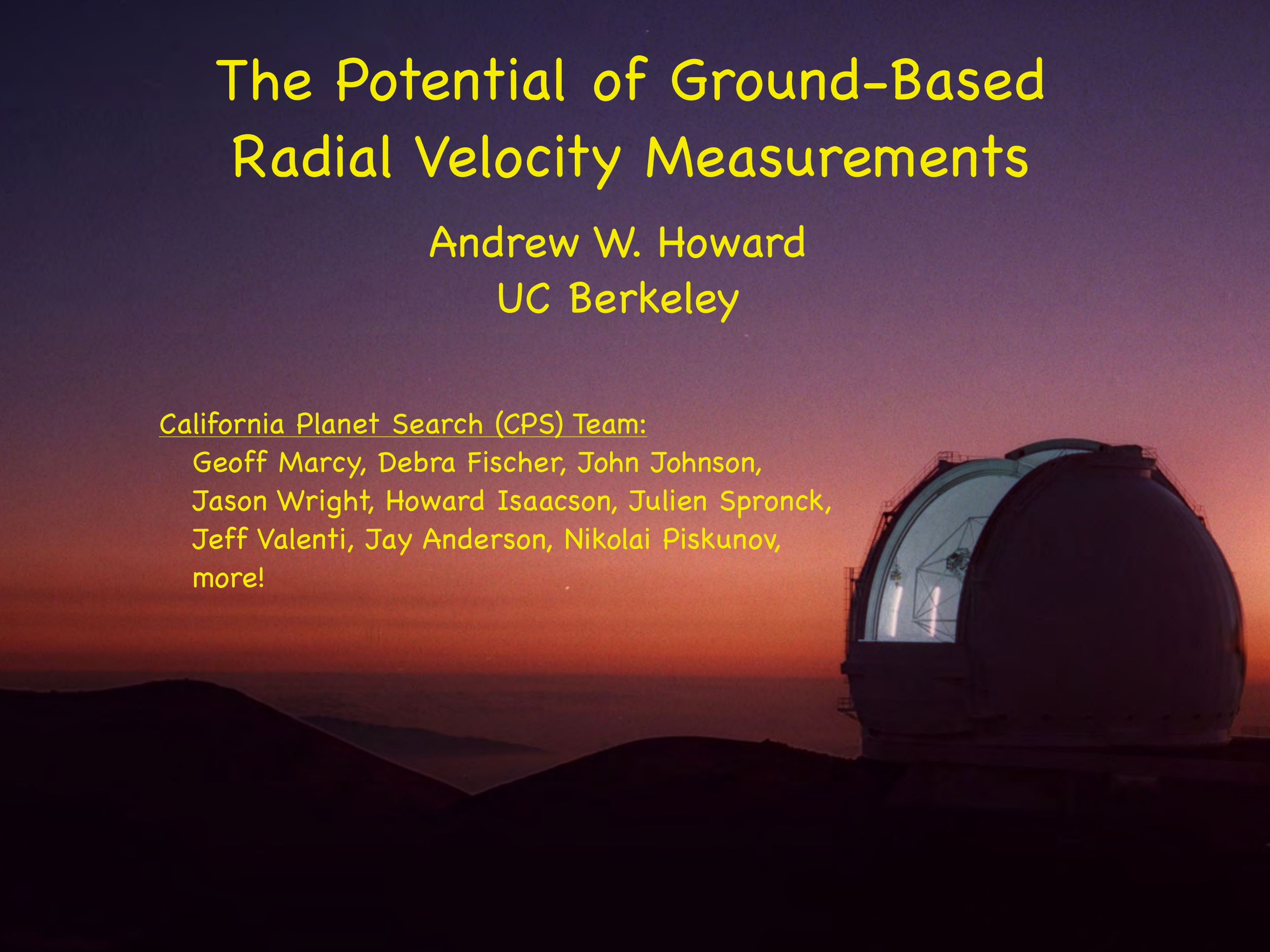
The Potential of Ground-Based Radial Velocity Measurements

Andrew W. Howard
UC Berkeley

California Planet Search (CPS) Team:
Geoff Marcy, Debra Fischer, John Johnson, Jason Wright, Howard Isaacson, Julien Spronck, Jeff Valenti, Jay Anderson, Nikolai Piskunov, more!



Decadal Survey

- "The role of target-finding for future direct-detection missions, one not universally accepted as essential, can be done at least partially by pushing ground- based radial-velocity capabilities to a challenging but achievable precision below 10 centimeters per second."
- *Exoplanet Initiatives: As already discussed, the discovery and study of exoplanets is developing at an extraordinarily rapid pace. It will be important to make strategic investments in new ground-based capabilities during the coming decade. One important component will be the aggressive development of ground-based high precision radial-velocity surveys of nearby stars at optical and near-infrared wavelengths (including efforts to determine the effect of stellar activity on these measurements).*

Agency Context

- NASA has a clear need for Doppler capabilities to support current and possible future space missions
- NSF has other priorities and does not currently have a program that is well-suited to building these facilities

Key RV questions: Astrophysical

- What are the near-term, medium-term, and long-term needs for Doppler measurements to support NASA missions - how many stars of what magnitudes and spectral types?
- What are the astrophysical limitations on radial velocity precision for measurements of nearby stars?
- How does this precision vary as a function of stellar type?
- How easily does single-measurement stellar jitter translate into detectable planet mass at various periods?

Key RV questions: technical

- What approaches can improve radial-velocity instrumental precision to the astrophysical limits?
- What can be done to increase the efficiency and sensitivity of radial-velocity facilities?
- What potential exists for infra-red radial velocity precision?

Programmatic and Political

- What are the benefits or disadvantages of increased investment in telescope time (and for which class of telescope)?
- How should we prioritise increased investment in existing telescope resources versus investment in new, dedicated facilities?

Outline

- State-of-the-art RV Detections (HIRES and HARPS)
- Astrophysical Jitter
- Instrumental Jitter
- Assessment and Recommendations

California Planet Search (CPS)

CPS Planet Searches:

- Eta-Earth Survey
- Long-term survey
- Kepler follow-up
- Sub-giant Search
- M dwarf Search
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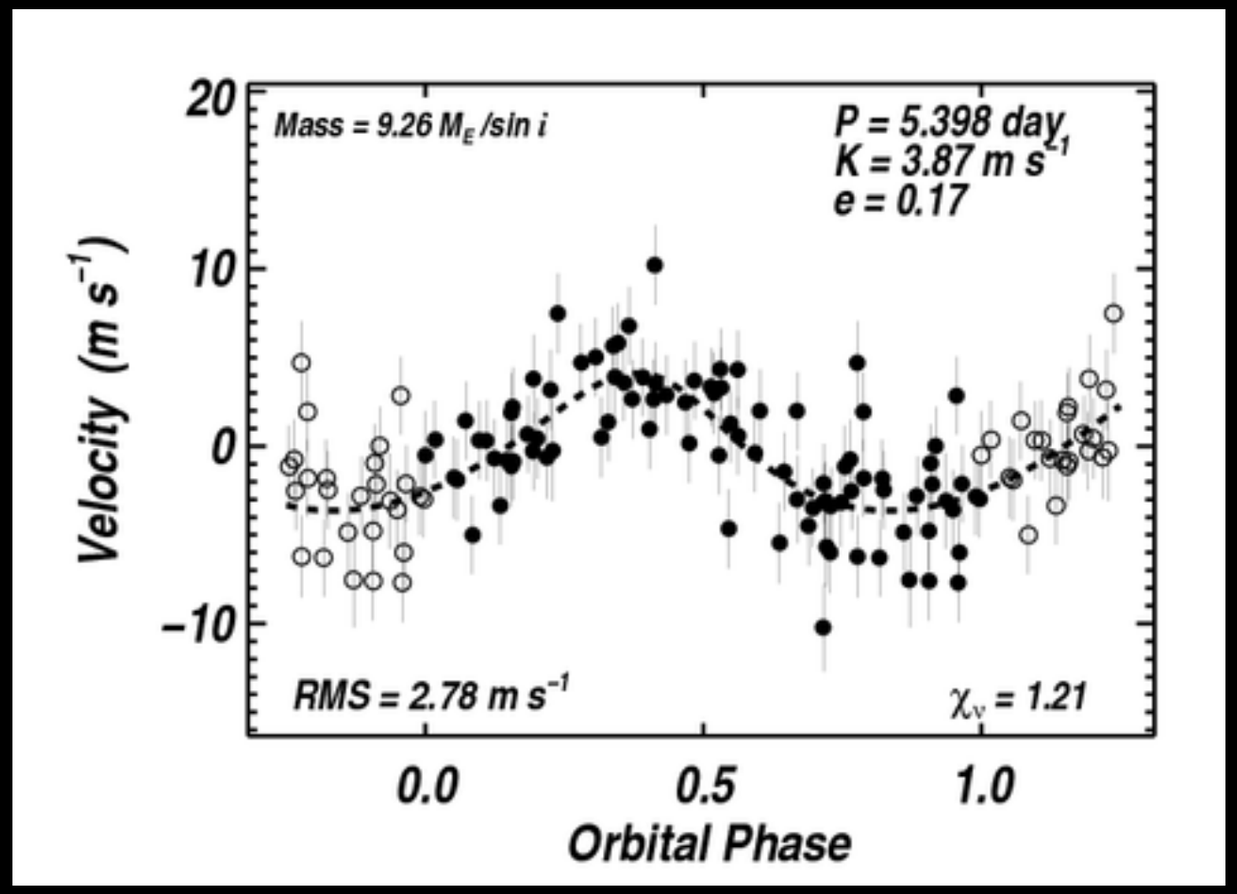
Eta-Earth Survey



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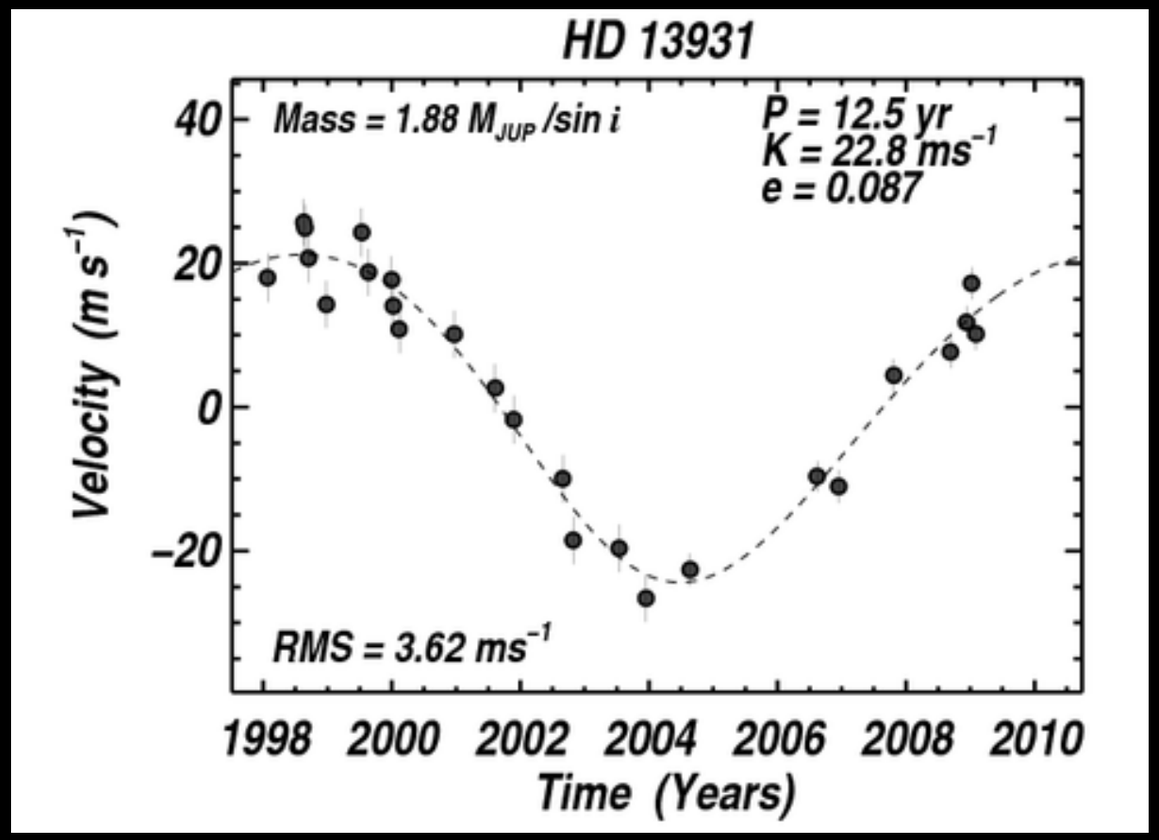
Long-term Survey



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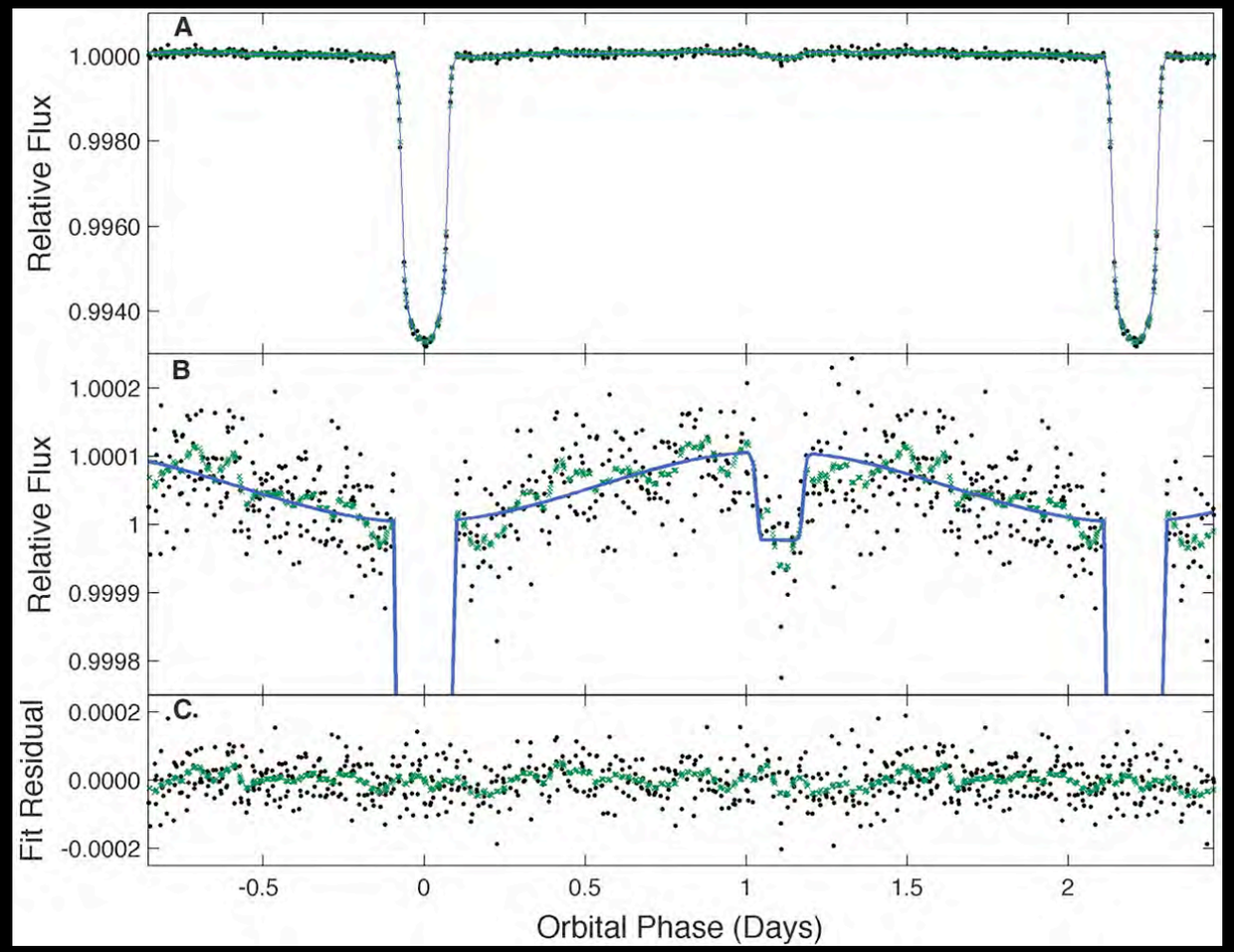
Kepler Followup



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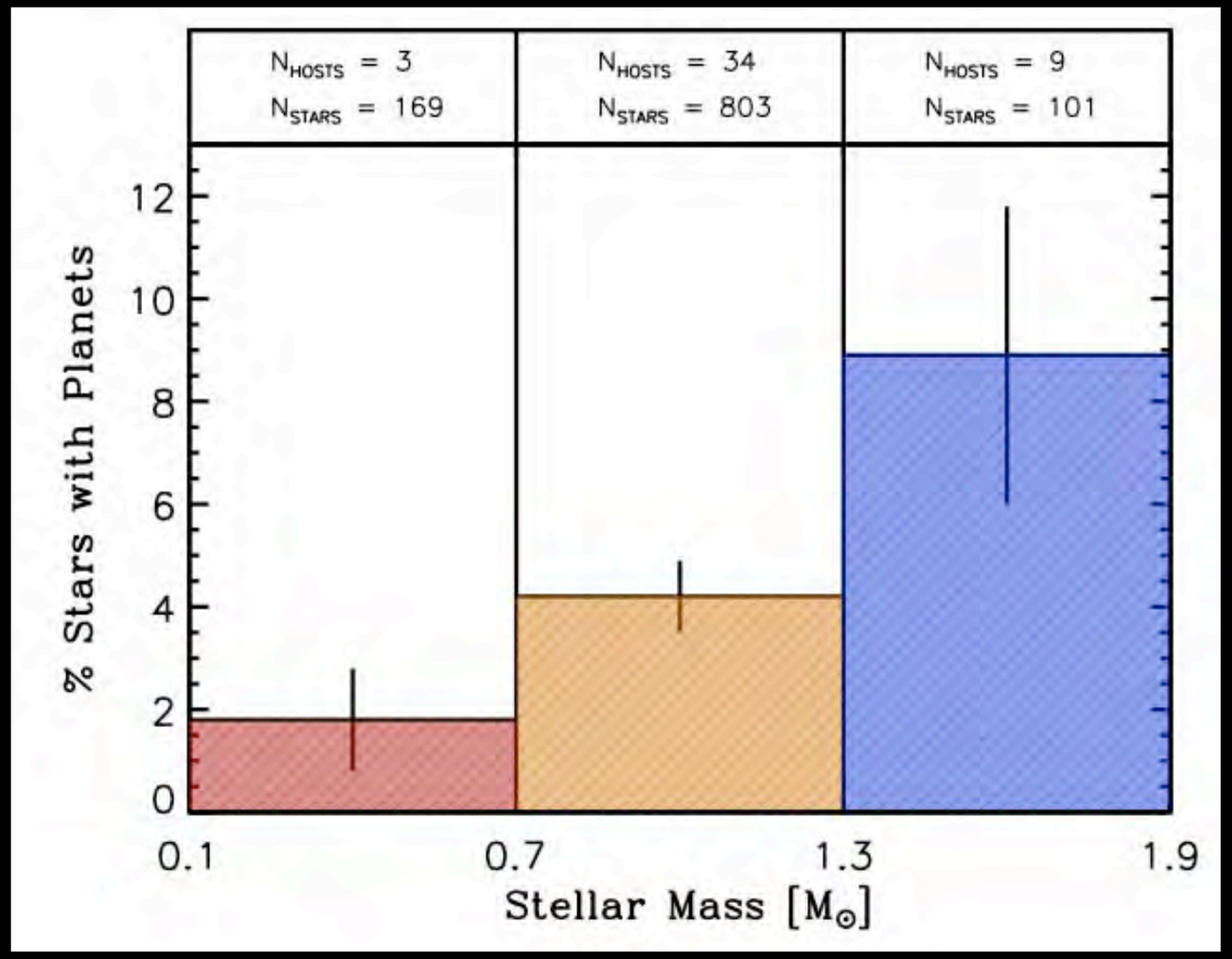
Sub-giant Search



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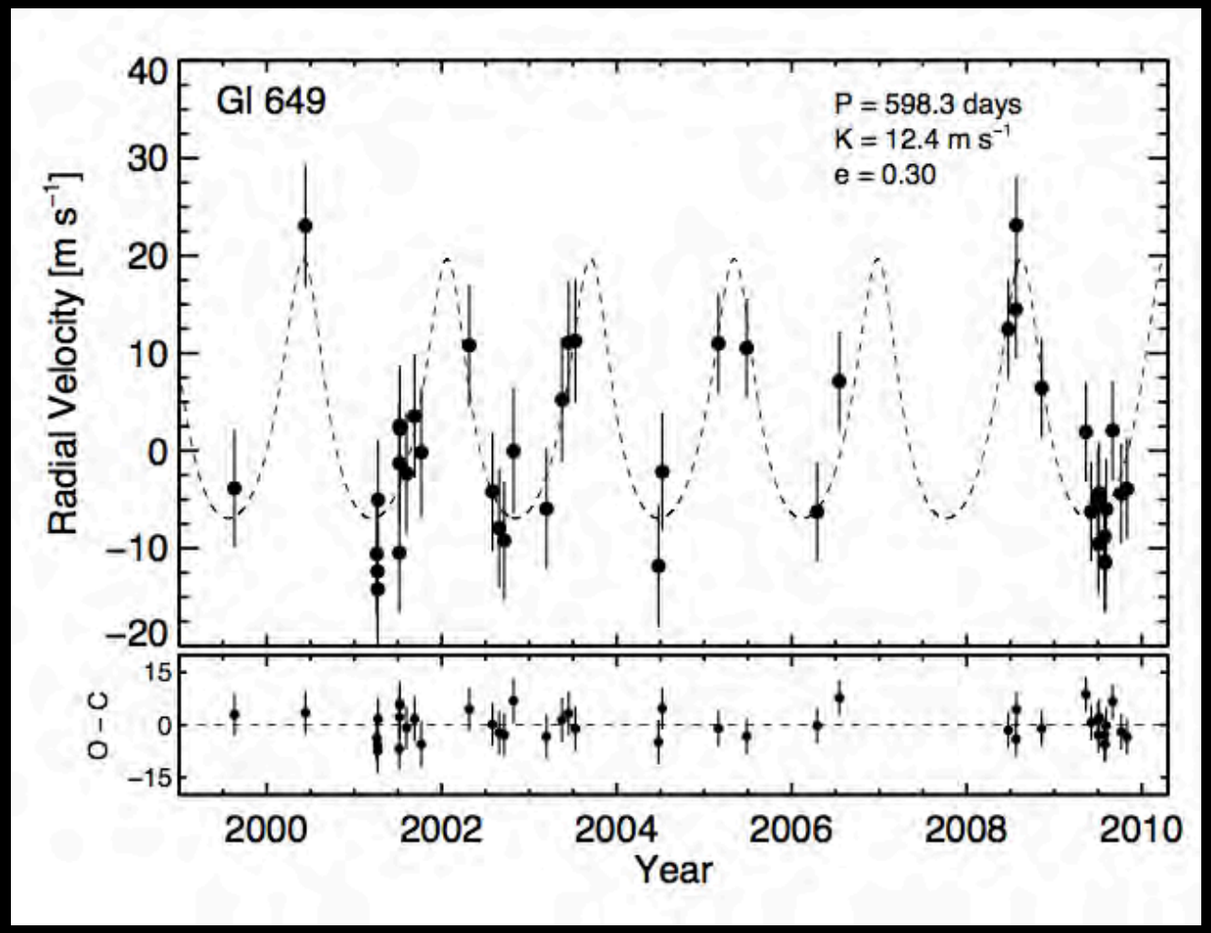
M dwarf Planet Search



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M2K Search

New Search led by Debra Fischer
Focus on K-stars and M-stars
First detections soon!

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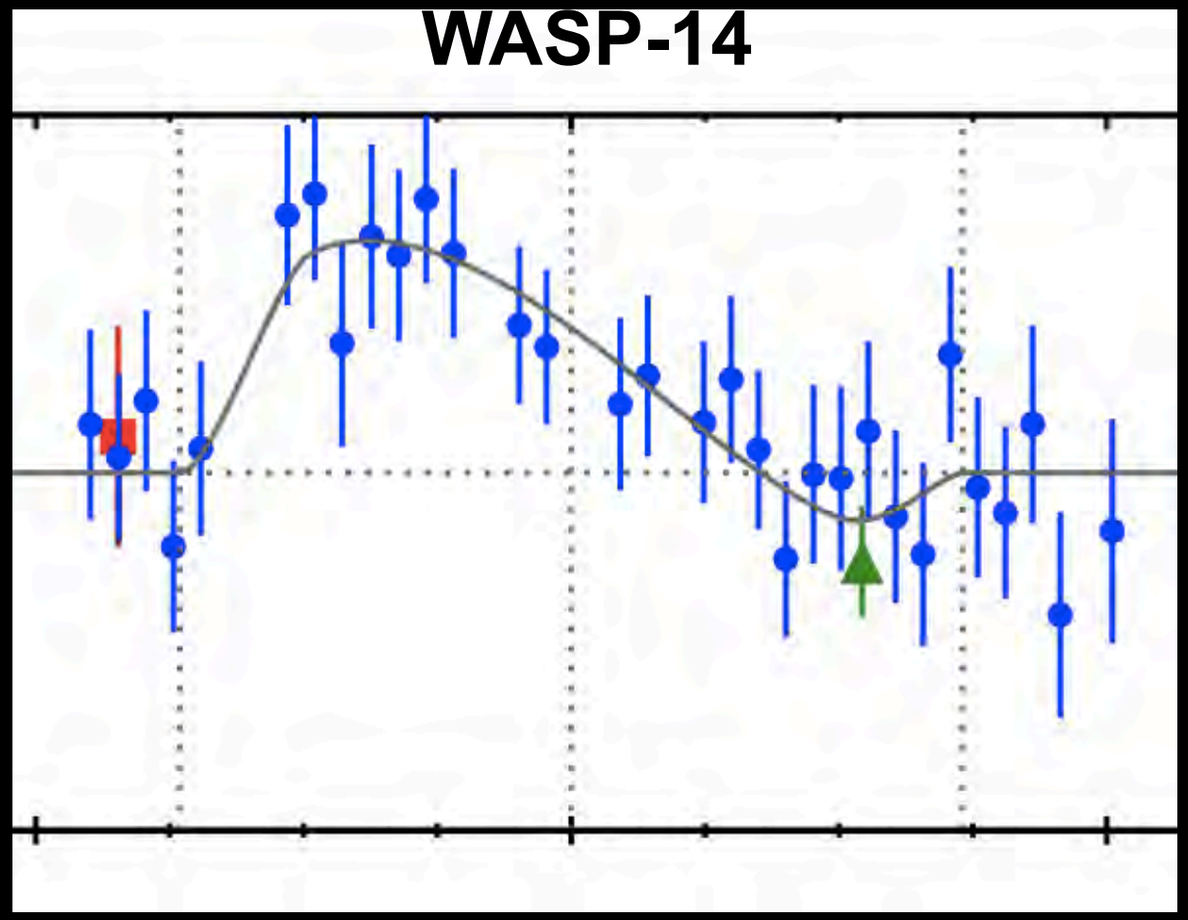
Rossiter Measurements



Spin-orbit *Mis*alignment

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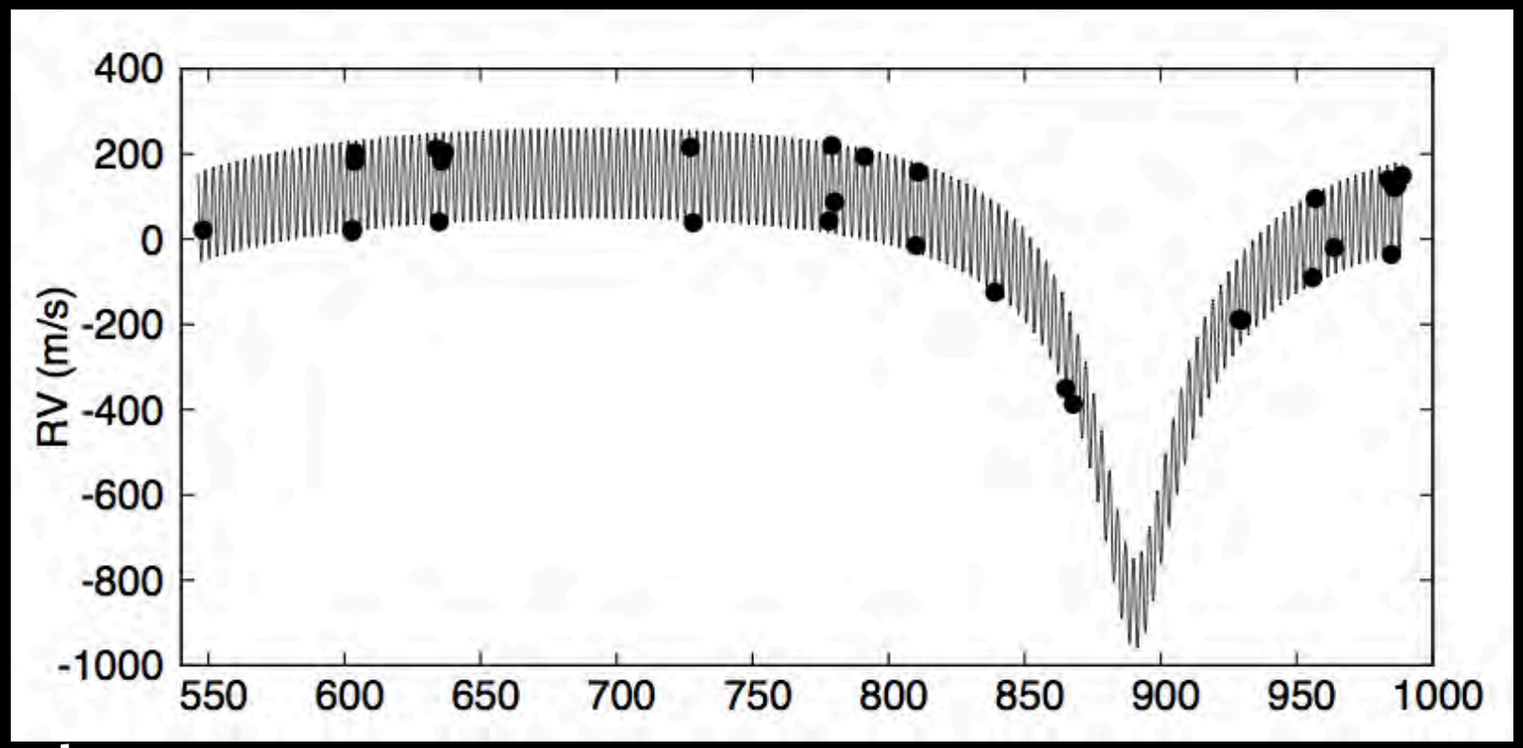

HAT-P-13b,c

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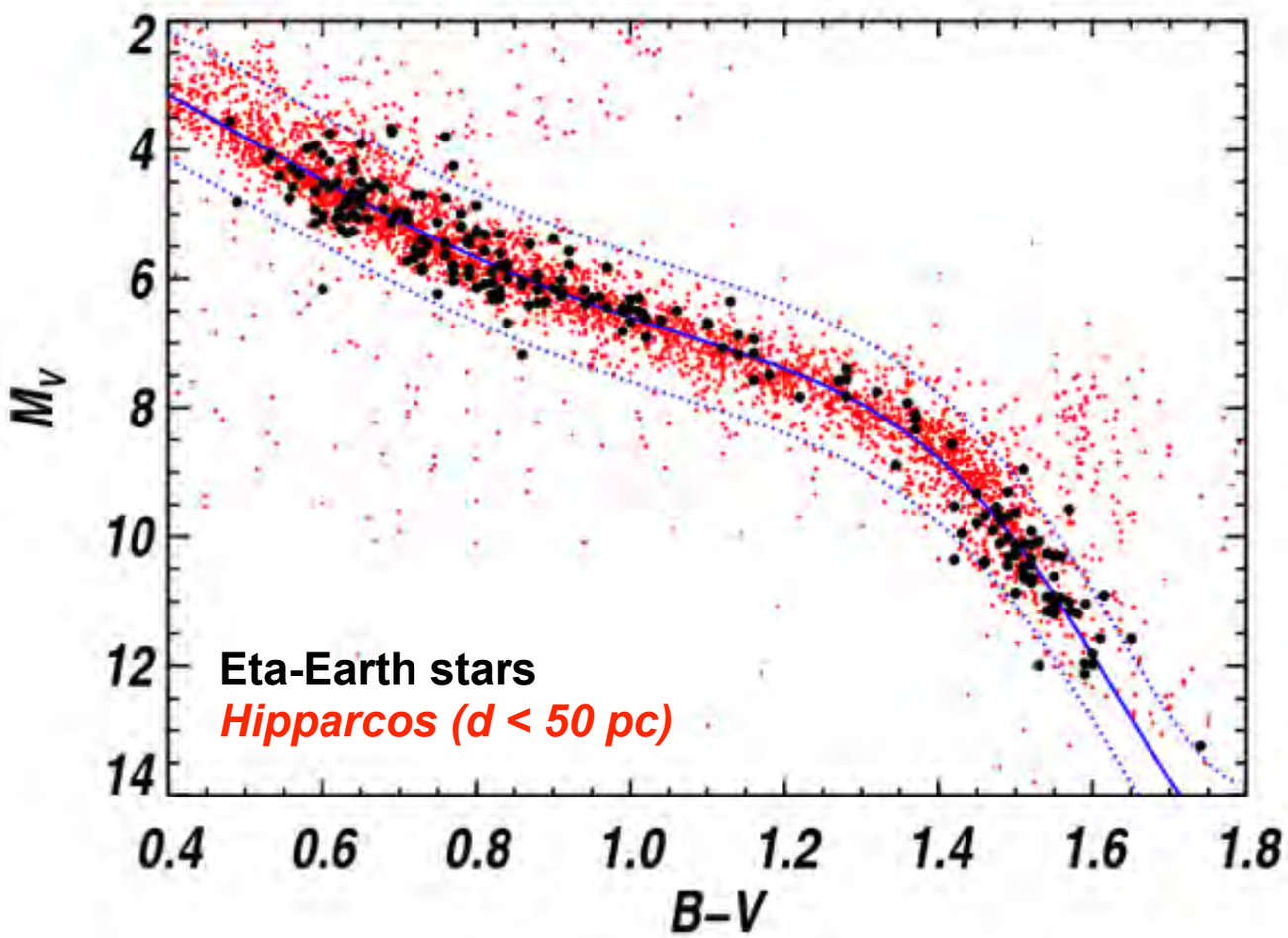
NASA-UC Eta-Earth Program

RV survey of 238 nearby GKM dwarfs

Search for low-mass planets (Msini = 3-30 M_{Earth})

Constrain population of low-mass planets
and planet formation theory



39% G stars
33% K stars
28% M stars

Statistically unbiased (nearly) stellar population:

- V < 11
- distance < 25 pc
- log R'HK < −4.7 (inactive)

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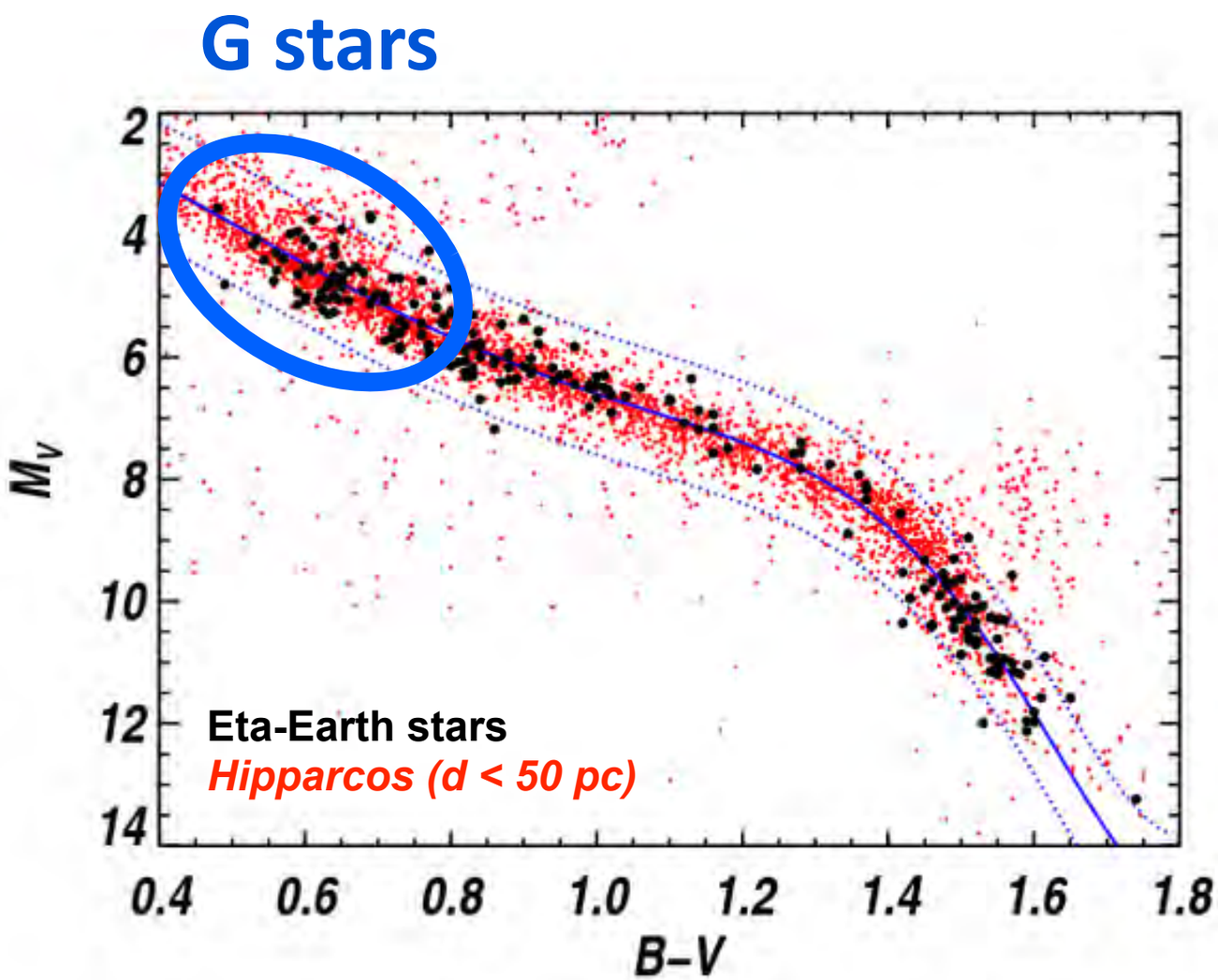

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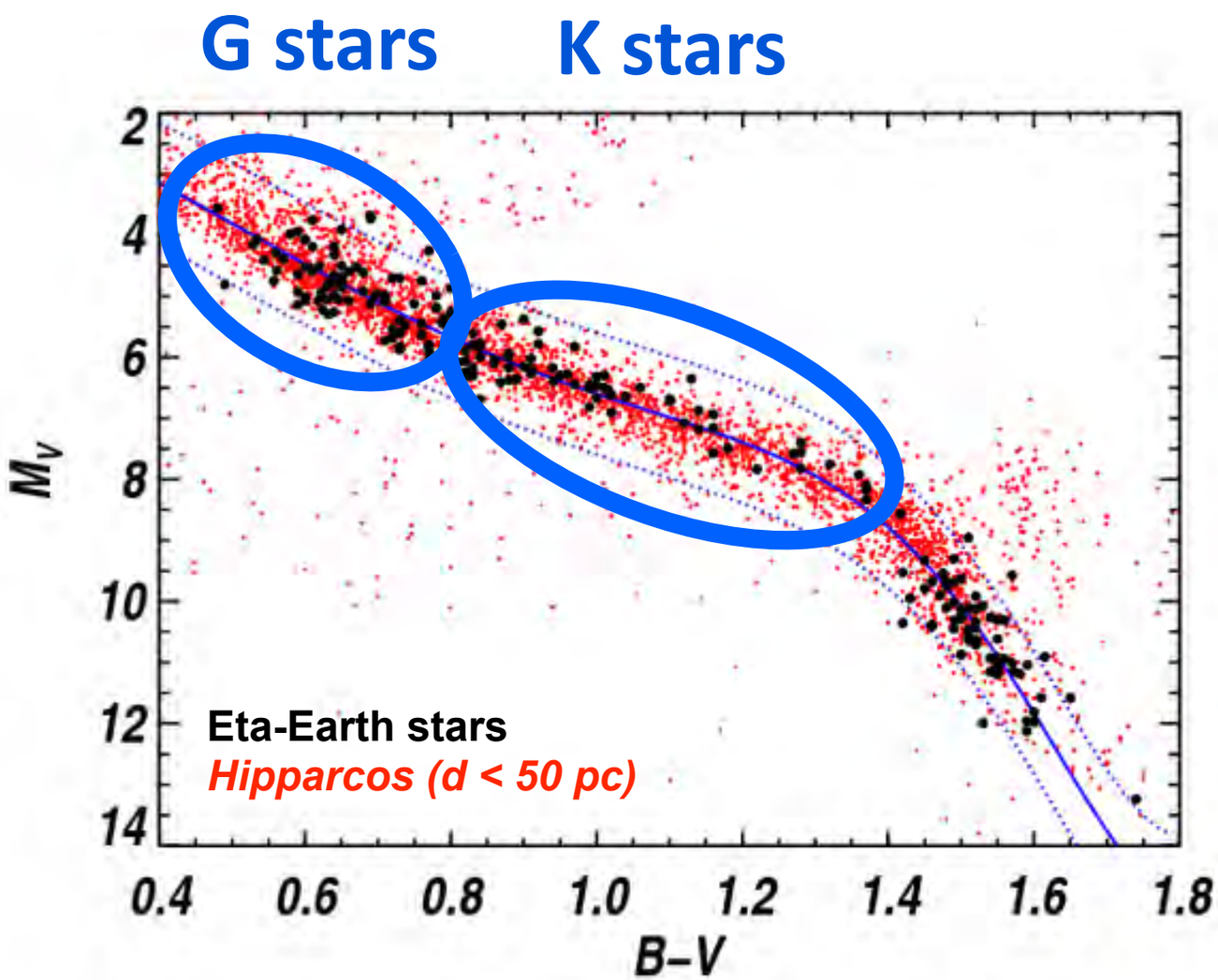

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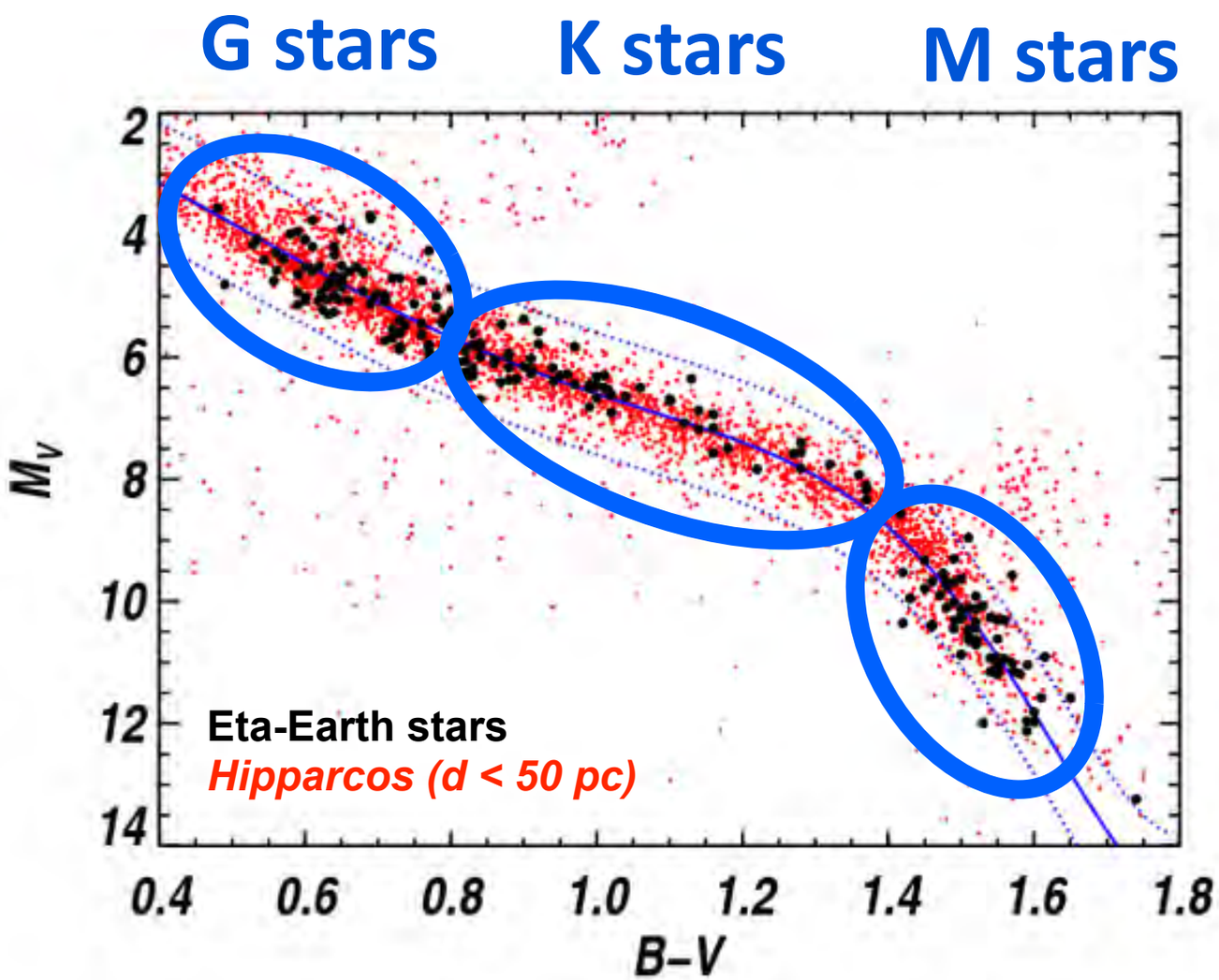

