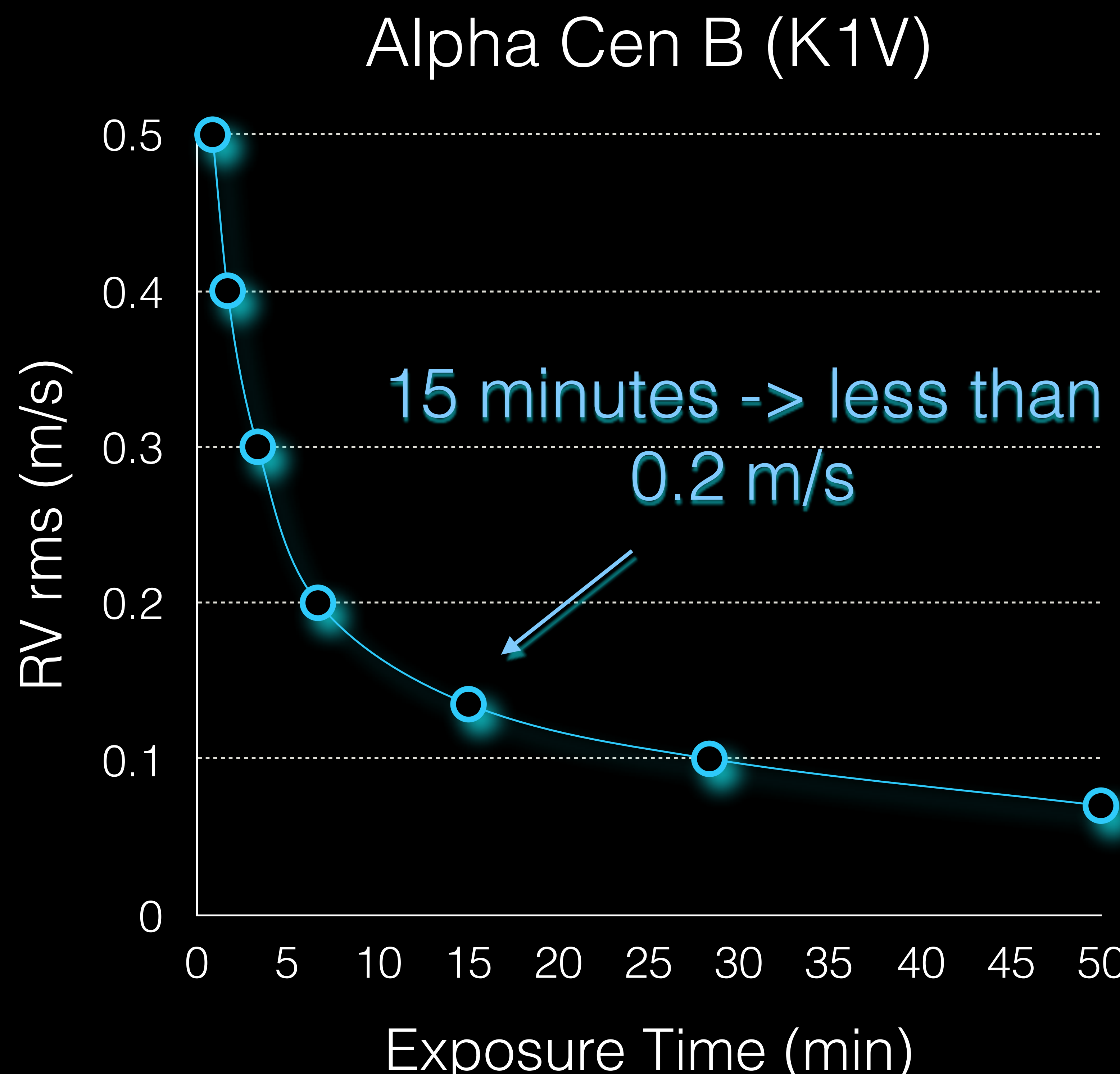
Credit: Charpinet

Kjeldsen+ 95, Bouchy & Carrier 01, Butler+ 04, Bedding & Kjeldsen 07

Oscillations

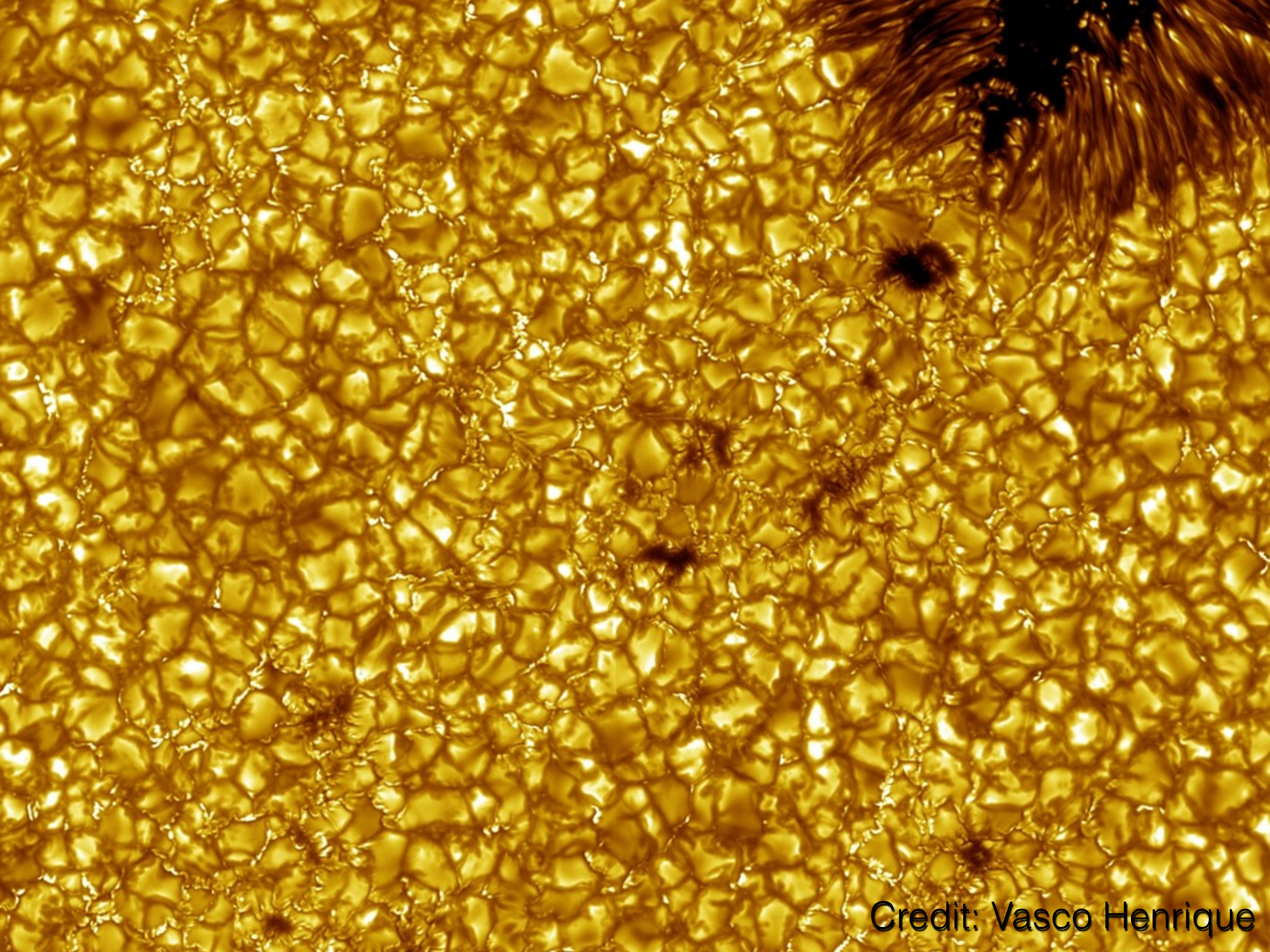
Oscillations





Credit: Charpinet

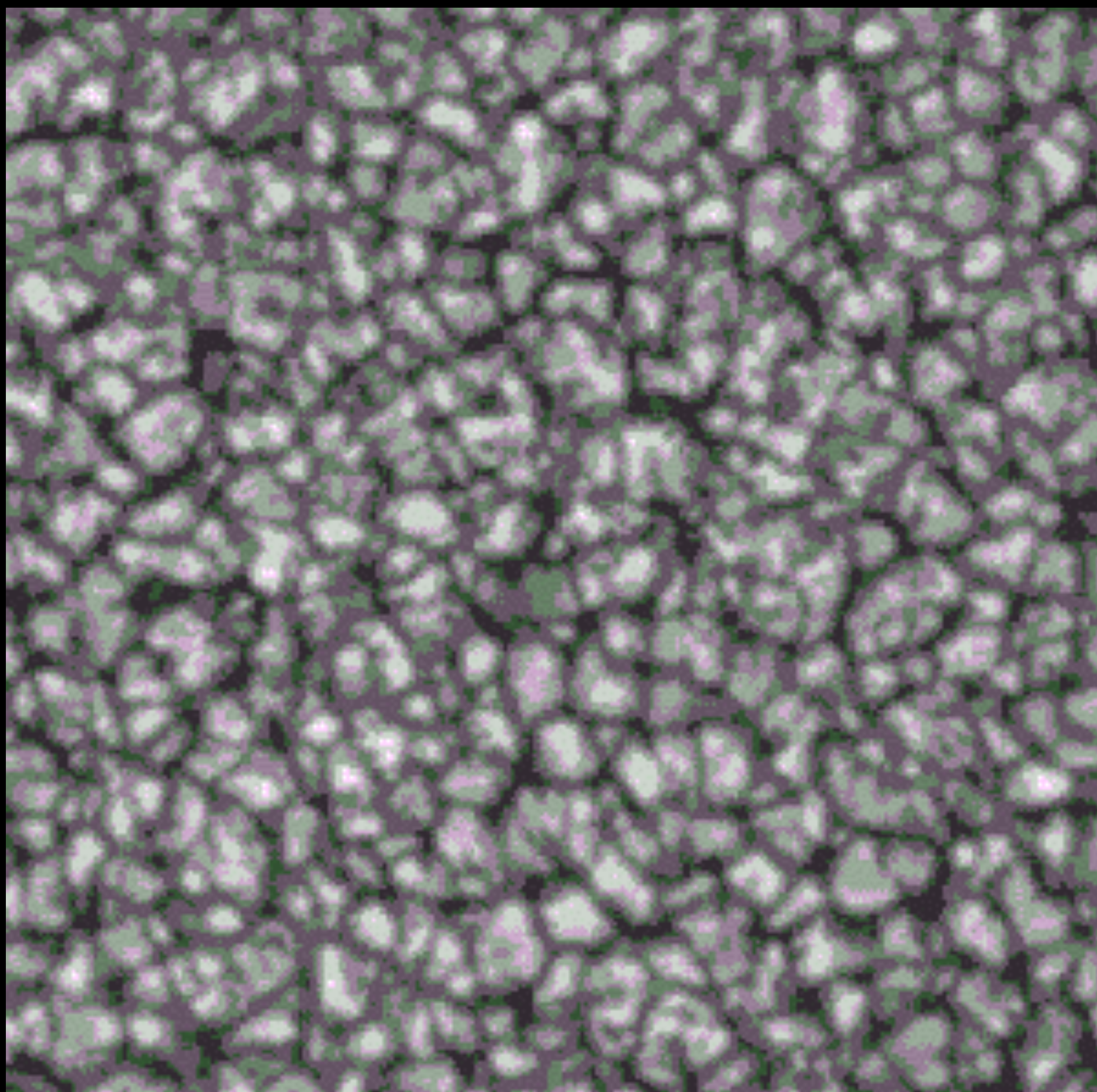
Granulation


Credit: Vasco Henrique

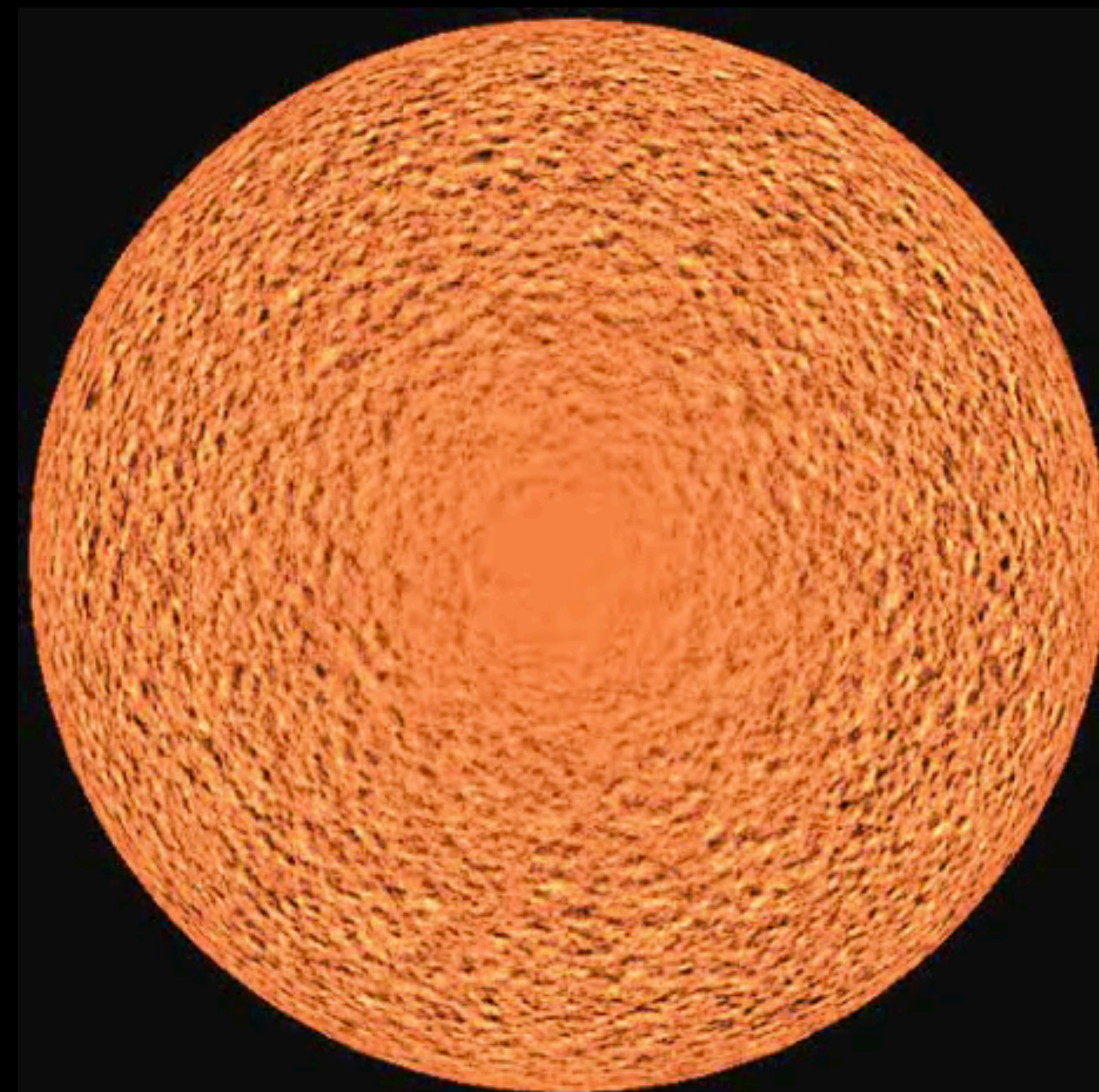
Granulation

Granulation

a few m/s (Dumusque+ 11)



