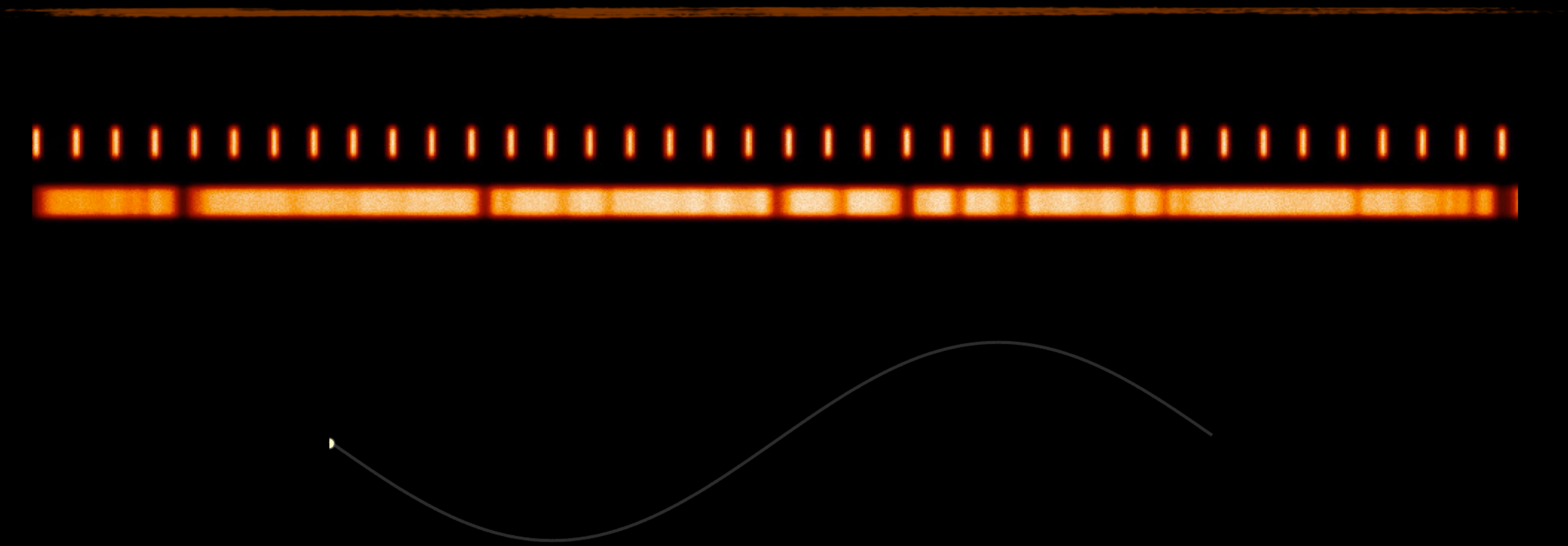
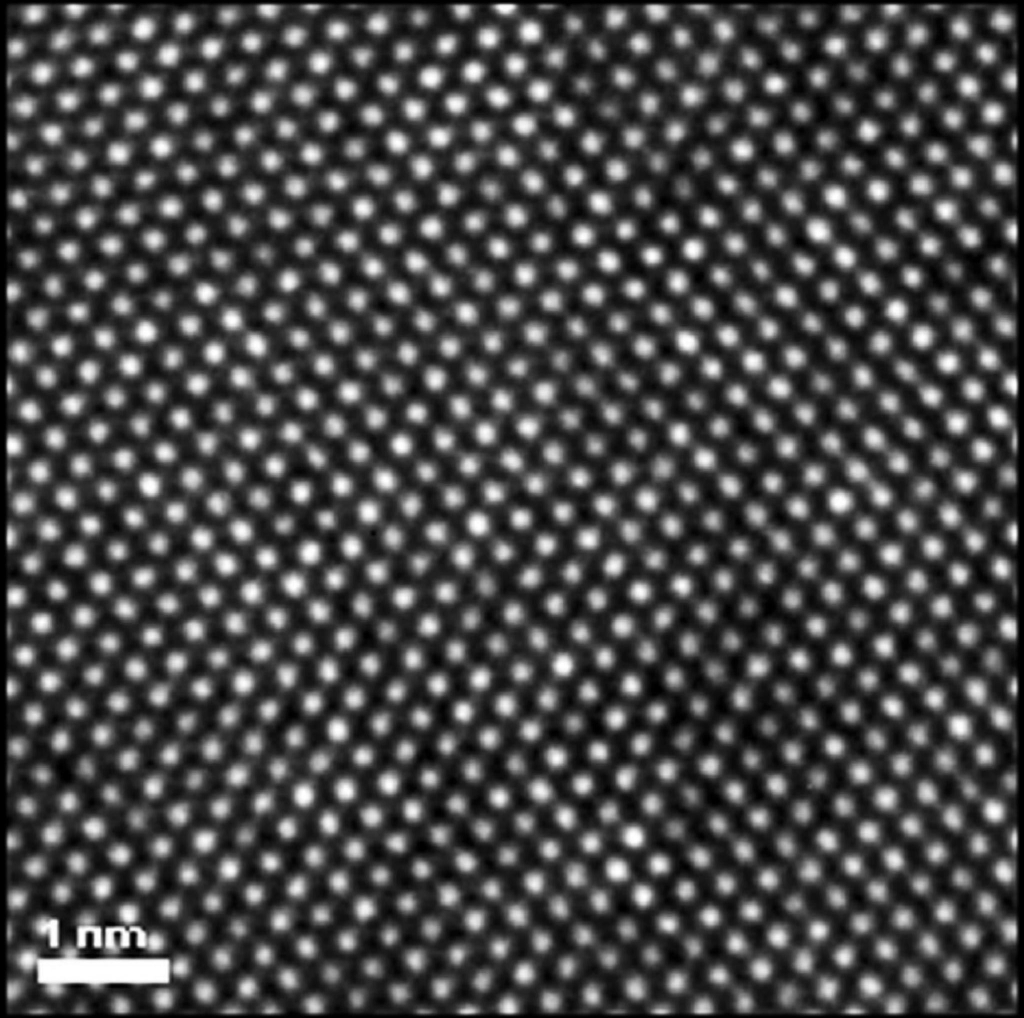
ERROR BUDGETS IN HIGH PRECISION RADIAL VELOCITY MEASUREMENTS



SAM HALVERSON

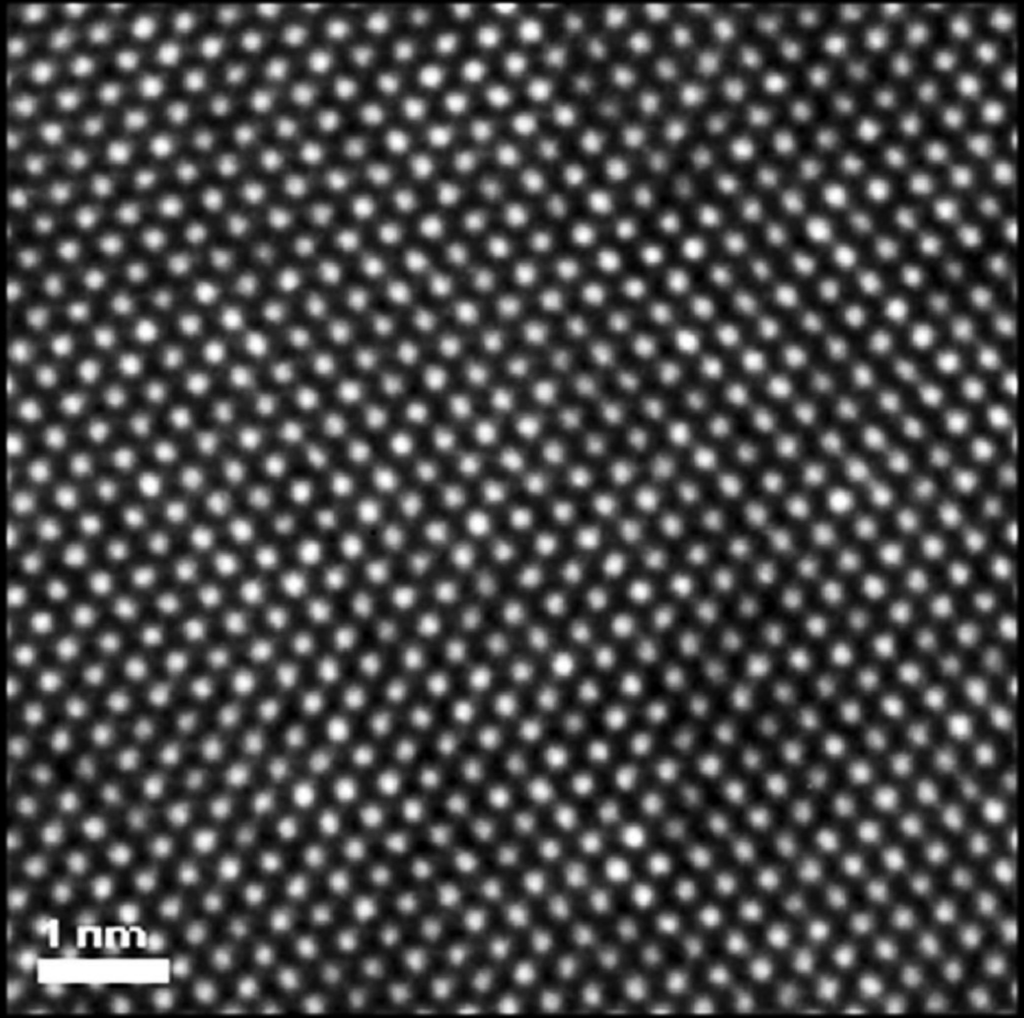
SAGAN FELLOW, MIT

What does a 10 cm s^{-1} shift in velocity look like?



TEM image of silicon wafer lattice (typical CCD)

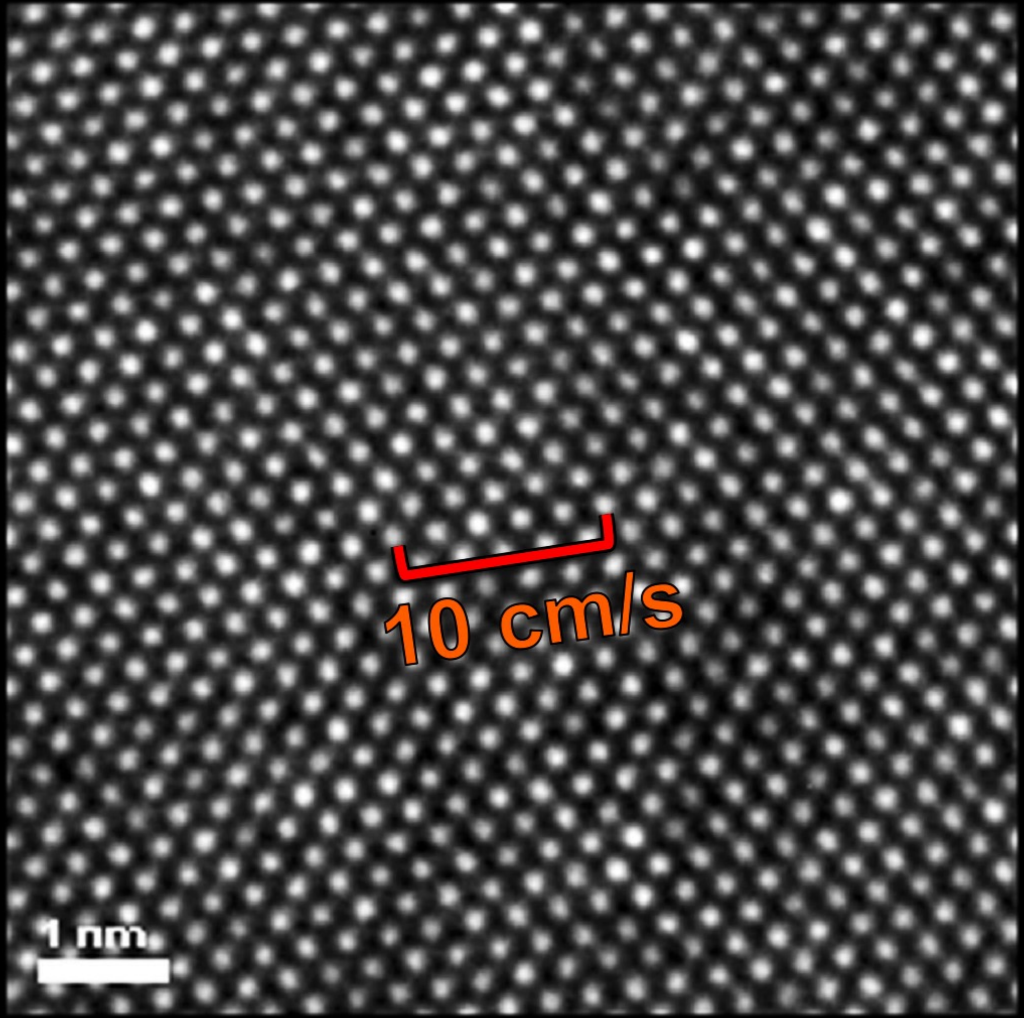
What does a 10 cm s^{-1} shift in velocity look like?



1/1000th of a pixel

TEM image of silicon wafer lattice (typical CCD)

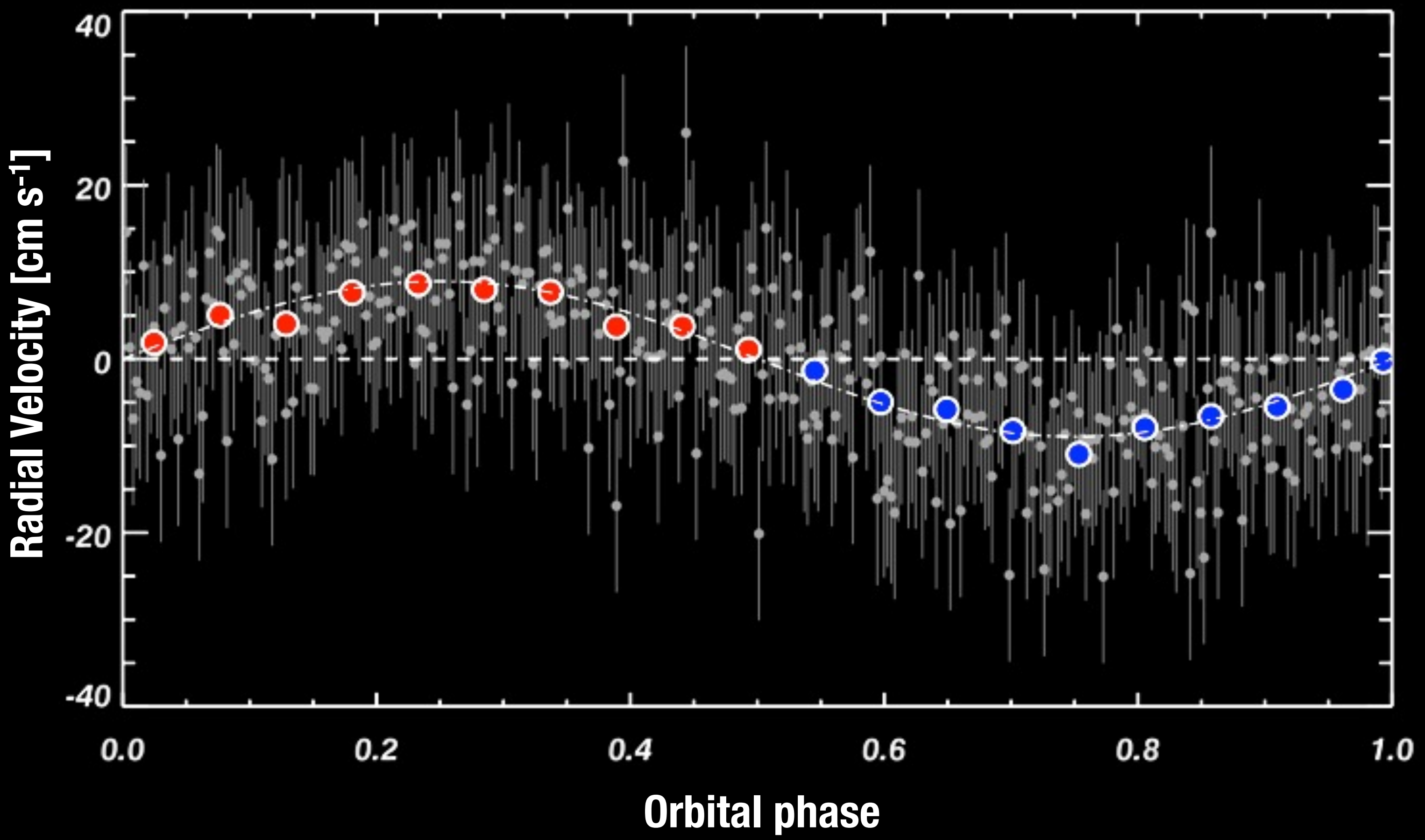
What does a 10 cm s^{-1} shift in velocity look like?



