Recent results in exoplanetology with the SOPHIE spectrograph

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LAM

IAP , Friday January 20th, 2012

Outline

1. Extrasolar planets & the RV method
2. SOPHIE. Past performances
3. SOPHIE & exoplanets
4. The new fibre link. New performances
5. The future. The realm of small planets

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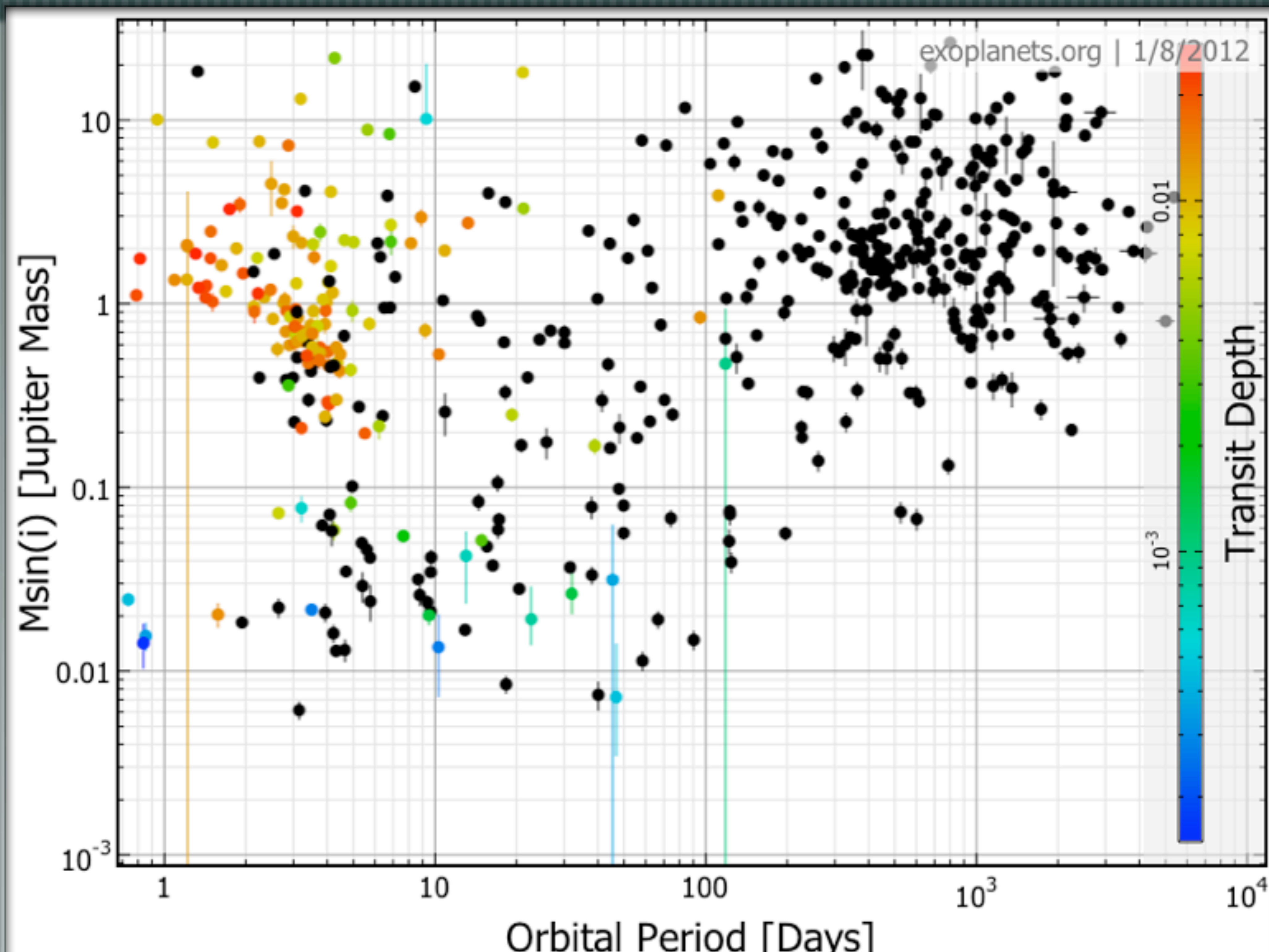
Extrasolar Planets



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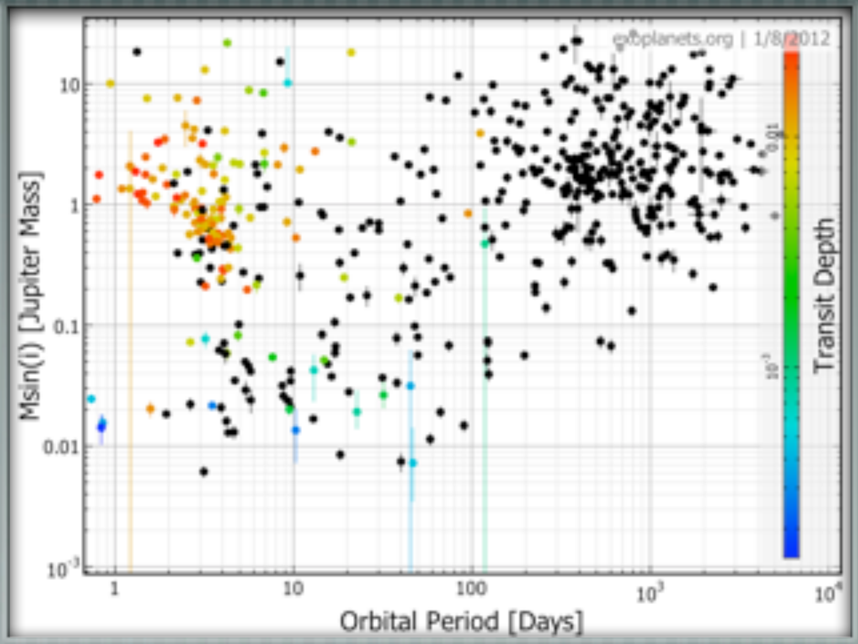
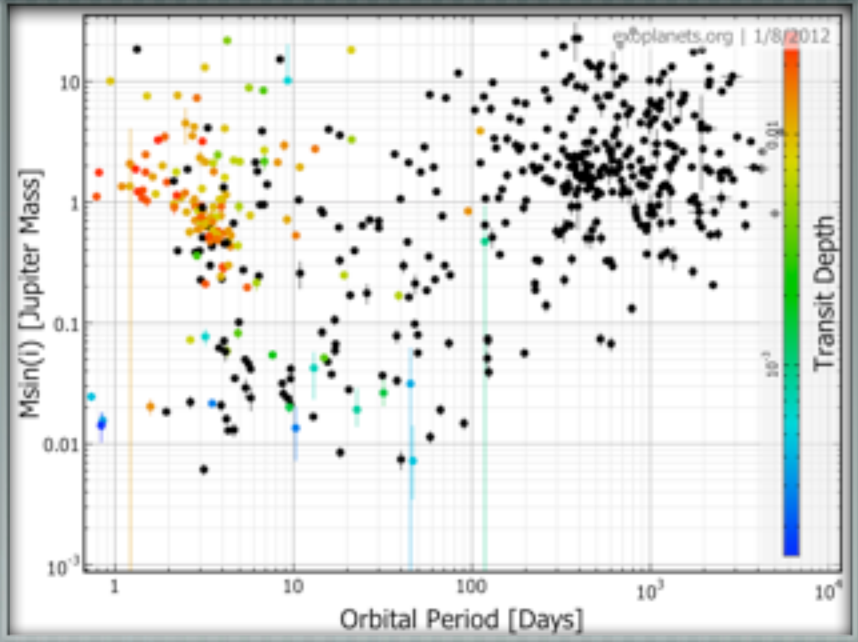


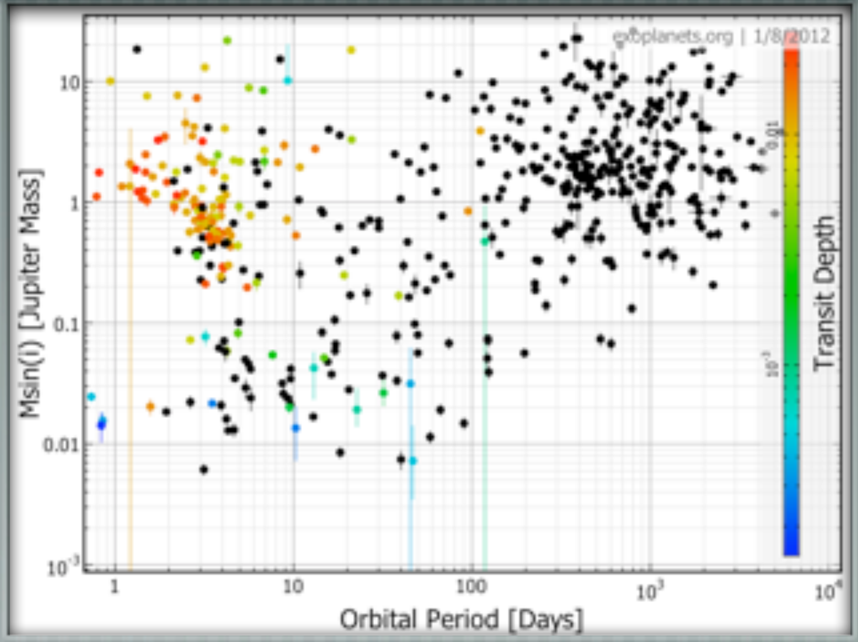
Extrasolar Planets

- Formation and evolution models



Extrasolar Planets

- Formation and evolution models
- Internal structure of giant and telluric planets



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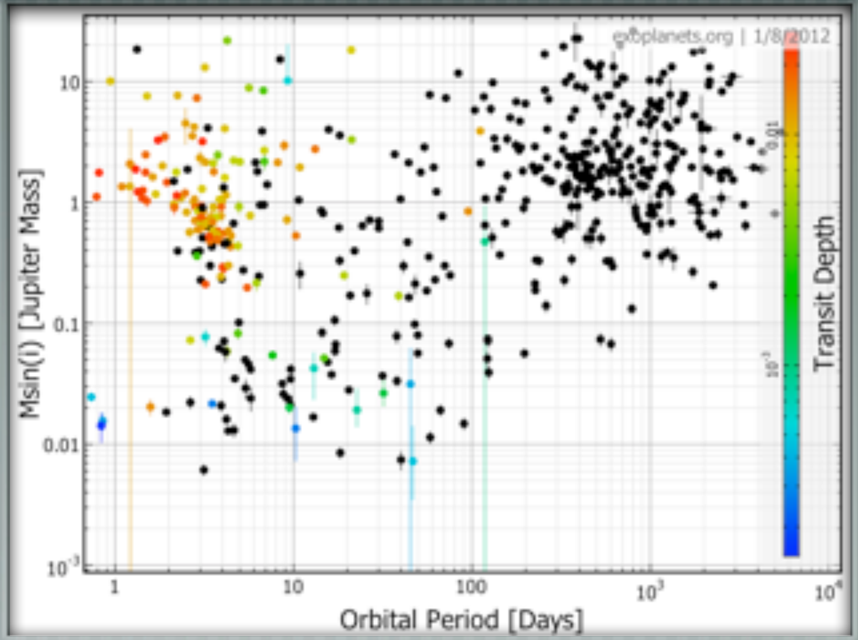
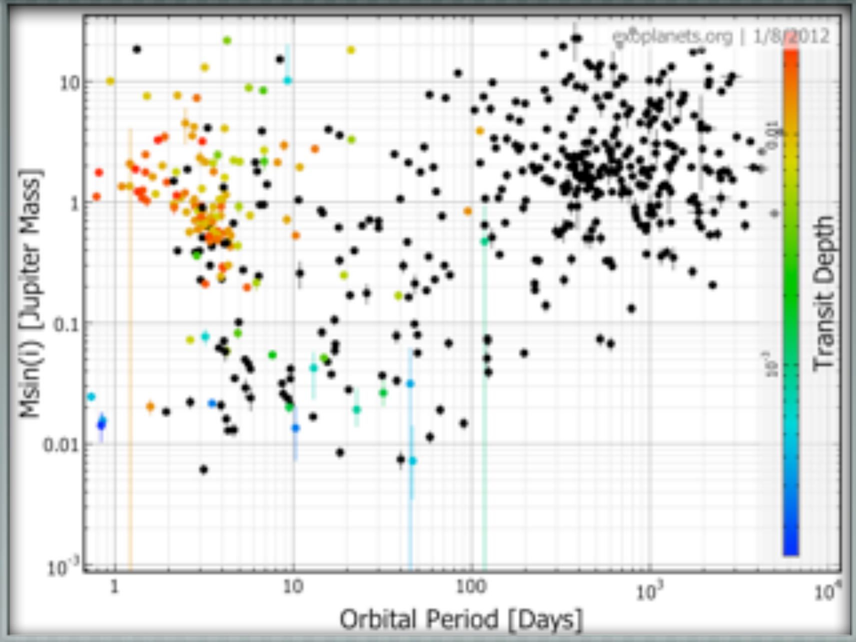
- Formation and evolution models
- Internal structure of giant and telluric planets
- Atmospheric composition and dynamics



Extrasolar Planets

- Formation and evolution models
- Internal structure of giant and telluric planets
- Atmospheric composition and dynamics
- Better understanding of stellar activity



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- Internal structure of giant and telluric planets
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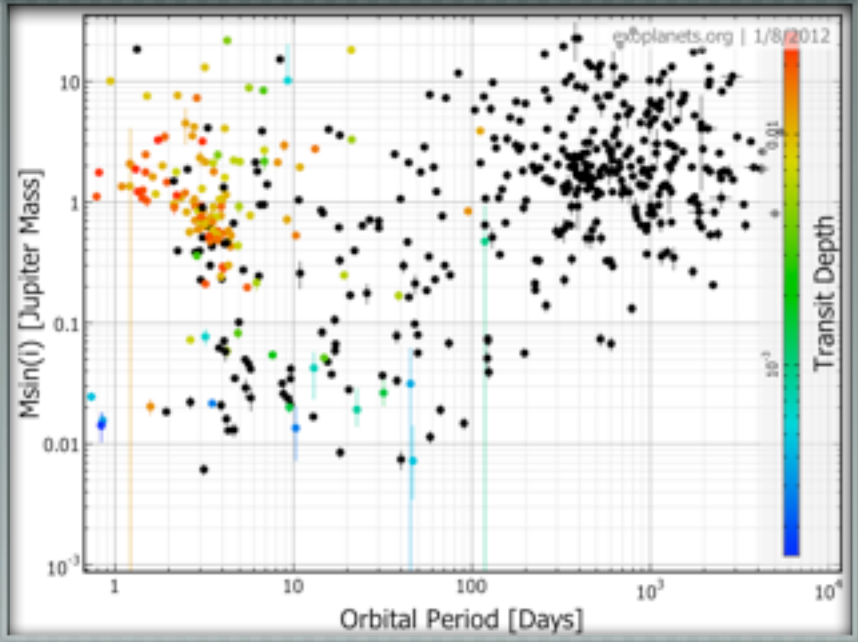
- Test tidal dissipation theory



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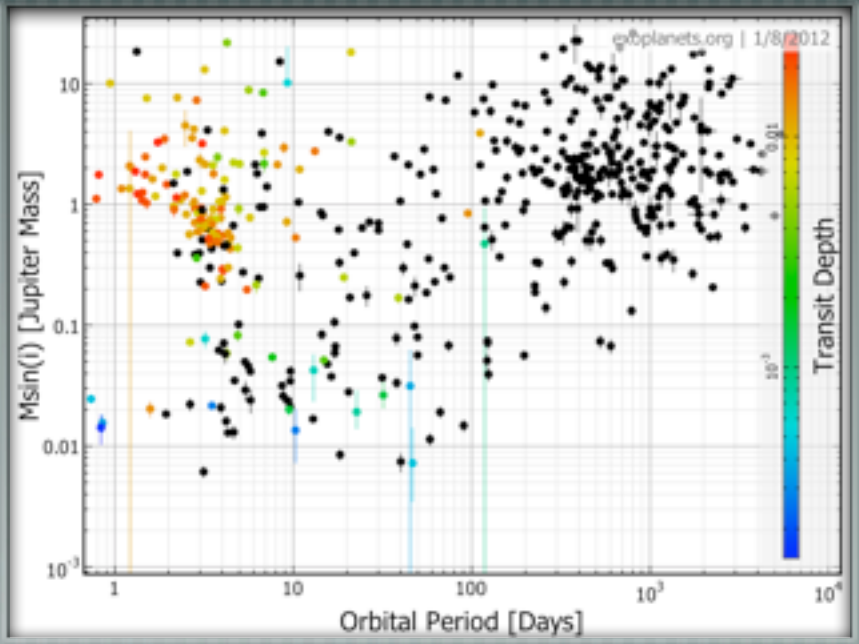

Extrasolar Planets

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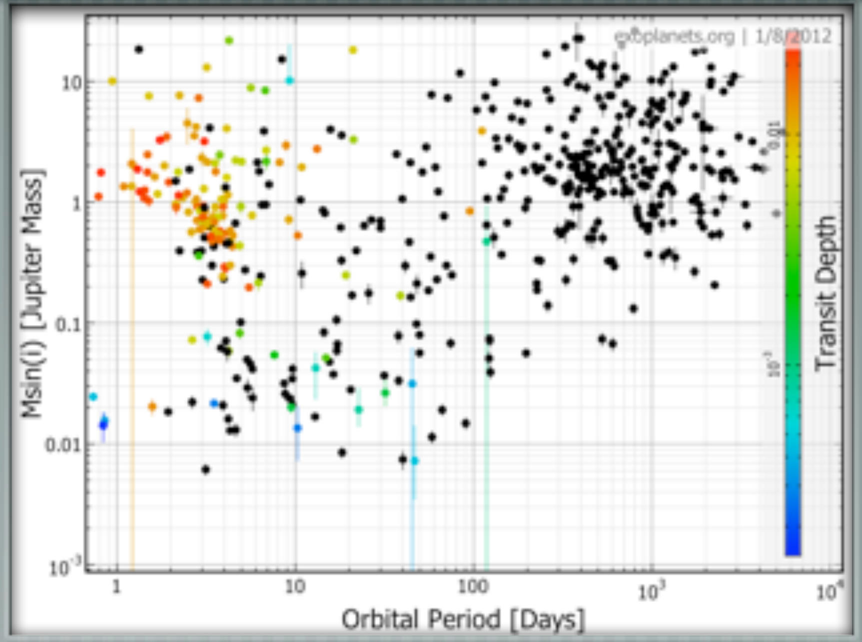
- Test tidal dissipation theory
- Galactic census
- Are we alone?



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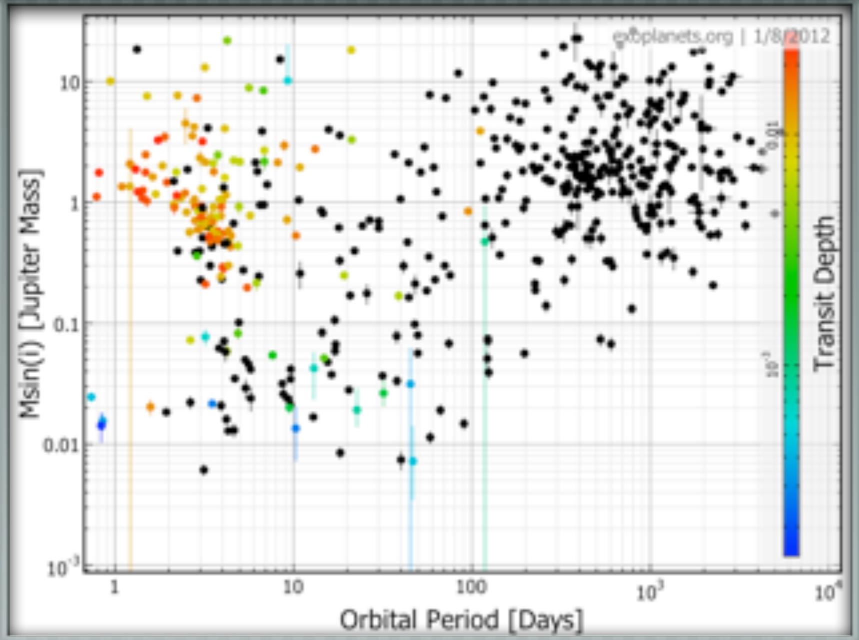
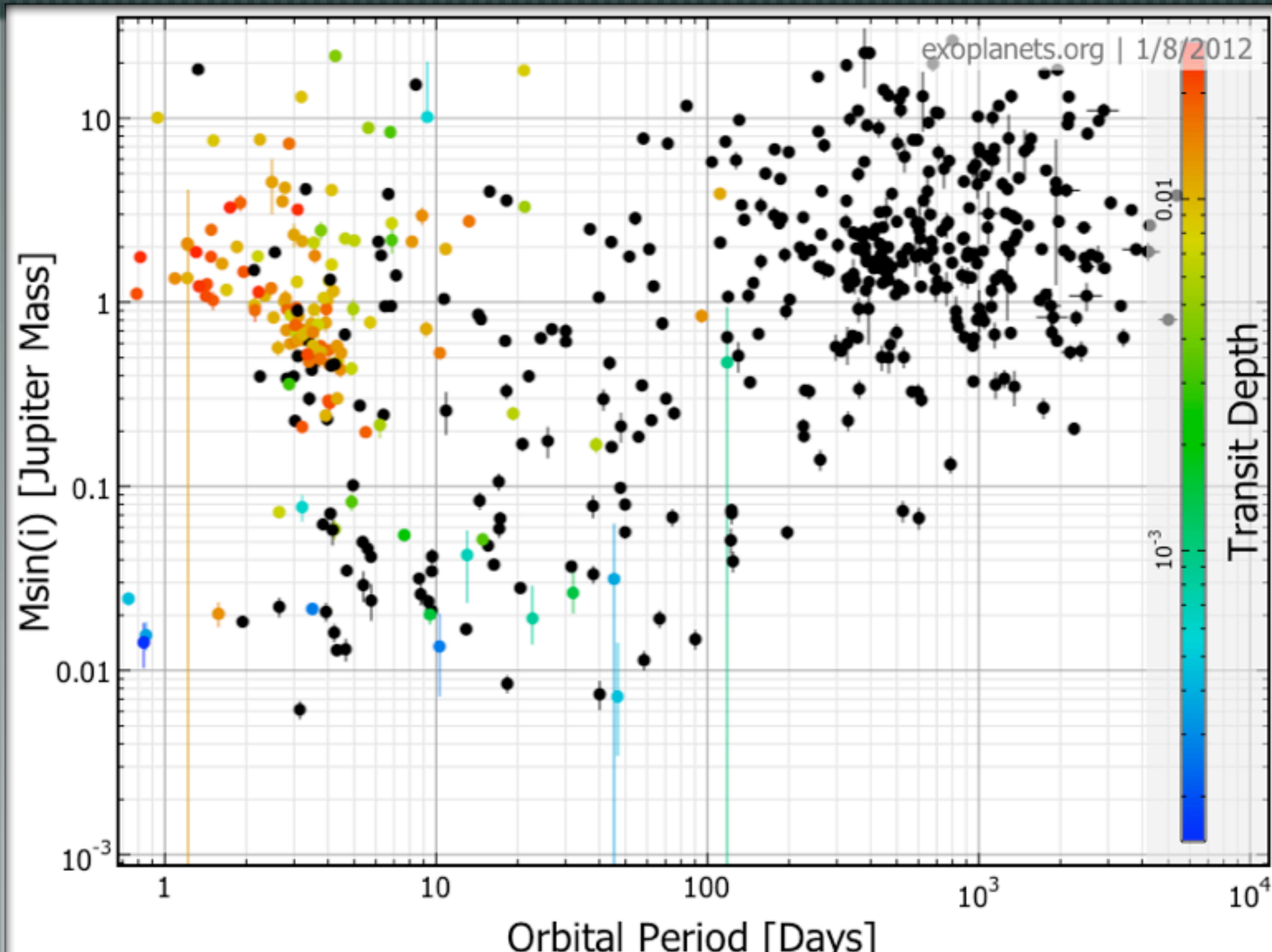


Comparative Exoplanetology

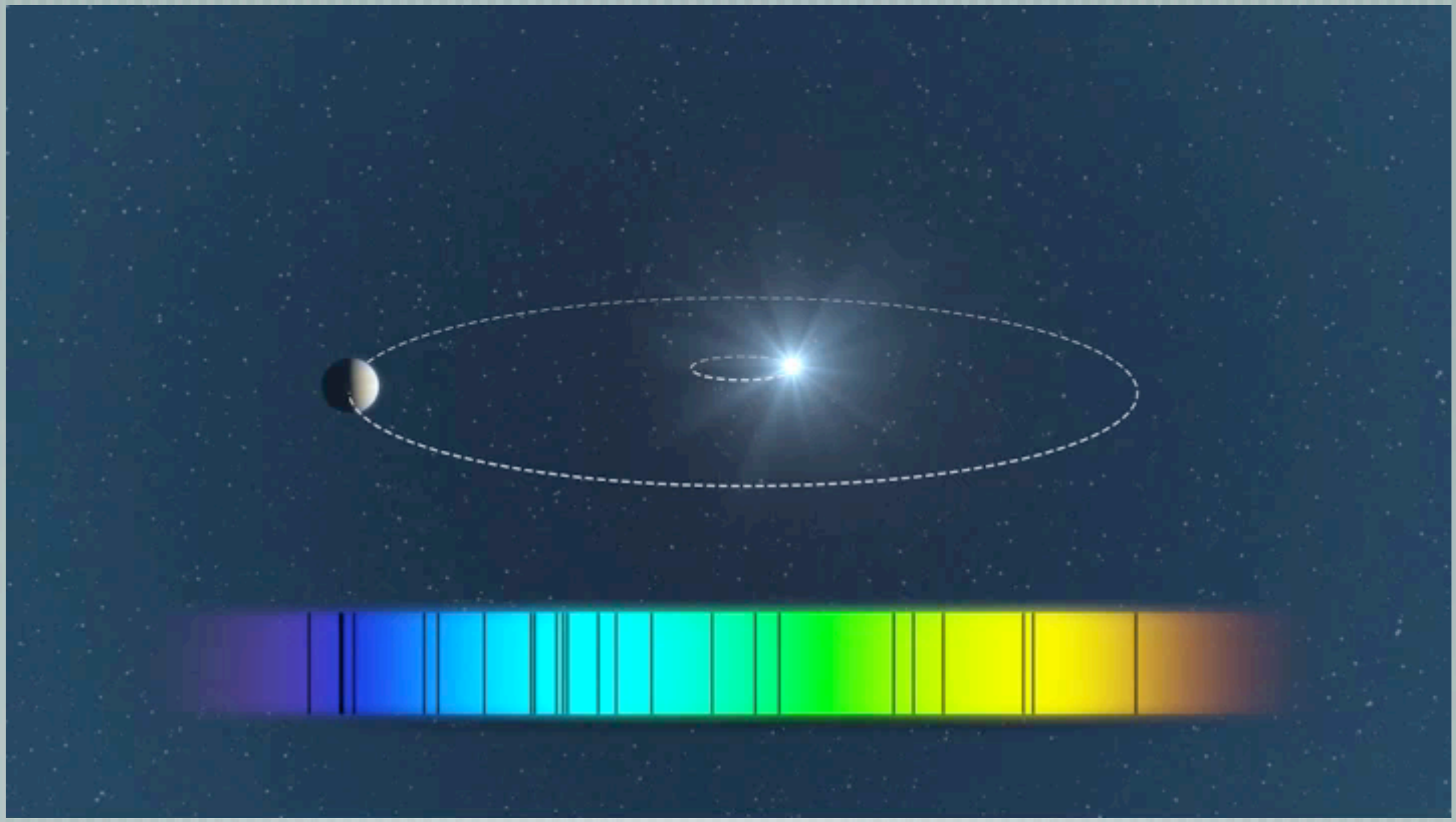
Extrasolar Planets



The RV method

Credit: ESO

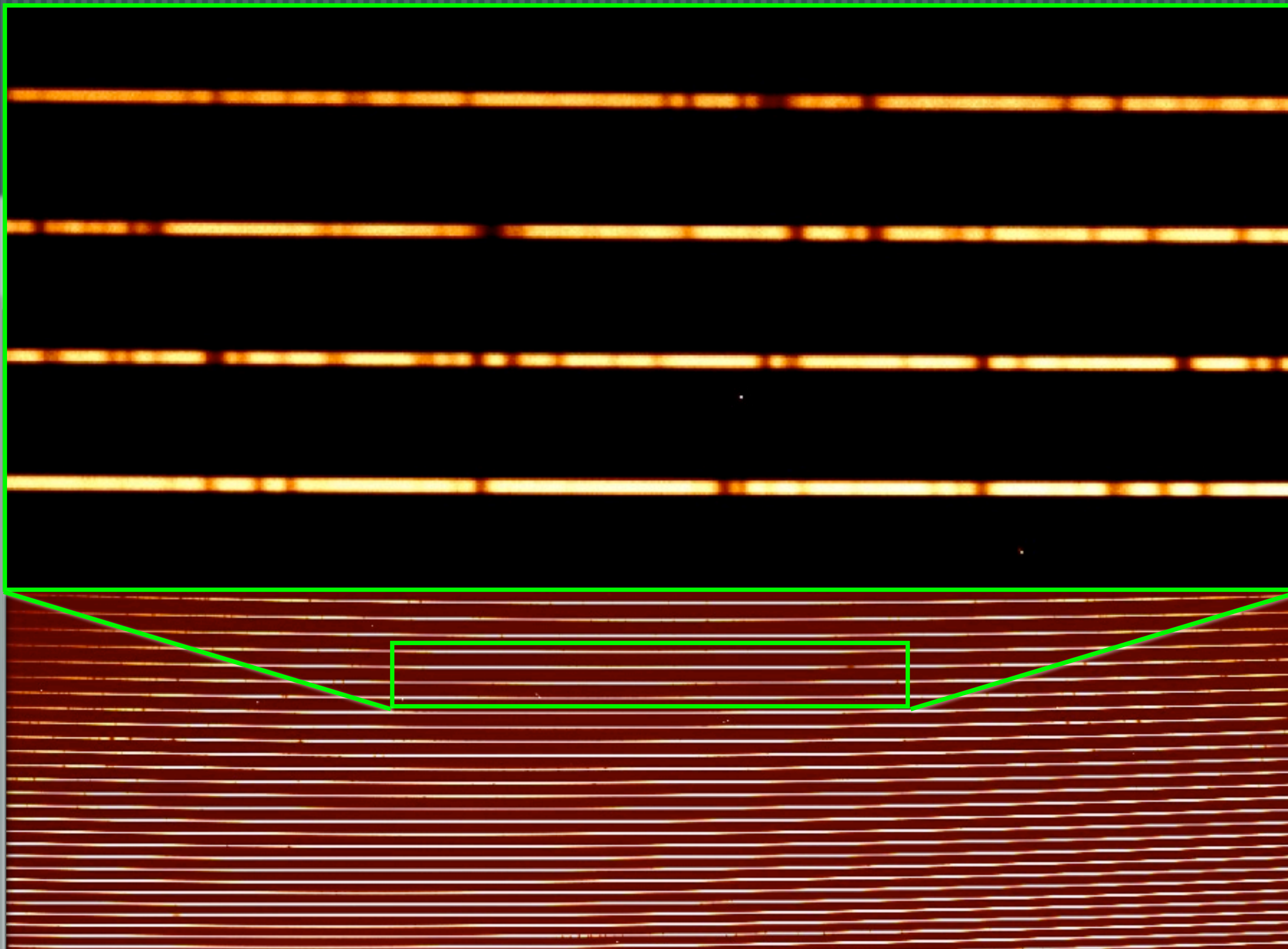
The RV method



Credit: ESO

The RV method

A SOPHIE spectrum



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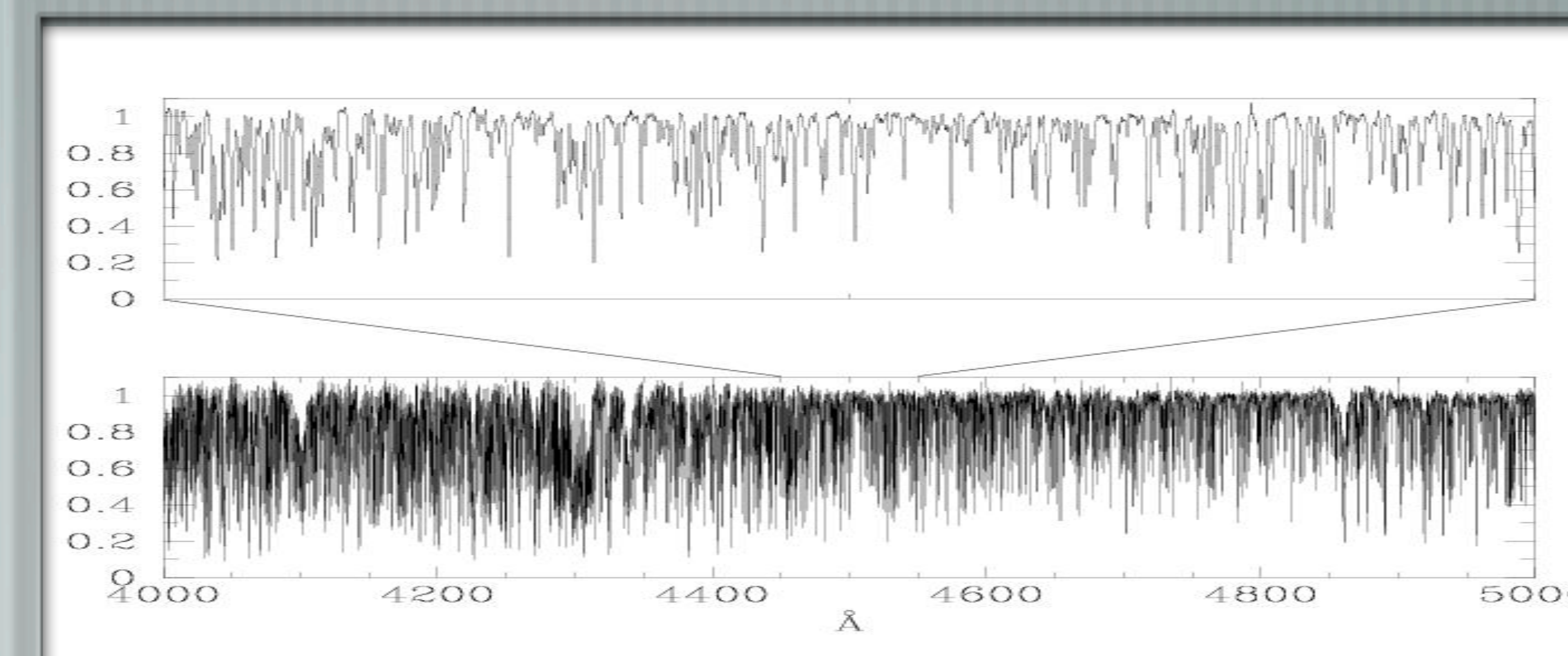

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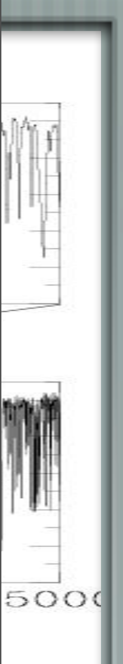

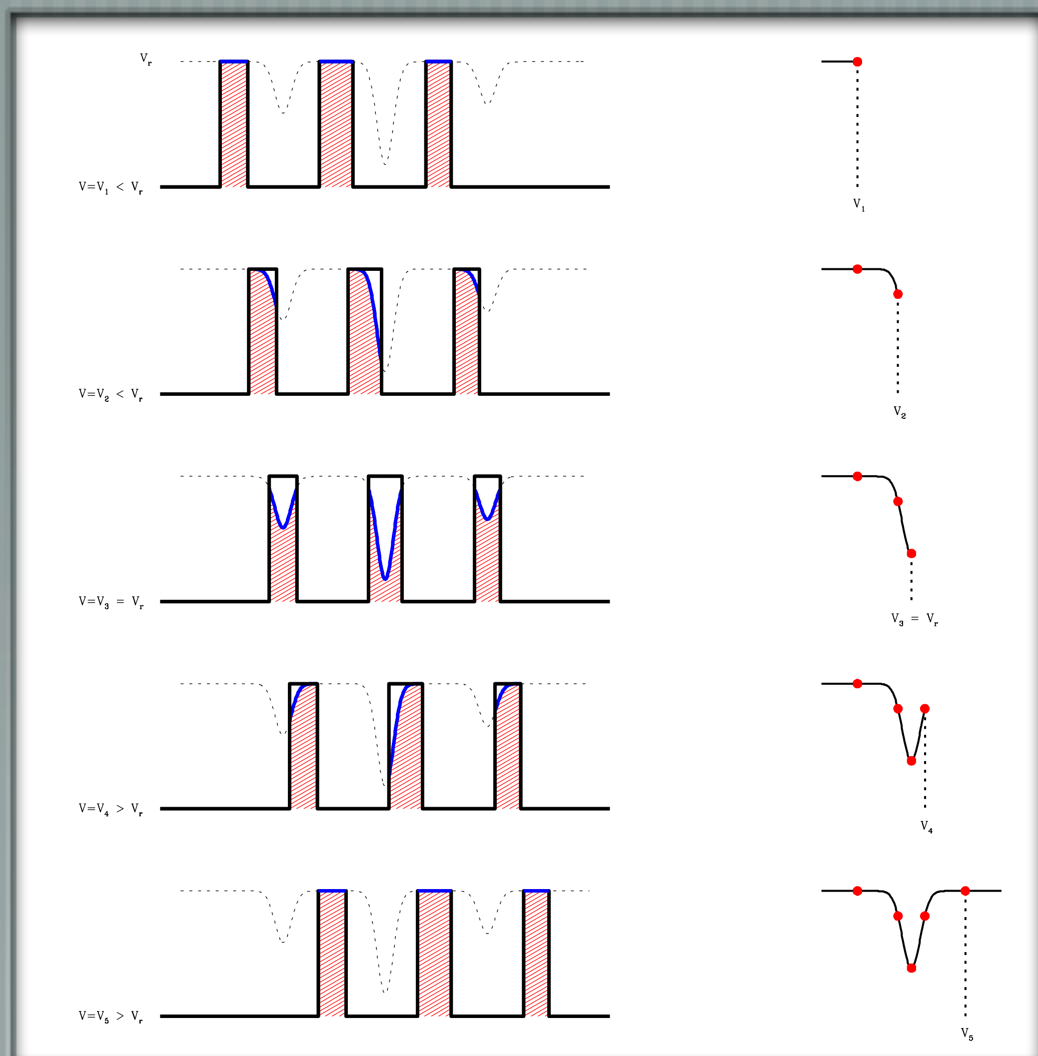

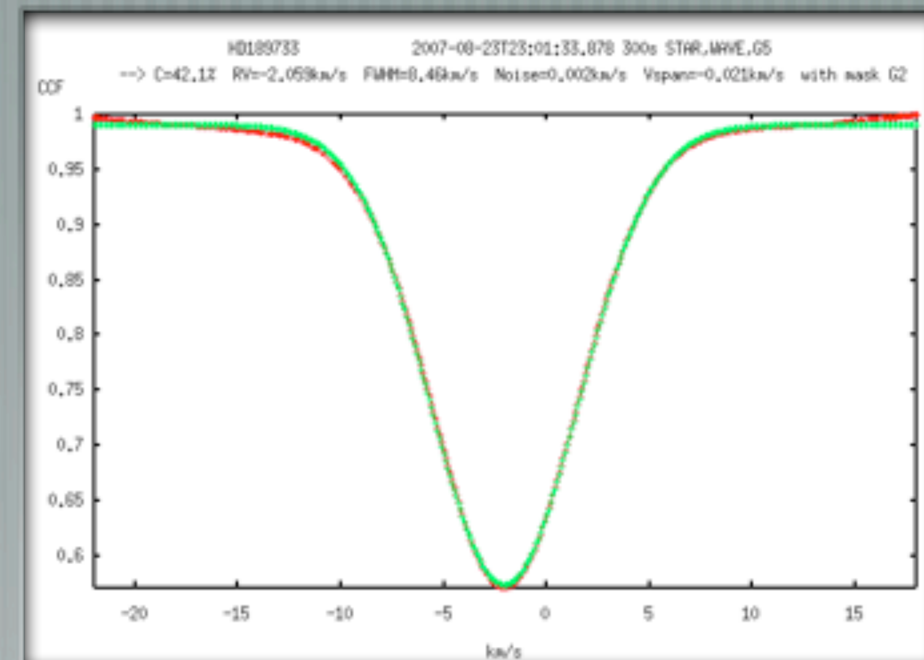

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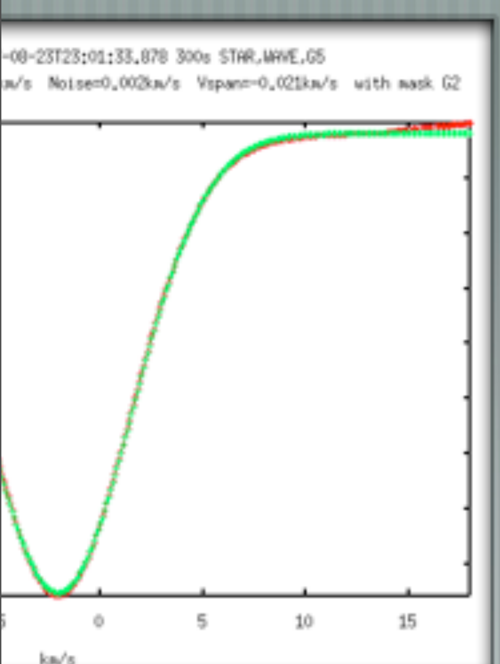
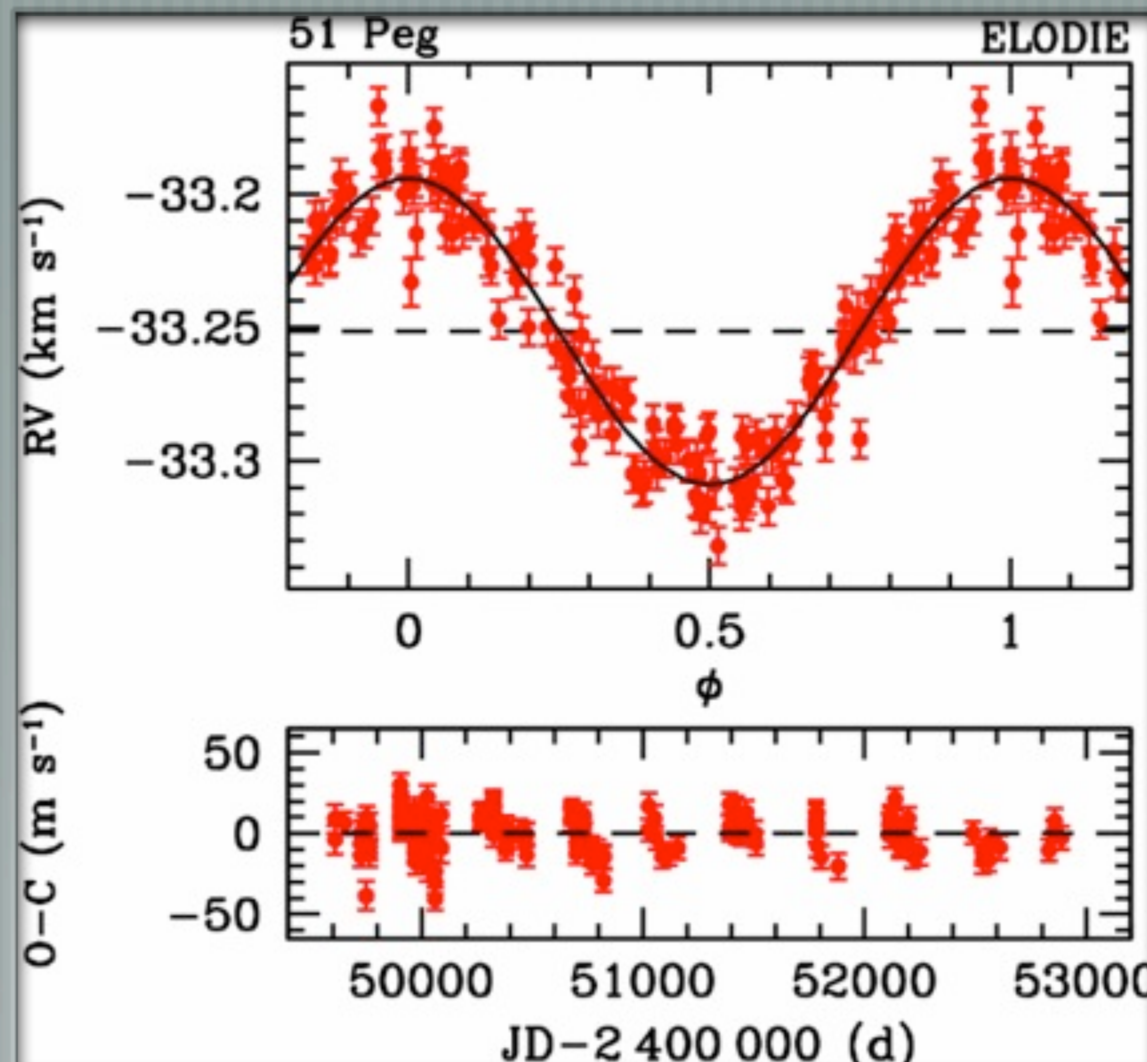
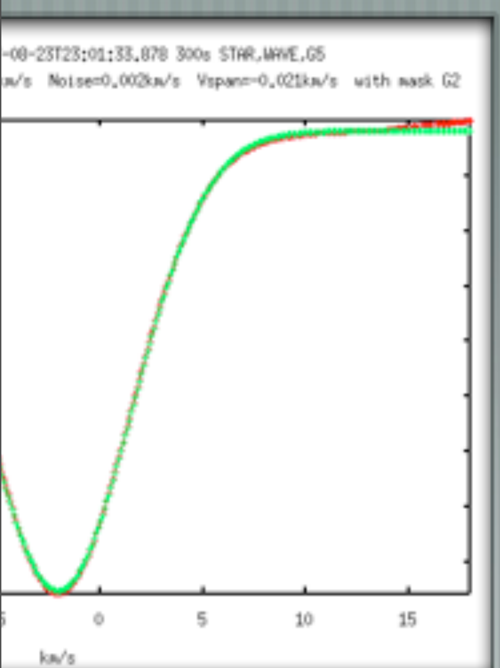
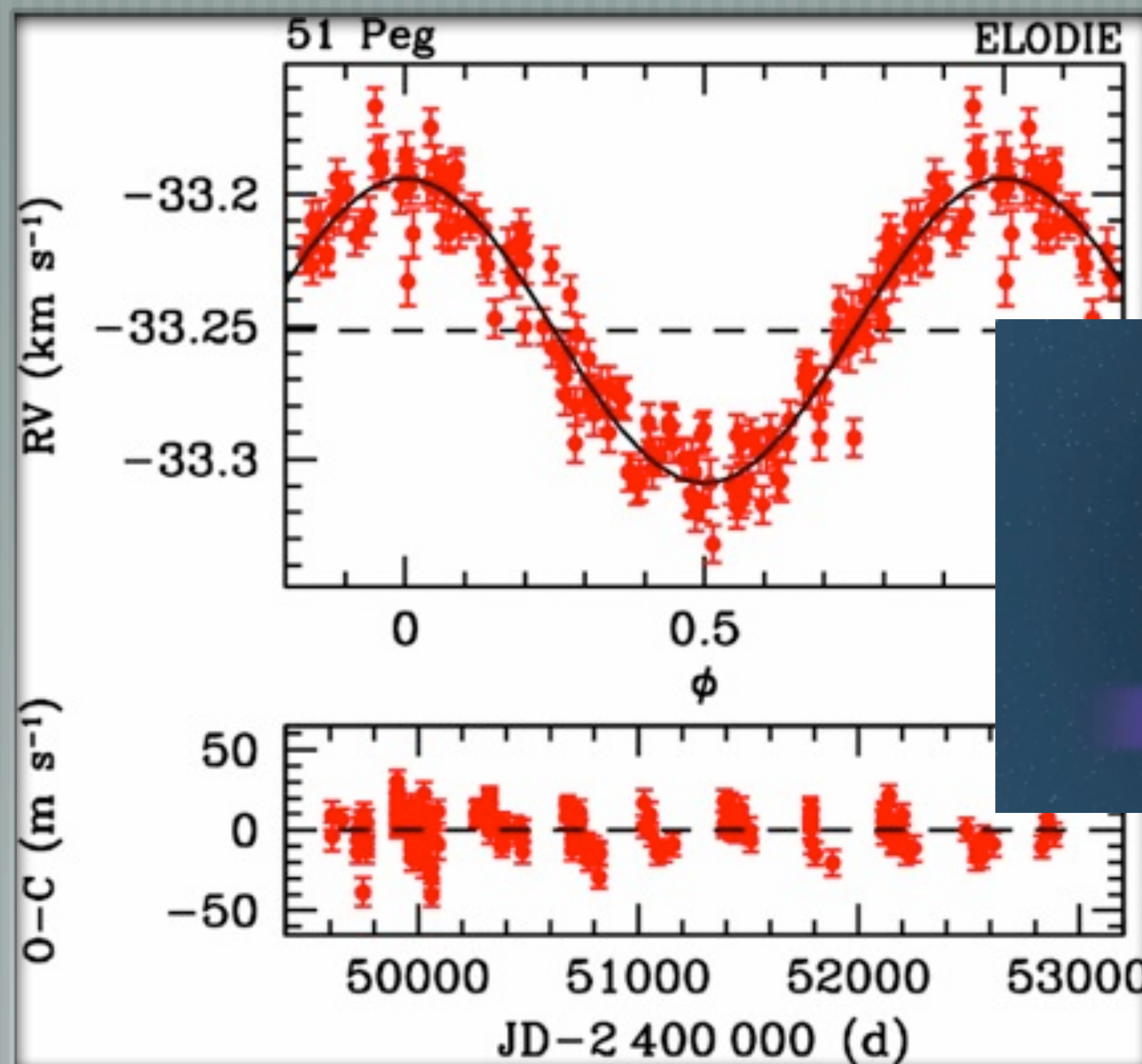


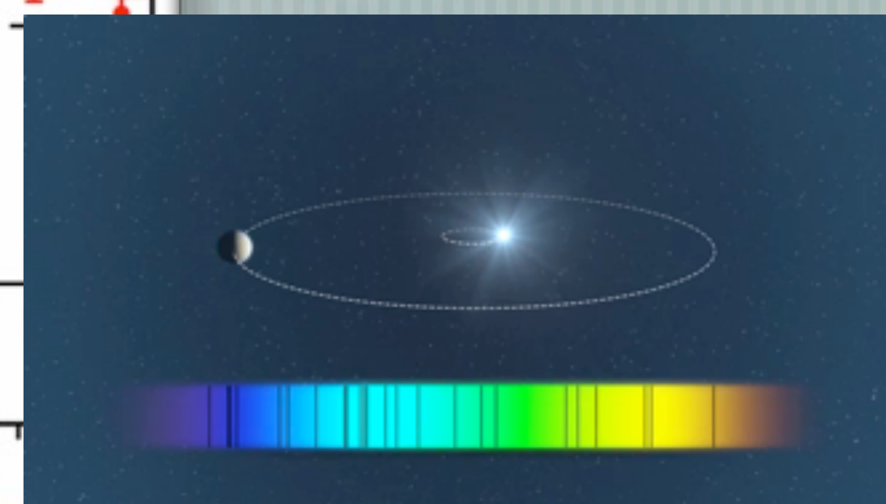


$$K = \left(\frac{2\pi G}{P}\right)^{1/3} \frac{M_p \sin i}{\left(M_p + M_*\right)^{2/3}} \cdot \frac{1}{\left(1 - e^2\right)^{1/2}}$$

The RV method







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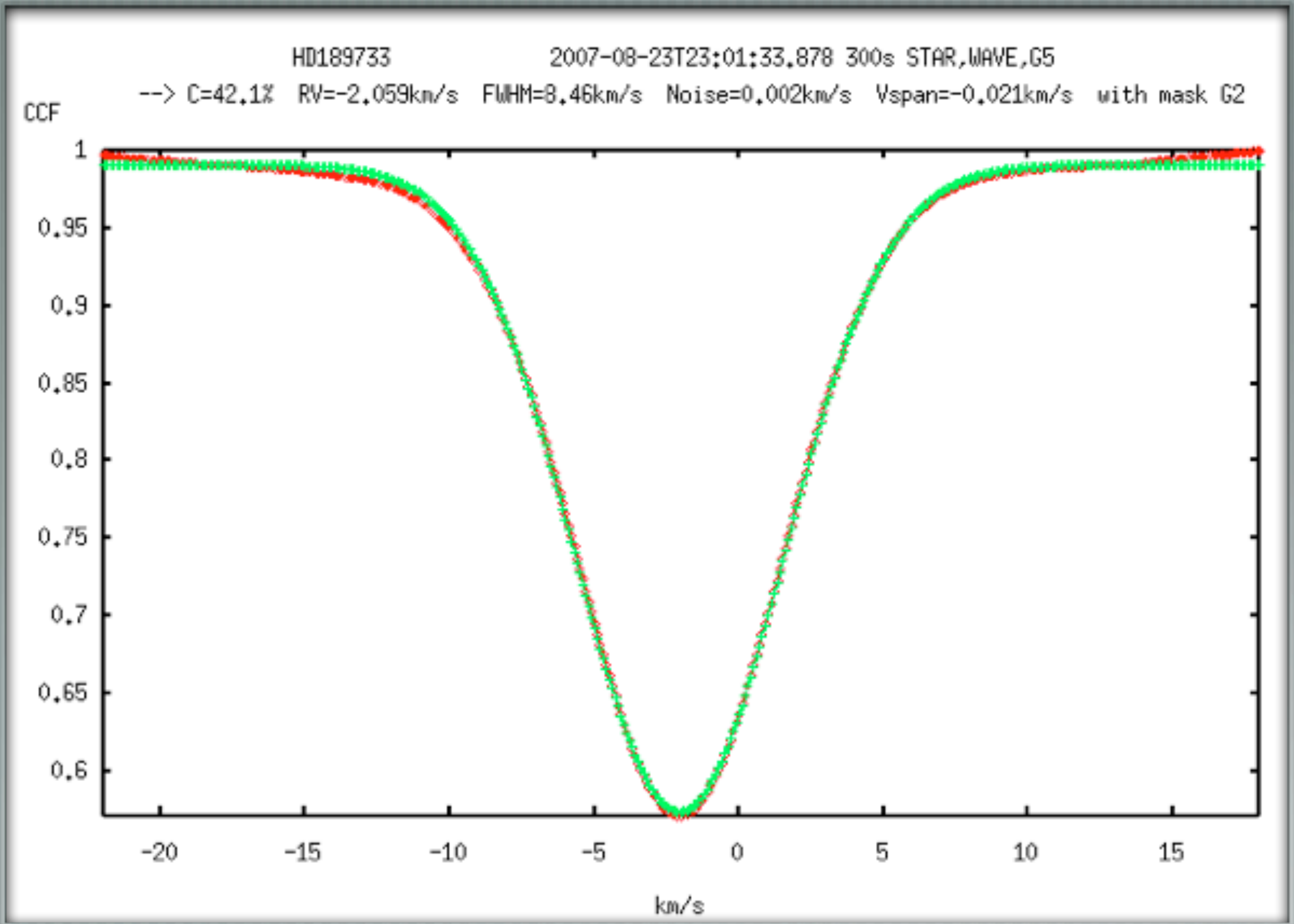

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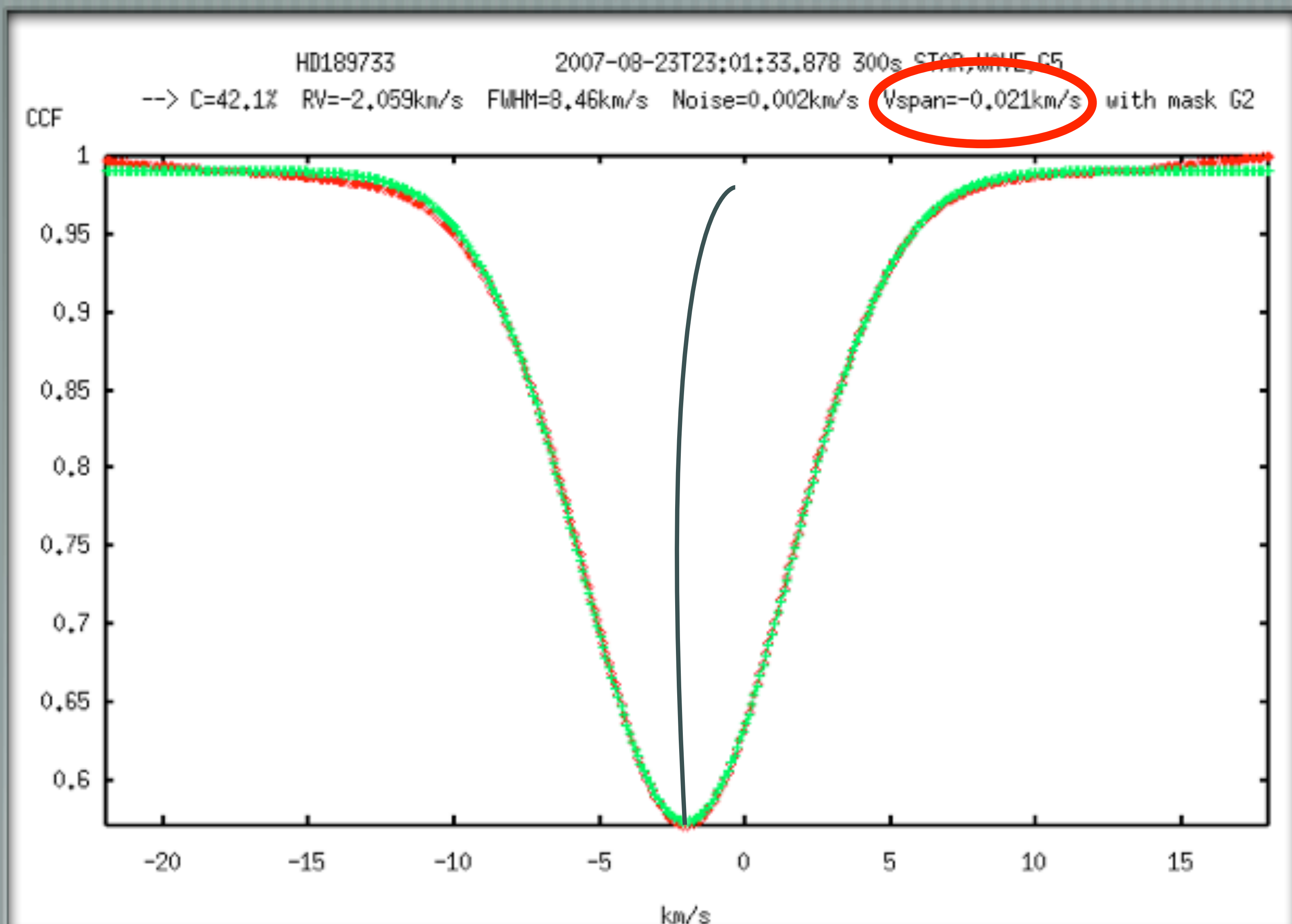
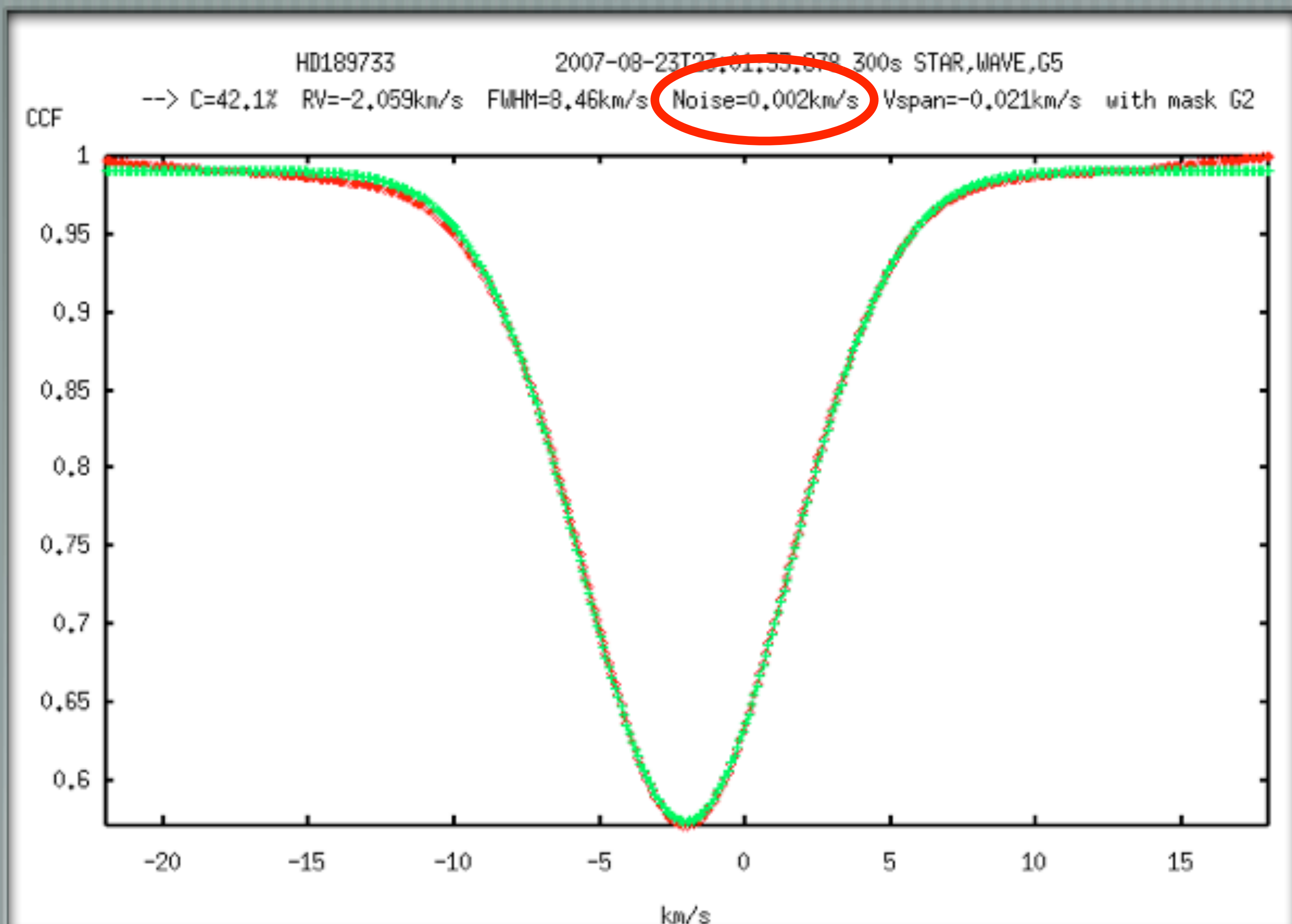