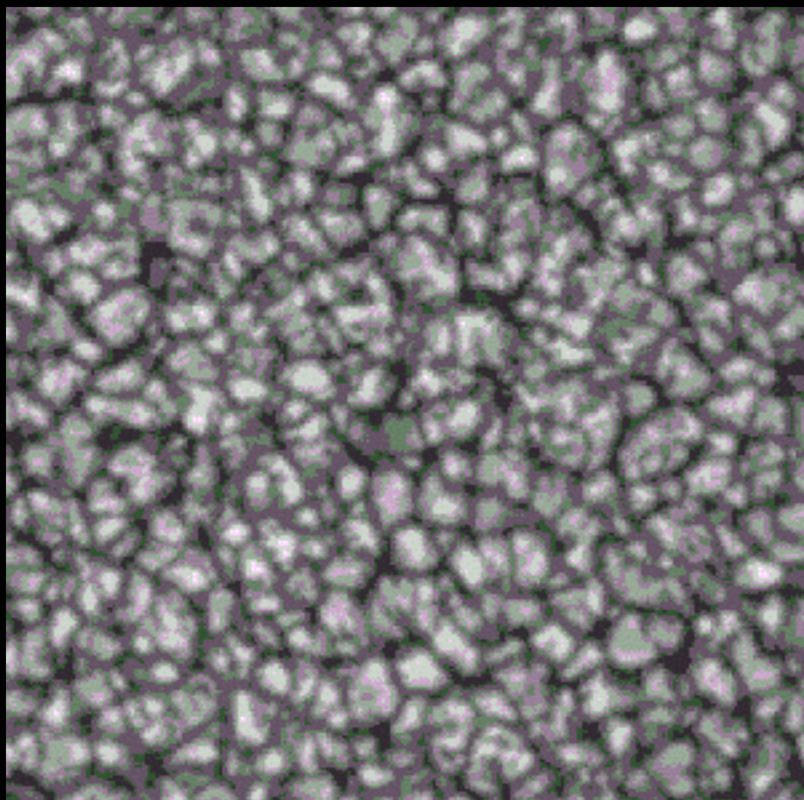
1000 km - 10^3 m.s^{-1} - > 10 min



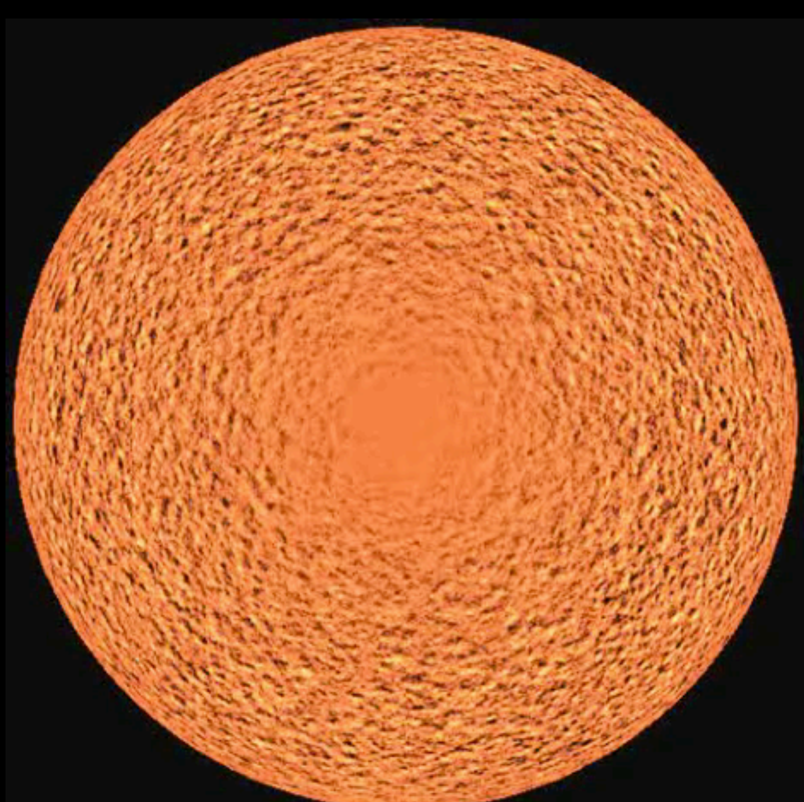
30000 km - 10^2 m/s - < 2 days

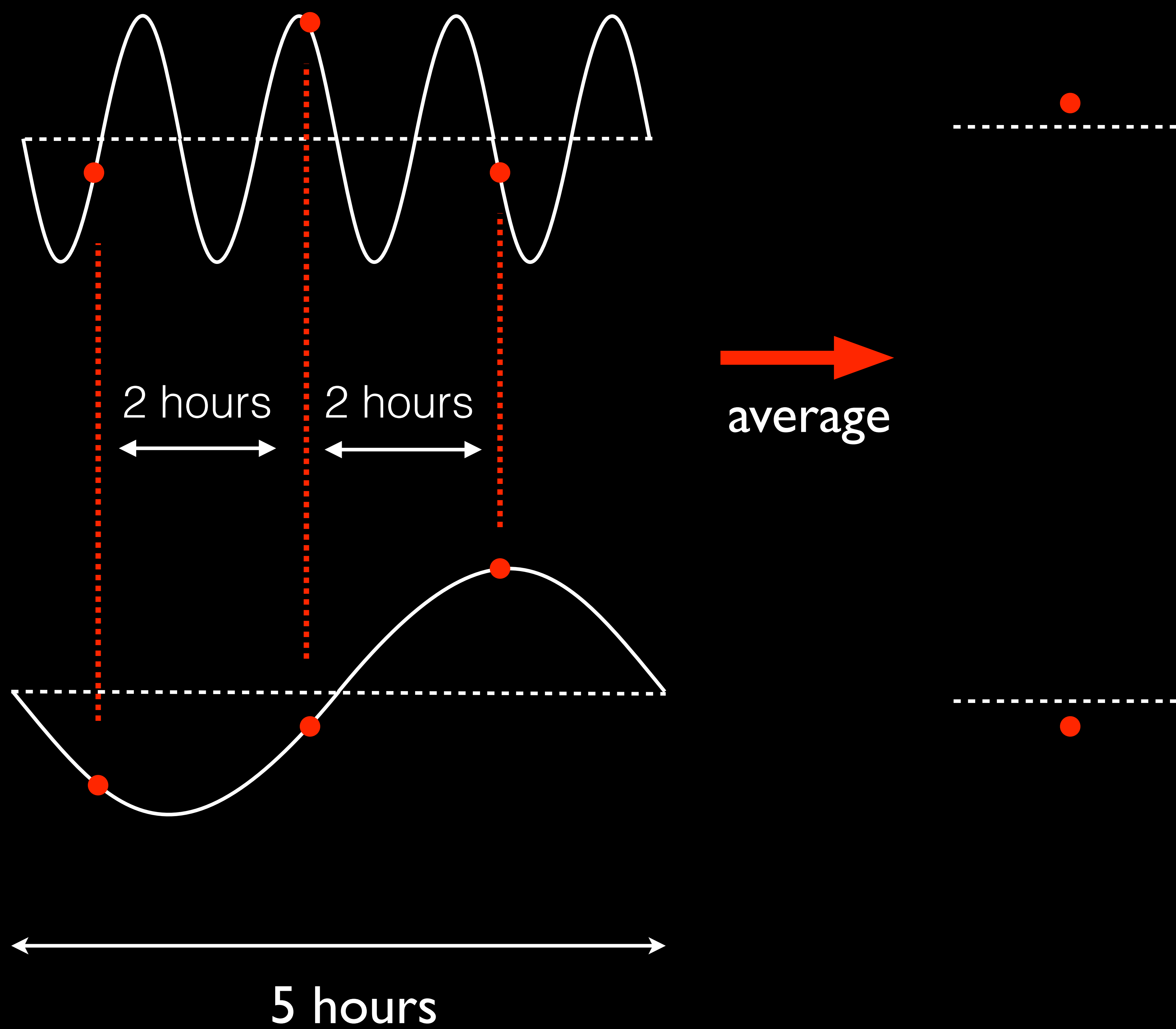
Granulation
Granulation

Granulation



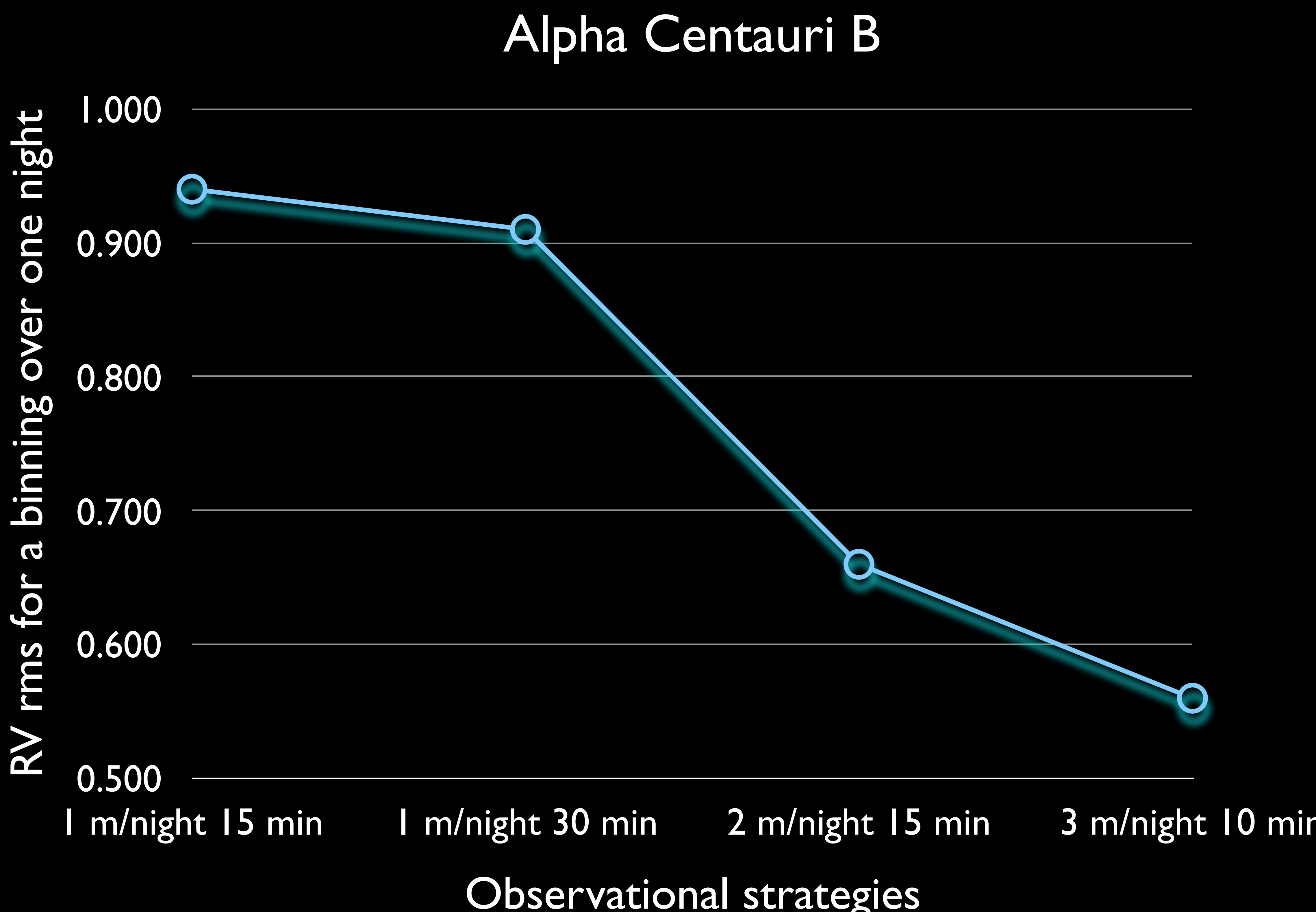
Supergranulation





Granulation

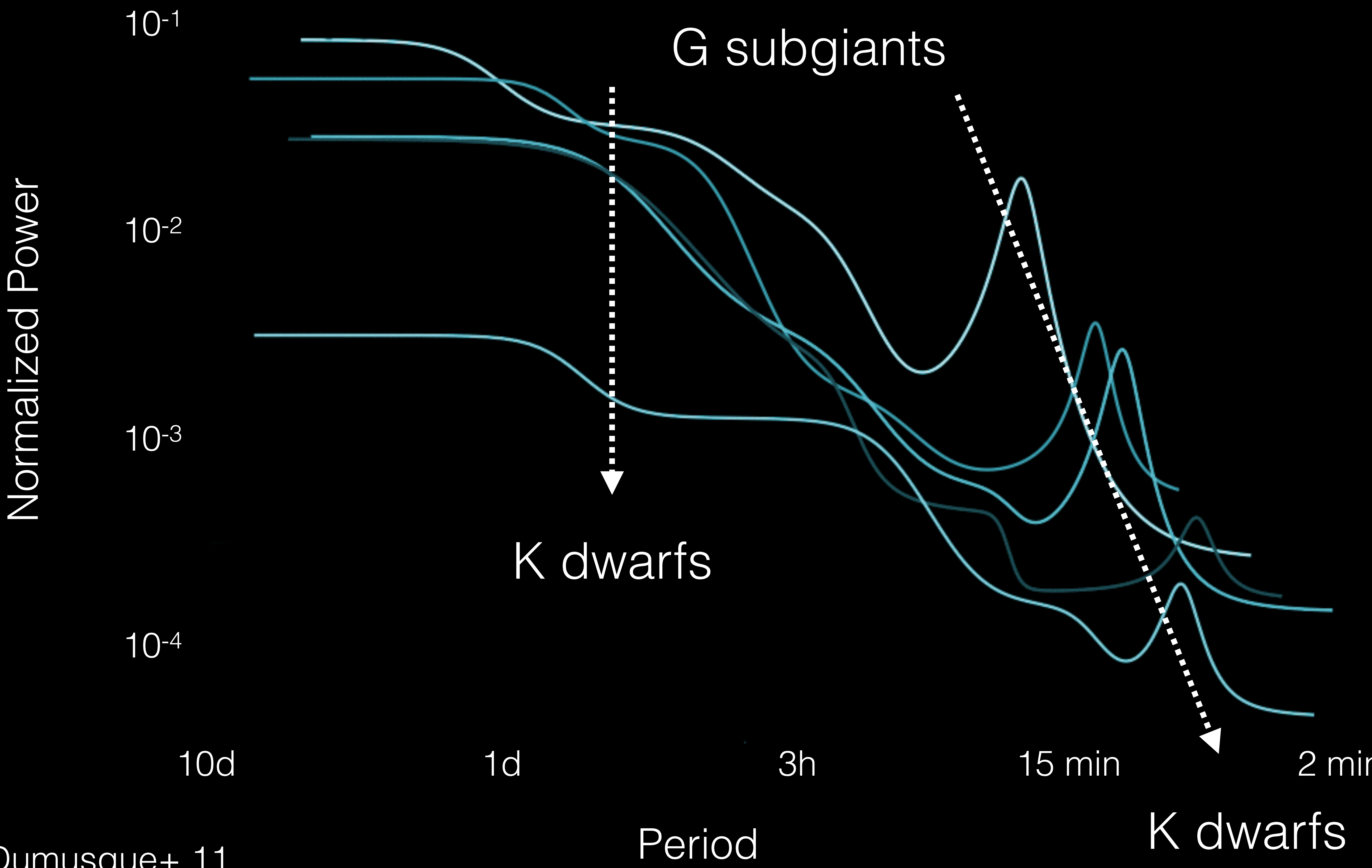
Granulation



Dumusque+ 11

Granulation

Granulation



Dumusque+ 11

Granulation

Granulation

RVs of K dwarfs are less affected by:

-> granulation
-> oscillation

than G dwarfs

Dumusque+ 11

