An Error Budget for Precise Radial Velocities from Keck-HIRES

Andrew W. Howard
Townes Fellow, UC Berkeley

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

ASTRO 2010


New Worlds,
New Horizons
in Astronomy and Astrophysics
Report Release e-Townhall
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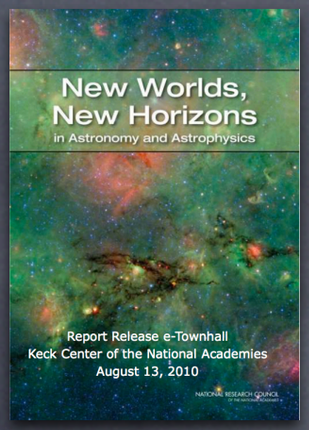
NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES



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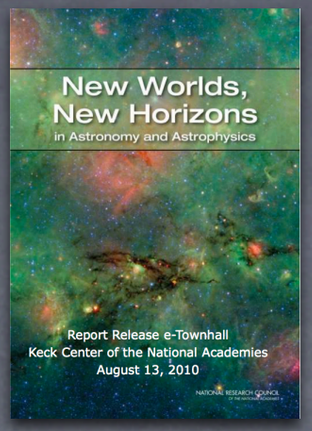
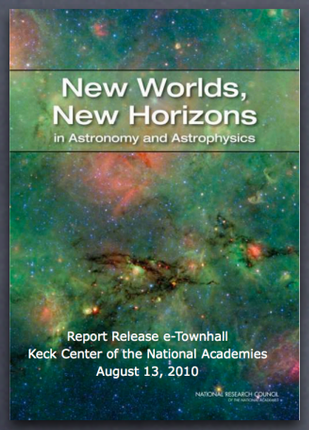


Three primary science objectives for the next decade:

1. Search for the first stars, galaxies, and black holes

2. Seek nearby habitable planets.

3. Advance our understandings of the fundamental physics of the universe.



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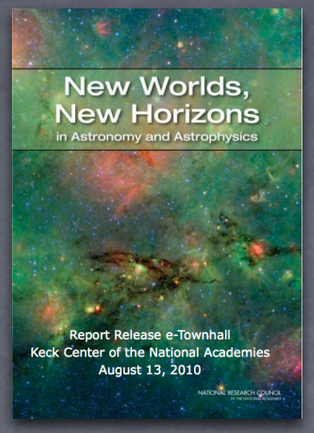
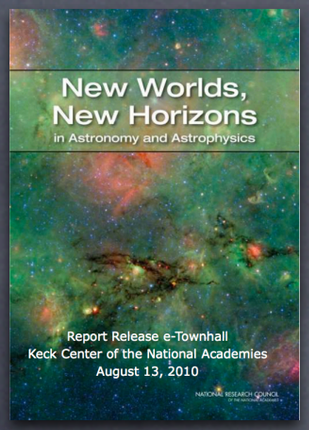


"This survey is recommending a program to explore the diversity and properties of planetary systems around other stars, and to prepare for the long-term goal of discovering and investigating nearby, habitable planets." - page 7-7

"Using existing large ground-based or new dedicated mid-size ground-based telescopes equipped with a new generation of high-resolution spectrometers in the optical and near-infrared, a velocity goal of 10 to 20 centimeters per second is realistic." - page 7-8



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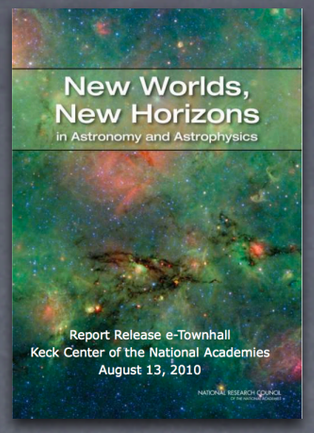

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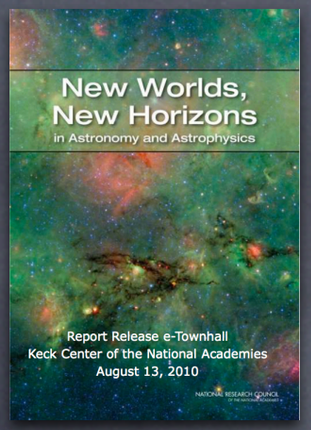

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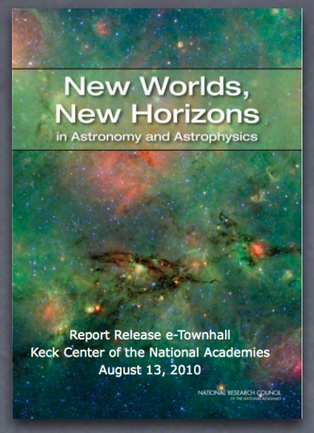

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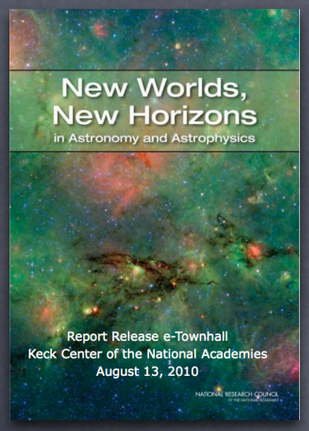

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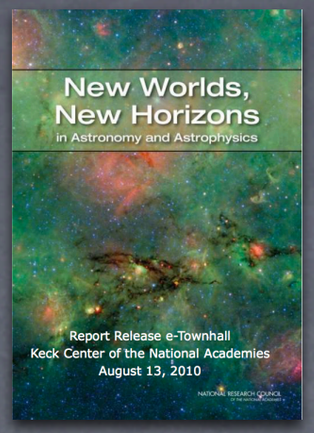
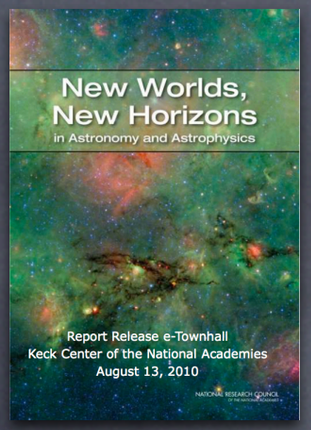


To prepare for direct imaging, "NASA and NSF should support an aggressive program of ground-based high-precision radial velocity surveys of nearby stars to identify potential candidates" - page 1-8



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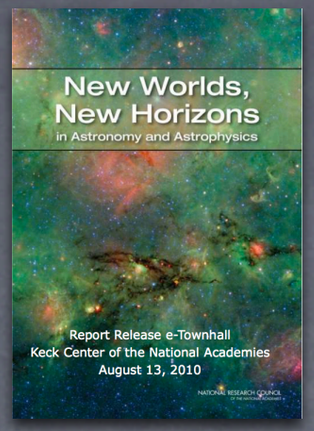
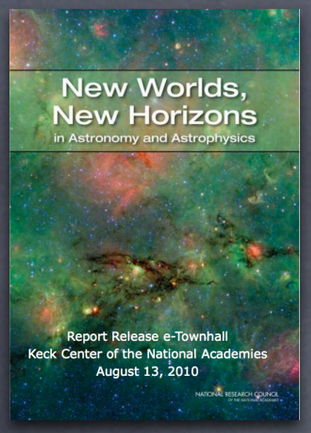


Top Ground-based Recommendations (Large Projects):

1. LSST
2. Mid-scale Innovations Projects - including "Develop RV surveys and spectrometers to determine the properties of extrasolar planets"
3. Giant Segmented Mirror Telescope (TMT or GMT)
4. ACTA (Cerenkov Telescope)



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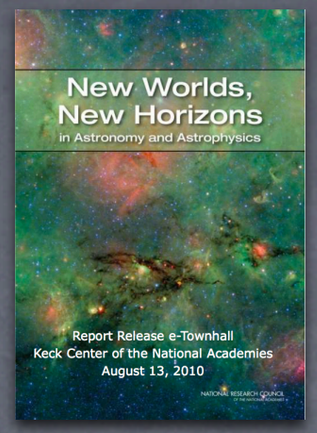
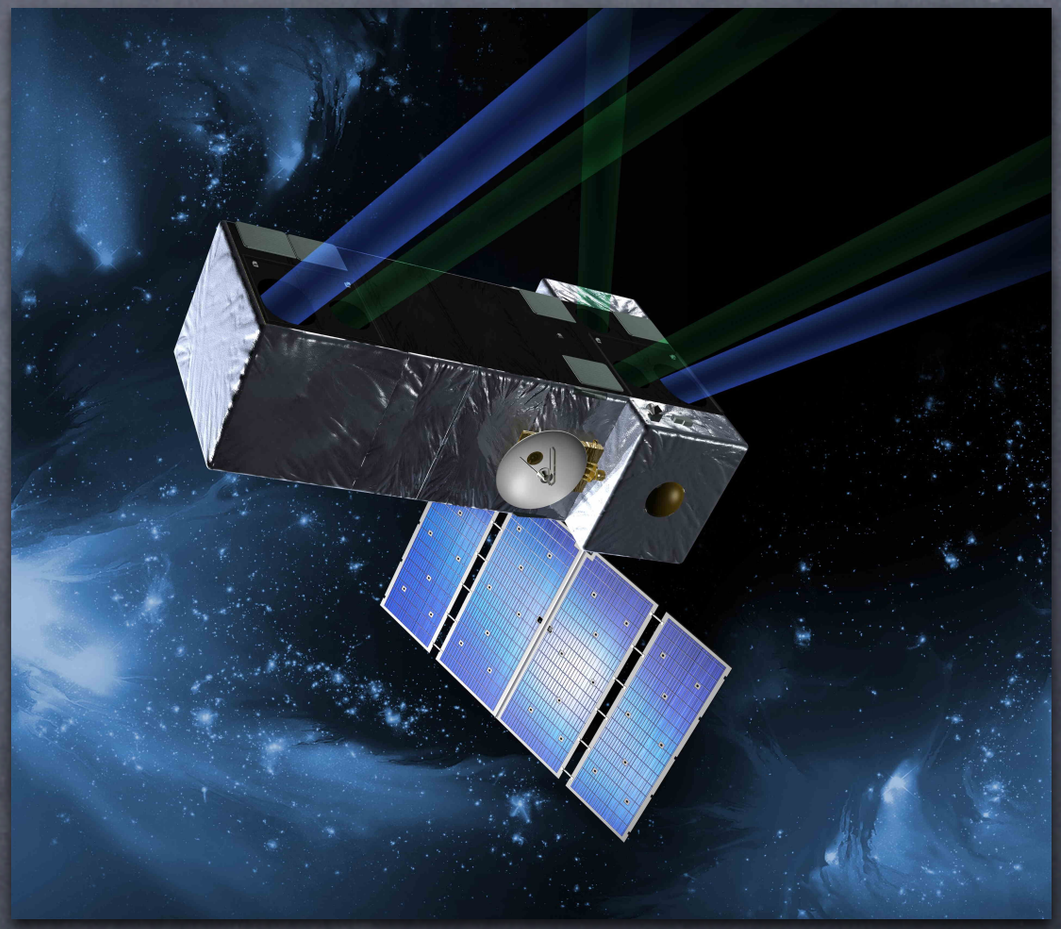


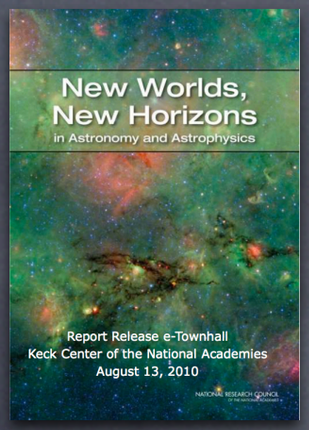
SIM-Lite could characterize 50 nearby planetary systems down to an Earth-mass

Rejected for 3 reasons:

1. Large cost ($1.9B)
2. Time to launch (8.5 yr)
3. Target-finding for direct missions can be done partially by RV with "challenging but achievable precision below 10 cm/s"



SIM-Lite



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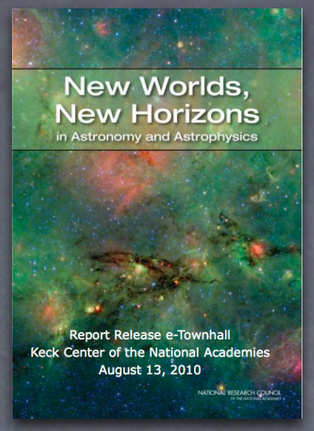