Bisector velocity span

a measurement of the symmetry of the lines

The RV method



Bisector velocity span

a measurement of the symmetry of the lines

The photon noise

the fundamental limit to the RV precision

$$\sigma \propto \frac{\sqrt{FWHM}}{constrast \times S/N}$$

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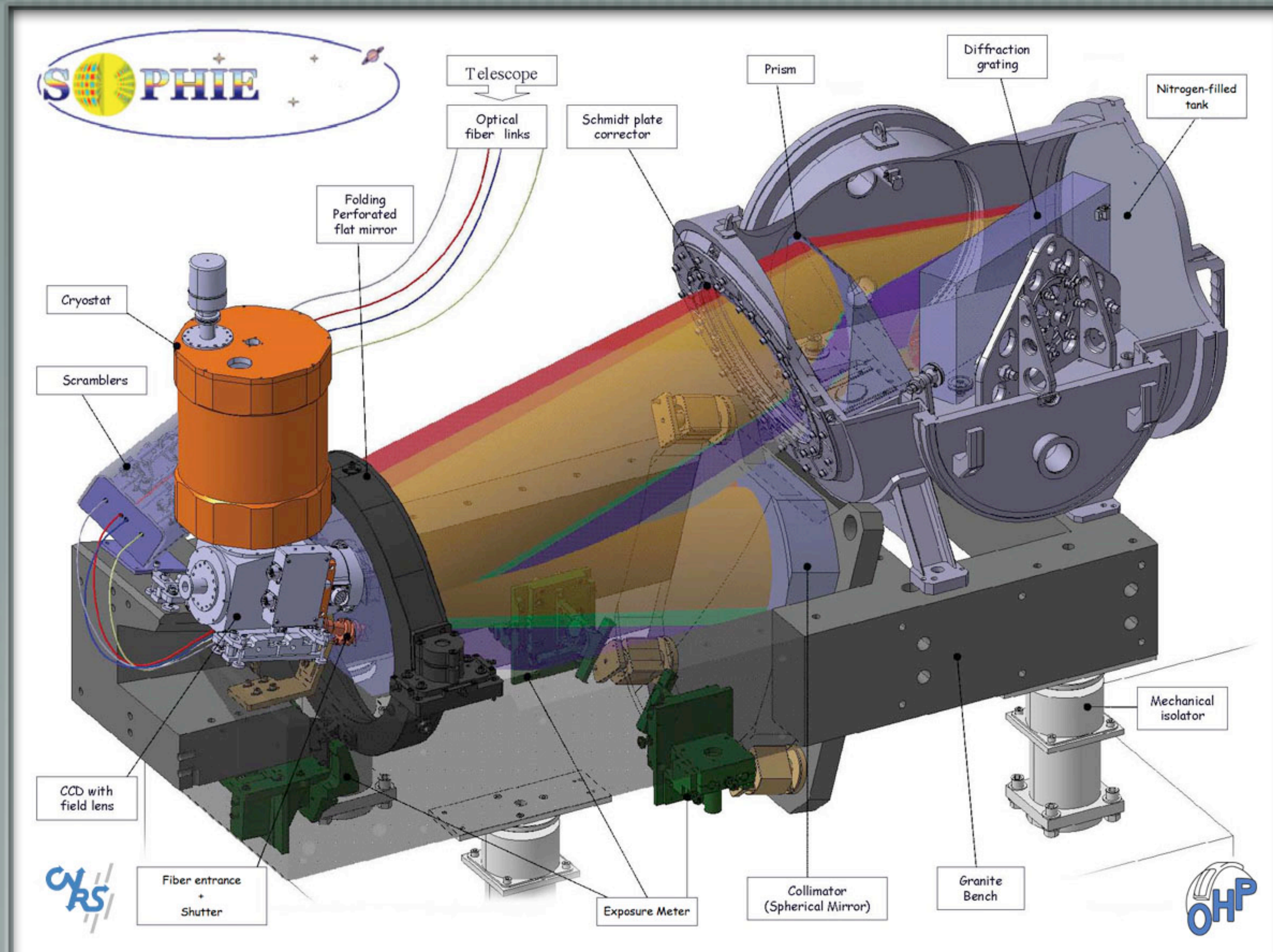
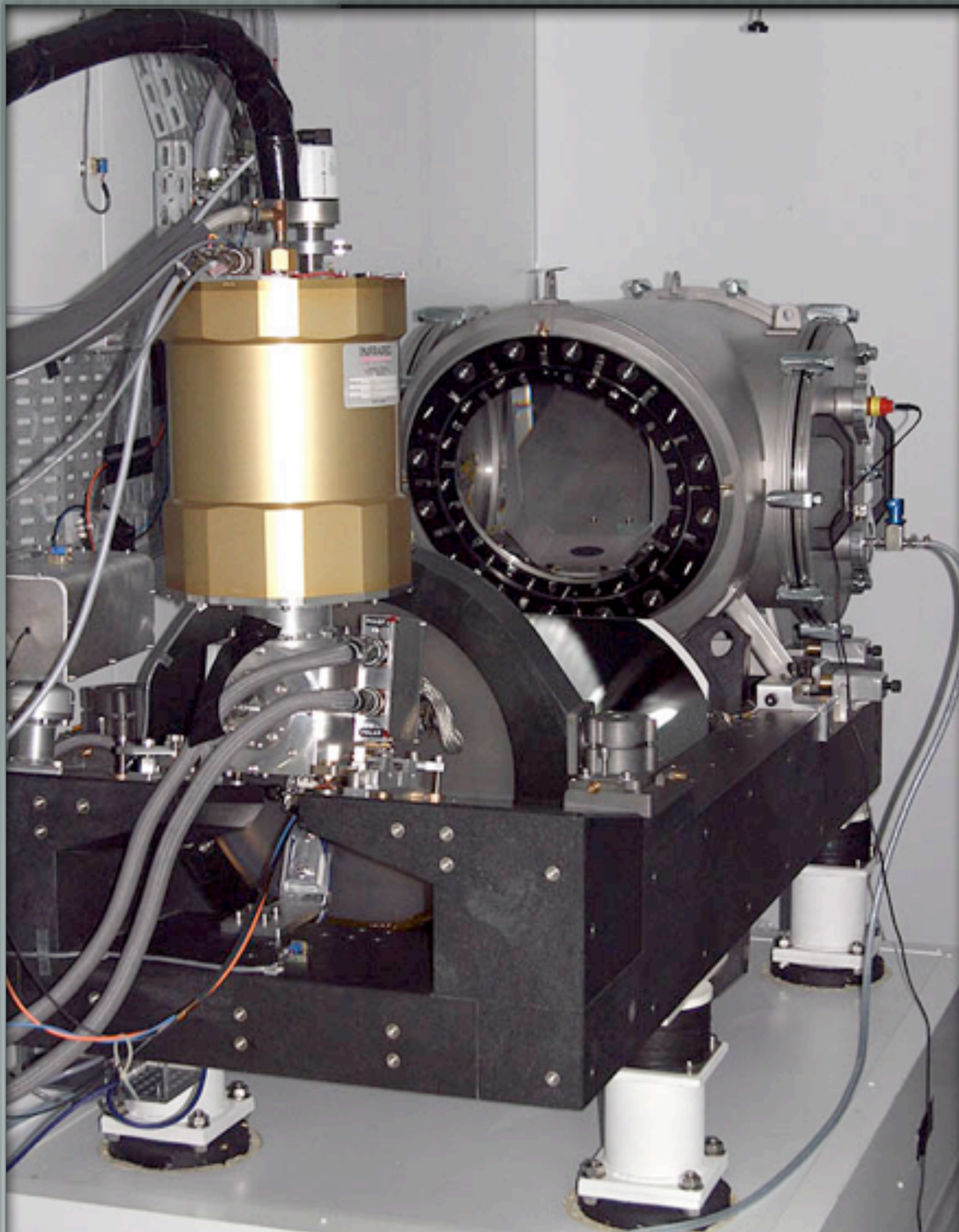
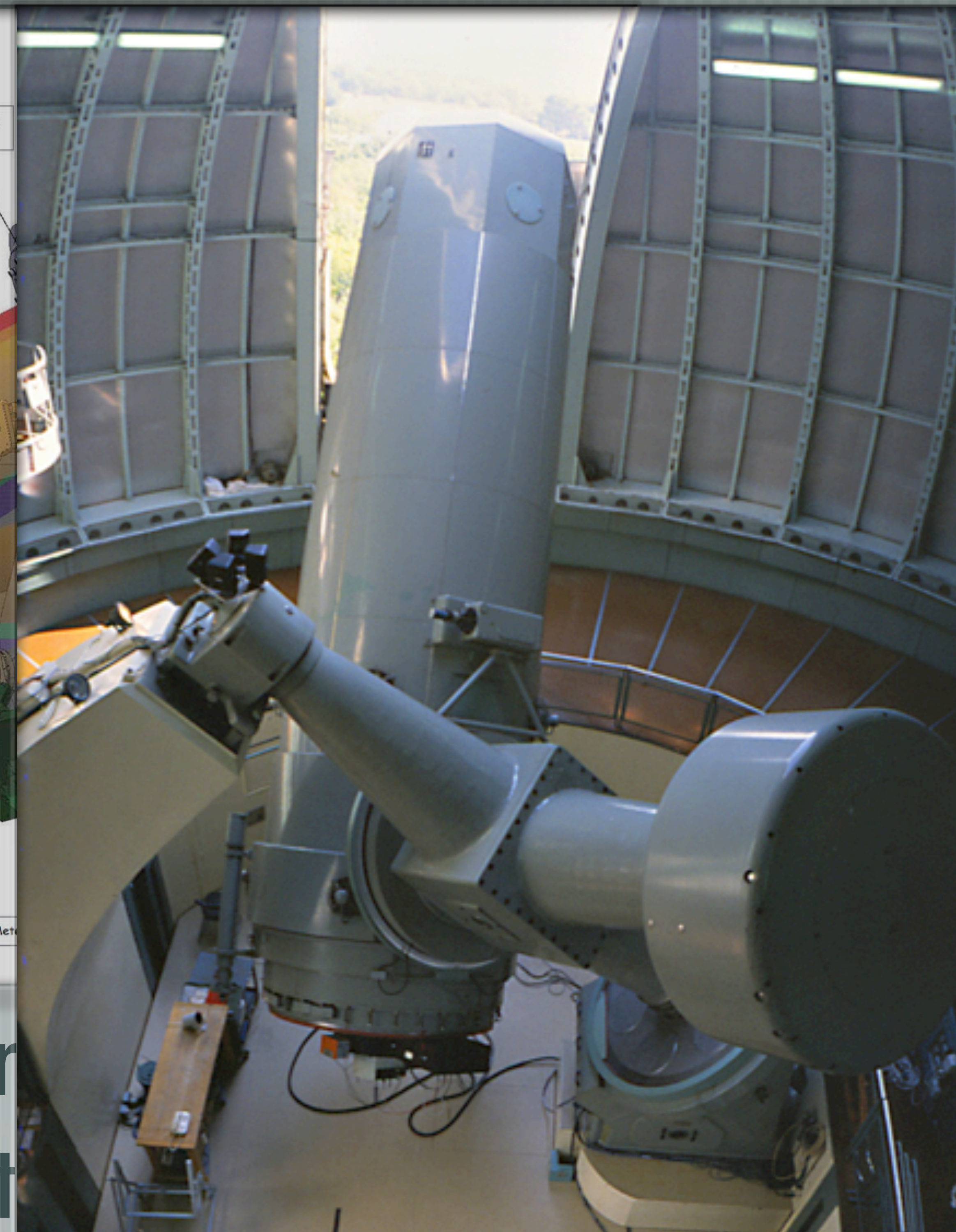
Meet SOPHIE



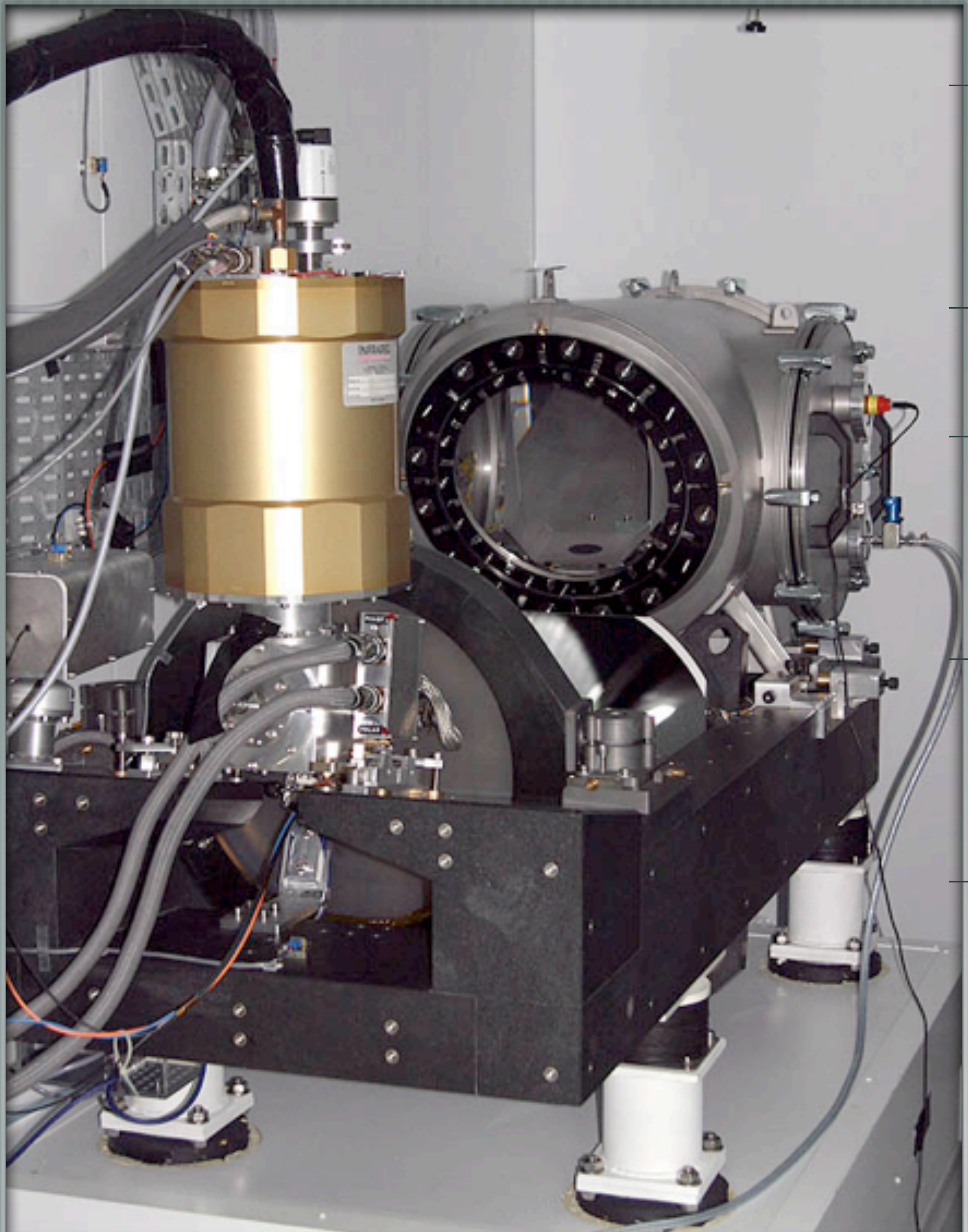
A high-resolution spectrograph at the 1.93-m telescope of the Observatoire de Haute-Provence

Meet SOPHIE



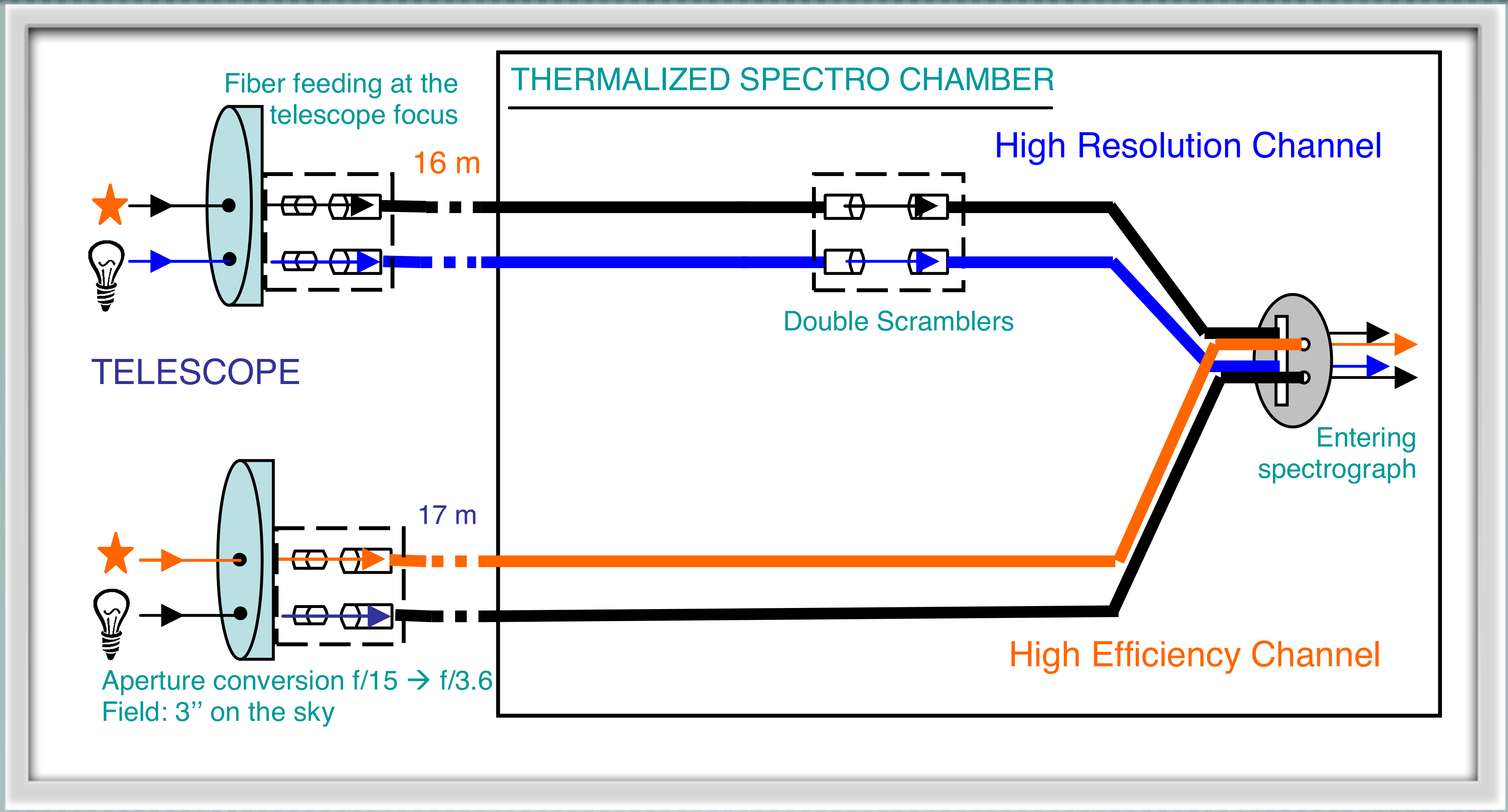


Meet SOPHIE (II)



- Fiber-fed (3″ on the sky) cross-dispersed echelle spectrograph.
- ThAr used for wavelength calibration.
- High mechanical and temperature stability.
- Dispersive elements kept at constant pressure.
- Two operation modes:
  - High Resolution: R = 70,000
  - High Efficiency: R = 40,000

Meet SOPHIE (III)



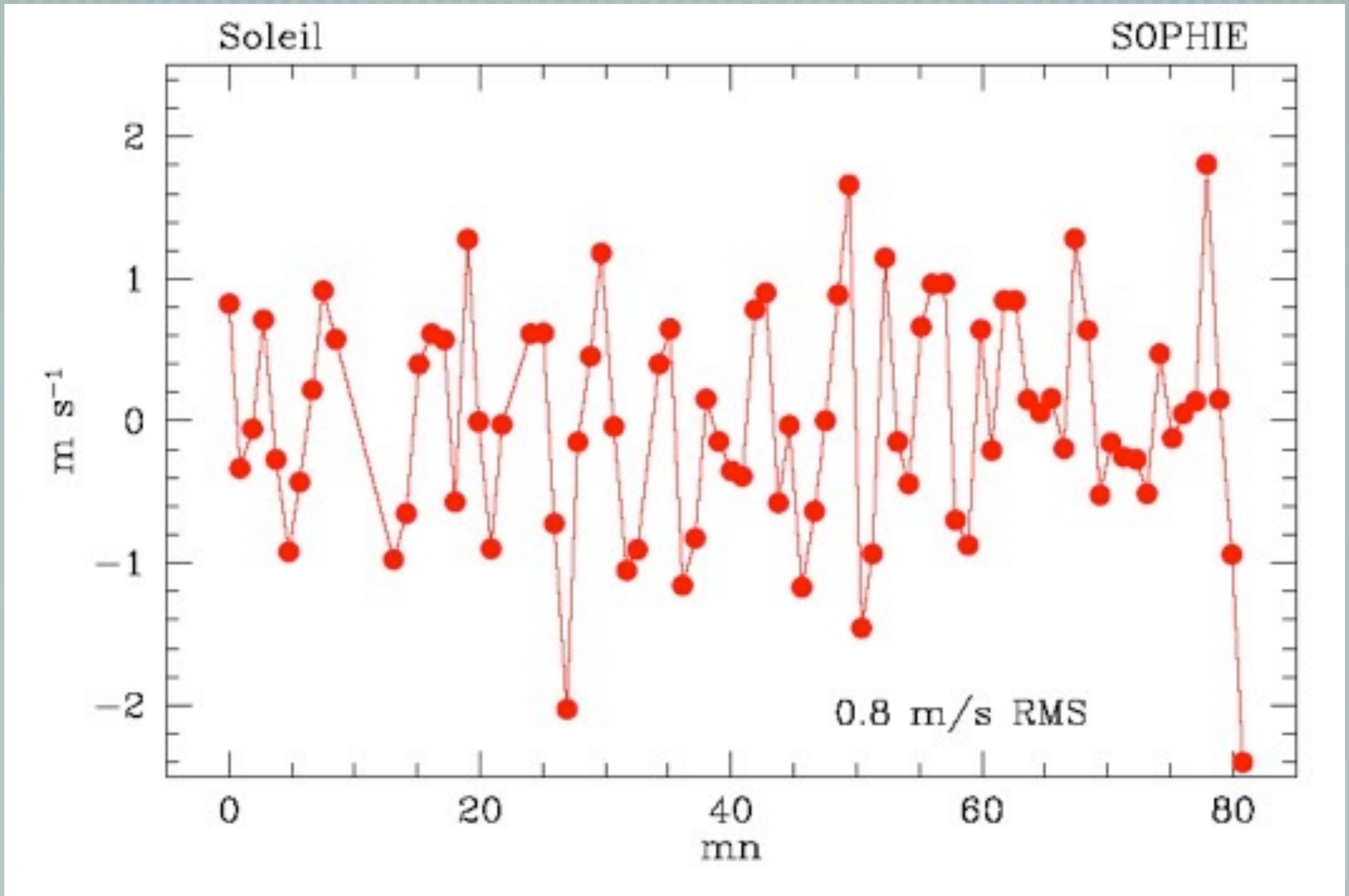
Perruchot, Bouchy, Chazelas, et al. (2011)

- High Resolution: R = 70,000
- High Efficiency: R = 40,000

Assessing SOPHIE's performance

Previous precision and limitations

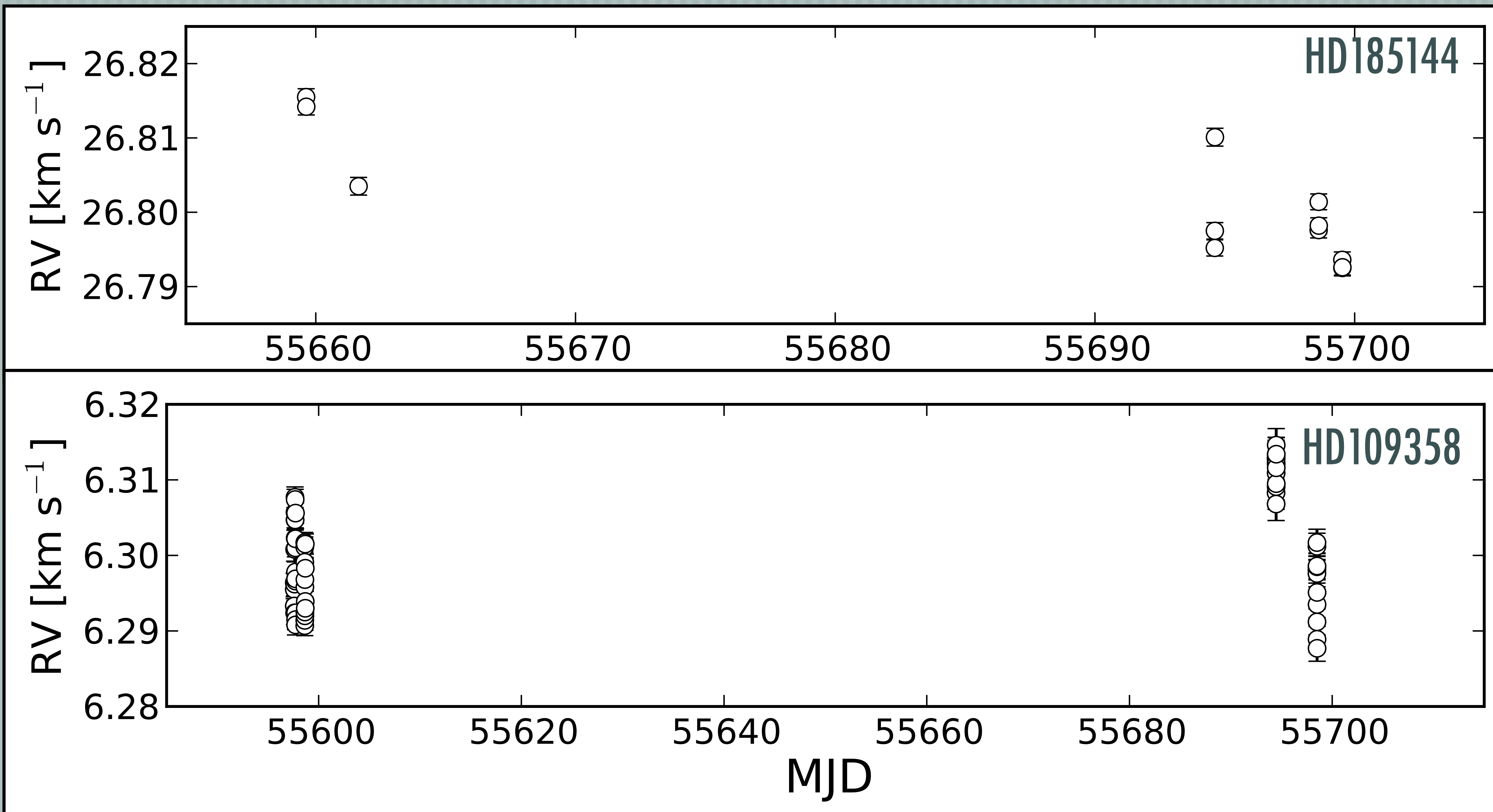
Series on the blue sky



Precision better than 1 m/s over little more than an hour.

Previous precision and limitations

Series on known constant stars (standards)



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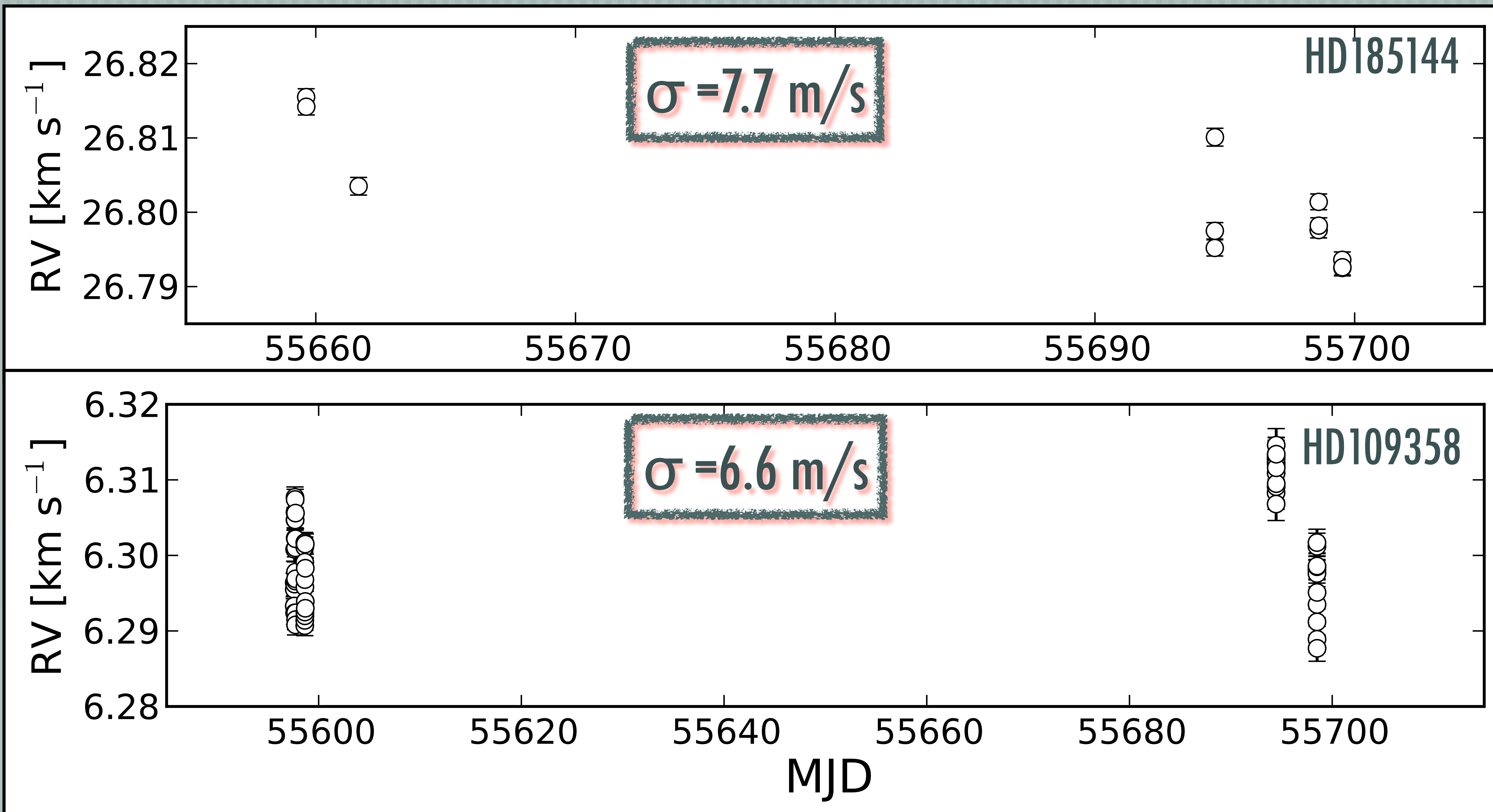
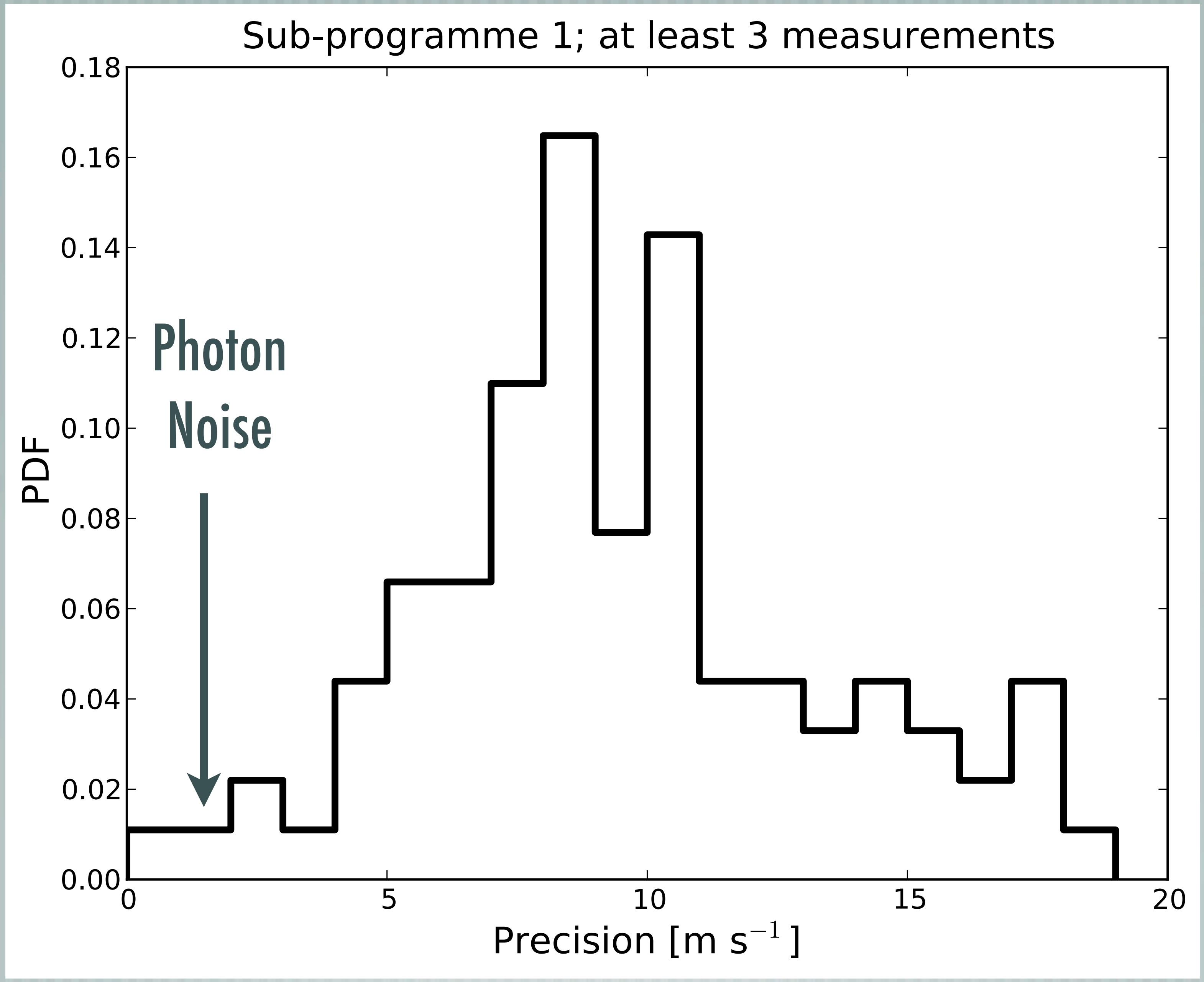


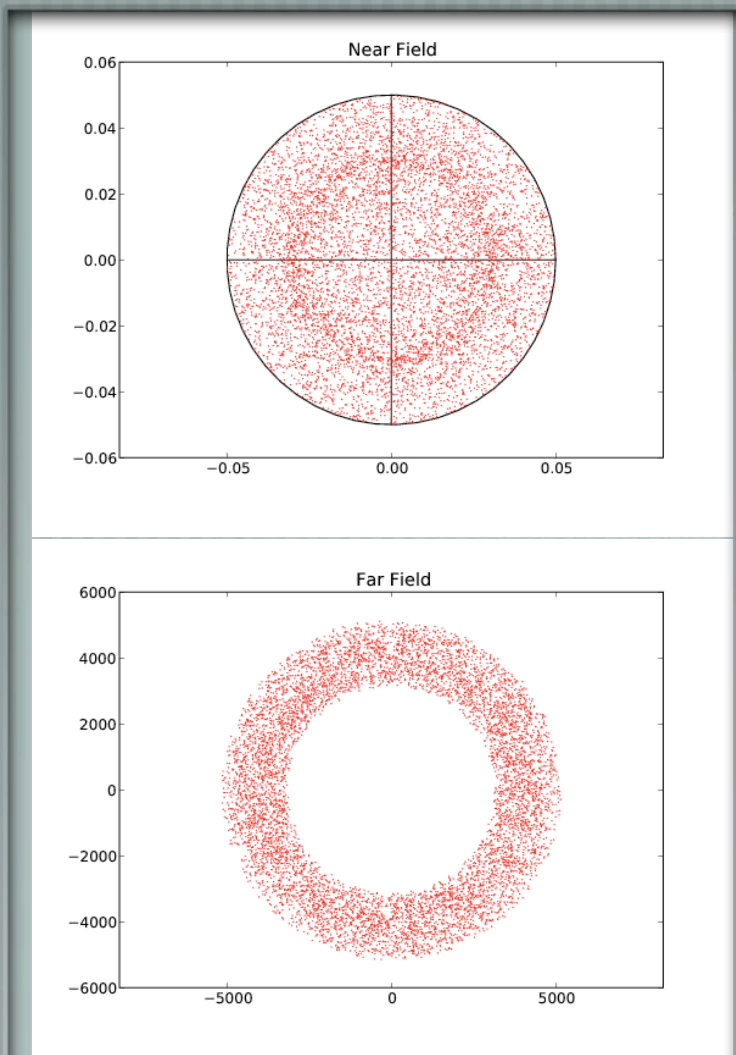
Previous precision and limitations

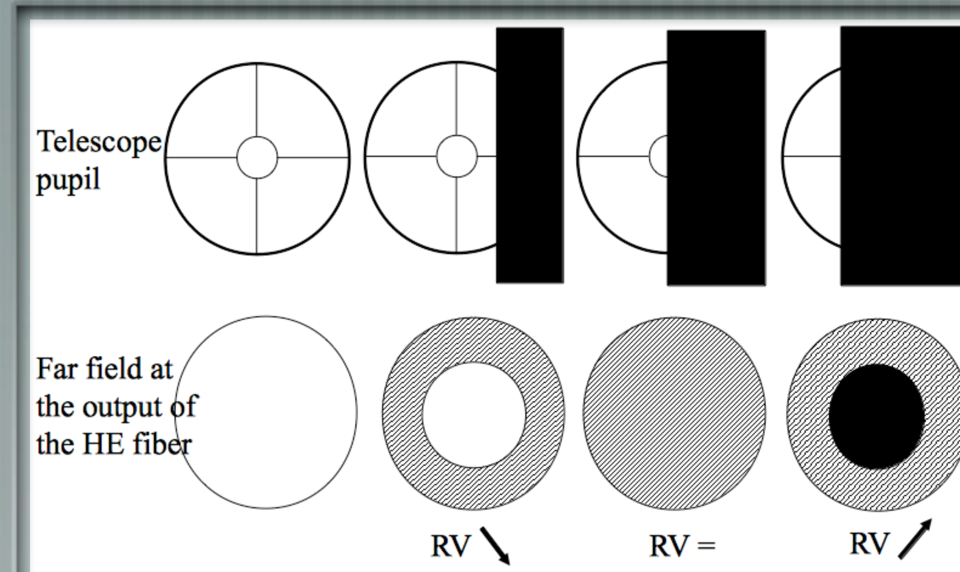
Dispersion on large number of stars

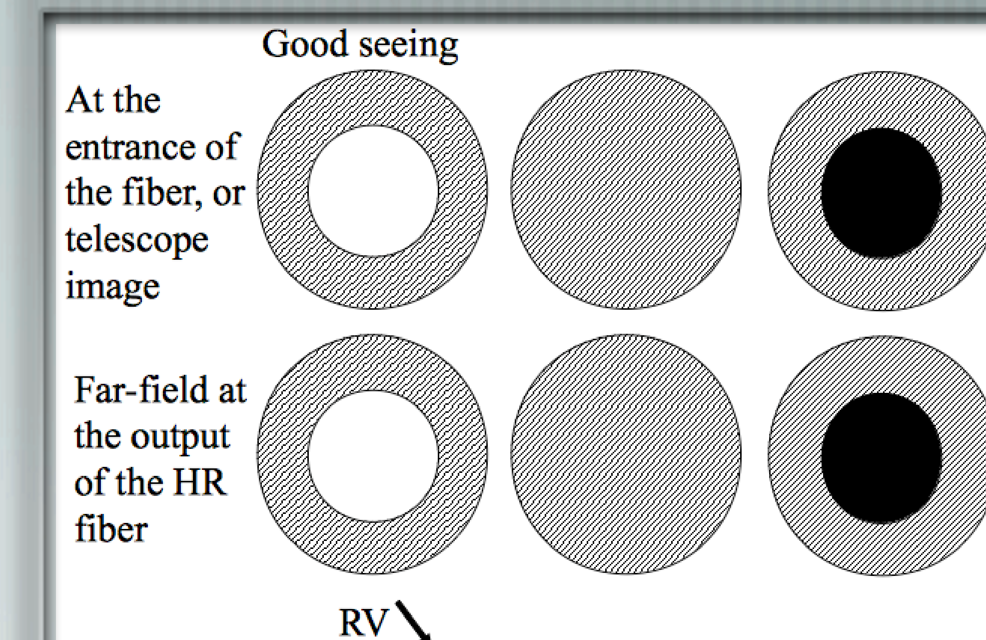


Previous precision and limitations

The seeing effect







Boisse, Bouchy, Chazelas, et al. (2011)

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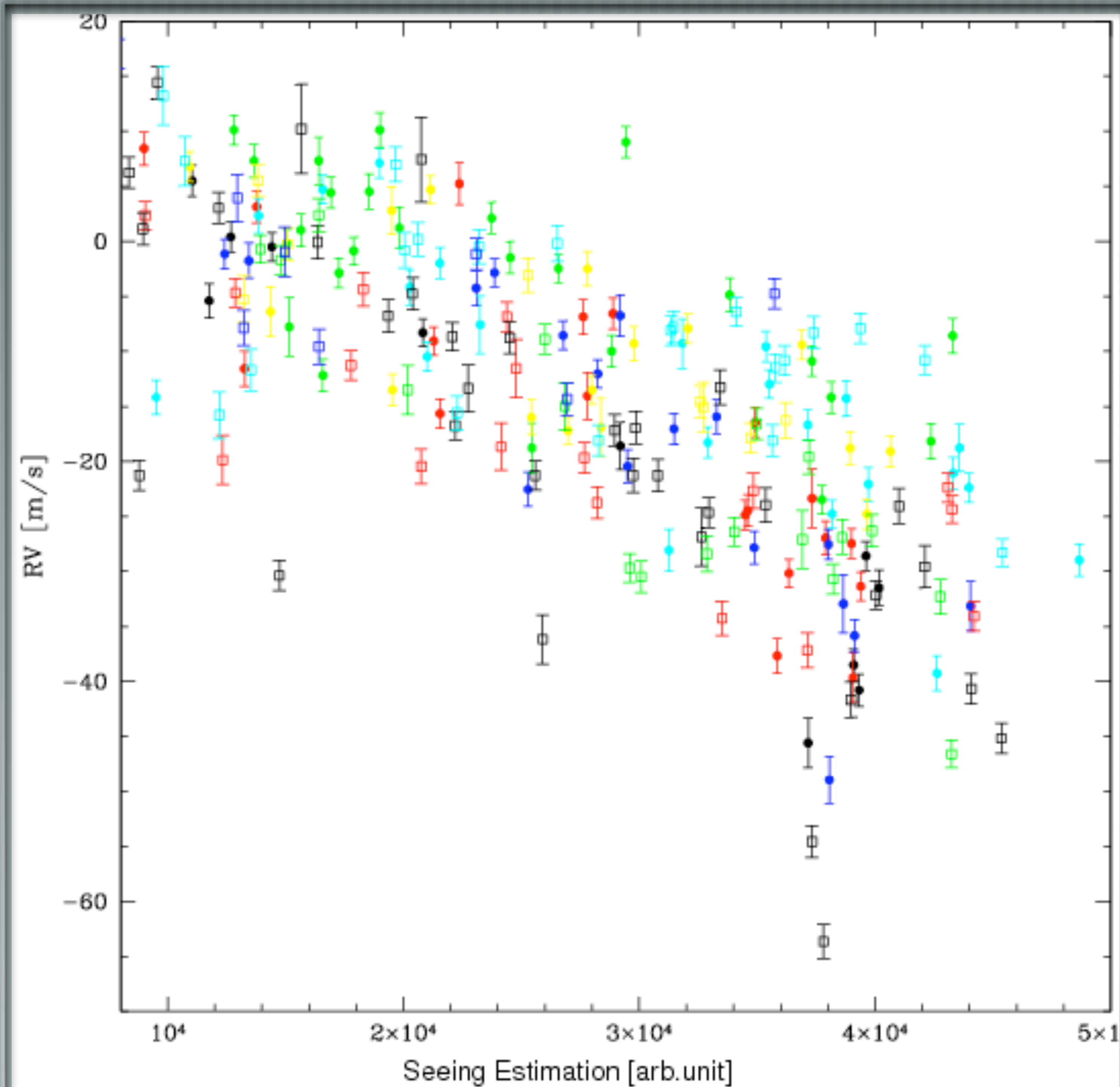

SOPHIE & exoplanets

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- Search for extrasolar planets
- Follow-up of transiting candidates (CoRoT, SuperWASP, Kepler)
- Characterisation of transiting planets via Rossiter-McLaughlin effect

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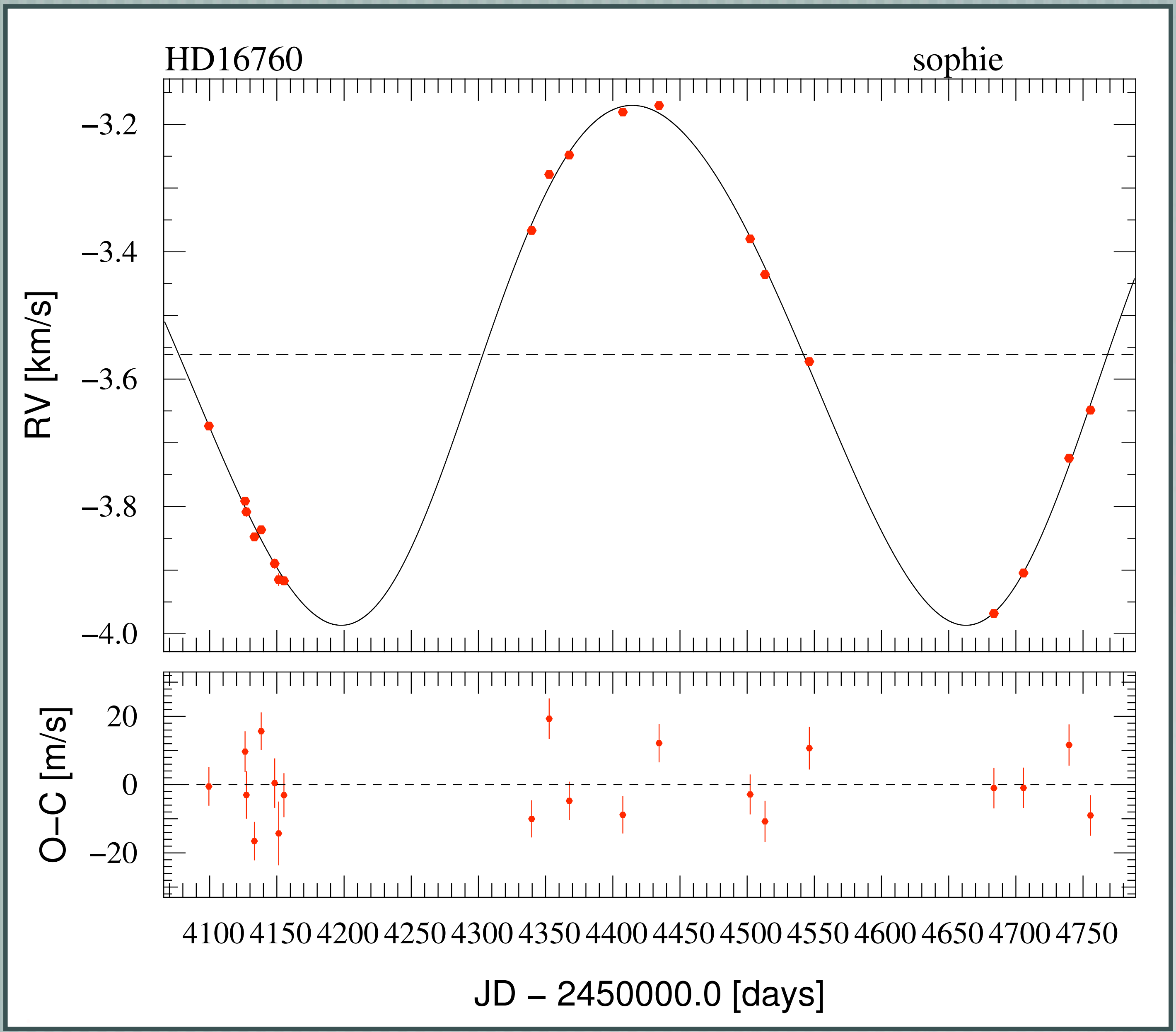
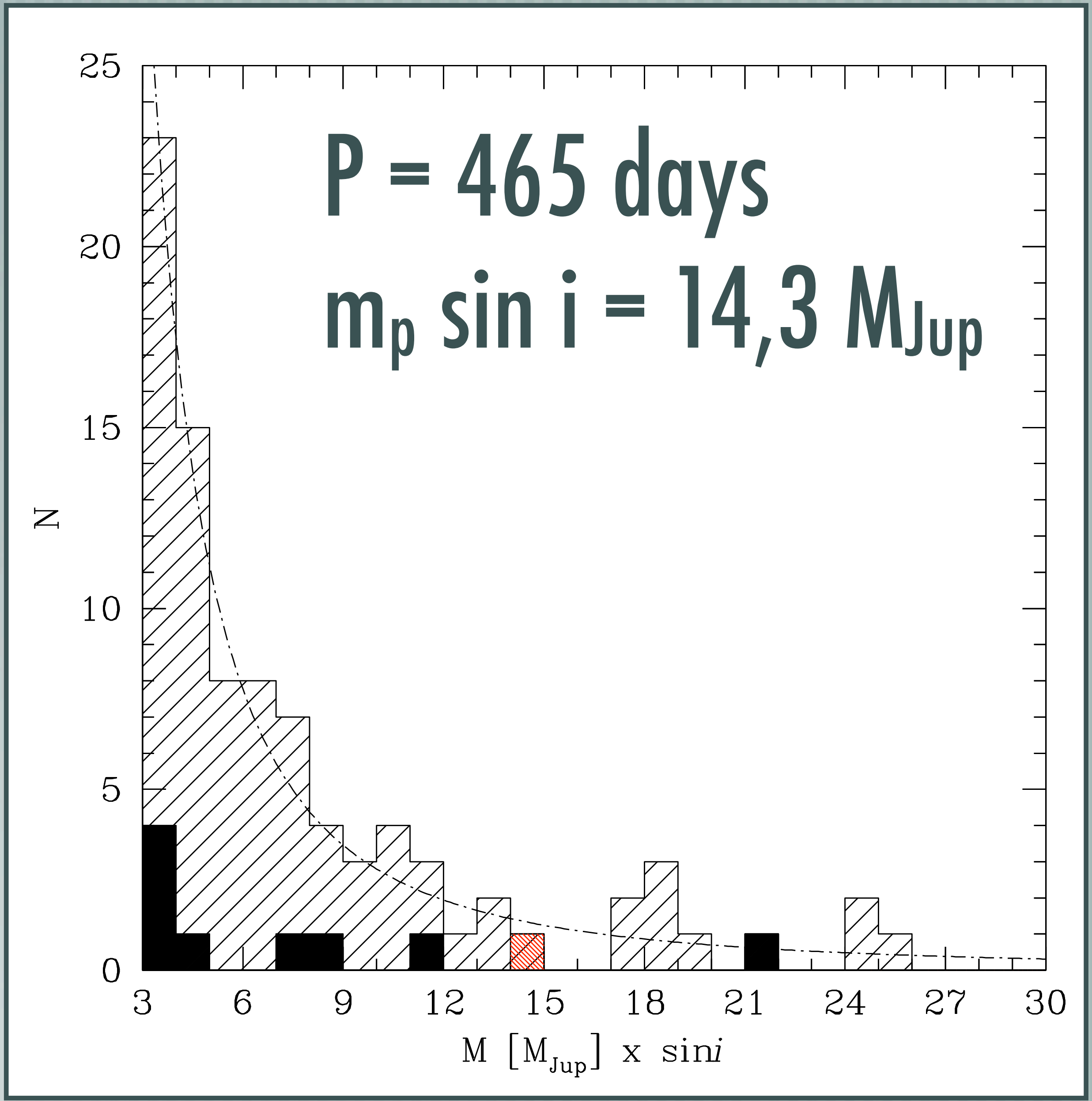
SOPHIE Consortium

- Large consortium formed for the scientific exploitation and improvement of SOPHIE.
- > 80 nights per semester (sometimes around 100 !)
- Five research sub-programmes
  - SP1: High-precision programme.
  - SP2: Hot Jupiters around solar-type stars.
  - SP3: Planets around M-dwarves.
  - SP4: Planets around hot stars (A & F).
  - SP5: Long-term follow-up of ELODIE planets/candidates.

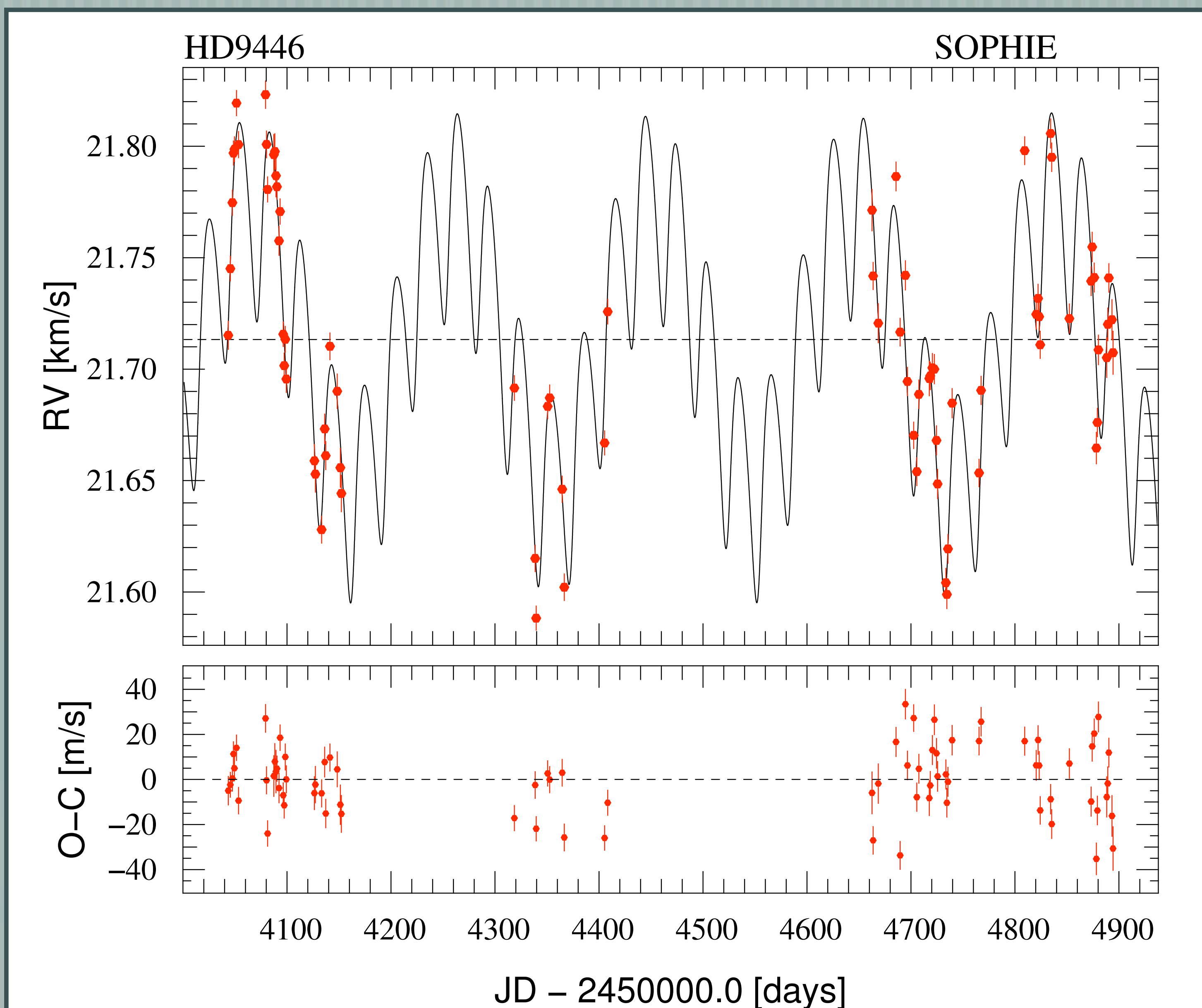
A planet or a brown dwarf?

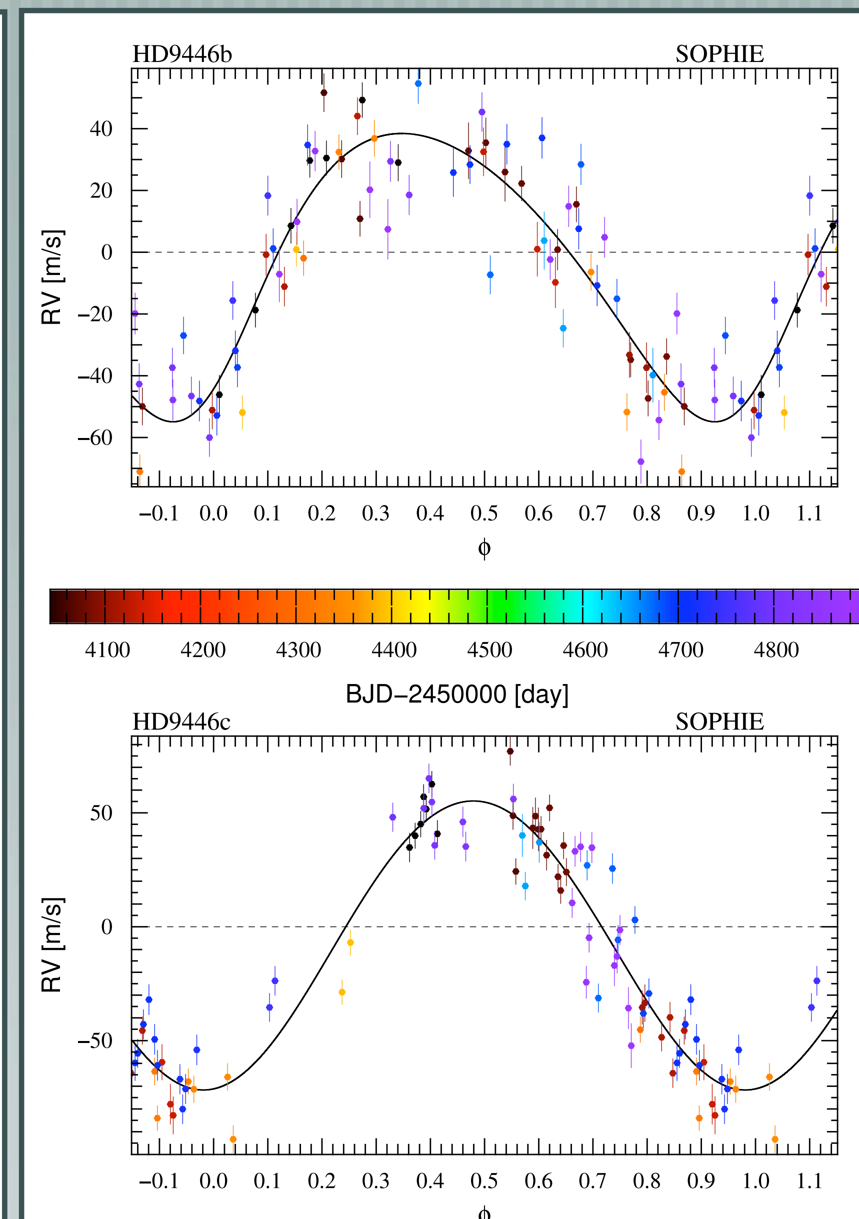




Bouchy, Hébrard, Udry, et al. (2009)

A multiple planet system around HD9446





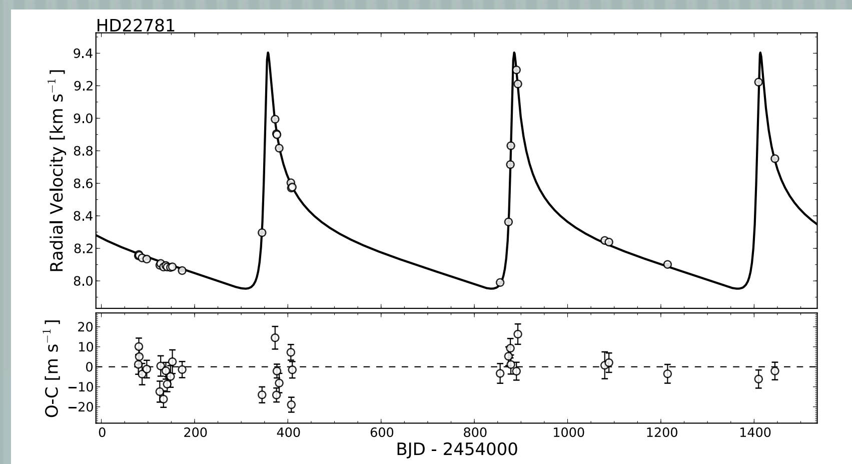
	HD 9446b	HD 9446c
P (j)	30.05 +/- 0.03	192.9 +/- 0.9
e	0.20 +/- 0.06	0.06 +/- 0.06
$m_2 \sin i$	0.70 +/- 0.06	1.82 +/- 0.17

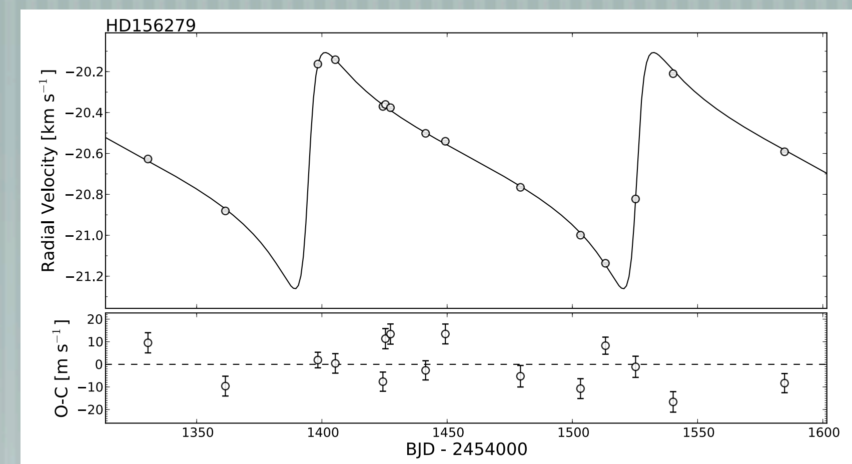
Hébrard, Bonfils, Segransan, et al. (2009)

Exploring the planet - brown dwarf boundary

Planet

P = 528 d
ecc = 0.82
Mc sin i = 13.7 Mjup



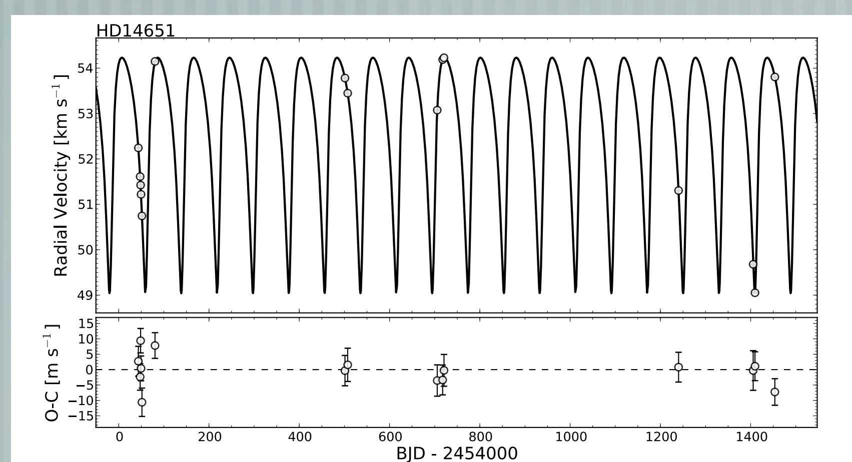


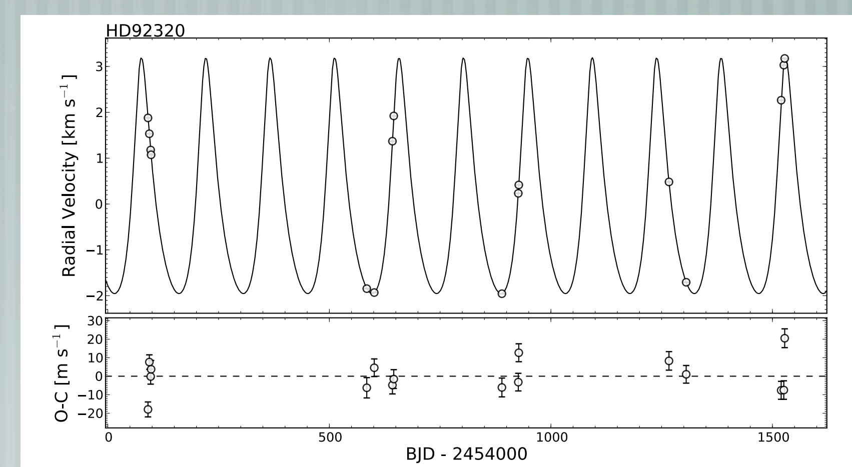
Planet

P = 131 d
ecc = 0.71
Mc sin i = 9.7 Mjup

Brown Dwarf

P = 79.4 d
ecc = 0.48
Mc sin i = 47.0 Mjup



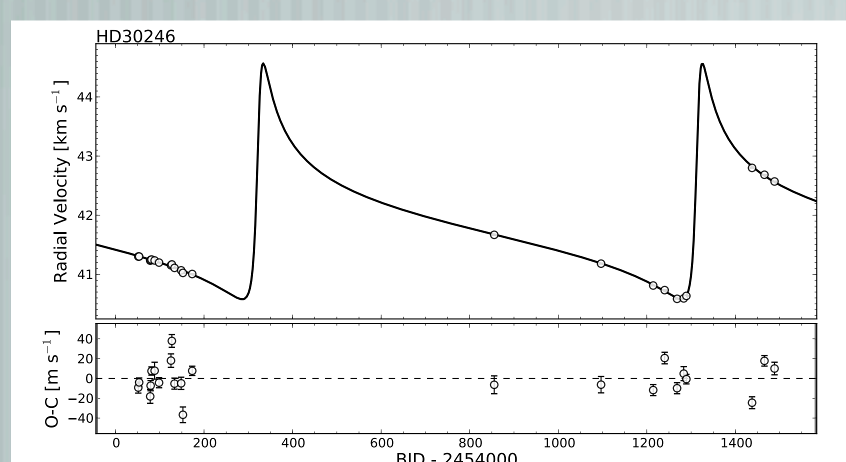


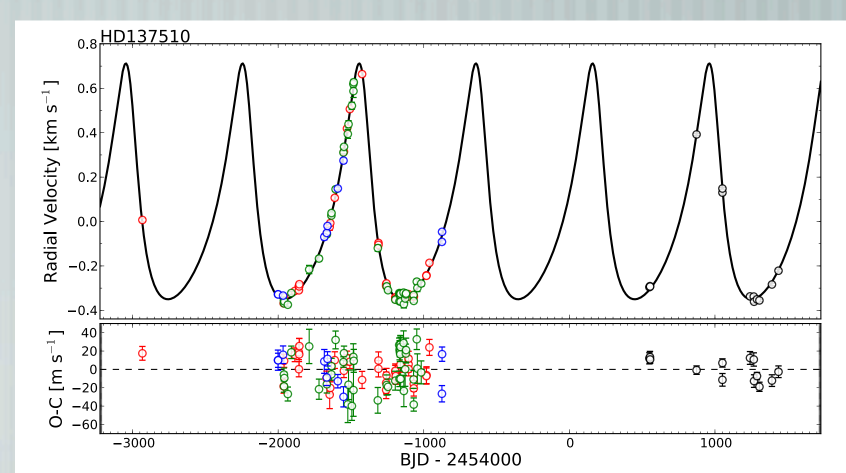
Brown Dwarf

P = 145 d
ecc = 0.32
Mc sin i = 59.4 Mjup

Brown Dwarf

P = 991 d
ecc = 0.84
Mc sin i = 55.1 Mjup





Brown Dwarf

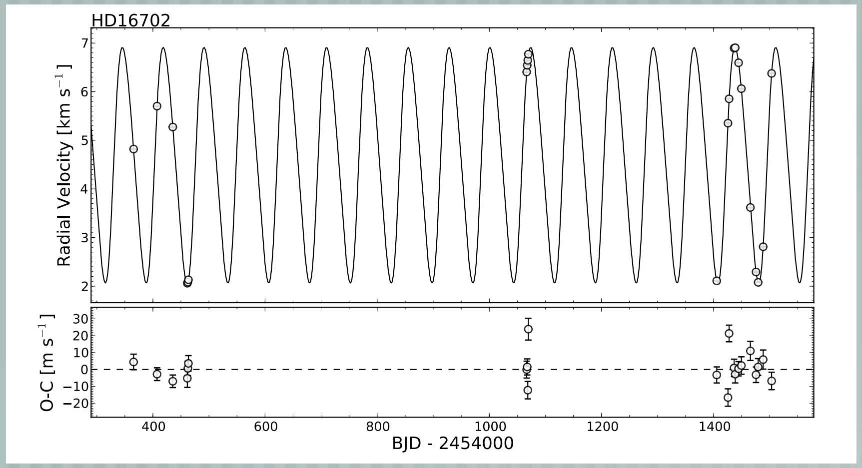
P = 801 d
ecc = 0.40
Mc sin i = 27.3 Mjup

