Xavier Dumusque
CfA

Radial velocity surveys

Detection method and limitations

Outline

Outline

Detection methods

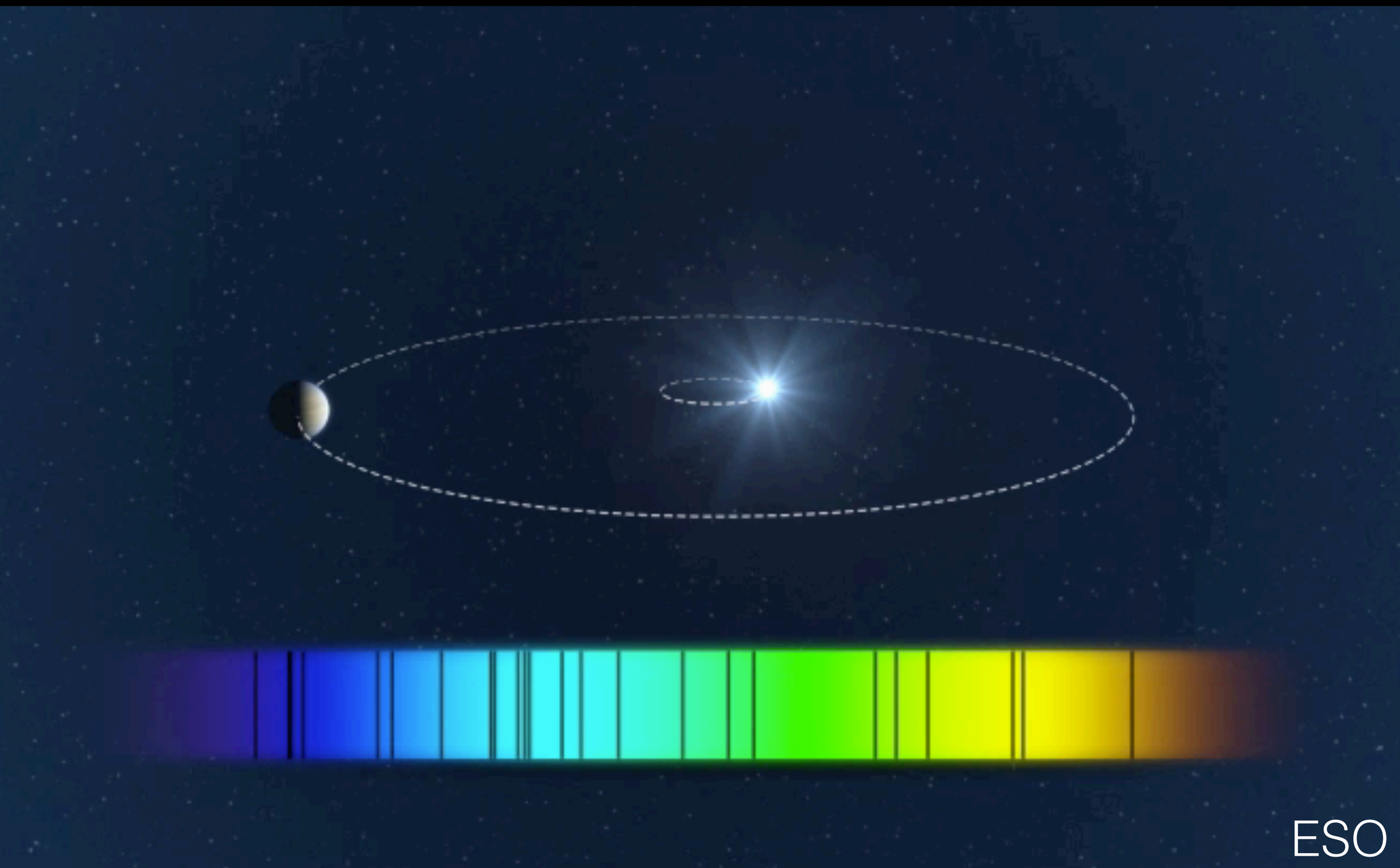
Instrumentation

Limitations

Future Prospect

The RV technique

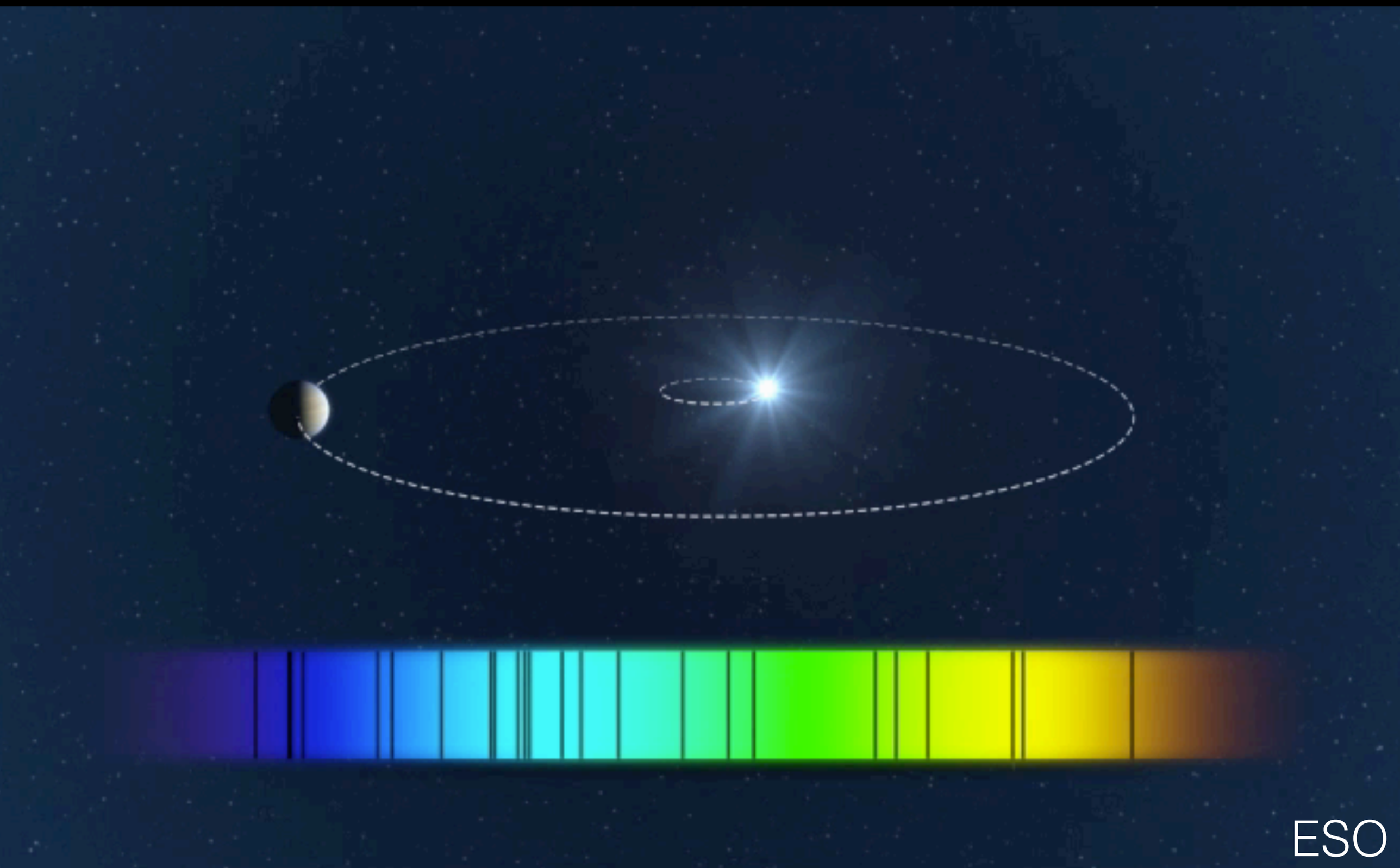
THE RV TECHNIQUE



ESO

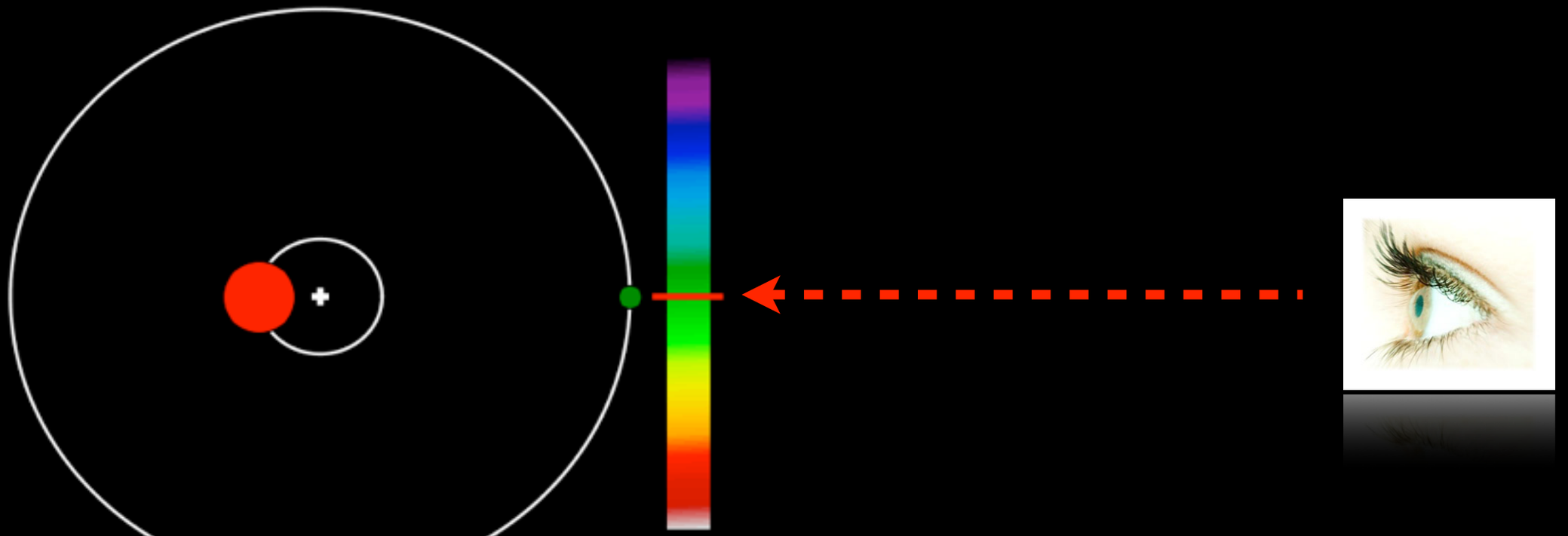
The RV technique

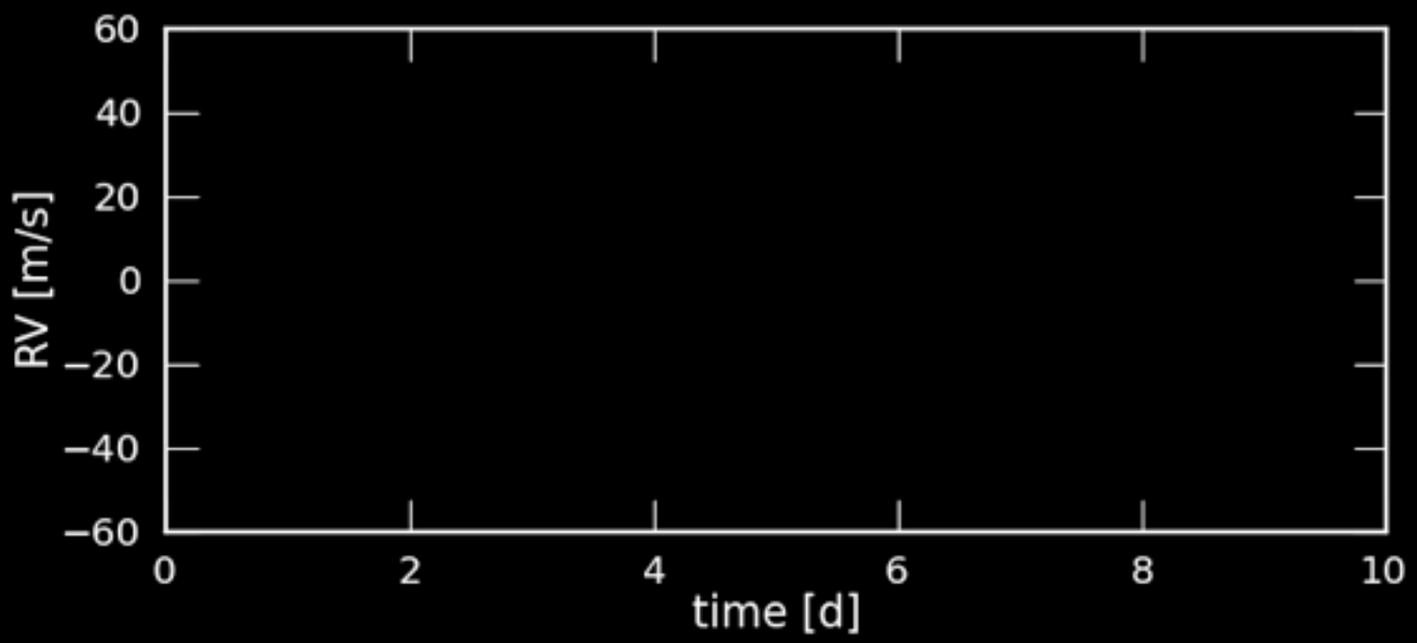
THE RV TECHNIQUE



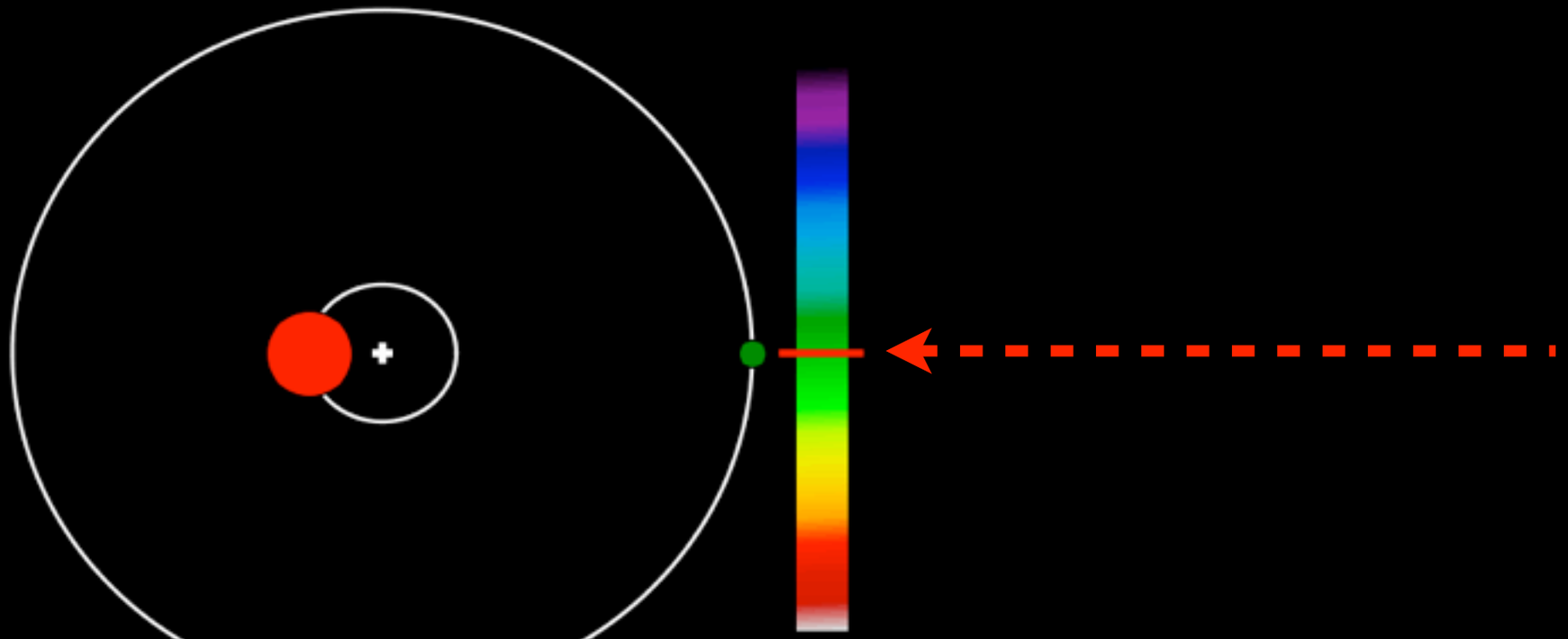
ESO

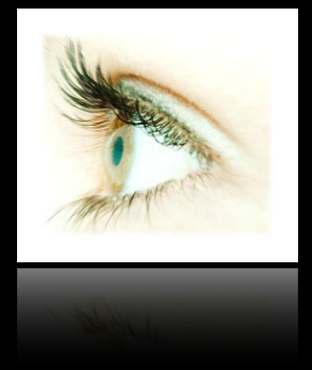
The RV technique

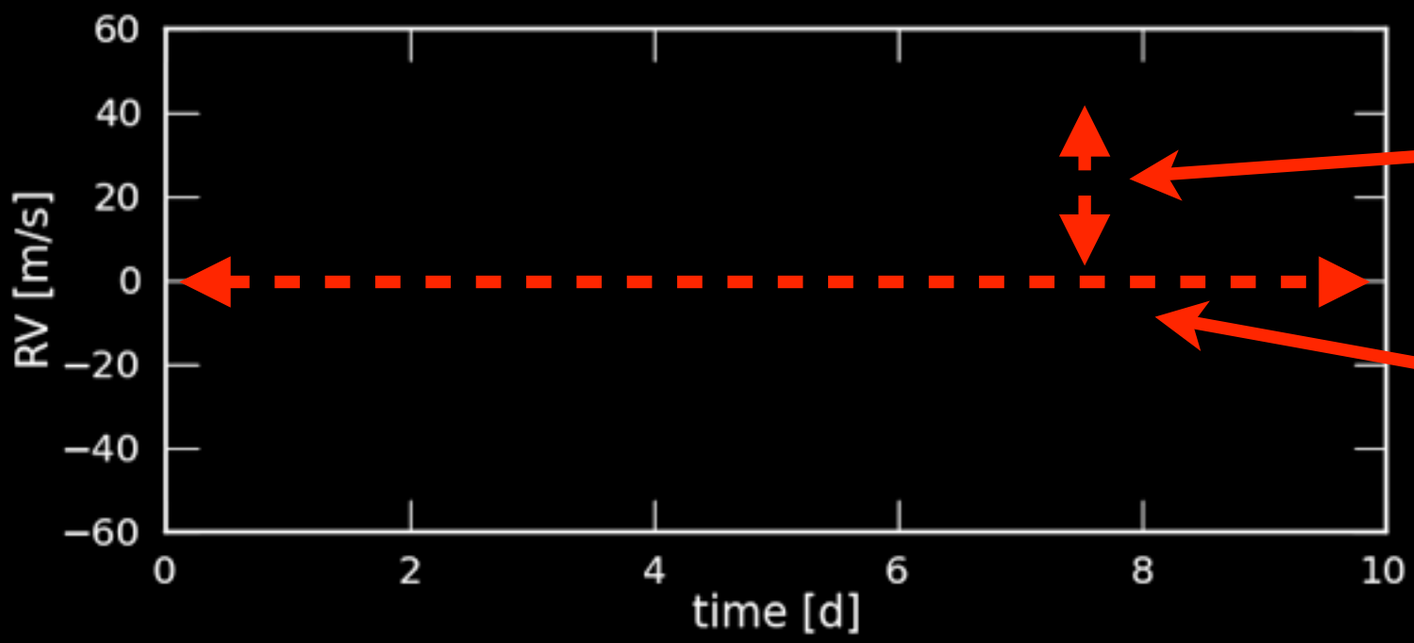




The RV technique





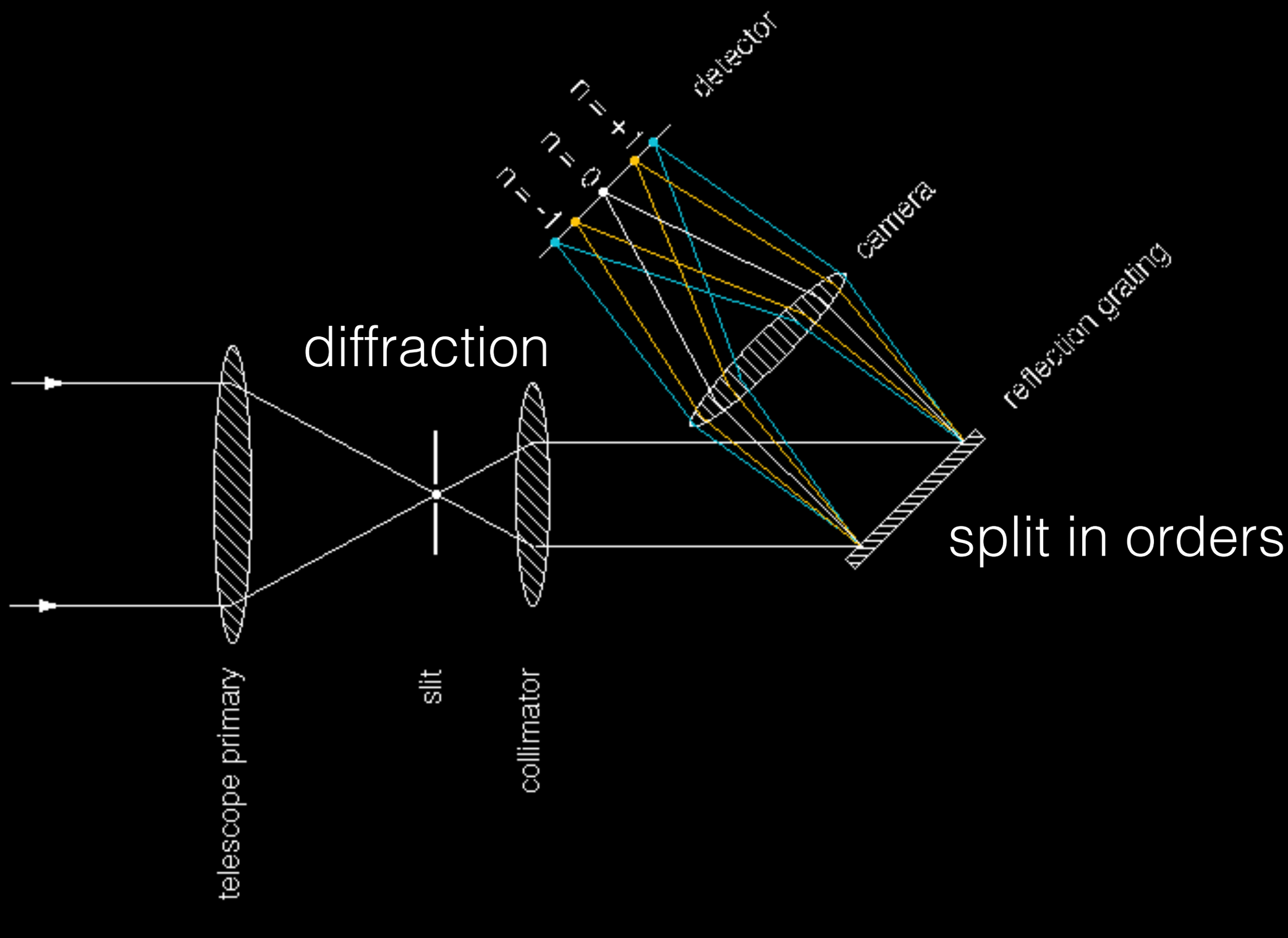


$$\sim \frac{M_{pl} \sin i}{M_\star^{2/3}}$$

P_{pl}

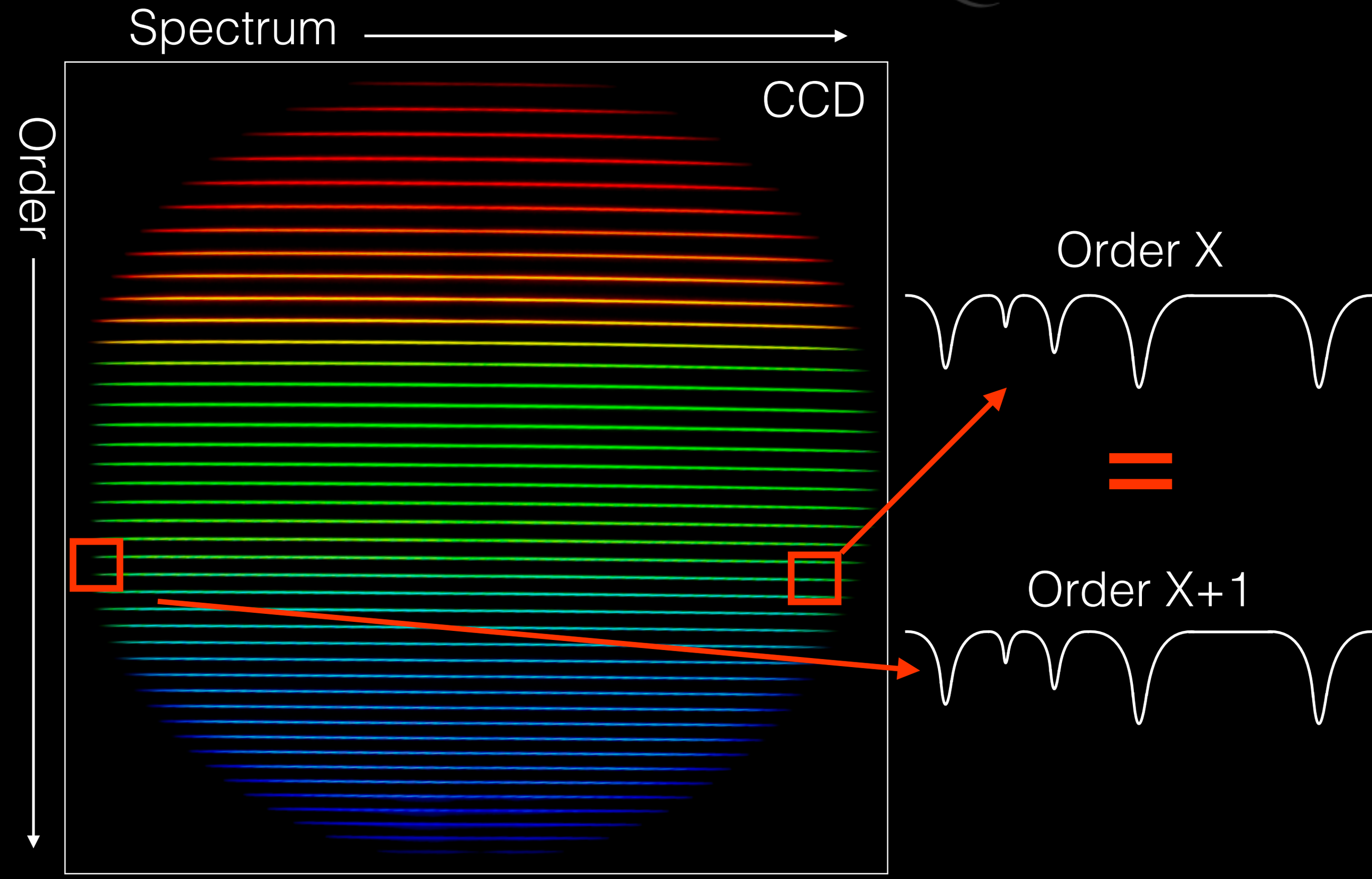
Spectrograph

Spectrograph



The RV technique

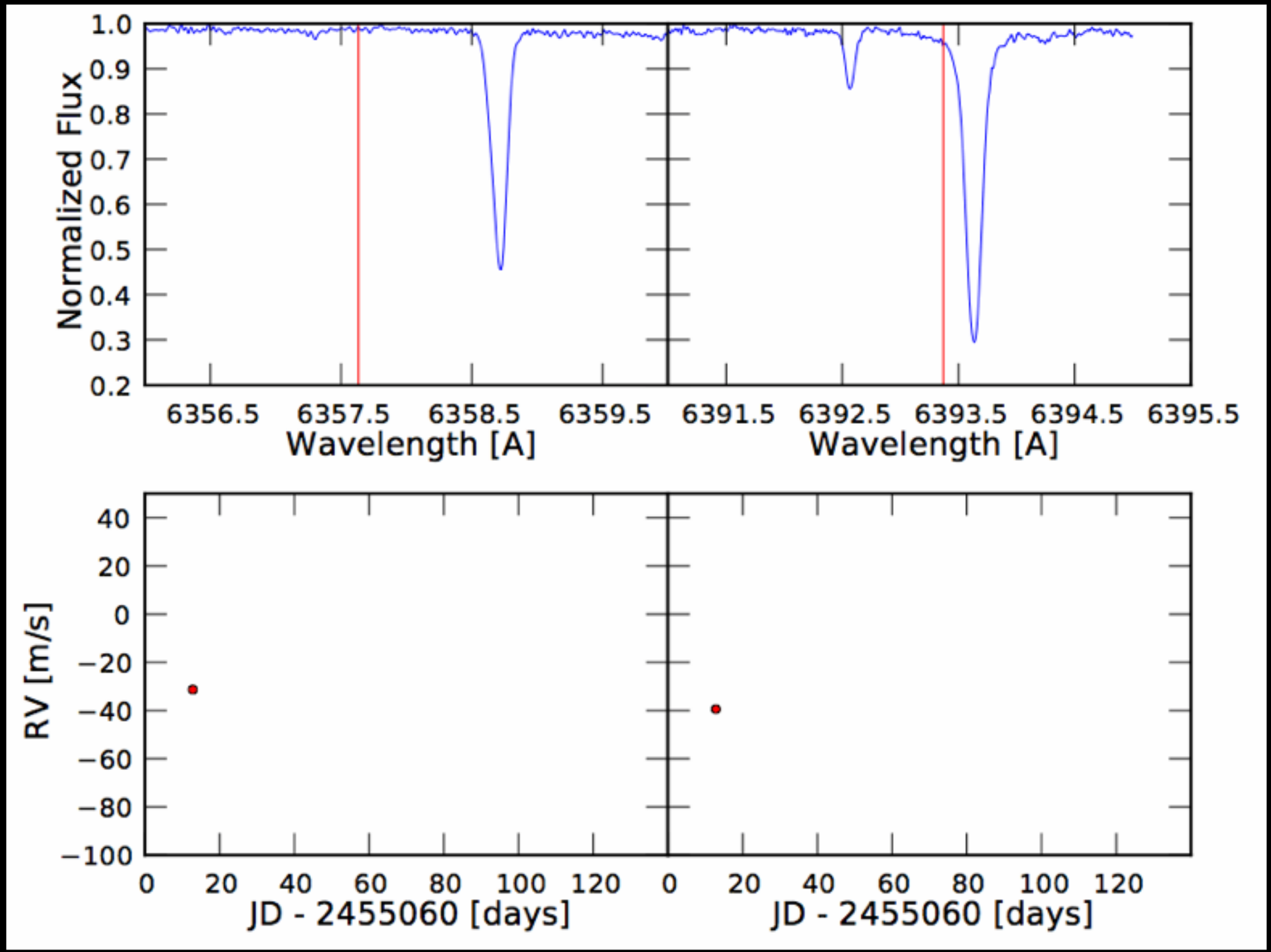
The RV technique



Challenges for measuring precise RVs

- 1 m/s = ~10^{-5} Angtroms = 1/1000 of a CCD pixel (R=100000)
- Variation in the index of refraction of air: 0.01 mbar or 0.01 K -> 1 m/s
- Thermal and mechanical effect -> PSF changes ->10 m/s
- Slit illumination variation (seeing, focus, guiding) -> 1/100 of the slit width -> 30 m/s

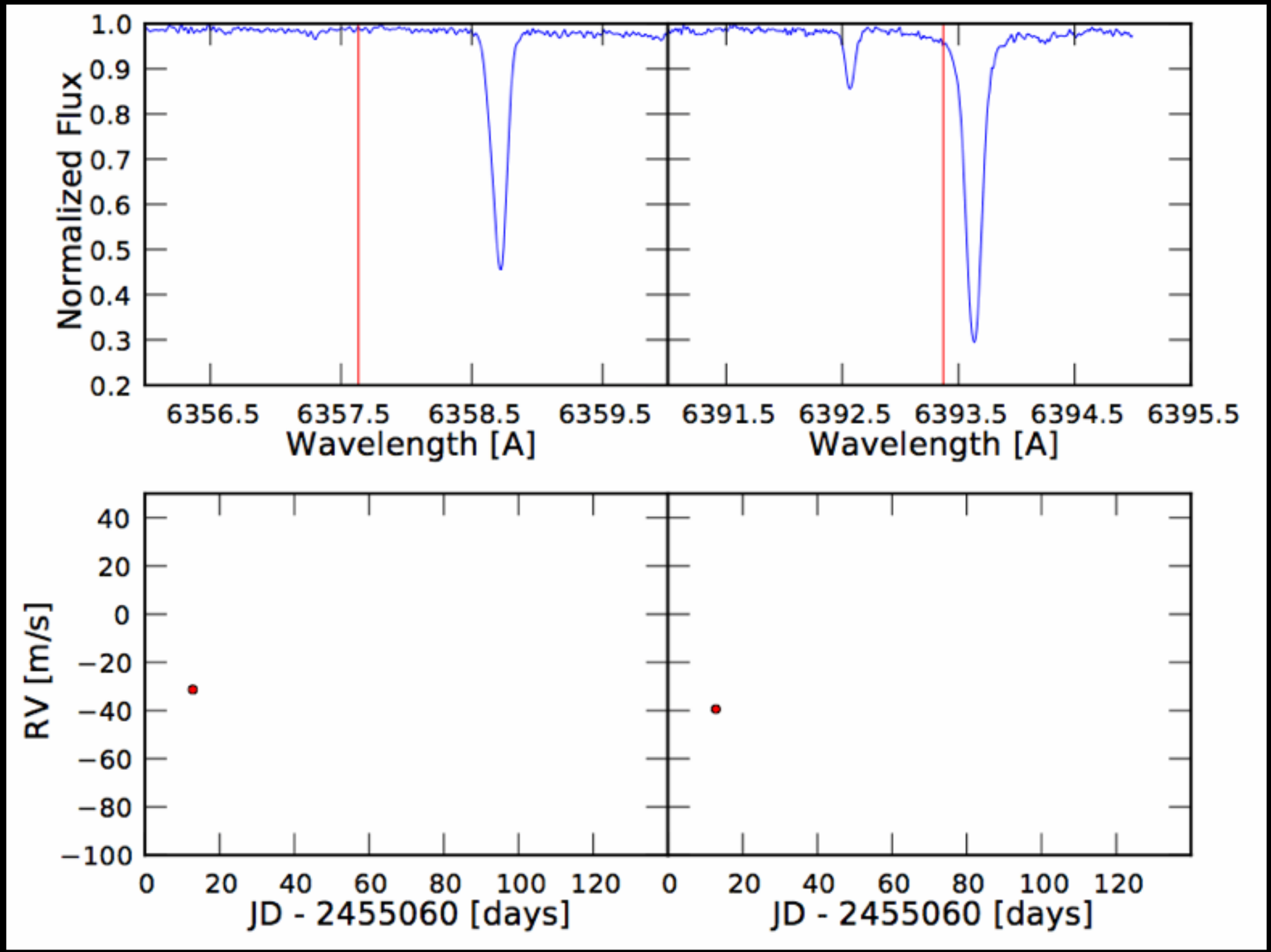
Lovis & Fischer 10



1 spectral line -> 30 m/s

4000 spectral lines -> 30/sqrt(4000) = 0.5 m/s

Dumusque+15



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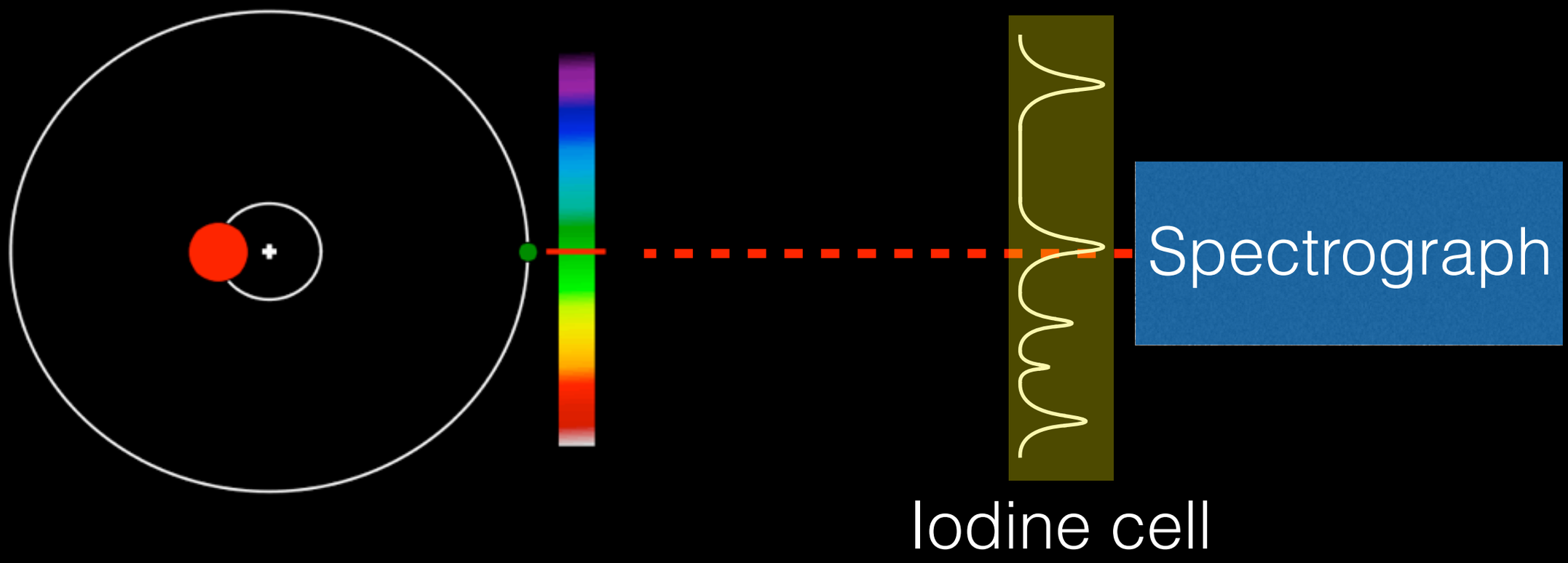
Dumusque+15

Instrumentation

The Iodine cell technique

