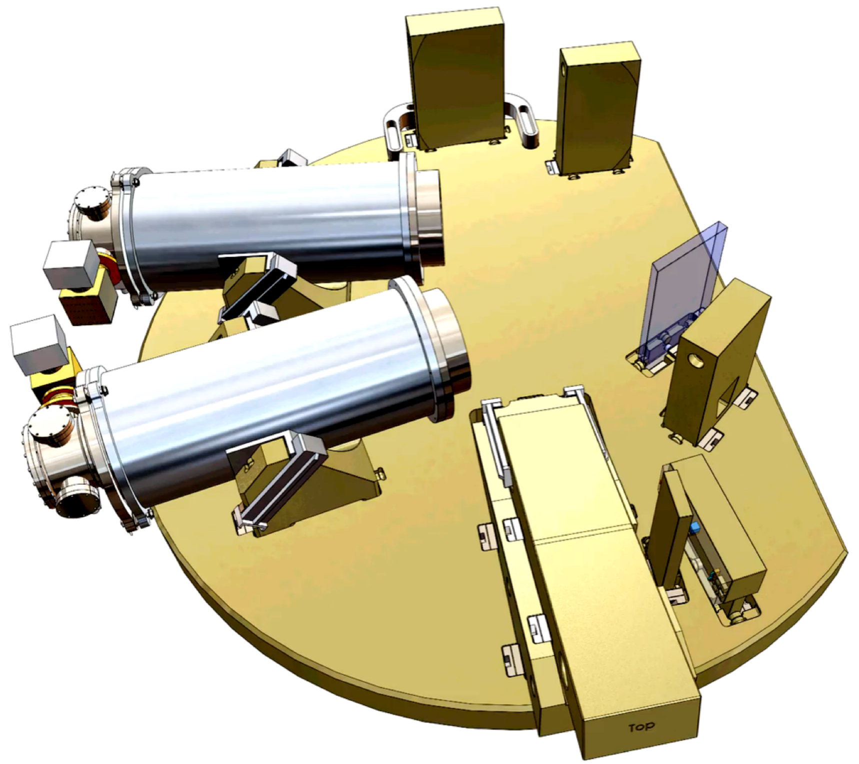
Instrumental challenges of high precision radial velocity measurements

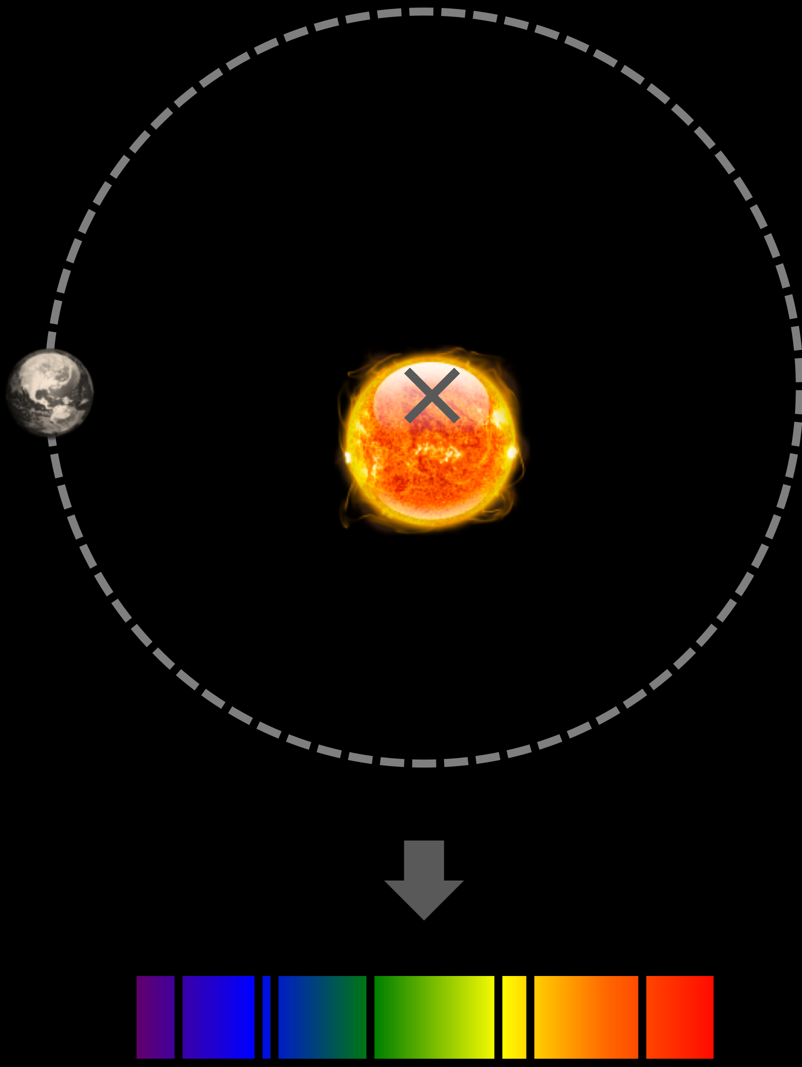


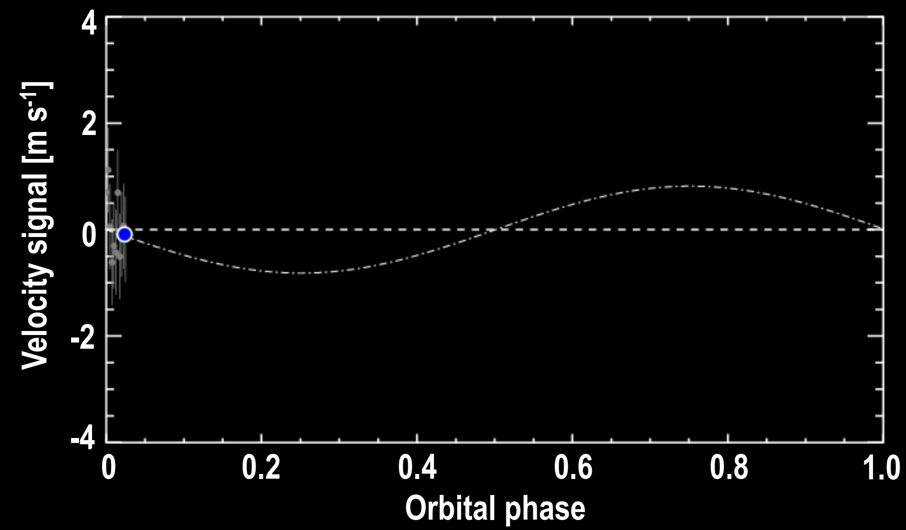
Chris smith, KPF team

Sam Halverson

NASA Sagan Fellow, MIT

Detecting exoplanets via Doppler velocimetry





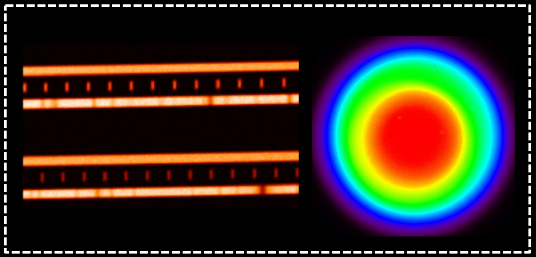
Period: 400 days

M_p (*msin(i)*): 10 M_{Earth}

eccentricity: 0.01

Technological challenges of high precision radial velocity measurements

Improved Doppler spectroscopy instrumentation



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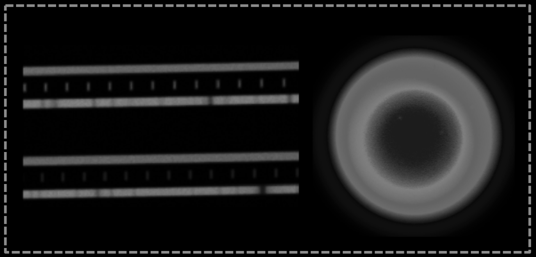
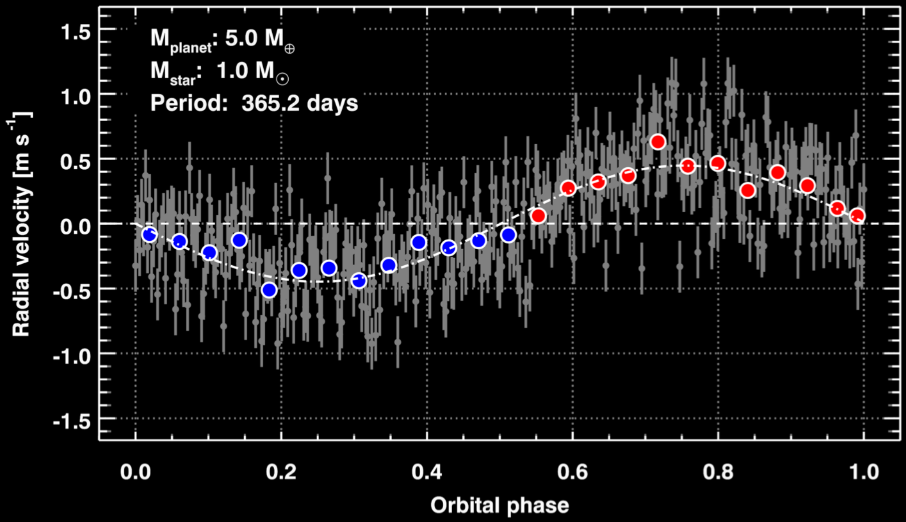


Higher precision radial velocity measurements



Technological challenges of high precision radial velocity measurements

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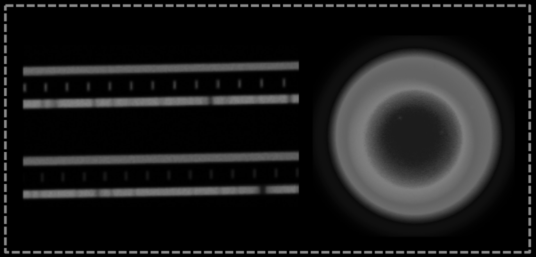

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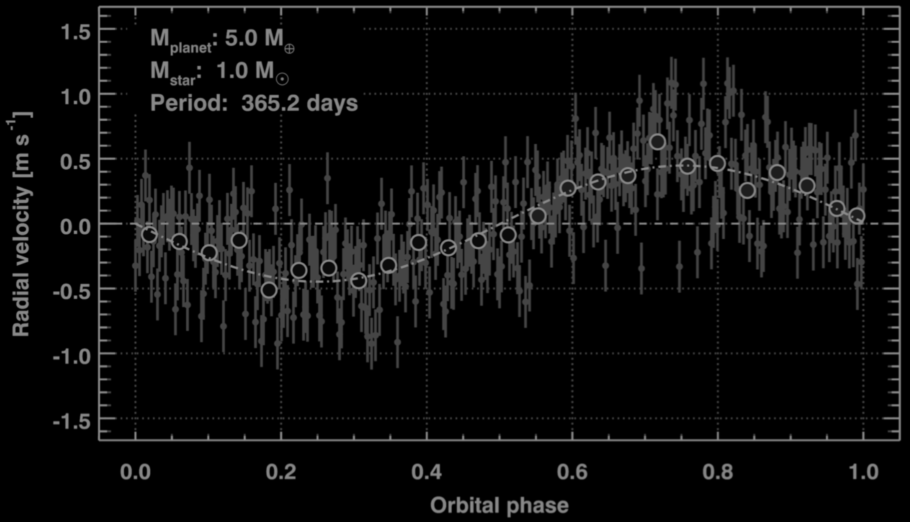


Better sensitivity to small planets

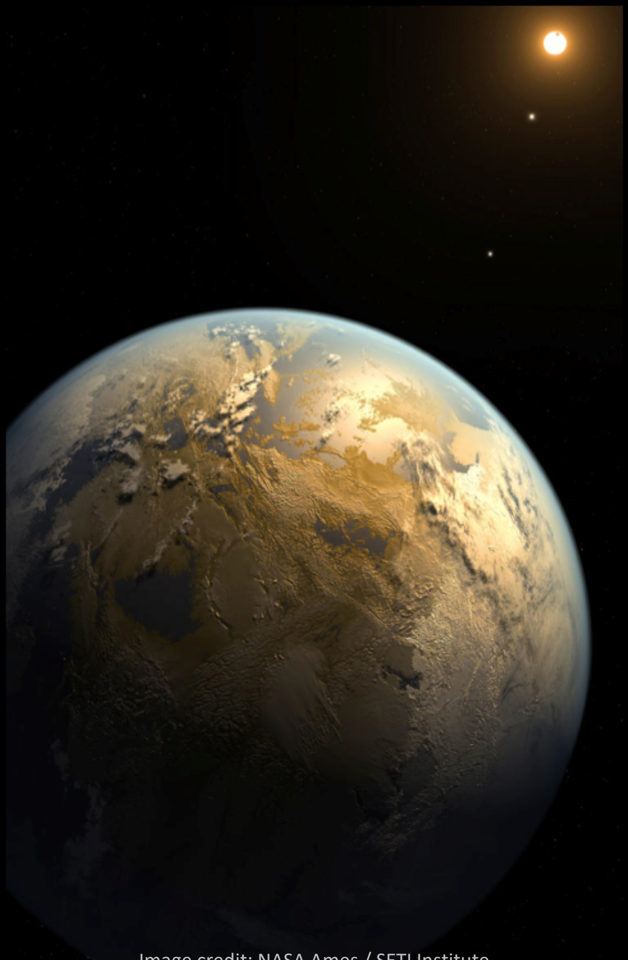
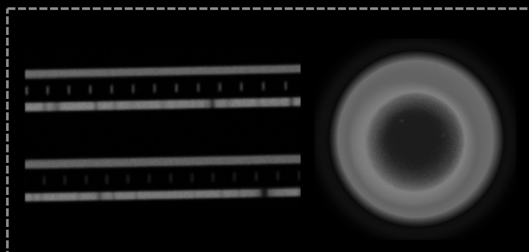


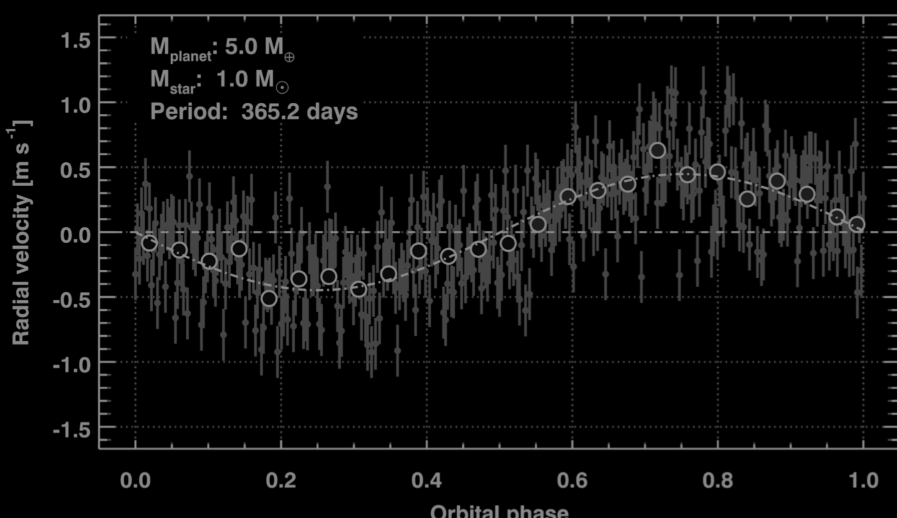
Image credit: NASA Ames / SETI Institute

Technological challenges of high precision radial velocity measurements

Improved Doppler spectroscopy instrumentation



Higher precision radial velocity measurements



Better sensitivity to
~~small planets~~
stellar activity

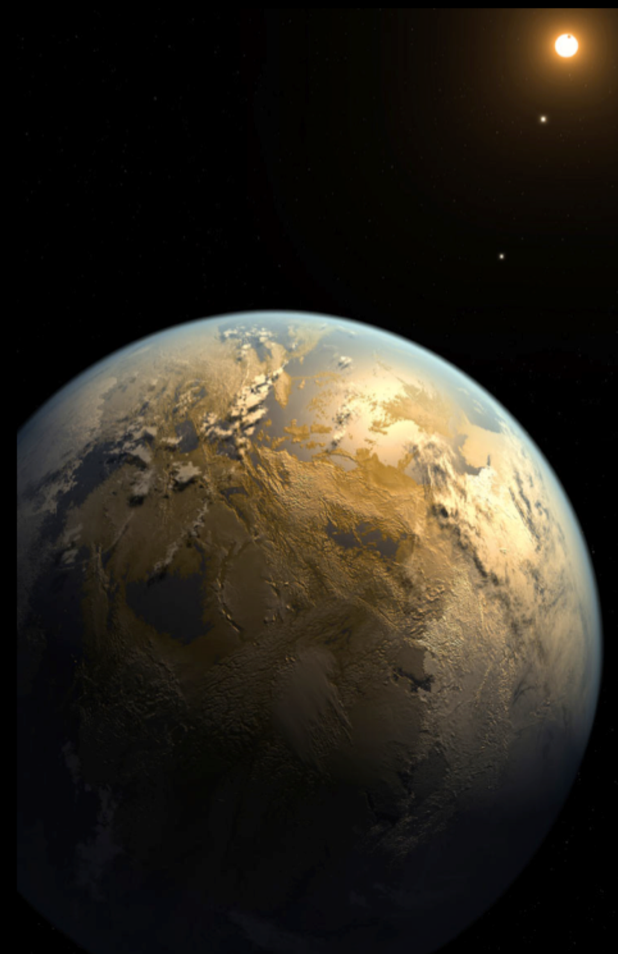
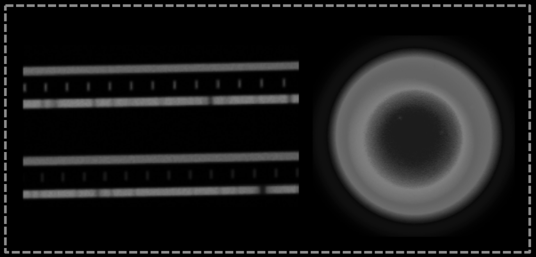


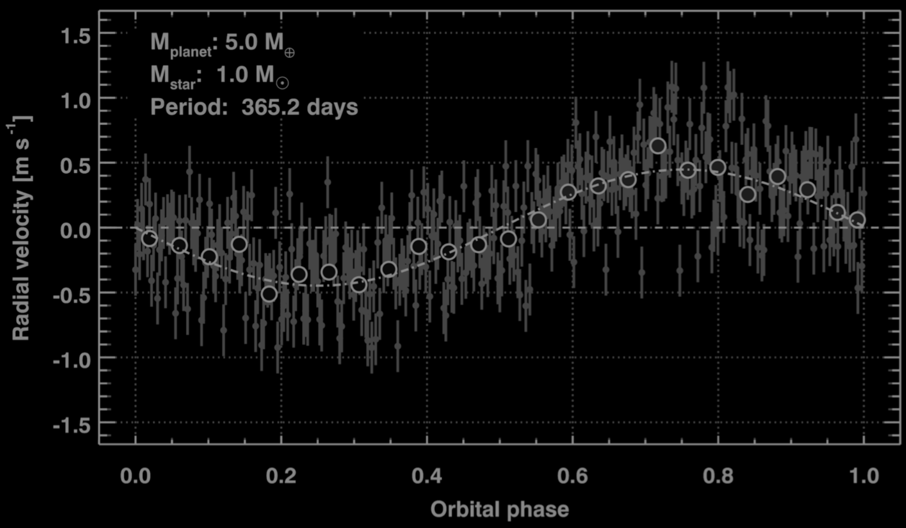
Image credit: NASA Ames / SETI Institute

Technological challenges of high precision radial velocity measurements

Improved Doppler spectroscopy instrumentation



Higher precision radial velocity measurements



Better sensitivity to ~~small planets~~
stellar activity
➡
(also small planets)