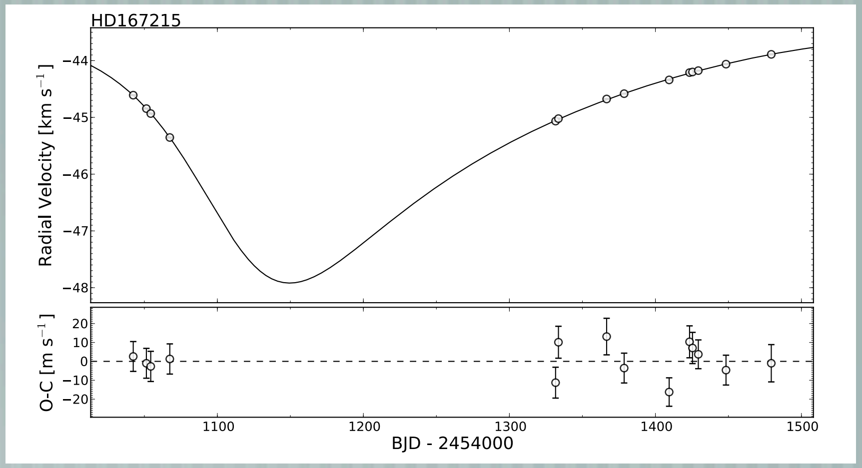
Díaz, Santerne, Sahlman, et al. (A&A, In press)

Exploring the planet - brown dwarf boundary

Low-mass star

P = 72.8 d
ecc = 0.14
Mc sin i = 48.7 Mjup



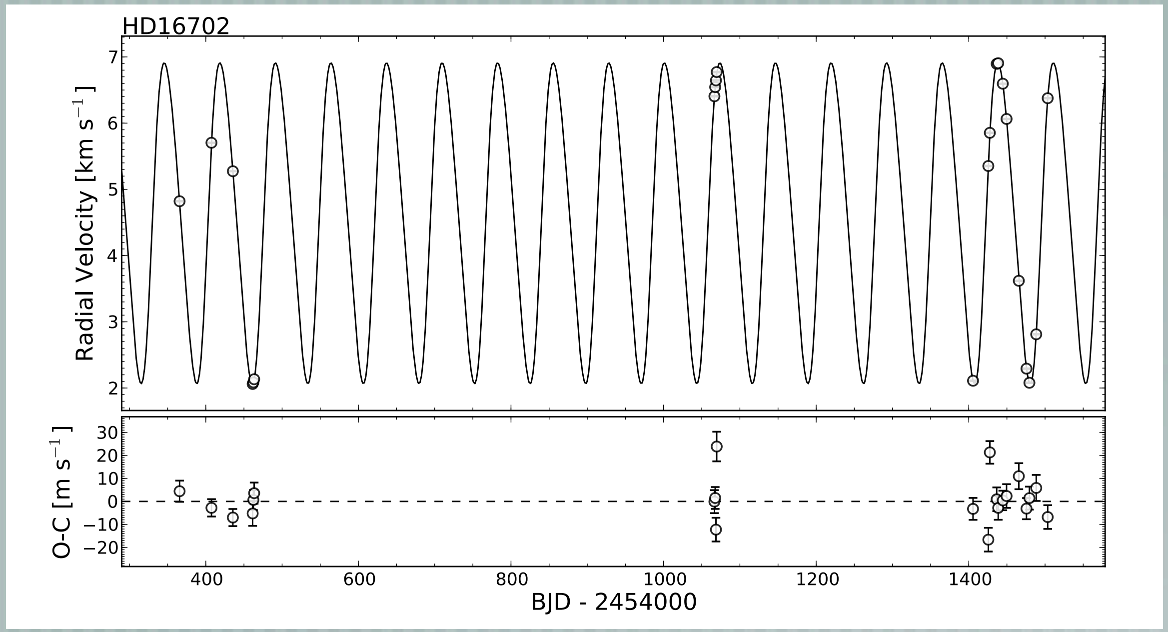


Díaz, Santerne, Sahlman, et al. (A&A, In press)

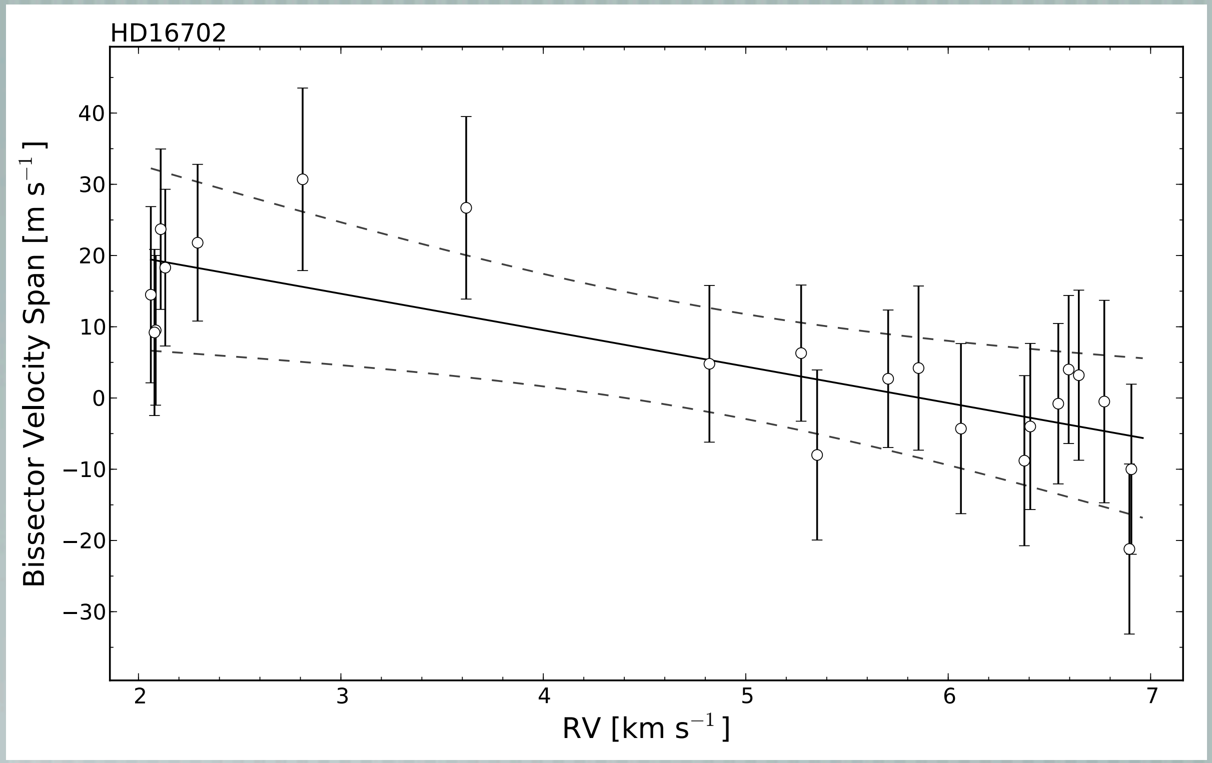
Low-mass star

P = 632 d
ecc = 0.37
Mc sin i = 92 Mjup

Exploring the planet - brown dwarf boundary



P = 72.8 d; ecc = 0.14; Mc sin i = 48.7 Mjup



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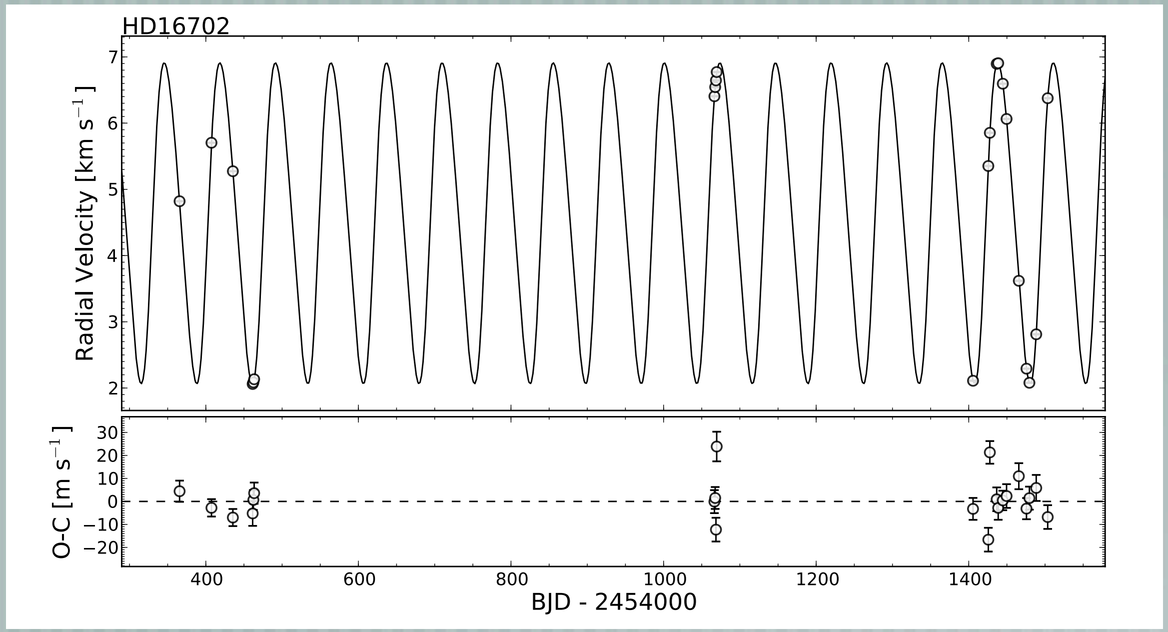

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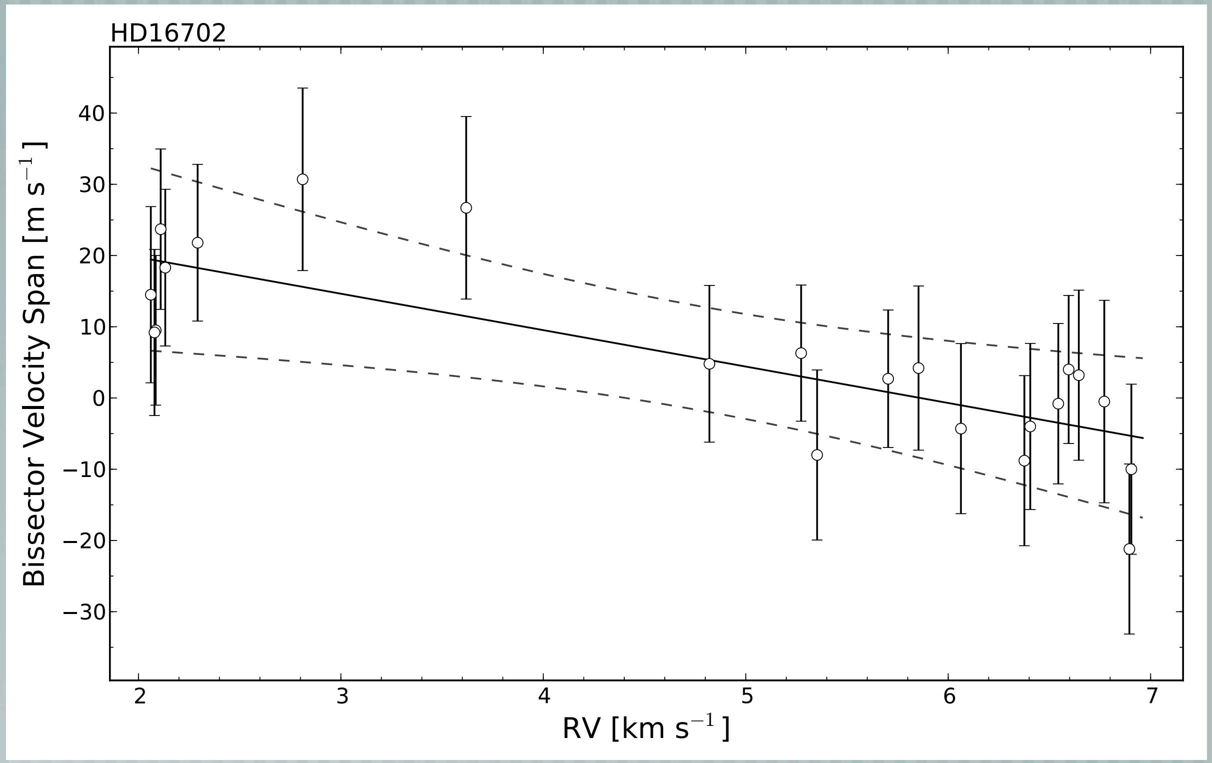

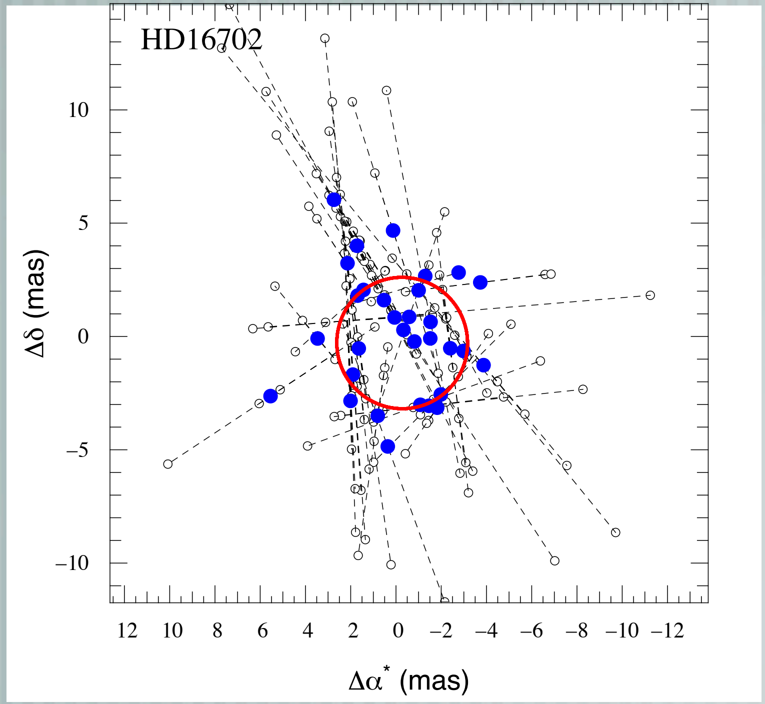

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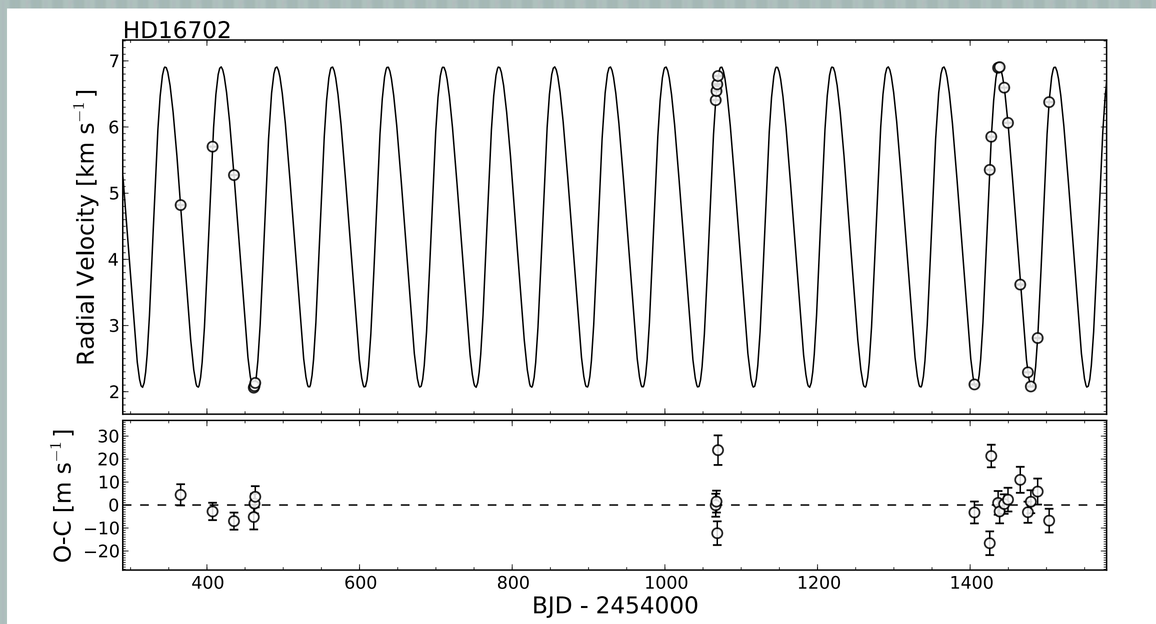

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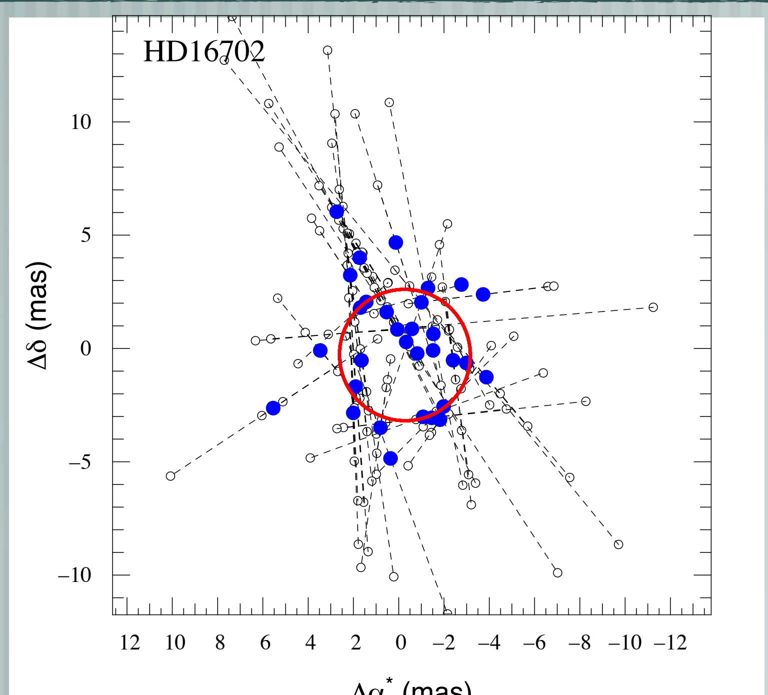
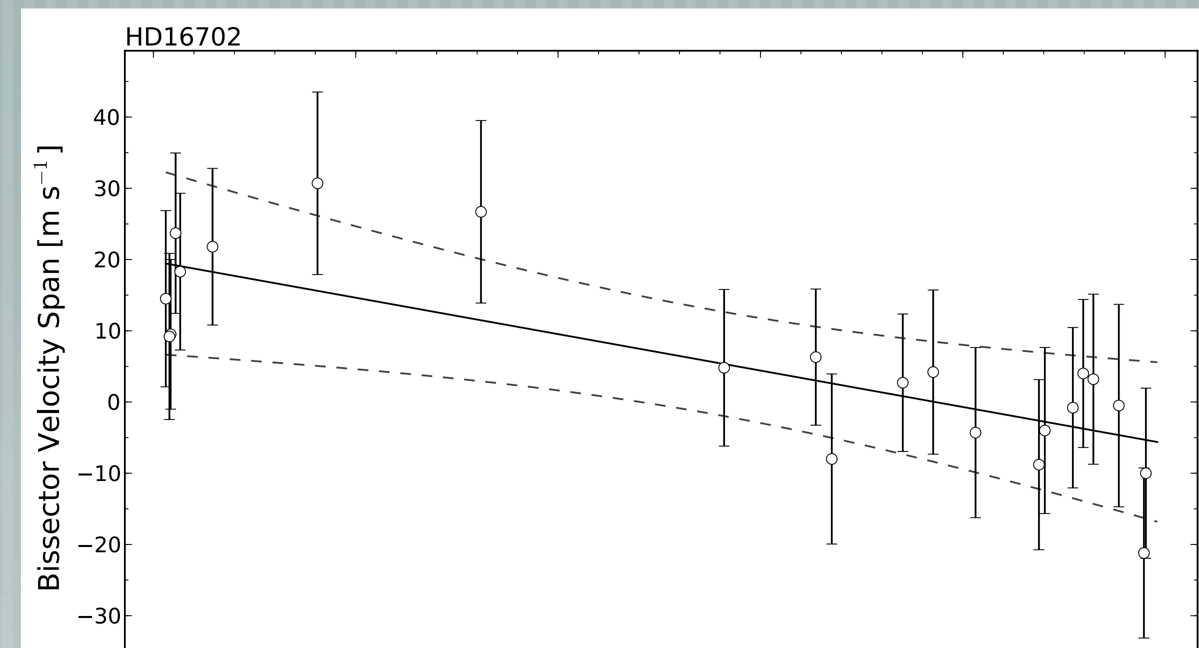
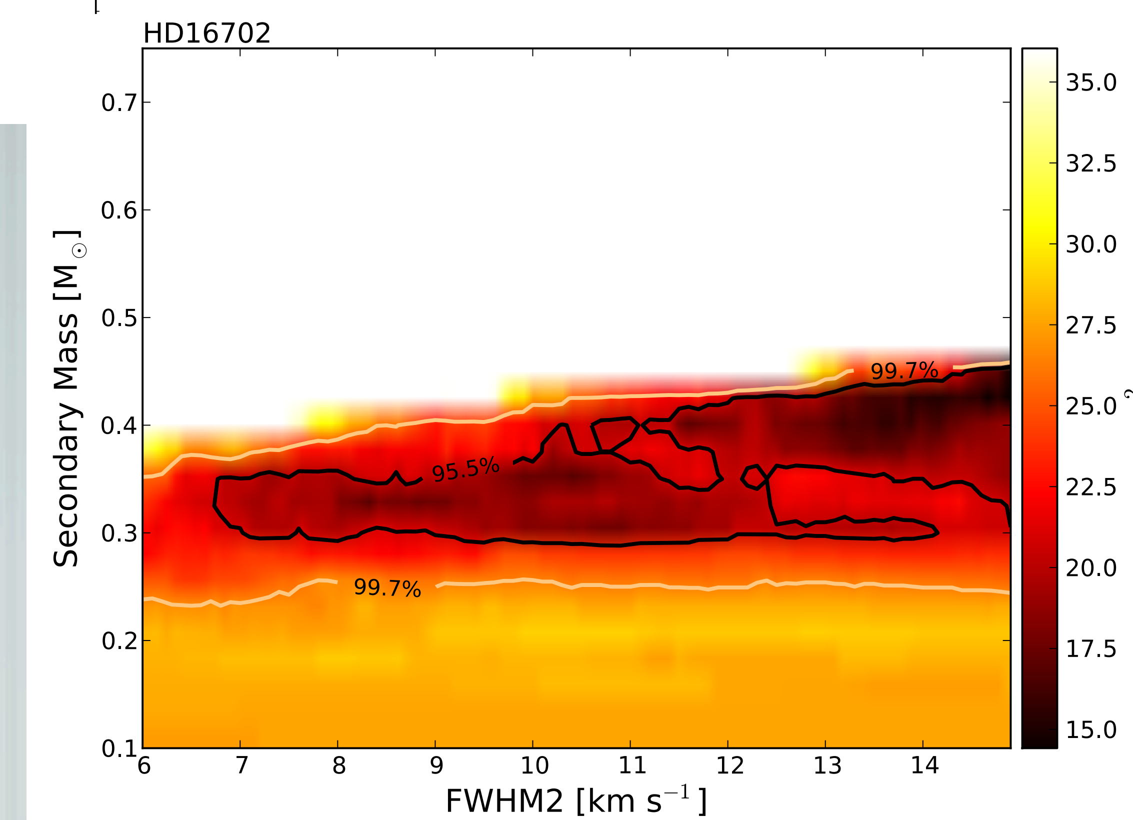
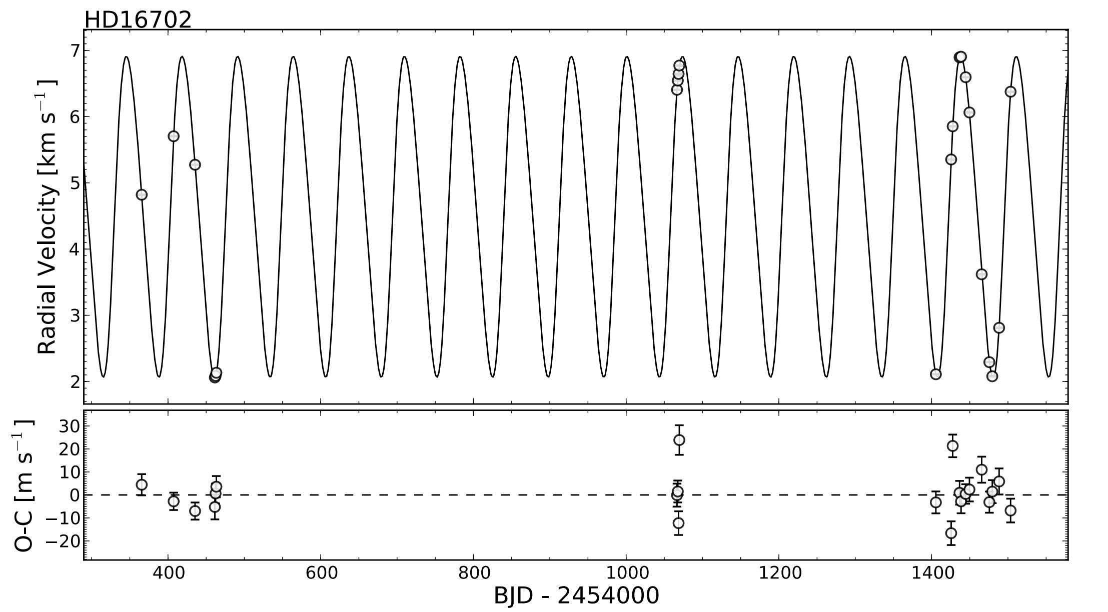






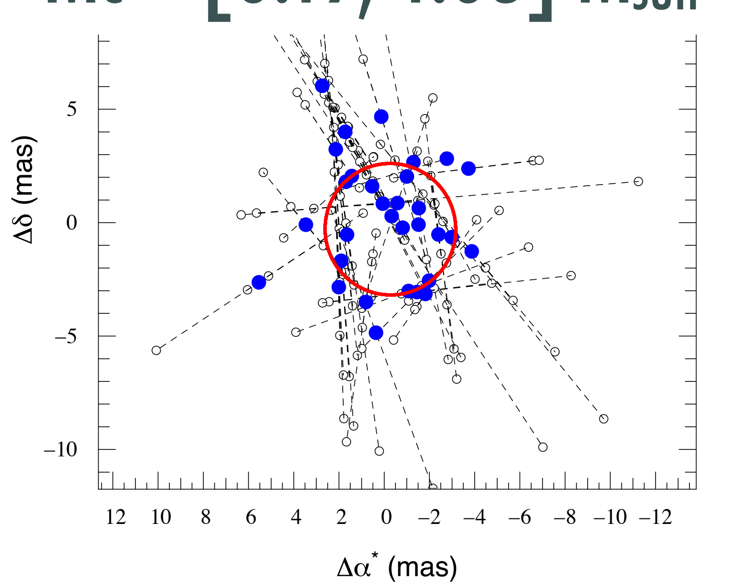
Díaz, Santerne, Sahlman, et al. (A&A, In press)

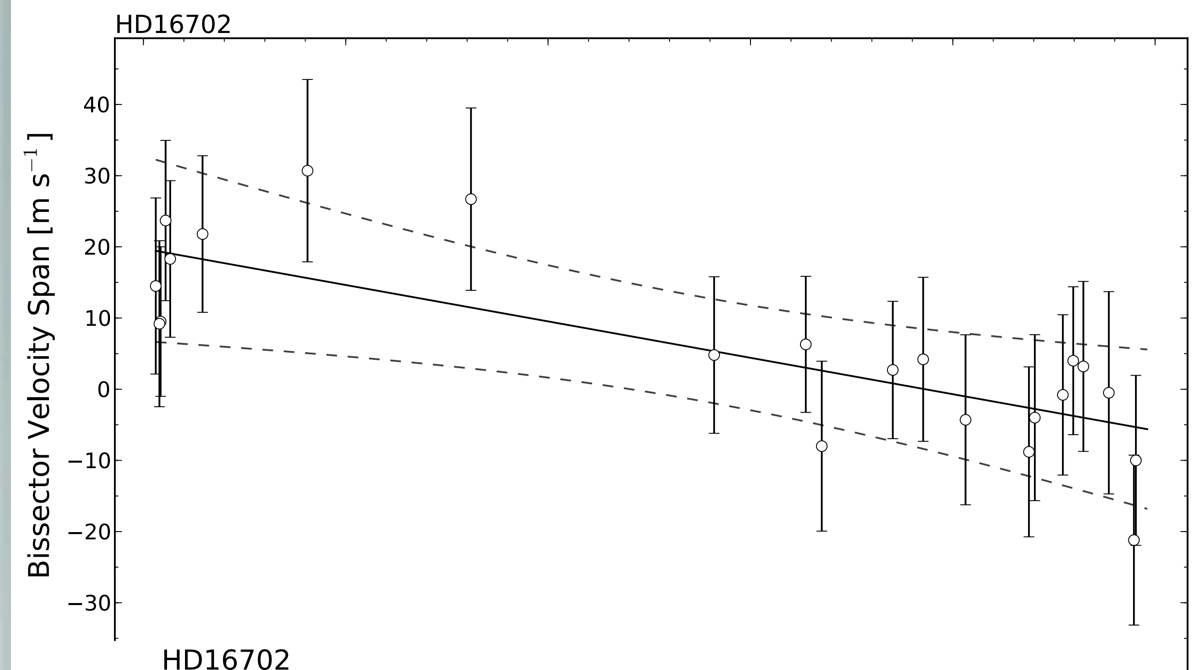
Exploring the planet - brown dwarf boundary

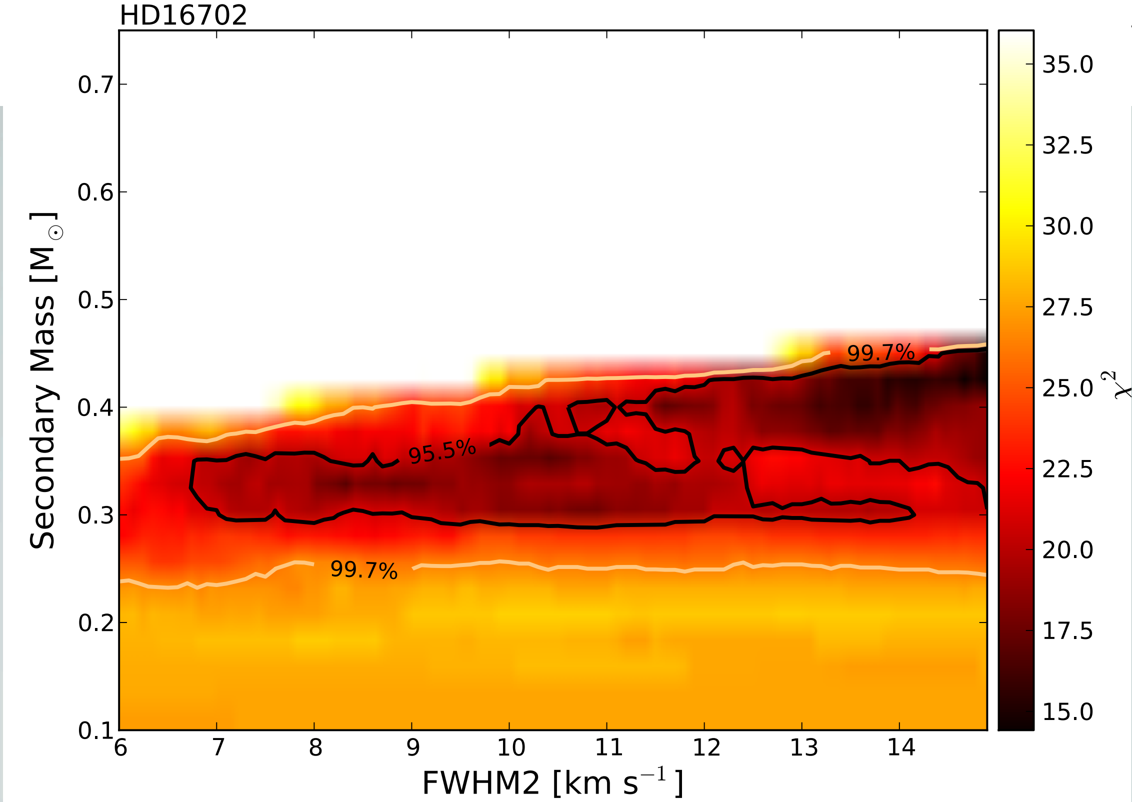


P = 72.8 d; ecc = 0.14; Mc sin i = 48.7 Mjup

Mc = [0.19, 1.03] Msun

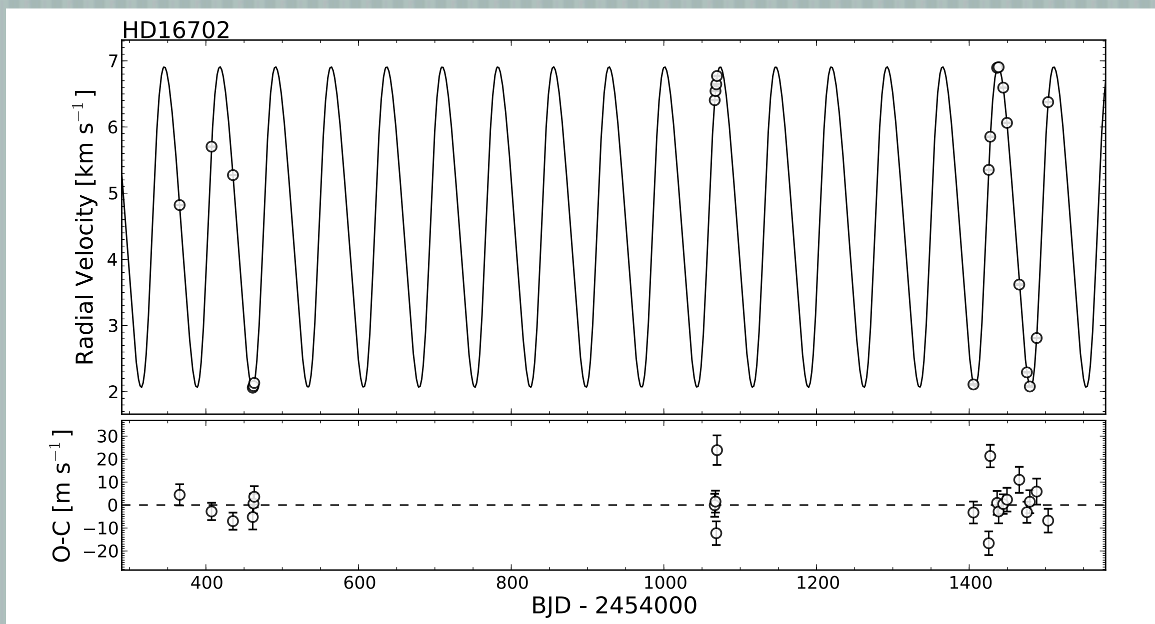






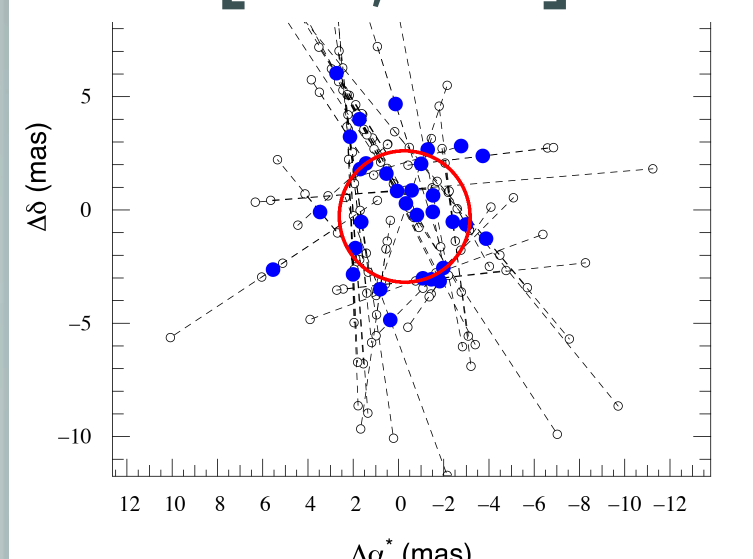
Díaz, Santerne, Sahlman, et al. (A&A, In press)

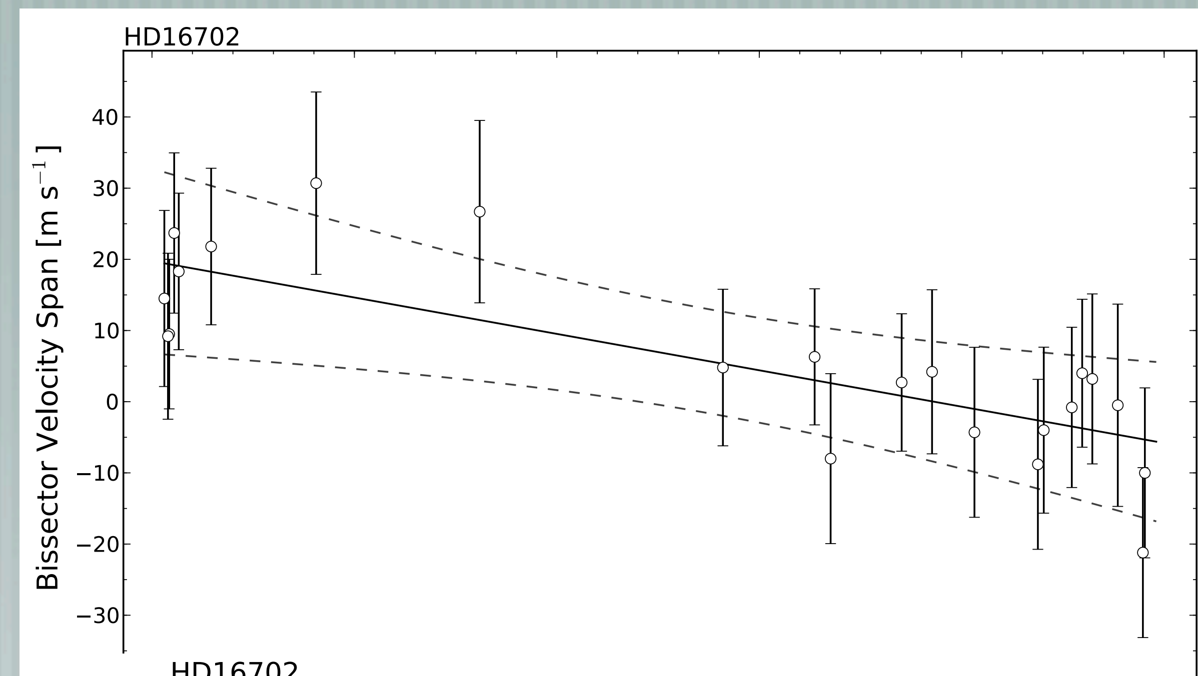
Exploring the planet - brown dwarf boundary

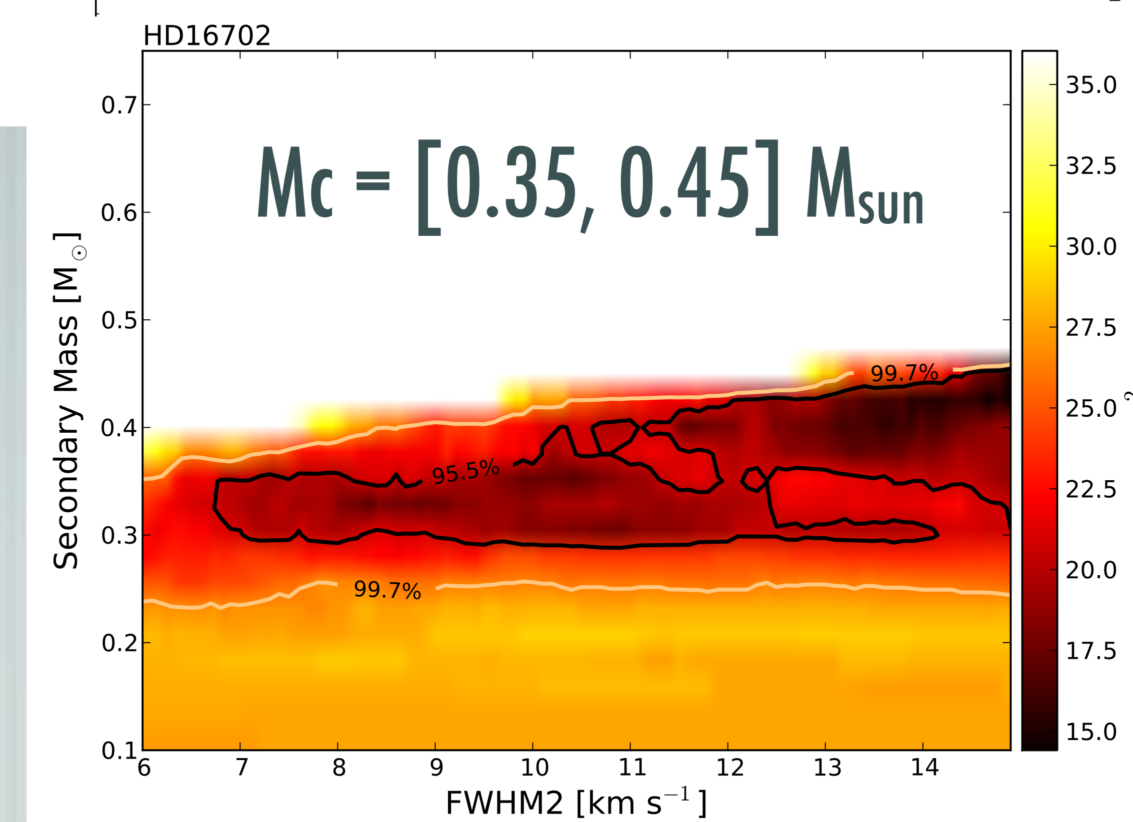


P = 72.8 d; ecc = 0.14; Mc sin i = 48.7 Mjup

Mc = [0.19, 1.03] M_{sun}





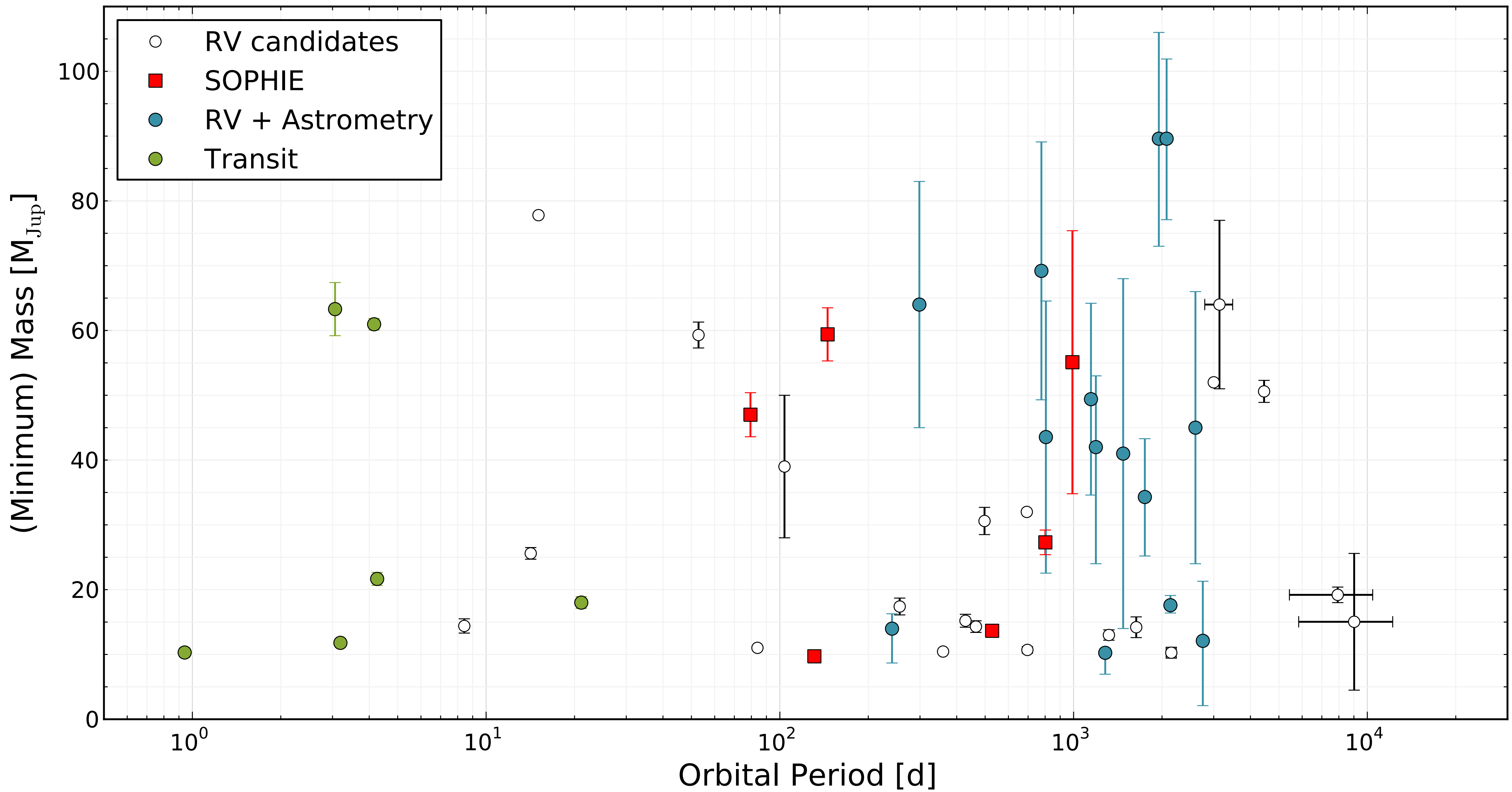


Mc = [0.35, 0.45] M_{sun}

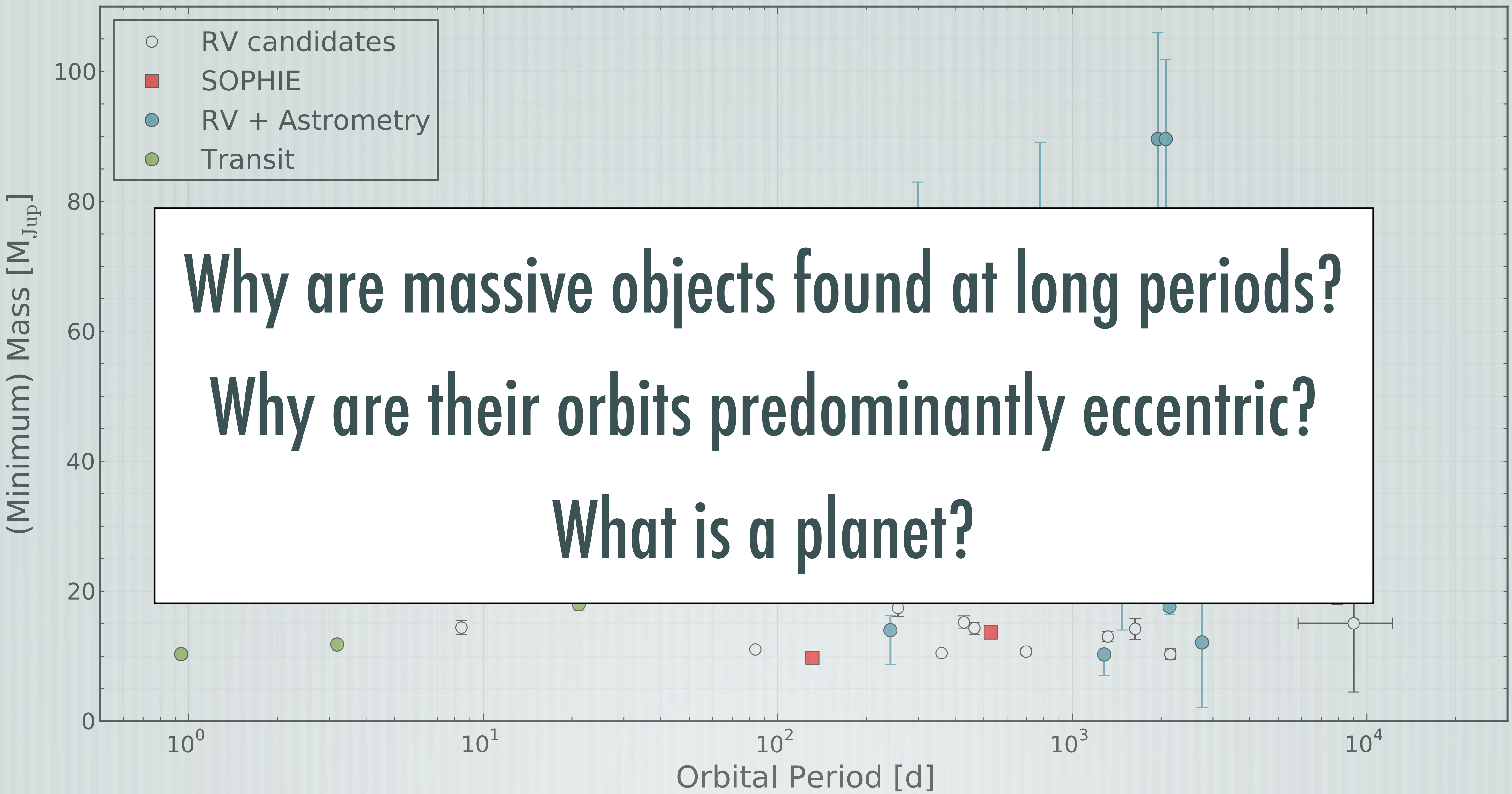
Díaz, Santerne, Sahlman, et al. (A&A, In press)

Friday, January 20, 2012

Exploring the planet - brown dwarf boundary



Exploring the planet - brown dwarf boundary



Why are massive objects found at long periods?

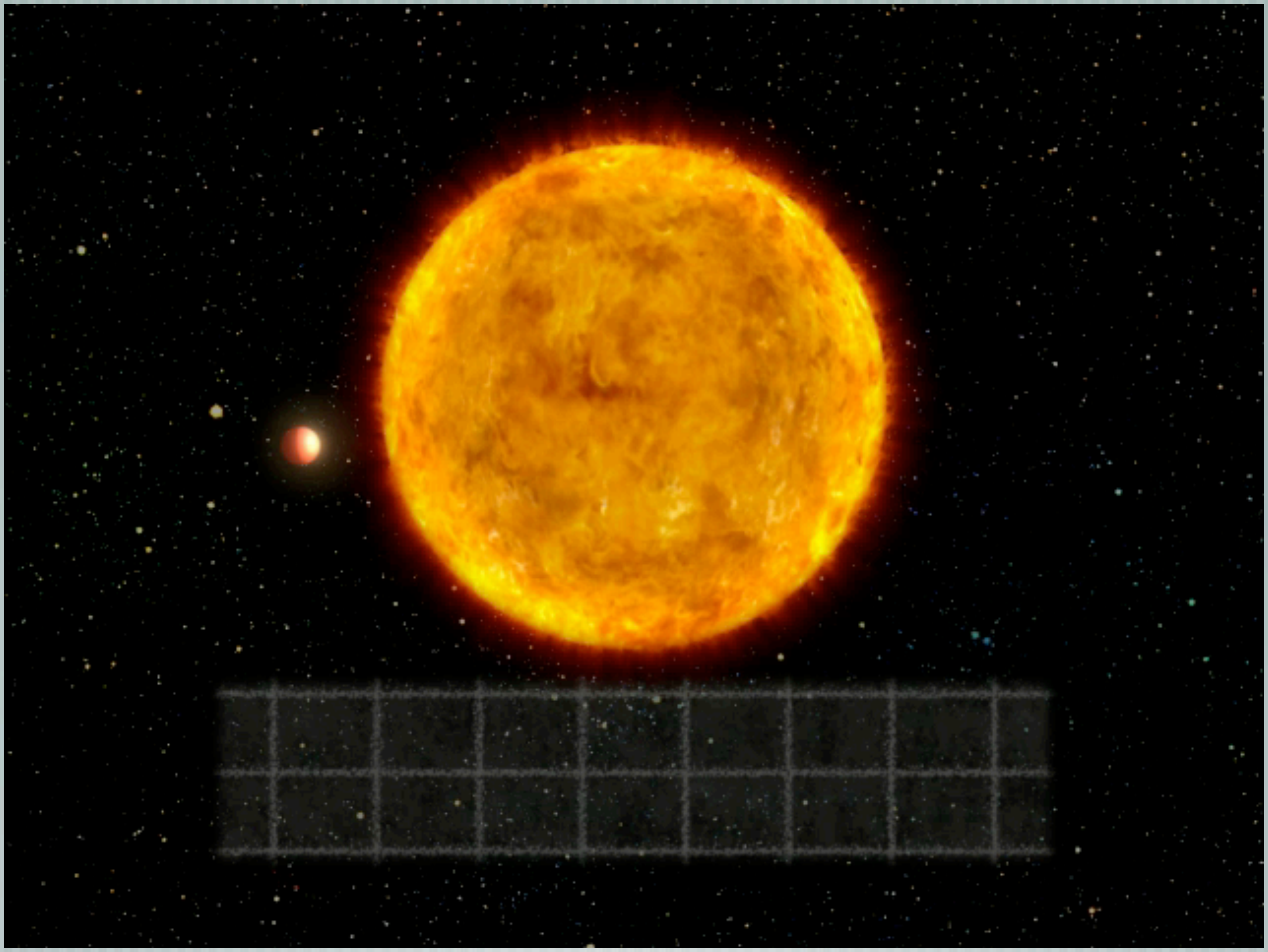
Why are their orbits predominantly eccentric?

What is a planet?

SOPHIE & exoplanets

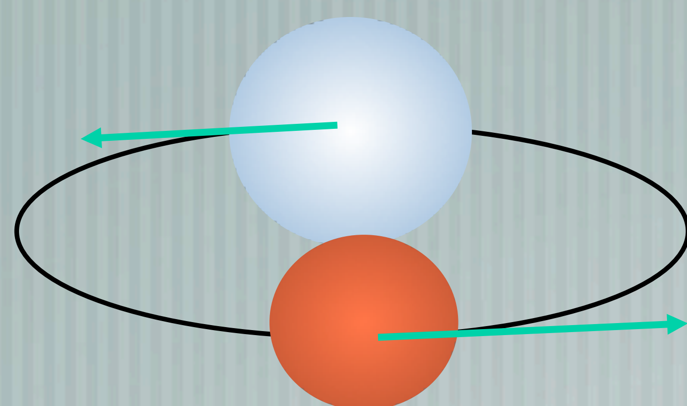
- Search for extrasolar planets
- Follow-up of transiting candidates (CoRoT, SuperWASP, Kepler)
- Characterisation of transiting planets via Rossiter-McLaughlin effect

Follow-up of transiting candidates

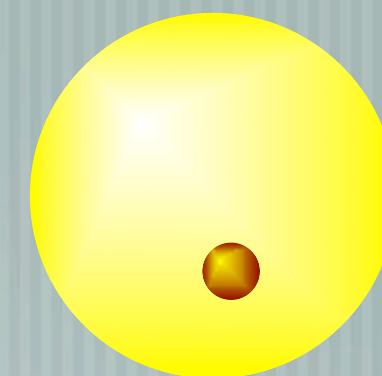


Follow-up of transiting candidates

- To discard impostors



Grazing eclipsing binaries

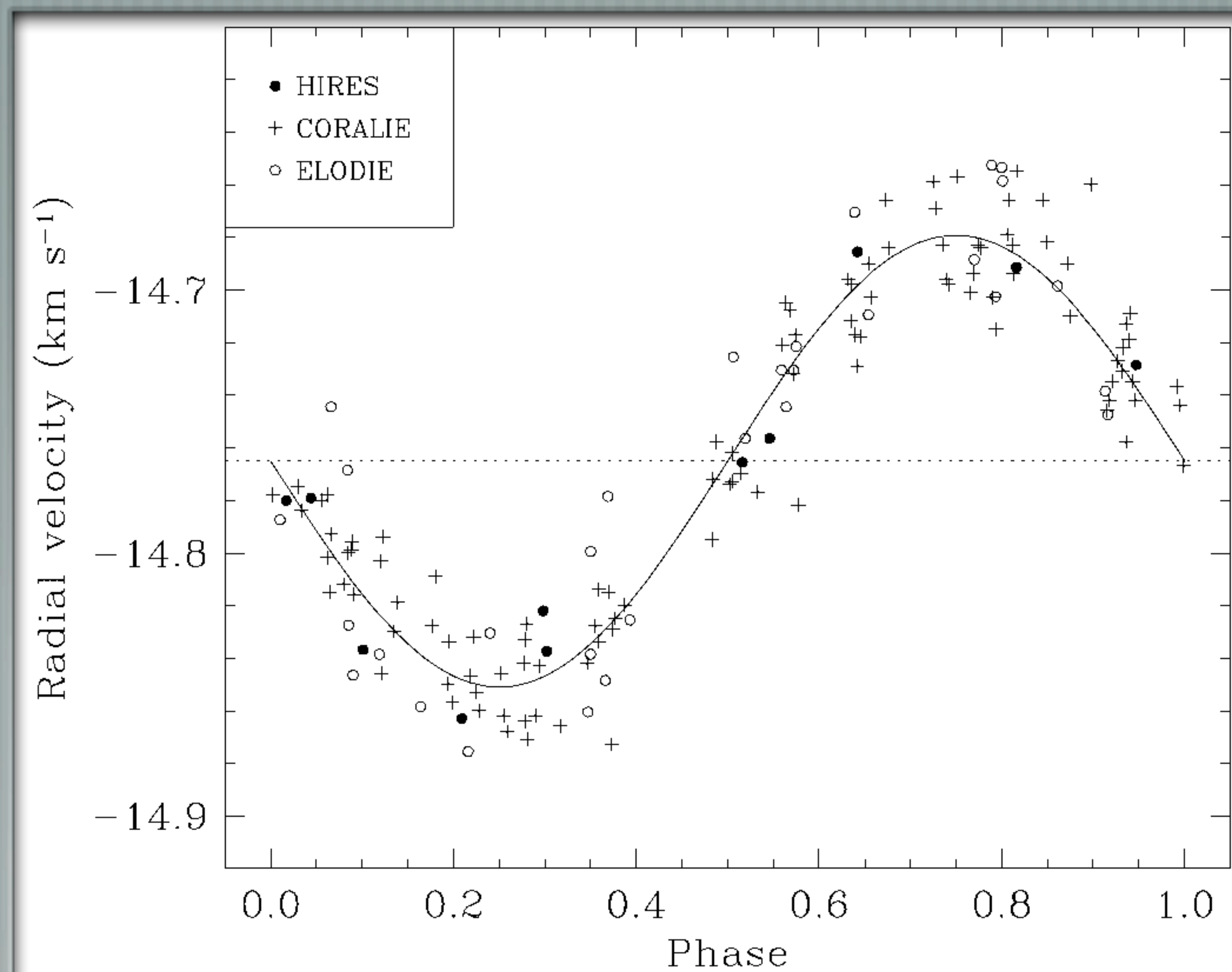


Low-mass eclipsing M-stars

Blended eclipsing binaries / Triple systems

Follow-up of transiting candidates

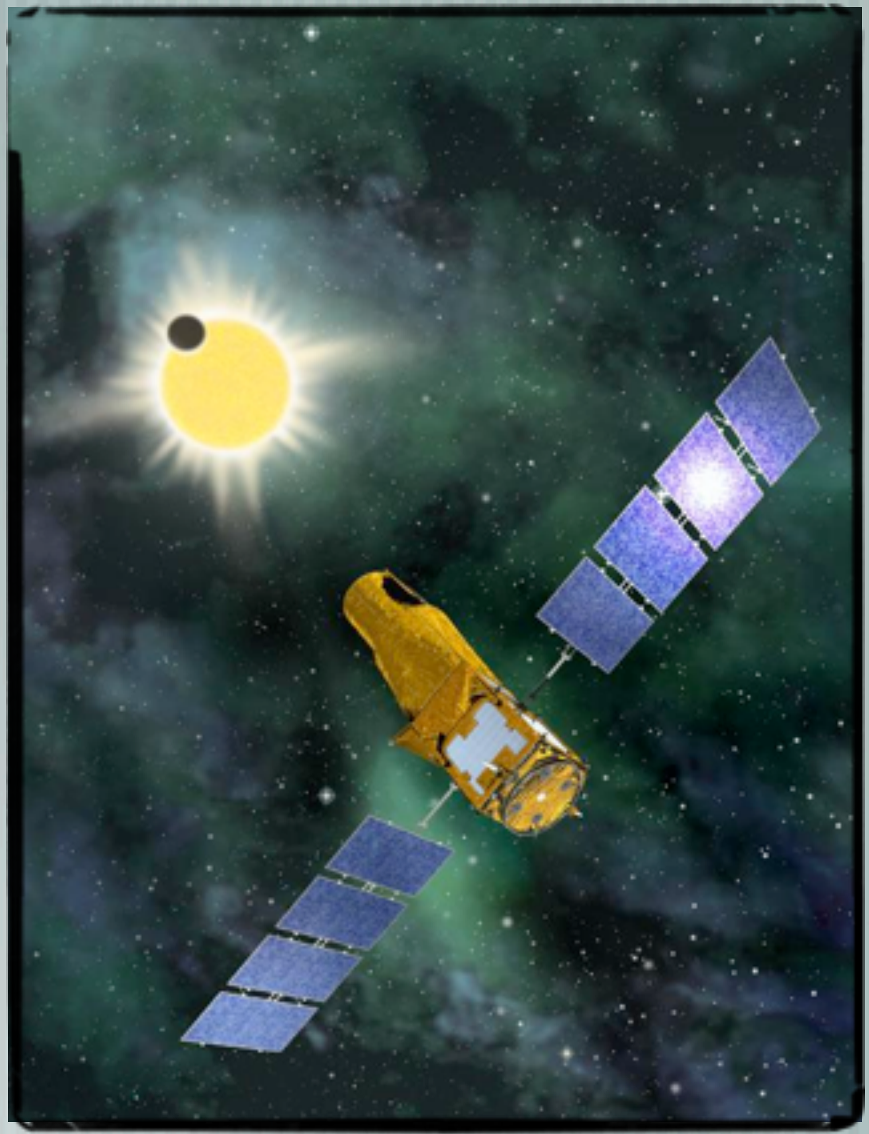
- To discard impostors



- and characterise the planet (mass, eccentricity, etc.)

