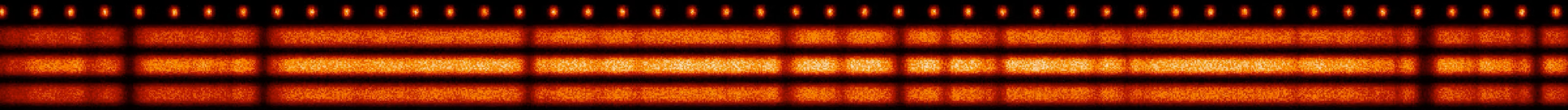
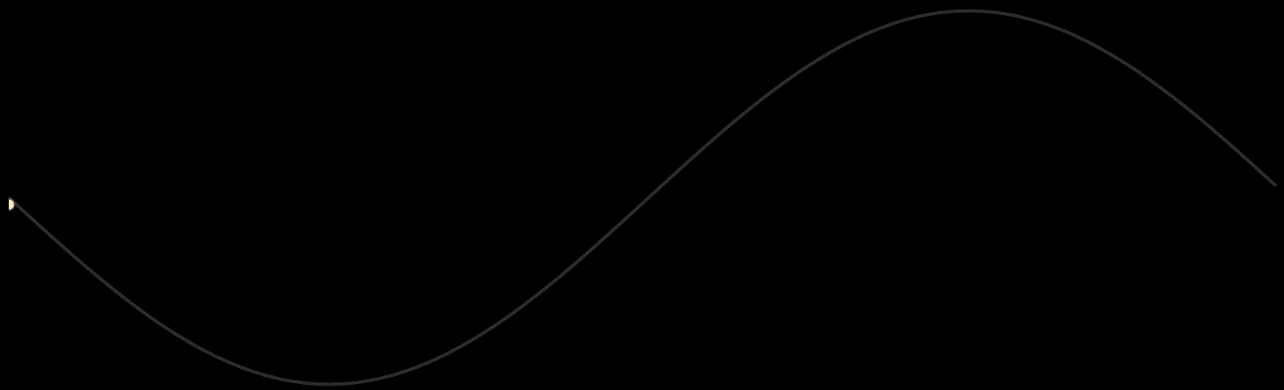
Error Budgets in Precision Radial Velocity Measurements