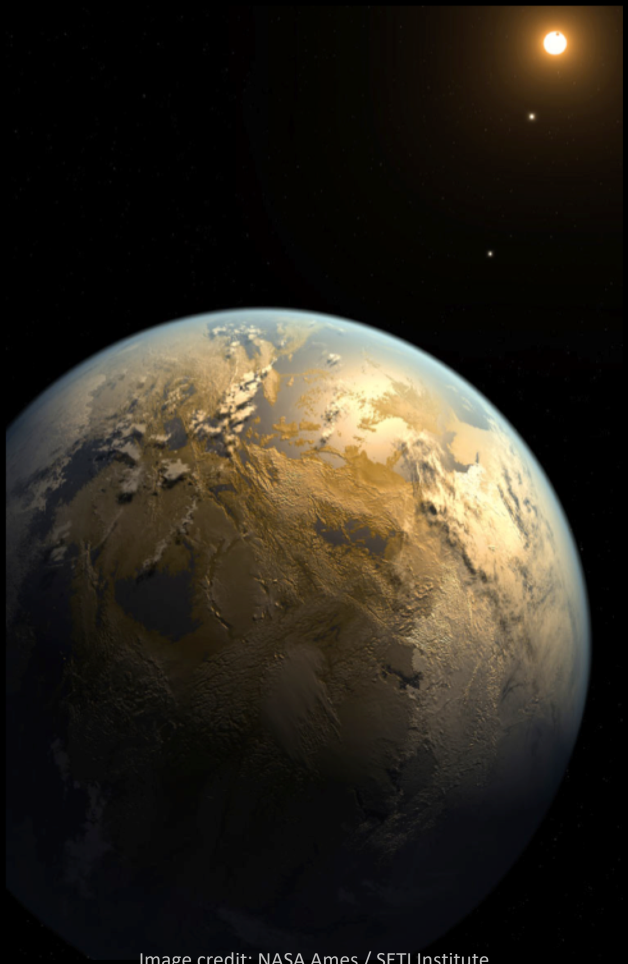
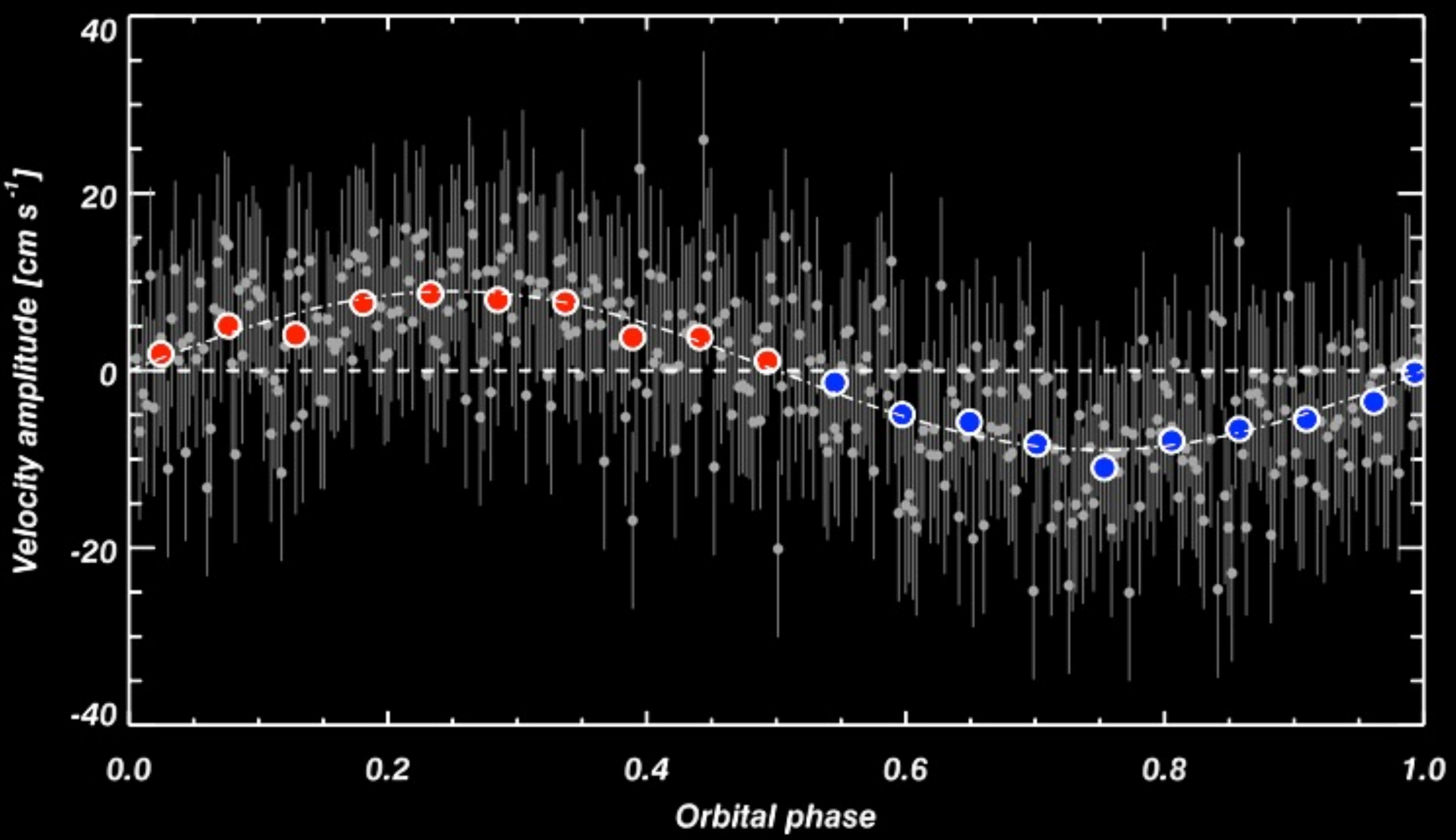


Image credit: NASA Ames / SETI Institute

What does instrumental precision mean?



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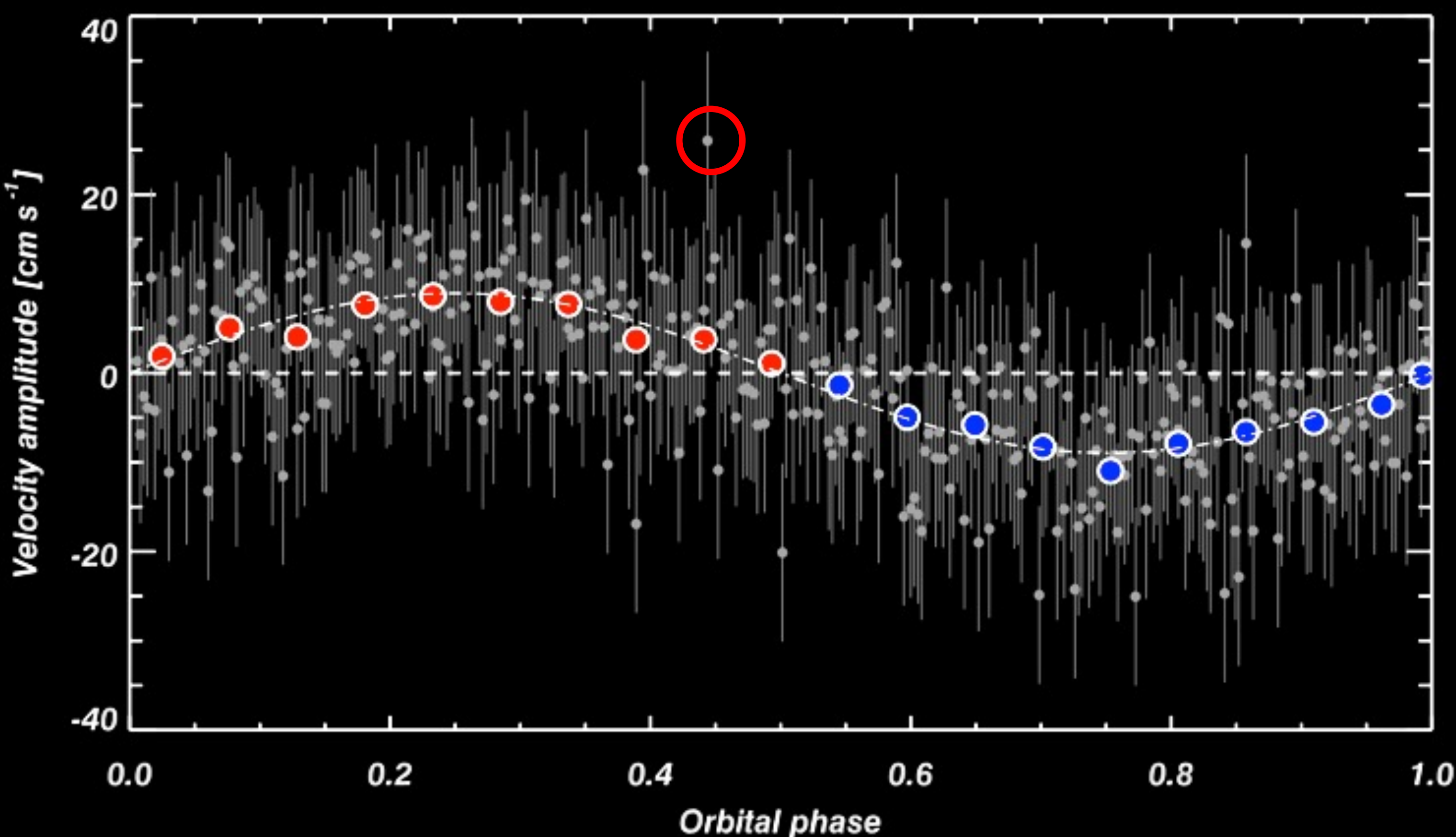

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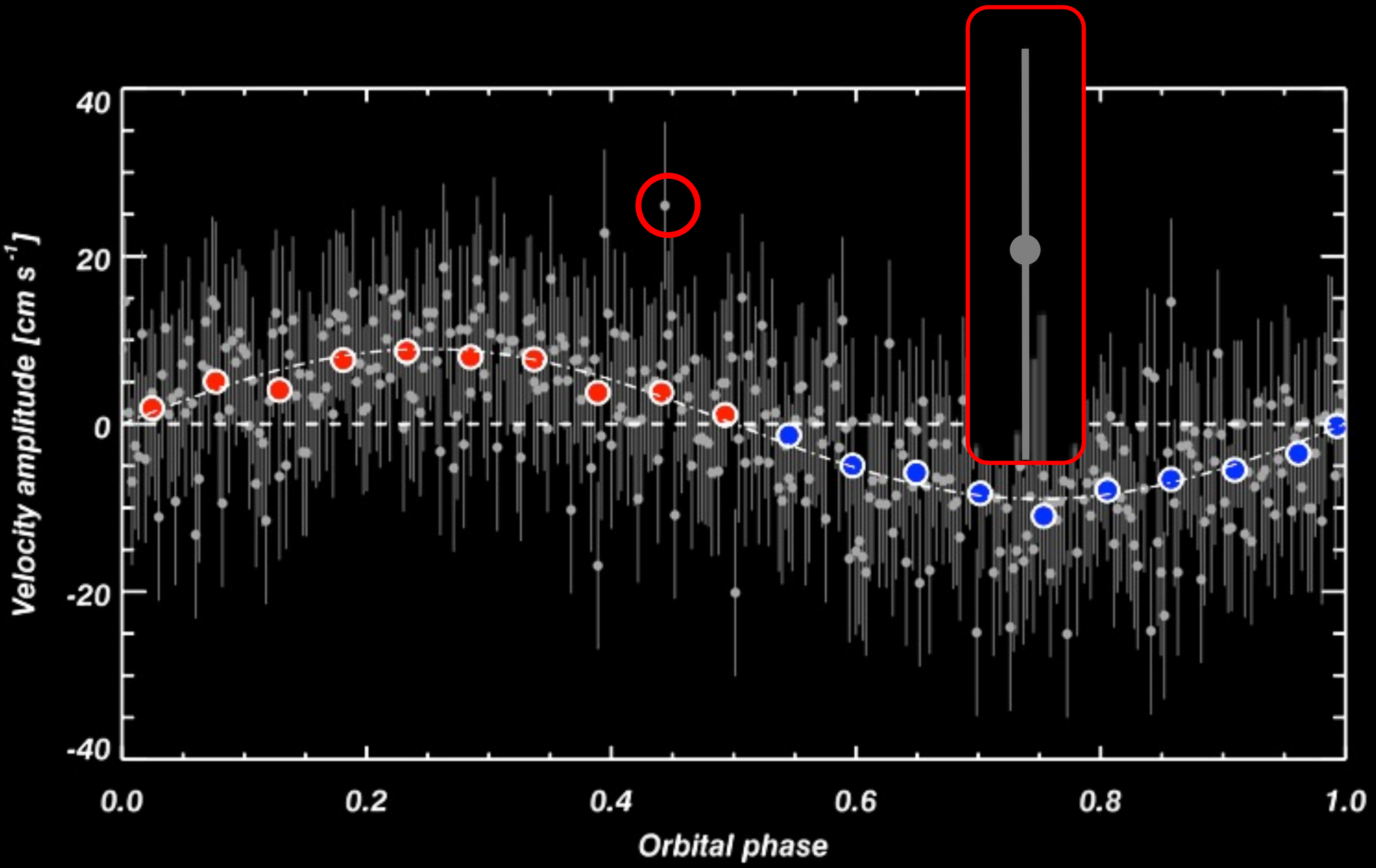

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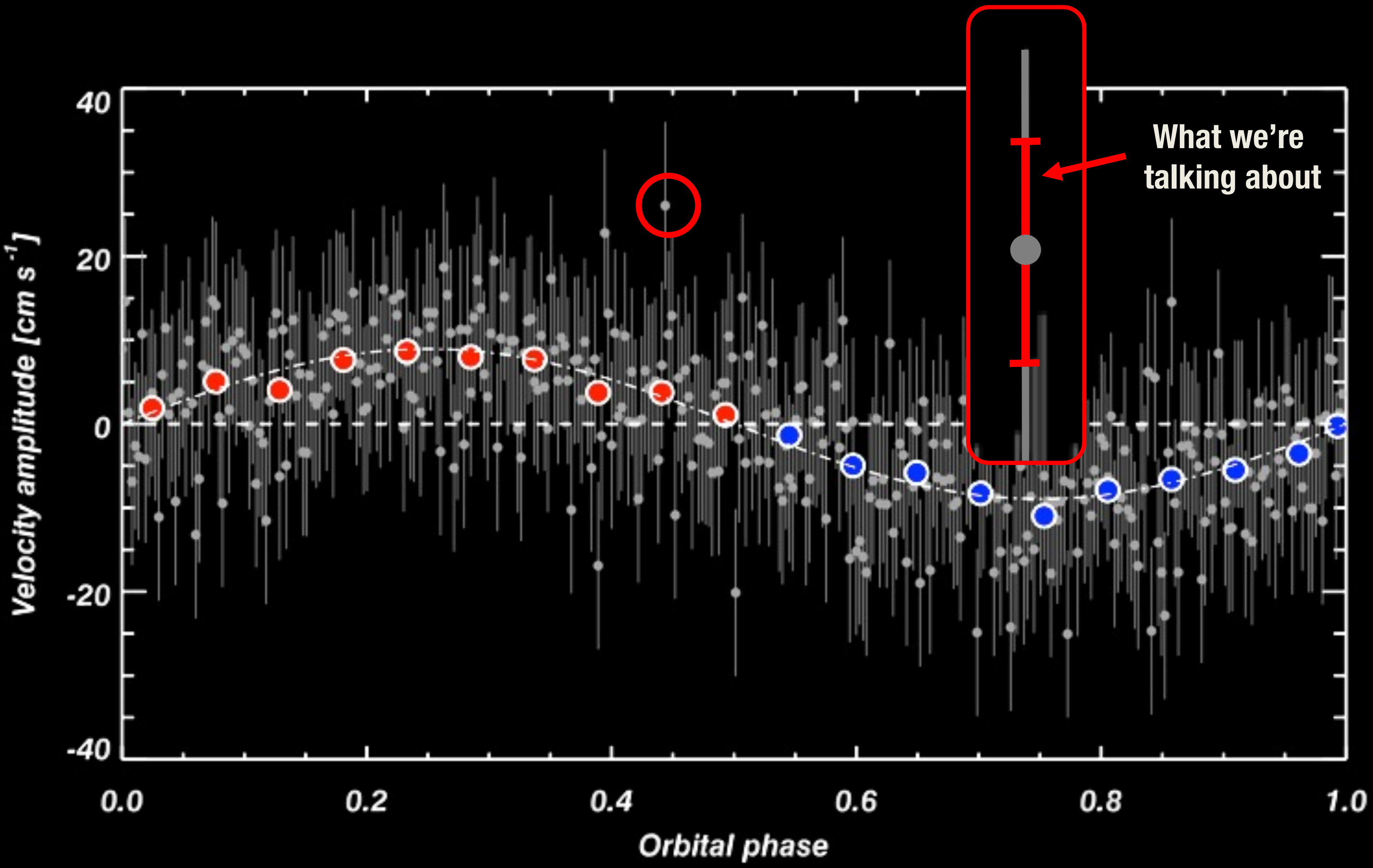
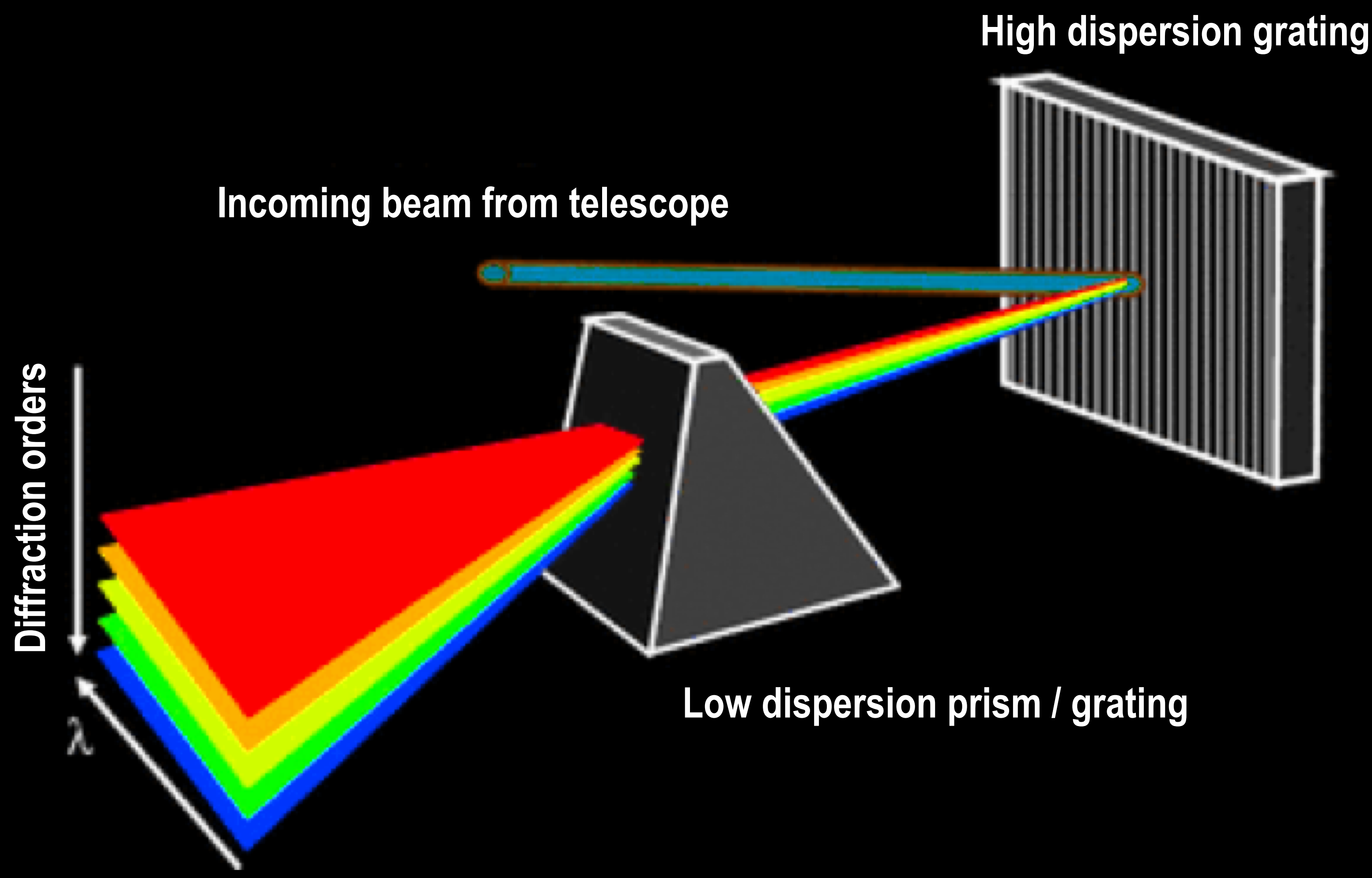
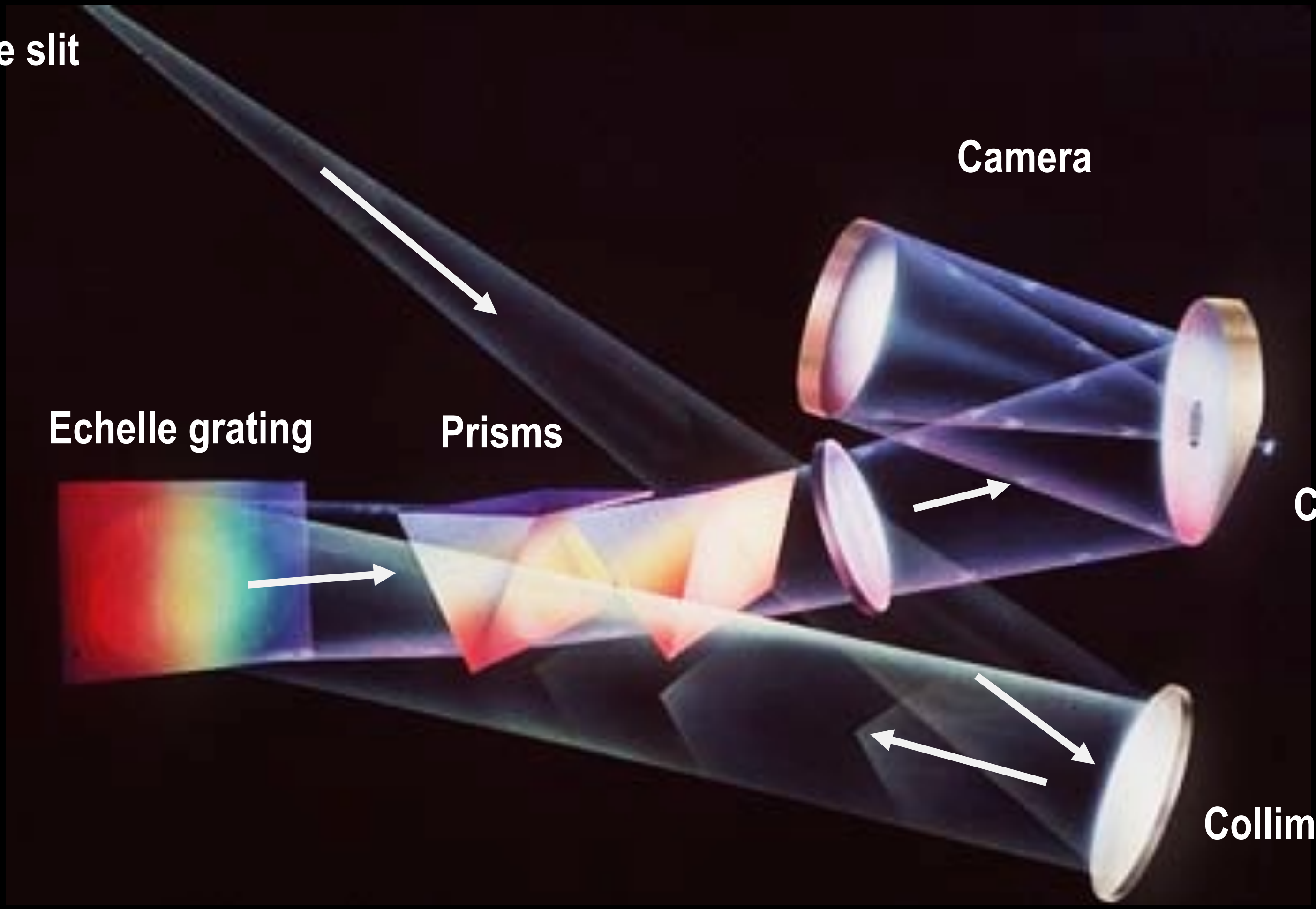