Idea Gas cell with Iodine before the stellar light is fed into the spectrograph. The iodine spectrum will be affected by the instrument



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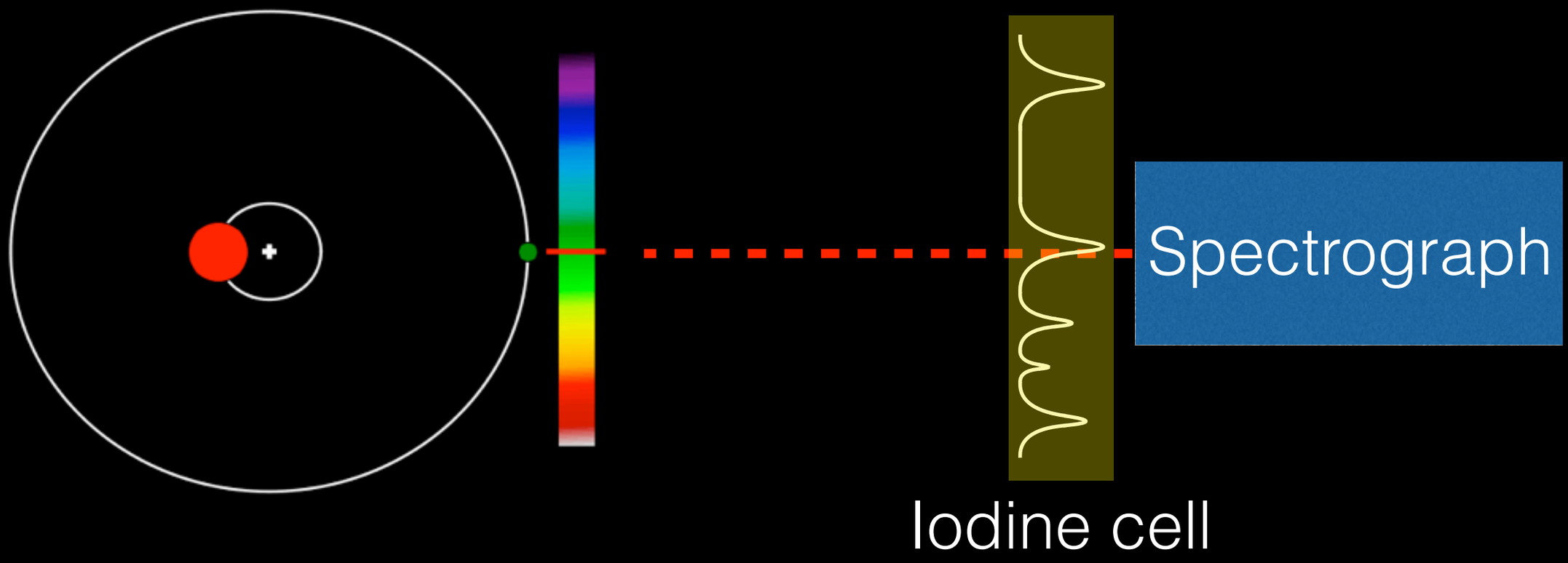
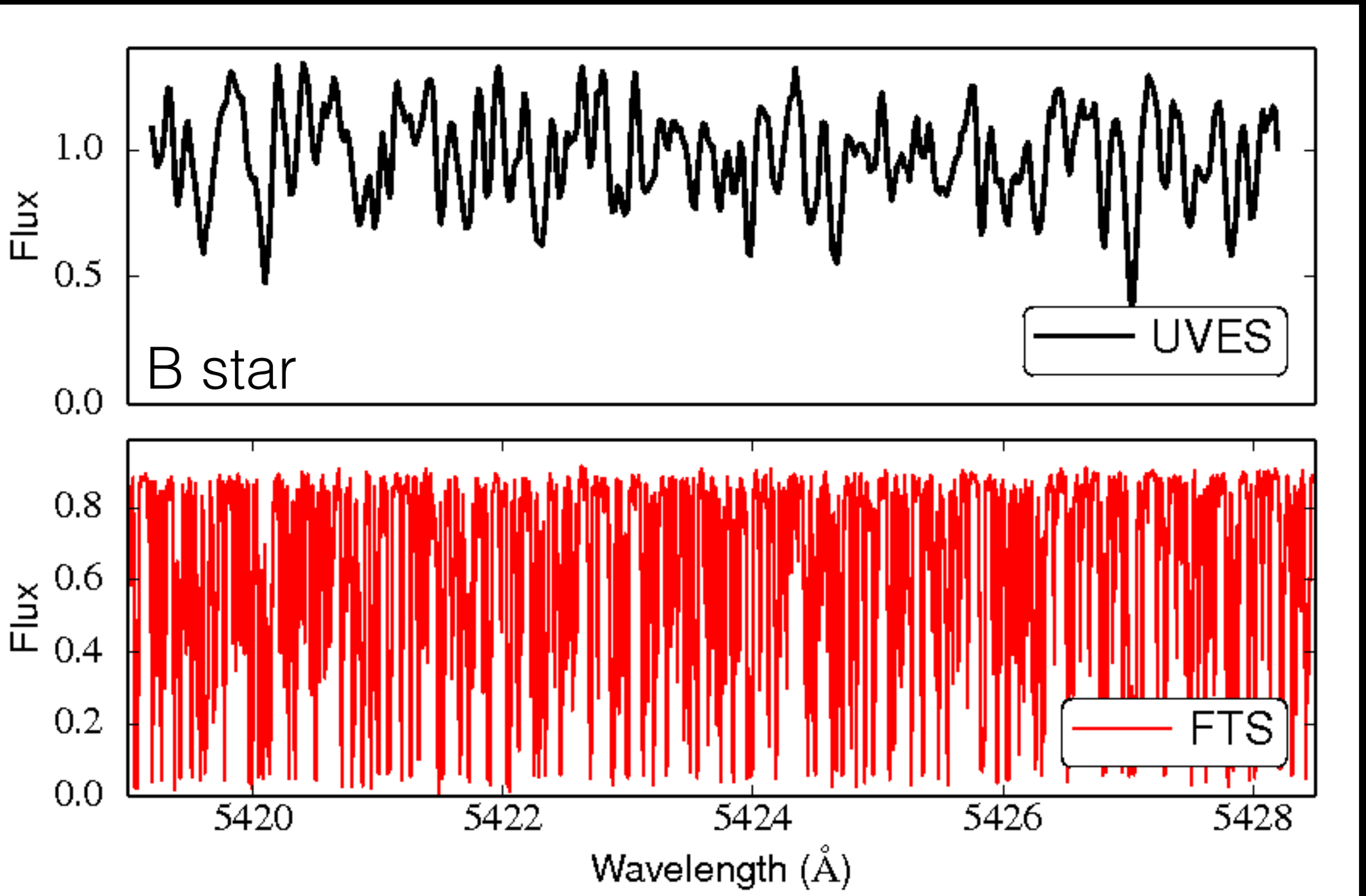


The iodine spectrum

The iodine spectrum



R = 40’000

R = 1e6

The Iodine cell technique

- The iodine cell spectrum is affected by the instrument in the same way that the stellar spectrum (slit illumination, temperature and pressure changes, PSF changes)

- Observe a B star with iodine to get the instrument PSF

- Observe a star without iodine, and deconvolve the spectrum from the PSF, to get the intrinsic stellar spectrum (the PSF do not change)

- Observe the star with the iodine, and model the spectrum as the convolution of the stellar intrinsic spectrum, the iodine high resolution spectrum and the instrument PSF

- The RV is the difference between the iodine spectrum and the observed spectrum

Stellar intrinsic spectrum

Iodine spectrum

Residual Intensity

Spectrum entering spectrograph

Air Wavelength (Å)

Spectrum broadened by LSF

Valenti & Anderson 10

The stabilized technique
(HARPS-type instruments)

Stability
0.01 mbar and 0.01 K -> no PSF changes

Fiber-Feed
scramble light -> reduce slit illumination
variations to < 1m/s

Reference Calibration
track any instrumental drift

Star

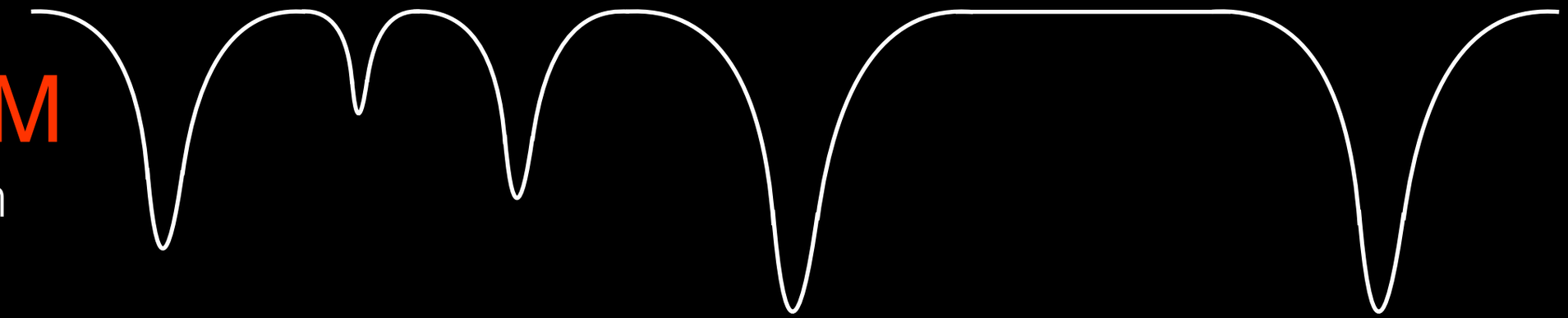
Thorium

HARPSN raw image

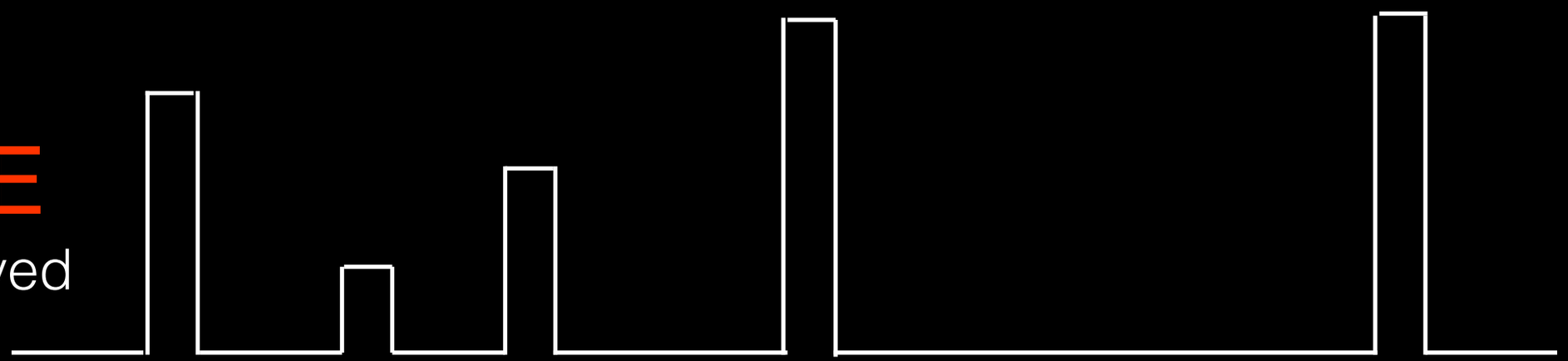
How to derive precise RV?

How to derive precise RV?