PRV Workshop

Describe instrumental difficulties

↓

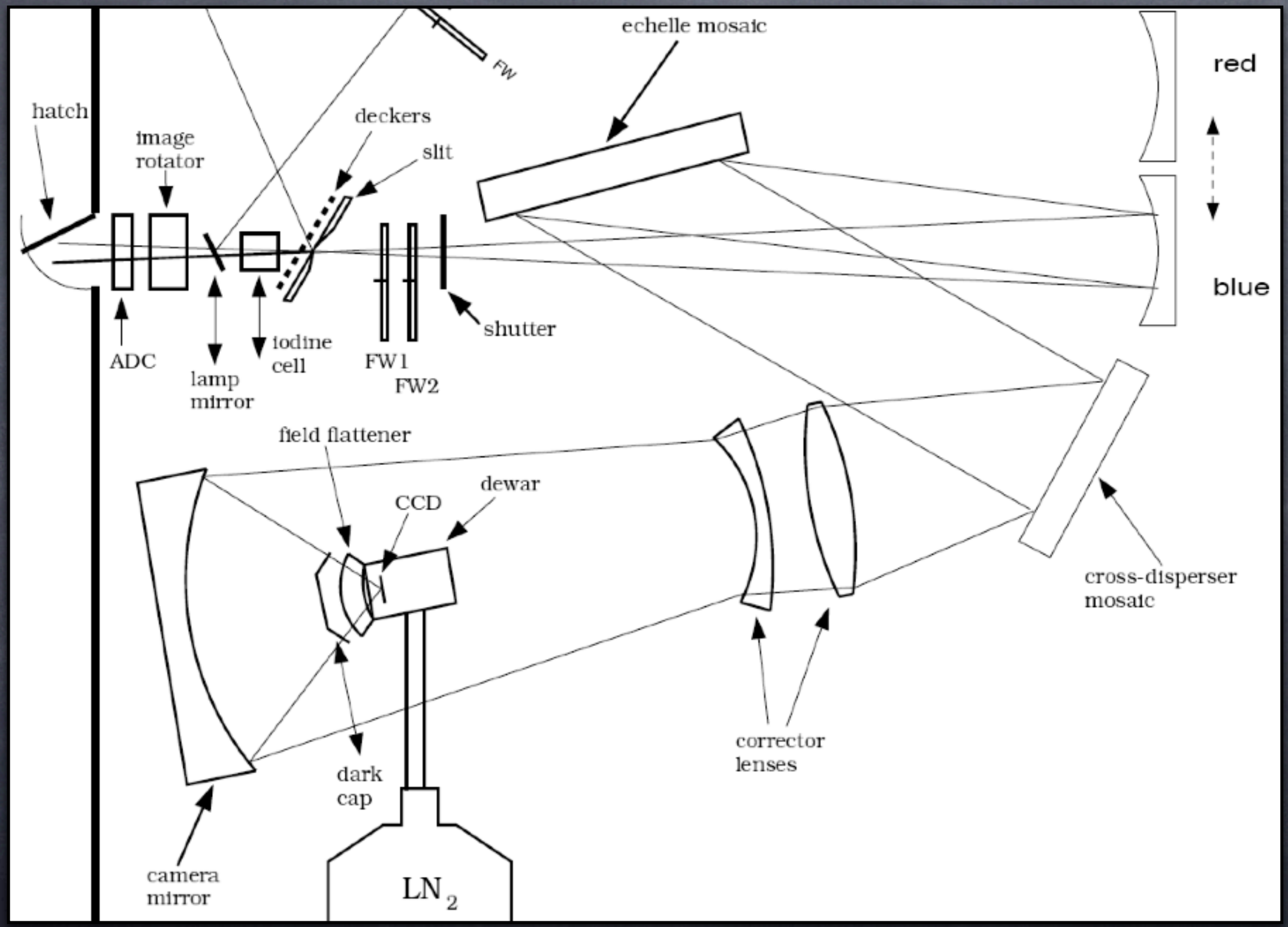
Value

Keck/HIRES

Keck 1 Telescope

Iodine Cell

HIRES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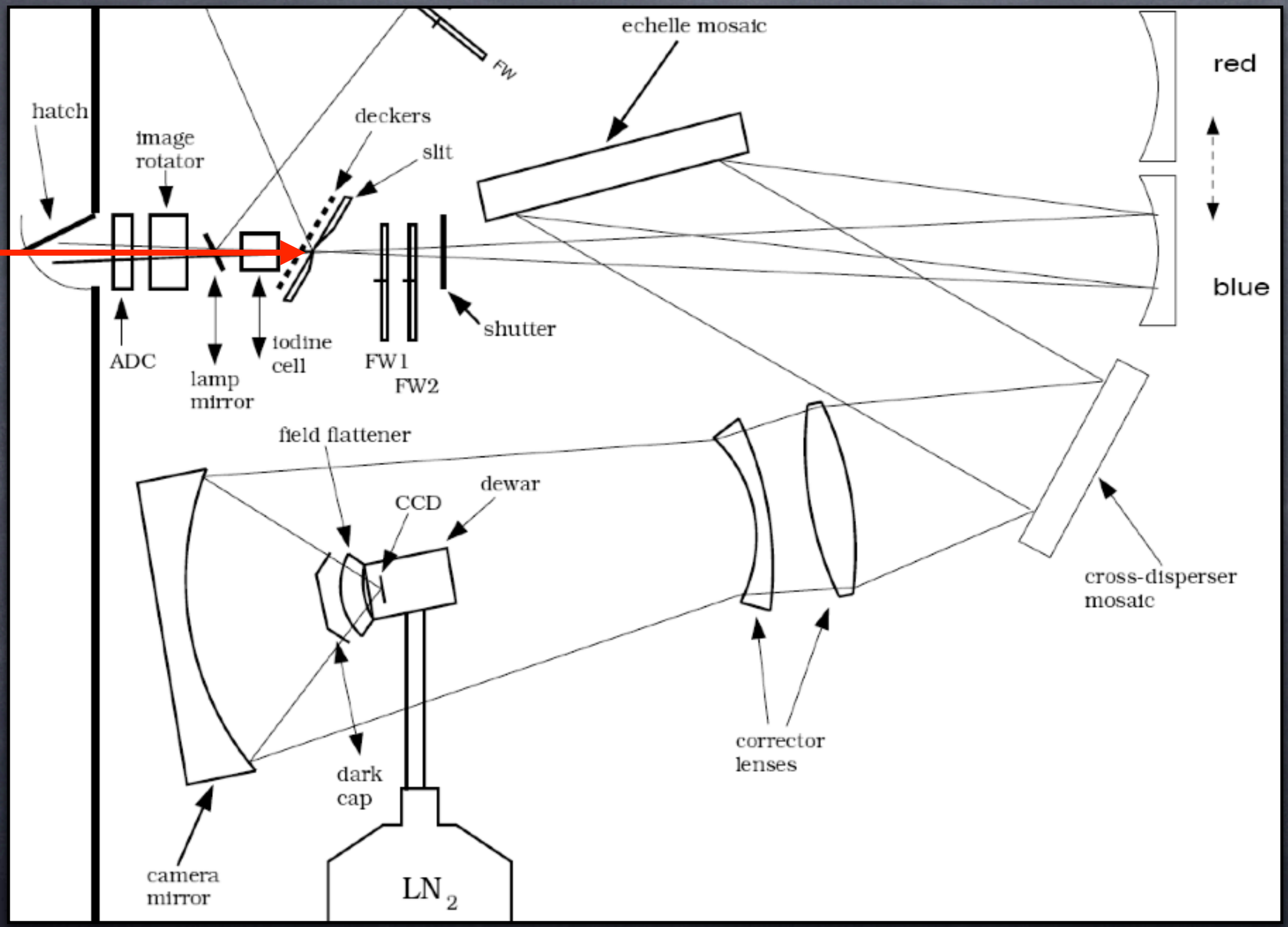
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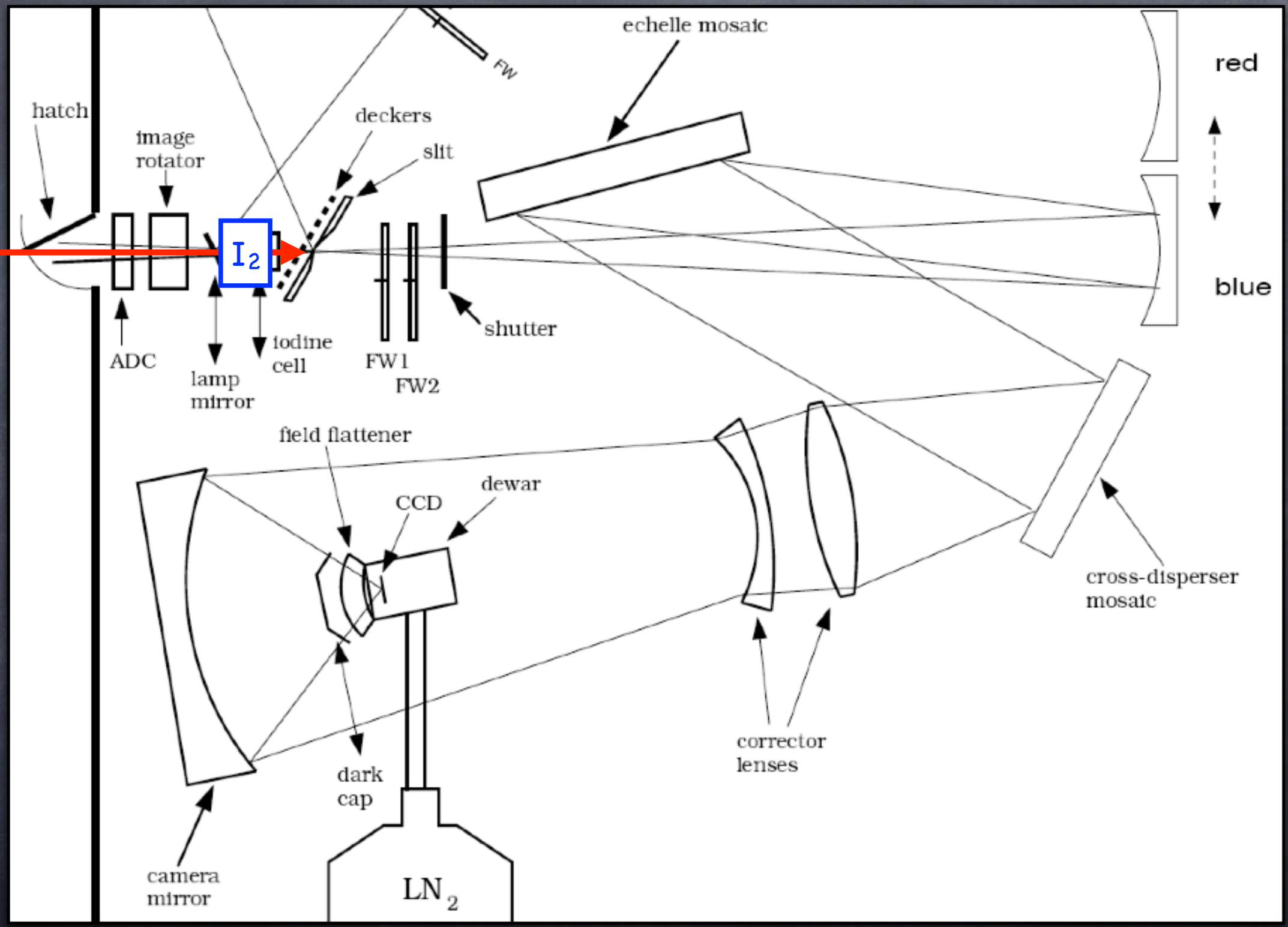
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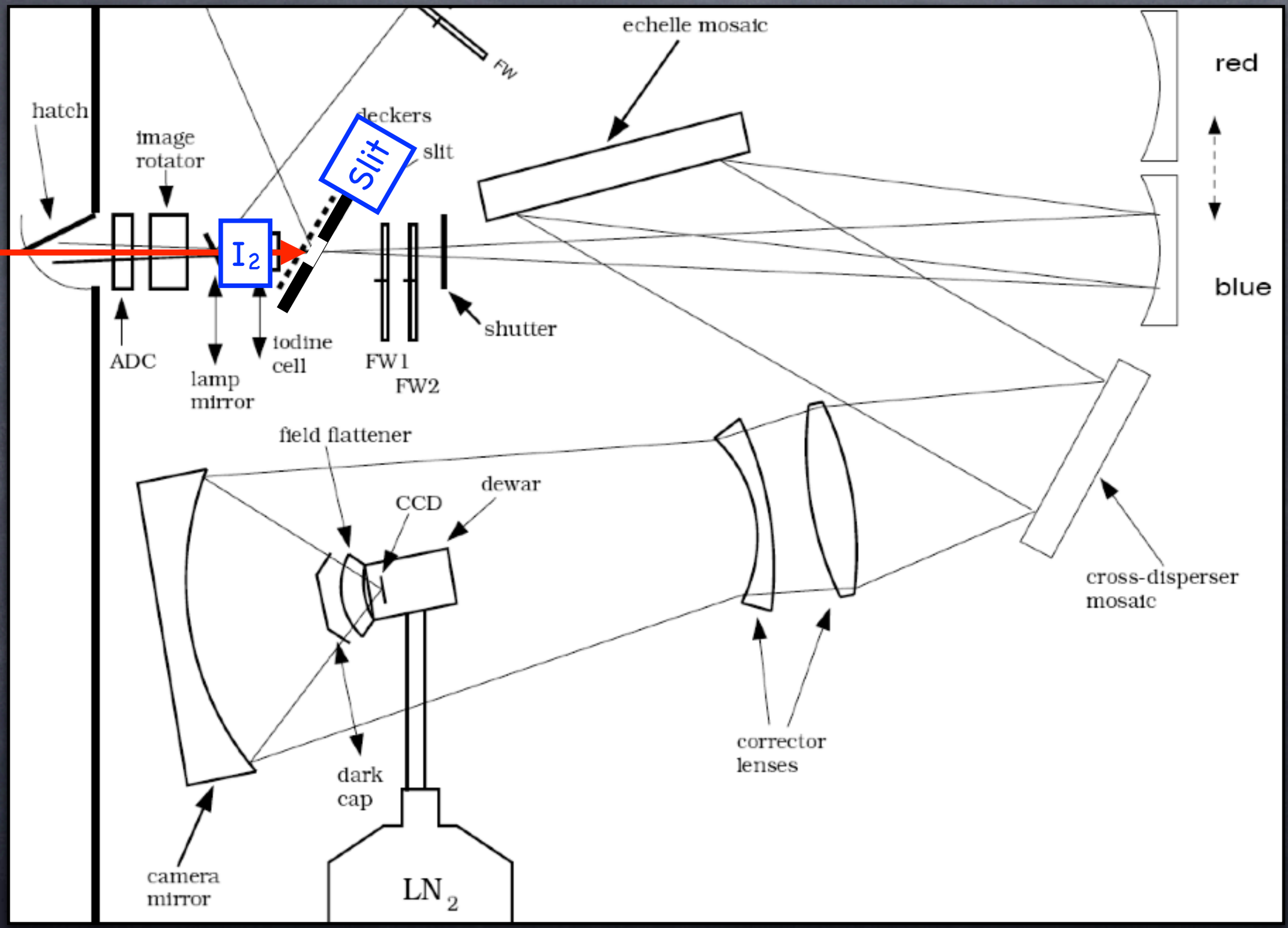
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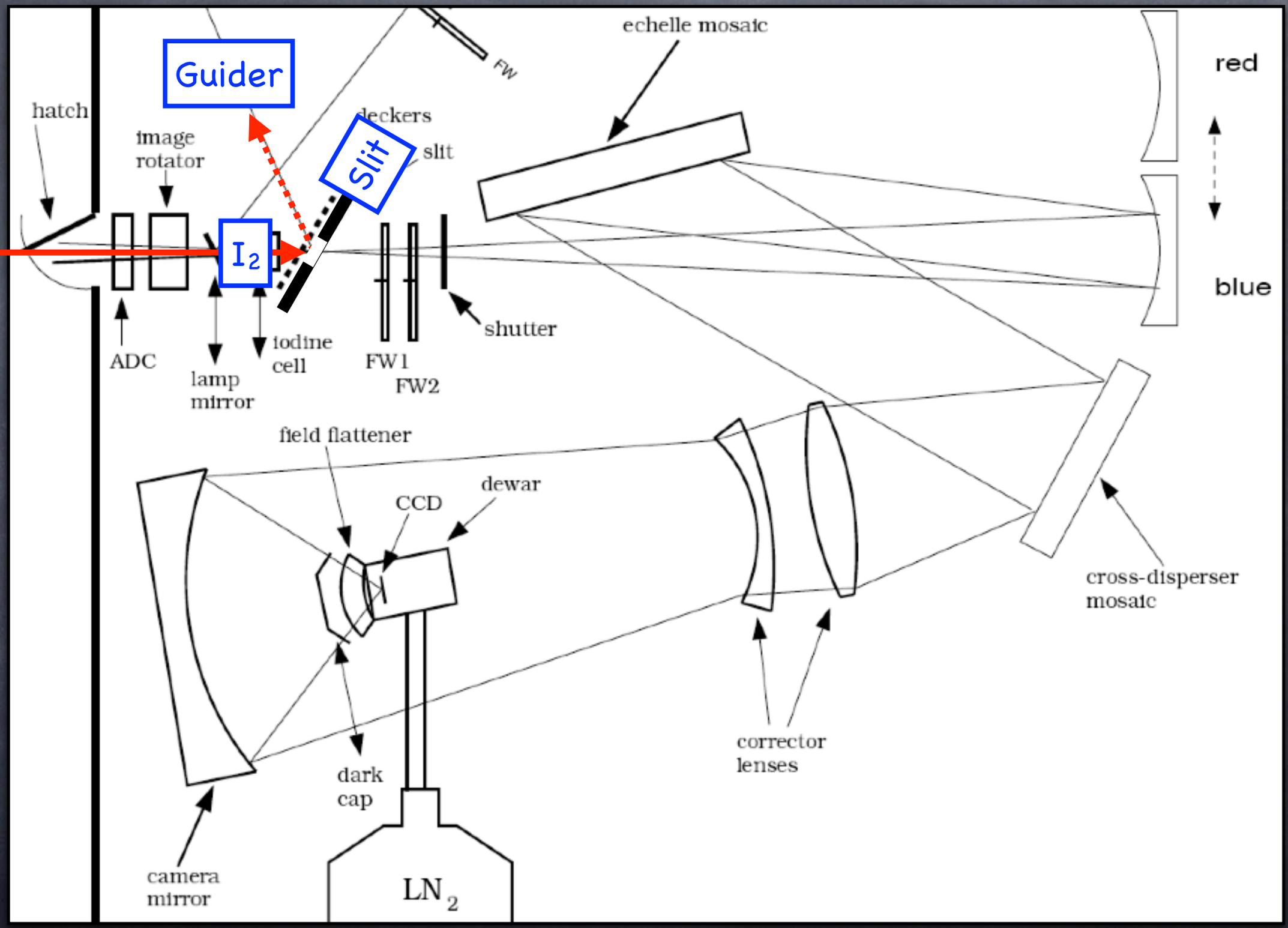
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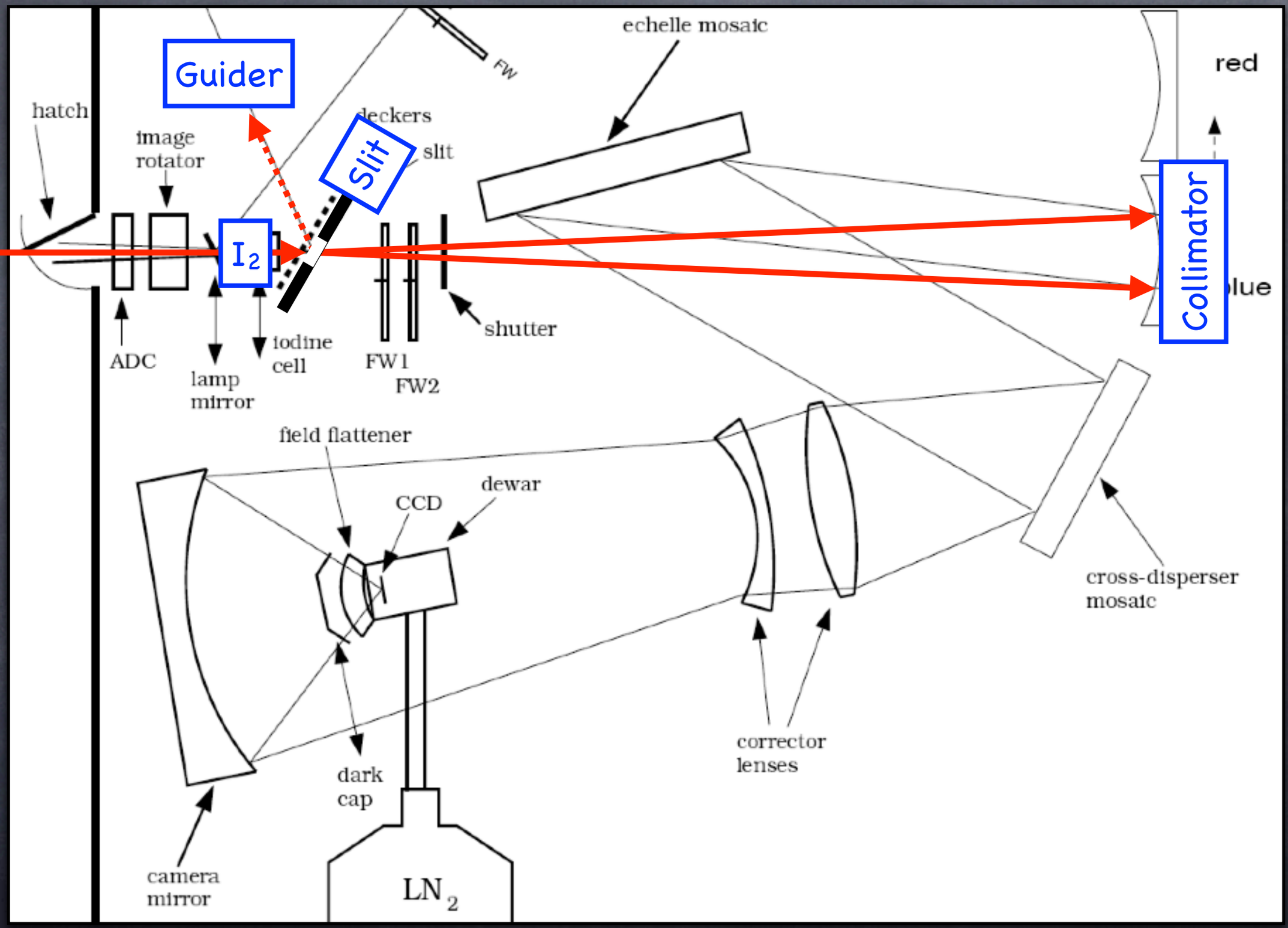
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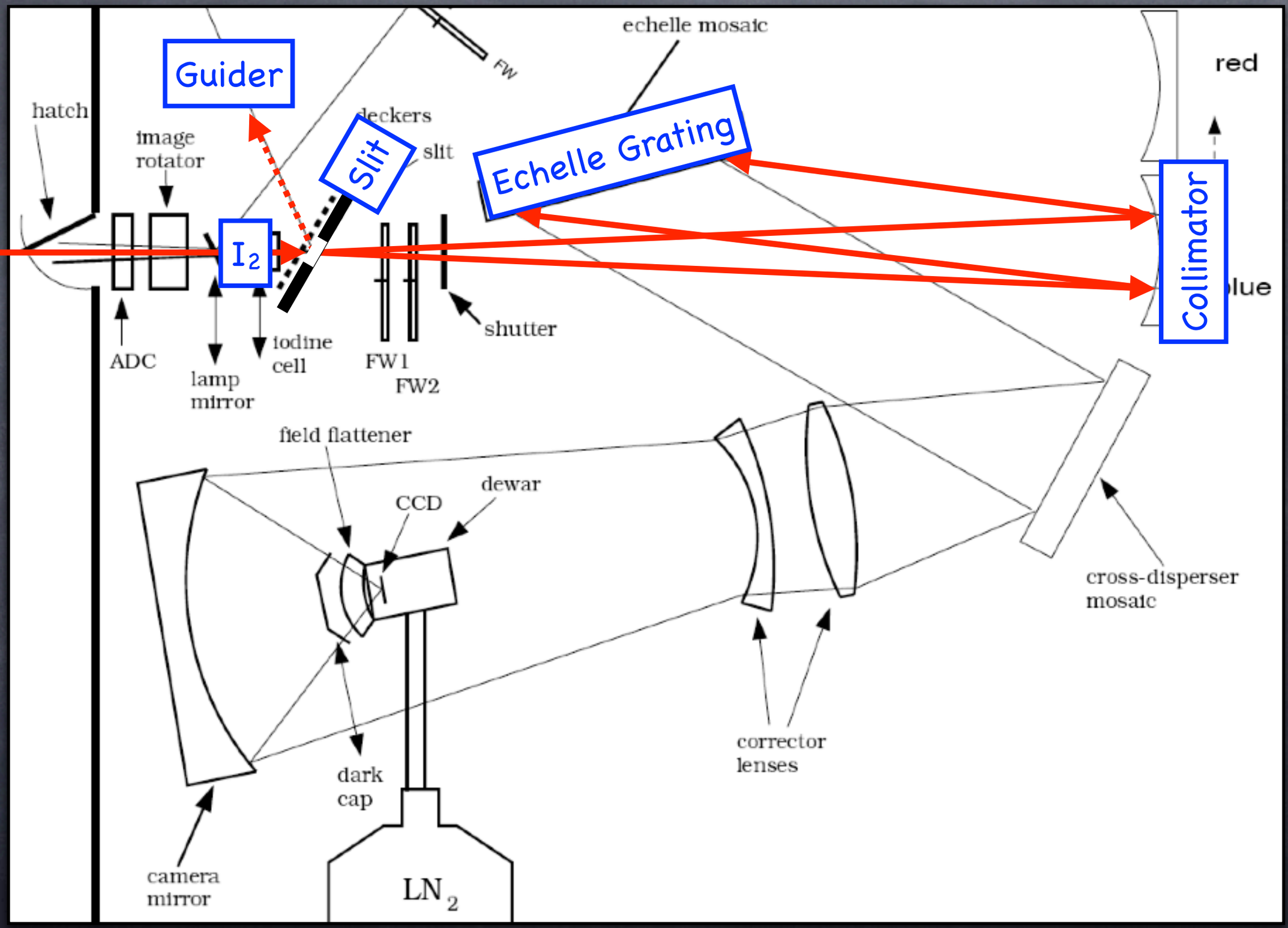
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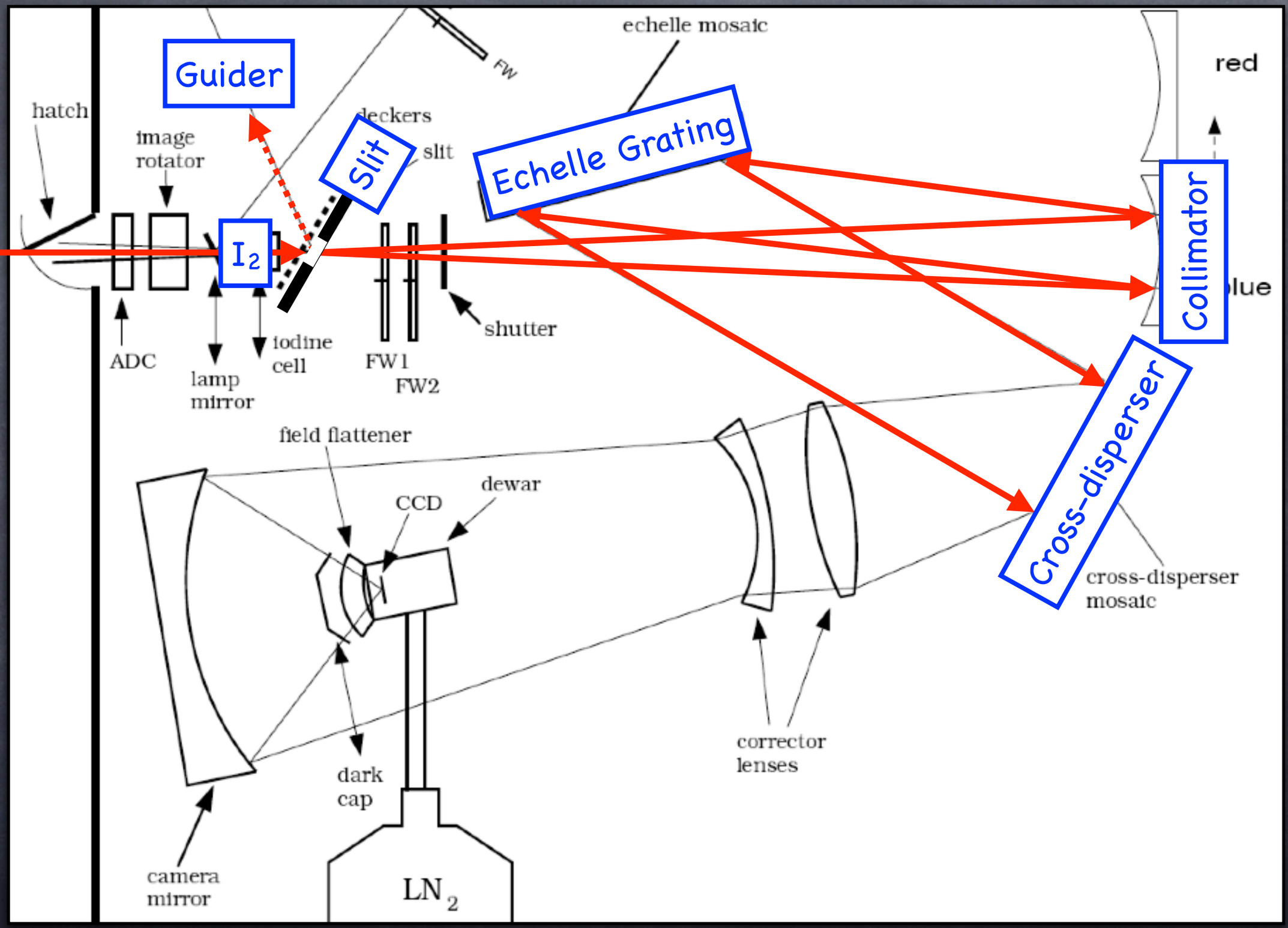
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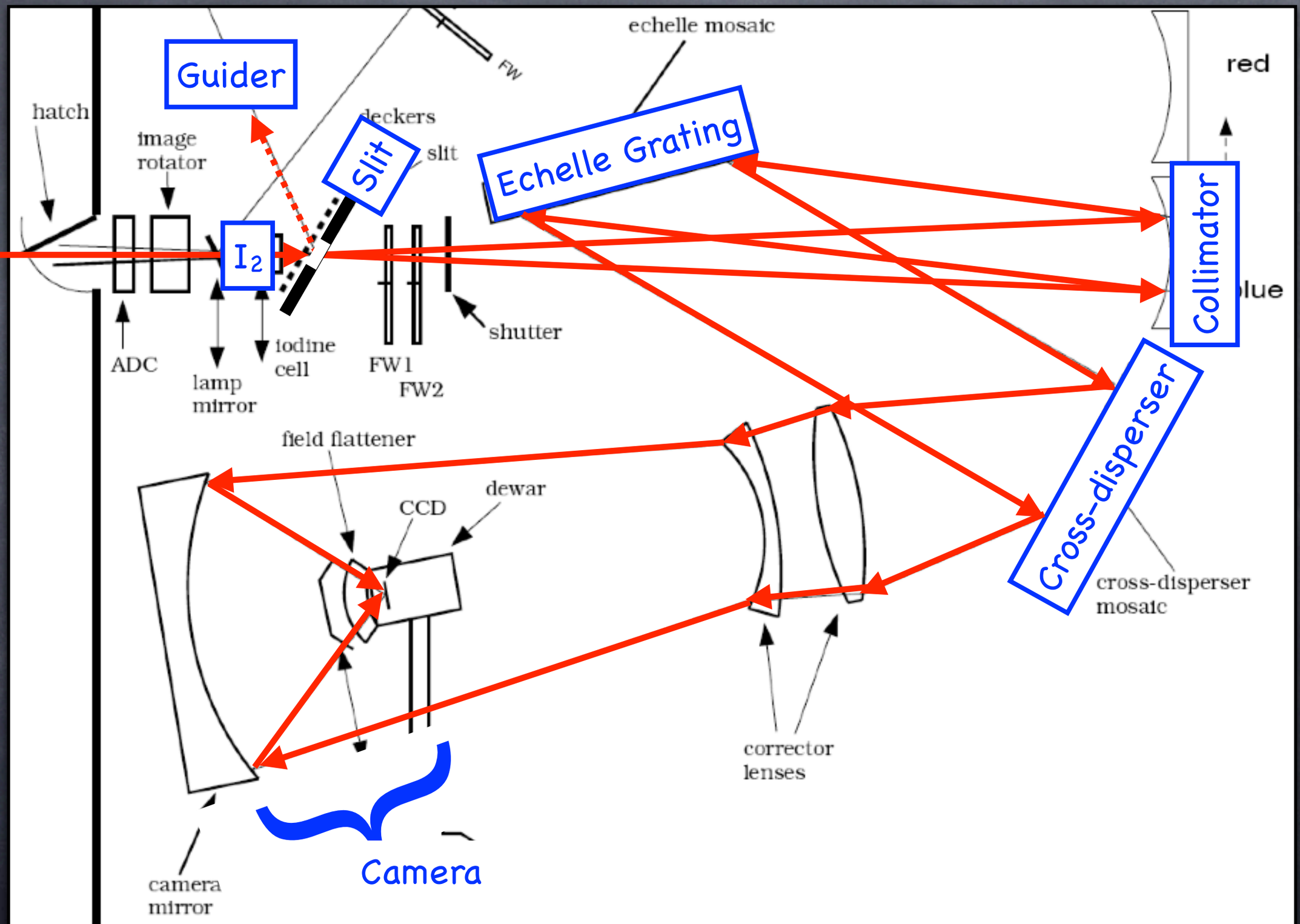
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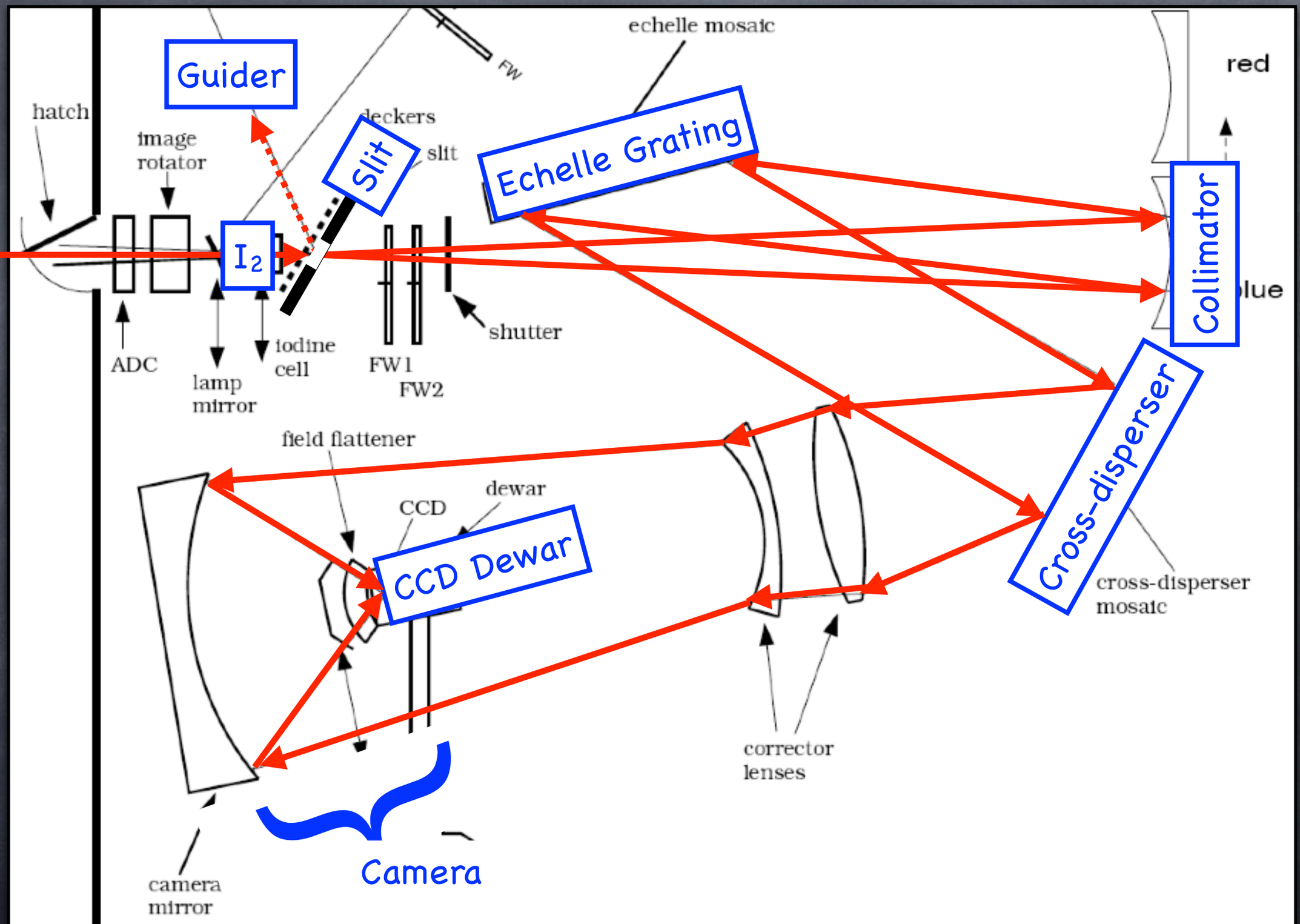
HIRES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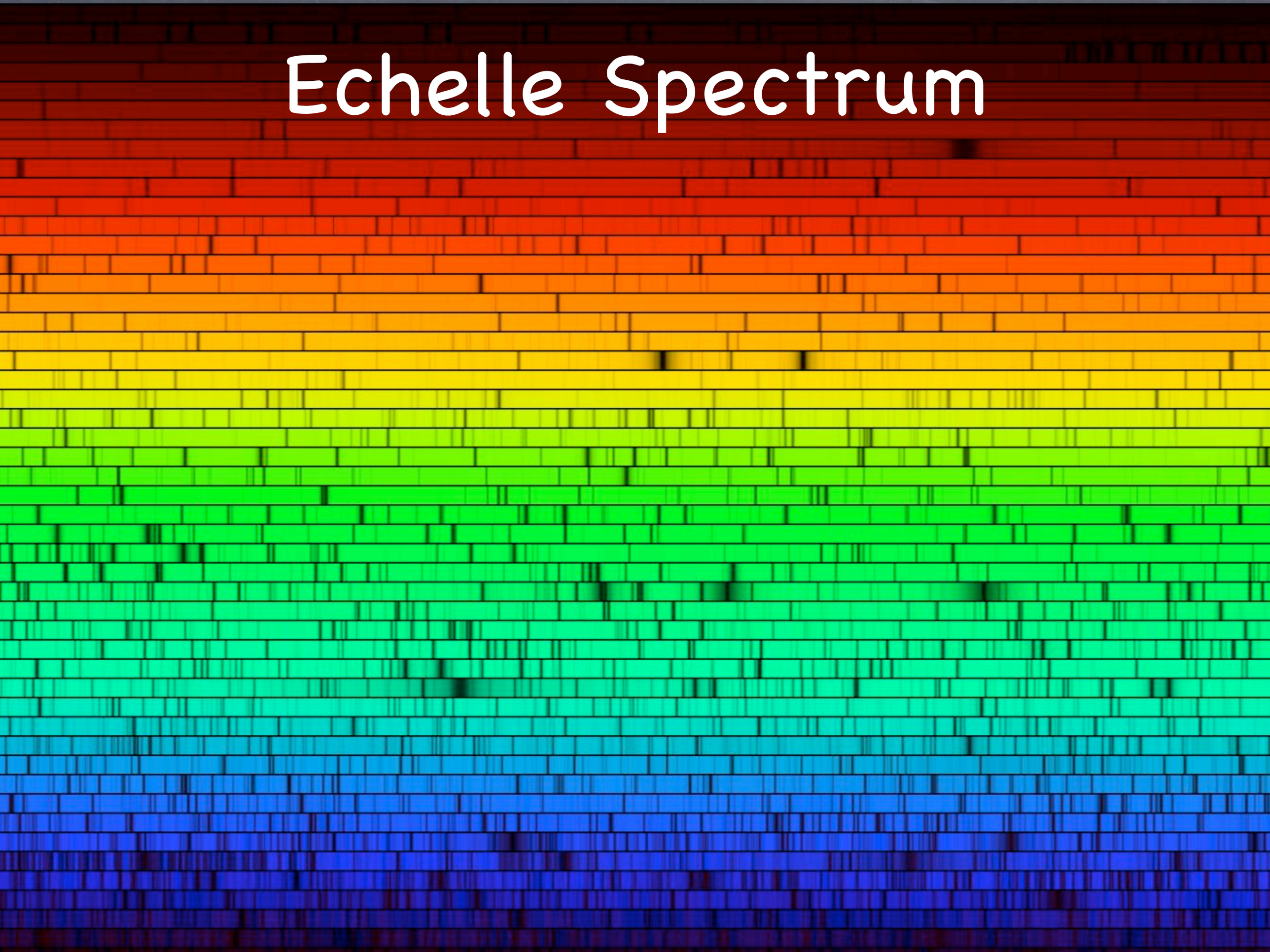
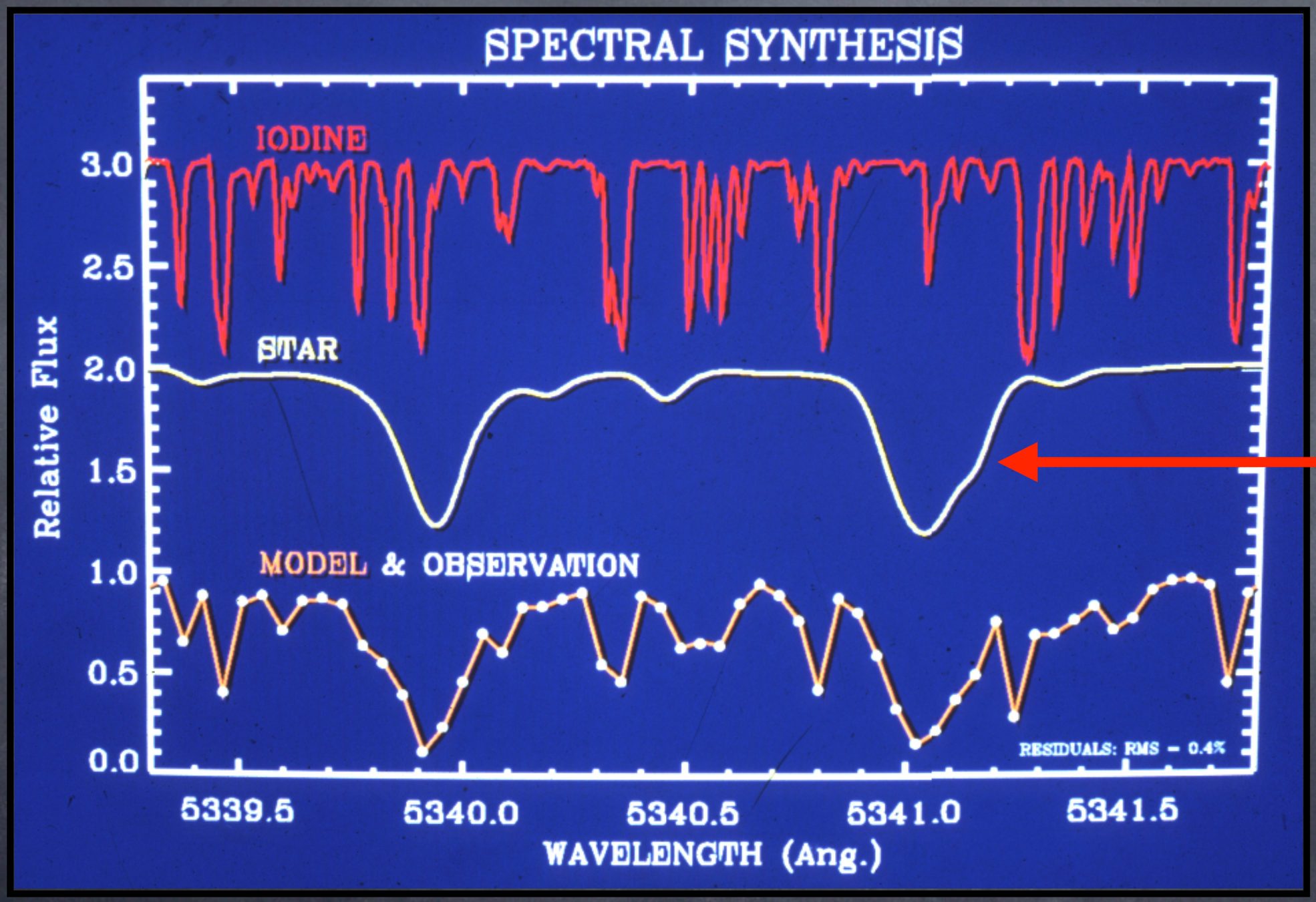
Echelle Spectrum

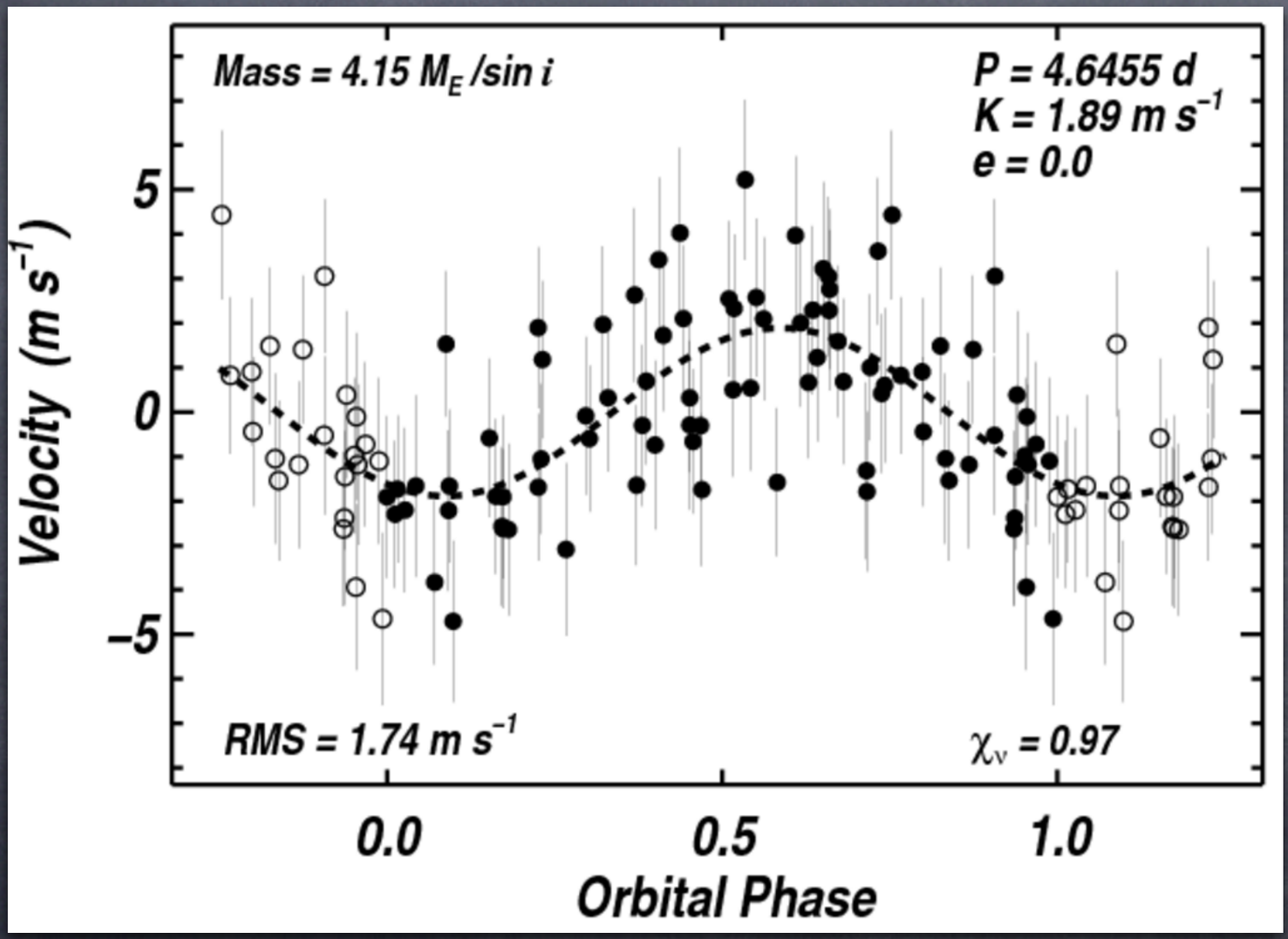


RVs with Iodine



$$I_{obs}(\lambda) = k[T_{I2}(\lambda) \cdot I_S(\lambda + \Delta\lambda)] \otimes PSF$$

Pushing down to K < 2 m/s



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. 2010, ApJ (submitted), arXiv 1003:3444

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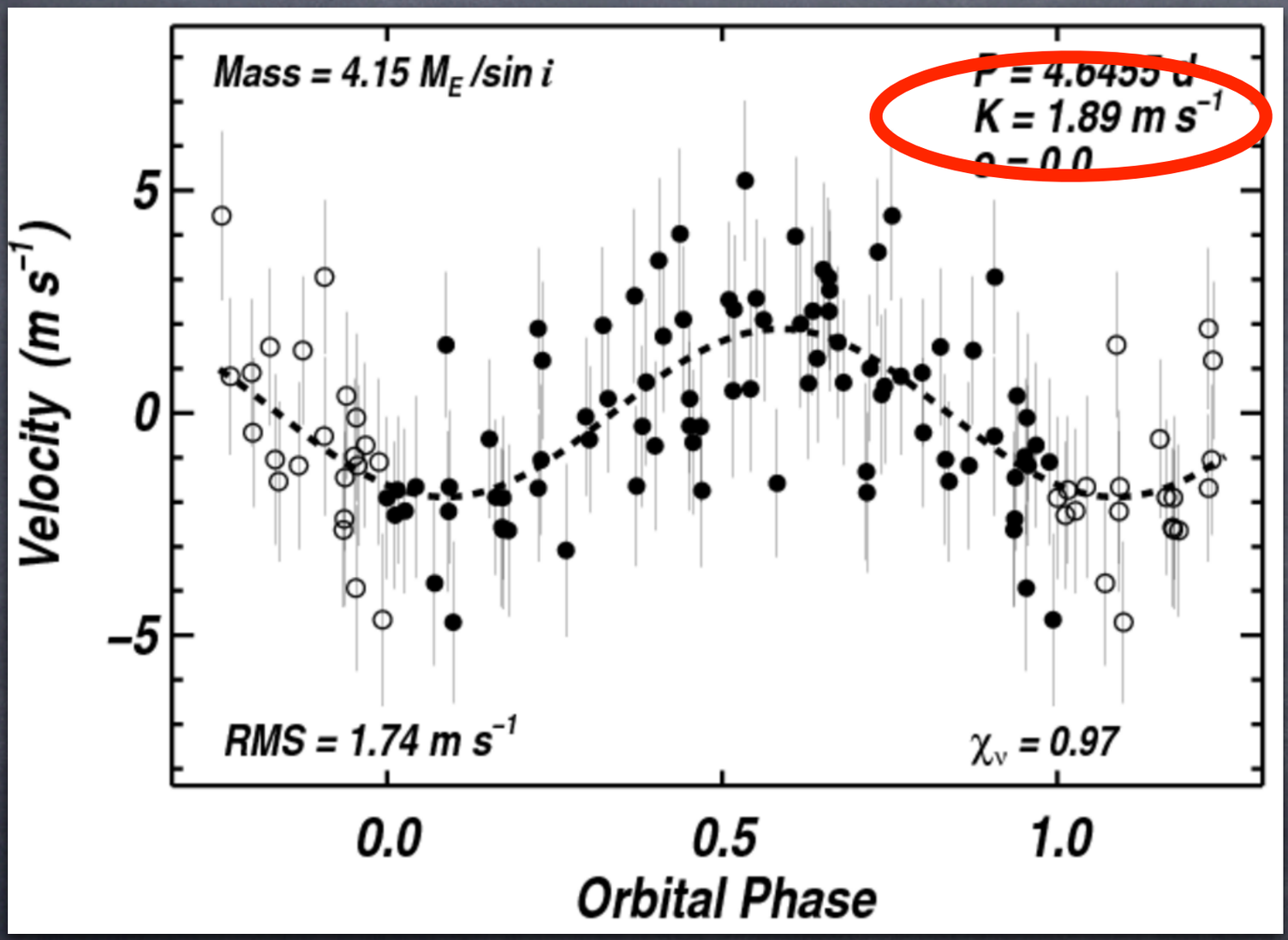

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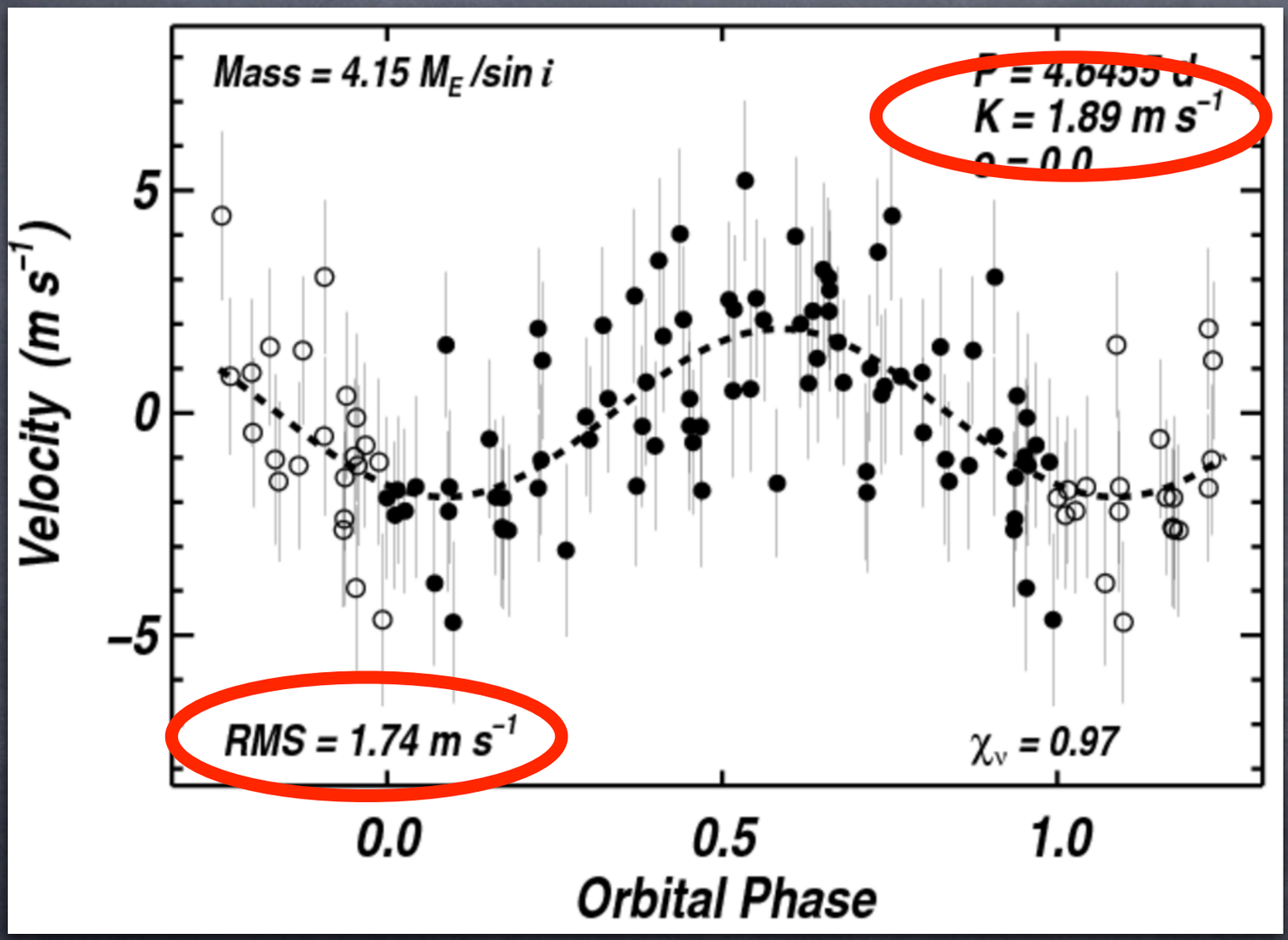

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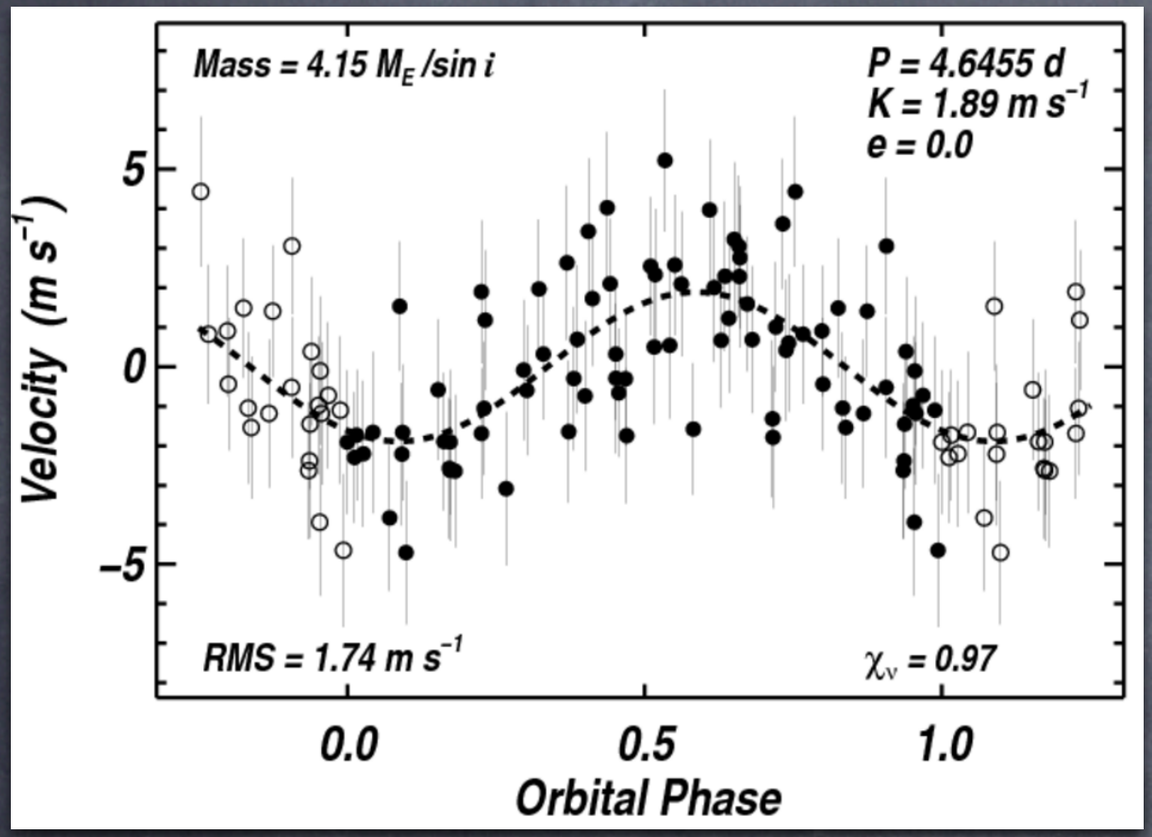
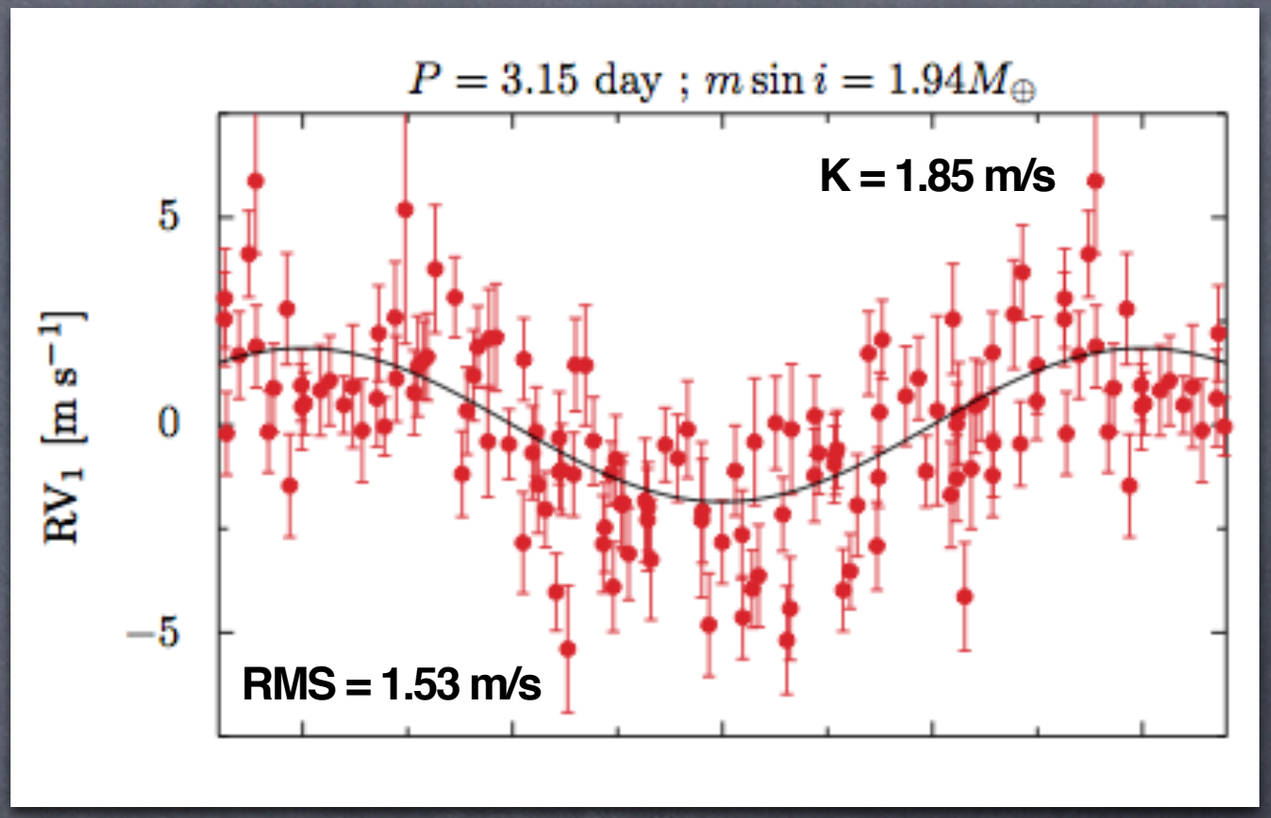
HIRES and HARPS