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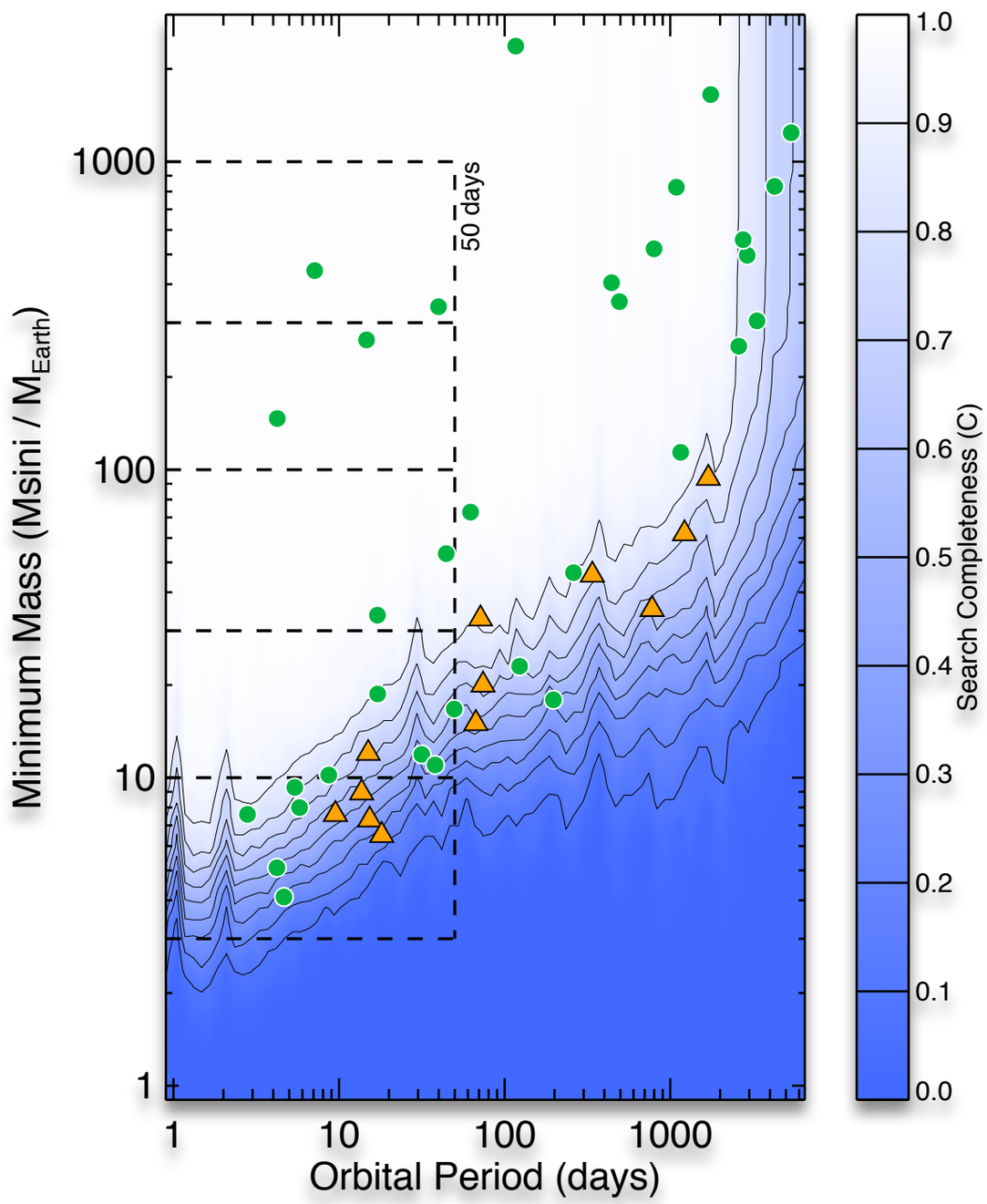
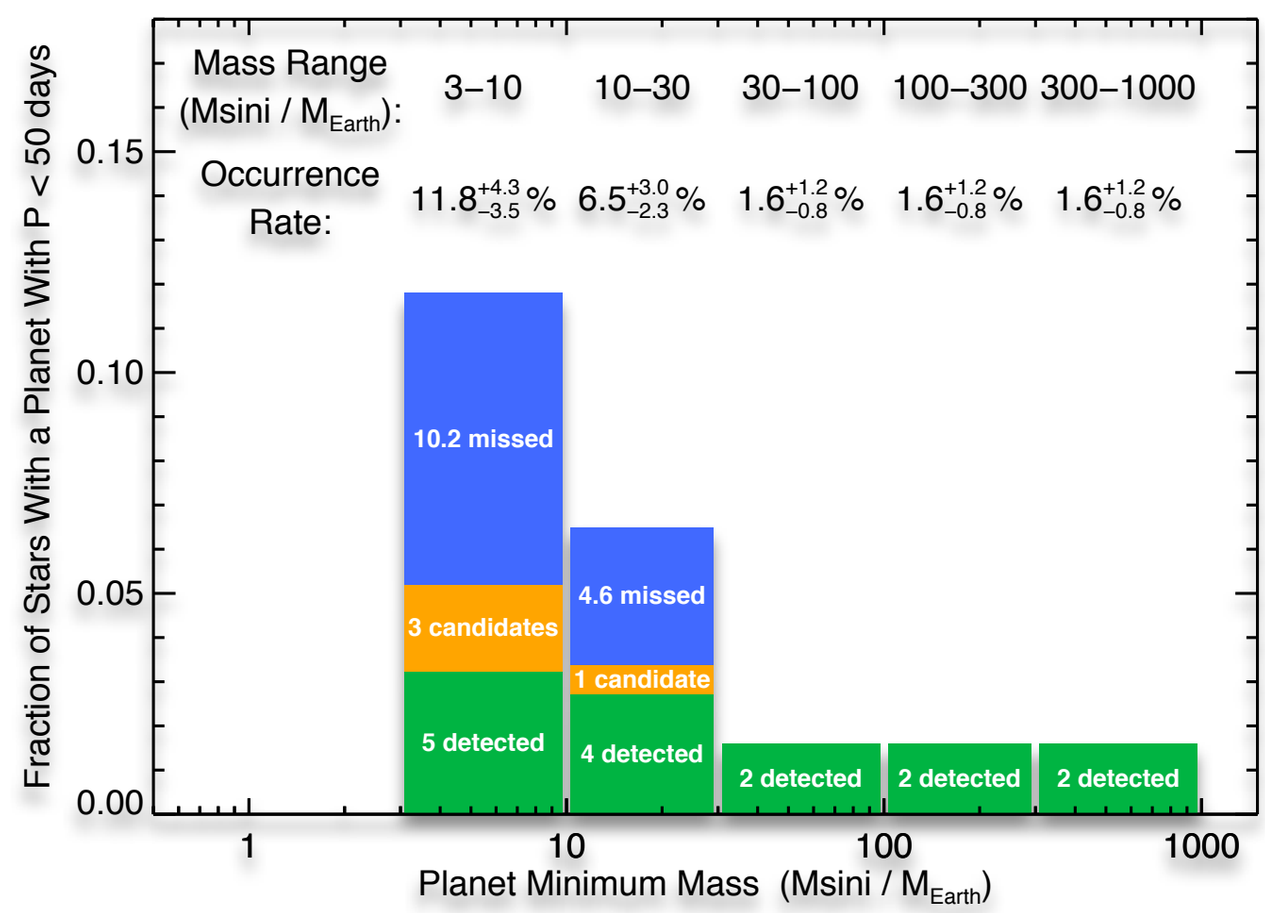
NASA/UC Eta-Earth Survey (Keck)



166 bright GK stars

20-100 Keck RVs each (median = 35)

Howard et al. (2010), Science, 330, 653



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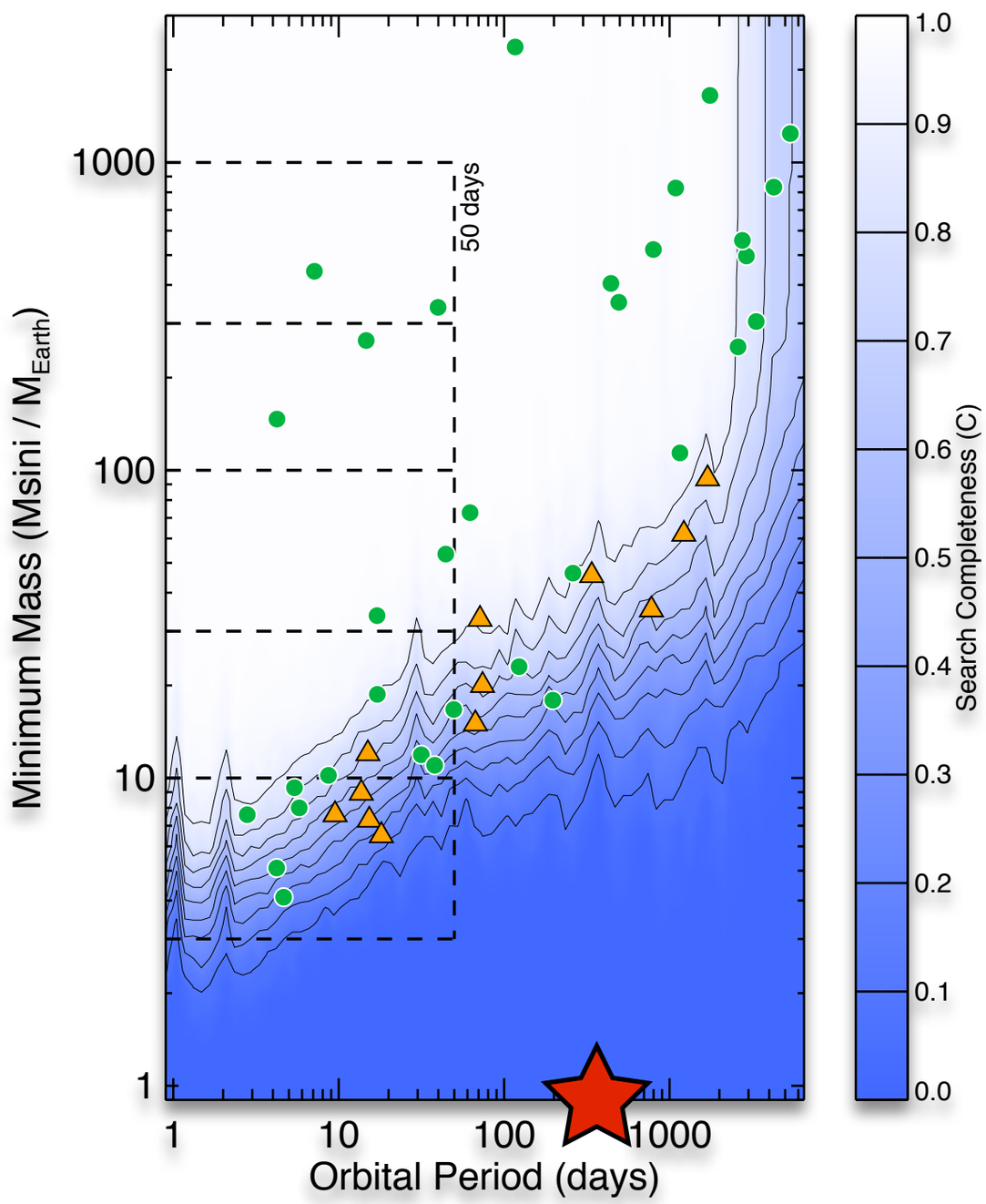

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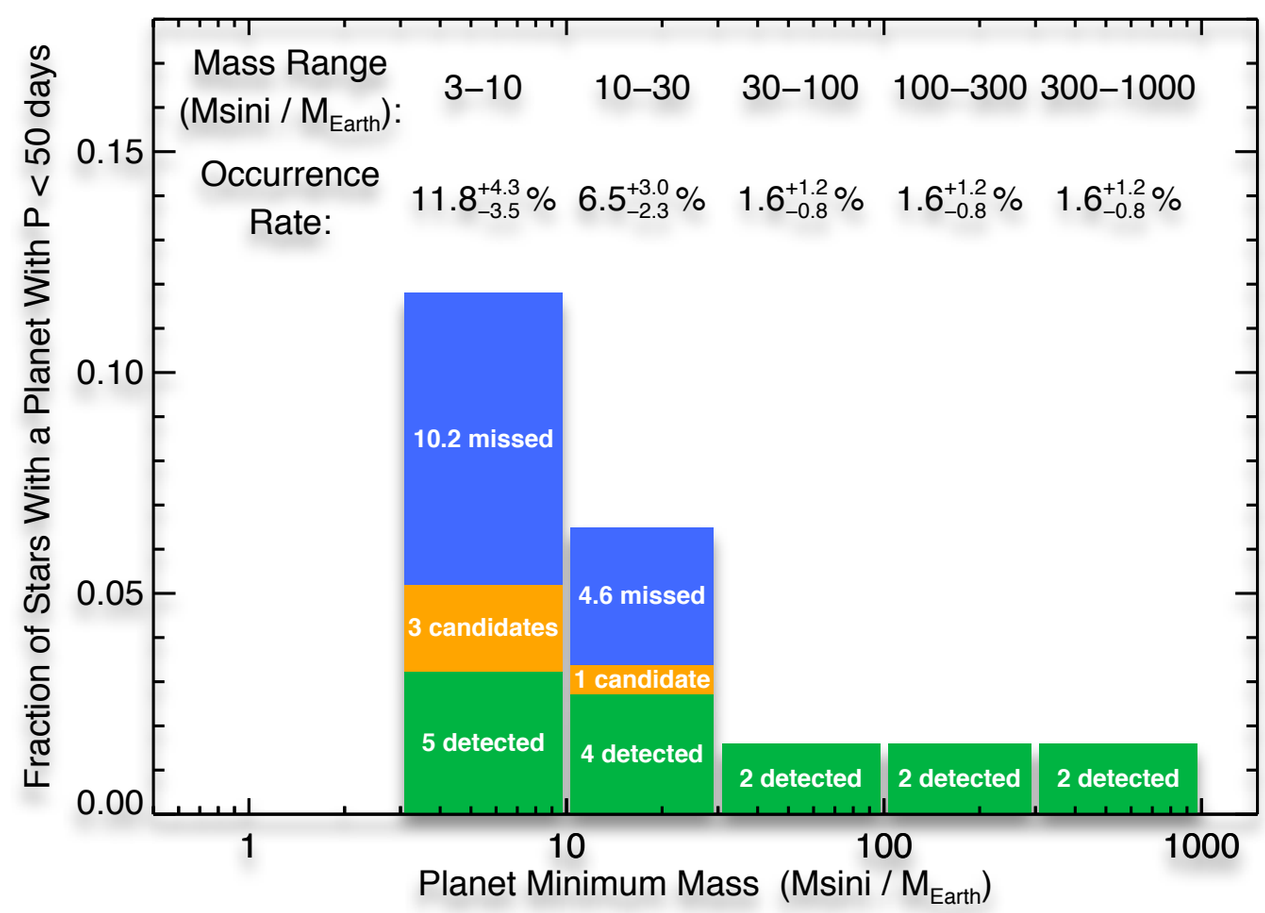
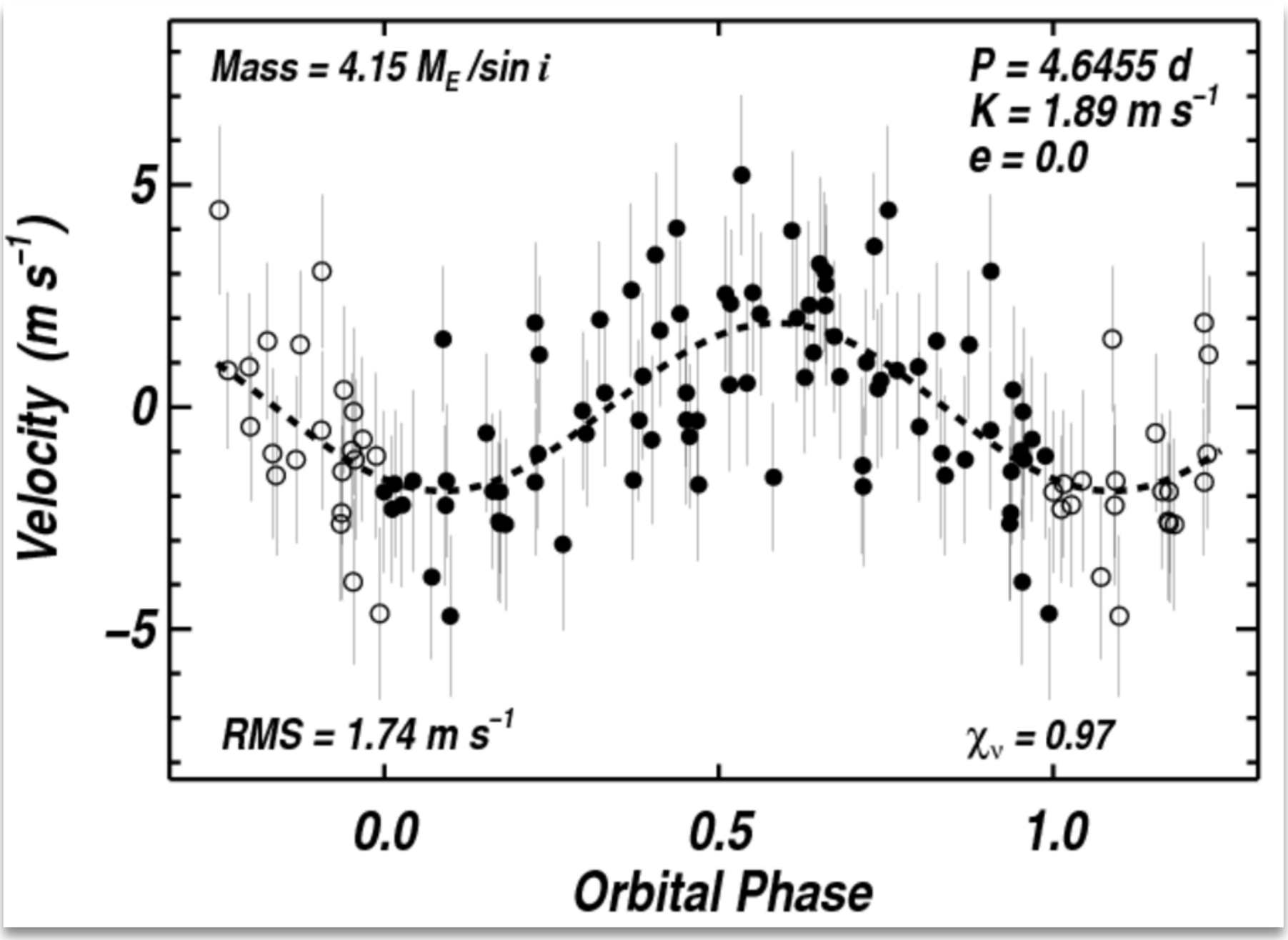


HD 156668 b

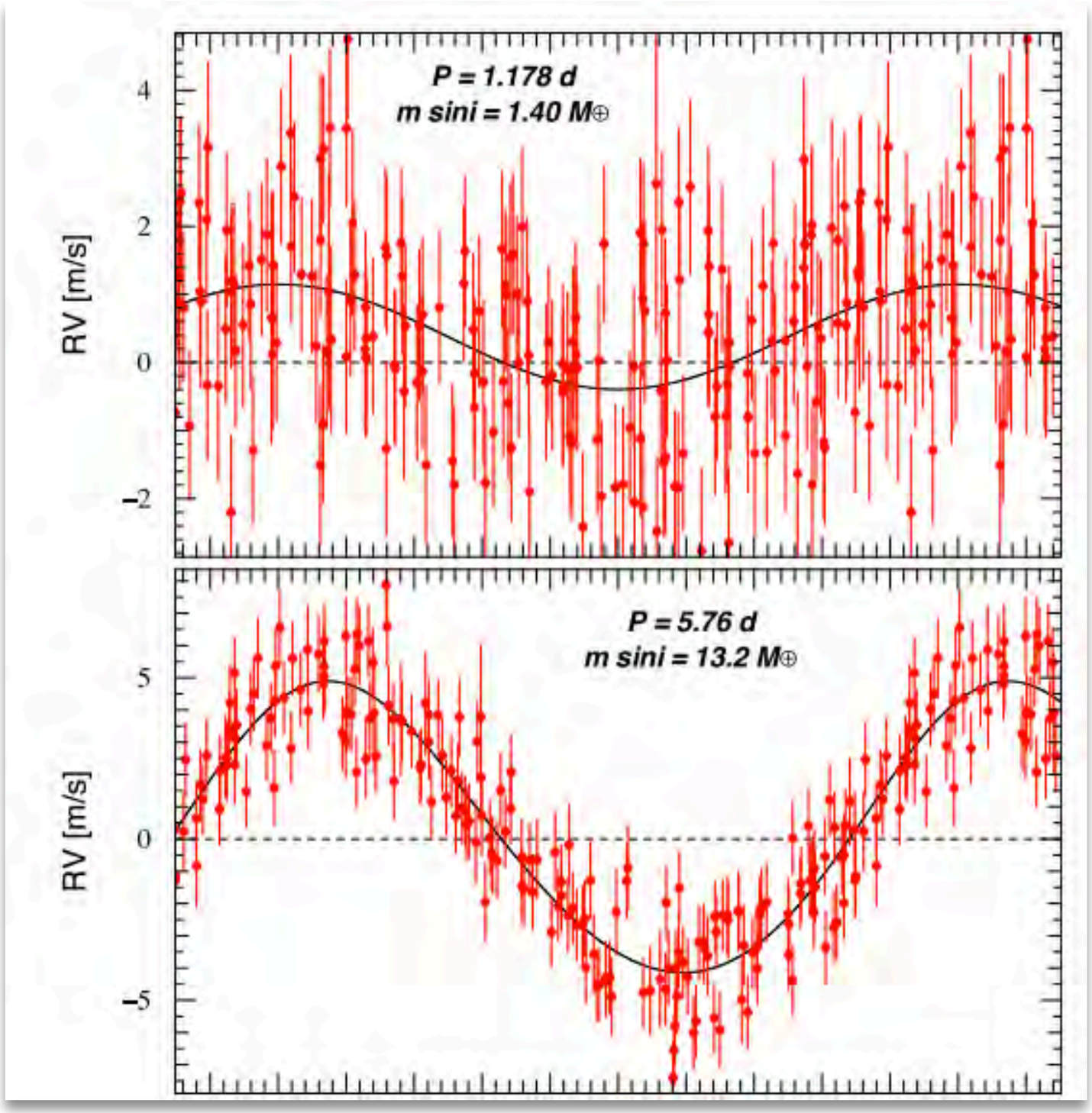


Star:
HD 156668 (K3V)
distance = 24 pc
V = 8.3
[Fe/H] = 0.05
quiet

Planet:
M sin i = 4.15 M_E
P = 4.6455 d
e = 0 (fixed)

Howard et al. (2011)

HD 10180 - multi-planet system



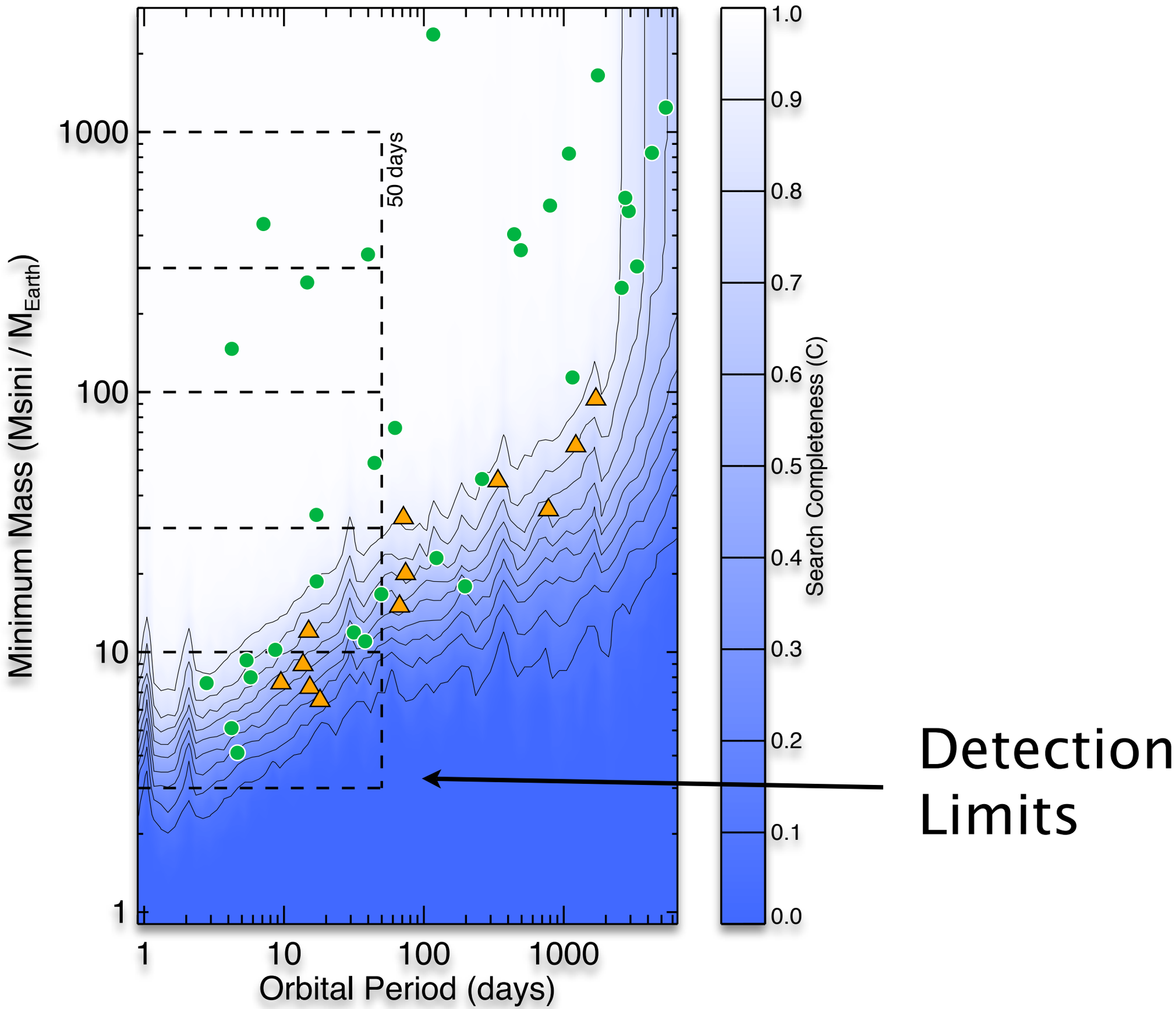
Candidate!

Star:
HD 100180 (G1V)
distance = 39 pc
V = 7.3
quiet

Planets:
5-7 planets
K = 0.8 - 4.8 m/s
RMS = 1.27-1.57 m/s
N_{meas} = 190

Note: Geneva group uses HARPS 100-120 nights/year for low-mass planet searches

Lovis et al. (2010)



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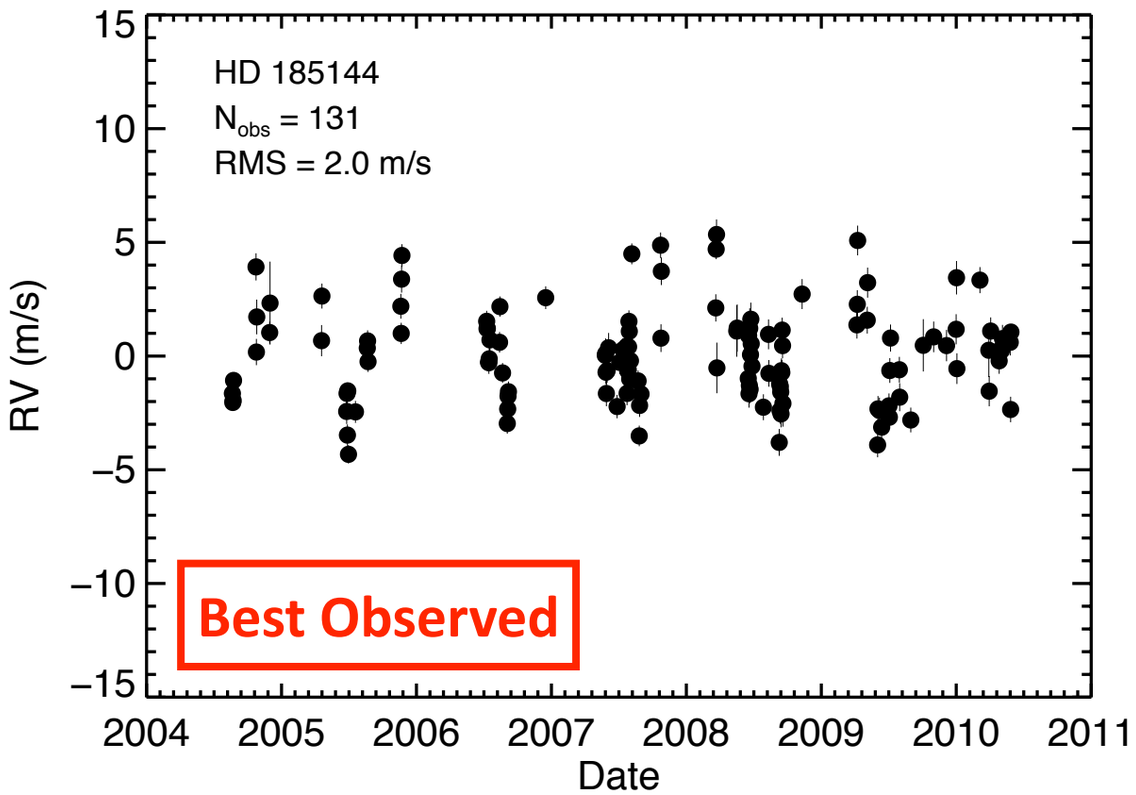
Limits on Non-detections of Planets



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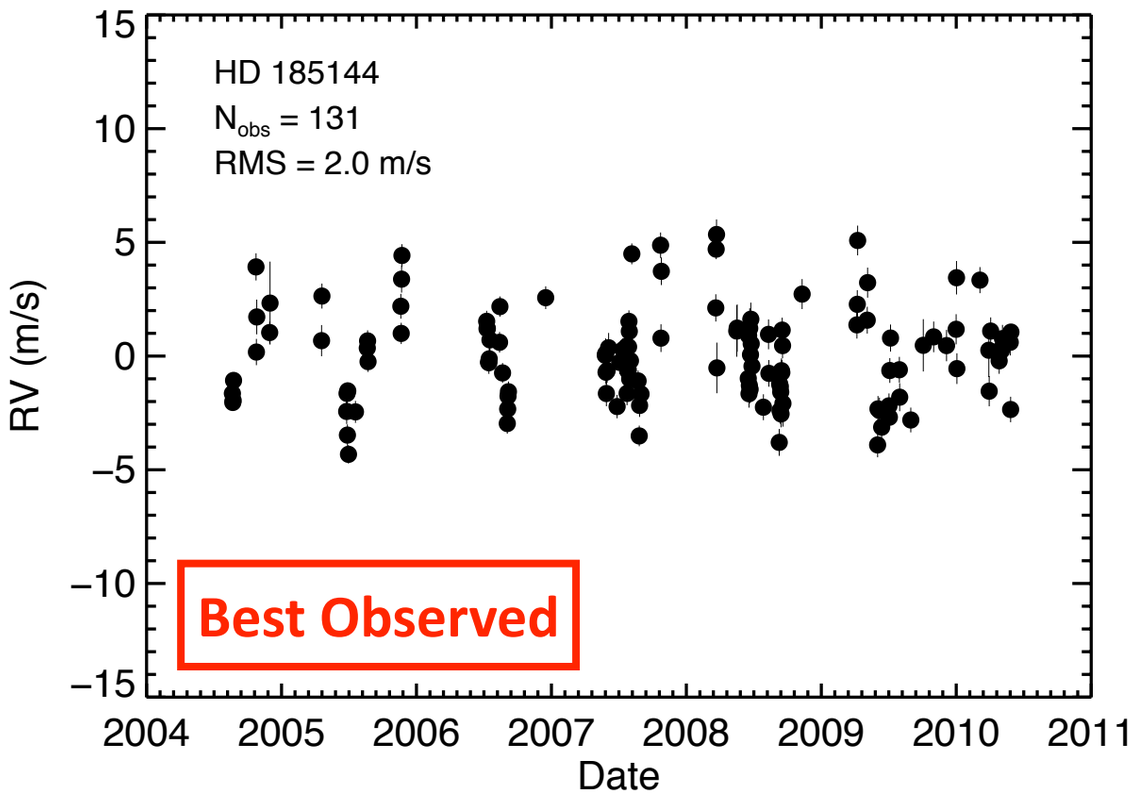

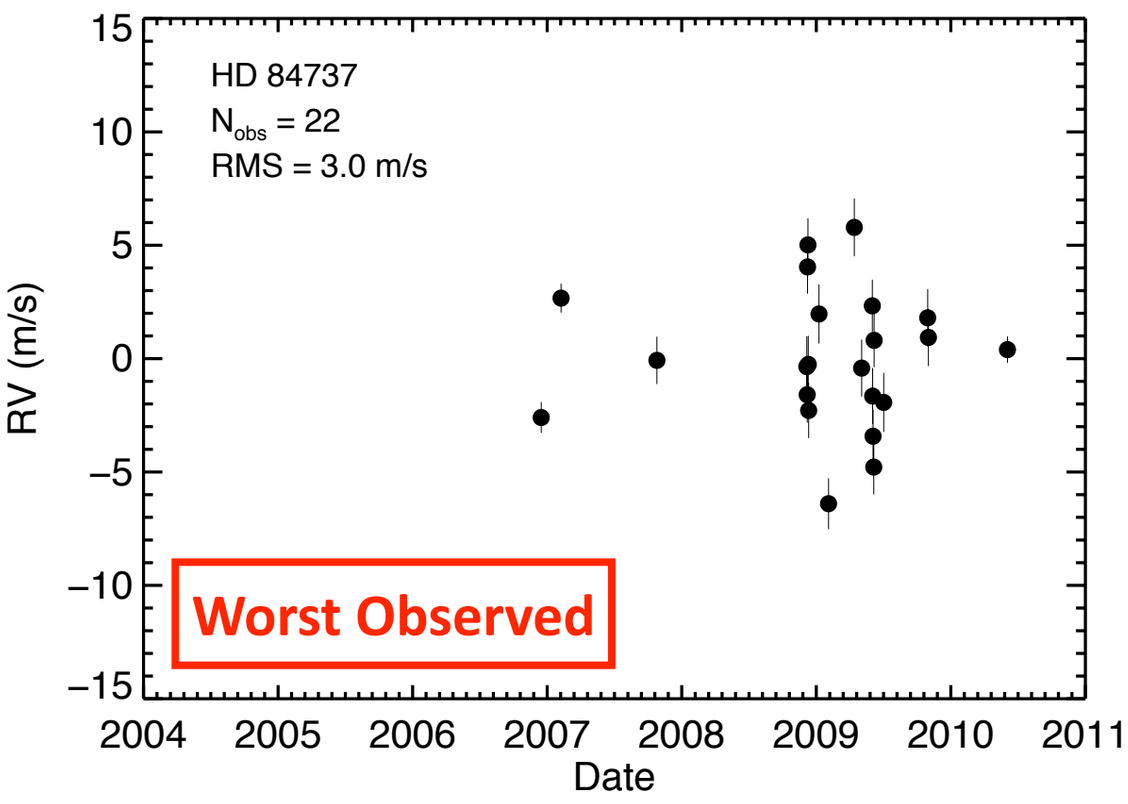

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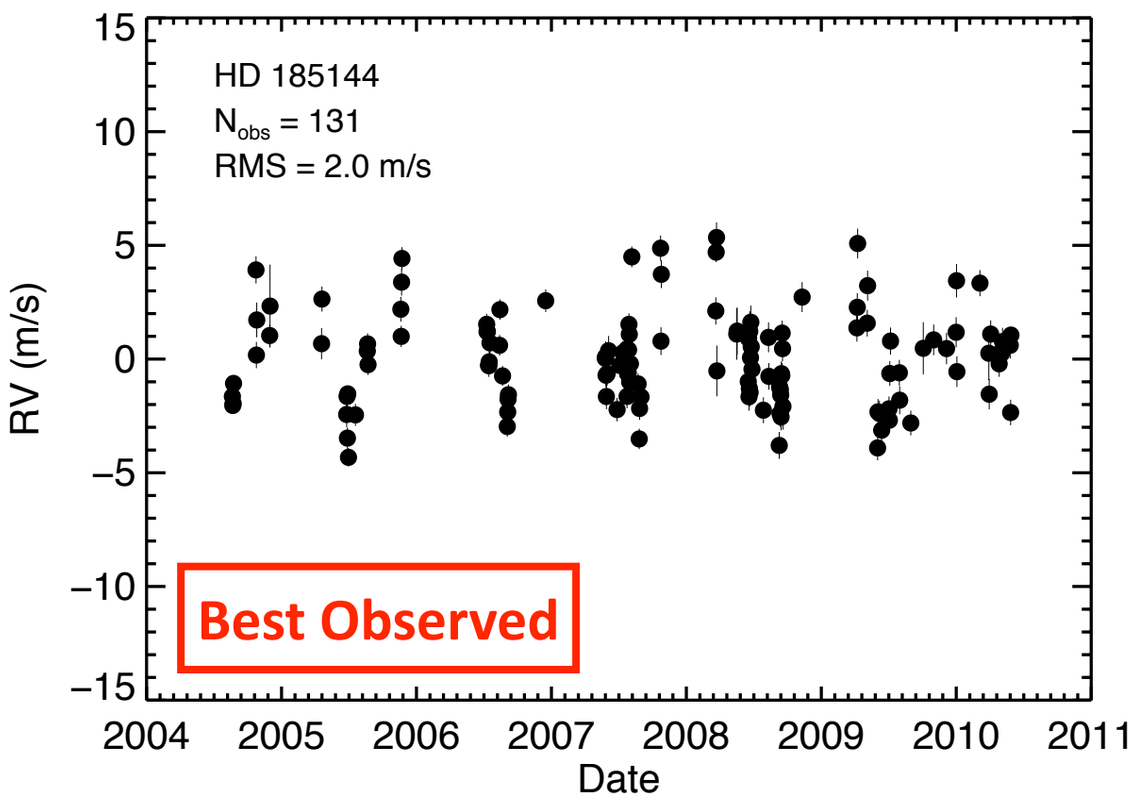