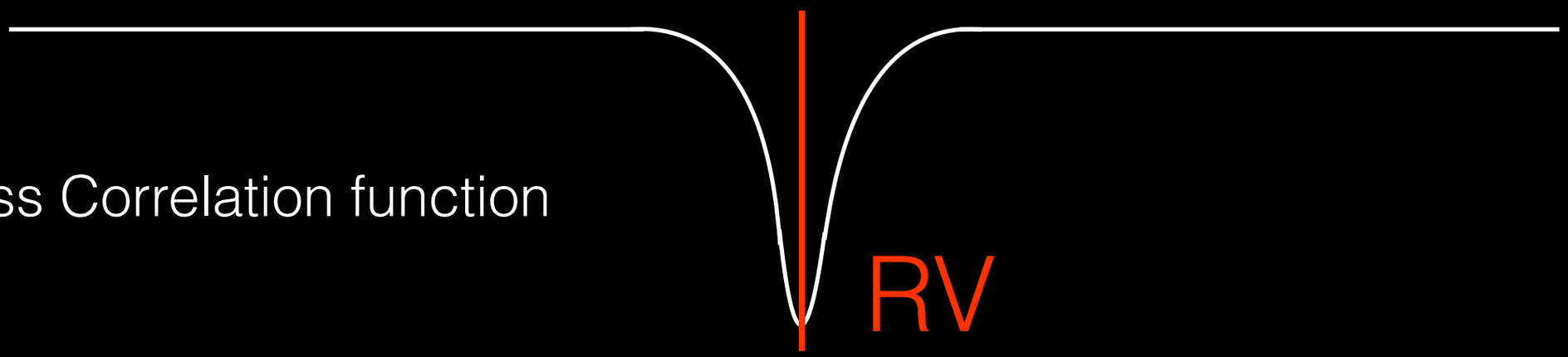
SPECTRUM
visible spectrum



TEMPLATE
synthetic or observed



CCF Cross Correlation function



Pros and Cons

Iodine Cell

- “Cheap”
- post processing of the data difficult (17 free parameters for fitting the PSF)
- Limited to ~1.5 m/s of precision

Stabilized

- Expensive (HARPS-type ~5 millions)
- post processing of the data extremely easy
- precision better than 1 m/s and can be improved

Instruments

Iodine Cell

- HIRES (KECK)
- APF (Lick Observatory)
- PFS (Magellan)
- CHIRON (CTIO)

Stabilized

- HARPS (3.6m ESO)
- HARPS-N (TNG)
- SOPHIE (OHP)
- CORALIE (La Silla)

Limitations of the RV technique

Limitations of the RV technique

Instrument

Challenging but possible

Stellar Signals

Current limitation

Stellar Signals

Lindegren & Dravins 03

Oscillations

a few m/s (Dumusque+ 11)

< 15 min

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

Flares

<1 m/s (only active M)

~ 1 h

Saar 09, Reiners 09

Granulation

a few m/s (Dumusque+ 11)

15 min - 2 d

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

Magnetic Cycles

1-20 m/s (Lovis+ 11)

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

~ 10 yrs

Gravitational Redshift

< 10 cm/s (Cegla+12)

10 d - 10 yrs

Active regions

a few m/s (Meunier+ 10)

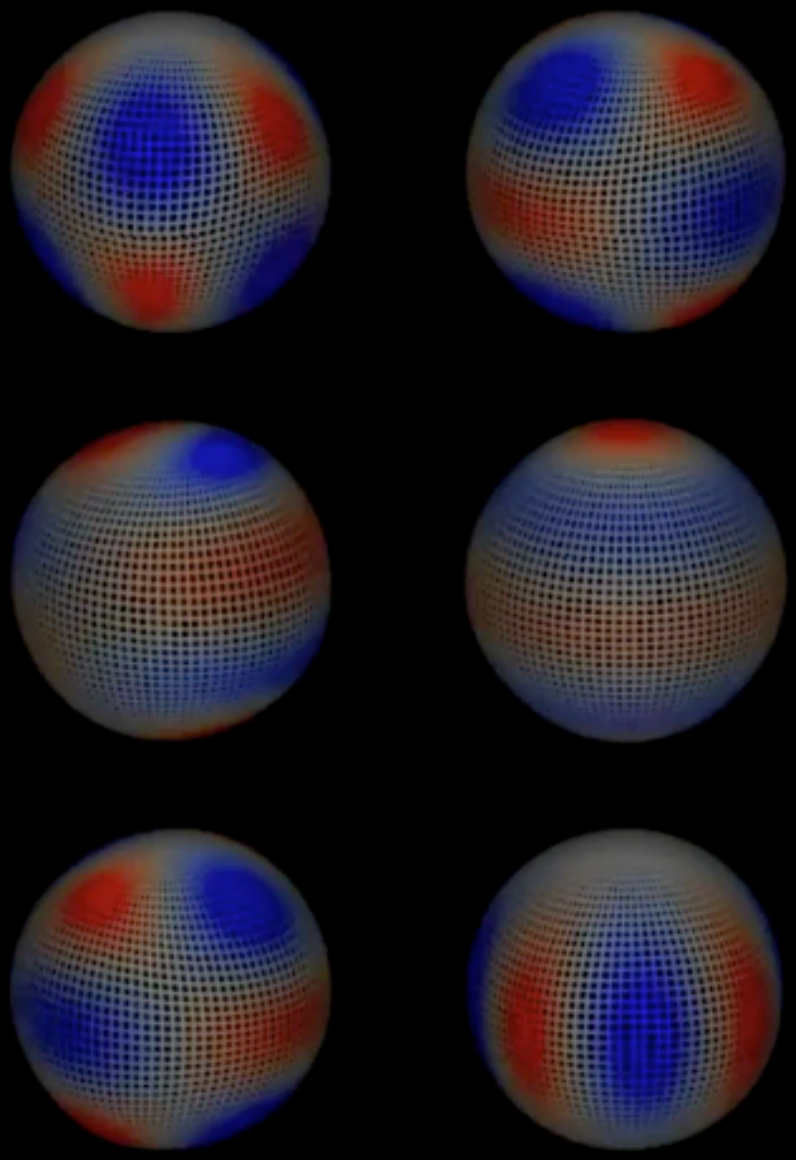
Saar & Donahue 97, Queloz+ 01
Hatzes 02, Meunier+ 10,
Boisse+ 11, Dumusque+ 11,
Lanza+ 11, Aigrain+12,
Boisse+ 12, Dumusque+ 14

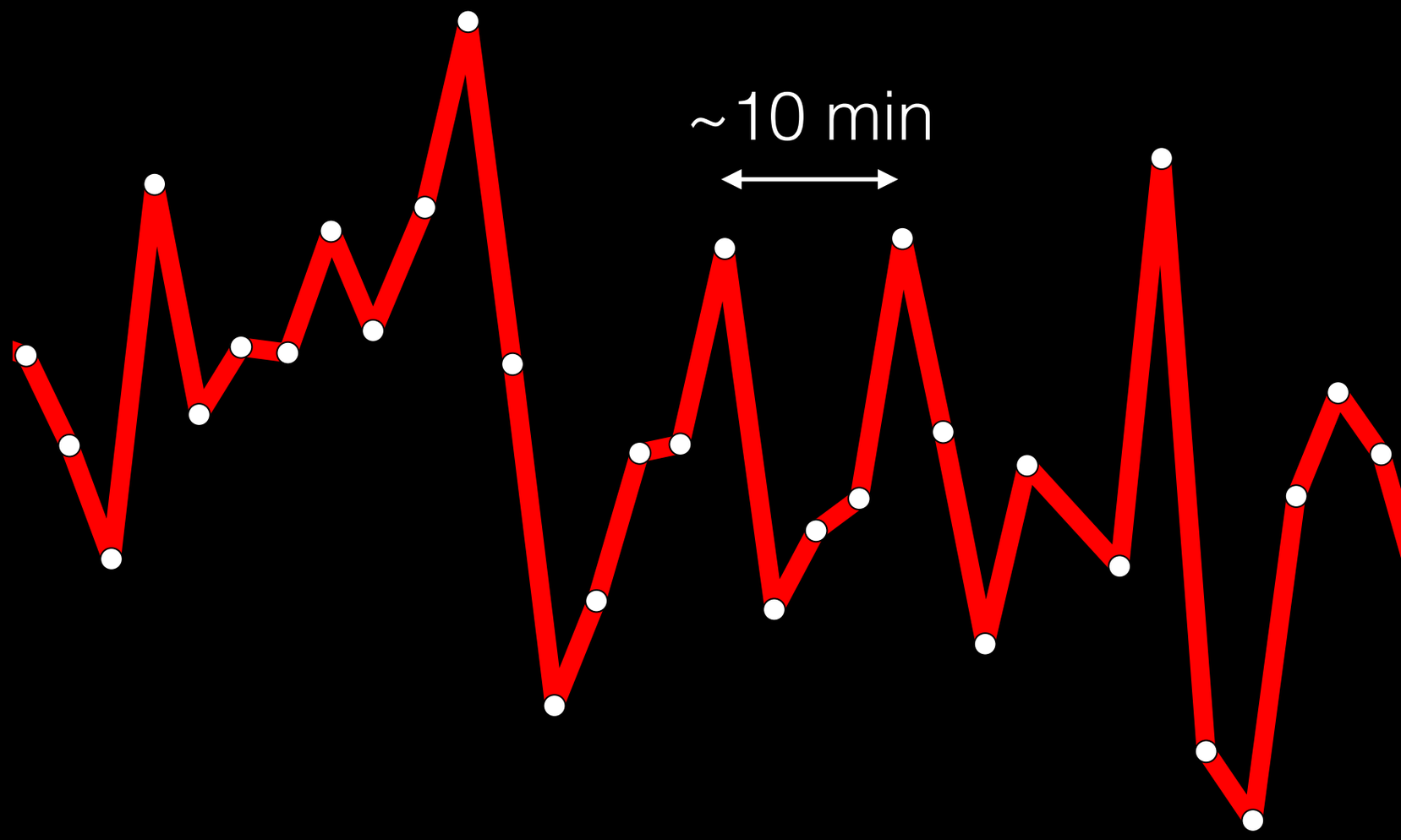
10 - 50 d

Oscillations

Oscillations

a few m/s (Dumusque+ 11)





Credit: Charpinet

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

Oscillations

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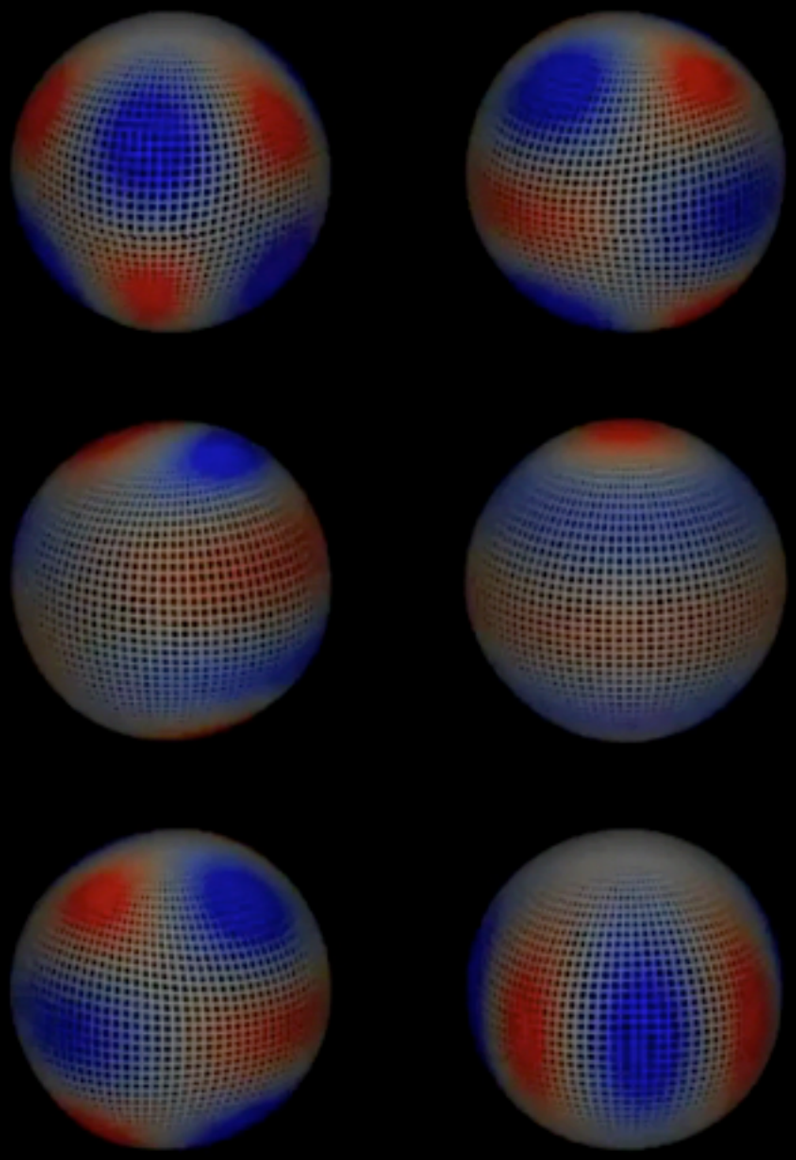

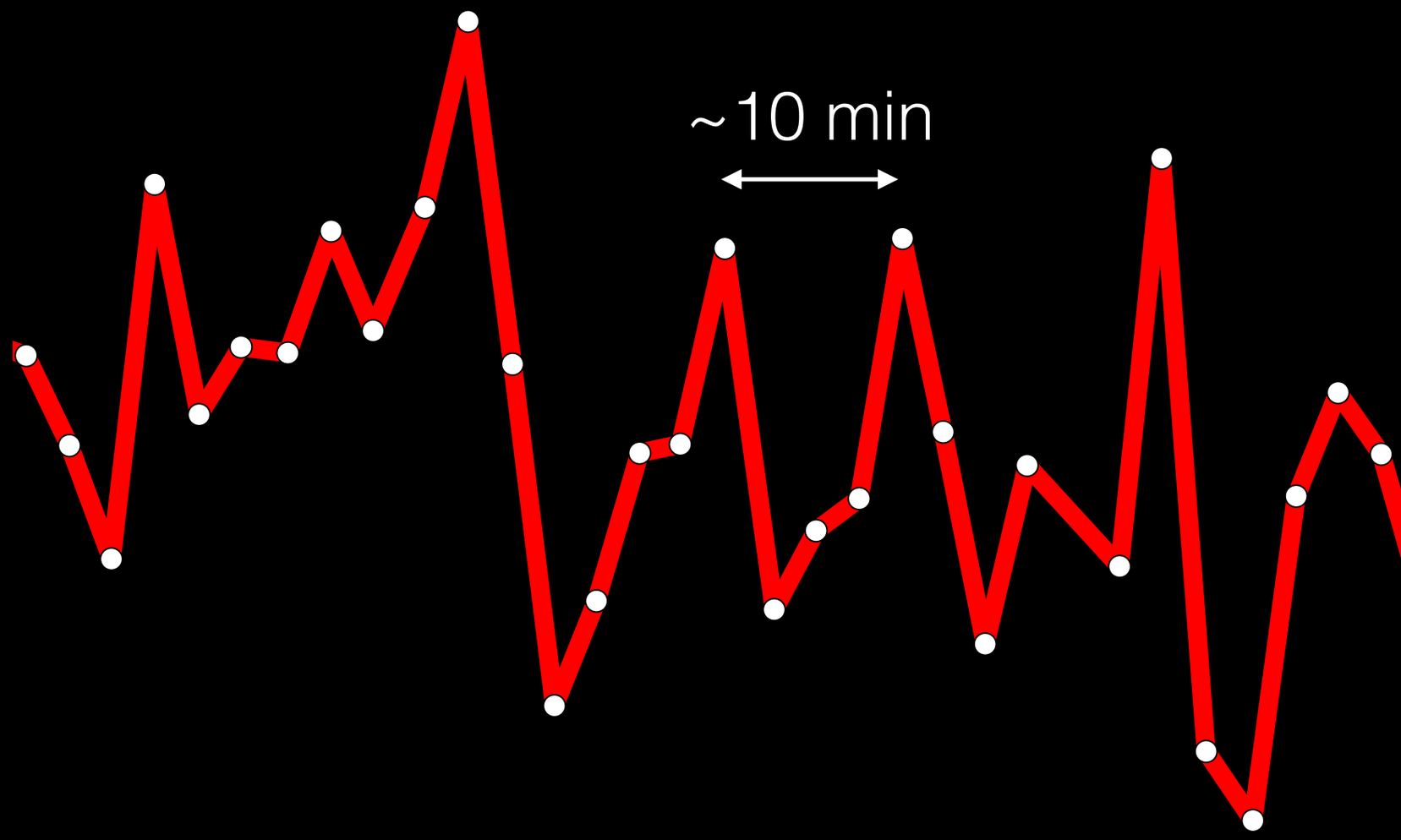

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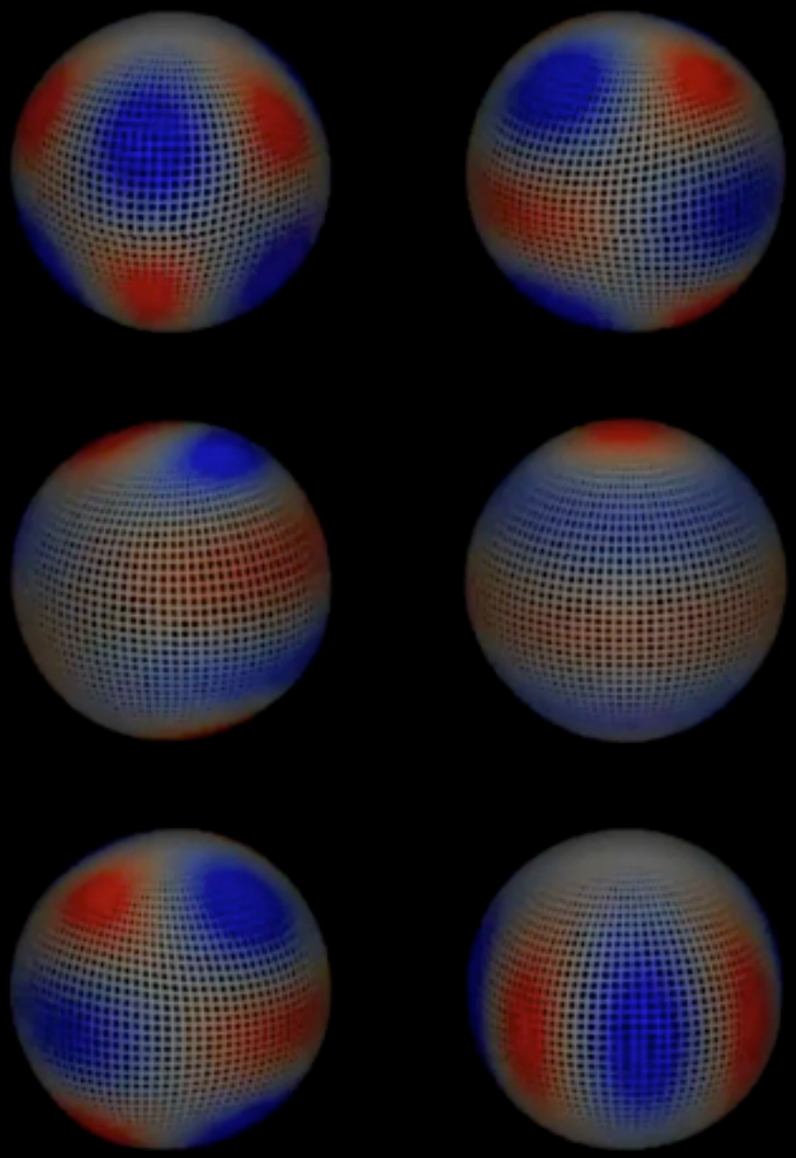

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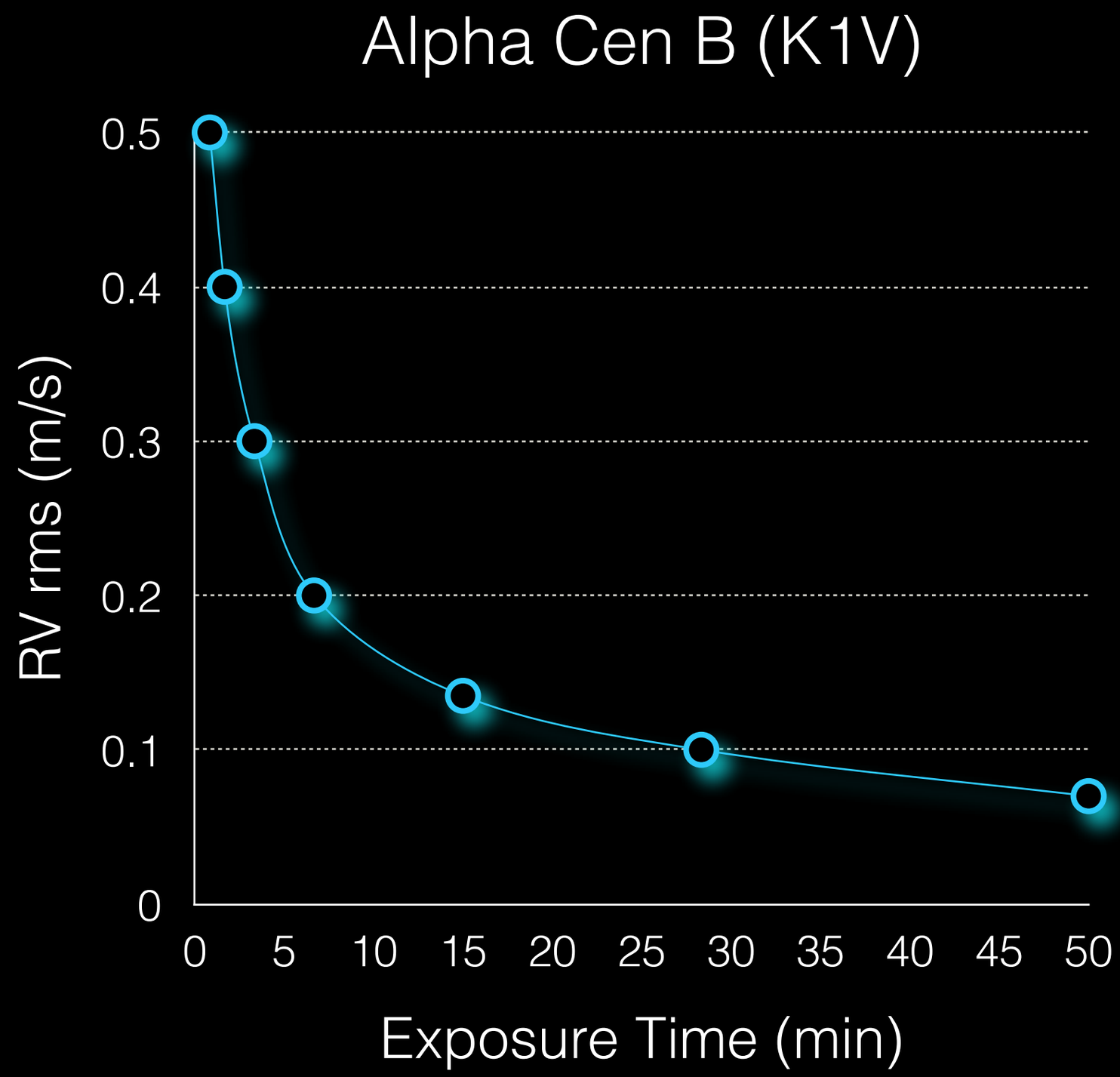
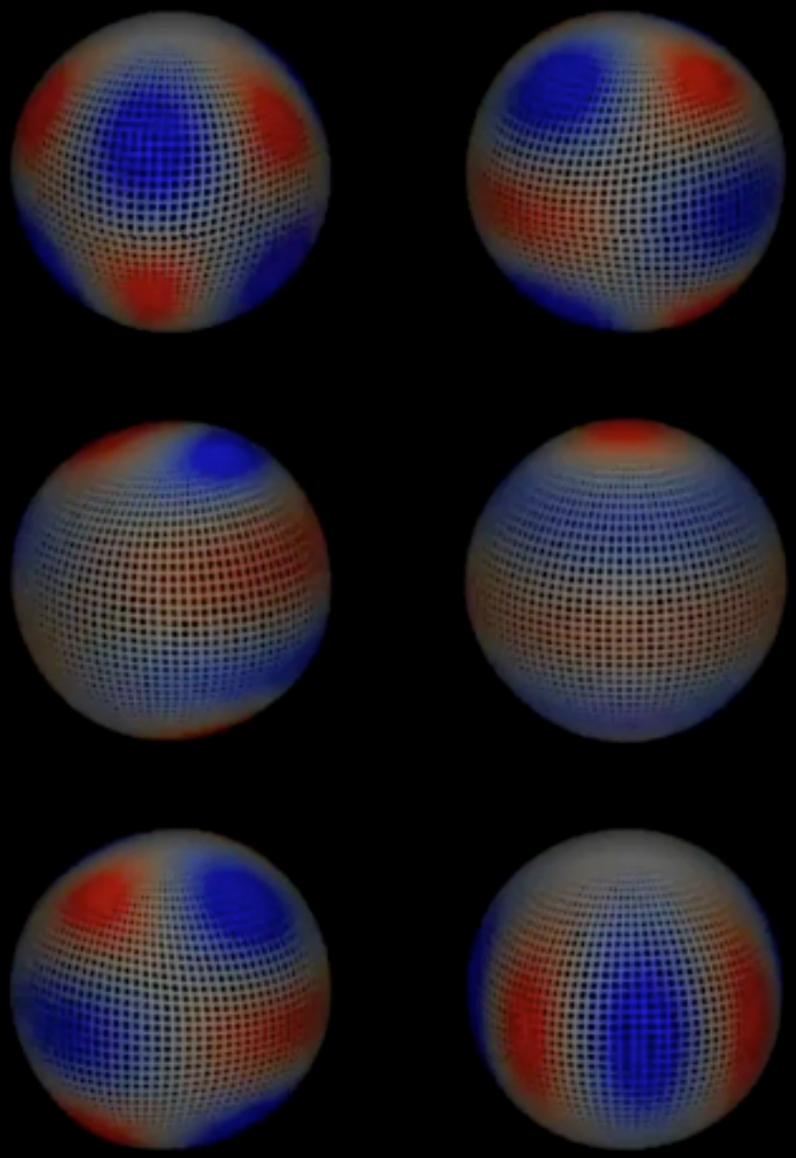


Oscillations



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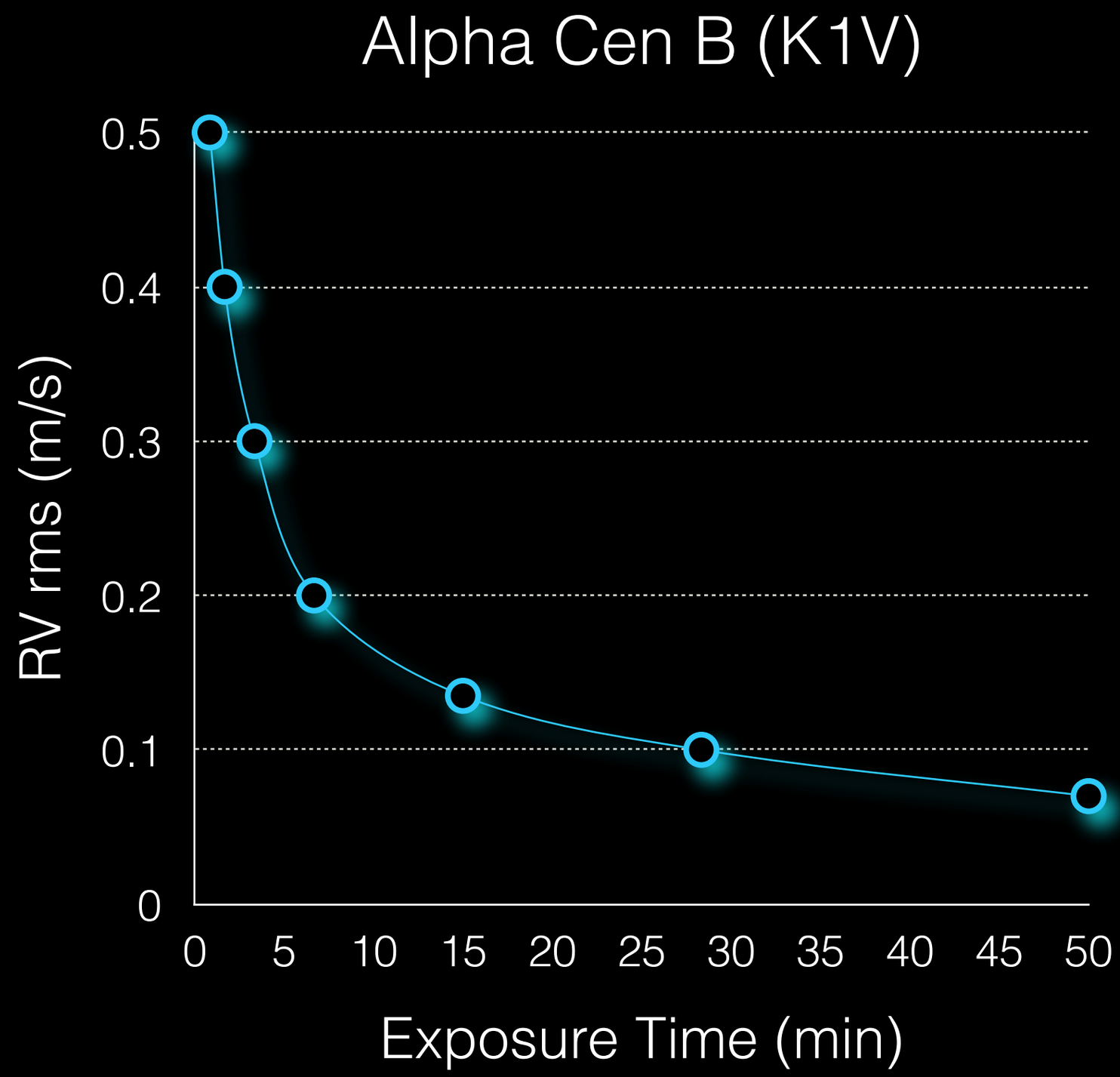