How we record spectra used for velocity measurements

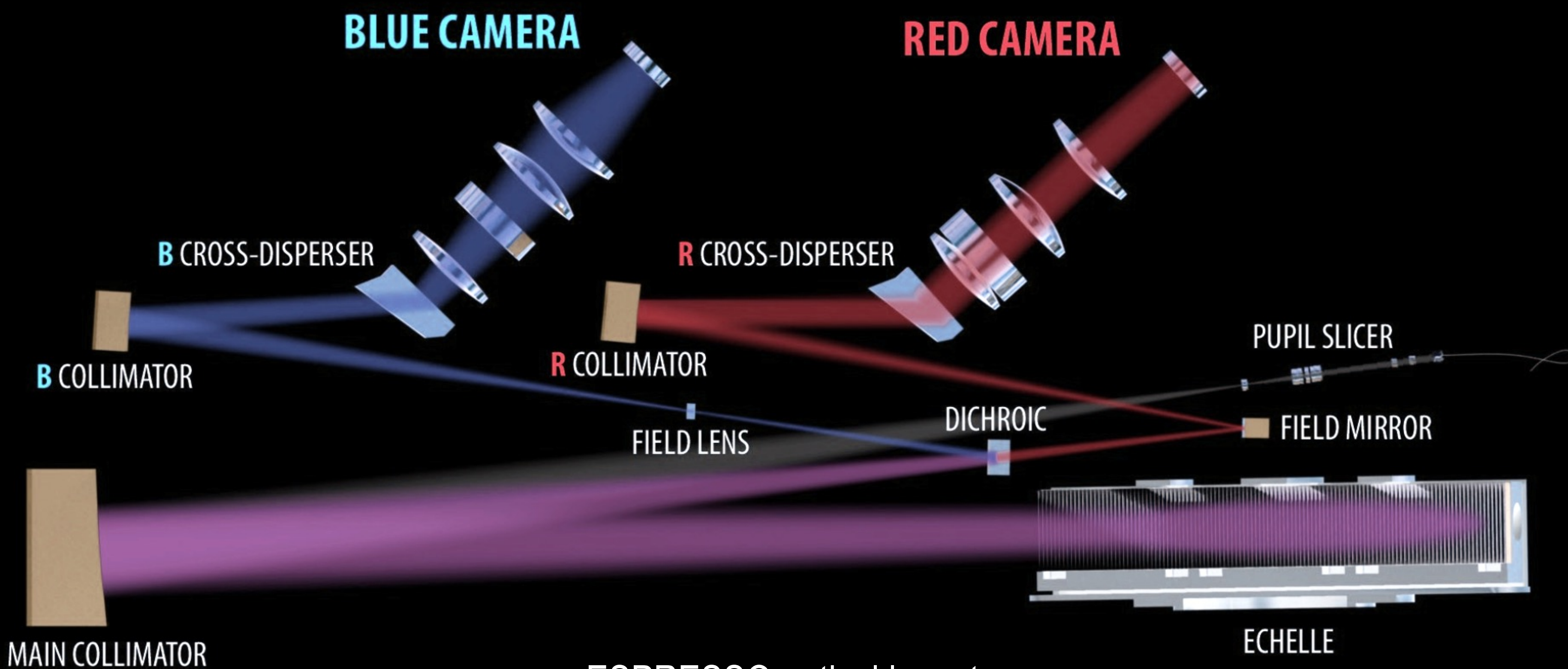


A more detailed view of cross-dispersed spectrometers



Hamilton spectrometer at Lick Observatory

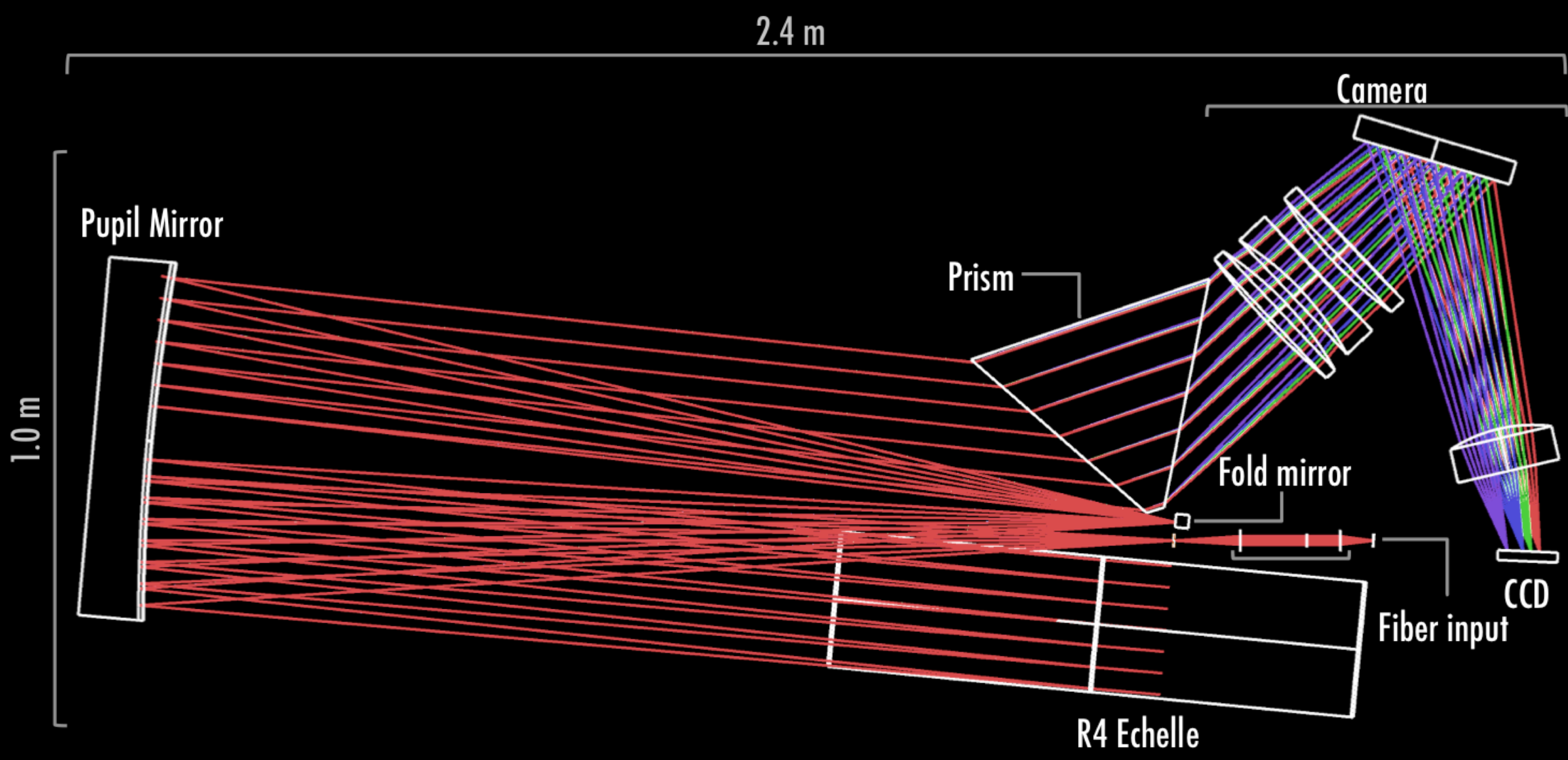
Example of more modern design



ESPRESSO optical layout

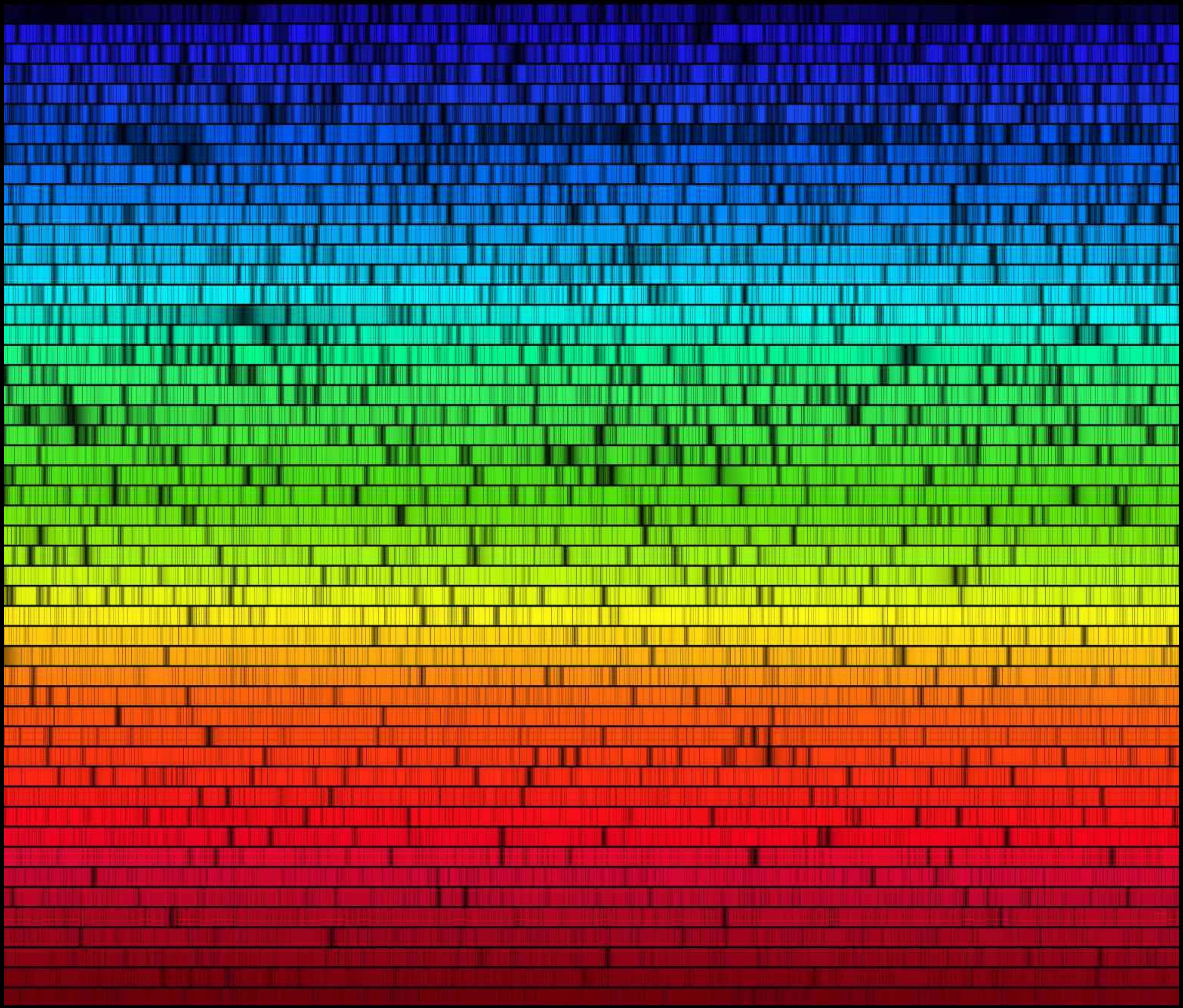
eso.org

Example of more modern design

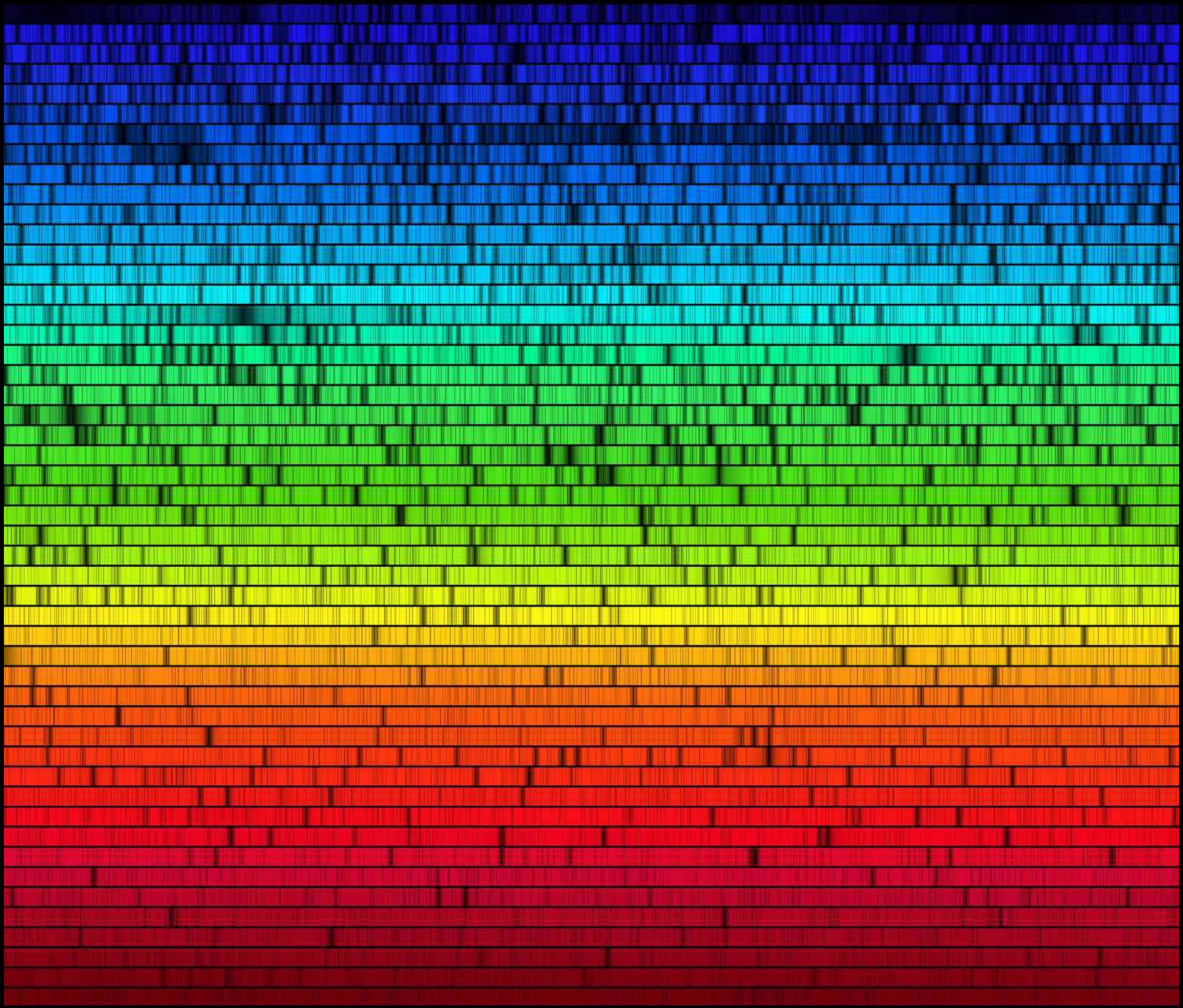


NEID spectrometer optical layout

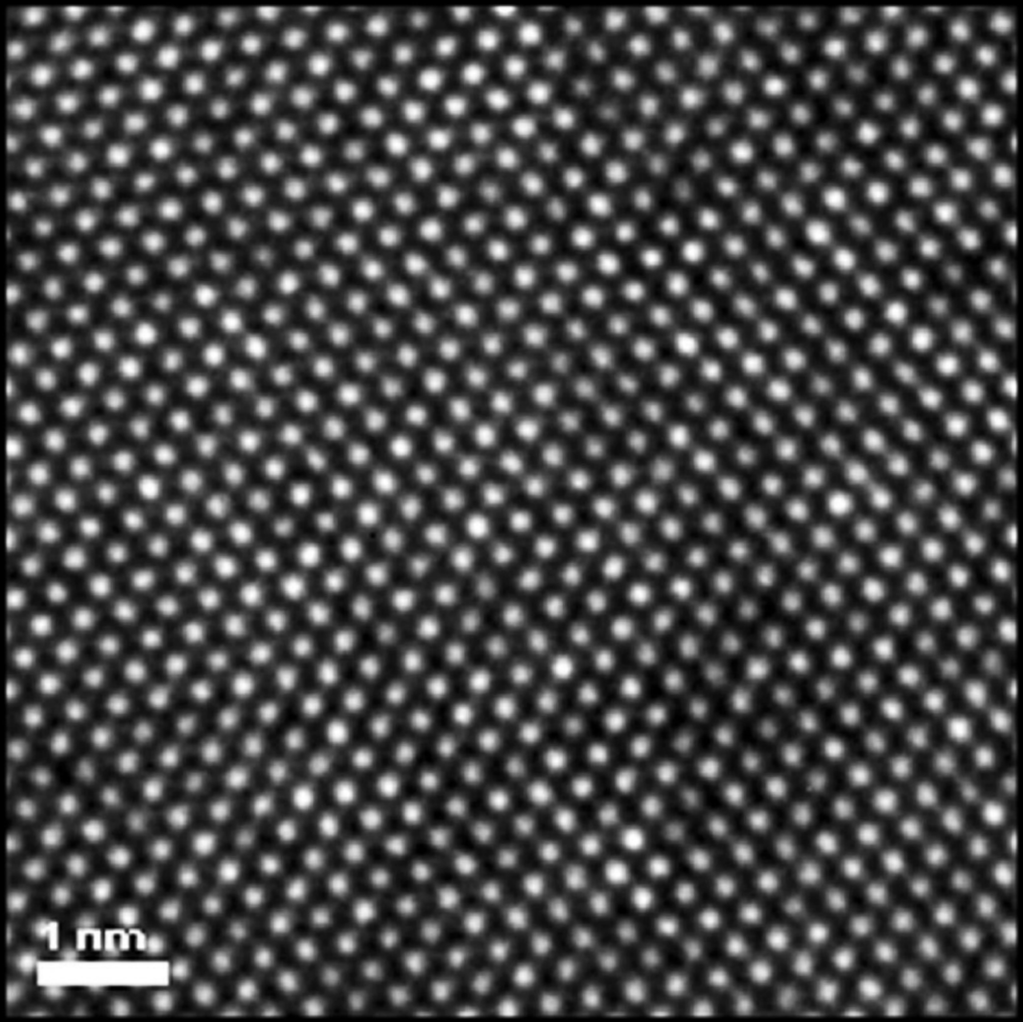
Result is a high resolution spectrum, spanning wide wavelength range



What do radial velocity signals look like?



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



TEM image of silicon wafer lattice (typical CCD)

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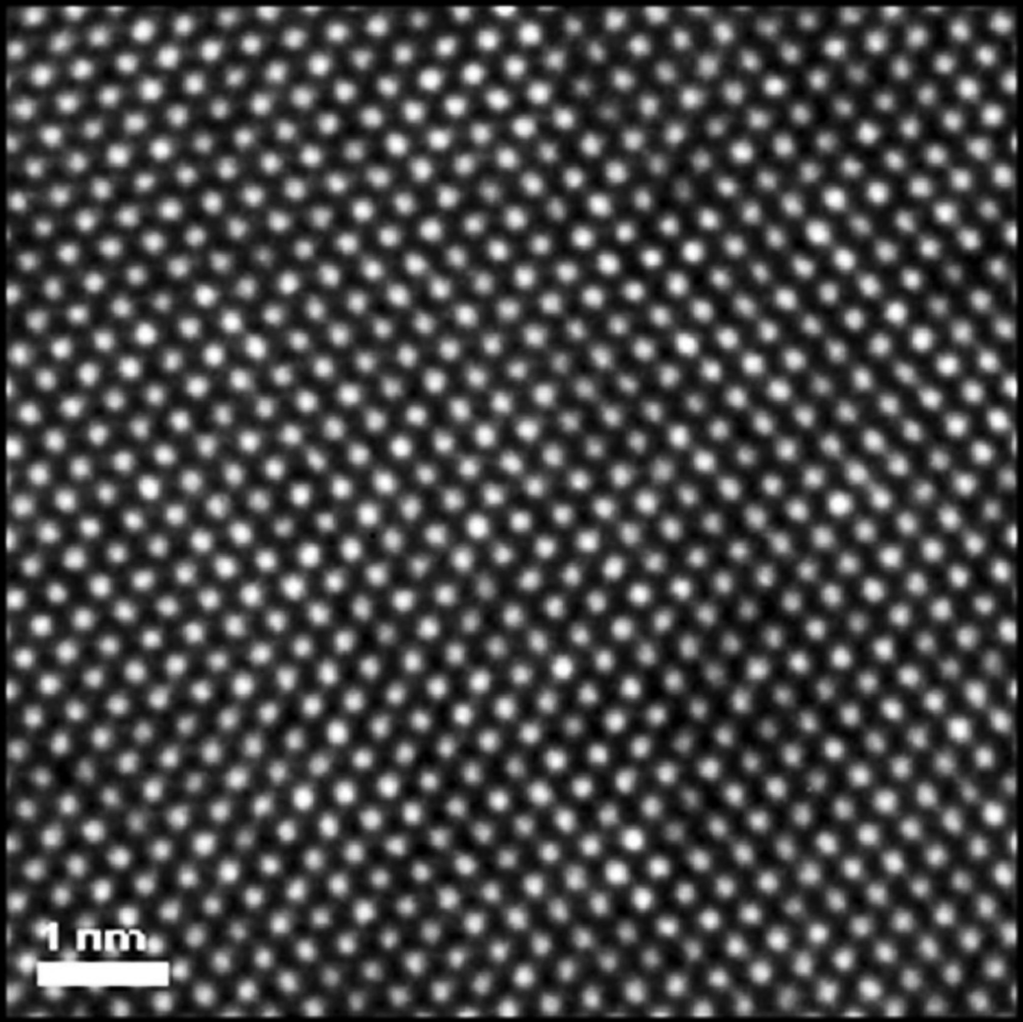

1/1000th of a pixel

TEM image of silicon wafer lattice (typical CCD)