Active regions

Active regions

Active regions

Active regions

a few m/s (Meunier+ 10)

Spots are cooler and fainter
Faculae are hotter and brighter

FLUX

Saar & Donahue 97, Queloz+ 01, Hatzes 02, Lagrange+ 10, Boisse+ 11, Dumusque+ 11, Boisse+ 12

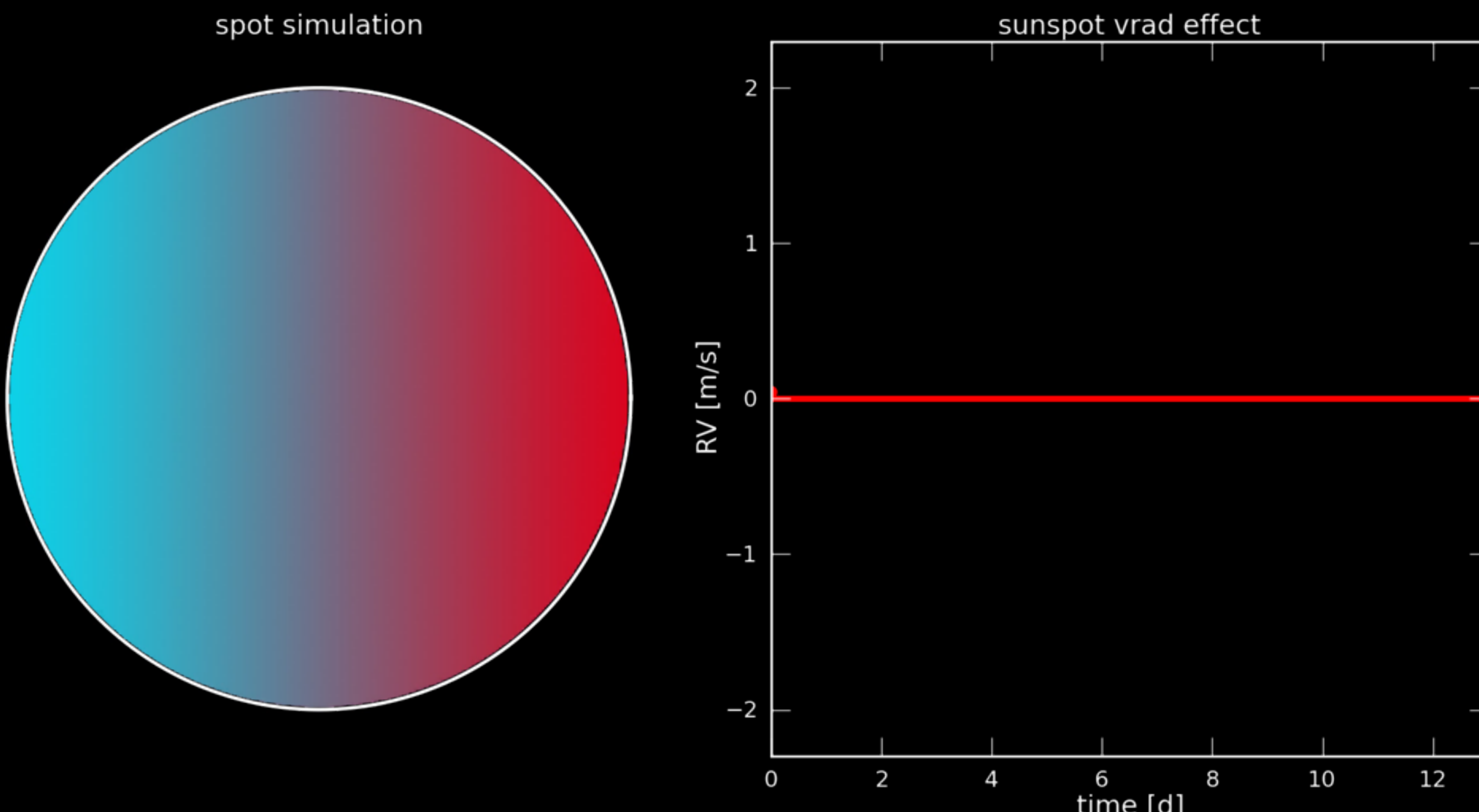
Convection outside active regions, inhibition of convection inside

CONVECTION

Dravins 81, Lindegren & Dravins 03, Saar 03, Saar 09, Lanza+ 11, Meunier+ 10, Aigrain+12, Dumusque+ 14

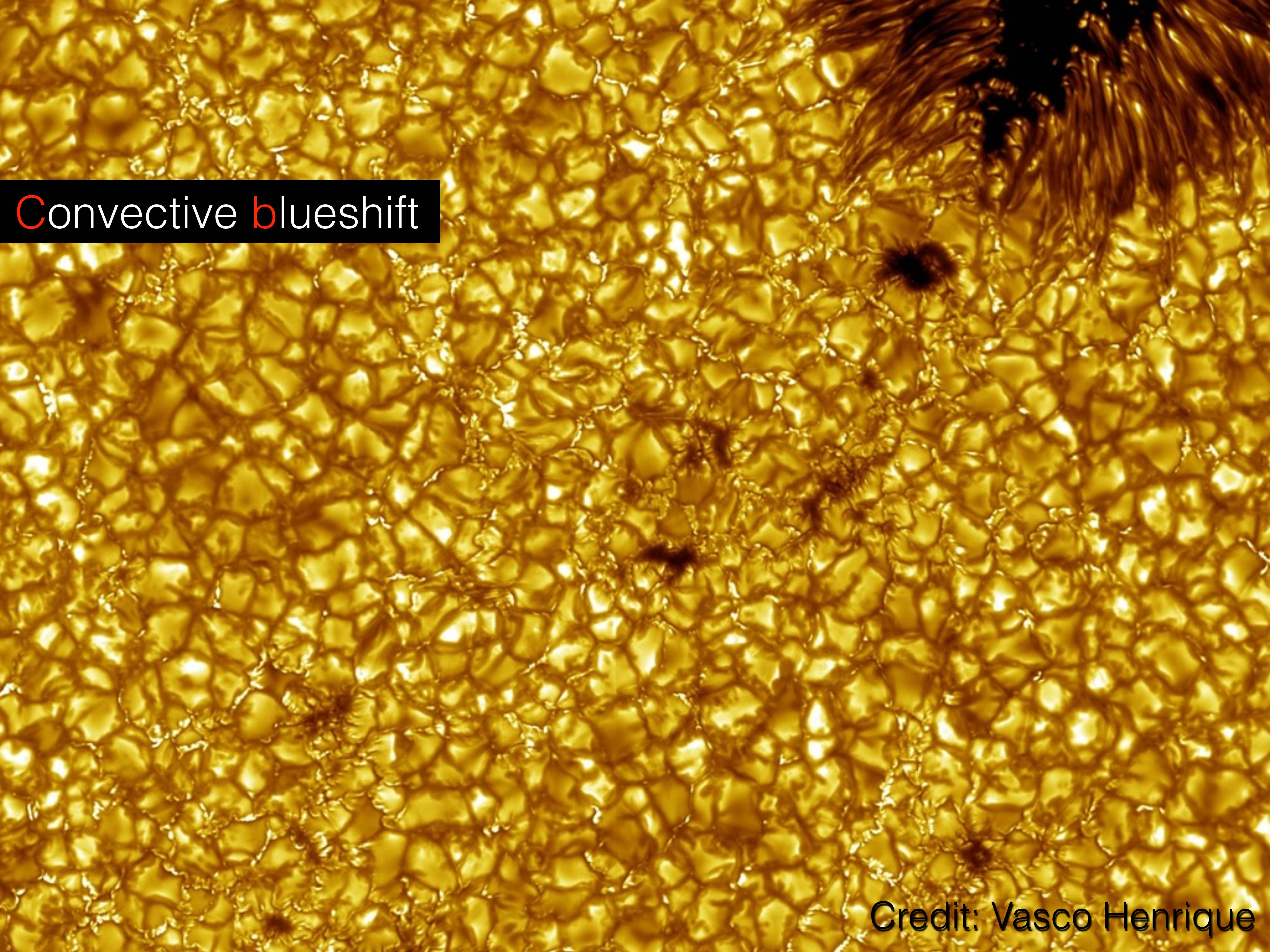
Active regions
a few m/s (Meunier+ 10)