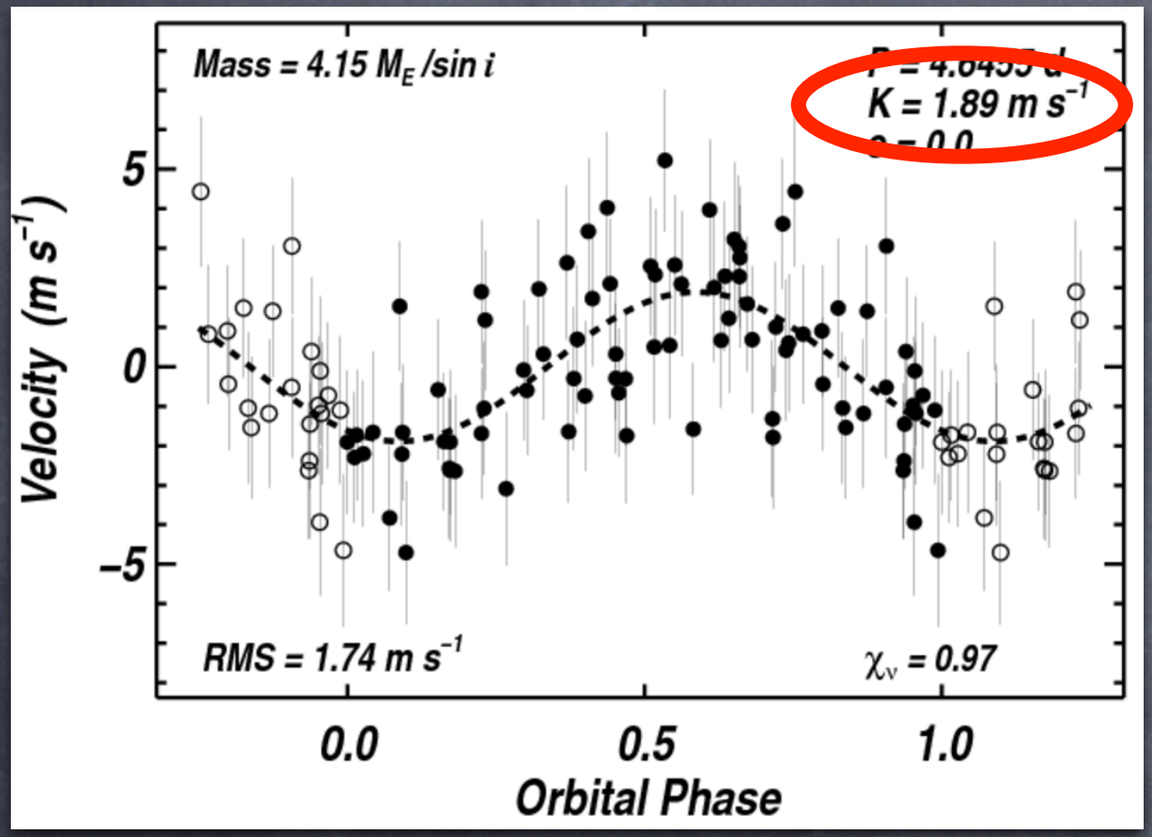


HD 156668 b
(HIRES)



GJ 581 e
(HARPS)

HIRES and HARPS



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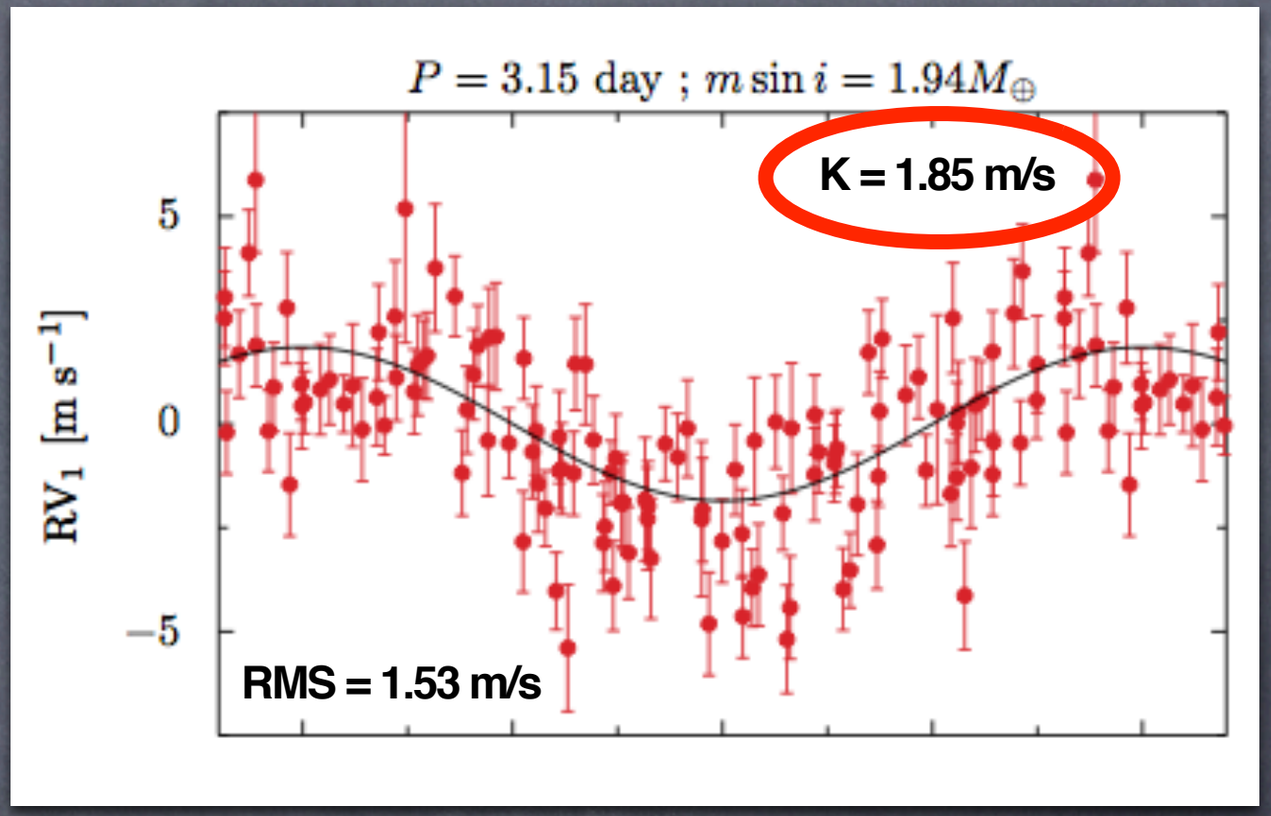

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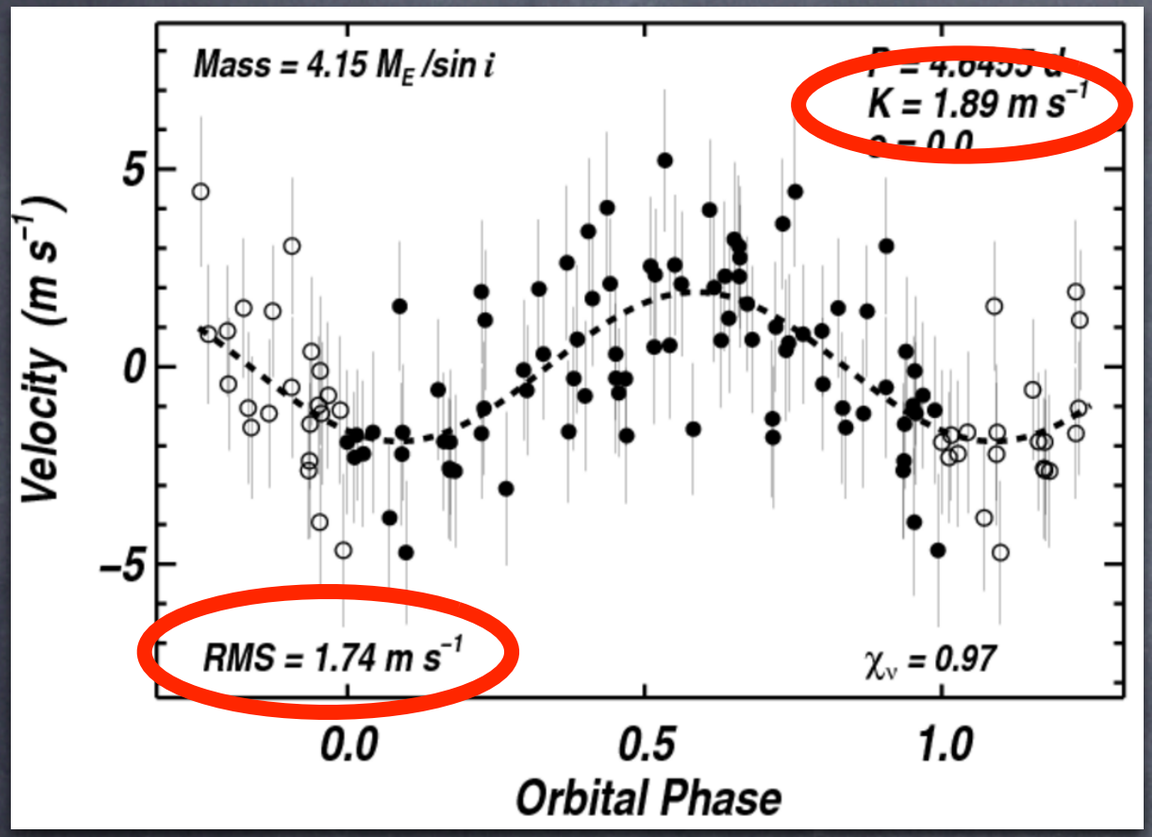
HIRES and HARPS



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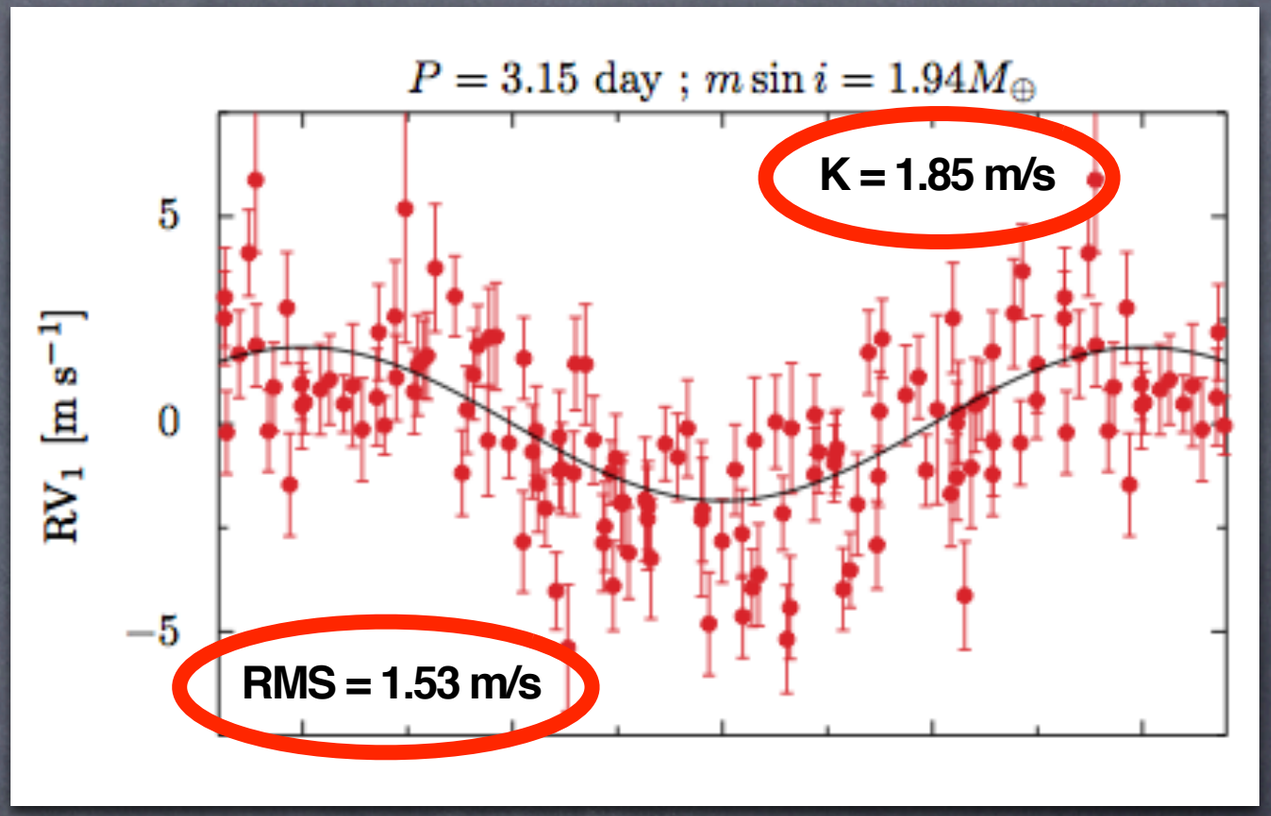

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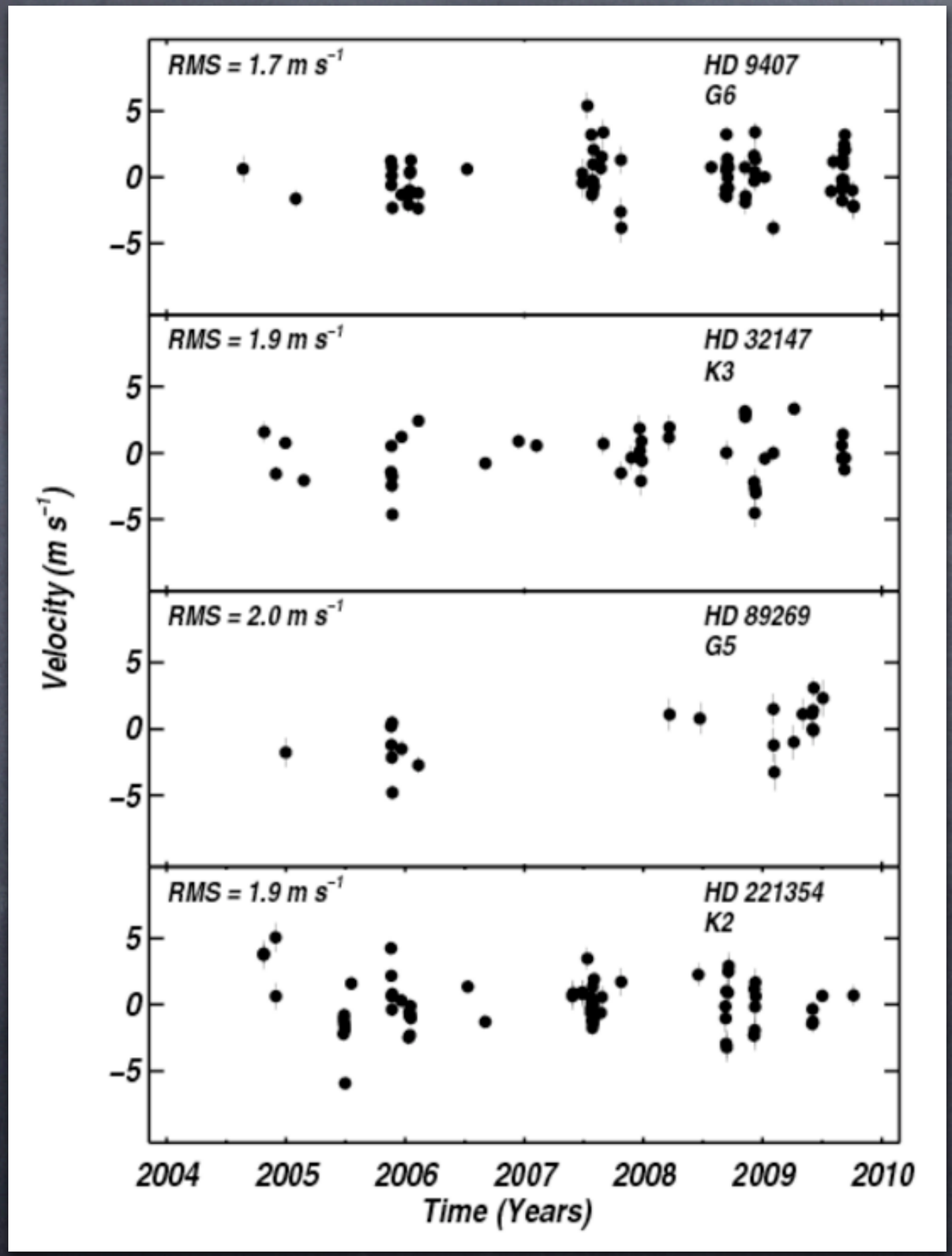
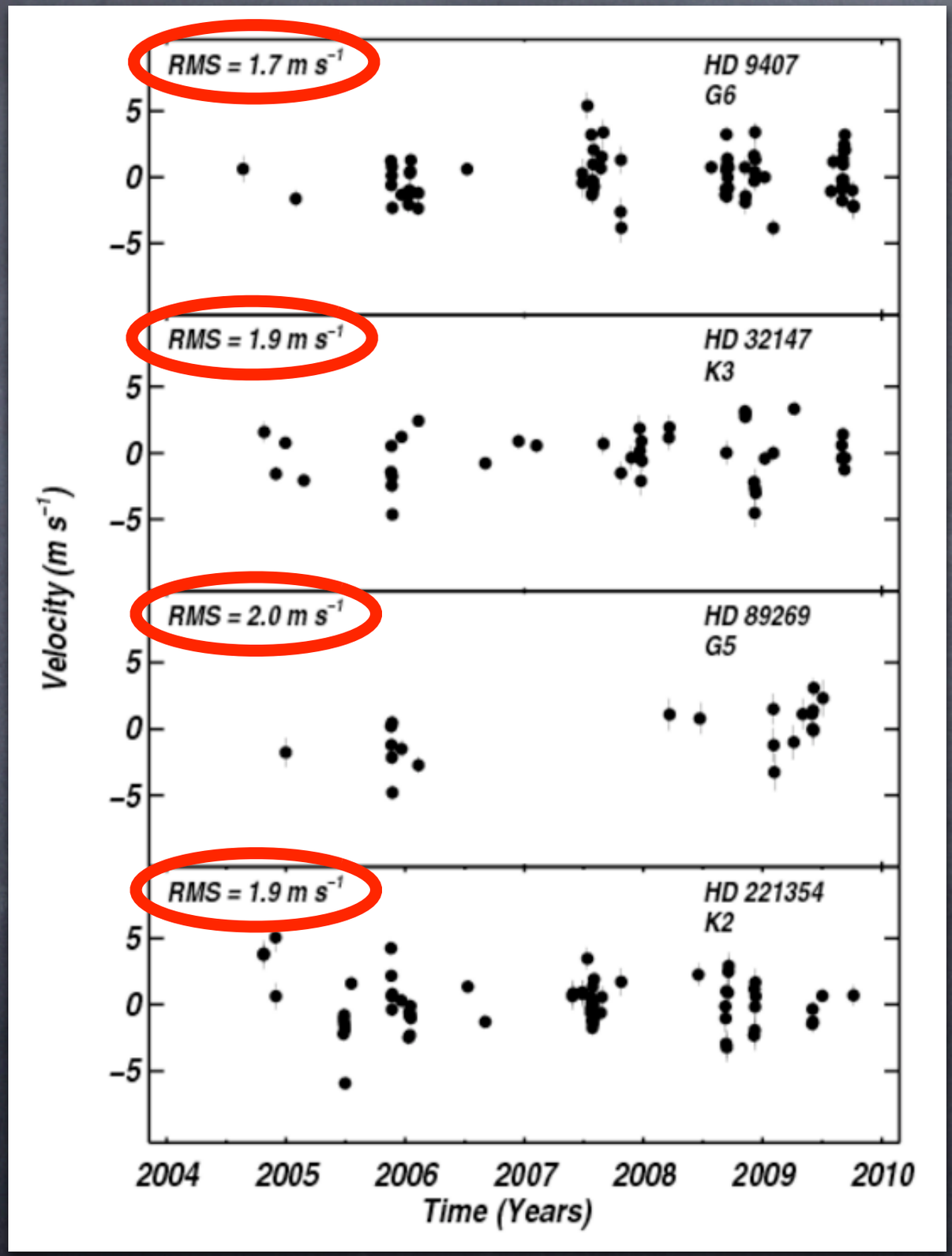
Standard Stars

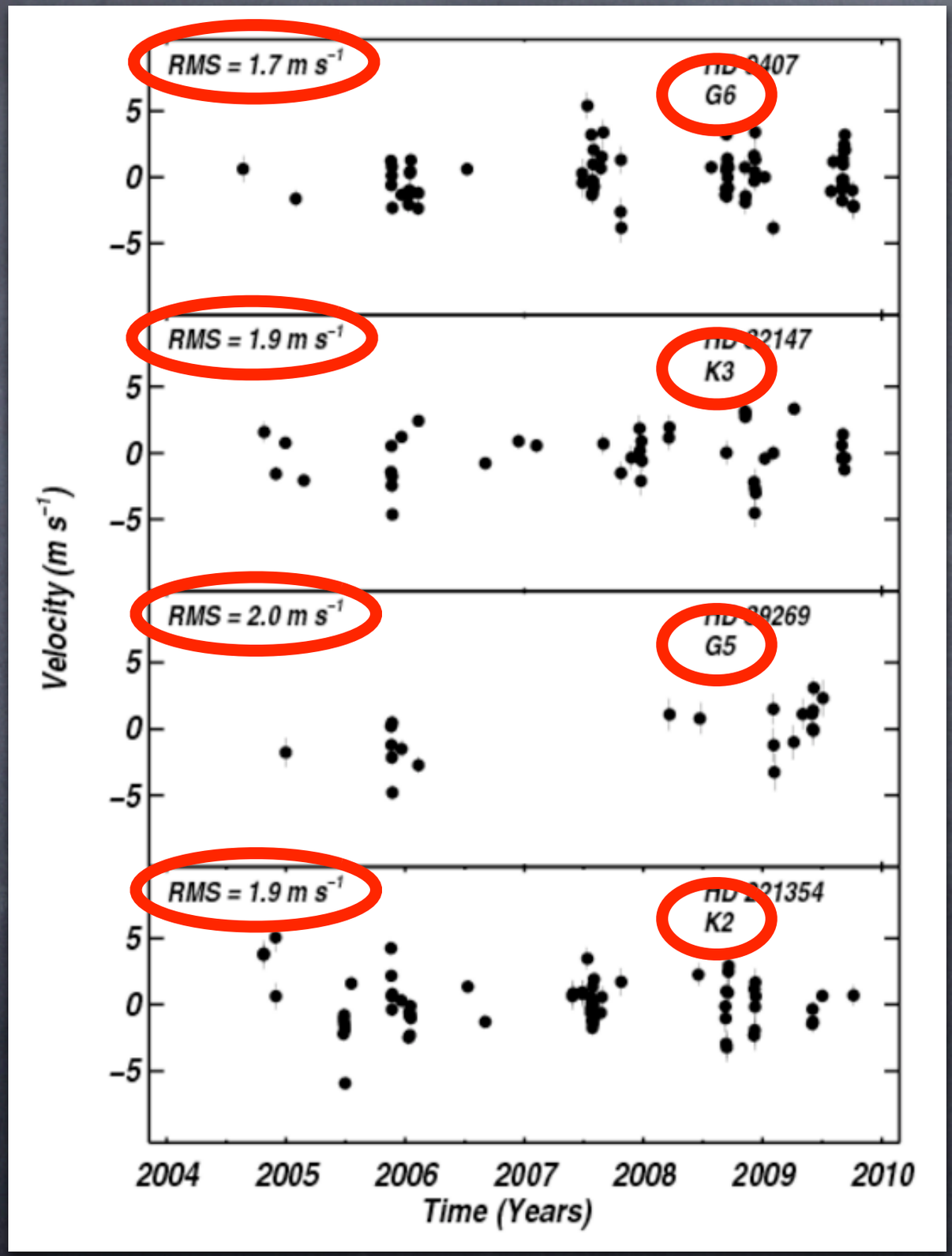


Standard Stars



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

Standard Stars



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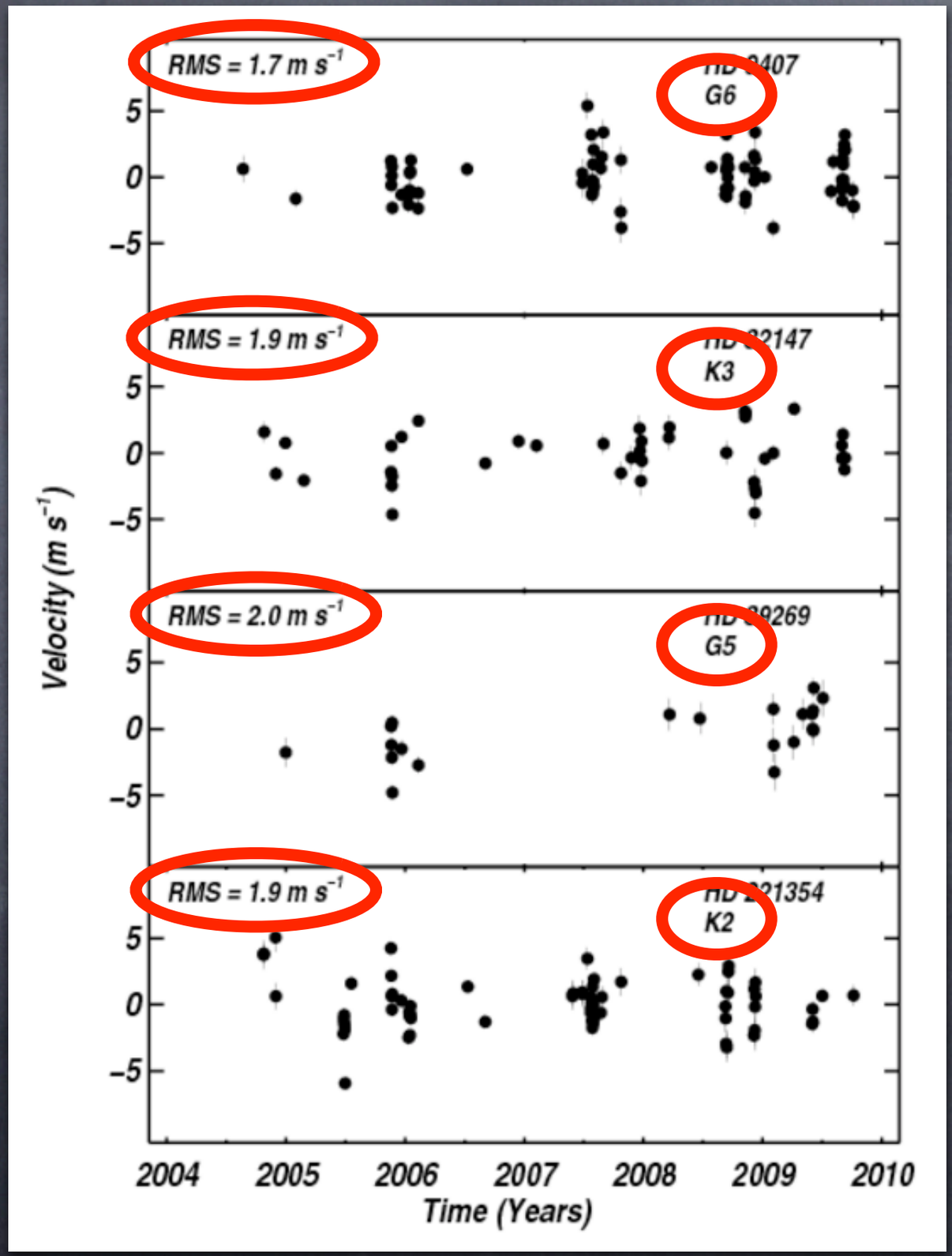
These are almost always late G / early K dwarfs.

Standard Stars



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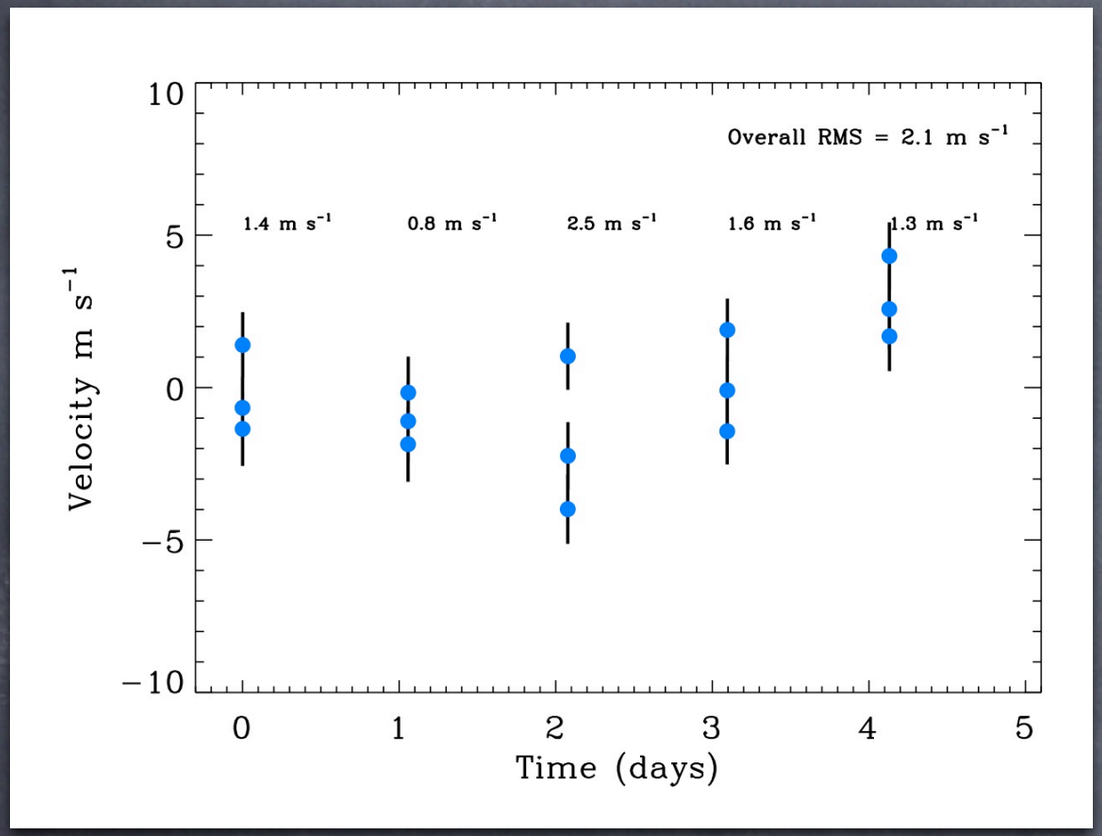
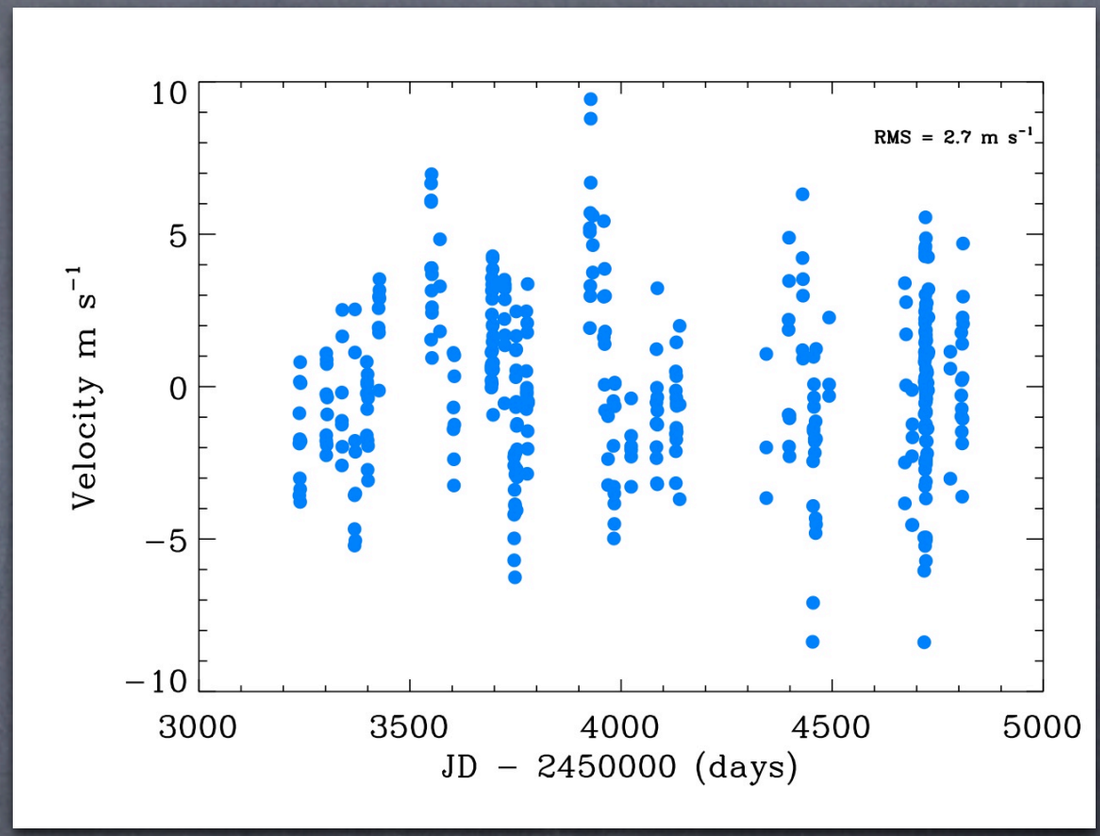
We do not explicitly average over P-modes; T_{exp} ~ 1-5 min