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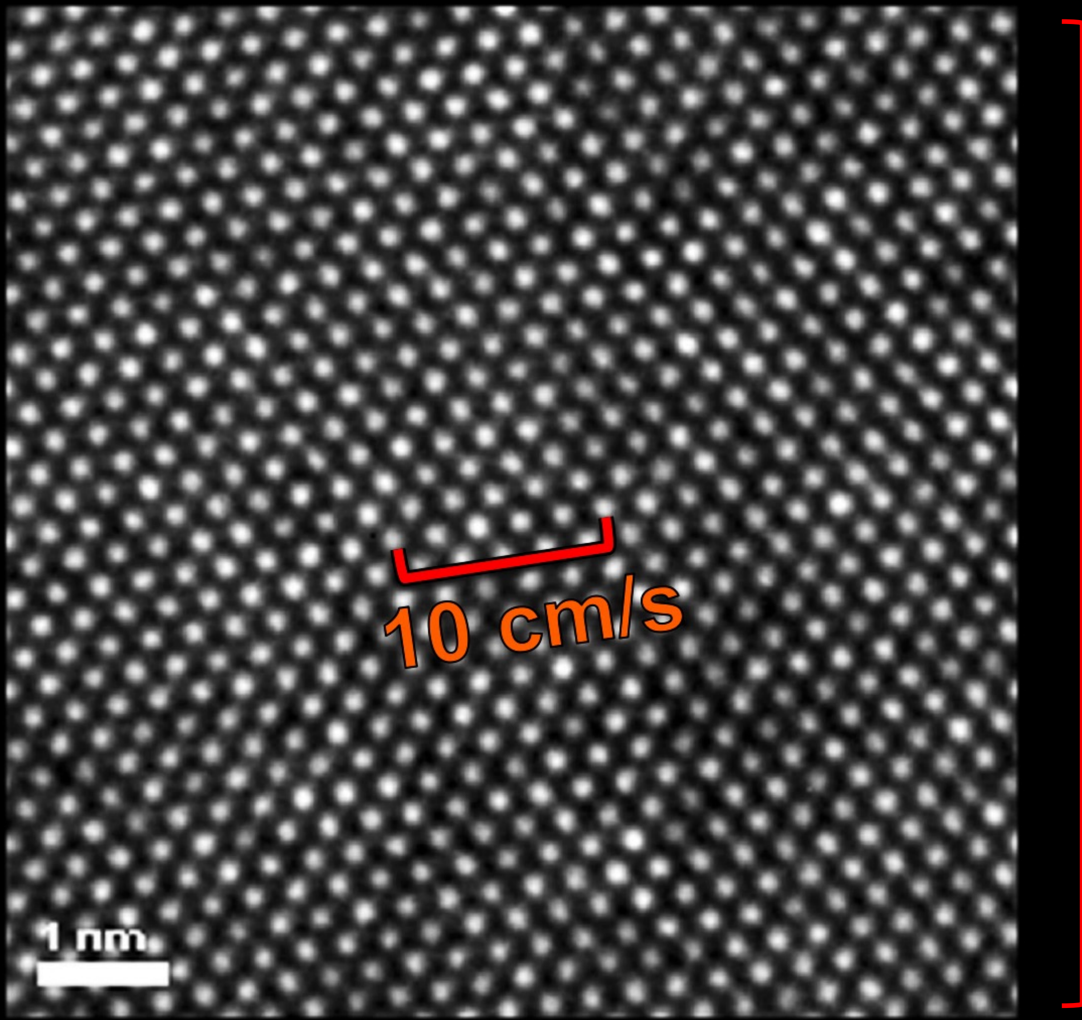
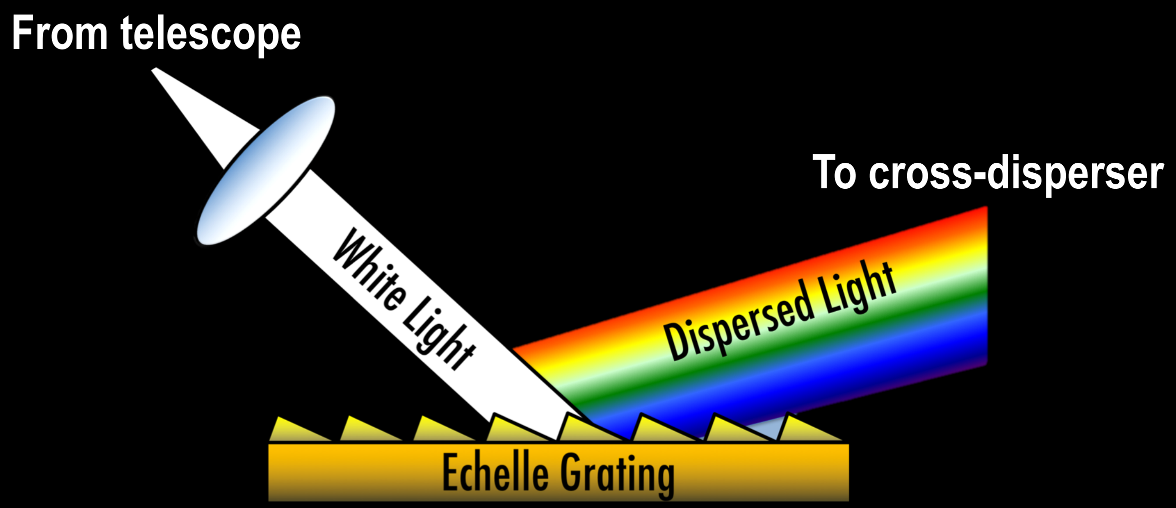


TEM image of silicon wafer lattice (typical CCD)

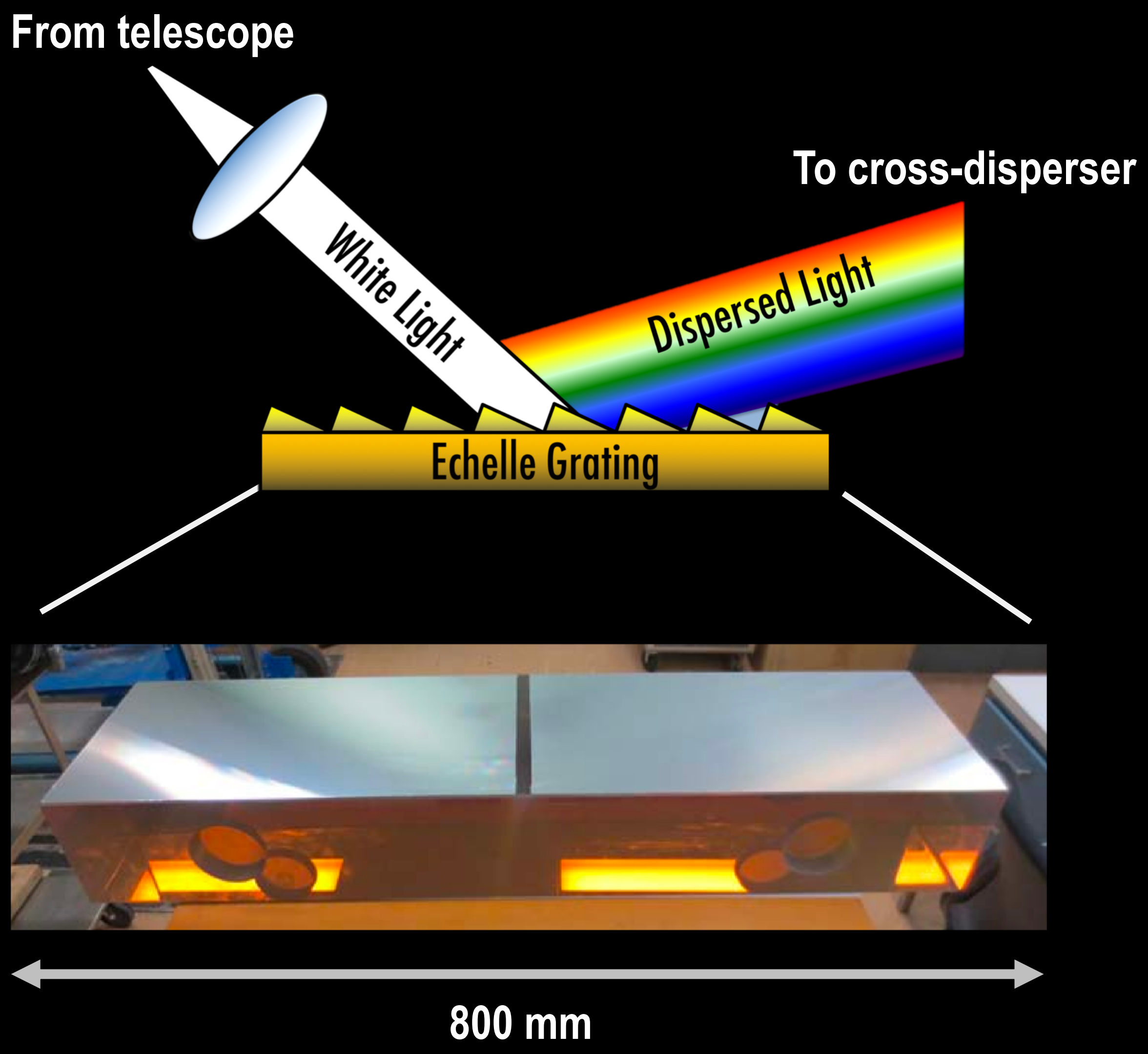
(Some) Instrumental challenges for Doppler spectroscopy

- Environmental stability
- Illumination stability
- Wavelength calibration

Thermal fluctuations on spectrometer optics



Thermal fluctuations on spectrometer optics



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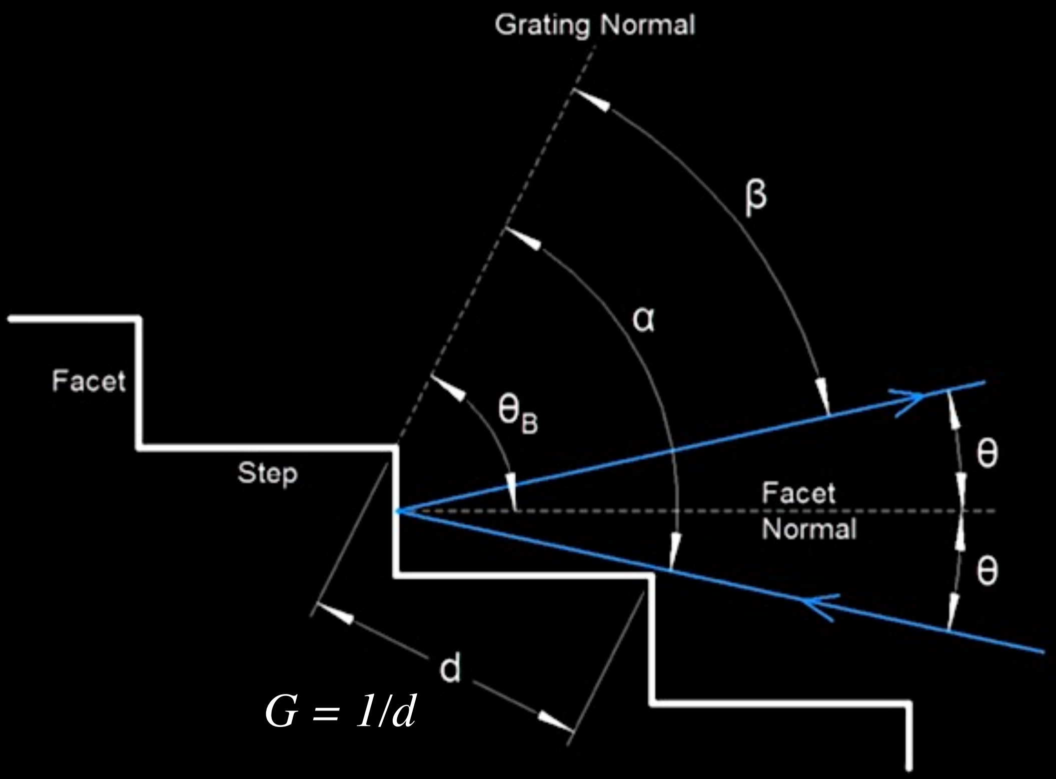
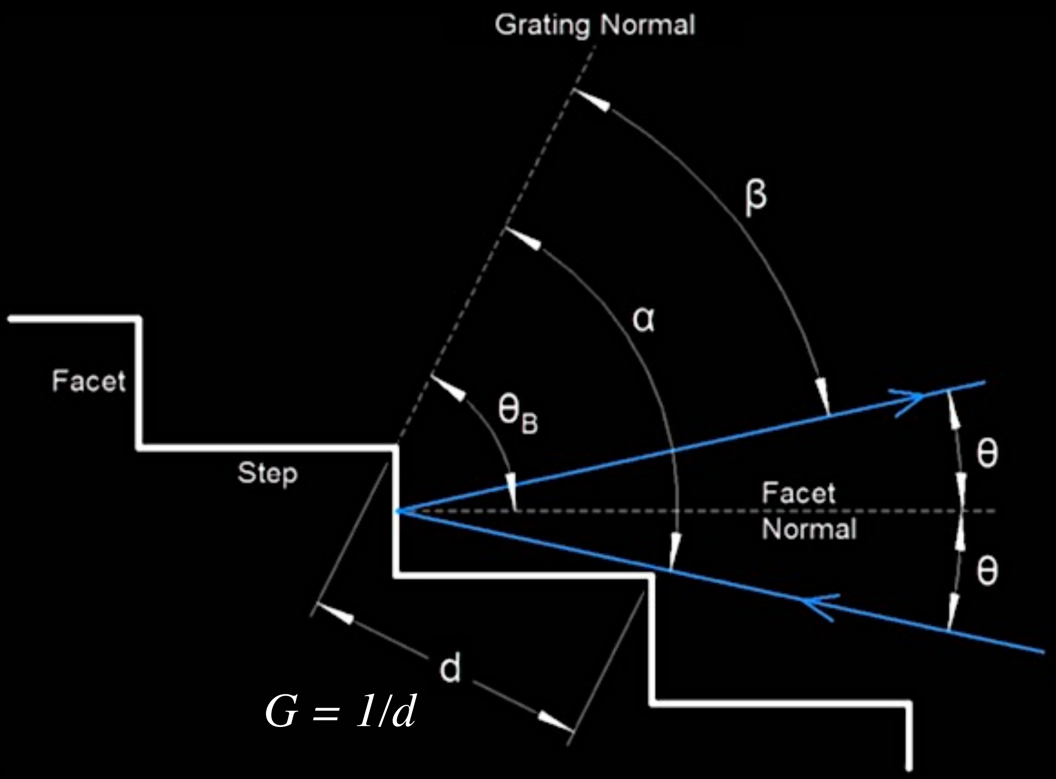


$$m\lambda G = 2\sin\theta_{\rm B}\cos\theta$$

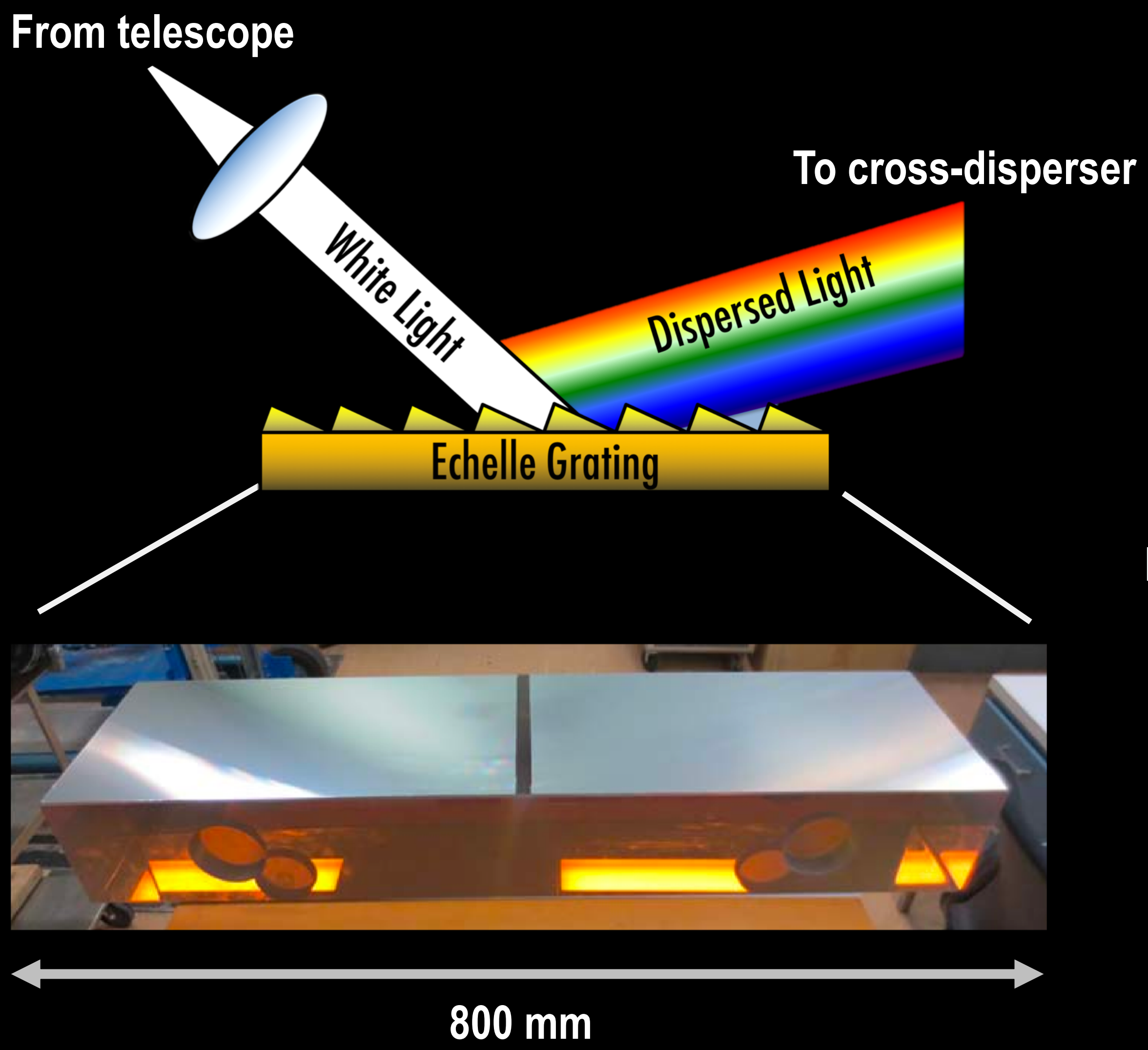
Thermal fluctuations on spectrometer optics