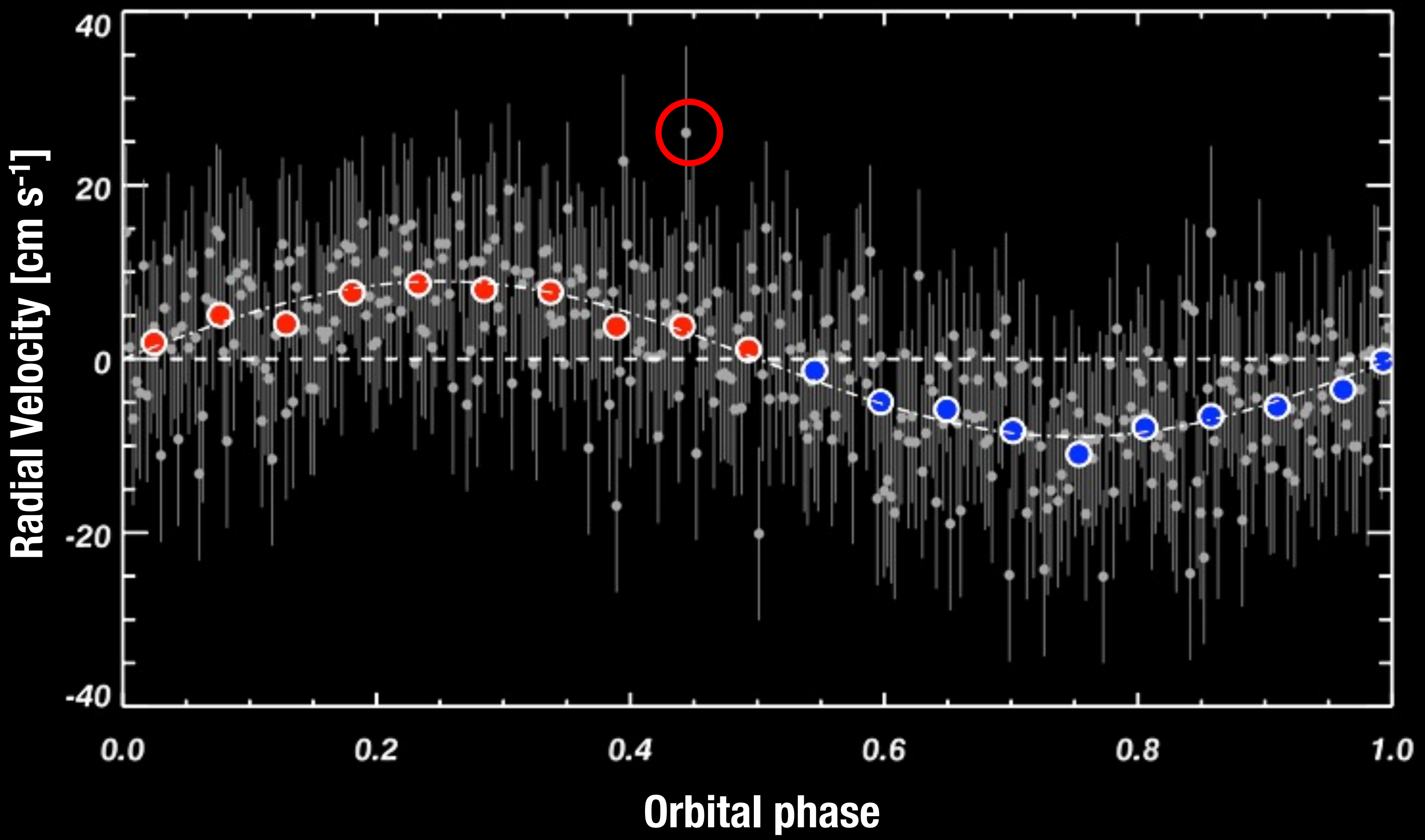
1/1000th of a pixel

TEM image of silicon wafer lattice (typical CCD)