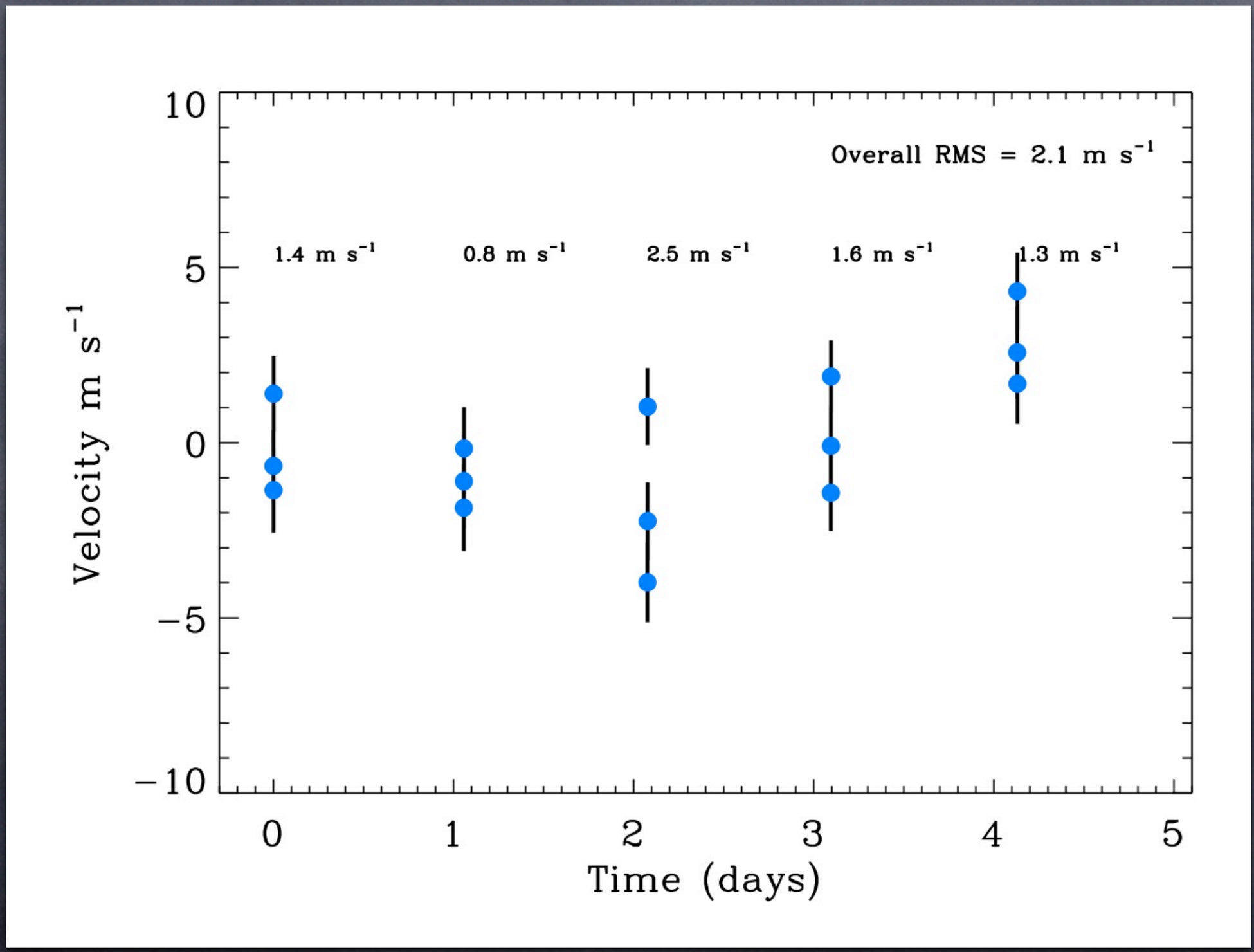
Standard Stars



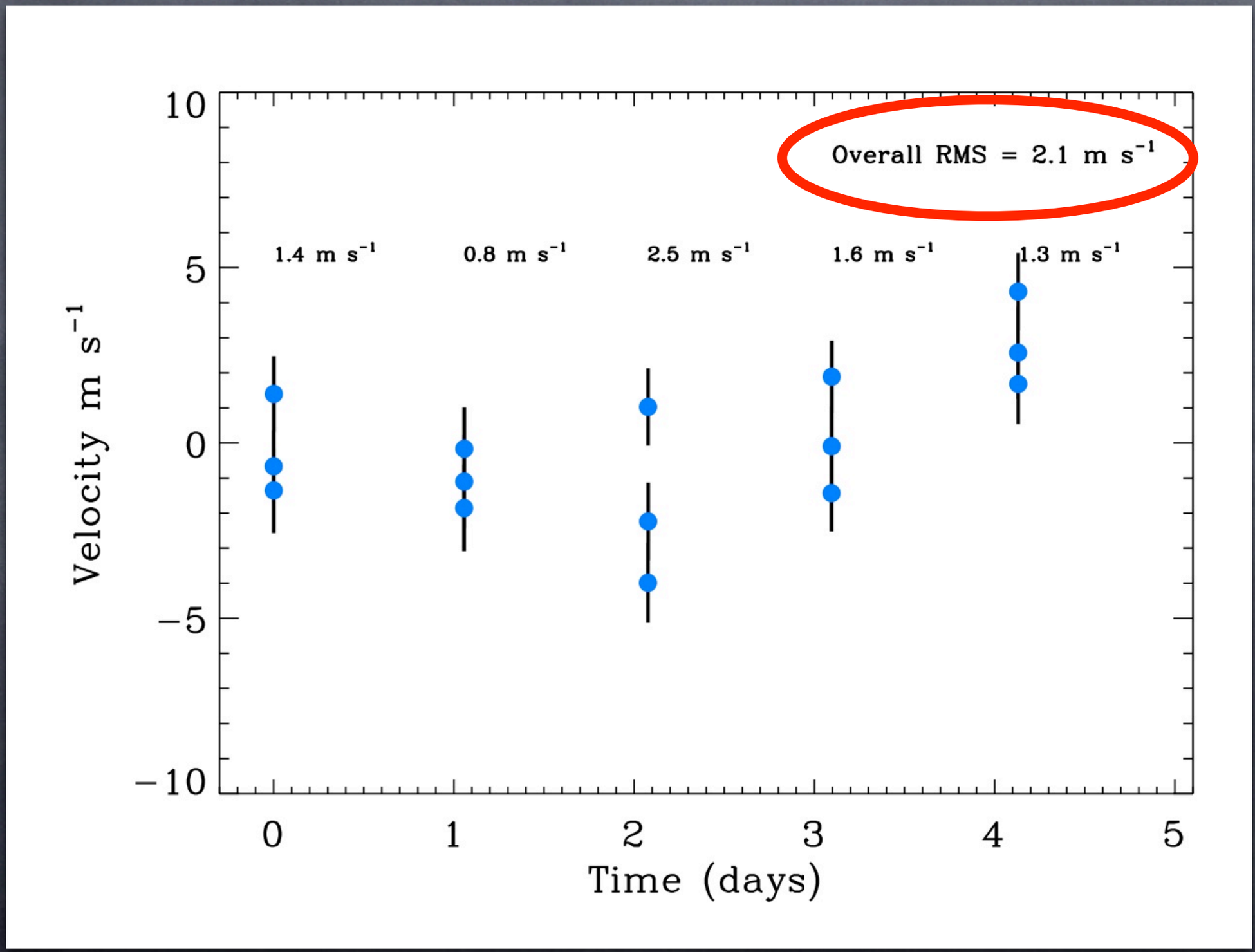


HD 10700 (Tau Ceti)

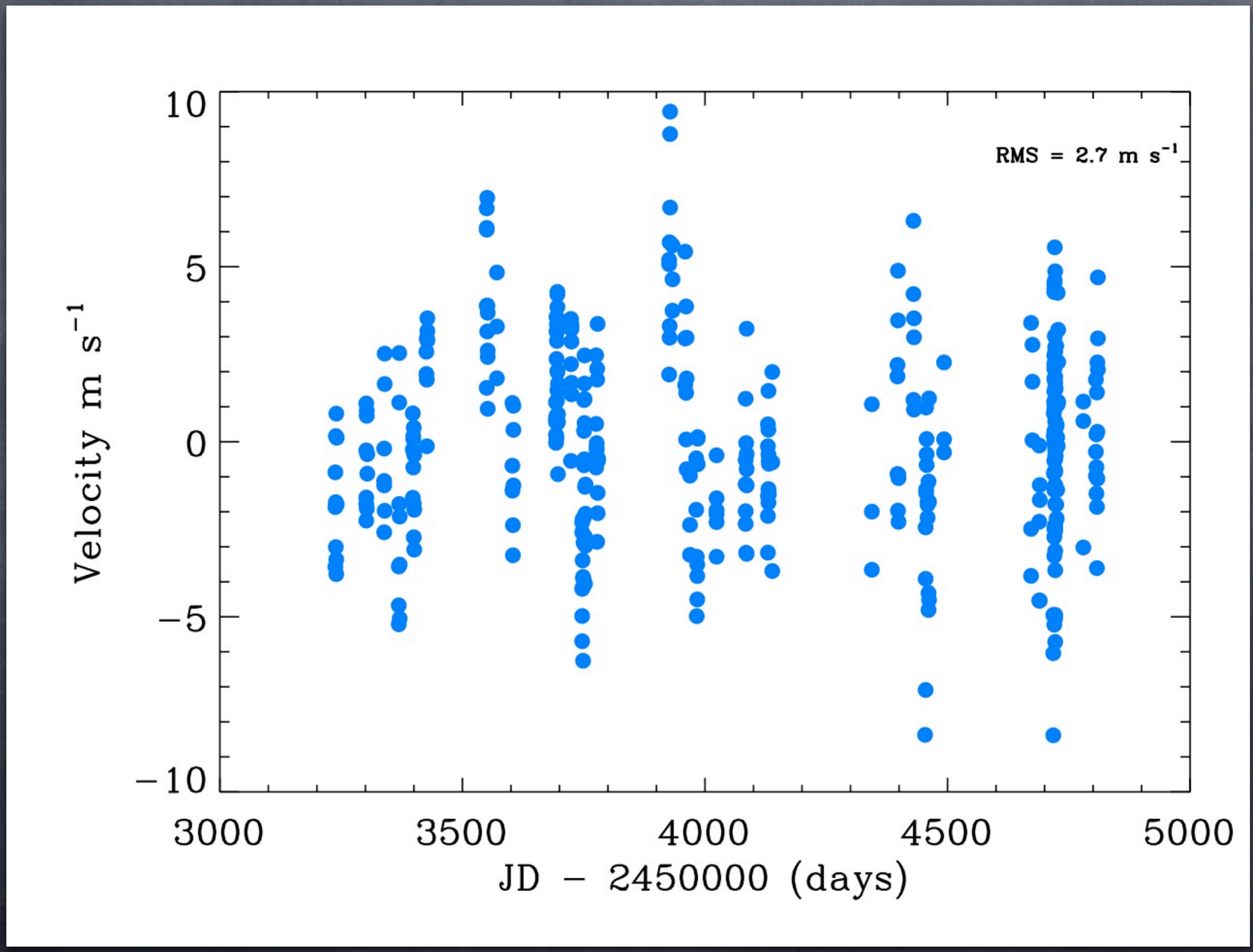
Standard Stars



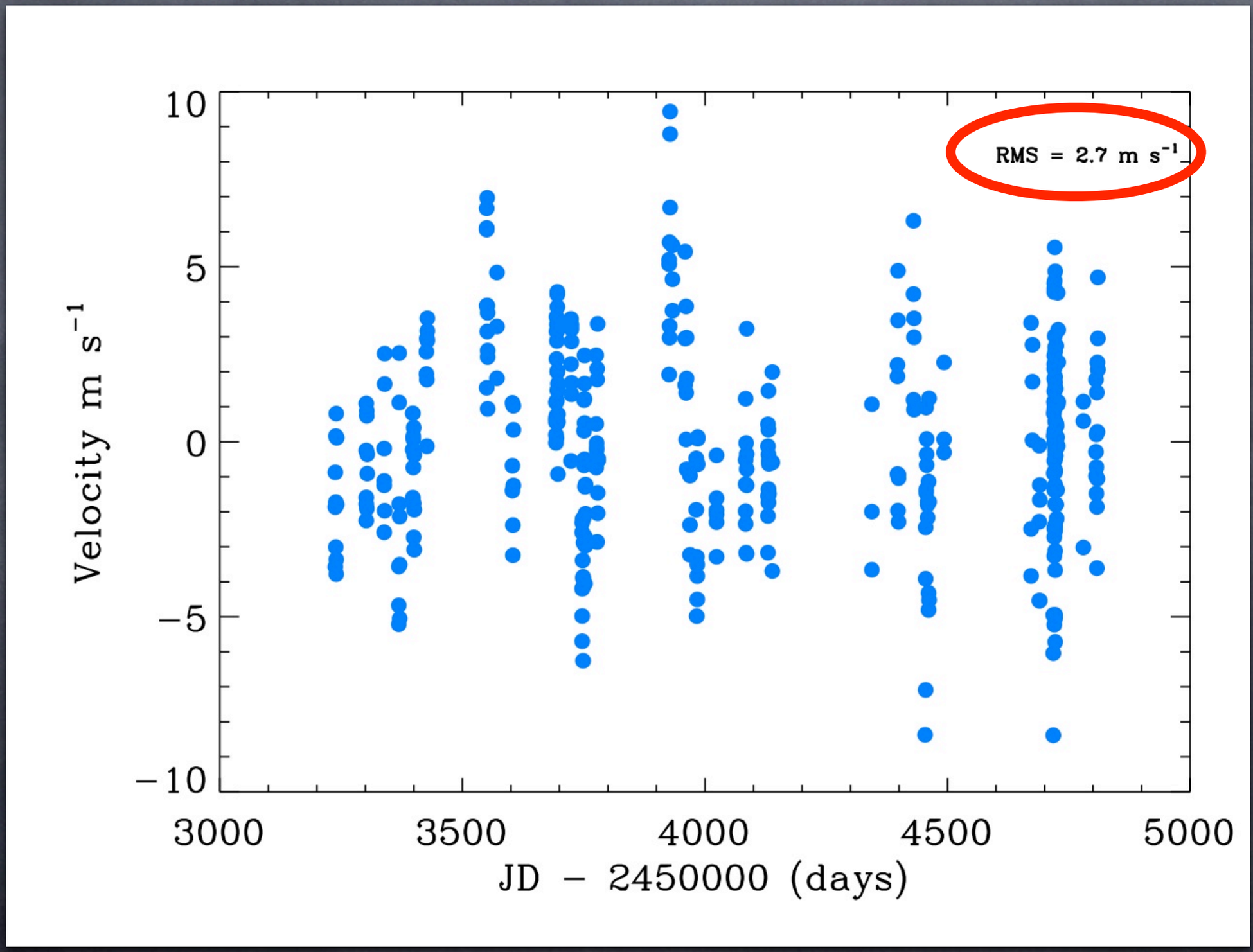
Standard Stars



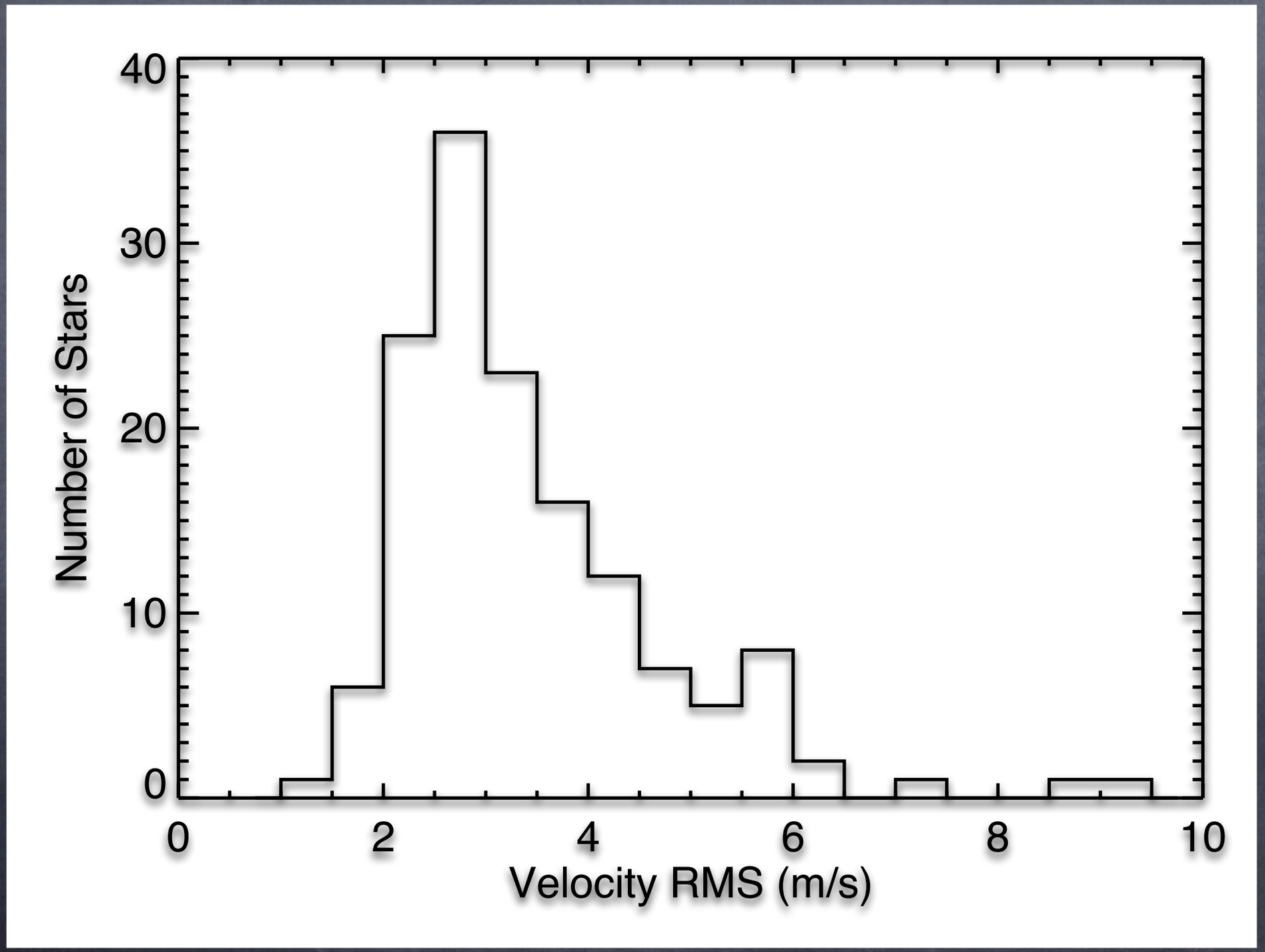
Standard Stars



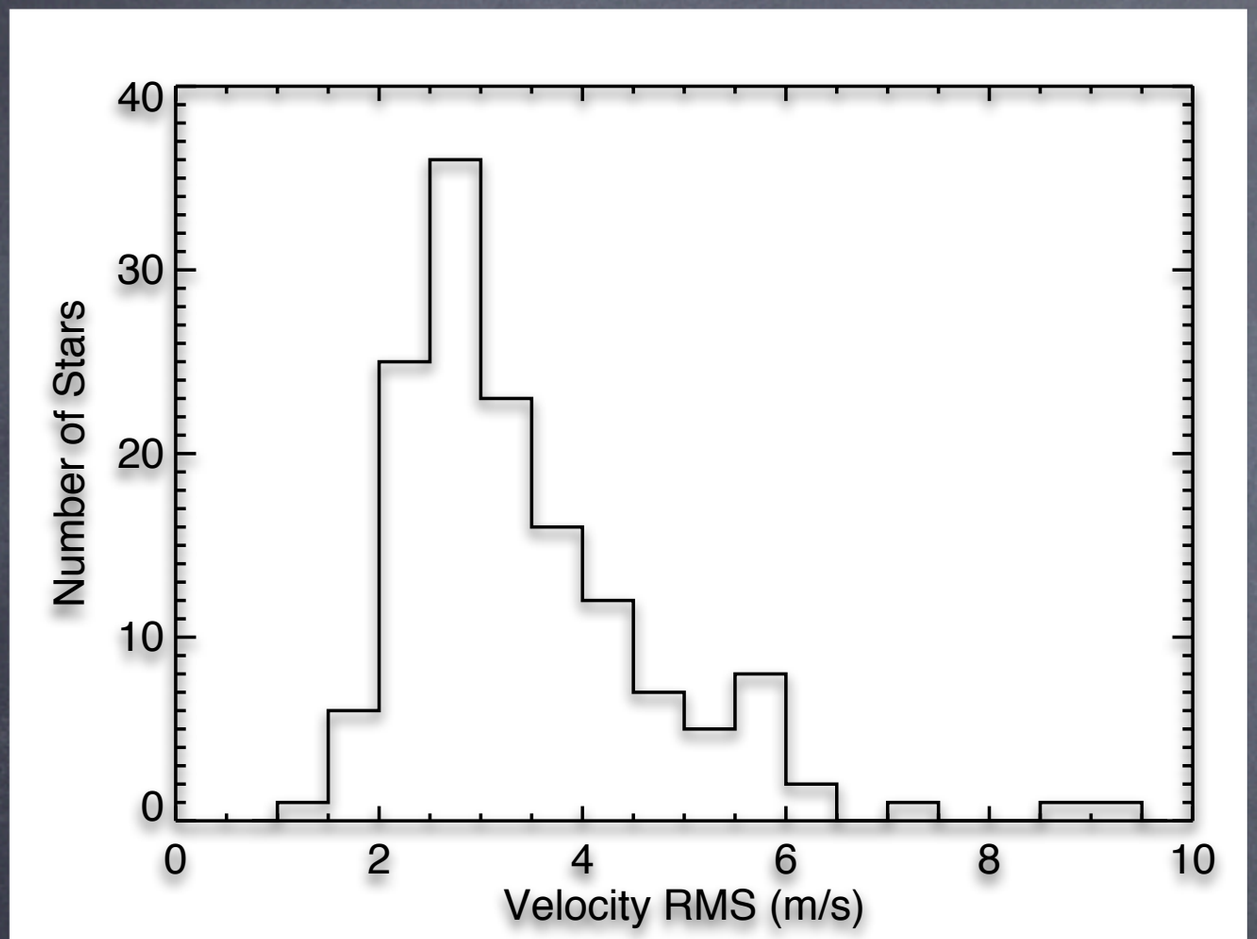
Standard Stars



HIRES Velocity RMS



Velocity RMS



HIRES

GK stars in Eta-Earth Survey
Known planets removed

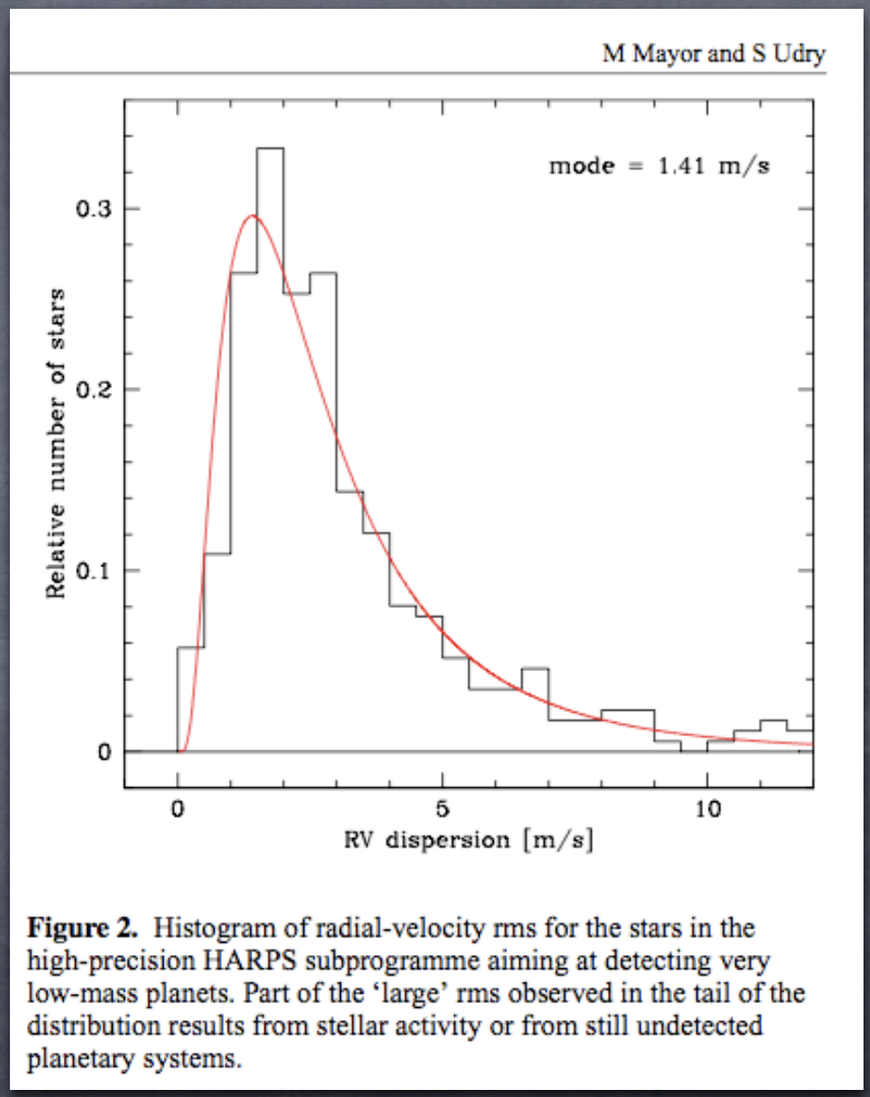


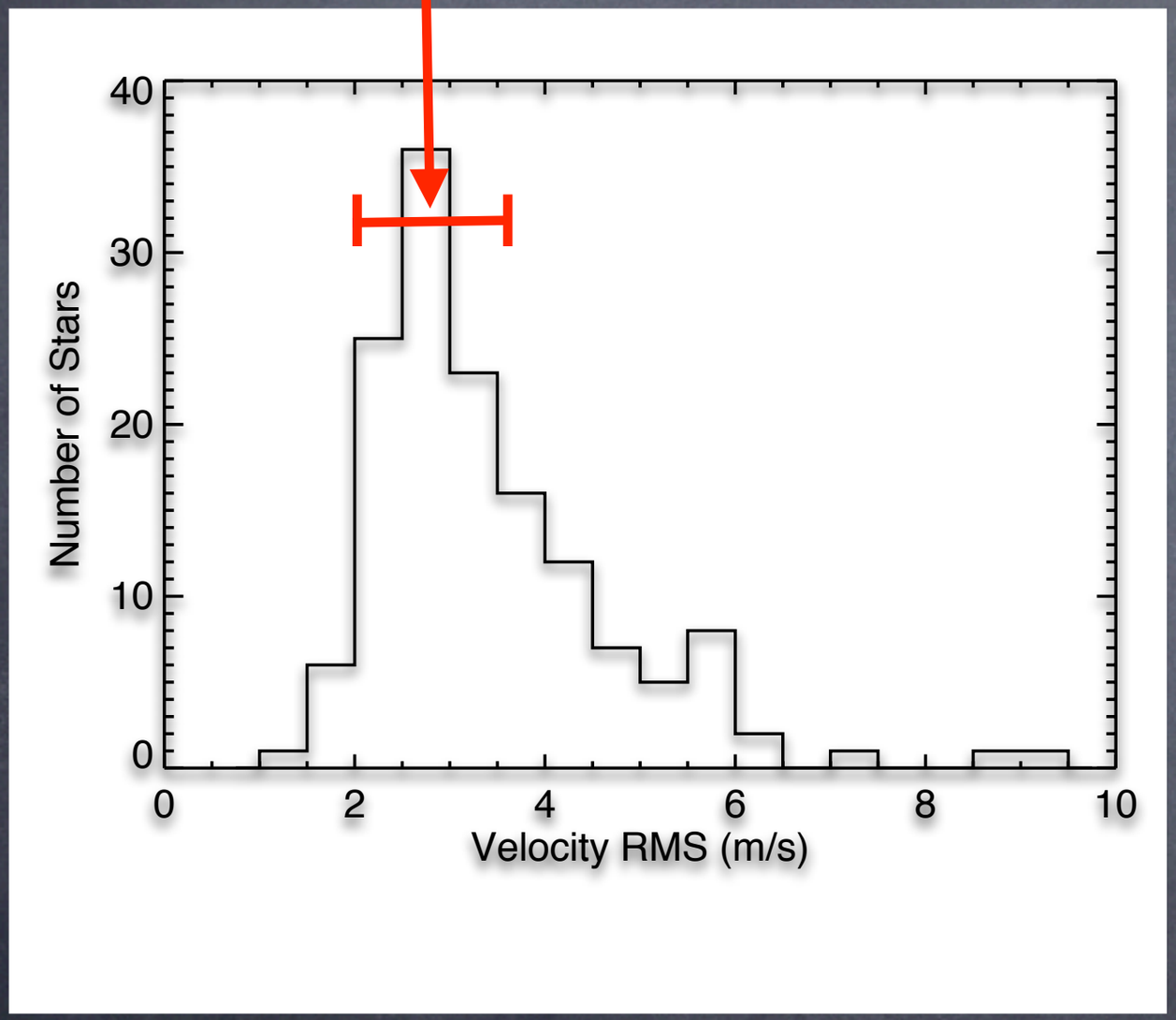
Figure 2. Histogram of radial-velocity rms for the stars in the high-precision HARPS subprogramme aiming at detecting very low-mass planets. Part of the 'large' rms observed in the tail of the distribution results from stellar activity or from still undetected planetary systems.

HARPS

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

Velocity RMS

2-3.5 m/s



HIRES

GK stars in Eta-Earth Survey
Known planets removed

1-3 m/s

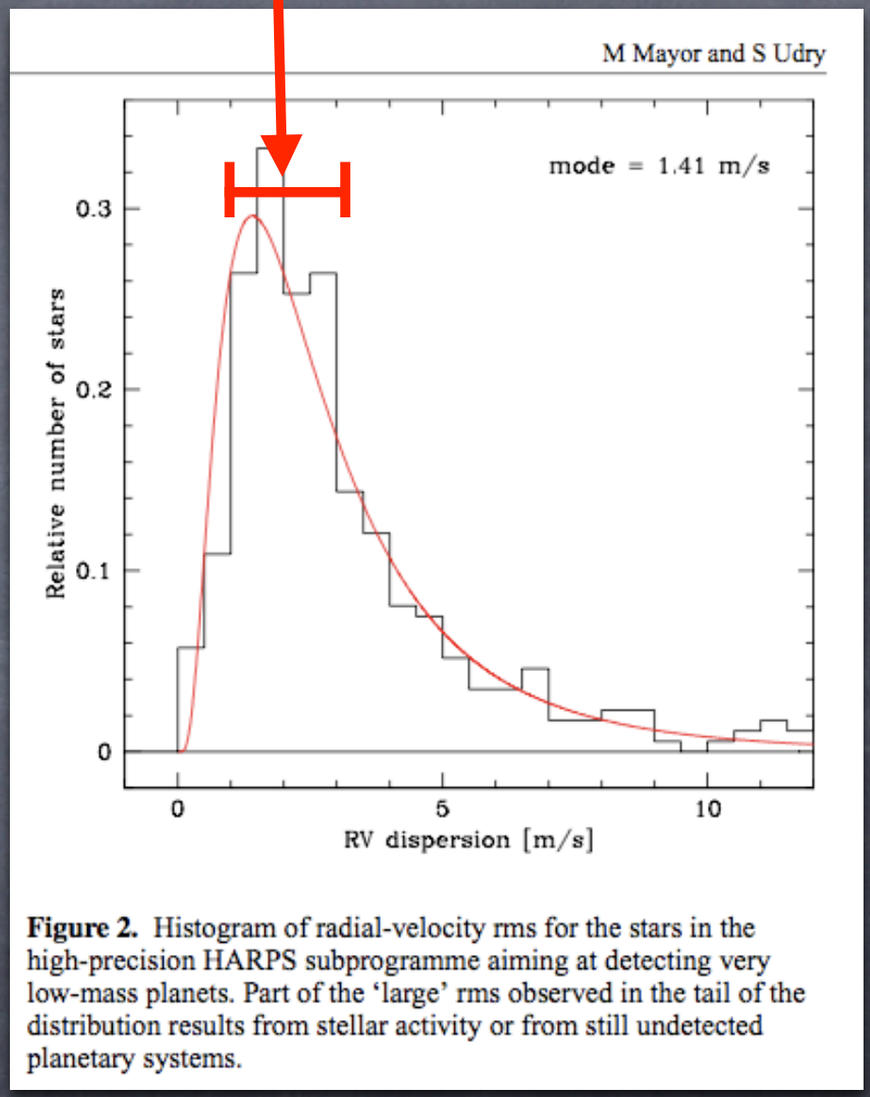


Figure 2. Histogram of radial-velocity rms for the stars in the high-precision HARPS subprogramme aiming at detecting very low-mass planets. Part of the 'large' rms observed in the tail of the distribution results from stellar activity or from still undetected planetary systems.