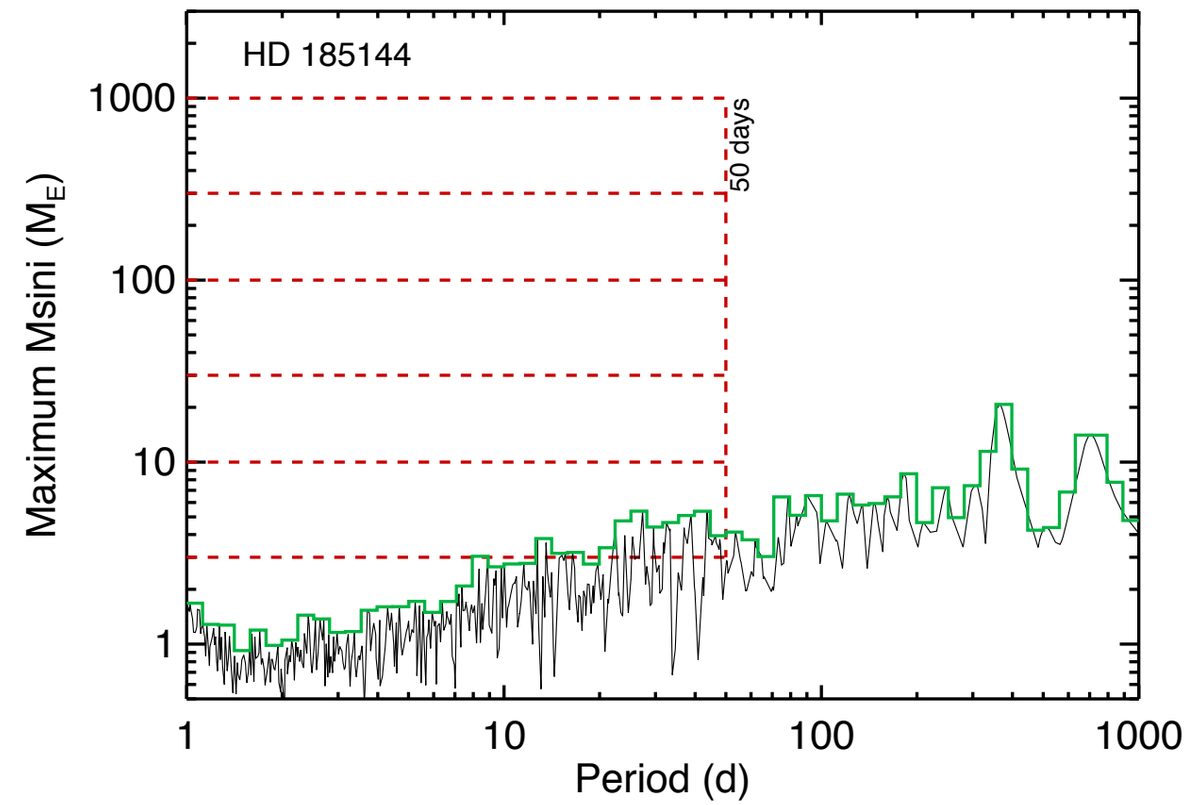

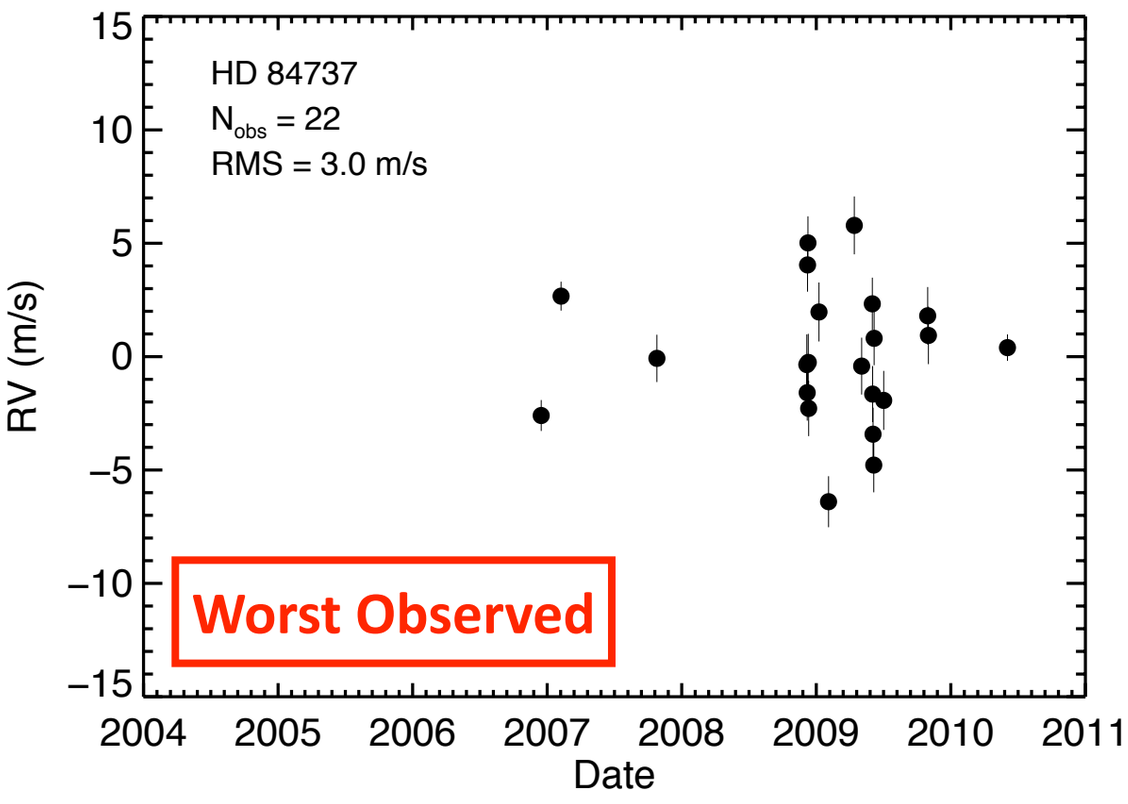

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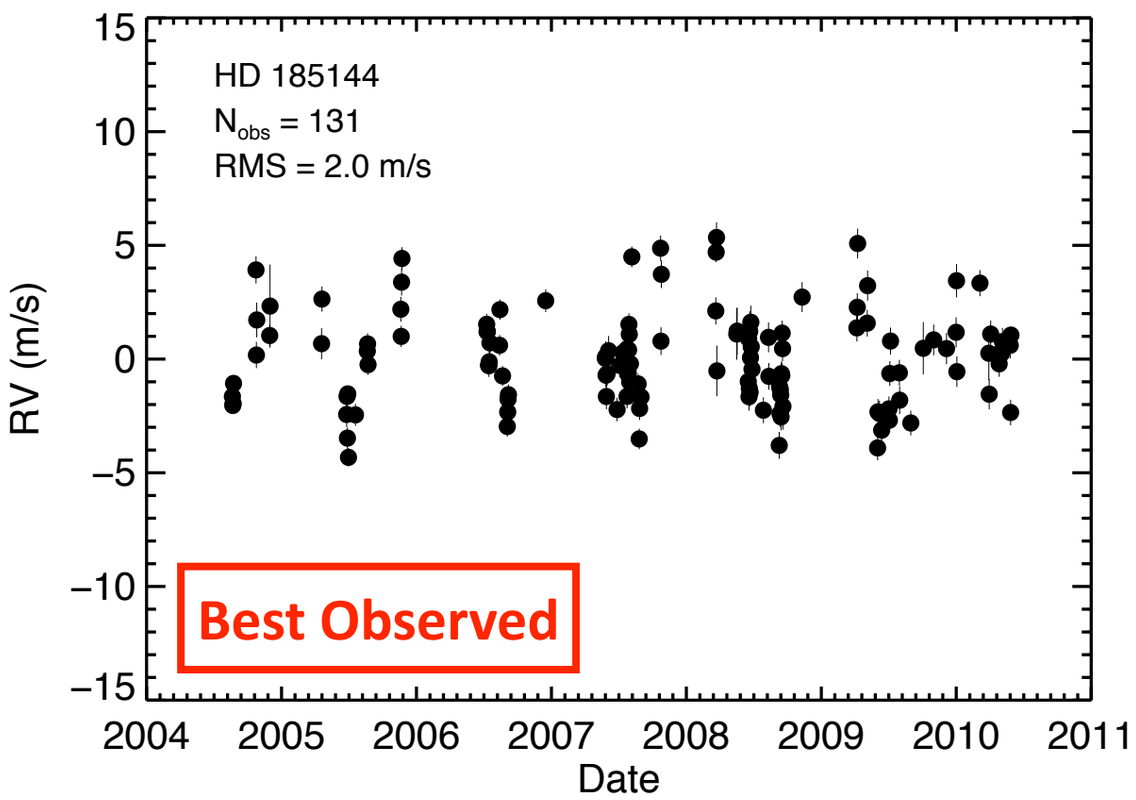
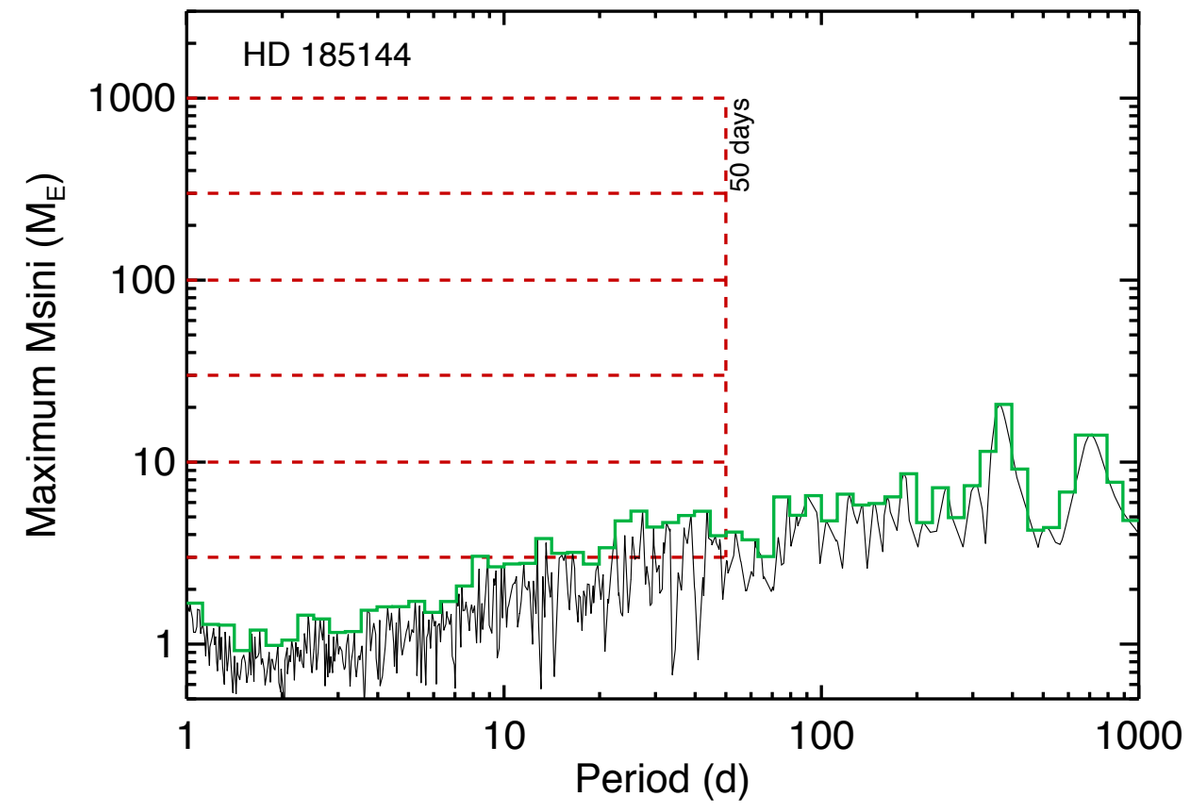
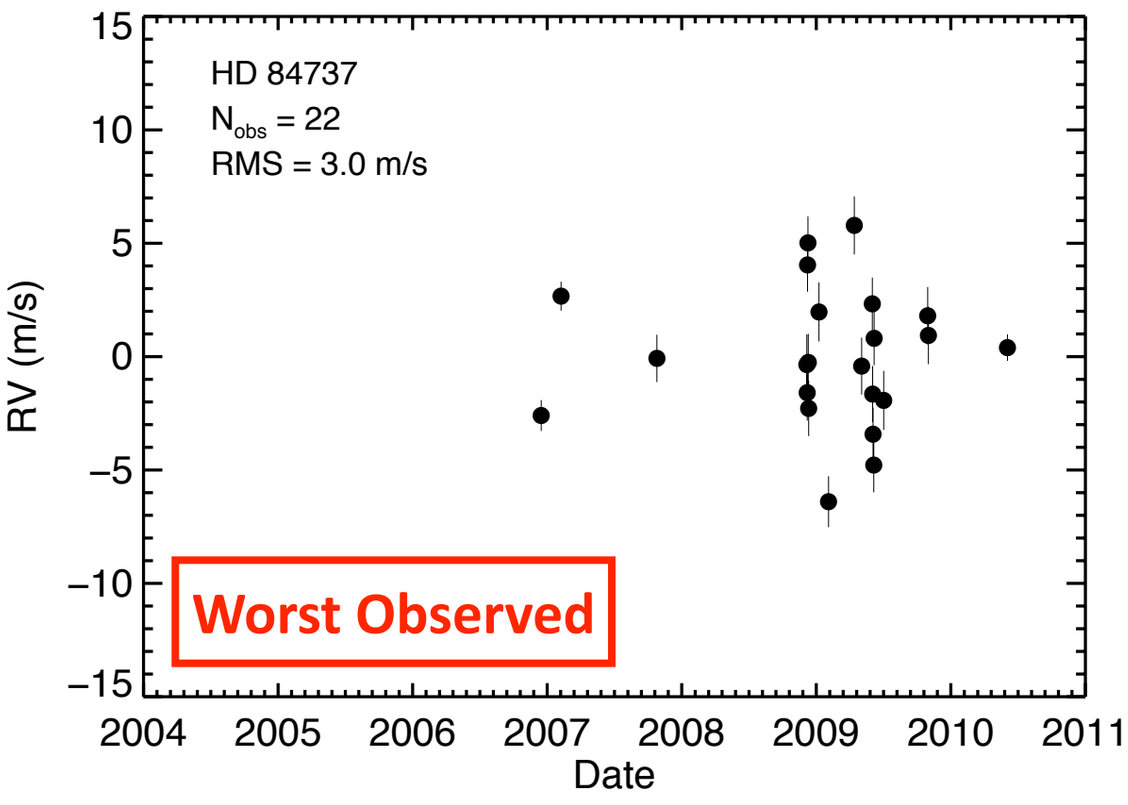
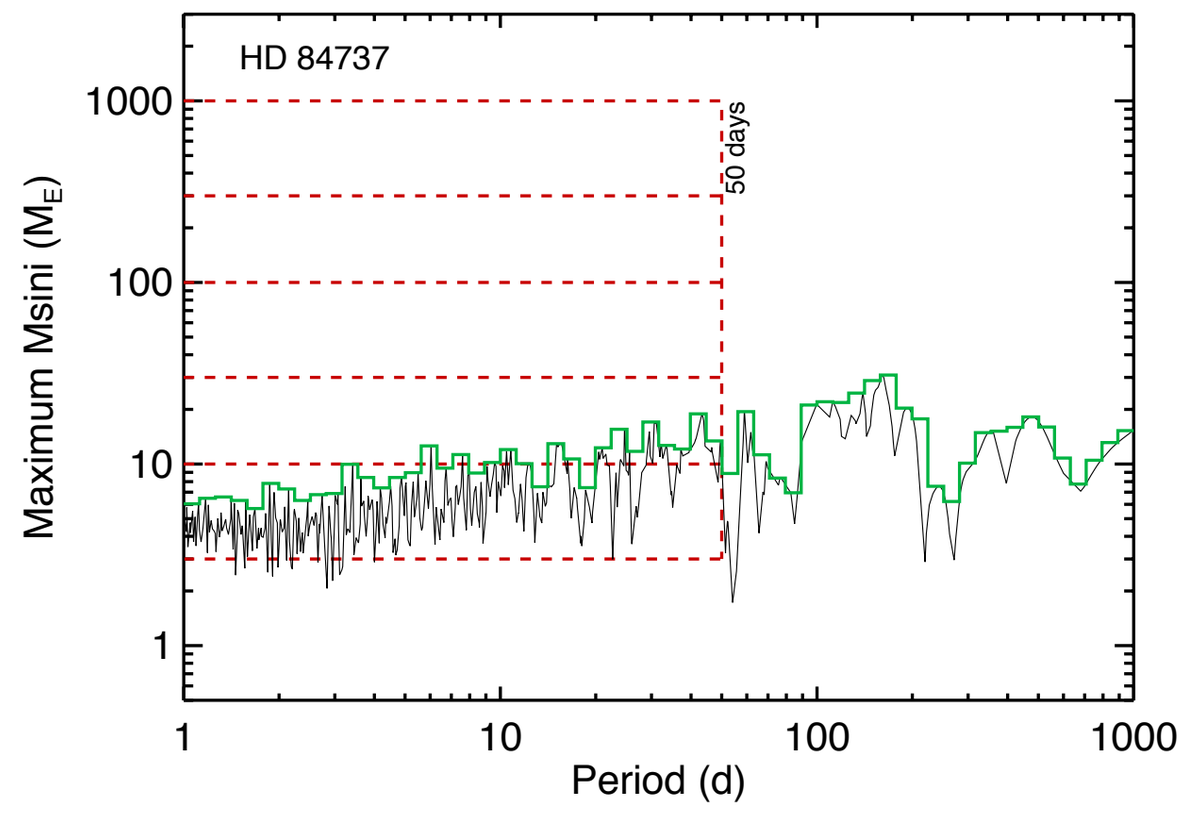




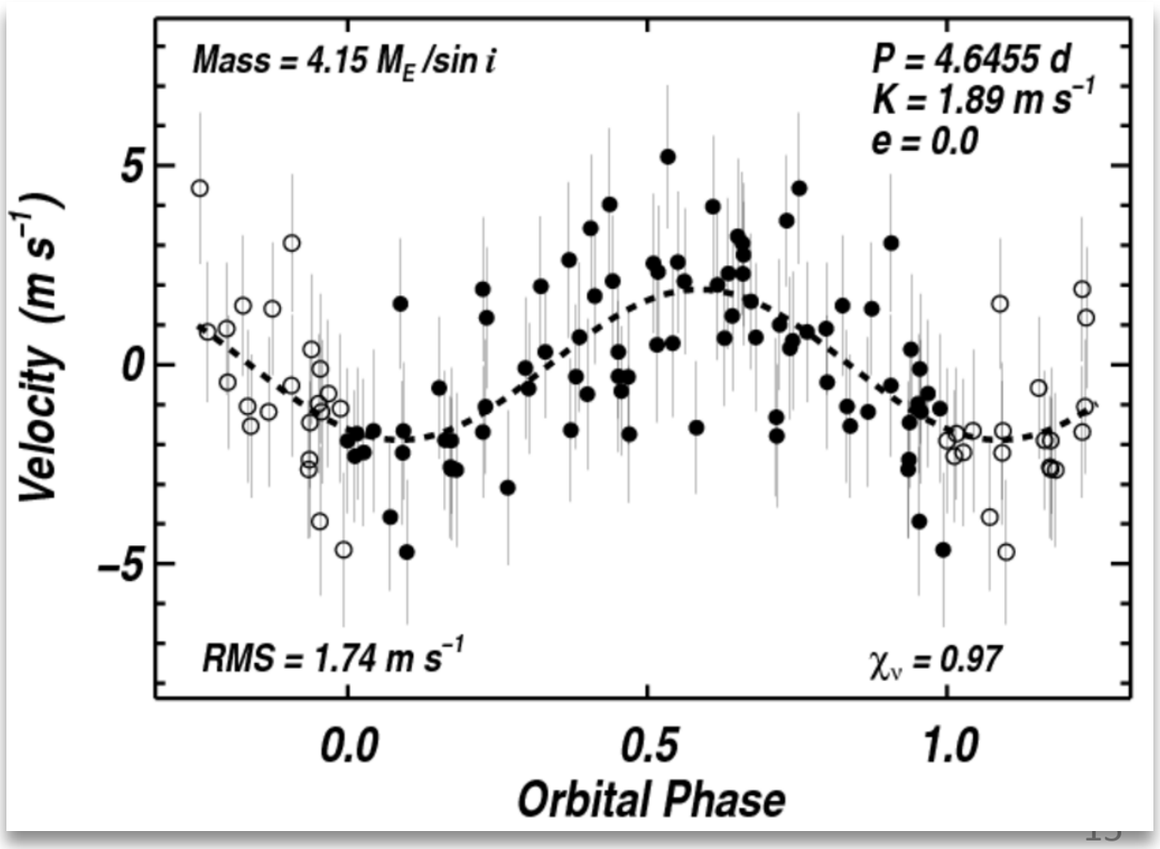




Measurement precision

<u>Distinguish between</u>:

- *K* - Doppler semi-amplitude
- Single-measurement precision - 1 m/s (HIRES)
- RMS (O-C)
  - Photon statistics
  - Astrophysical jitter
  - Instrumental jitter



Photon Statistics - Naive Scaling

HD 156668 (V = 8.3)

M sin i = 4 M_{Earth}

P = 4.6 d

K = 1.9 m/s

0.6-1.0 m/s precision/meas

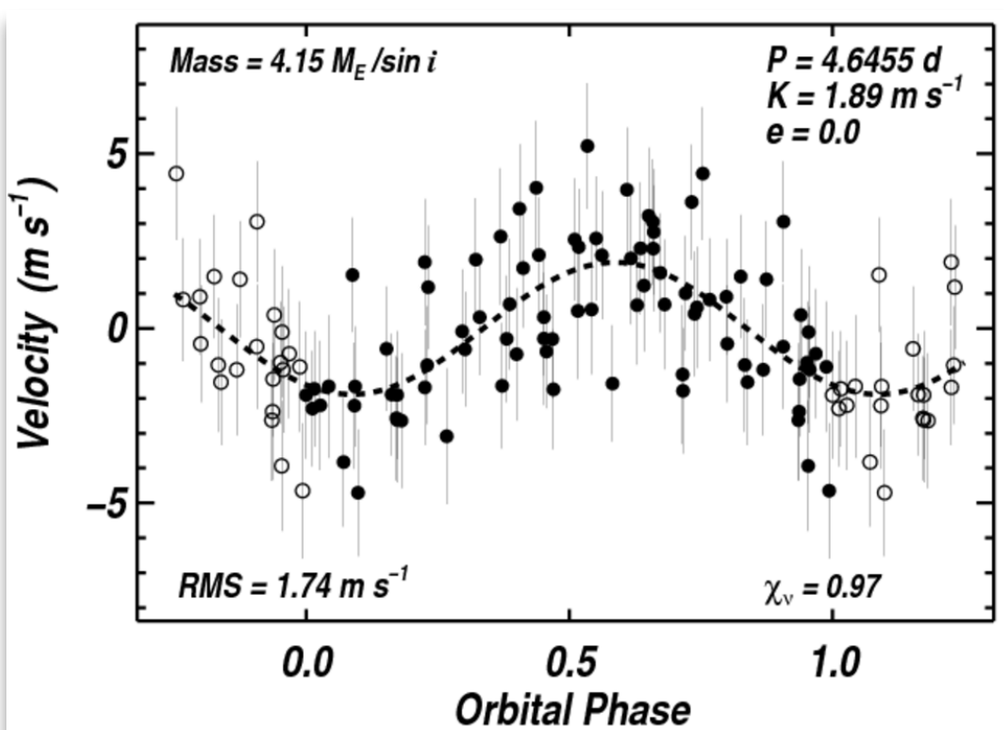
Nobs ~ 100 (~15 hr)

M sin i = 1 M_{Earth}

P = 365 d

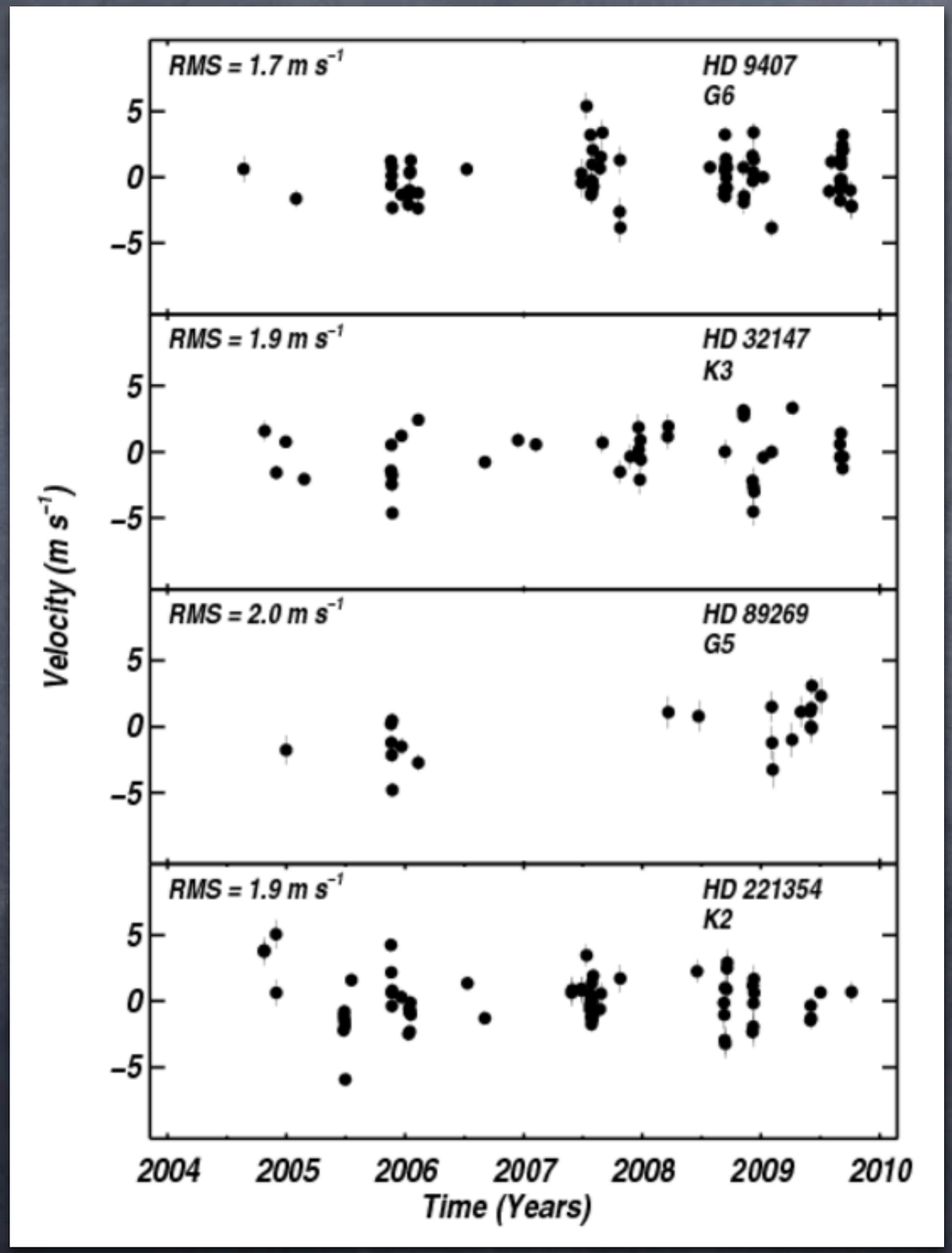
K = 0.09 m/s

400X photons



$$K = \frac{3.7\ \mathrm{m\ s^{-1}}}{(1-e^2)^{1/2}} \left(\frac{P}{5\ \mathrm{d}}\right)^{-1/3} \left(\frac{M_\star}{M_\odot}\right)^{-2/3} \frac{M_{\mathrm{pl}} \sin i}{10 M_\oplus}$$

Standard Stars - Jitter Estimate



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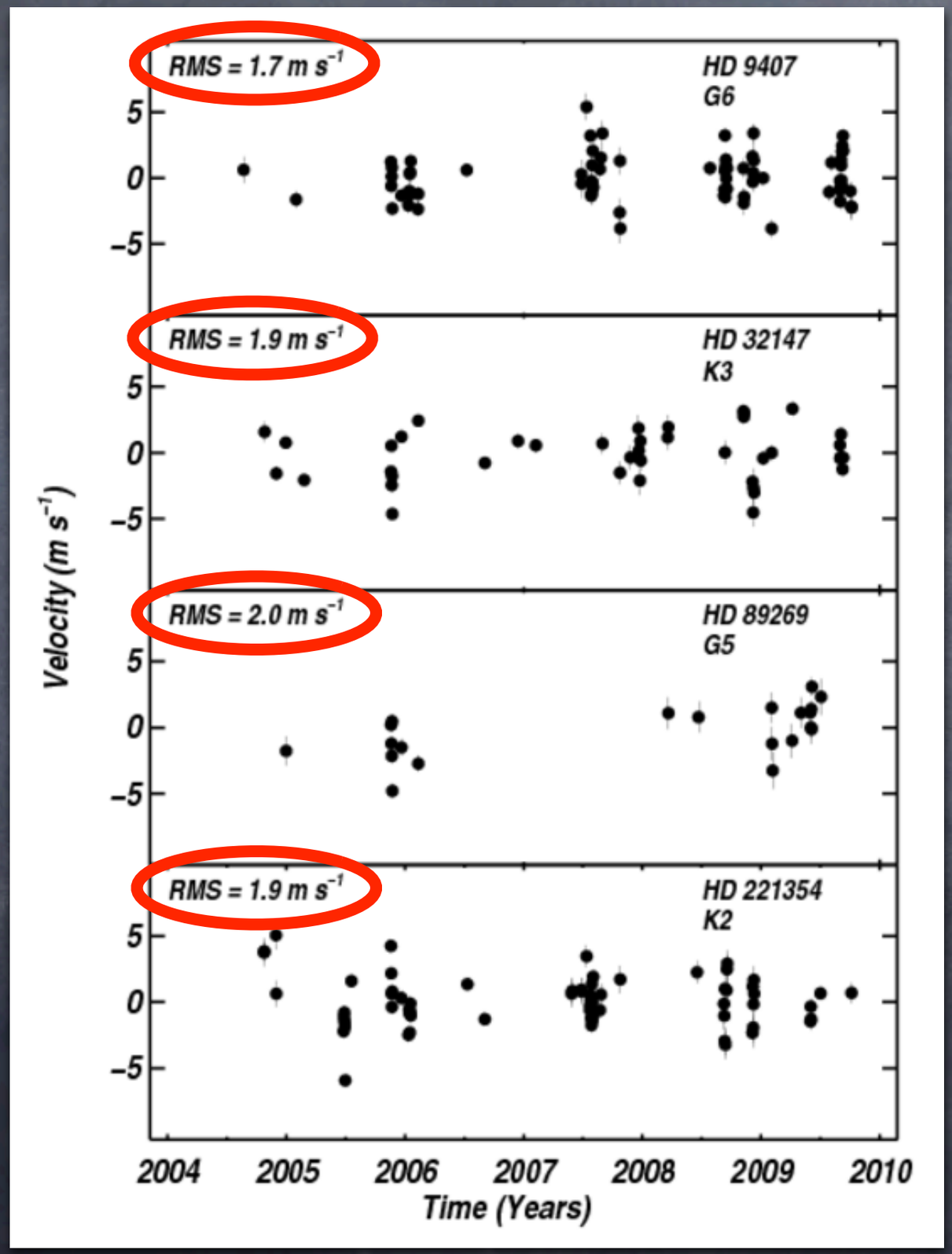

The best standards have an RMS of 1.5-2.0 m/s.

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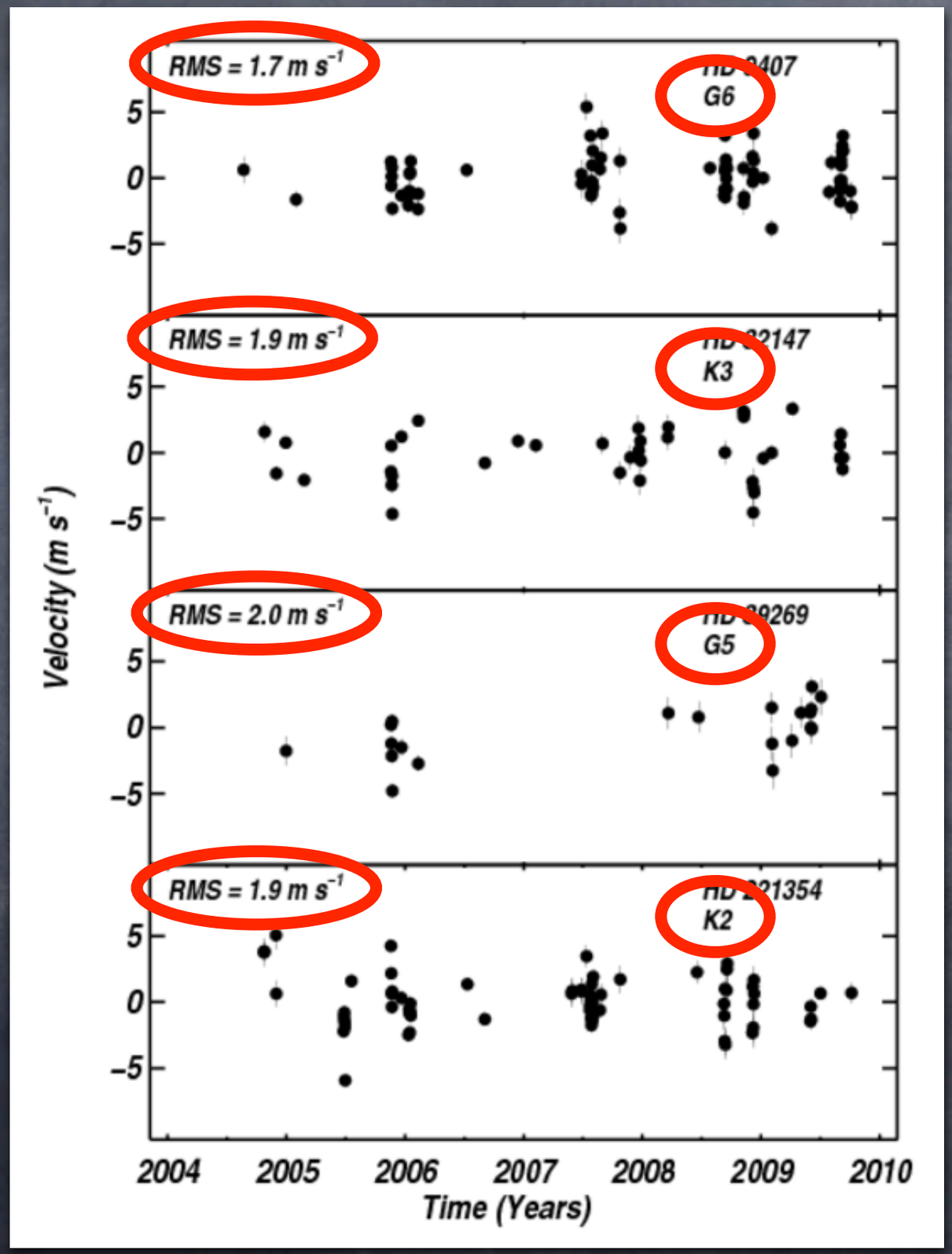

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These are almost always late G / early K dwarfs.

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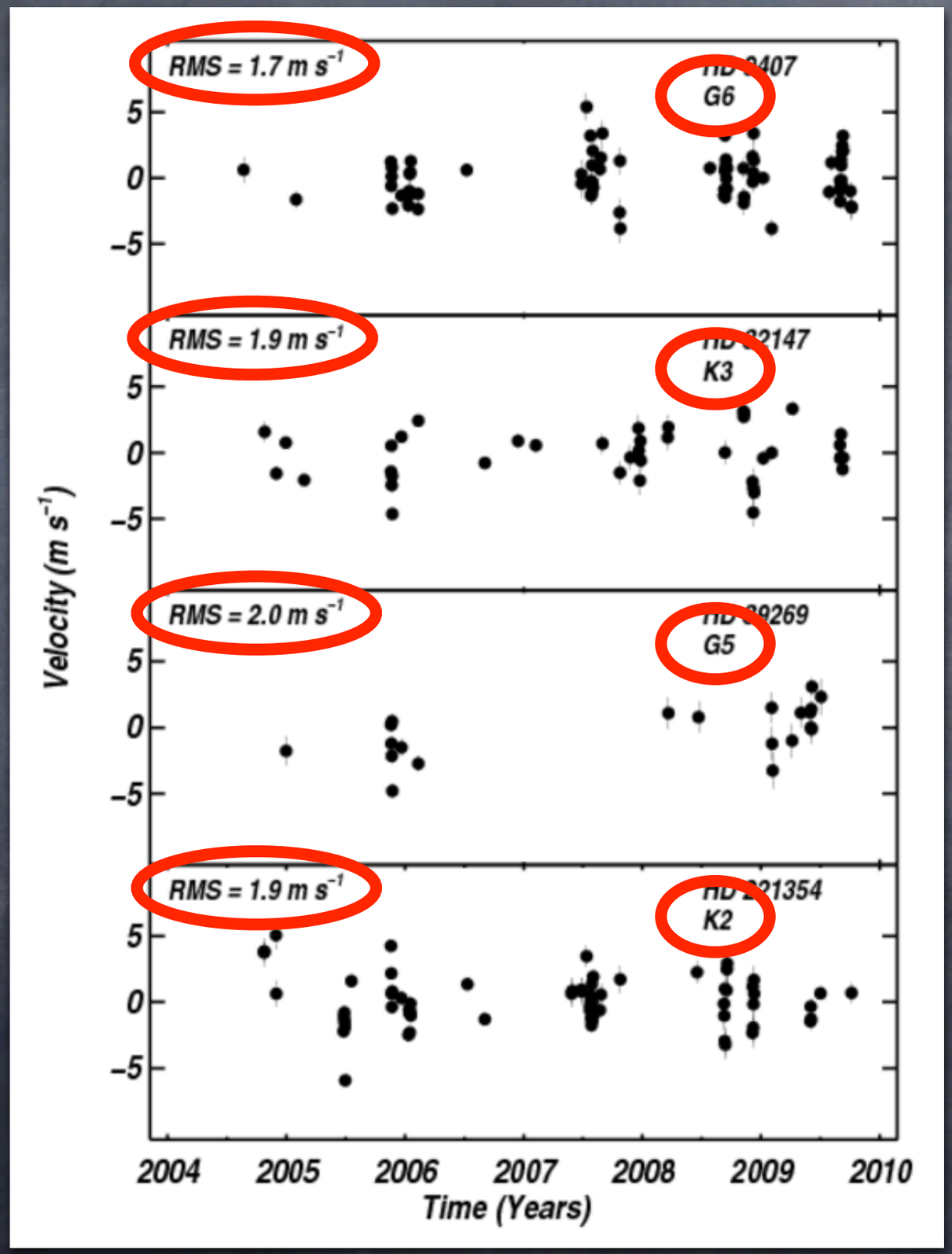

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We do not explicitly average over P-modes; T_{exp} ~ 1-5 min

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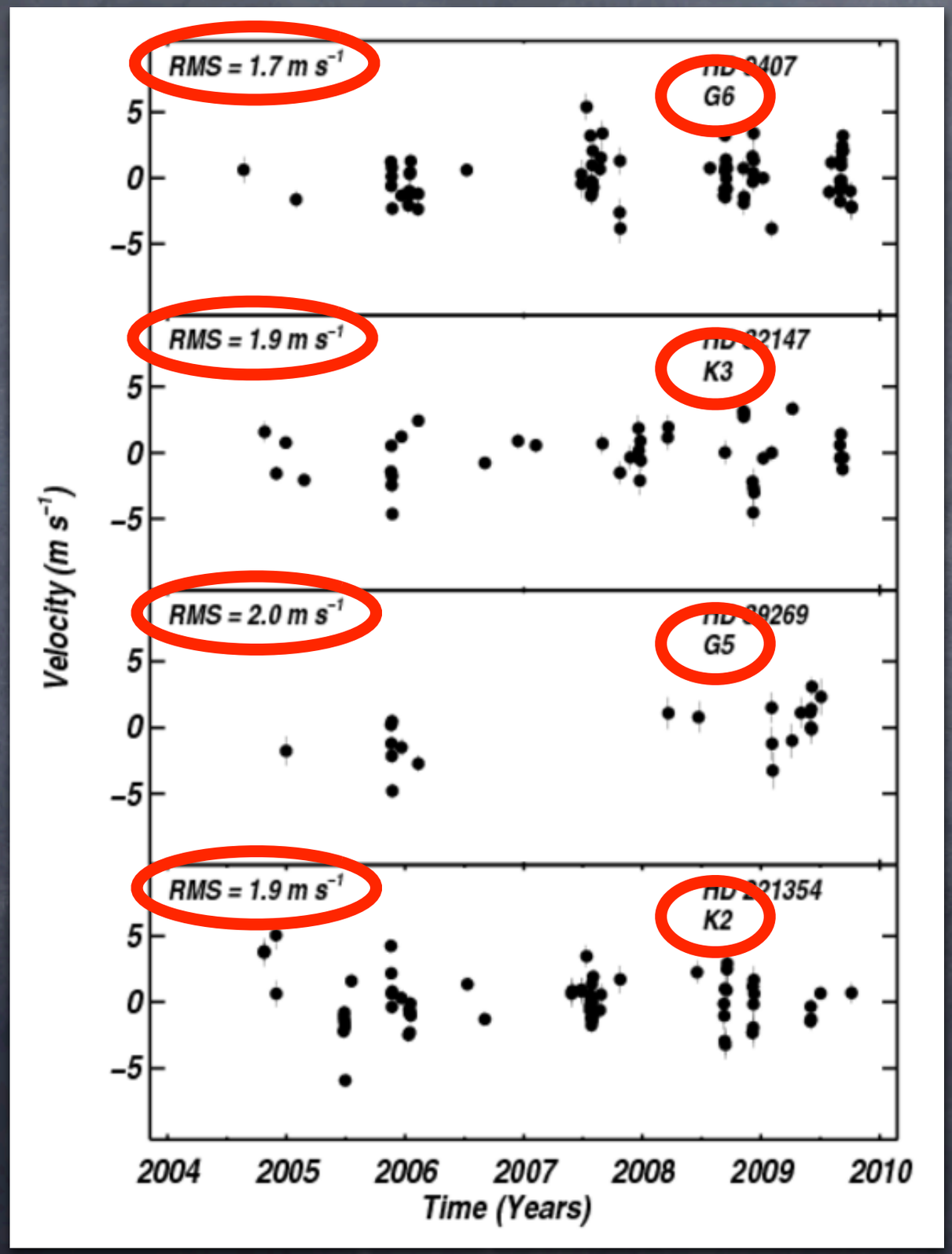

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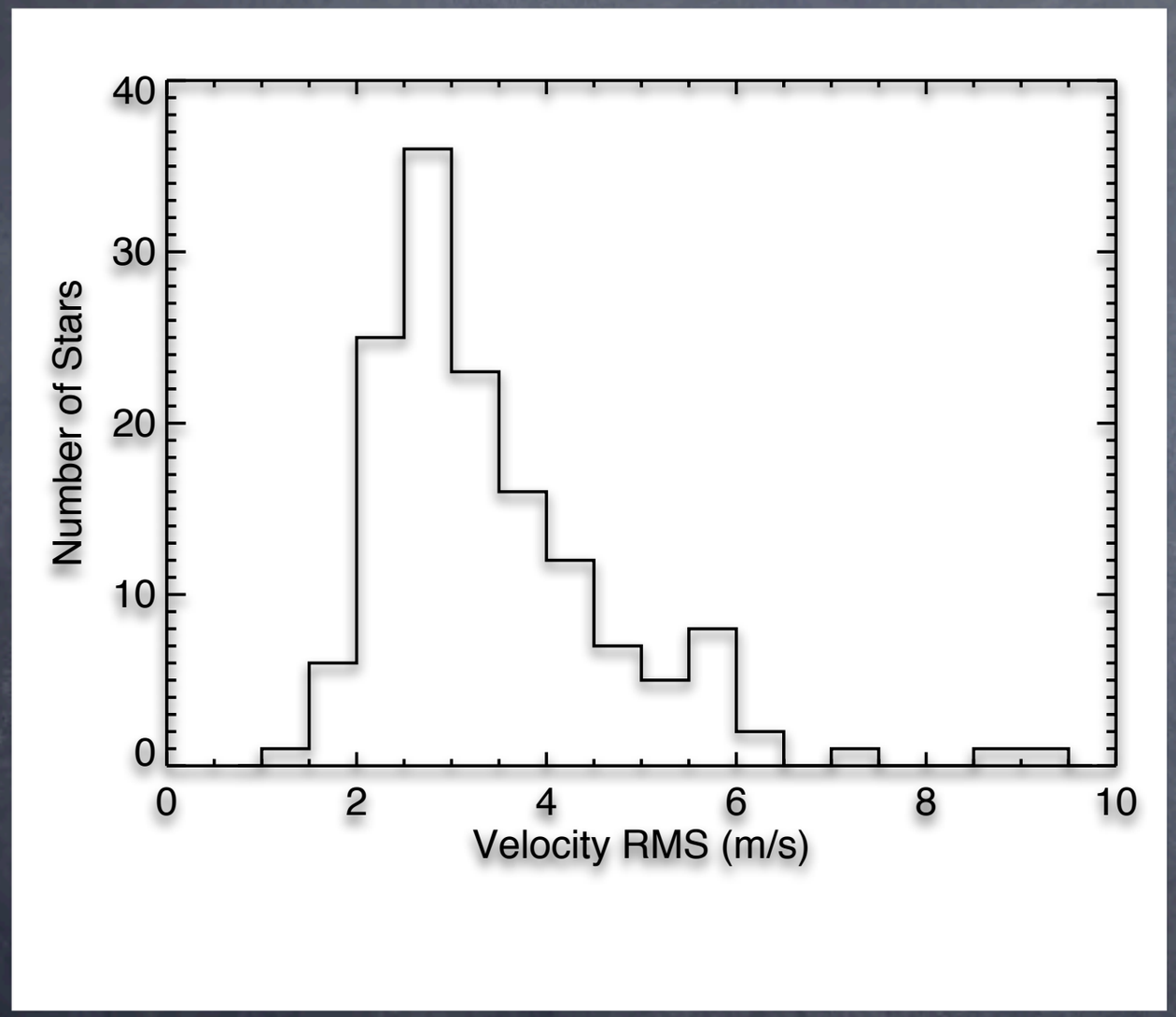
~2+ m/s precision for quiet M stars down to M4

Velocity RMS



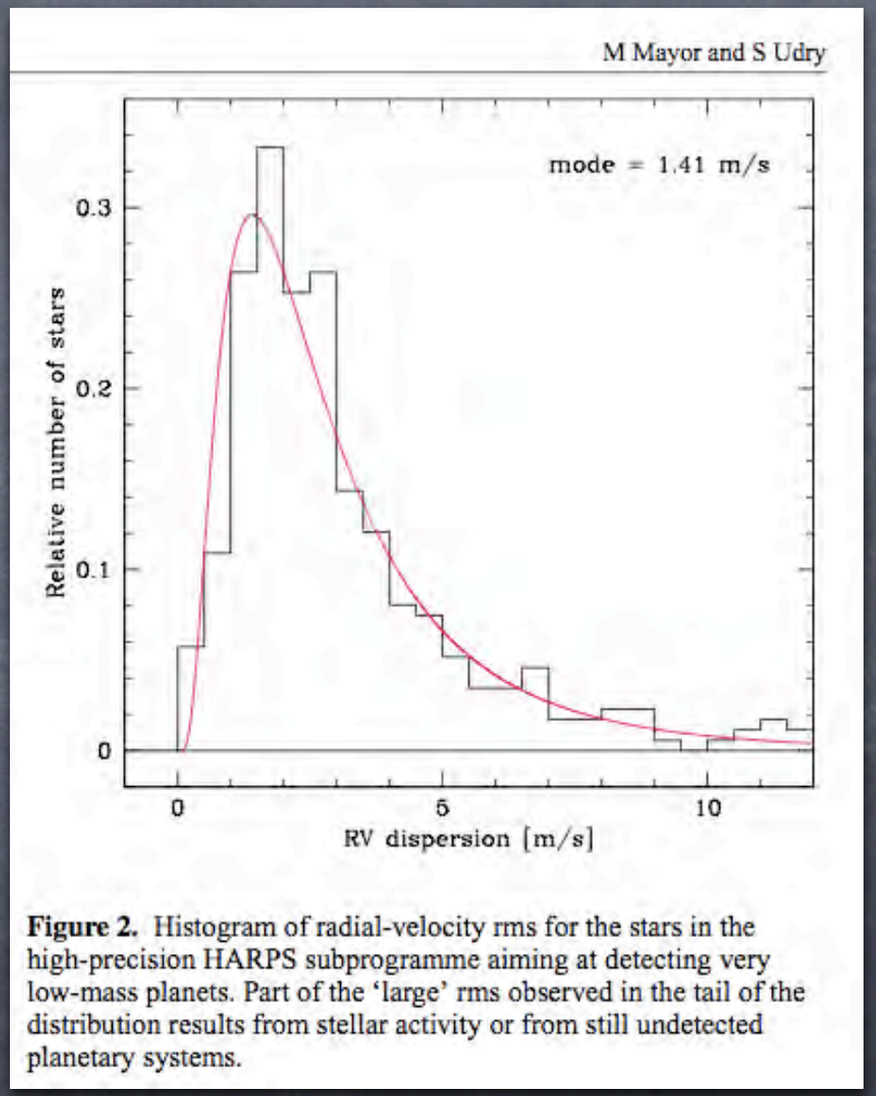


Figure 2. Histogram of radial-velocity rms for the stars in the high-precision HARPS subprogramme aiming at detecting very low-mass planets. Part of the 'large' rms observed in the tail of the distribution results from stellar activity or from still undetected planetary systems.