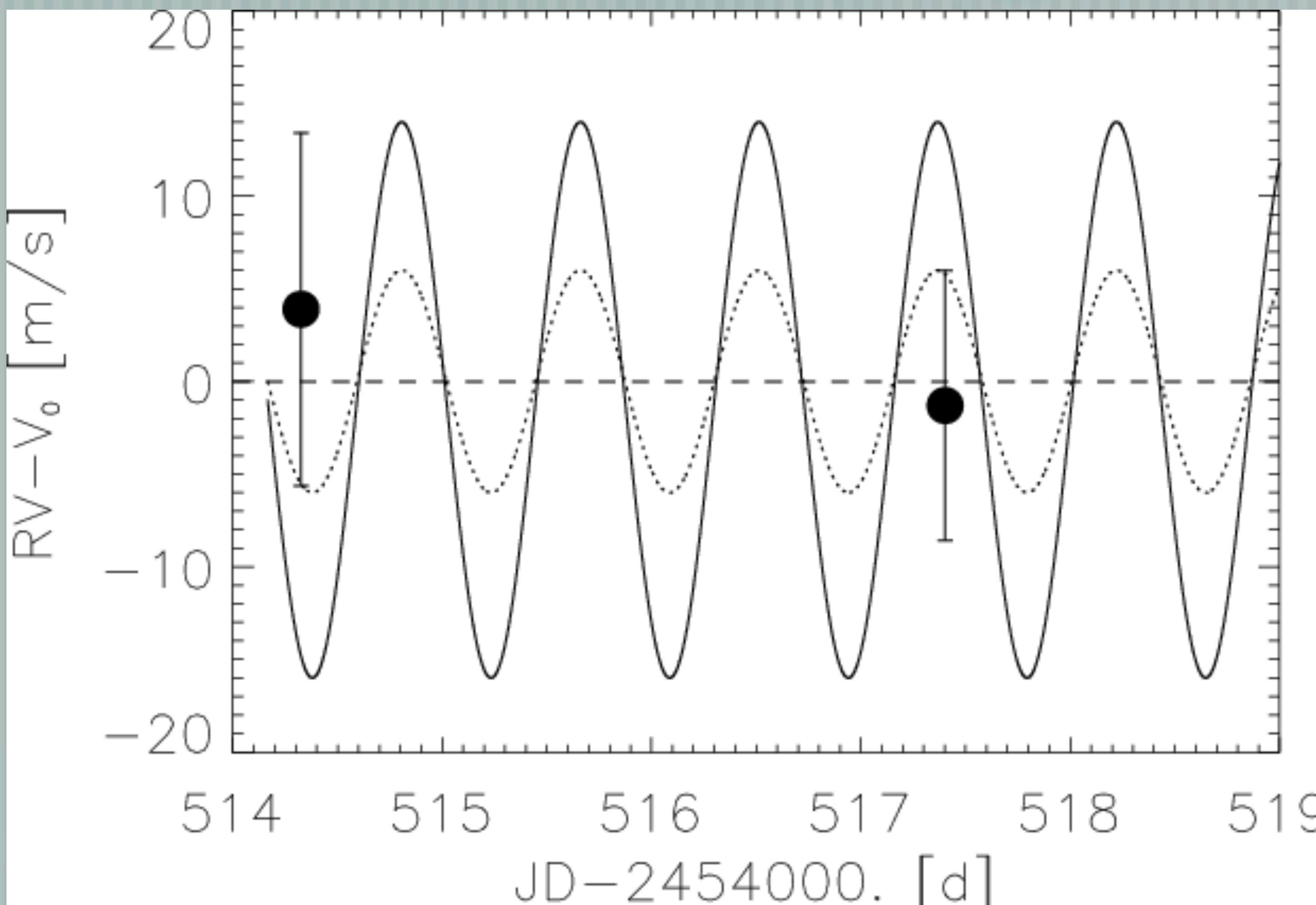
Follow-up of CoRoT candidates

- The CoRoT space mission
  - December 2006 - April 2013 (extended mission)
  - 0.3-m telescope; 4 CCDs (2 kpix); 2 for ExP; 1 down since 2009
  - Orbit around Earth ~900 km
  - >140,000 stars observed in 22 fields
  - About 650 planetary candidates
  - > 70% false positives
  - New extension being evaluated



Follow-up of CoRoT candidates

First screening process to discard false positives

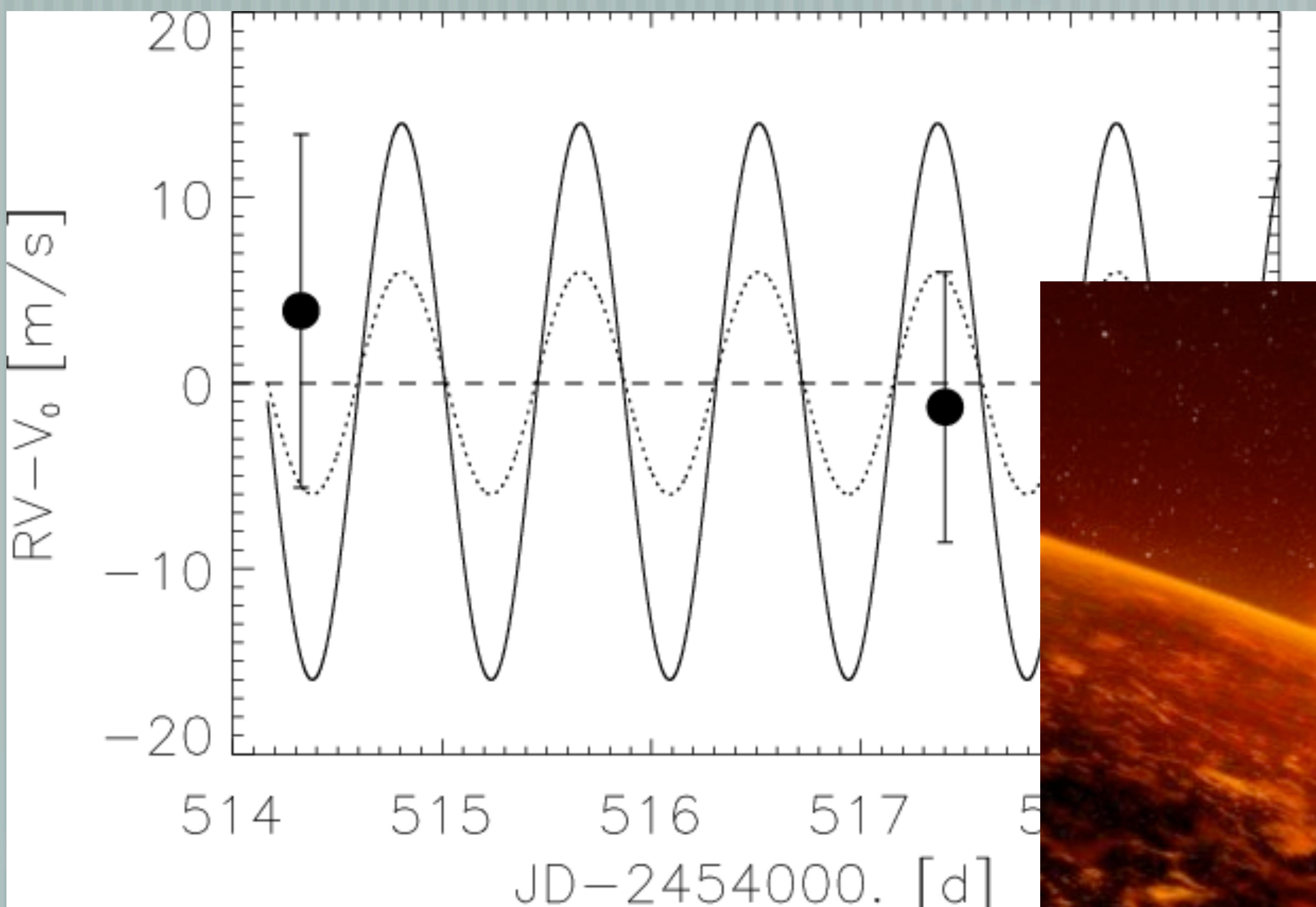


Léger et al. (2009)

CoRoT-7

Follow-up of CoRoT candidates

- First screening process to discard false positives

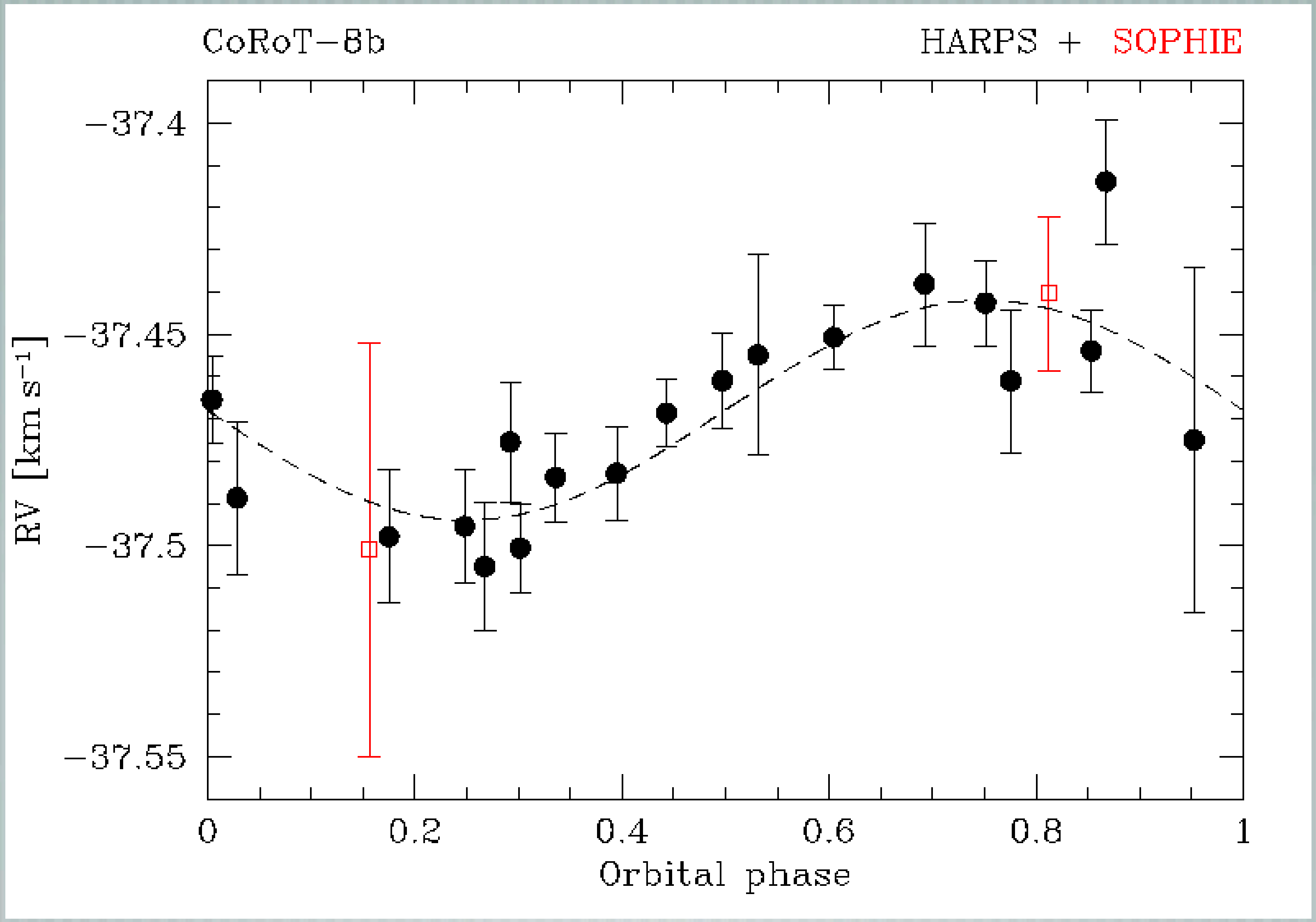


Léger et al. (2009)

CoRoT-7

Follow-up of CoRoT candidates

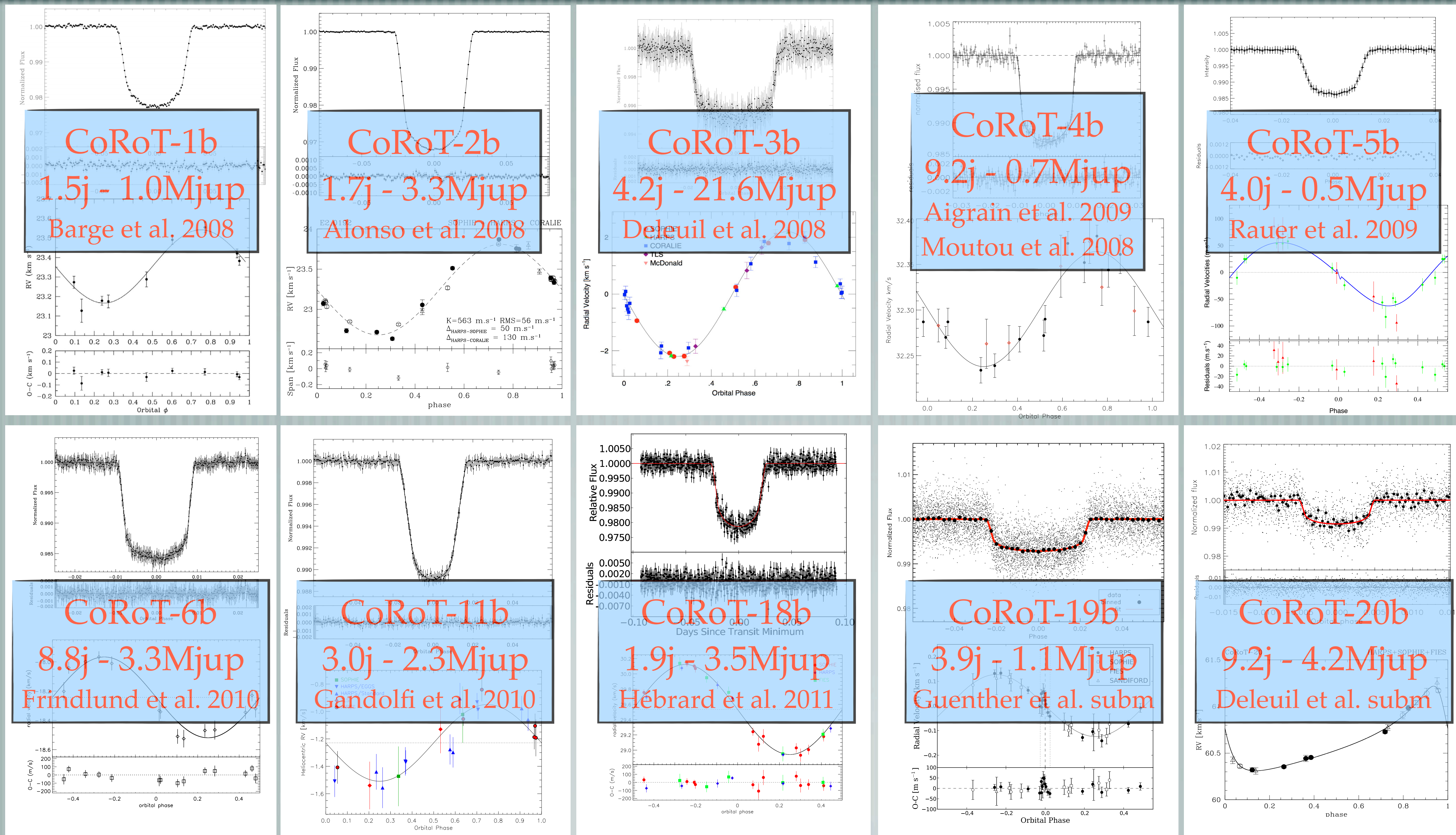
- First screening process to discard false positives



Bordé et al. (2009)

CoRoT-8

The family of CoRoT/SOPHIE planets

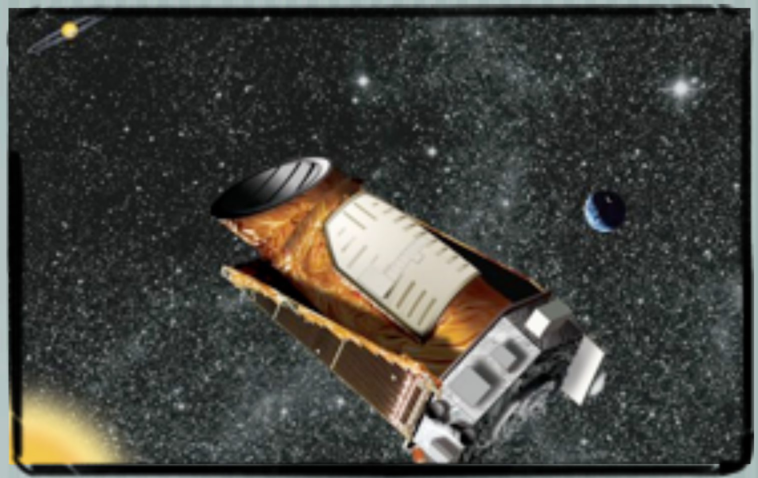


Follow-up of Kepler candidates

- The Kepler space mission
  - March 2009 - 2012 (possible extension)
  - 0.95-m telescope; 42 CCDs (2 kpix)
  - Orbit around Sun (L1)
  - >150,000 stars observed continuously in a single field
  - More than 1200 planetary candidates
  - Low fraction of false positives expected

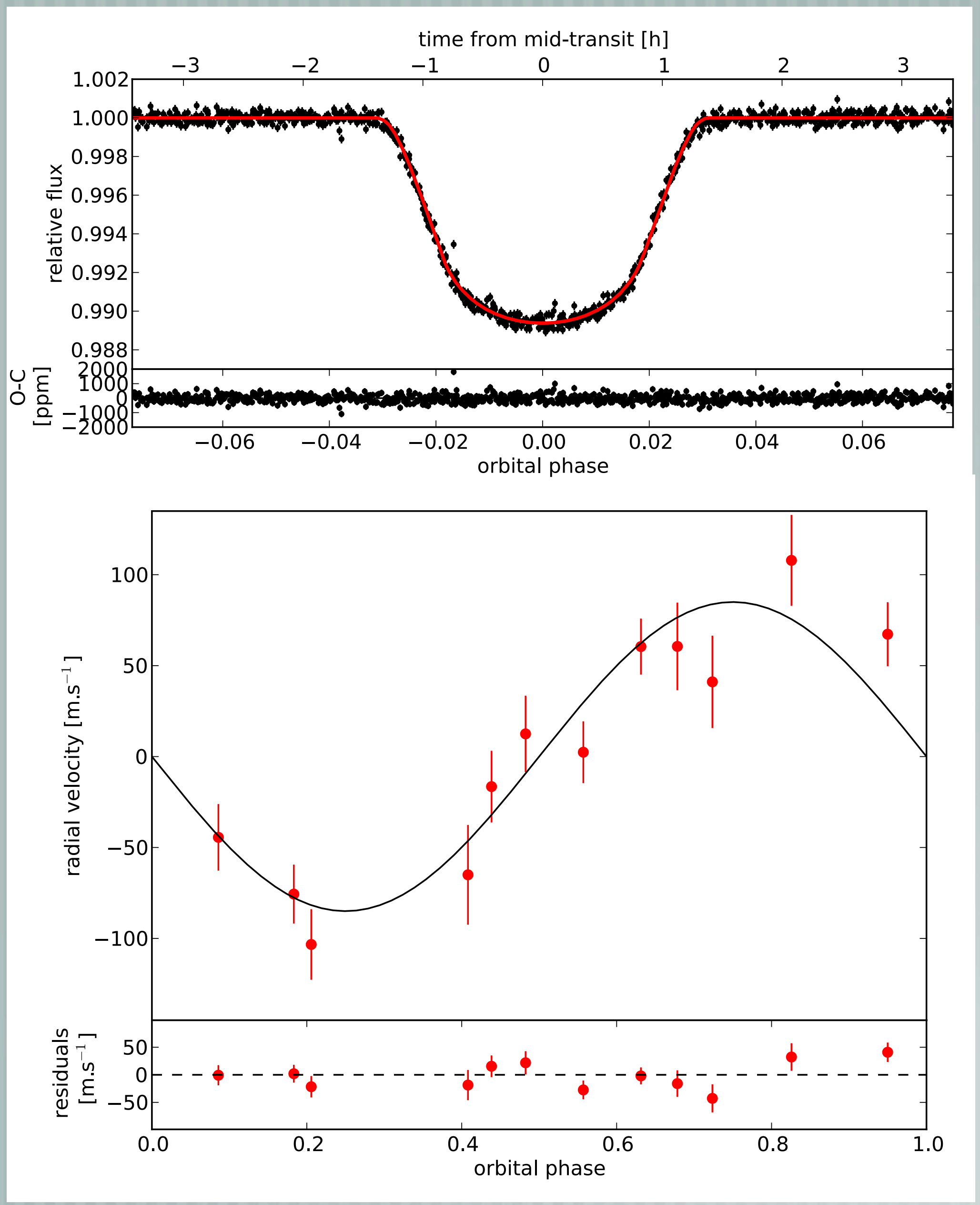
Follow-up of Kepler candidates

- Kepler candidates

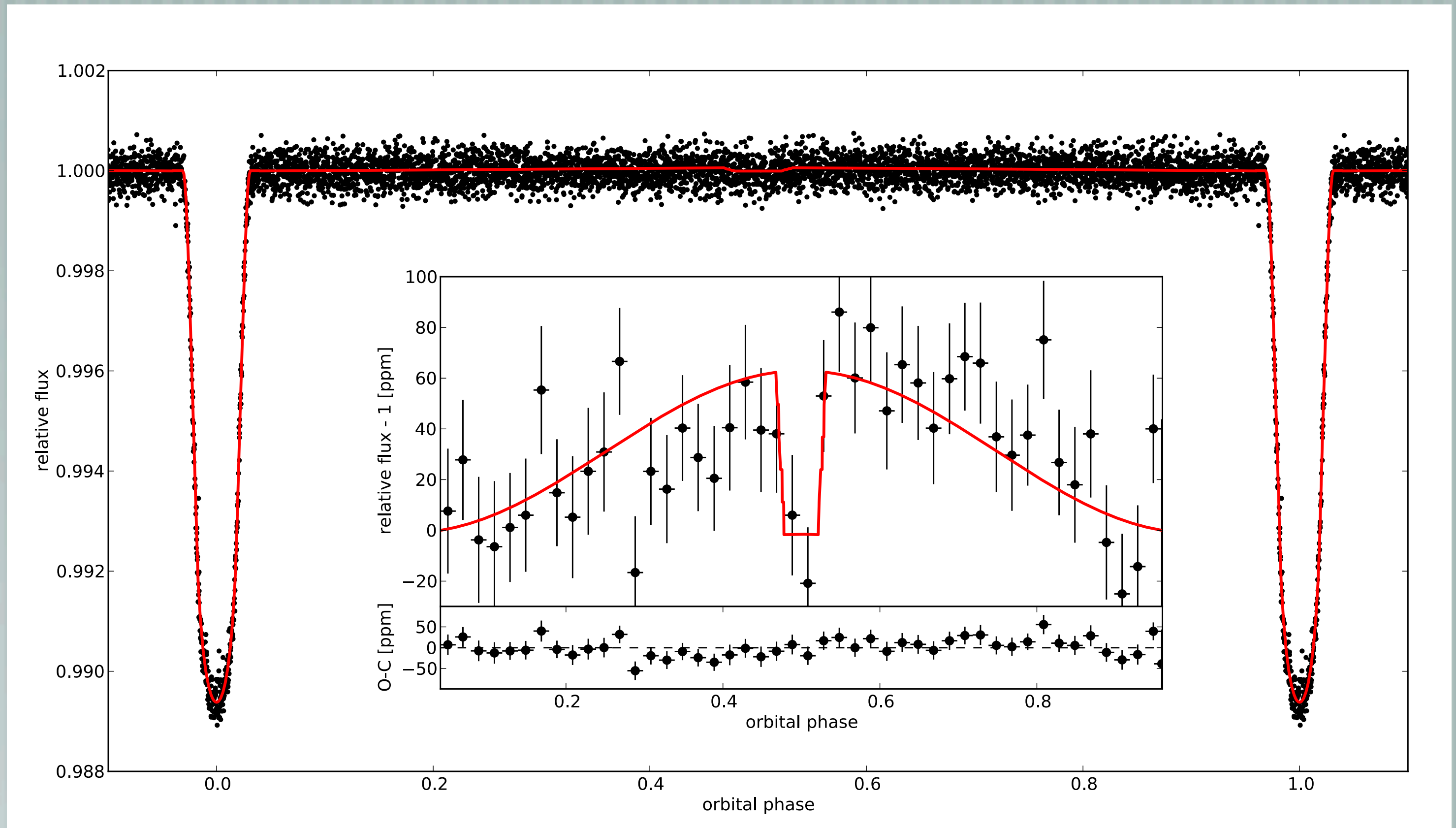


  - KOI 428 b Santerne, Díaz, Bouchy et al. (2011)
  - KOI 423 b Bouchy, Bonomo, Santerne et al. (2011)
  - KOI 196 b Santerne, Bonomo, Hébrard et al. (2011)
  - KOI 135 b, KOI 204 b, KOI 203 b Bonomo, Hébrard, Santerne, et al. (2012)
  - Many others on their way

KOI 196 b, a Hot Jupiter with a high albedo



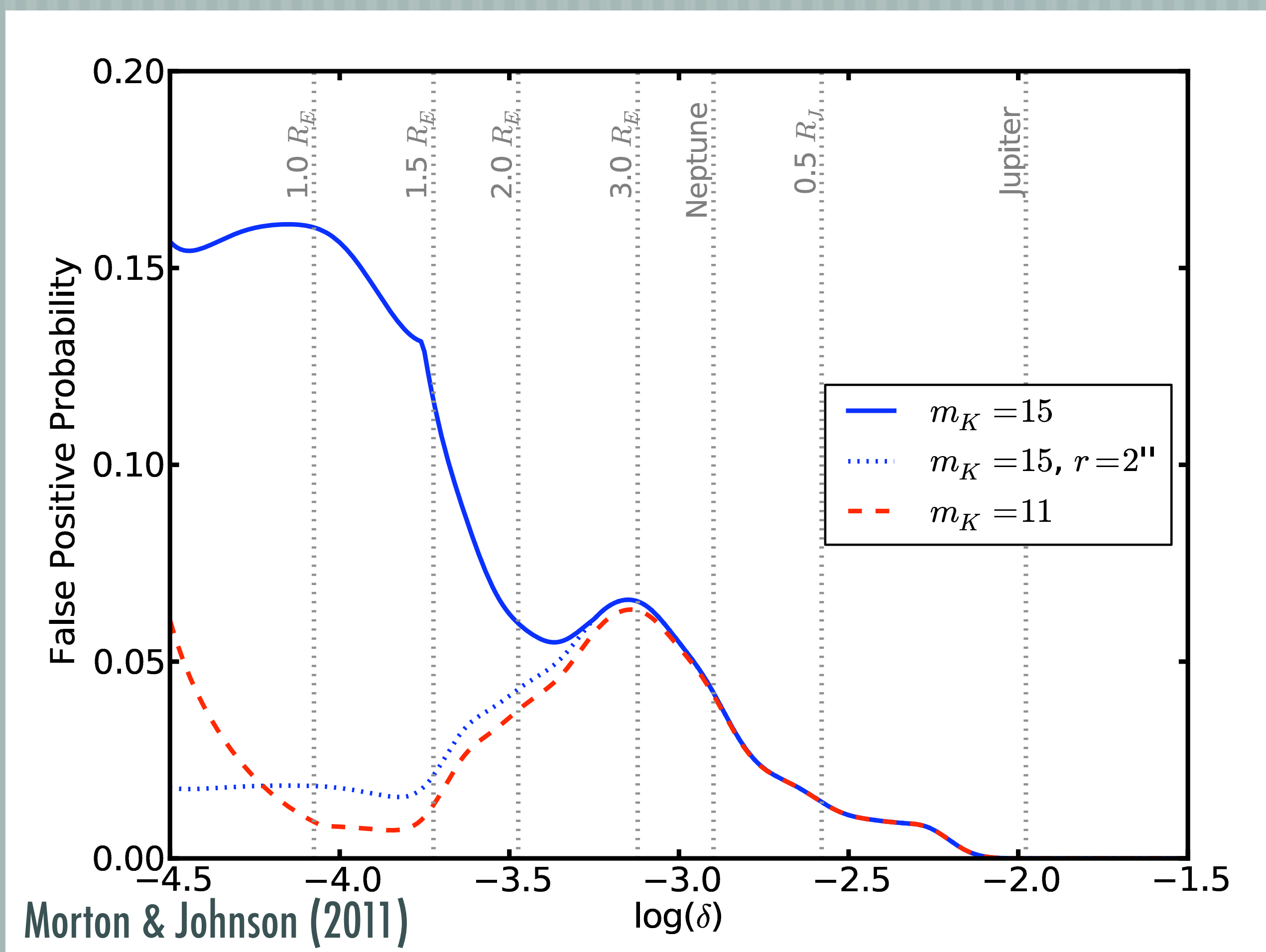
Santerne, Bonomo, Hébrard et al. (2011)

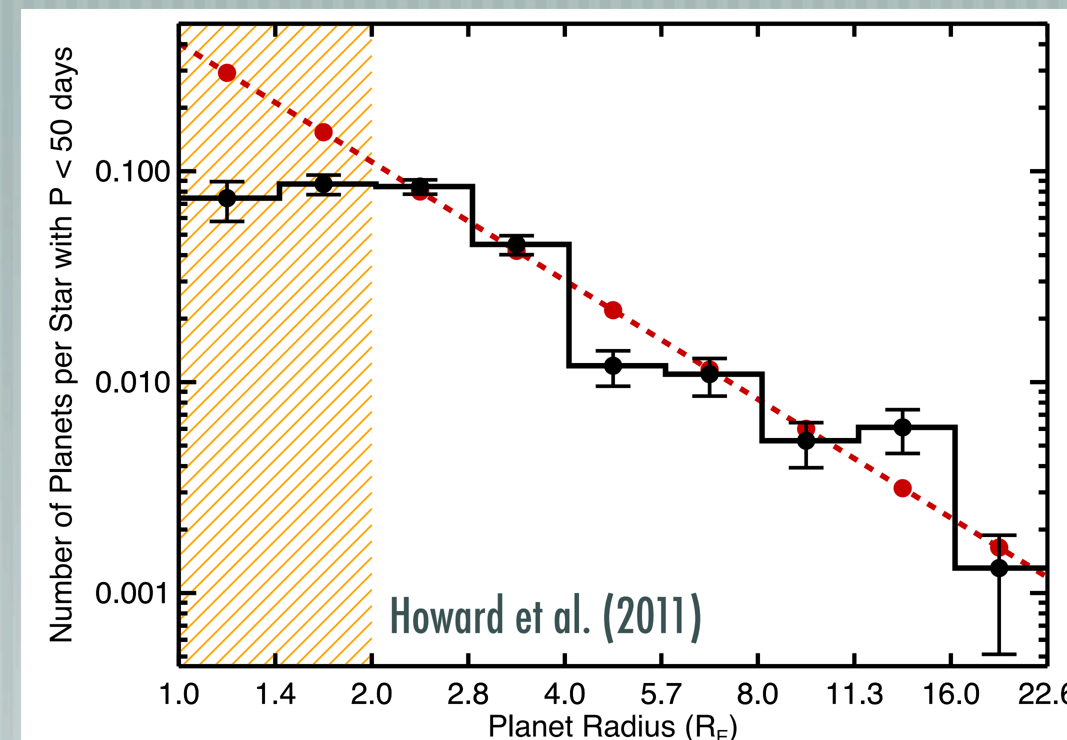


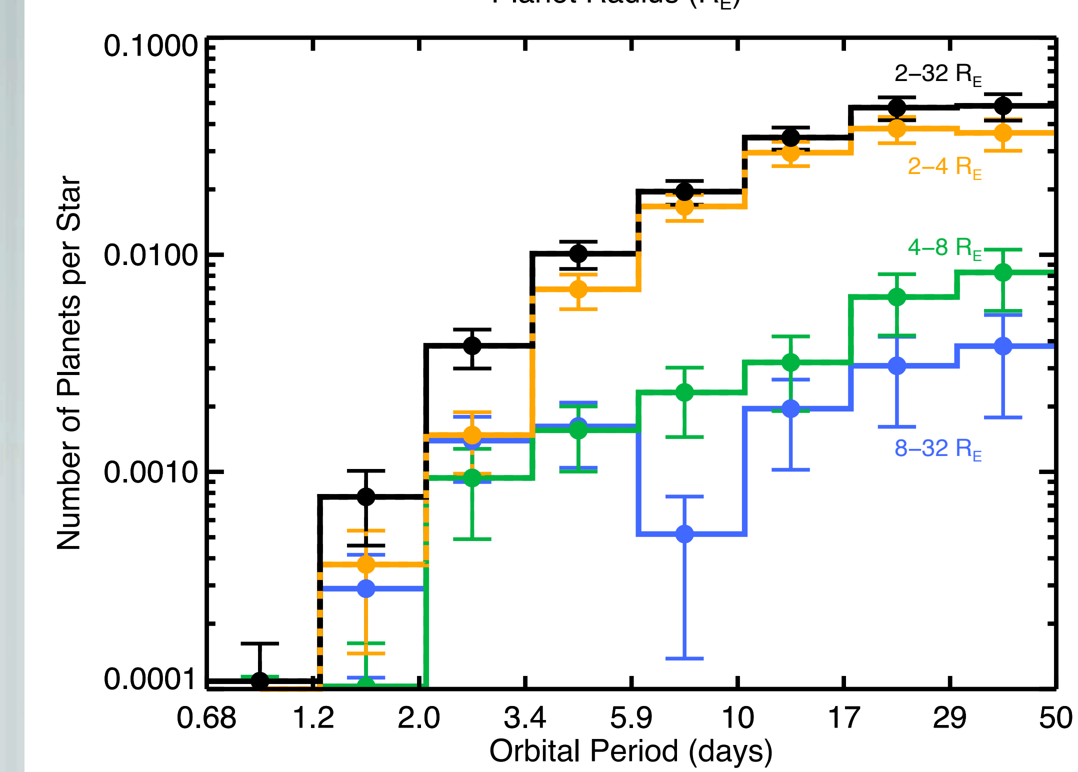
High geometric albedo, Ag = 0.30 ± 0.08.

Only two other planets with such a high albedo (Kepler-7 b, HAT-P-7 b).

Measure the Kepler False Positive rate







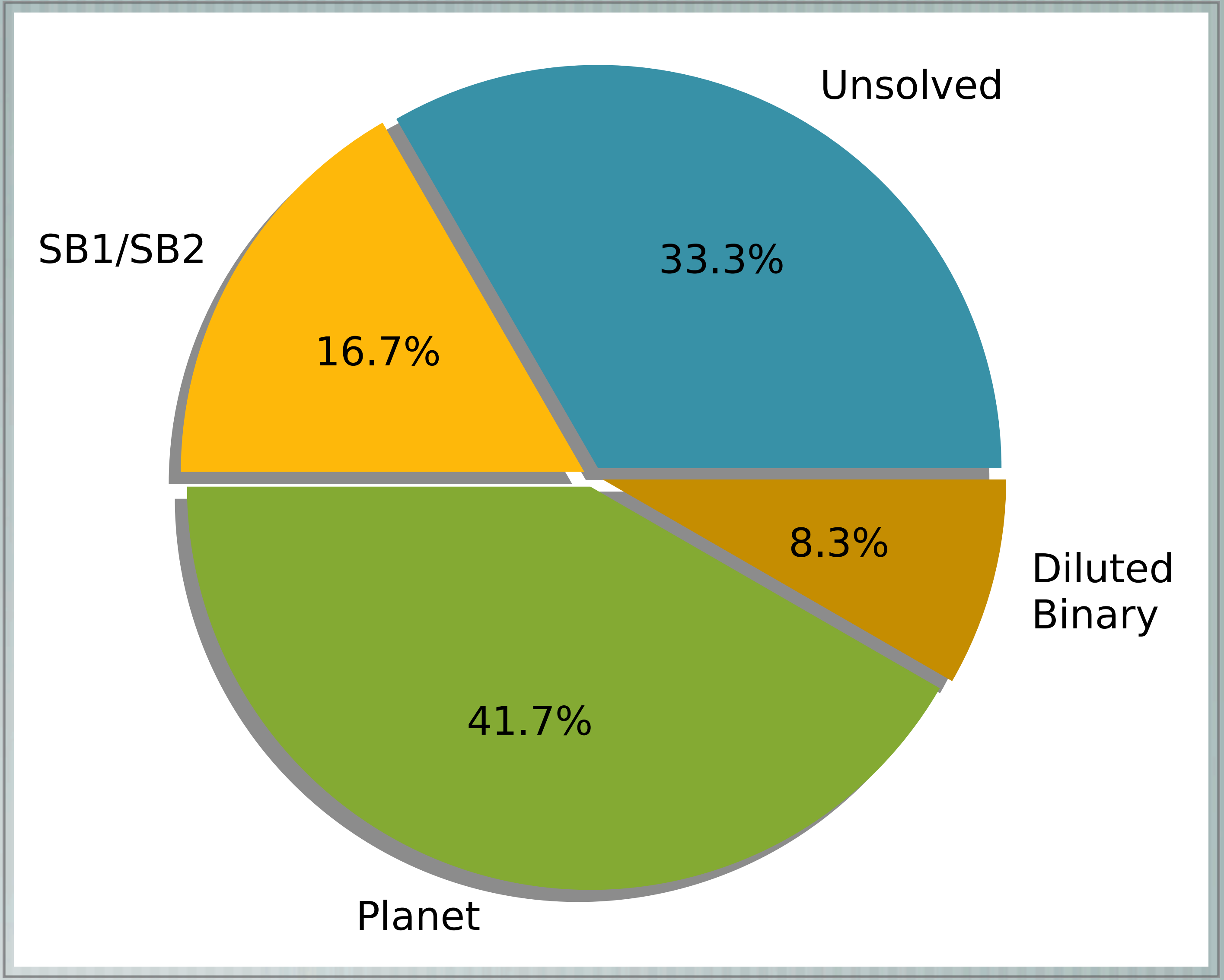
Estimation based on galactic population models.

Does not consider unblended binaries !

Measure the Kepler False Positive rate

Based on results of 24 giant planet candidates with concluded follow-up.

- Kp < 14.7
- Depth < 2%
- Rp > 0.6 Rjup
- Only Rank 2



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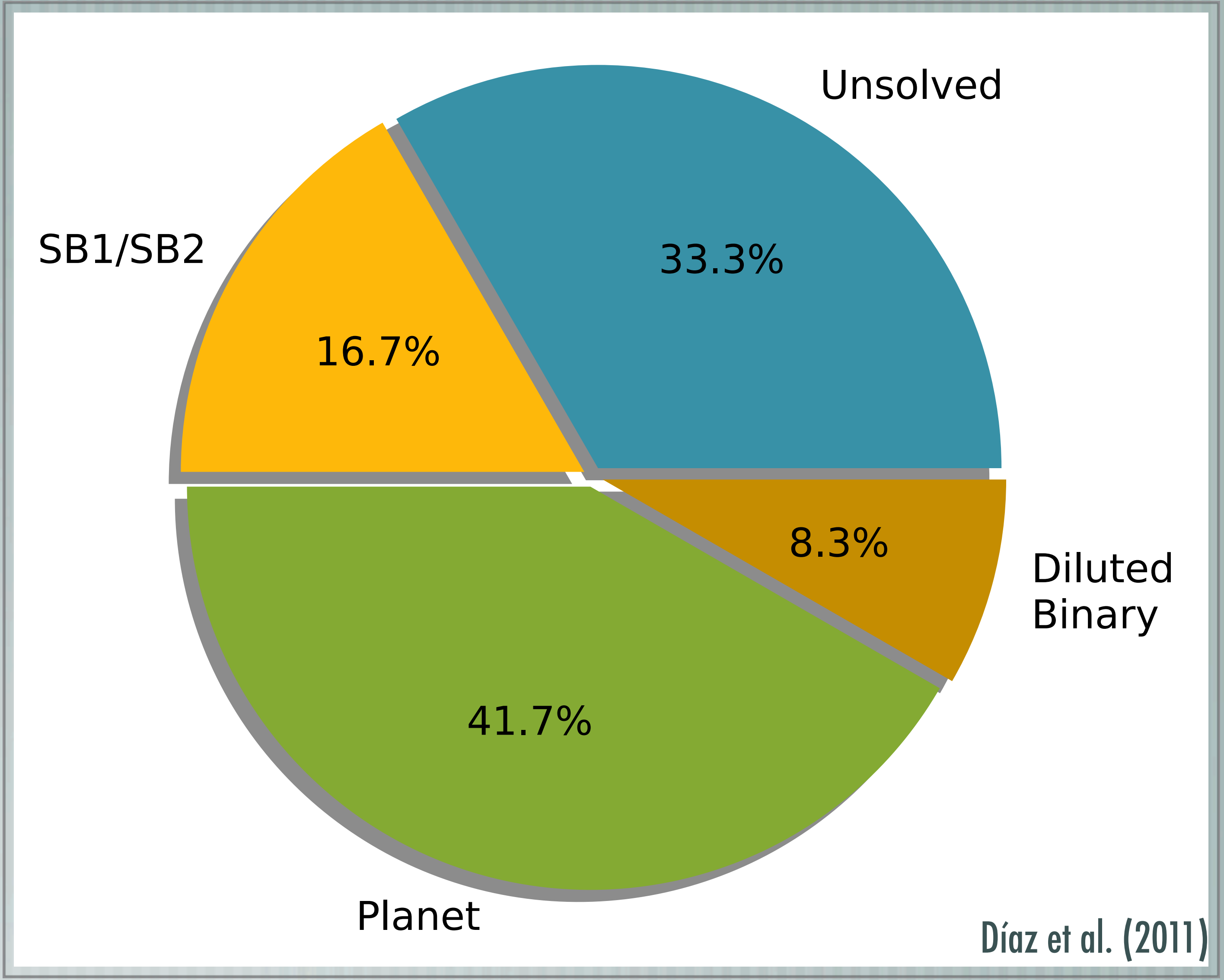
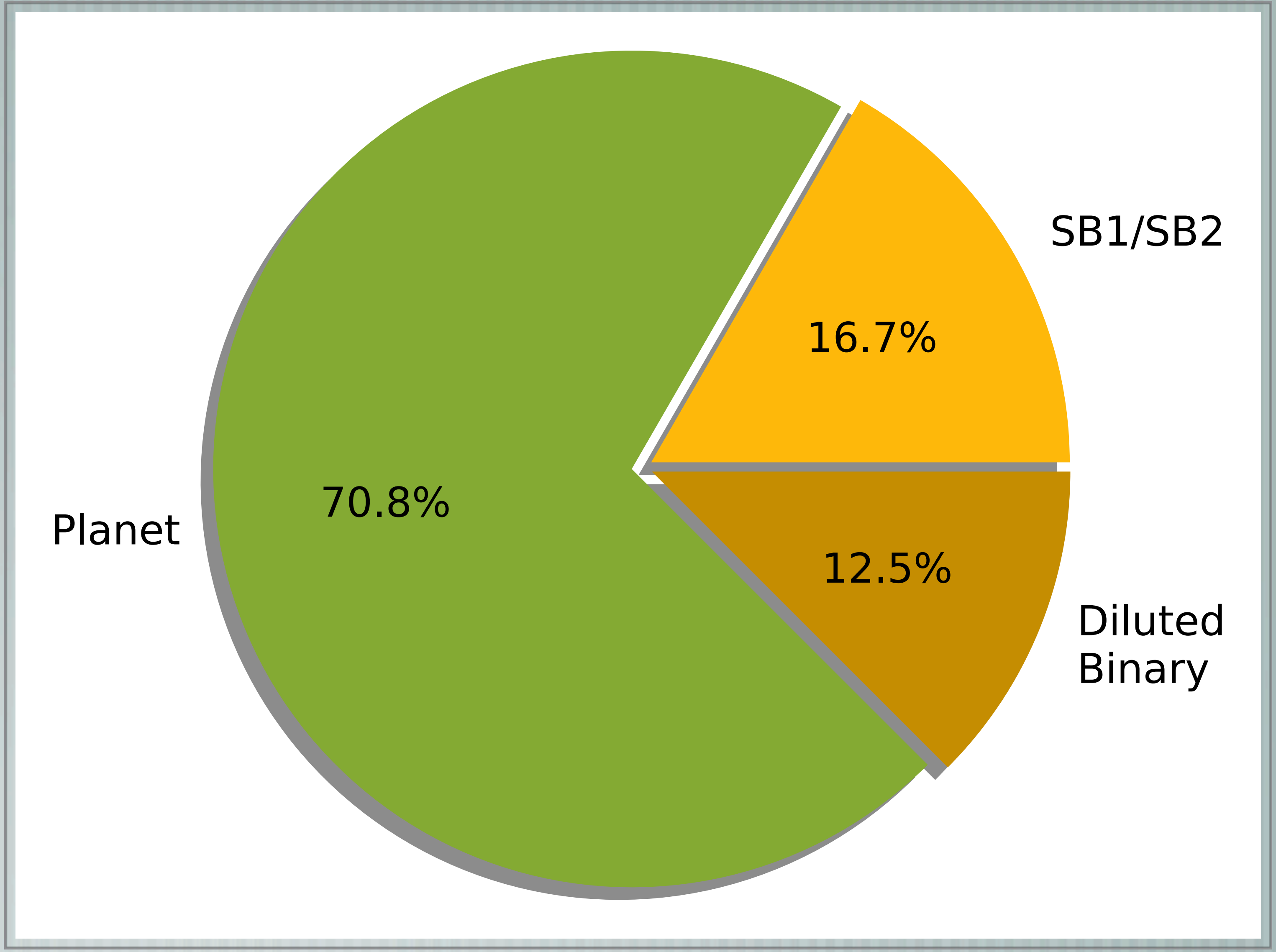


False Positive Rate: 25 – 58 %

Measure the Kepler False Positive rate

False Positive Rate ~30 %

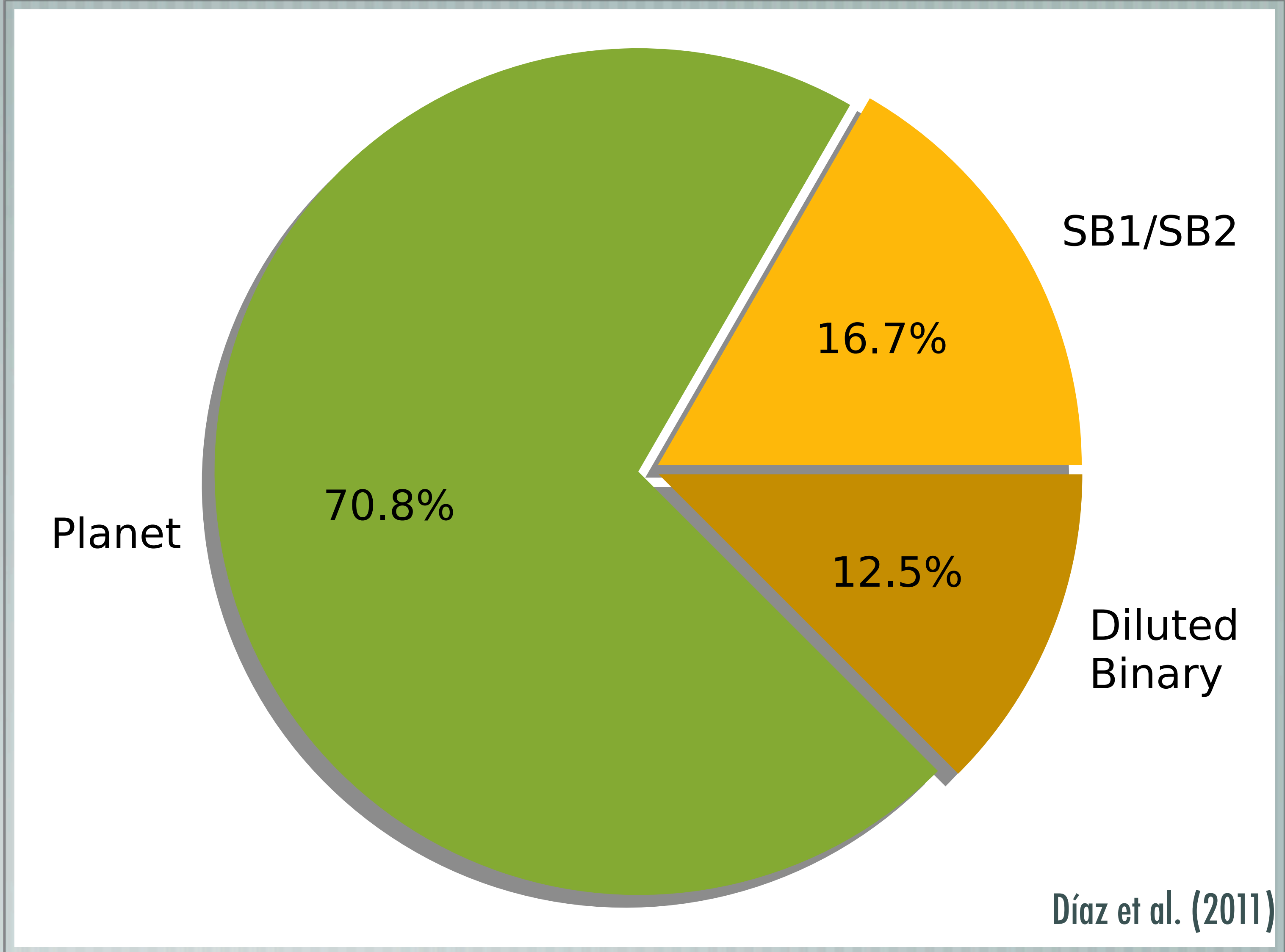
measured for giant planet candidates



Measure the Kepler False Positive rate

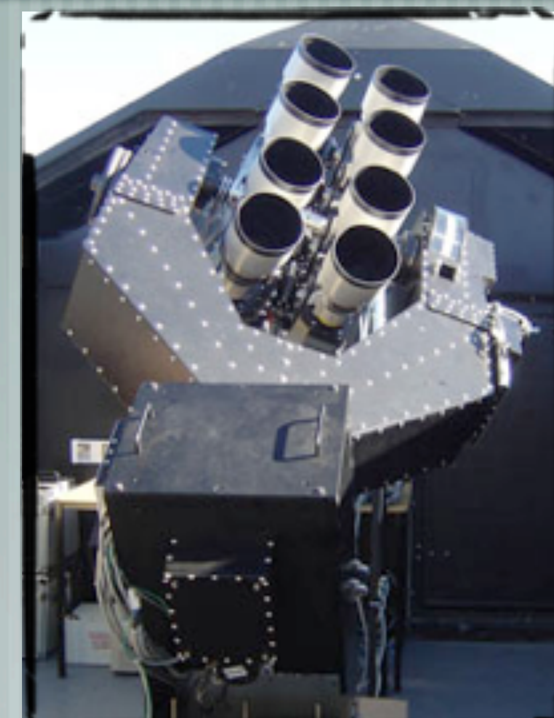
False Positive Rate
~30 %

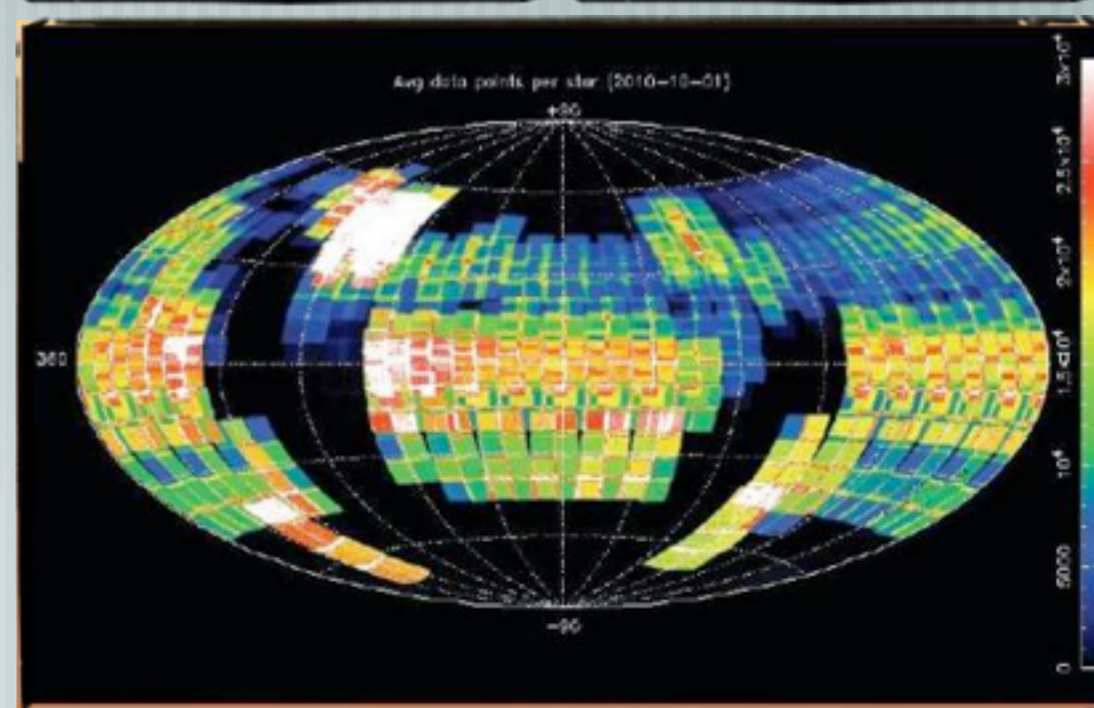
measured for giant planet candidates



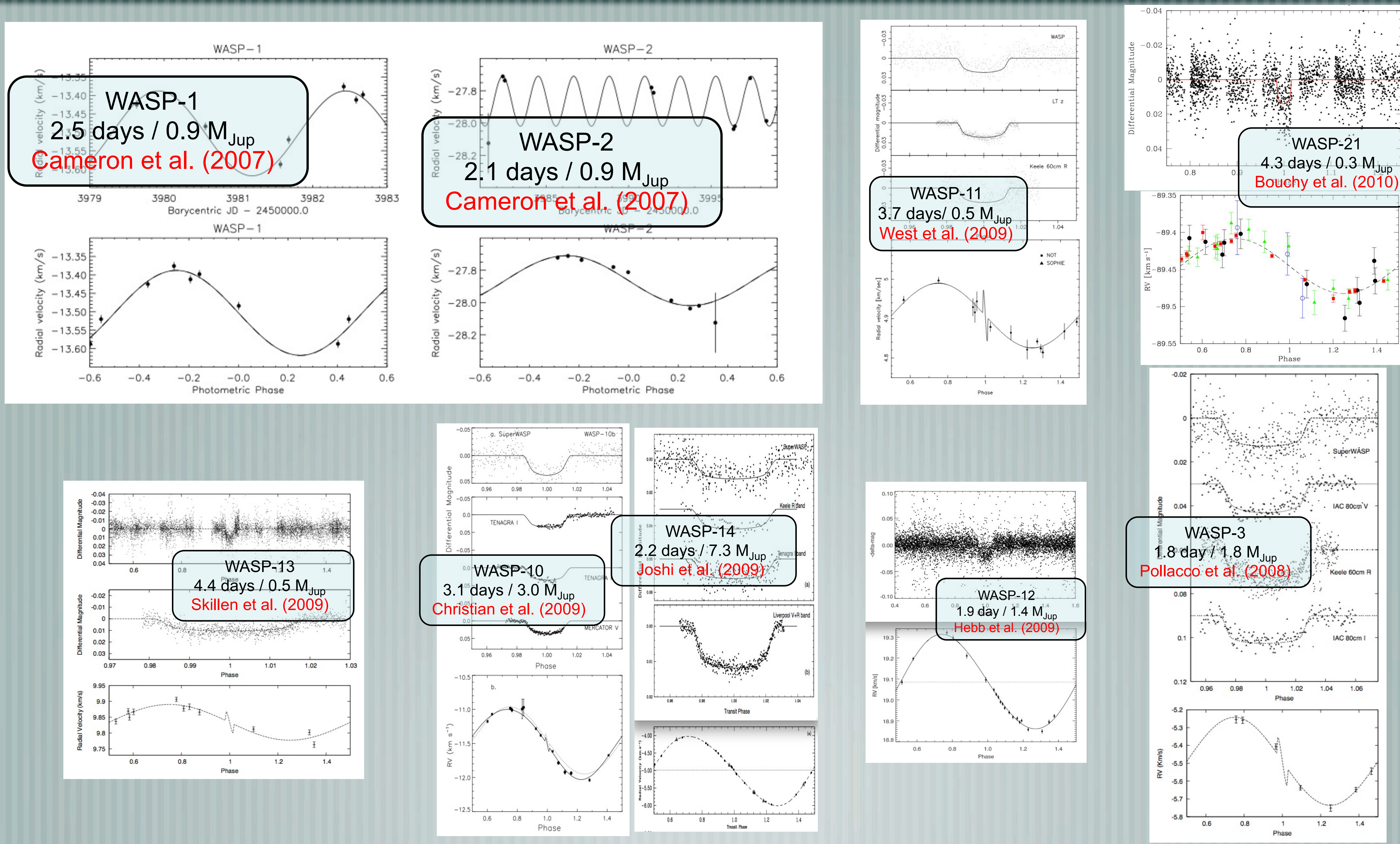
Follow-up of SuperWASP candidates

- The SuperWASP survey of transiting planets
  - Wide Area Search for Planet.
  - Two locations to cover Southern and Northern sky.
  - Over 60 planets found.

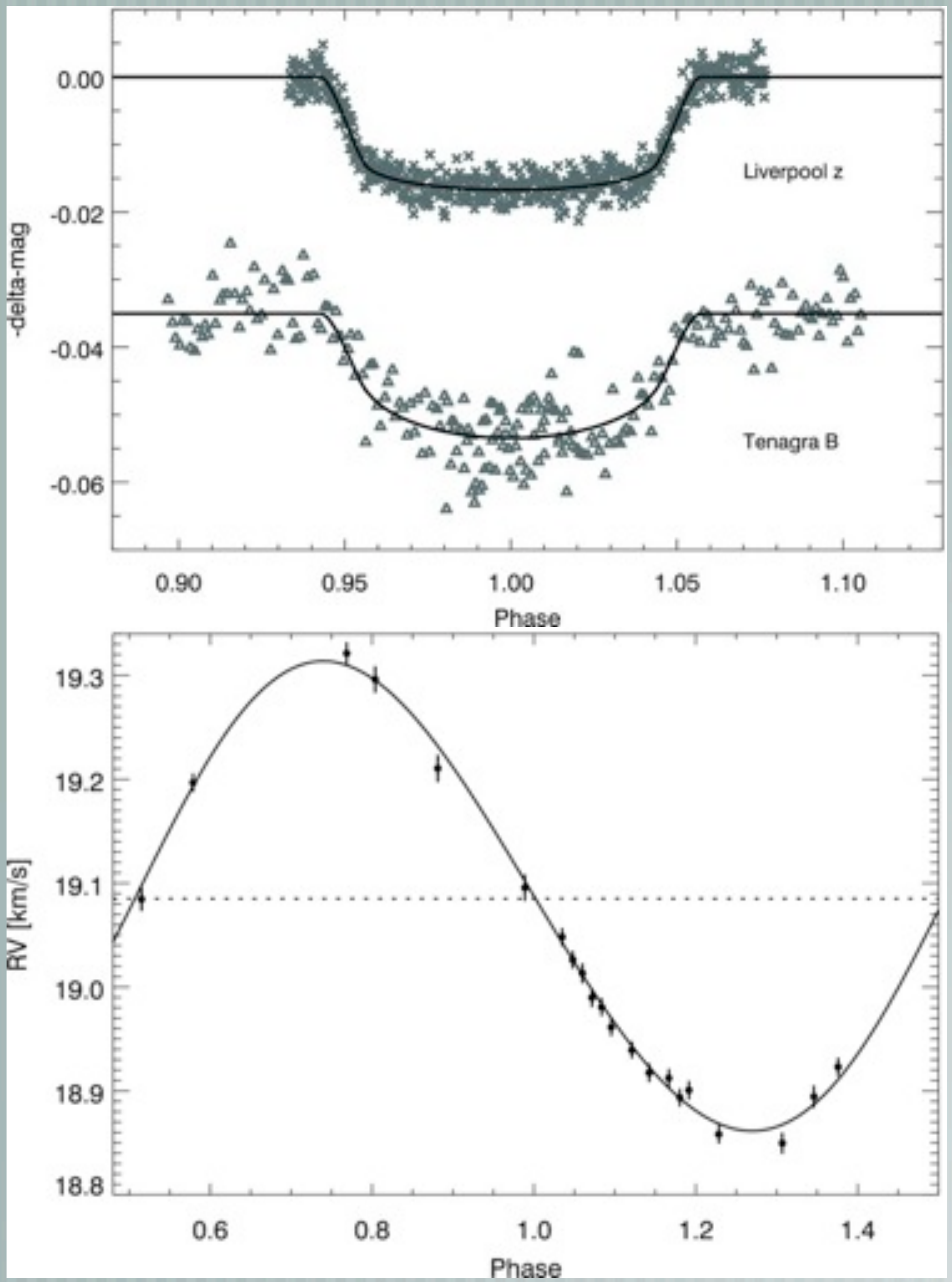


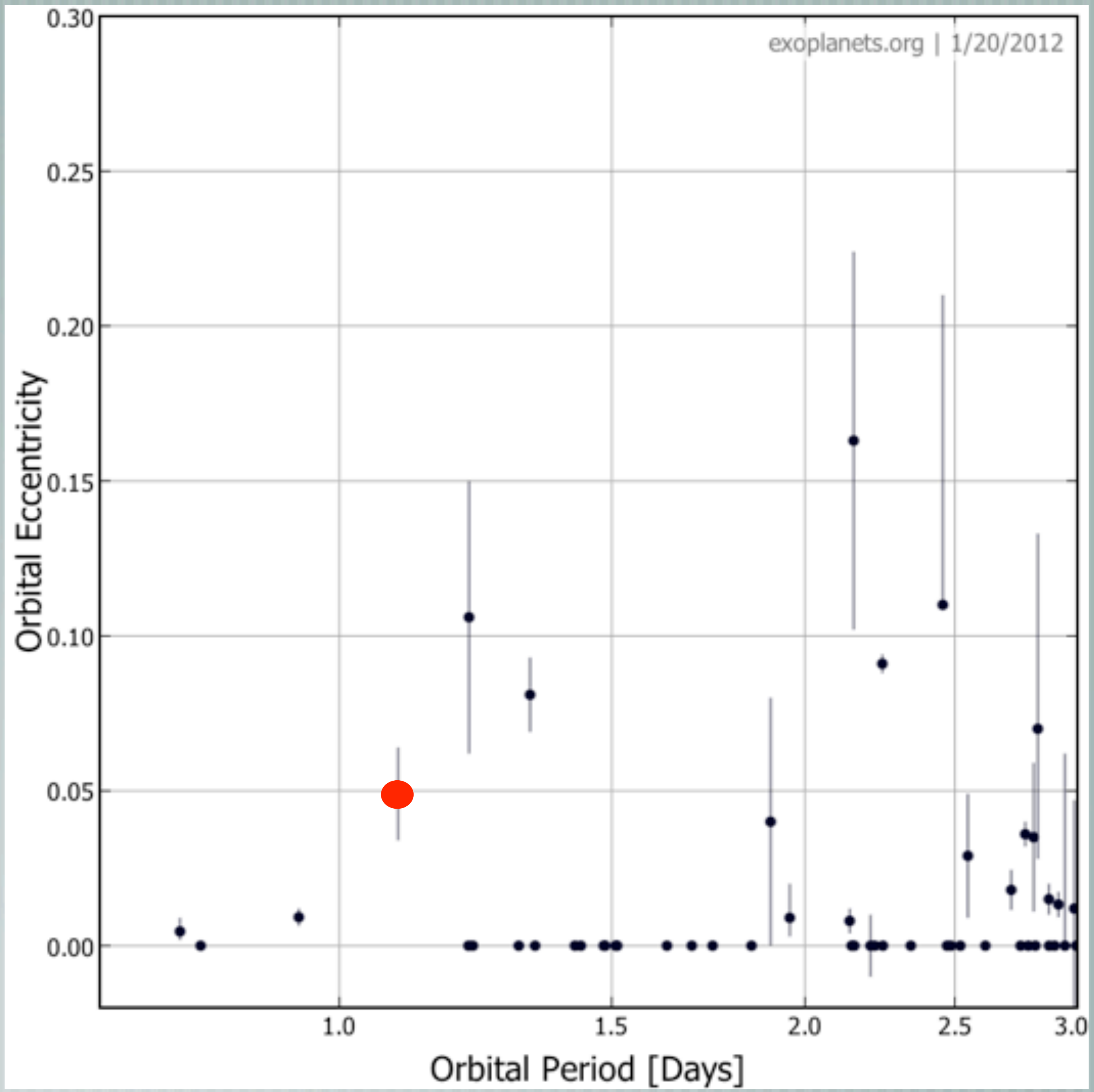


The WASP / SOPHIE family



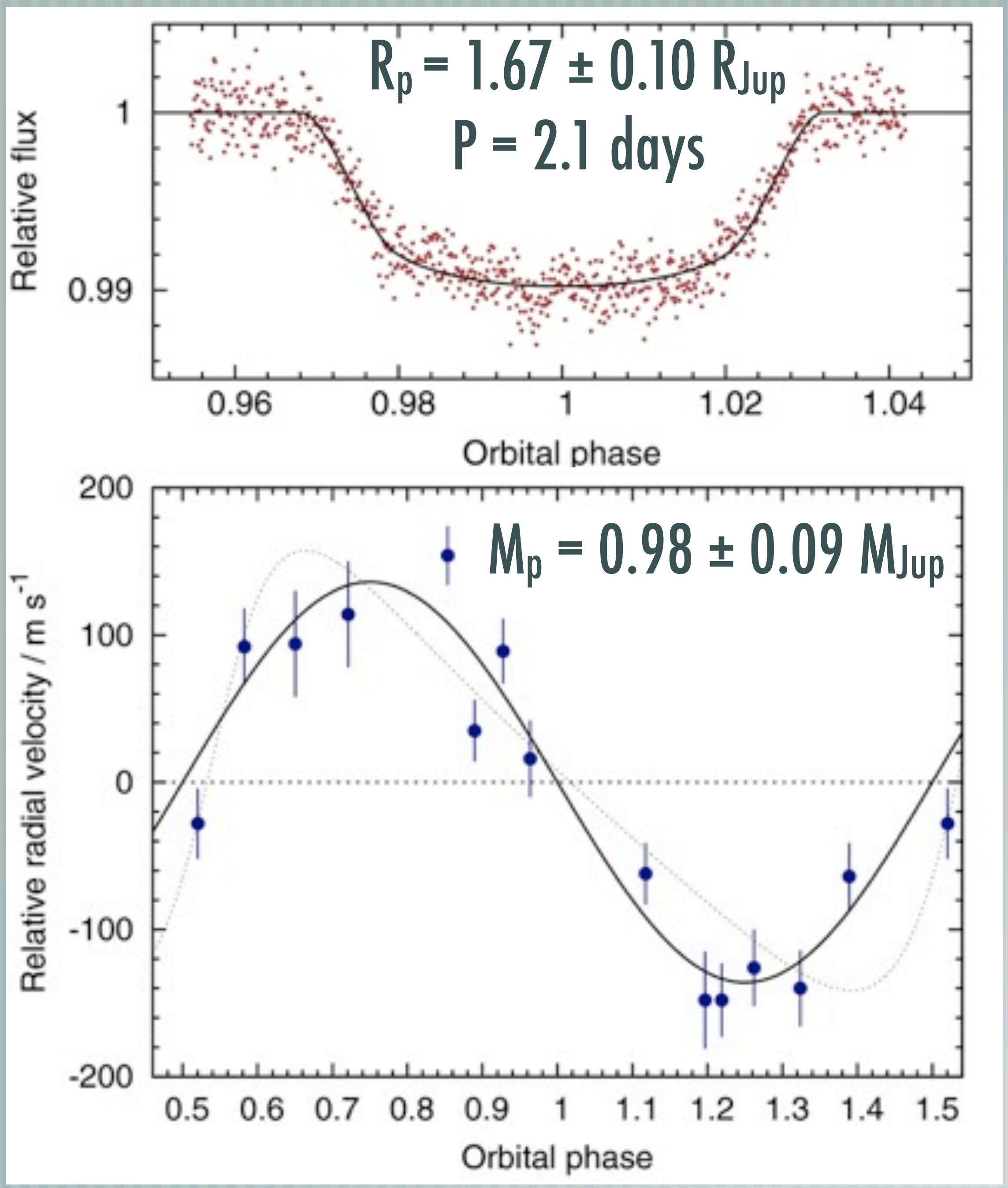
WASP-12 b, a Hot Jupiter in an eccentric orbit