HARPS

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

Challenge:

Stability and Precision at 0.3-0.5 m/s

Sources of RV Errors

Instrumental
(and modeling)

Poisson
(0.5–1.0 m/s)

Astrophysical

Sources of RV Errors

Instrumental

(and modeling)

Poisson

(0.5–1.0 m/s)

Not Limiting

Astrophysical

Sources of RV Errors

Instrumental
(and modeling)

Poisson
(0.5–1.0 m/s)

Not Limiting

Astrophysical

see talks today

Sources of RV Errors

Instrumental
(and modeling)

This Talk

see also talks by Valenti, Spronck

Poisson
(0.5–1.0 m/s)

Not Limiting

Astrophysical

see talks today

HIRES RV Errors

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

HIRES RV Errors

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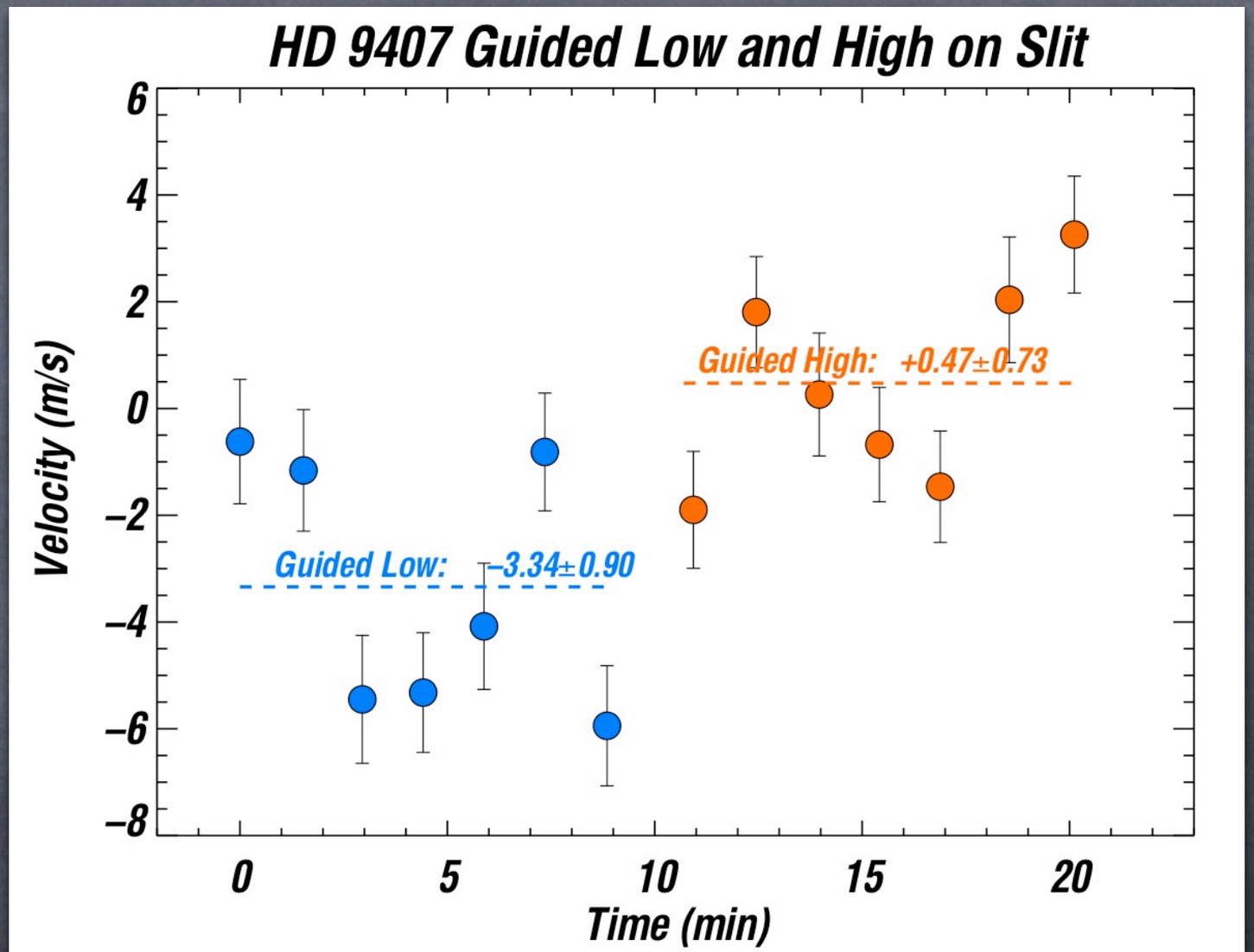
Intentional Mis-guiding

Guide High

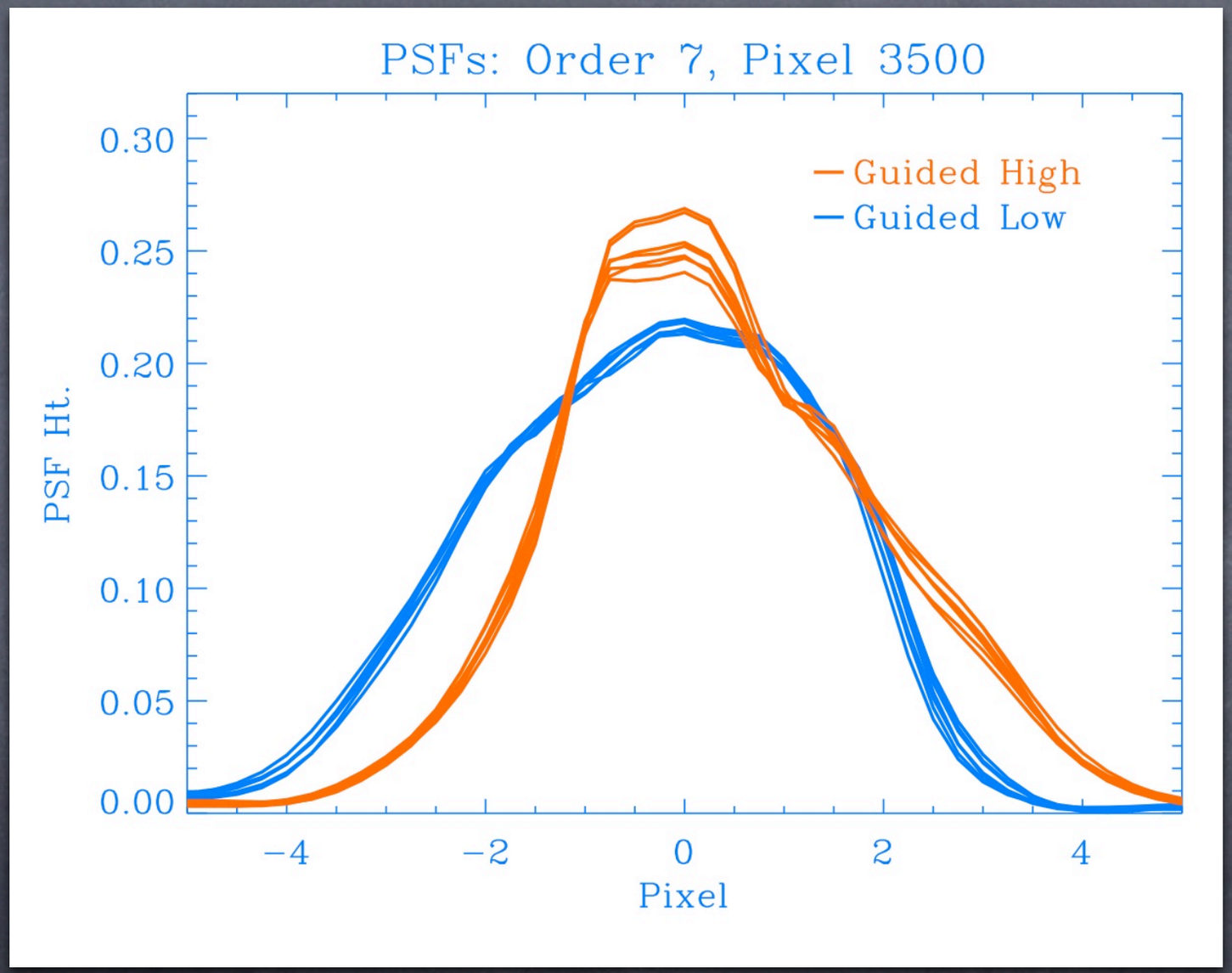
Guide Middle

Guide Low



Extreme mis-guiding -> 4 m/s

Intentional Mis-guiding - PSF Asymmetry



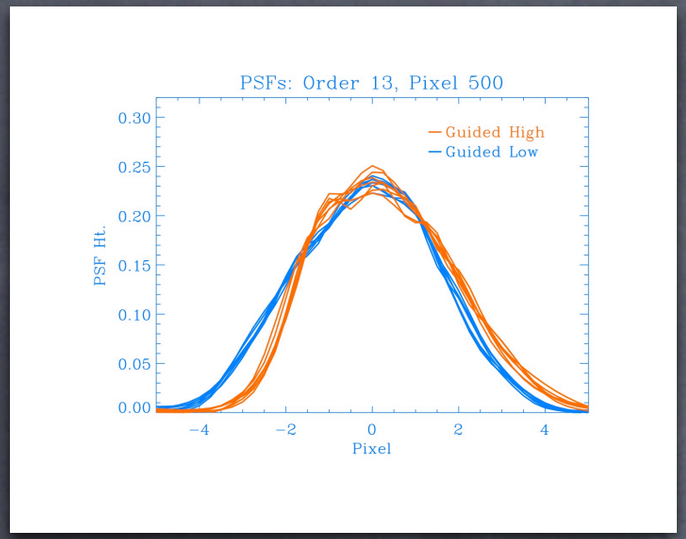
PSF shape changes with mis-guiding

PSFs: Order 7, Pixel 3500

Guided High
Guided Low

0.30
0.25
0.20
0.15
0.10
0.05
0.00

−4
−2
0
2
4


PSFs: Order 13, Pixel 500
Guided High
Guided Low
PSF Ht.
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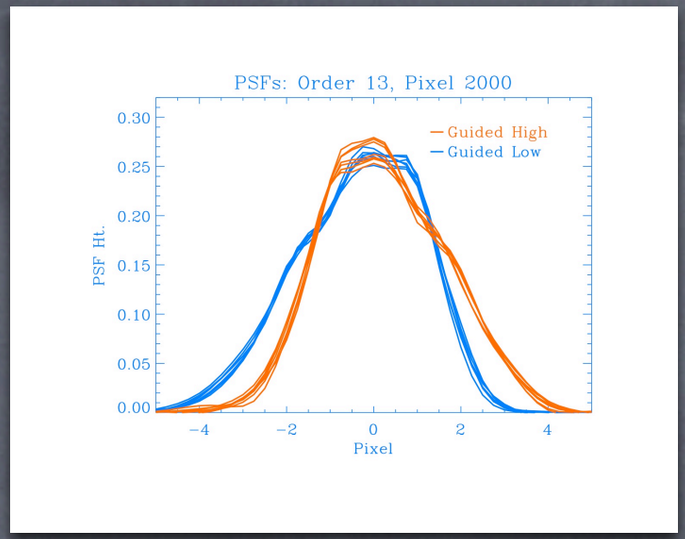
0.25
0.20
0.15
0.10
0.05
0.00
−4
−2
0
2
4
Pixel


PSFs: Order 13, Pixel 2000
Guided High
Guided Low
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0.20
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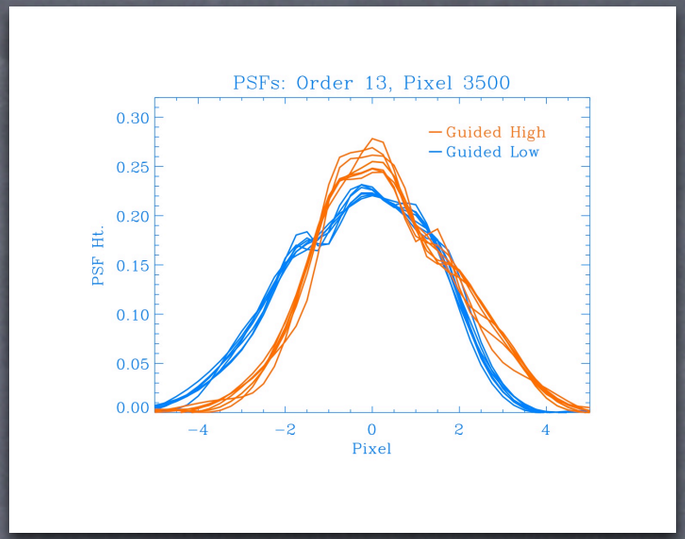
0.10
0.05
0.00
−4
−2
0
2
4
Pixel


PSFs: Order 13, Pixel 3500
Guided High
Guided Low
PSF Ht.
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0.15
0.10
0.05
0.00
−4
−2
0
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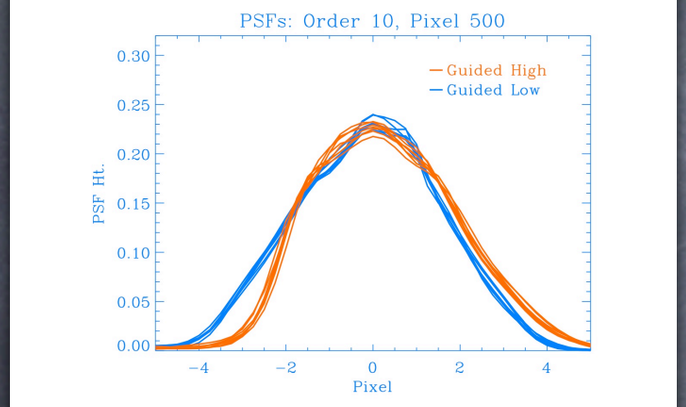
4
Pixel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Guided Low
PSF Ht.
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0.05
0.00
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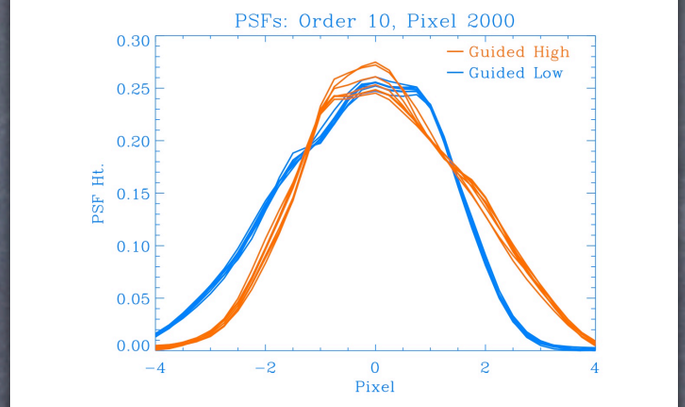
−2
0
2
4
Pixel


PSFs: Order 10, Pixel 2000
Guided High
Guided Low
PSF Ht.
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0.20
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0.10
0.05
0.00
−4
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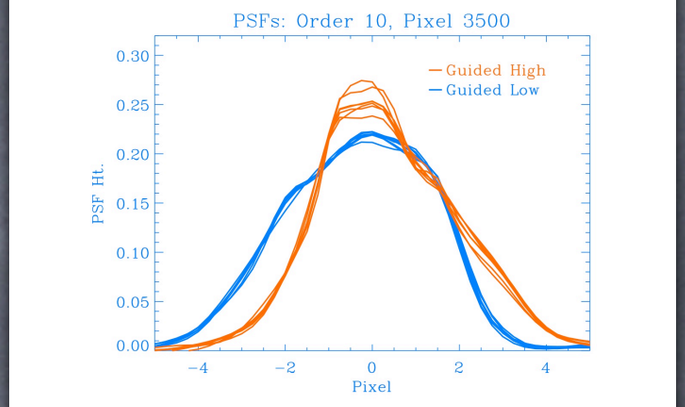
Pixel


PSFs: Order 10, Pixel 3500
Guided High
Guided Low
PSF Ht.
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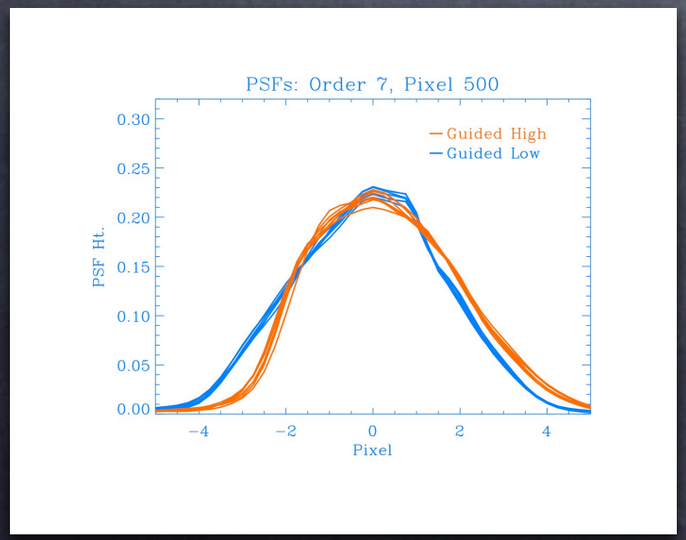
Pixel


PSFs: Order 7, Pixel 500
Guided High
Guided Low
PSF Ht.
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0.25
0.20
0.15
0.10
0.05
0.00
−4
−2
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2
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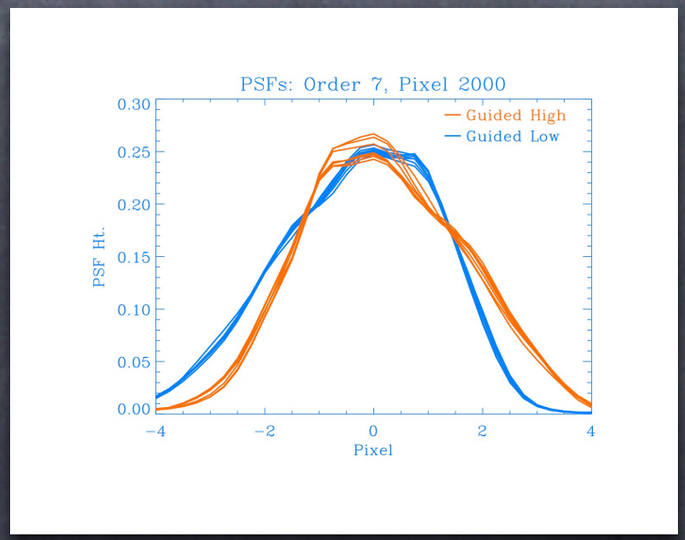
Pixel


PSFs: Order 7, Pixel 2000
Guided High
Guided Low
PSF Ht.
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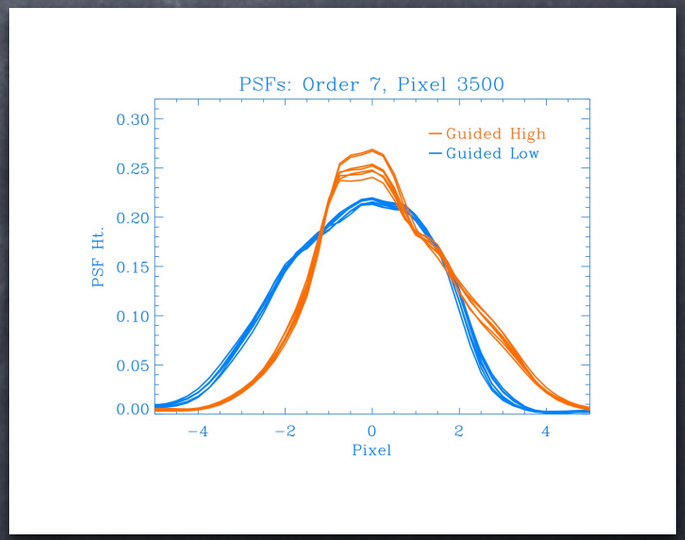
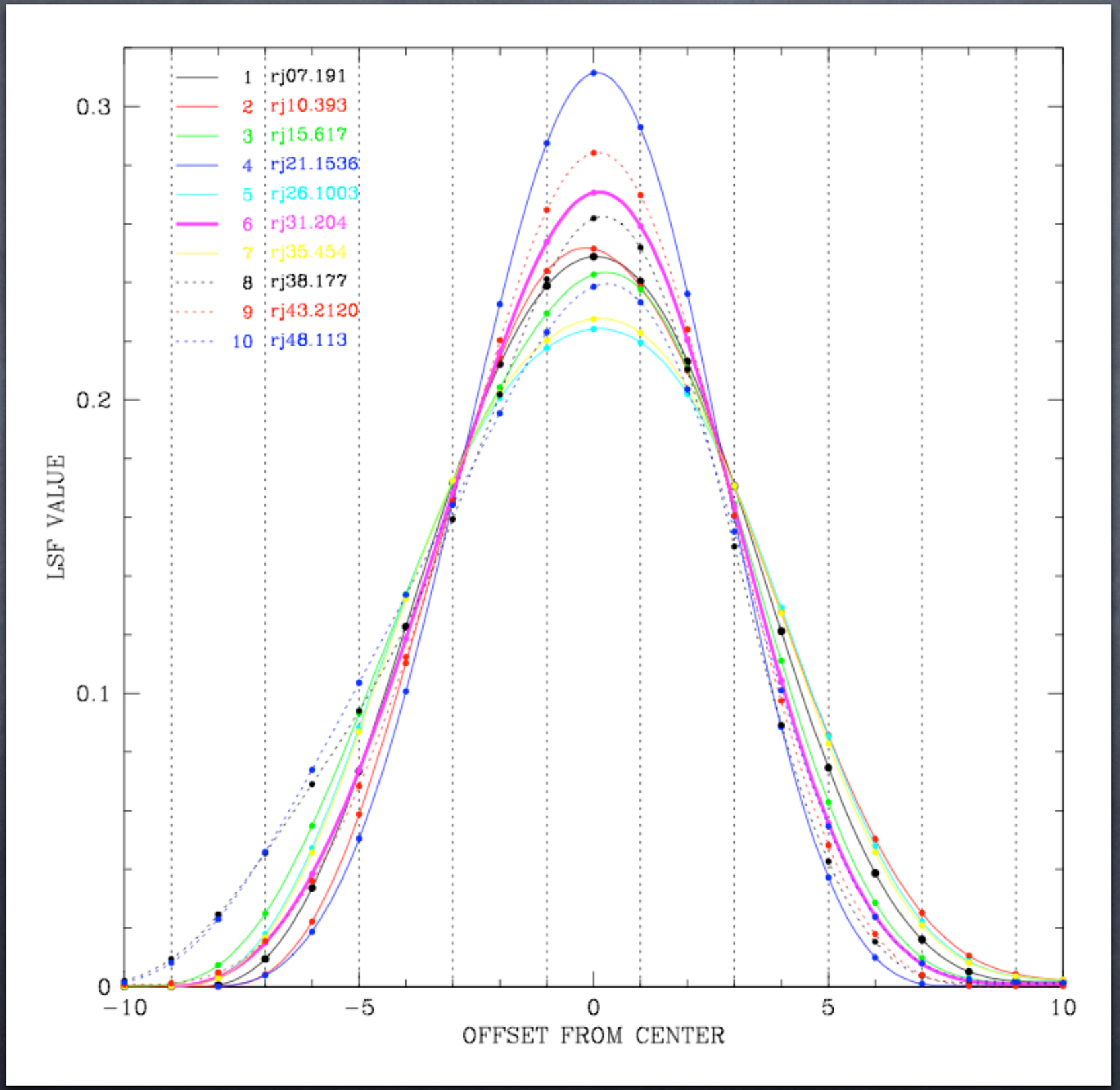
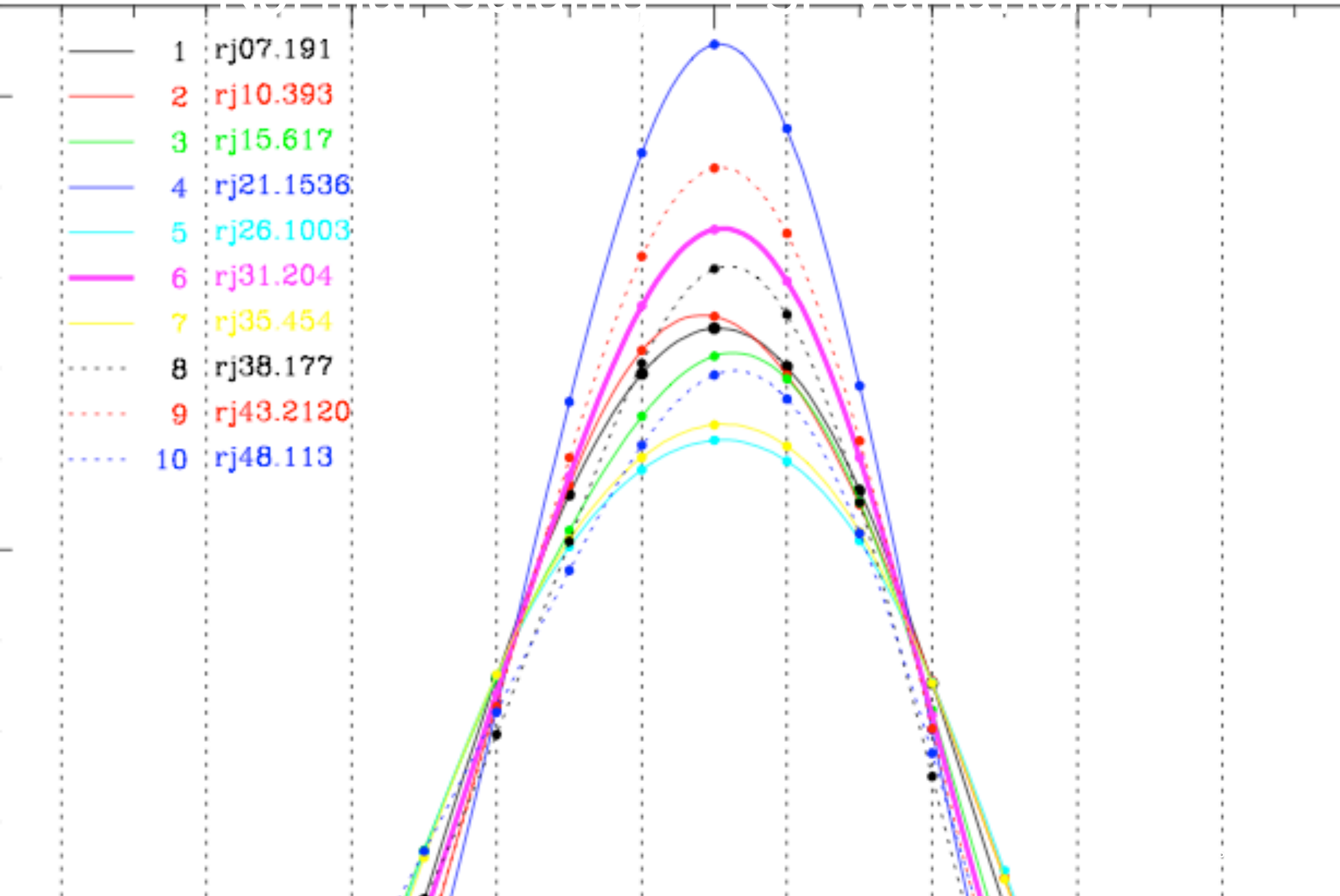
0.25
0.20
0.15
0.10
0.05
0.00
−4
−2
0
2
4
Pixel


PSFs: Order 7, Pixel 3500
Guided High
Guided Low
PSF Ht.
0.30
0.25
0.20
0.15
0.10
0.05
0.00
−4
−2
0
2
4
Pixel

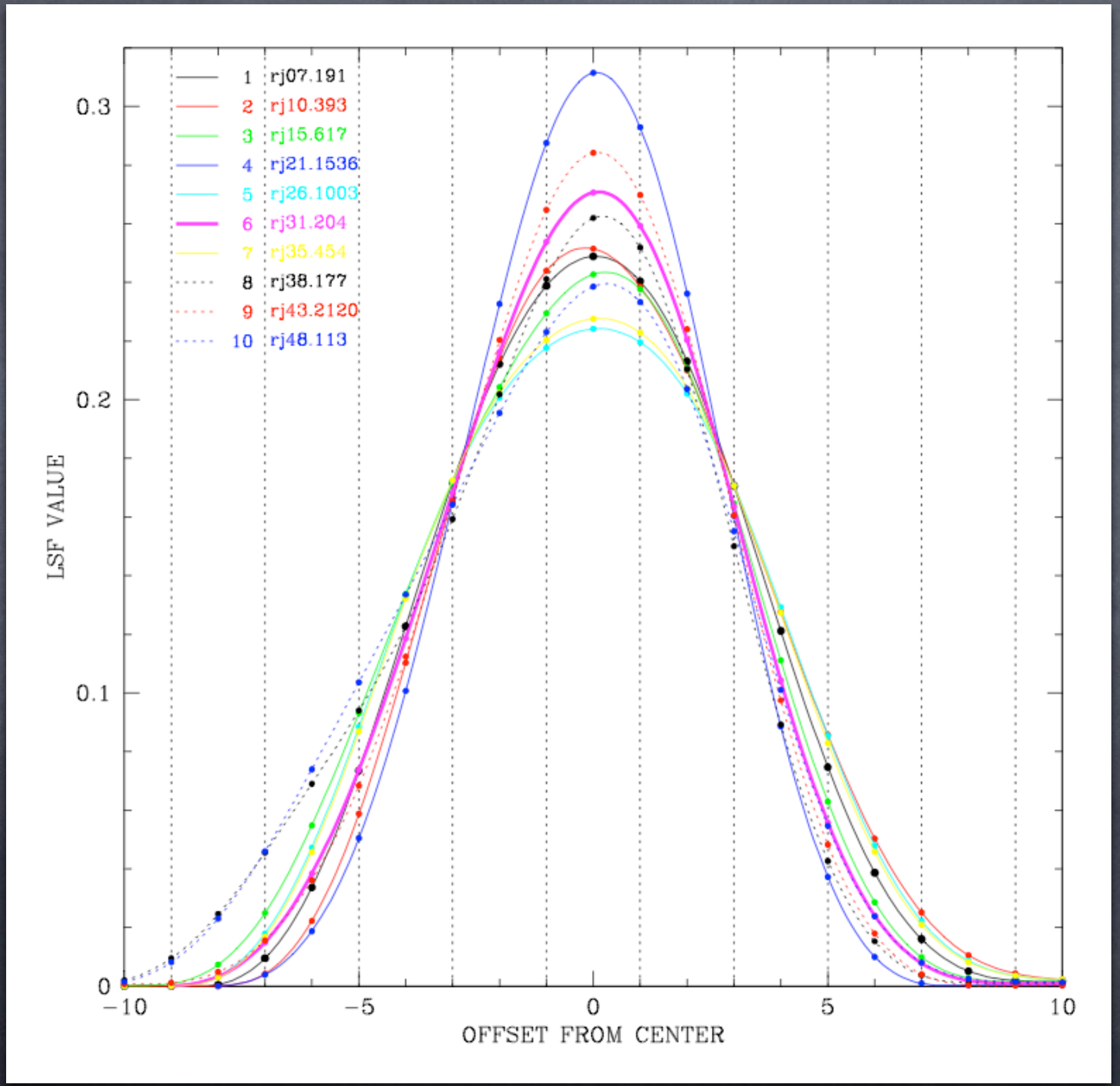
Normal Guiding - PSF Variations



Jay Anderson, STSCI

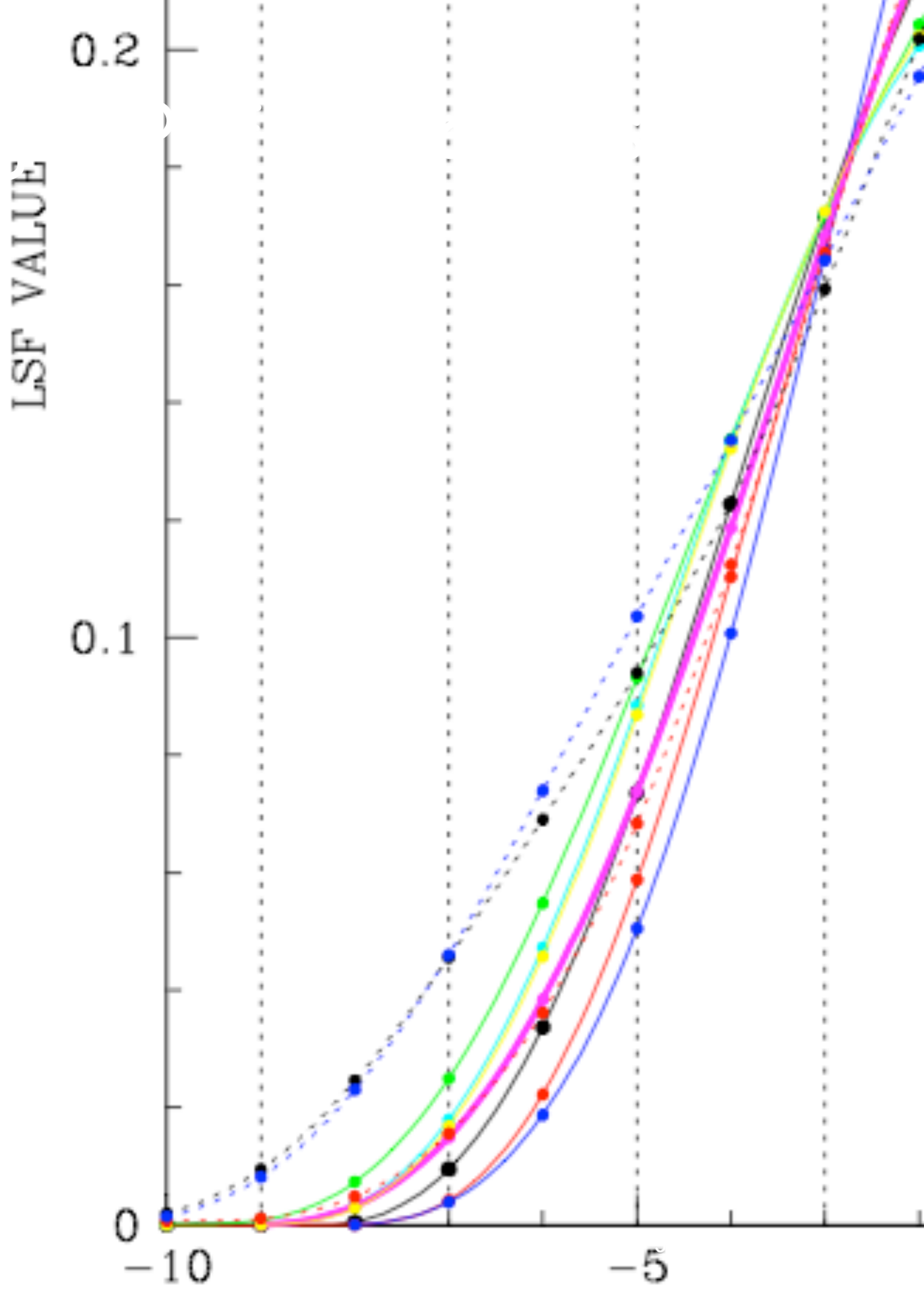

1 rj07.191
2 rj10.393
3 rj15.617
4 rj21.1536
5 rj26.1003
6 rj31.204
7 rj35.454
8 rj38.177
9 rj43.2120
10 rj48.113