HIRES

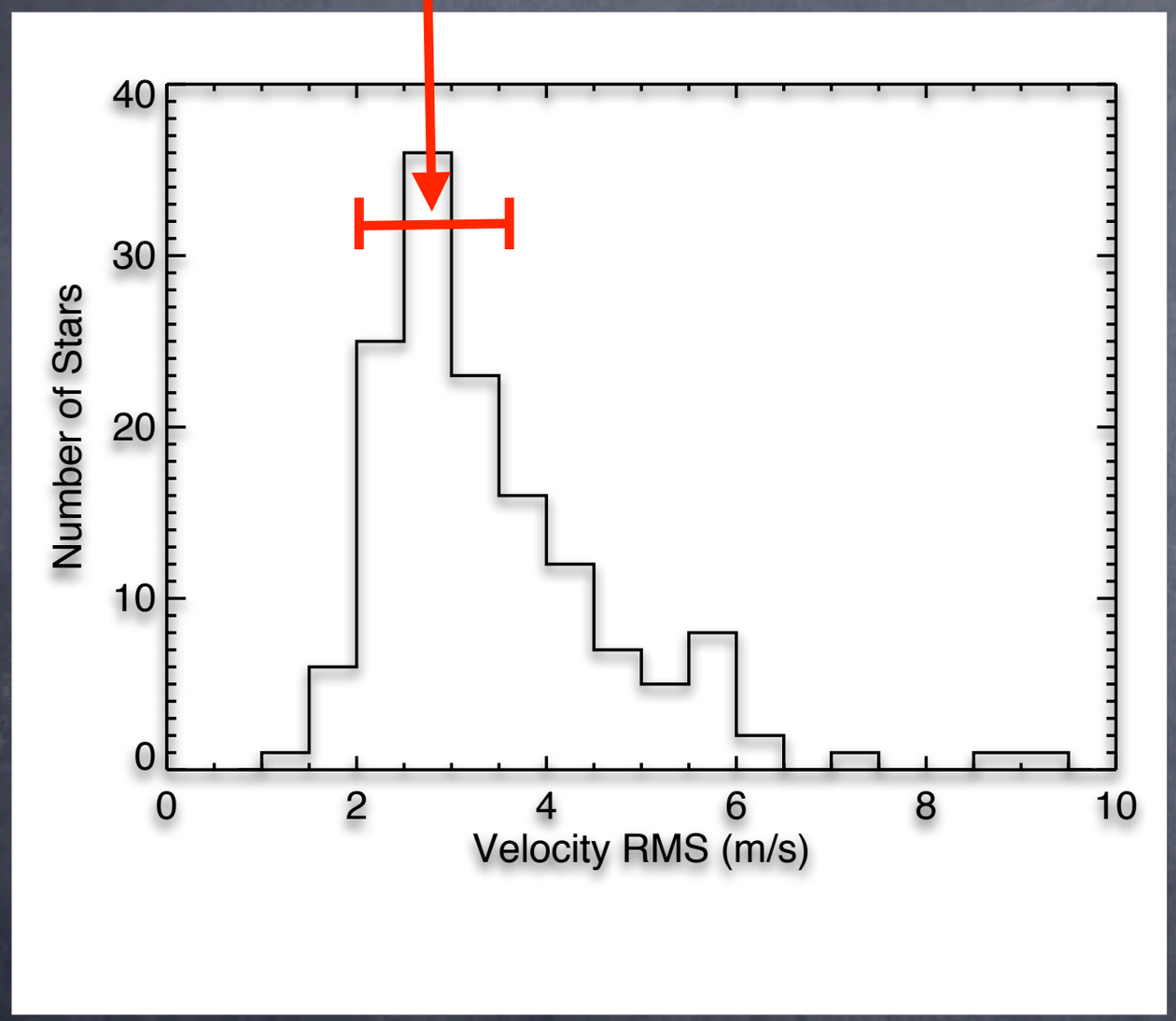
GK stars in Eta-Earth Survey
Known planets removed

HARPS

Mayor and Udry, 2008,
Phys. Scr. T130, 014010

Velocity RMS

2–3.5 m/s



HIRES

GK stars in Eta-Earth Survey
Known planets removed

1–3 m/s

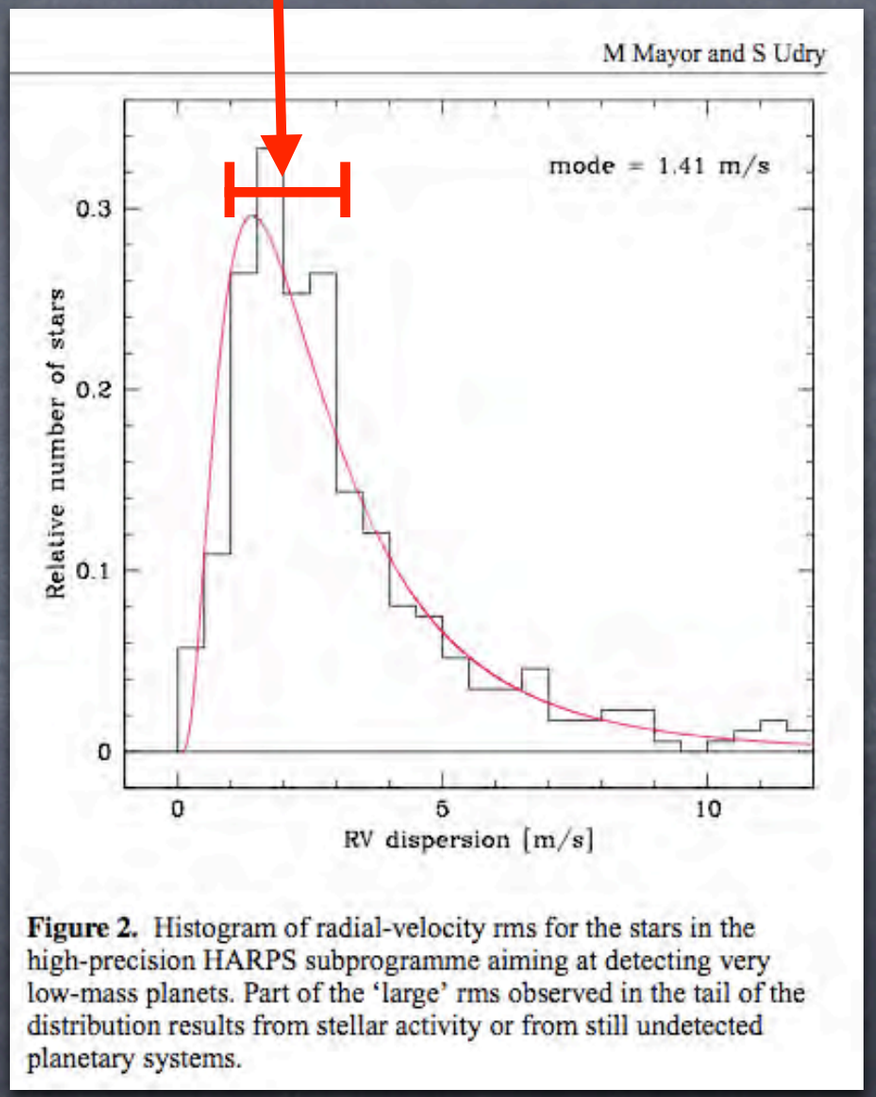


Figure 2. Histogram of radial-velocity rms for the stars in the high-precision HARPS subprogramme aiming at detecting very low-mass planets. Part of the 'large' rms observed in the tail of the distribution results from stellar activity or from still undetected planetary systems.

HARPS

Mayor and Udry, 2008,
Phys. Scr. T130, 014010

Astrophysical Jitter

Sources

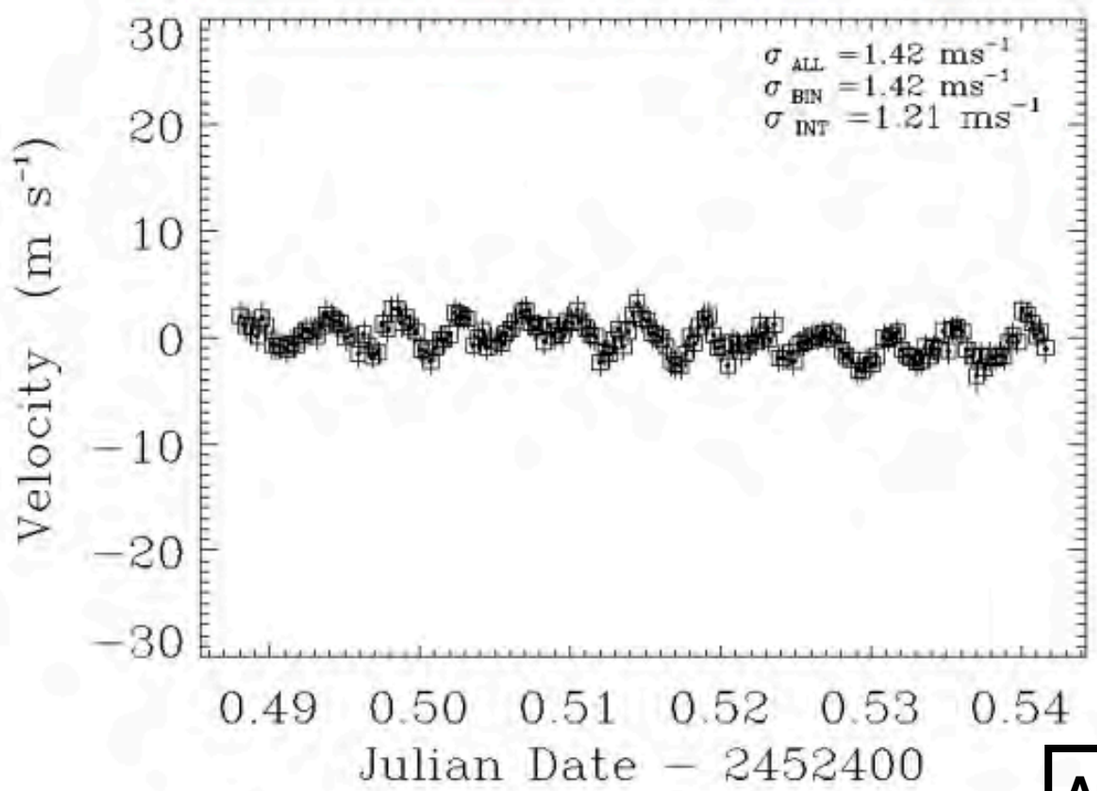
- Acoustic Oscillations - p-modes
- Granulation
- Magnetic Activity
- Meridional Flows

Acoustic Oscillations – p-modes

Impact on RV technique

Example: p-modes

R. P. Butler: observations of αCen, a chromospherically inactive, old, slowly rotating, sunlike star



P-mode oscillations

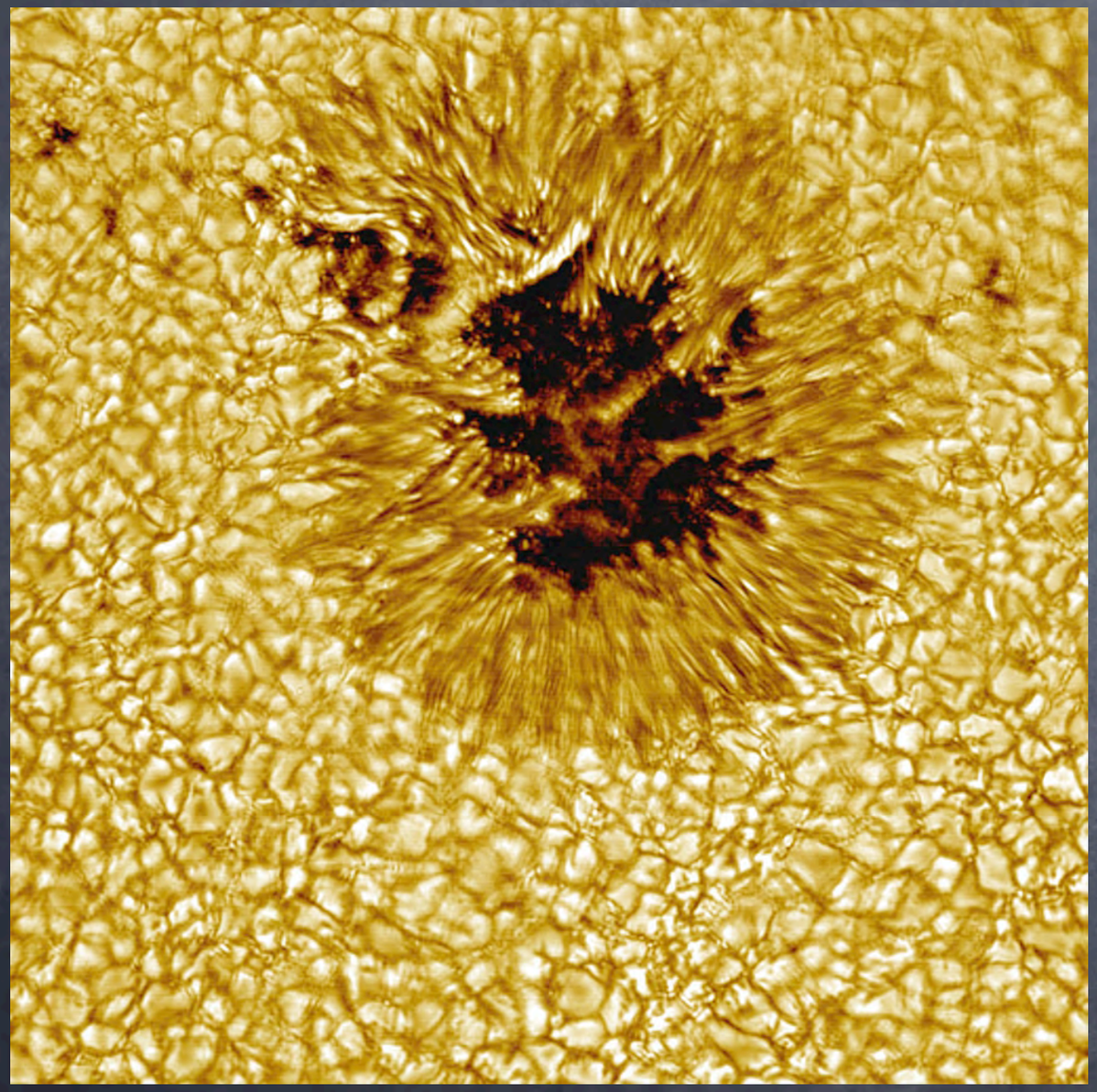
5 minute periodicity, amplitude of about 3 m/s

Short exposure times would register snapshots of this RV variablility

Amplitude ~ Luminosity/Mass

→ K-dwarfs better

Granulation



~10^6 granules on Sun
~1 km/s velocities
~1 m/s effect
~1 hr - a few days (or longer?)

Planetary detection limits taking into account stellar noise

I. Observational strategies to reduce stellar oscillation and granulation effects★

X. Dumusque[1,2], S. Udry[2], C. Lovis[2], N. C. Santos[1,3], and M. J. P. F. G. Monteiro[1,3]

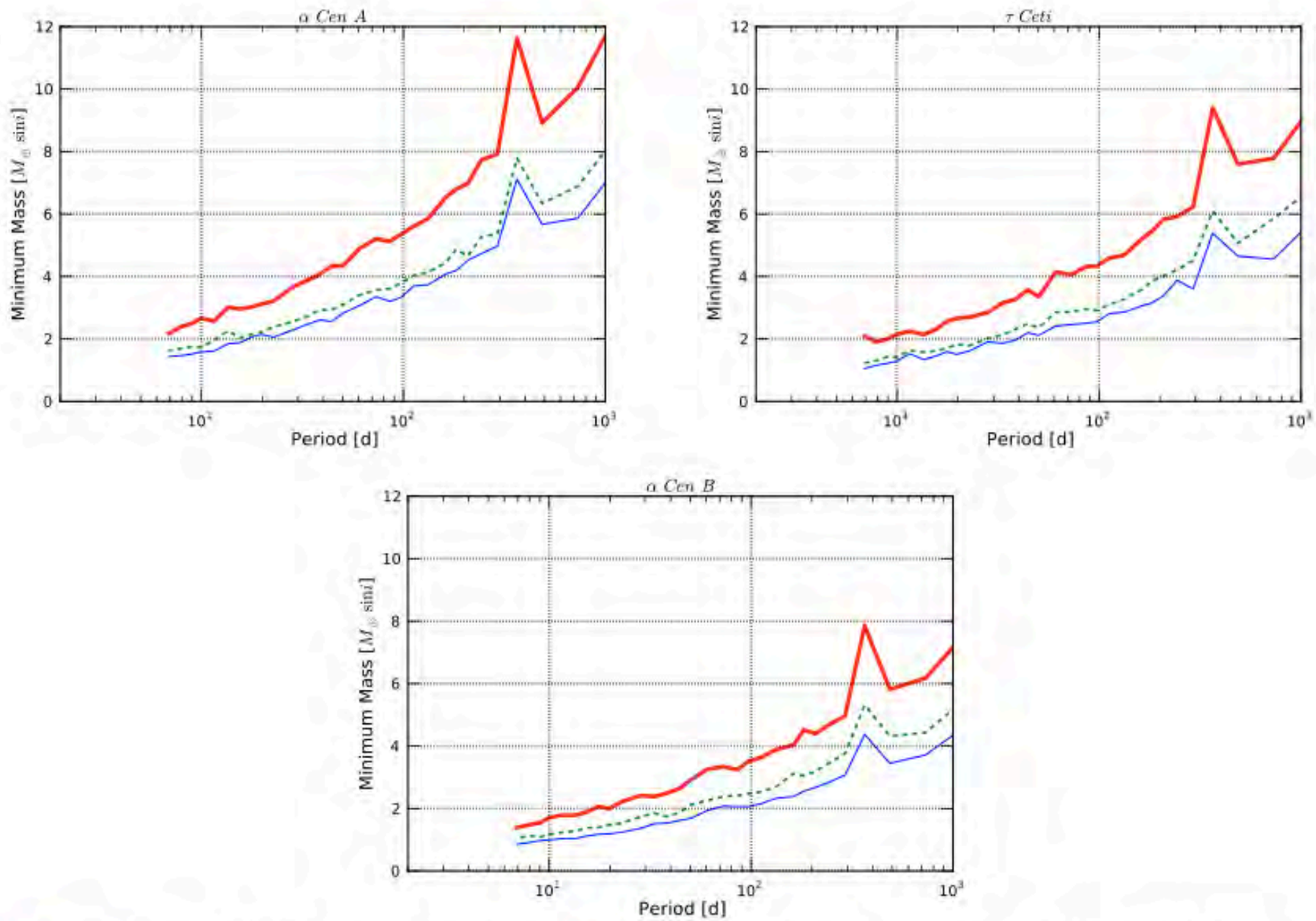
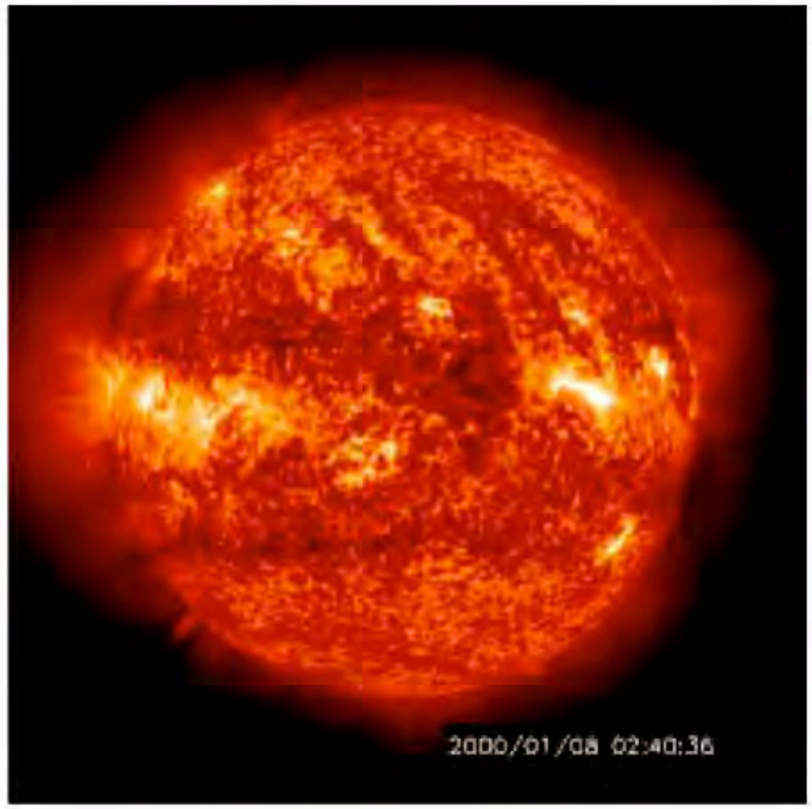


Fig. 5. Mass-period diagrams for our star sample. We can see on each graph, the 3 strategies studied. one measurement of 15 min per night (continuous thick line), 2 measurements per night of 15 min 5 h apart (dashed line) and 3 measurements per night of 10 min 2 h apart (continuous thin line).

Magnetic Activity

Noise sources: Spots and flares



Convective dynamos spawn magnetic fields and result in spots and flares with km s^{-1} outflows producing convective blue shifts in spectral line profiles.

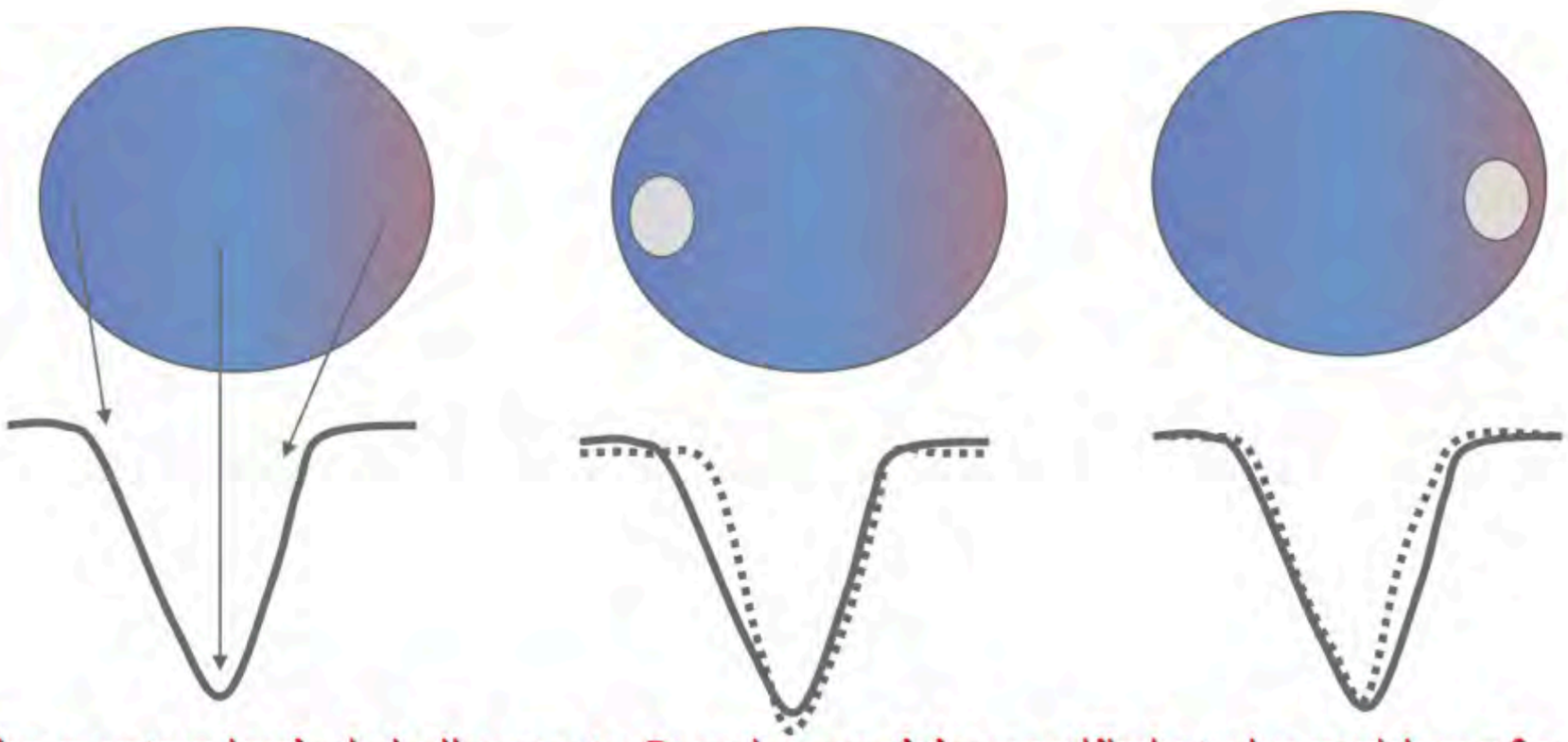
These arise from the photosphere and are not dynamical Doppler shifts, but how to tell the difference?

This is the quiet, steady old Sun!

Magnetic Activity

Impact on RV technique

High rotational velocities are associated with chromospheric activity and starspots. As starspots rotate across the star, the line centroid shifts.



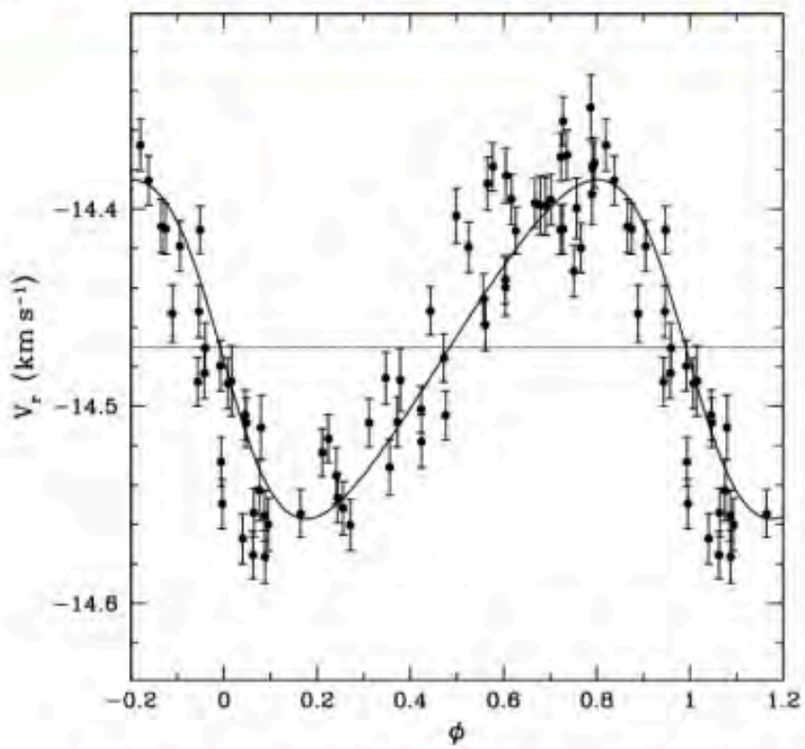
These astrophysical challenges to Doppler precision are likely to be problems for other detection techniques, too.

Magnetic Activity

Impact on RV technique

Example: Spots

HD166435 (Queloz et al. A&A 2001)



Phase diagram of radial velocities with a 3.7987-d period, amplitude of ~100 m s^{-1} in a two year data set. HD166435 is a G0V star, vsini = 7.6 km s^{-1}. Age (X-ray) ~ 200 Myr.

Doppler Periodicities from Starspots:
RMS Doppler Velocity = 0.5 Δmag V_{eq} sin i

STARSPOT JITTER IN PHOTOMETRY, ASTROMETRY AND RADIAL VELOCITY MEASUREMENTS

V.V. Makarov[1], C.A. Beichman[1], J.H. Catanzarite [2], D.A. Fischer[3], J. Lebreton[1], F. Malbet[1,4], M. Shao[2]

[1] *NASA Exoplanet Science Institute, Caltech, Pasadena, CA 91125*

[2] *JPL, Pasadena, CA 94550*

[3] *Department of Physics and Astronomy, San Francisco State University, San Francisco, CA 94132*

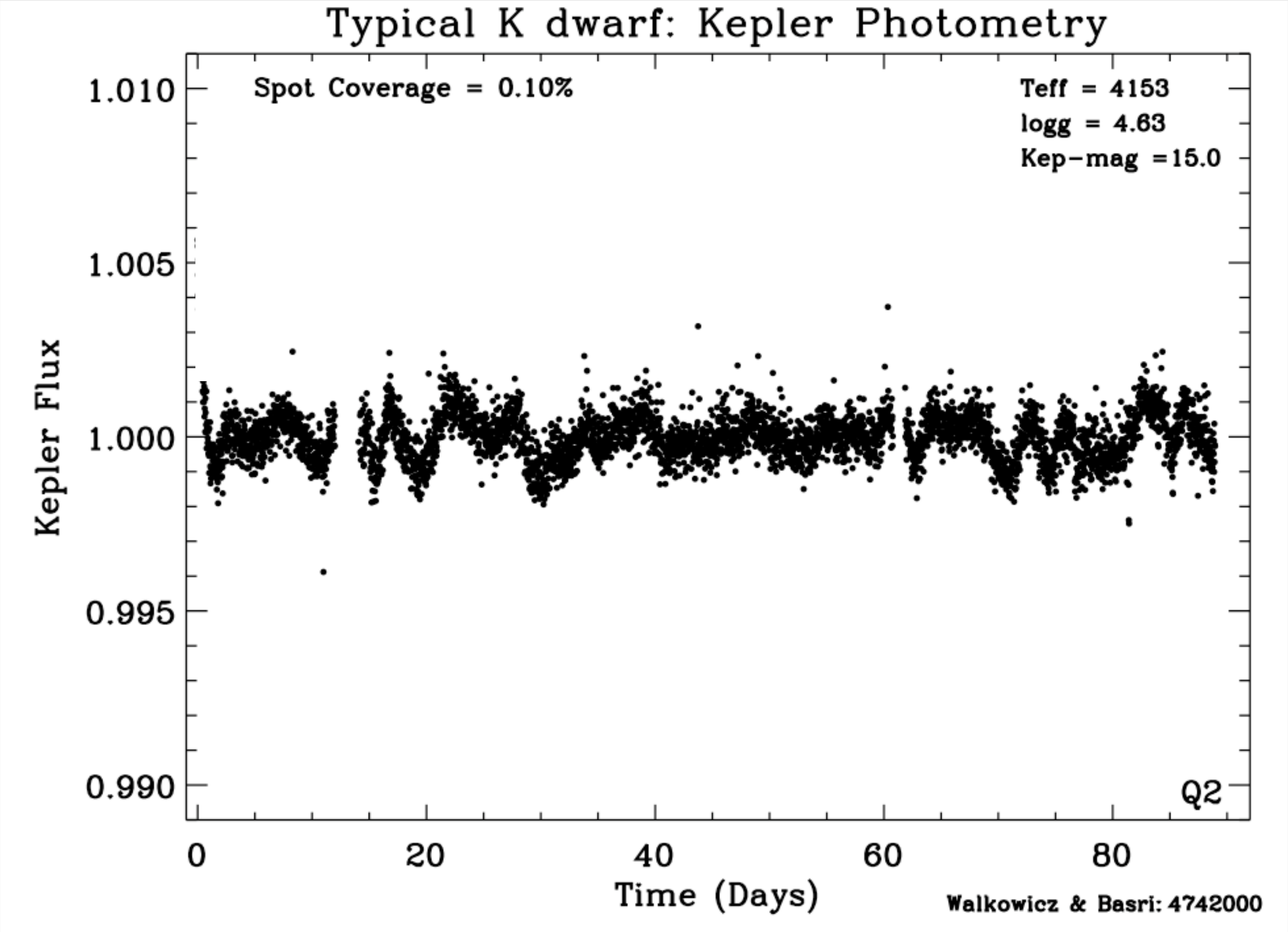
[4] *Centre National de la Recherche Scientifique, Paris, France*

vvm@caltech.edu

ABSTRACT

Analytical relations are derived for the amplitude of astrometric, photometric and radial velocity perturbations caused by a single rotating spot. The relative power of the star spot jitter is estimated and compared with the available data for κ^1 Ceti and HD 166435, as well as with numerical simulations for κ^1 Ceti and the Sun. A Sun-like star inclined at $i = 90°$ at 10 pc is predicted to have a RMS jitter of 0.087 μas in its astrometric position along the equator, and 0.38 m s^{-1} in radial velocities. If the presence of spots due to stellar activity is the ultimate limiting factor for planet detection, the sensitivity of SIM Lite to Earth-like planets in habitable zones is about an order of magnitude higher that the sensitivity of prospective ultra-precise radial velocity observations of nearby stars.

Makarov et al. 2010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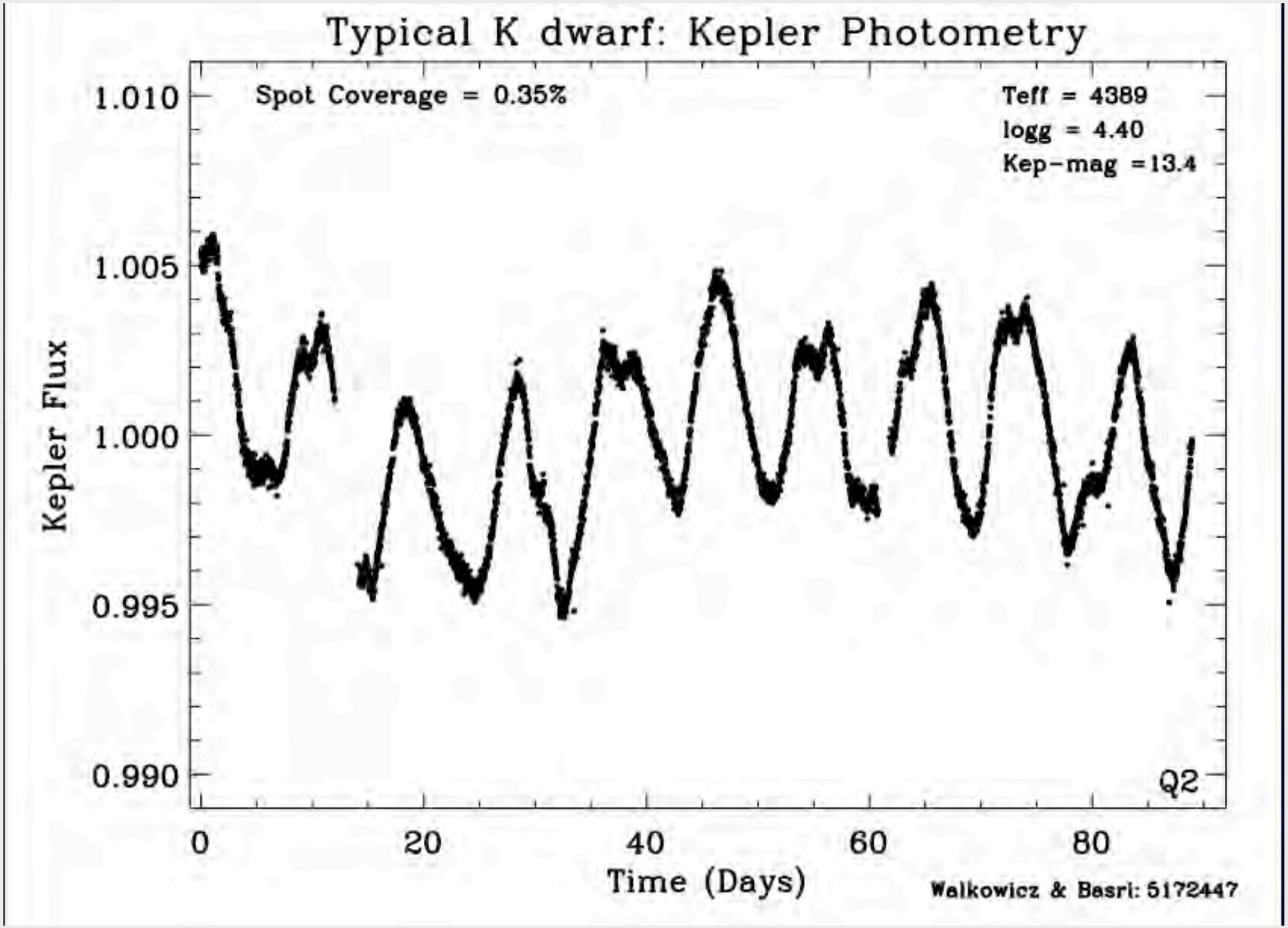
Spot Coverage = 0.10%
Teff = 4153
logg = 4.63
Kep-mag =15.0
Kepler Flux
1.010
1.005
1.000
0.995
0.990
Q2
0
20
40
60
80
Time (Days)
Walkowicz & Basri: 4742000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Kep-mag = 13.4
Q2
Kepler Flux
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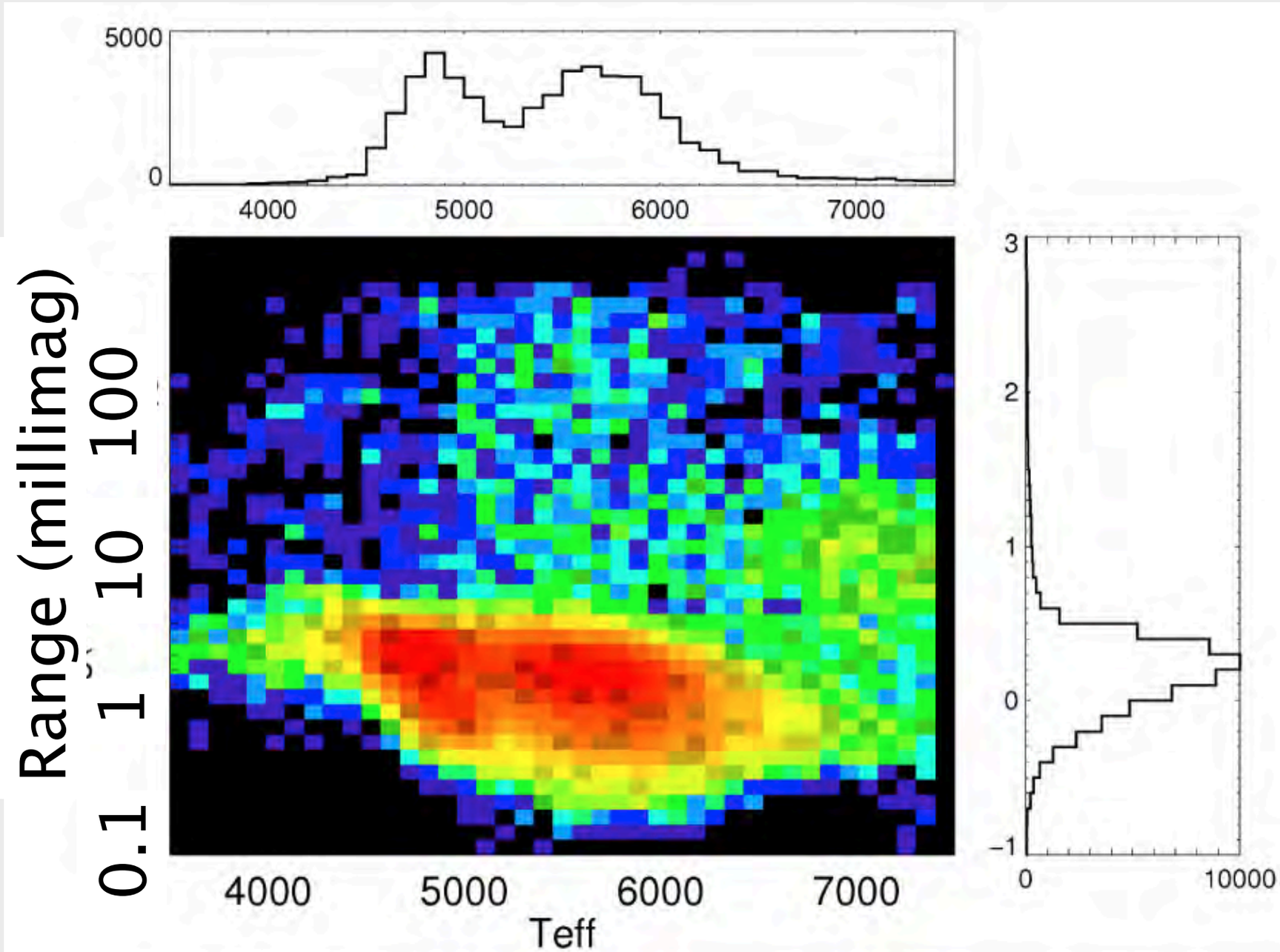
1.005
1.000
0.995
0.990
0
20
40
60
80
Time (Days)
Walkowicz & Basri: 5172447

Kepler:
Photometric Variability



1 millimag
is common

→

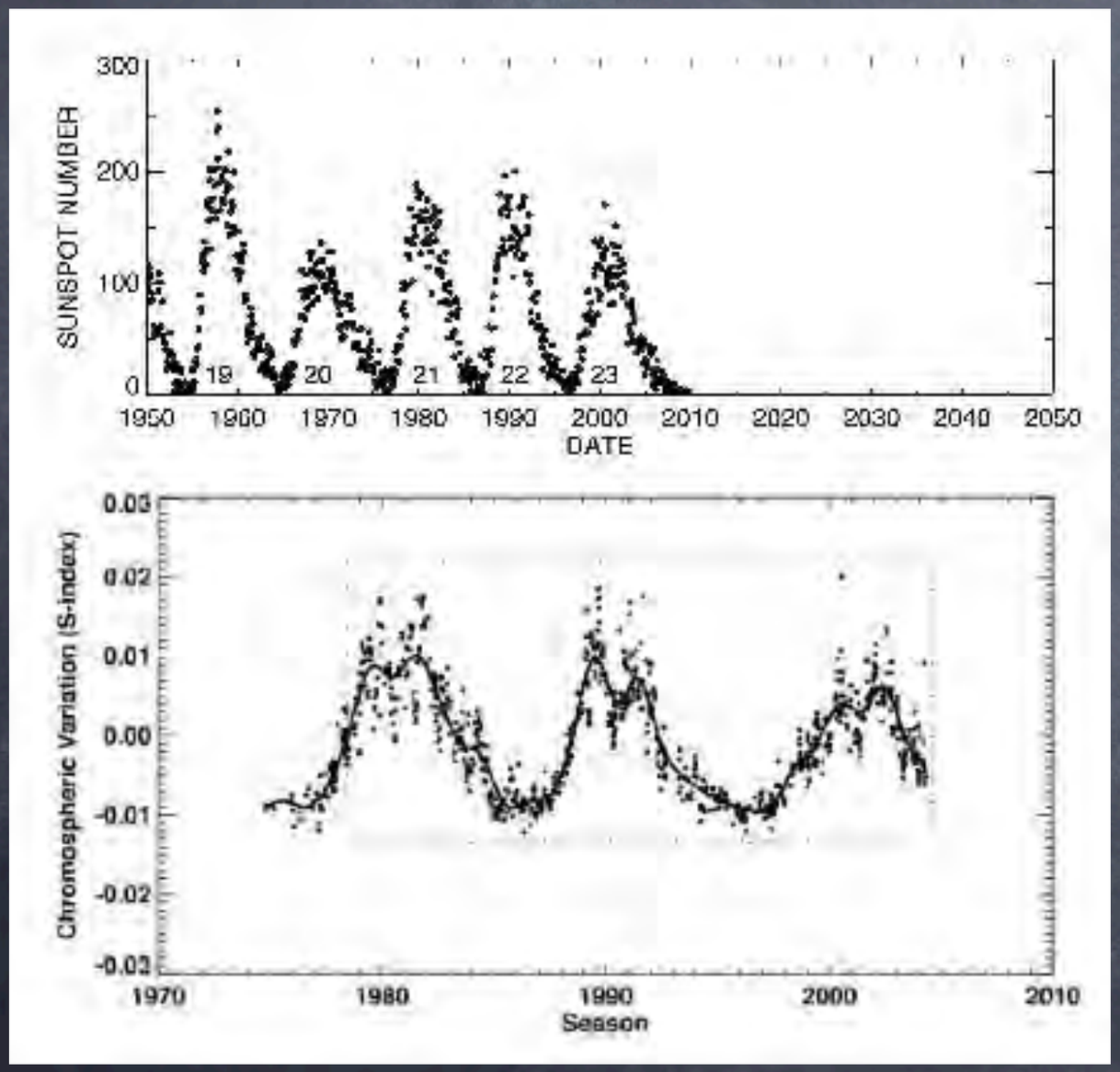
1–2 m/s
Jitter w/
periodicity:
P ~ 10–40d

Walkowicz & Basri 2010

Planetary detection limits taking into account stellar noise

II. Effect of stellar spot groups on radial-velocities

X. Dumusque[1,2], N.C. Santos[1,3], S. Udry[2], C. Lovis[2], and X. Bonfils[4]



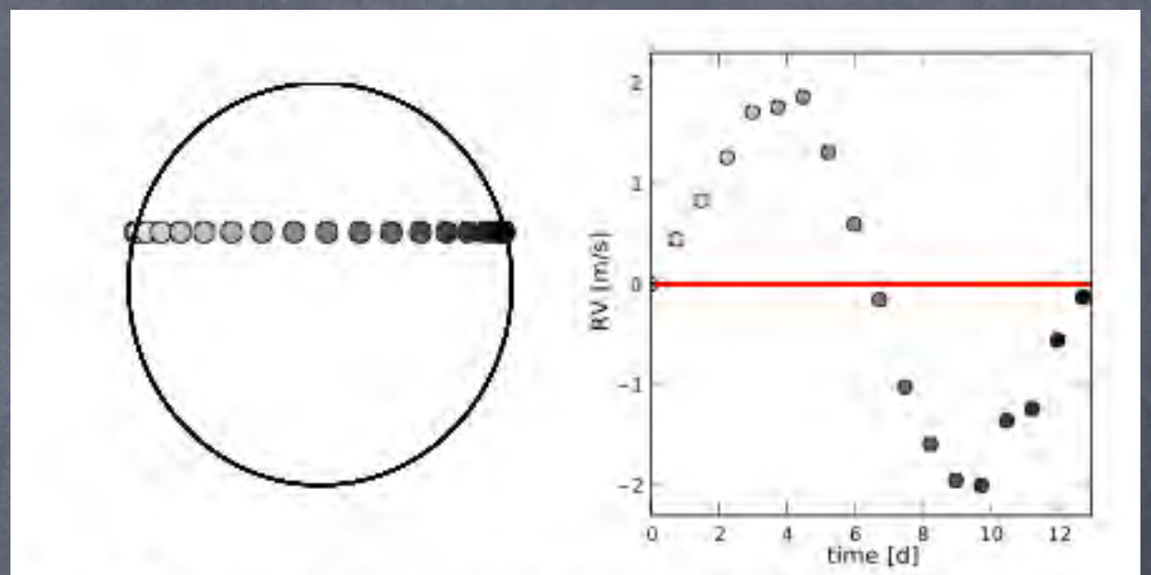


Fig. 3. RVs produced by a spot group at 15^{deg} of latitude, with a filling factor of 0.001. The simulation is made using the program SOAP.