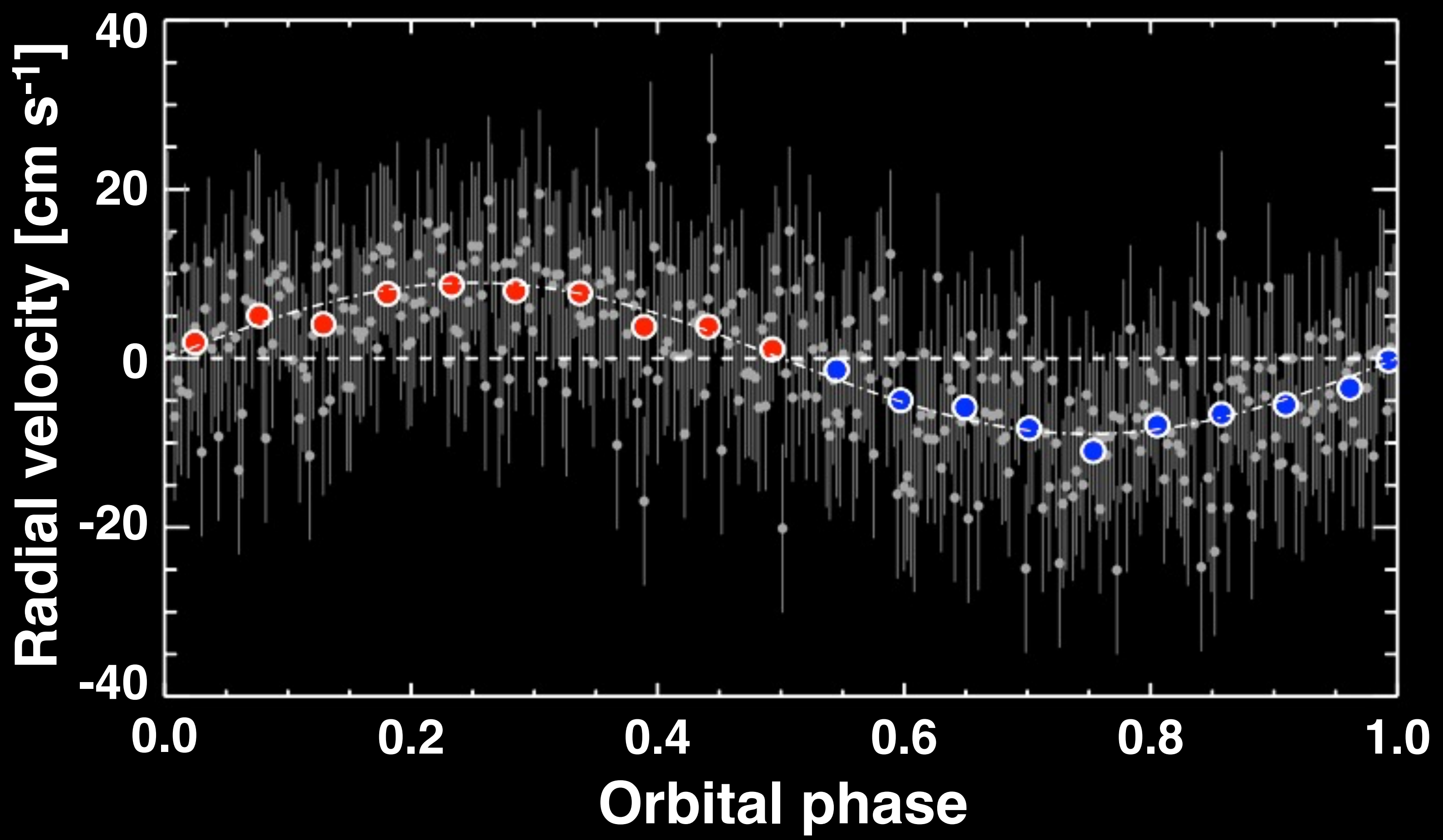


SAM HALVERSON

JET PROPULSION LABORATORY, CALIFORNIA INSTITUTE OF TECHNOLOGY

Jet Propulsion Laboratory
California Institute of Technology

Deconstructing measurement precision



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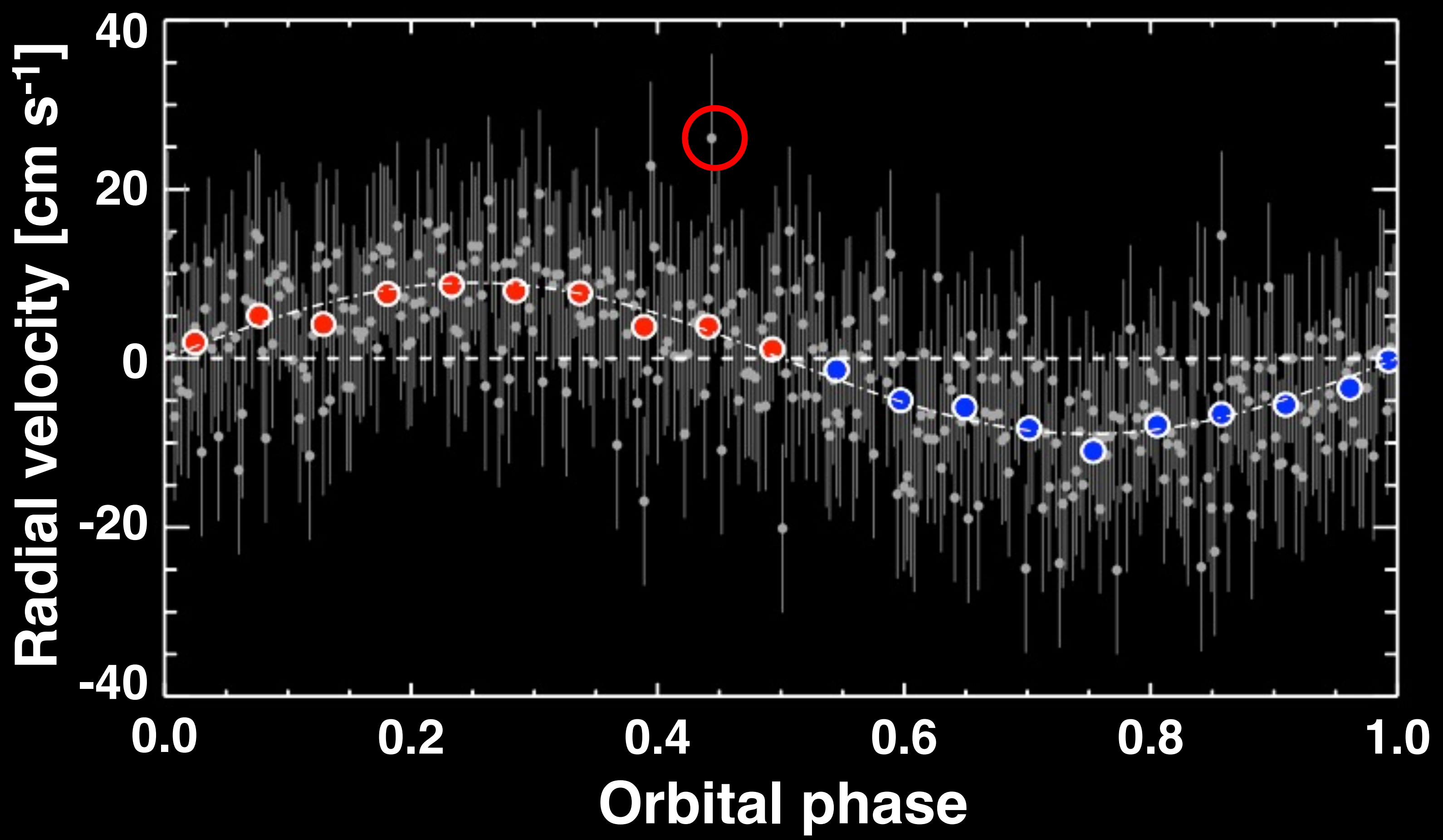