FLUX



Estimation using SOAP, Boisse+ 12, Dumusque + 14

Convective blueshift



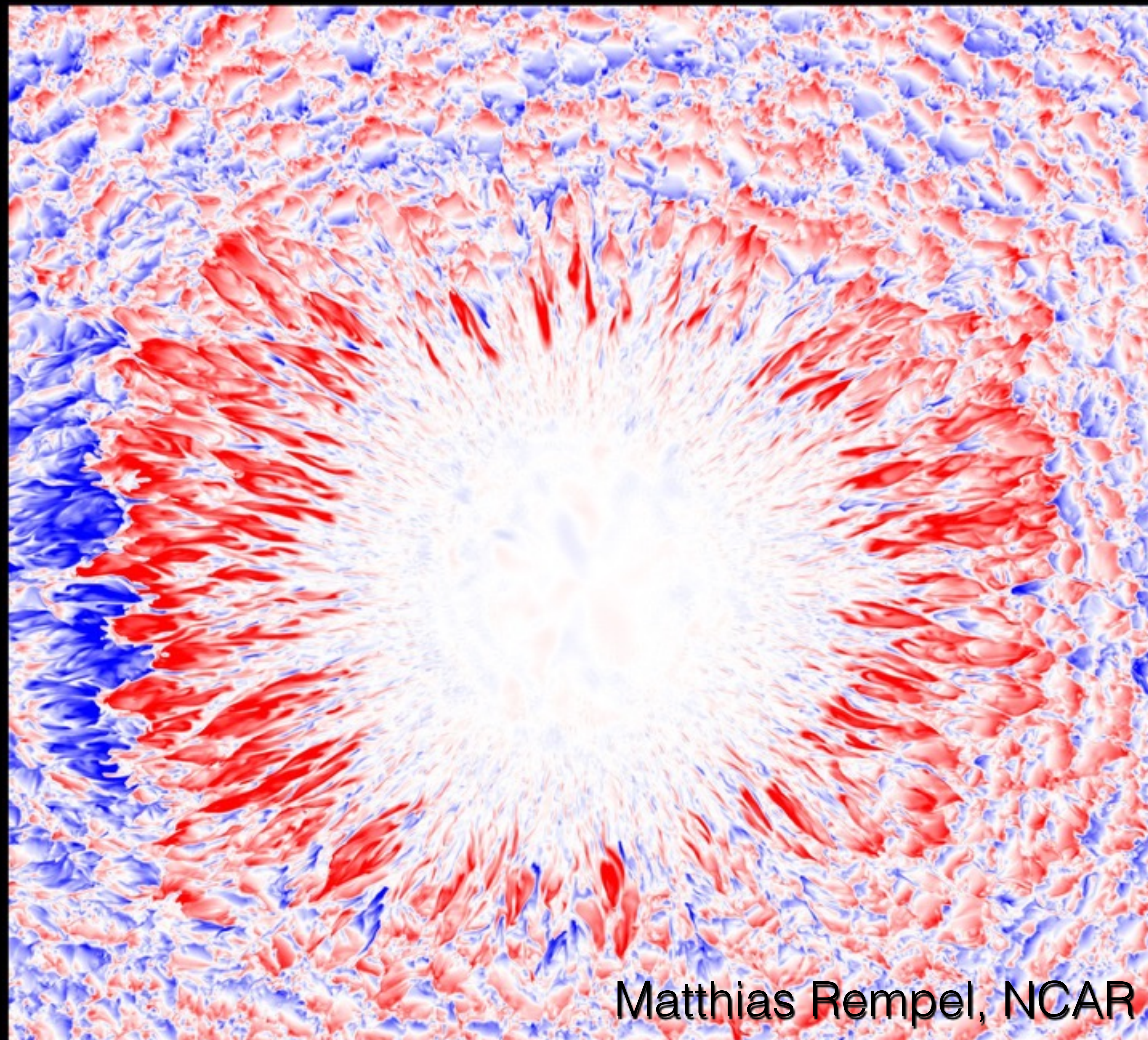
Credit: Vasco Henrique

Active regions

Active regions

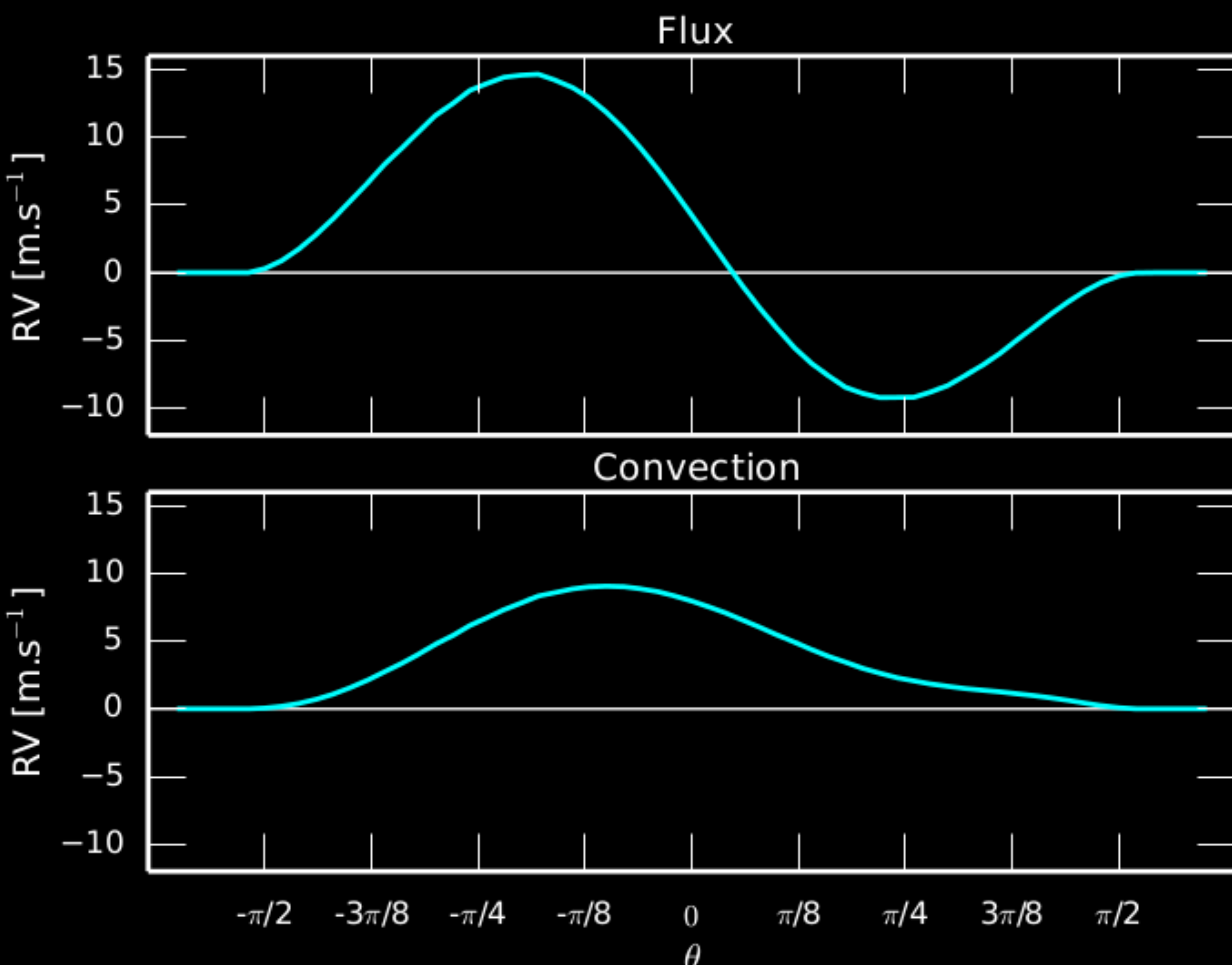
a few m/s (Meunier+ 10)

CONVE
CTION



Active regions

a few m/s (Meunier+ 10)