Simulation based on Sun

Model: spot group evolution, RV signature, observing strategies

Planetary detection limits taking into account stellar noise

II. Effect of stellar spot groups on radial-velocities

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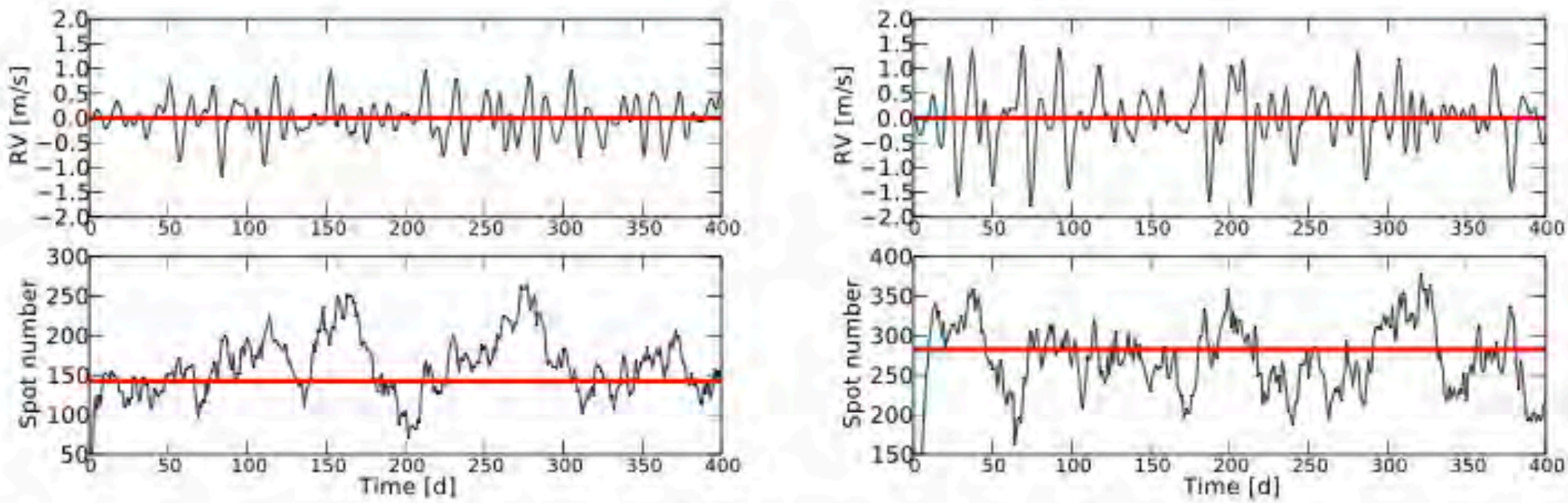

Fig. 5. Simulations for an equatorial rotational period of 26 days and an activity level $\log(R'_{HK}) = -4.9$ (left panel) and for $\log(R'_{HK}) = -4.75$ (right panel). The horizontal line on the top and bottom graphs are the RV mean and the spot number mean over the 4 years of the simulation, respectively. Just the 400 first days are shown here for clearness.

Planetary detection limits taking into account stellar noise

II. Effect of stellar spot groups on radial-velocities

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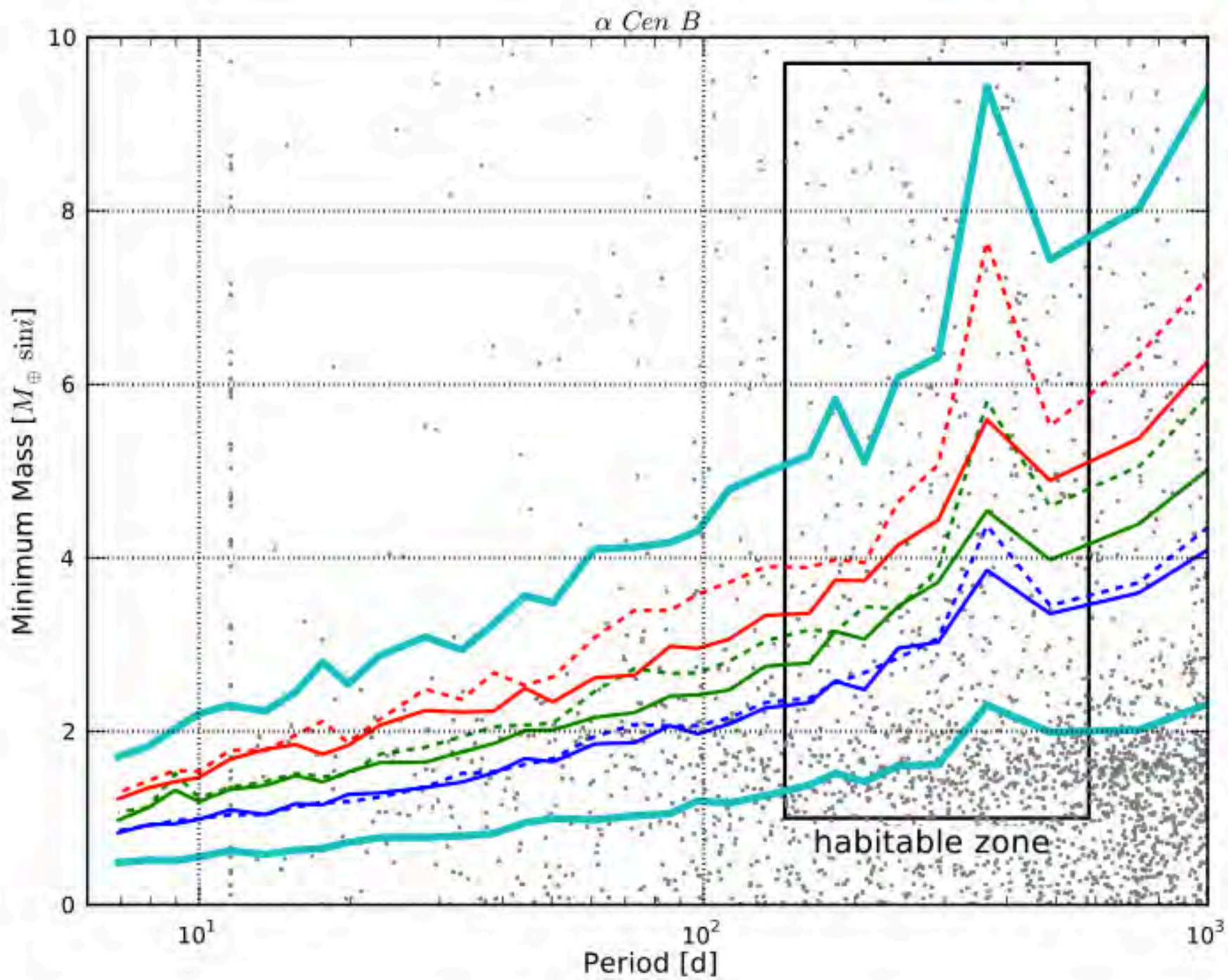
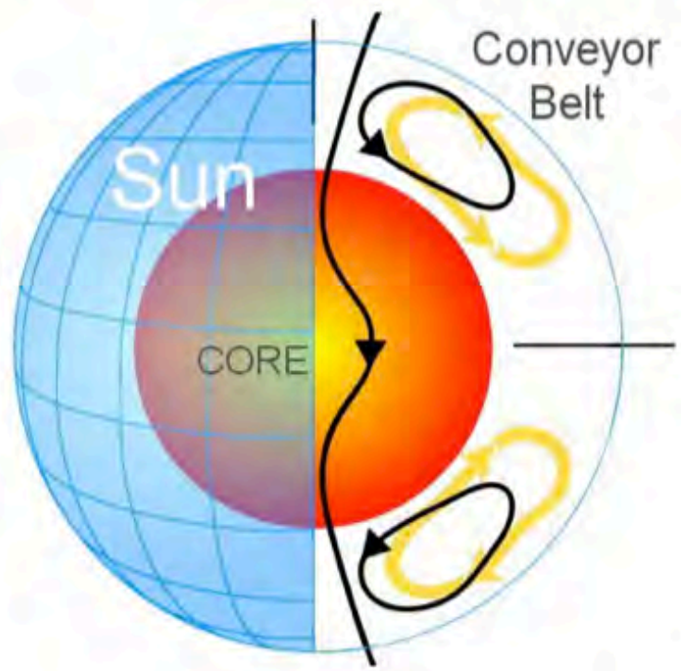


HARPS (1m/s)
30 min/night
10 nights/month
4 years

Most Optimistic Scenario
ESPRESSO (10 cm/s)
30 min/night
10 nights/month
4 years
most quiet star

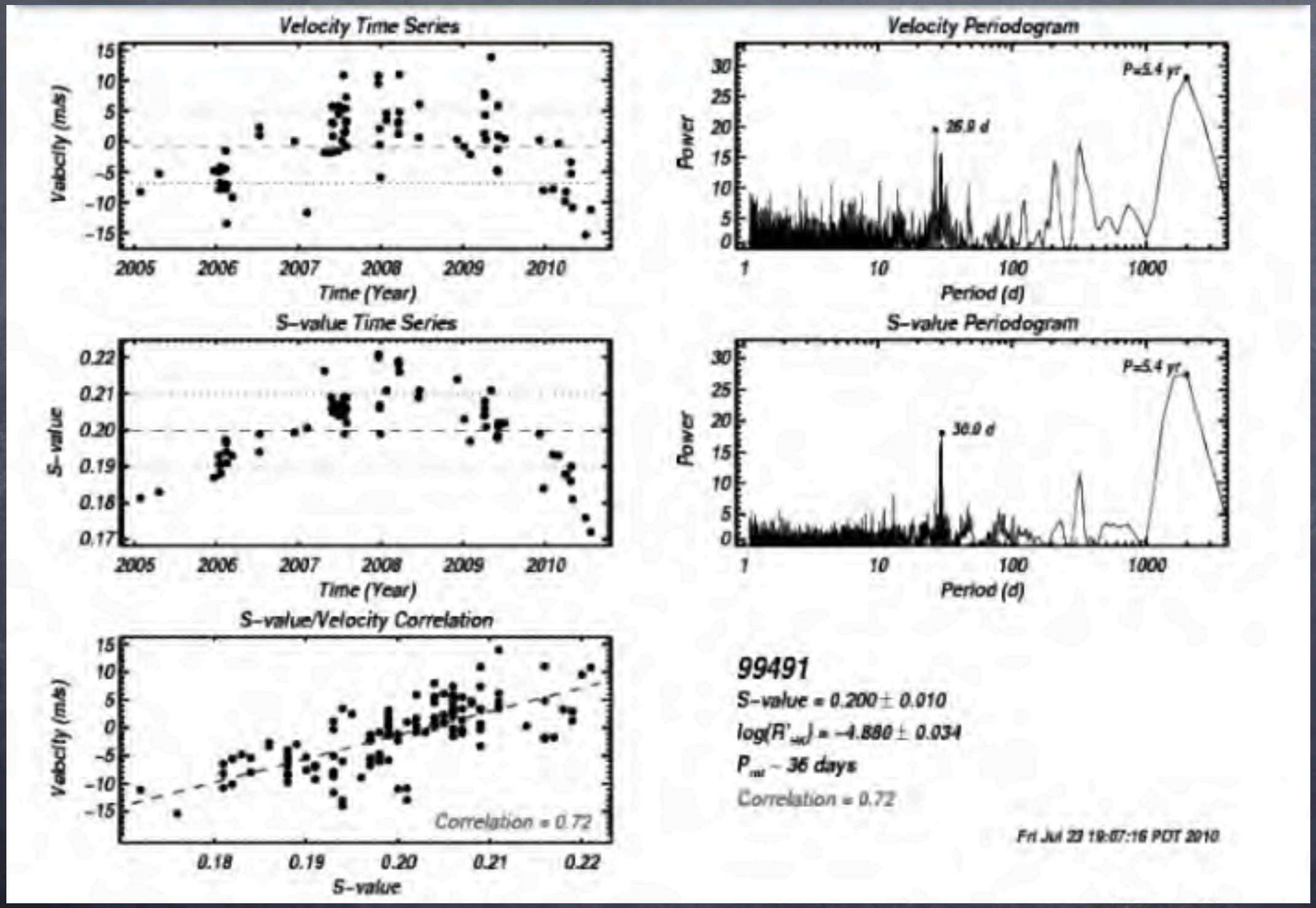
Meridional Flows

Example: Solar meridional flow



Meridional Circulation: massive flow pattern that transports hot plasma to the poles and deeper CZ layers. Flows are thought to be ~10 m s^{-1} (slow, relative to the outflows from plages or spot rotation). Meridional flow may govern the strength of the polar magnetic field and strength of sunspots.

Meridional Flows / Activity Cycles



Instrumental Jitter HIRES RV Errors

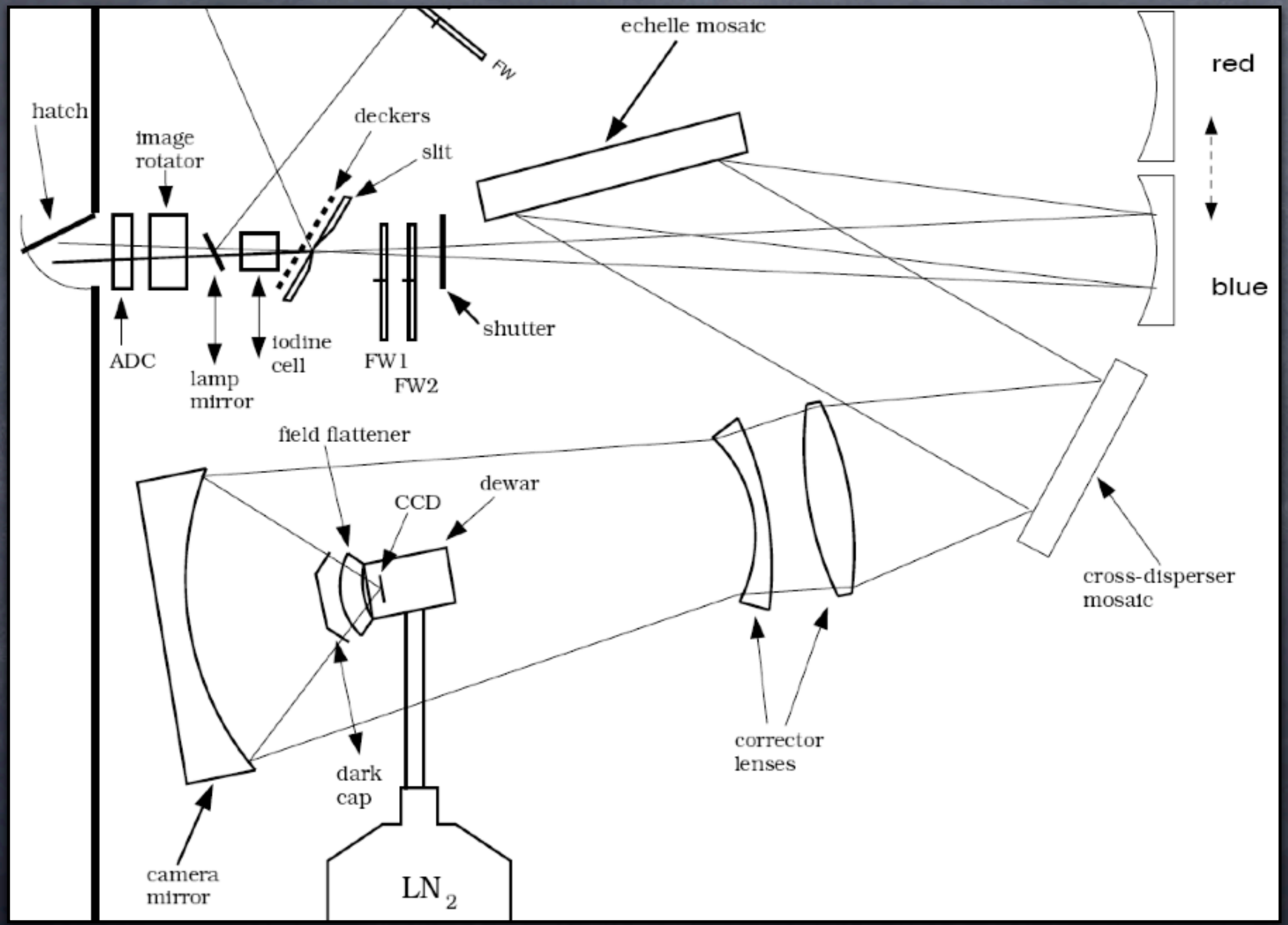
- Guiding
- Zonal aberrations / vignetting
- Fibers (The Solution!)
- Scattered light - HIRES
- Sky subtraction for faint targets

Keck/HIRES

Keck 1 Telescope

Iodine Cell

HIRES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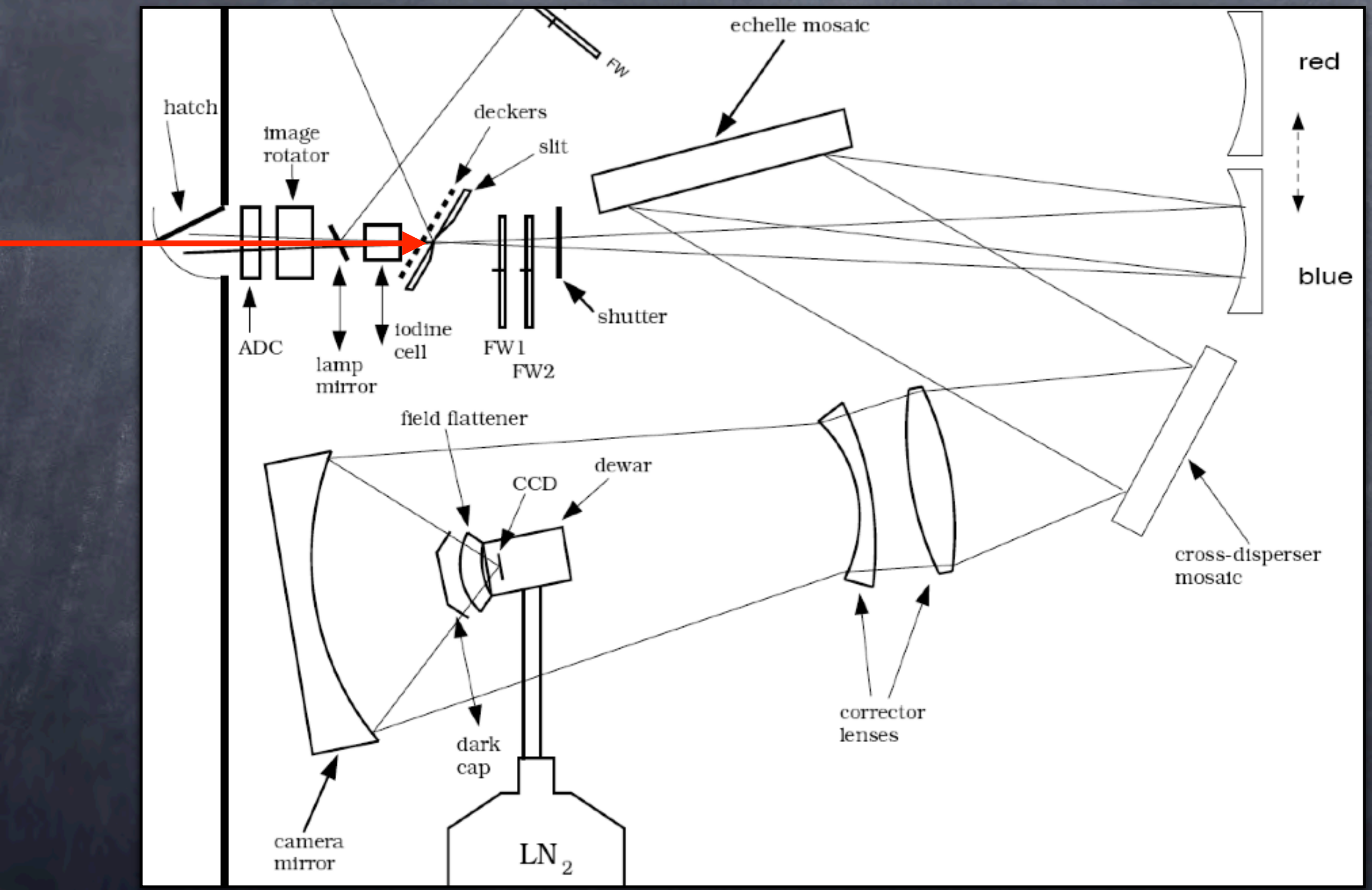
HIRES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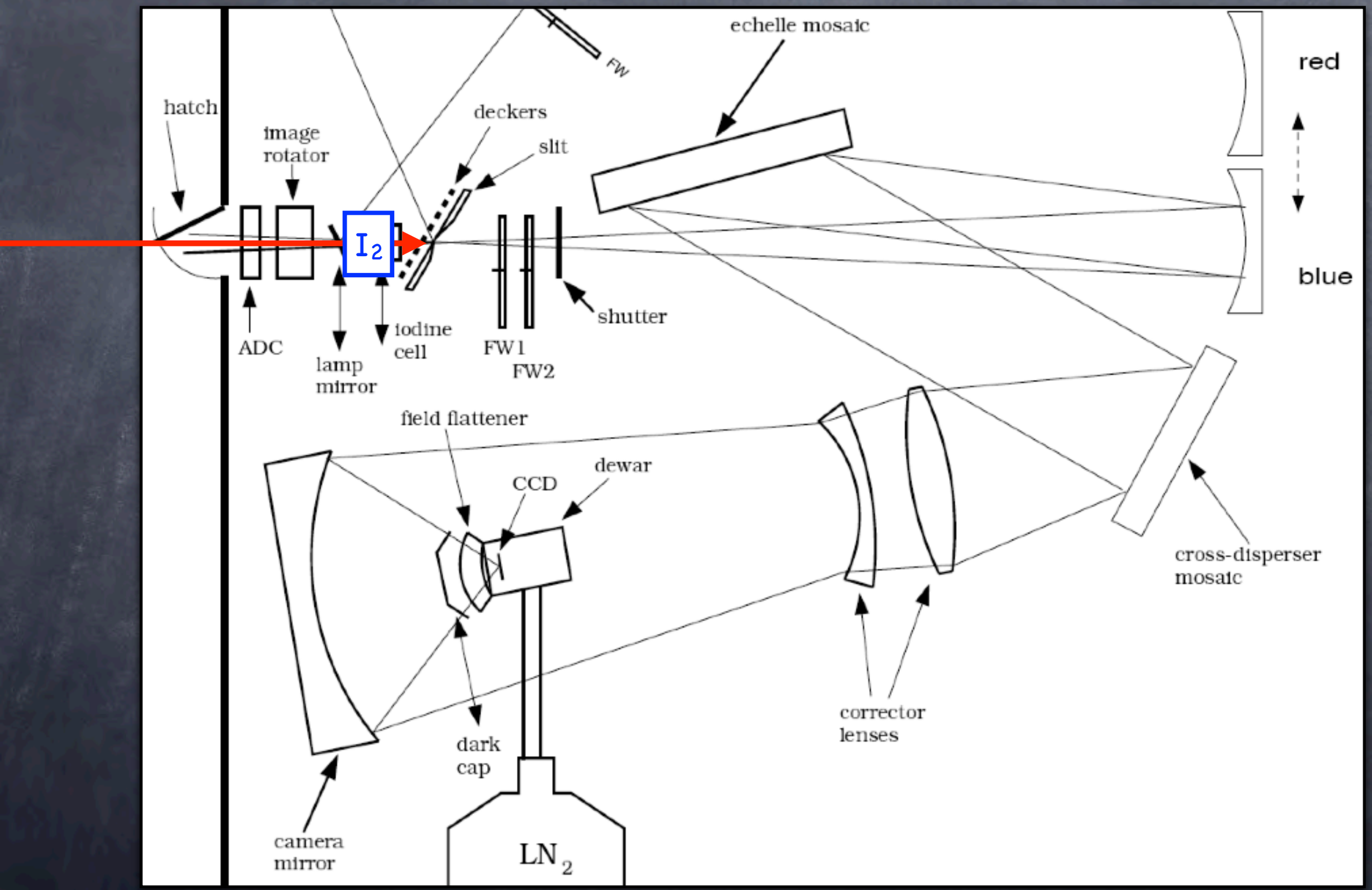
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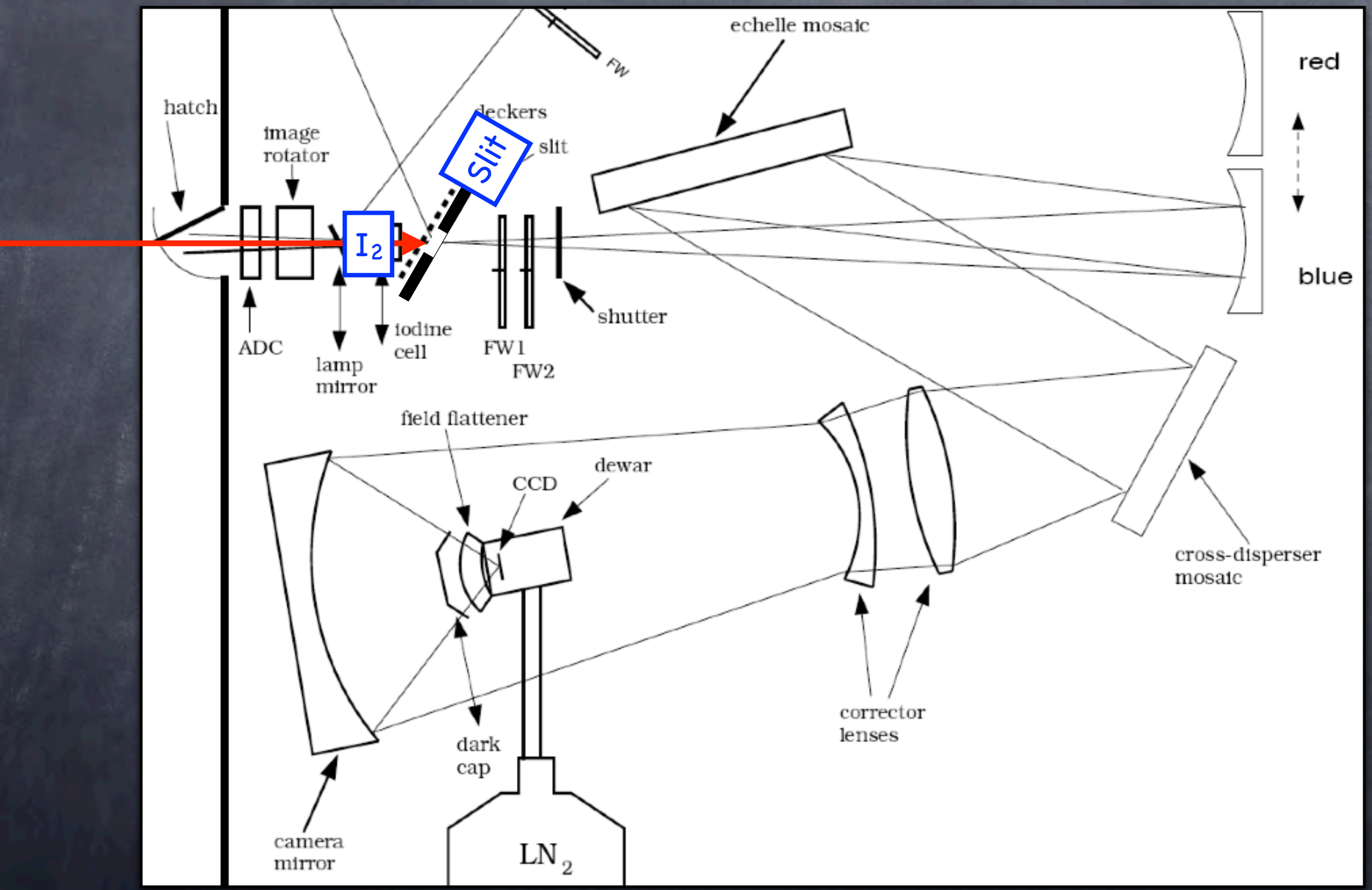
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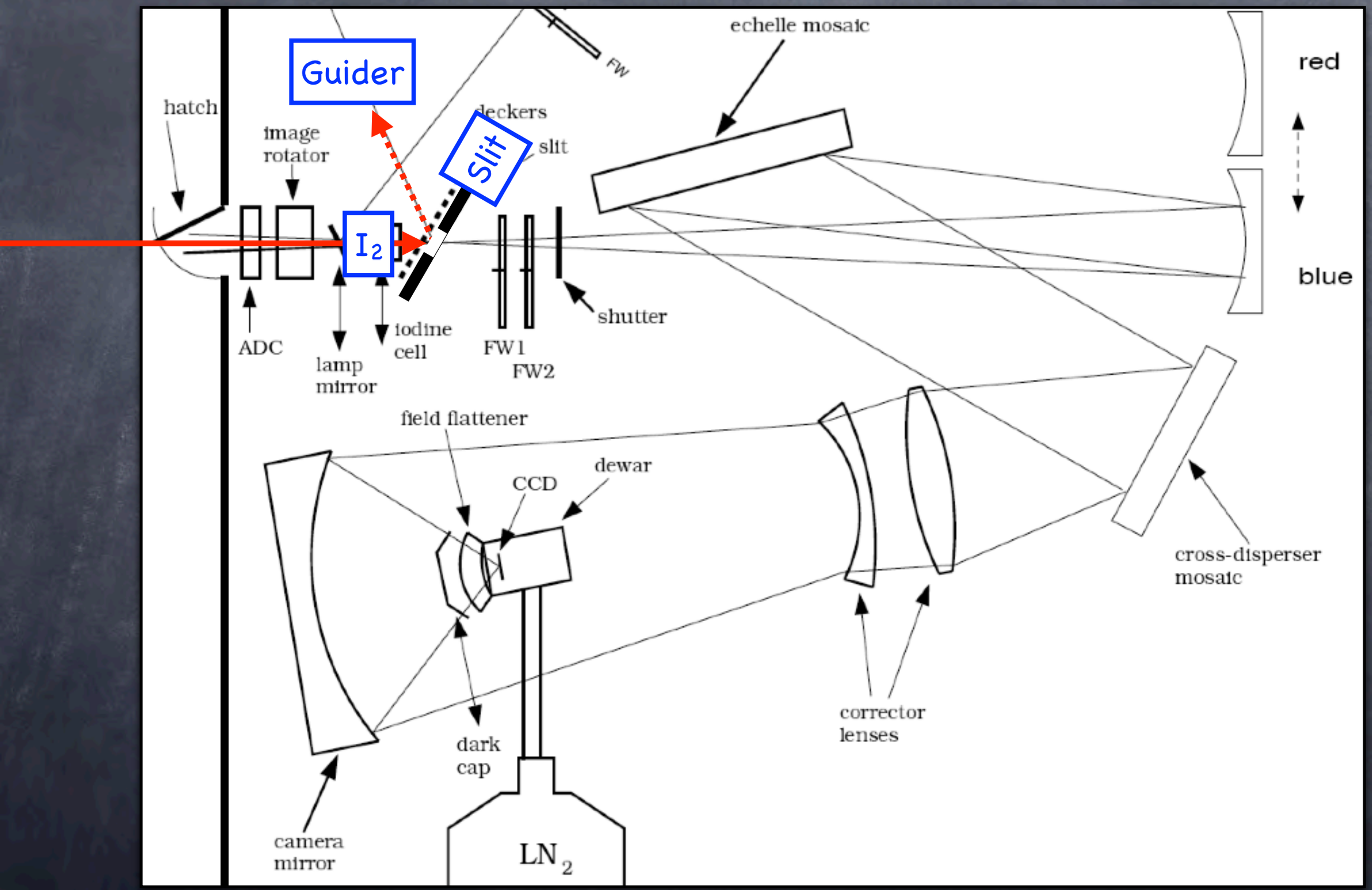
HIRES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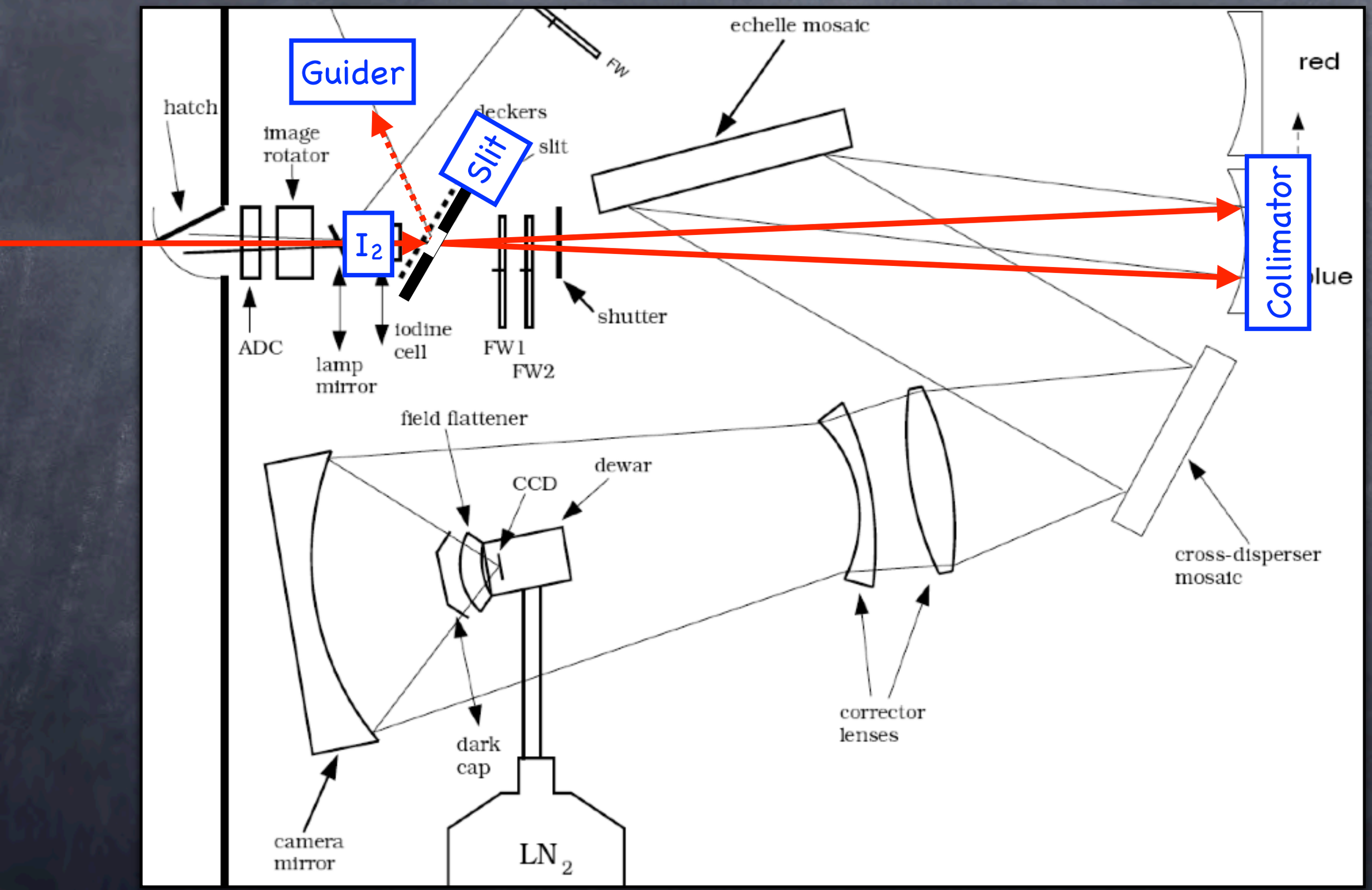
HIRES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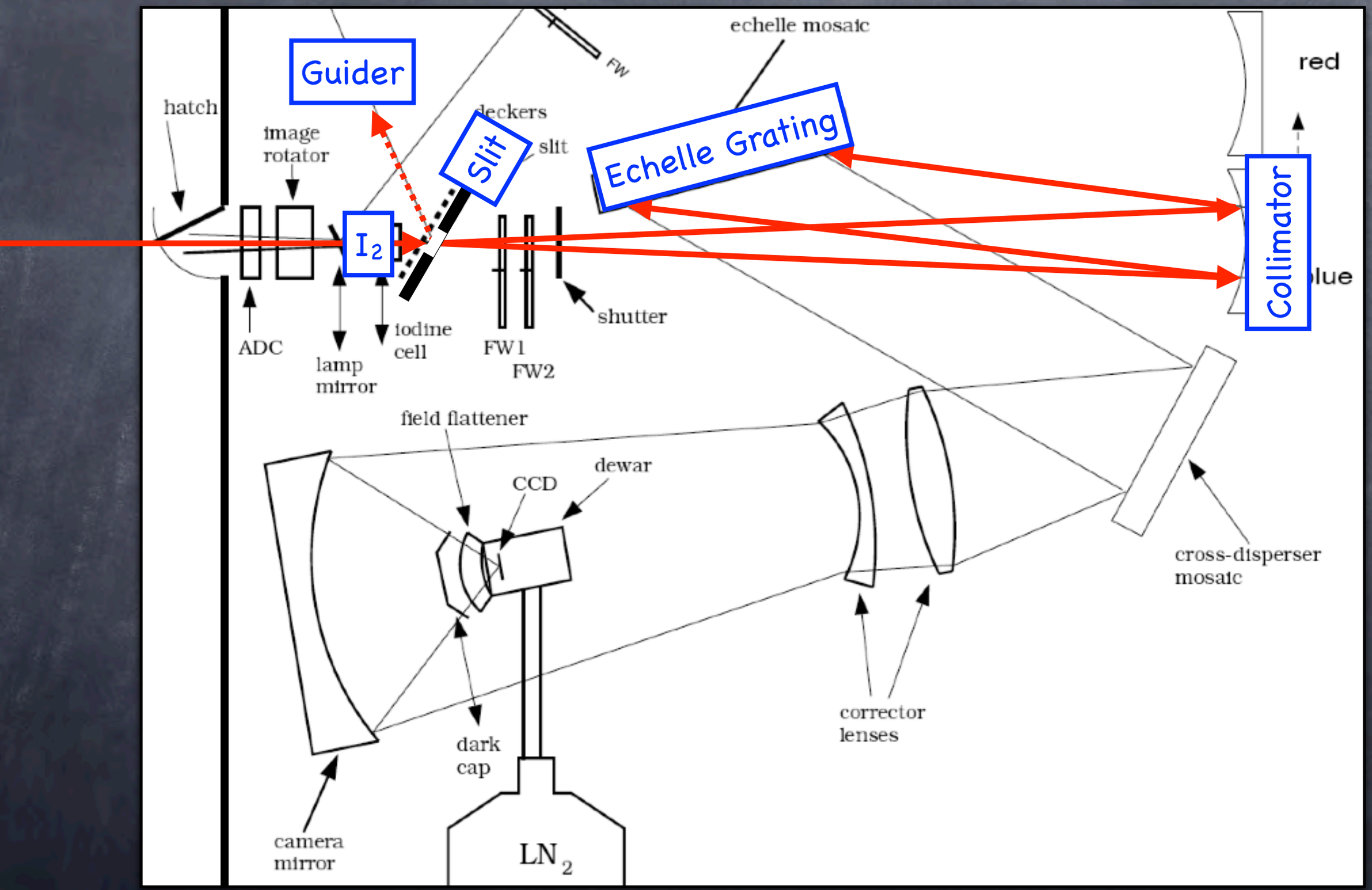
HIRES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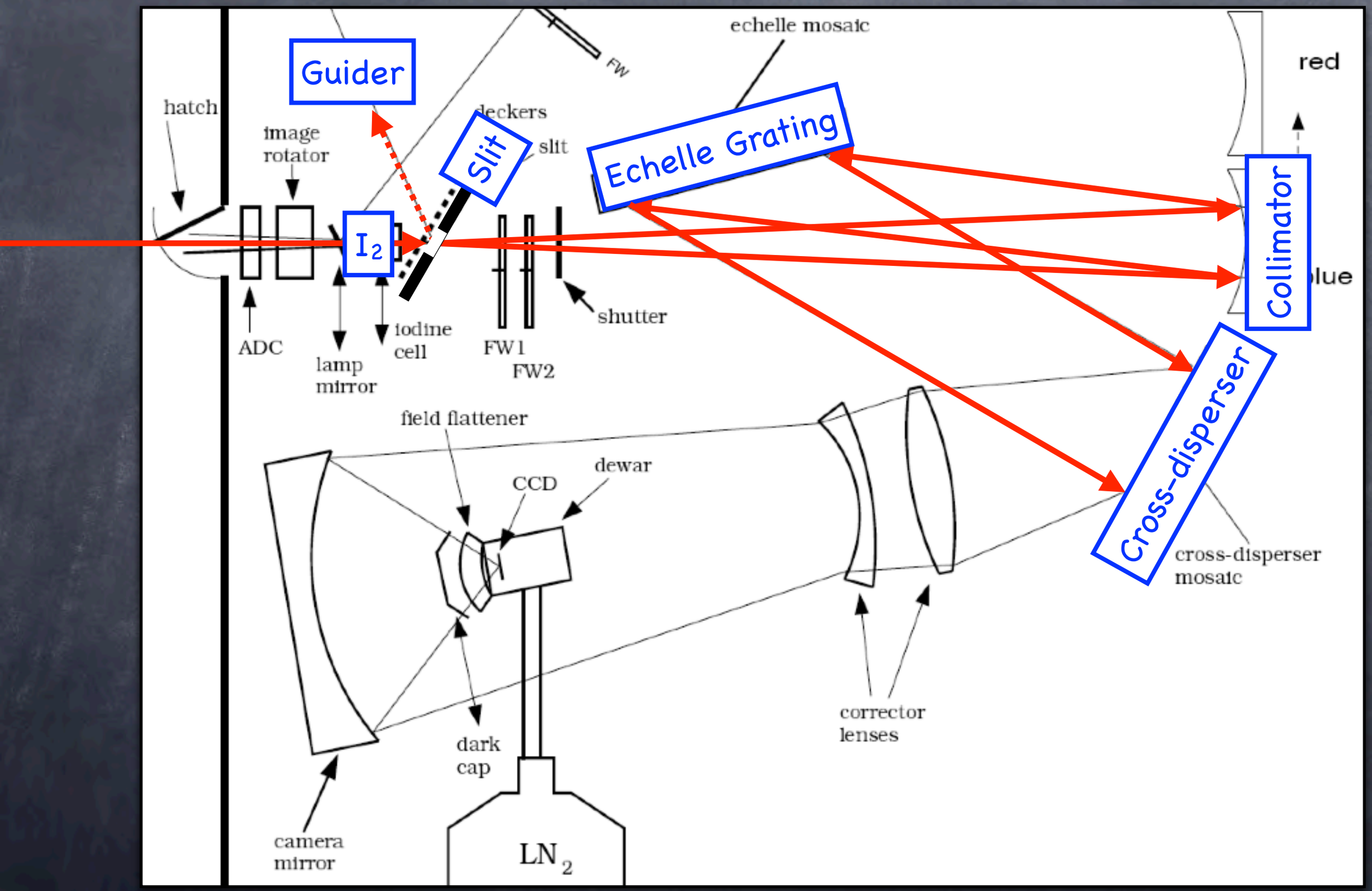
HIRES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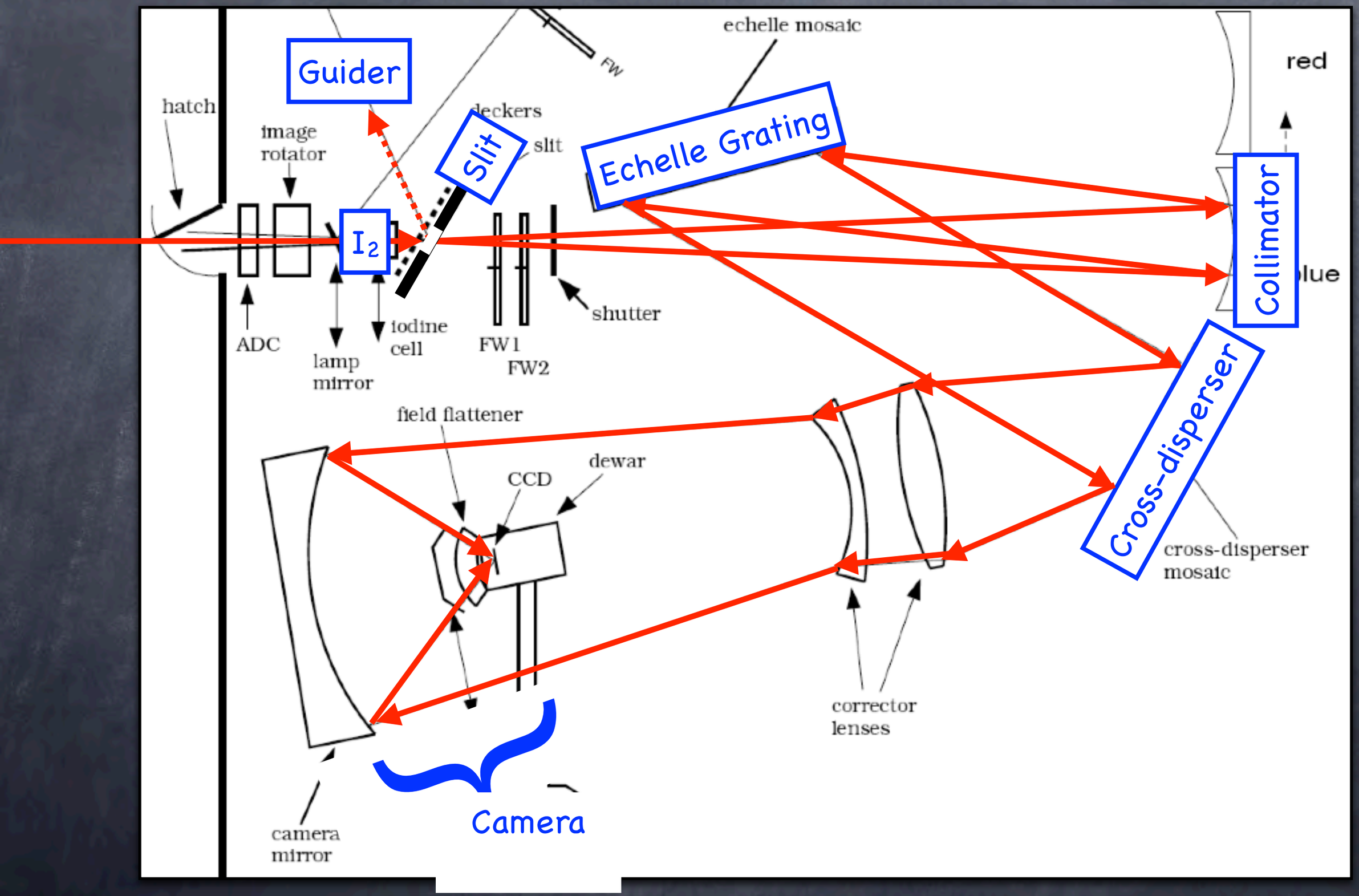
HIRES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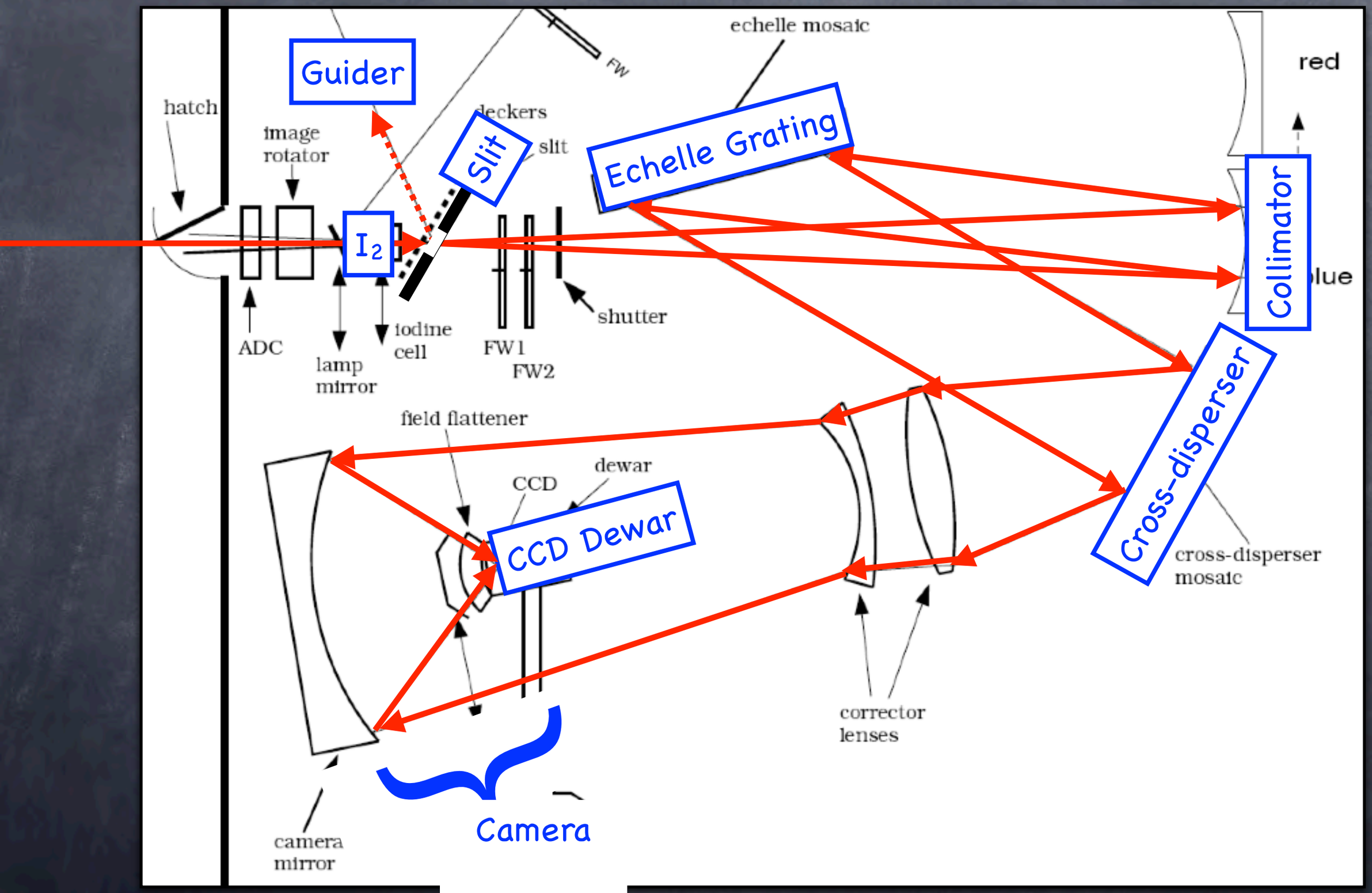
Camera