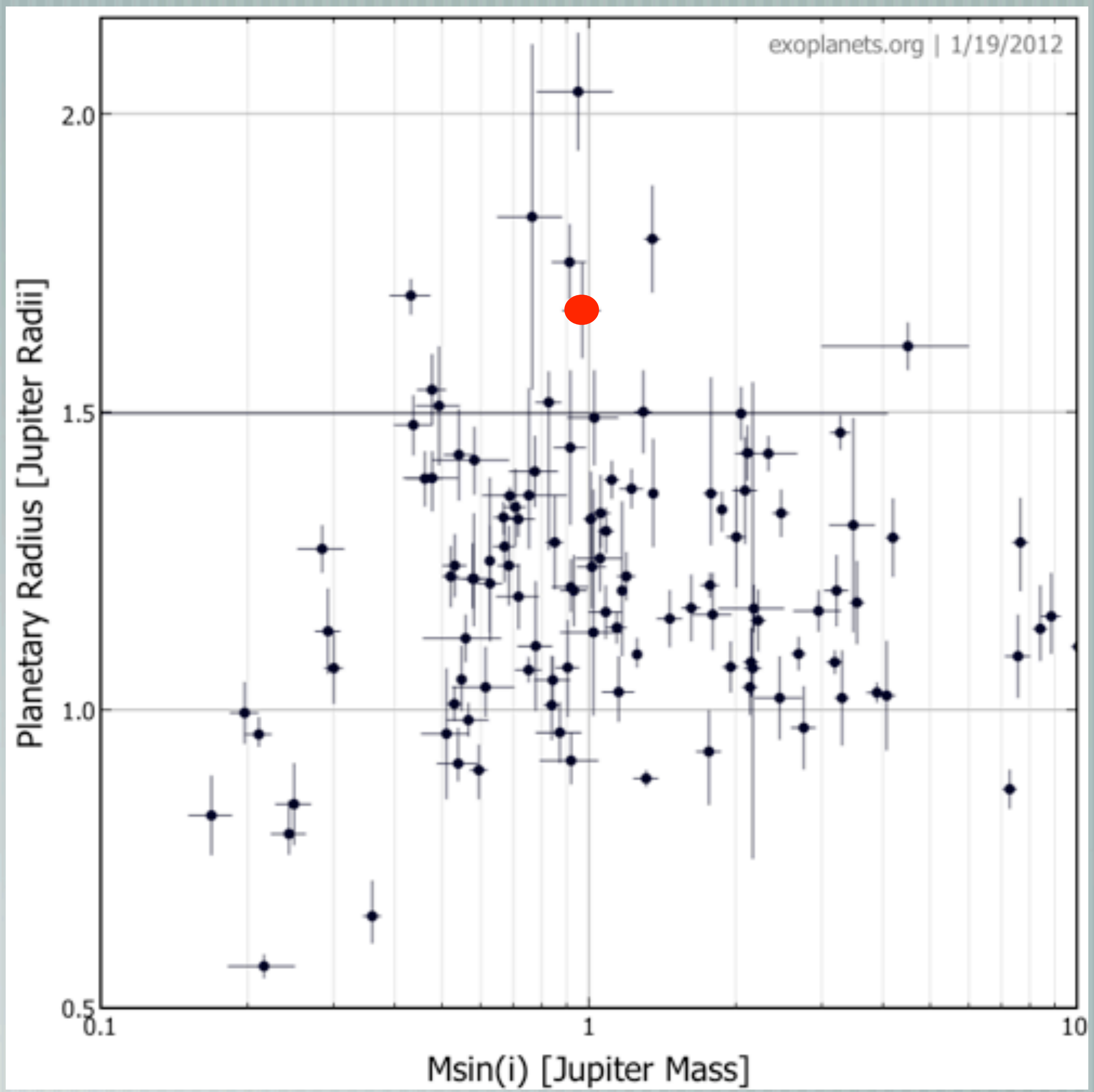




Hebb, Collier-Cameron, Loelliet et al. (2009)

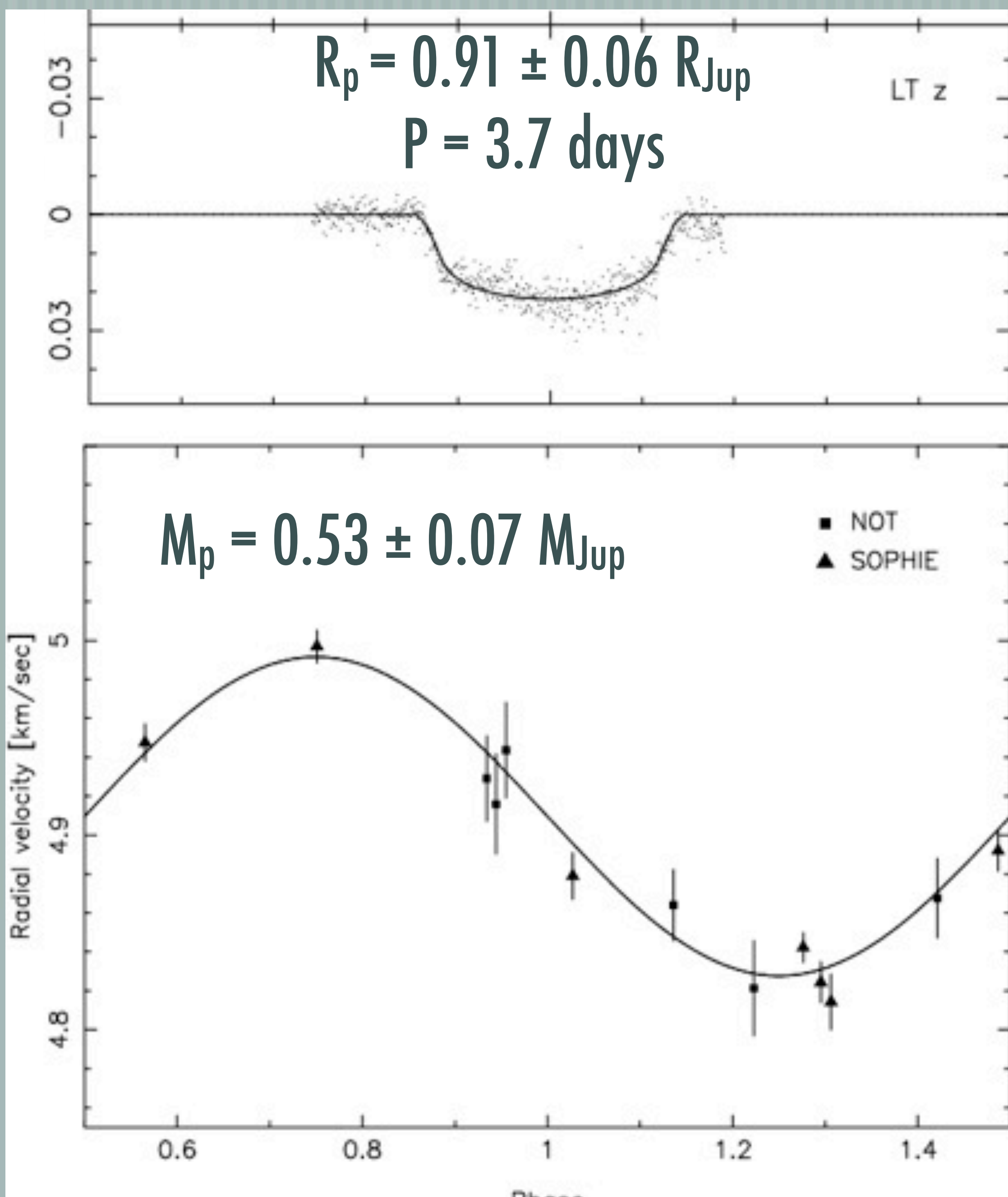
WASP-48 b, an inflated Hot Jupiter



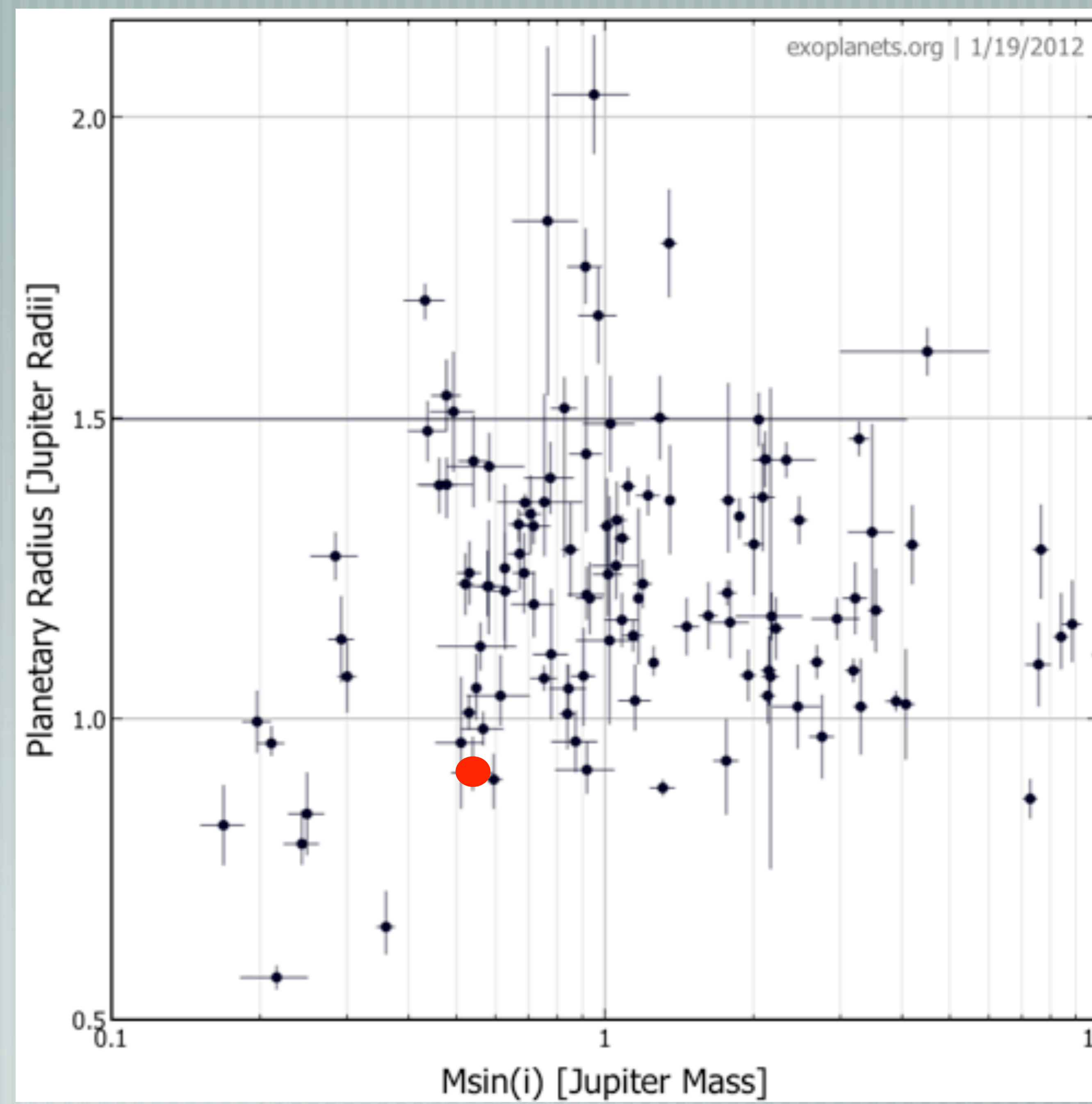


Enoch, Anderson, Barros et al. (2011)

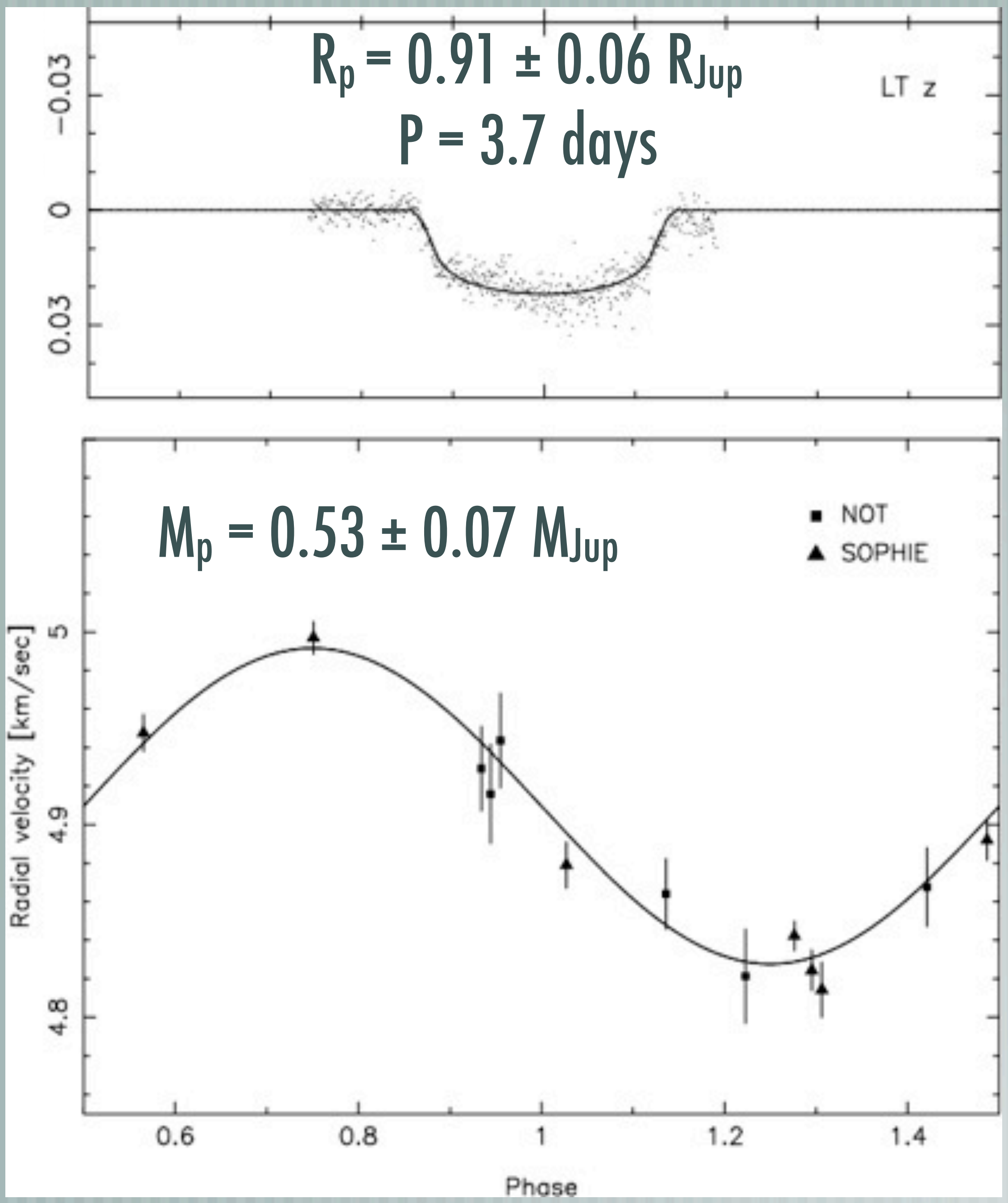
WASP-11 b, a compact sub-Jupiter



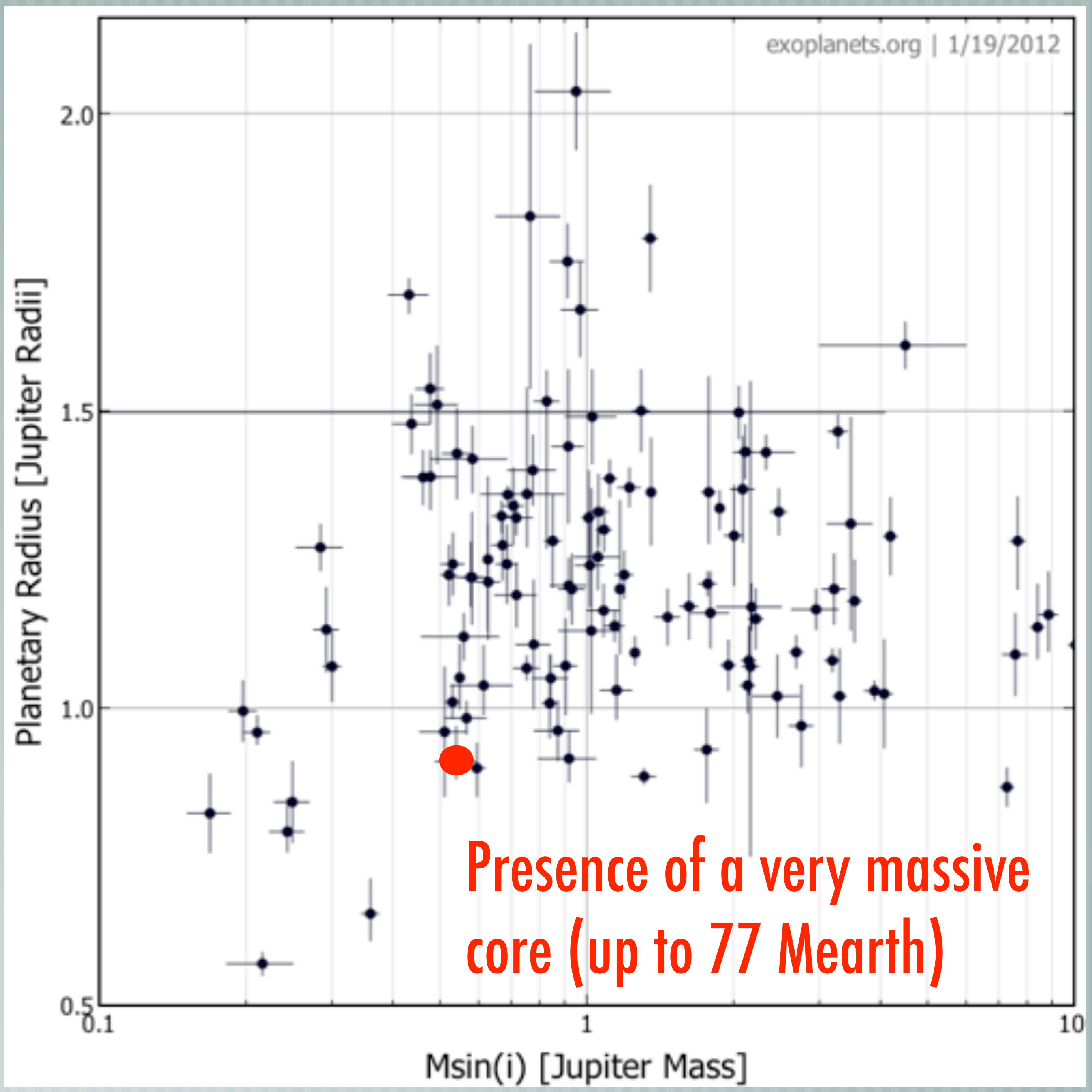
West, Collier Cameron, Hebb, et al. (2009)



WASP-11 b, a compact sub-Jupiter



West, Collier Cameron, Hebb, et al. (2009)



SOPHIE & exoplanets

- Search for extrasolar planets
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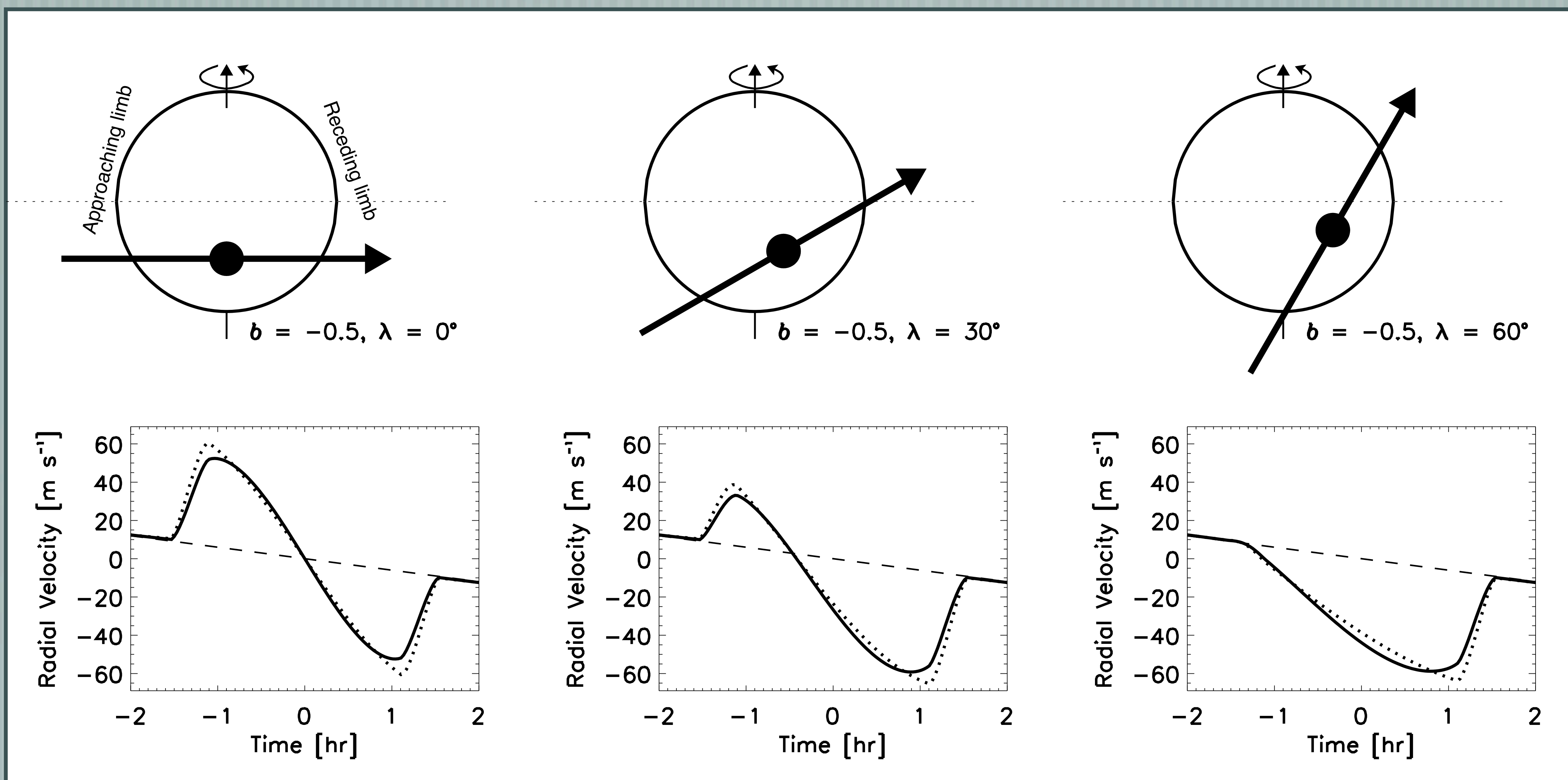
- Characterisation of transiting planets via Rossiter-McLaughlin effect

Rossiter-McLaughlin effect

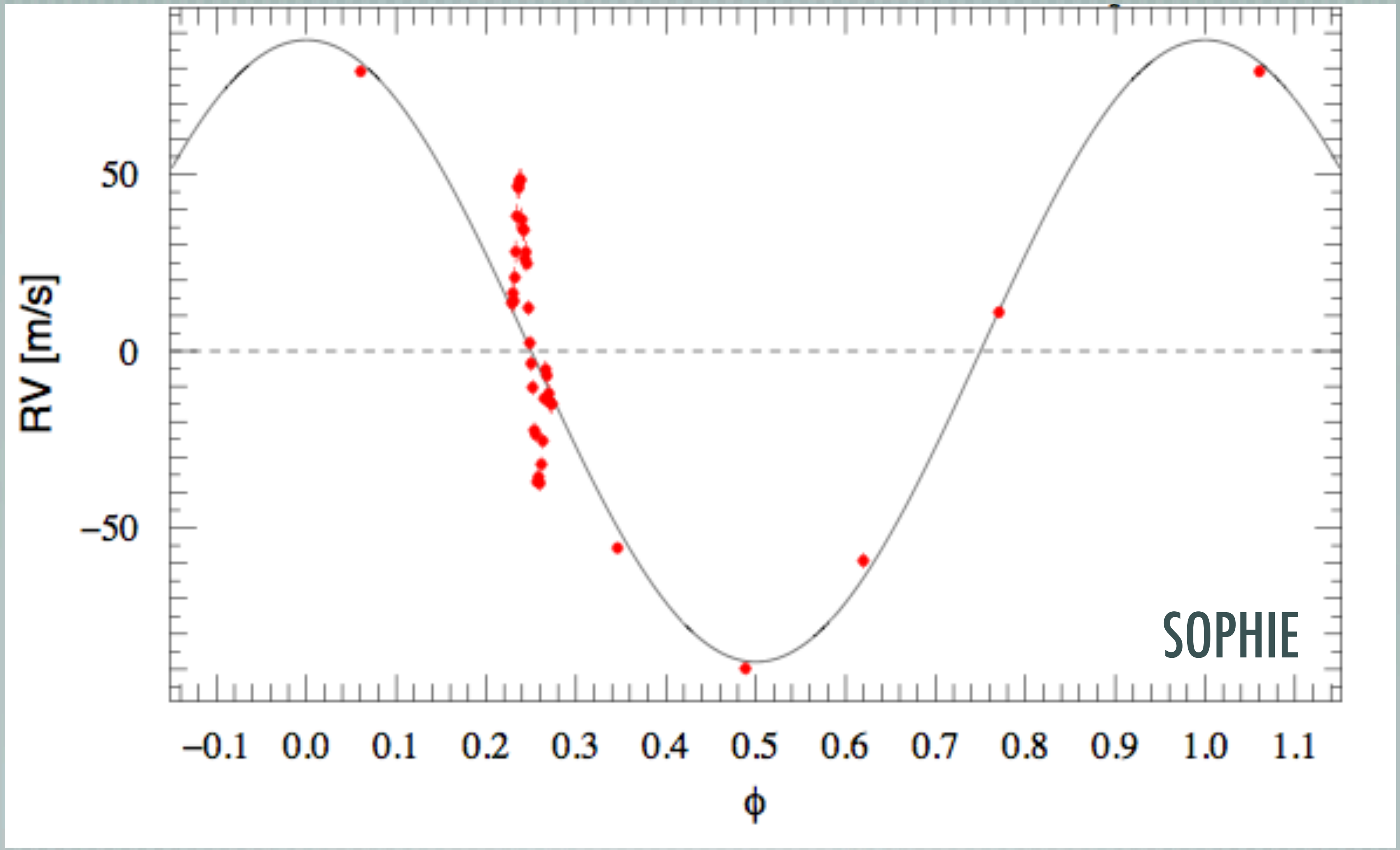
A method to measure the spin-orbit angle of planets



Winn (2009)

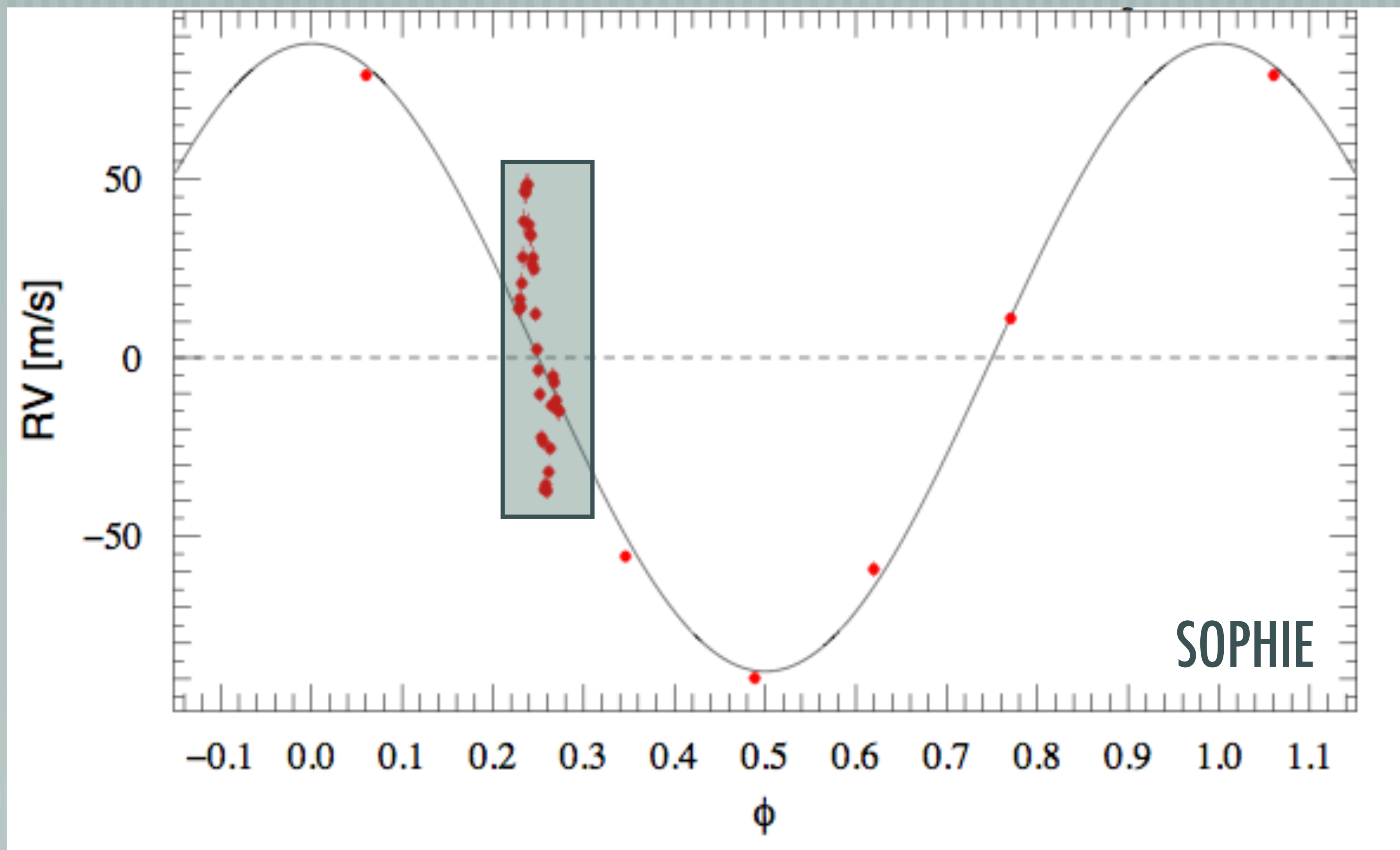
Rossiter-McLaughlin effect

HD209458 b



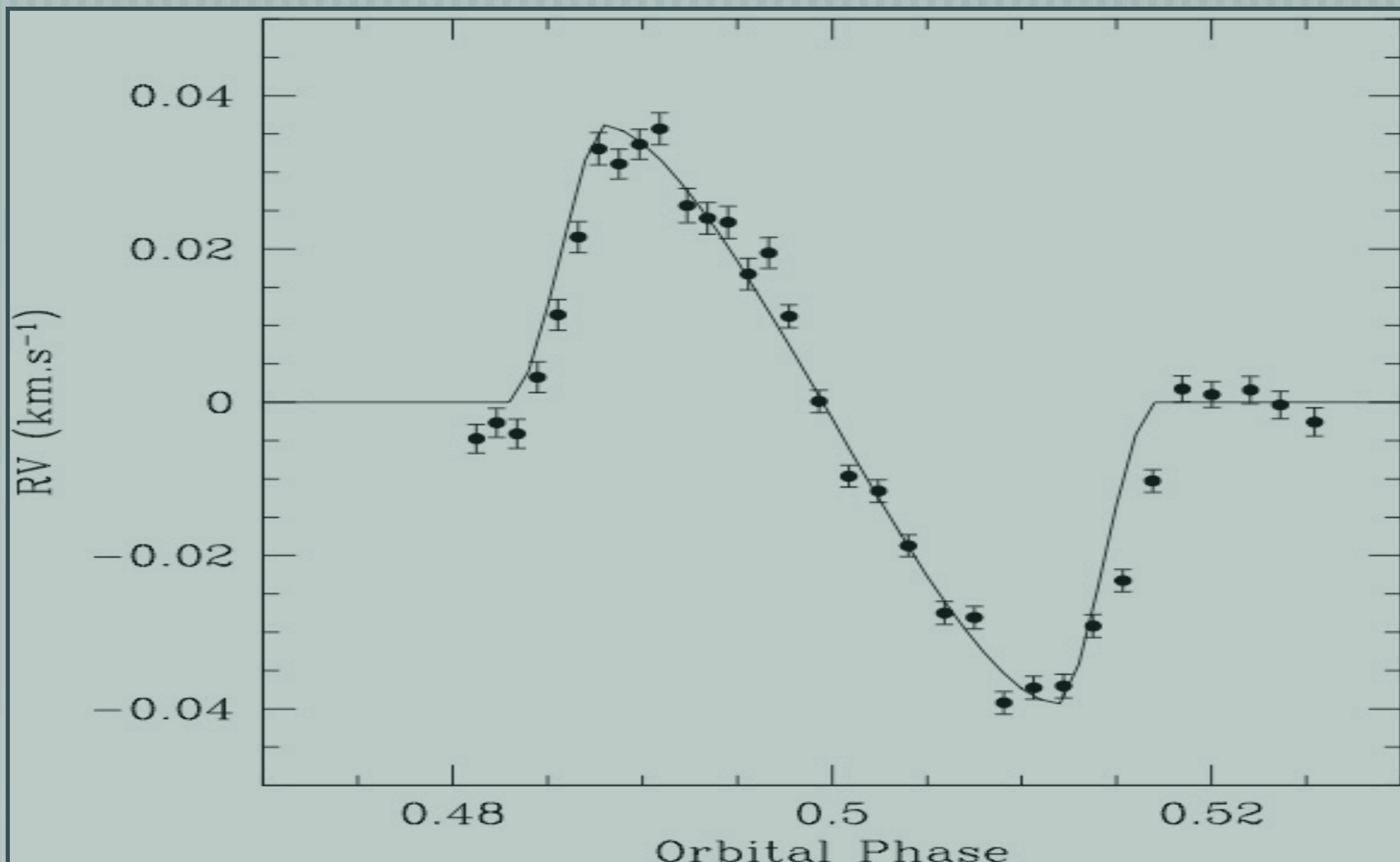
Rossiter-McLaughlin effect

HD209458 b



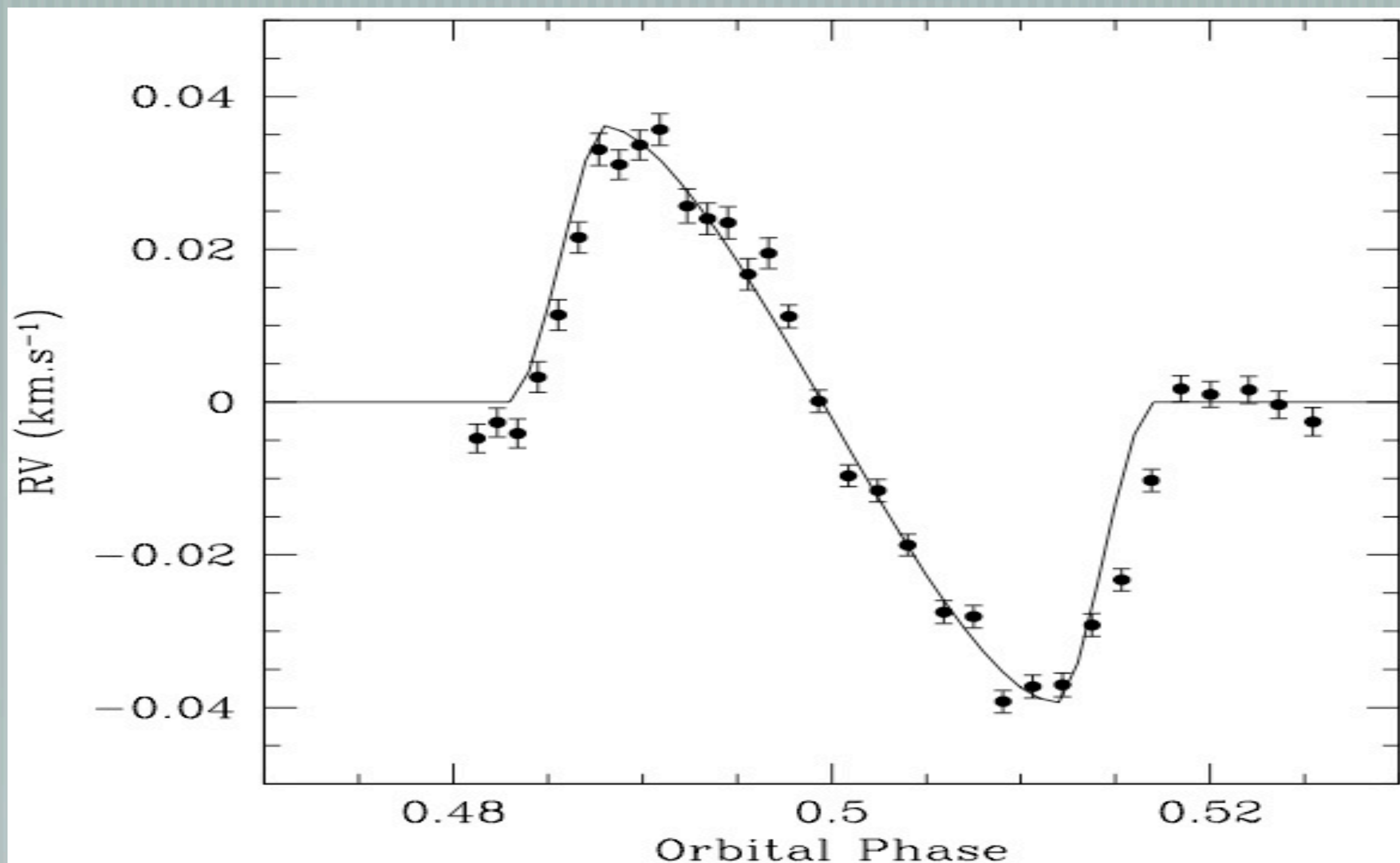
Rossiter-McLaughlin effect

HD209458 b



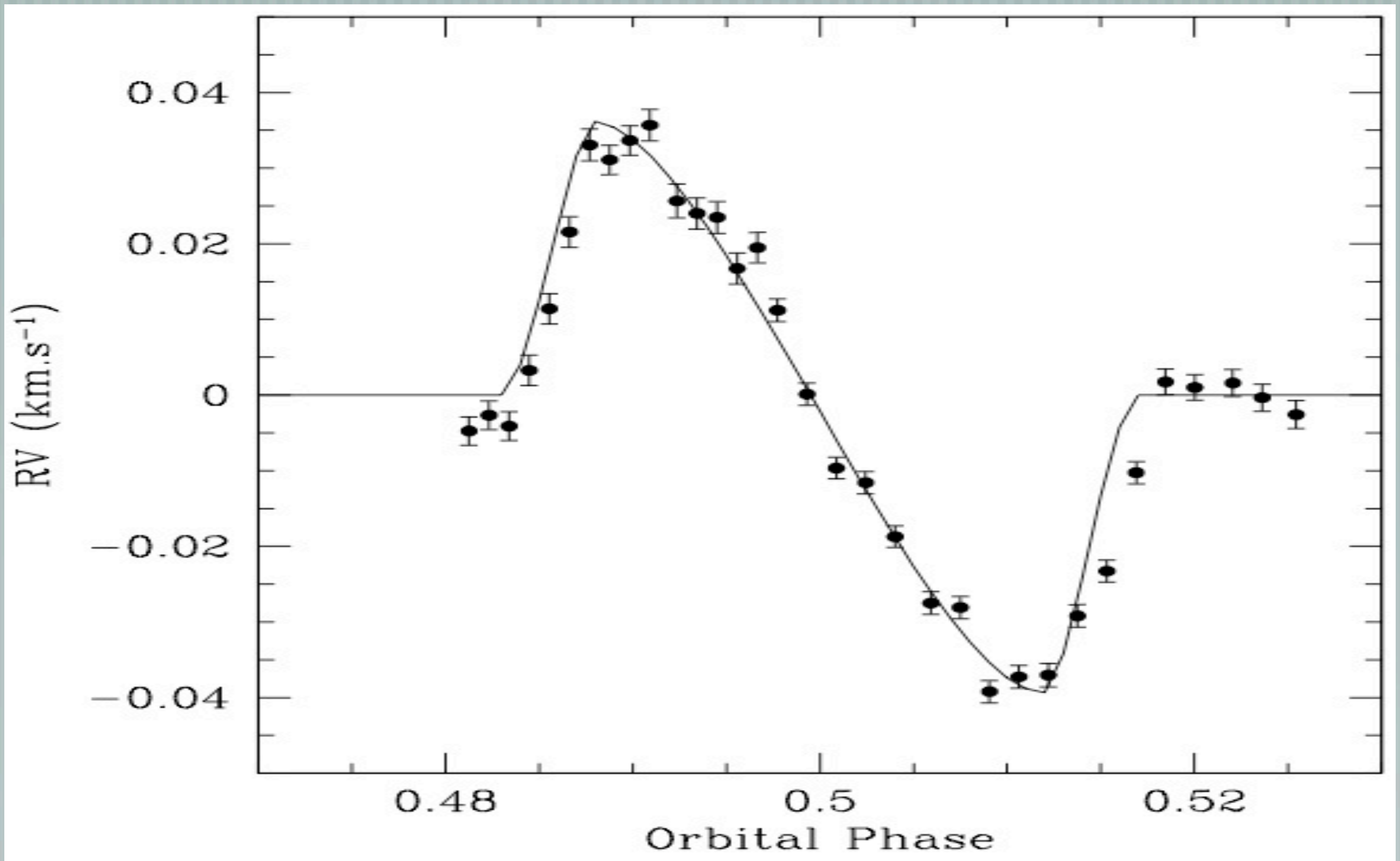
Rossiter-McLaughlin effect

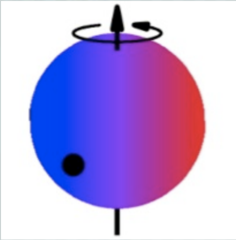
HD209458 b



Rossiter-McLaughlin effect

HD209458 b





Rossiter-McLaughlin effect

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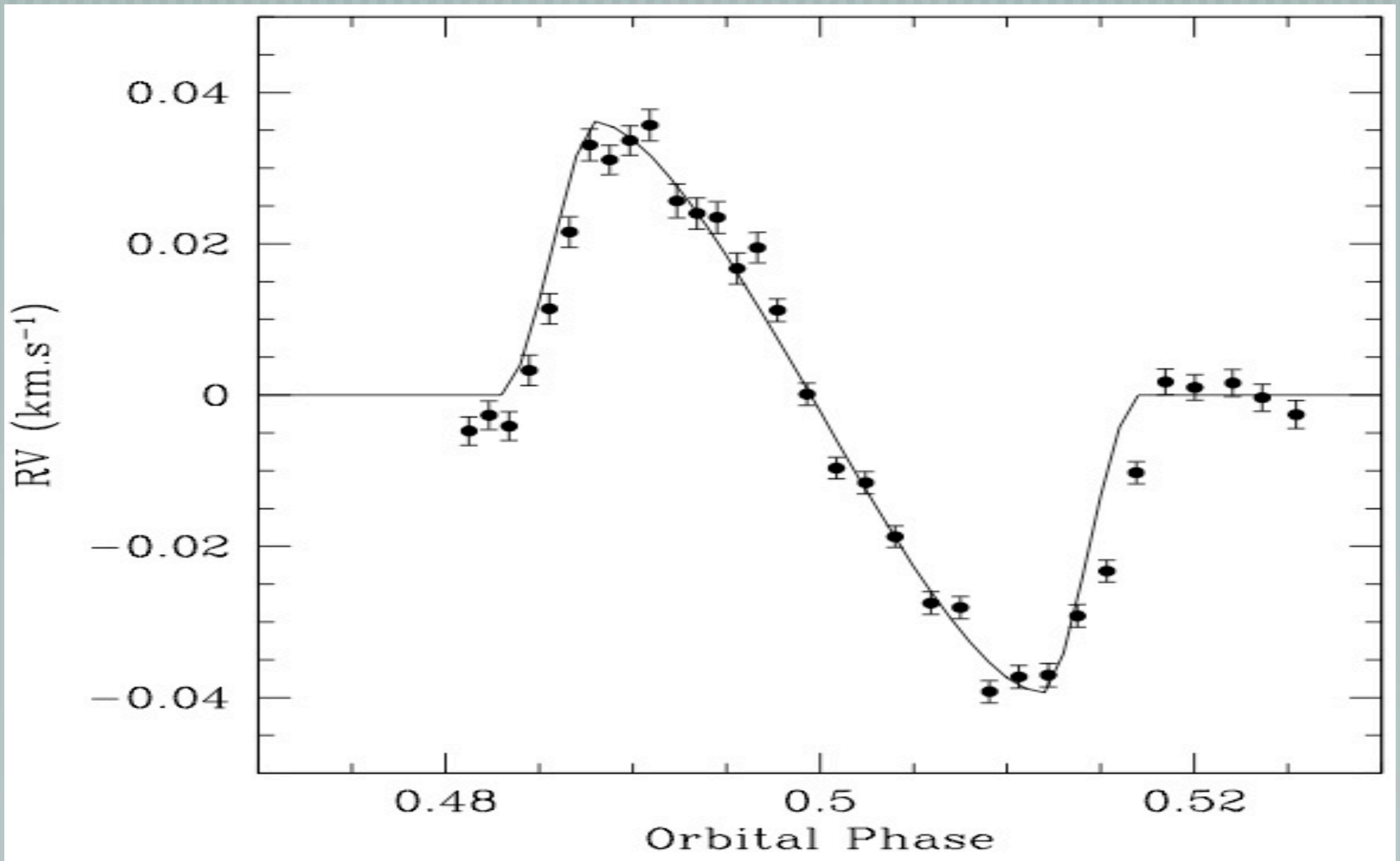
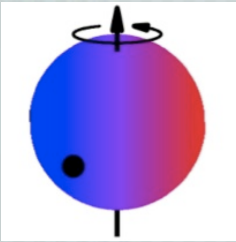
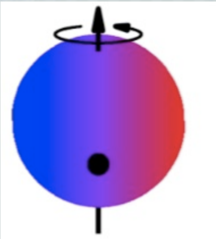
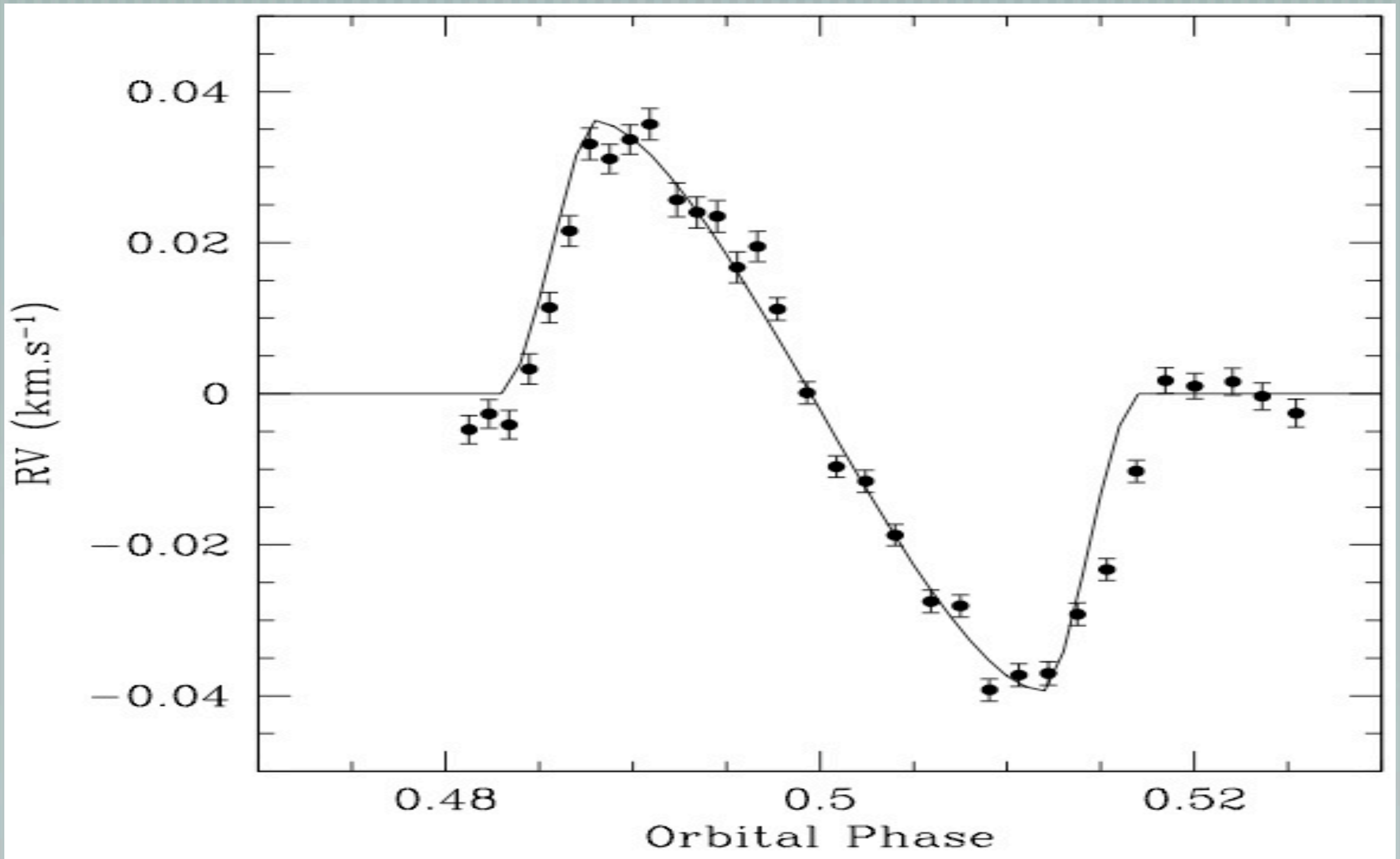


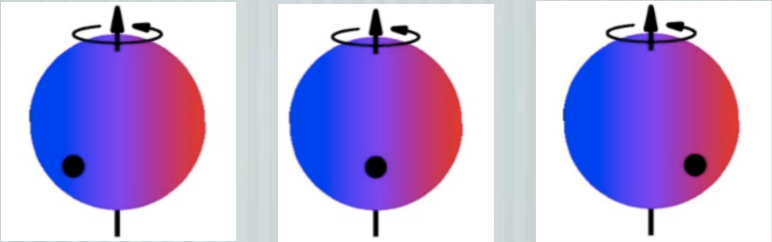




Rossiter-McLaughlin effect

HD209458 b





Rossiter-McLaughlin effect

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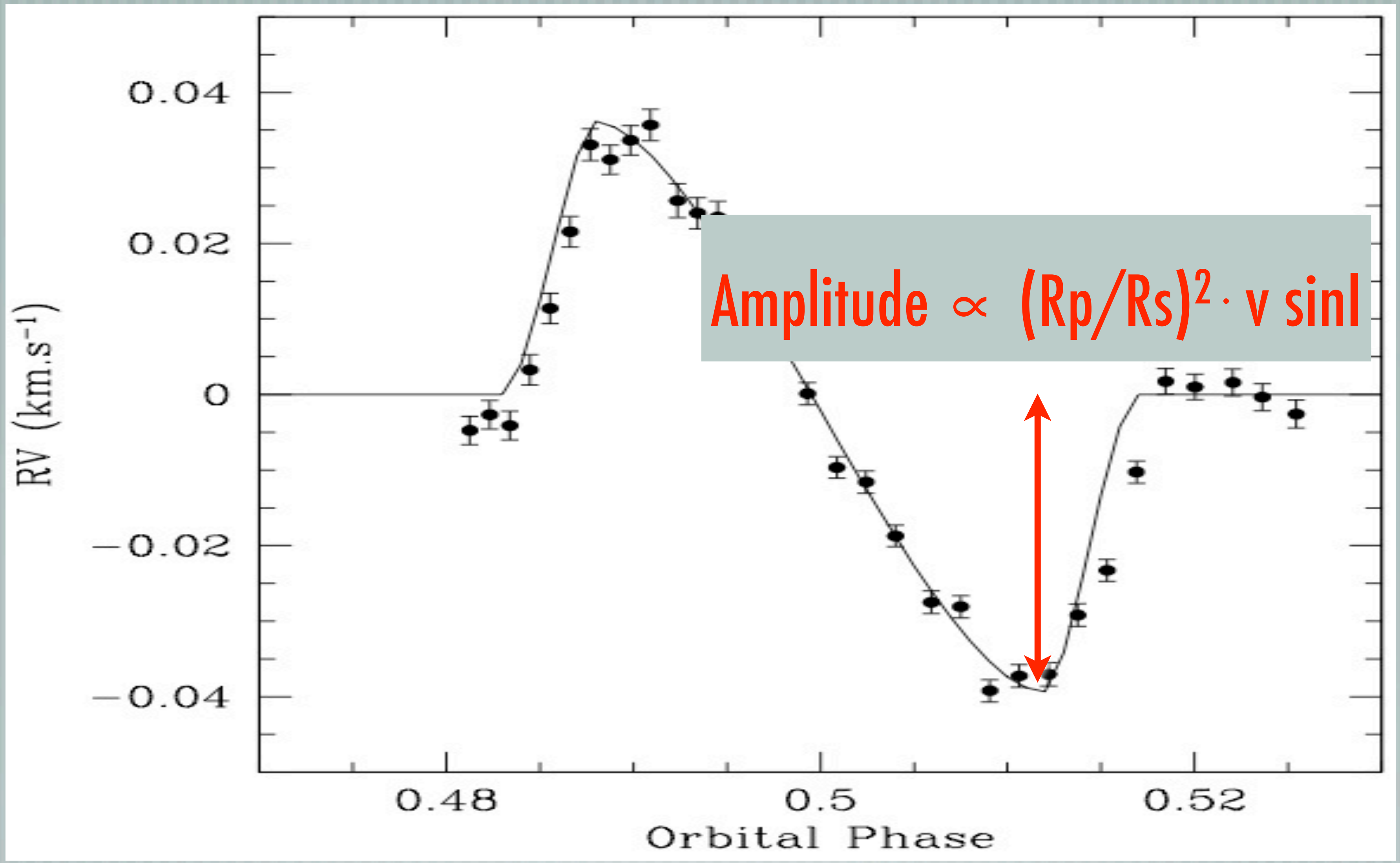
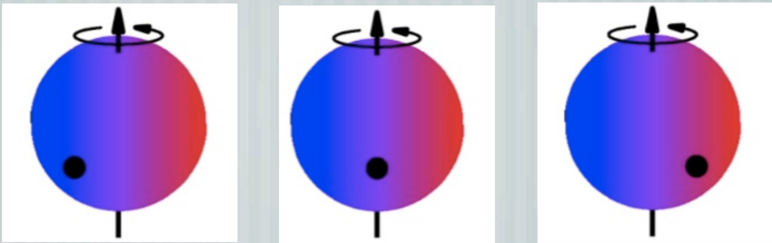
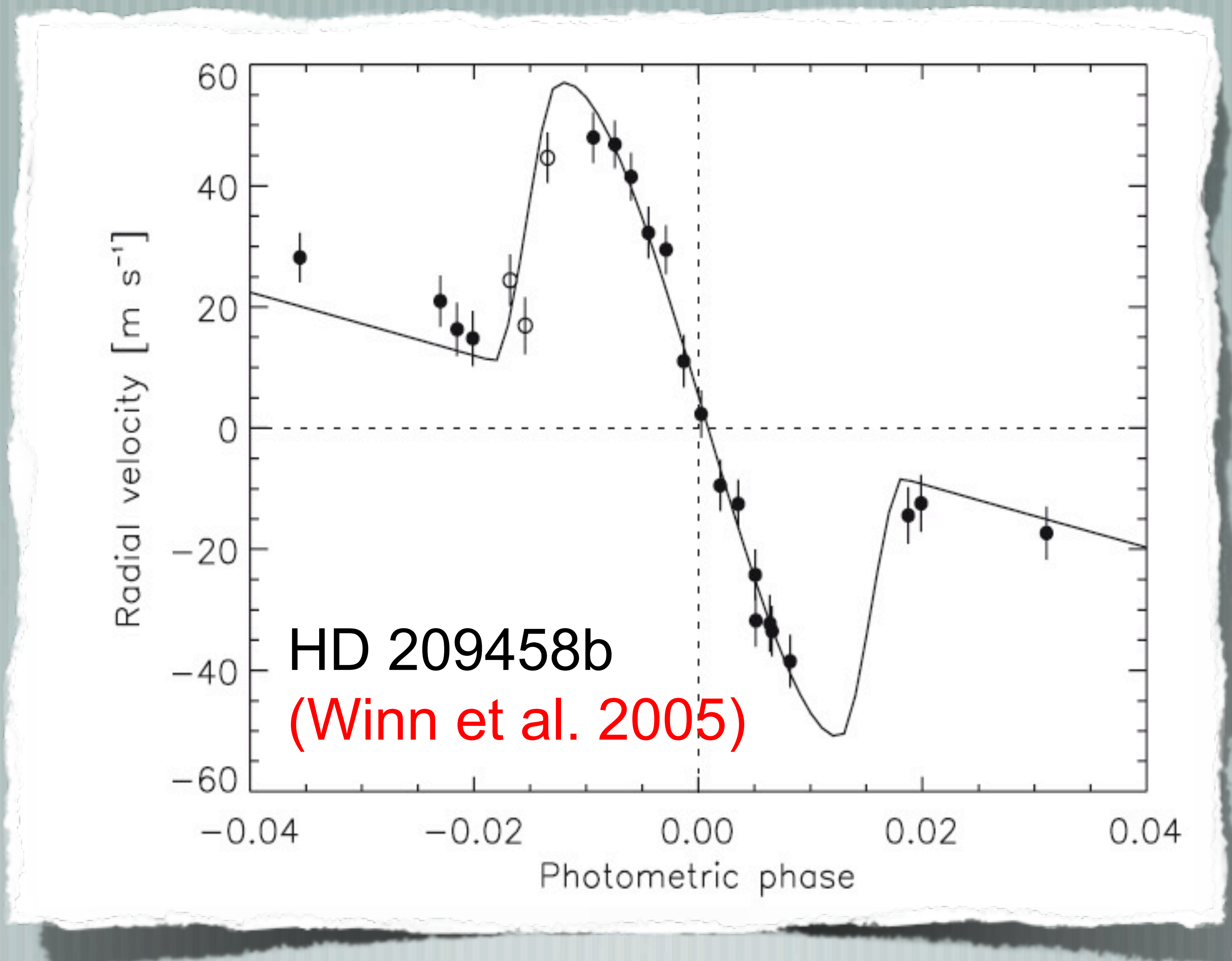
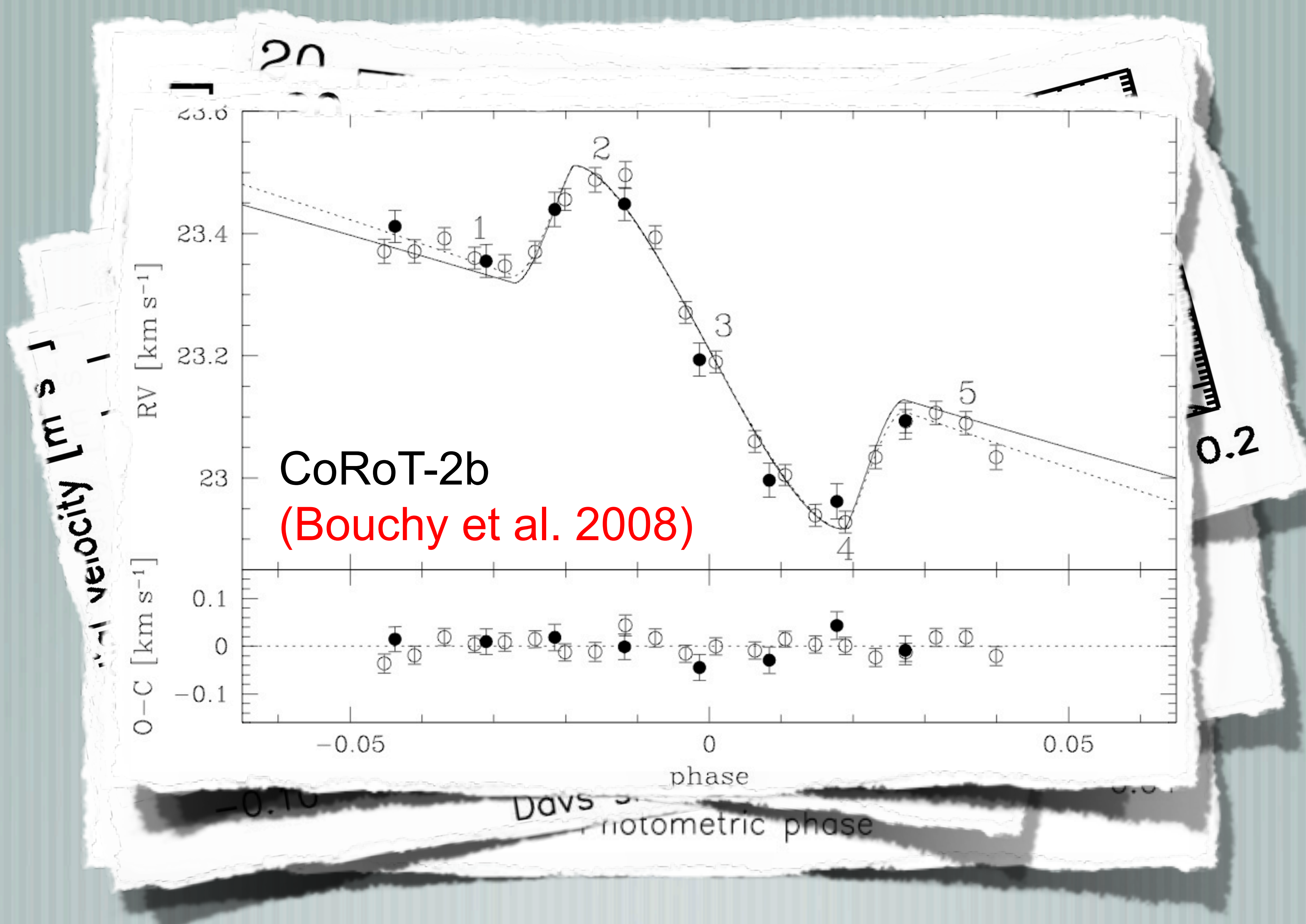