$$m\lambda G = 2\sin\theta_\mathrm{B}\cos\theta$$

Depends on grating length

Thermal fluctuations in the spectrometer will shift spectra



Warming the grating makes it longer

Groove density goes down

Diffraction angle changes

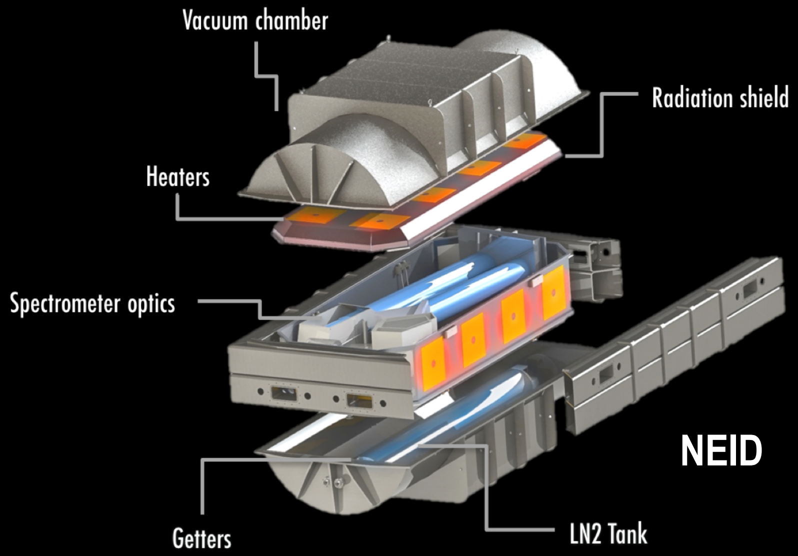
Location of spectrum on CCD changes

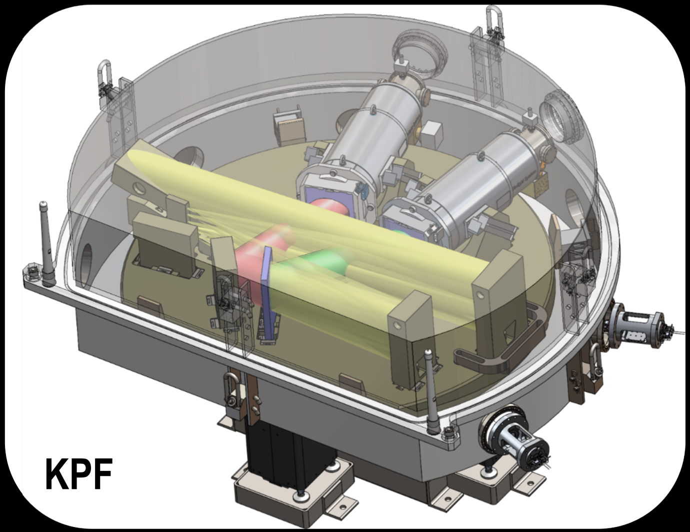
$$\Delta v = \alpha_L c \Delta T,$$

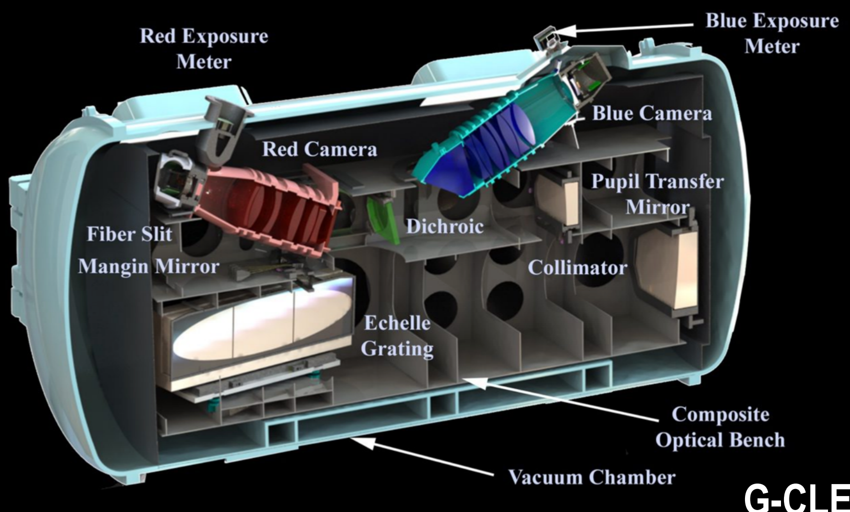
$\Delta T = 10$ mK

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

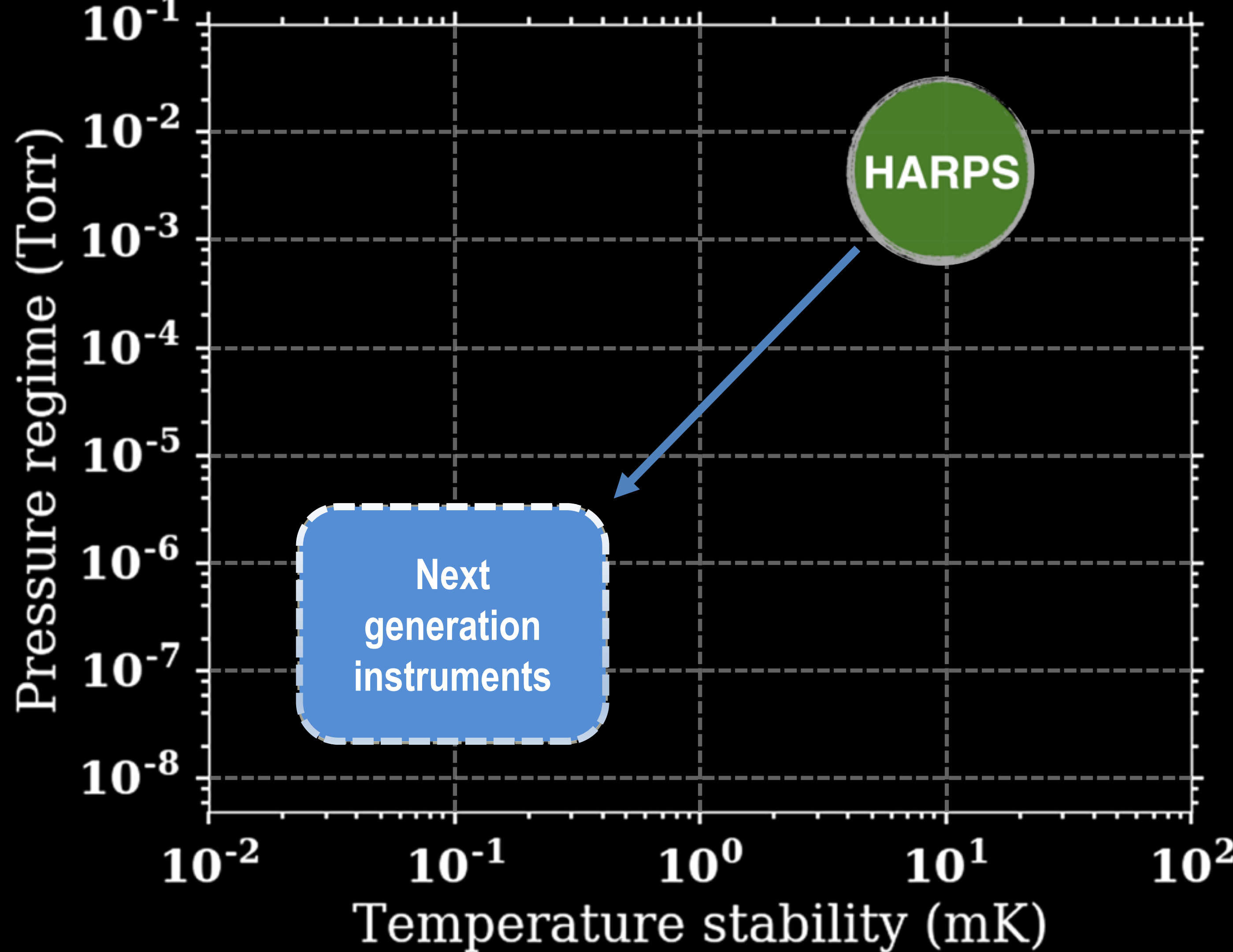
The solution: Encase spectrometer in vacuum chamber, actively control temperature







Pushing beyond 1 m s^{-1} will require improved environmental control



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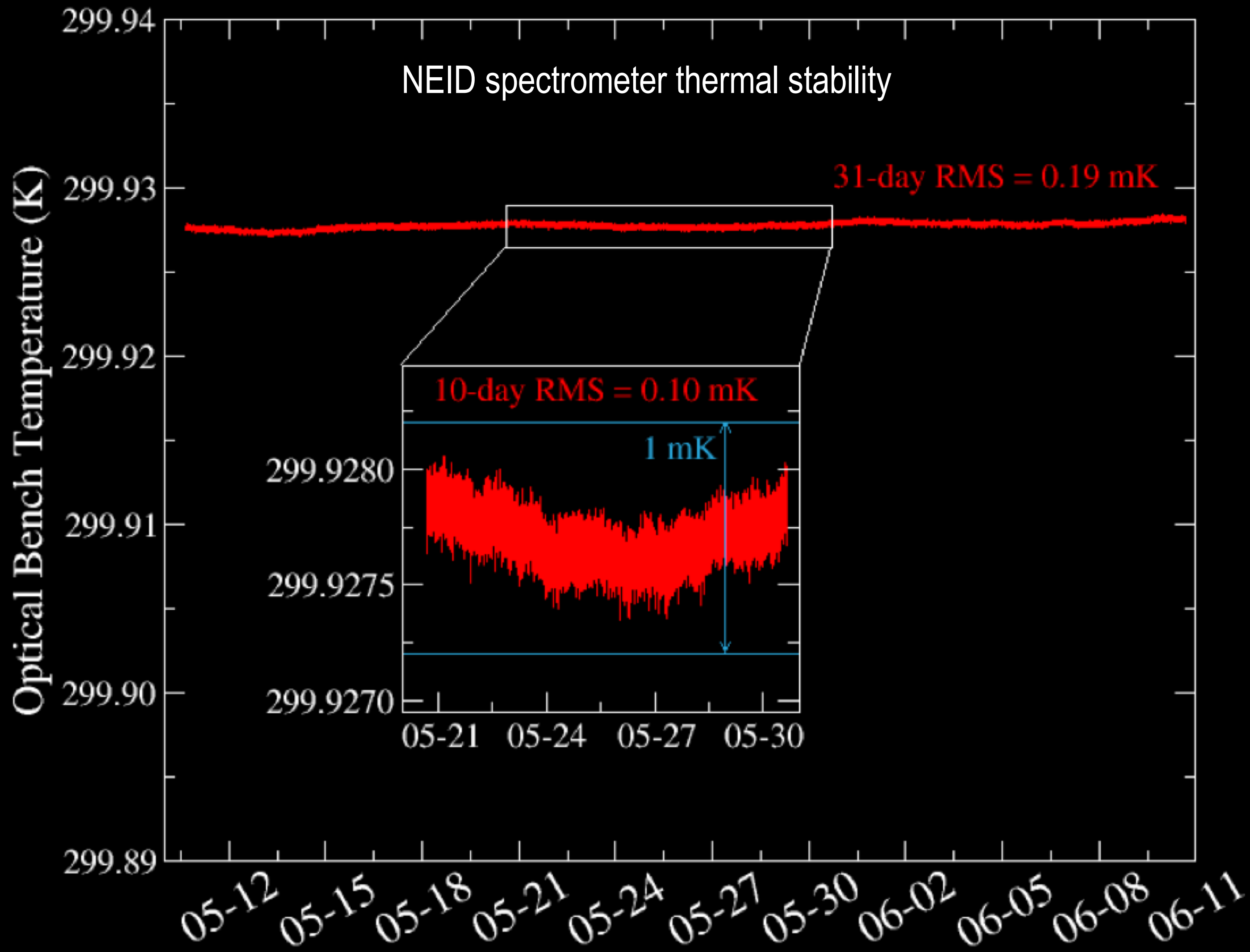


Robertson+ 2016

(Some) Instrumental challenges for Doppler spectroscopy

- Environmental stability
- Illumination stability
- Wavelength calibration

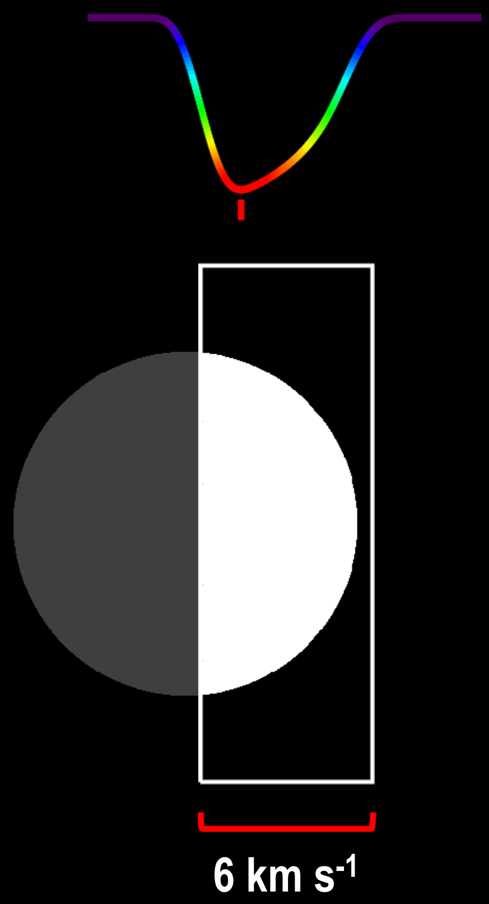
The image of your star on the slit

Spectrometer line profile

'Spectral' domain

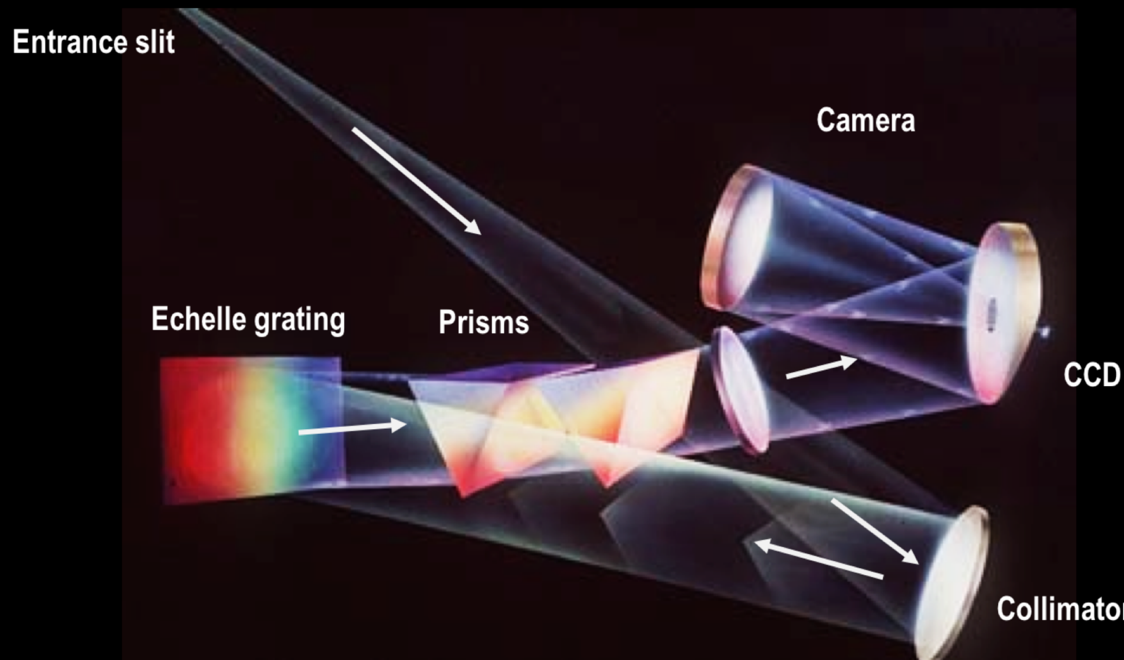
Entrance slit

'Spatial' domain



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

Telescope pupil variations also introduce errors



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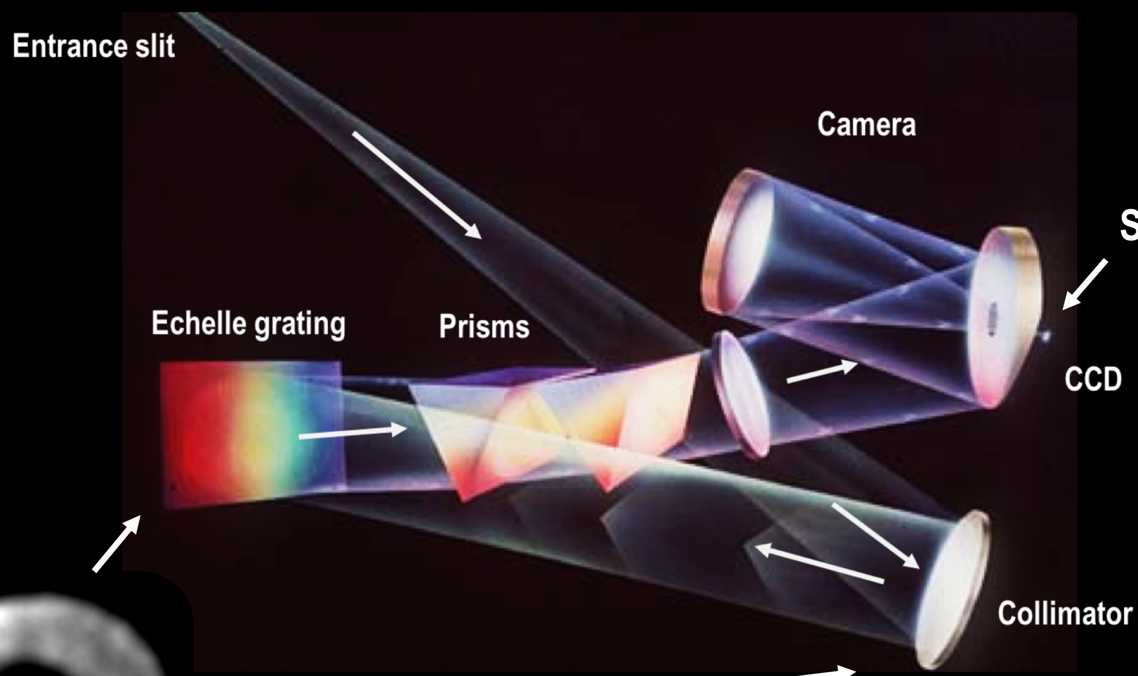
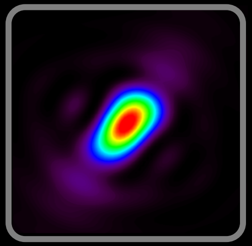
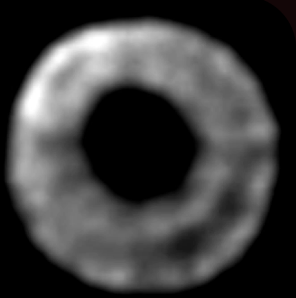




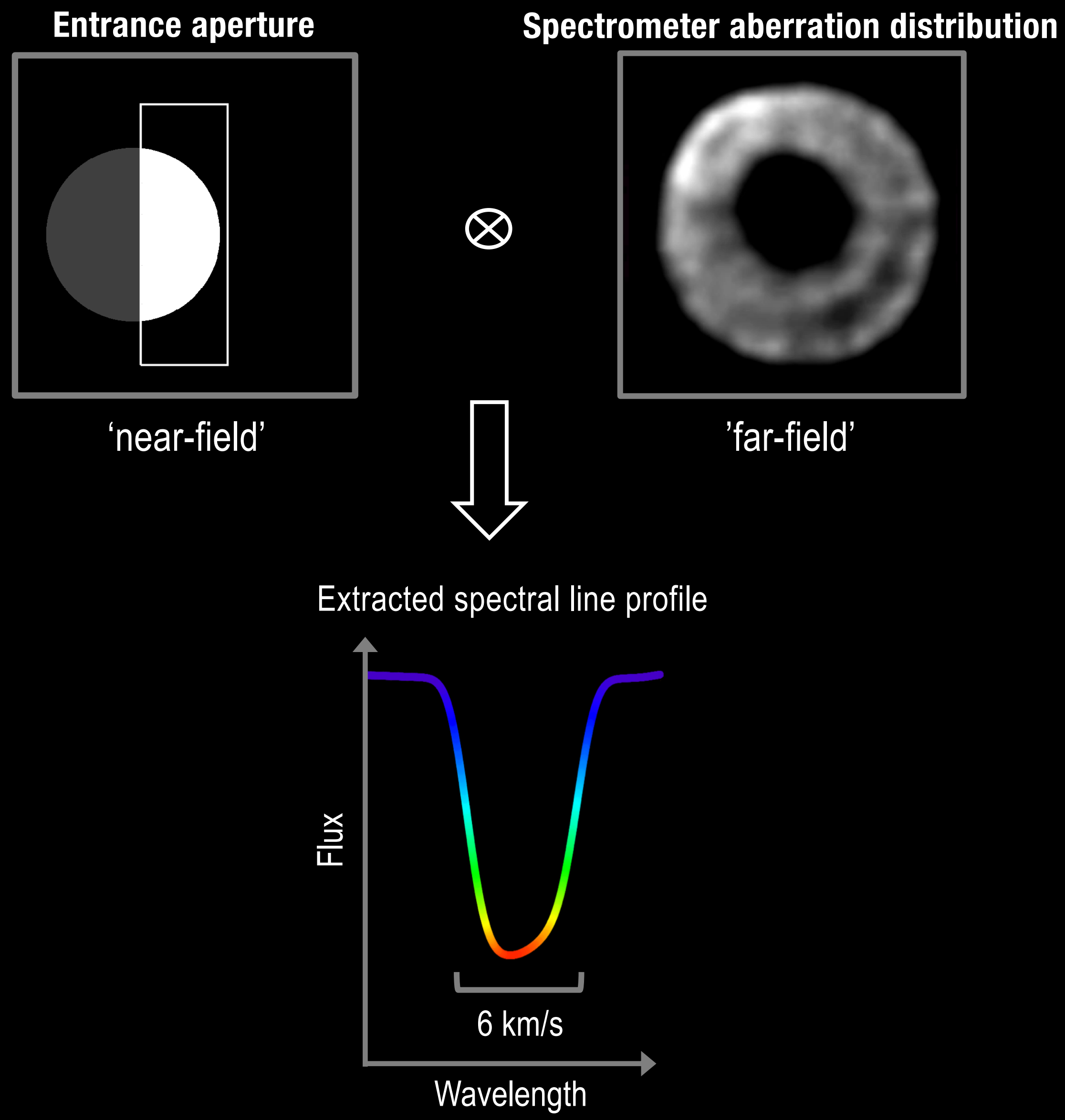
Spectrometer PSF



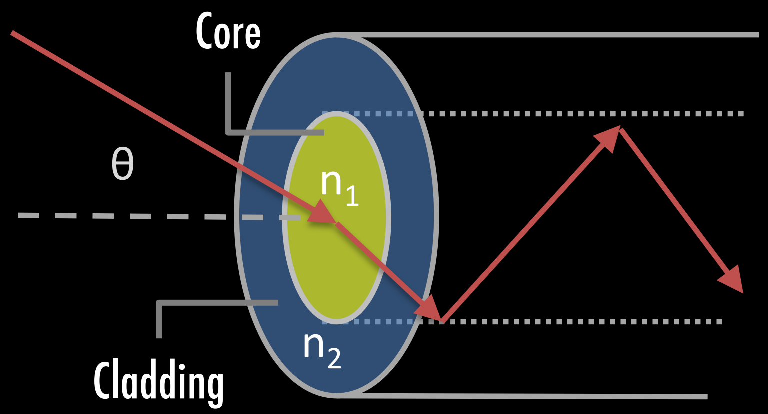
Telescope pupil

Beam profile on grating, camera optics sets the aberration distribution

Both near and far-fields entering the spectrometer need to be 'scrambled'

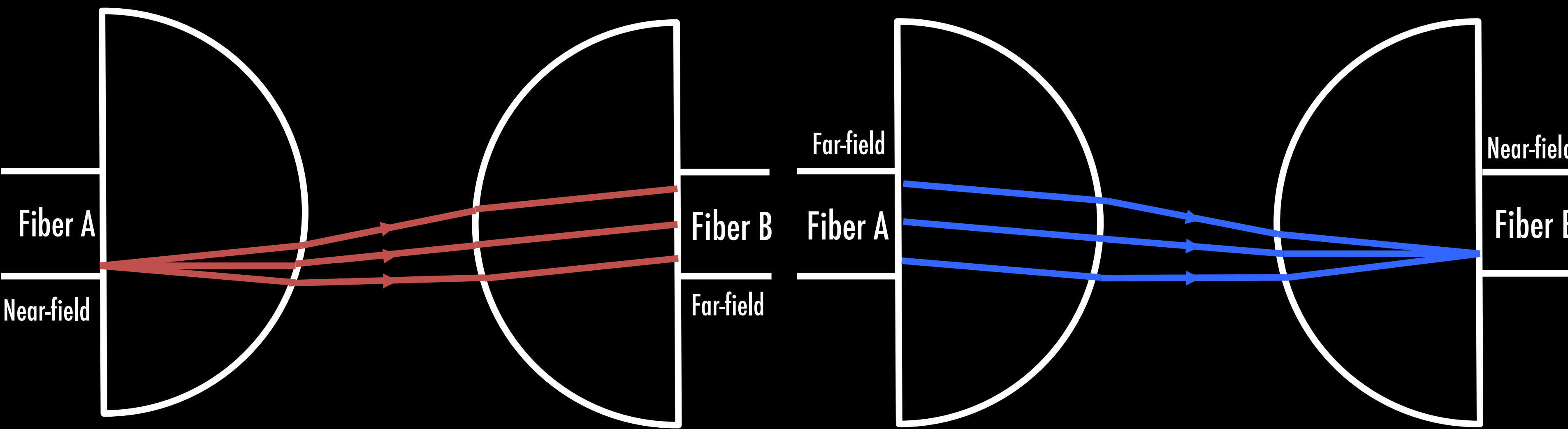


Optical fibers provide some degree of ‘scrambling’, but are not perfect



Optical fiber double-scramblers stabilize near and far-fields

- Exchange the pupil and image planes.
- Can combine with fibers to scramble *both* near and far-field.