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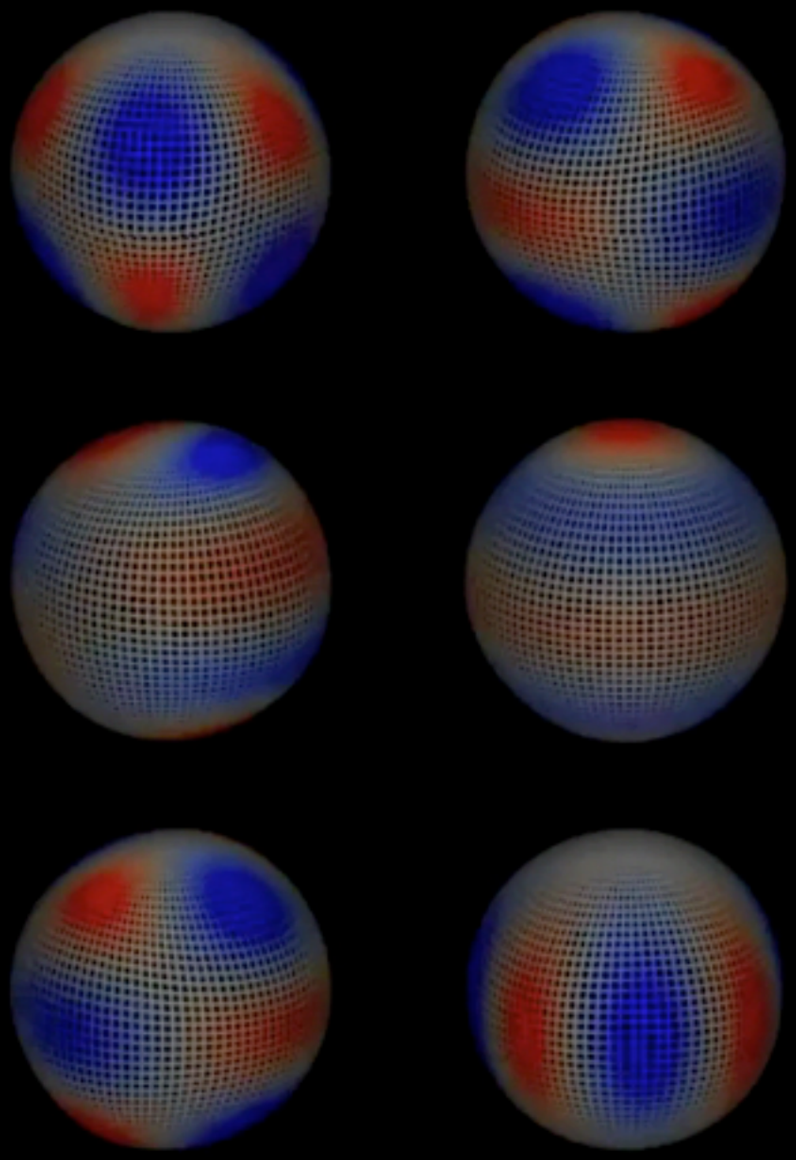
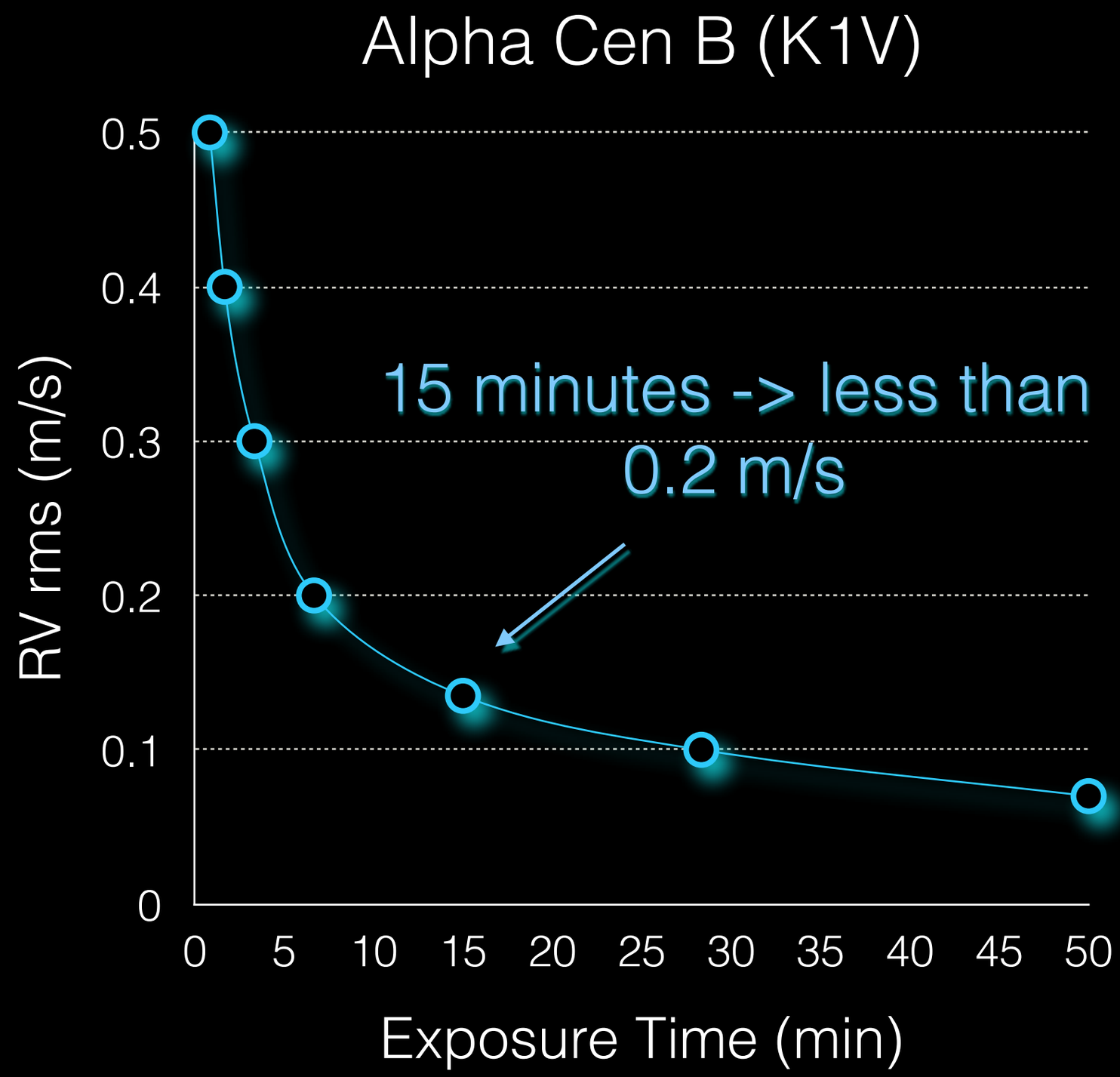




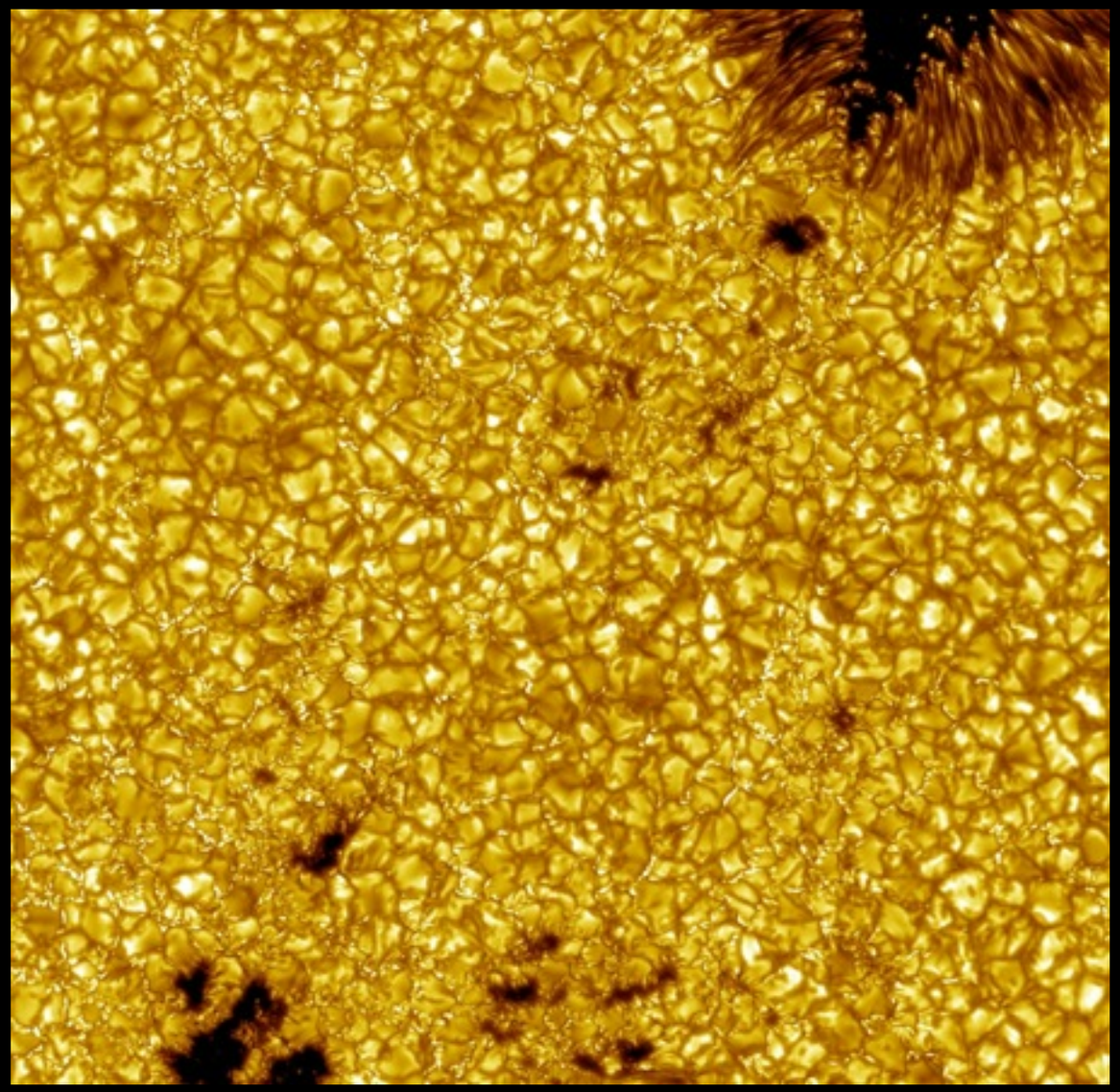
Credit: Charpinet

Granulation

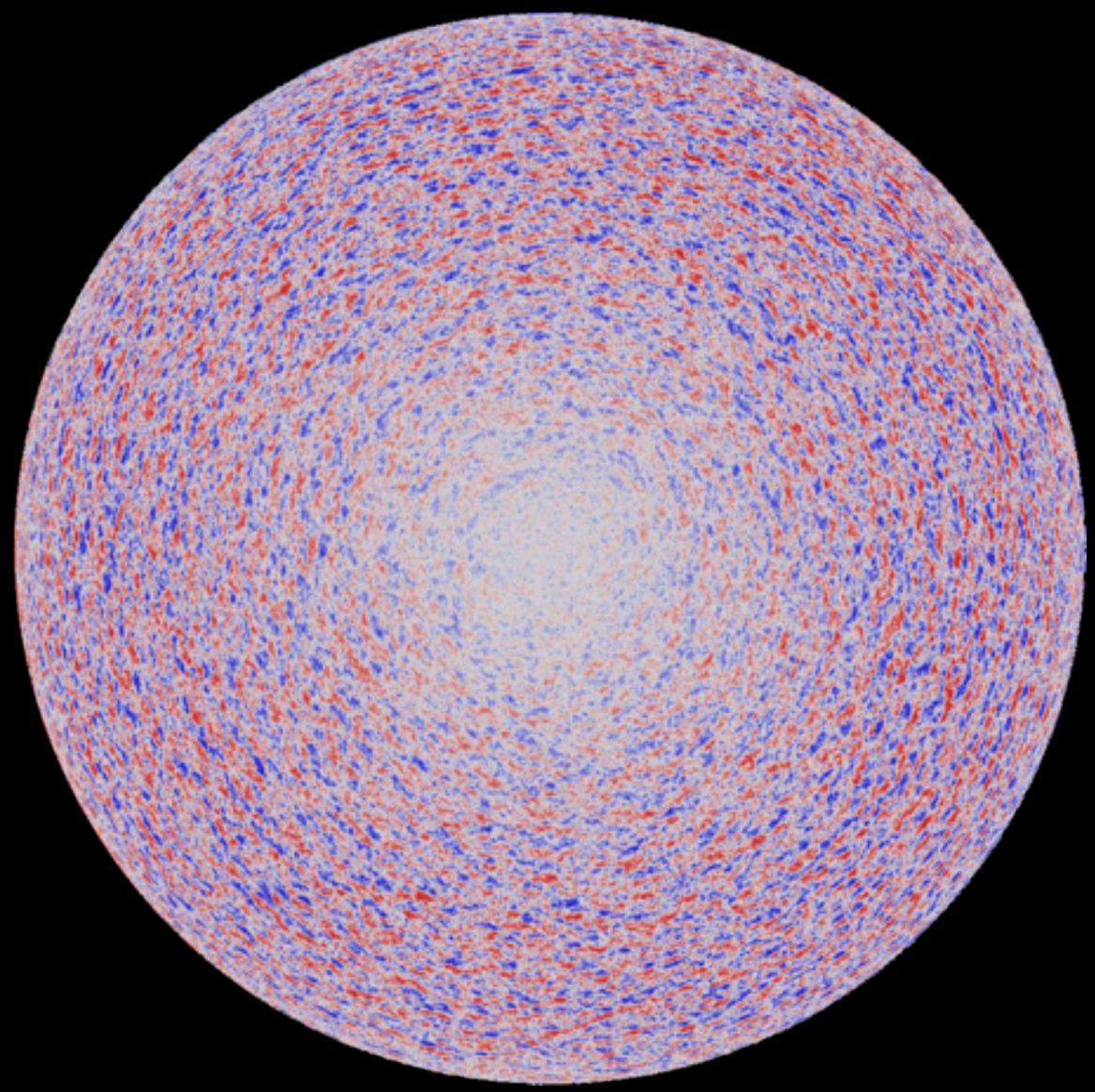
Credit: Vasco Henrique

Granulation

a few m/s (Dumusque+ 11)



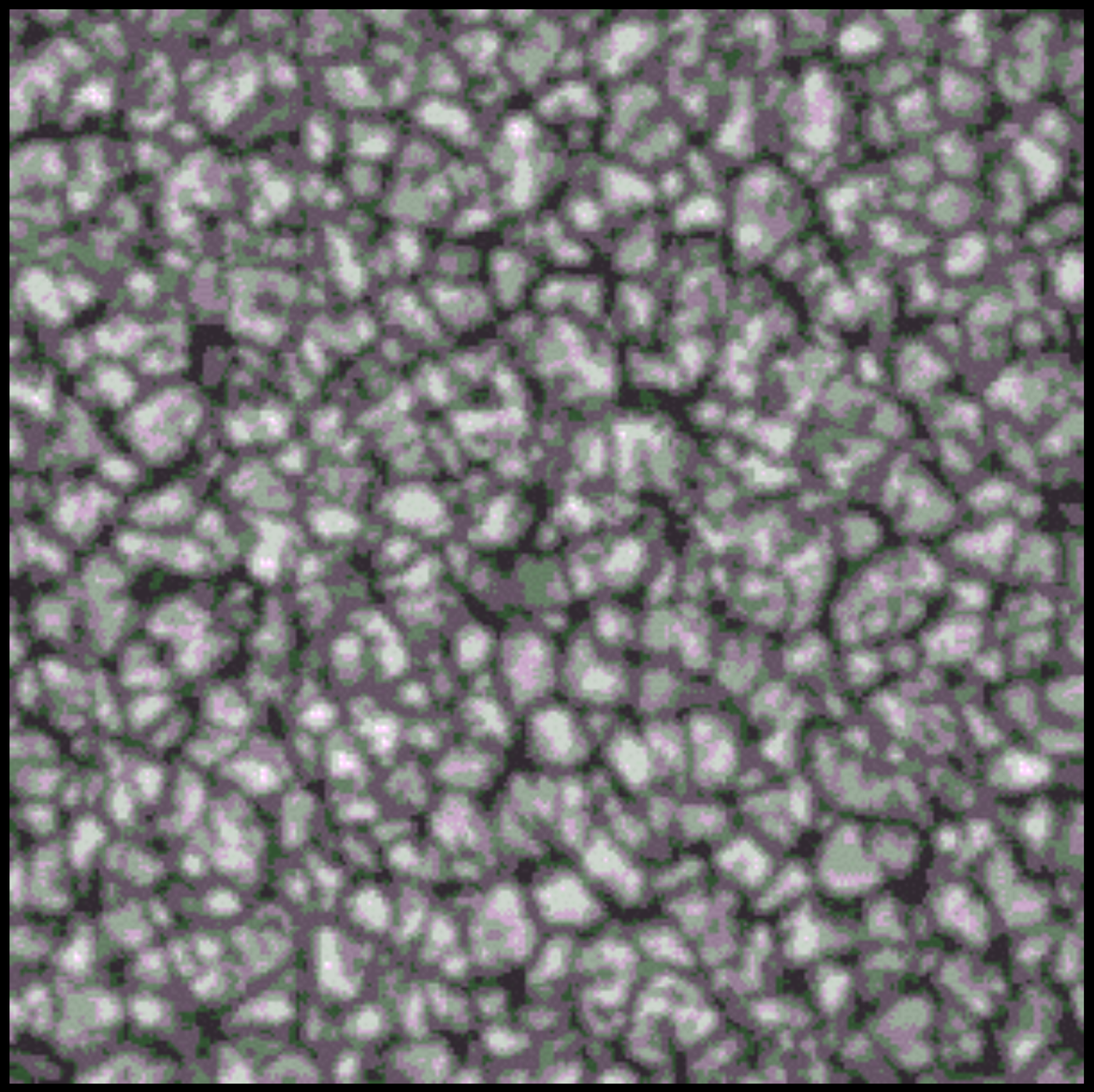
1000 km - 10^3 m.s^{-1} - > 10 min



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

Granulation

a few m/s (Dumusque+ 11)



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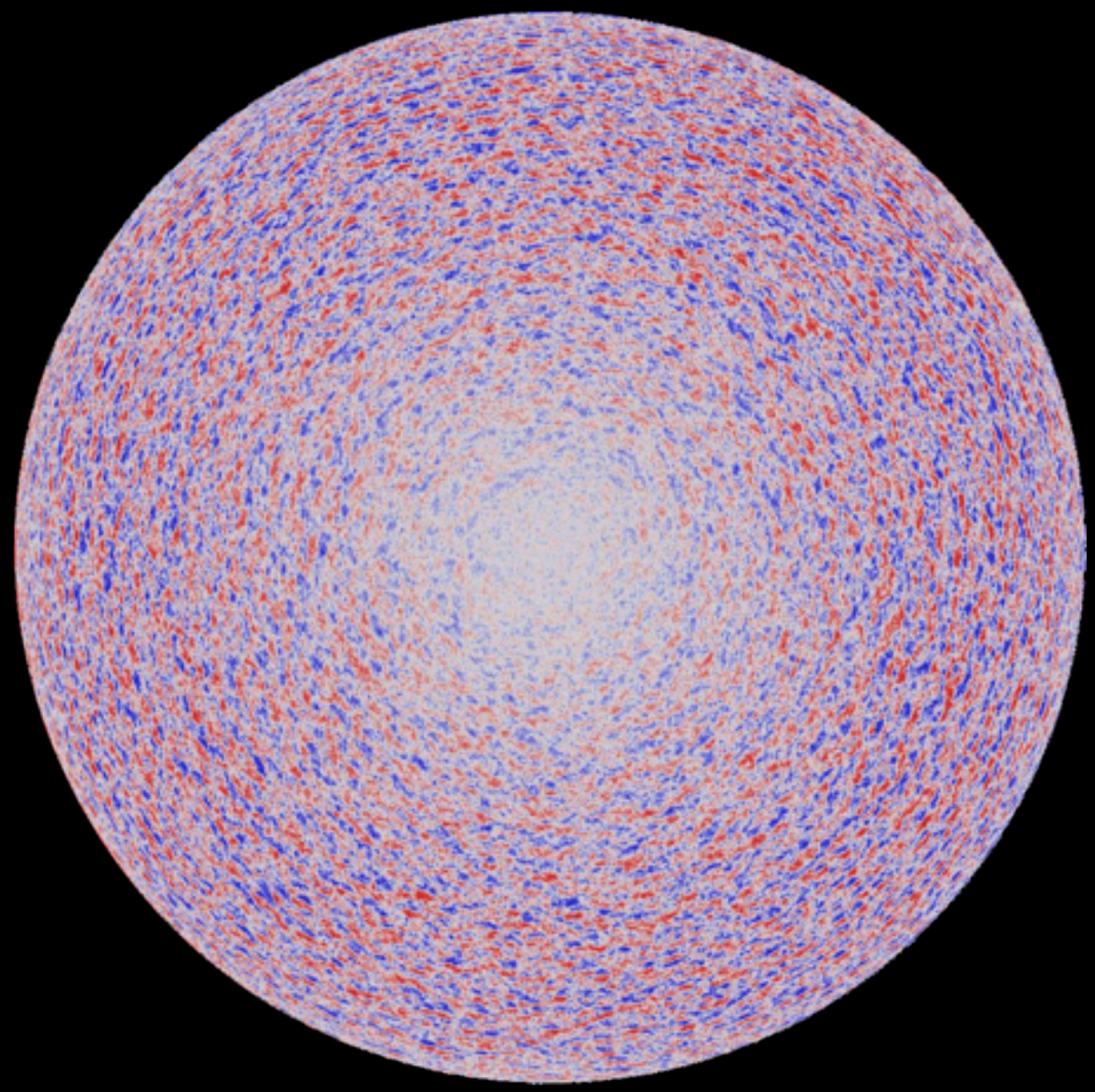

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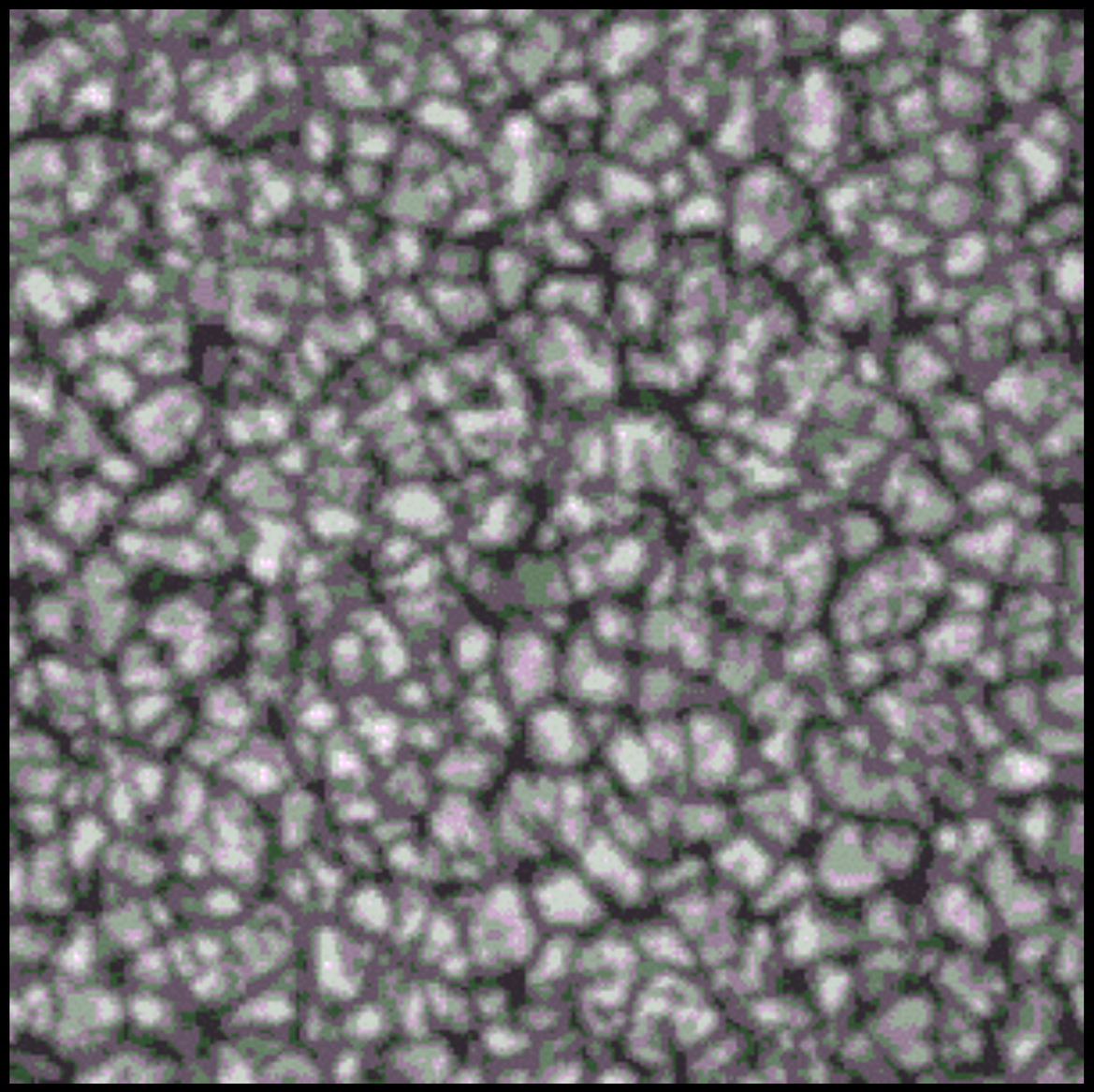