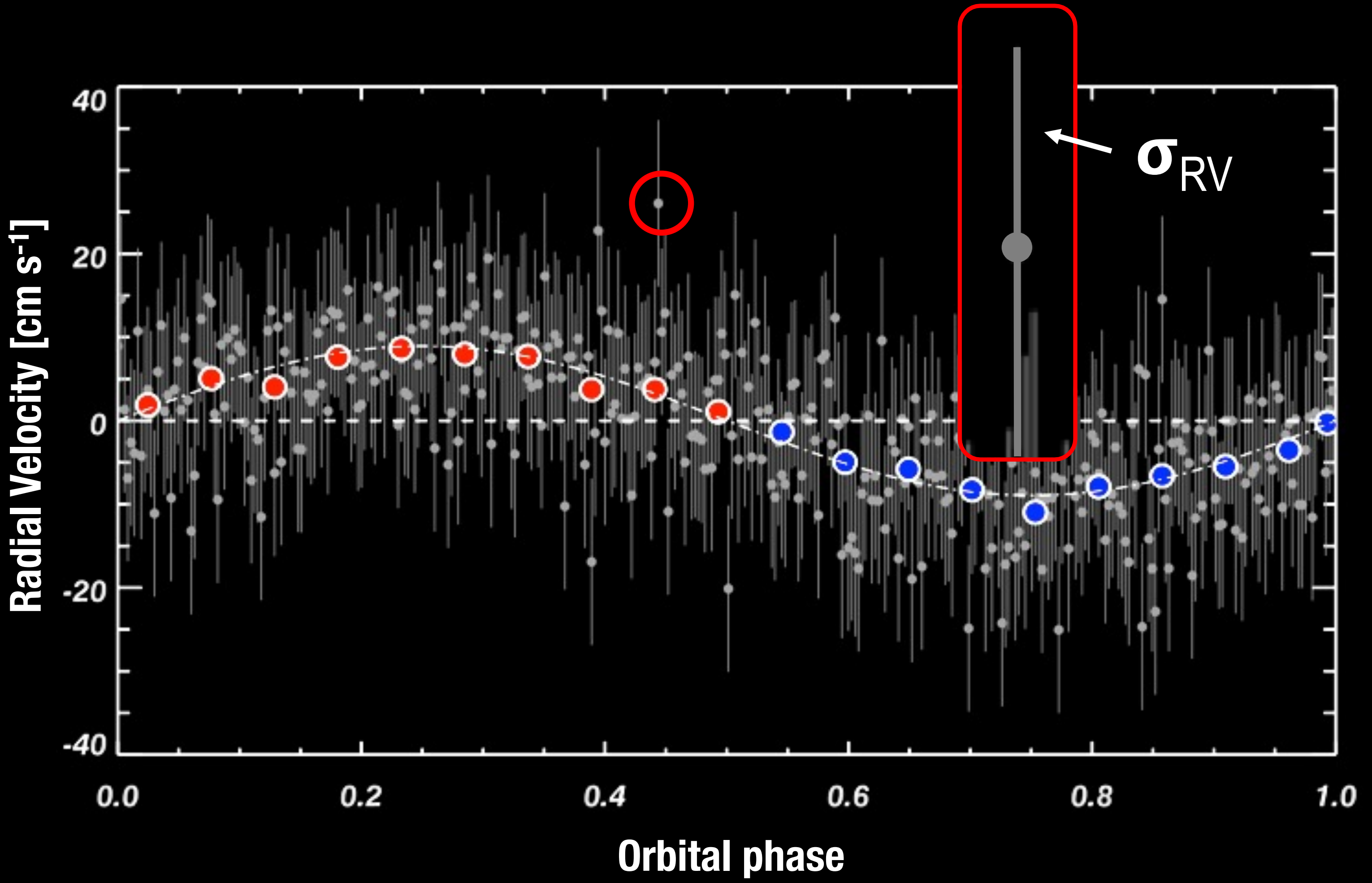
Deconstructing measurement precision



Deconstructing measurement precision



Deconstructing measurement precision



Deconstructing measurement precision

σ_{RV}

σ_{photon} | $\sigma_{facility}$ | σ_{jitter}

Deconstructing measurement precision

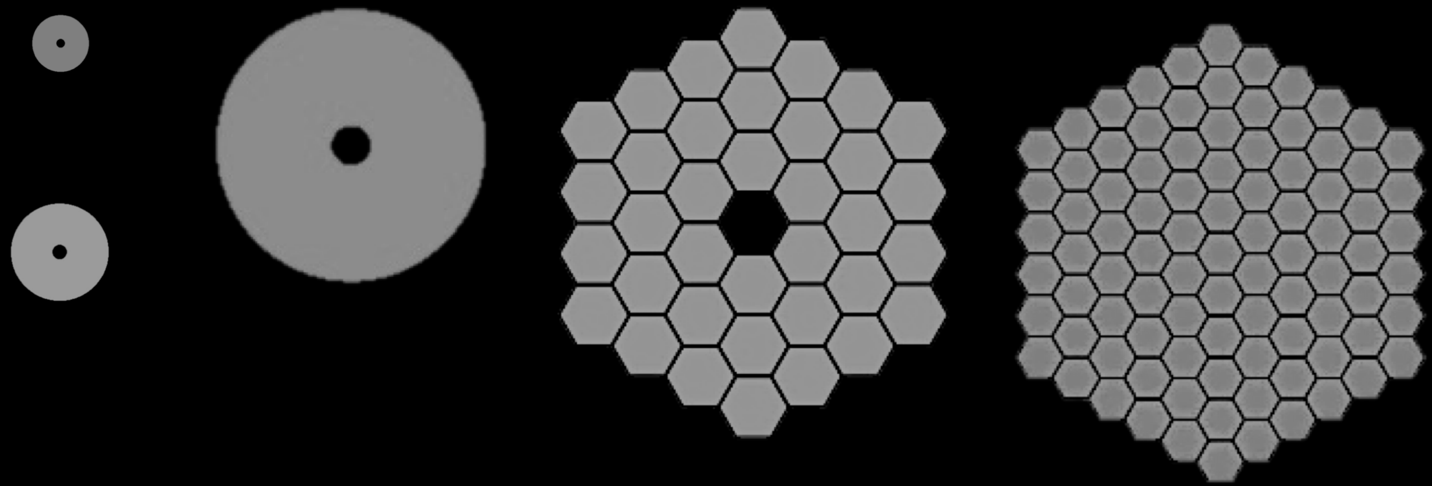
σ_{RV}

σ_{photon} $\sigma_{facility}$ σ_{jitter}

Aperture

Efficiency

Information content



Deconstructing measurement precision

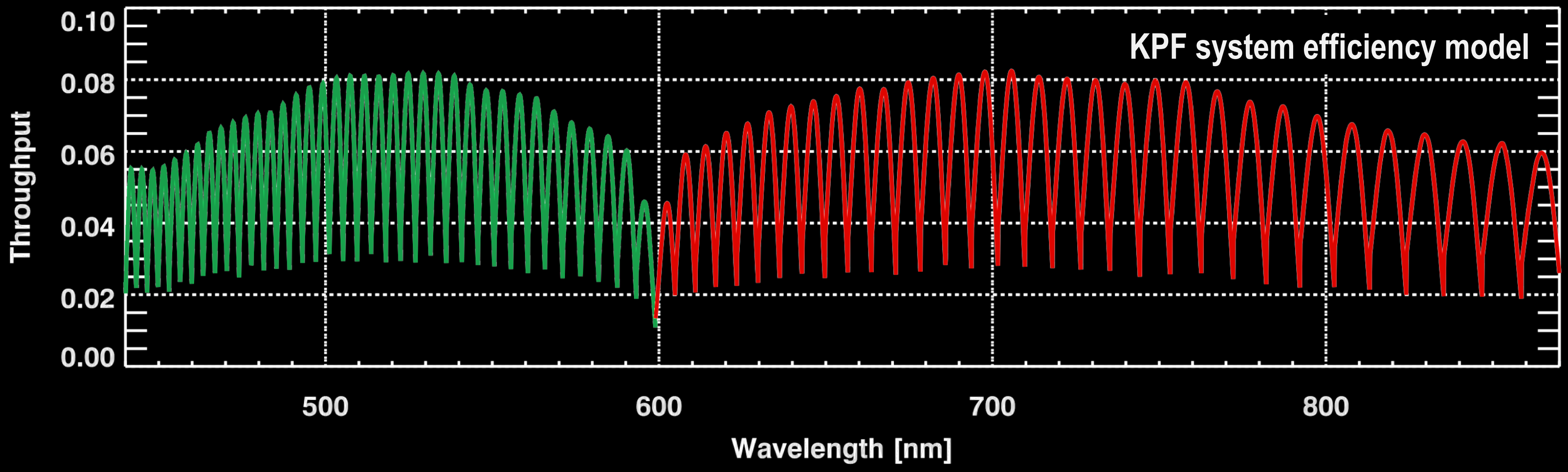
σ_{RV}

σ_{photon} $\sigma_{facility}$ σ_{jitter}

Aperture

Efficiency

Information content



Deconstructing measurement precision

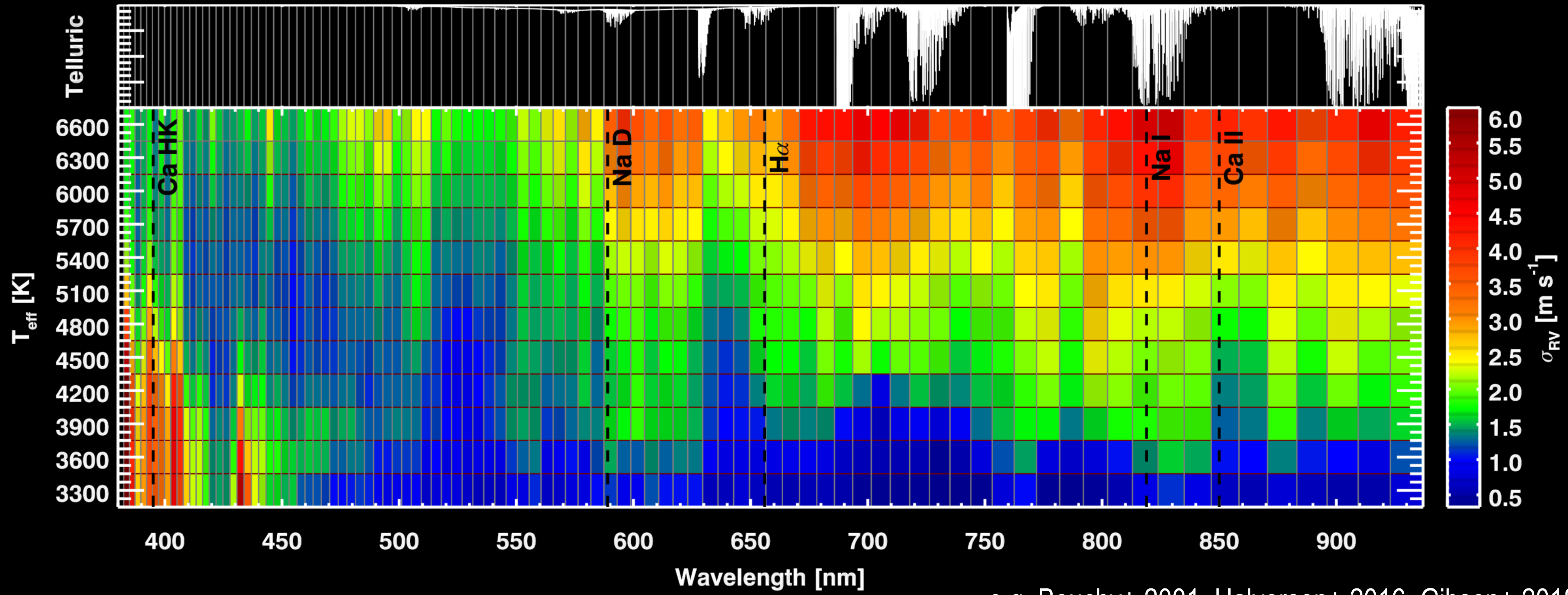
σ_{RV}

σ_{photon} $\sigma_{facility}$ σ_{jitter}

Aperture

Efficiency

Information content



e.g. Bouchy+ 2001, Halverson+ 2016, Gibson+ 2018

Deconstructing measurement precision

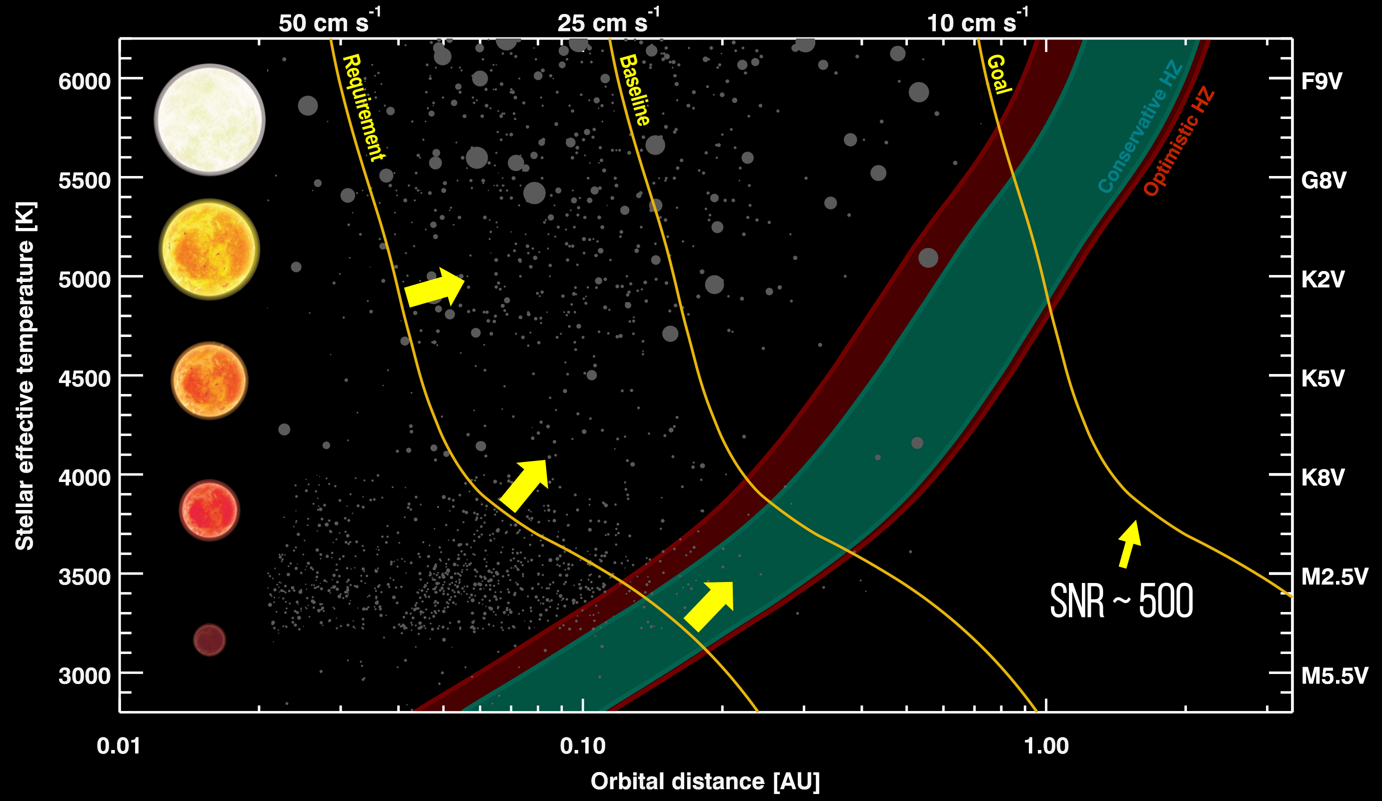
$\boldsymbol{\sigma}_{RV}$

$\boldsymbol{\sigma}_{photon}$ | $\boldsymbol{\sigma}_{facility}$ | $\boldsymbol{\sigma}_{jitter}$

Aperture

Efficiency

Information content



Deconstructing measurement precision

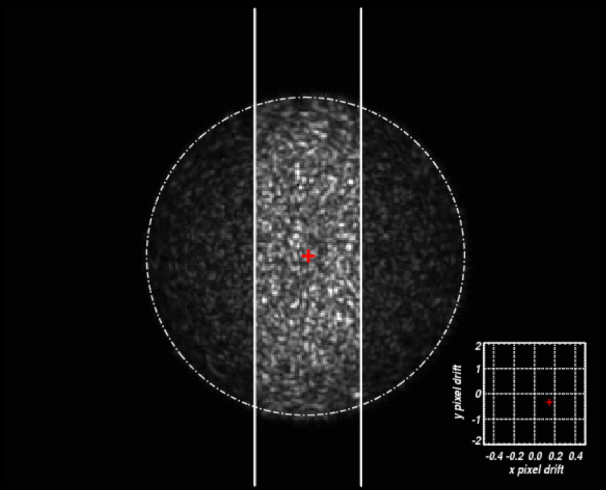
σ_{RV}

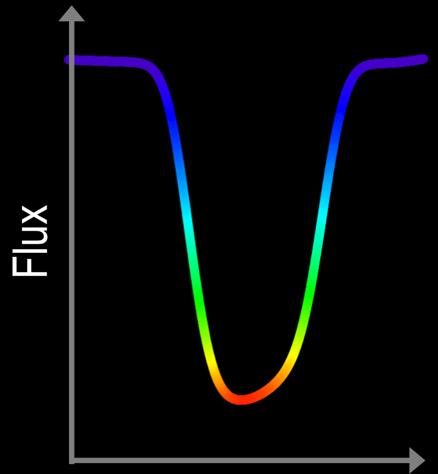
σ_{photon} $\sigma_{facility}$ σ_{jitter}

Instrumental stability

Calibration ability

External errors, analysis





e.g. Avila+ 2008, Sturmer+ 2014, Halverson & Roy+ 2015

Deconstructing measurement precision

σ_{RV}

σ_{photon} | $\sigma_{facility}$ | σ_{jitter}

Instrumental stability

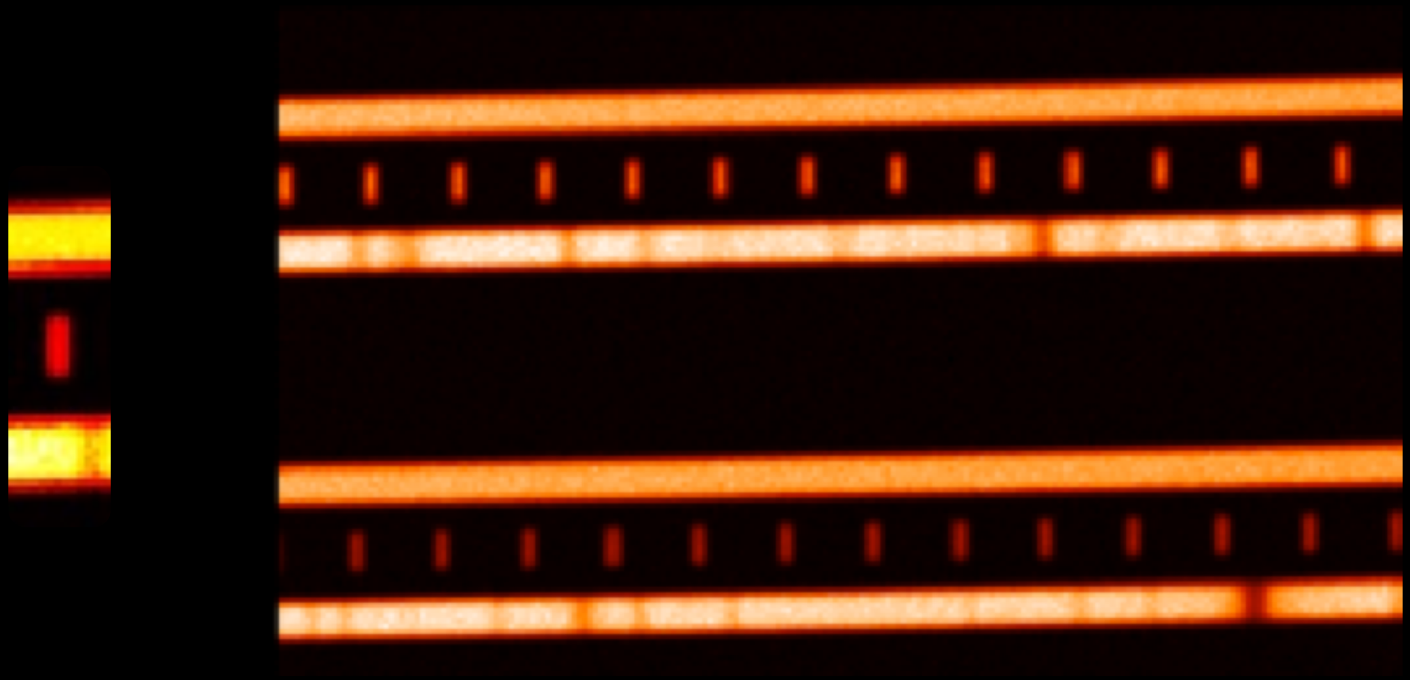
Calibration ability

External errors, analysis

Sky fiber (A)

Calibration source (B)

Starlight (C)