Normal Guiding - PSF Variations

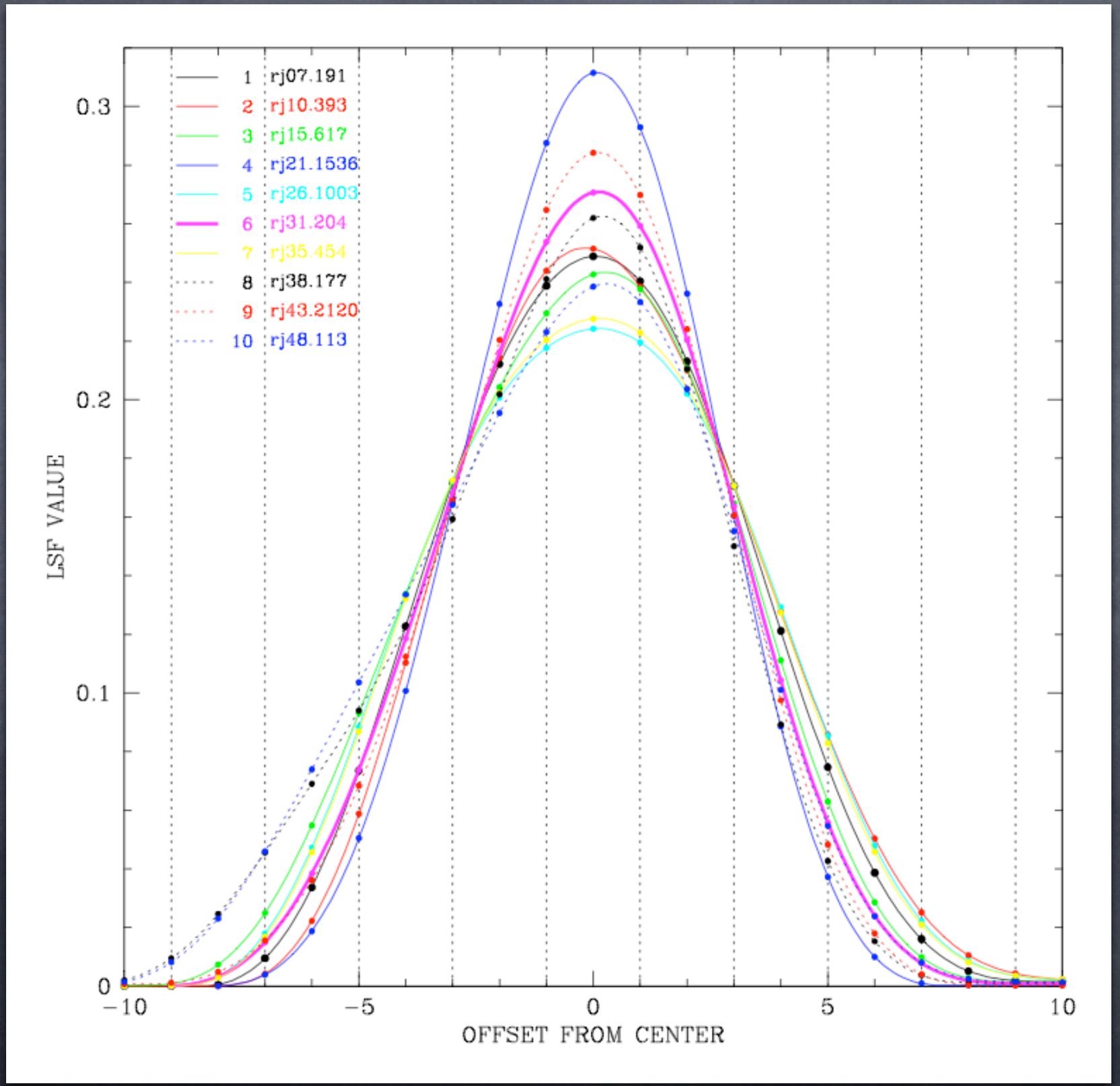


Jay Anderson, STSCI

Normal Guidi

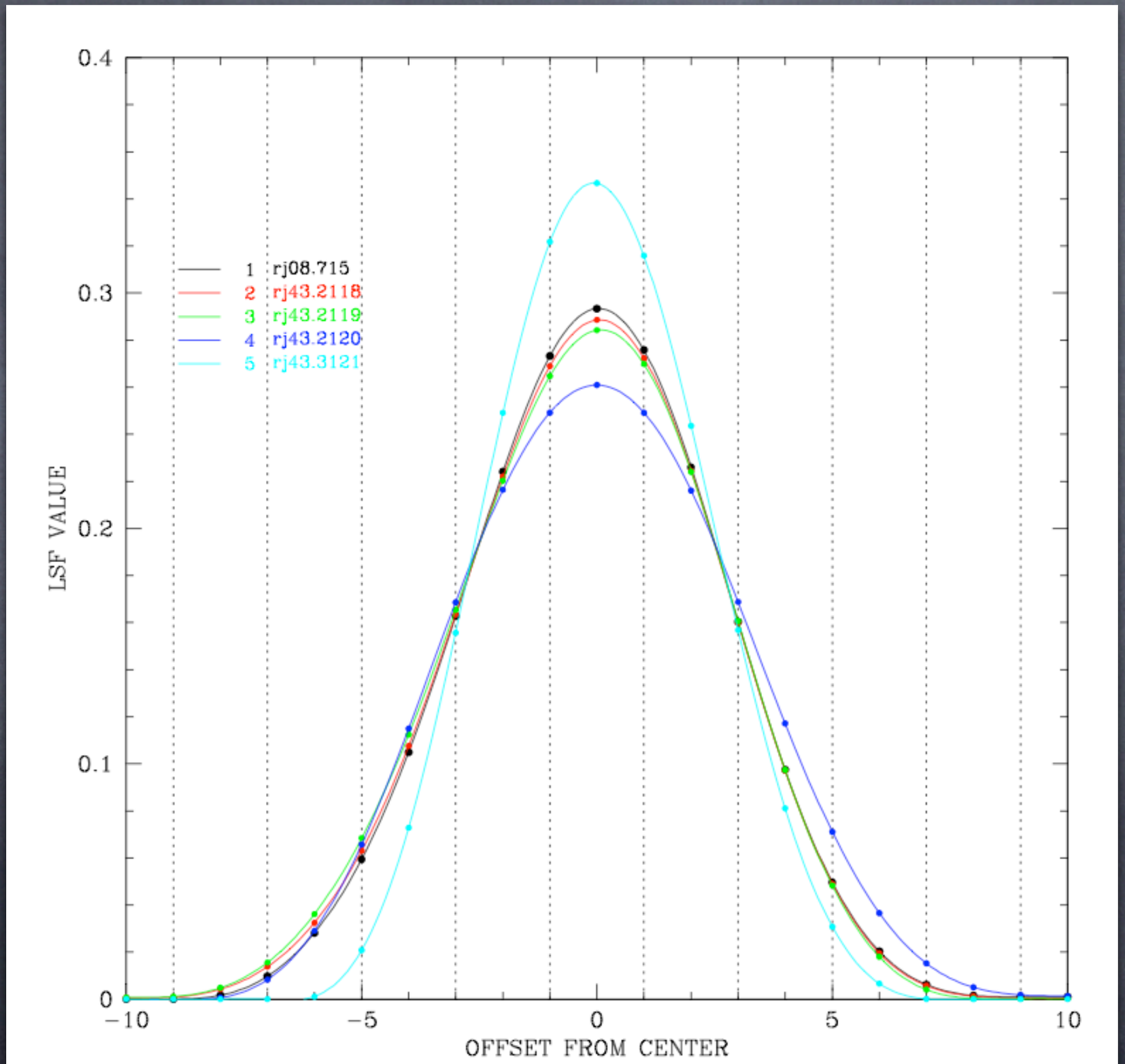


Normal Guiding - PSF Variations



Jay Anderson, STSCI

Normal Guiding - PSF Variations

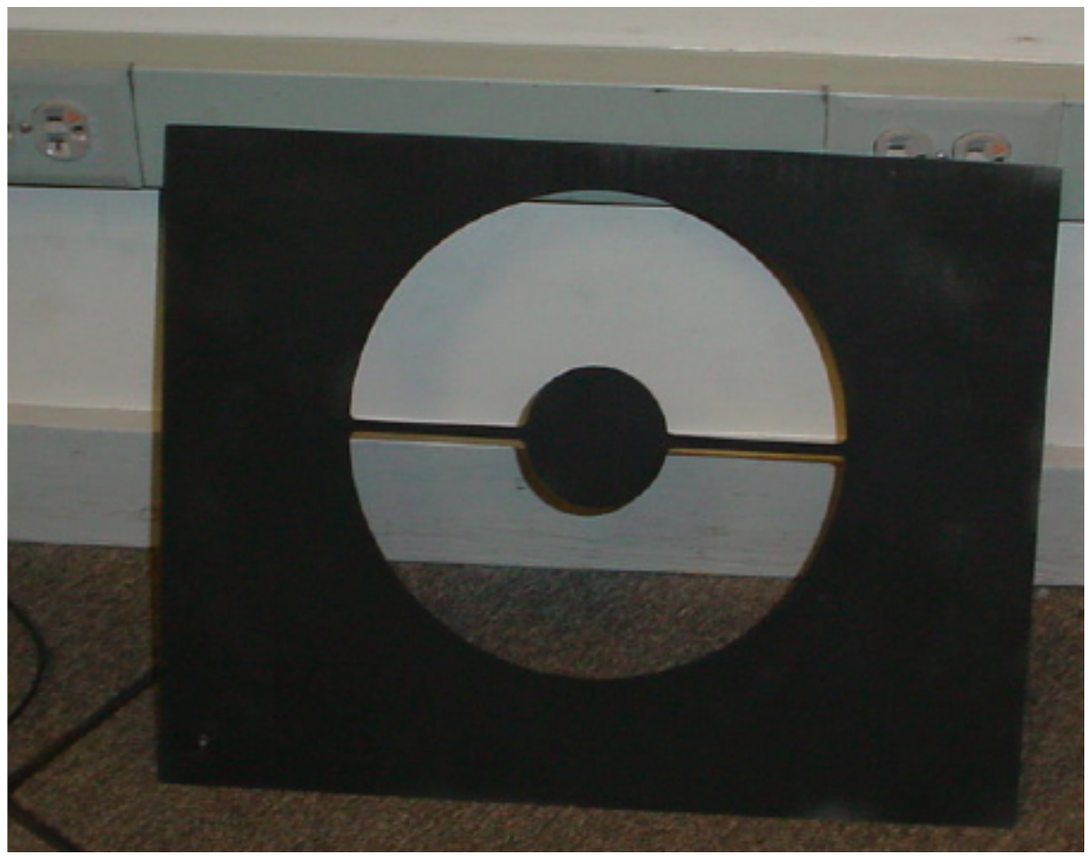


Jay Anderson, STSCI

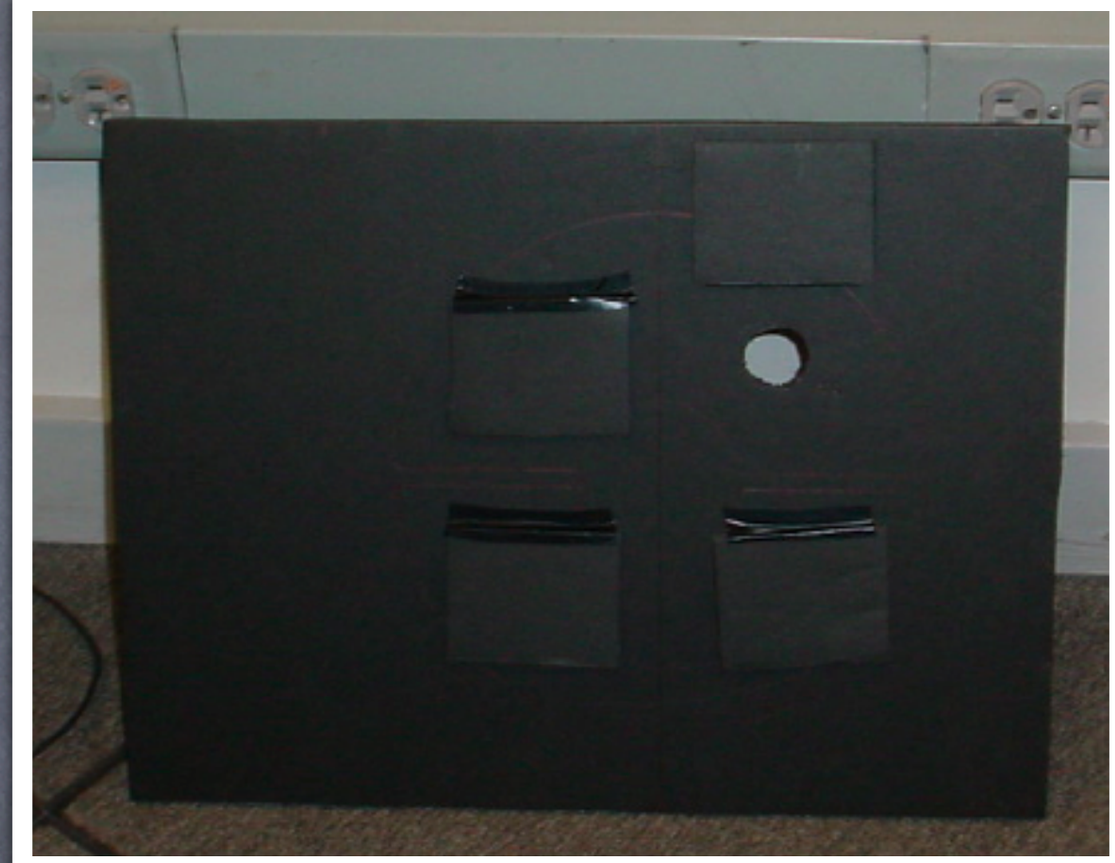
HIRES RV Errors

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

Hartmann Mask Tests

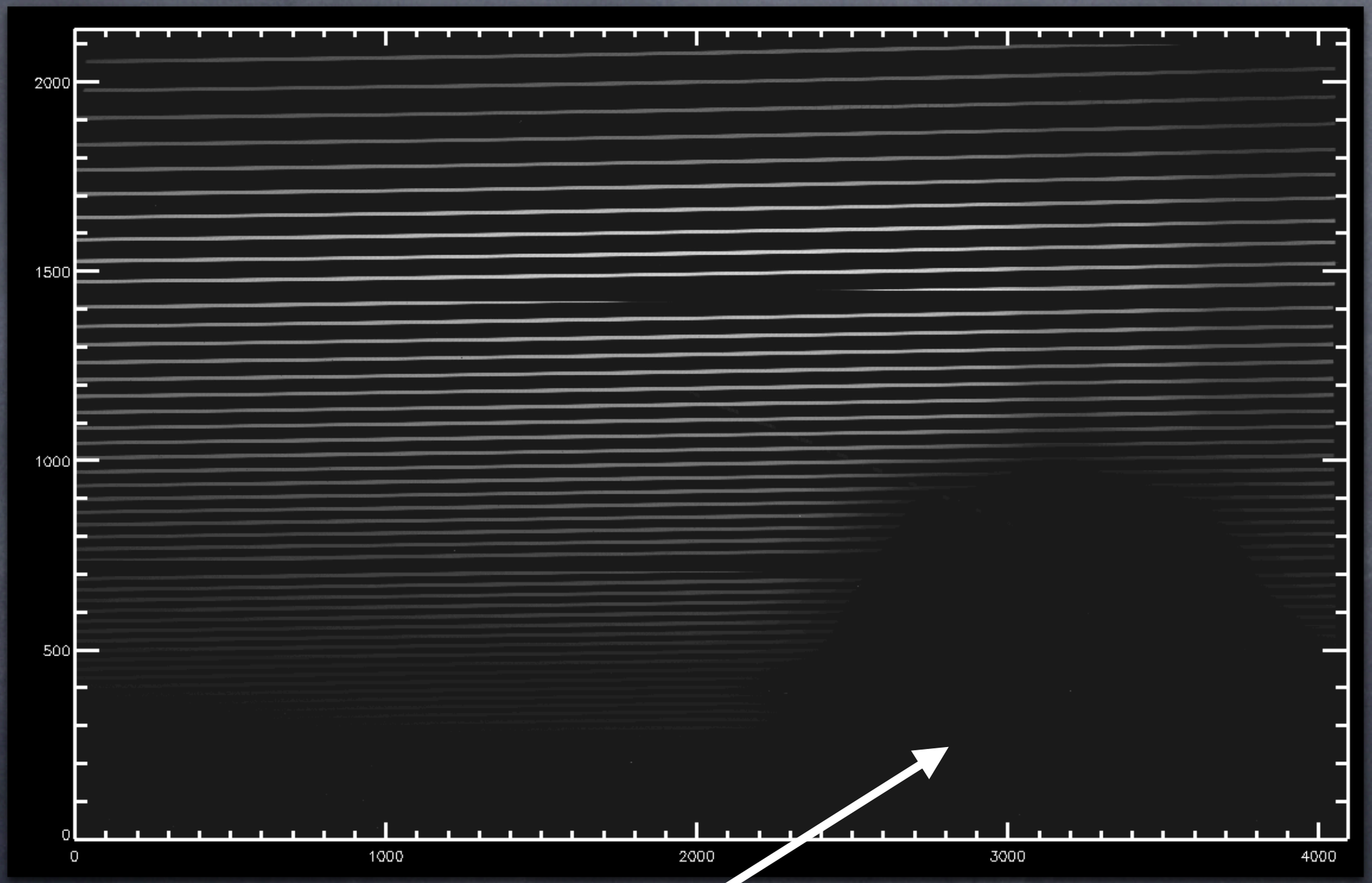


Standard Collimator Mask



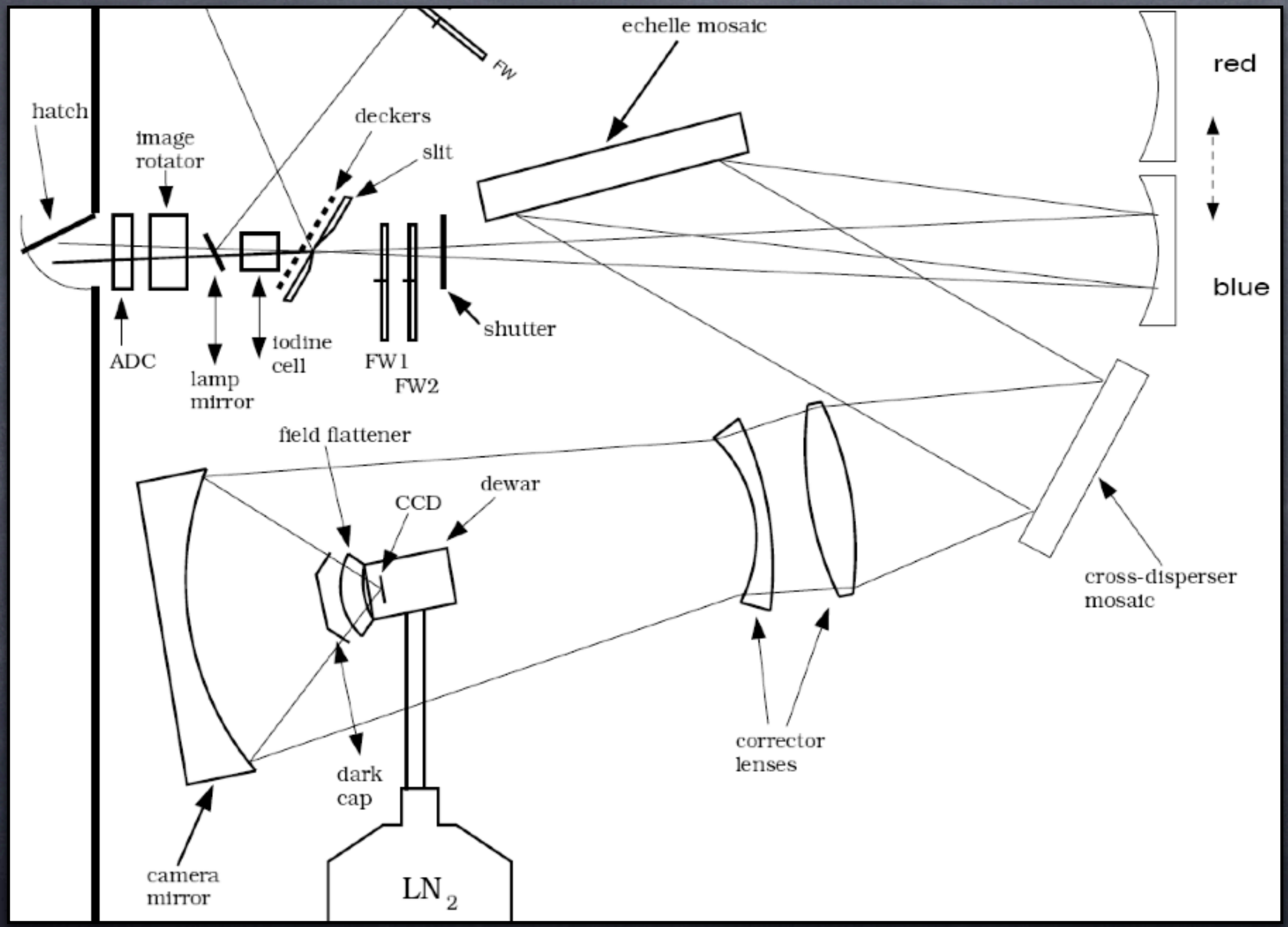
Hartmann Mask

Vignetting

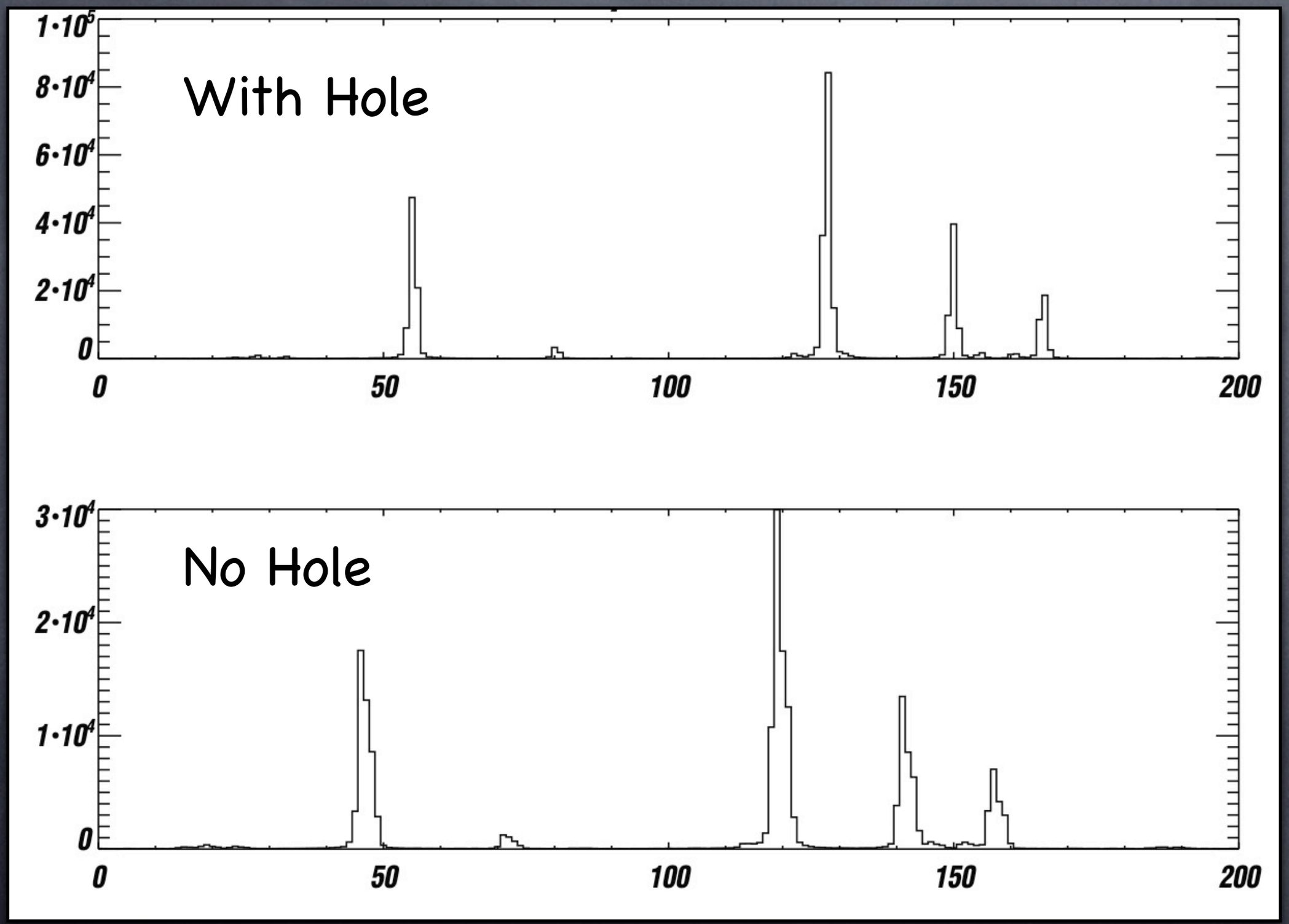


Dewar shadow

HIRES Vignetting



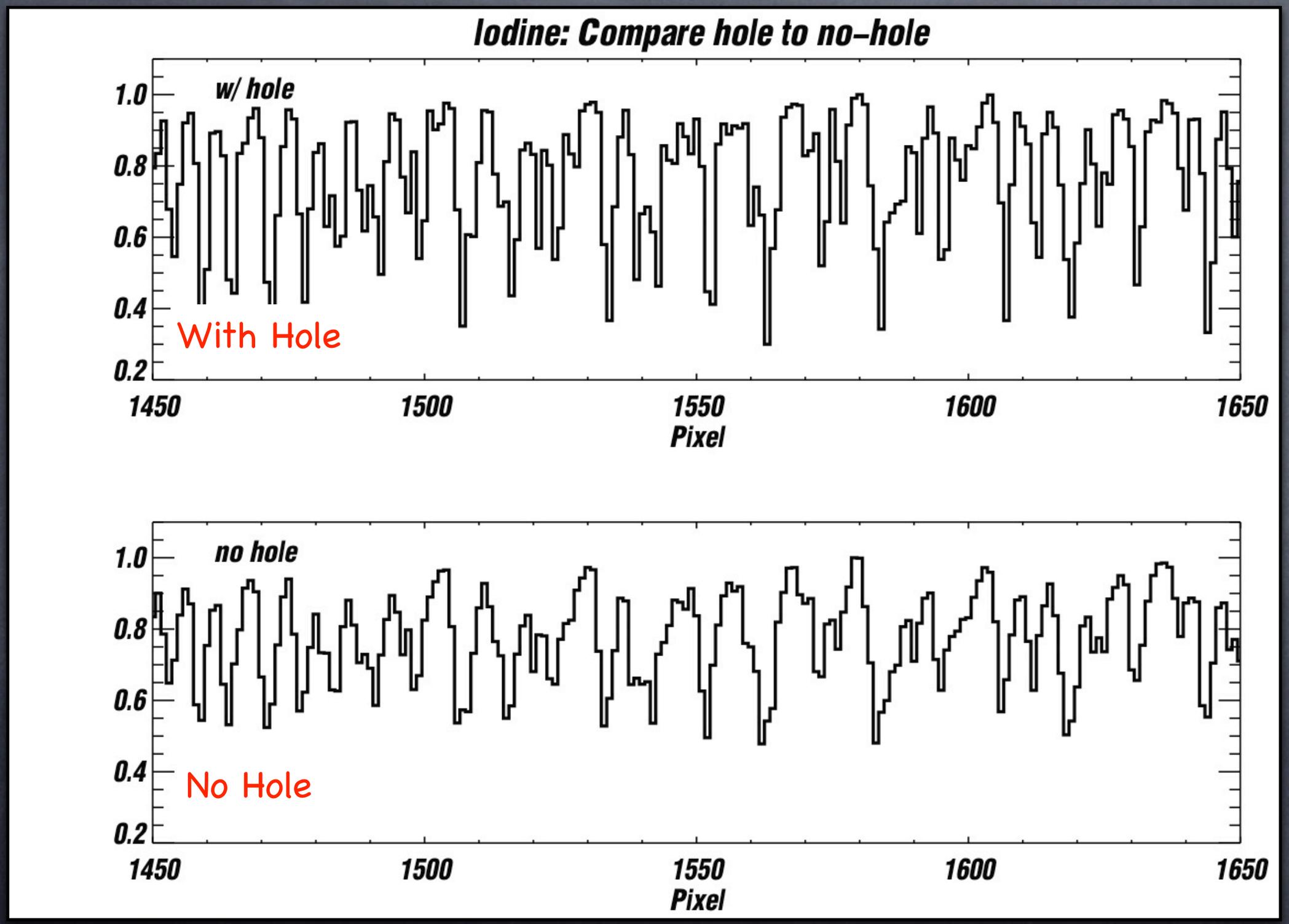
ThAr Spectra



R ~ 150,000

R = 60,000

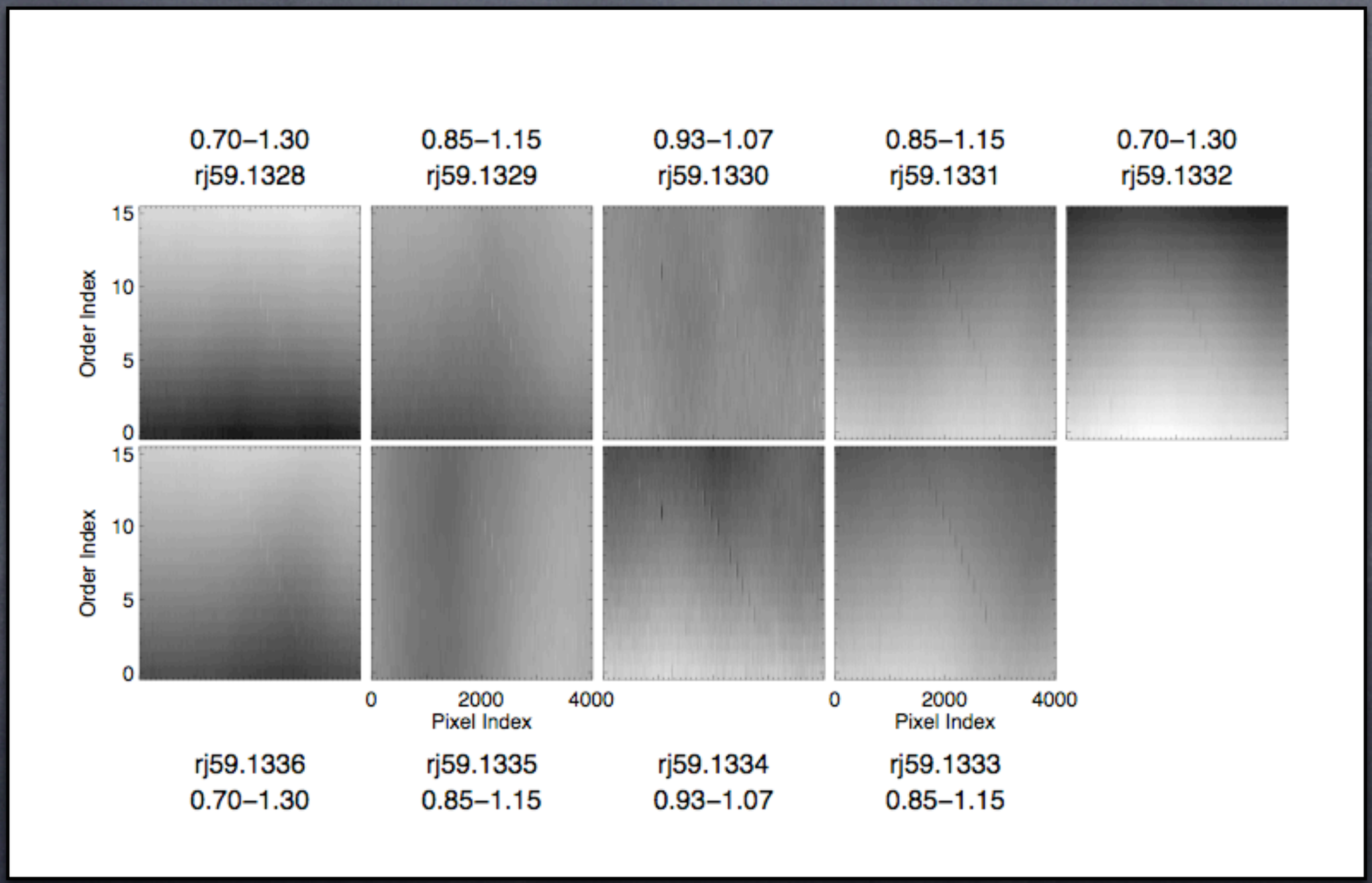
Iodine Spectra



R ~ 150,000

R = 60,000

Vignetting & Pupil Illumination



Intentional mis-guiding along spatial direction → varying continuum

HIRES RV Errors Summary So Far:

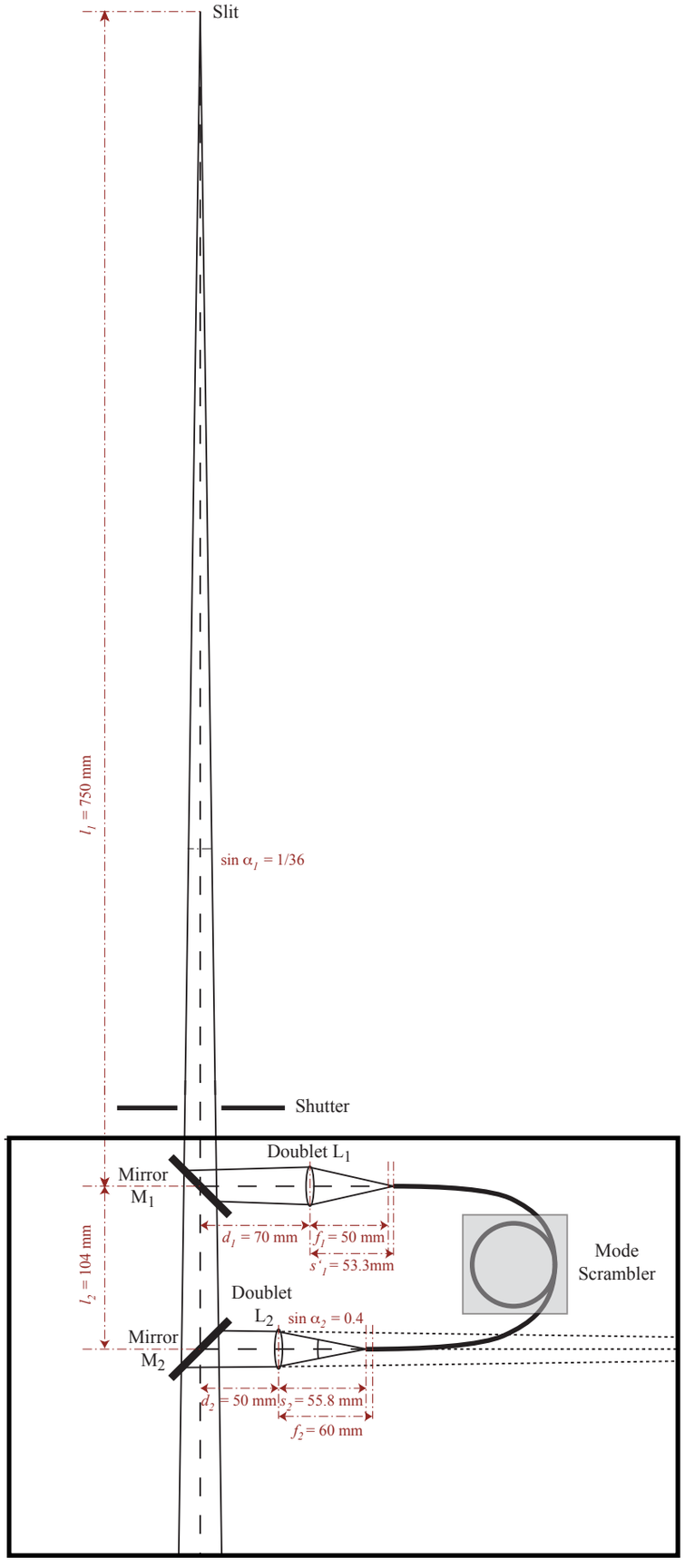
HIRES PSF will vary due to two effects:

1. The non-uniformly imaged slit that is imaged on the CCD

2. The non-uniform pupil illumination of the imperfect HIRES optics by the knife-edge effect on the pupil when the telescope is not in perfect focus.