a) Field point to angle (near-field to far-field)   b) Angle to field point (far-field to near-field)

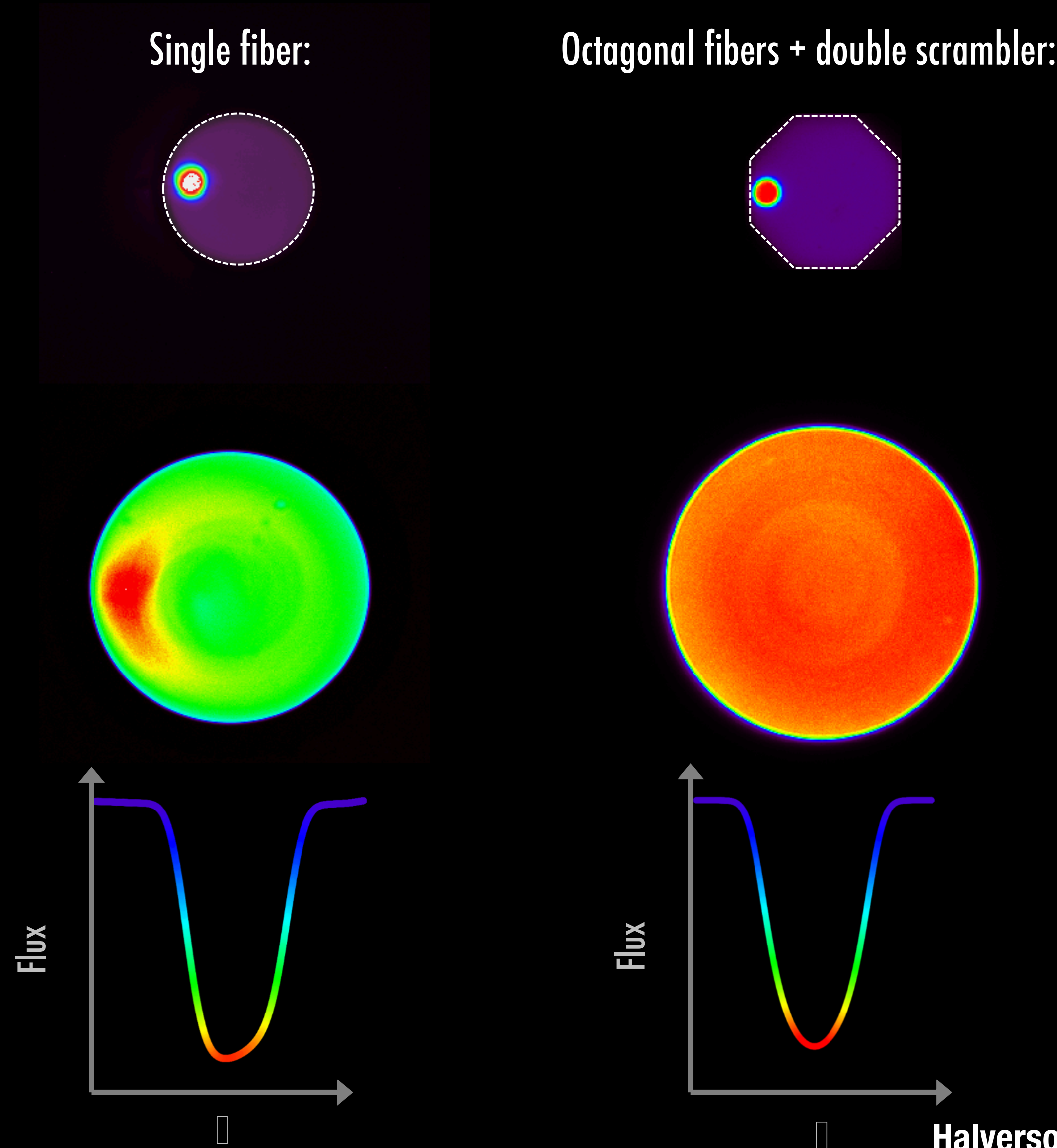
e.g. Hunter & Ramsey, 1992

Specialty fibers essential for stabilizing spectrometer PSF

Telescope focal plane

Fiber output

Instrument profile
(spectral line)



Halverson & Roy+ 2015b

(Some) Instrumental challenges for Doppler spectroscopy

- Environmental stability
- Illumination stability
- Wavelength calibration

Calibration is key for any RV measurements

- **1 m s^{-1} velocity change is *3 part per billion* spectral shift**

Calibration is key for any RV measurements

- 1 m s^{-1} velocity change is 3 *part per billion* spectral shift
- High-precision instruments require stable, repeatable calibration.
  - Dense set of features, stable over long time intervals.
  - High line density in regions with lots of stellar features.

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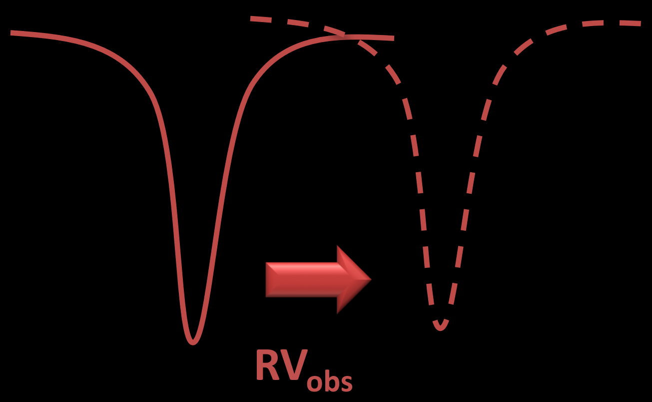
Observed stellar spectral shift



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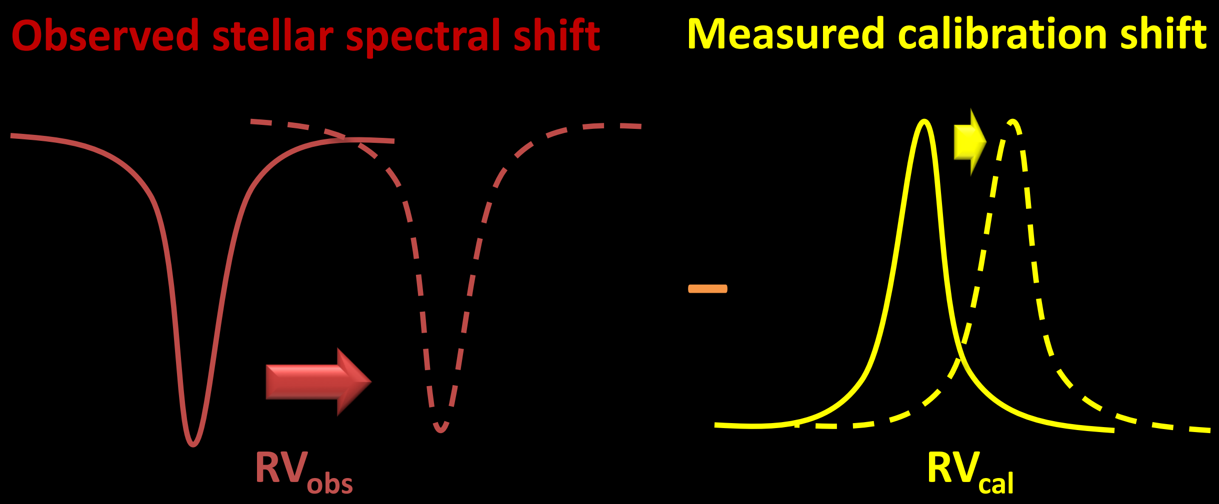

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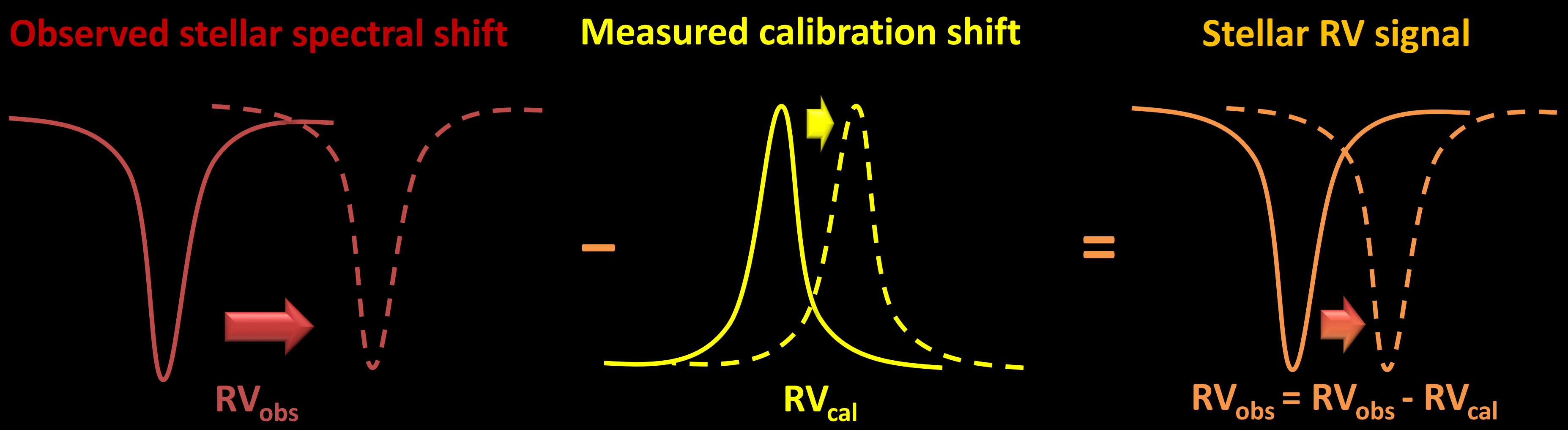
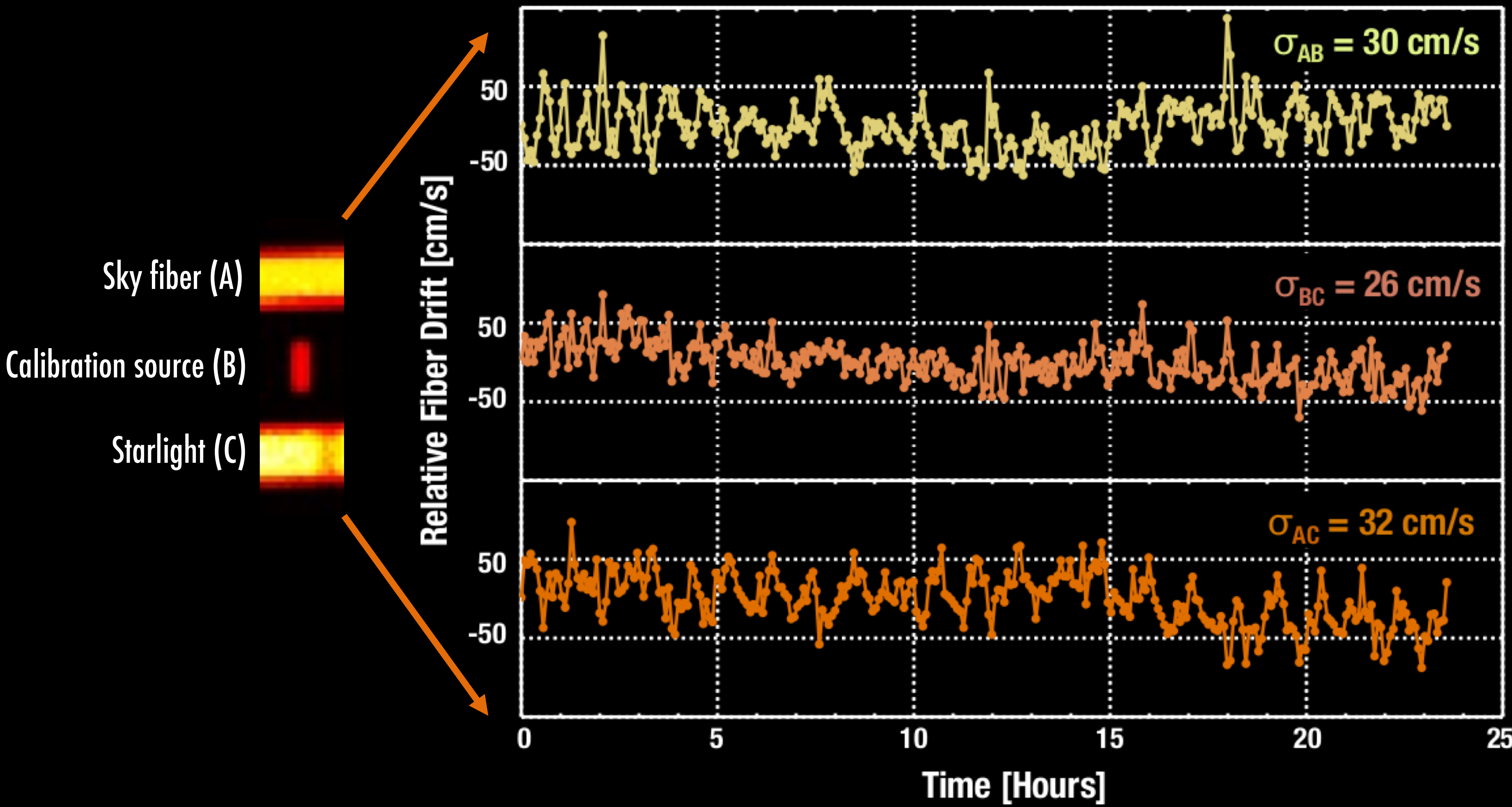
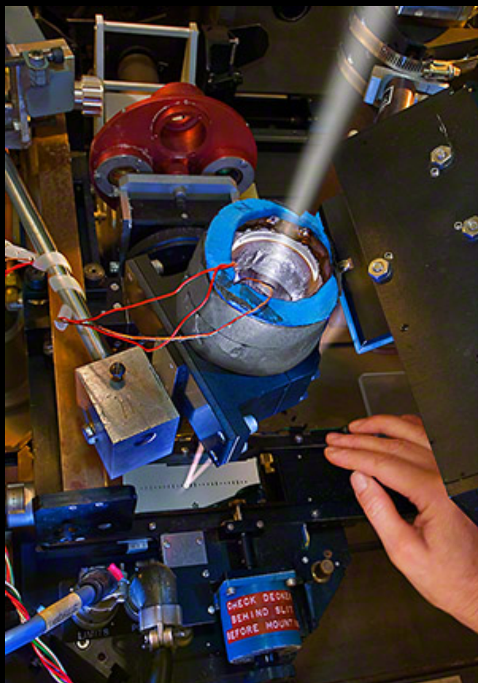


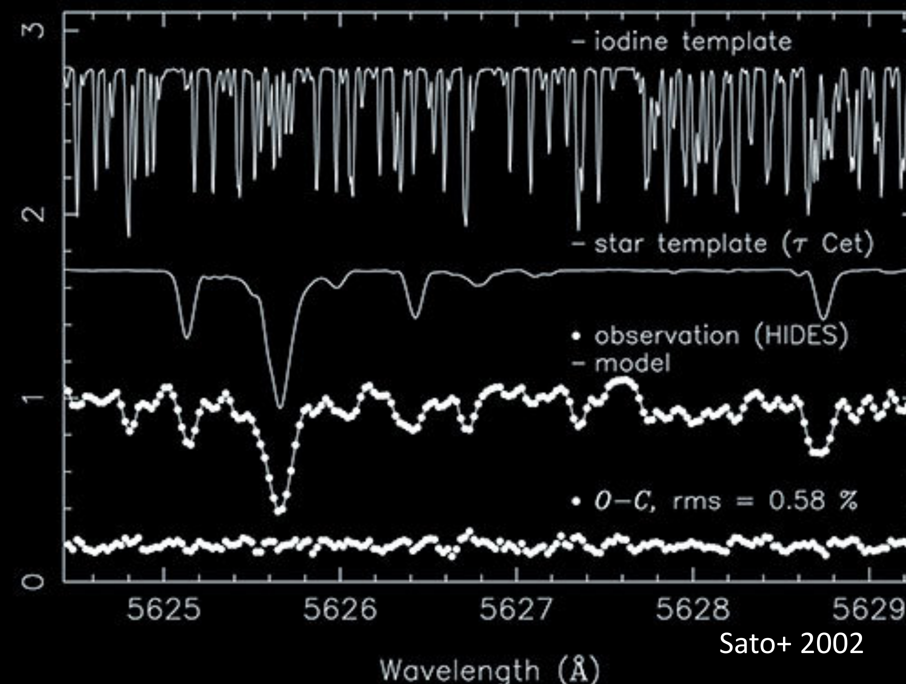
Tracking instrumental drift using dedicated fiber



Classically, calibration has been done using molecular absorption cells



I_2 cell on the Shane telescope



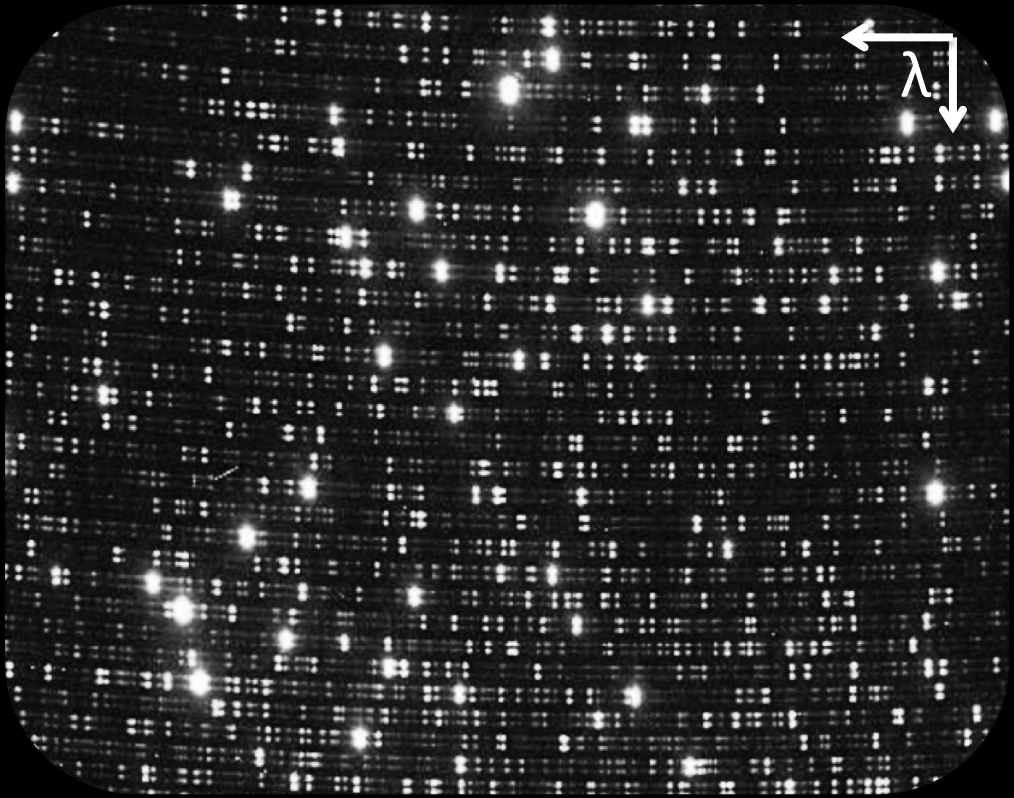
Sato+ 2002

$$I_{\text{obs}}(\lambda) = [S_\star(\lambda) \times S_{I2}(\lambda + d\lambda)] \otimes \text{PSF}$$

- Molecular lines imprinted directly onto on stellar spectrum.
- Precisely tracks instrument drift and profile variations, since I_2 molecules seeing same variations.
- Limited wavelength coverage.
- Complex extraction required.