Deconstructing measurement precision

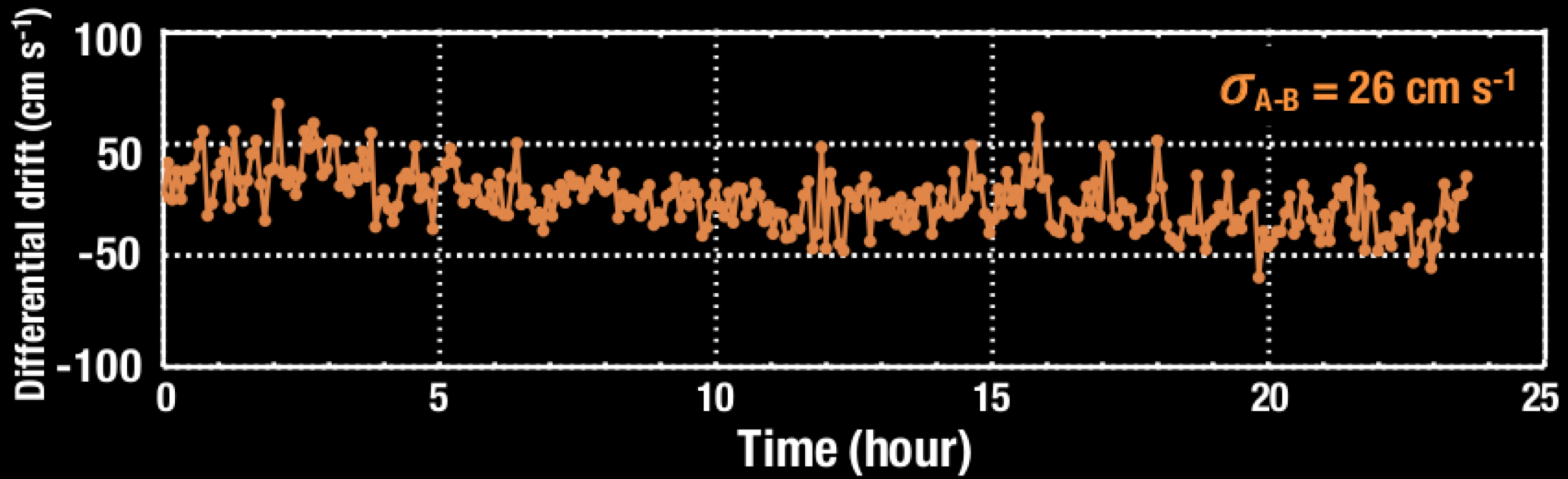
σ_{RV}

σ_{photon} $\sigma_{facility}$ σ_{jitter}

Instrumental stability

Calibration ability

External errors, analysis



Deconstructing measurement precision

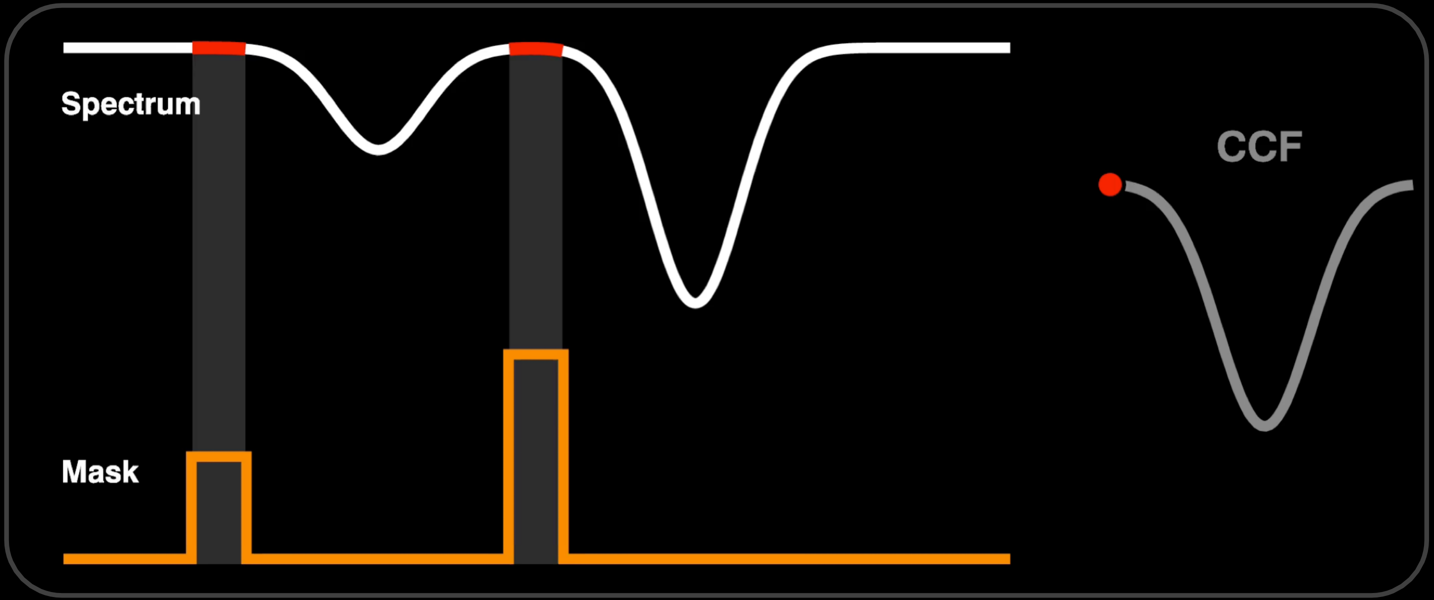
σ_{RV}

σ_{photon} $\sigma_{facility}$ σ_{jitter}

Instrumental stability

Calibration ability

External errors, analysis



Deconstructing measurement precision

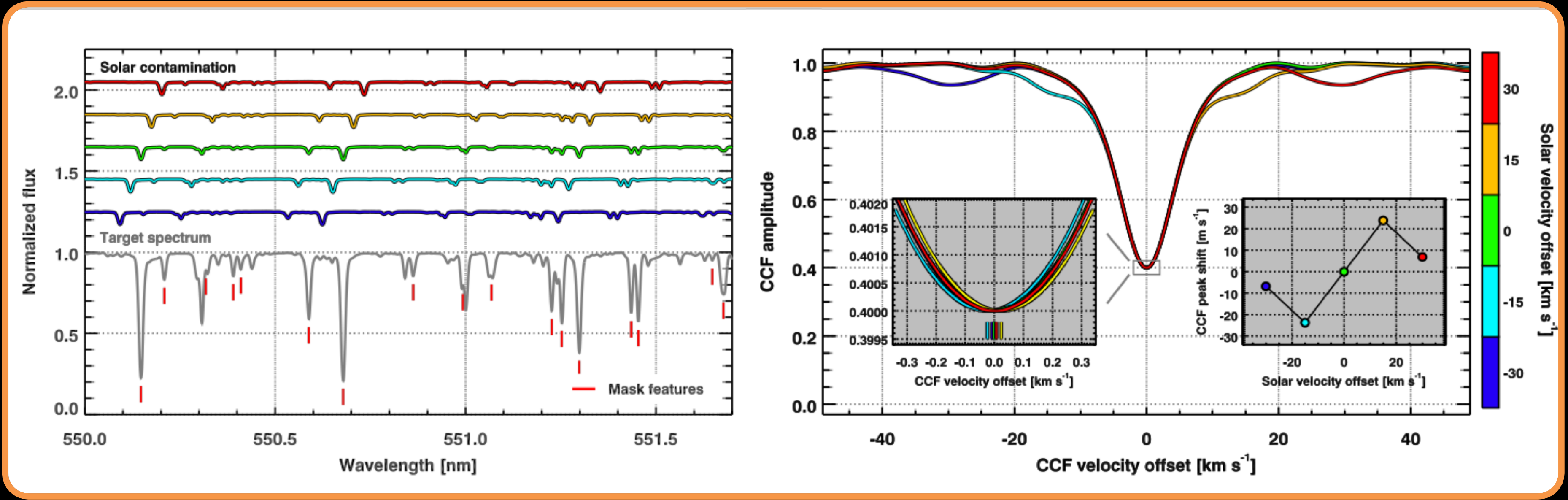
σ_{RV}

σ_{photon} $\sigma_{facility}$ σ_{jitter}

Instrumental stability

Calibration ability

External errors, analysis

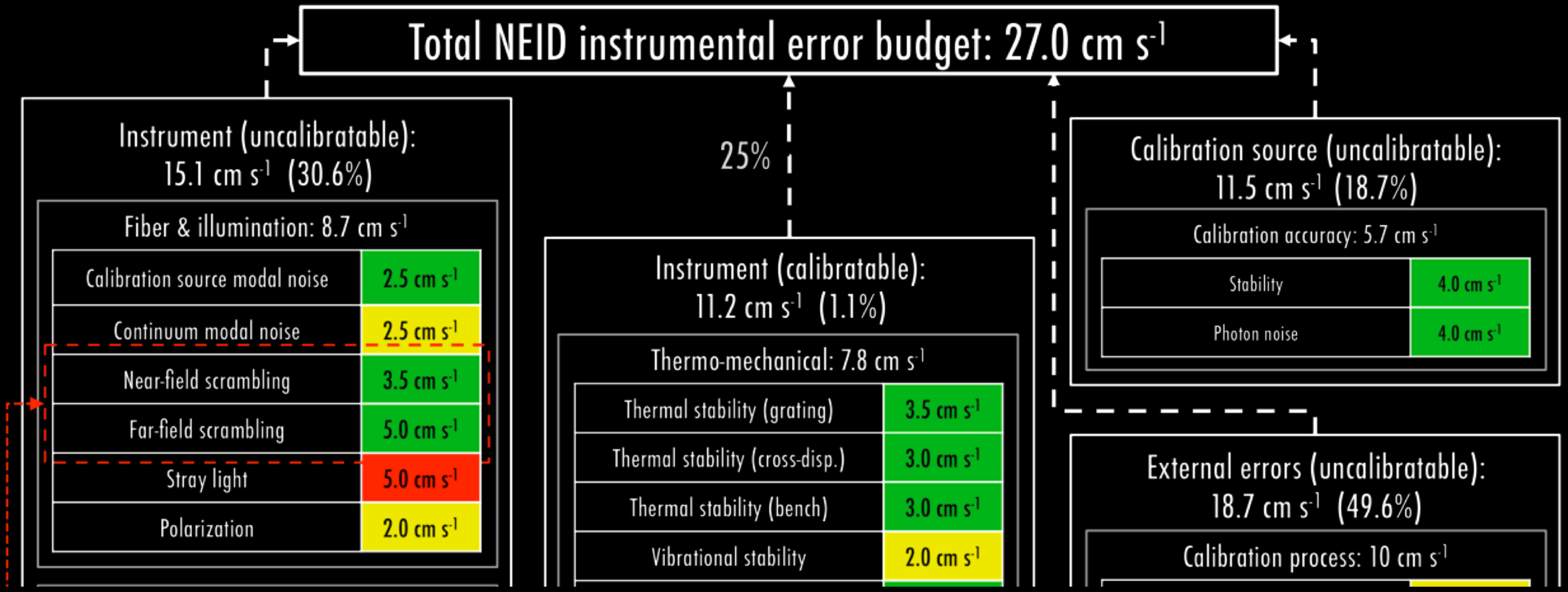


Roy+ 2018

Deconstructing measurement precision

σ_{RV}

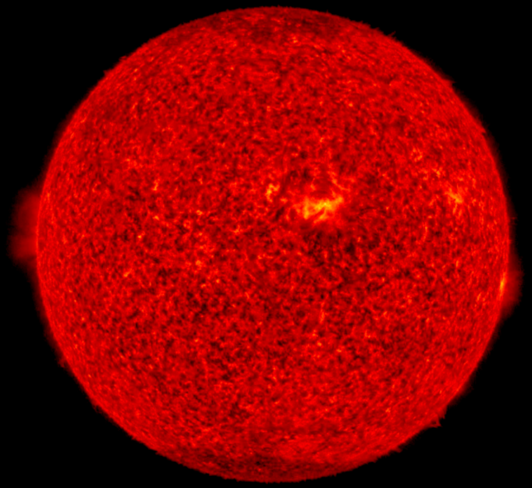
σ_{photon} $\sigma_{facility}$ σ_{jitter}



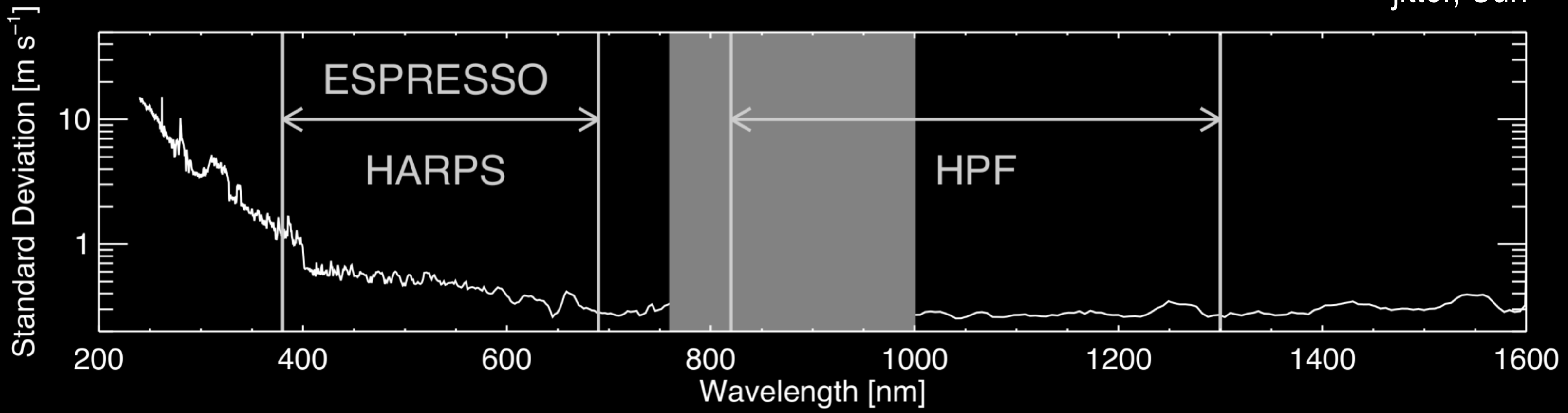
Deconstructing measurement precision

σ_{RV}

σ_{photon} $\sigma_{facility}$ σ_{jitter}

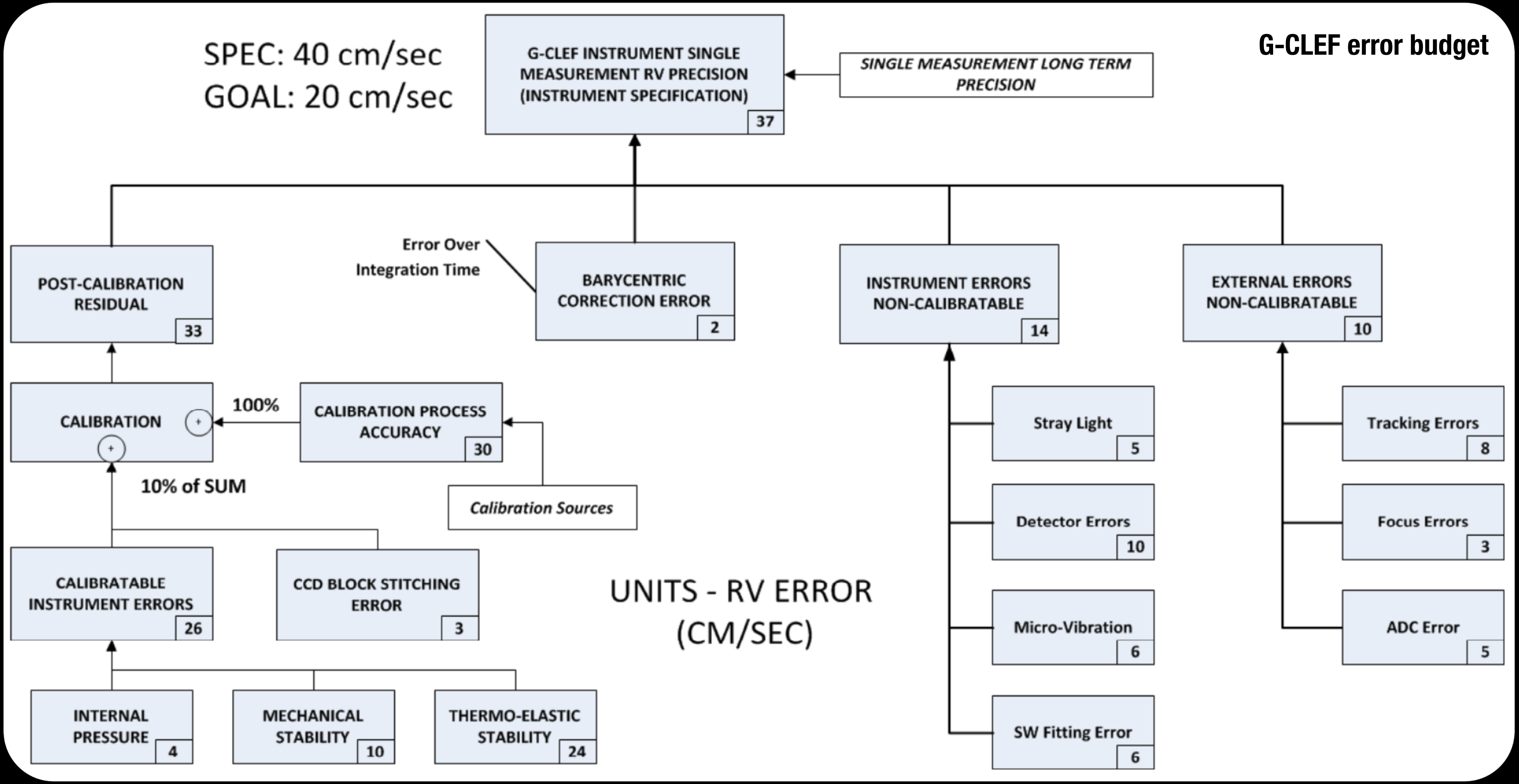


estimated $\sigma_{jitter, Sun}$



Marchwinski et al. 2015

Now in the era where no single source of instrumental noise dominates



e.g. Podgorski 2014

Now in the era where no single source of instrumental noise dominates

Total NEID instrumental error budget: 27.0 cm s^{-1}

Instrument (uncalibratable): 15.1 cm s^{-1} (30.6%)

Fiber & illumination: 8.7 cm s^{-1}	
Calibration source modal noise	2.5 cm s^{-1}
Continuum modal noise	2.5 cm s^{-1}
Near-field scrambling	3.5 cm s^{-1}
Far-field scrambling	5.0 cm s^{-1}
Stray light	5.0 cm s^{-1}
Polarization	2.0 cm s^{-1}

Detector effects: 7.1 cm s^{-1}	
Readout thermal change	5.0 cm s^{-1}
Charge transfer inefficiency	5.0 cm s^{-1}

Barycentric correction: 1.7 cm s^{-1}	
Algorithms	1.0 cm s^{-1}
Exposure midpoint time	1.0 cm s^{-1}
Coordinates and proper motion	1.0 cm s^{-1}

Reduction pipeline: 10 cm s^{-1}	
Software algorithms	10 cm s^{-1}

25%

Instrument (calibratable): 11.2 cm s^{-1} (1.1%)