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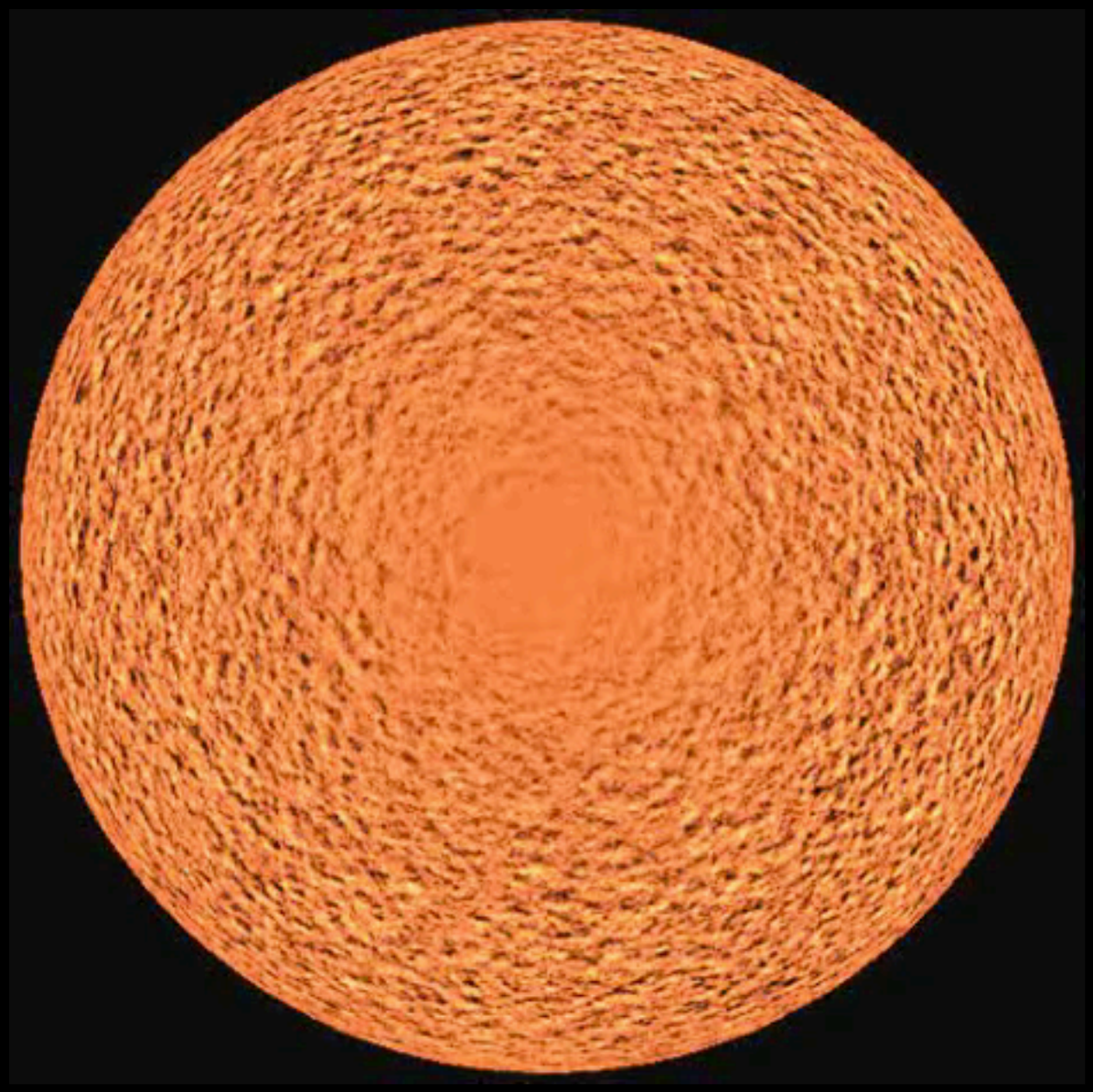

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Granulation

Granulation

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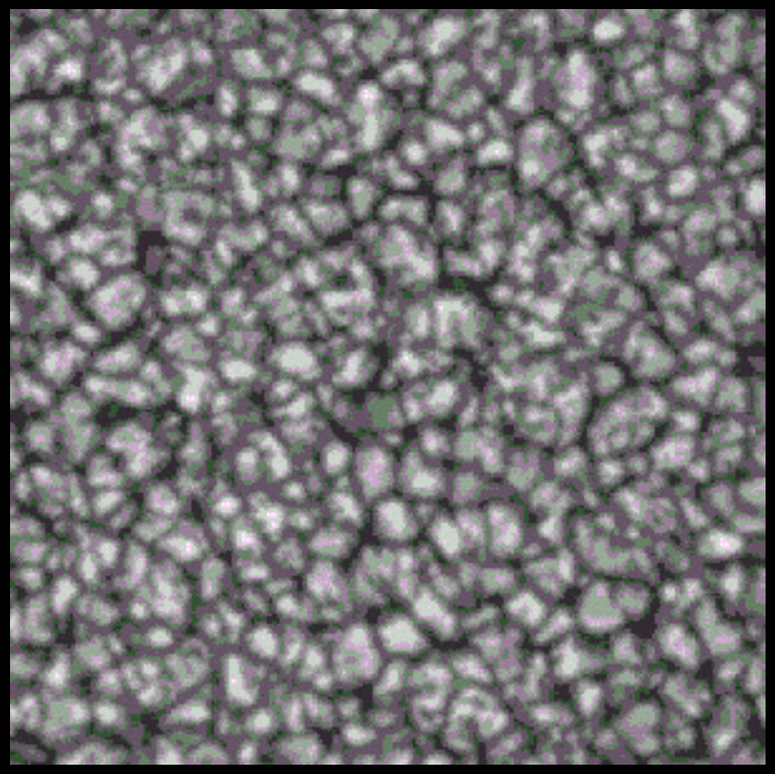
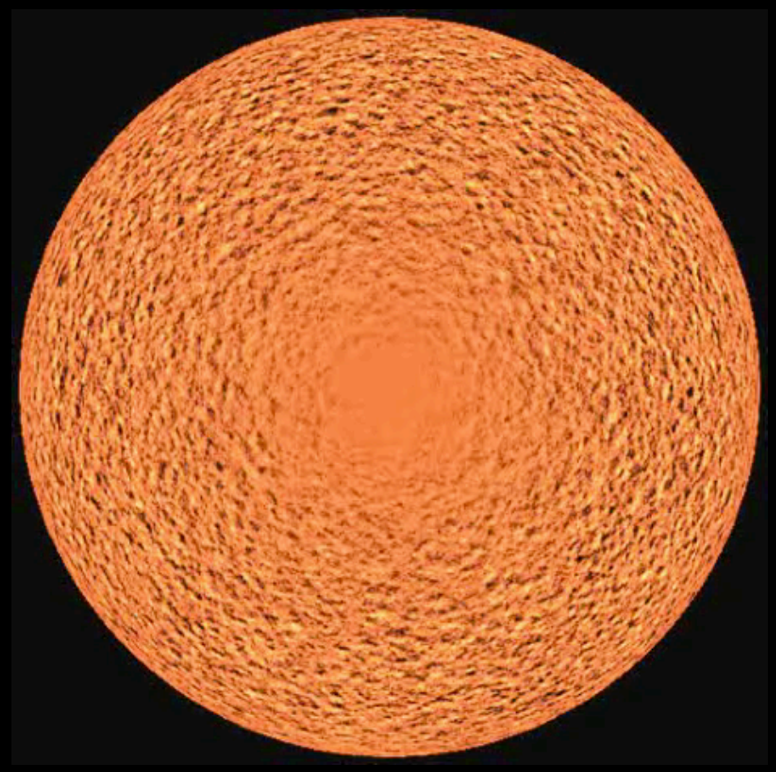
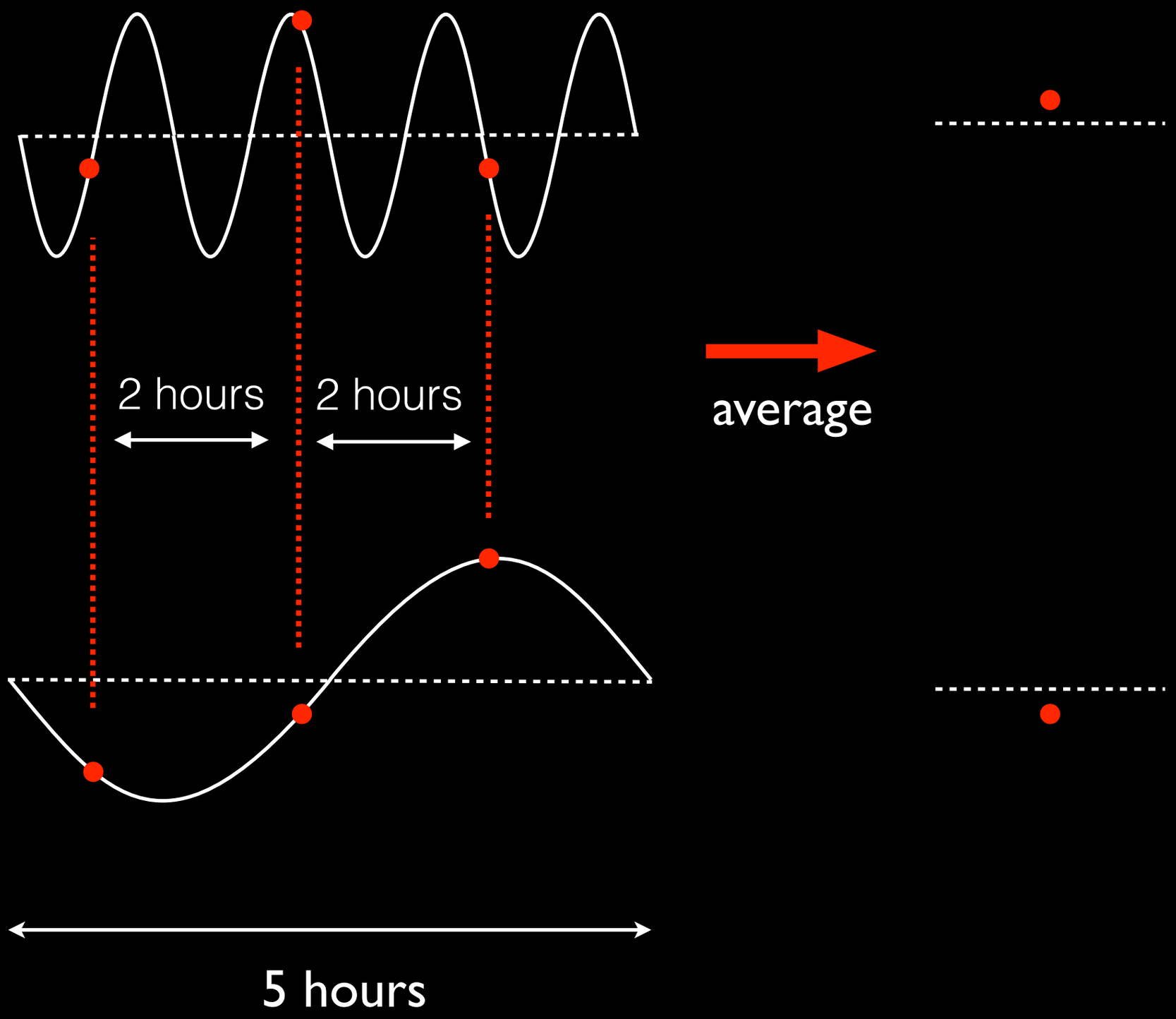


Supergranulation





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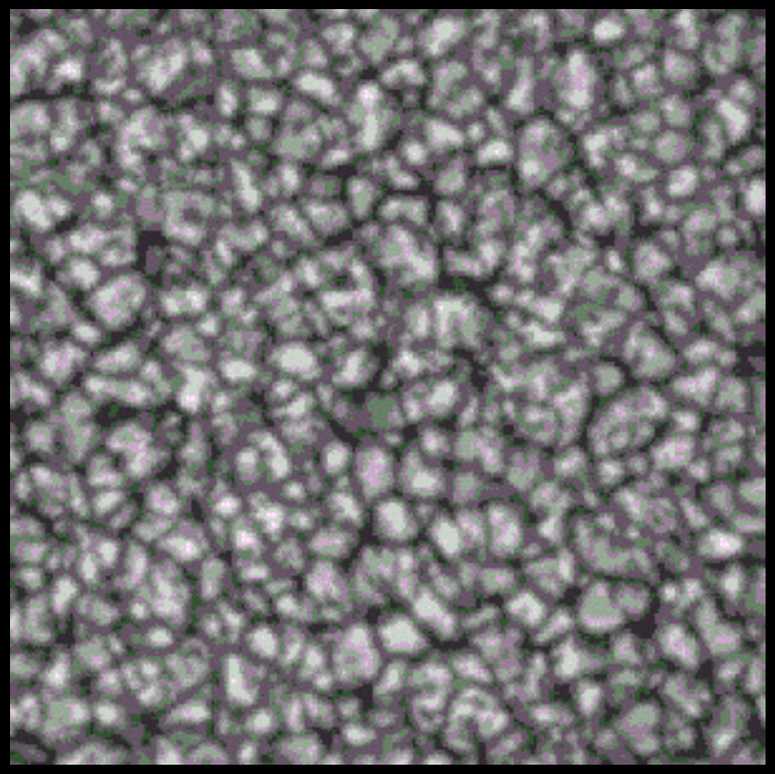

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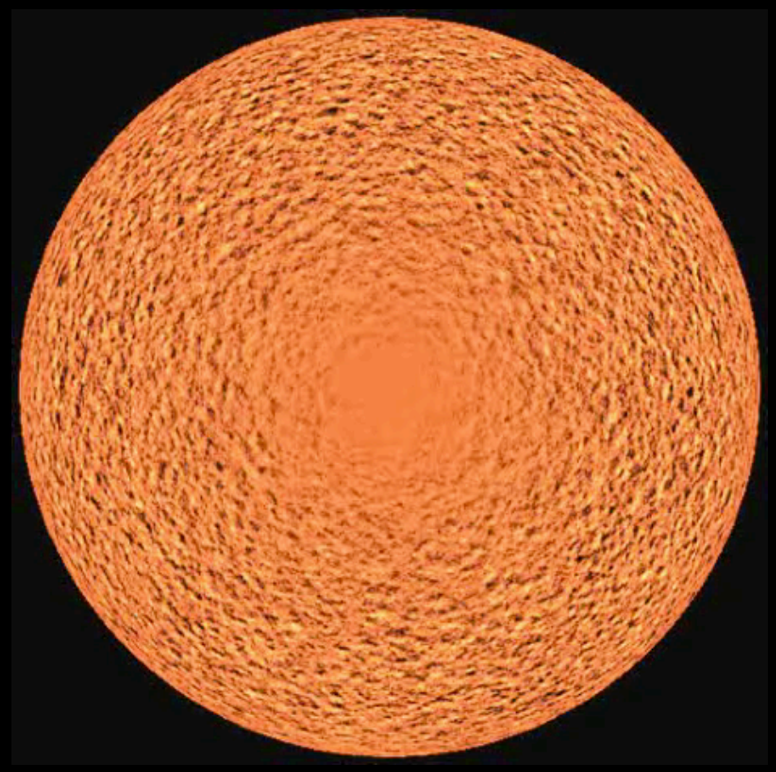

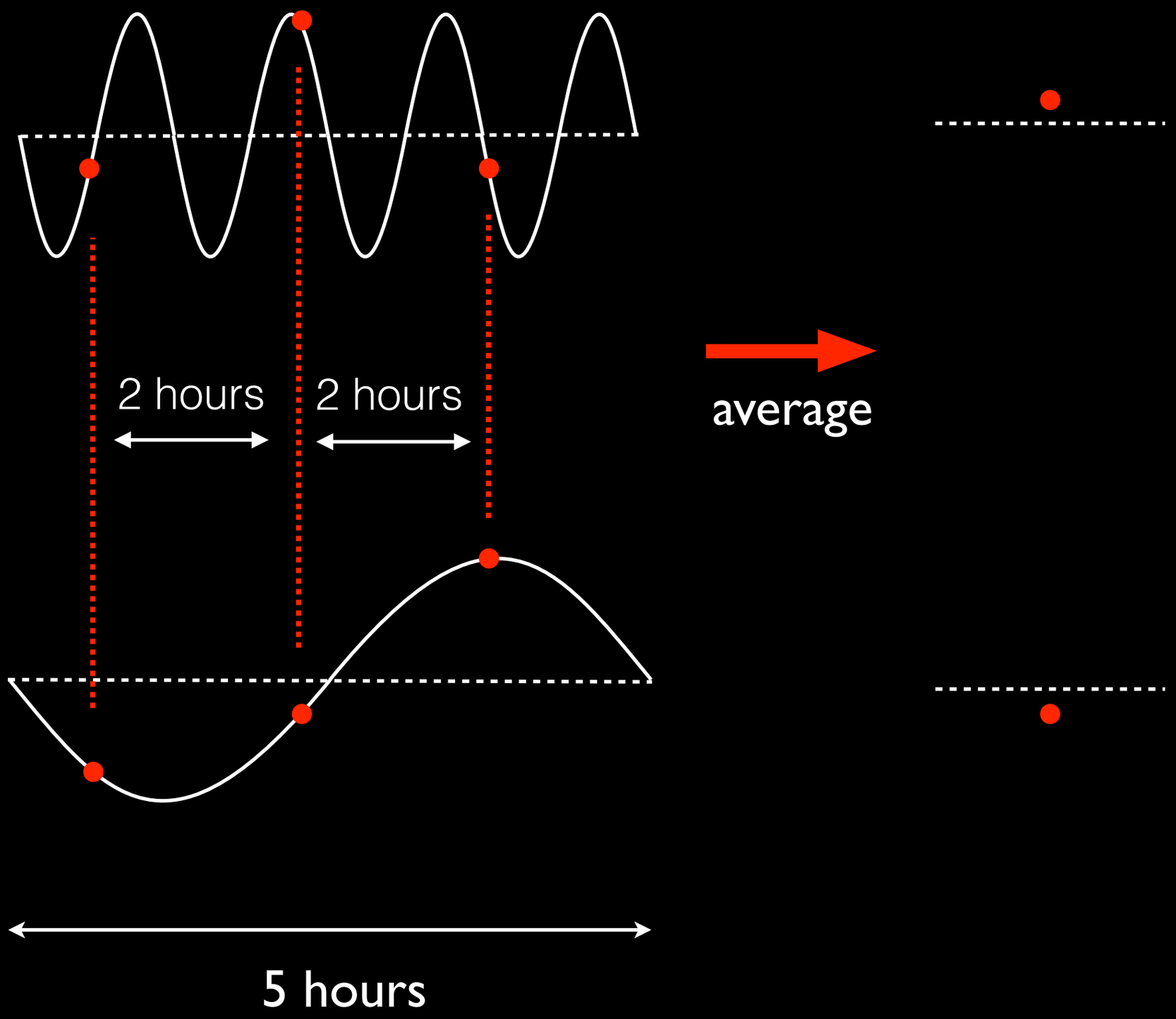

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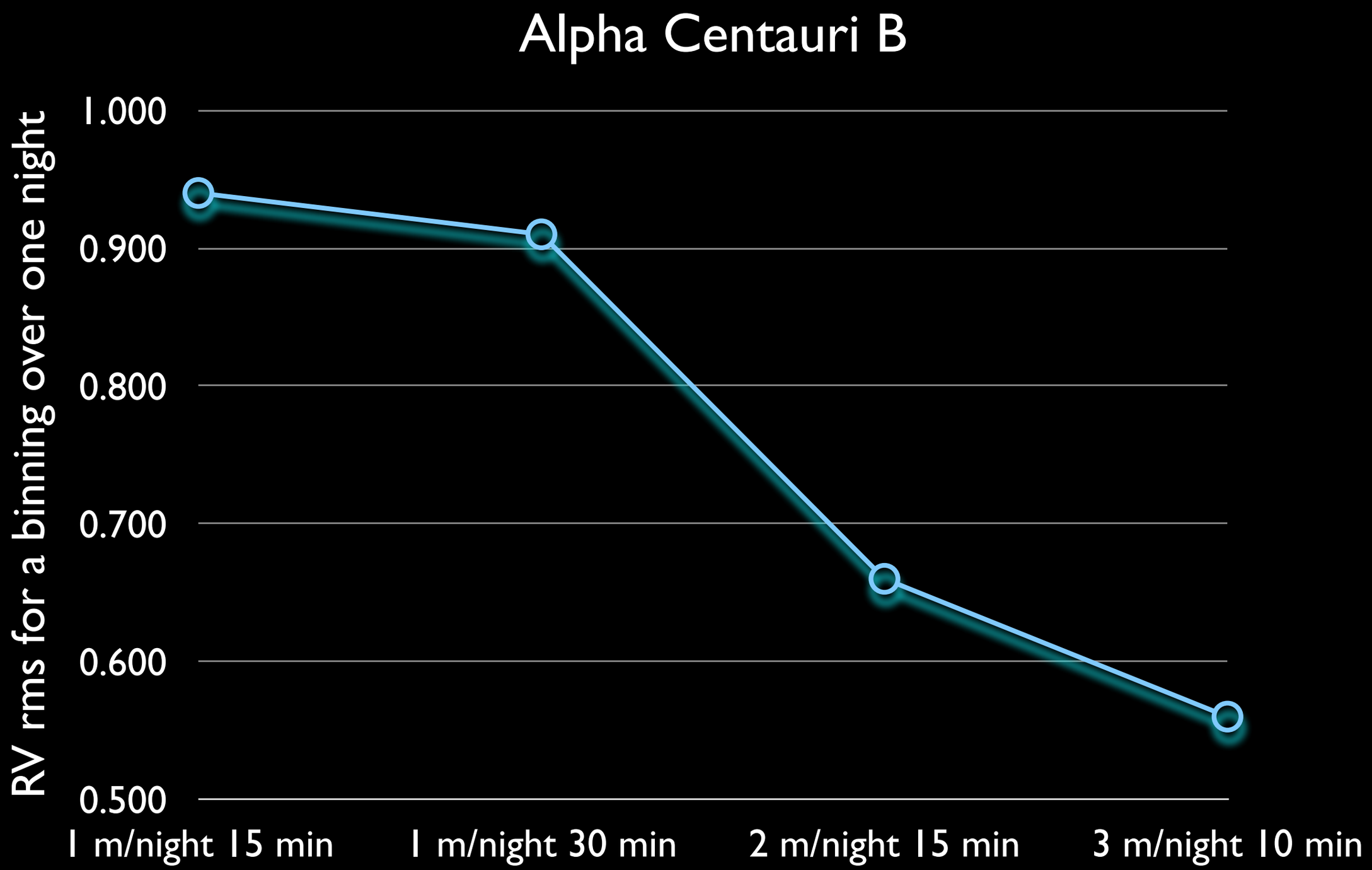

Dumusque+ 11

Granulation

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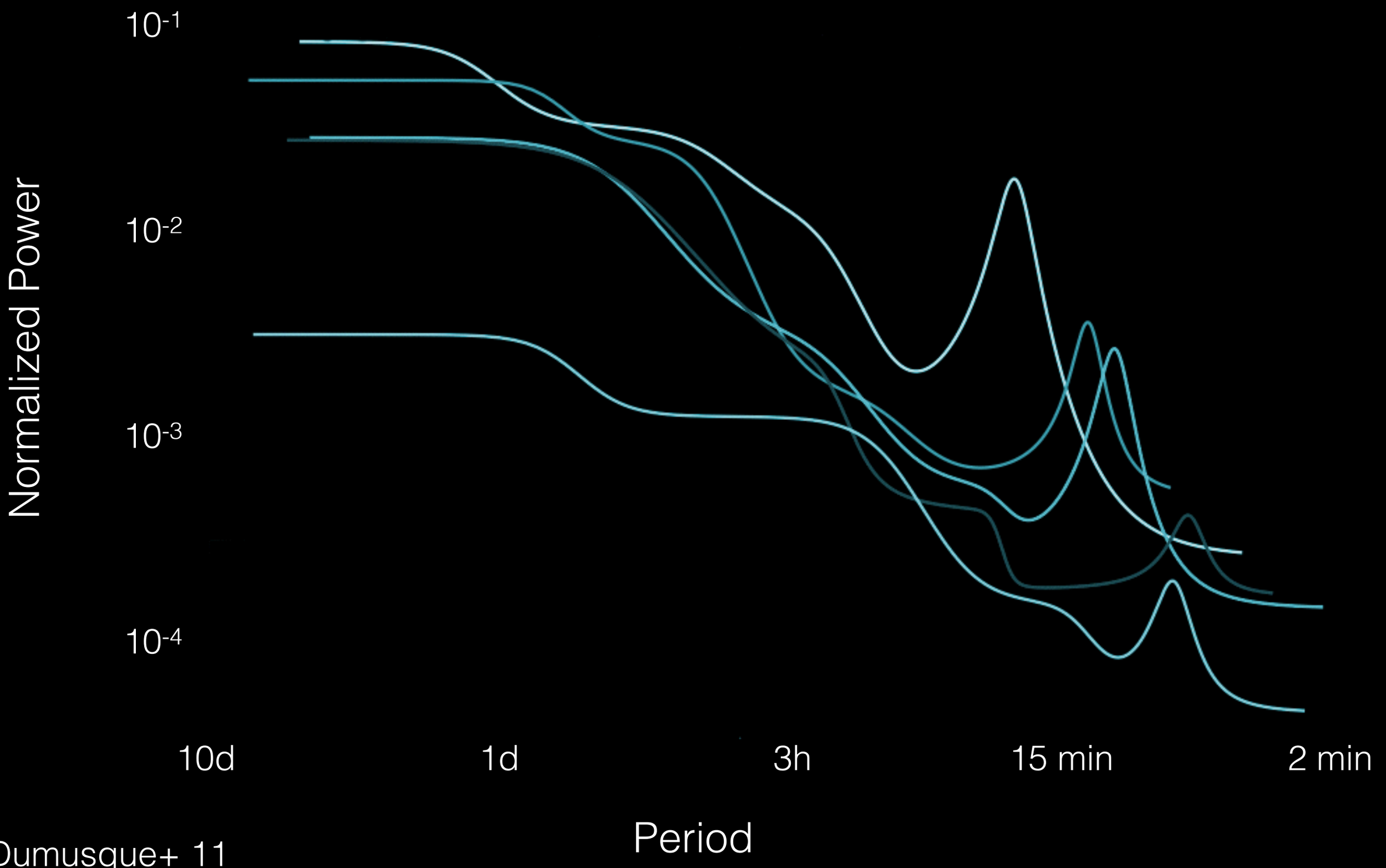