HIRES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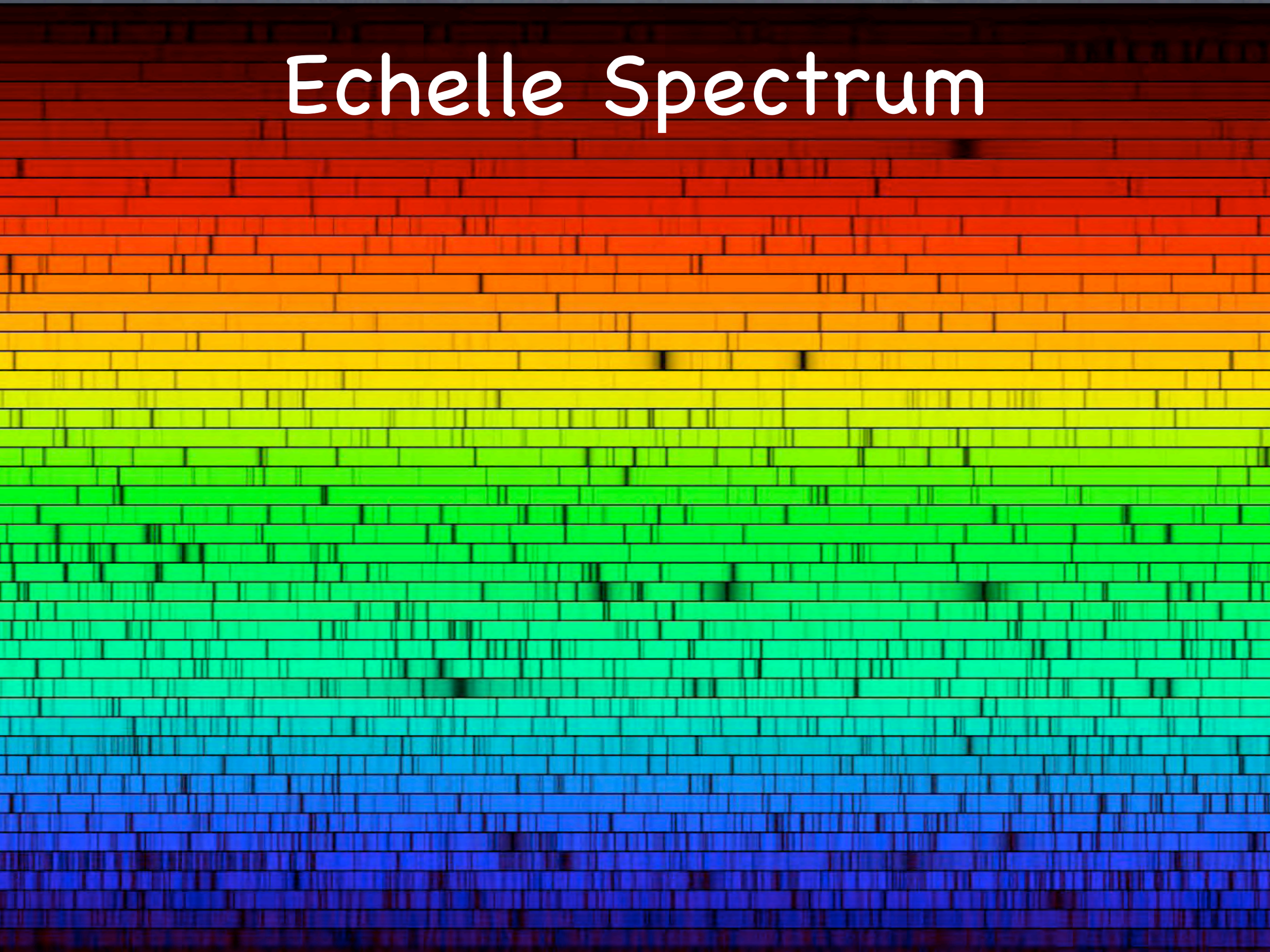
Echelle Spectrum



HIRES RV Errors

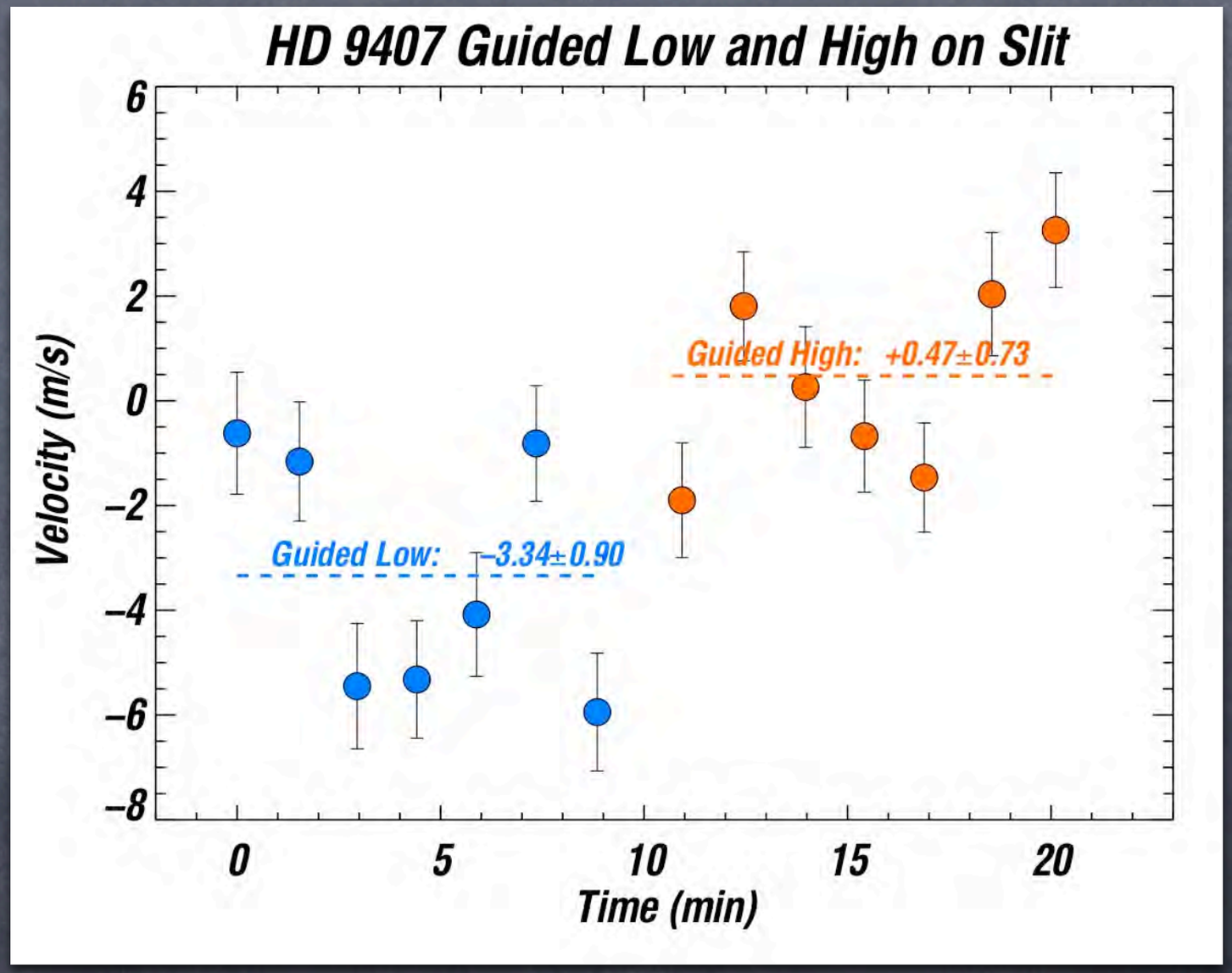
- Guiding
- Zonal aberrations / vignetting
- Fibers (The Solution!)
- Scattered light - HIRES
- Sky subtraction for faint targets

Intentional Mis-guiding

Guide High

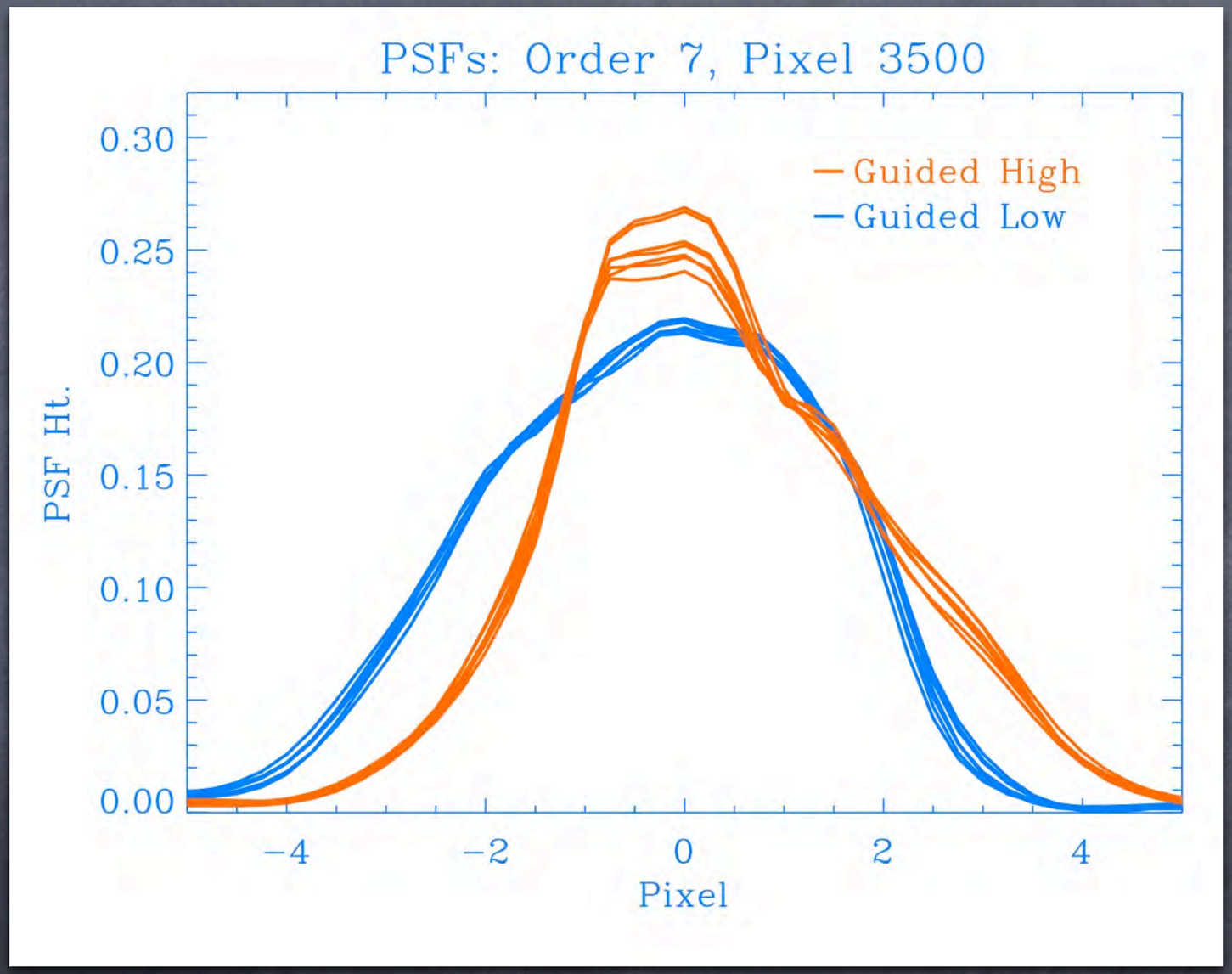
Guide Middle

Guide Low

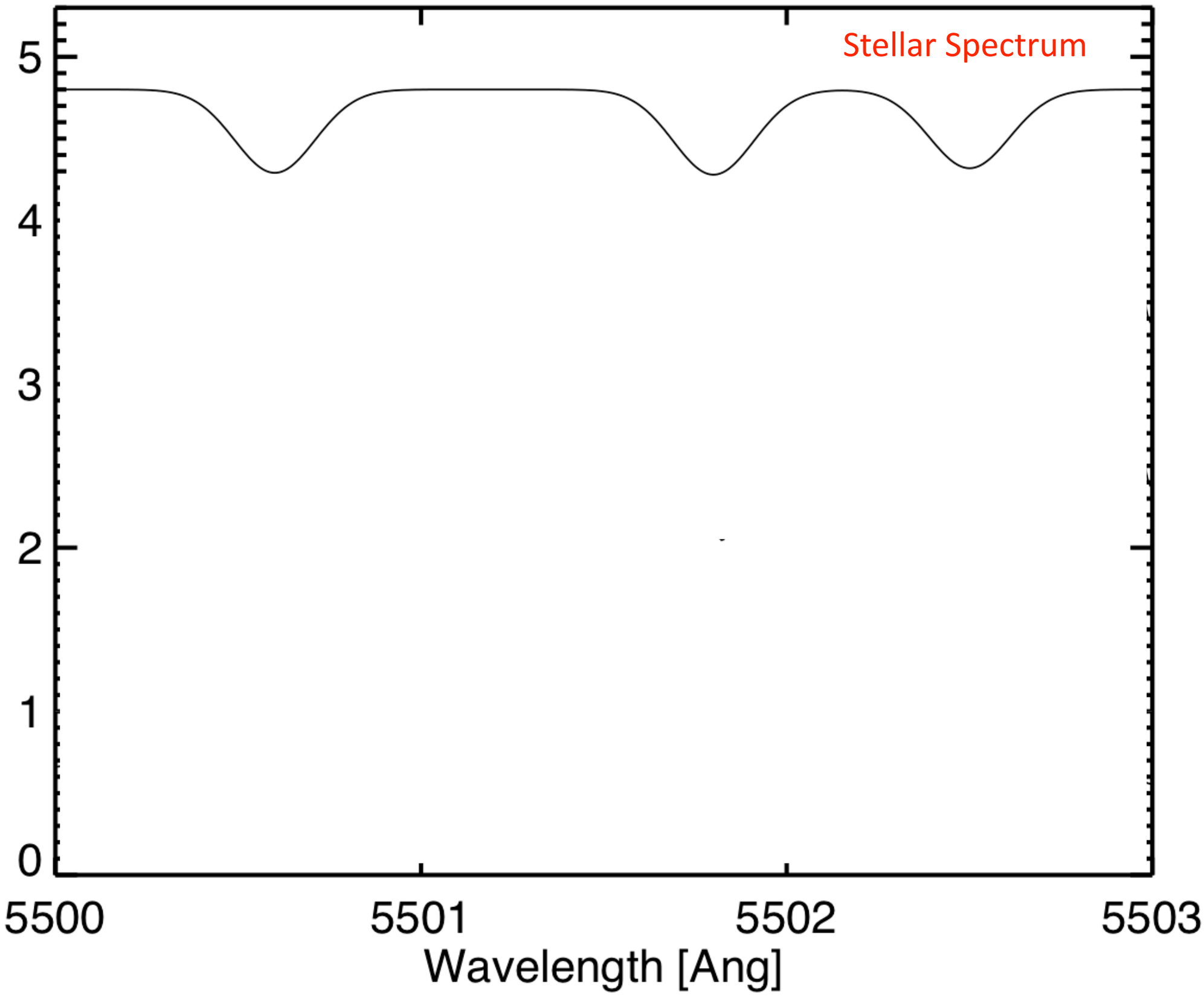


Extreme mis-guiding → 4 m/s

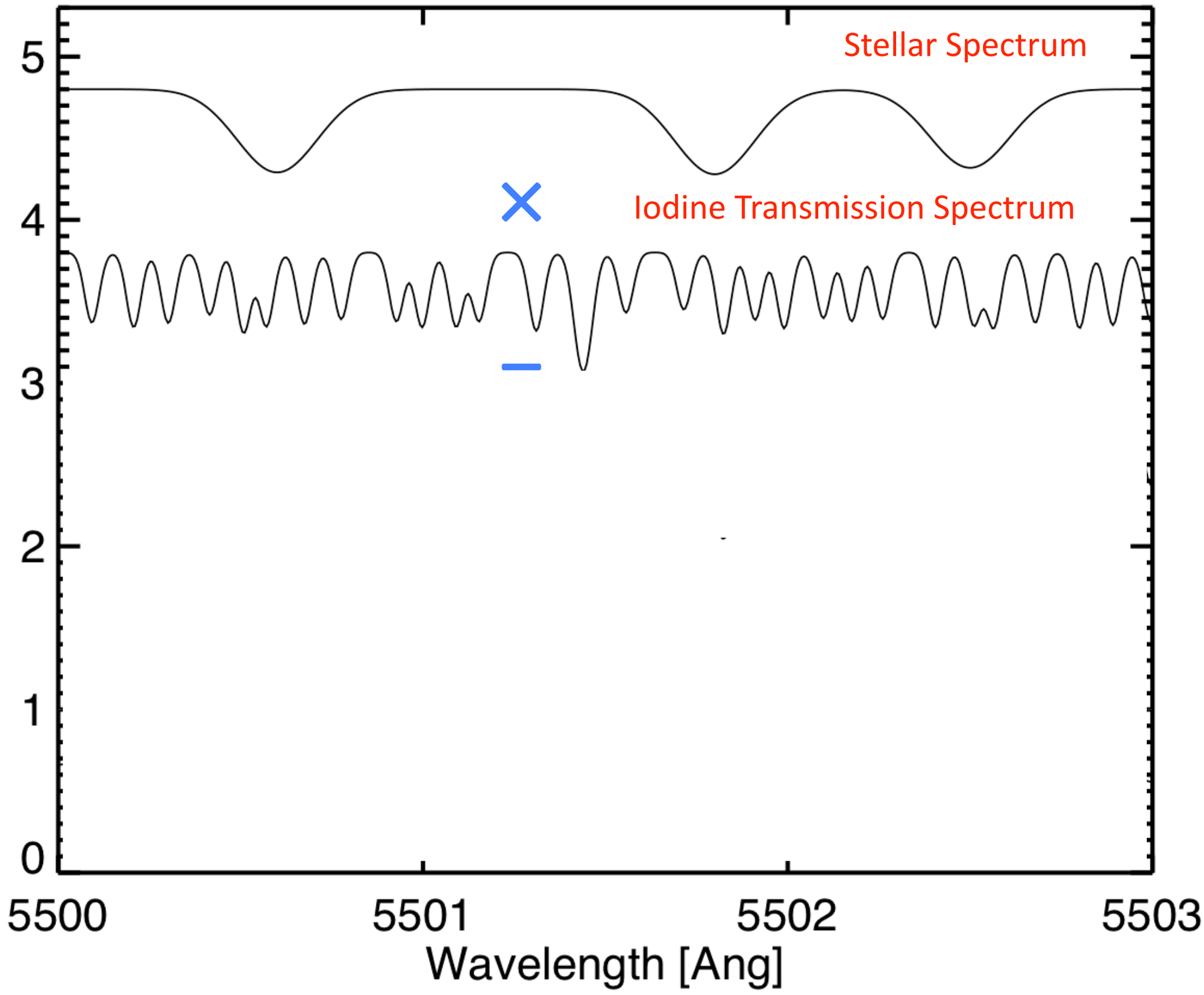
Intentional Mis-guiding - PSF Asymmetry



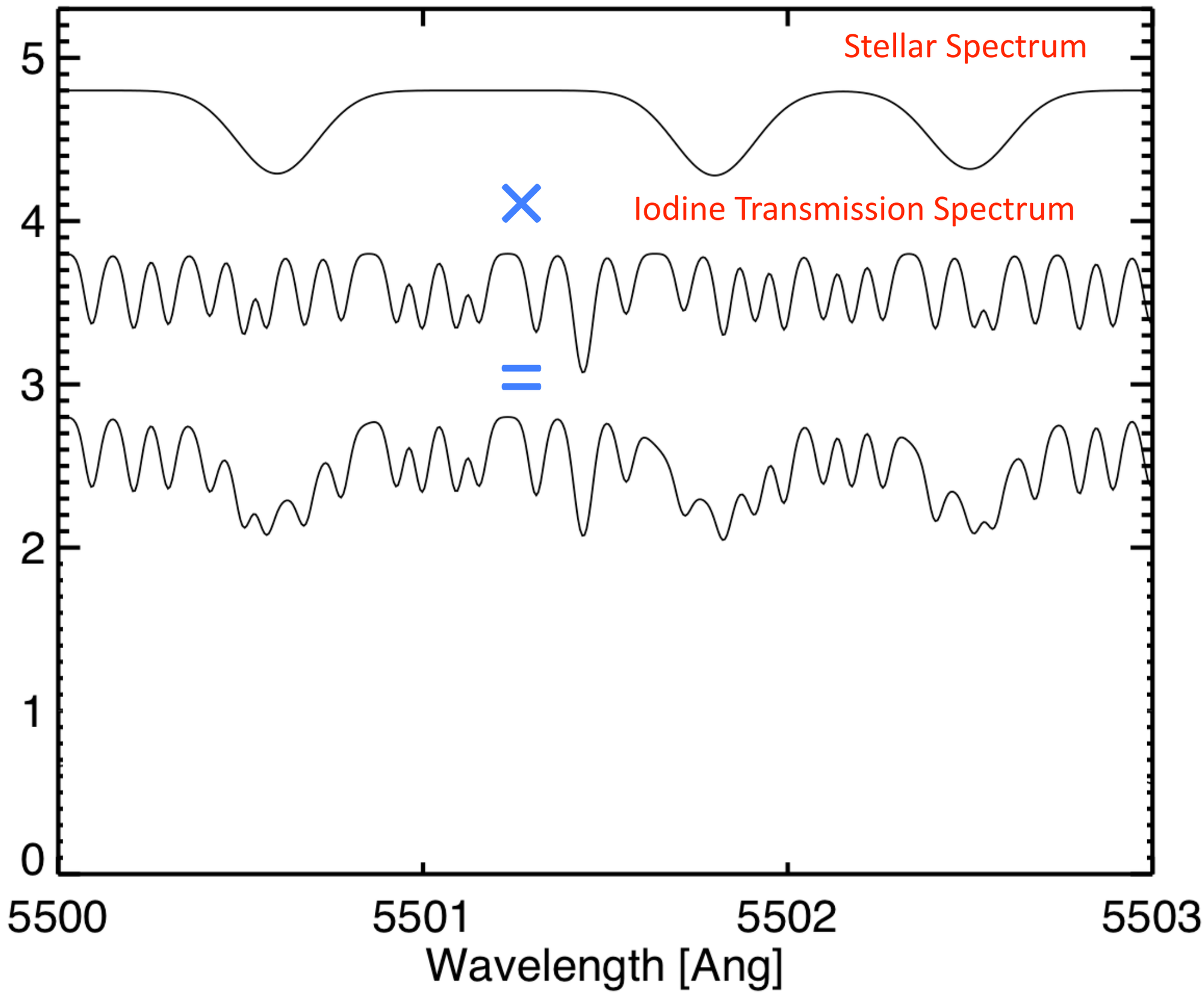
PSF shape changes with mis-guiding



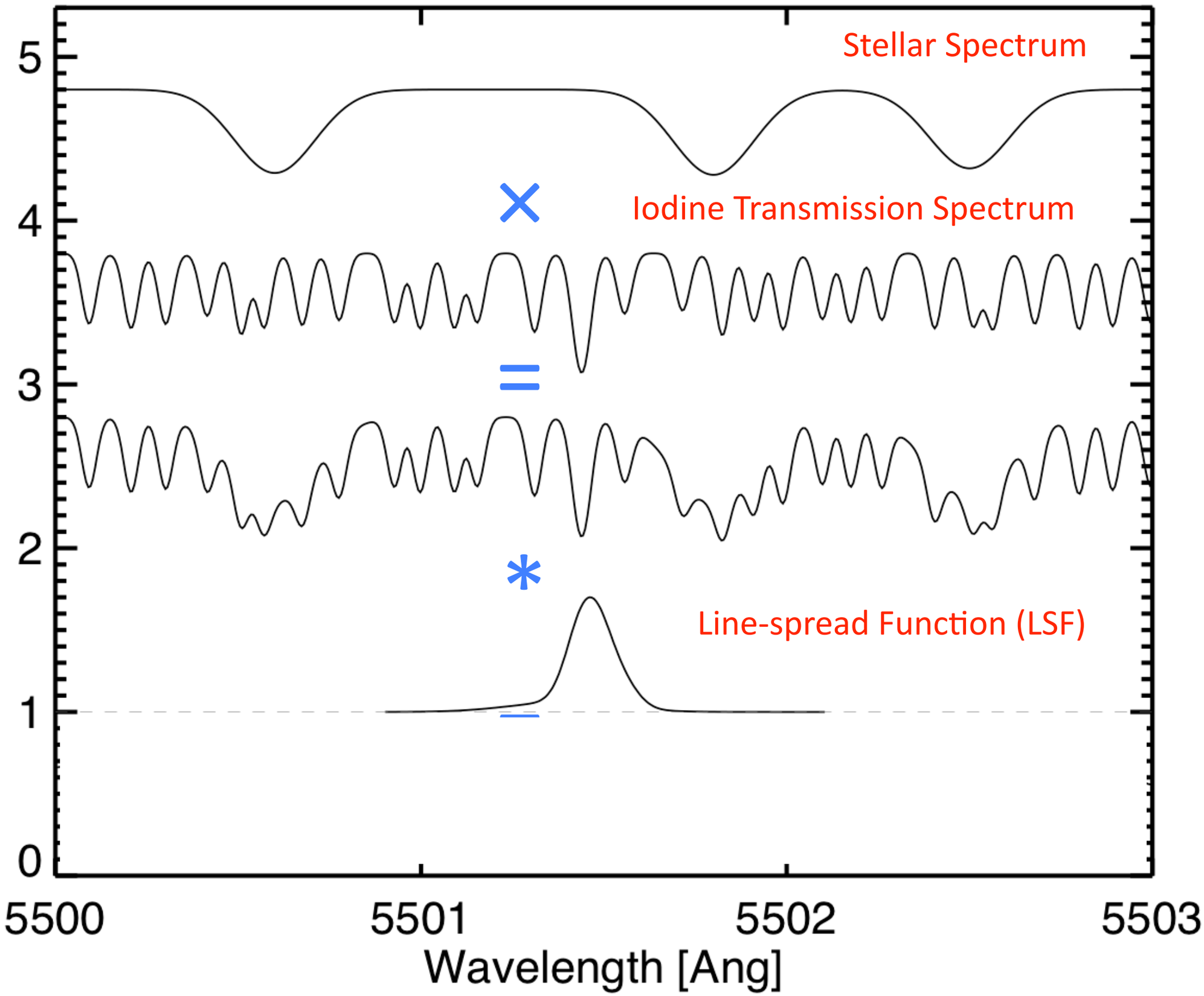
Simulation by John Johnson



Simulation by John Johnson



Simulation by John Johnson



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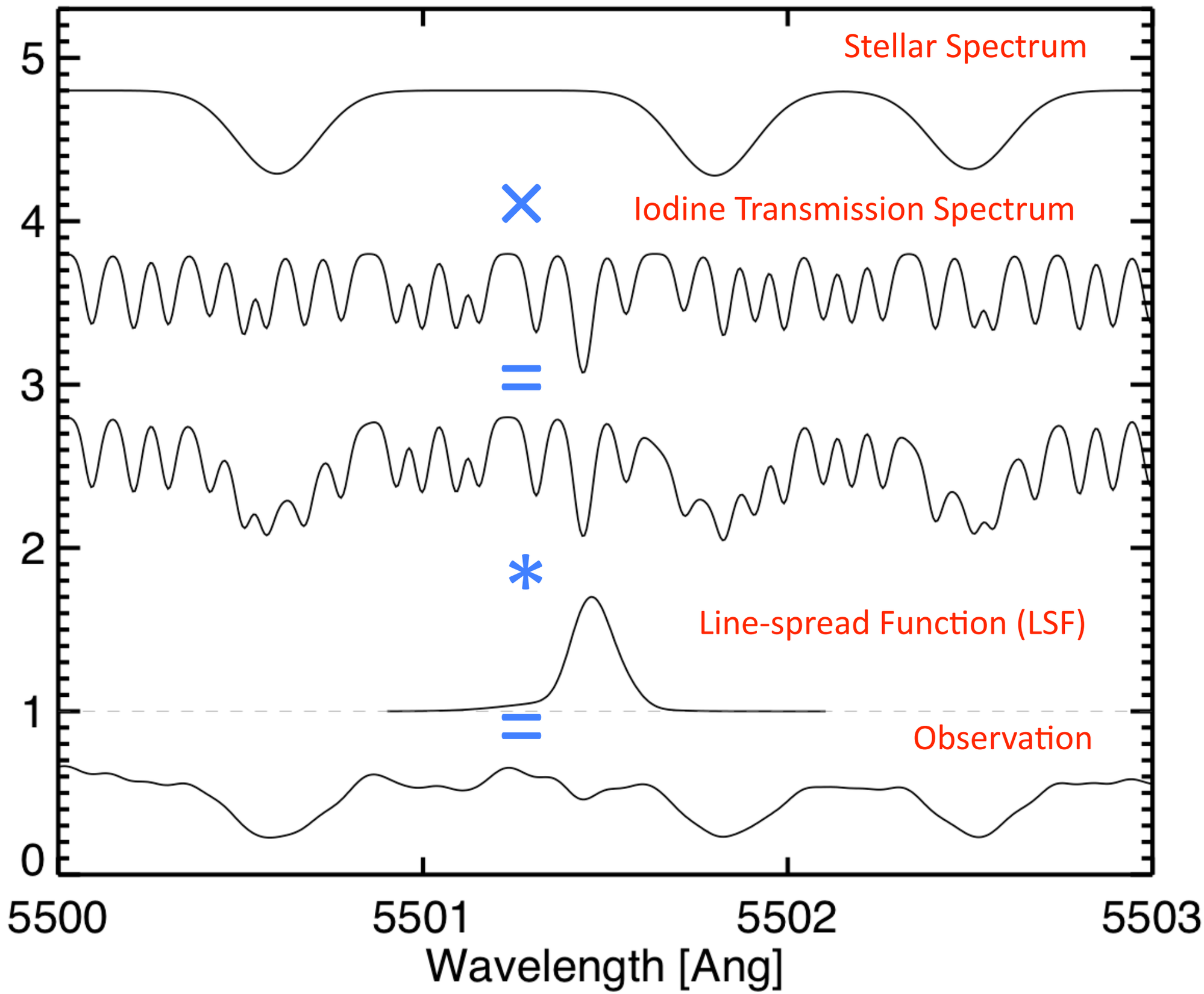
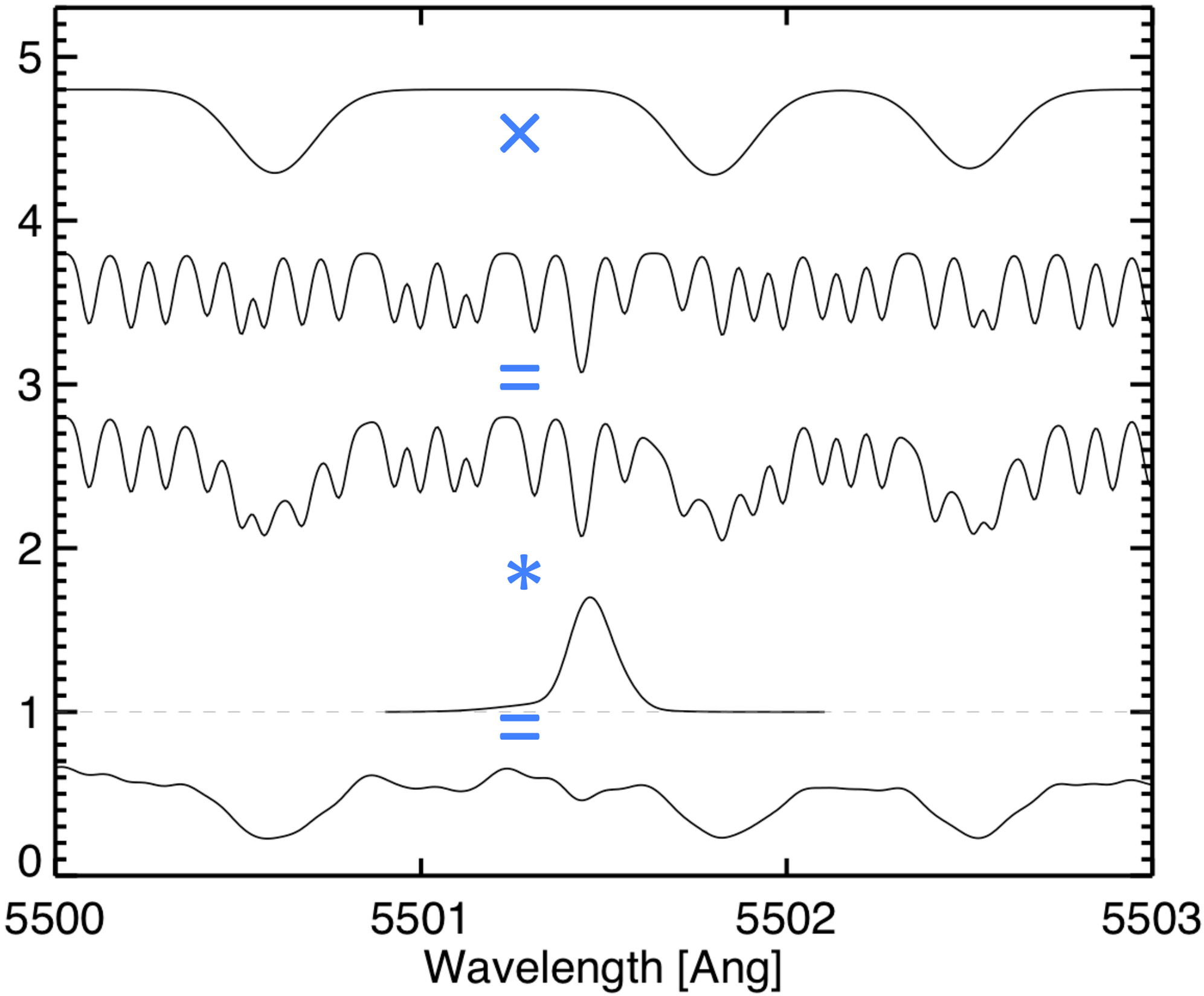
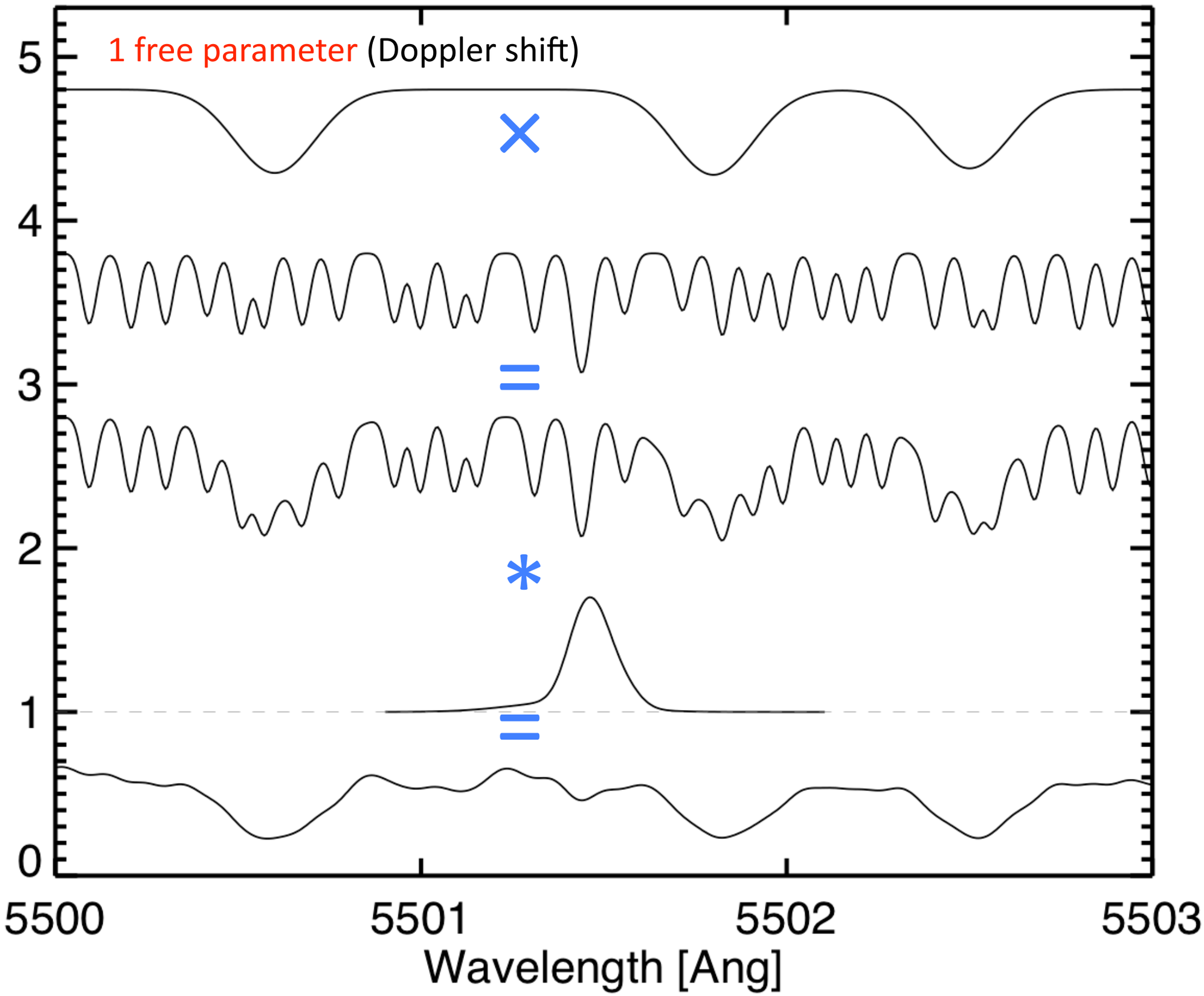