Thermo-mechanical: 7.8 cm s^{-1}	
Thermal stability (grating)	3.5 cm s^{-1}
Thermal stability (cross-disp.)	3.0 cm s^{-1}
Thermal stability (bench)	3.0 cm s^{-1}
Vibrational stability	2.0 cm s^{-1}
Pressure stability	<0.1 cm s^{-1}
LN2 fill transient	1.0 cm s^{-1}
Zerodur phase change	5.0 cm s^{-1}

Detector effects: 8.1 cm s^{-1}	
Pixel inhomogeneities	1.0 cm s^{-1}
Electronics noise	1.0 cm s^{-1}
Stitching error	3.0 cm s^{-1}
CCD thermal expansion	2.0 cm s^{-1}
Readout thermal change	5.0 cm s^{-1}
Charge transfer inefficiency	5.0 cm s^{-1}

Calibration source (uncalibratable): 11.5 cm s^{-1} (18.7%)

Calibration accuracy: 5.7 cm s^{-1}	
Stability	4.0 cm s^{-1}
Photon noise	4.0 cm s^{-1}

External errors (uncalibratable): 18.7 cm s^{-1} (49.6%)

Calibration process: 10 cm s^{-1}	
Software algorithms	10 cm s^{-1}

Telescope: 12.2 cm s^{-1}	
Guiding	scrambling
ADC	6.9 cm s^{-1}
Focus	5.0 cm s^{-1}
Windshake	8.0 cm s^{-1}

Atmospheric effects: 14.1 cm s^{-1}	
Micro-telluric contamination	10 cm s^{-1}
Sky fiber subtraction	10 cm s^{-1}

e.g. Halverson+ 2016

Now in the era where no single source of instrumental noise dominates

KPF PDR error budget spreadsheet, all units in cm/s

Instrumental errors (uncalibratable)	22.23
Fiber & illumination	18.47
Calibration source modal noise	2.50
Continuum modal noise	2.50
Near-field scrambling	8.00
Far-field scrambling	5.00
Stray light & ghosts	5.00
Fiber-fiber contamination	5.00
Polarization	2.00
Focal ratio degradation (science)	7.80
Focal radio degradation (calibration)	7.80
Double scrambler drift	8.00
Detector effects	7.07
Pixel center offsets	5.00
Charge transfer inefficiency	5.00
Barycentric correction	1.73
Algorithms	1.00
Exposure midpoint time	1.00
Coordinates and proper motion	1.00
Reduction pipeline	10.00
Software algorithms	10.00

Instrumental errors (calibratable)	18.53
Calibratable error contribution	1.85
Thermo-mechanical	12.13
Thermal stability (grating)	3.00
Thermal stability (cross-disp.)	5.00
Thermal stability (bench)	4.00
Thermal stability (cameras)	6.80
Vibrational stability	1.00
Pressure stability	5.00
Zerodur phase change (Echelle)	5.00
Detector effects	14.00
Pixel inhomogeneities	5.00
CCD thermal expansion	5.00
Readout thermal change	11.00
Charge transfer inefficiency	5.00

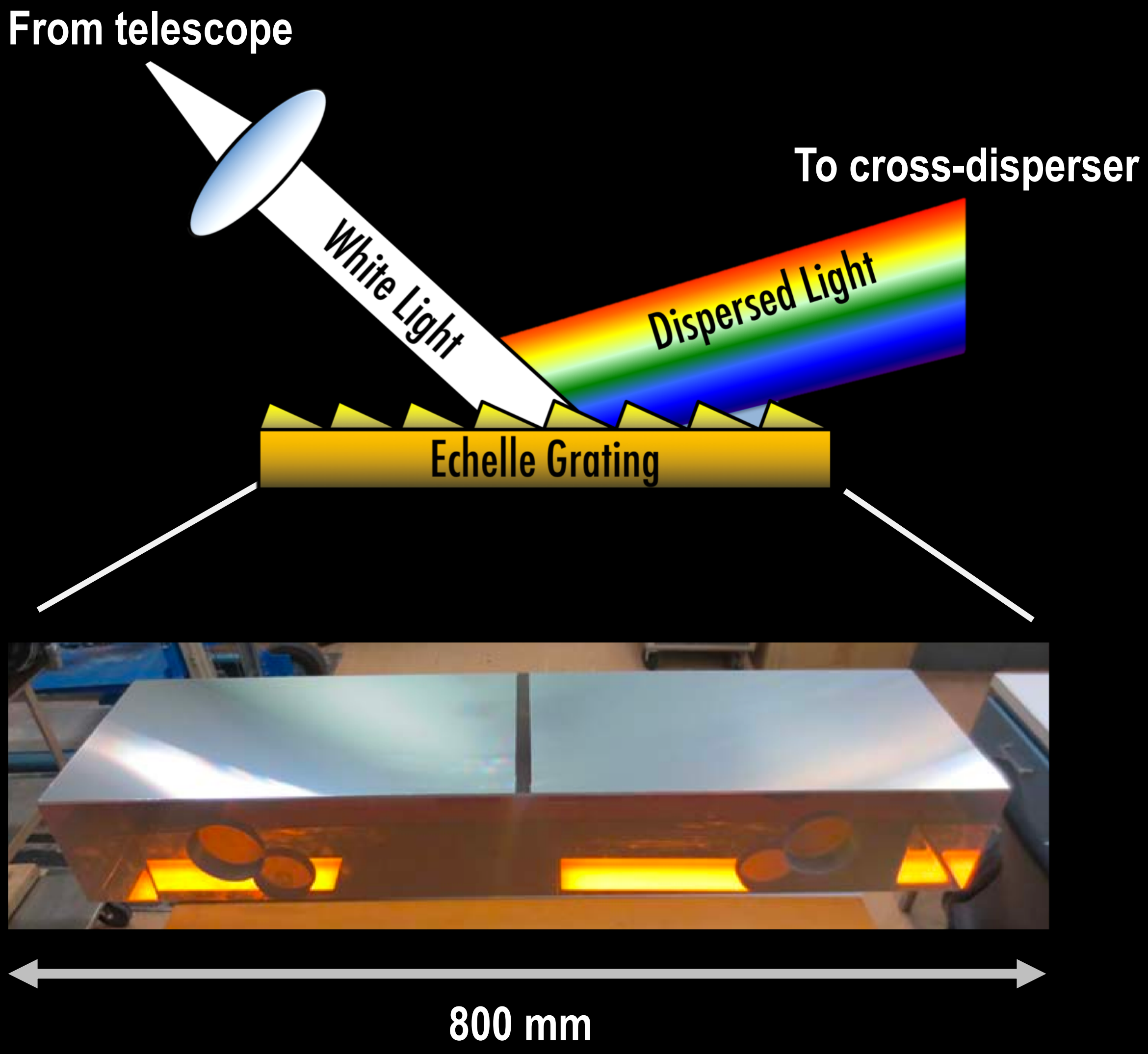
Traced with calibration fiber

Calibration source (uncalibratable)	15.00
Calibration accuracy	11.18
Wavelength stability	10.00
Photon noise	5.00
Calibration process	10.00
Software algorithms	10.00
External errors (uncalibratable)	18.94
Telescope	12.60
Guiding (")	0.05
ADC	5.80
Focus	5.00
Injection angle variations	10.00
Atmospheric effects	14.14
Micro-telluric contamination	10.00
Scattered sunlight contamination	10.00