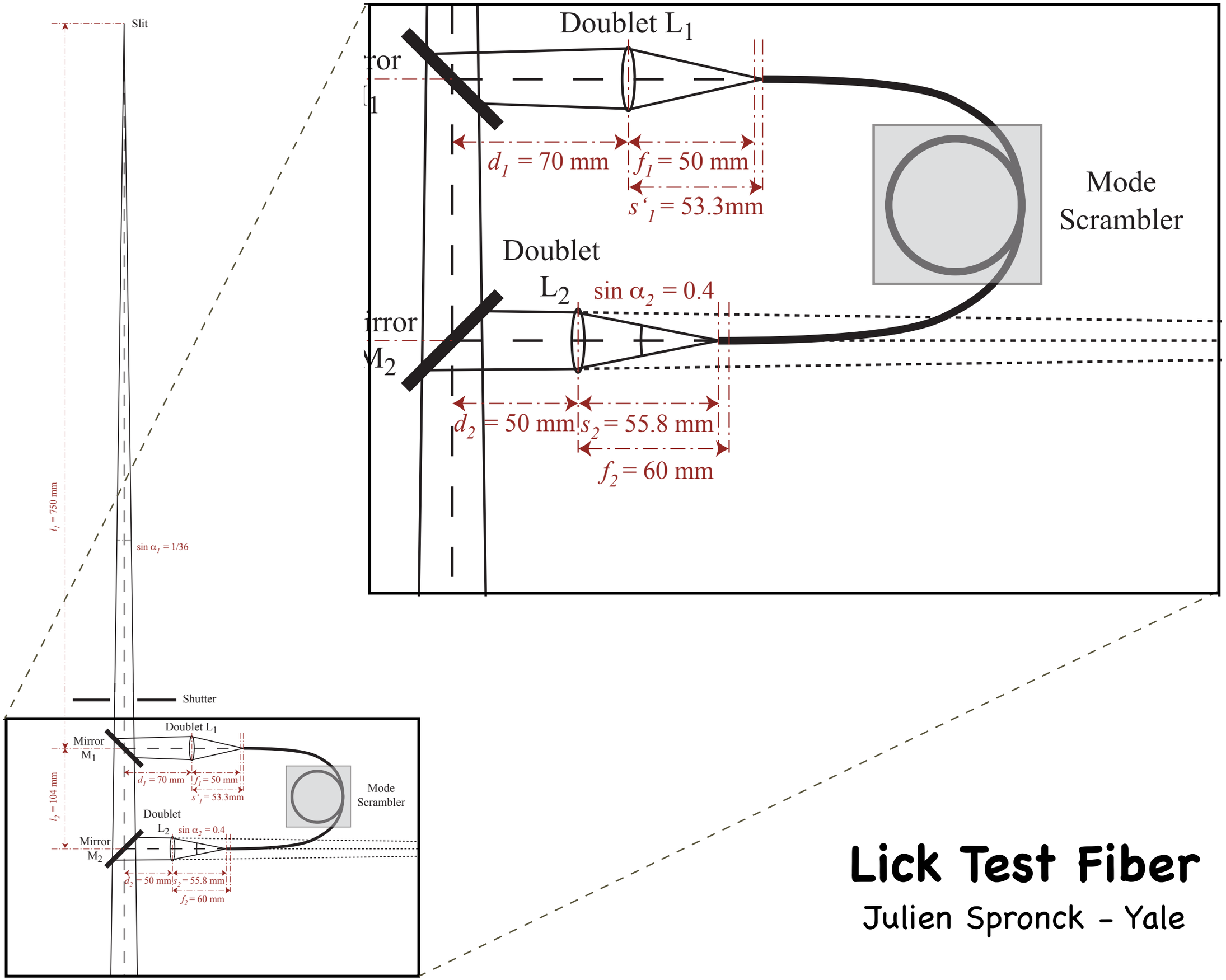
HIRES RV Errors

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



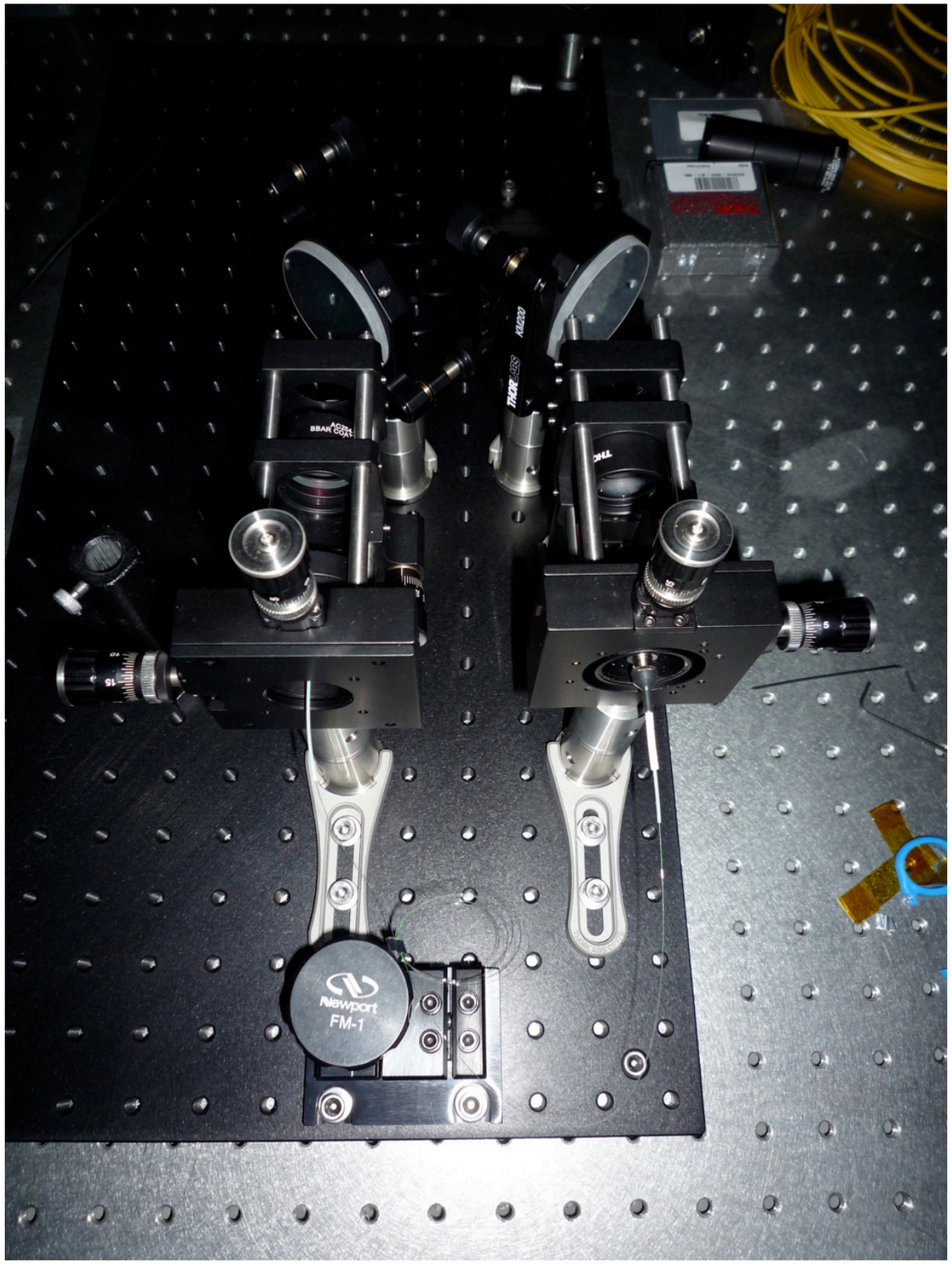
Lick Test Fiber

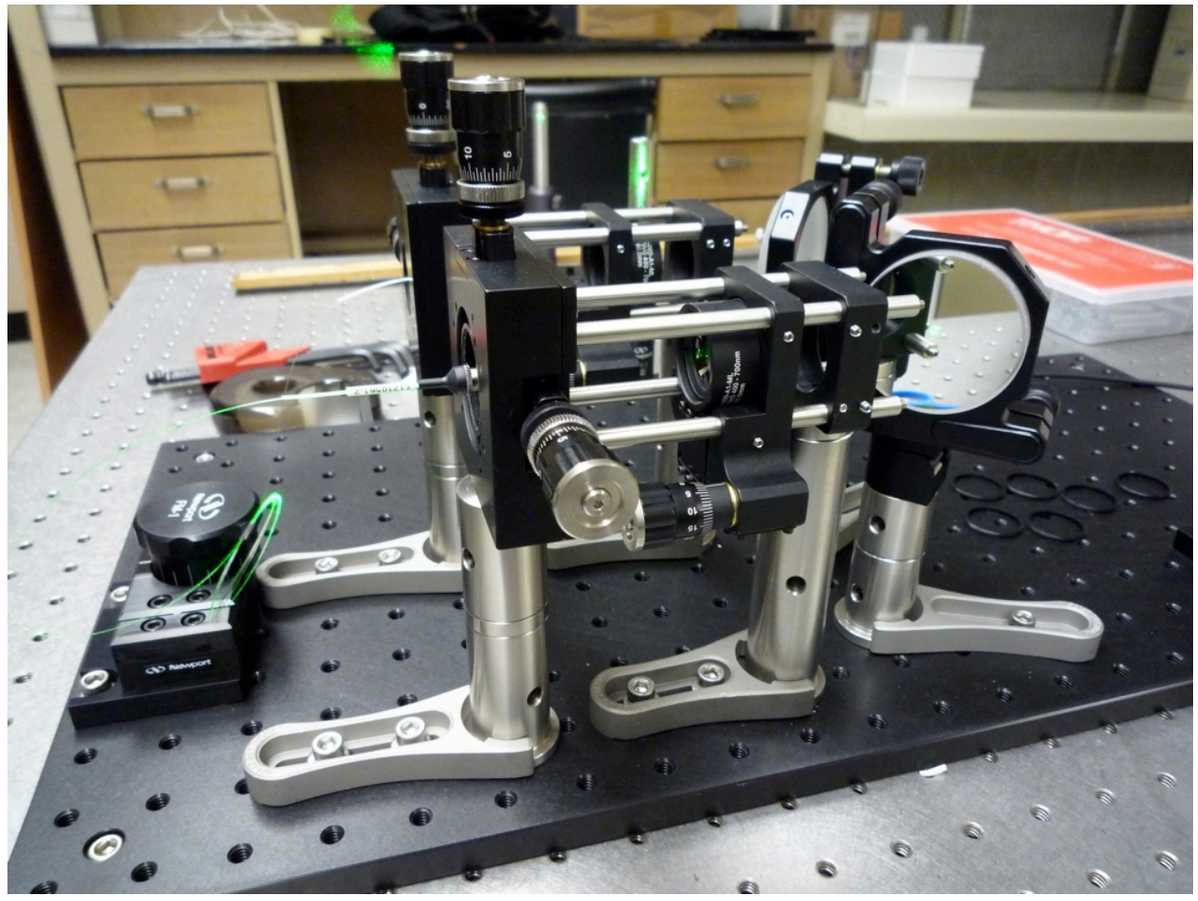
Julien Spronck - Yale



Lick Test Fiber

Julien Spronck - Yale

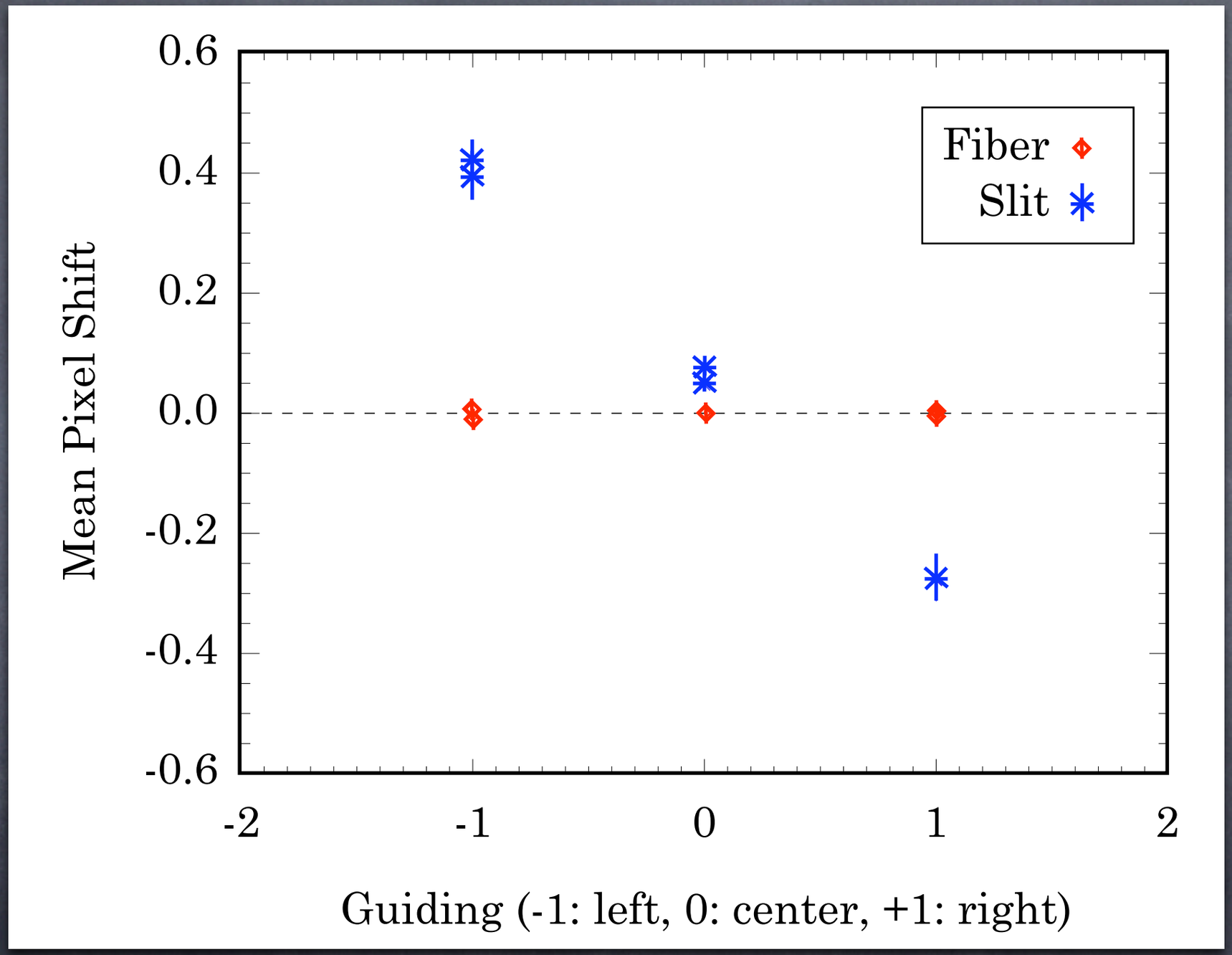




Lick Test Fiber

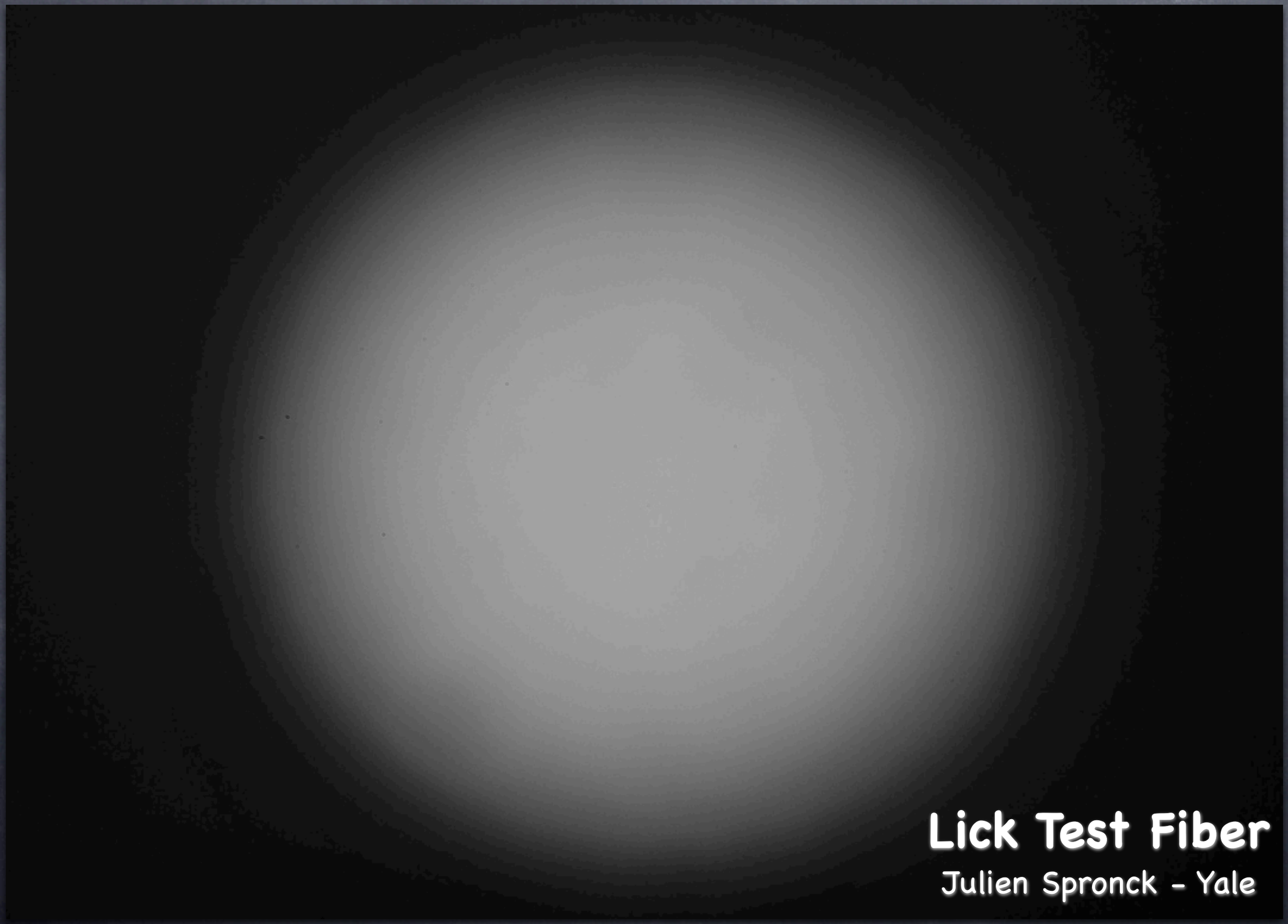
Julien Spronck - Yale

Fiber Input - Lick Mis-guiding Tests



PSF Stability: ~1.0 pixel → <0.01 pixels

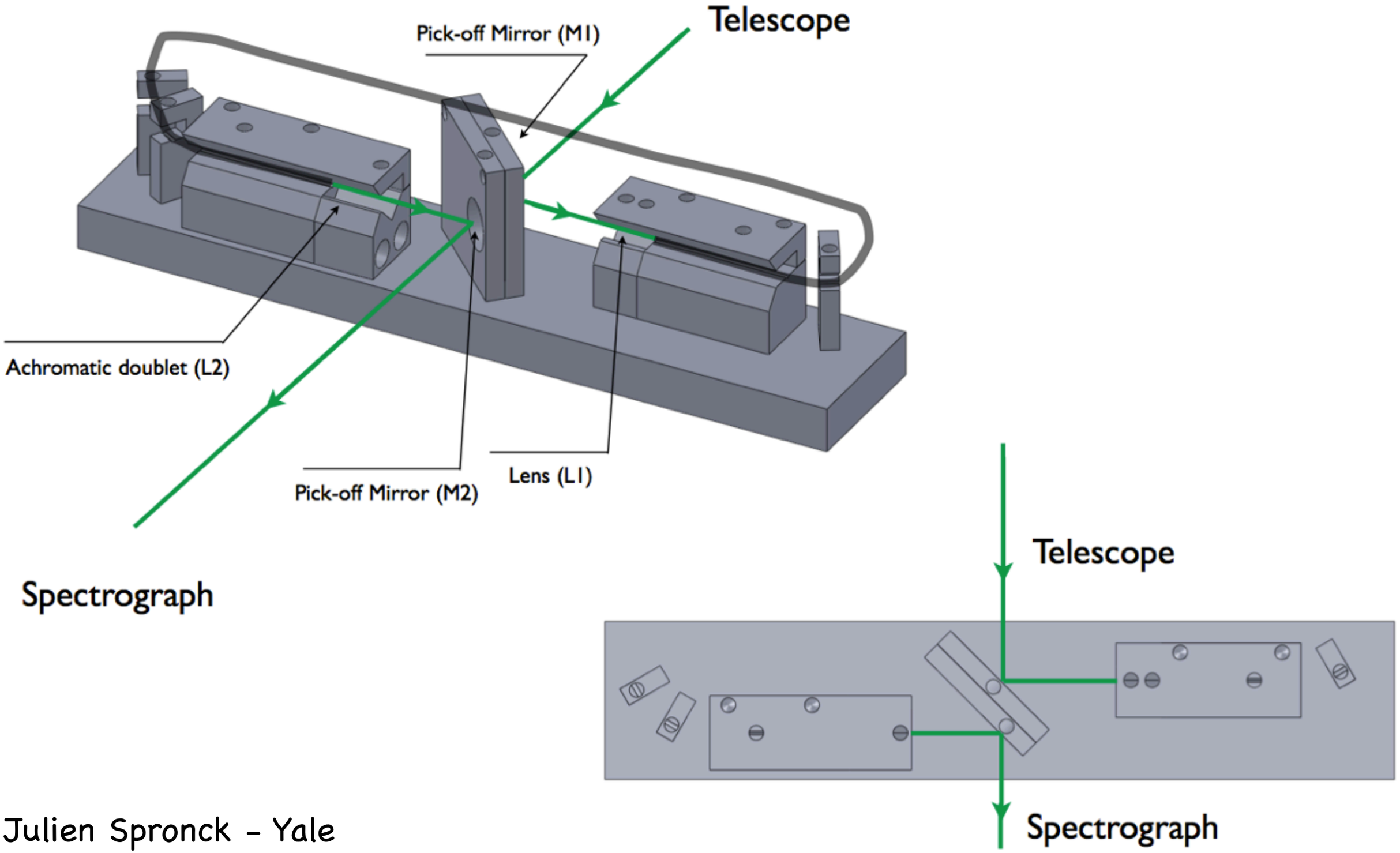
Image of Fiber output



Lick Test Fiber

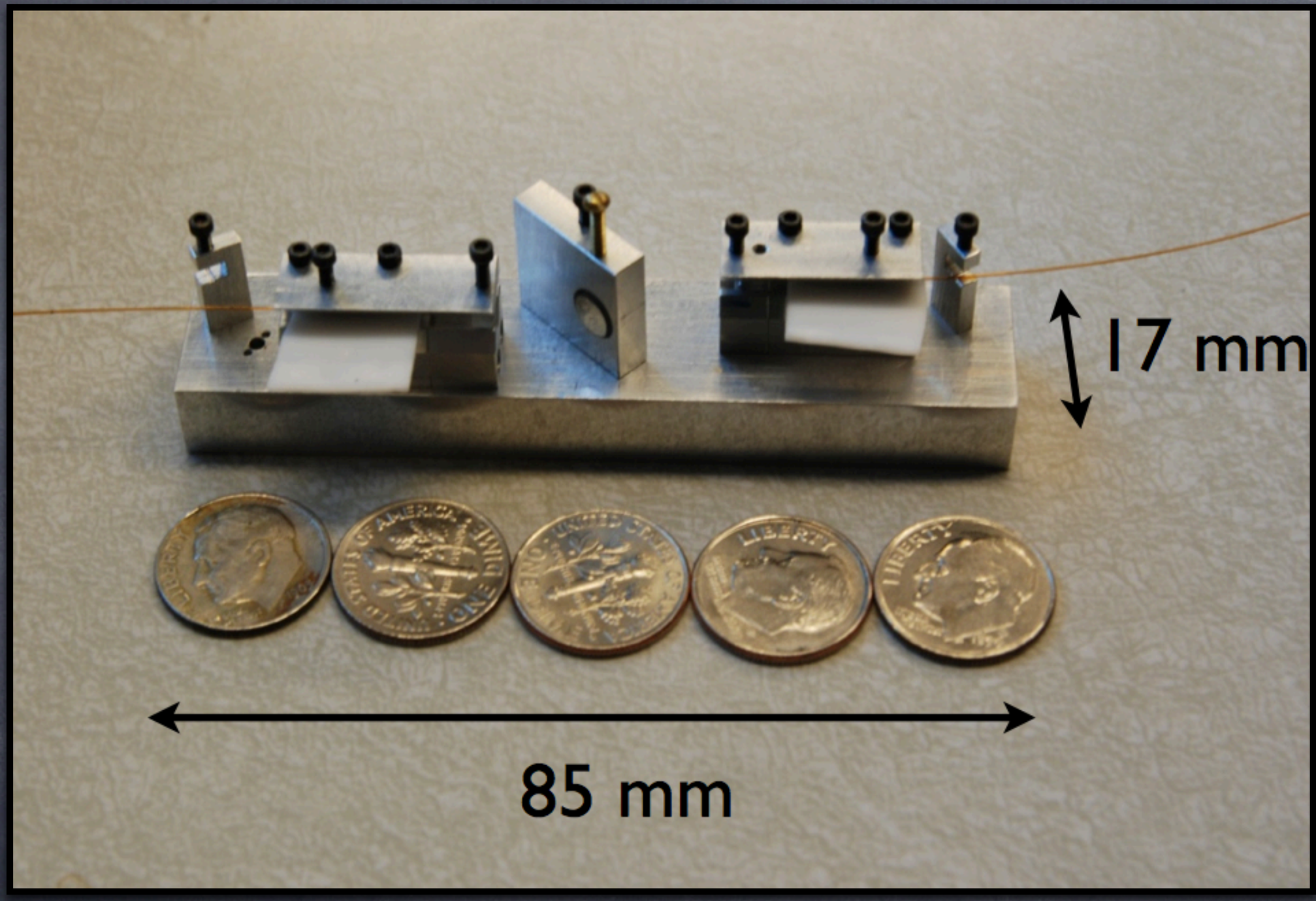
Julien Spronck - Yale

Keck Fiber Scrambler



Julien Spronck - Yale

Keck Fiber Scrambler



Julien Spronck - Yale

See Julien Spronck's Talk
on Wednesday

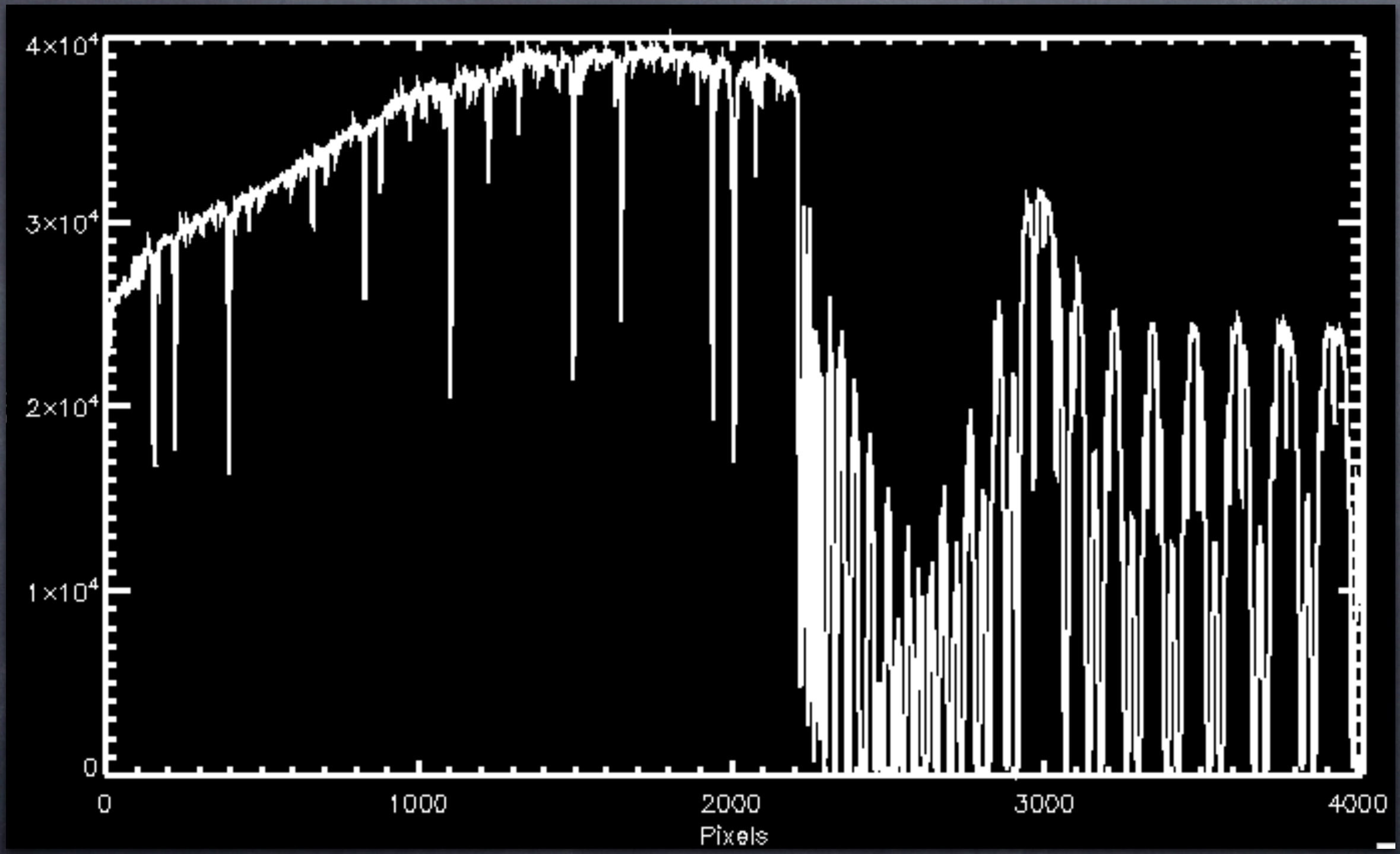
"Fiber Scrambling at Lick
and Keck Observatory"


Julien Spronck

HIRES RV Errors

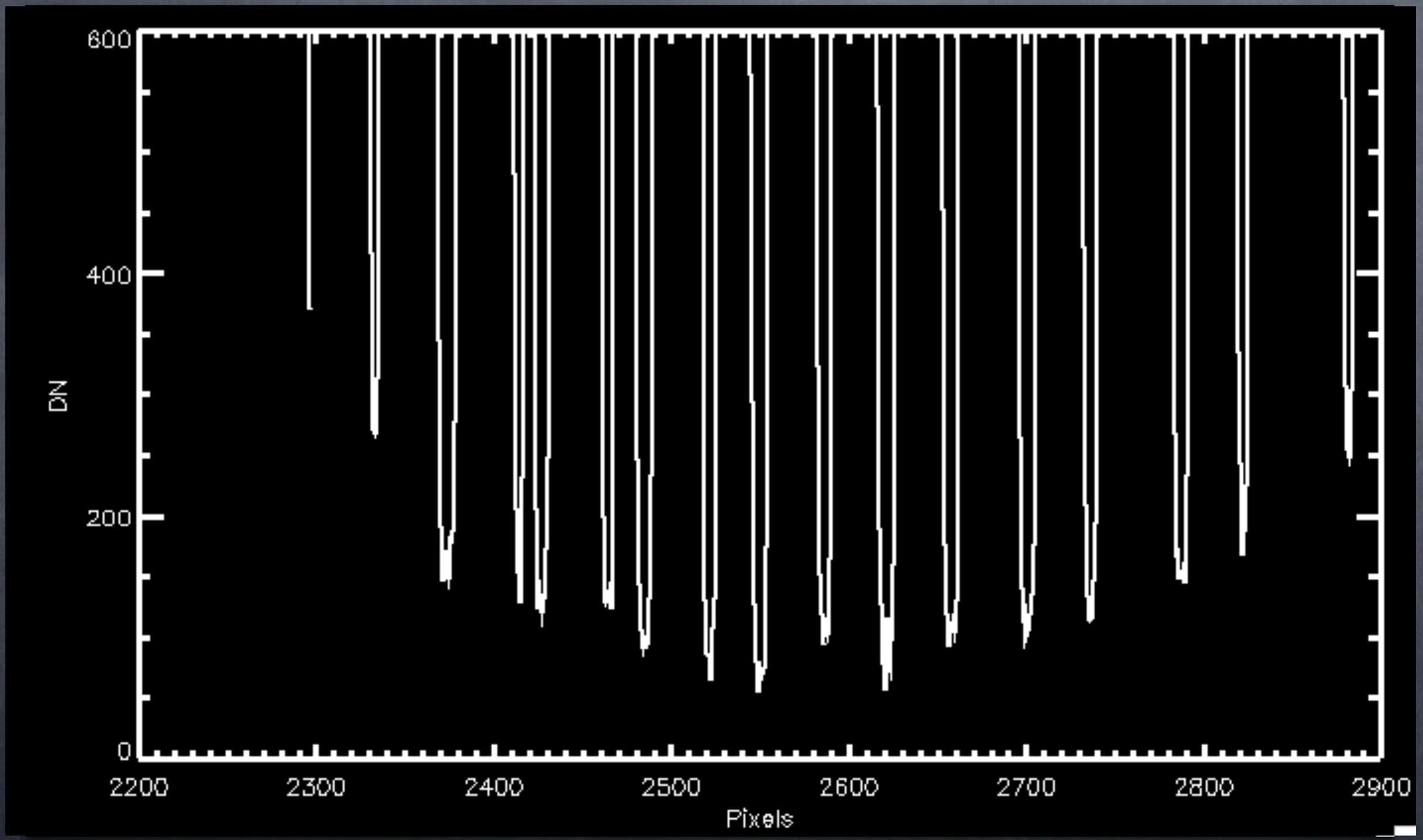
- Guiding
- Zonal aberrations / vignetting
- Fibers (The Solution!)
- Scattered light - HIRES
- Sky subtraction for faint targets

A-band (O_2) at 760 nm



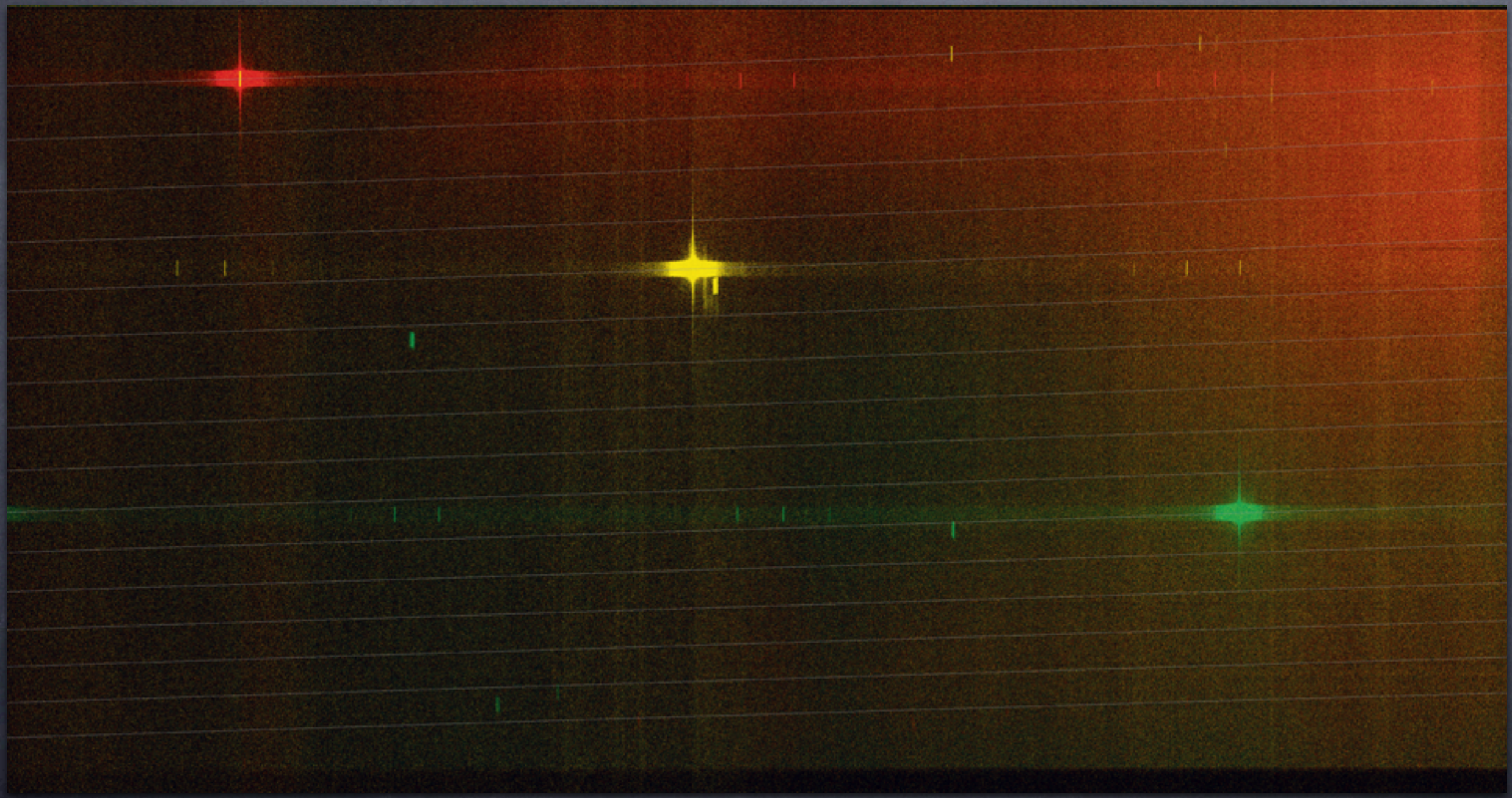
Scattered Light < 70/4e4 = 0.002
Intrinsically Black? Probably No.