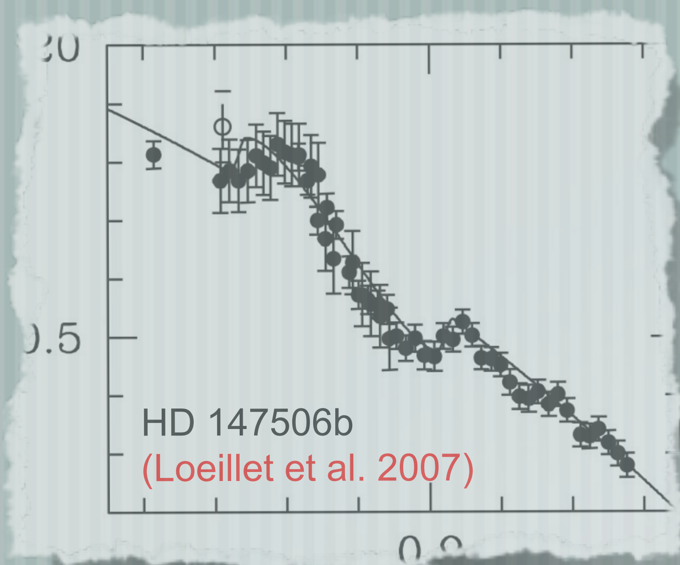
First measurements: alignment galore

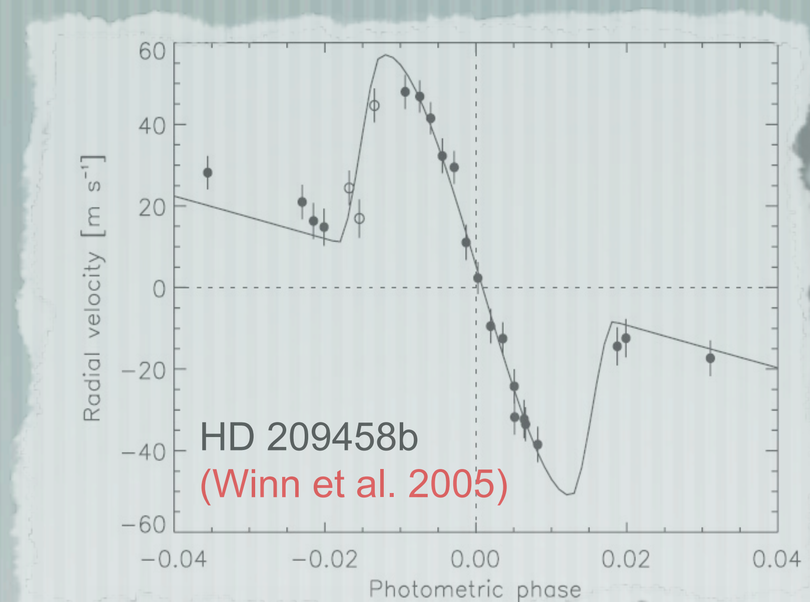


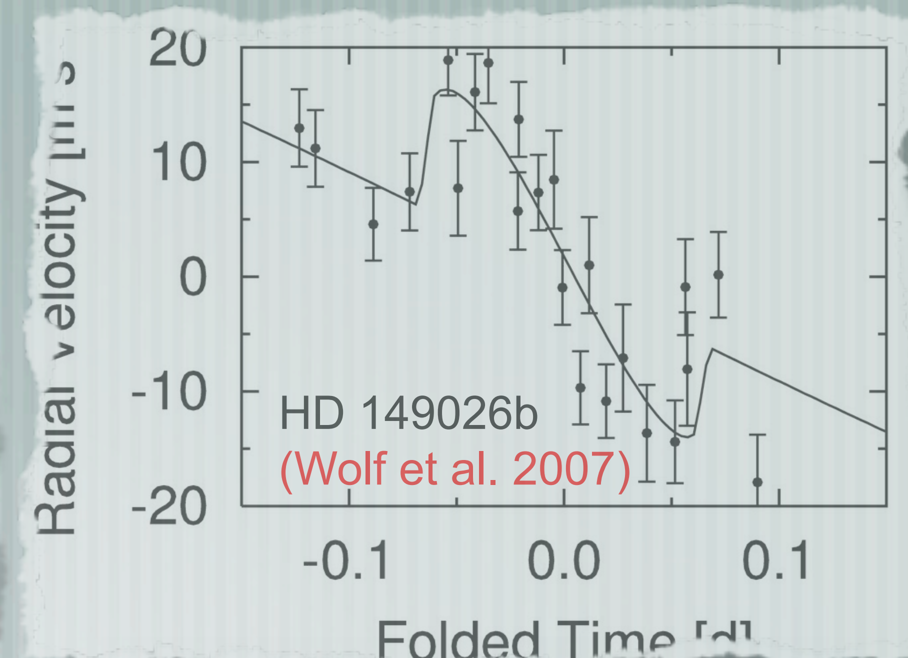
First measurements: alignment galore

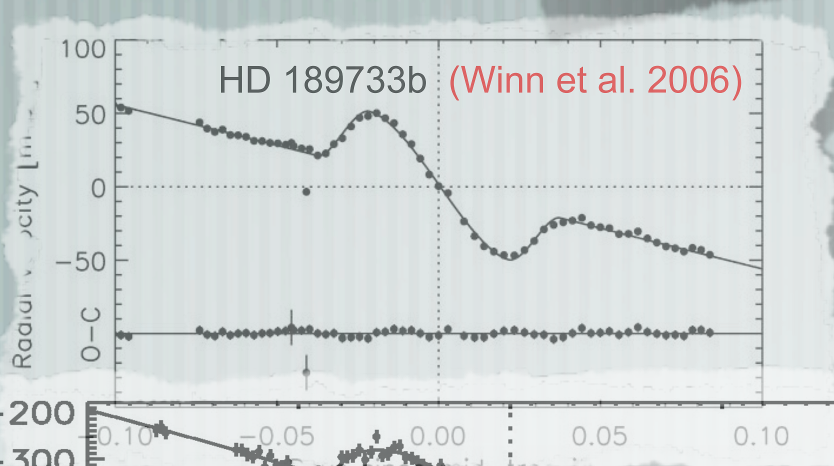


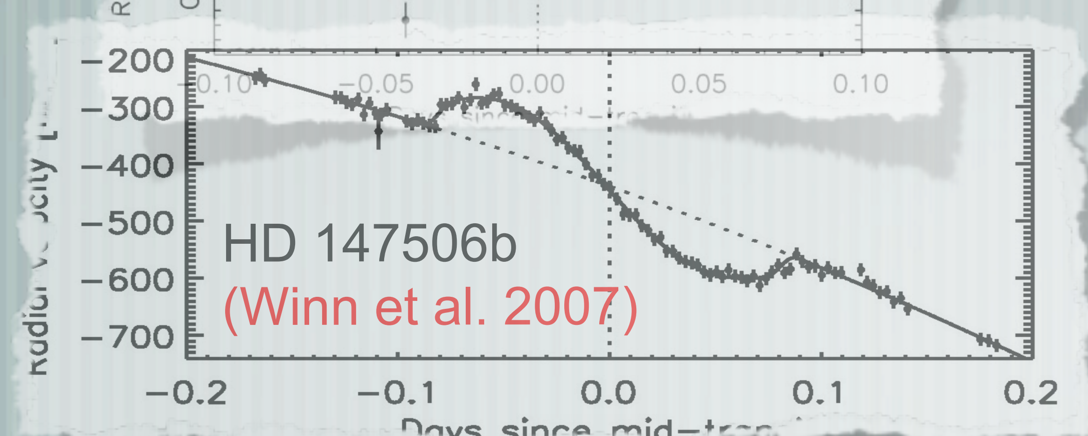
First measurements: alignment galore

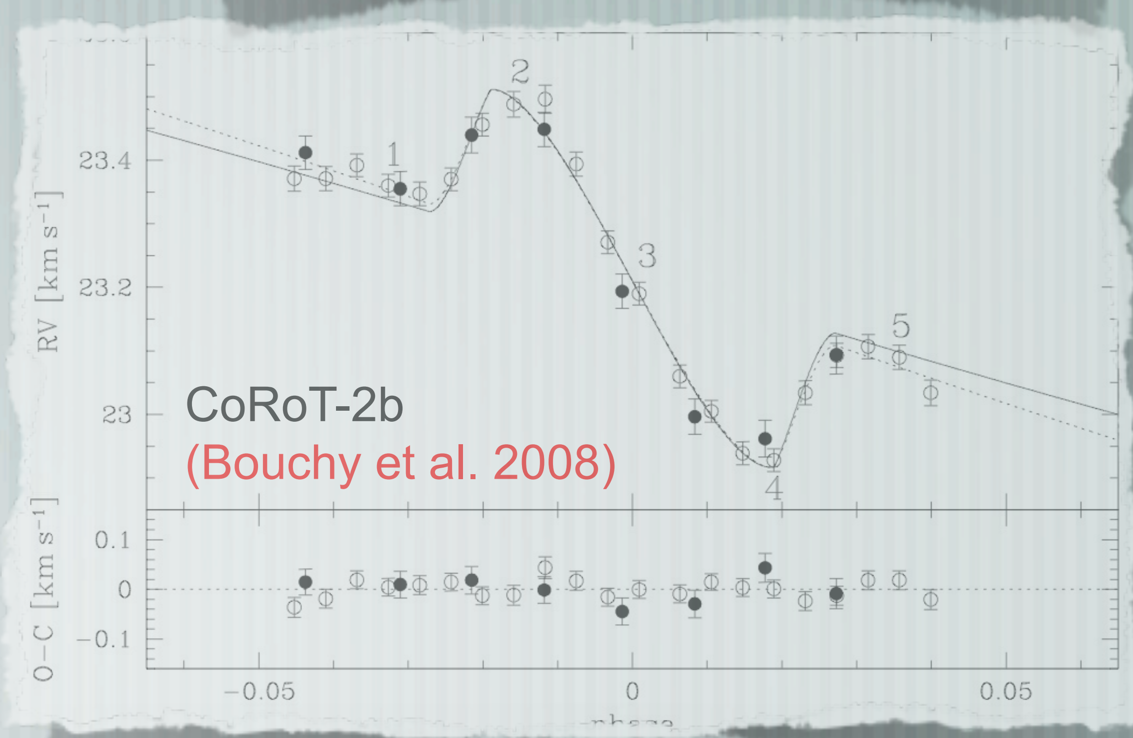








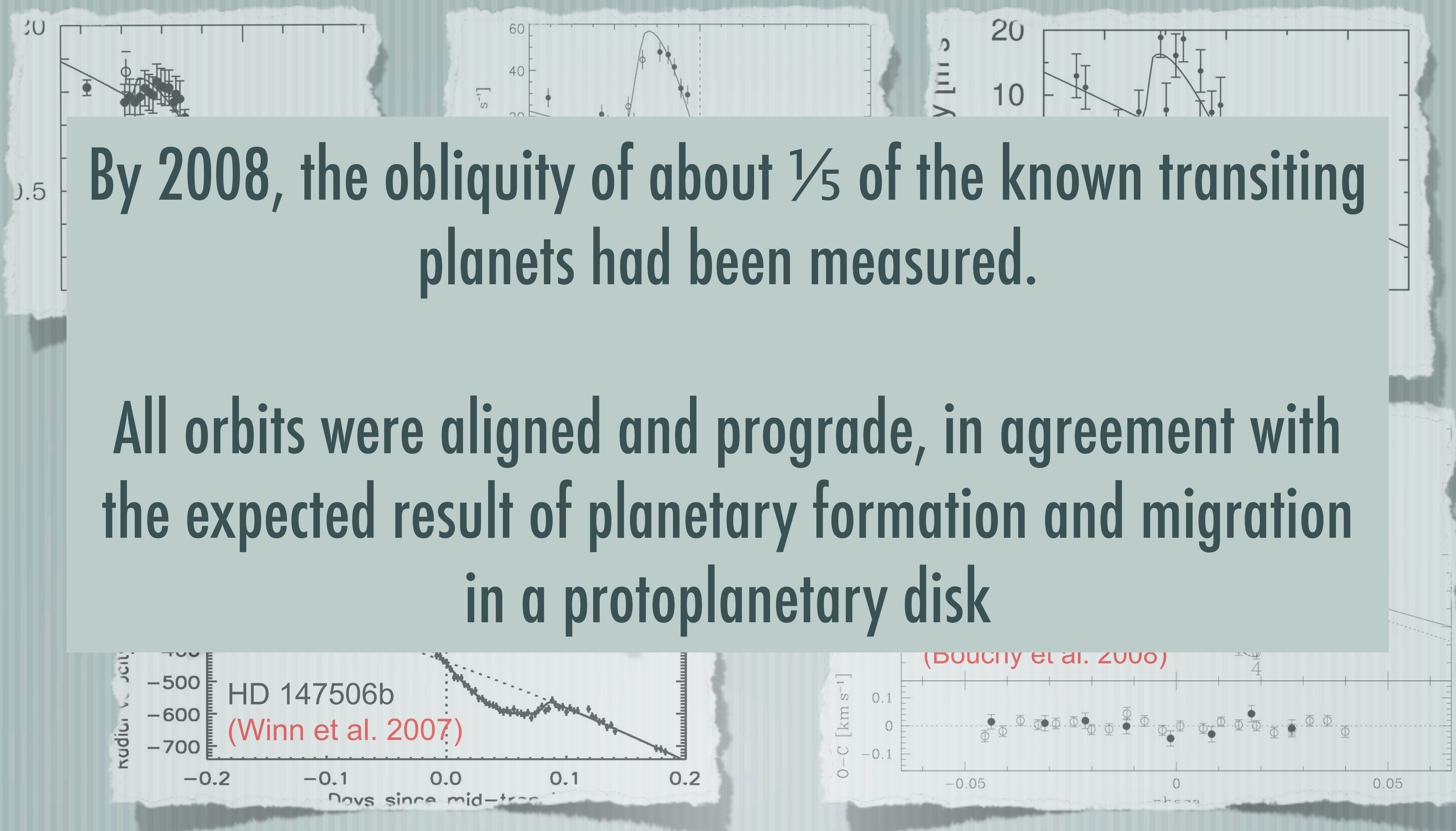




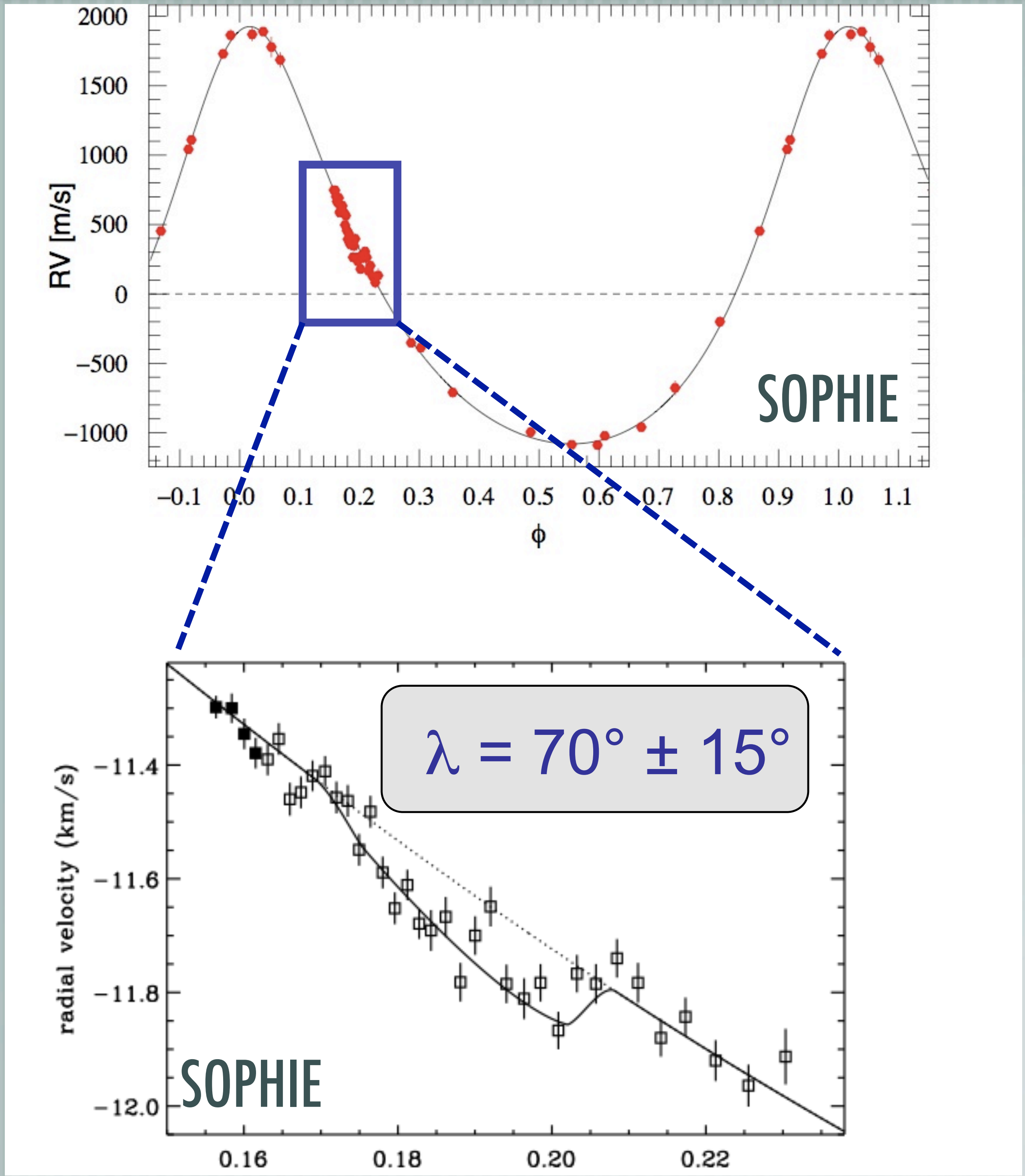
First measurements: alignment galore

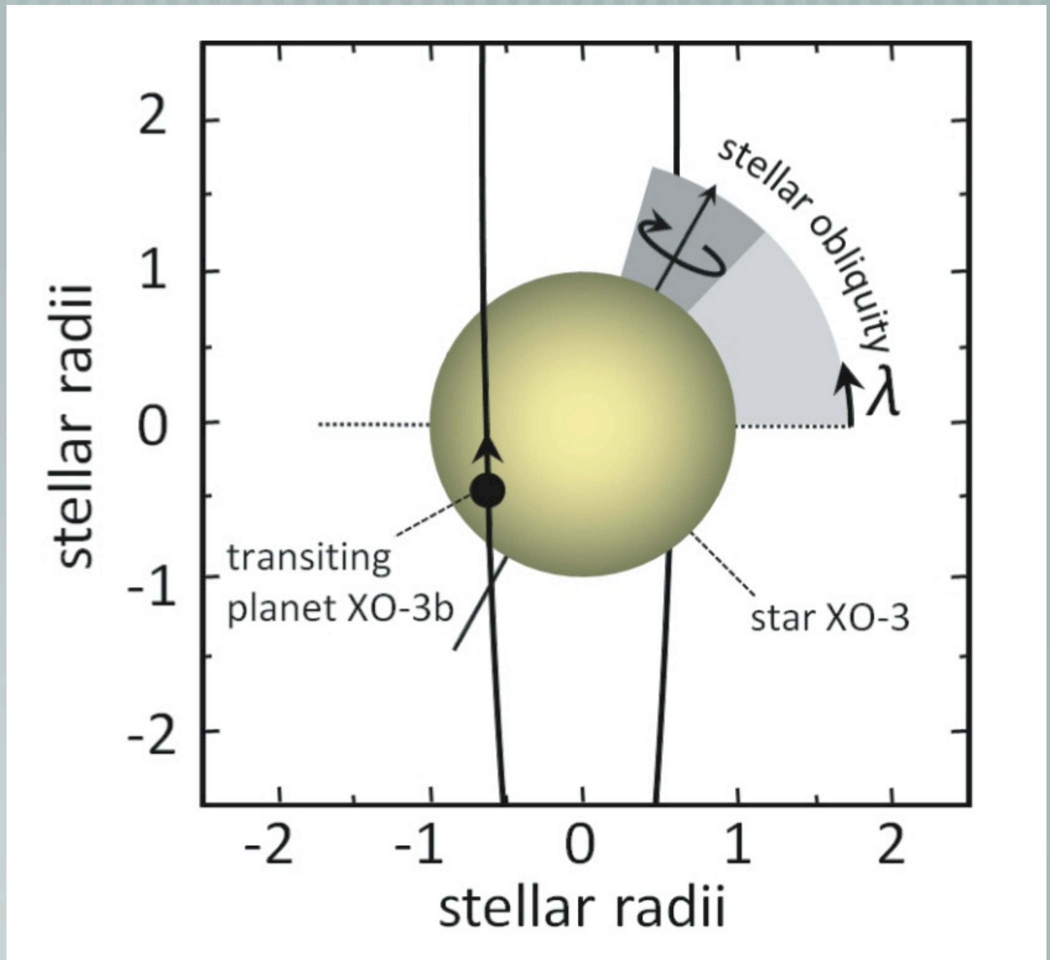
By 2008, the obliquity of about ⅕ of the known transiting planets had been measured.

All orbits were aligned and prograde, in agreement with the expected result of planetary formation and migration in a protoplanetary disk



The first case of a misaligned system, XO-3 b



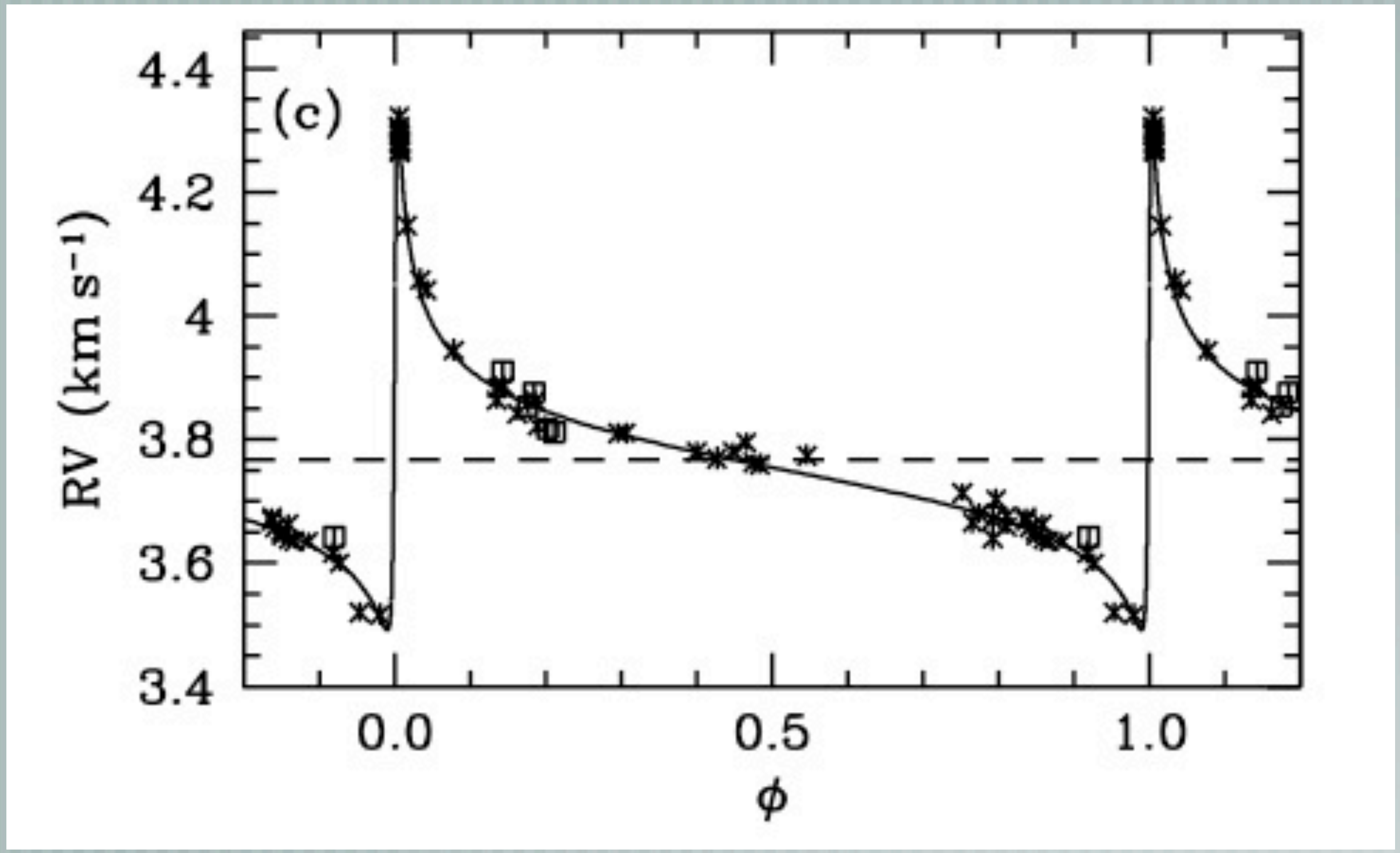


Confirmed in 2009 by Winn et al.

Hébrard, Bouchy, Pont et al. (2008)

A long-period transiting planet in a very eccentric misaligned orbit

HD 80606 b; P = 111 days; ecc = 0.93



Naef, et al. (2001)

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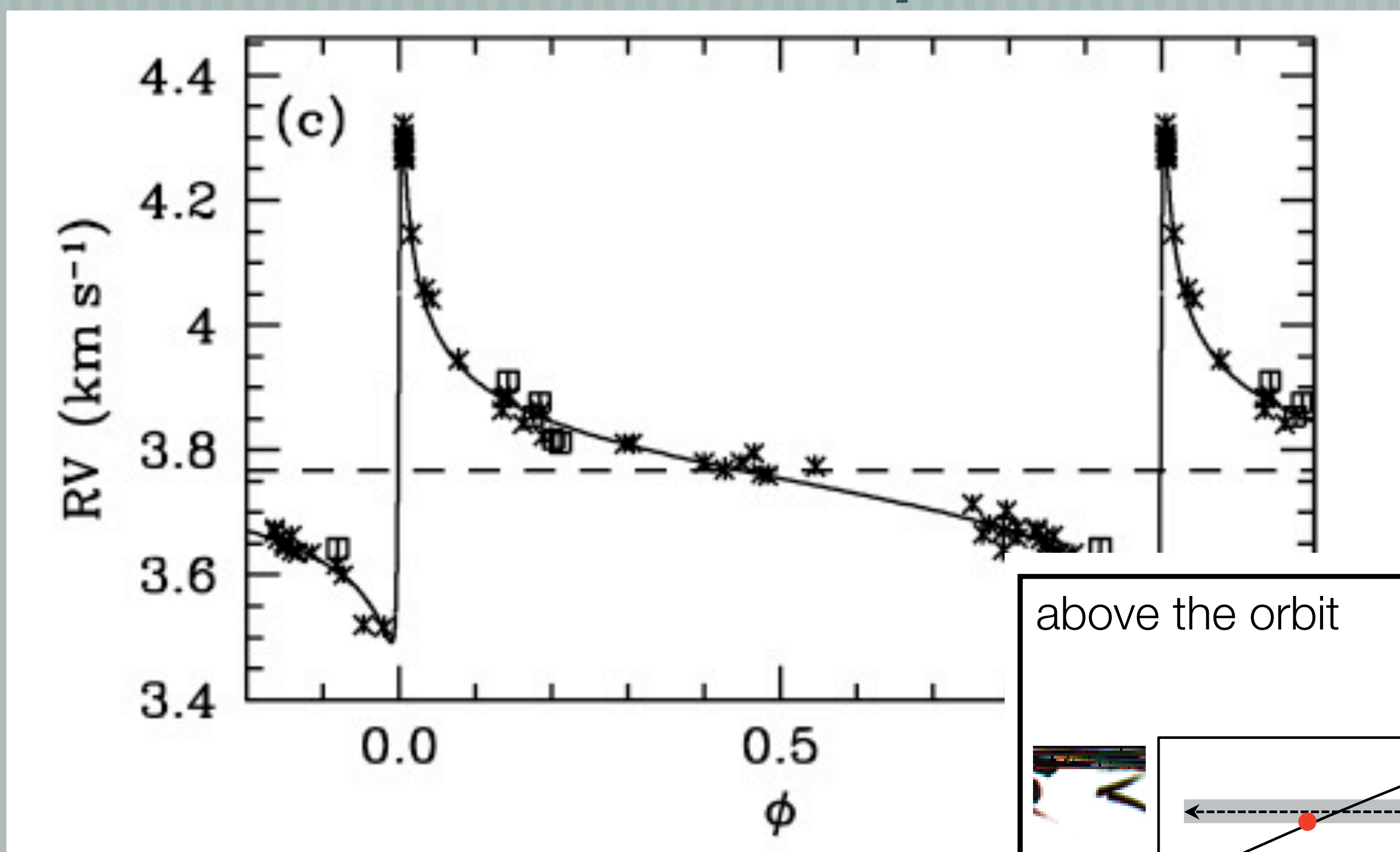
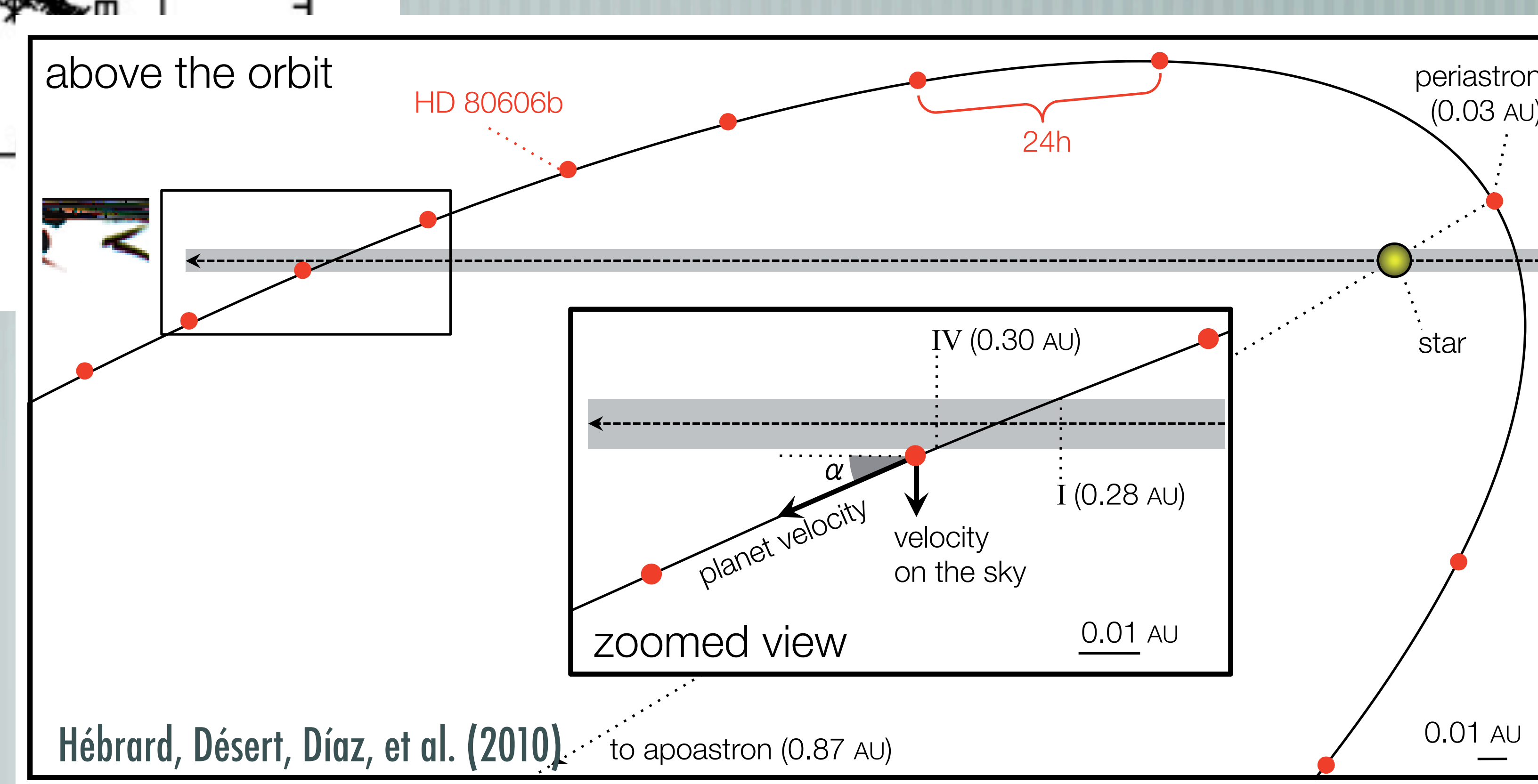


Naef, et al. (2001)



Hébrard, Désert, Díaz, et al. (2010)

A long-period transiting planet in a very eccentric misaligned orbit

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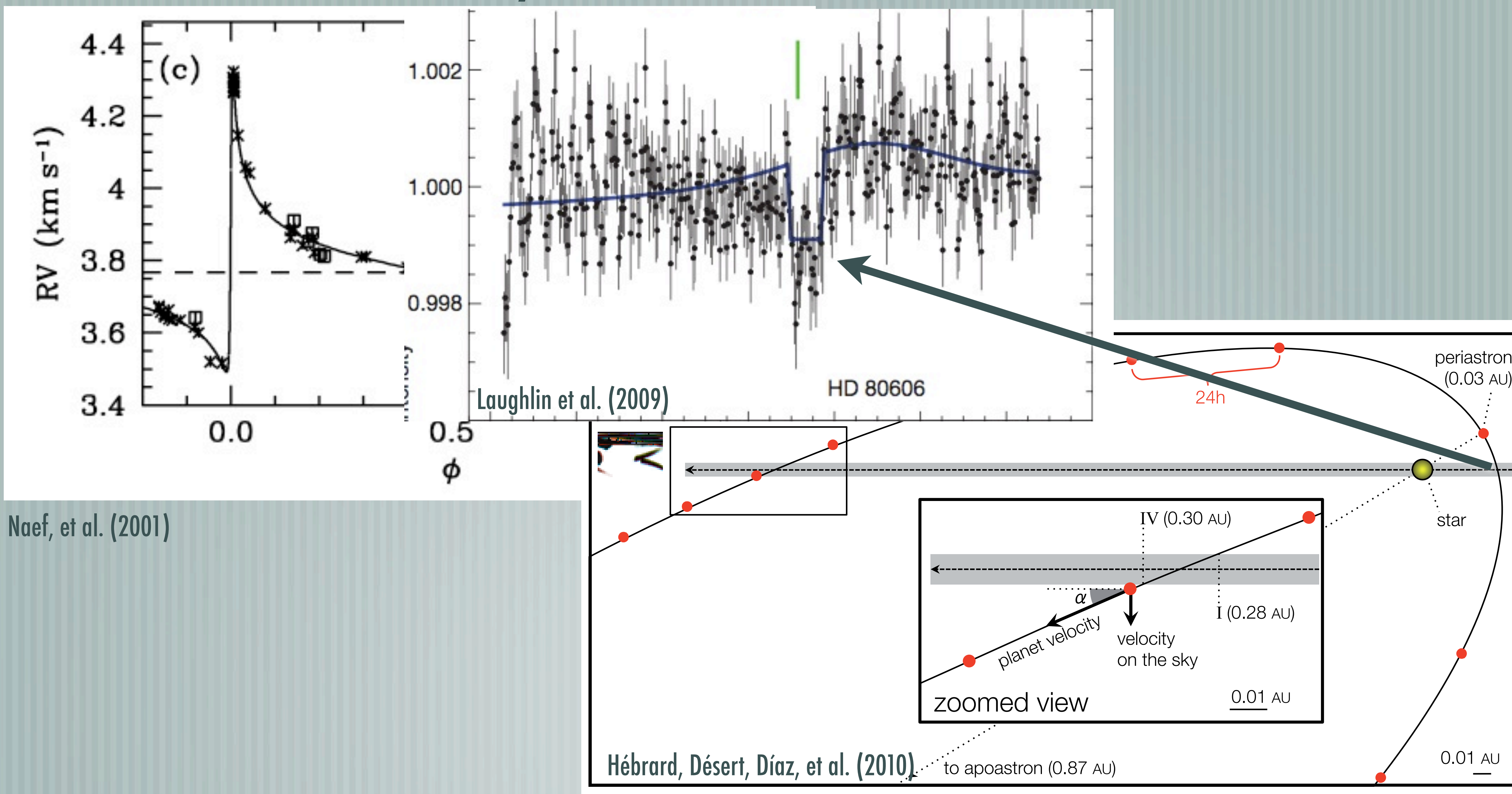

Naef, et al. (2001)

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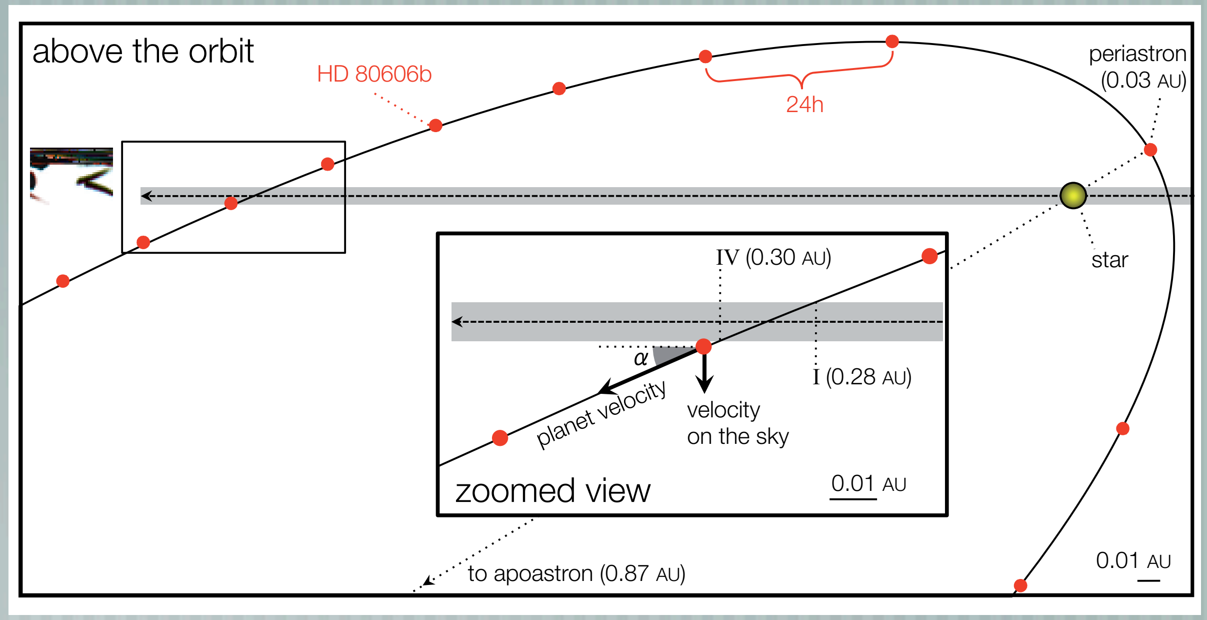

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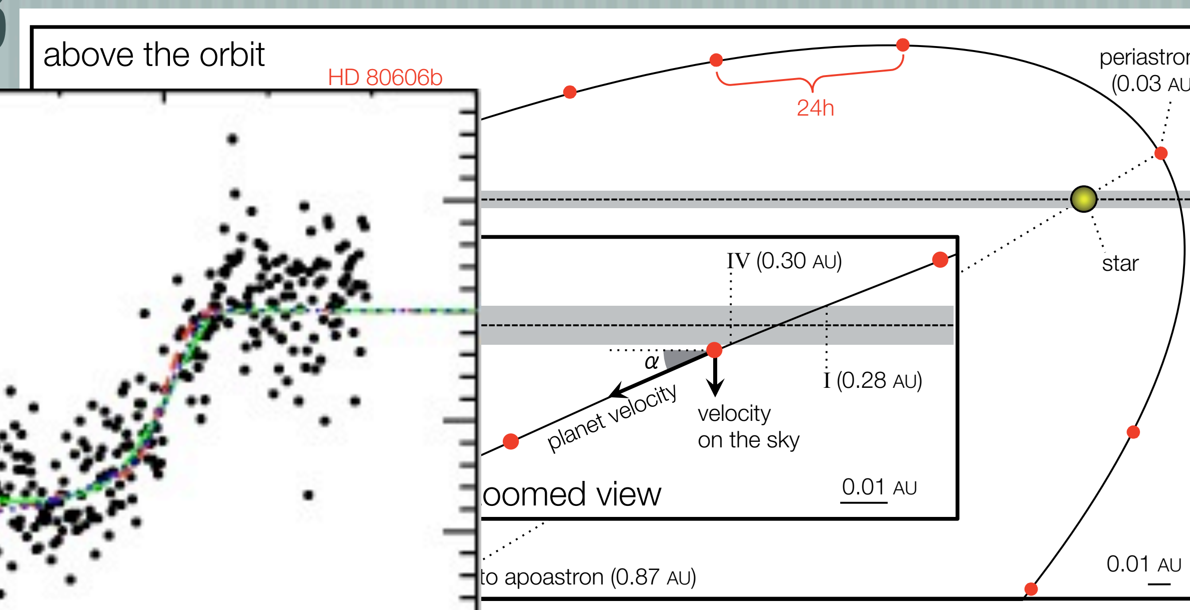
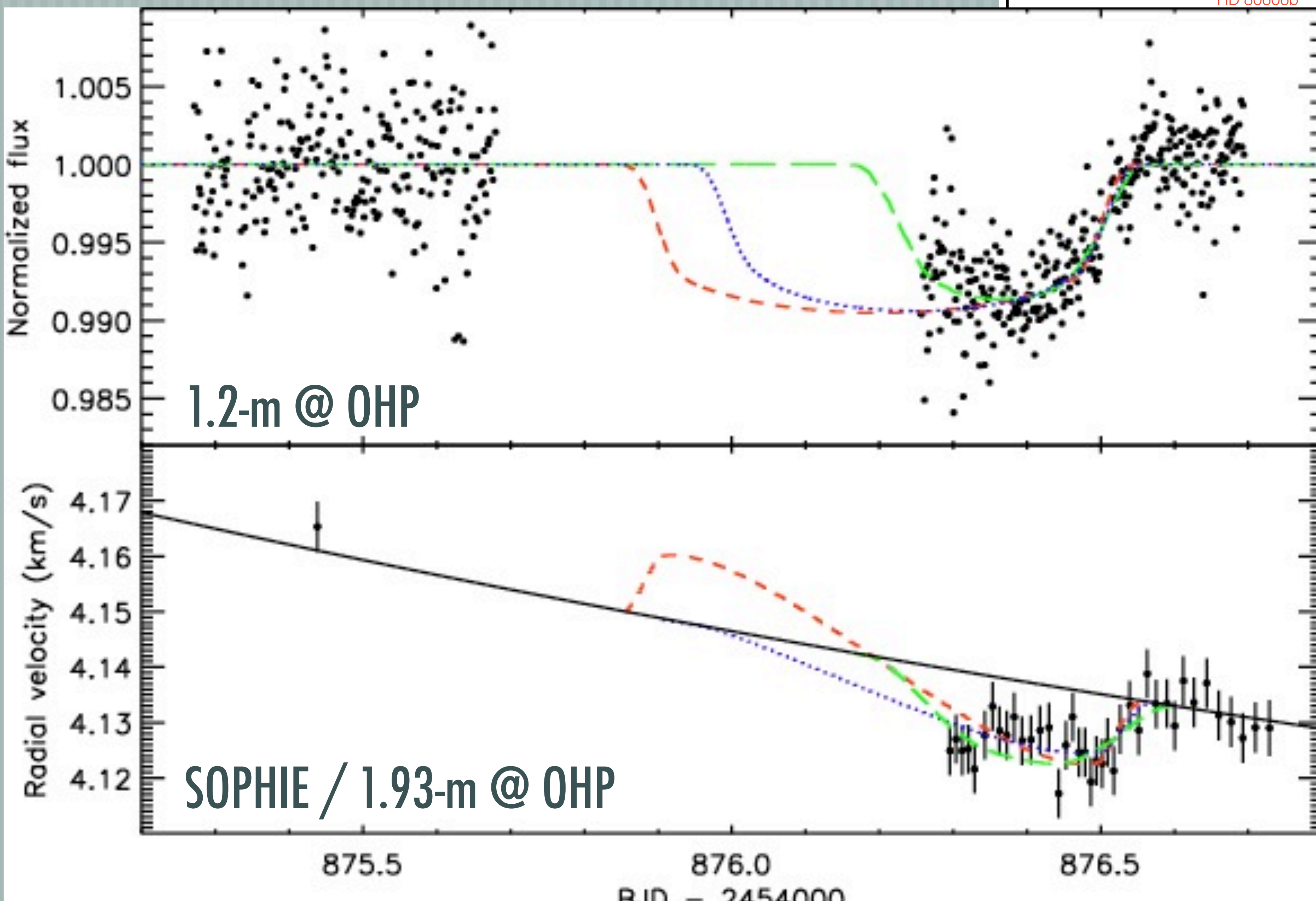
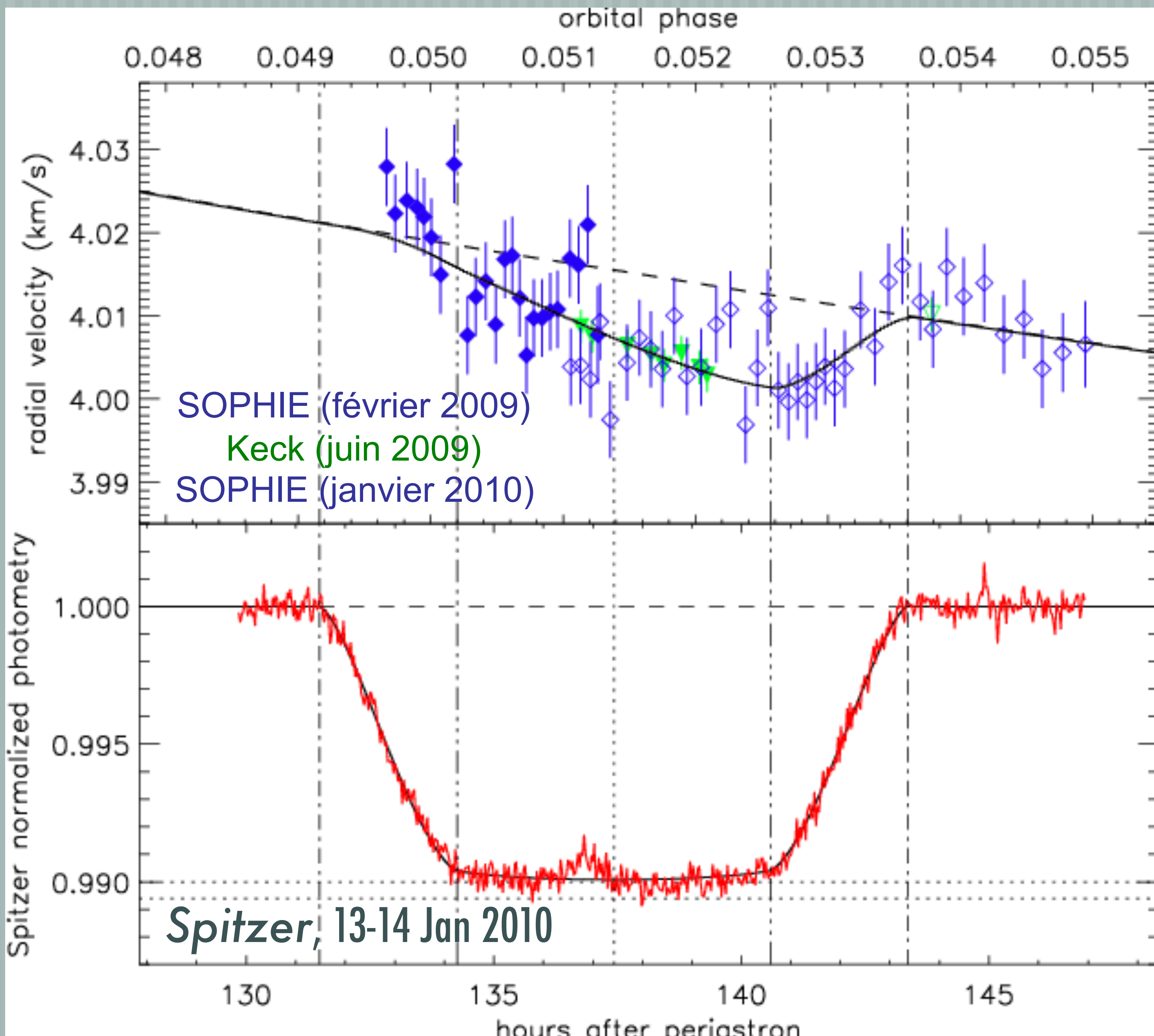
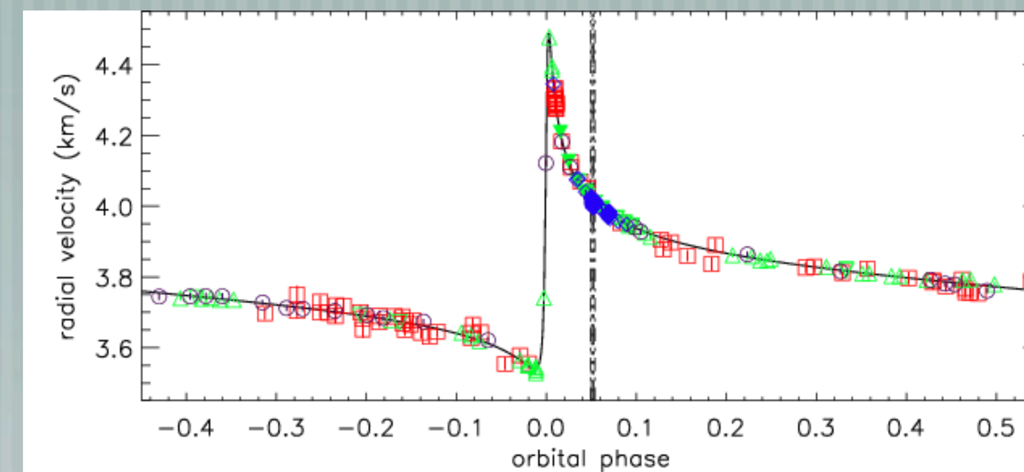




Moutou, Hébrard, Bouchy, et al. (2010)

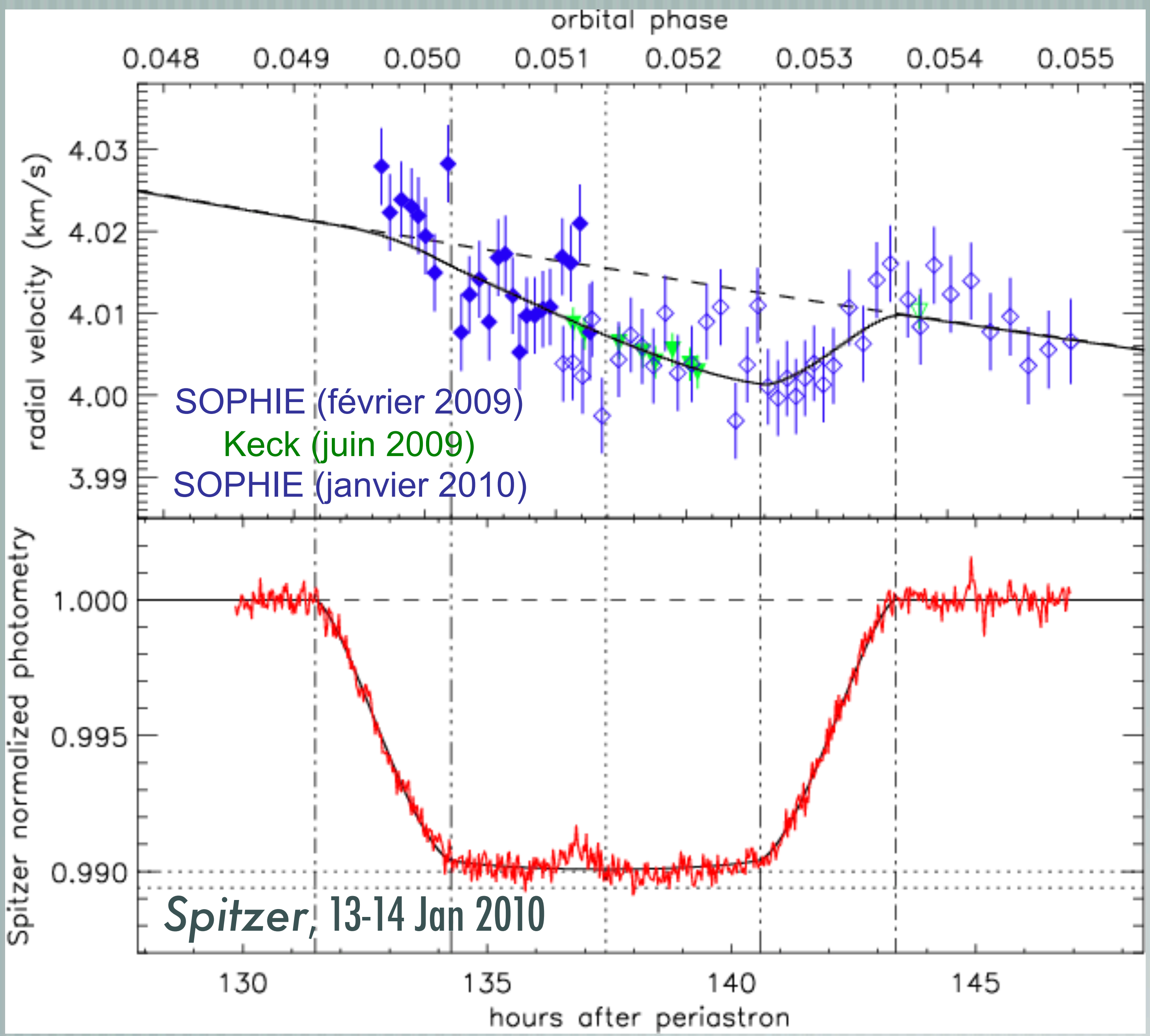
A long-period transiting planet in a very eccentric misaligned orbit



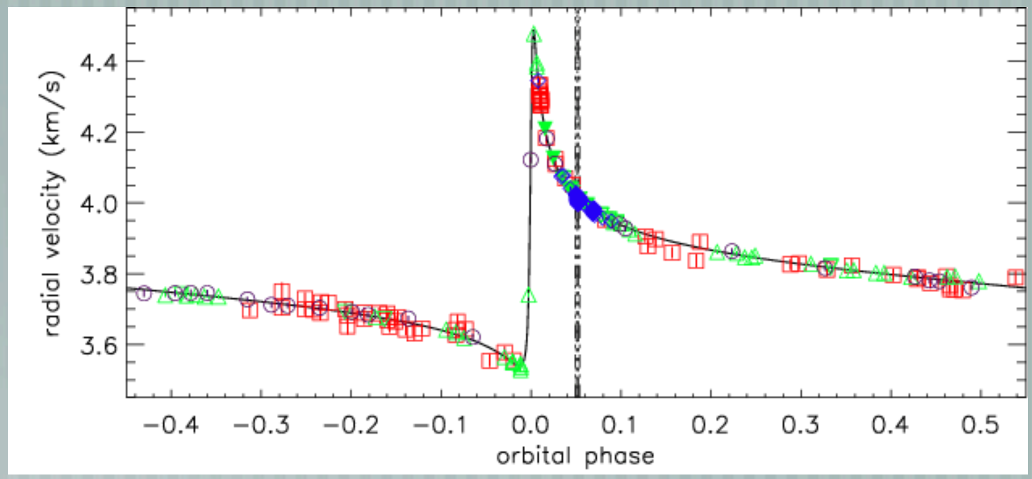


Hébrard, Désert, Díaz, et al. (2010)

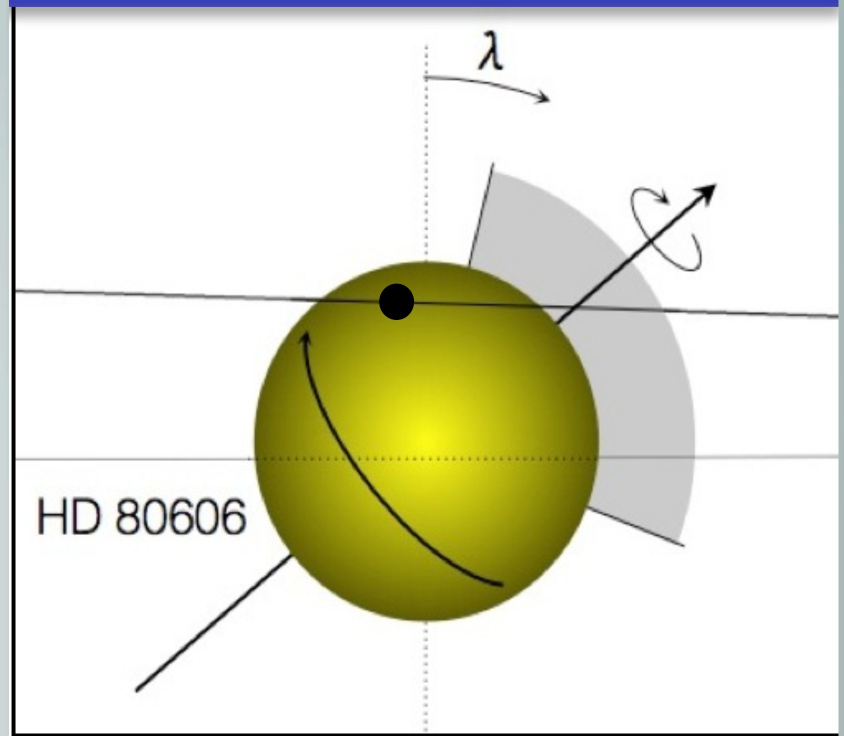
A long-period transiting planet in a very eccentric misaligned orbit



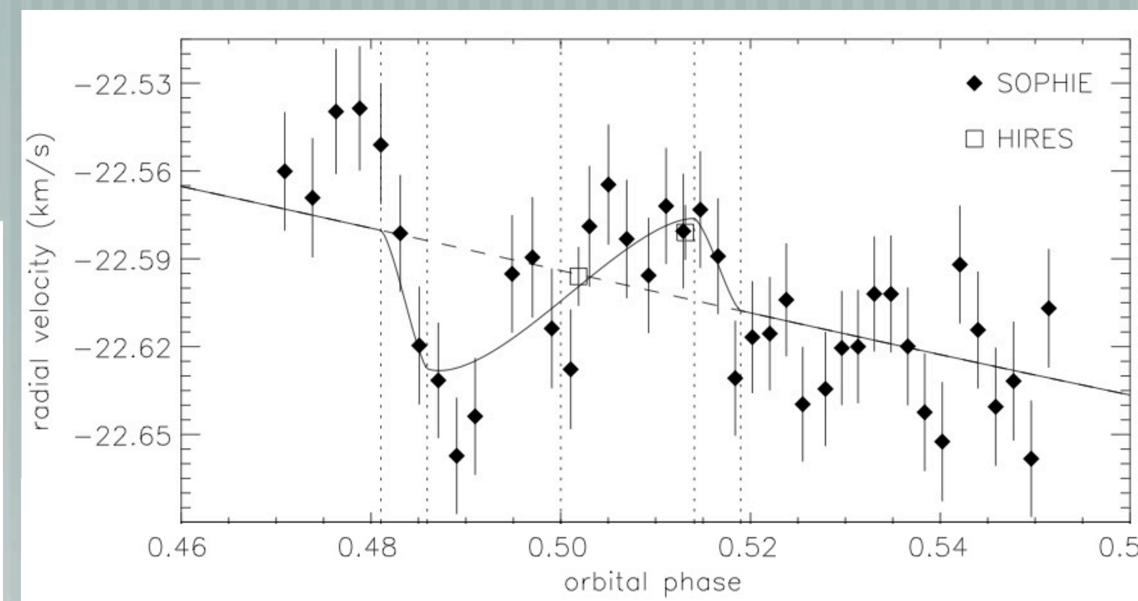
Hébrard, Désert, Díaz, et al. (2010)



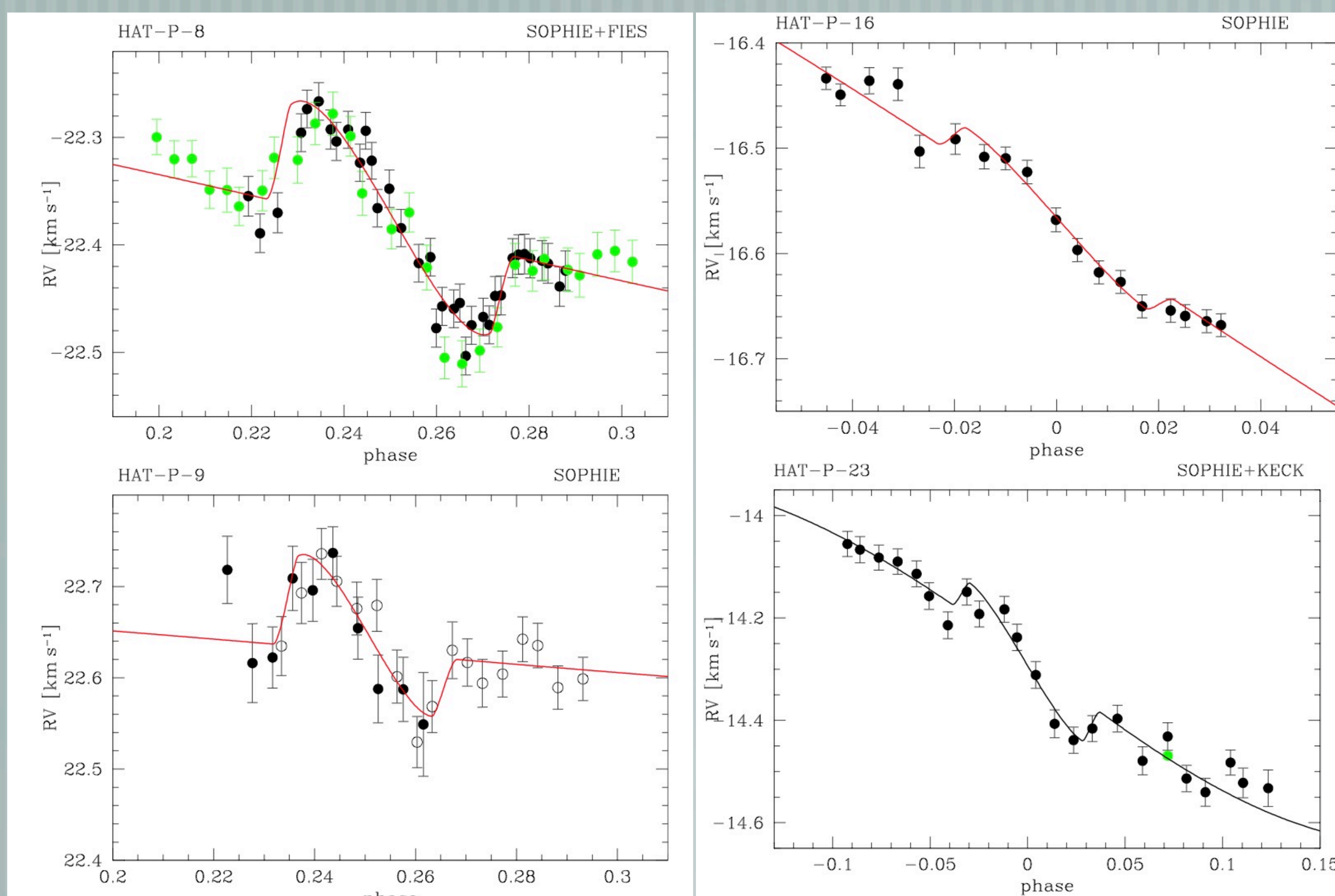
λ = 42° +/- 8°



Towards an explanation of the orbit diversity of giant planets

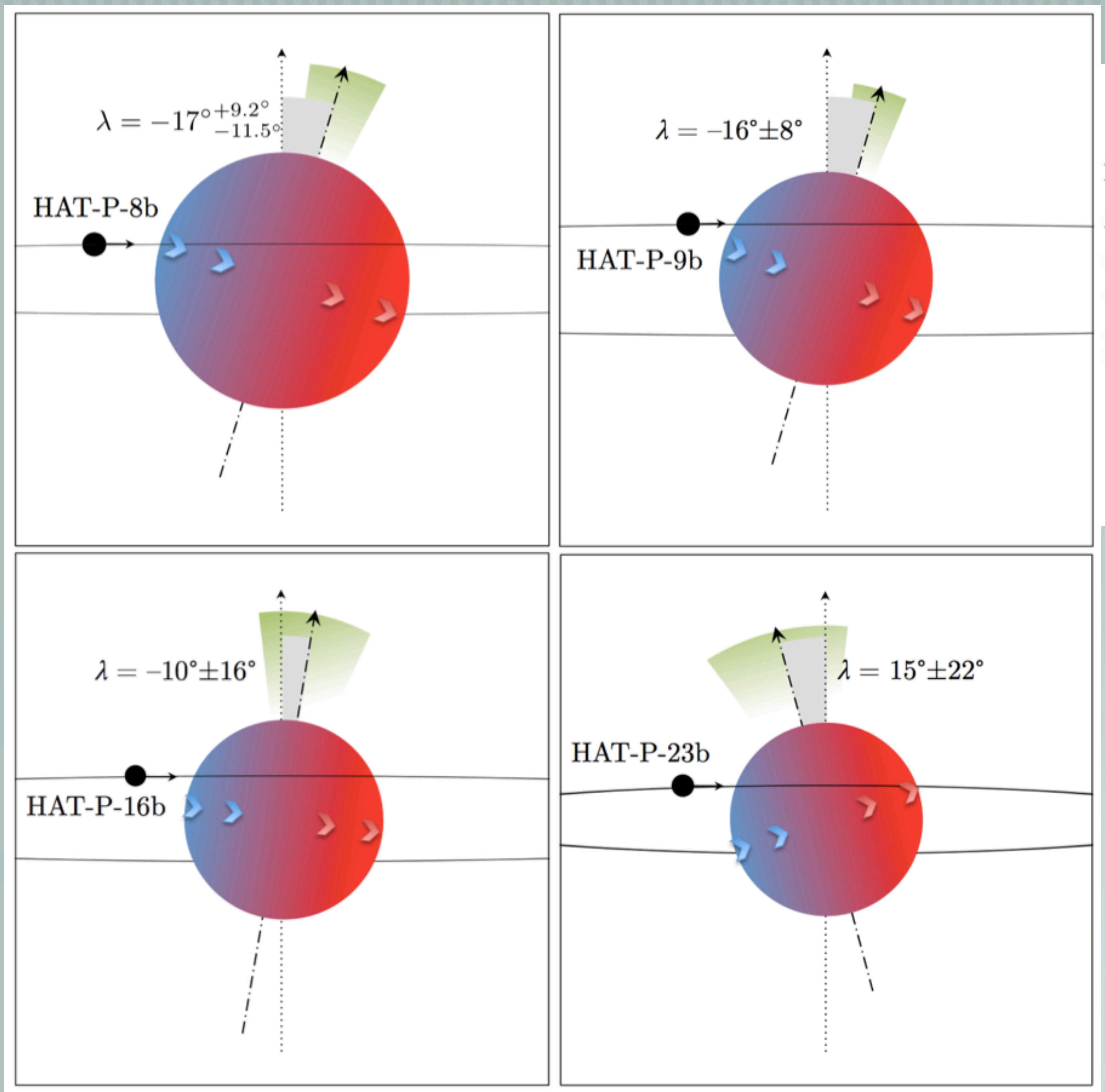


Hébrard, Ehrenreich, Bouchy, et al. (2011)

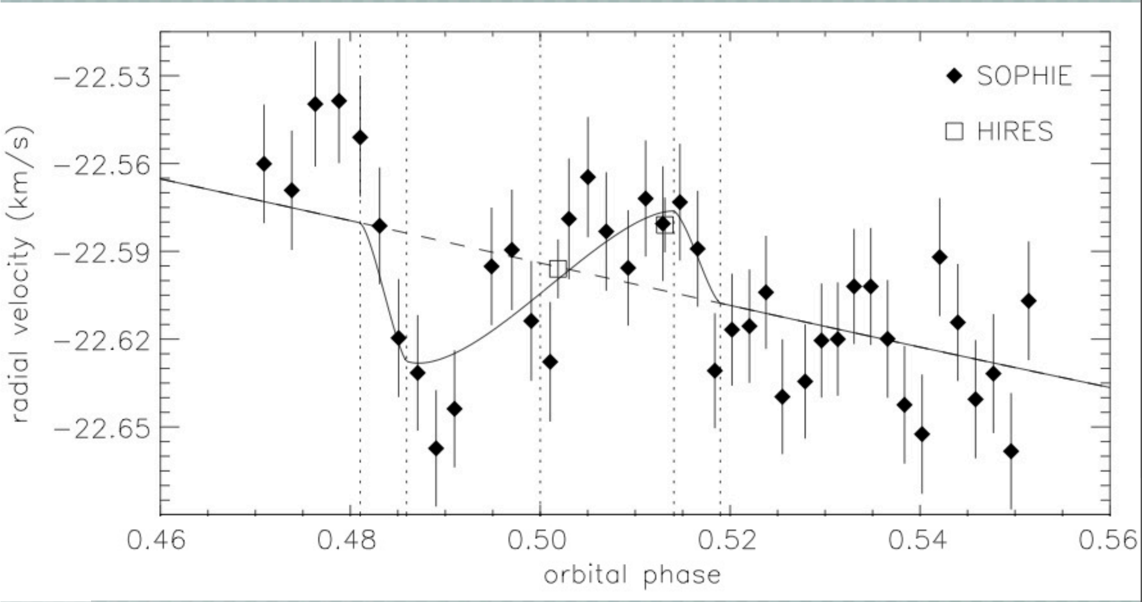


Moutou, Díaz, Udry et al. (2011)