FLUX

CONVE
CTION

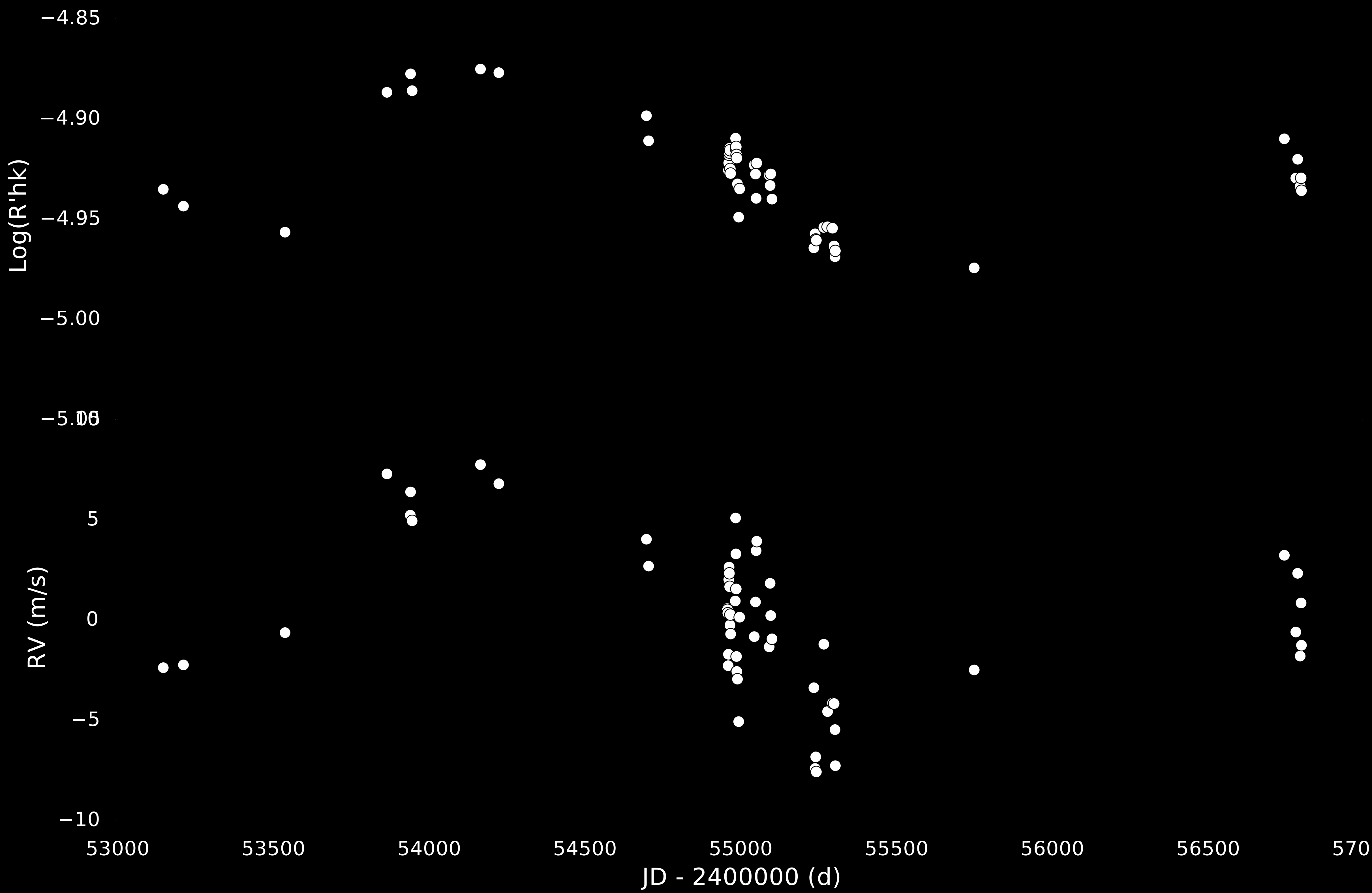
SOAP 2.0 Dumusque+ 2014

Magnetic Cycles

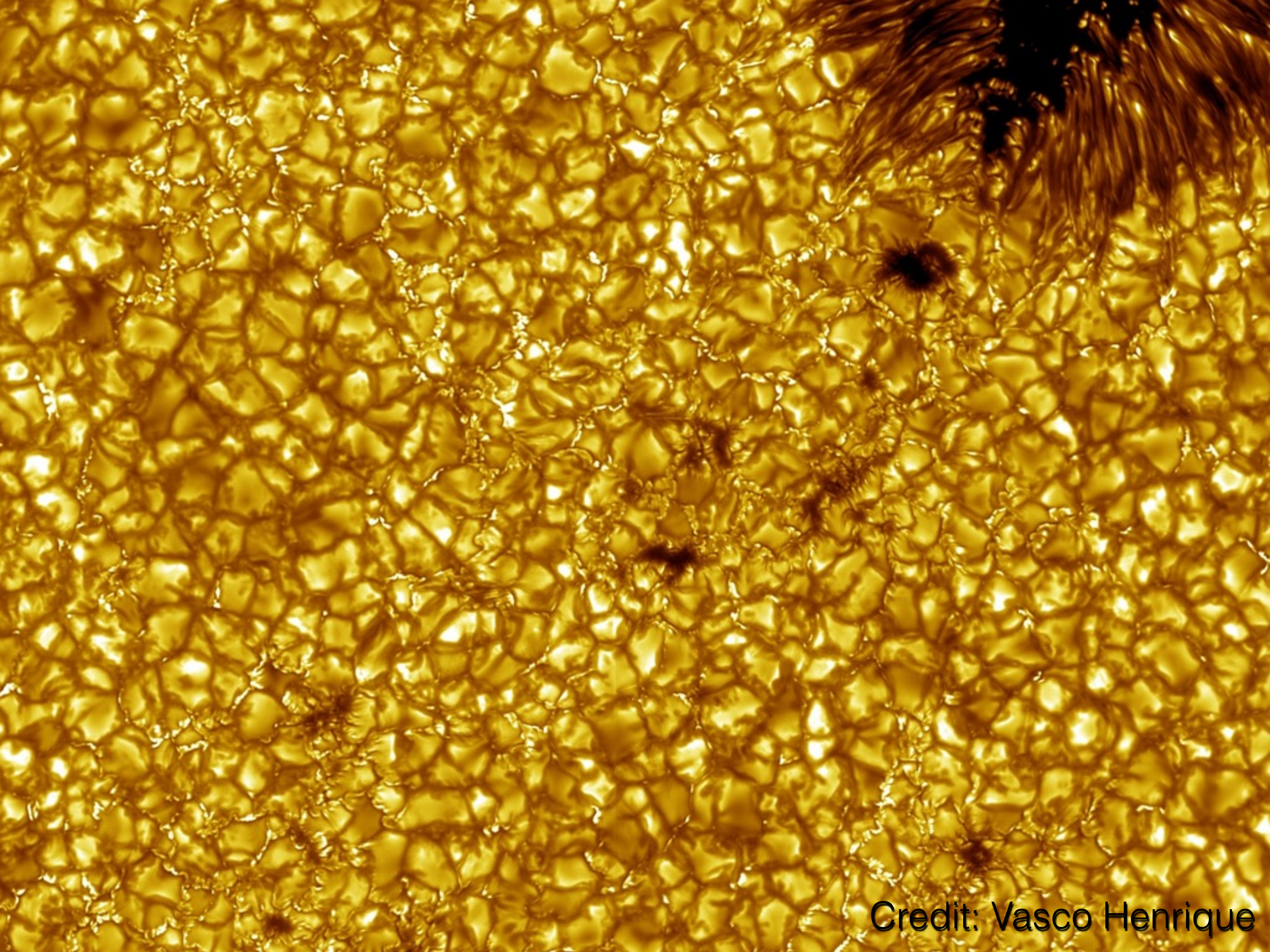
Magnetic Cycles

Magnetic Cycles

Magnetic Cycles



HARPS data


Credit: Vasco Henrique

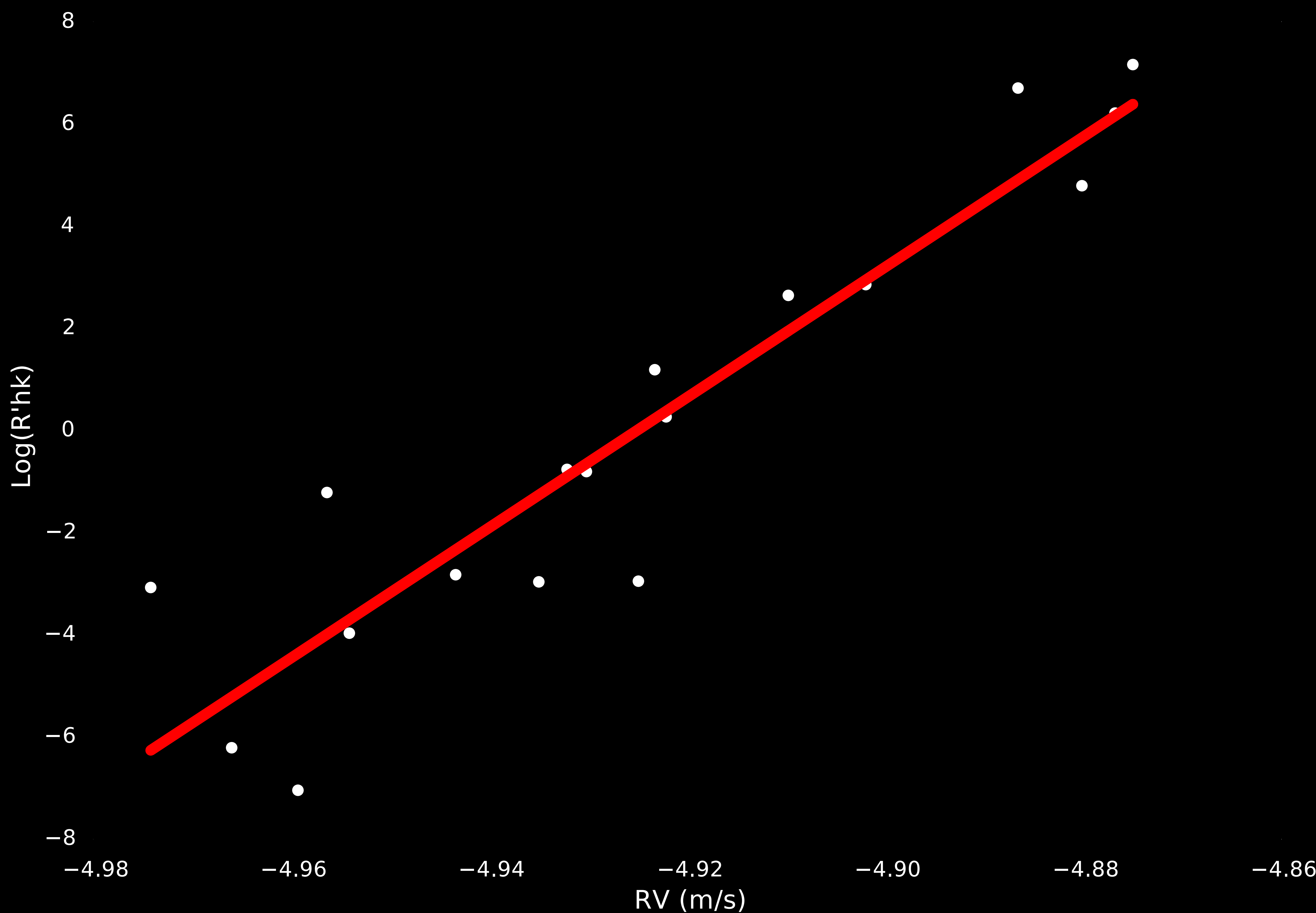
Magnetic Cycles

Magnetic Cycles

1-20 m/s (Lovis+ 11)

- More active regions,
  - -> more convective blueshift inhibition
  - -> positive RV (Meunier+ 10,Lindegren & Dravins 03)

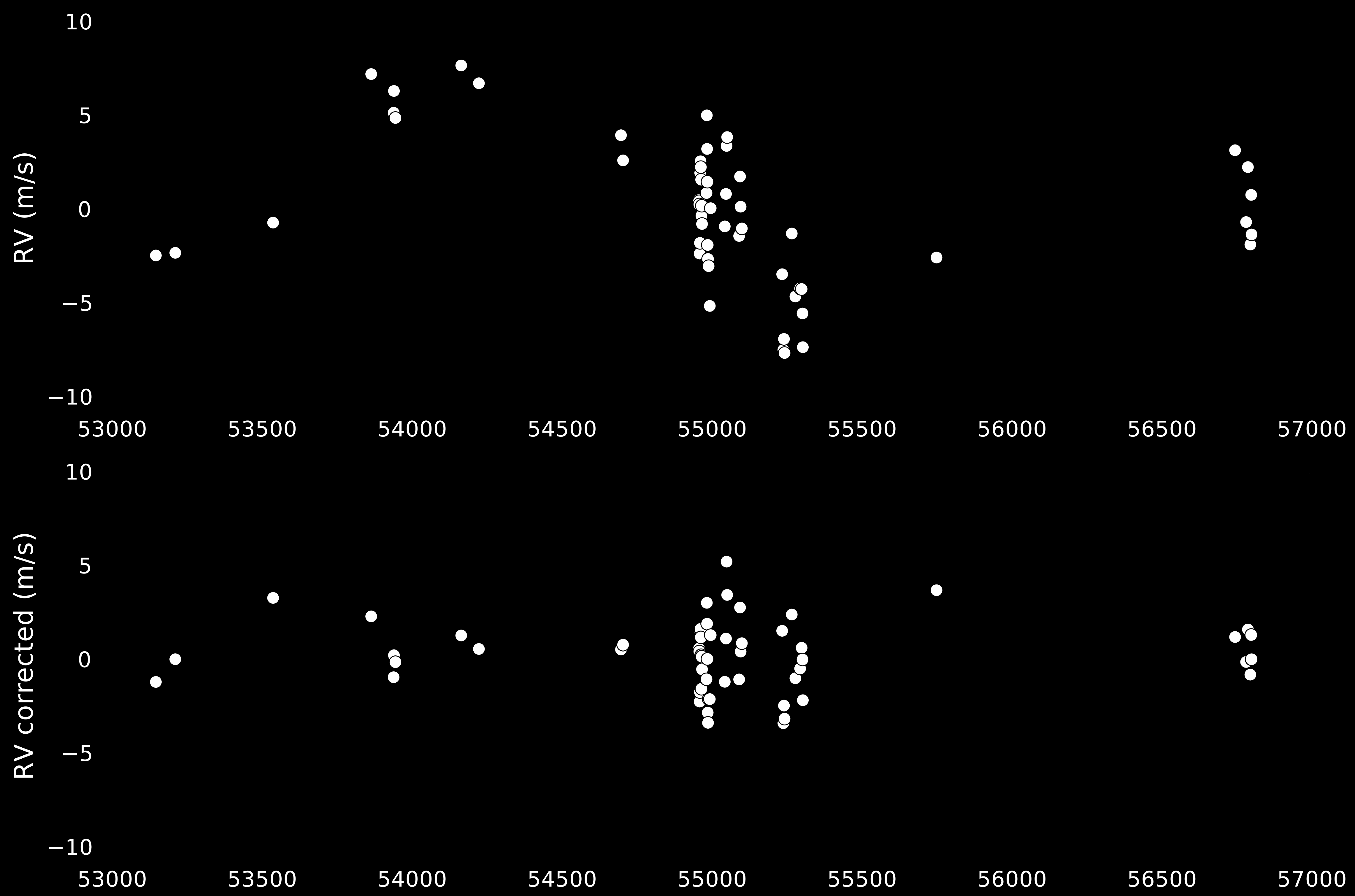
Magnetic Cycles



Meunier+ 13

HARPS data

Magnetic Cycles



Meunier+ 13

HARPS data

Magnetic Cycles

Magnetic Cycles

Because of smaller convention velocities in K dwarfs, those stars are less affected by:

-> Magnetic cycles

than G dwarfs

Dumusque+ 11

Lovis+ 11

Stellar Signals

Lindegren & Dravins 03

Flares

~ 1 h

<1 m/s (only active M)

Saar 09

Granulation

15 min - 2 d

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Rajpaul+ 15, Haywood+ 16

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Oscillations

< 15 min

a few m/s (Dumusque+ 11)

Kjeldsen+ 95, Bouchy & Carrier 01,
Butler+ 04, Bedding & Kjeldsen 07

How Can we Model Stellar Activity to Find Tiny Planetary Signals ?

The RV Fitting Challenge

(https://rv-challenge.wikispaces.com)

(Google rv challenge wikispace)

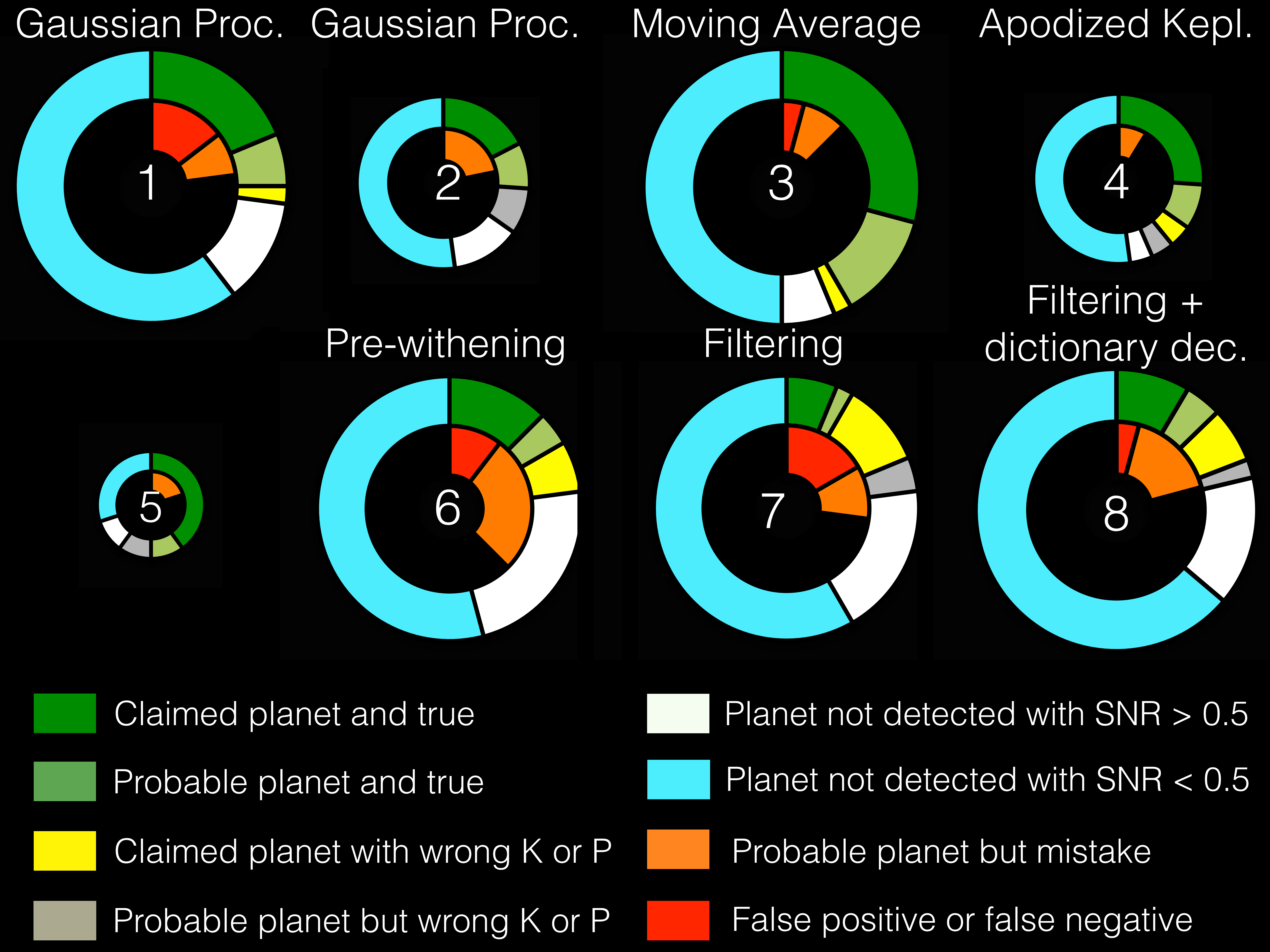
Simulation

Stellar signals
+ Planets

Challenge

Can we find
the planets ?

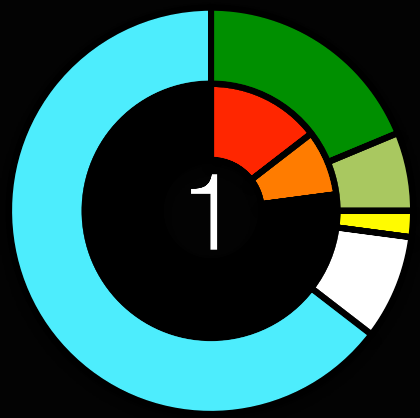
Dumusque+ 16, submitted


Gaussian Proc.
Gaussian Proc.
Moving Average
Apodized Kepl.
1
2
3
4
Filtering +
dictionary dec.
Pre-withening
Filtering
5
6
7
8
Claimed planet and true
Probable planet and true
Claimed planet with wrong K or P
Probable planet but wrong K or P
Planet not detected with SNR > 0.5
Planet not detected with SNR < 0.5
Probable planet but mistake
False positive or false negative

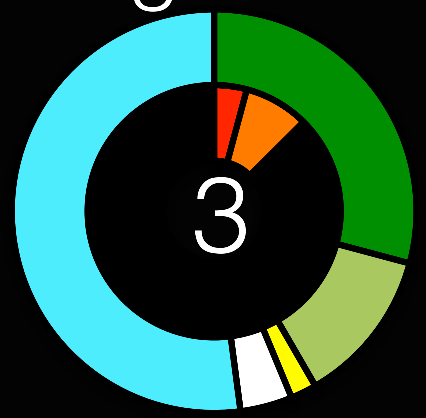
Planetary signals Recovery

$$\frac{K}{N} = \frac{K}{RV_{\mathrm{rms}}} \cdot \sqrt{N_{\mathrm{obs}}}$$

Gaussian Proc.