Atomic emission lamps have been used for simultaneous cross-calibration

Thorium-Argon emission lamp



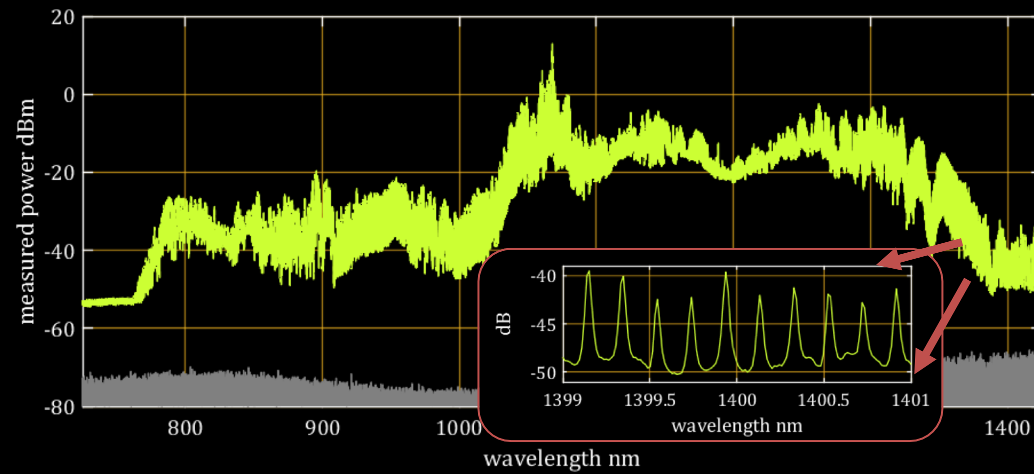
Th-Ar spectrum on PARAS instrument

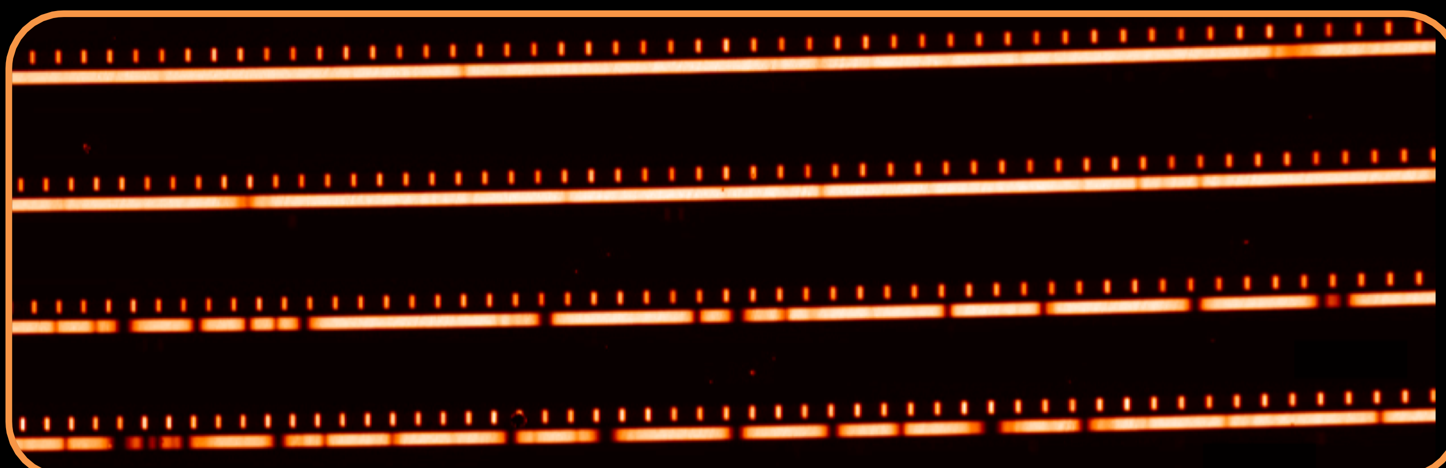
- Filled with heavy atoms, lots of transitions.
- ~1 m/s measurement precision achieved on HARPS, setting the standard for the field.
- Variable line density, line blending.
- Emission lines from fill gases unstable, bright.

Laser frequency combs for wavelength calibration

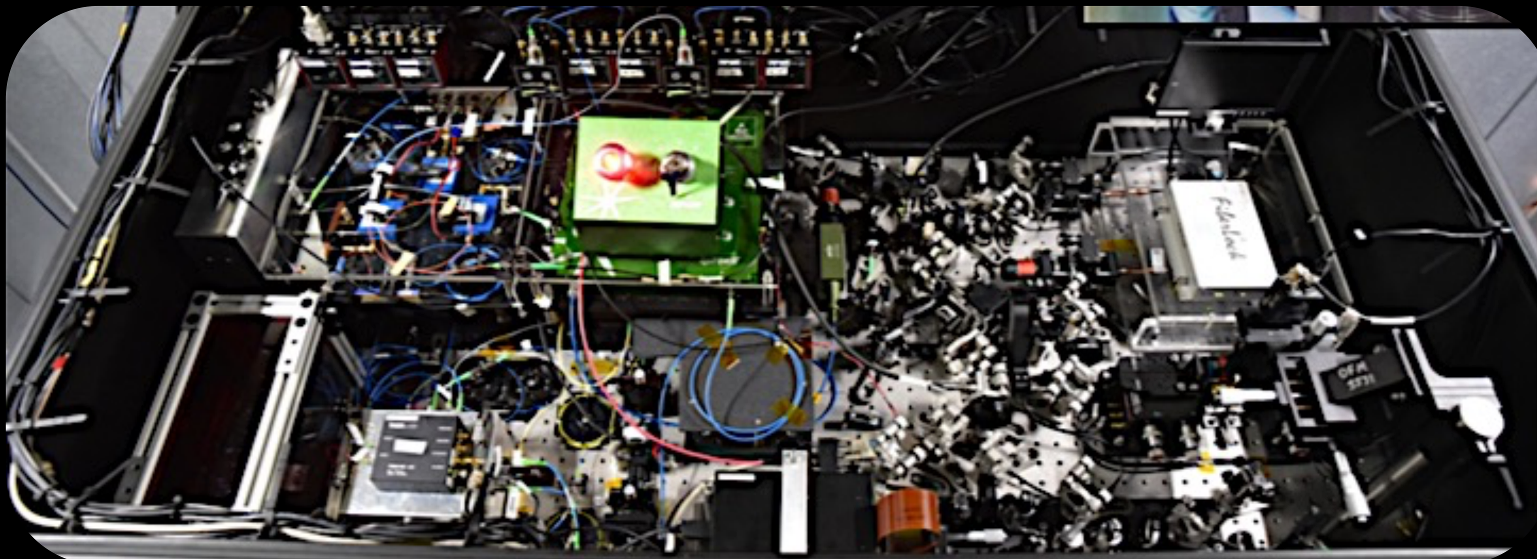
- Picket fence of lines tied to atomic standard.
- Stable at the $<1\ cm\ s^{-1}$ level.
- Essentially a local optical atomic clock.

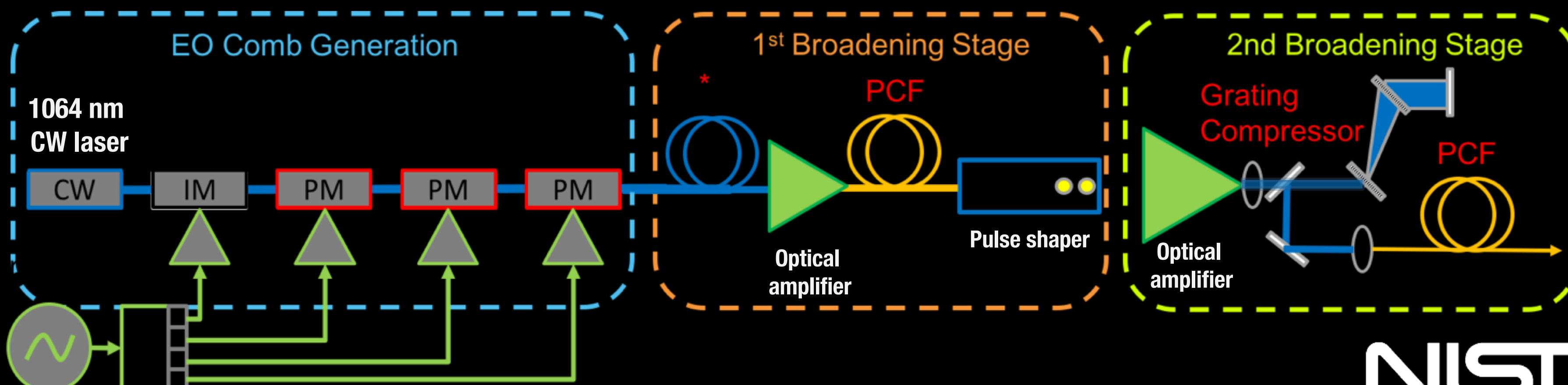
- Highly complicated piece of engineering, Nobel prize-winning physics.





Frequency combs are significantly more complicated than the actual spectrometers





Block diagram of HPF EOM laser comb

NIST

Slide credit: AJ Metcalf, NIST

(Some) Instrumental challenges for Doppler spectroscopy

- Environmental stability
- Illumination stability
- Wavelength calibration

Now in the era where no single source of error (other than the star) 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}

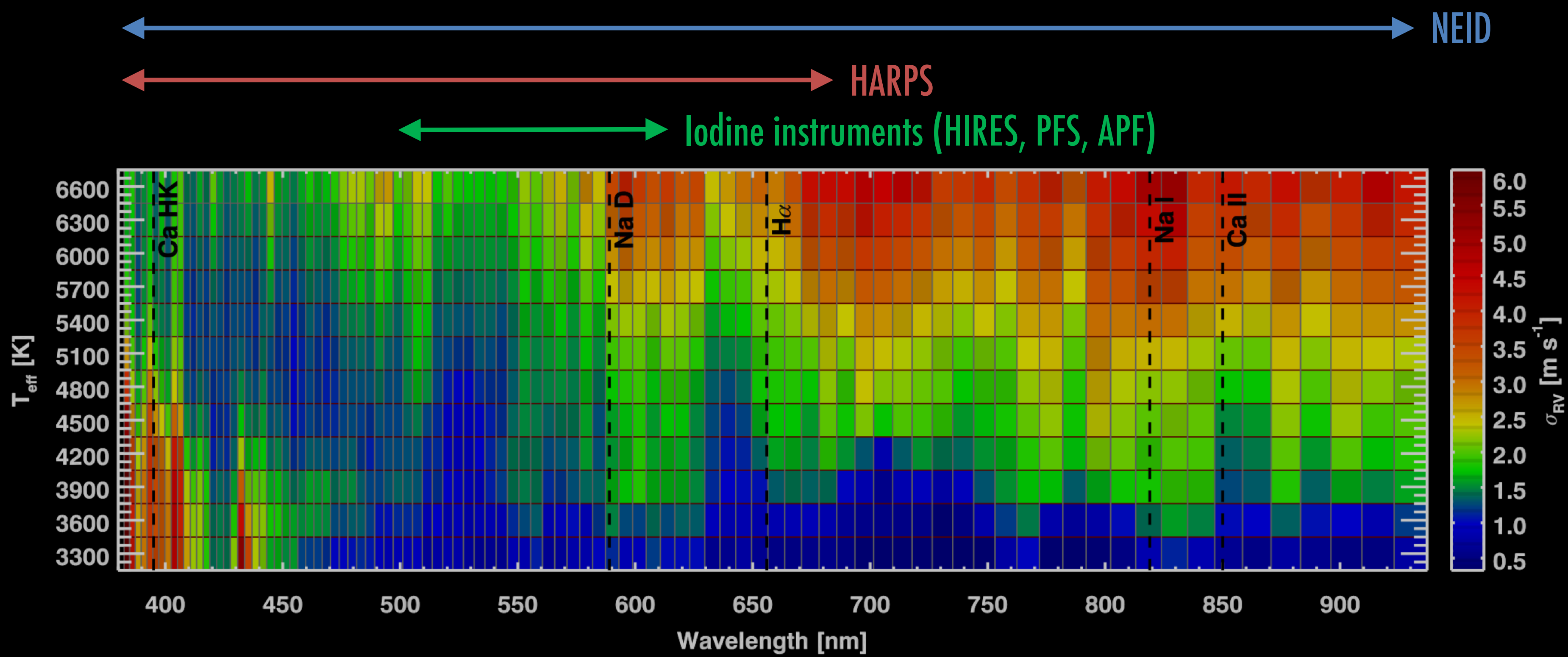
Guiding	scrambling
ADC	6.9 cm s^{-1}
Focus	5.0 cm s^{-1}
Windshake	8.0 cm s^{-1}

Atmospheric effects: 14.1 cm s^{-1}

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

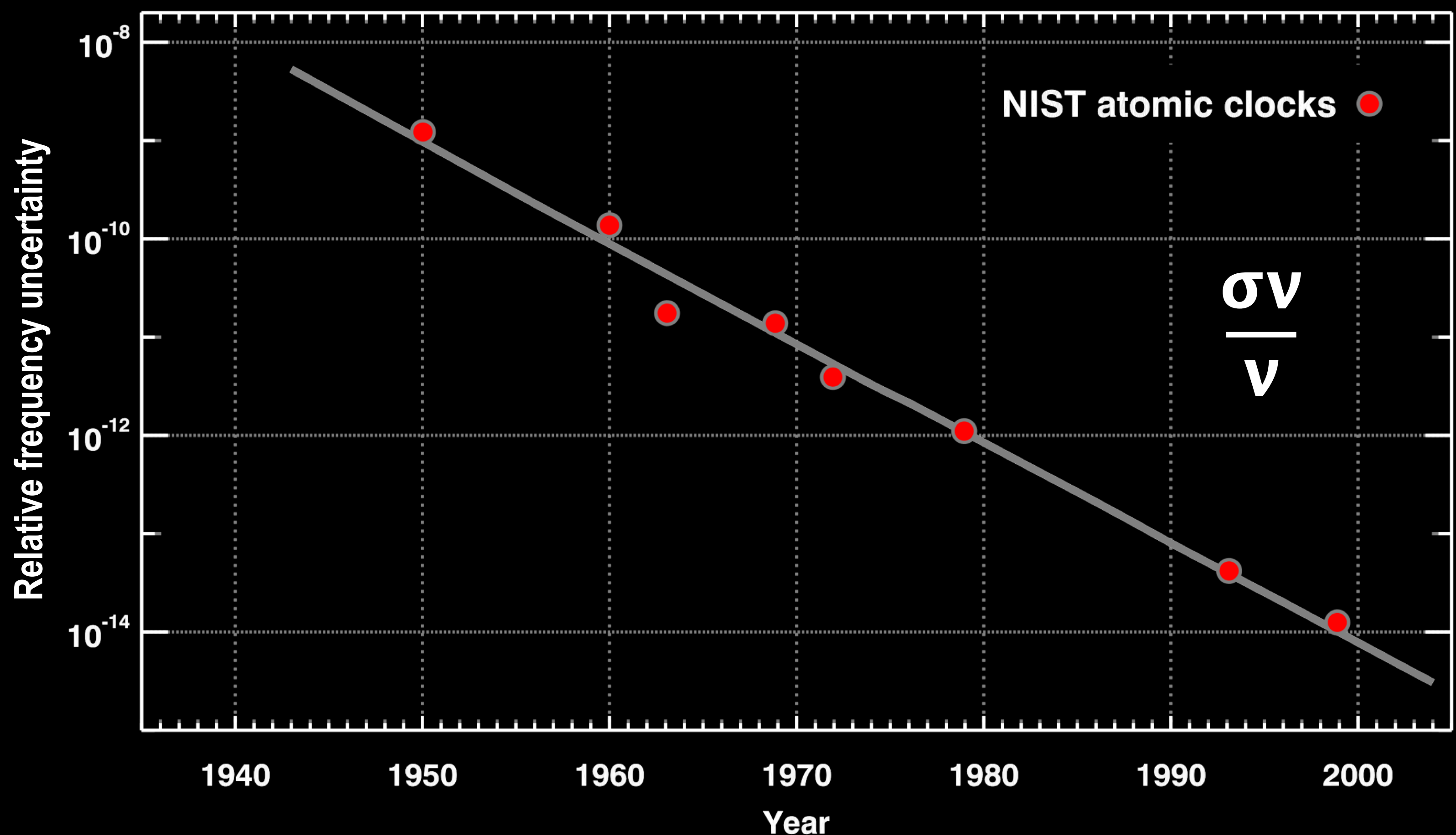
Halverson+ 2016b

Need to cover wide wavelength range to maximize information content

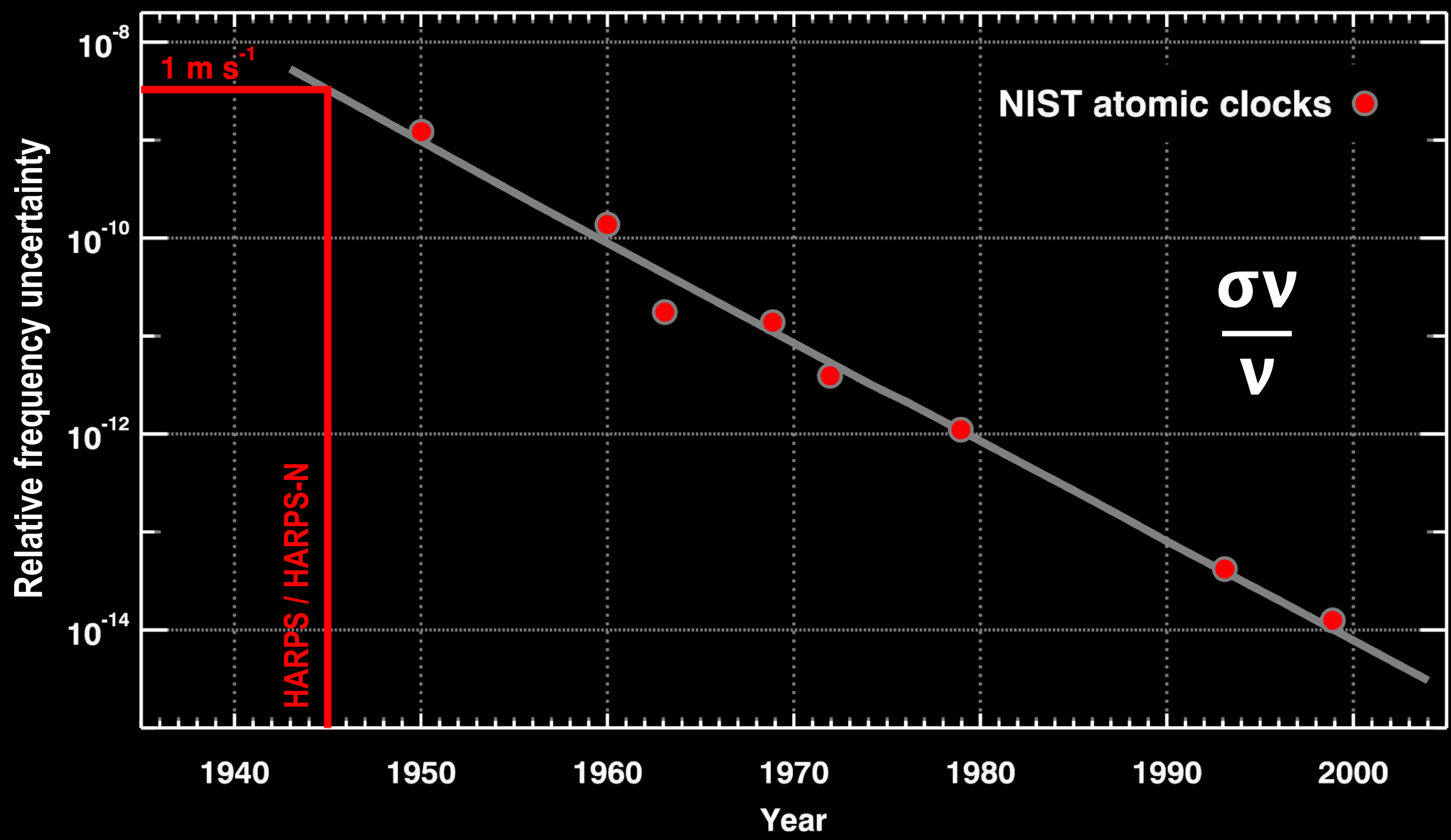


- Diverse range of stellar activity indicators
- Enables study of wide range of spectral types

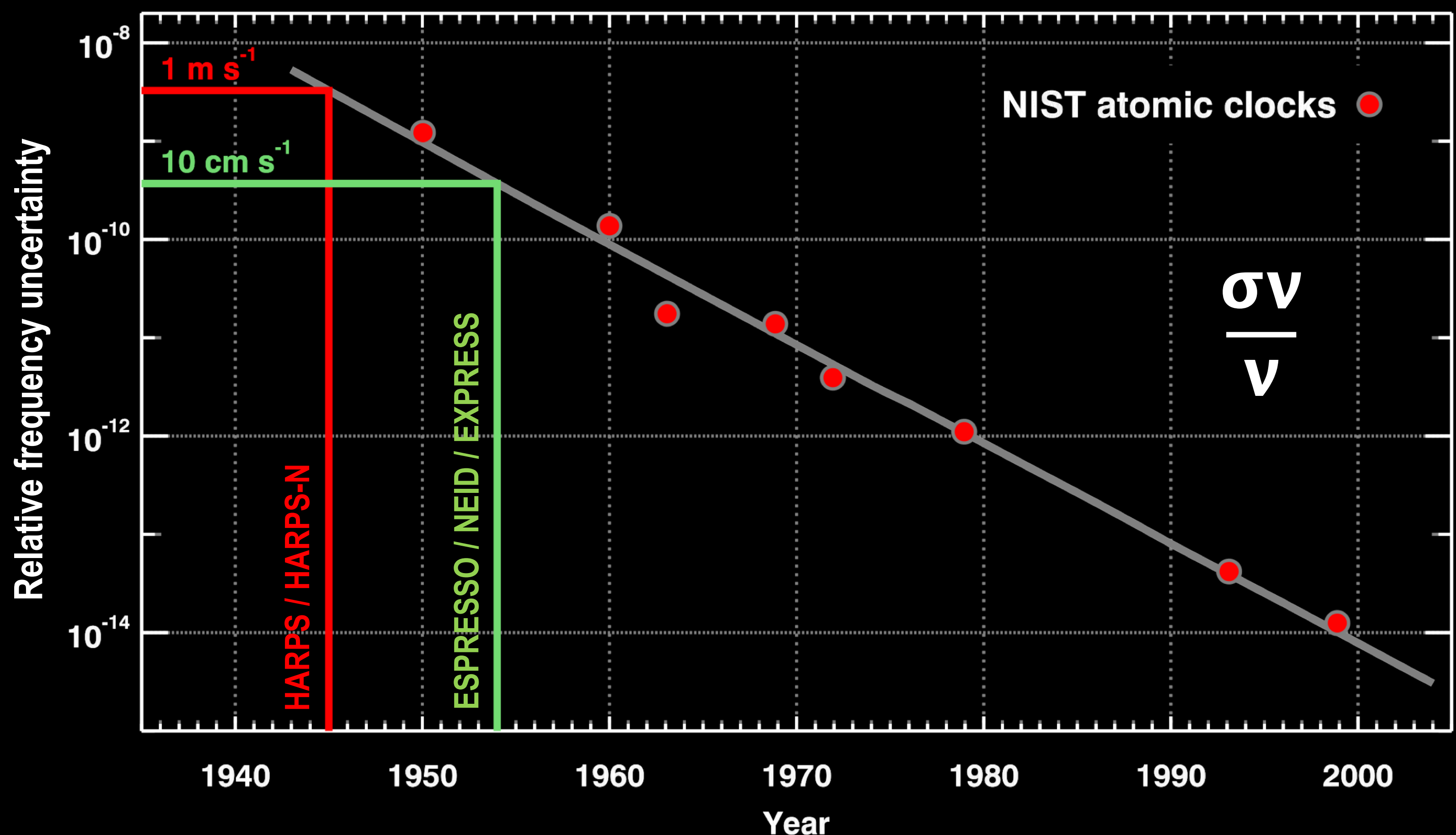
Placing precision in context – how precise can we measure optical frequencies?