Towards an explanation of the orbit diversity of giant planets

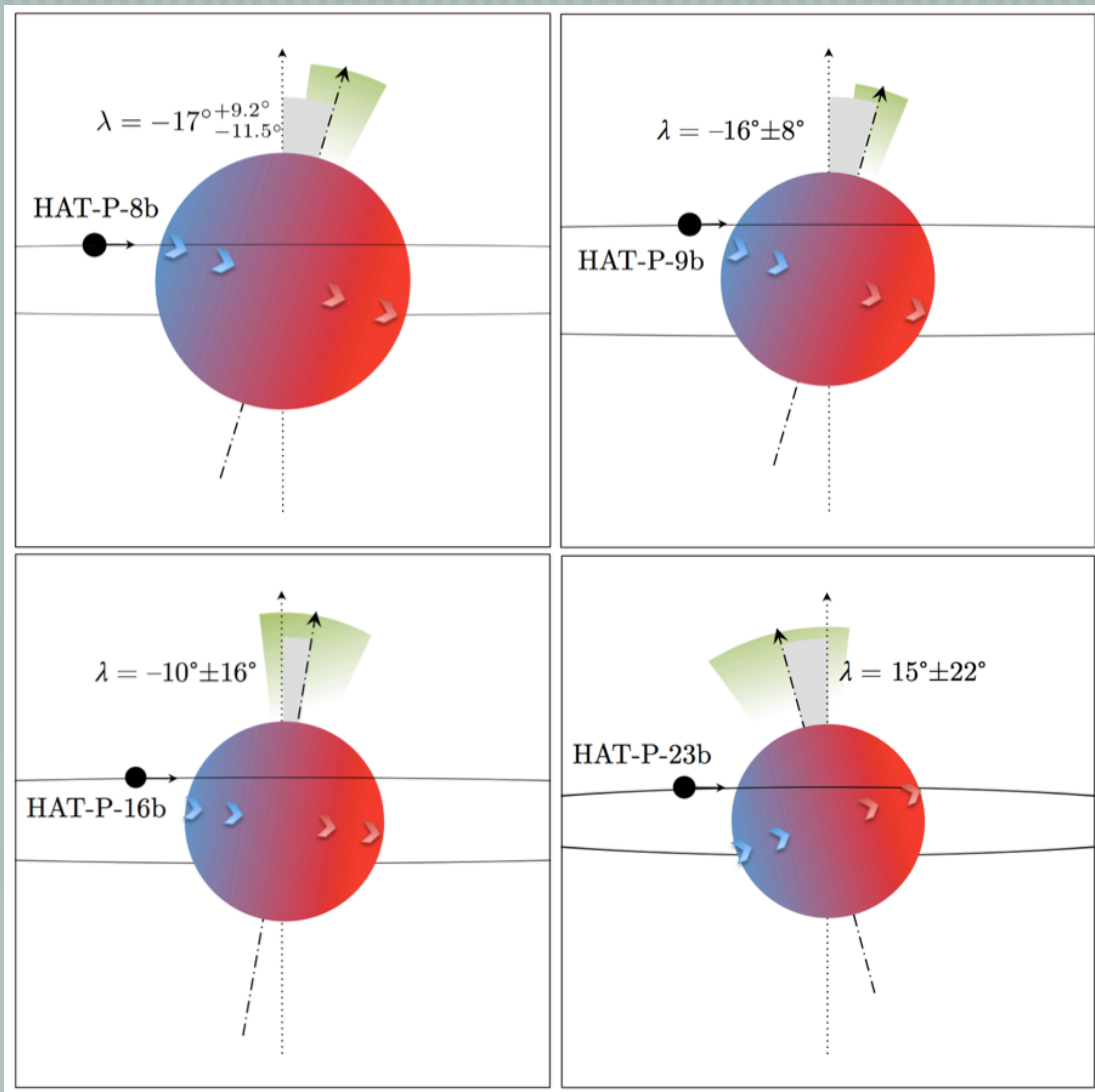


Moutou, Díaz, Udry et al. (2011)

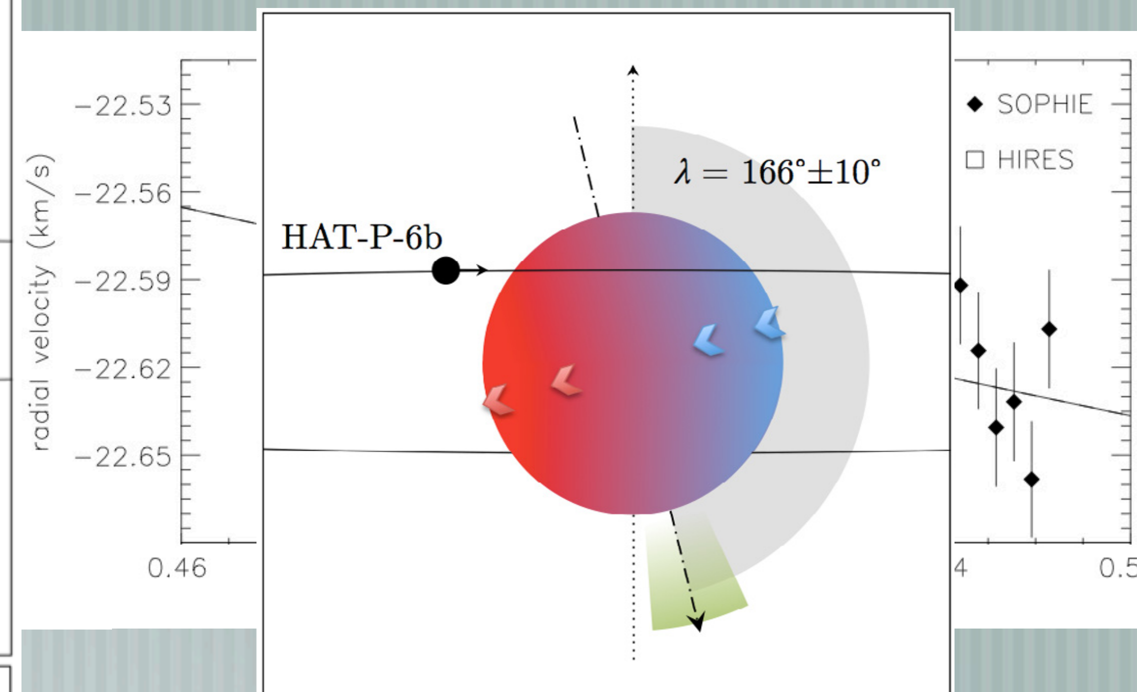


Hébrard, Ehrenreich, Bouchy, et al. (2011)

Towards an explanation of the orbit diversity of giant planets

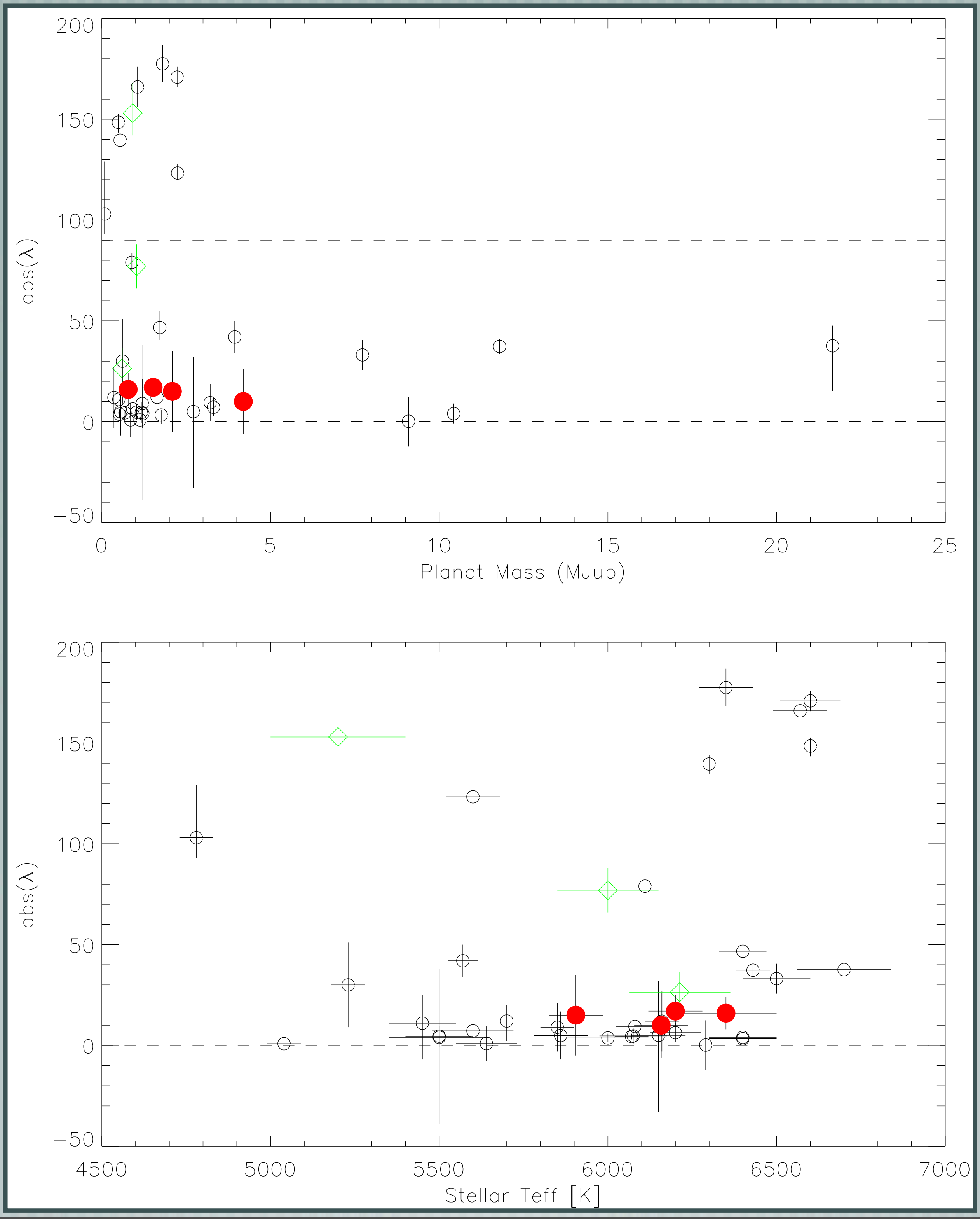


Moutou, Díaz, Udry et al. (2011)



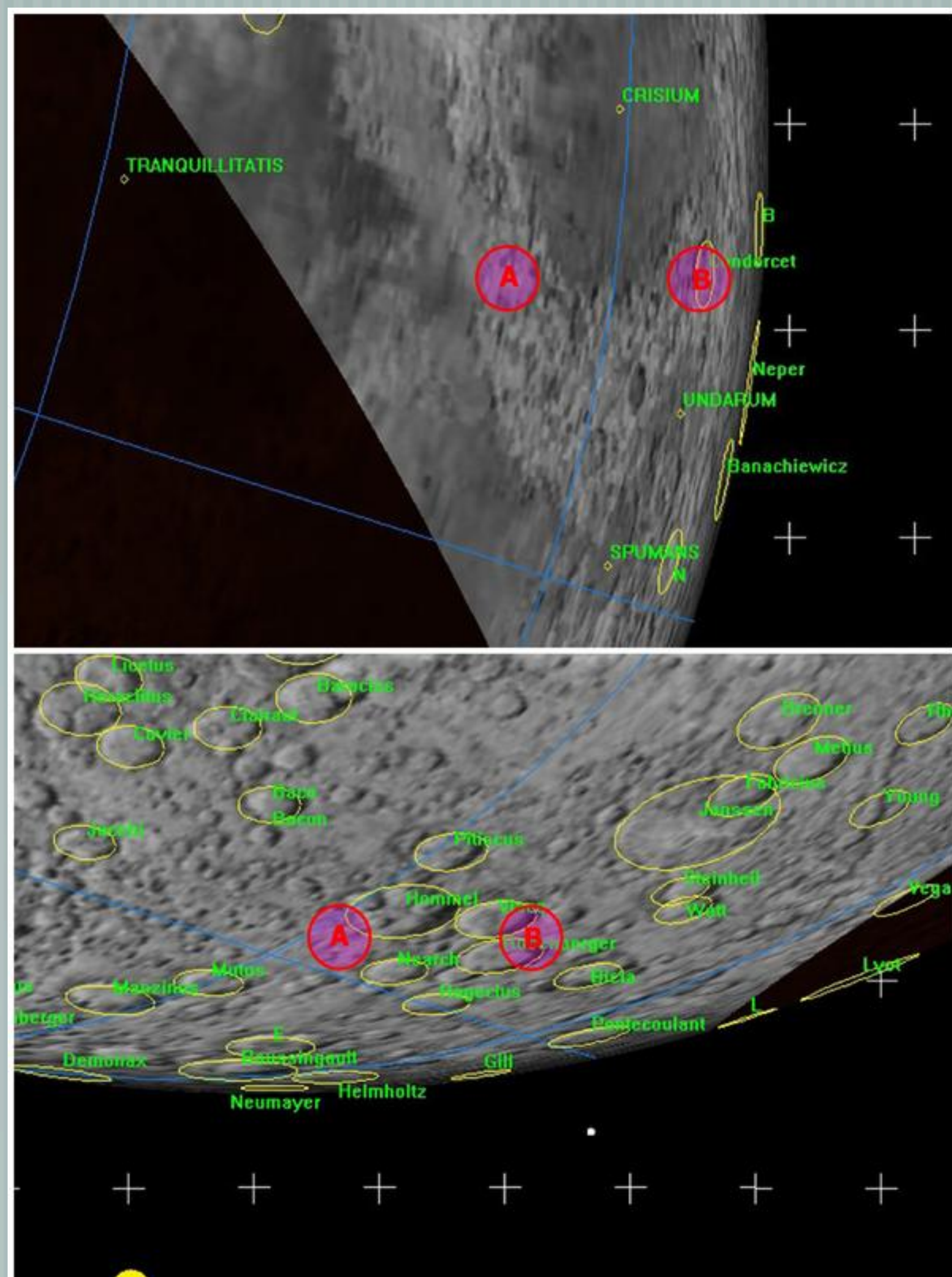
Hébrard, Ehrenreich, Bouchy, et al. (2011)

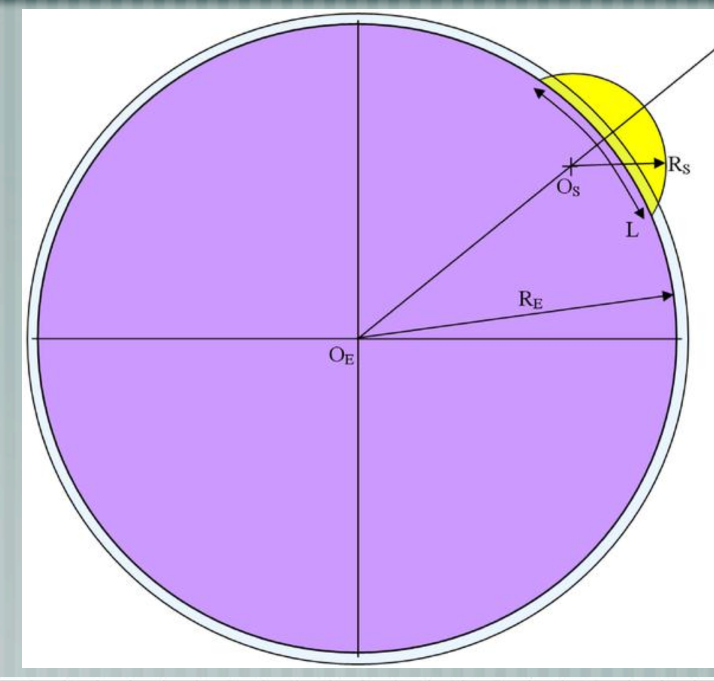
Towards an explanation of the orbit diversity of giant planets

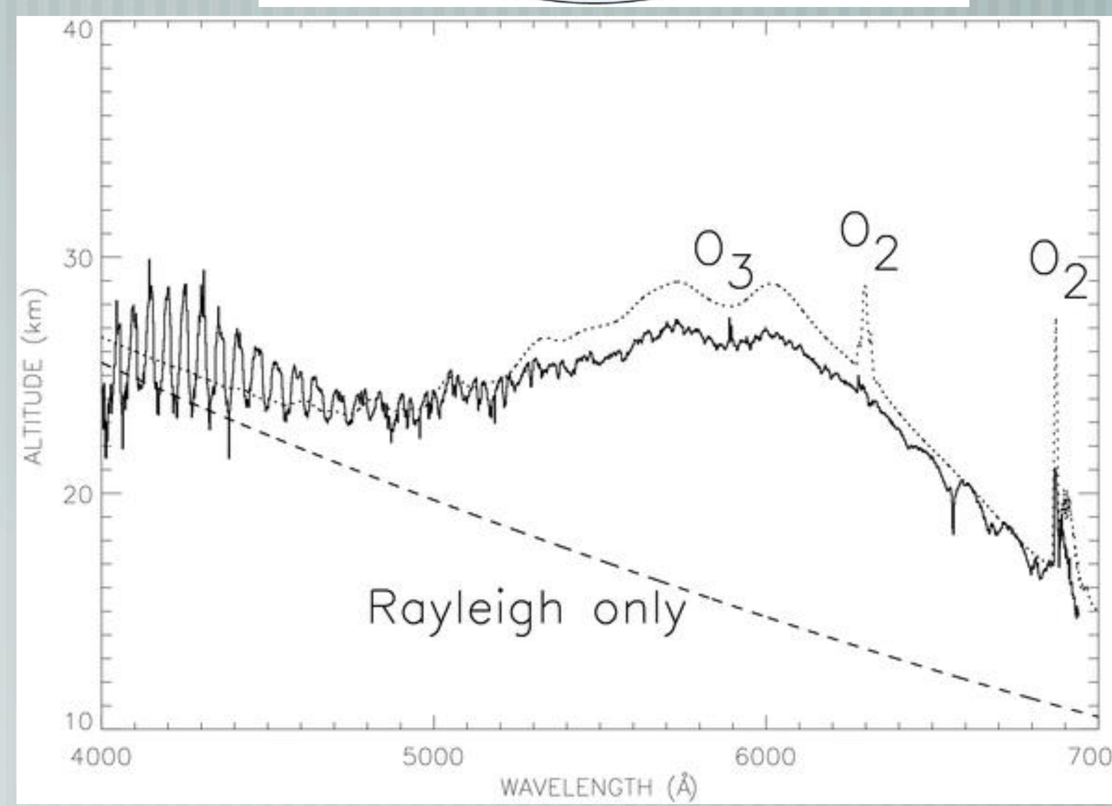


Moutou, Díaz, Udry et al. (2011)

The Earth as a transiting extrasolar planet





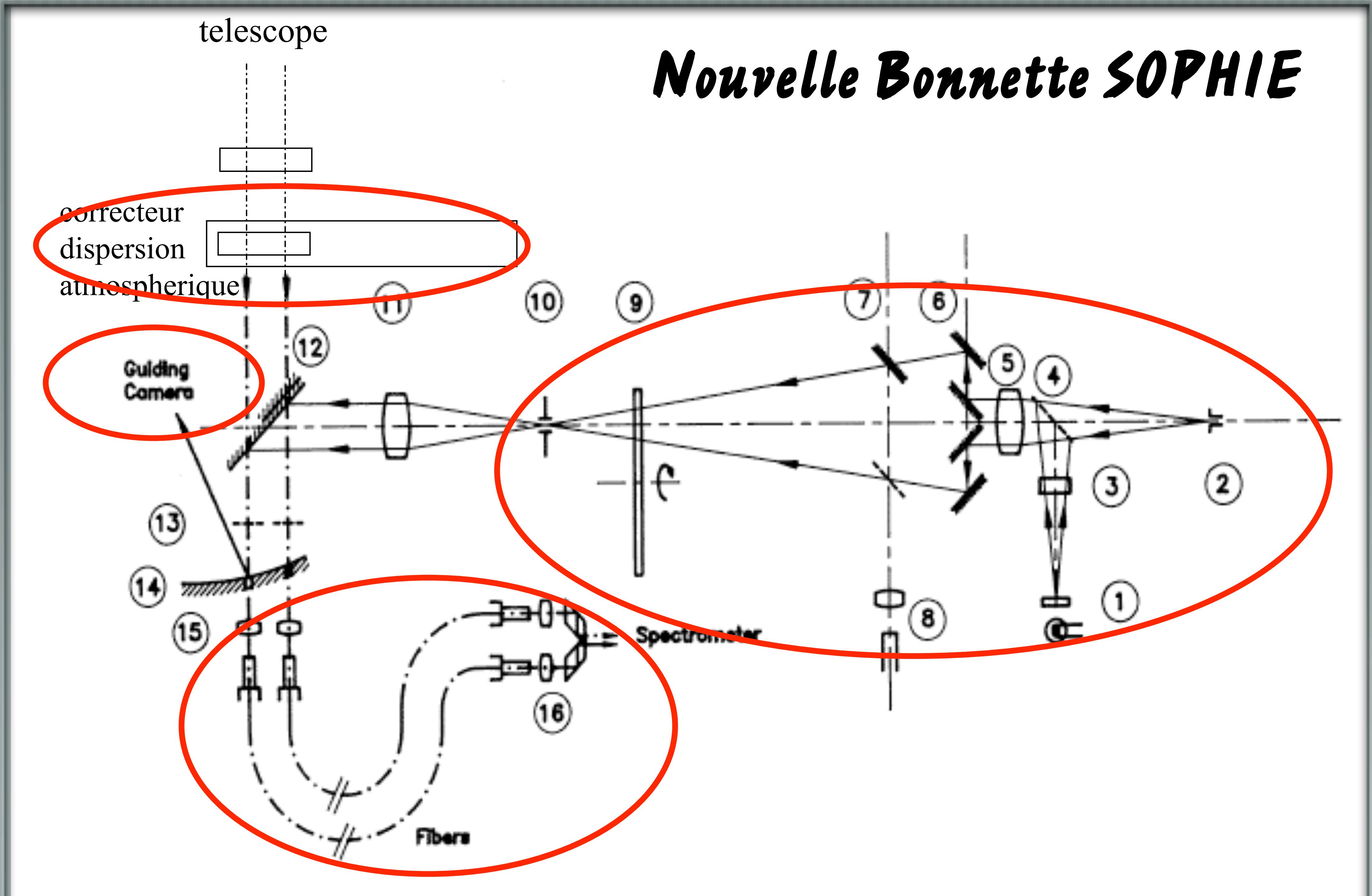


Vidal-Madjar, Arnold, Ehrenreich et al. (2010)

Improving SOPHIE

The new fibre link

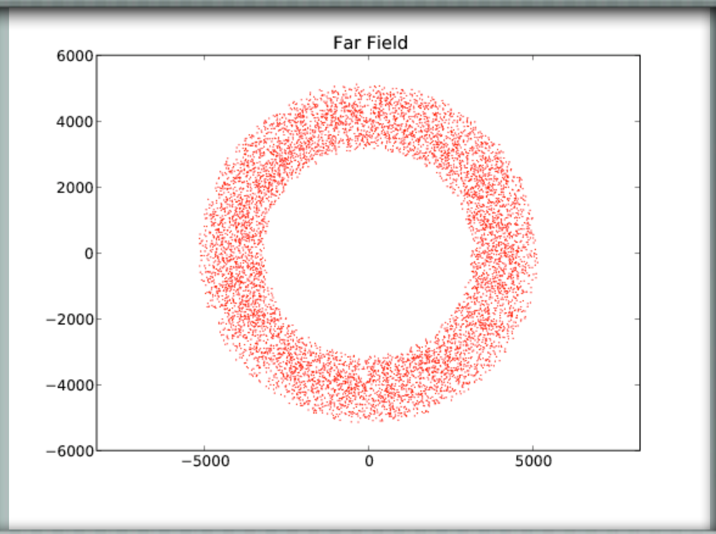
Operation "Nouvelle Bonnette"



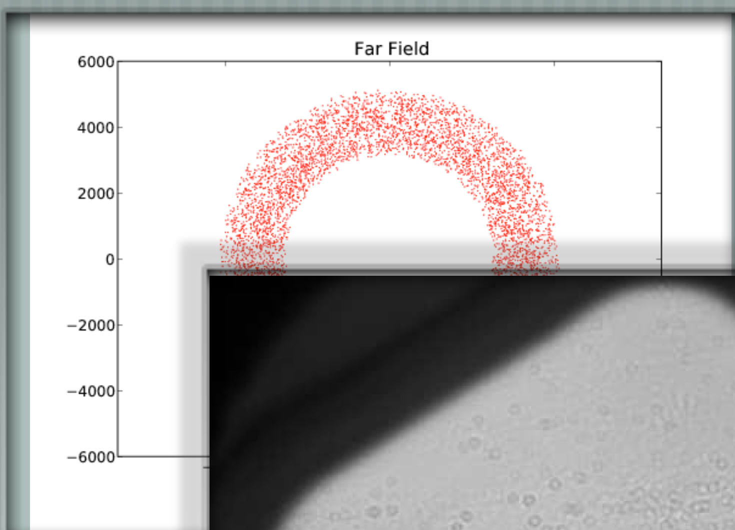
Operation “Nouvelle Bonnette”

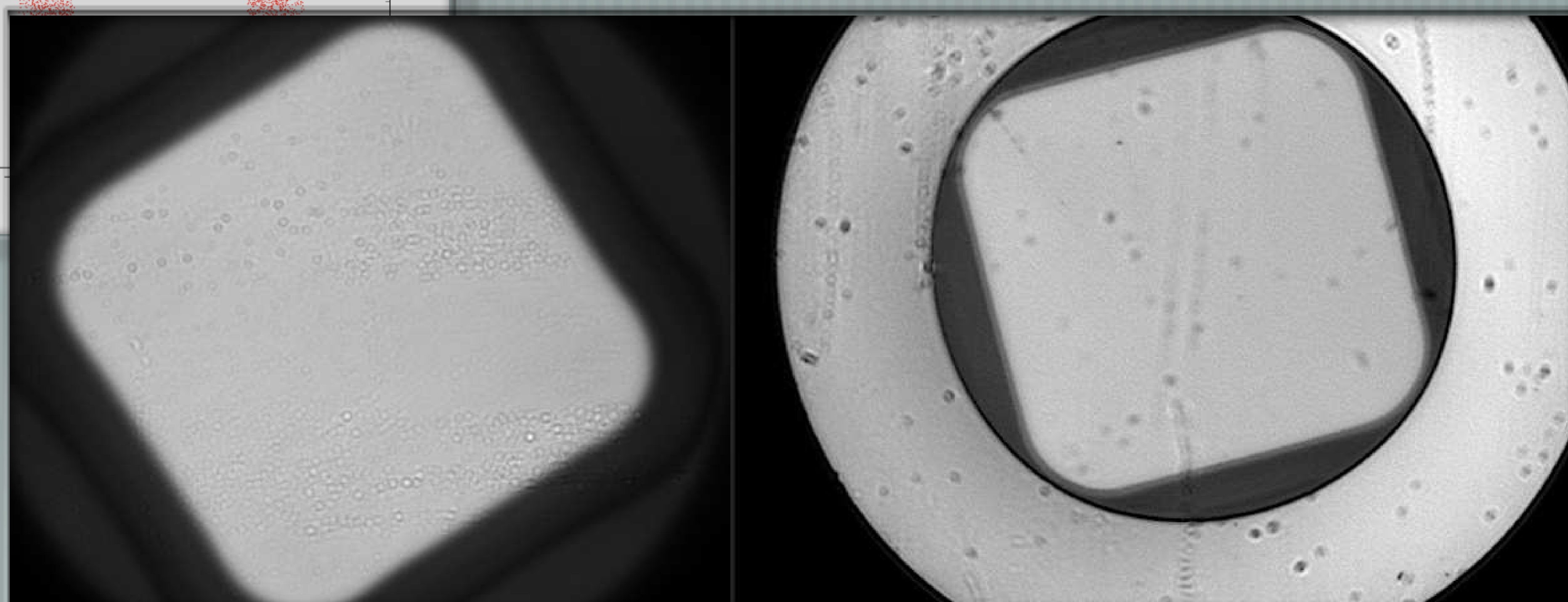
- Some other improvements:
  - New Guiding System
  - ADC correction
  - New N2 refilling system
  - New Thermal Isolation
  - Improvements in data reduction pipeline

The new fibre link

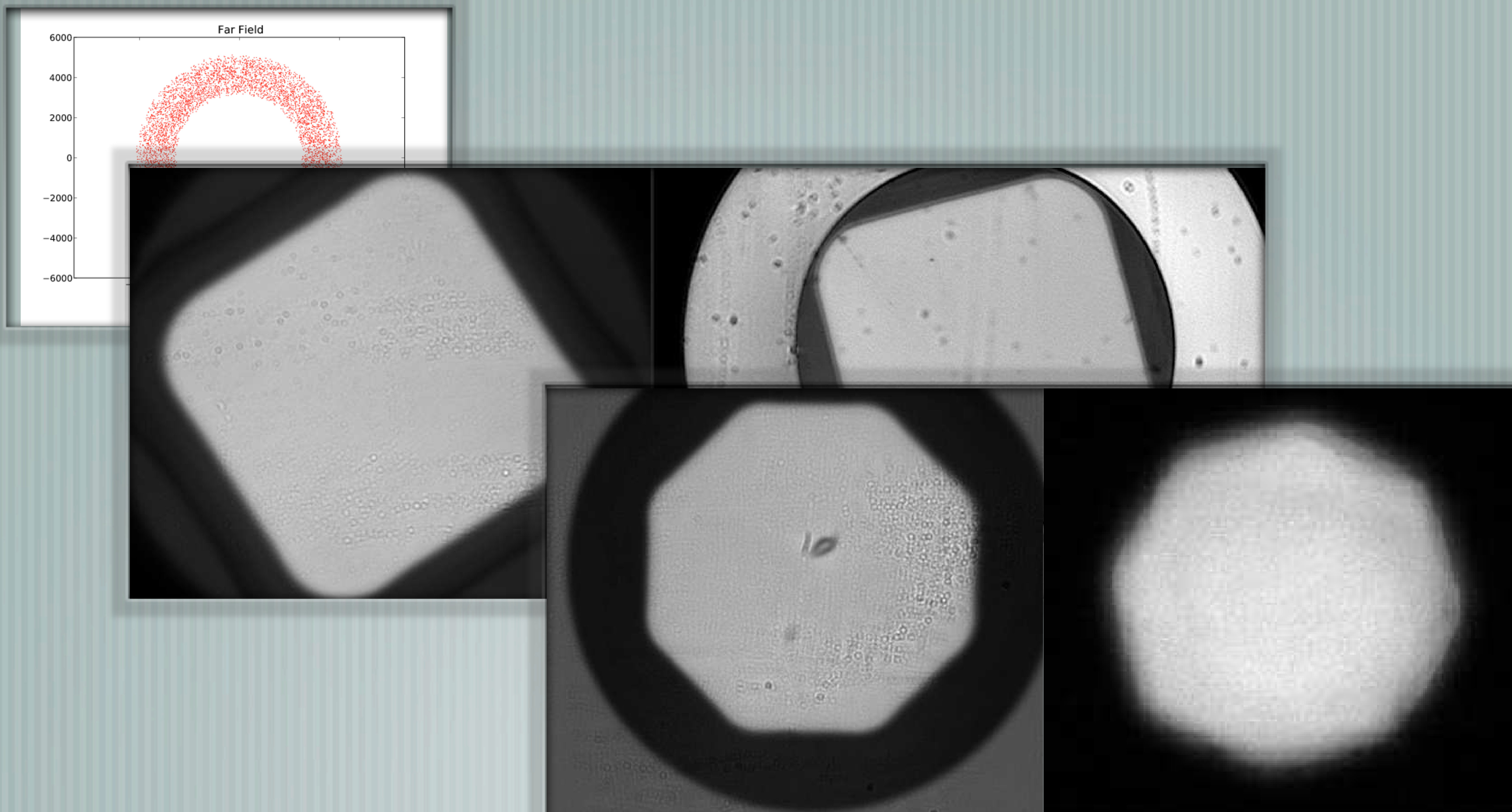


The new fibre link

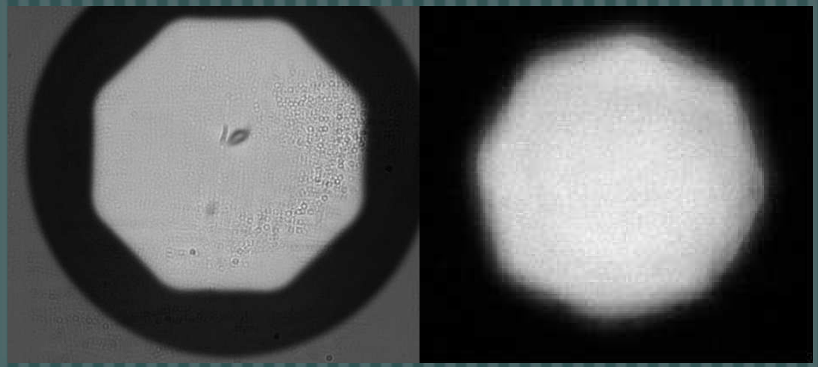


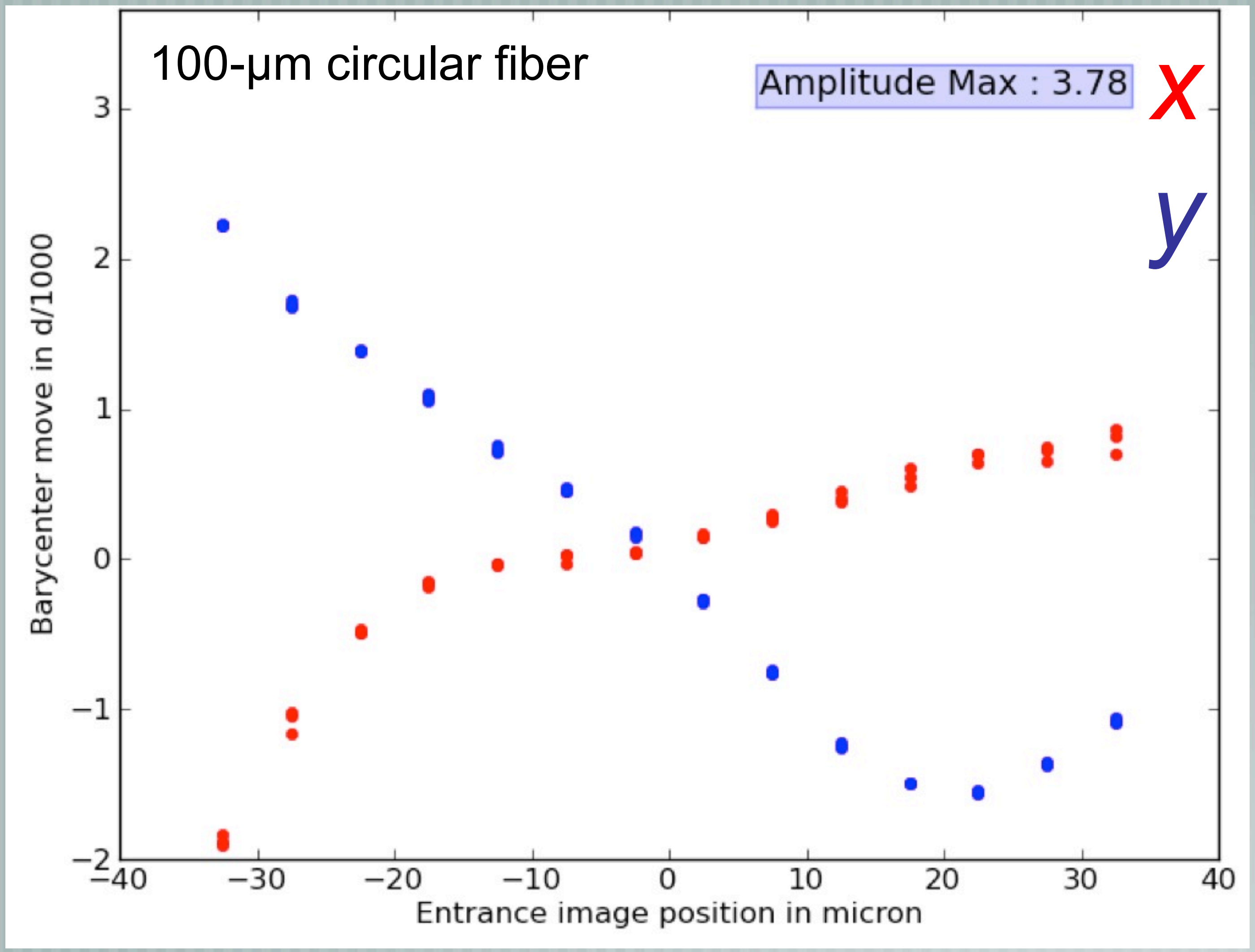


The new fibre link



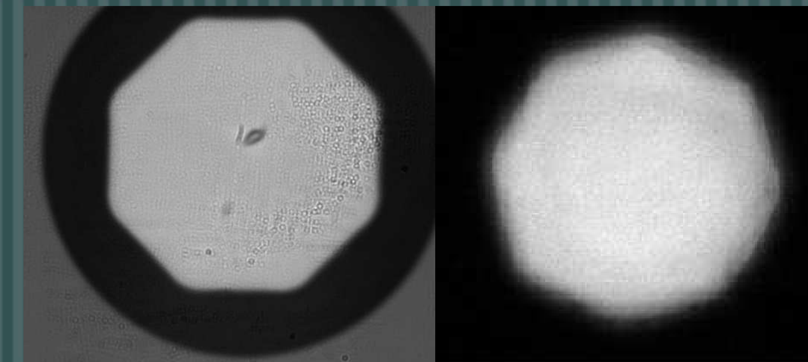
The new fibre link

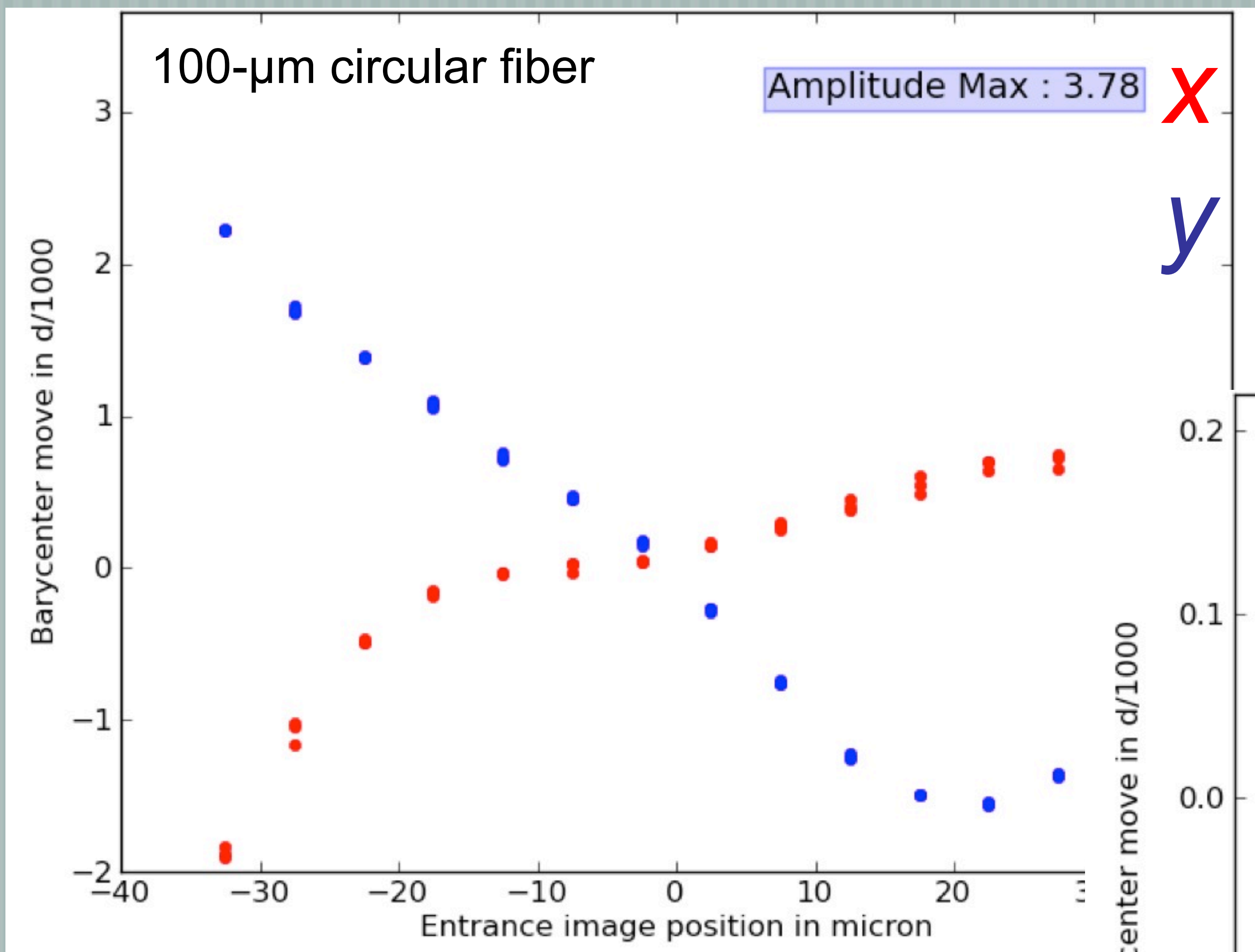




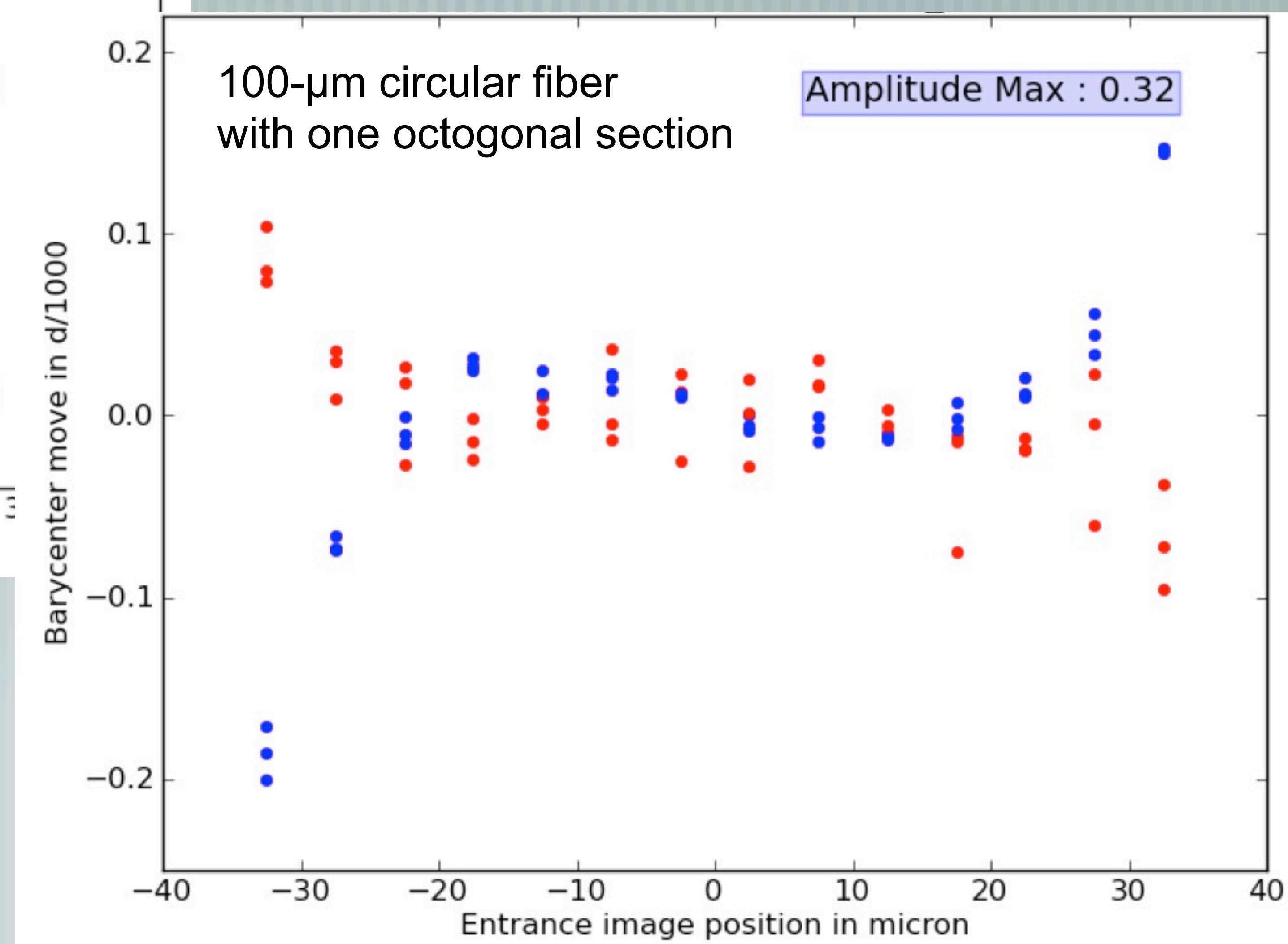
Perruchot, Bouchy, Chazelas, et al. (2011)

The new fibre link



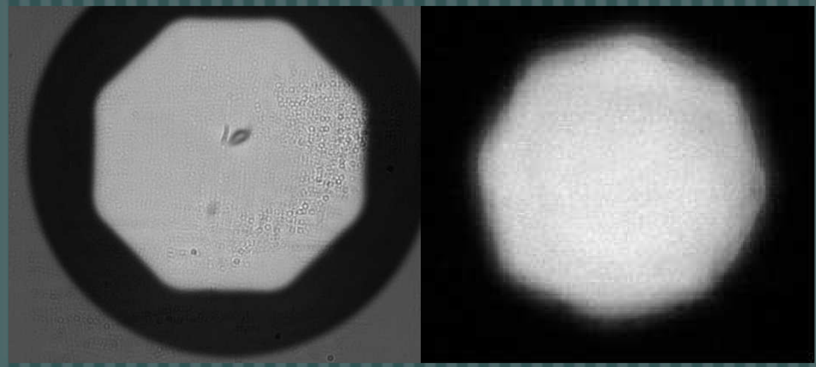


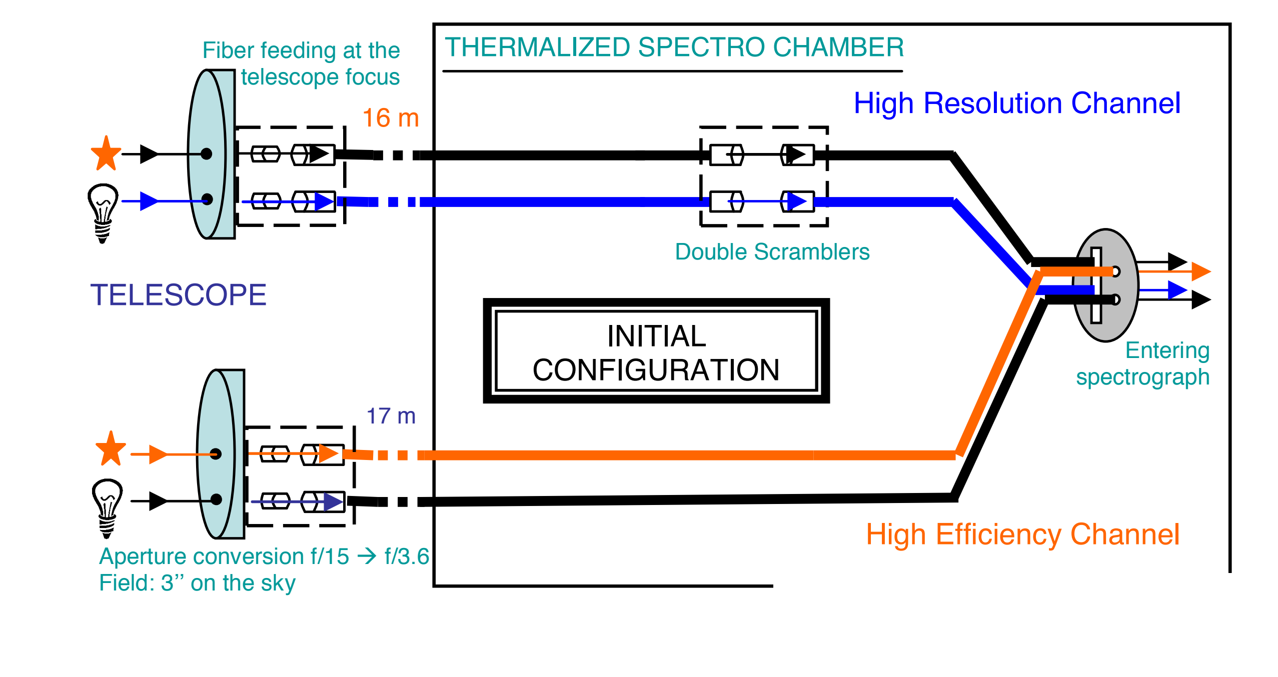
Scrambling increases by a factor larger than 10.



Perruchot, Bouchy, Chazelas, et al. (2011)

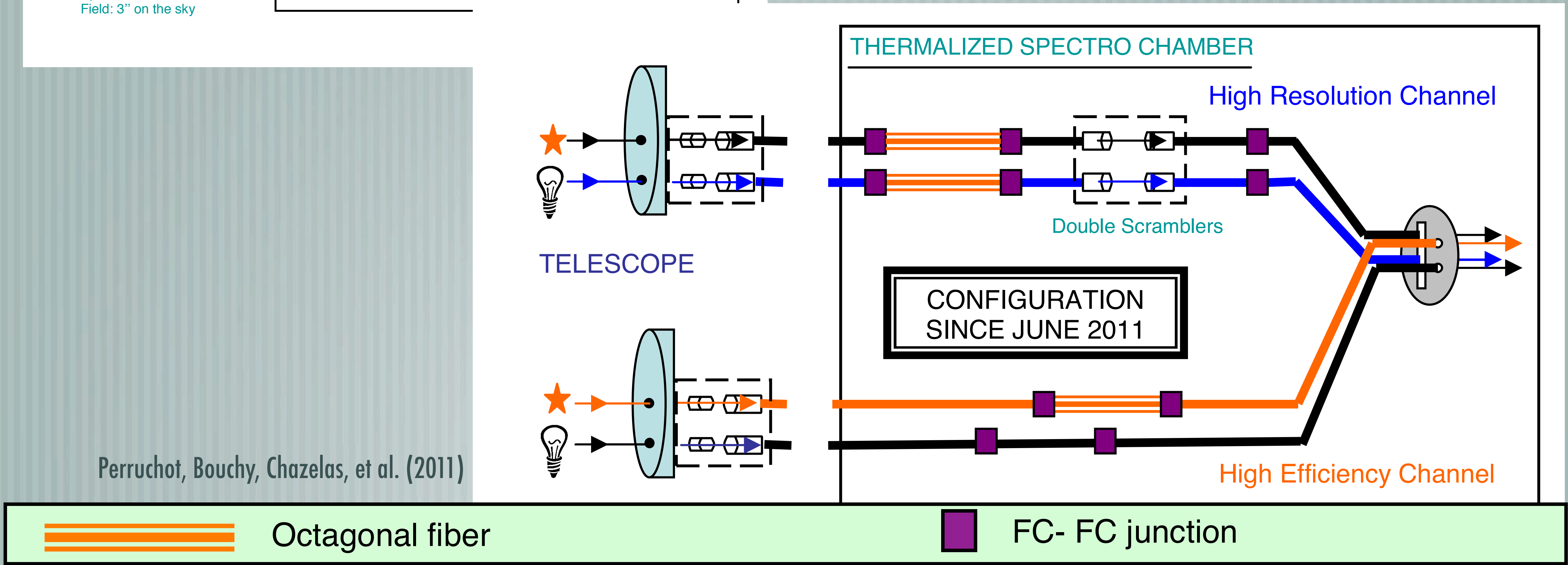
The new fibre link





Installation of the new fibre link (as of June 2011).

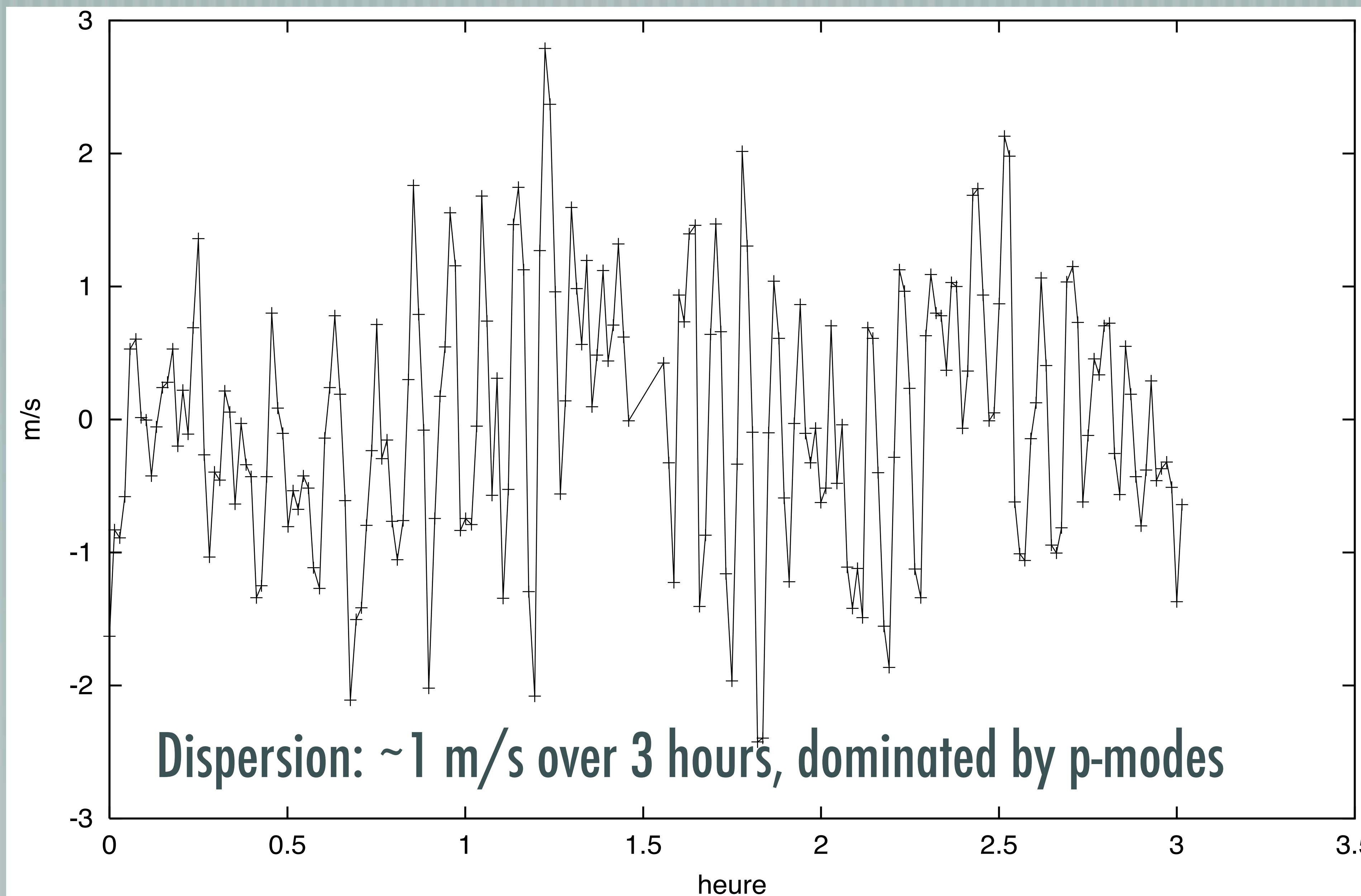
Only three good-quality octagonal fibres available.



Perruchot, Bouchy, Chazelas, et al. (2011)

Improved precision

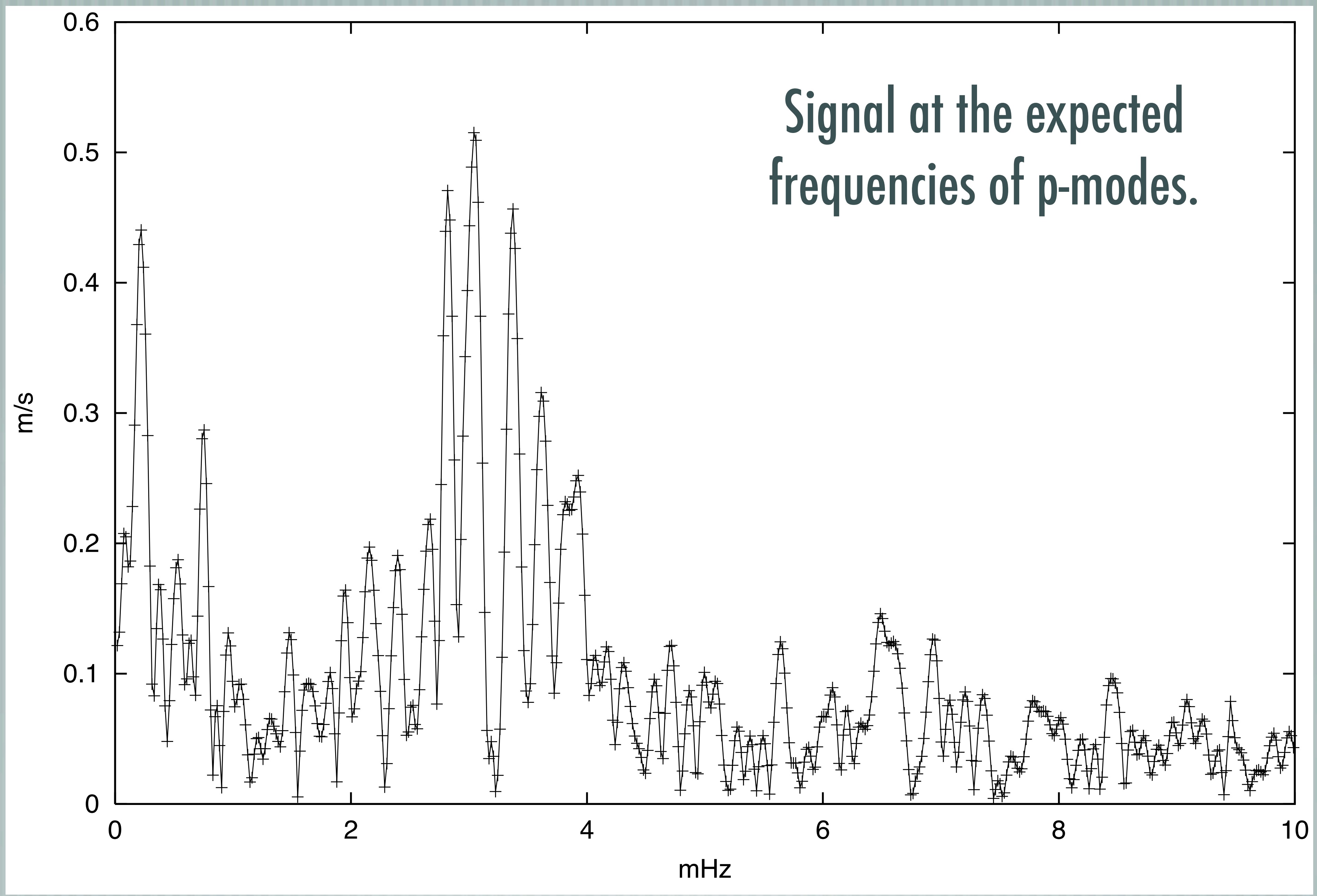
- New Series on the blue sky



Dispersion: ~1 m/s over 3 hours, dominated by p-modes

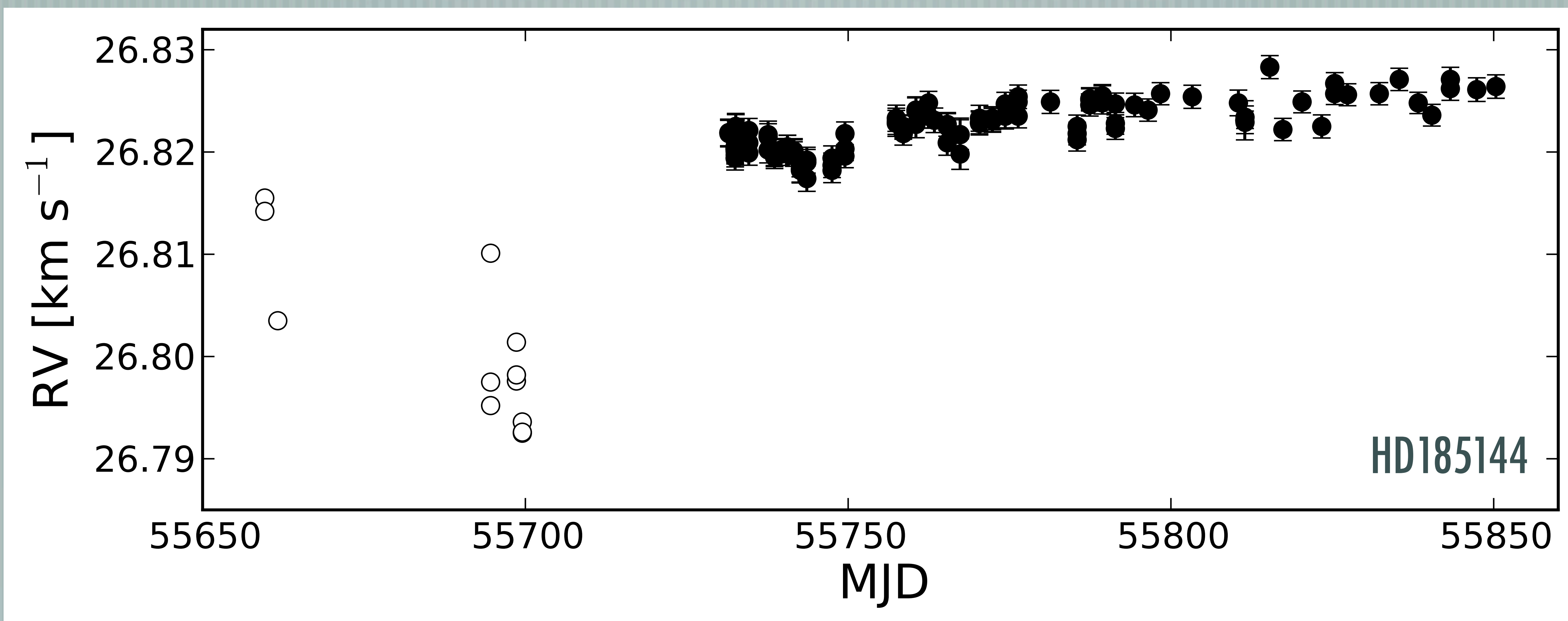
Improved precision

New Series on the blue sky



Improved precision

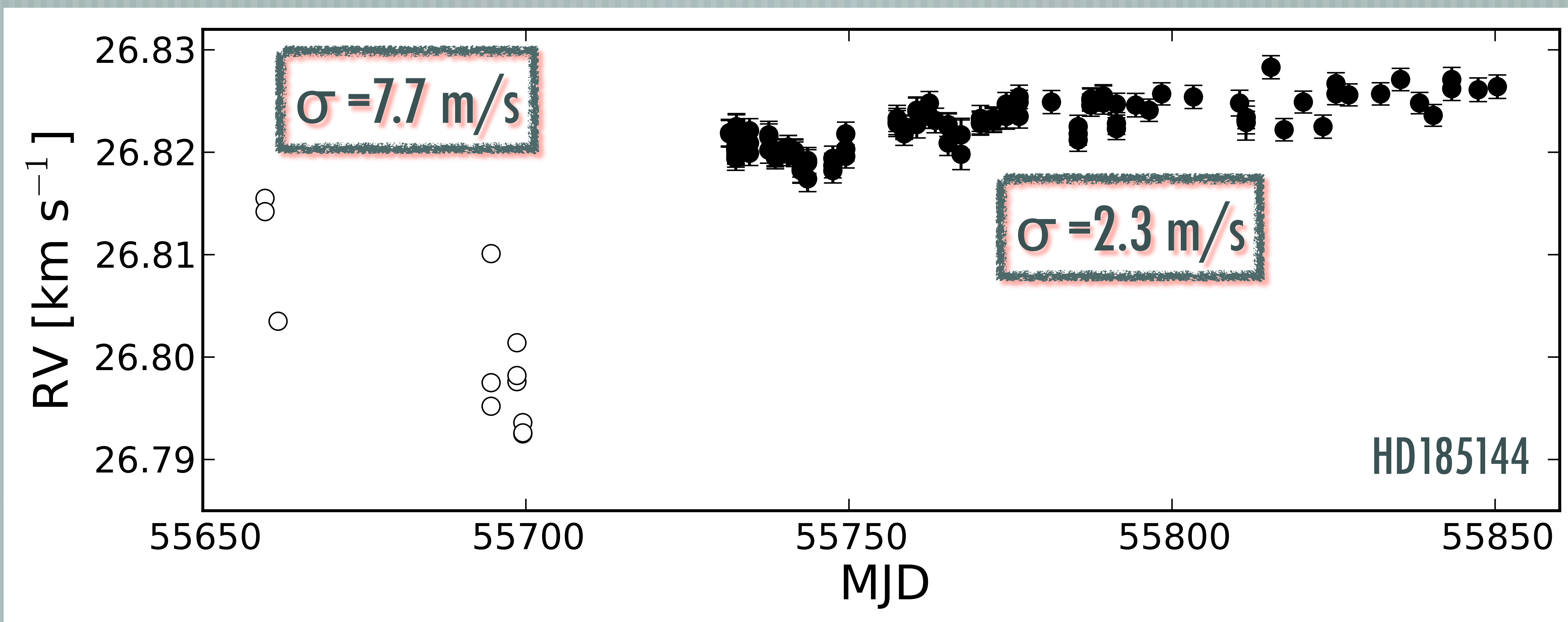
- Series on known constant stars (standards)



Dispersion: about 2 m/s over 119 days. Still room to improve.