A-band (O_2) at 760 nm



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

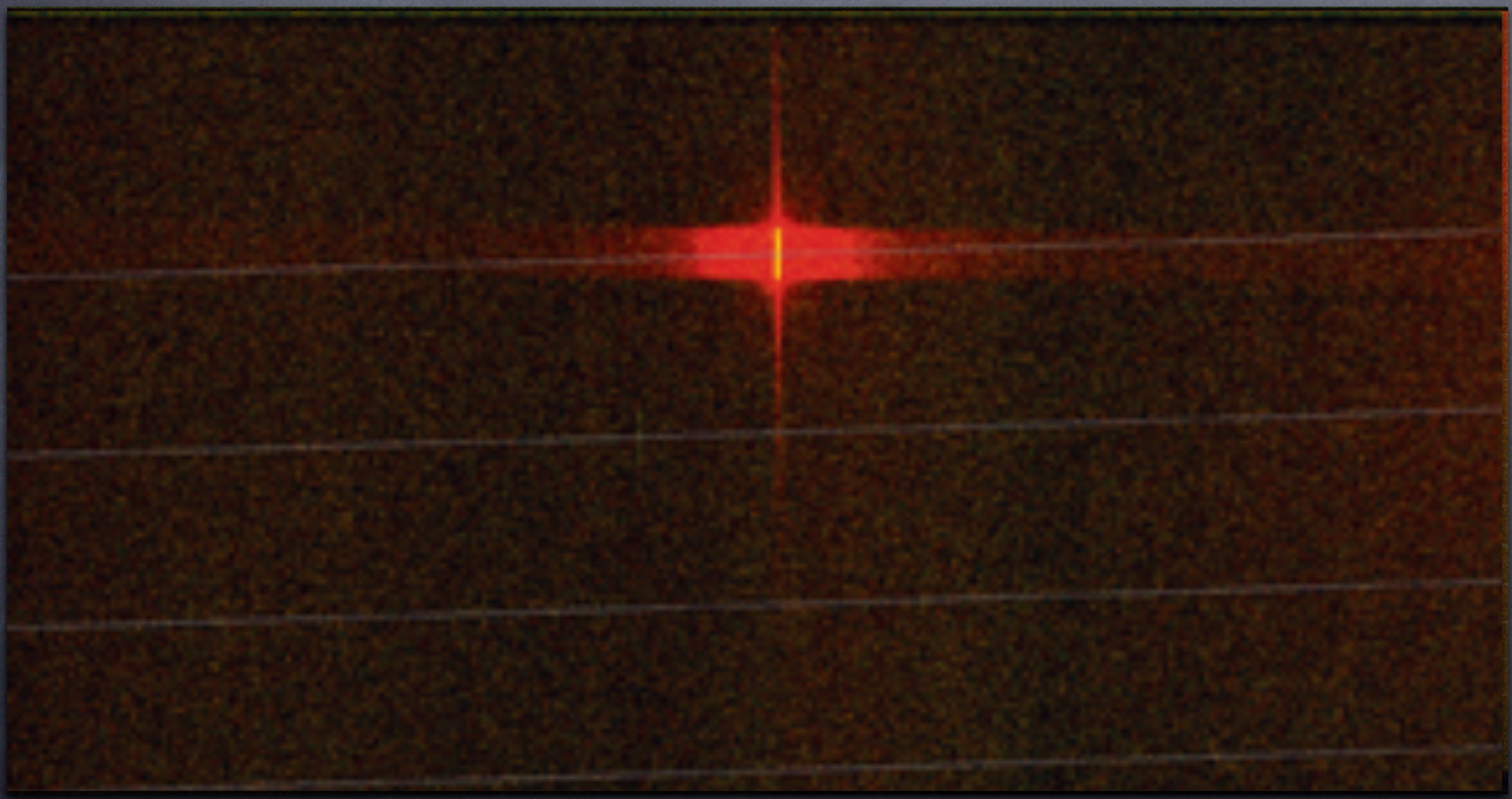
Scattered Light - Laser Tests



Laser Exposures by Grant Hill (Keck Observatory)

Stacked Image by Jeff Valenti (STScI)

Scattered Light - Laser Tests



Laser Exposures by Grant Hill (Keck Observatory)

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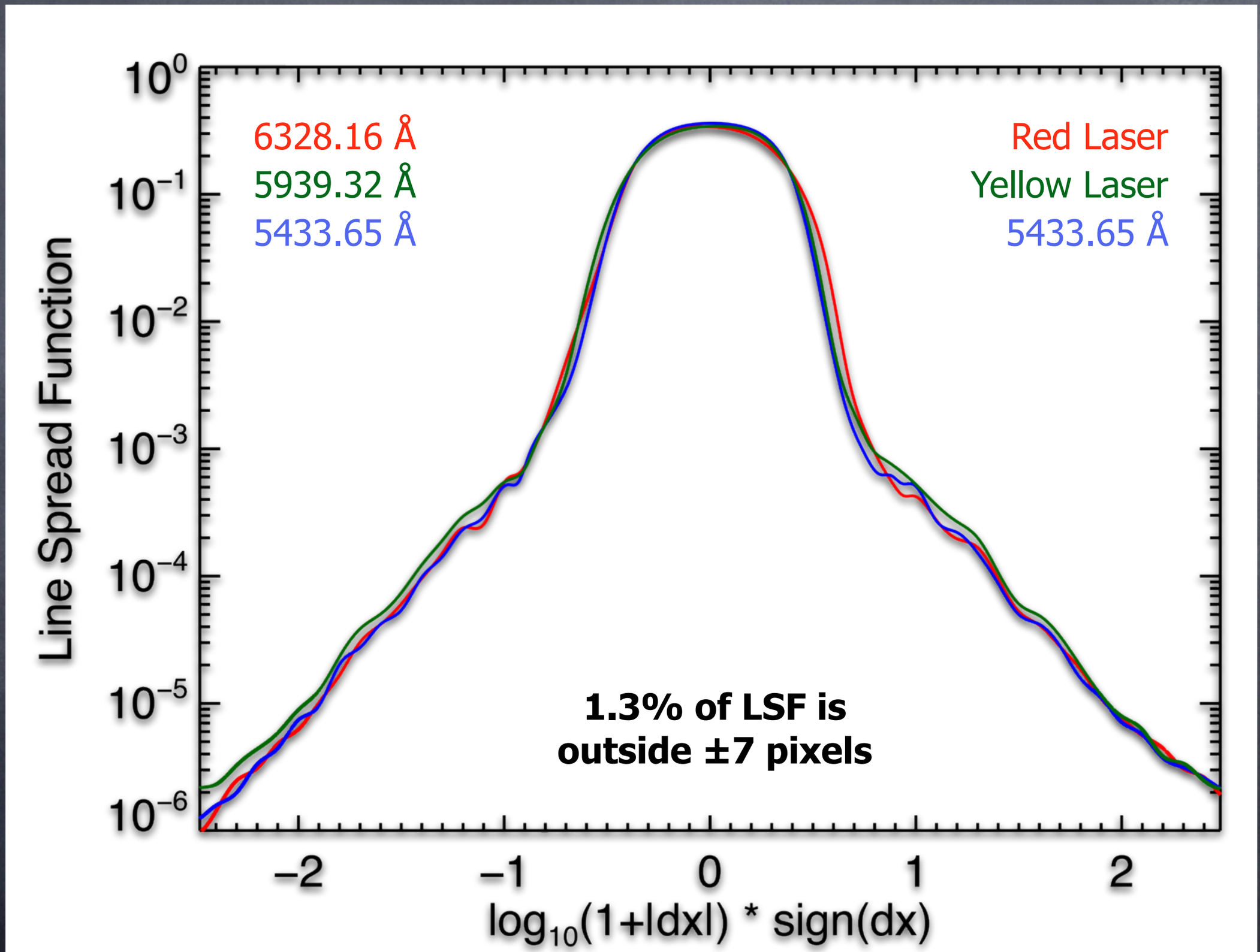
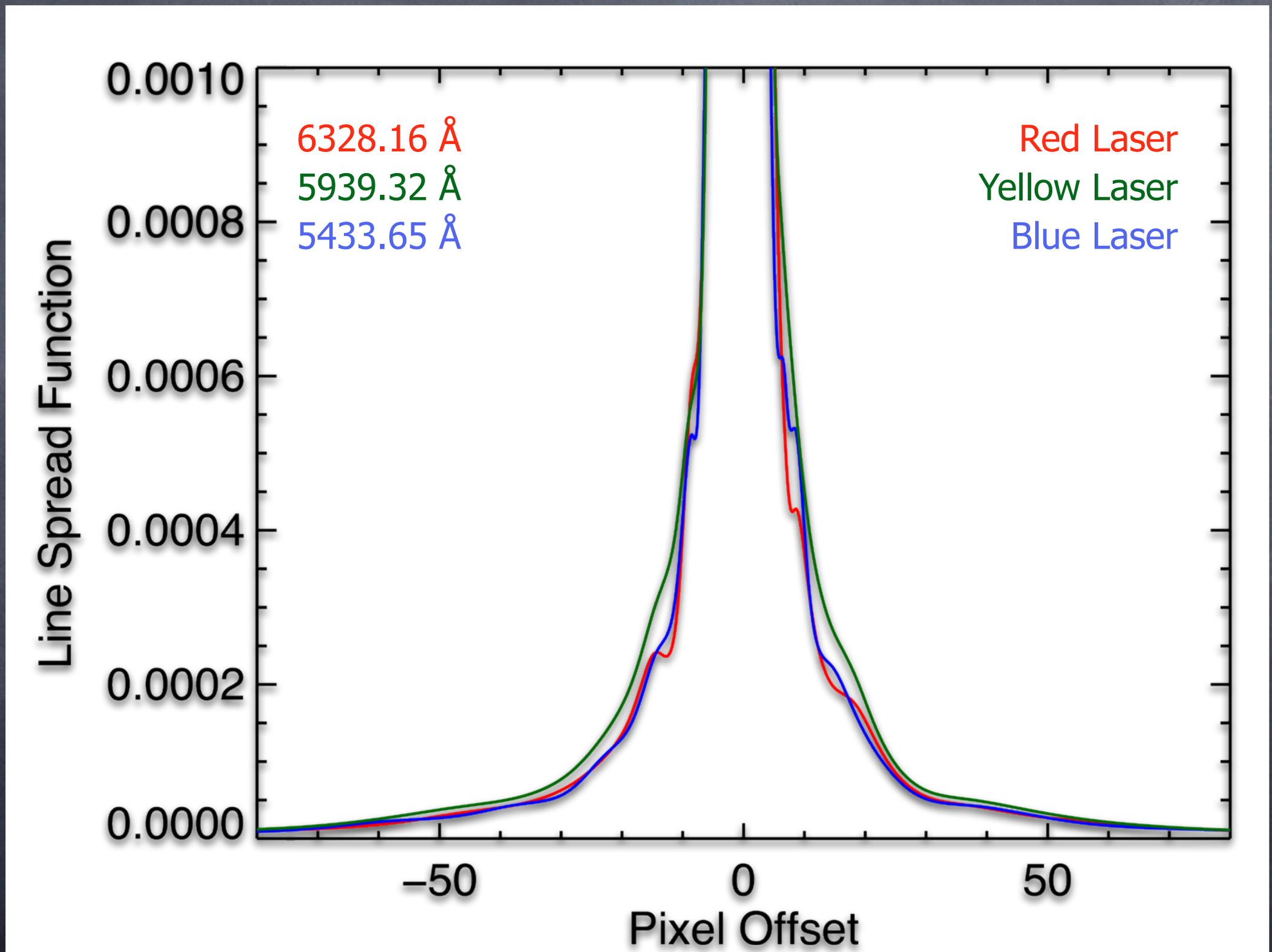
Entire Laser Profile on Log Scale



Entire Laser Profile on Log Scale



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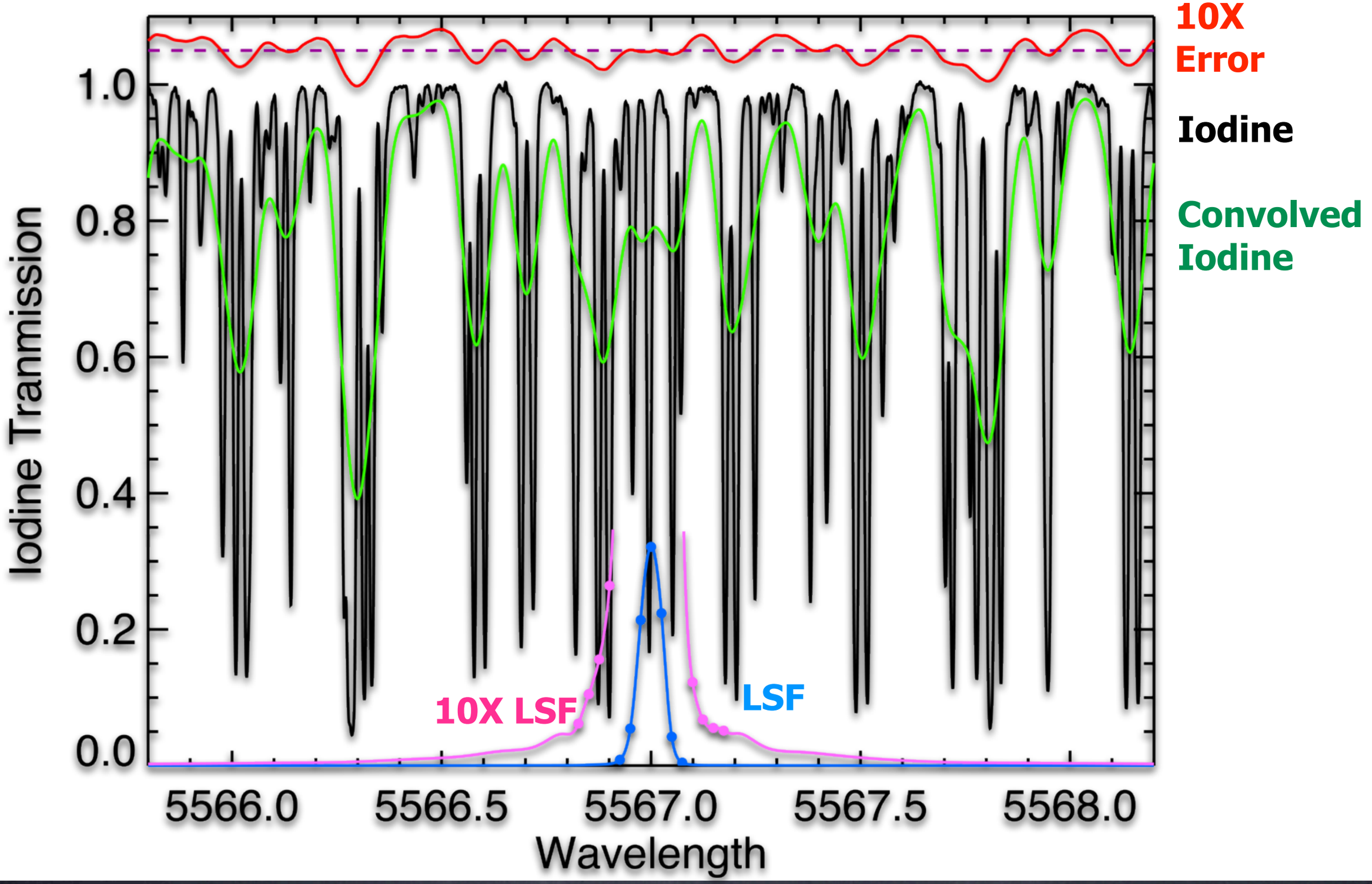
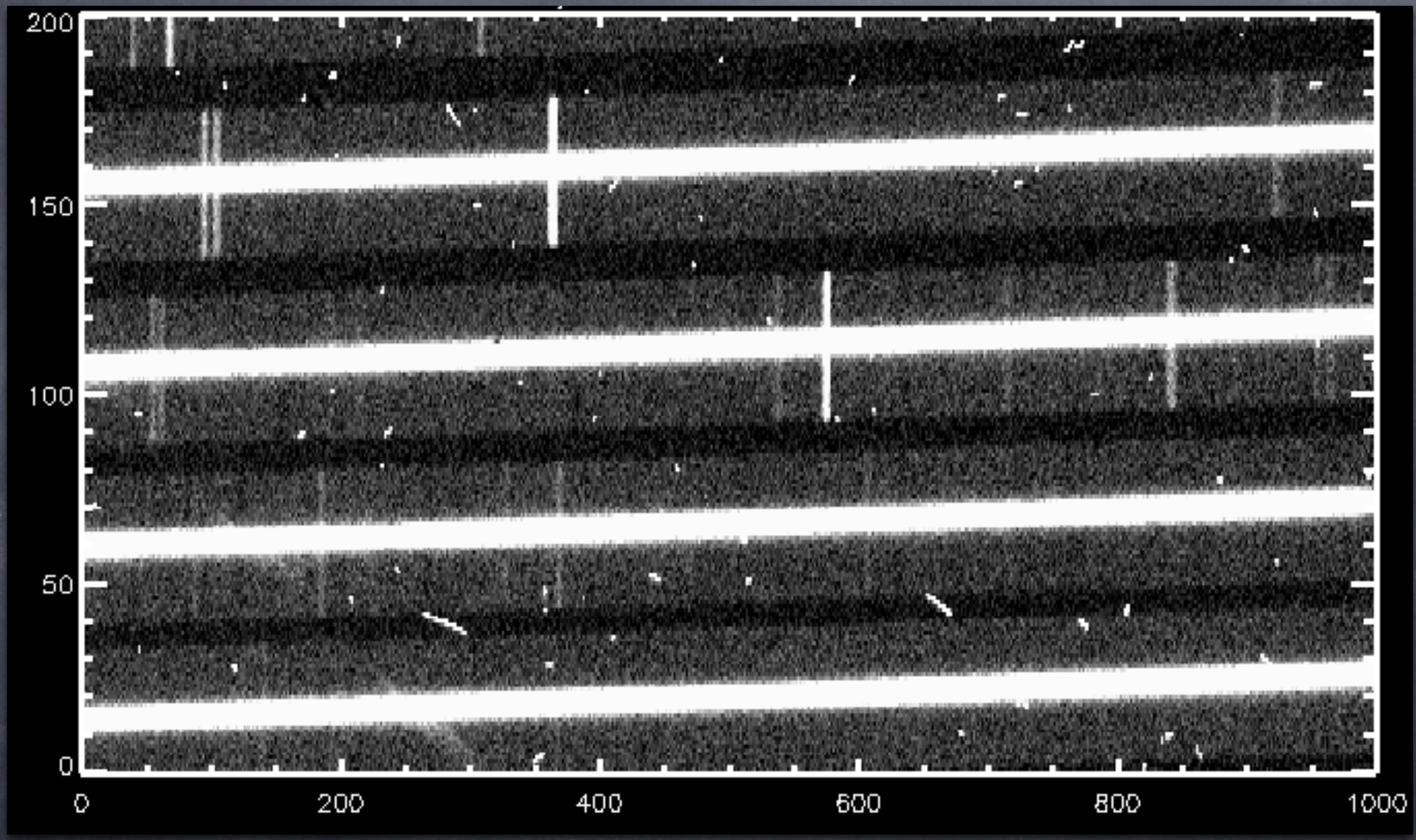


HIRES RV Errors

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

Sky Contamination - Faint Stars



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

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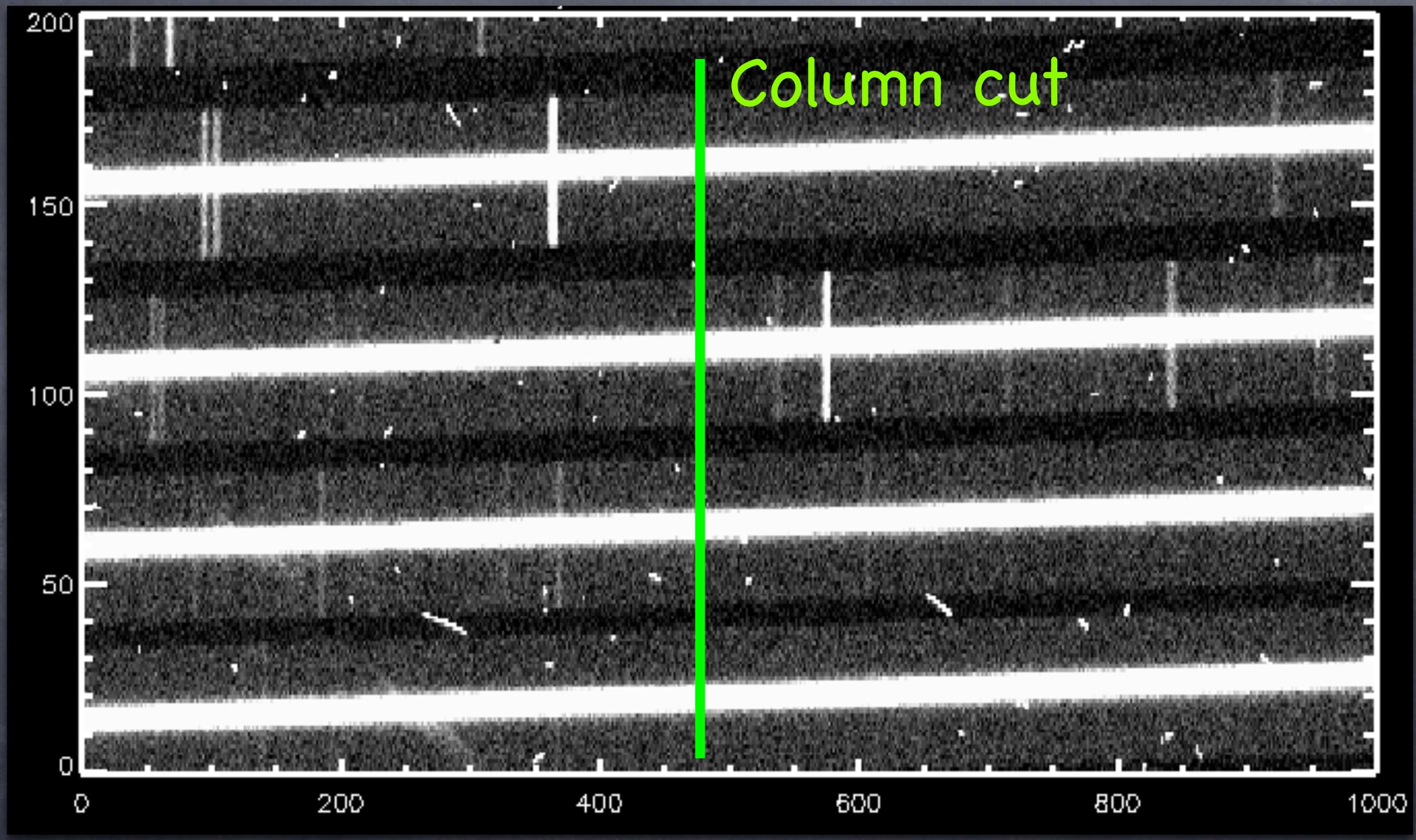

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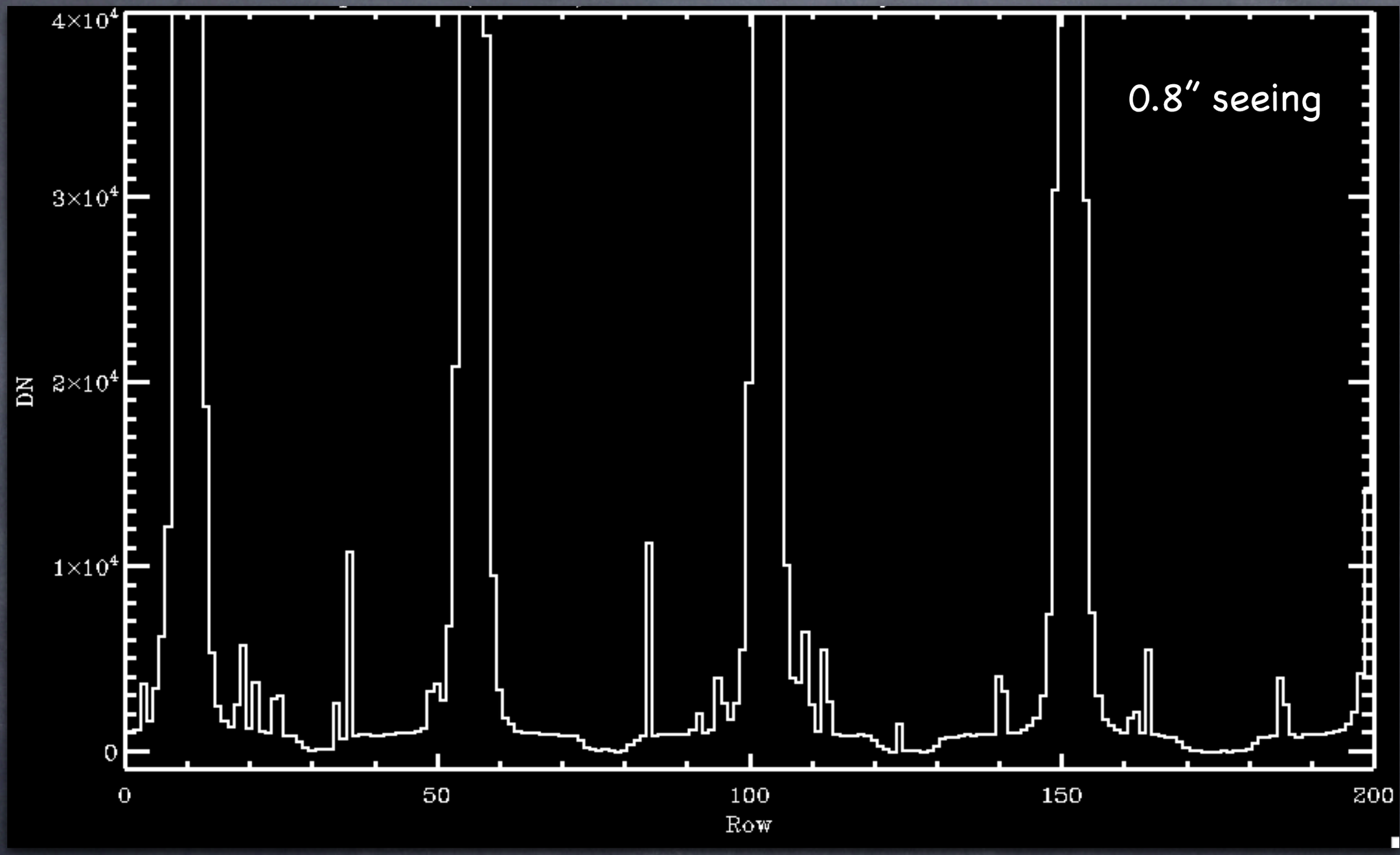
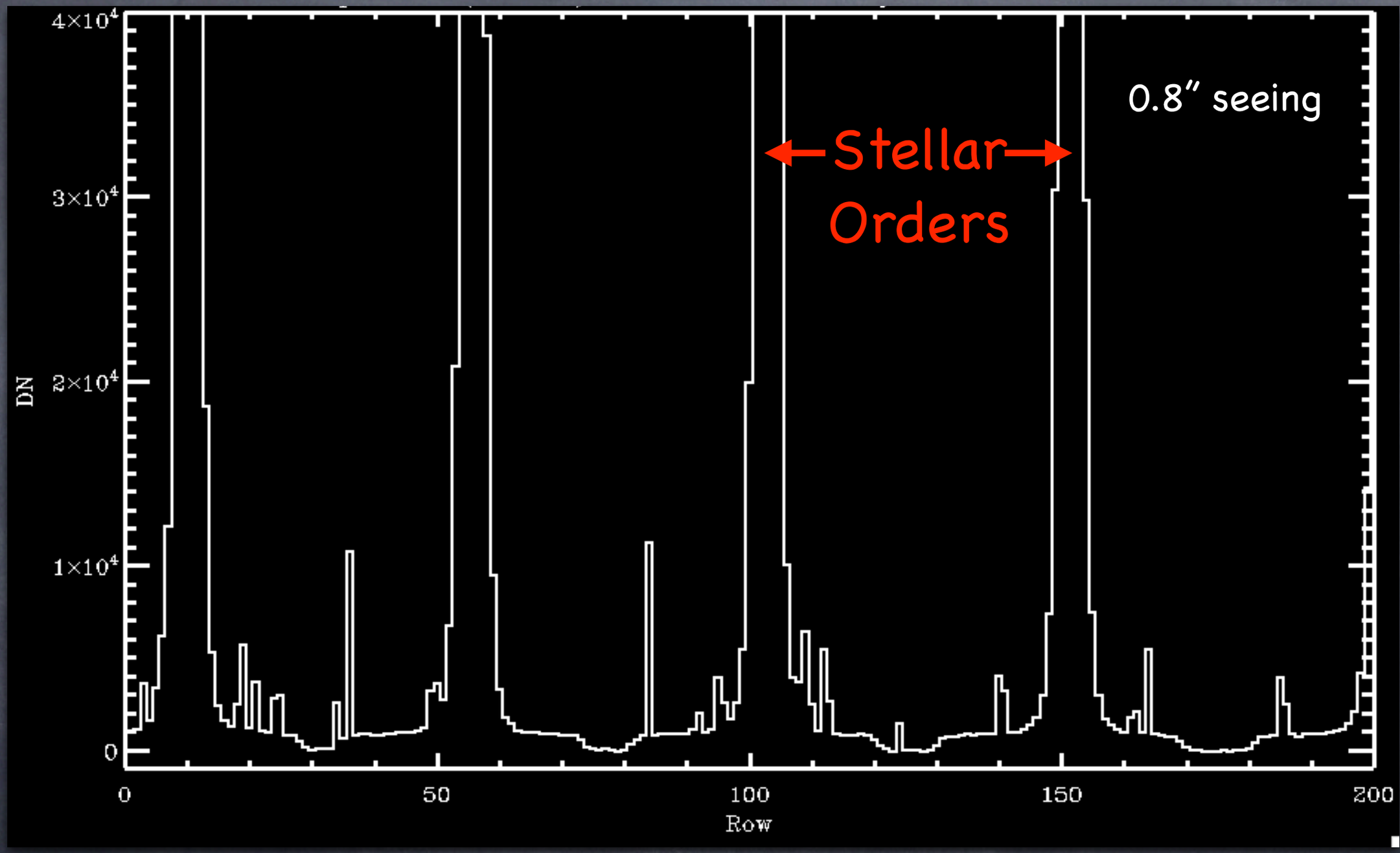


Full Moon, Clear skies: Sky is ~3% of 14th mag star (3 arcsec long slit)

Sky Contamination - Faint Stars



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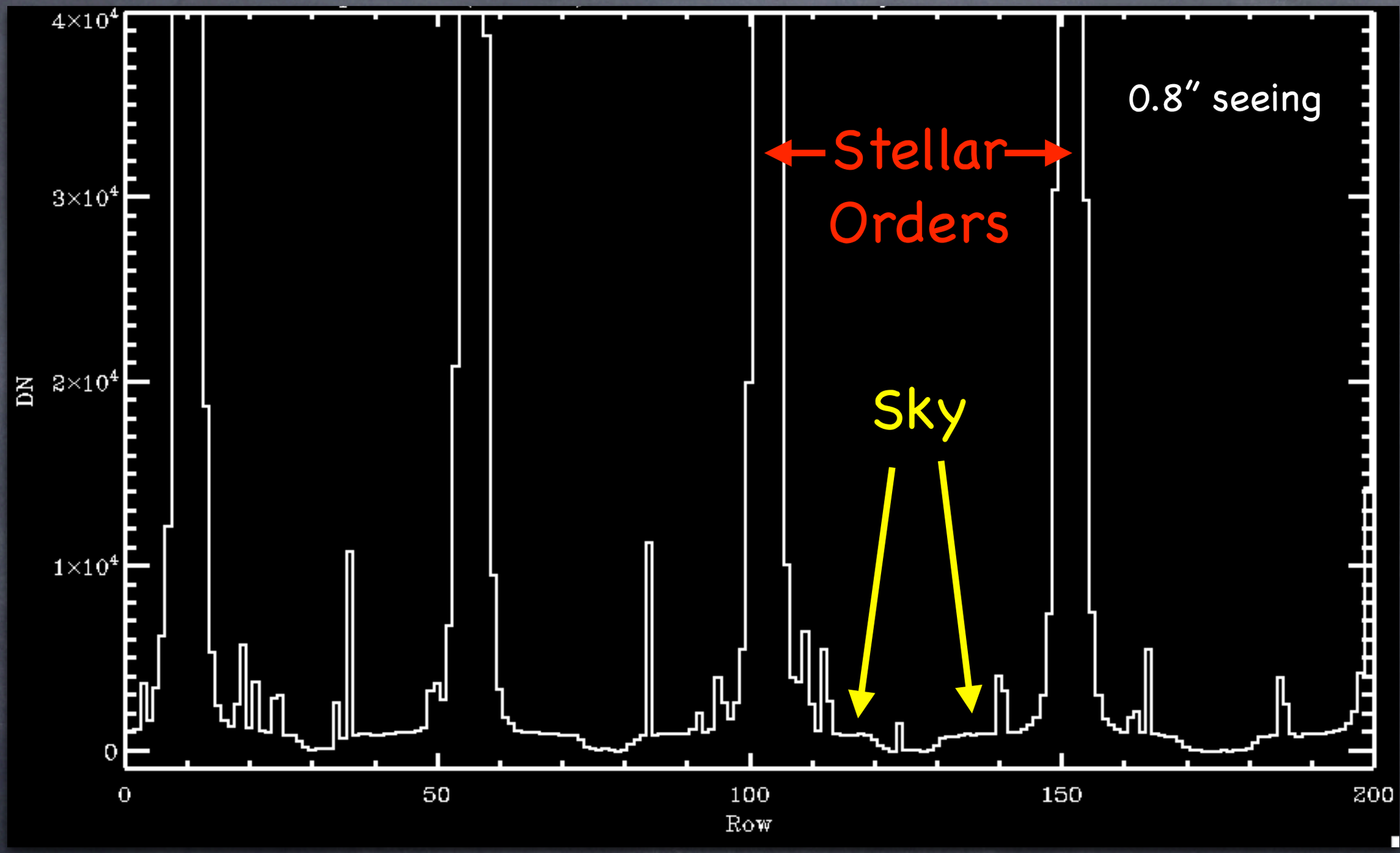
Sky Contamination - Faint Stars



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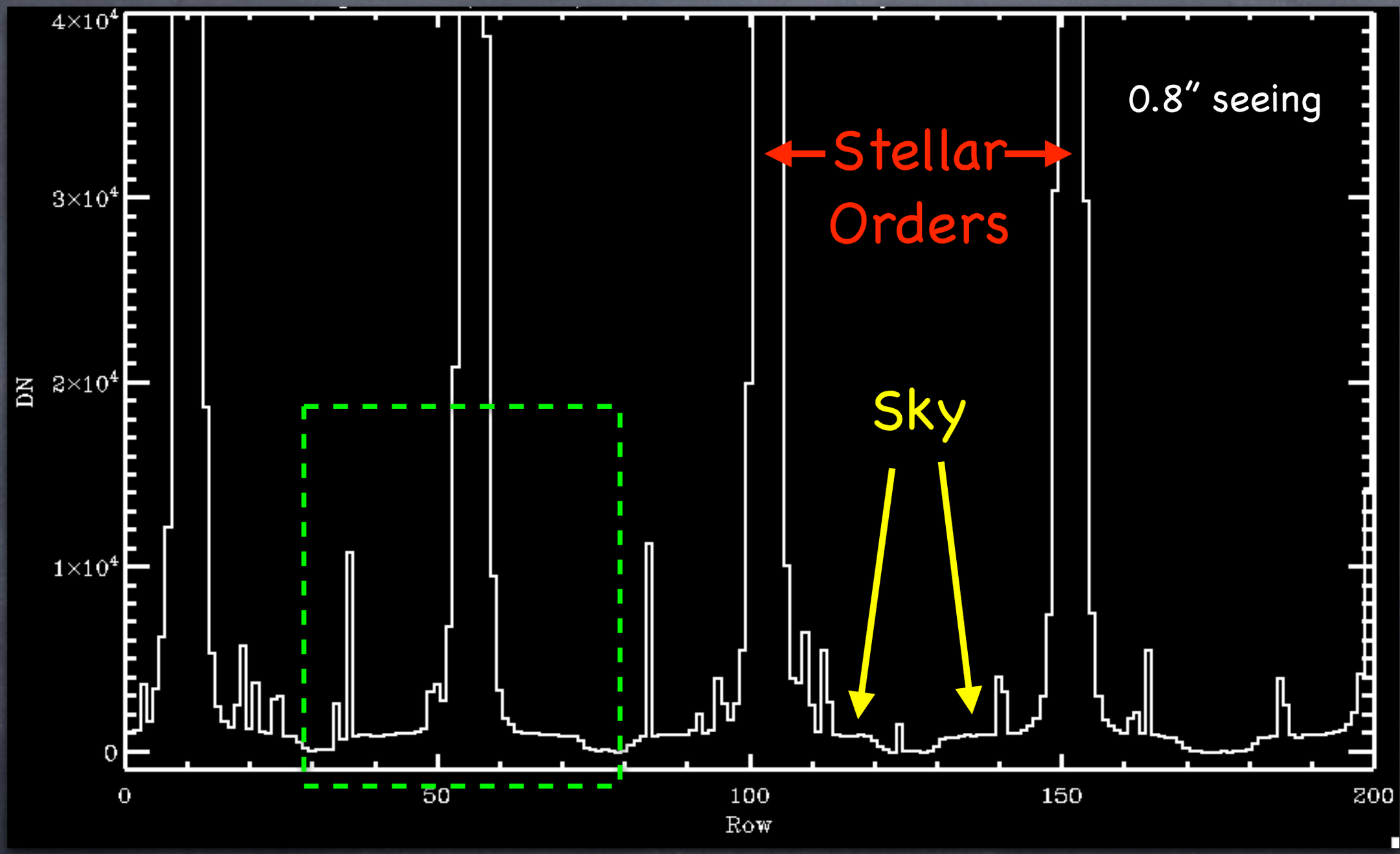

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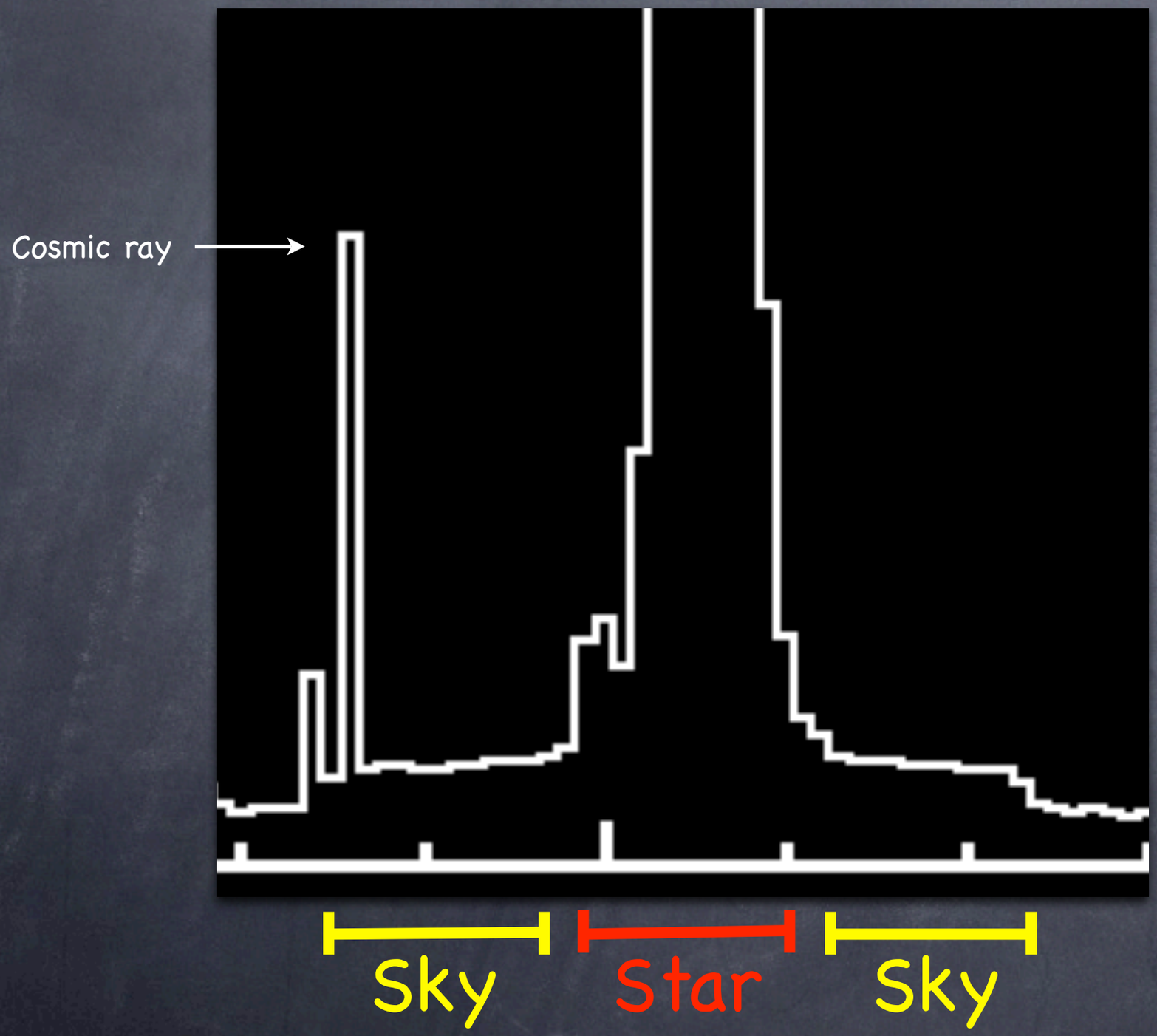
Sky subtraction



Subtract median sky value from each pixel in extraction region

Essential for V ≥ 10 for 1 m/s

Summary:
HIRES RV Errors

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

Questions?