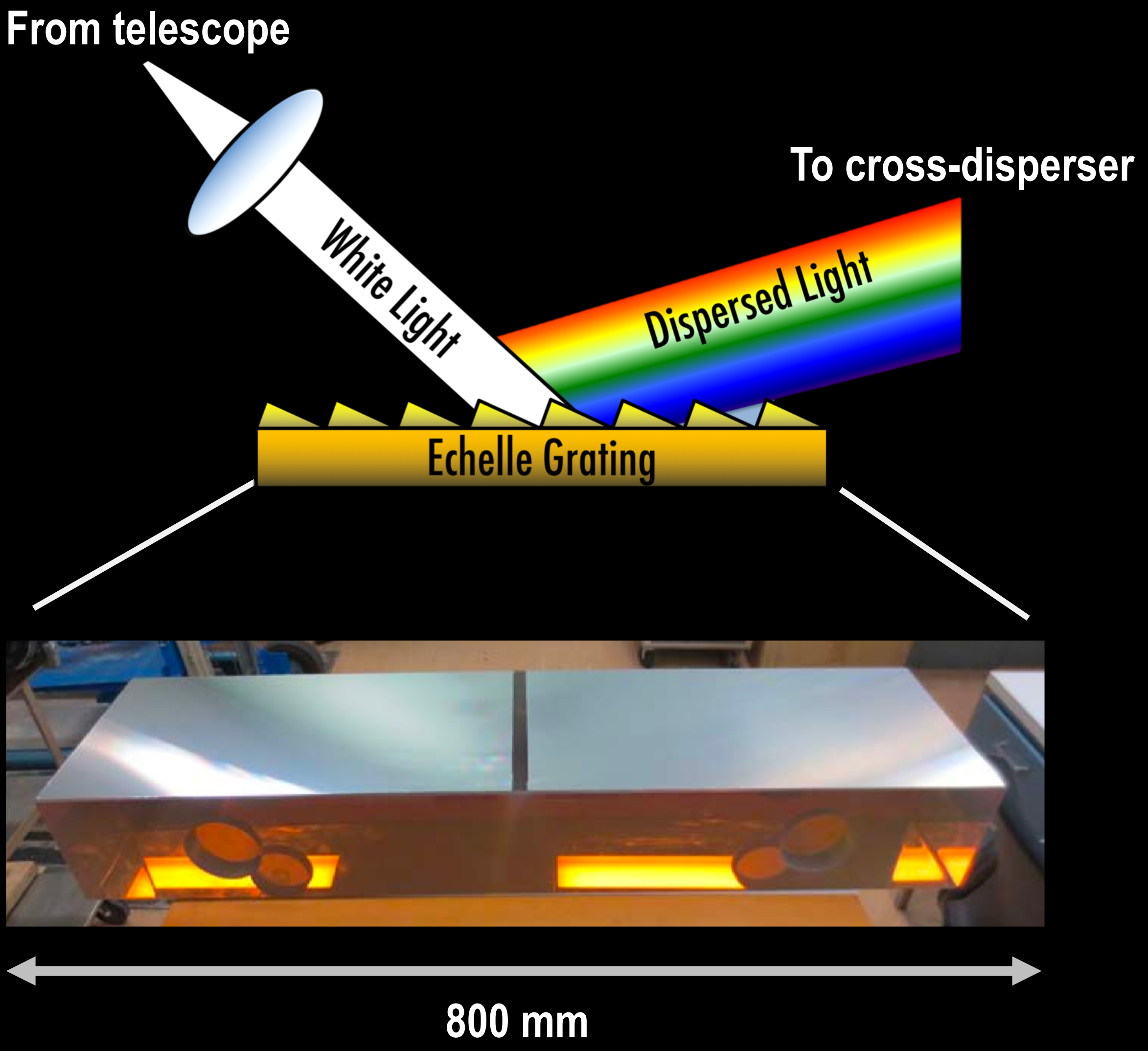
Not traced with calibration fiber

Total instrumental error (cm/s): 32.8824

Calibratable error examples



Thermal fluctuations on spectrometer optics



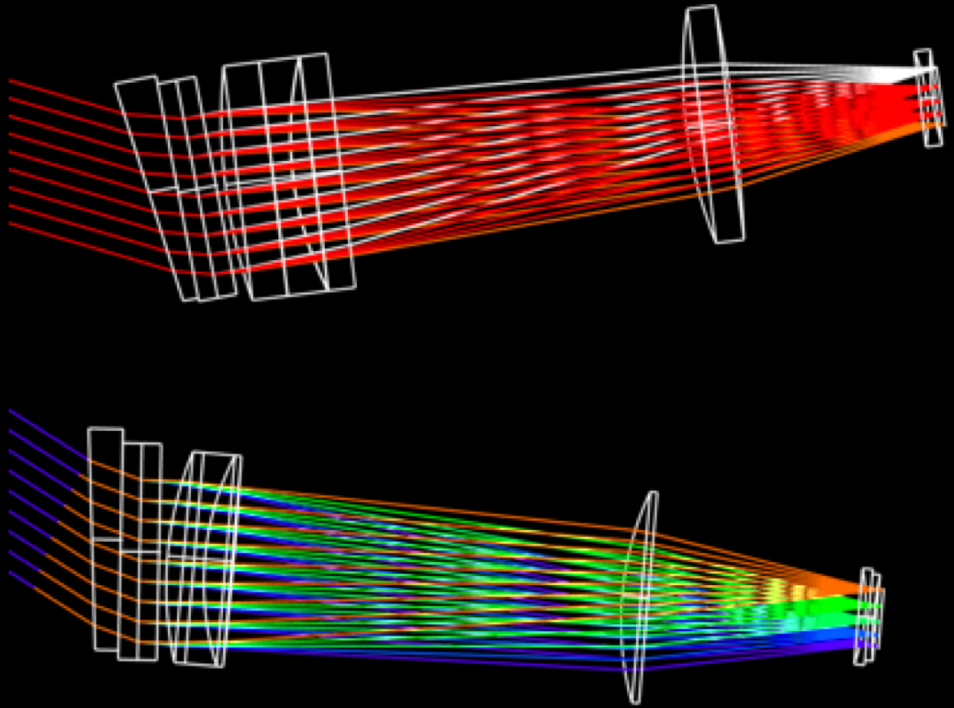
$$\Delta v = \alpha_L c \Delta T,$$

$\Delta T = 10$ mK

$\Delta v = 15$ cm s^{-1}

Thermal fluctuations on spectrometer optics

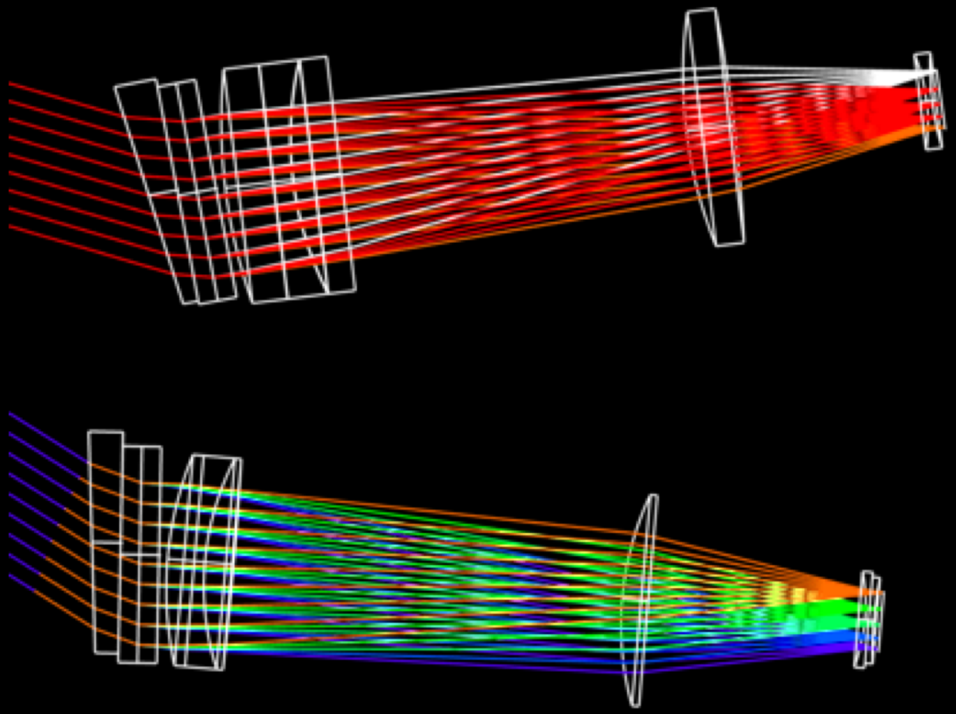
KPF green / red cameras



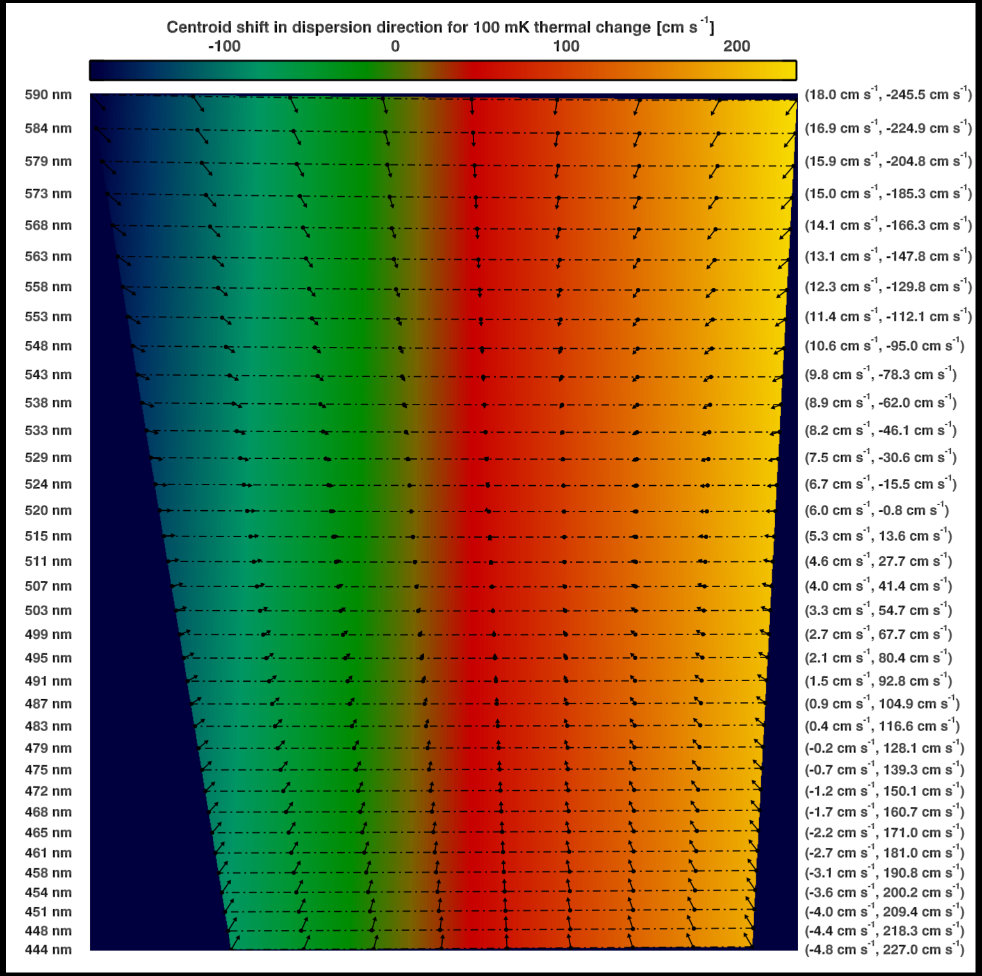
Camera optical elements have measurable dn/dT, CTE

Thermal fluctuations on spectrometer optics

KPF green / red cameras

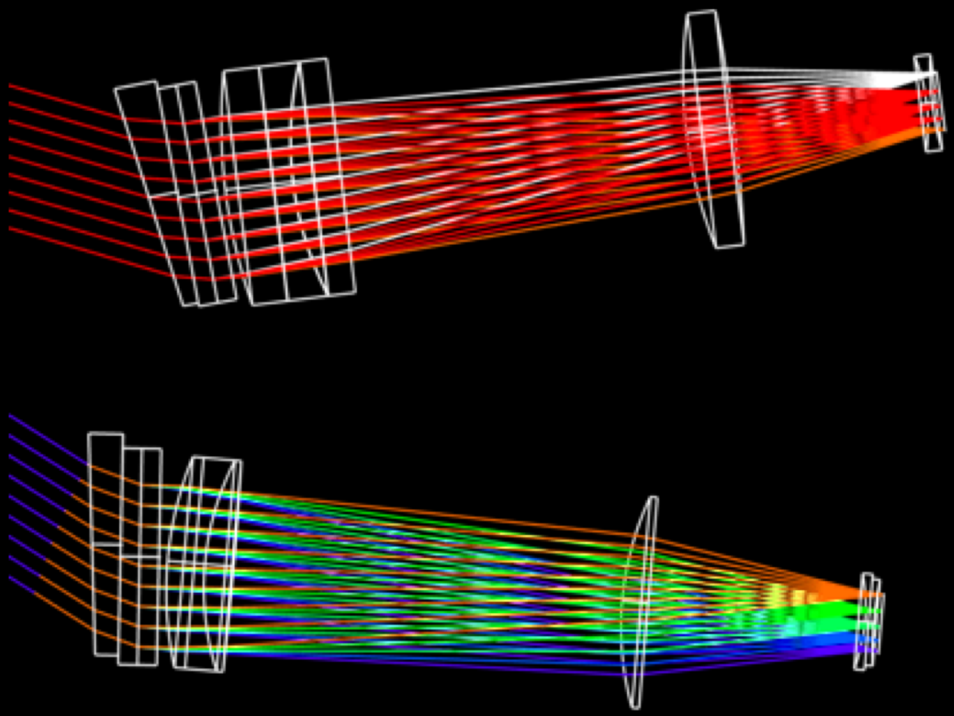


Camera optical elements have measurable dn/dT, CTE

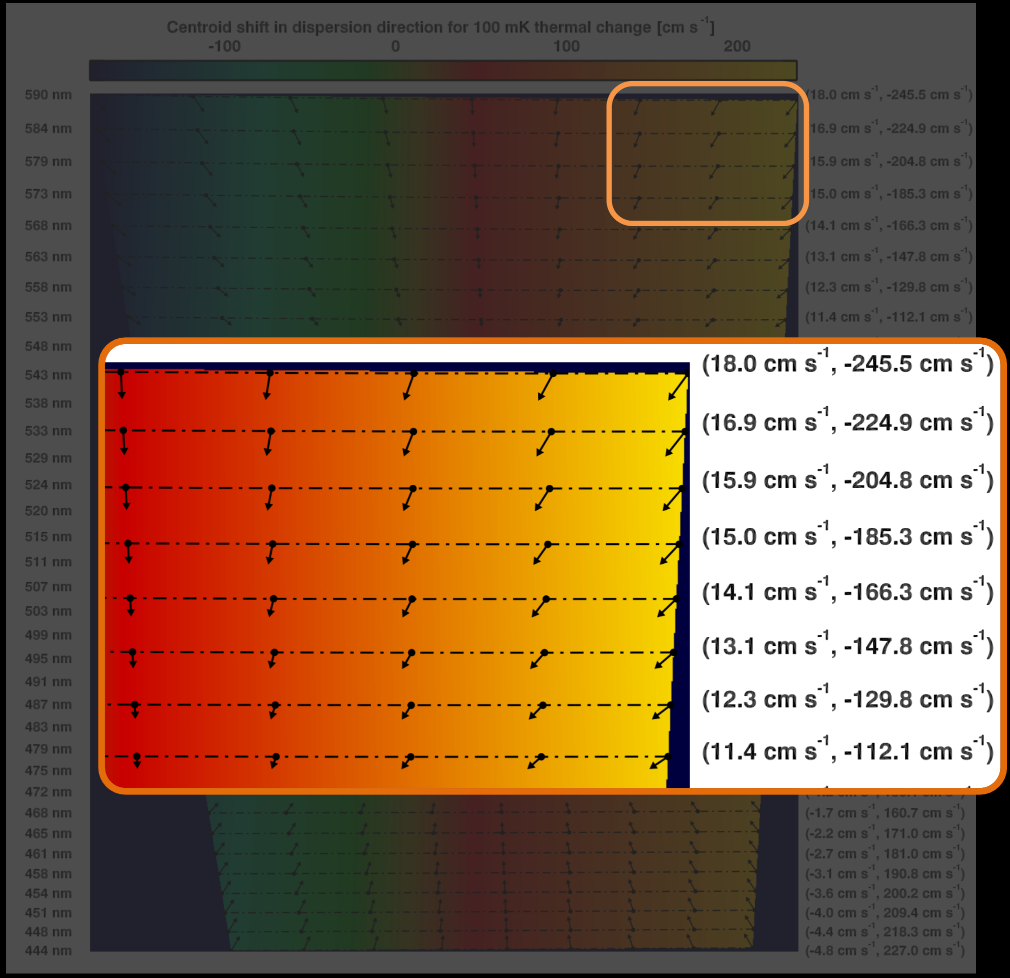


Thermal fluctuations on spectrometer optics

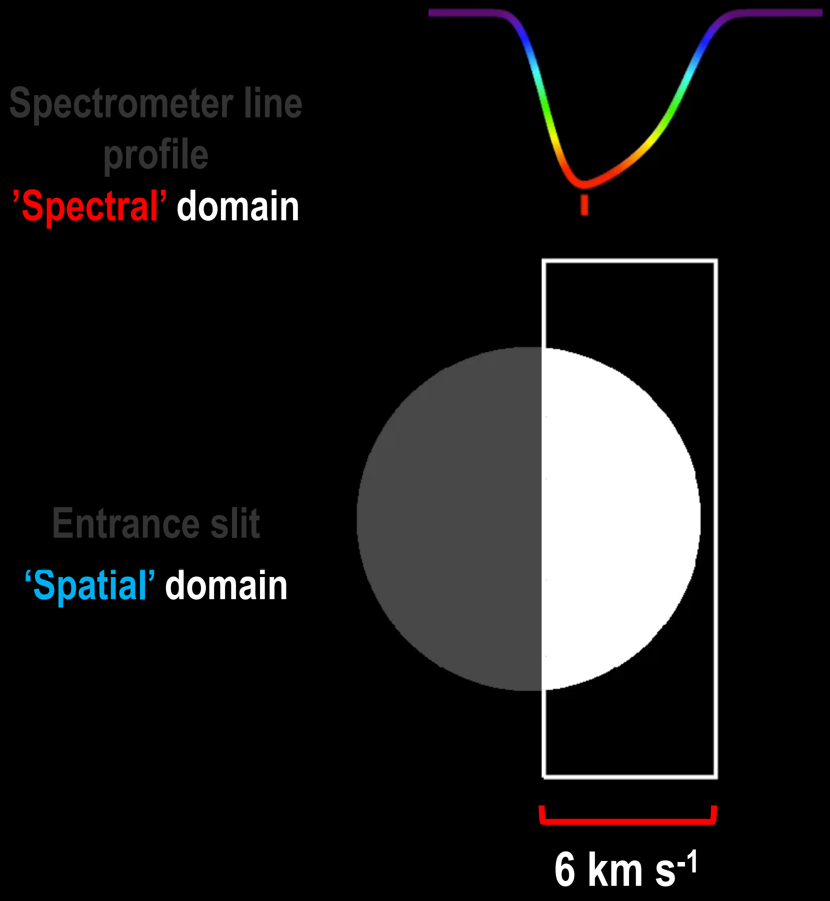
KPF green / red cameras



Camera optical elements have measurable dn/dT, CTE

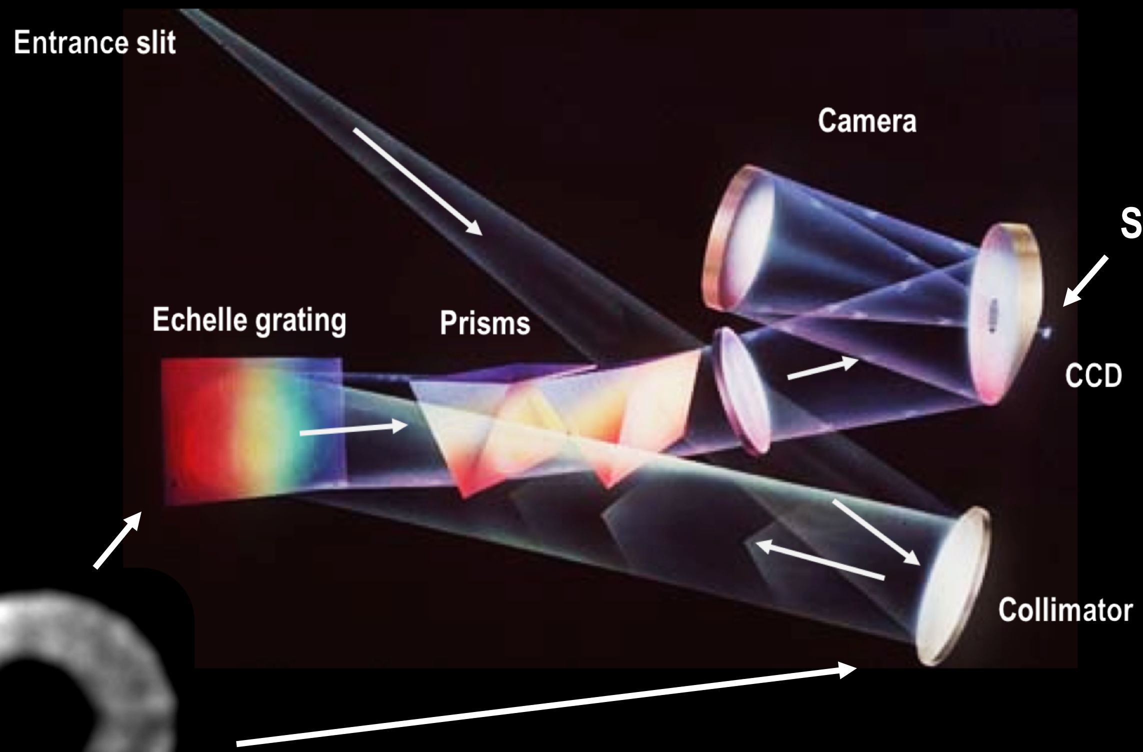


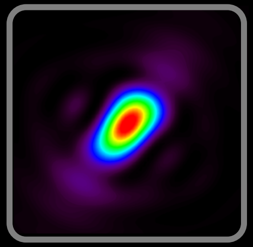
Examples of errors *not* tracked by calibration source



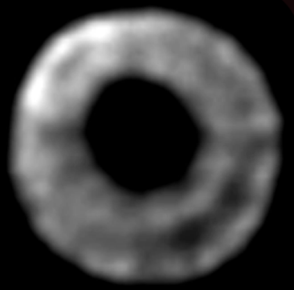
- Fundamentally, *spectrometer records monochromatic images of entrance aperture*