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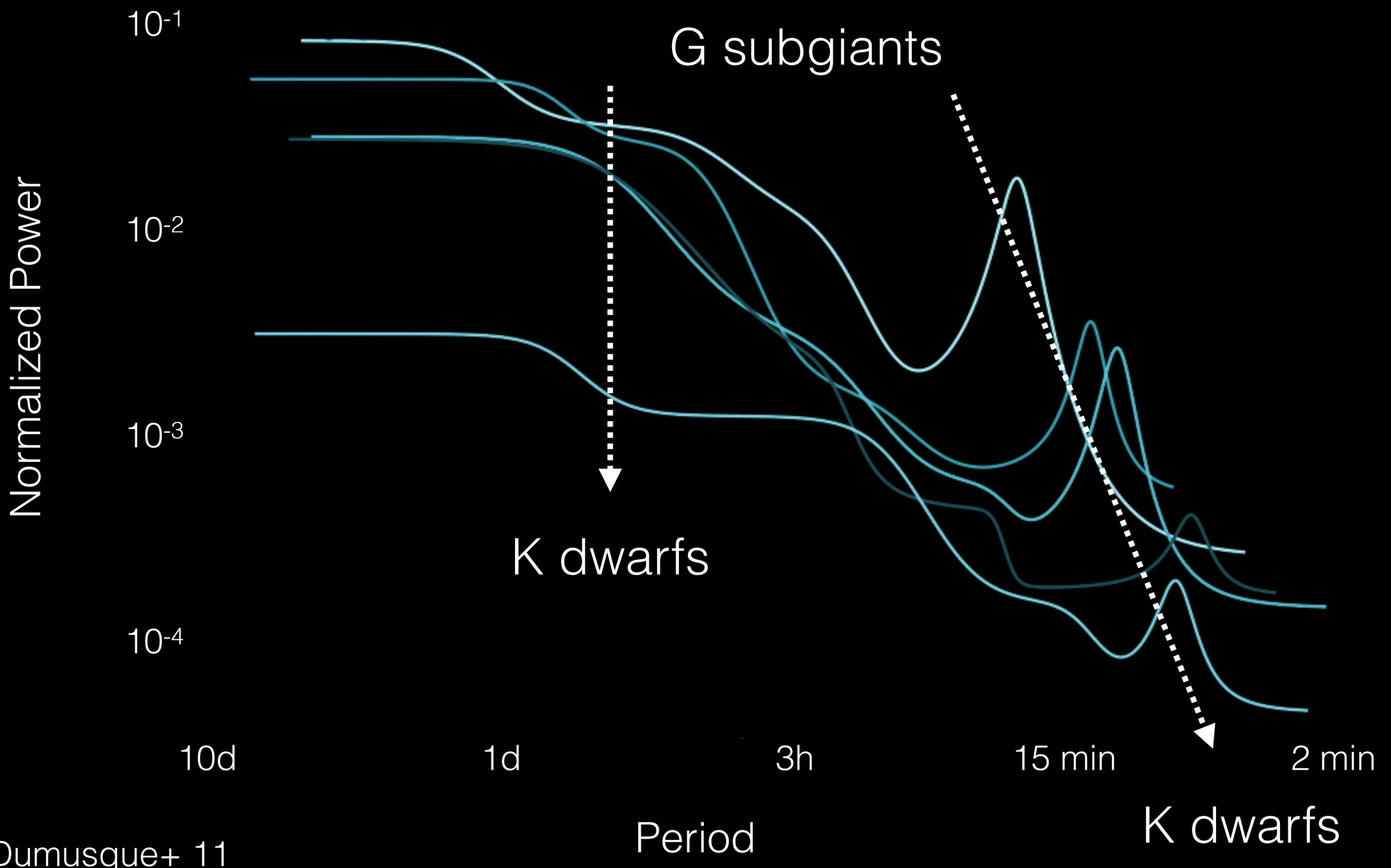


Dumusque+ 11

Granulation

Granulation

RVs of K dwarfs are less affected by:

-> granulation

-> oscillation

than G dwarfs

Dumusque+ 11

Active regions

ACTIVITY INDUCED RV EFFECT

FLUX

Spots are cooler and fainter
Plages are hotter and brighter

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

CONVECTION

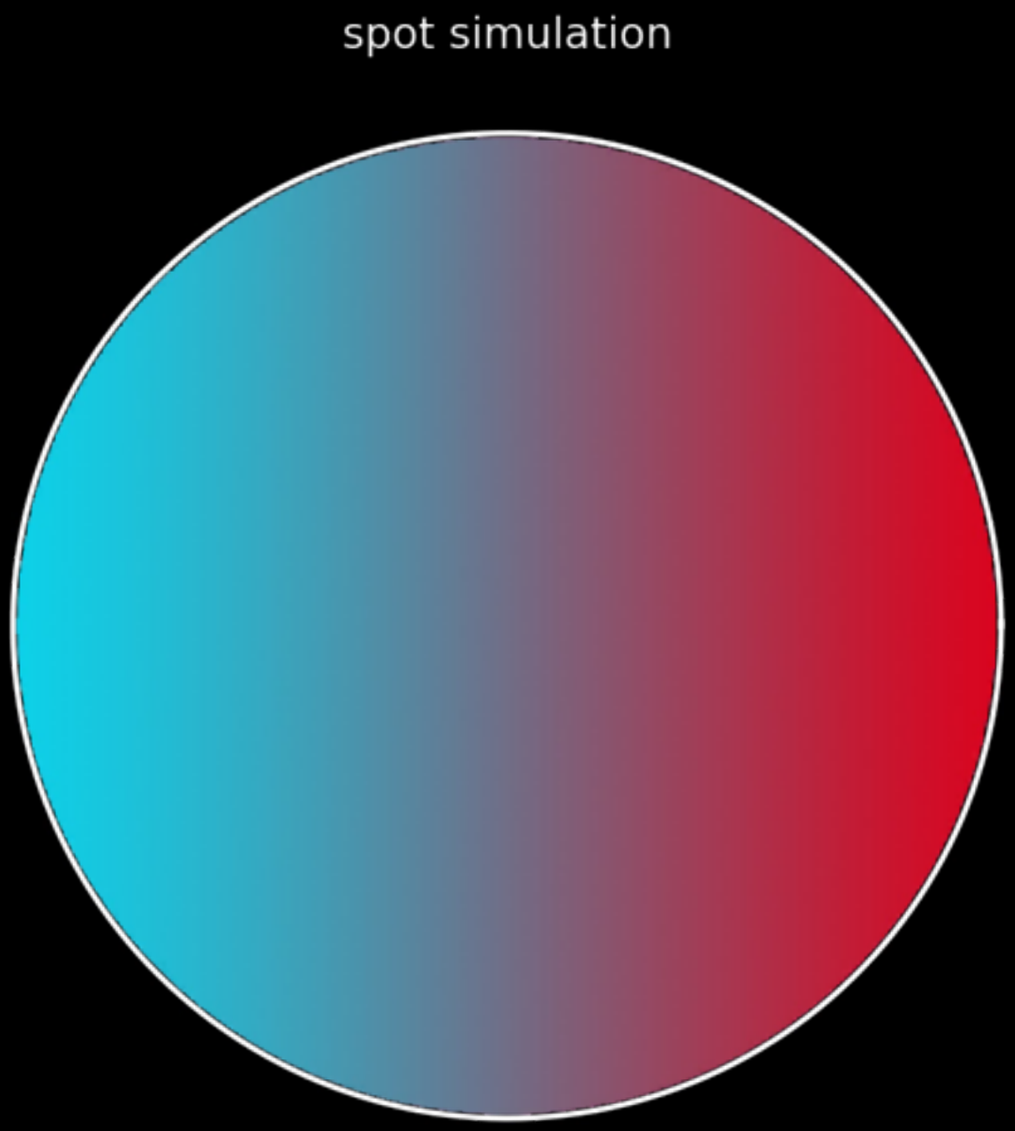
Convection outside active regions, inhibition of convection inside

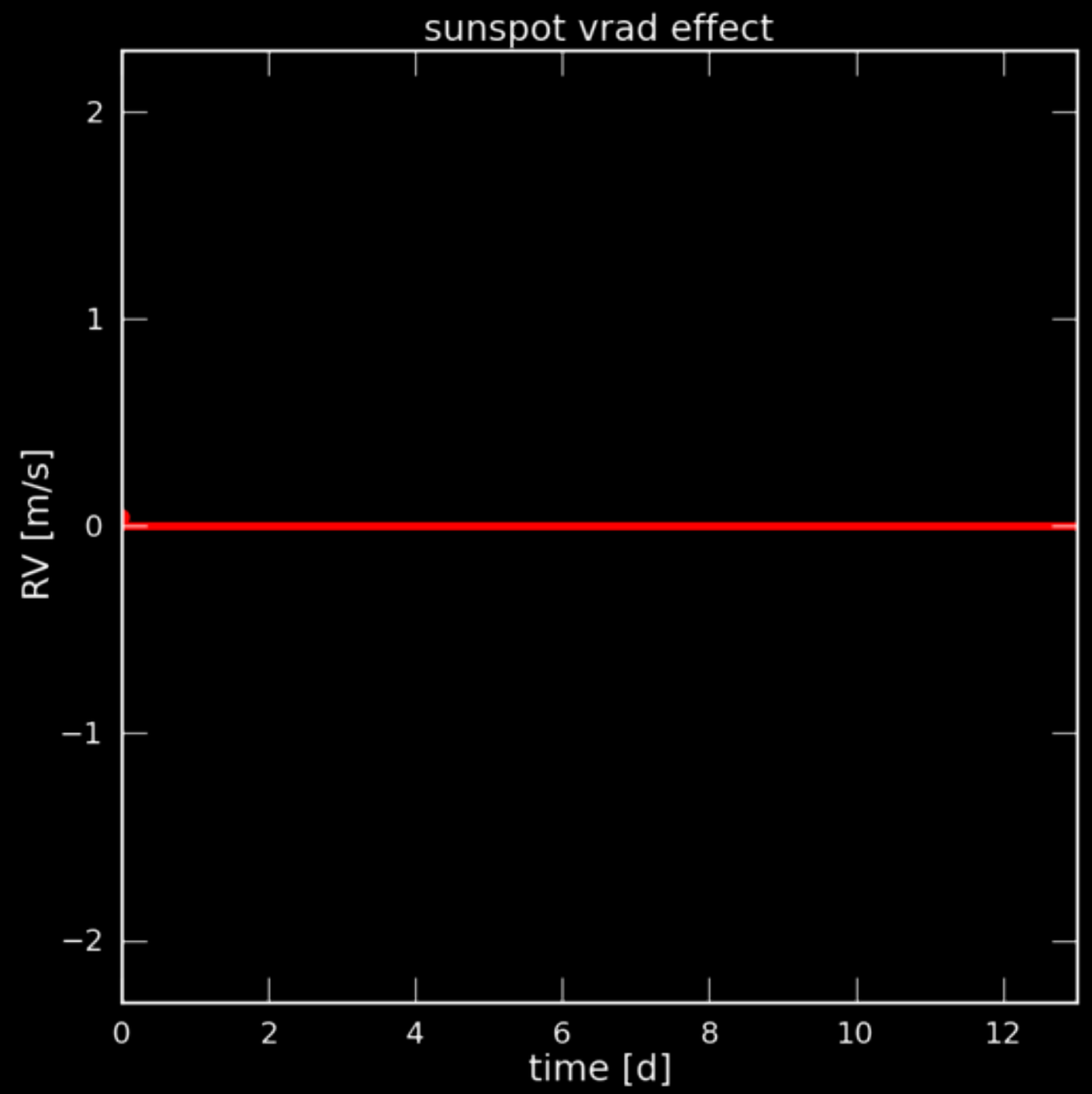
Dravins 81, Lindegren & Dravins 03, Saar 03,
Saar 09, Lanza+ 11, Meunier+ 10, Aigrain+12,
Dumusque+ 14

FLUX

Active regions

a few m/s (Meunier+ 10)





FLUX

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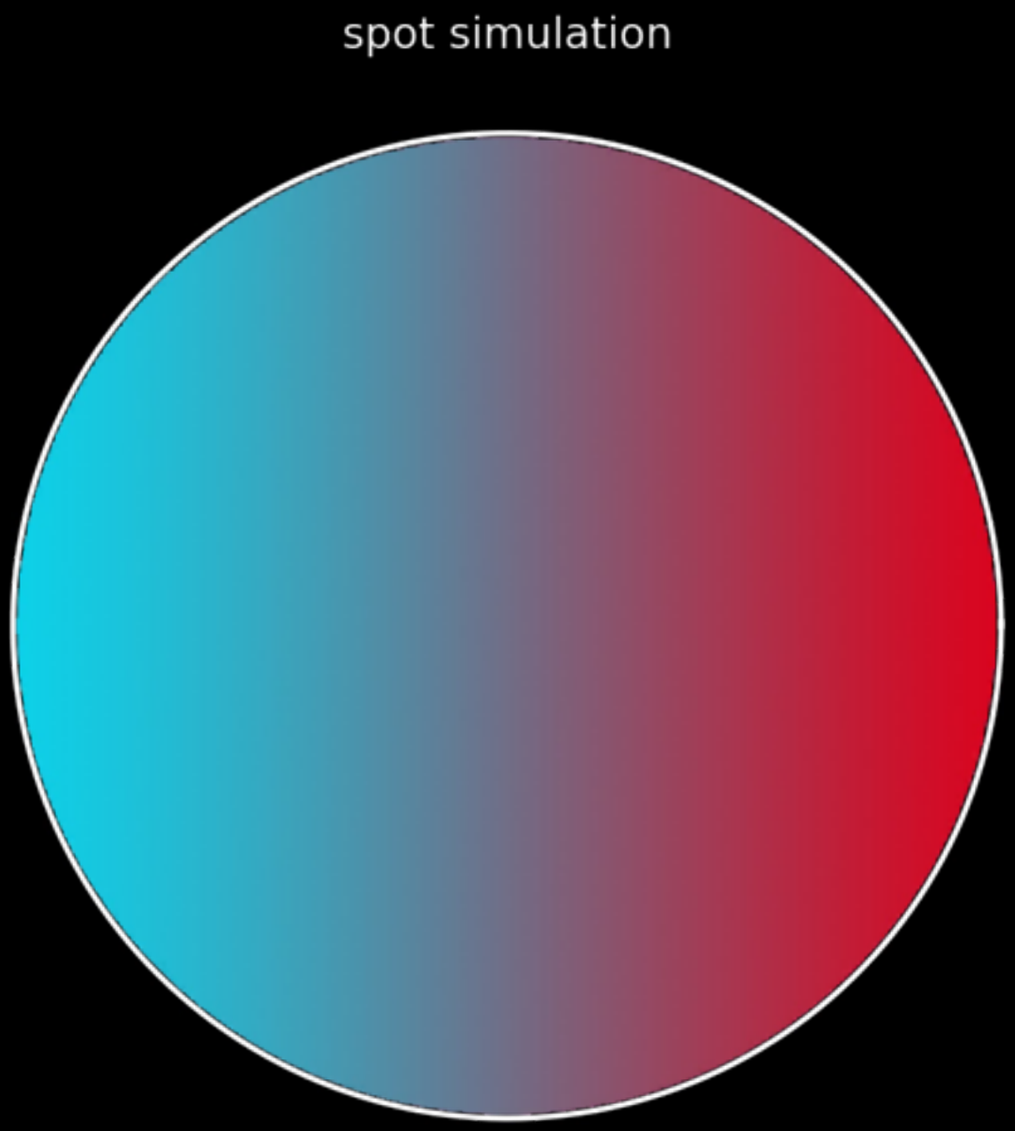
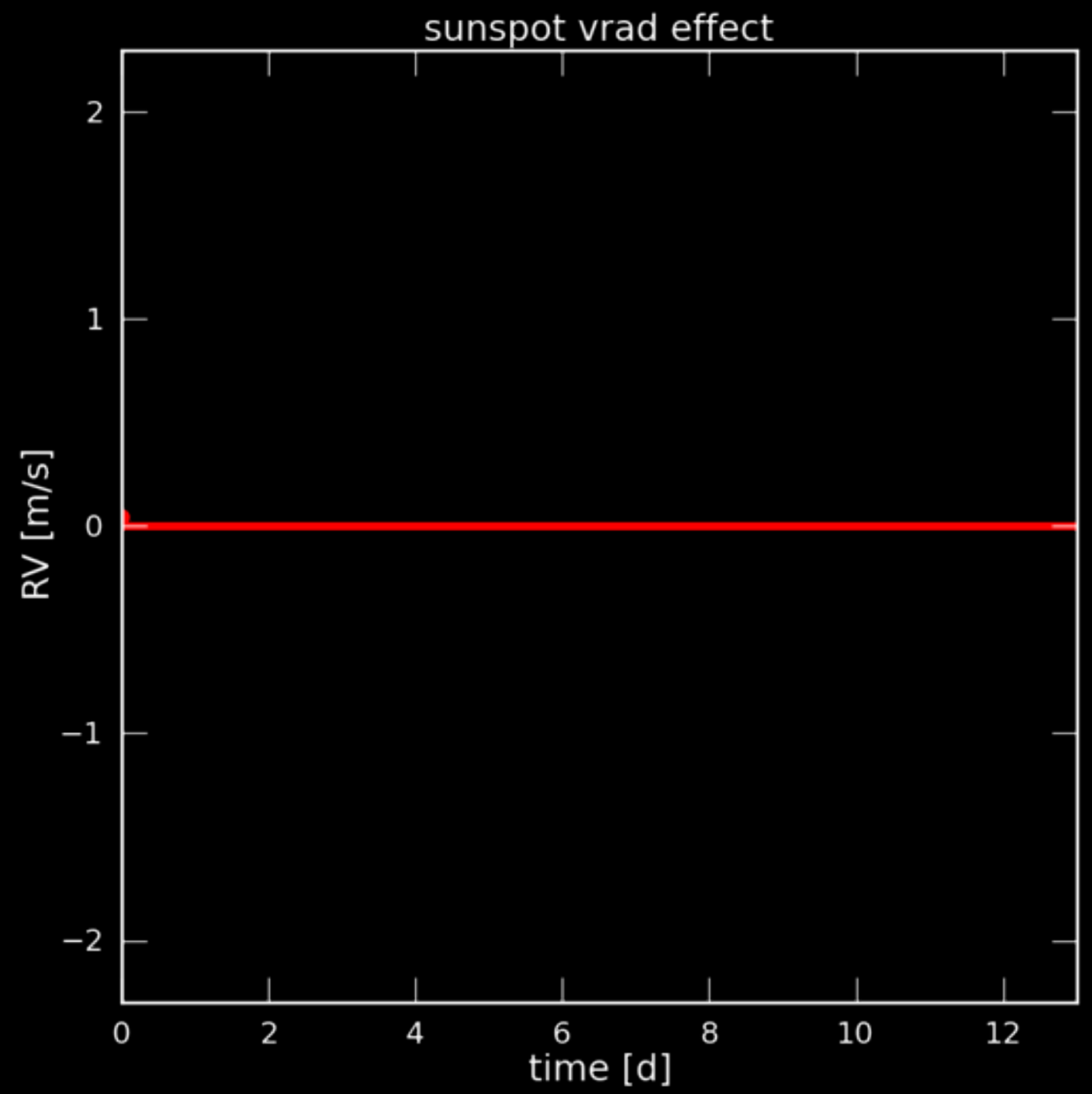


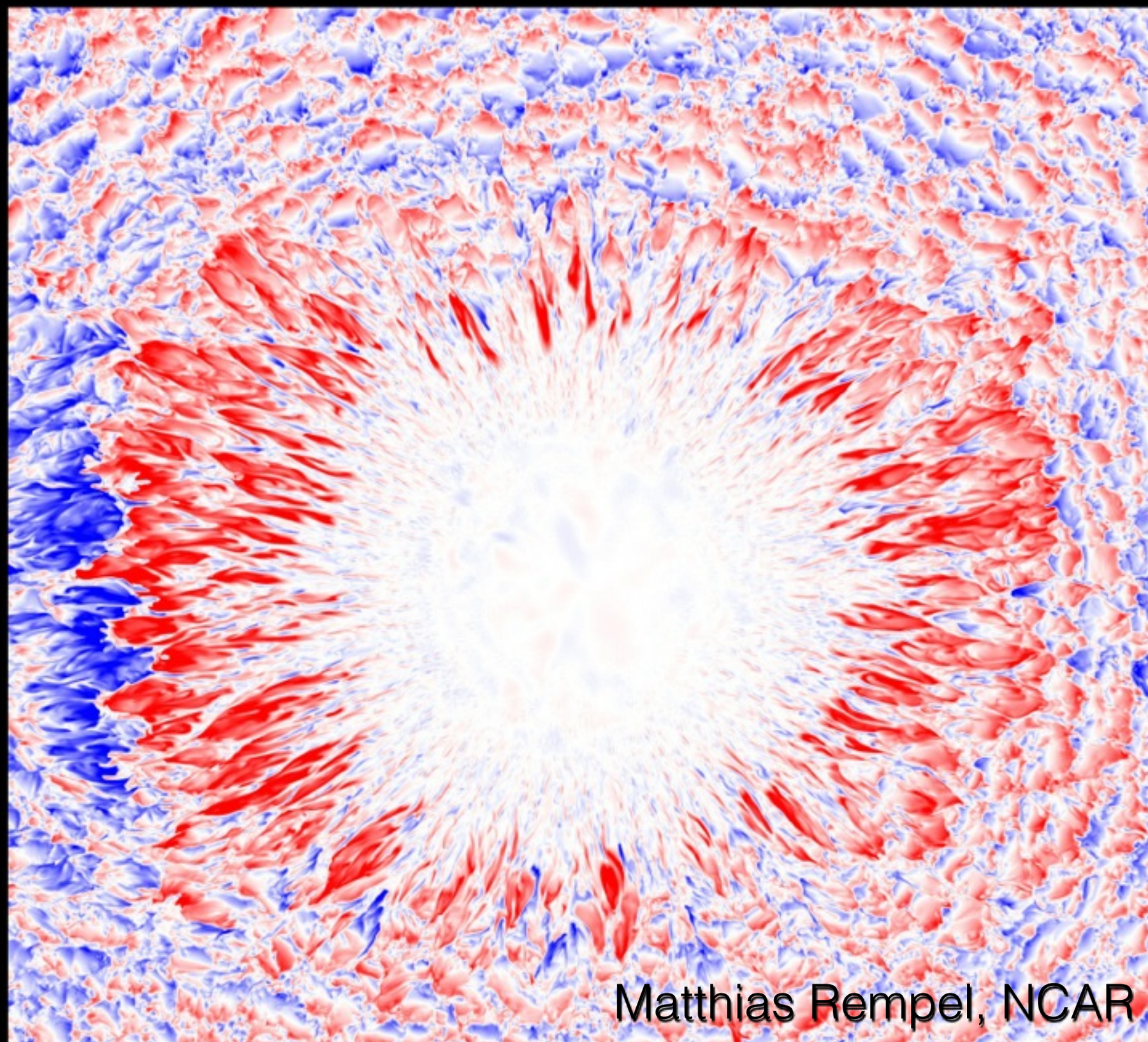


Credit: Vasco Henrique

Active regions

a few m/s (Meunier+ 10)