Moving Average



	Gaussian Proc.	Moving Average
Planets with K/N > 7.5	11/15 (73%)	13/15 (87%)
Planets with K/N < 7.5	2/32 (6%)	8/32 (25%)
Mistakes with K/N > 7.5	3 (2 because wrong Prot)	0
Mistakes with K/N < 7.5	4	2

Dumusque+ 16, submitted

Take Away Message

Best Techniques

Moving Average

Gaussian Process

Apodized Keplerian

Red Noise models

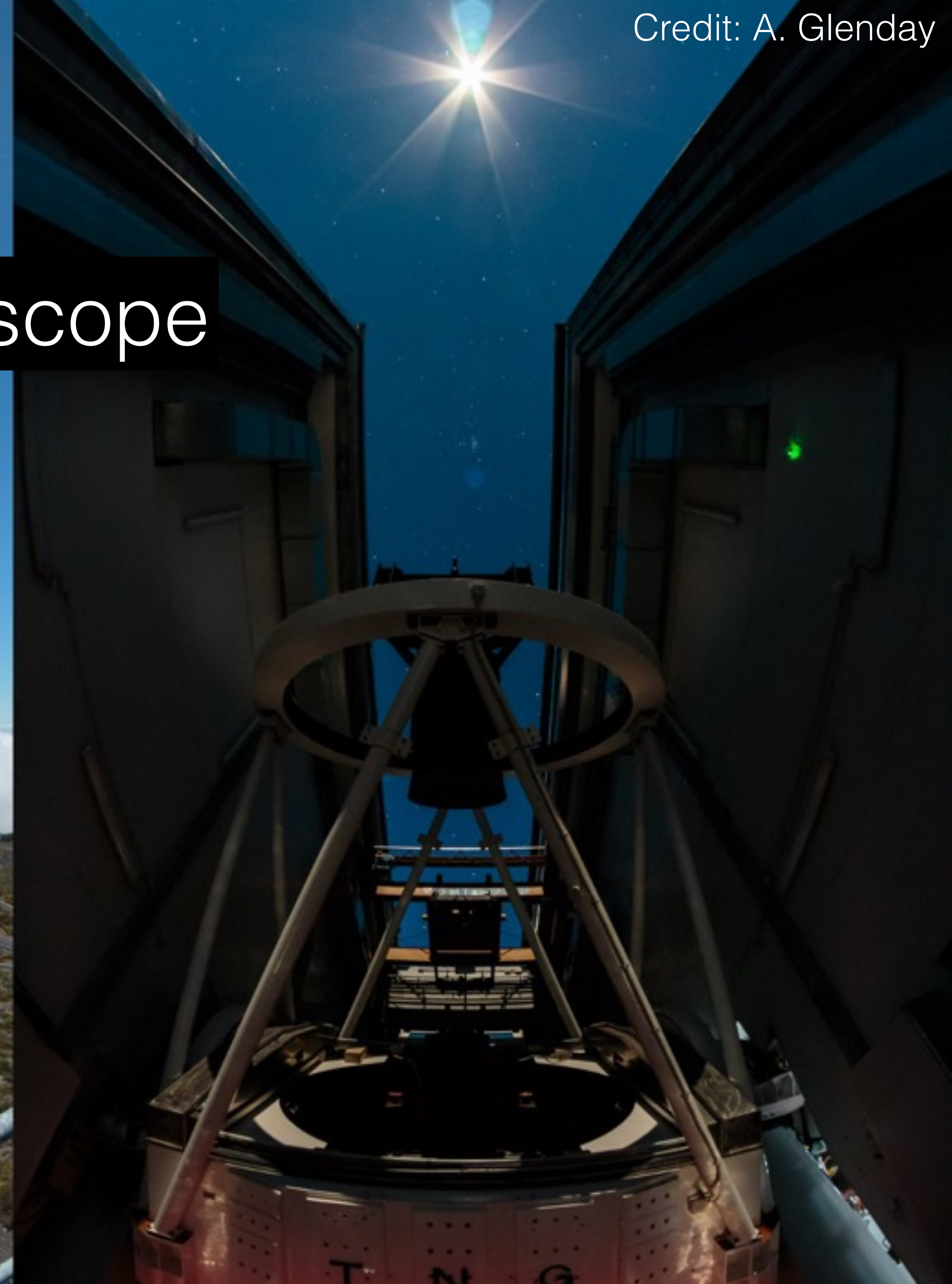
Correlation between measurements

Bayesian Framework

Model comparison

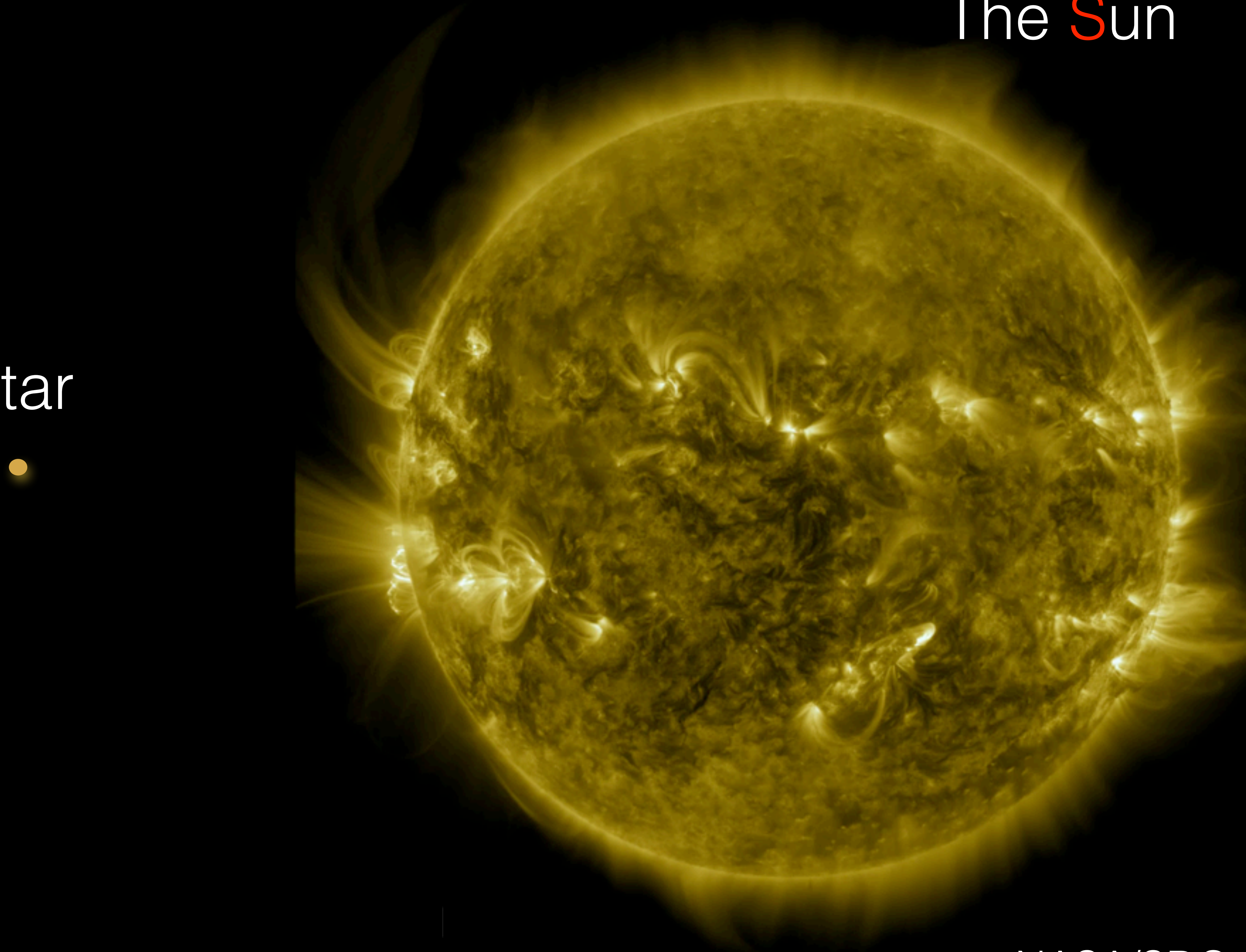
Dumusque+ 16, submitted

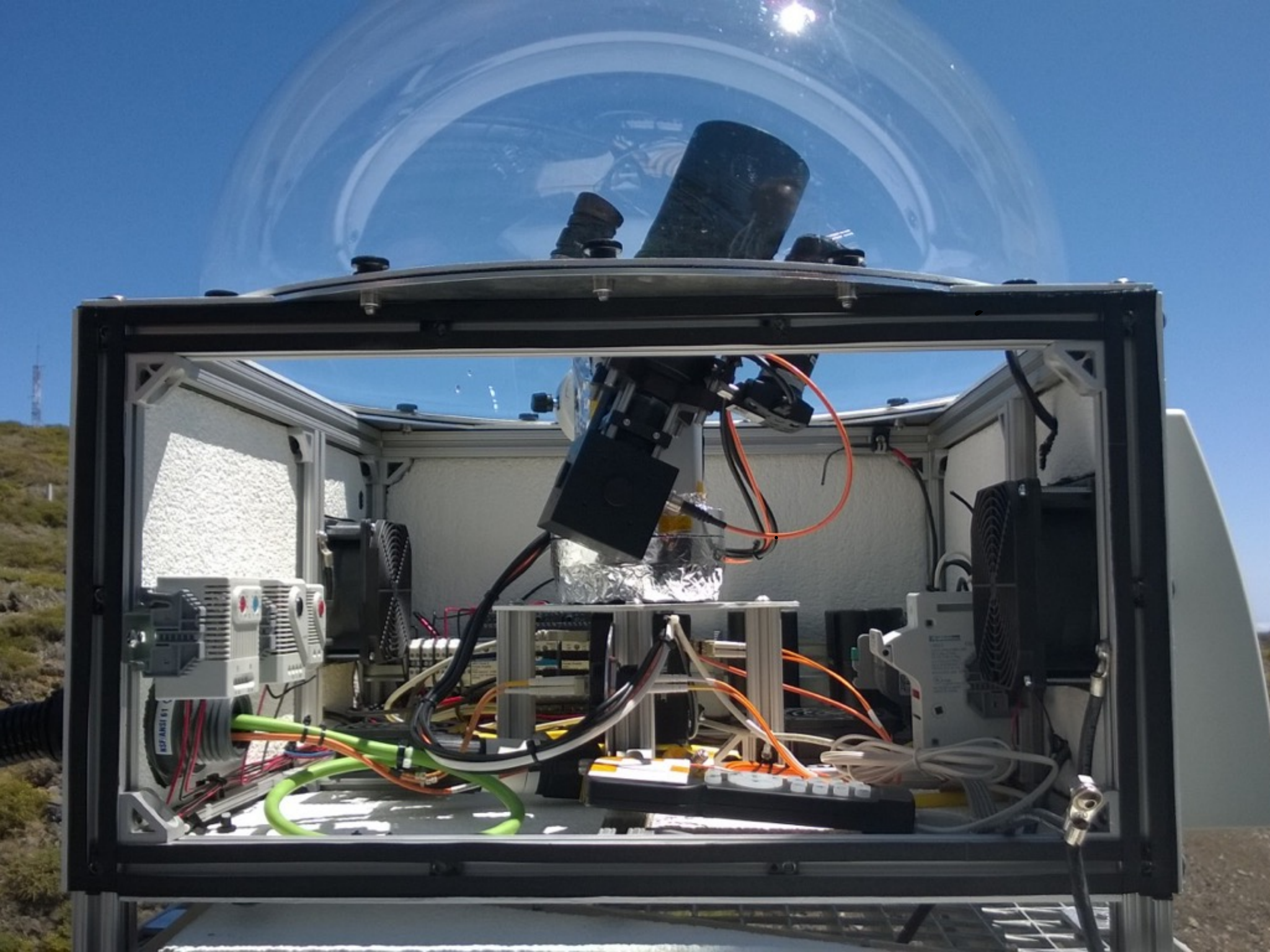
The HARPS-N Solar Telescope



Credit: A. Glenday

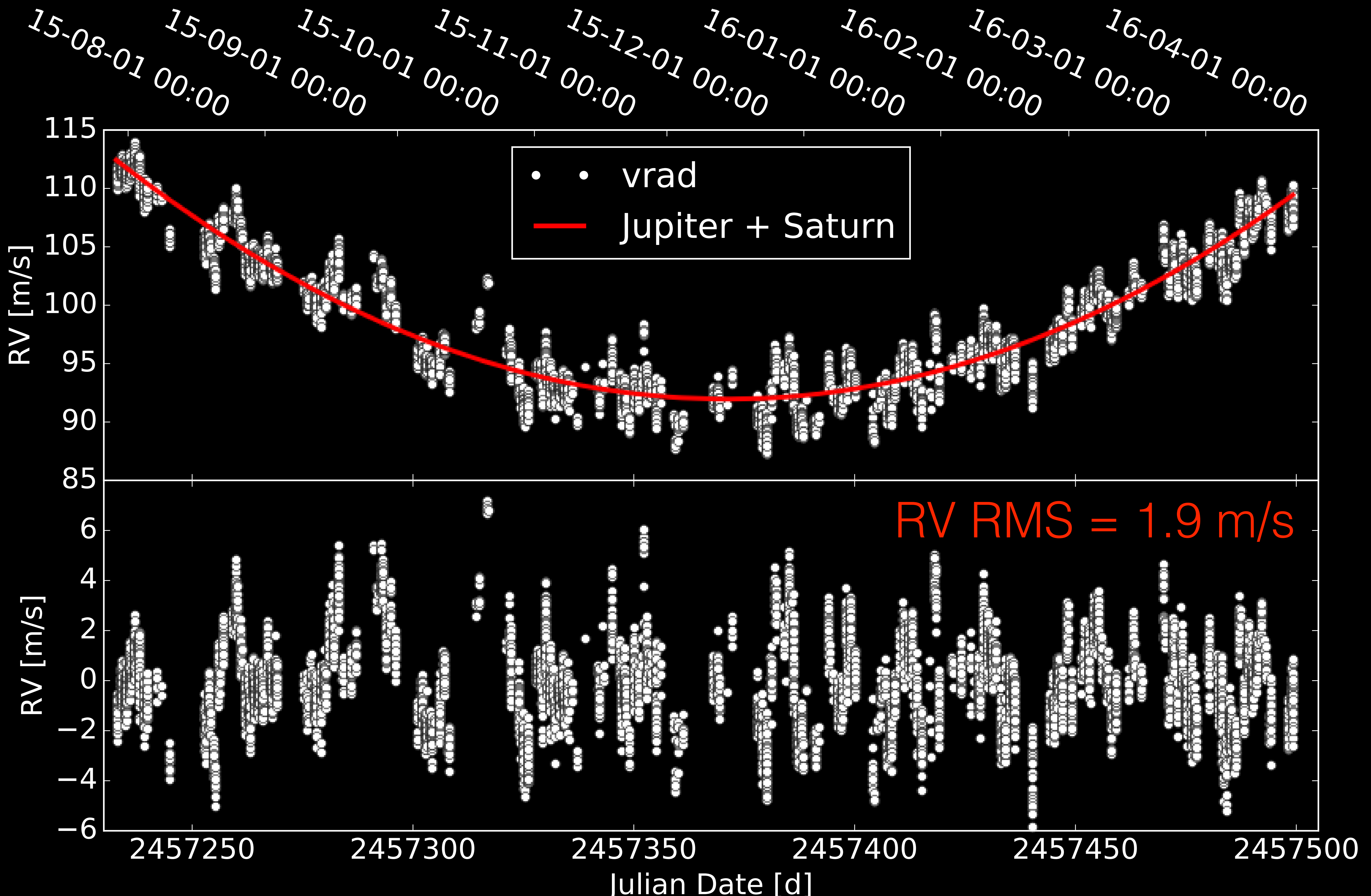
X.Dumusque, D. F. Phillips, A. Glenday, D. Charbonneau, A. Collier Cameron, R. D. Haywood, D. W. Latham, C. Lovis, J. Maldonado, G. Micela, E. Molinari, F. Pepe, S. Udry