Illumination stability





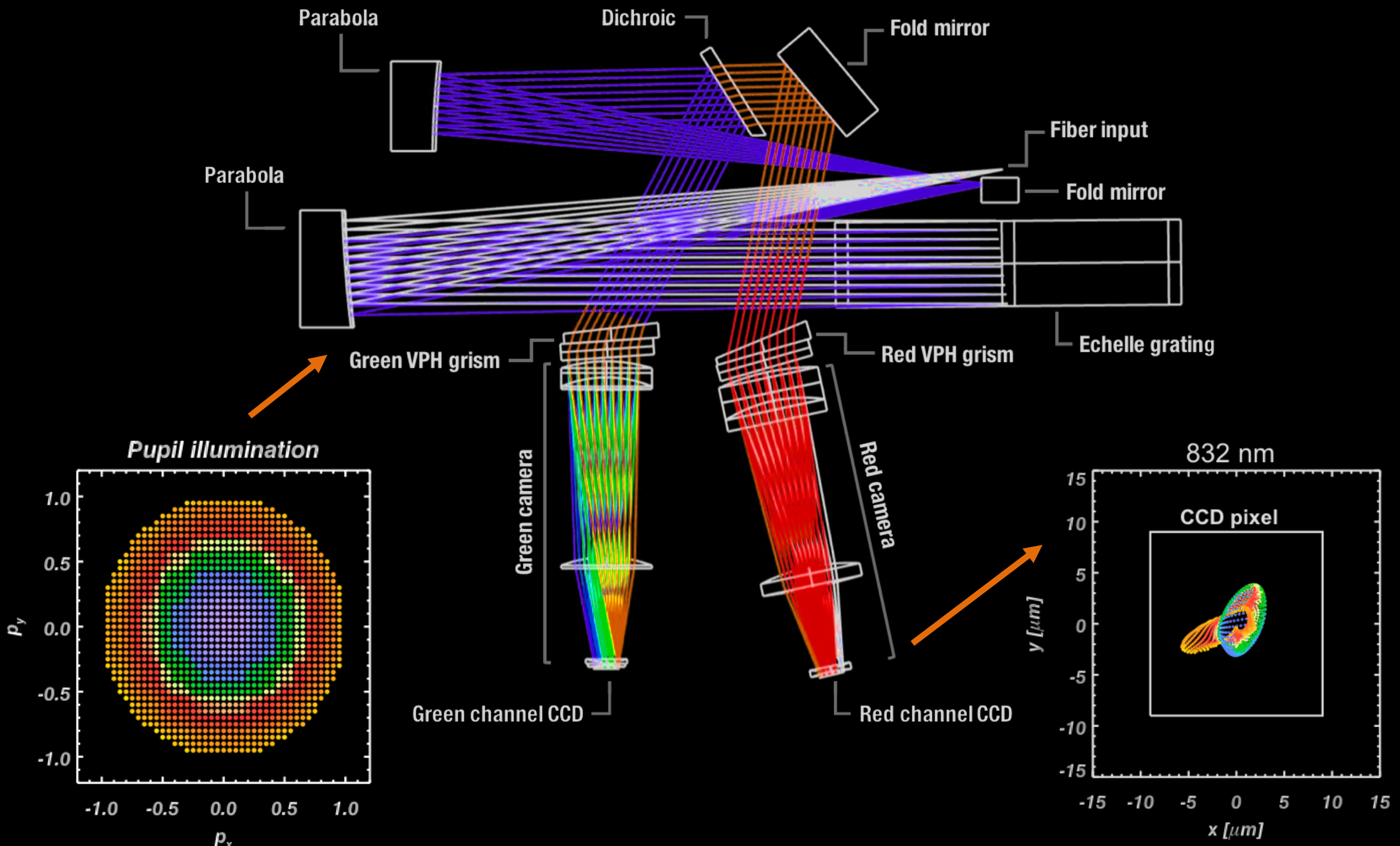
Spectrometer PSF



Telescope pupil

Beam profile on grating, camera optics sets the aberration distribution, final PSF

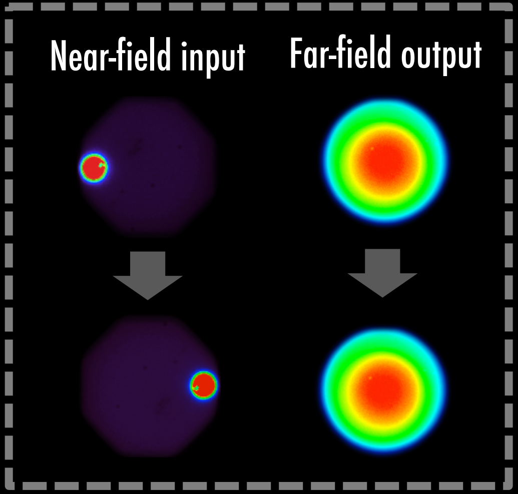
Far-field variations impacting RV measurement performance



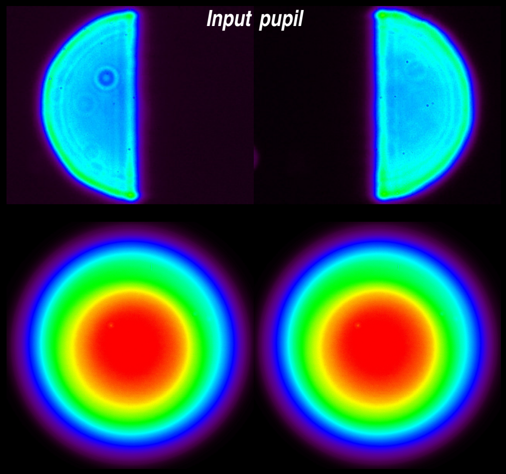
e.g. Sturmer+ 2014, Halverson+ 2016

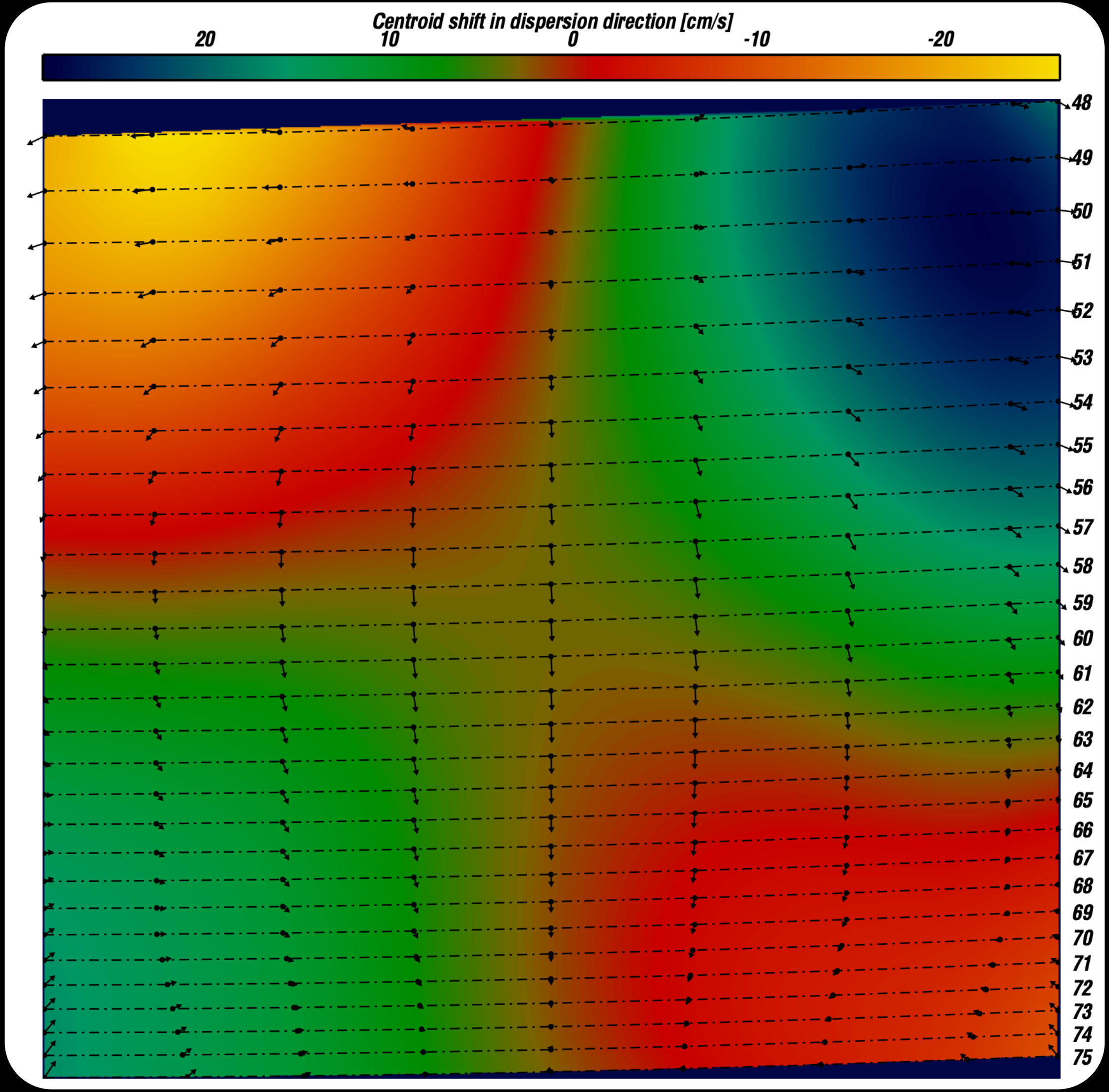
Pupil variation within spectrometer lead to changes in effective aberrations

1″ shift on fiber face (near-field)

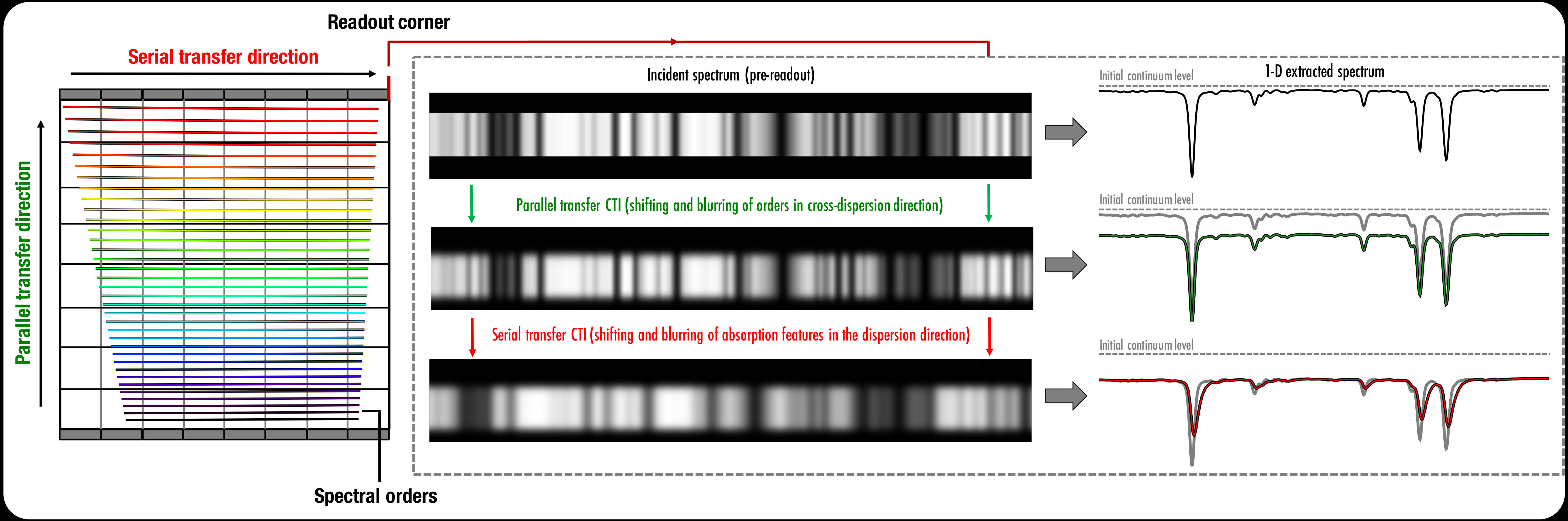


Input pupil shift (far-field)