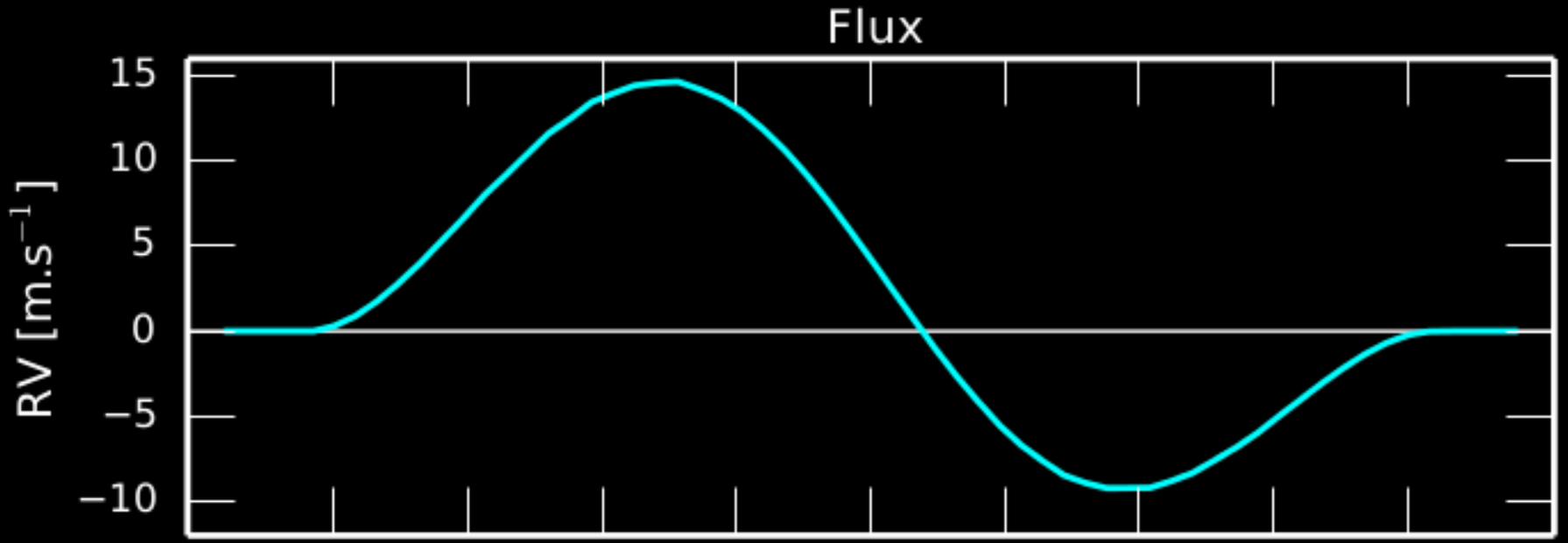
CONVECTION



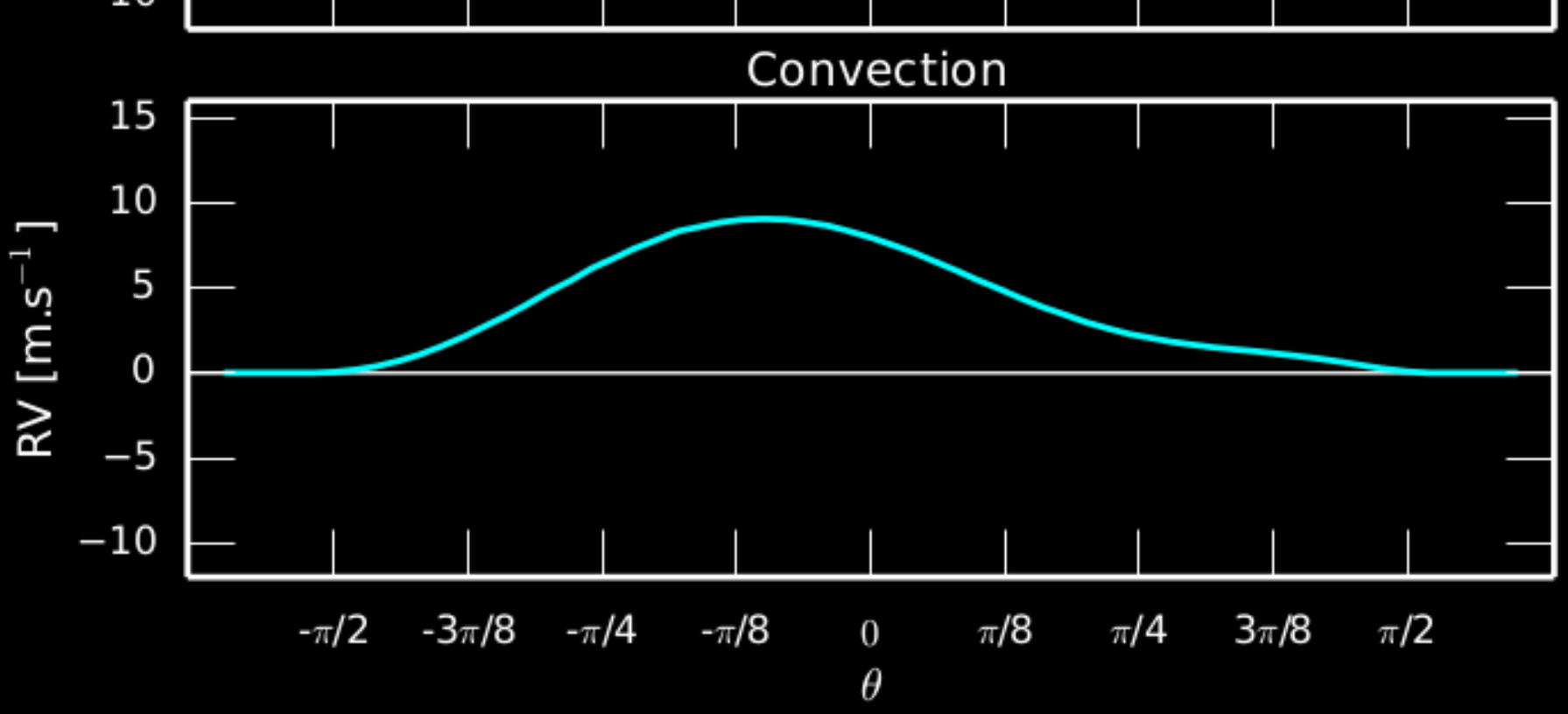
Matthias Rempel, NCAR

Active regions

a few m/s (Meunier+ 10)



FLUX



CONVECTION

SOAP 2.0 Dumusque+ 2014

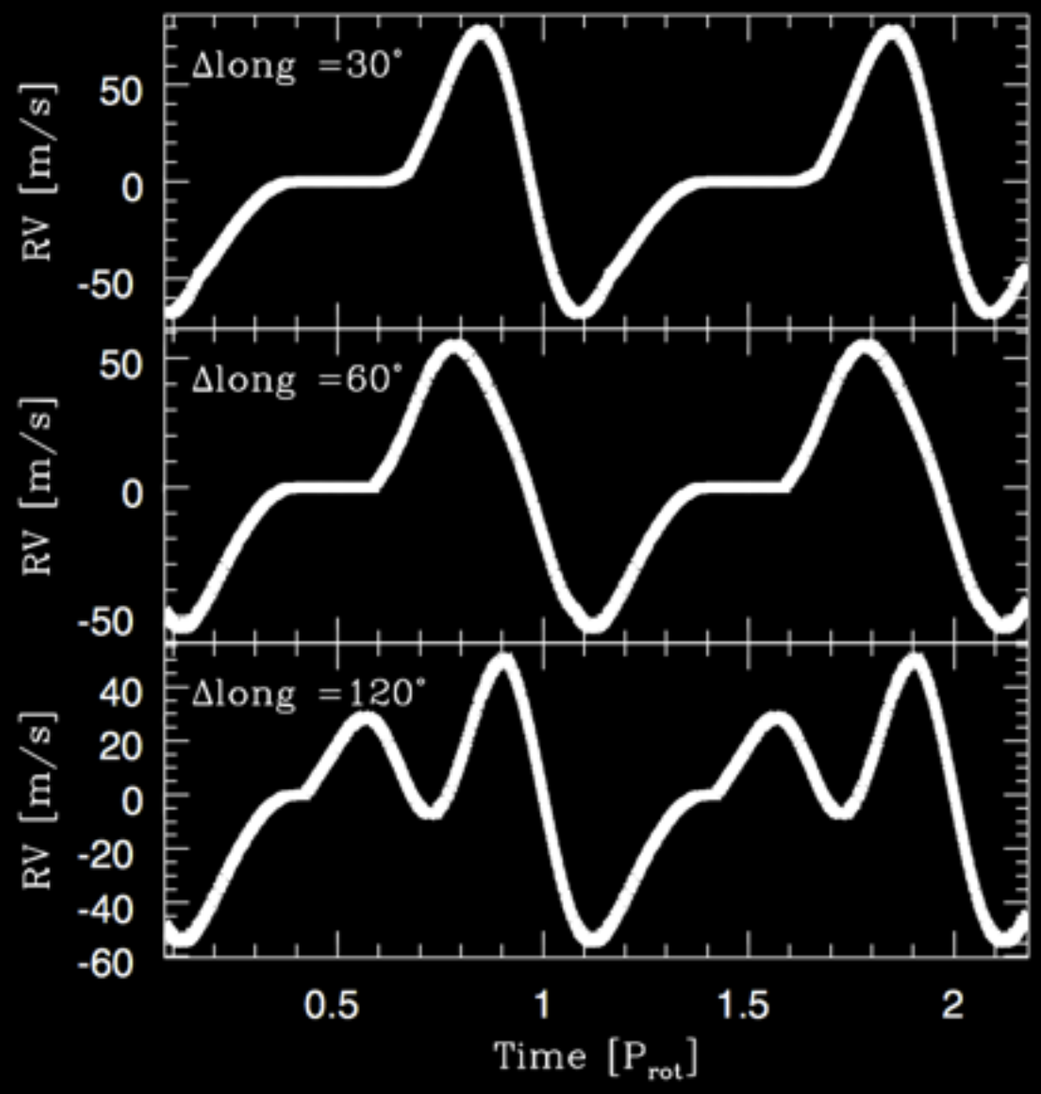
How to probe Stellar Activity and Correct for it?

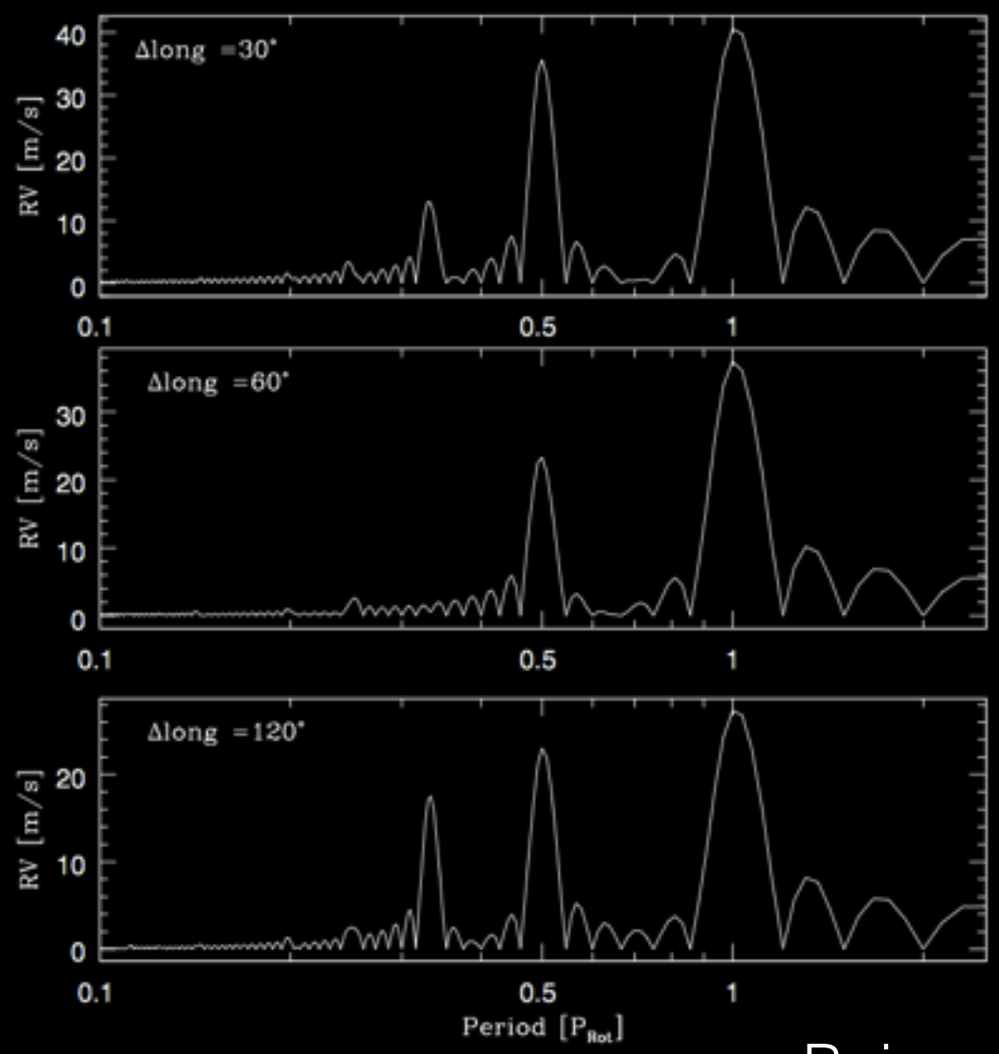
Active regions

Active regions

Active regions rotates with the star:

-> Signal at the rotational period and harmonics





Boisse+ 11

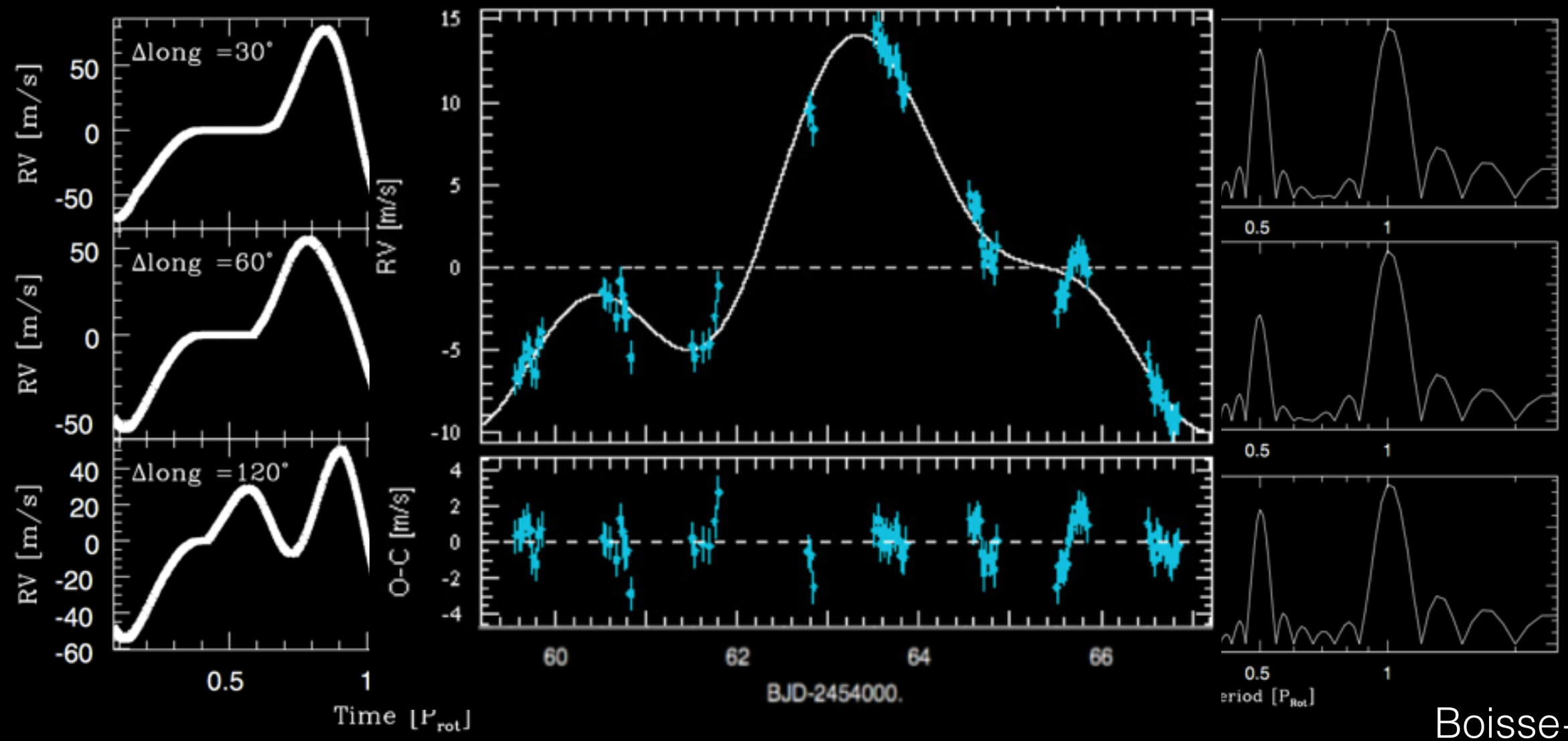
Active regions

Active regions

Active regions rotates with the star:

-> Signal at the rotational period and harmonics

Fit sin waves at the rotational period and harmonics

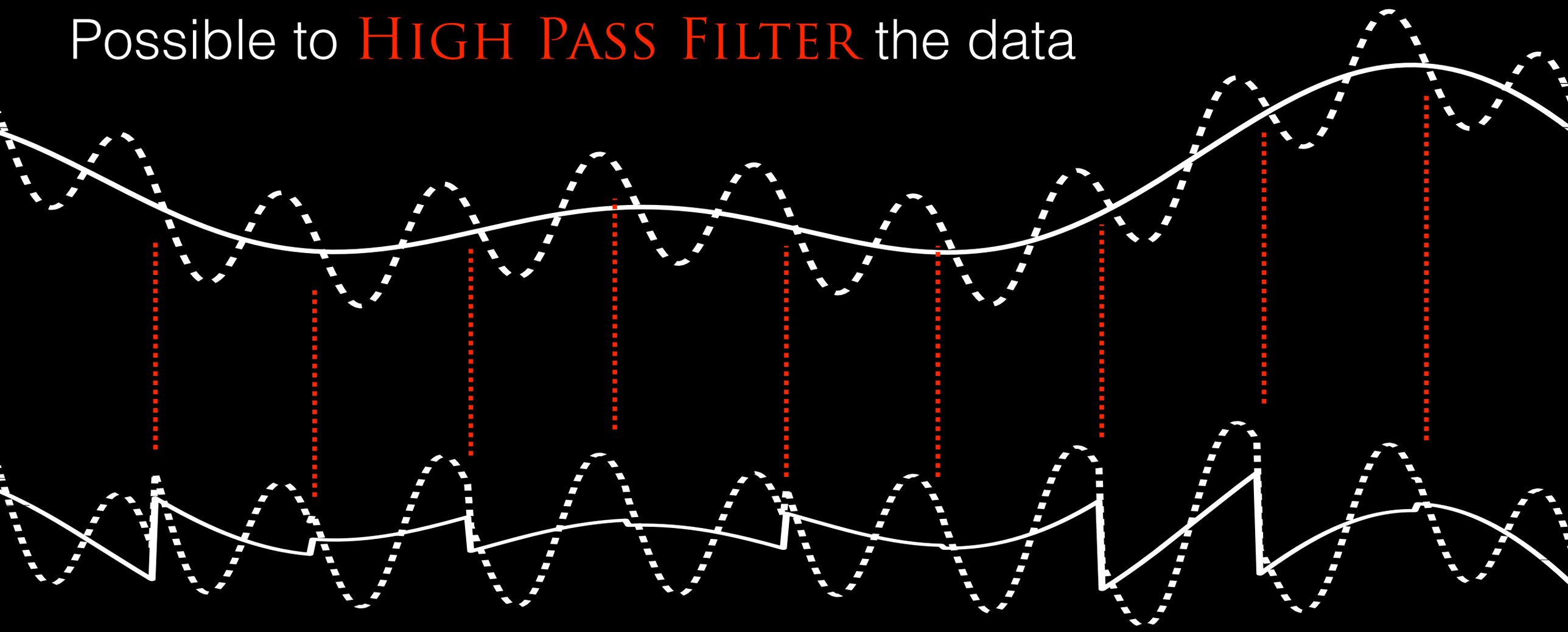


Boisse+ 11

Active regions

If the Planet have a period much shorter than the stellar rotation

Possible to High Pass Filter the data



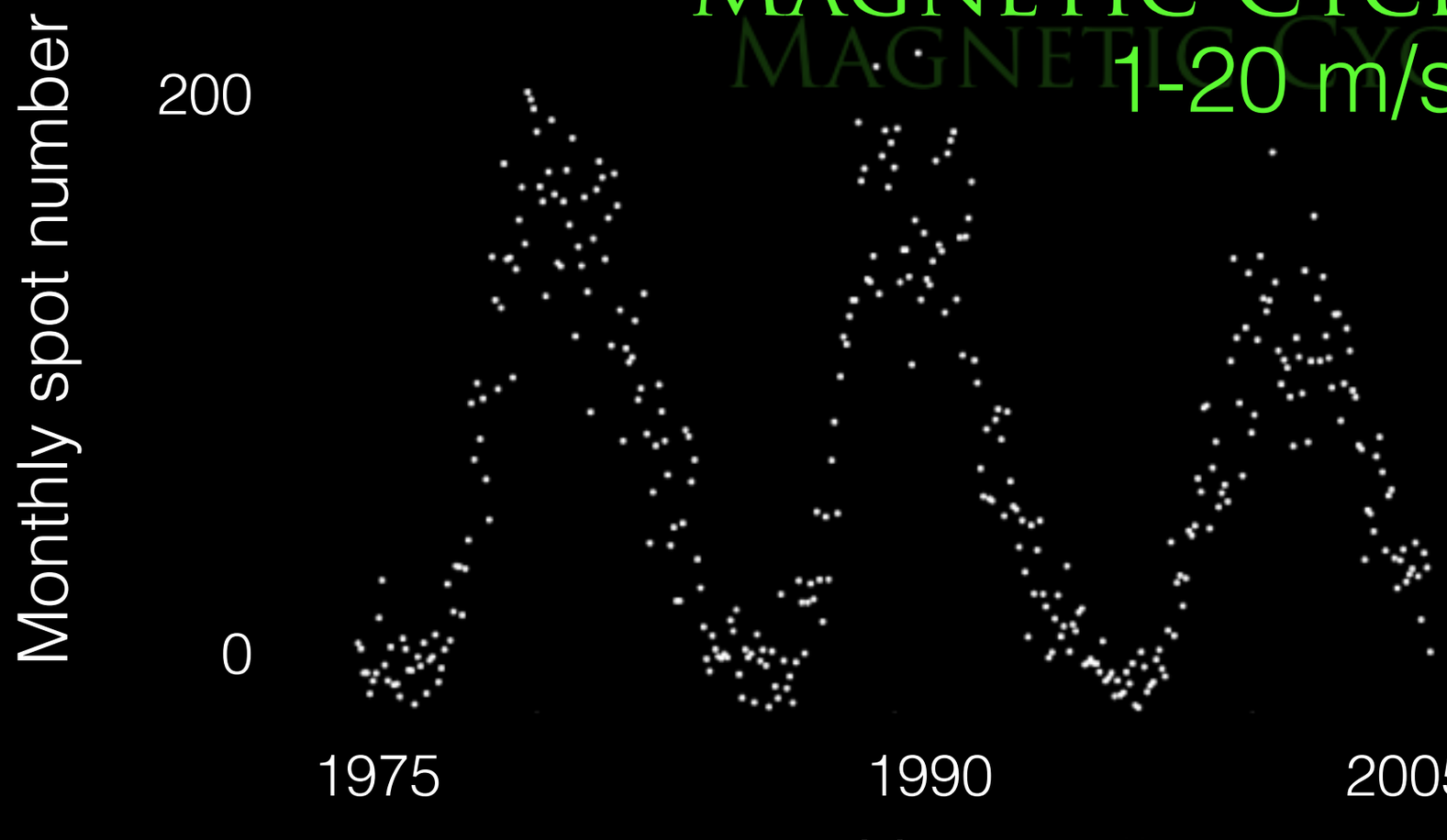
Problem: Only for short-period planets

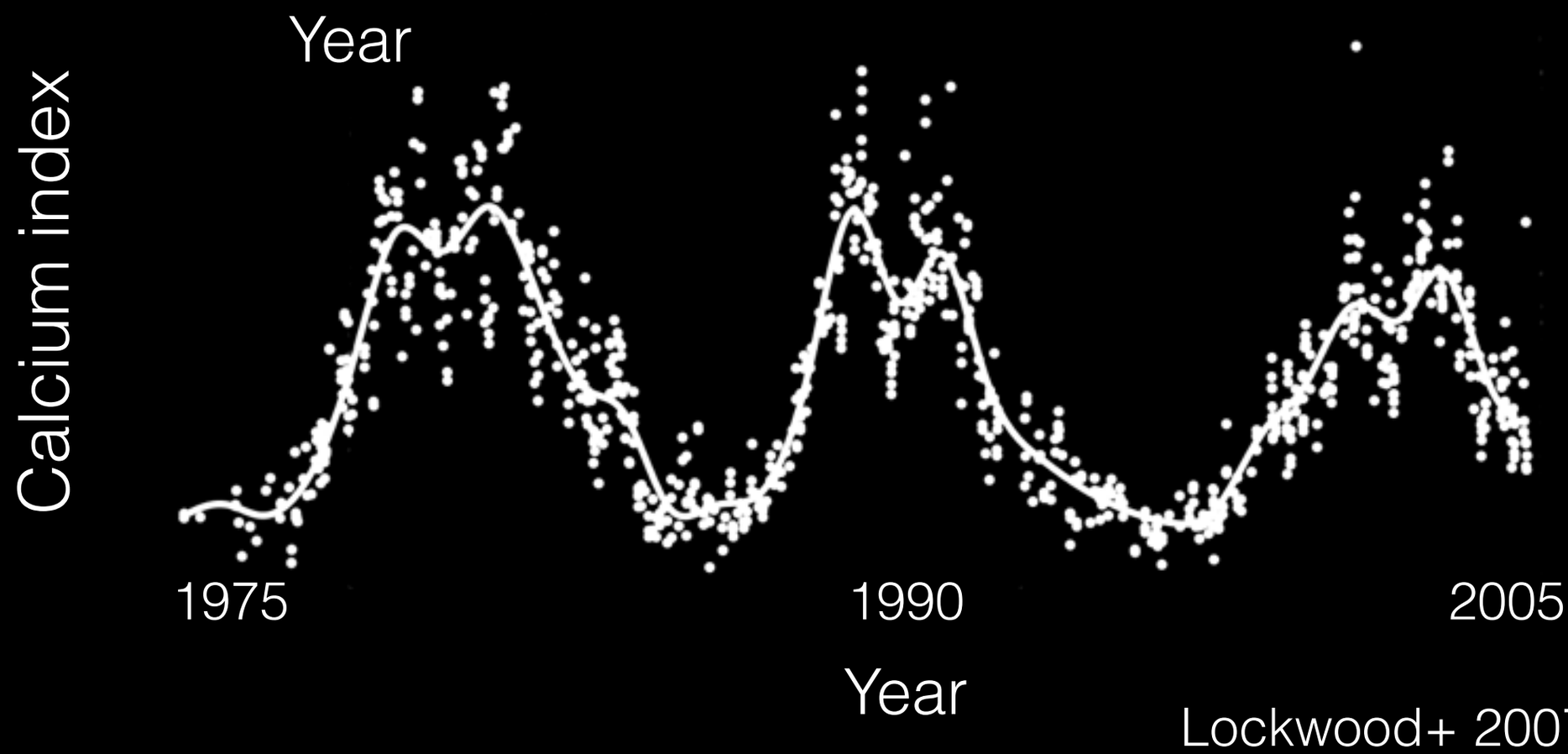
Magnetic Cycles

Magnetic Cycles

Magnetic Cycles

1-20 m/s (Lovis+ 11)