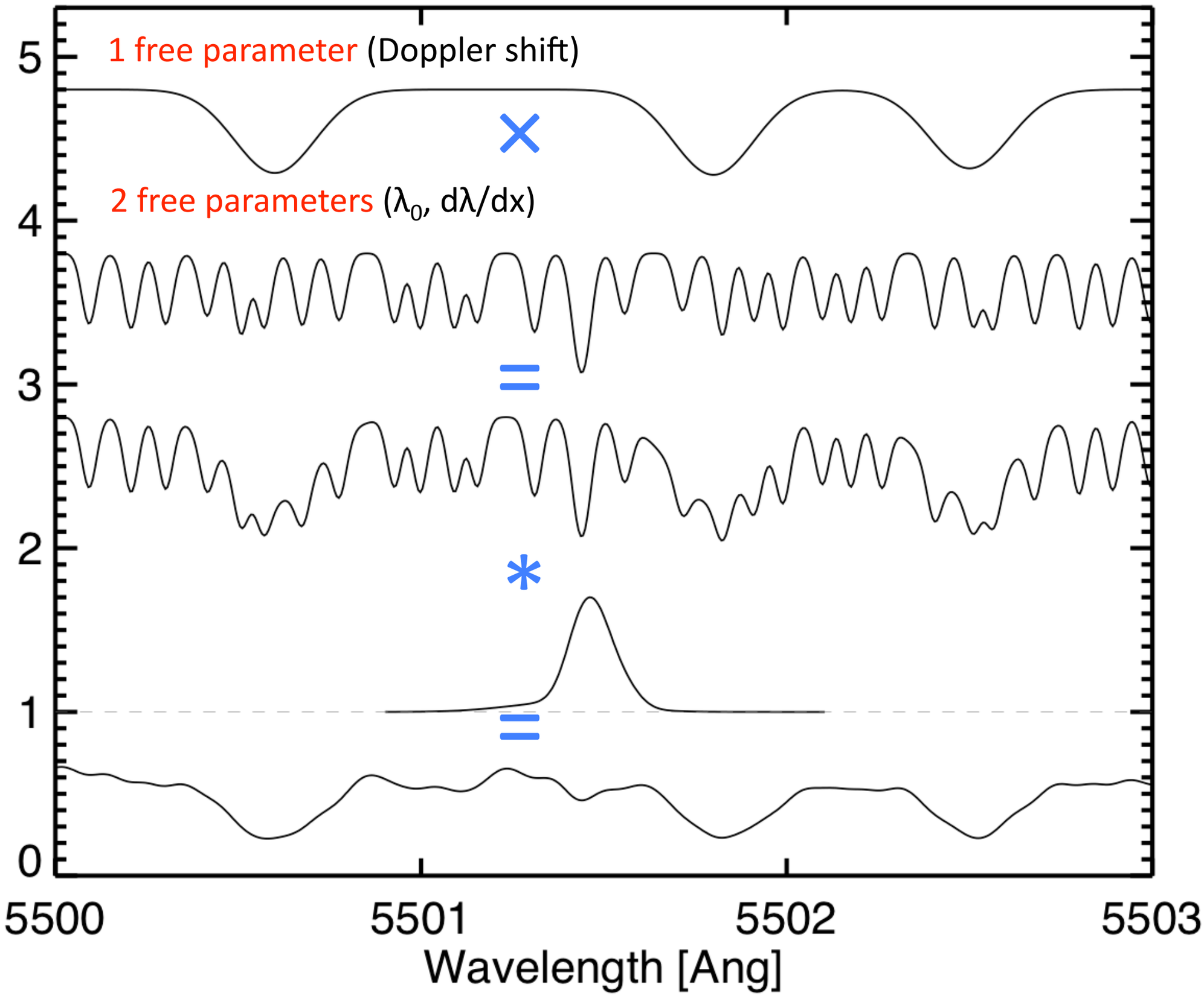
Simulation by John Johnson



Simulation by John Johnson



Simulation by John Johnson



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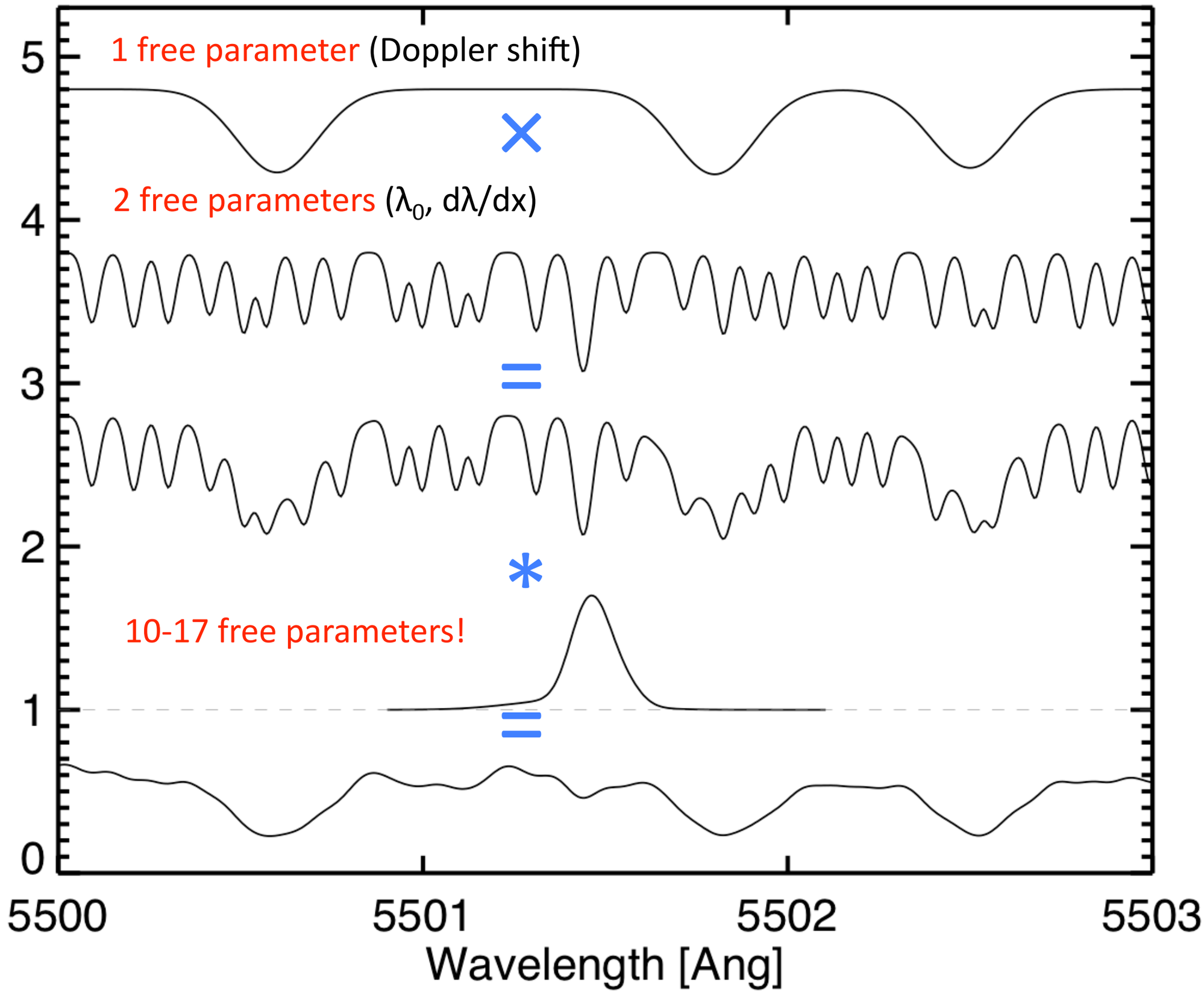
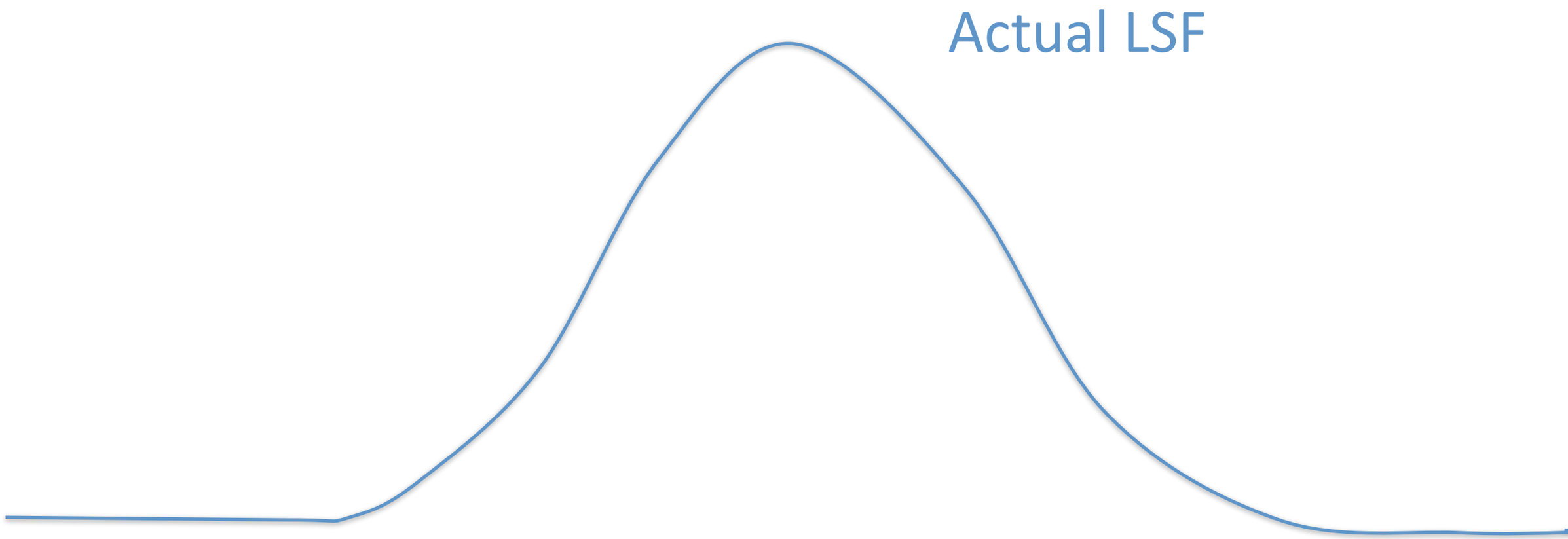


Simulation by John Johnson

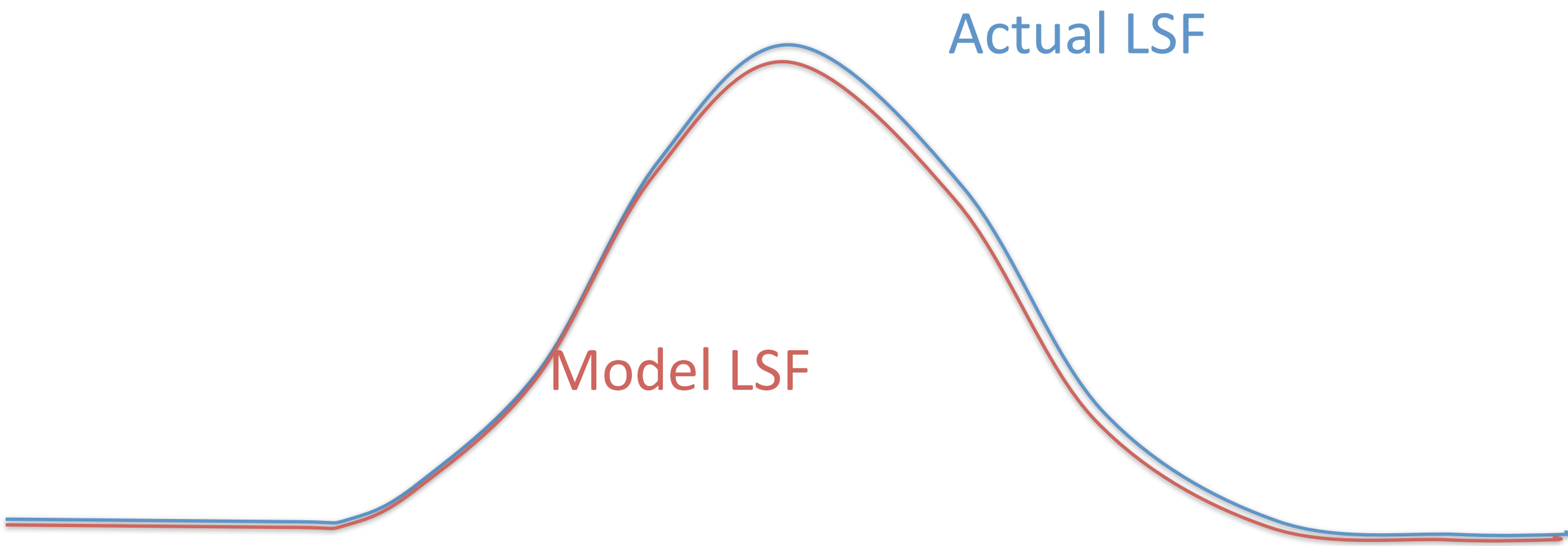
The Effect of LSF Mismatches



Cartoon Line-Spread Function (LSF)

Simulation by John Johnson

The Effect of LSF Mismatches



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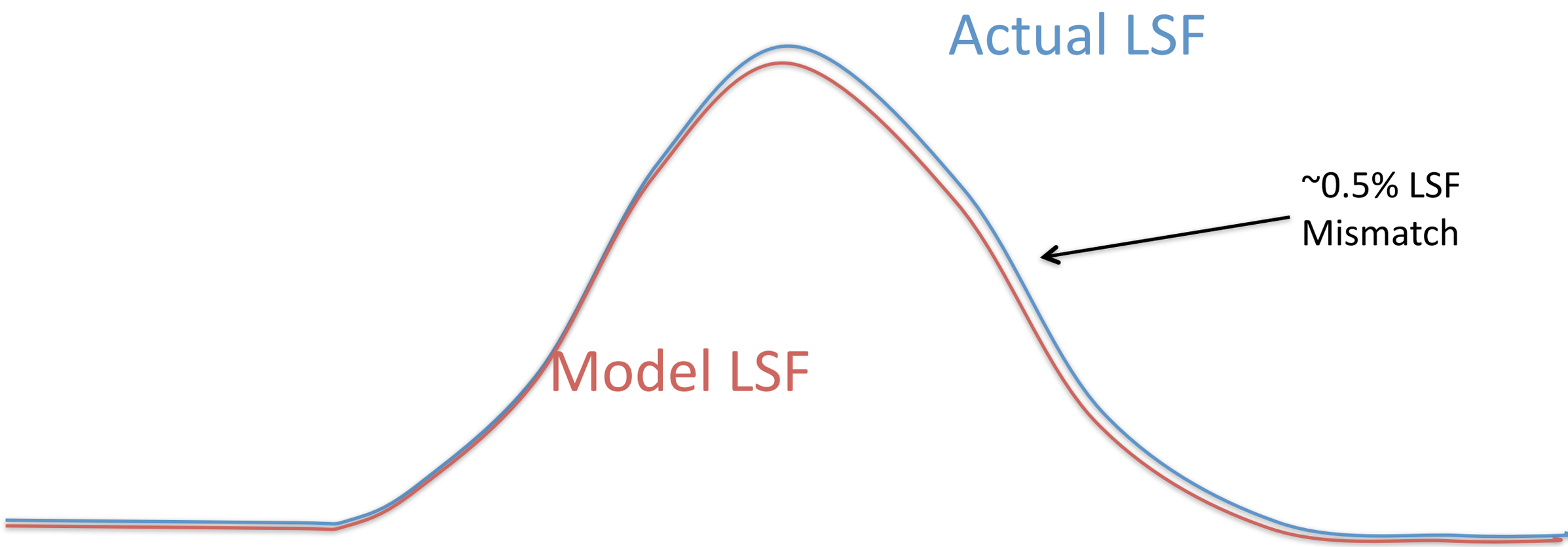
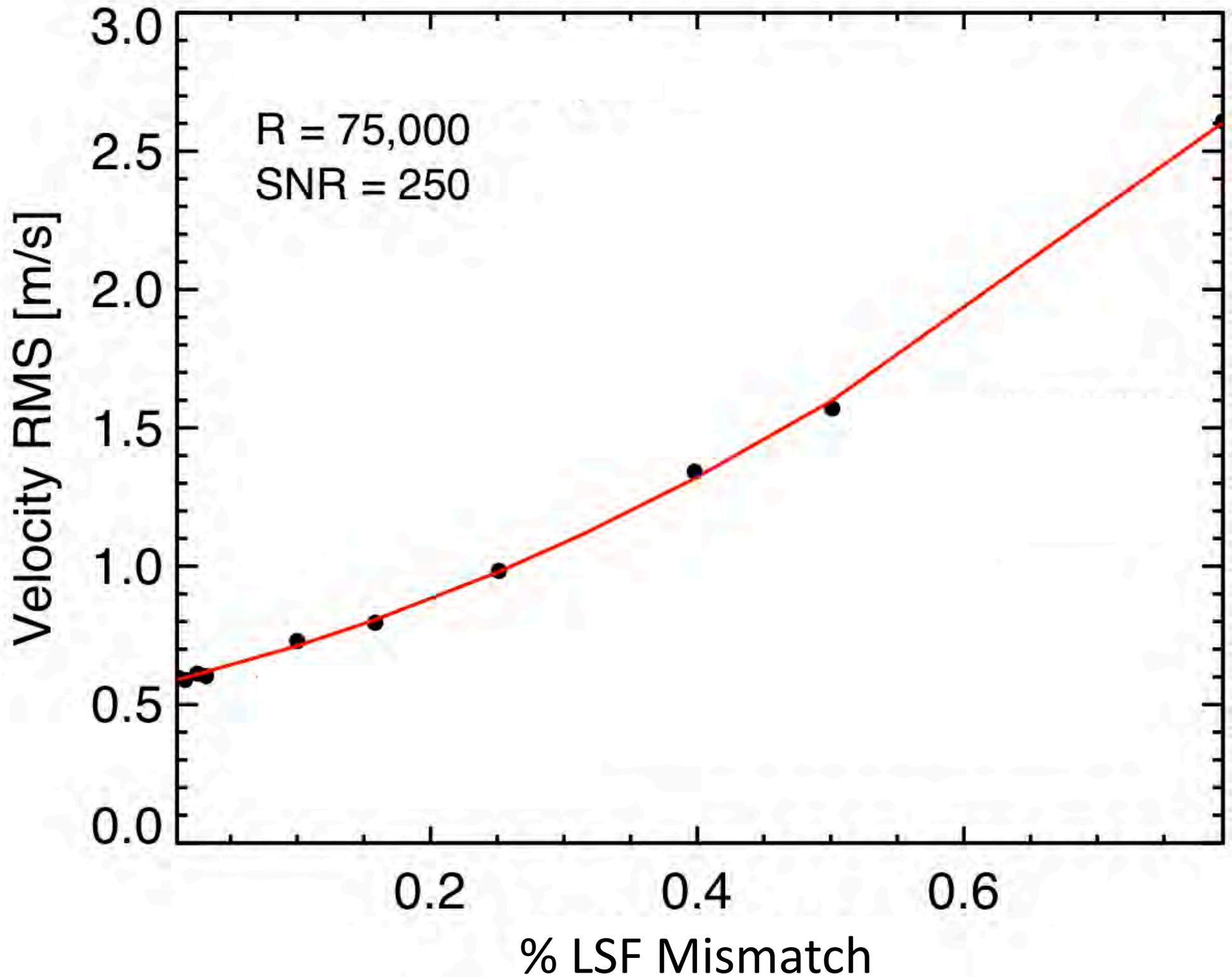


Cartoon Line-Spread Function (LSF)

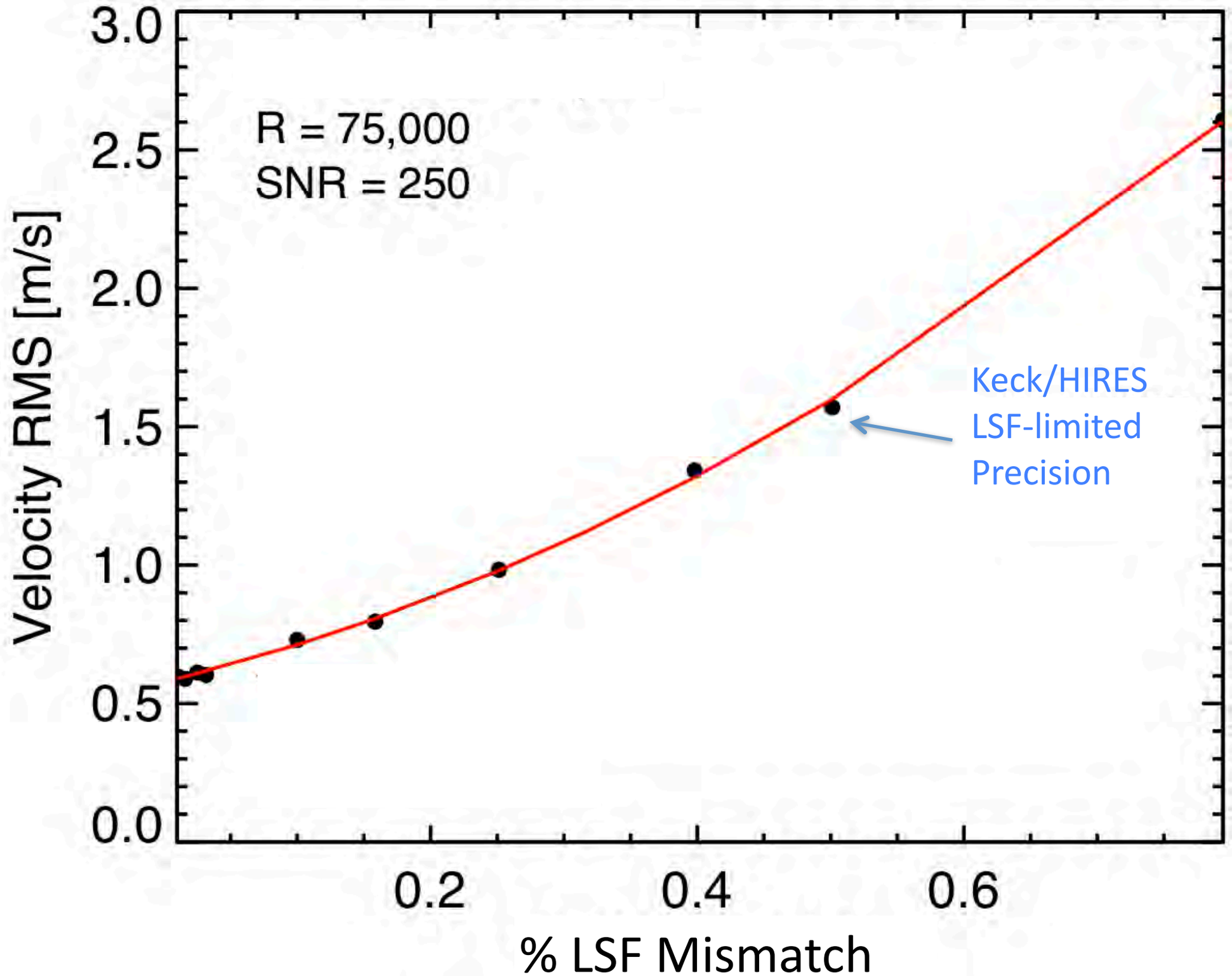
Simulation by John Johnson

Simulated LSF Mismatches



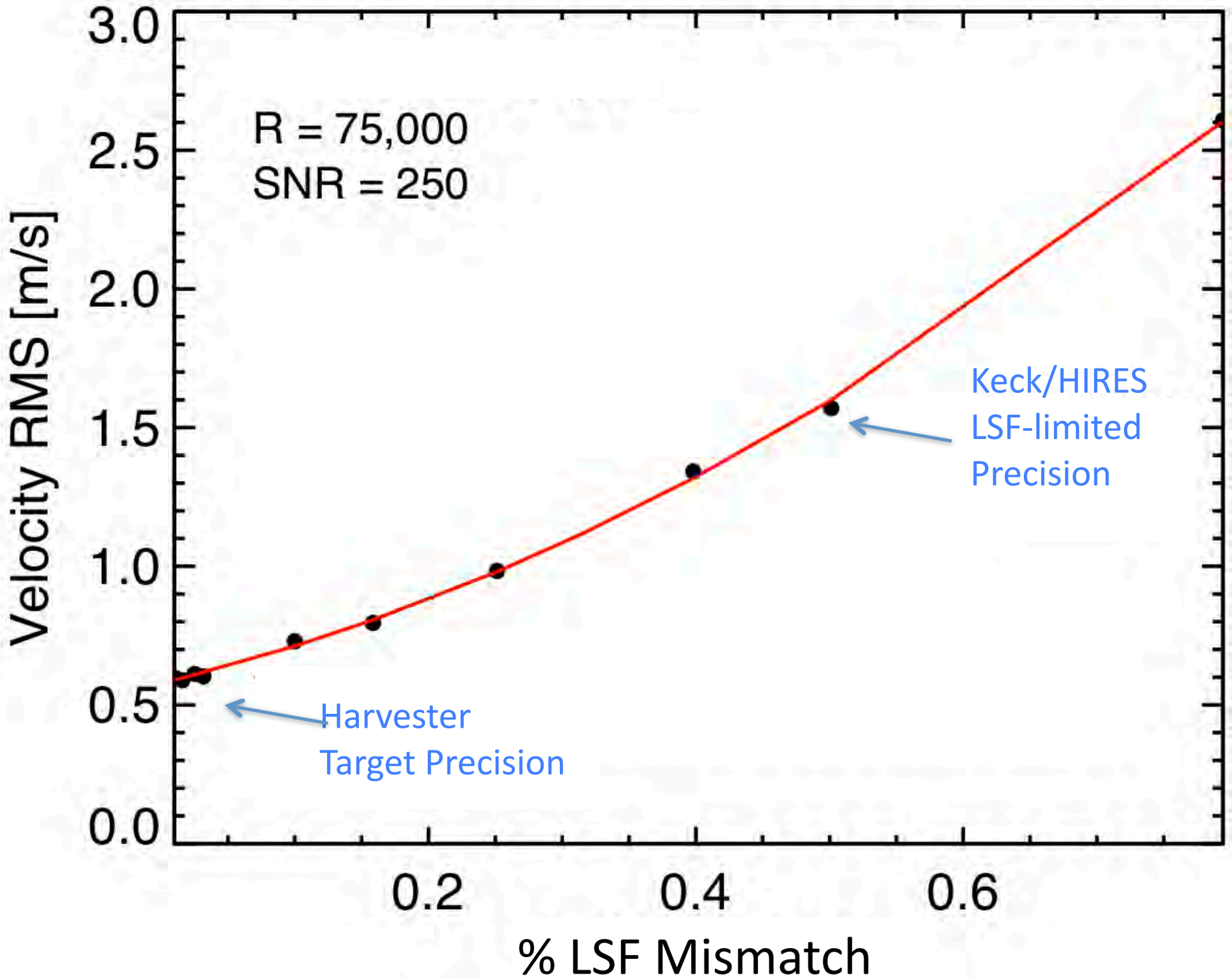
Simulation by John Johnson

Simulated LSF Mismatches



Simulation by John Johnson

Simulated LSF Mismatches



Simulation by John Johnson

HIRES RV Errors

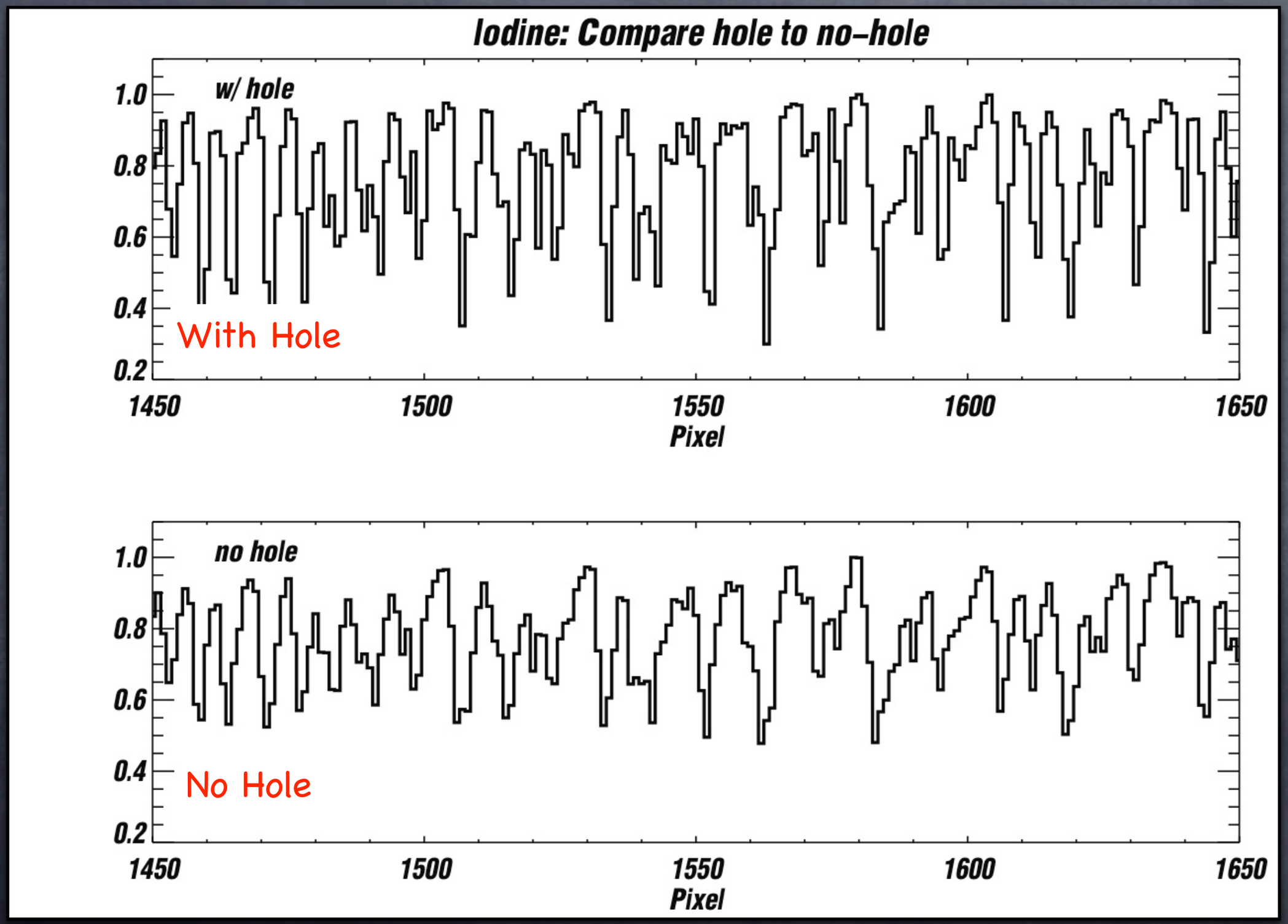
- Guiding
- Zonal aberrations / vignetting
- Fibers (The Solution!)
- Scattered light - HIRES
- Sky subtraction for faint targets

Hartmann Mask Tests

Standard Collimator Mask

Hartmann Mask

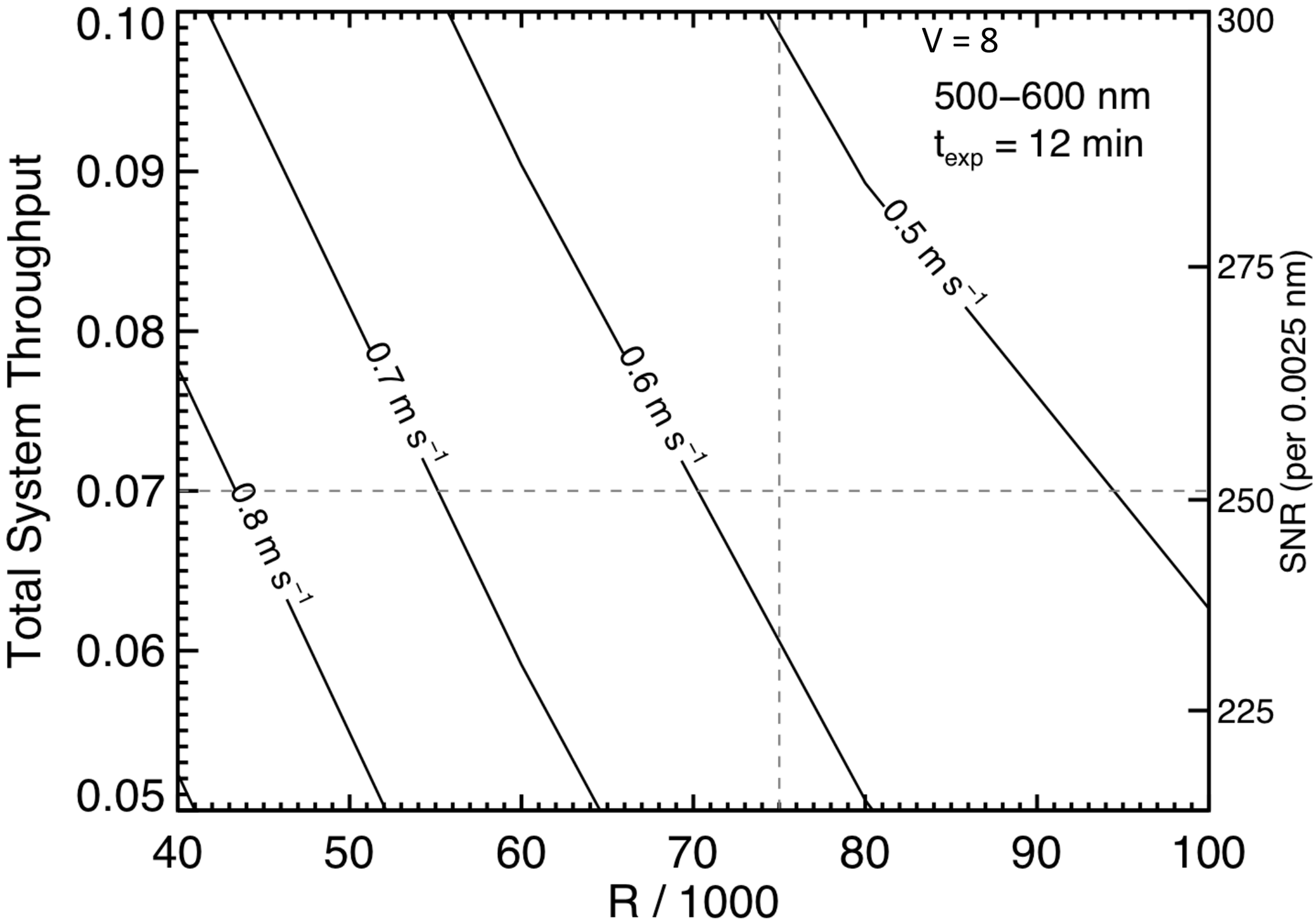
Iodine Spectra



R ~ 150,000

R = 60,000

RV precision vs. Spectral Resolution (λ/Δλ)



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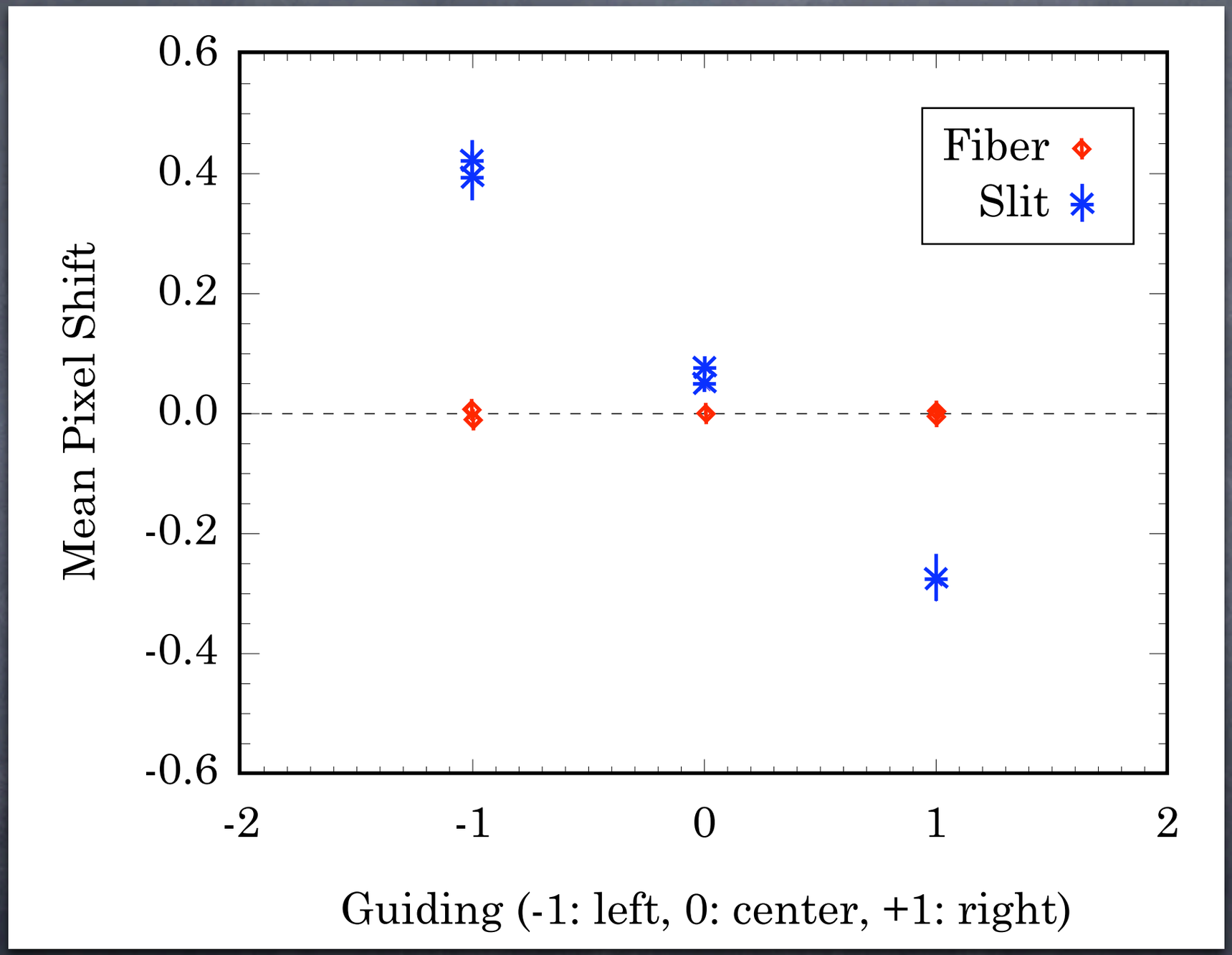
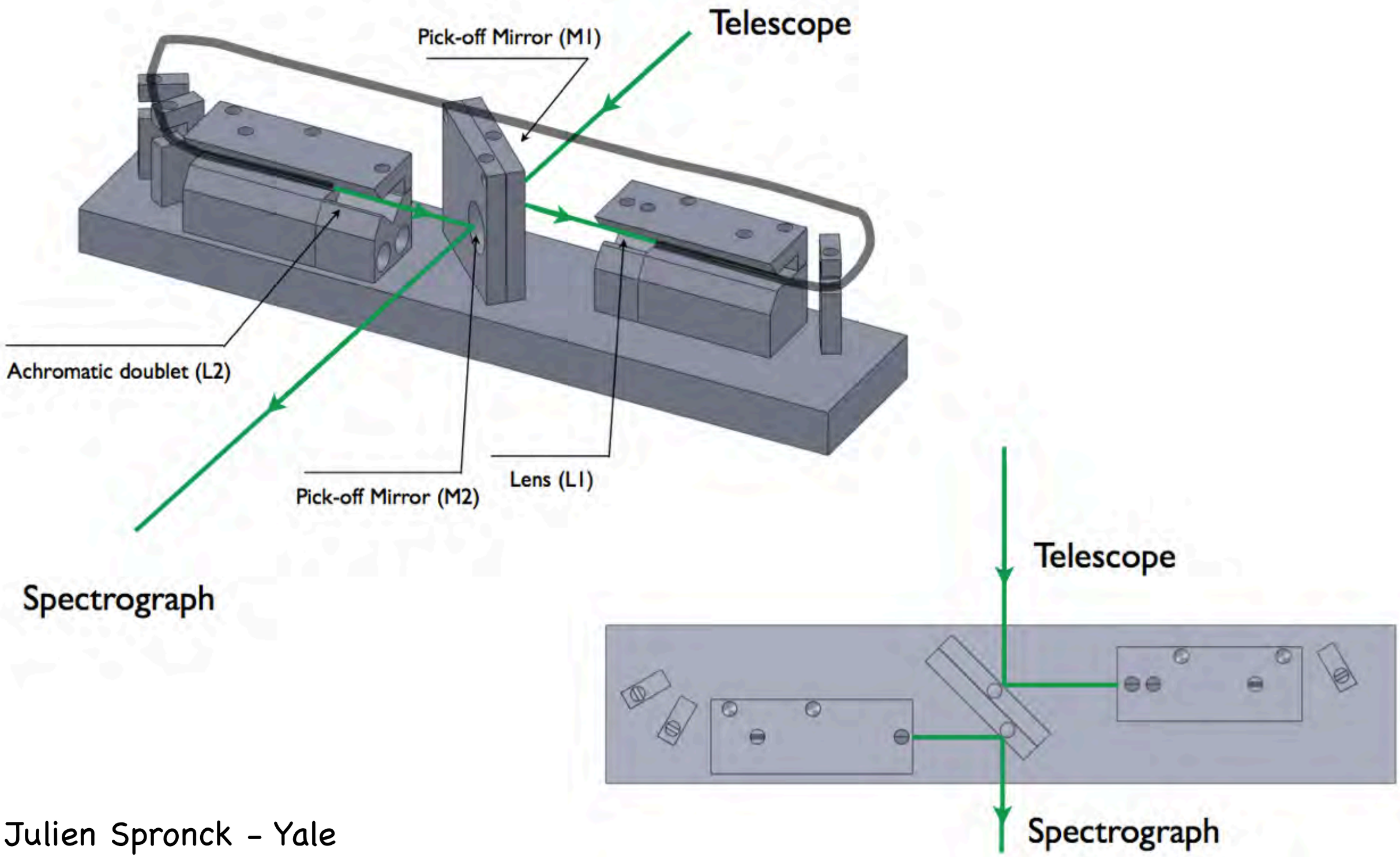
Fiber Input - Lick Mis-guiding Tests