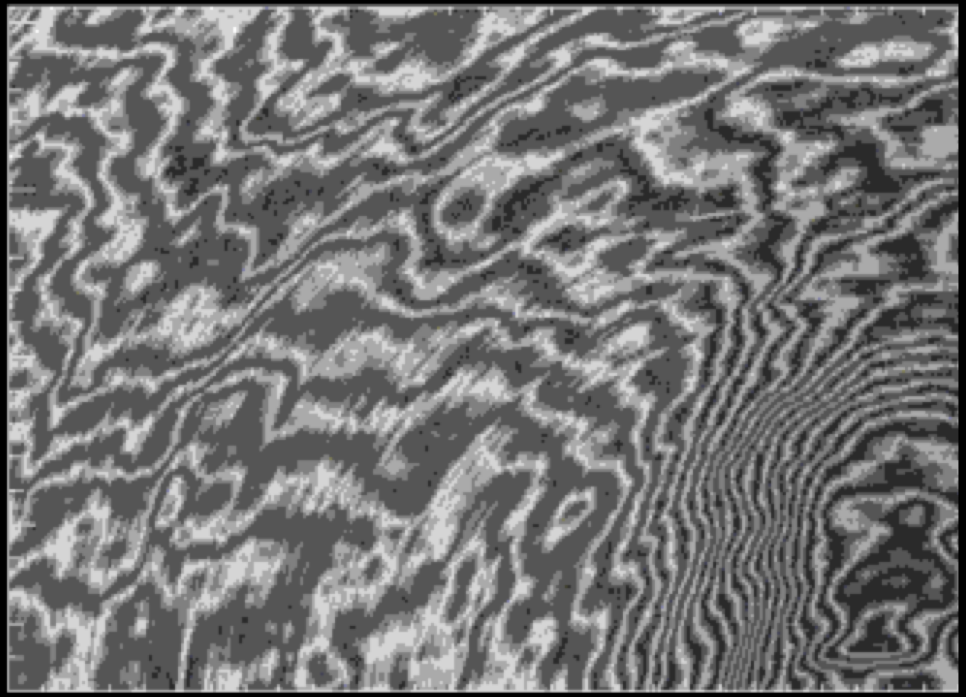


Detector effects: Charge transfer *inefficiency*

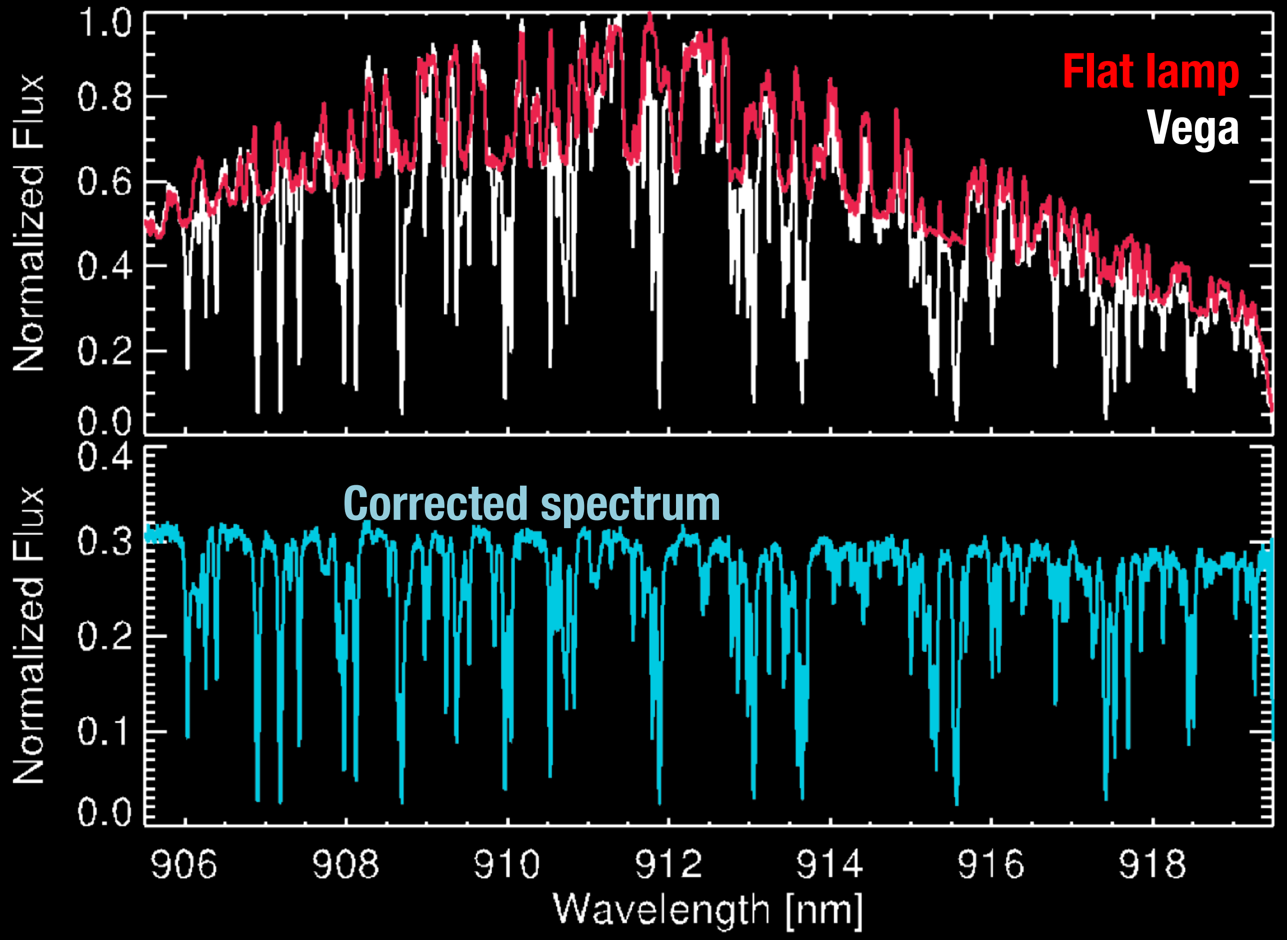


Bouchy+ 2009, Blake+ 2017, Halverson+ 2018

CCD fringing can introduce systematic error



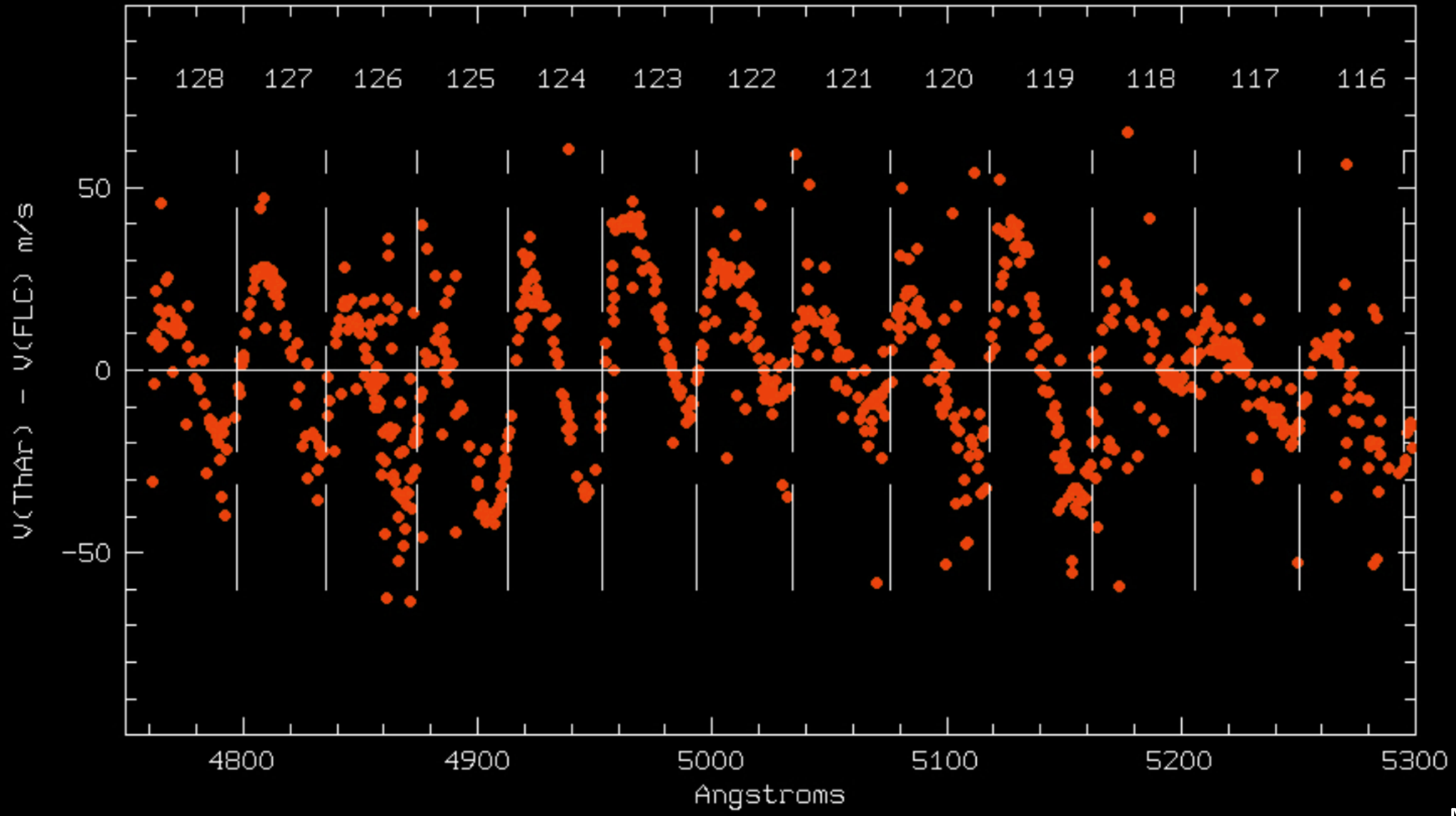
Example CCD flat, showing clear fringing structure



~1 m s^{-1} precision not demonstrated at reddest (>800 nm) wavelengths on CCDs

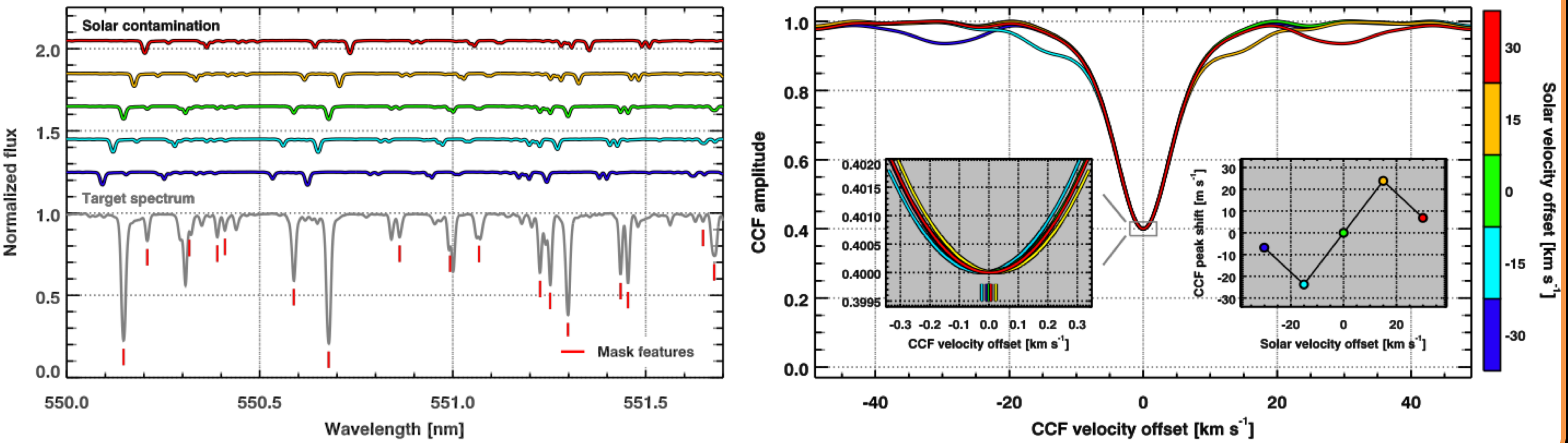
Slide credit: Arpita Roy

CCD stich boundaries

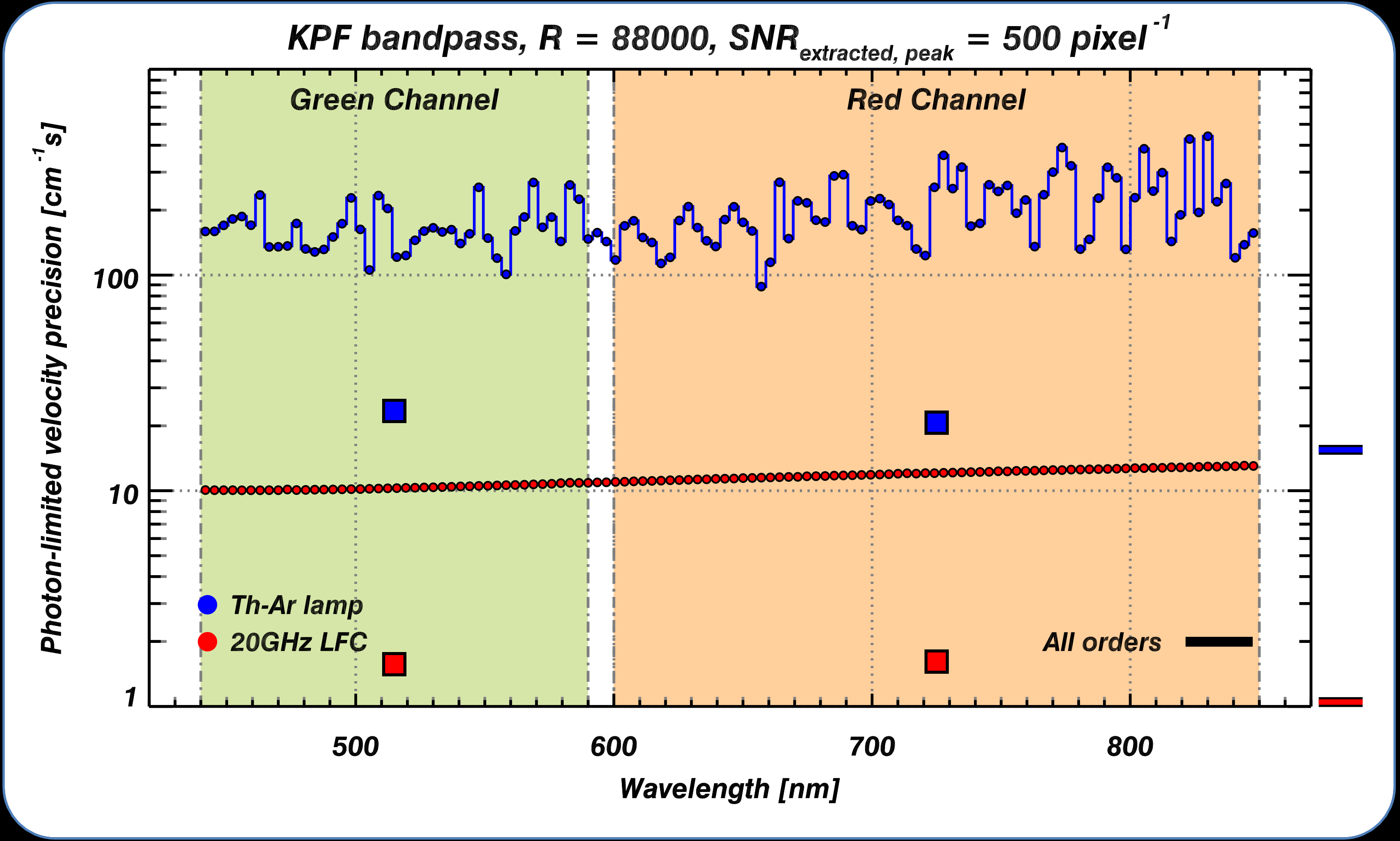


Molaro+ 2013

The atmosphere contributes more than telluric absorption



You are only as precise as your calibration source



e.g. Bouchy+ 2001, Murphy+ 2007, Halverson+ 2014

Pushing to 10 cm s^{-1} will unveil a forest of new challenges

Total NEID instrumental error budget: 27.0 cm s^{-1}

Instrument (uncalibratable): 15.1 cm s^{-1} (30.6%)

Fiber & illumination: 8.7 cm s^{-1}

Calibration source modal noise	2.5 cm s^{-1}
Continuum modal noise	2.5 cm s^{-1}
Near-field scrambling	3.5 cm s^{-1}
Far-field scrambling	5.0 cm s^{-1}
Stray light	5.0 cm s^{-1}
Polarization	2.0 cm s^{-1}

Detector effects: 7.1 cm s^{-1}

Readout thermal change	5.0 cm s^{-1}
Charge transfer inefficiency	5.0 cm s^{-1}

Barycentric correction: 1.7 cm s^{-1}

Algorithms	1.0 cm s^{-1}
Exposure midpoint time	1.0 cm s^{-1}
Coordinates and proper motion	1.0 cm s^{-1}

Reduction pipeline: 10 cm s^{-1}

Software algorithms	10 cm s^{-1}

Instrument (calibratable): 11.2 cm s^{-1} (1.1%)

25%

Thermo-mechanical: 7.8 cm s^{-1}

Thermal stability (grating)	3.5 cm s^{-1}
Thermal stability (cross-disp.)	3.0 cm s^{-1}
Thermal stability (bench)	3.0 cm s^{-1}
Vibrational stability	2.0 cm s^{-1}
Pressure stability	<0.1 cm s^{-1}
LN2 fill transient	1.0 cm s^{-1}
Zerodur phase change	5.0 cm s^{-1}

Detector effects: 8.1 cm s^{-1}

Pixel inhomogeneities	1.0 cm s^{-1}
Electronics noise	1.0 cm s^{-1}
Stitching error	3.0 cm s^{-1}
CCD thermal expansion	2.0 cm s^{-1}
Readout thermal change	5.0 cm s^{-1}
Charge transfer inefficiency	5.0 cm s^{-1}

Calibration source (uncalibratable): 11.5 cm s^{-1} (18.7%)

Calibration accuracy: 5.7 cm s^{-1}

Stability	4.0 cm s^{-1}
Photon noise	4.0 cm s^{-1}

External errors (uncalibratable): 18.7 cm s^{-1} (49.6%)

Calibration process: 10 cm s^{-1}

Software algorithms	10 cm s^{-1}

Telescope: 12.2 cm s^{-1}

Guiding	scrambling
ADC	6.9 cm s^{-1}
Focus	5.0 cm s^{-1}
Windshake	8.0 cm s^{-1}

Atmospheric effects: 14.1 cm s^{-1}

Micro-telluric contamination	10 cm s^{-1}
Sky fiber subtraction	10 cm s^{-1}