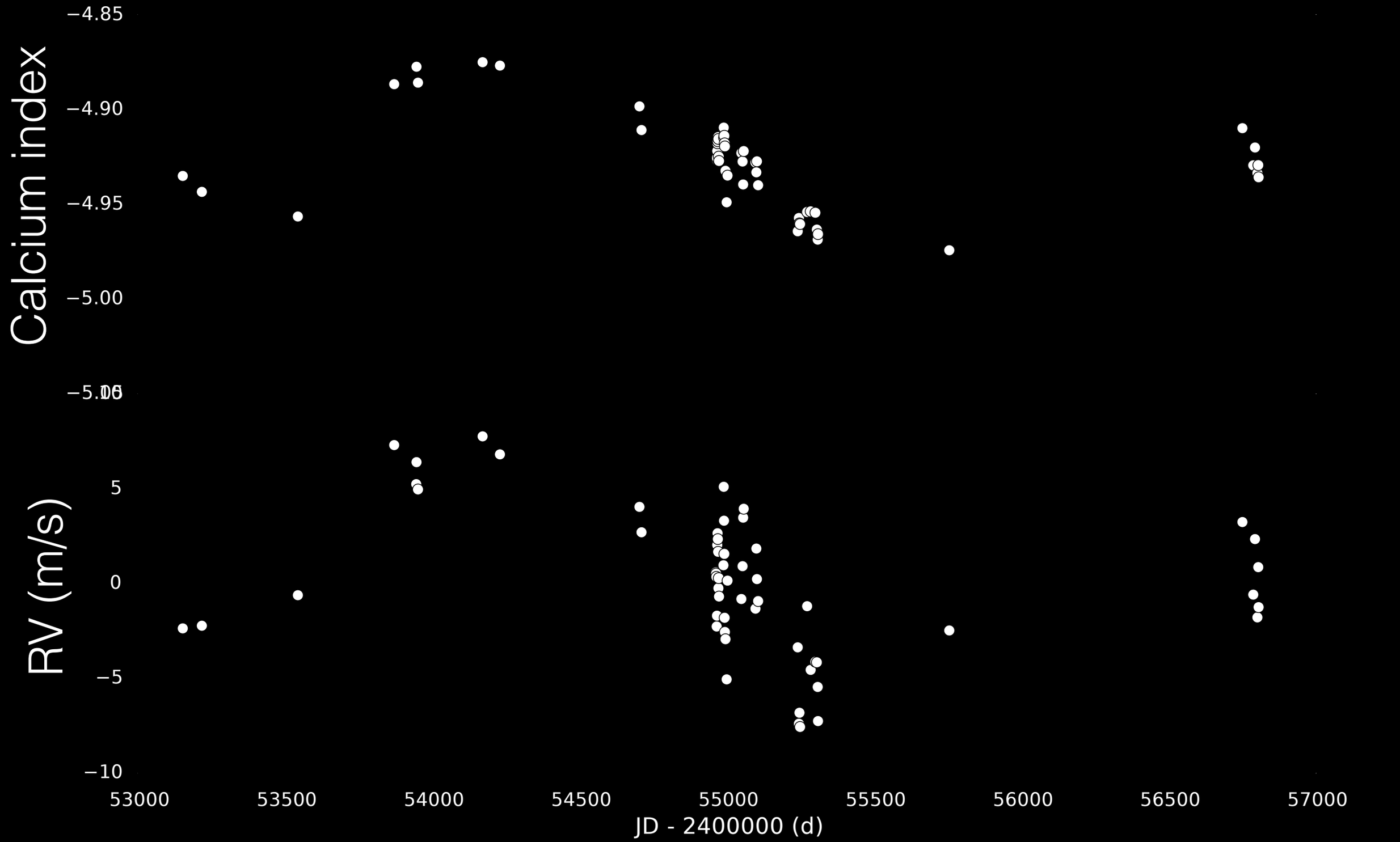


NASA / Solar Physics

Lockwood+ 2007

Magnetic Cycles

Magnetic Cycles



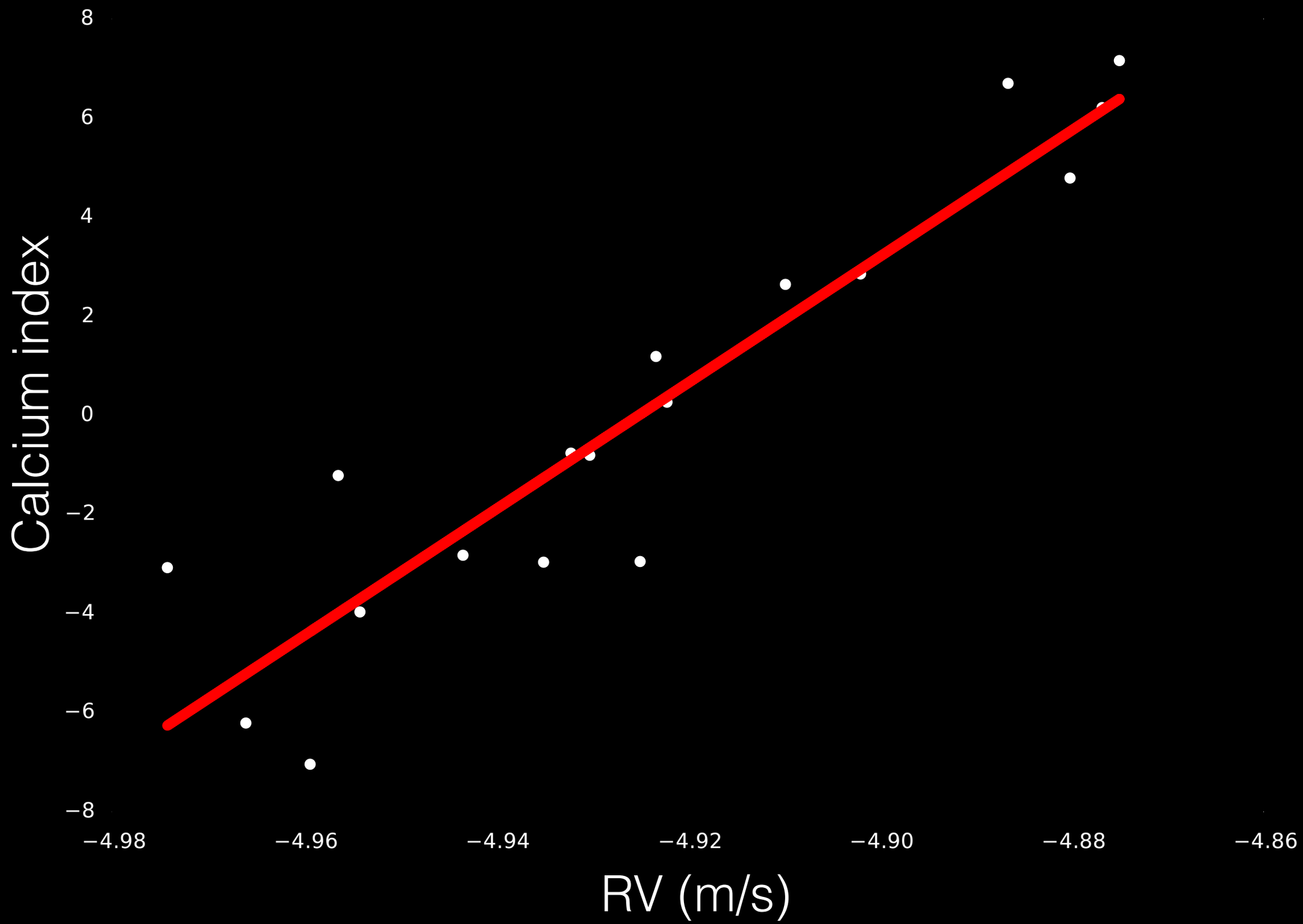
HARPS data

Magnetic Cycles

1-20 m/s (Lovis+ 11)

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

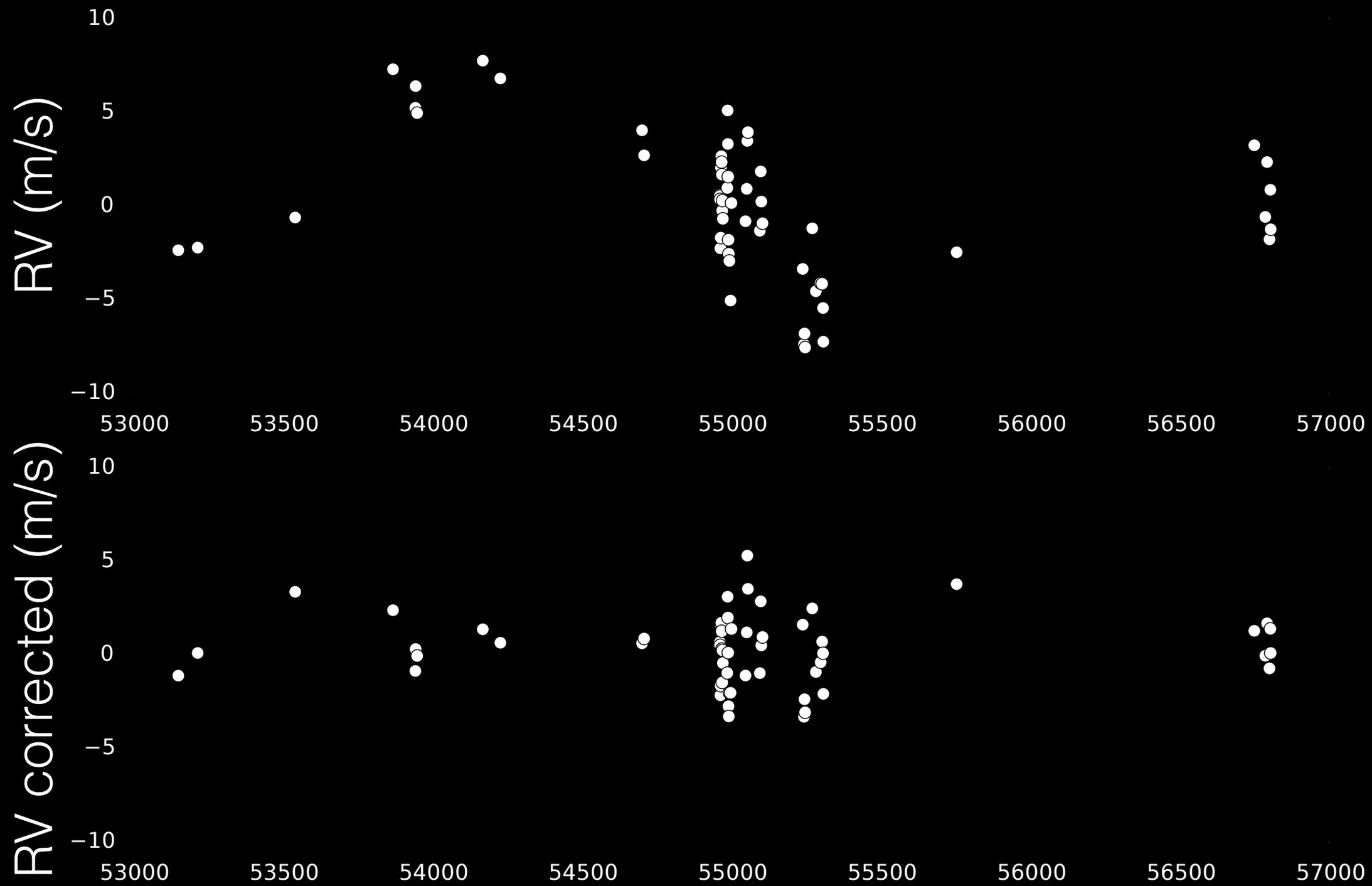
Magnetic Cycles



Meunier+ 13

HARPS data

Magnetic Cycles



Meunier+ 13

HARPS data

Future Prospects

Extremely precise visible spectrographs

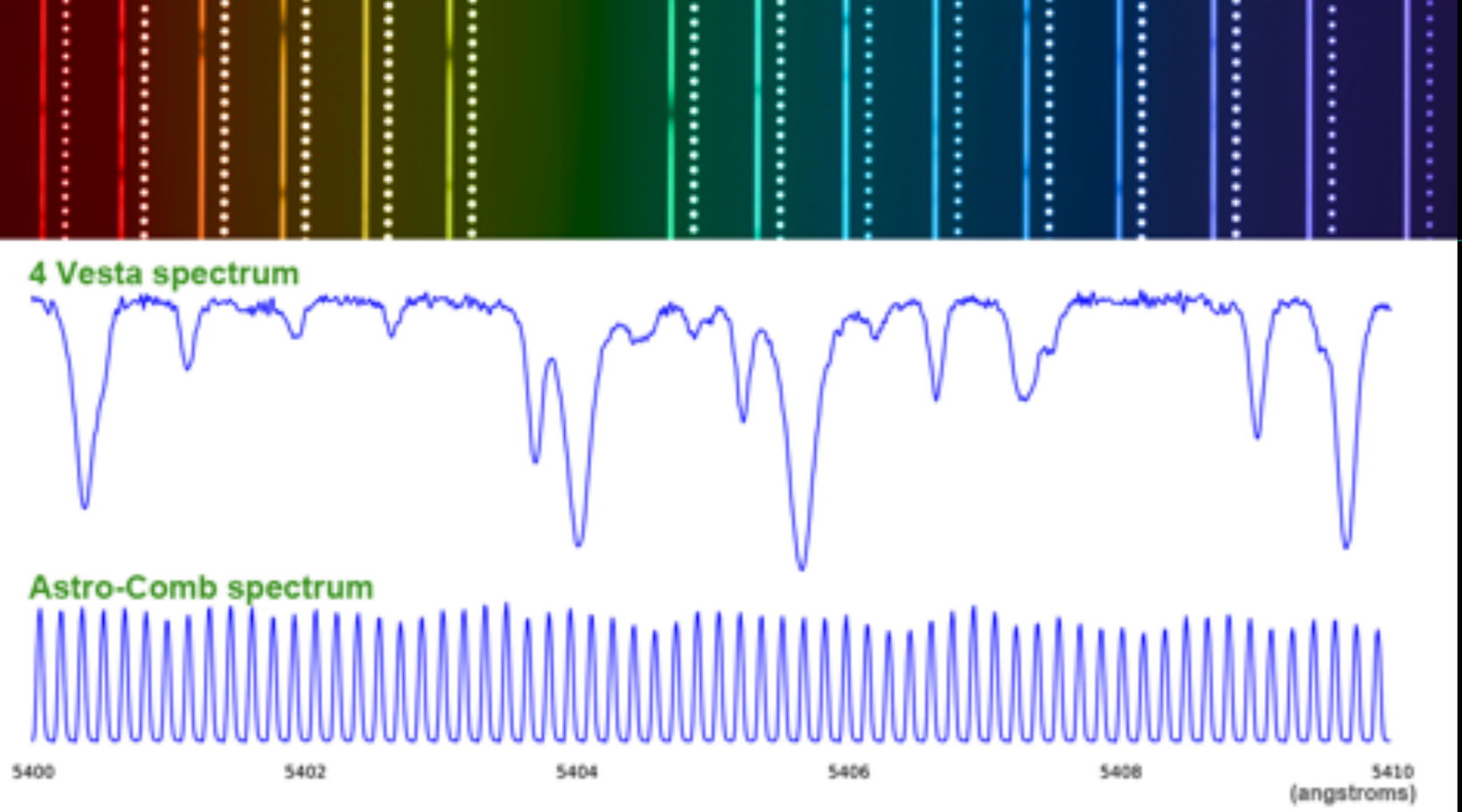
- ESPRESSO (2017, VLT) & G-CLEF (2021, GMT)
- Extremely stabilized
- octogonal fibers -> better scrambling
- laser frequency comb for simultaneous reference -> better track of instrument drift

Laser Frequency Comb

Thorium

4 Vesta

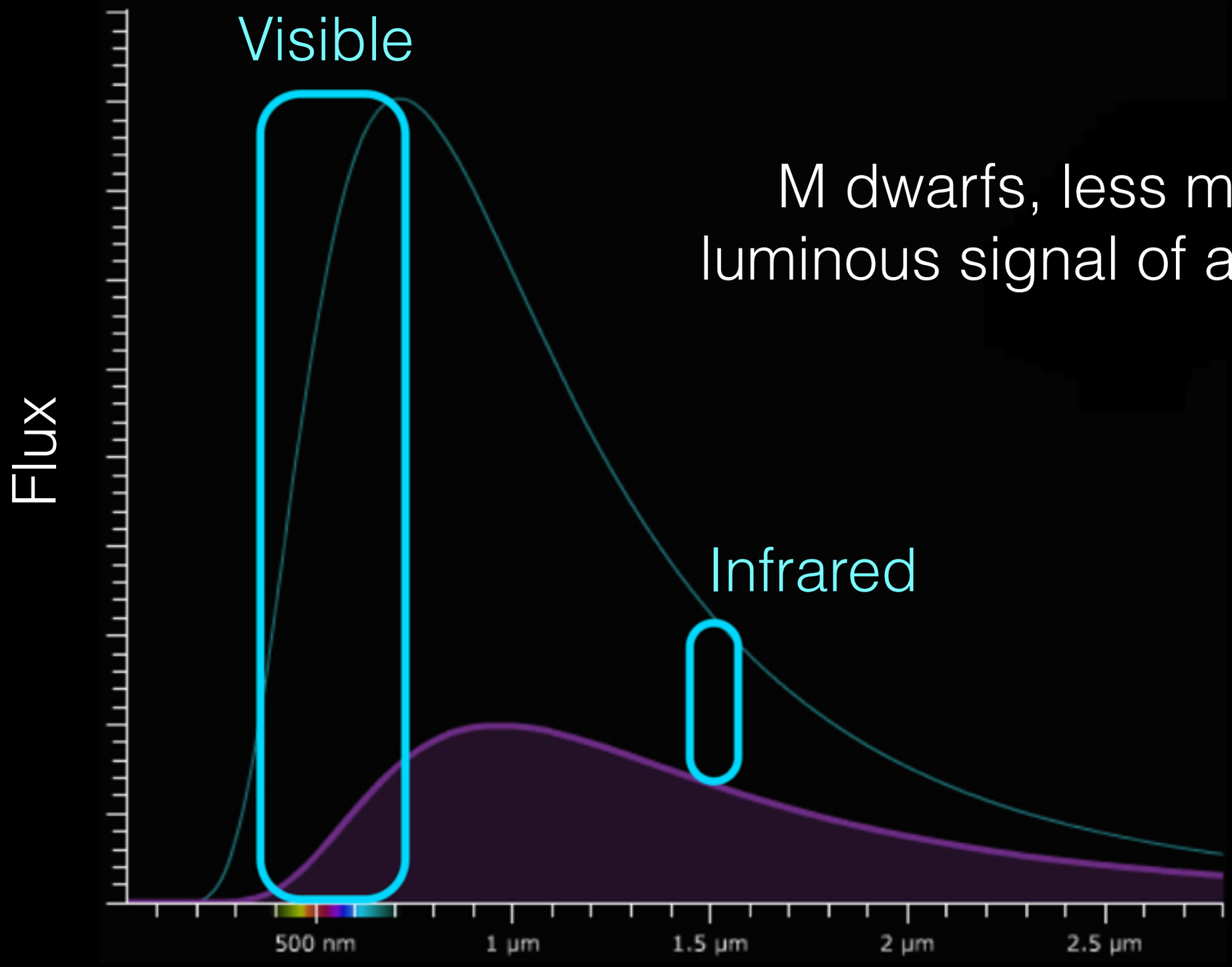
Astro-Comb



Chih Hao+14

Infrared spectrographs

Infrared spectrographs



M dwarfs, less massive, less luminous signal of an Earth bigger

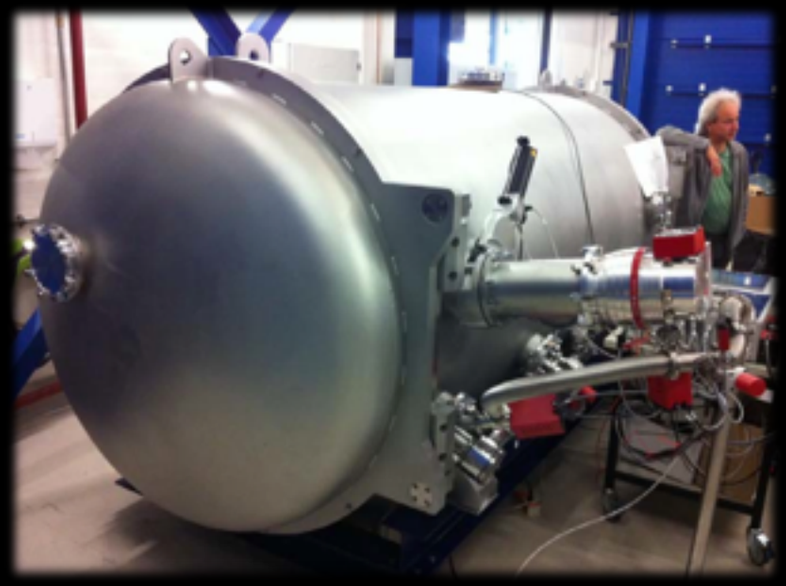
P. Figuera

Infrared spectrographs

Infrared spectrographs

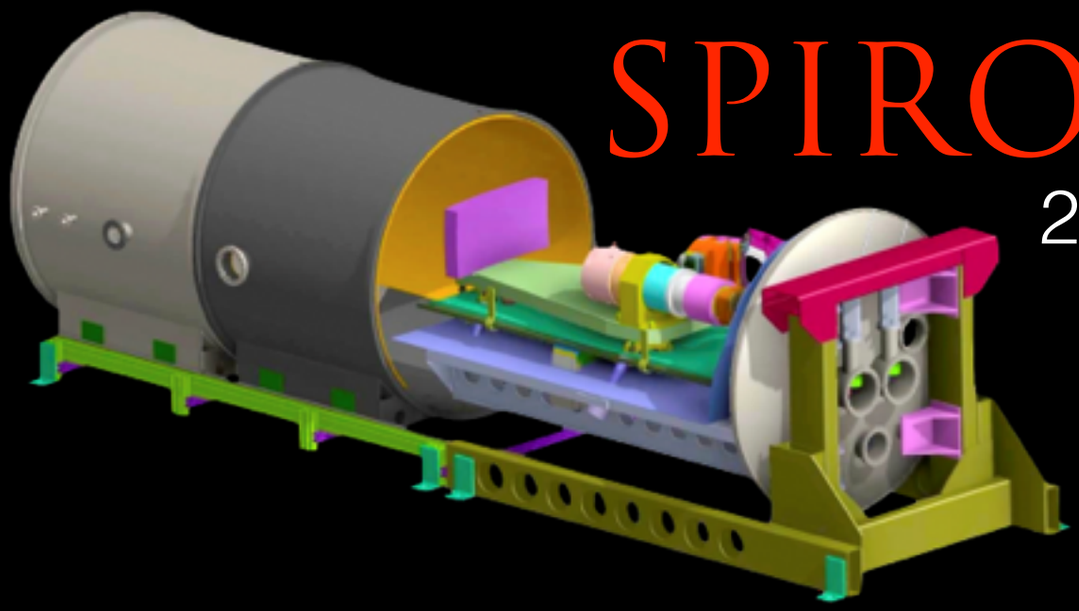
Carmenes

2016



SPIROU

2017

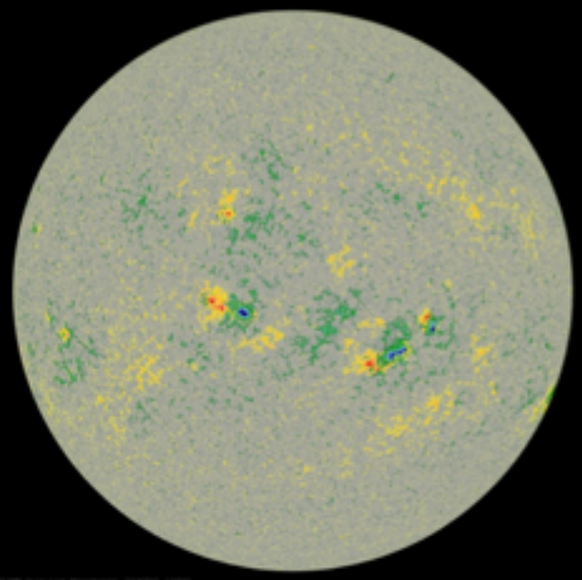


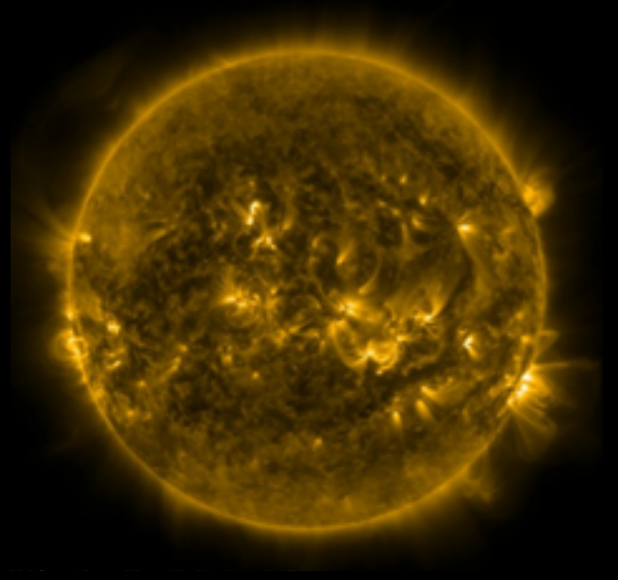
HPF

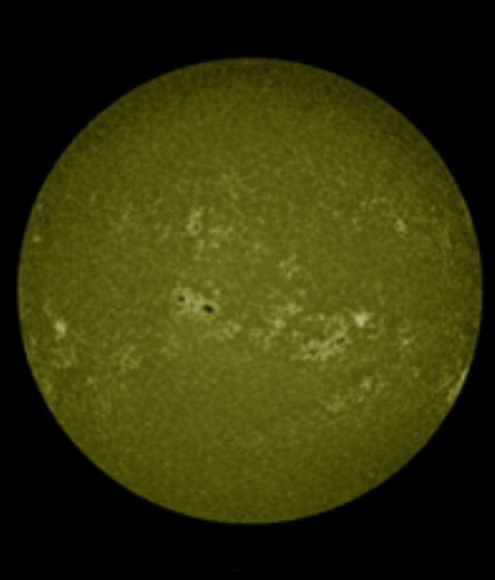
2017

HARPS-N Solar Telescope

X. Dumusque, D. Phillips, A. Glenday, D. Latham, R. Walworth







6
4
2
0
−2
−4
RV [m/s]
0.37
0.49
0.40
0.43
0.47
0.87
0.54
RMS 1st run = 1.33 m/s
56776
56778
56780
56782
BJD - 2400000 [d]

6
4
2
0
−2
−4
RV [m/s]
res. RMS 1st run = 0.59 m/s
56776
56778
56780
56782
BJD - 2400000 [d]

Questions ?