PSF Stability: ~1.0 pixel → <0.01 pixels

Keck Fiber Scrambler



Julien Spronck - Yale

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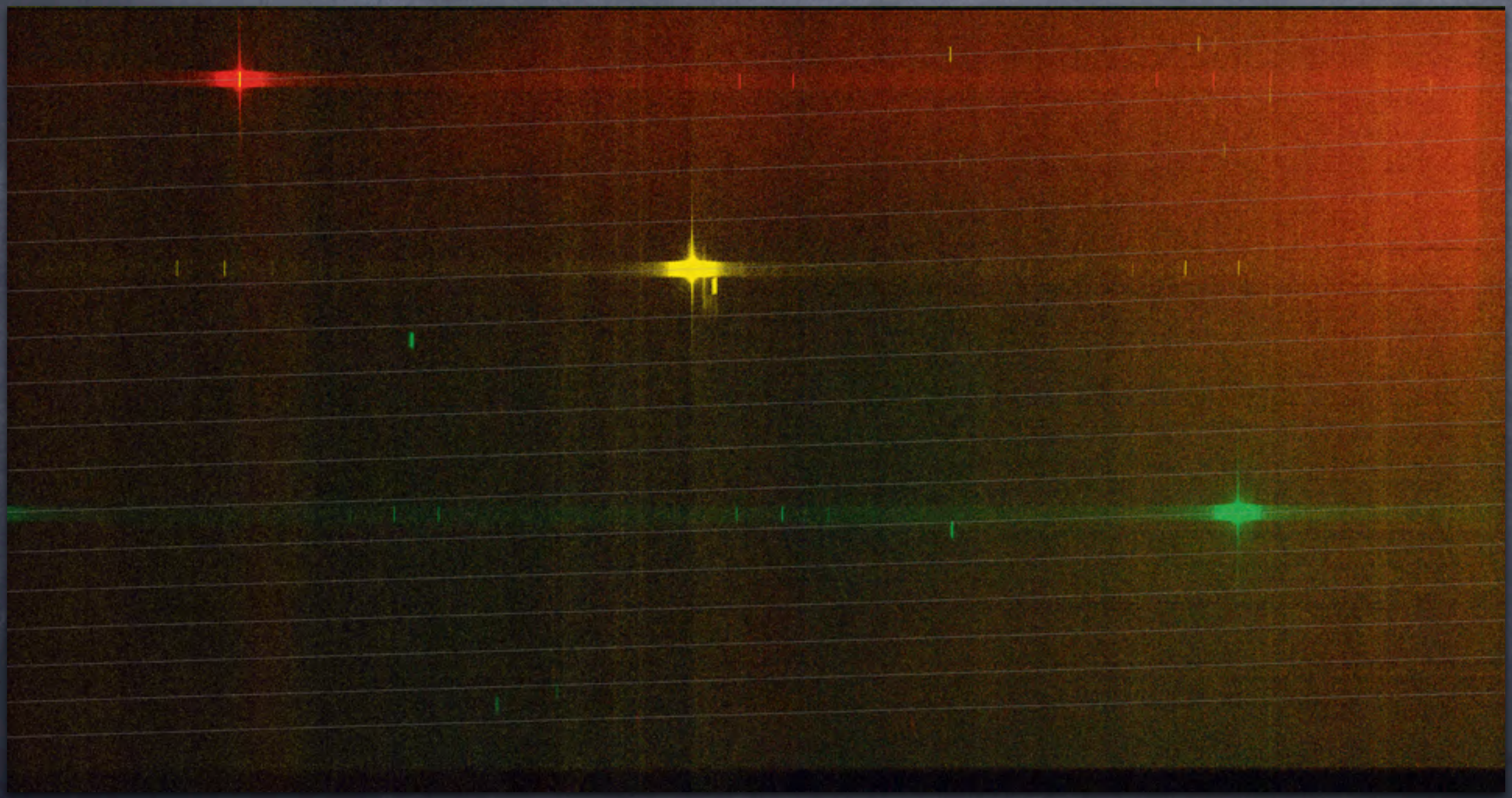
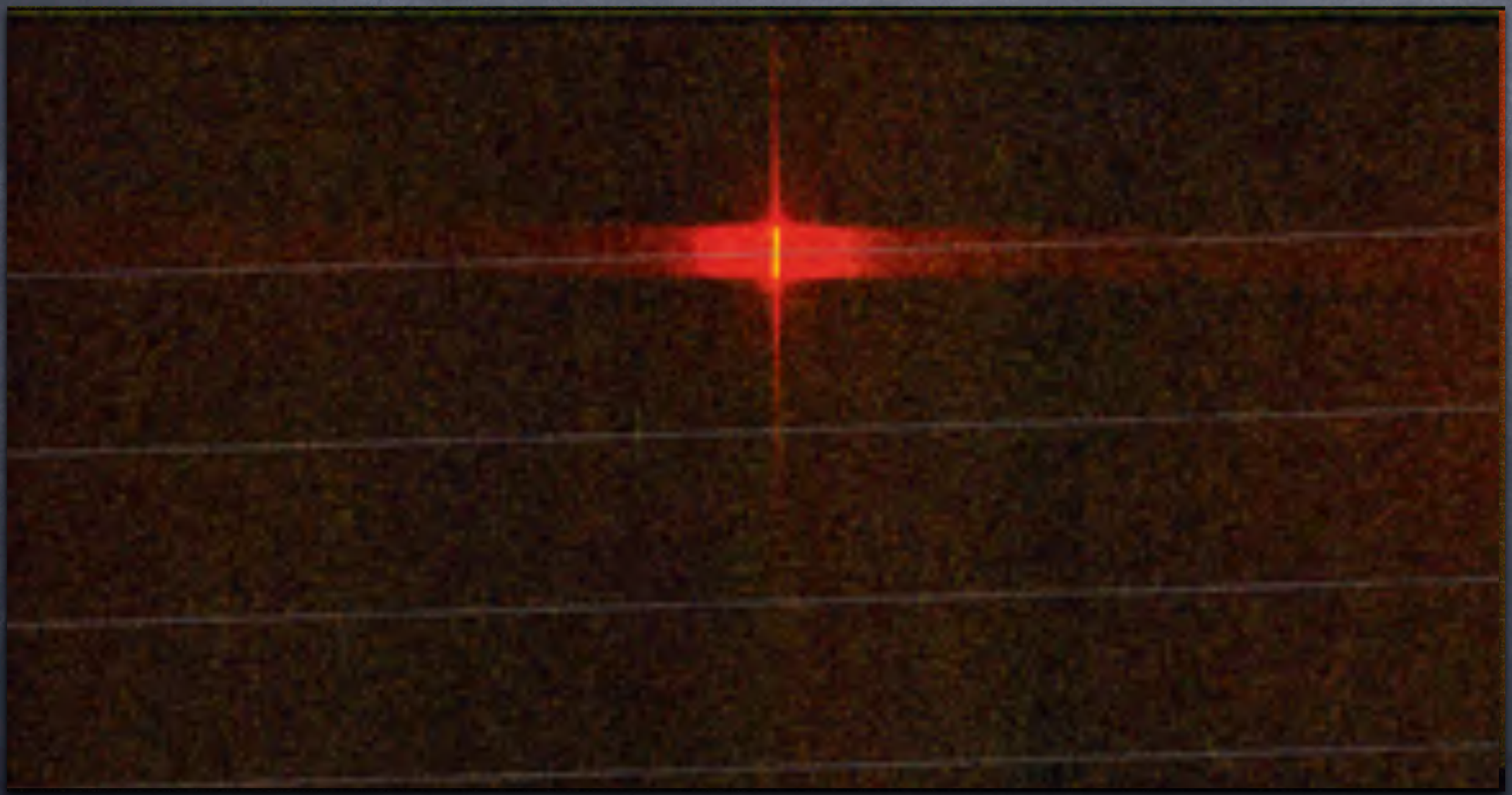
Scattered Light - Laser Tests



Laser Exposures by Grant Hill (Keck Observatory)

Stacked Image by Jeff Valenti (STScI)

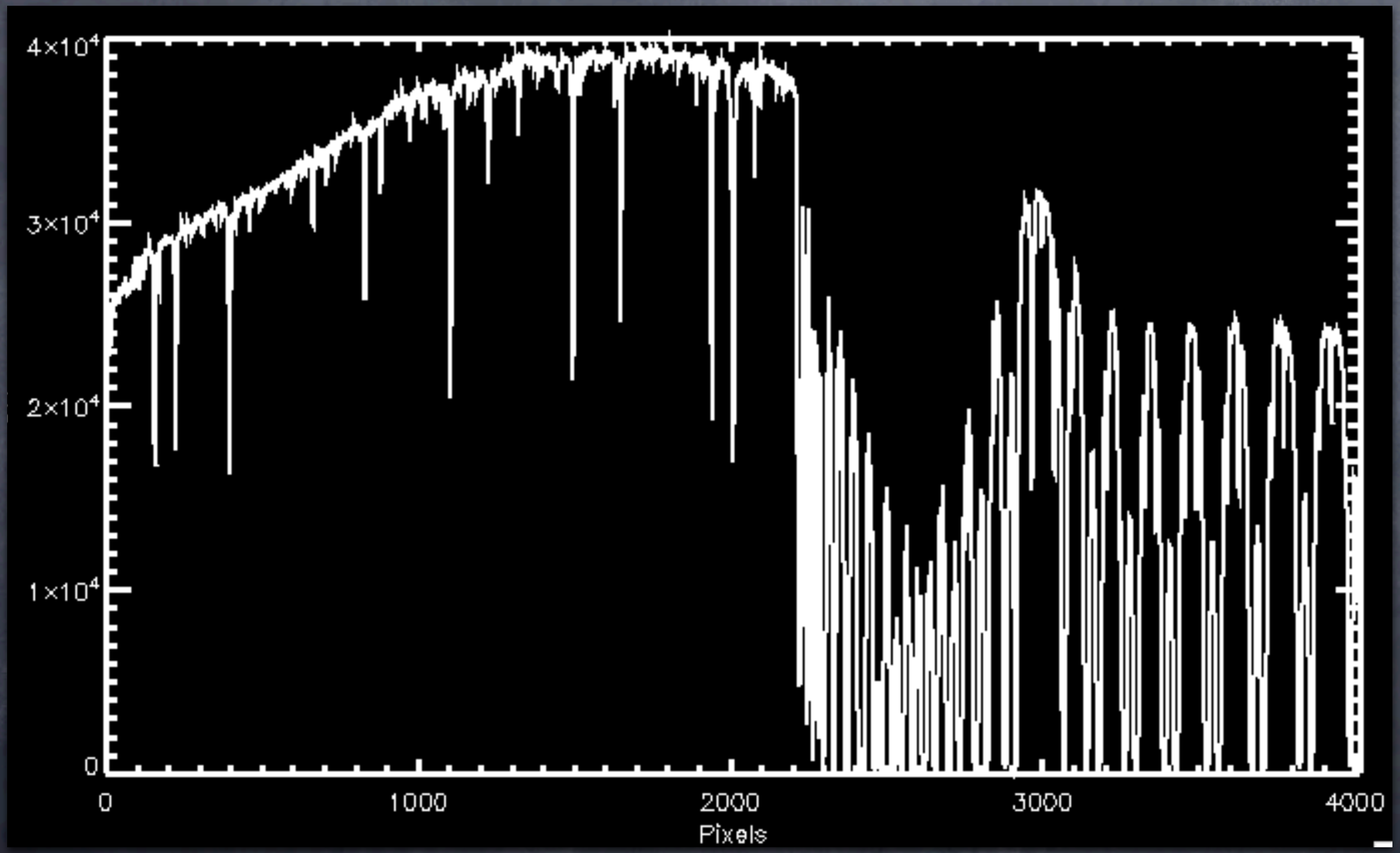
Scattered Light - Laser Tests



Laser Exposures by Grant Hill (Keck Observatory)

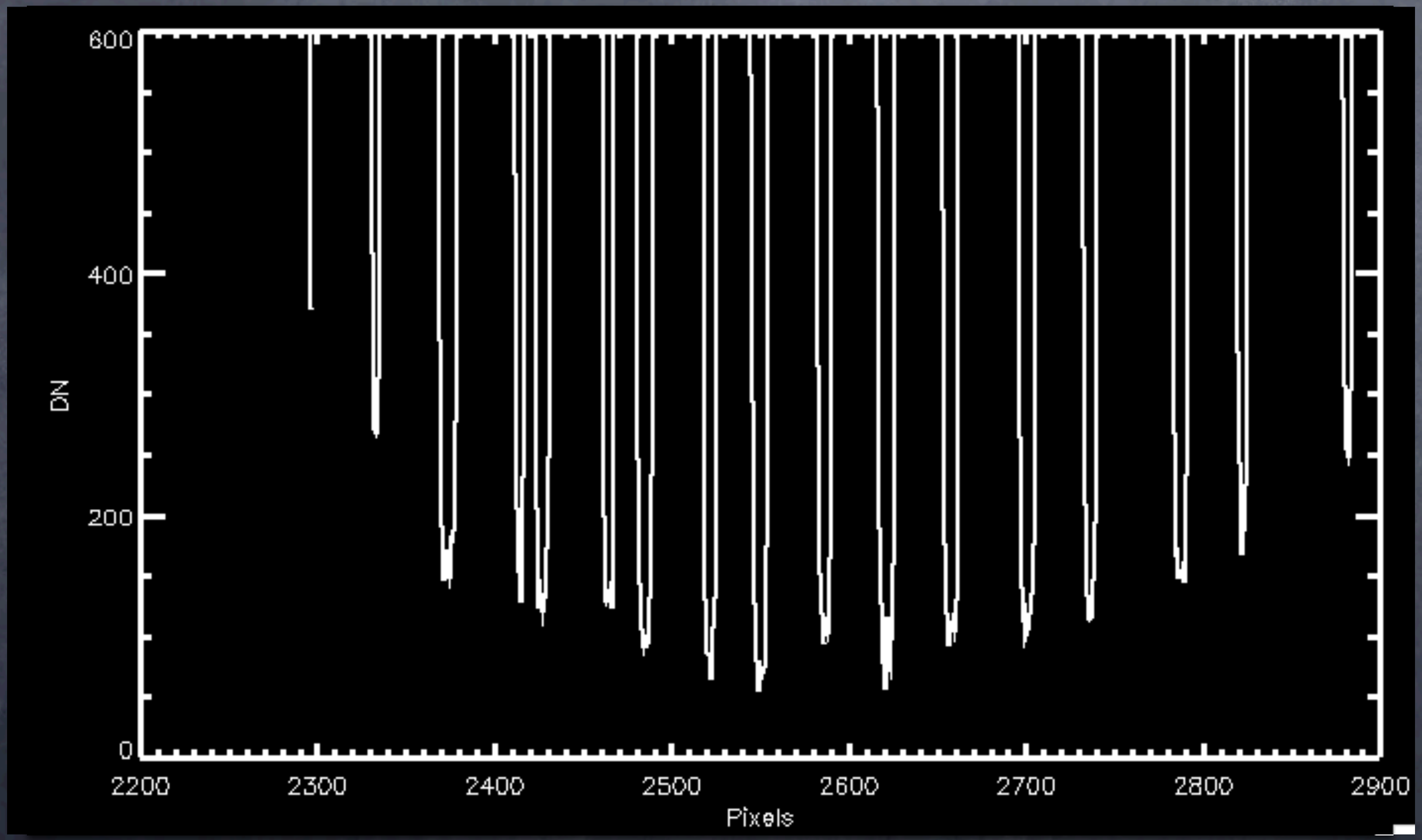
Stacked Image by Jeff Valenti (STScI)

A-band (O_2) at 760 nm



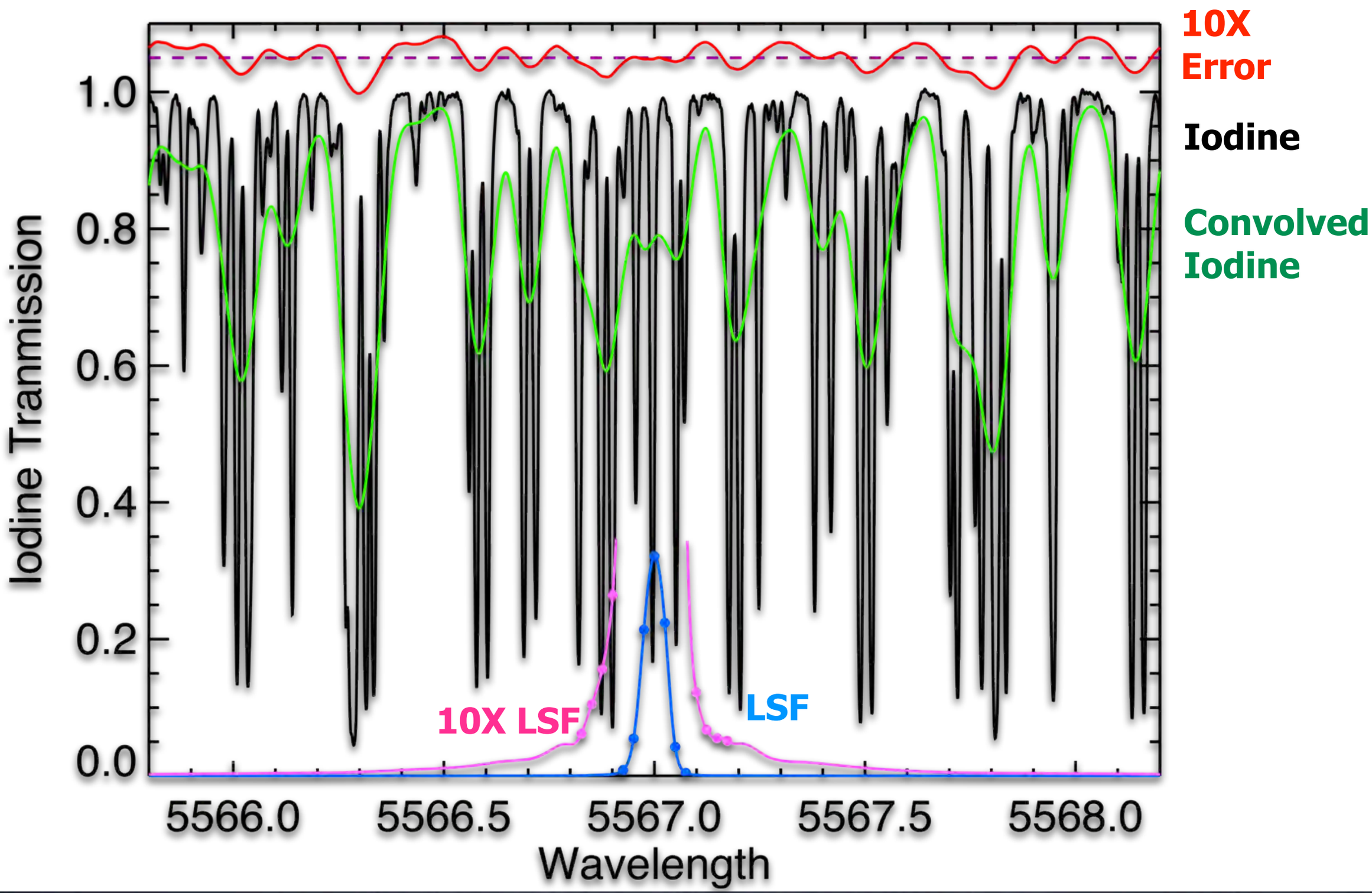
Scattered Light < 70/4e4 = 0.002
Intrinsically Black? Probably No.

A-band (O_2) at 760 nm



Scattered Light < 70/4e4 = 0.002
Intrinsically Black? Probably No.

Entire Laser Profile on Log Scale



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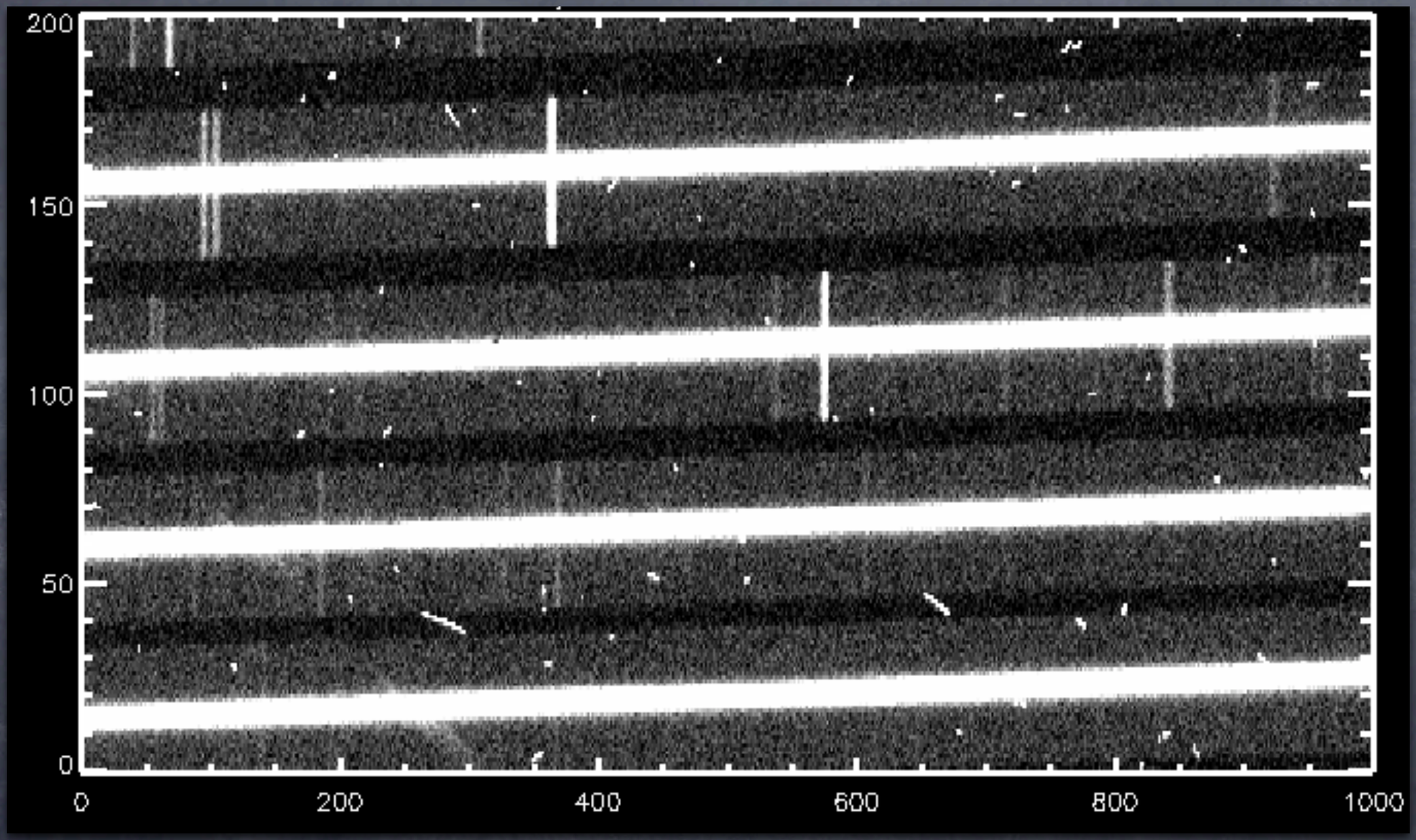
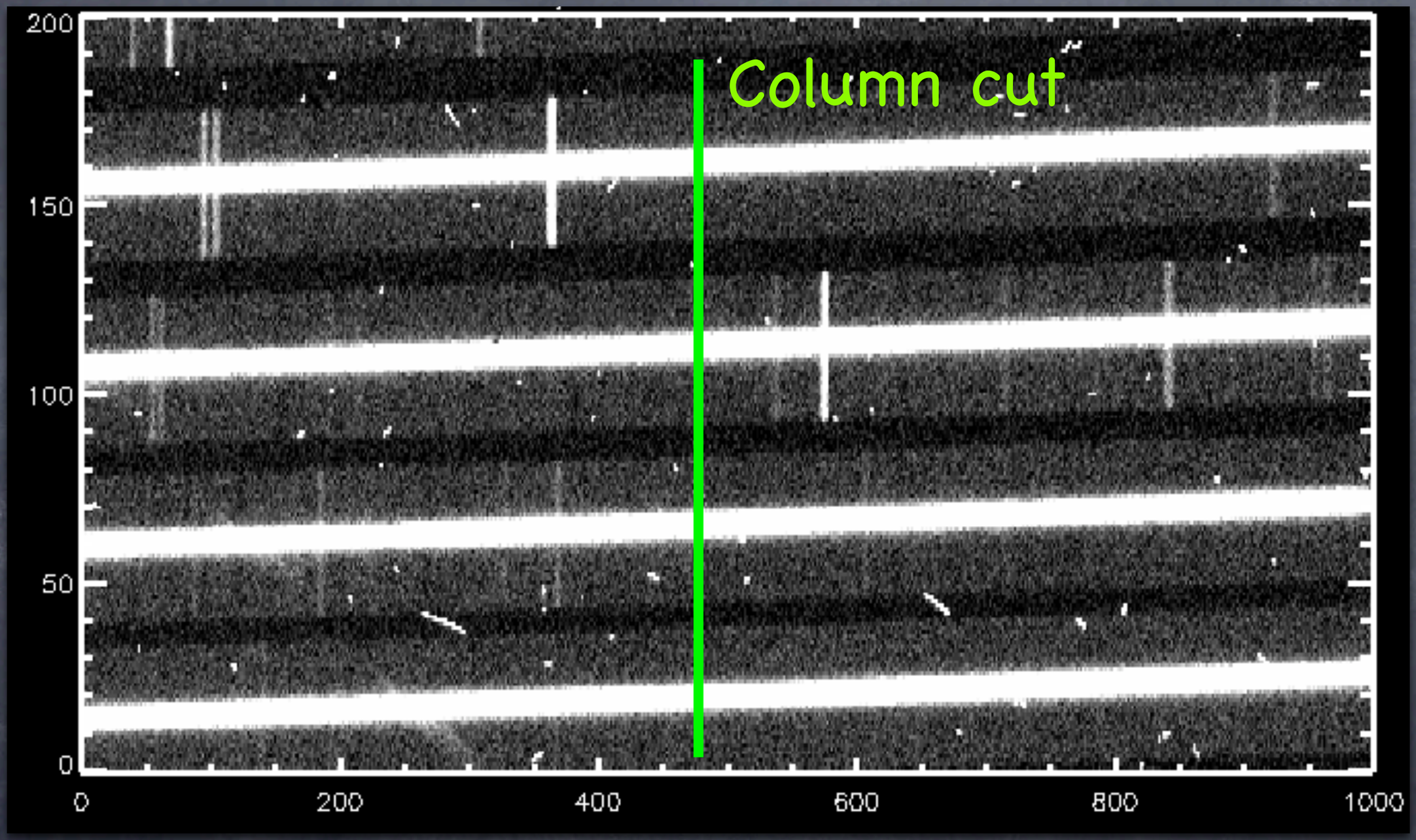
Sky Contamination - Faint Stars



Kepler-8, V=13.9 mag (45 min, full moon)
4 Echelle orders: Moonlight, Sky lines, Cosmic rays

Sky Contamination - Faint Stars



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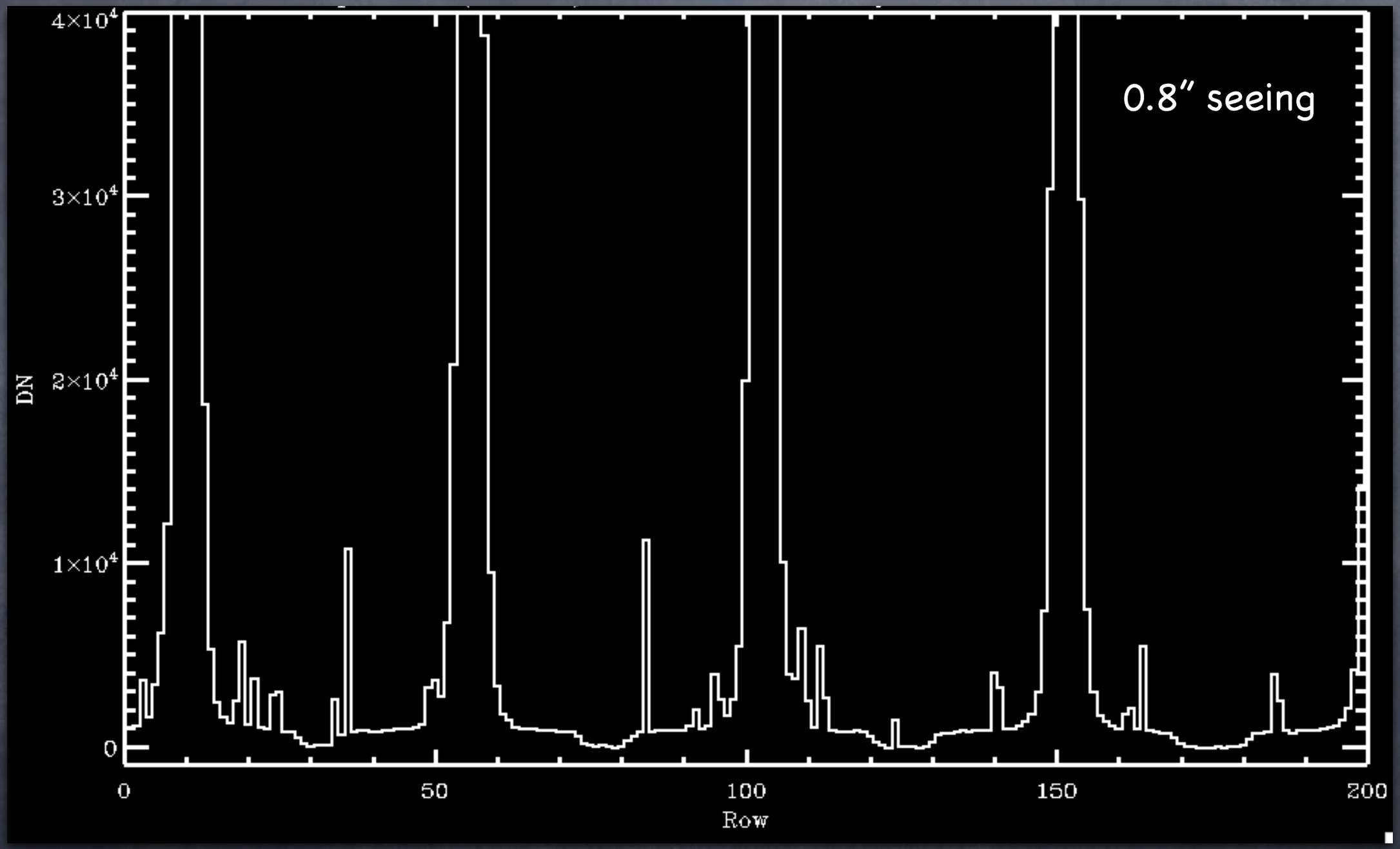
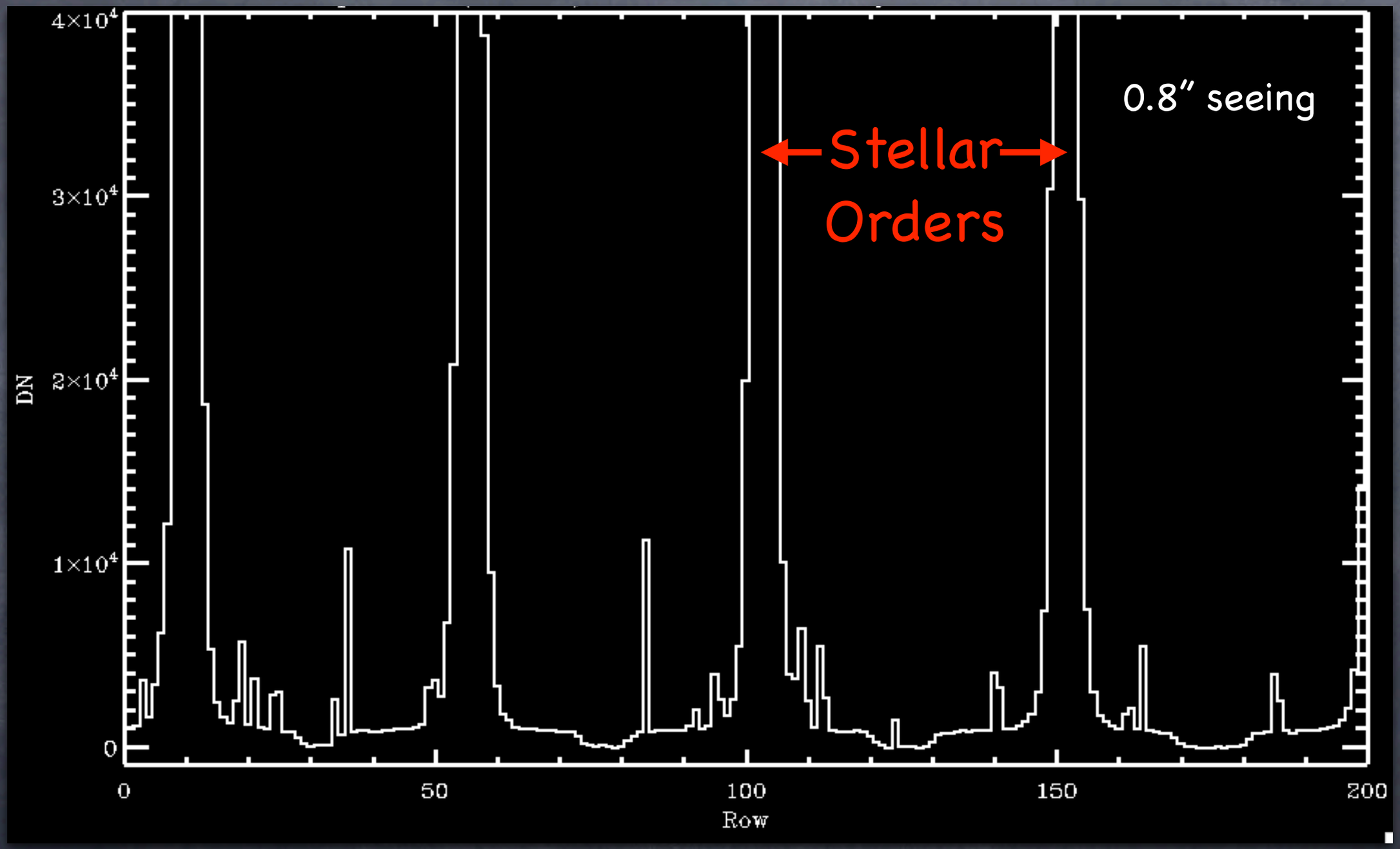


Full Moon, Clear skies: Sky is ~3% of 14th mag star (3 arcsec long slit)

Sky Contamination - Faint Stars



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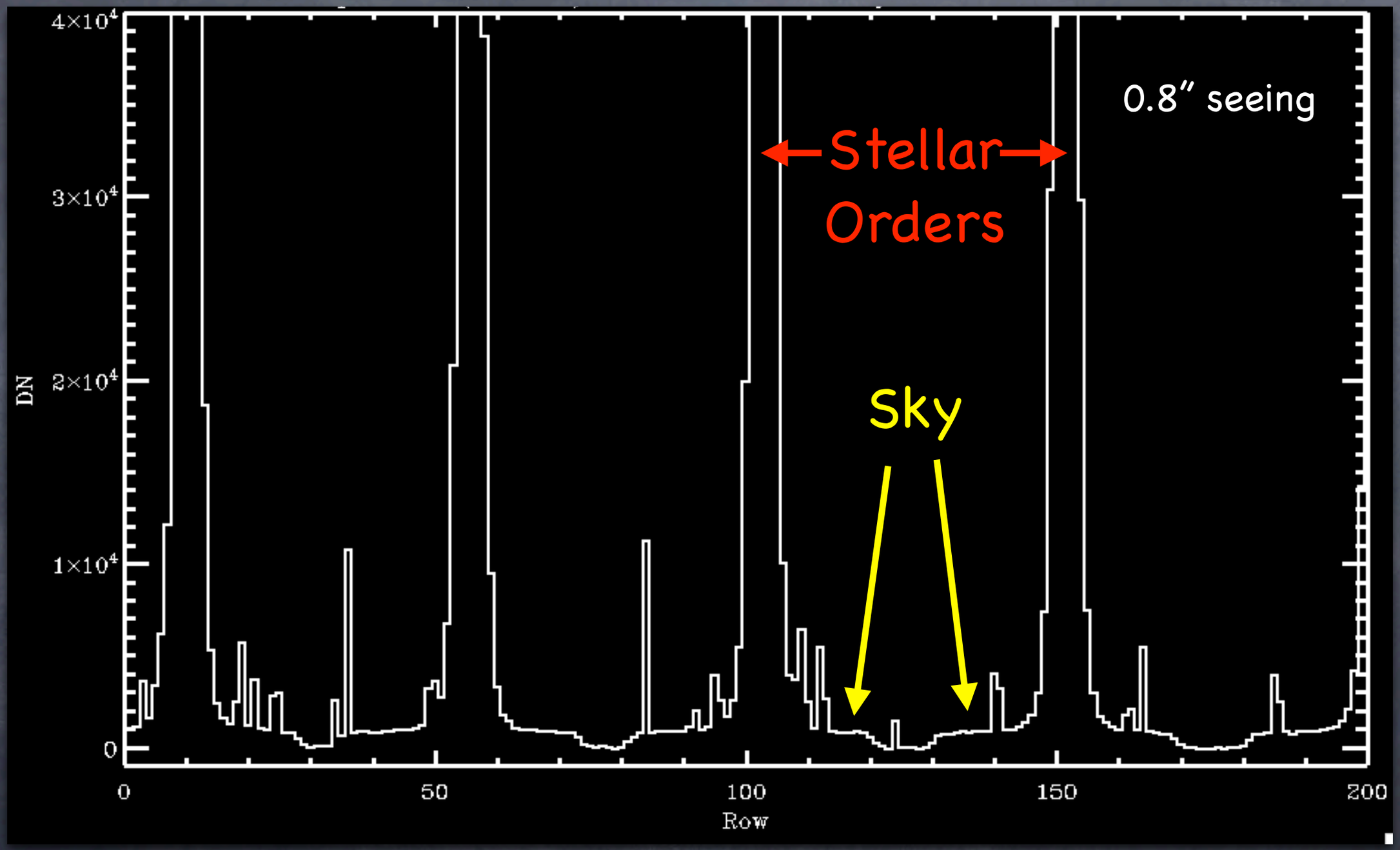

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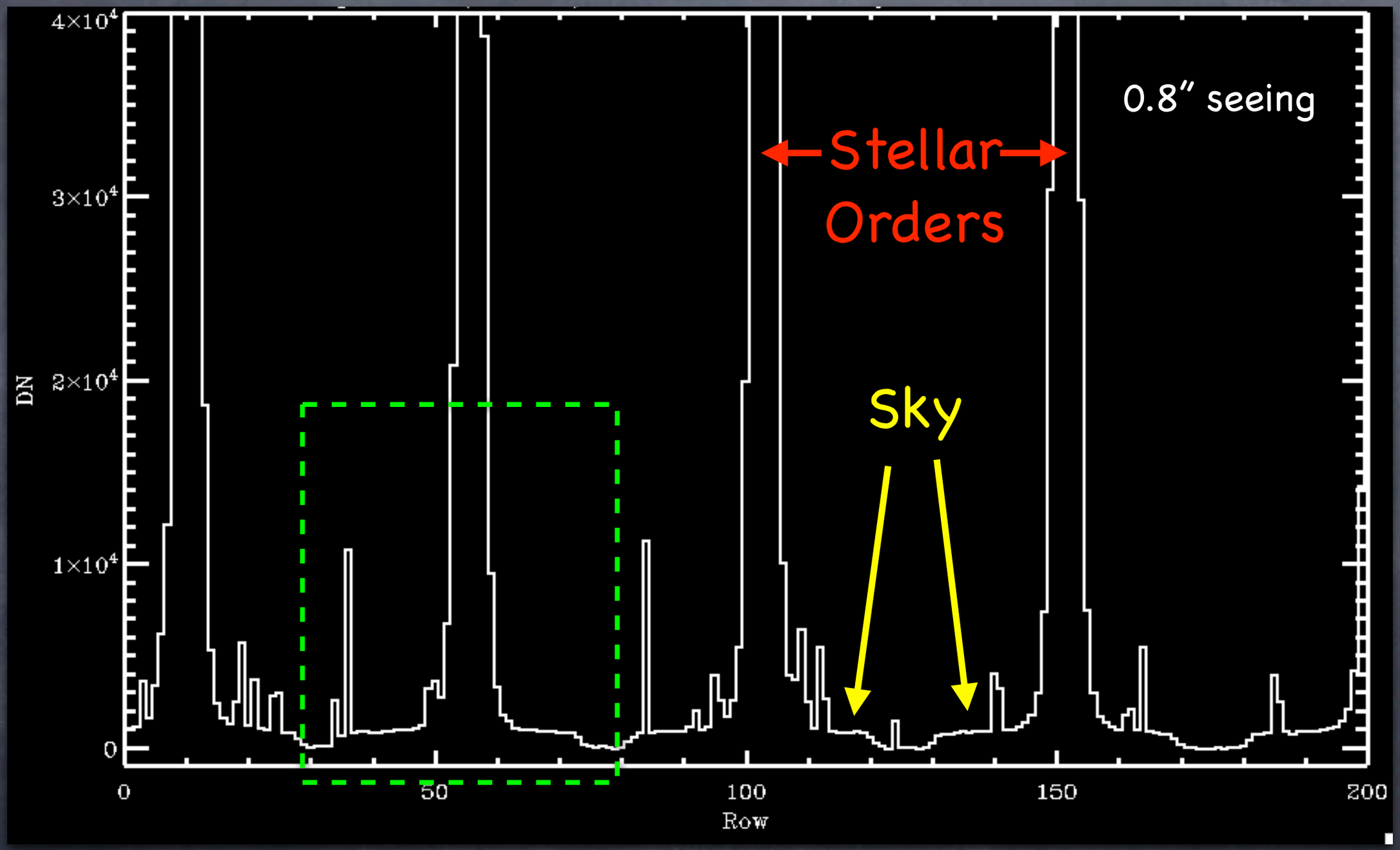

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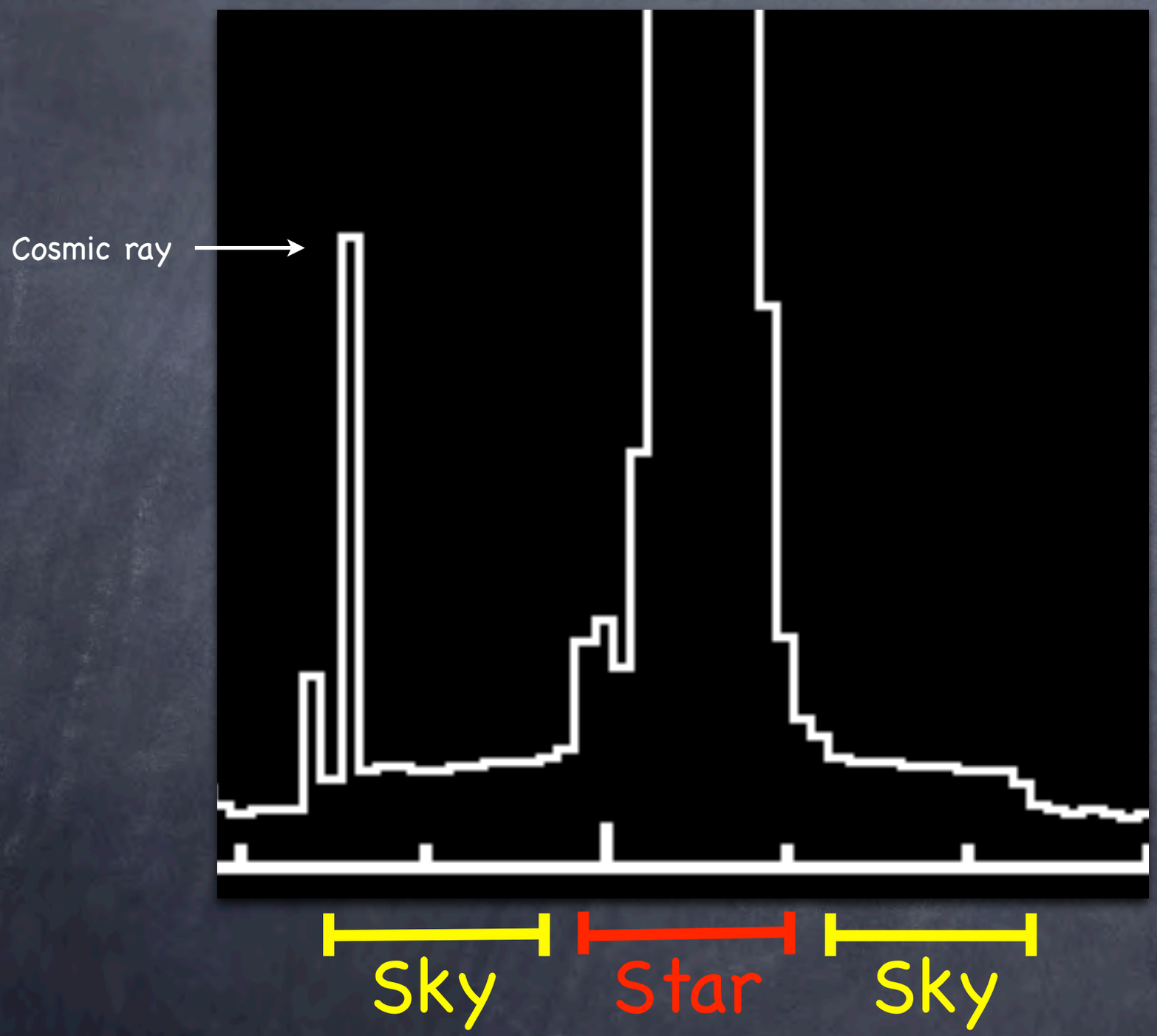
Sky subtraction



Subtract median sky value from each pixel in extraction region

Essential for V ≥ 10 for 1 m/s

Assessment and Recommendations

- Current state of the art: K = 1-2 m/s, quiet stars
- Photon statistics: K << 1 m/s only possible for a handful of bright stars
- Astrophysical Jitter: Need for demonstration at ~0.3-0.5 m/s before trusting simulations at 0.1 m/s
- Instrumental Jitter: new spectrometers needed - stability, fibers, high spectral resolution, high cadence

Assessment and Recommendations

- Kepler follow-up:
  - 10-m telescope (Keck) is key for faint stars (V ~ 13)
  - sky subtraction
  - New spectrometer needed: 3X throughput, 2X precision, fiber input
- TESS/ASTRO follow-up:
  - 3-5 meter telescopes adequate for V ≤ ~11 *if* new spectrometers built
- Hunt for low-mass planets:
  - Cadence and measurement precision drive mass limits
  - Dedicated facility with new spectrometer on 3-5 meter telescope
  - Keck: new spectrometer needed + better cadence (or scheduling)

Questions?