The Sun
Star
NASA/SDO

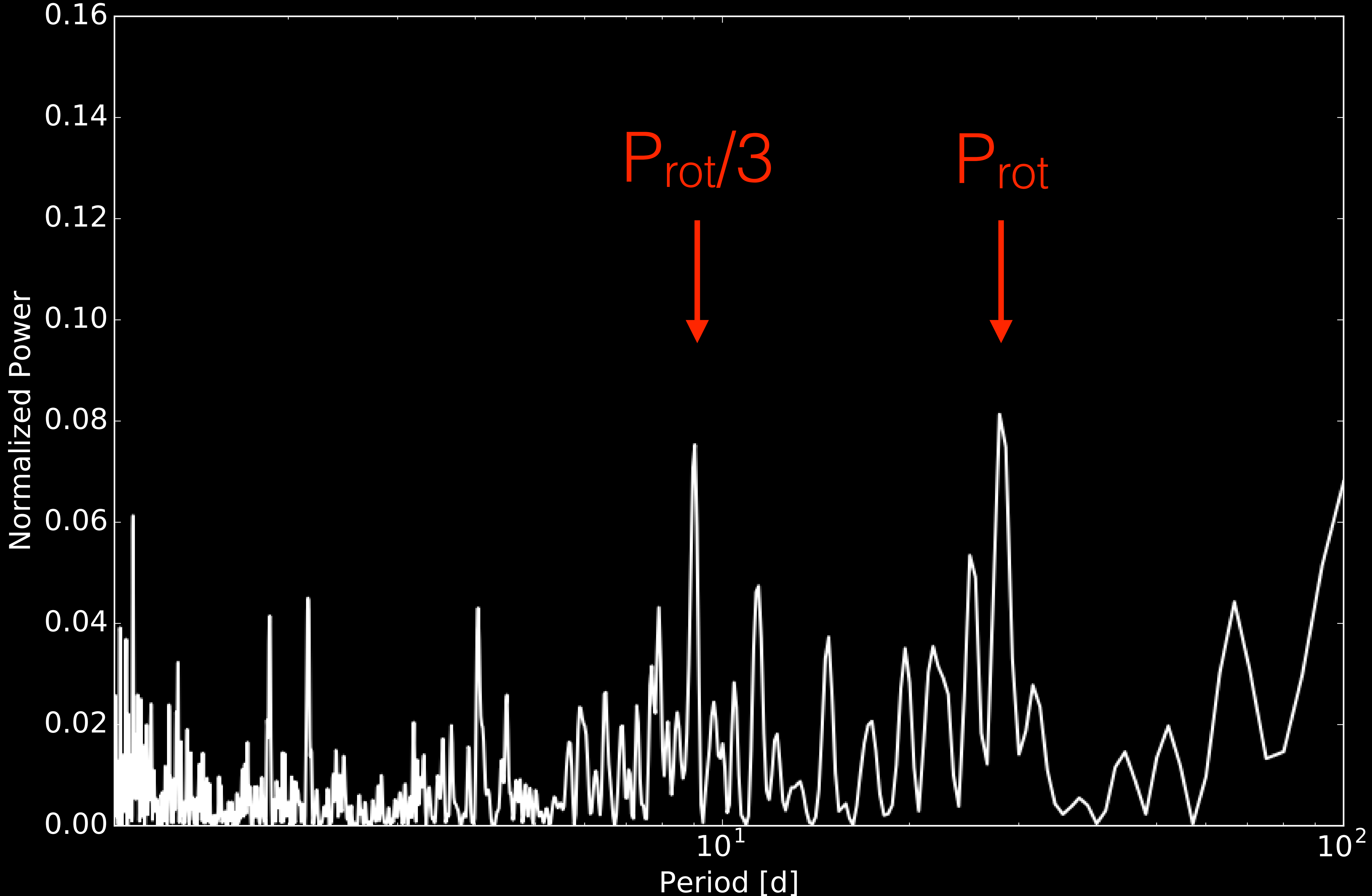


Data

Sun as a Star RVs

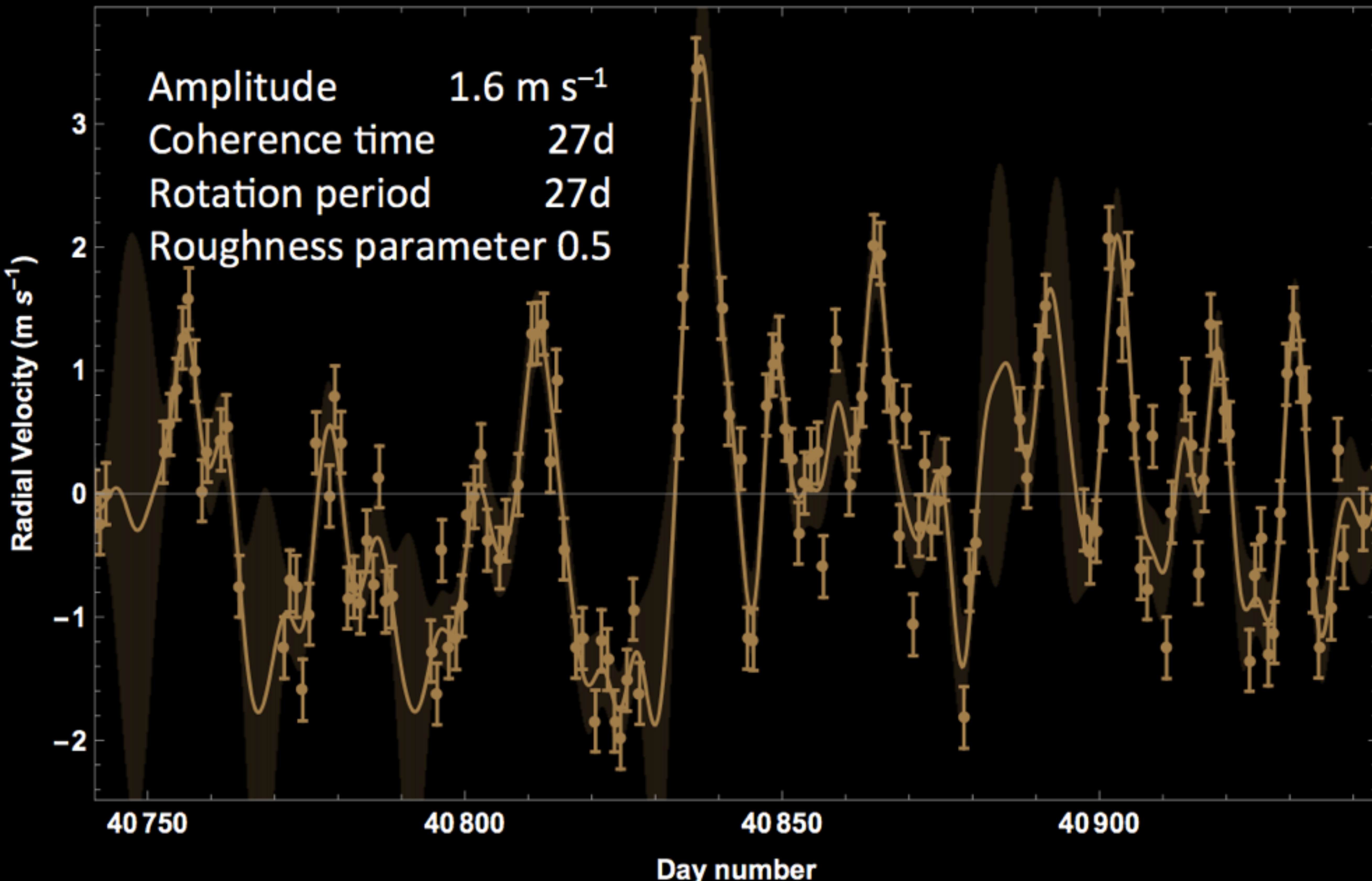


Periodogram Sun as a Star RVs



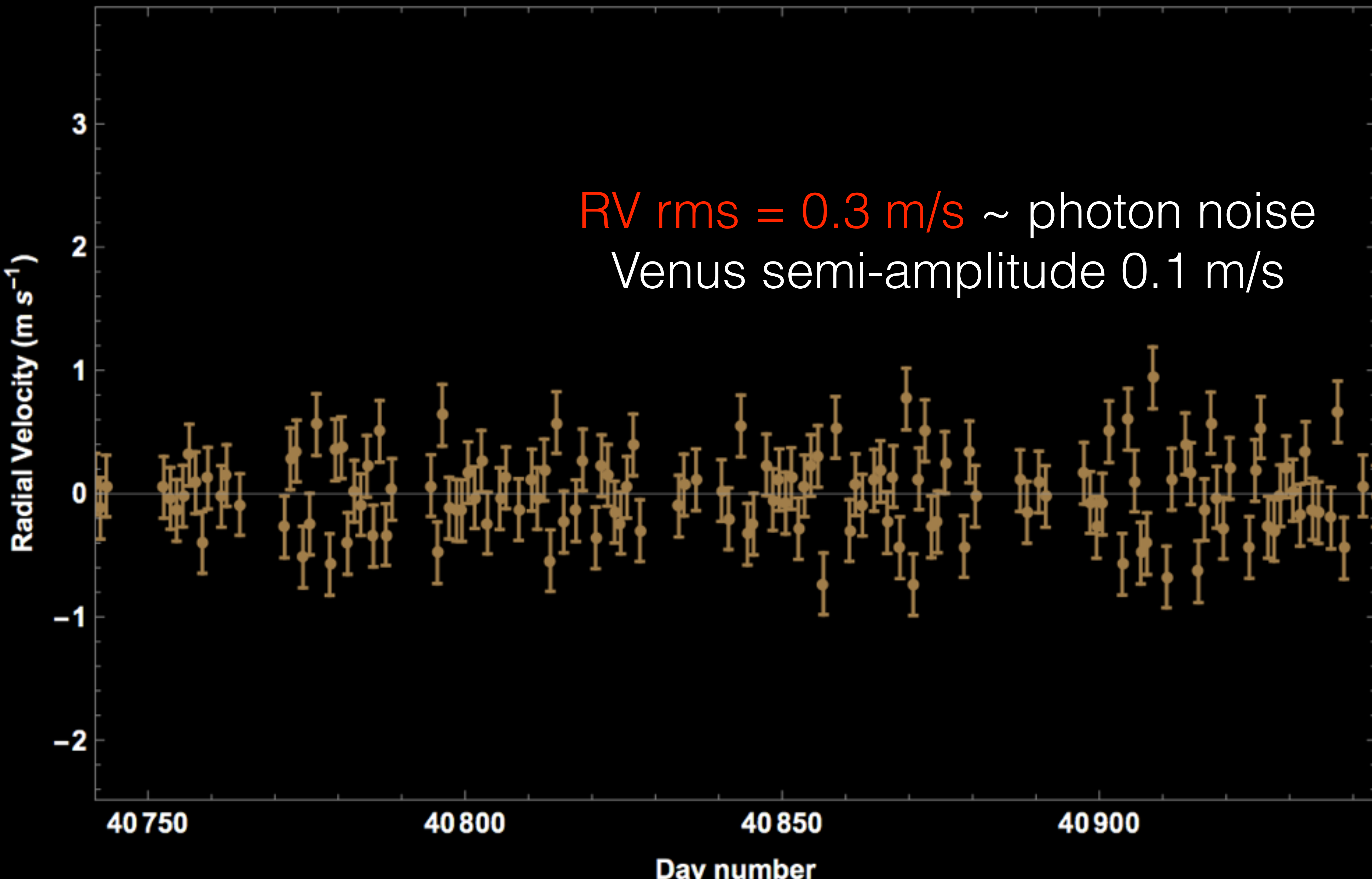
Correction Techniques

Gaussian Process Regression



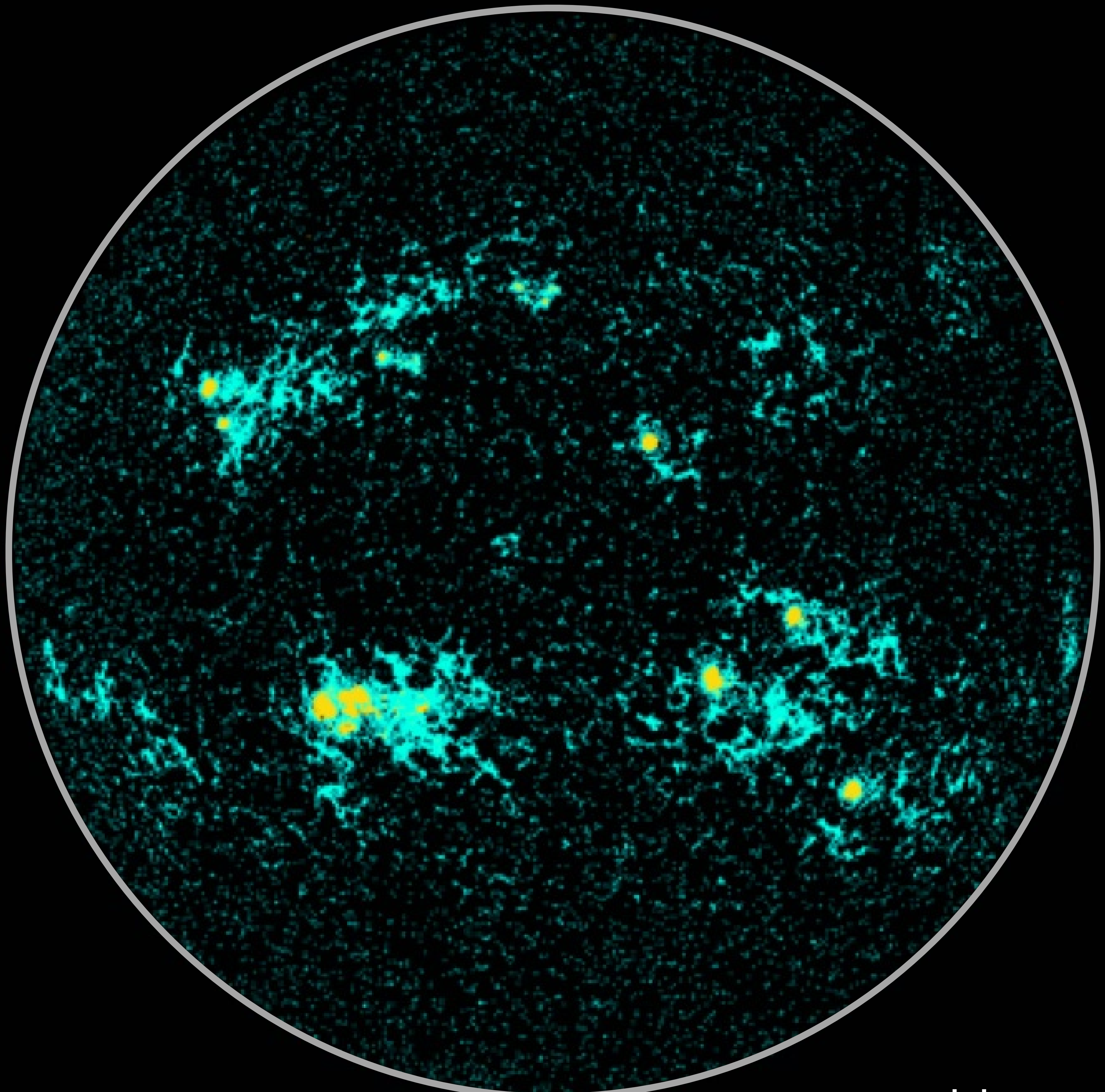
A. Collier Cameron

Residuals after Gaussian Process Regression



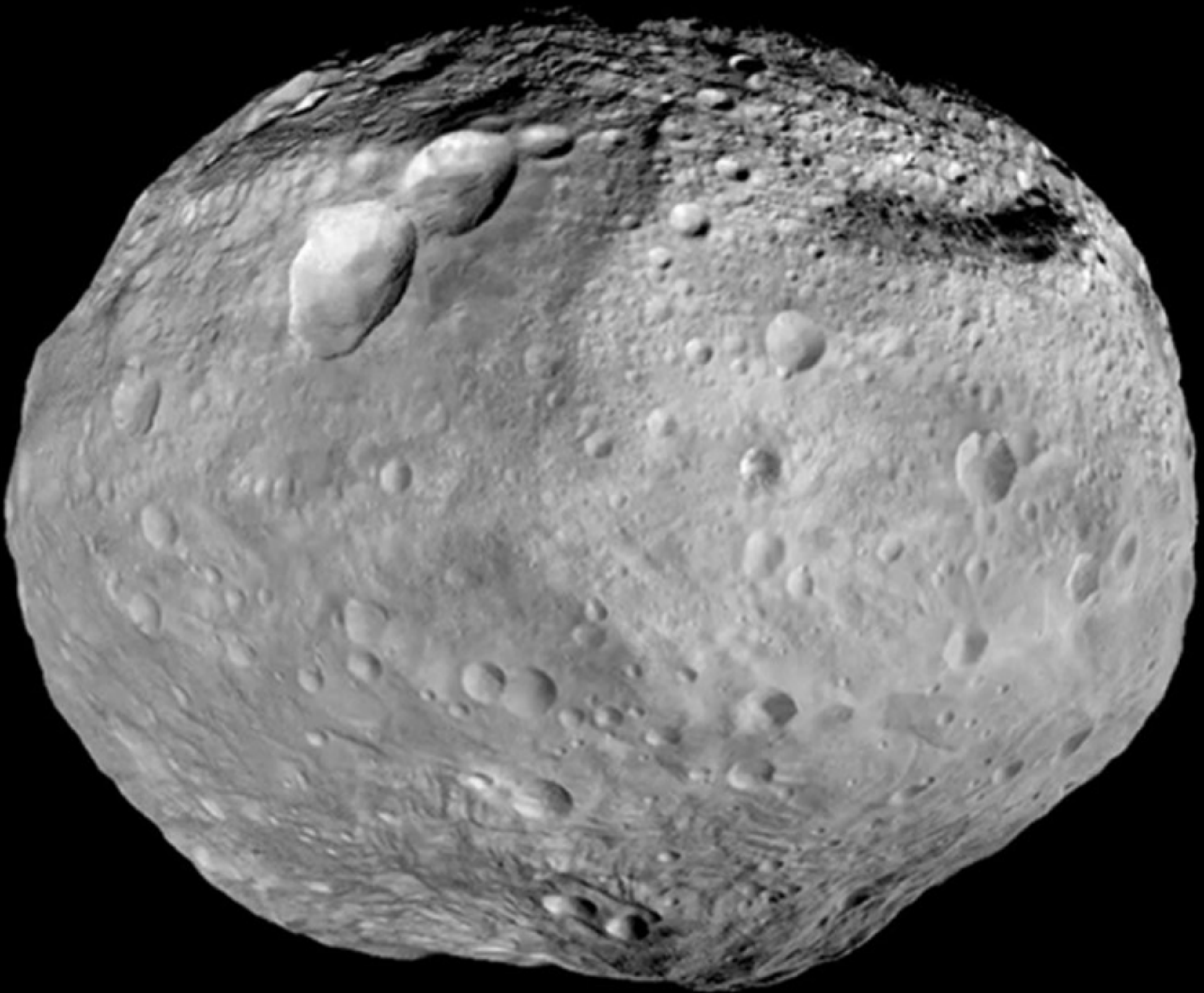
A. Collier Cameron

Using SDO To Recover The Sun's RV



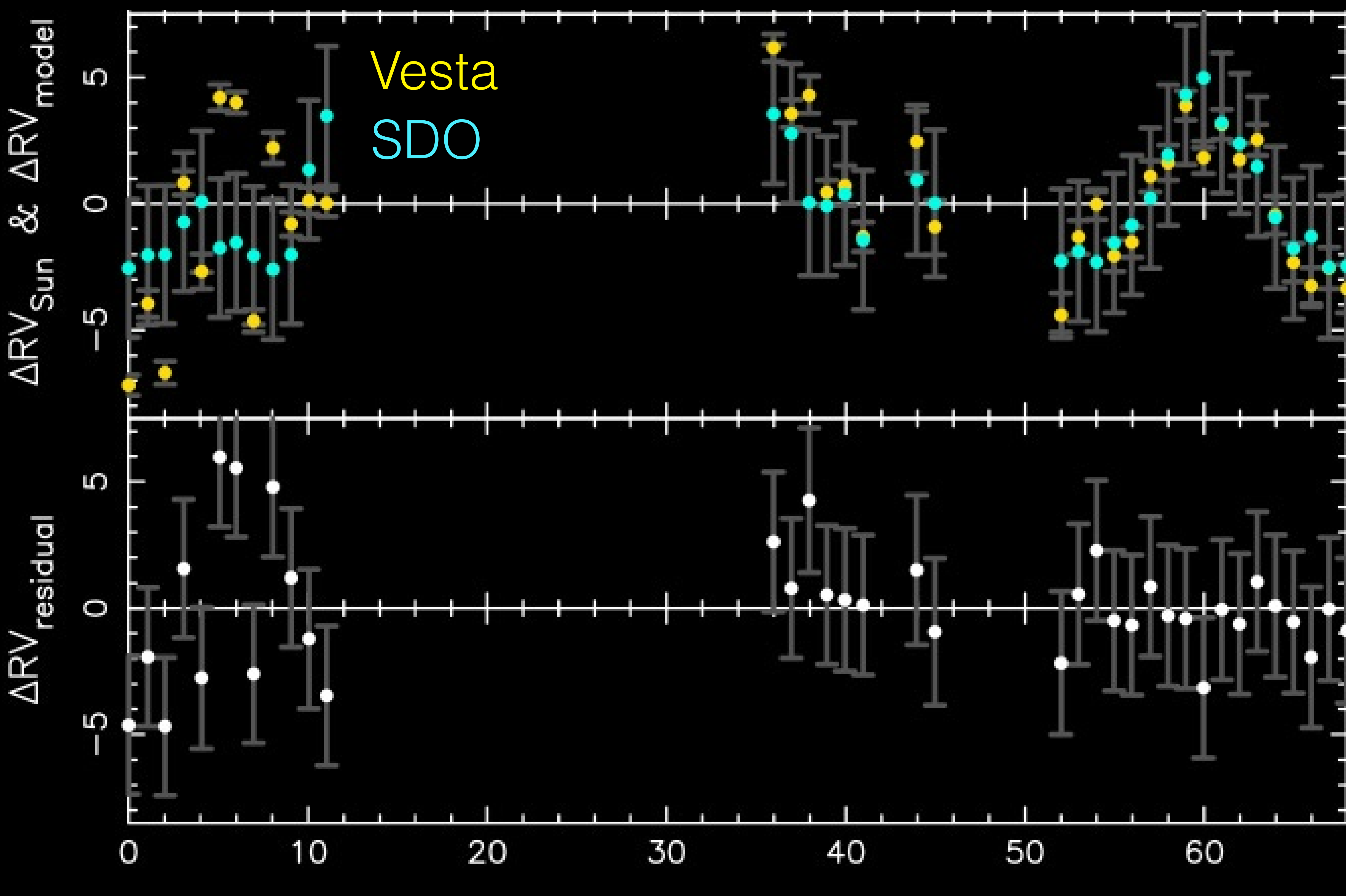
Haywood+ 2016

Using SDO To Recover The Sun's RV



Haywood+ 2016

Using SDO To Recover The Sun's RV