Improved precision

Series on known constant stars (standards)



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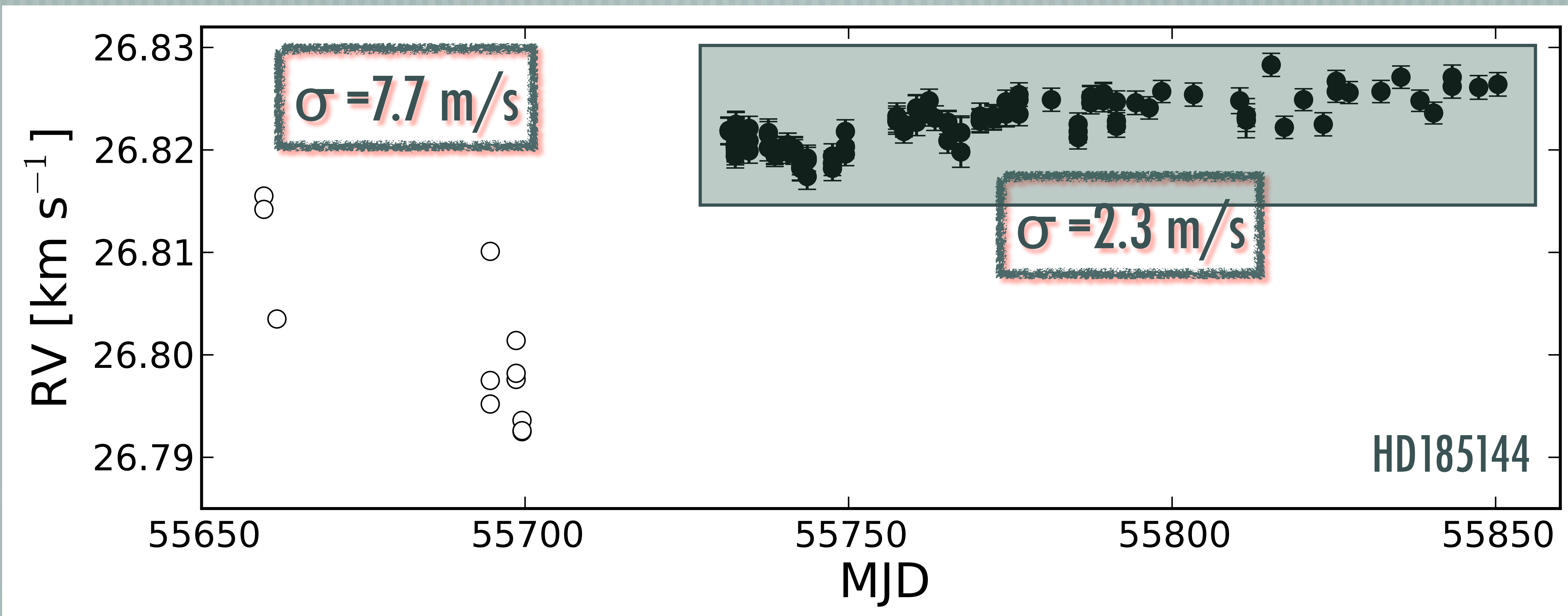

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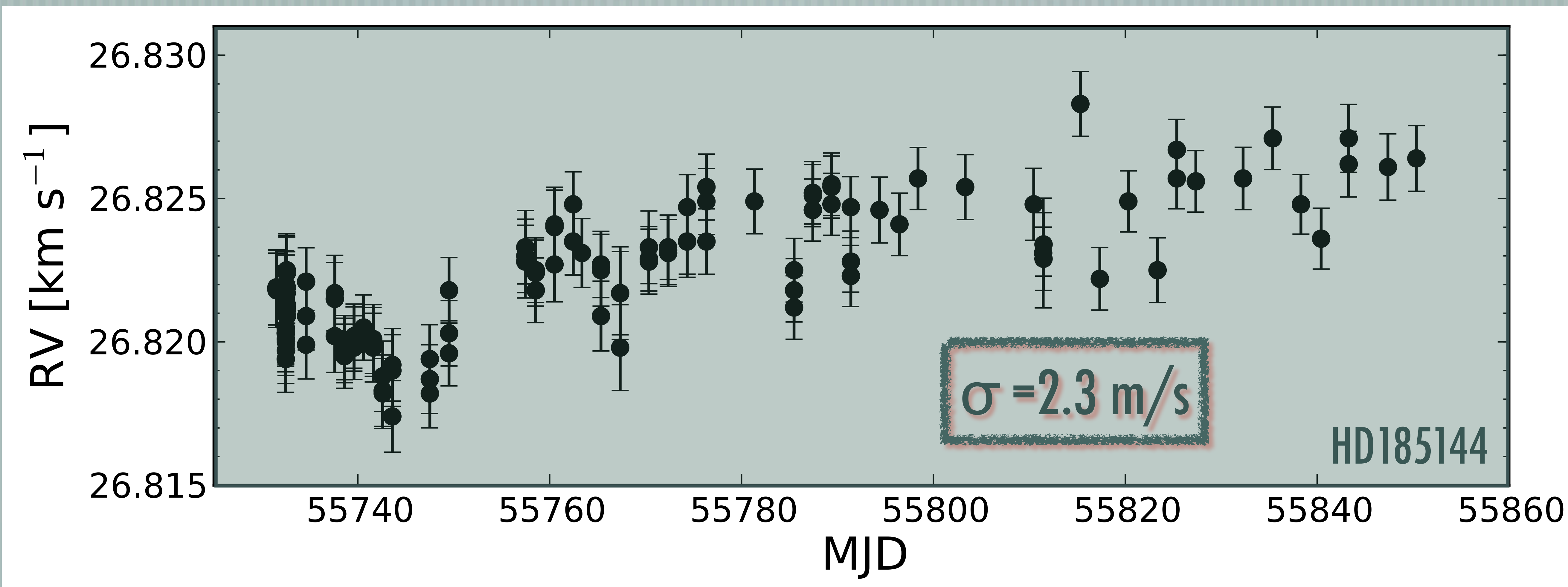

Trend is probably due to ageing of ThAr lamp. This will be corrected soon.

In all, there's a factor of about 6 in the precision improvement.

Improved precision

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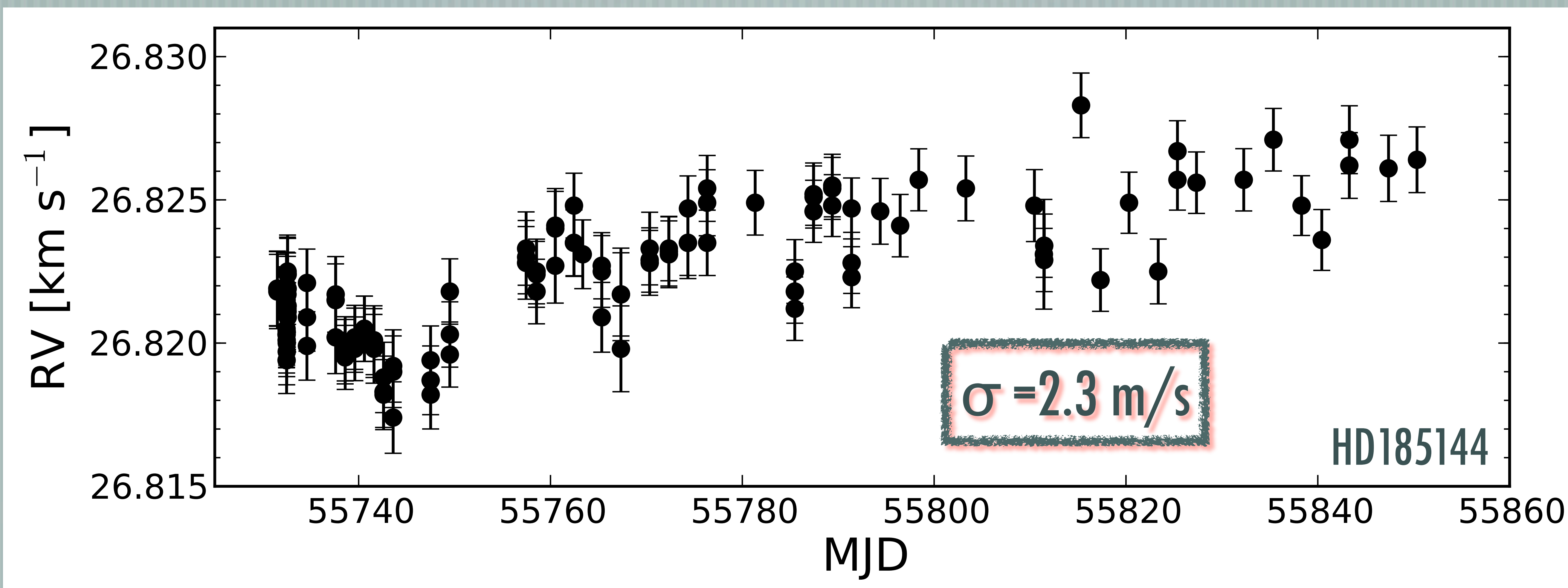

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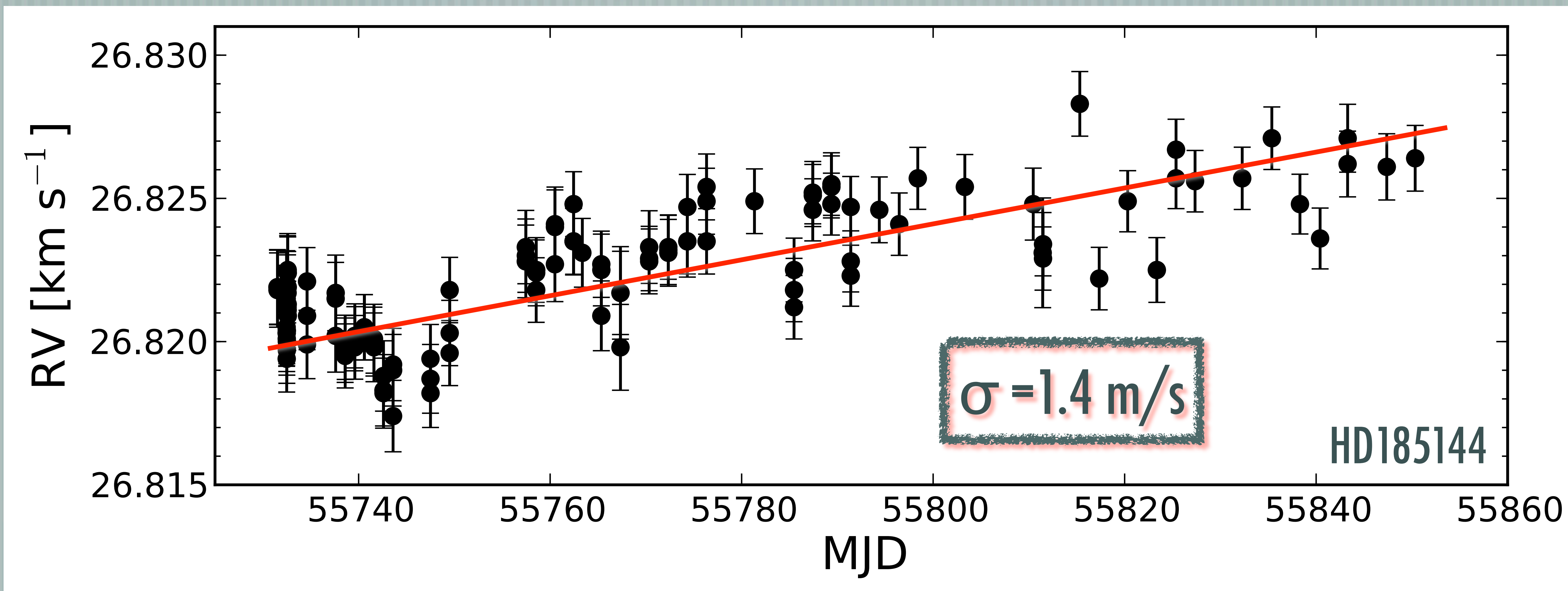

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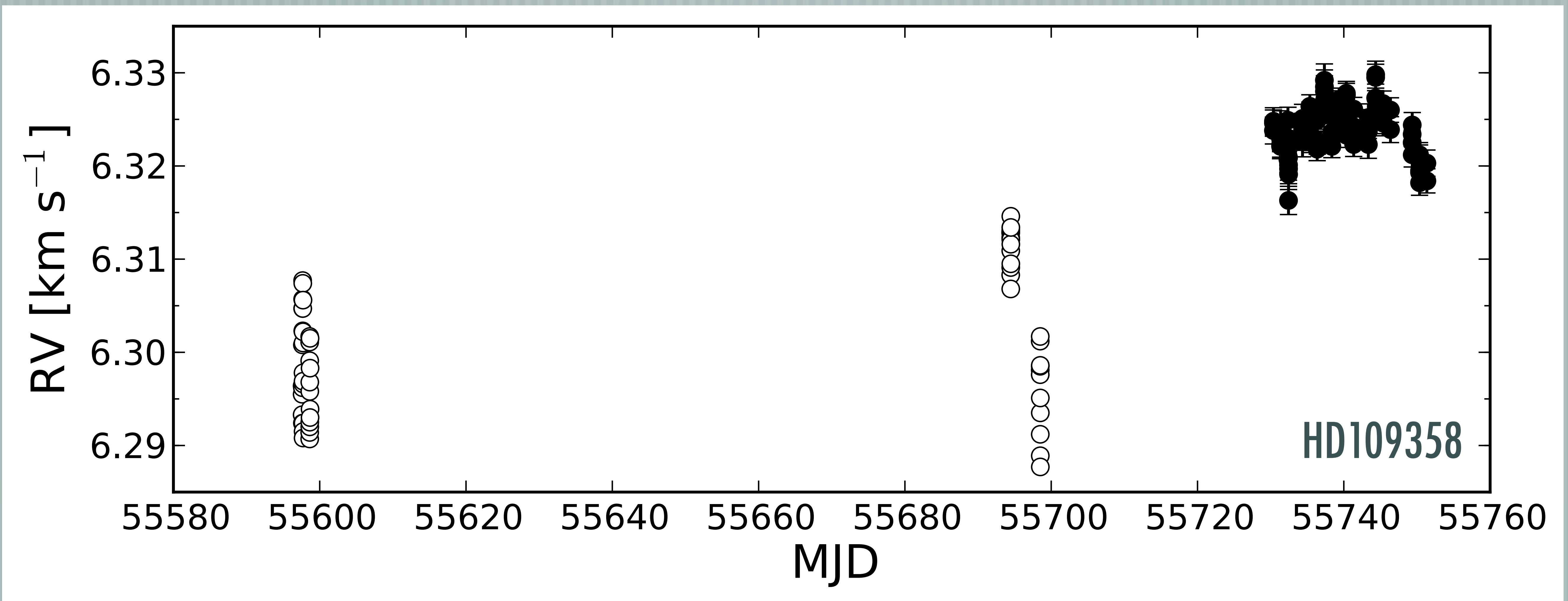
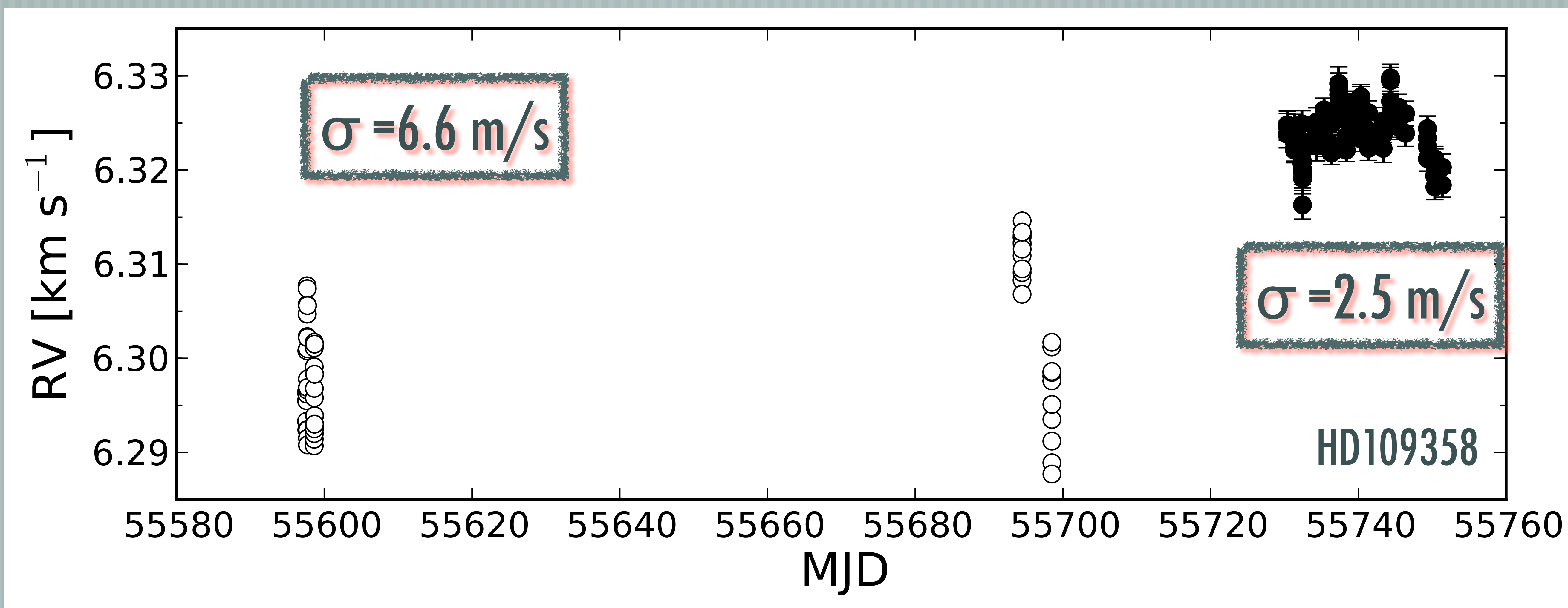


Dispersion: 2.5 m/s over 21 days; photon noise = 1.4 m/s

Improved precision

Series on known constant stars (standards)



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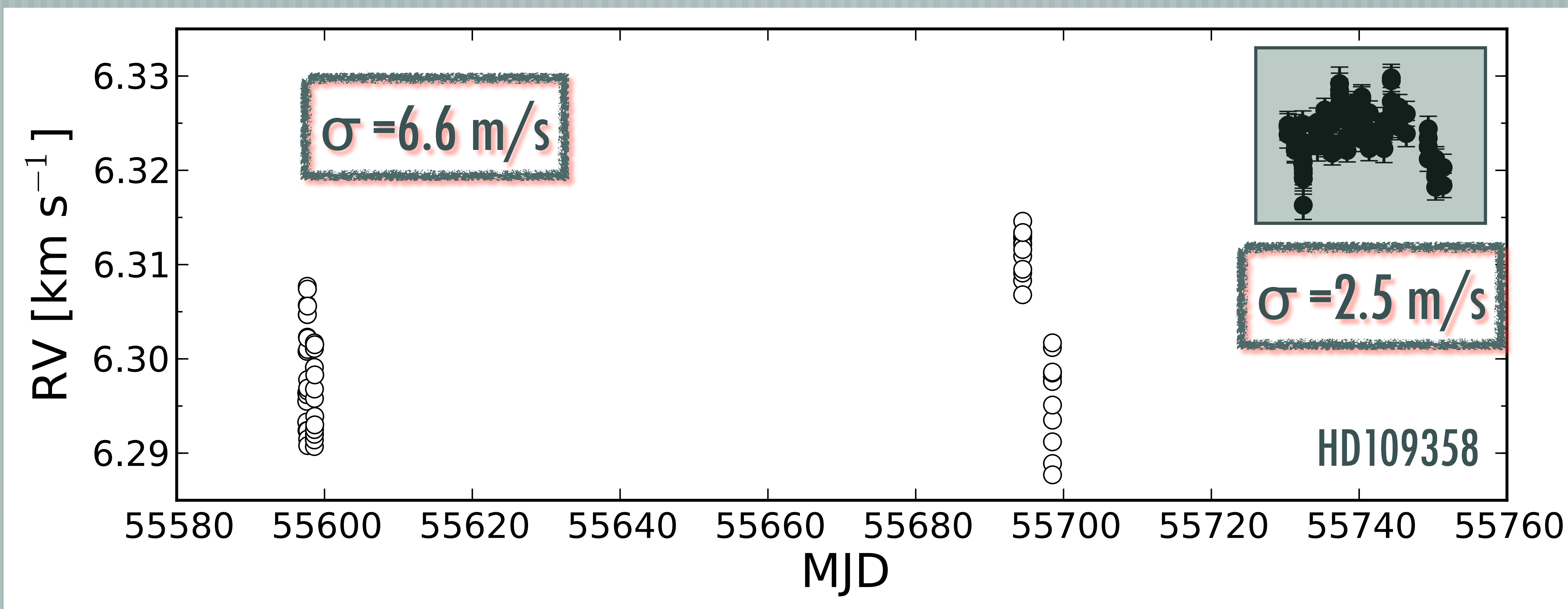

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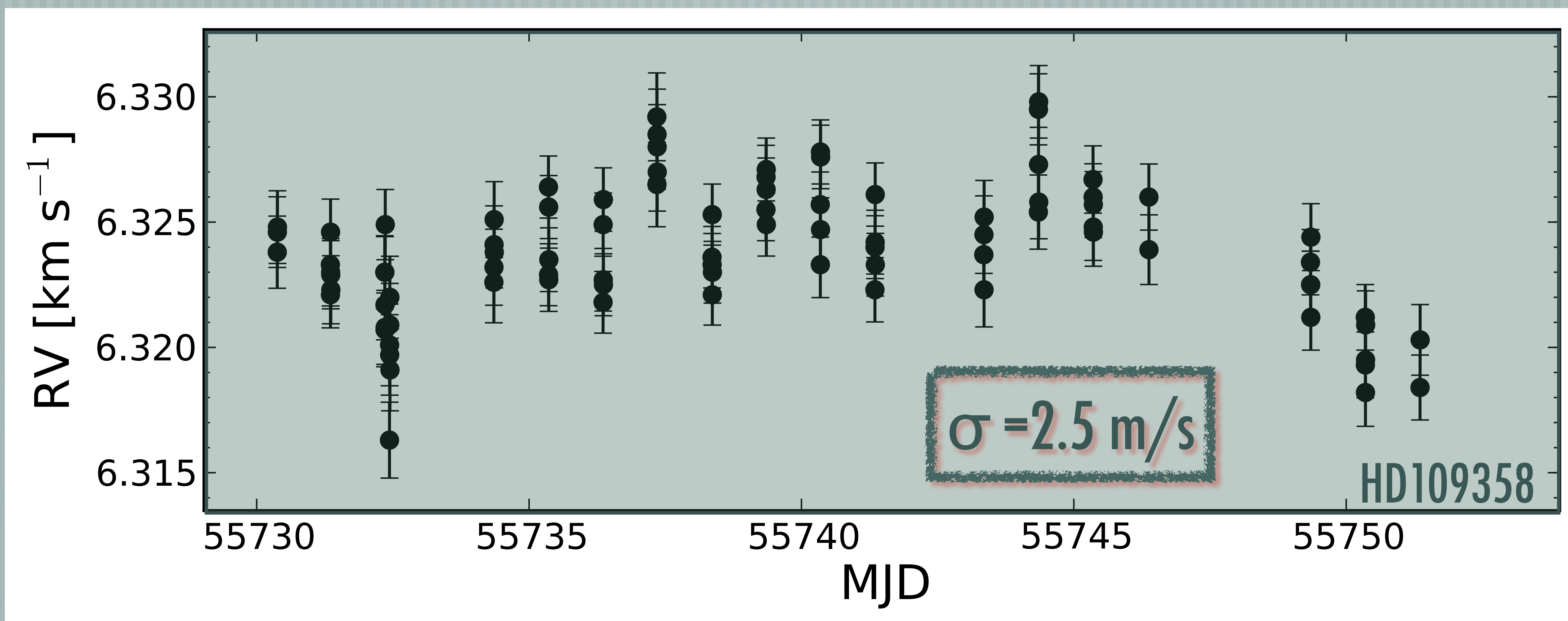
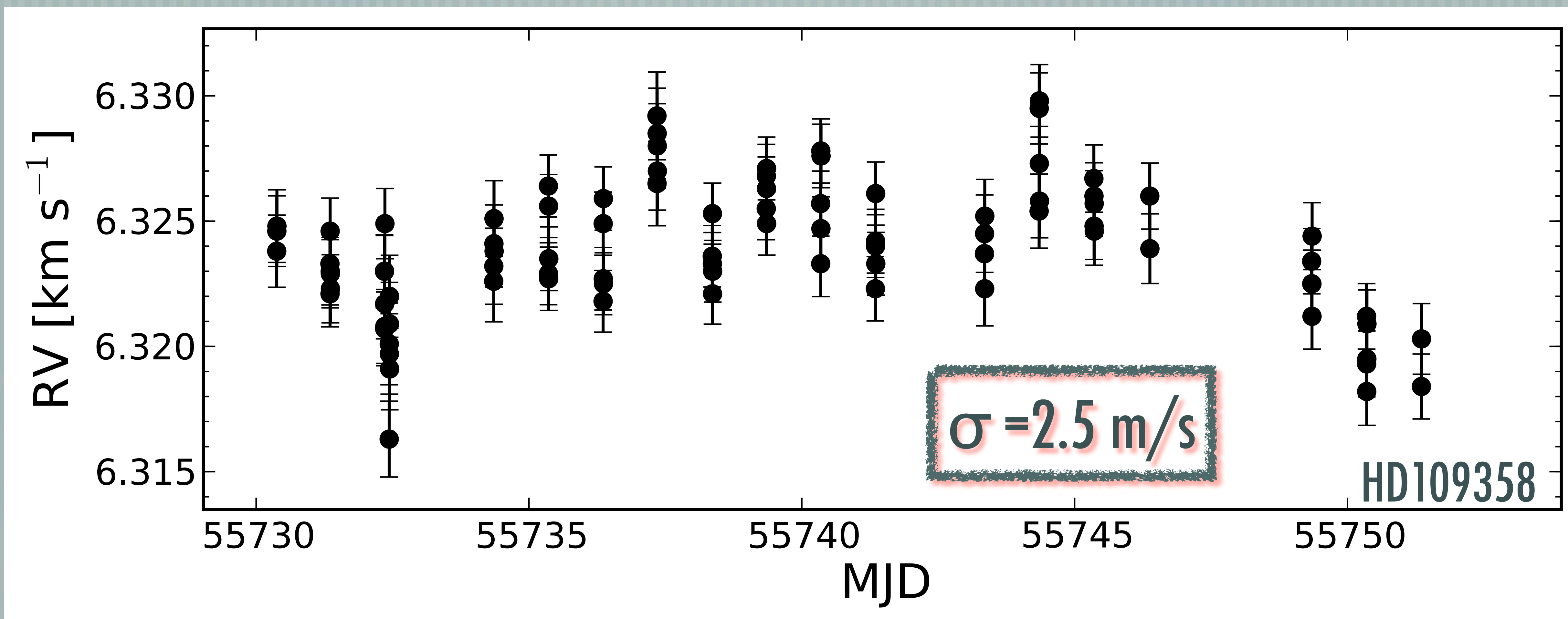


Trend is repeated on many stars.

Improved precision

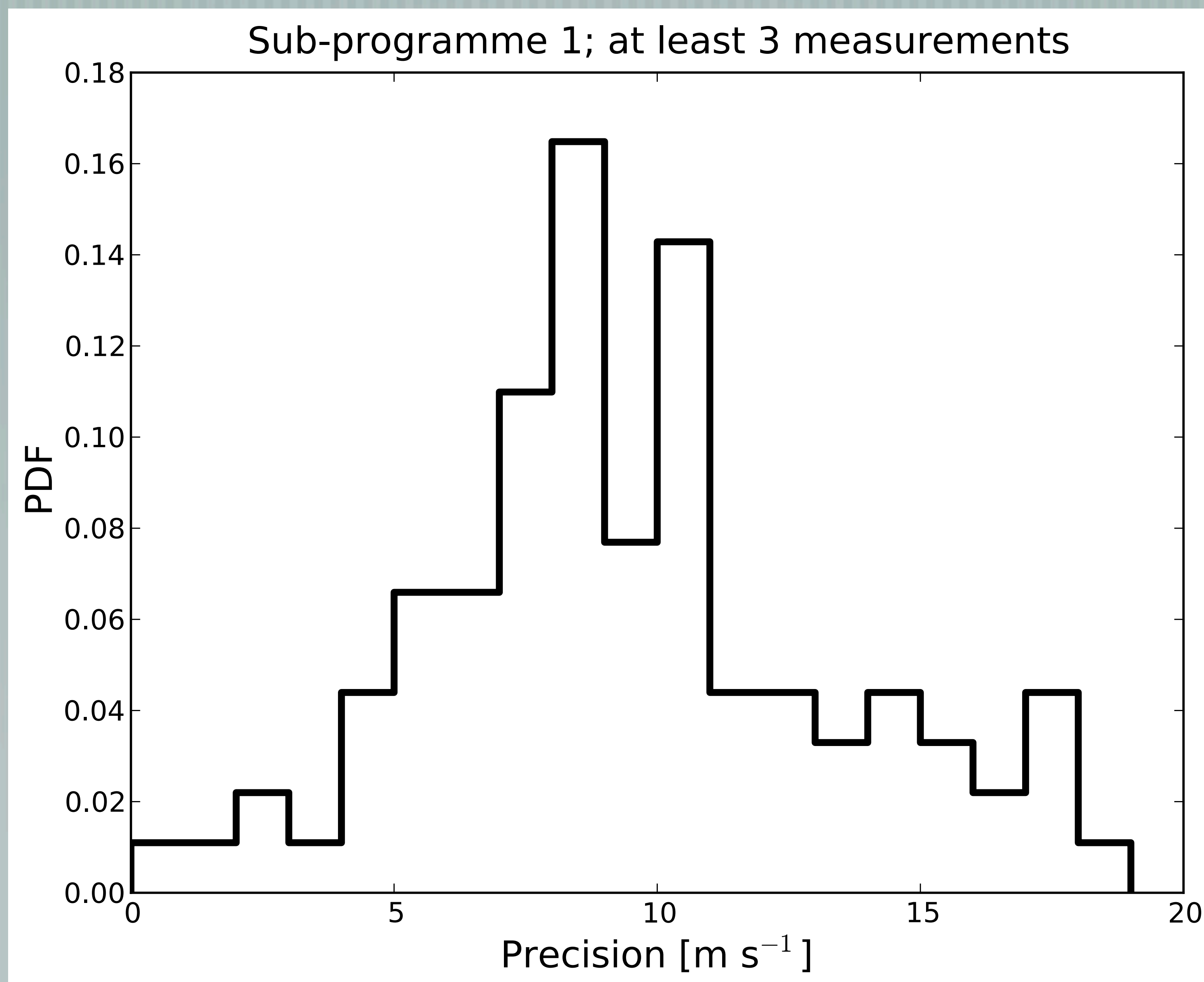
- Series on known constant stars (standards)



Trend is repeated on many stars.

Improved precision

- Dispersion on large number of stars



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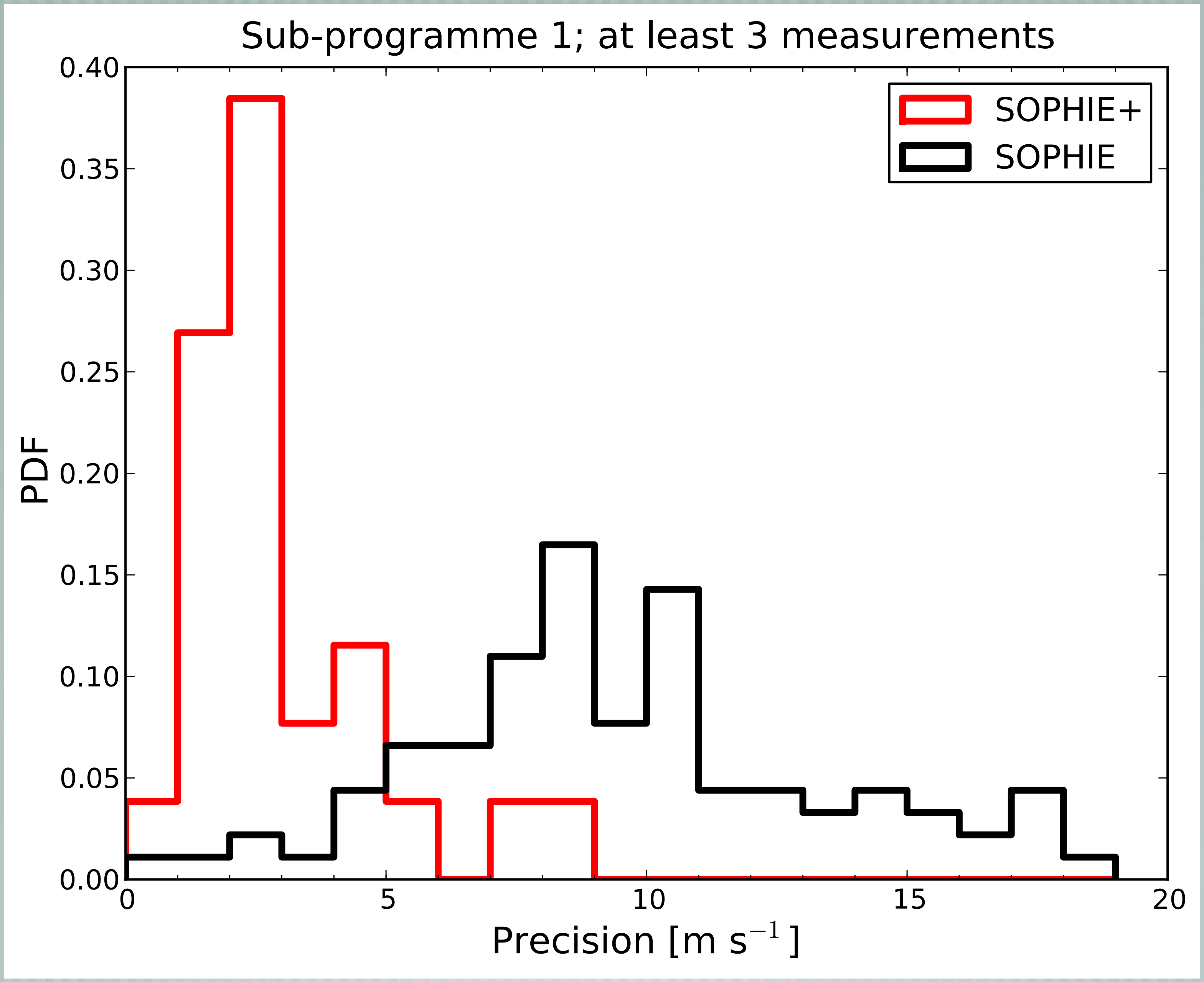

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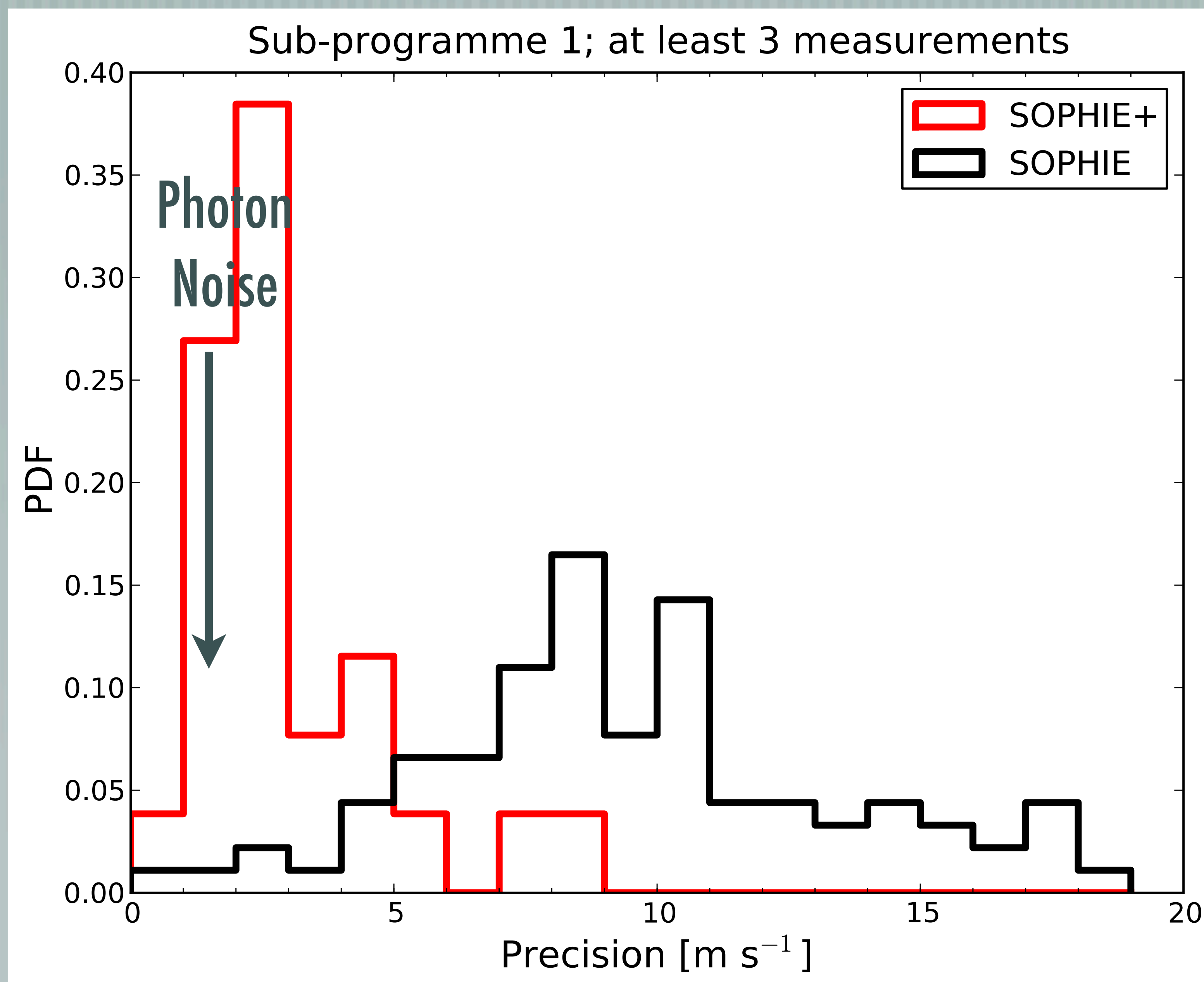


Epilogue

The realm of small planets

The realm of small planets

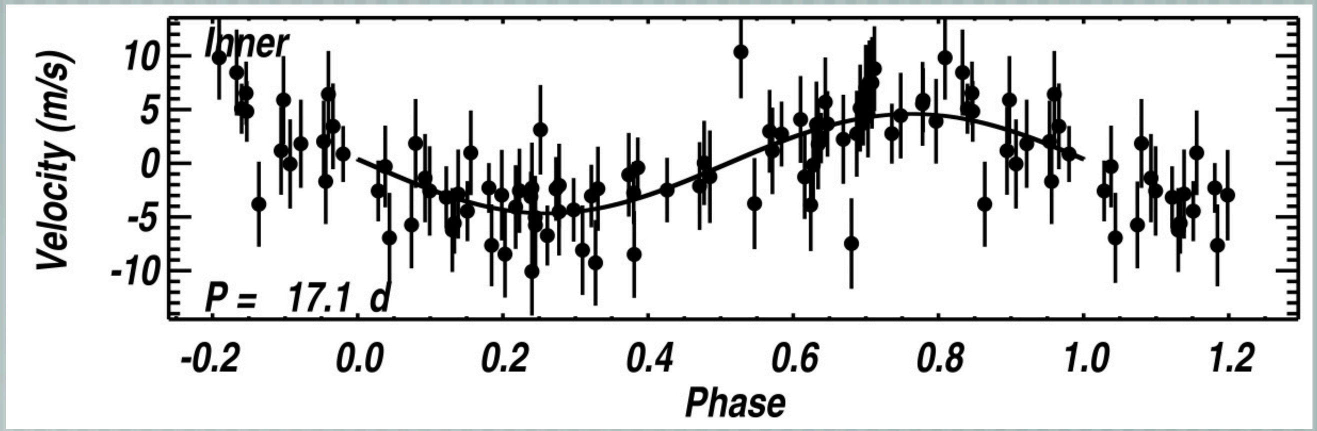
Observation of known small-mass planets

HD190360 c (Vogt et al. 2005)

P = 17.10 ± 0.02 d; K = 4.6 ± 1.1 m/s

$m_2 \sin(i)$ = 18.1 ± 4.8 Mearth

HIRES@Keck σ =3.5 m/s



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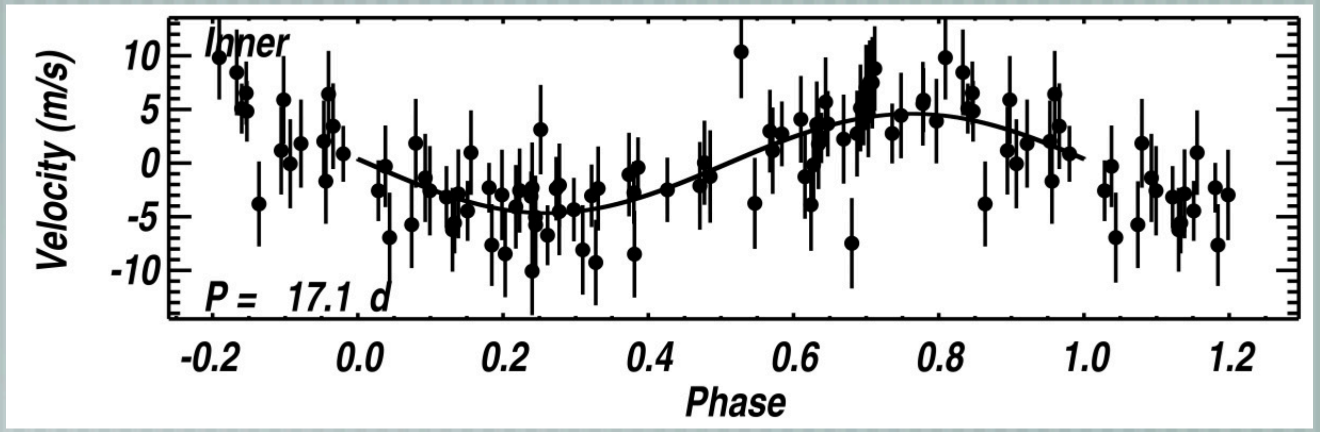
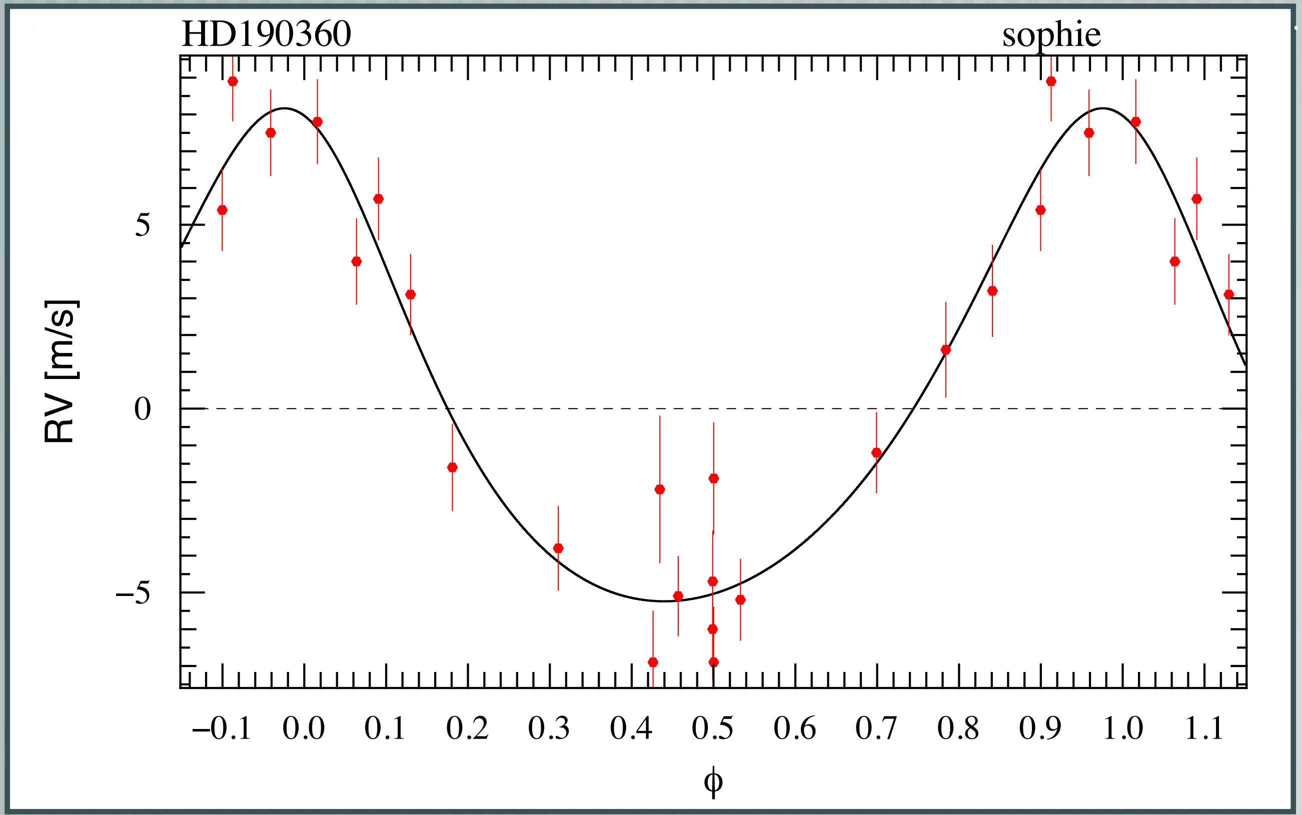




P = 17.33 ± 0.22 d; K = 6.7 ± 1.0 m/s

σ =1.1 m/s over about 50 days

But slightly eccentric orbit...

The realm of small planets

Observation of known small-mass planets

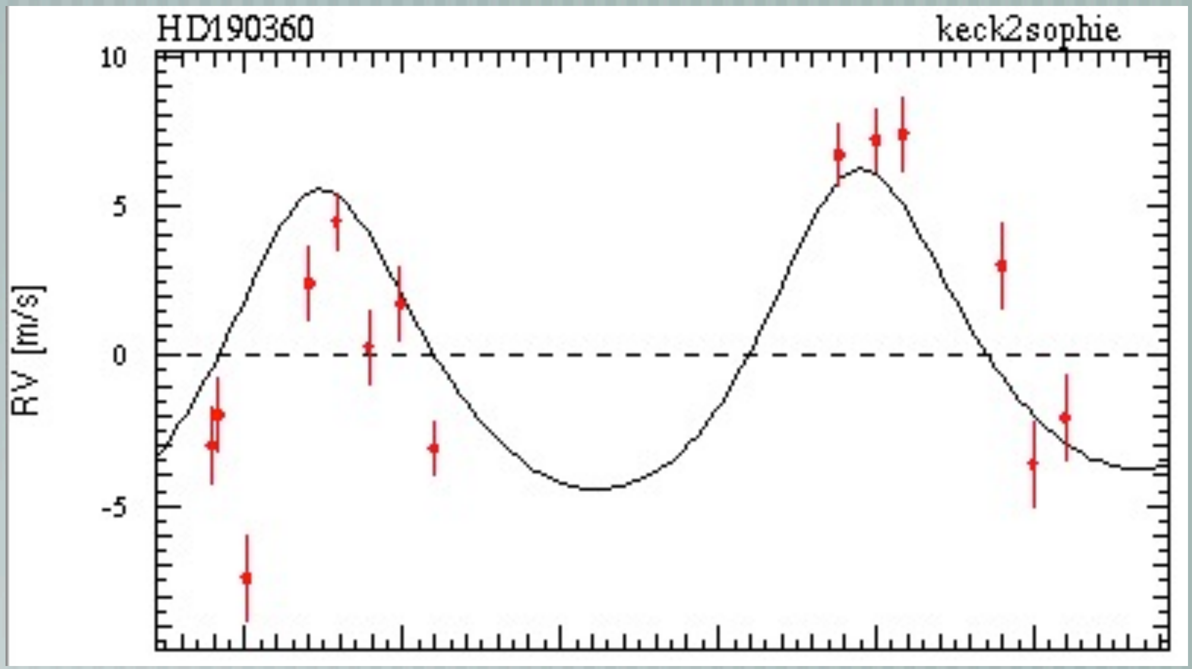
HD190360 c (Vogt et al. 2005)

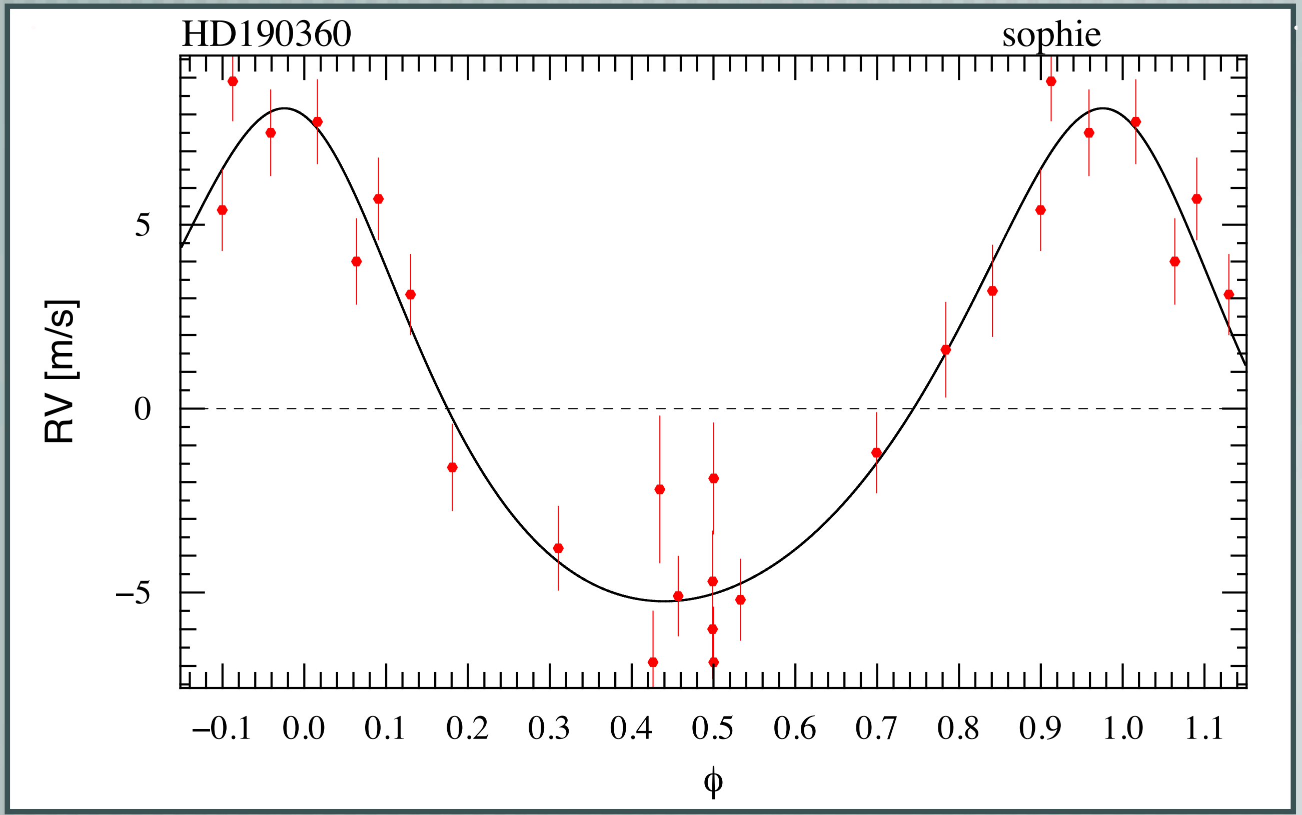
P = 17.10 ± 0.02 d; K = 4.6 ± 1.1 m/s

$m_2 \sin(i)$ = 18.1 ± 4.8 Mearth

HIRES@Keck

σ =2.7 m/s over 27 days



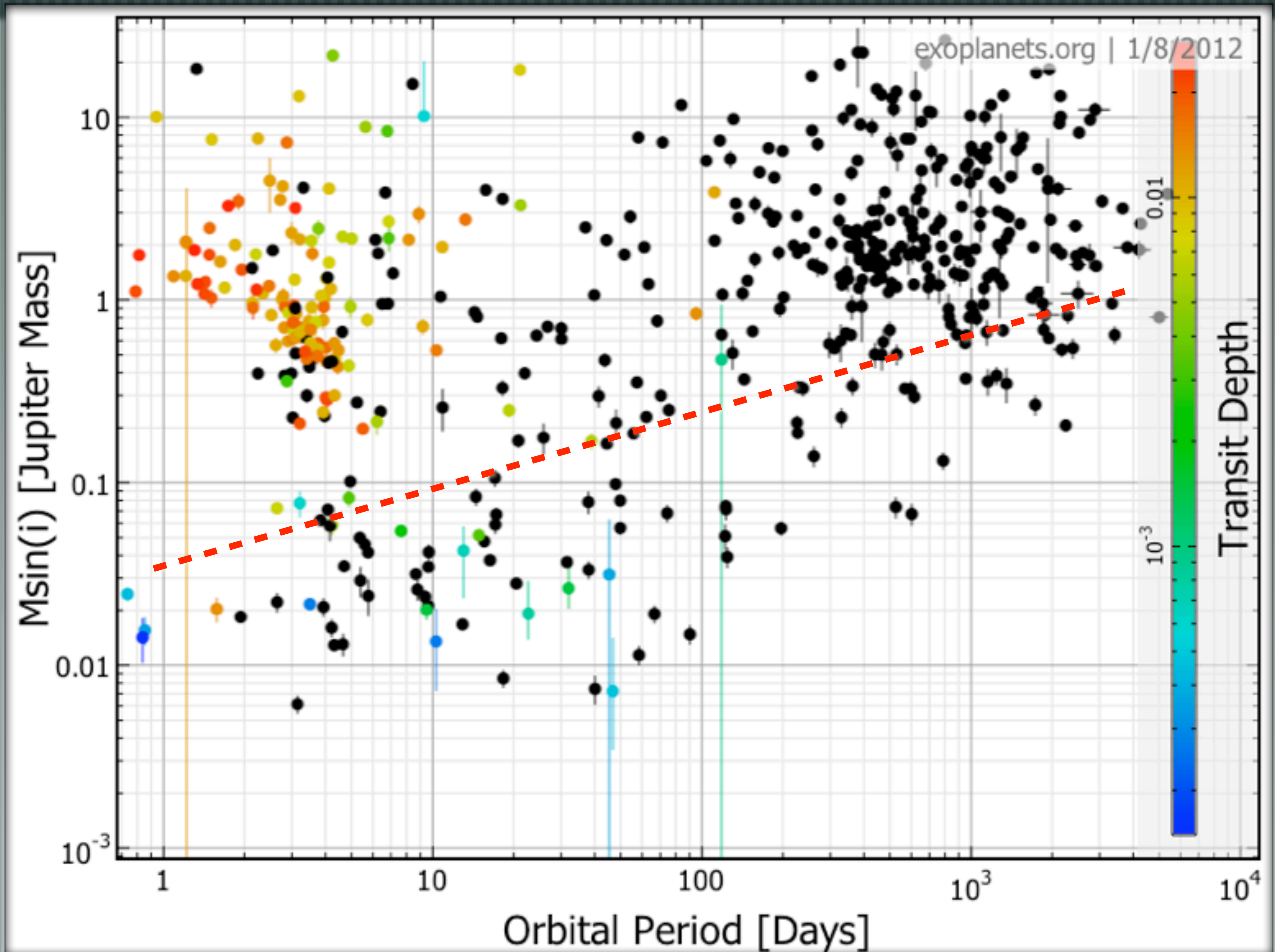


P = 17.33 ± 0.22 d; K = 6.7 ± 1.0 m/s

σ =1.1 m/s over about 50 days

But slightly eccentric orbit...

The realm of small planets



“ I do not know what I may appear to the world, but to myself I seem to have been only like a boy playing on the seashore, and diverting myself in now and then finding a smoother pebble or a prettier shell than ordinary, whilst the great ocean of truth lay all undiscovered before me. “

– Isaac Newton

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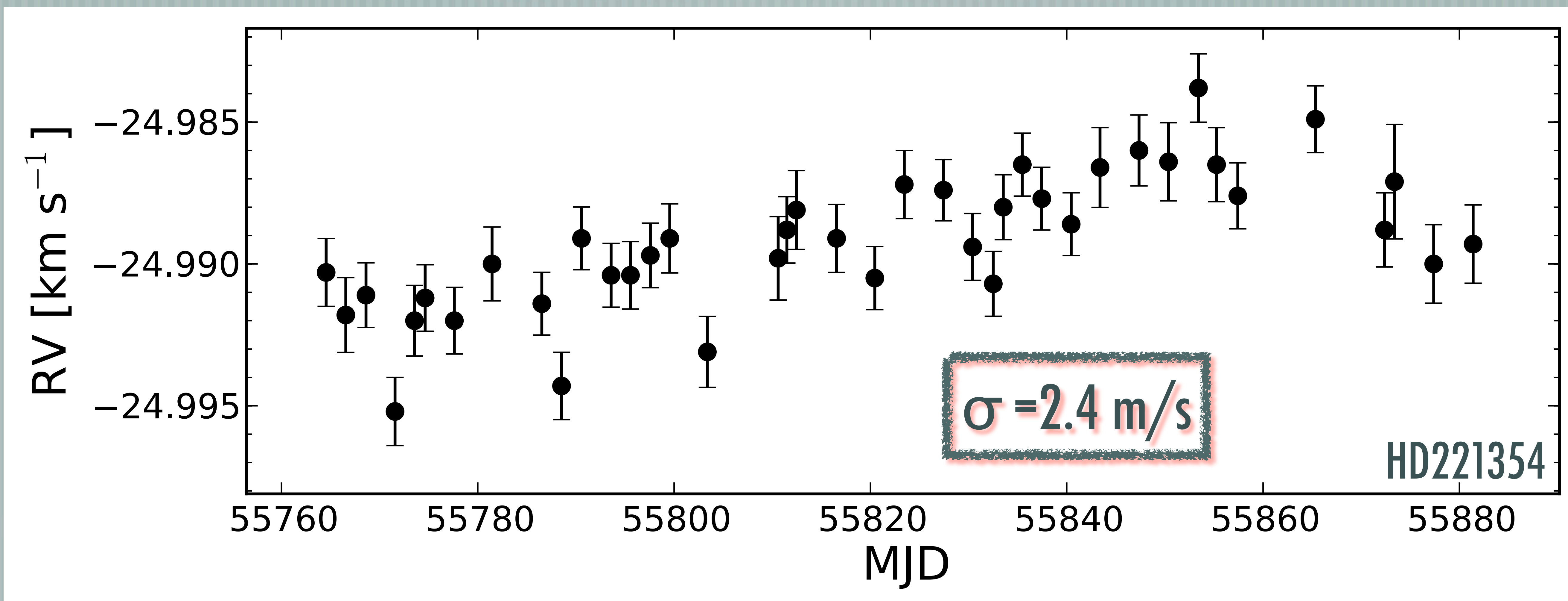
Thank you very much

Additional slides

Improved precision

- Series on known constant stars (standards)



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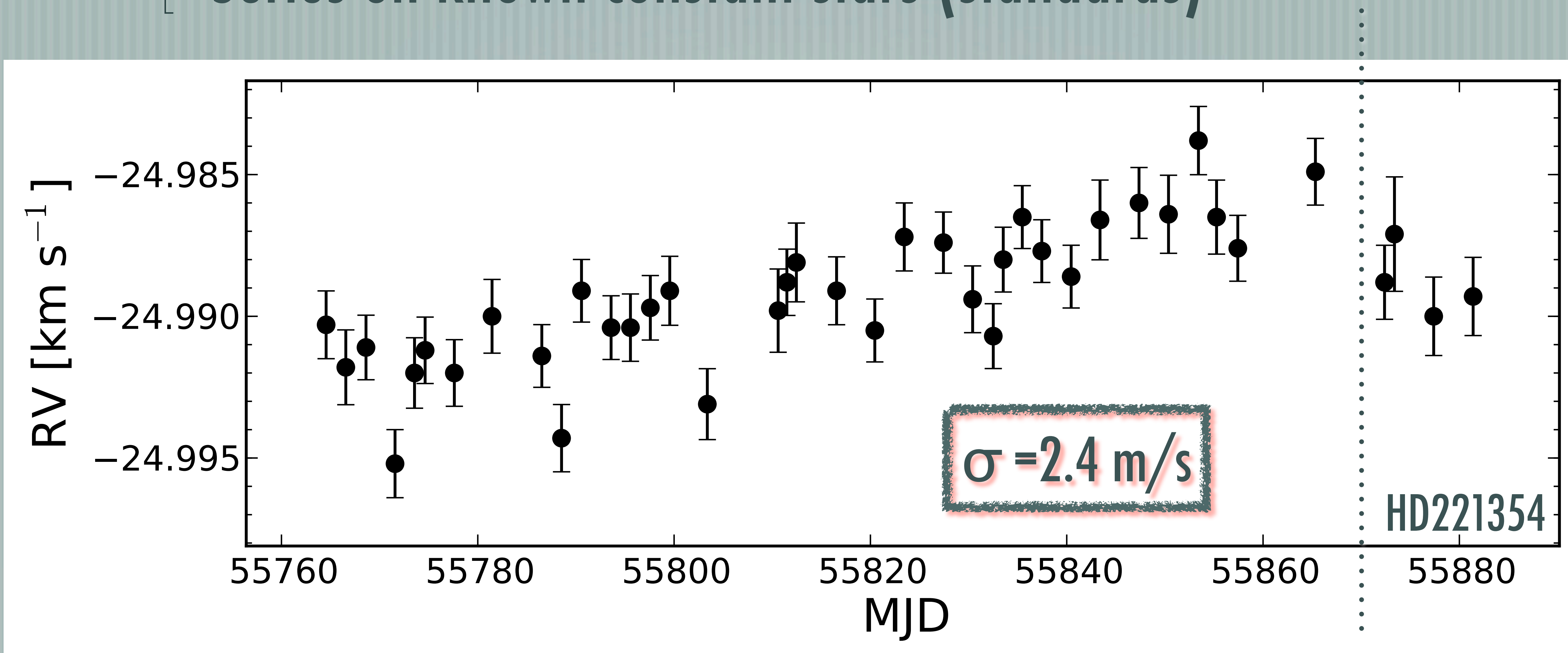
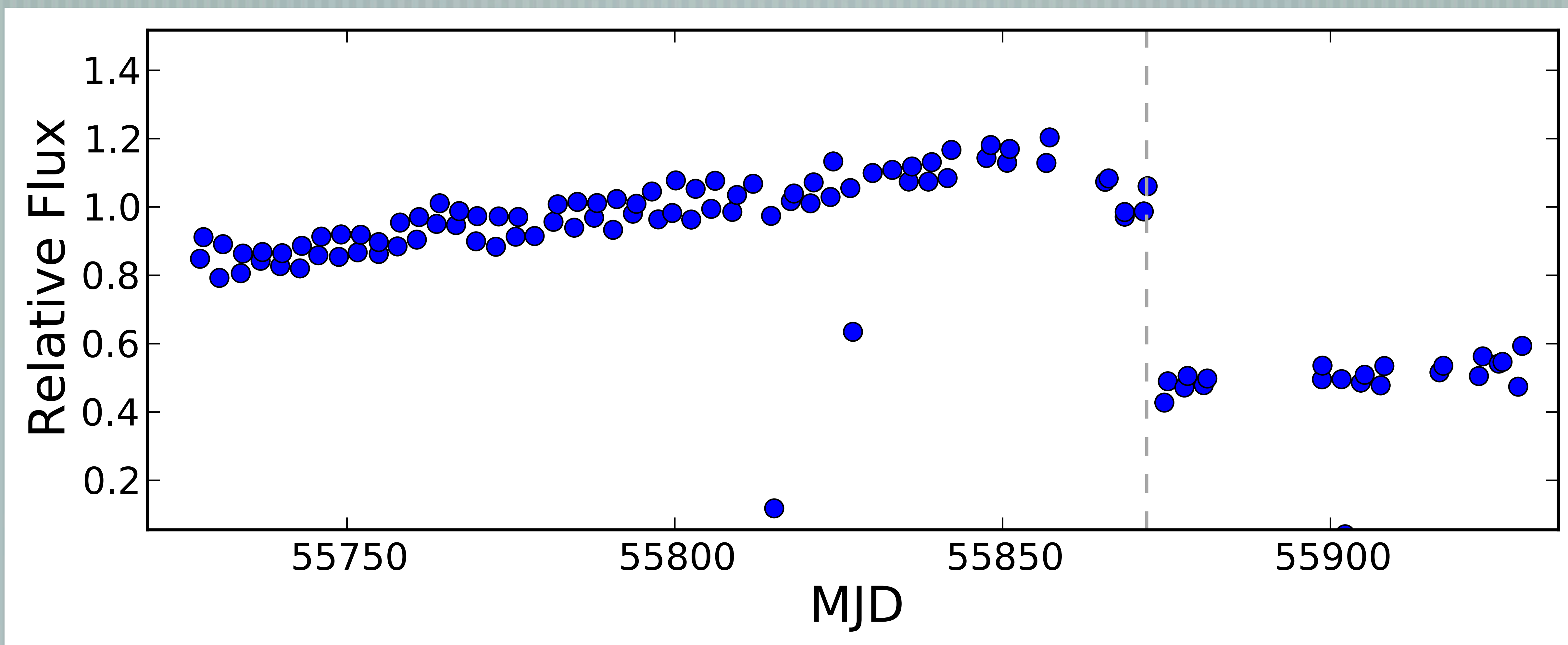


Trend is reverted at the time of installation of new ThAr lamp.

Room for further improvement

- New Systematic effects already identified



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