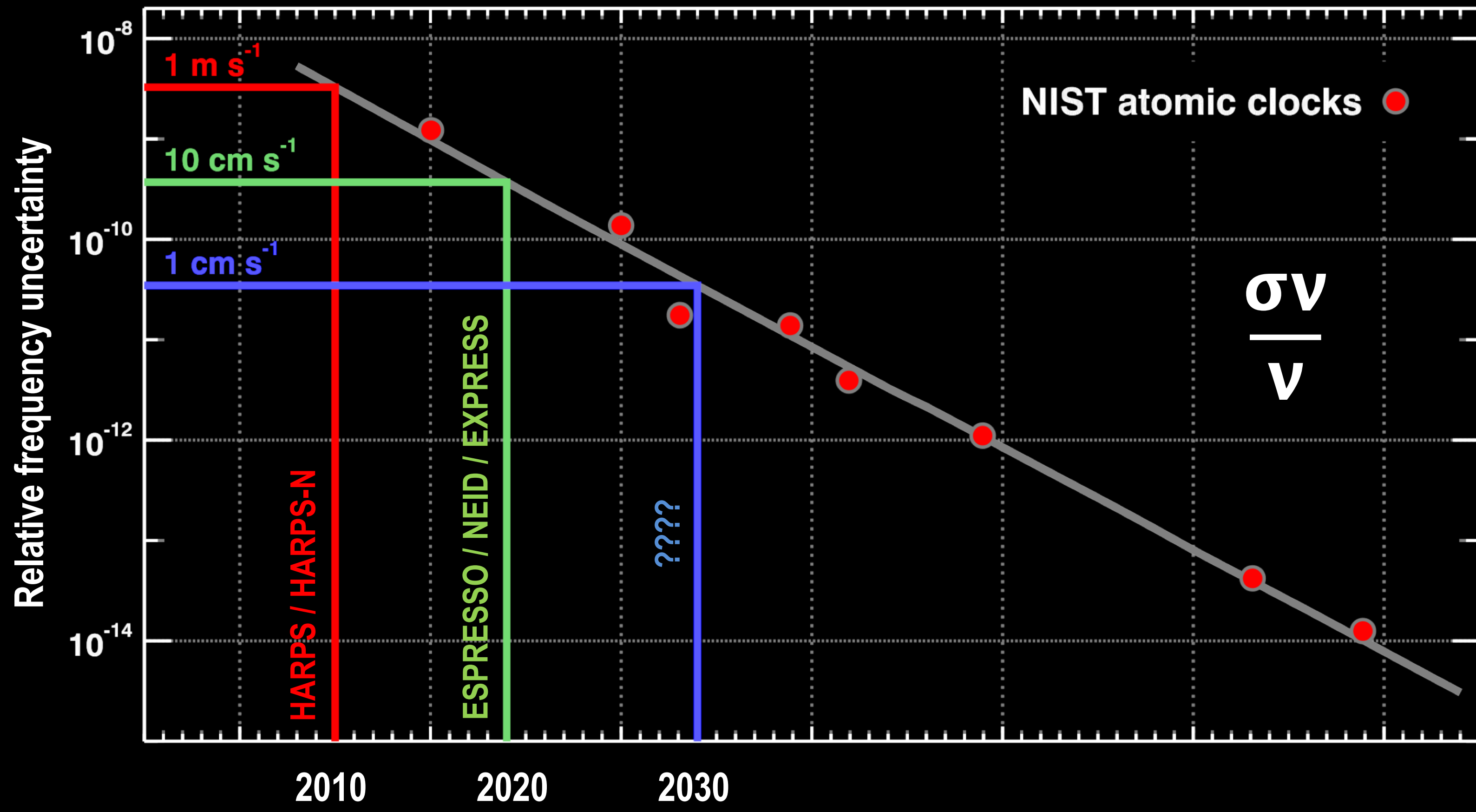
Placing precision in context – how precise can we measure optical frequencies?



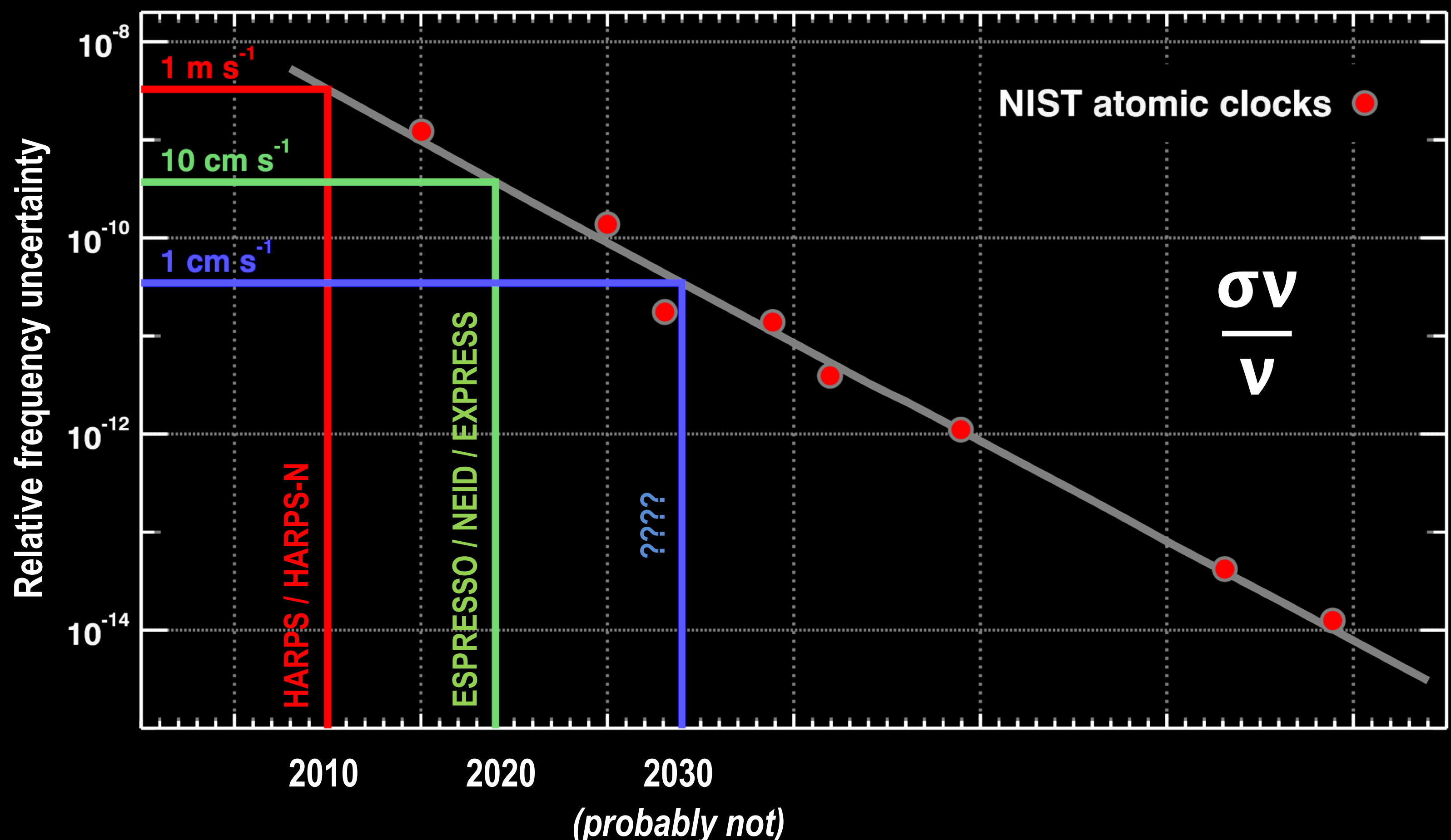
Placing precision in context – how precise can we measure optical frequencies?



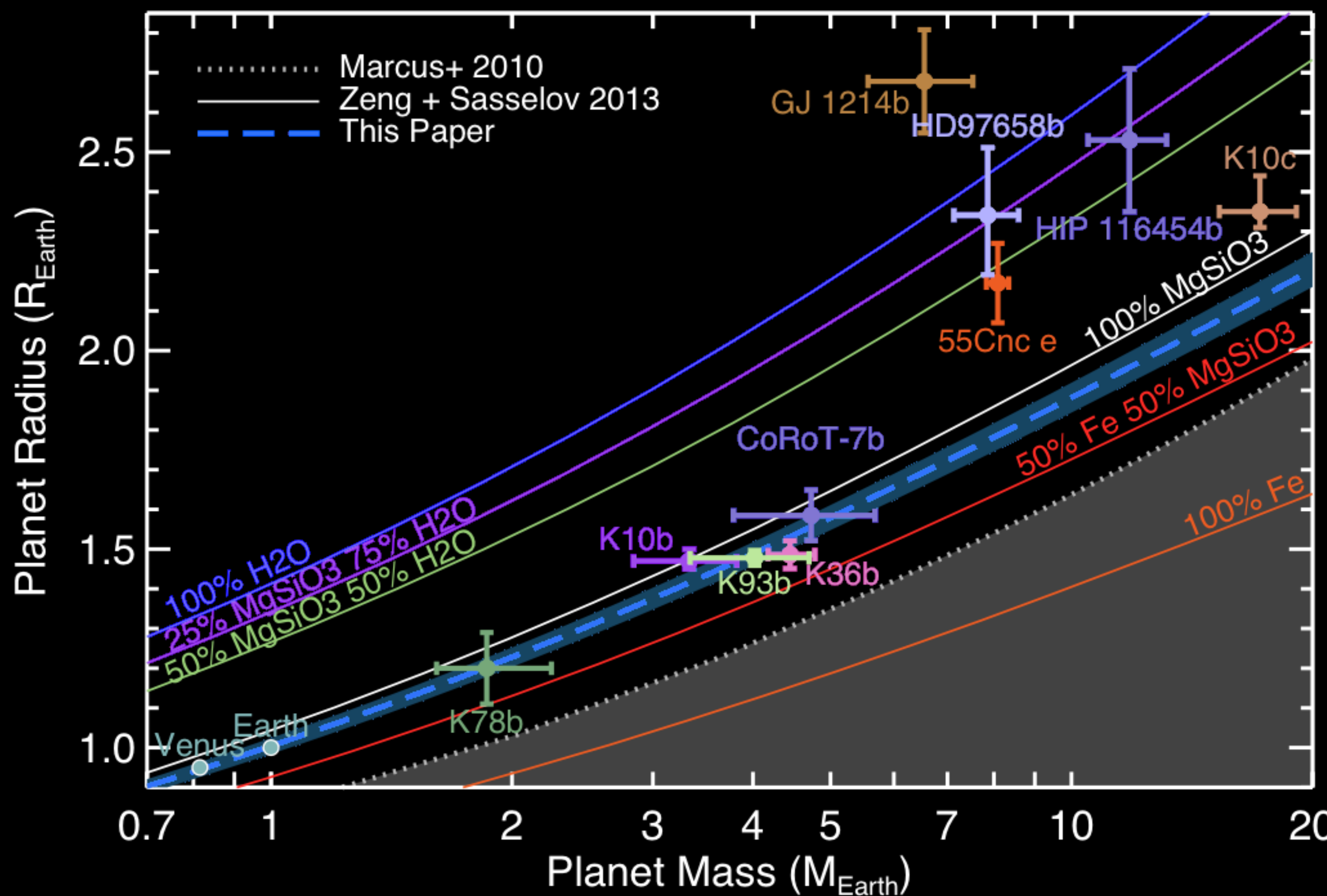
Placing precision in context – how precise can we measure optical frequencies?



Placing precision in context – how precise can we measure optical frequencies?

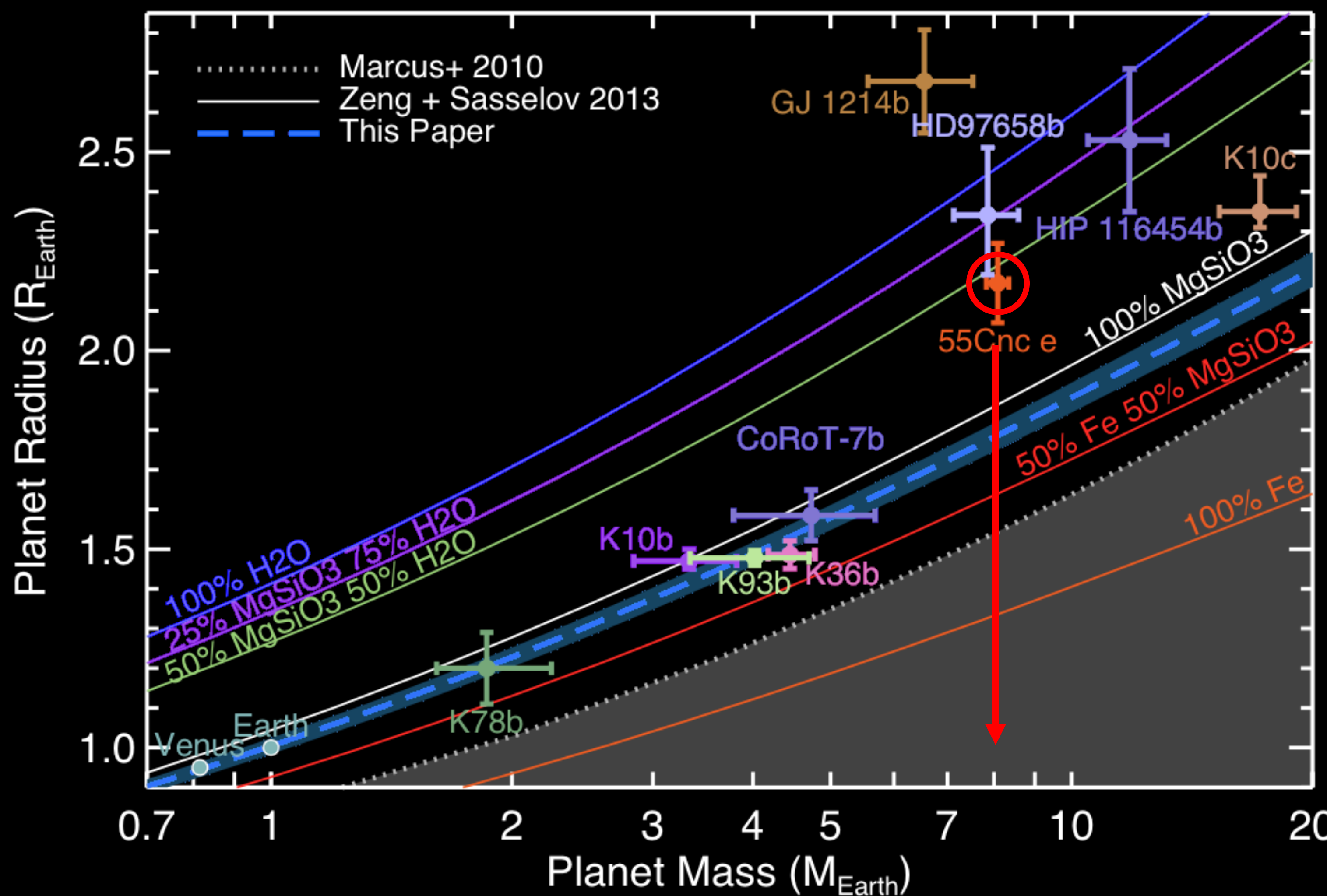


Ultimate goal: detect rocky, Earth-like planets



Dressing+ 2015

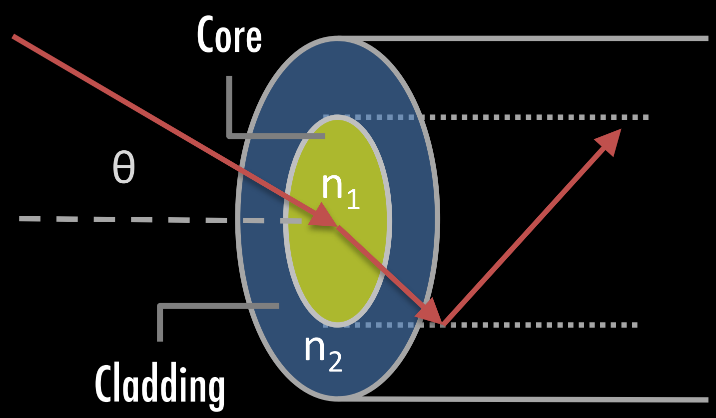
Ultimate goal: detect rocky, Earth-like planets



Dressing+ 2015

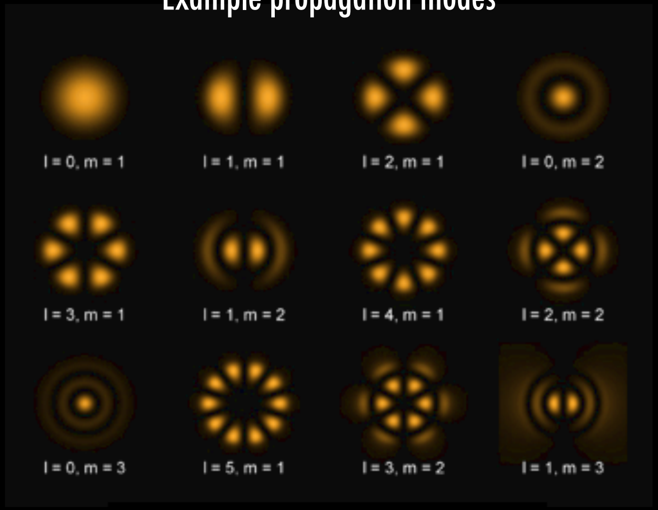
Modal noise in multi-mode optical fibers

- Light of finite bandwidth fills finite number of modes.
- Modes will interfere at fiber boundary
  - *Leads to speckle pattern at fiber output*



$$\mathrm{NA} = \sin(\theta) < \sqrt{n_1^2 + n_2^2}$$

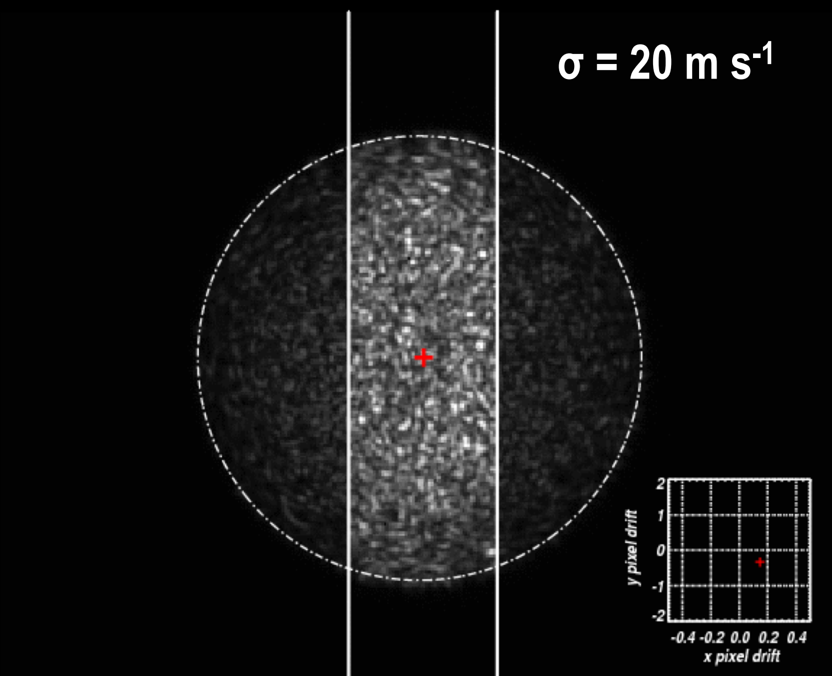
Example propagation modes



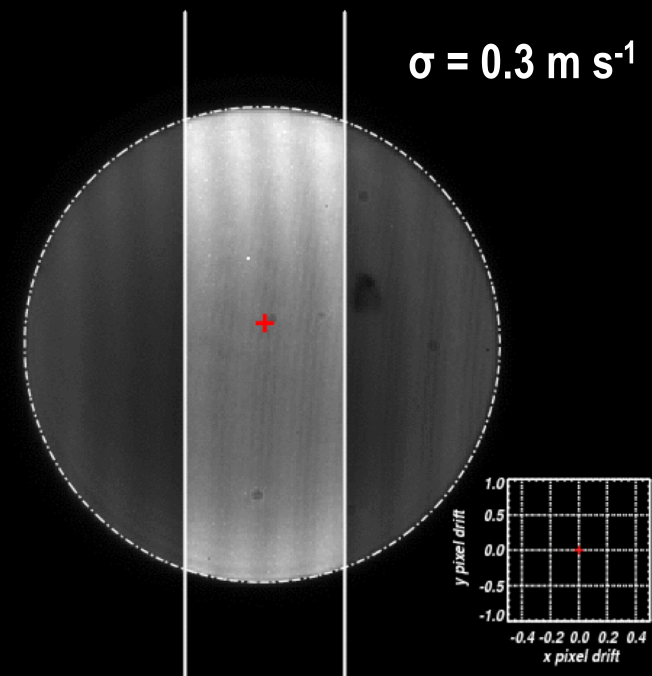
$$M = \frac{1}{2}\left(\frac{\pi d \mathrm{NA}}{\lambda}\right)^2$$

Hill et al. 1980

Solving modal noise is *crucial* for systems using coherent calibration sources



Fiber alone



Fiber with phase mixing optics

- Without phase randomization, *wavelength calibration process is entirely dominated by speckle noise*

Halverson+ 2014b

Will also place fundamental SNR limit on recorded stellar spectra