Haywood+ 2016

Data

Sub-m/s RV precision of the Sun as a star

Long-term stability

4-5 hours every possible day, with 5-minute cadences (can go as short as 20 seconds)

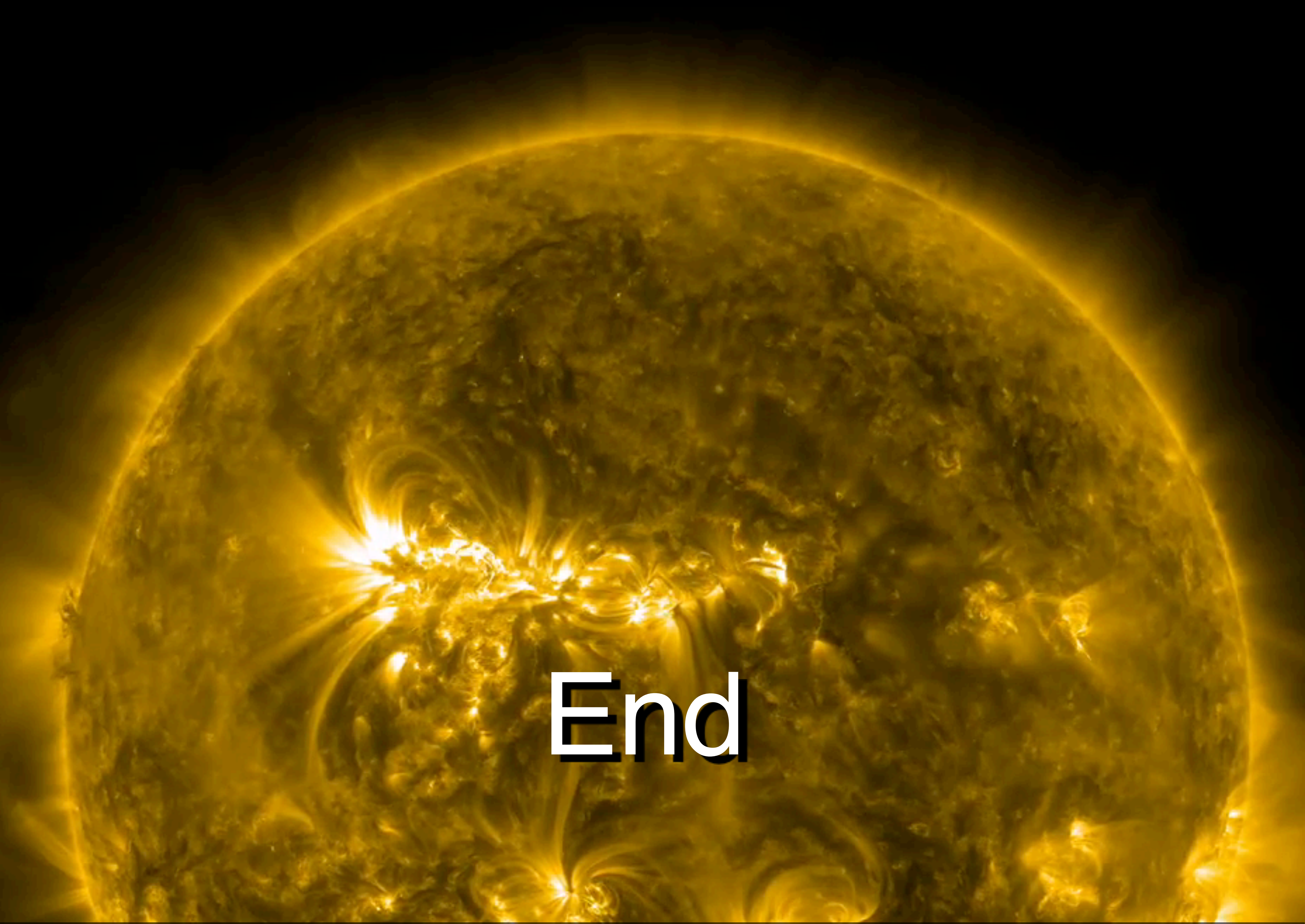
BEST DATA EVER TO STUDY STELLAR SIGNALS

Goals

Understanding stellar signals

Find correction techniques to mitigate them

Detect the signal of Venus, as proof of concept for detecting Earth 2.0



End

Detecting Venus

Simu RVs: oscillations + granulation + stellar activity + magnetic cycle + Venus (no other planets)

RVs low-pass filtered with a cut at 200 days