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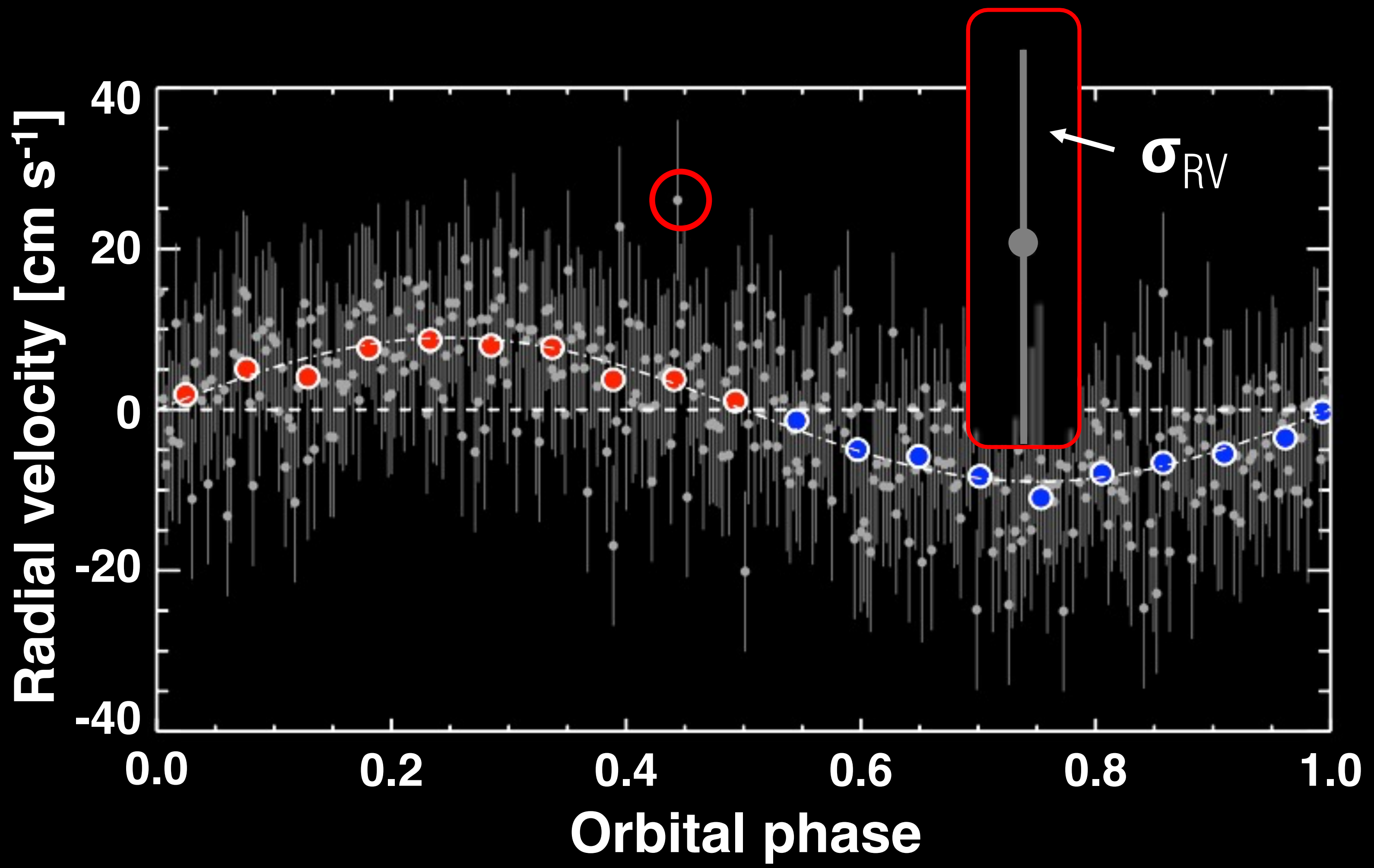

Deconstructing measurement precision (toy model)

σ_{RV}

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

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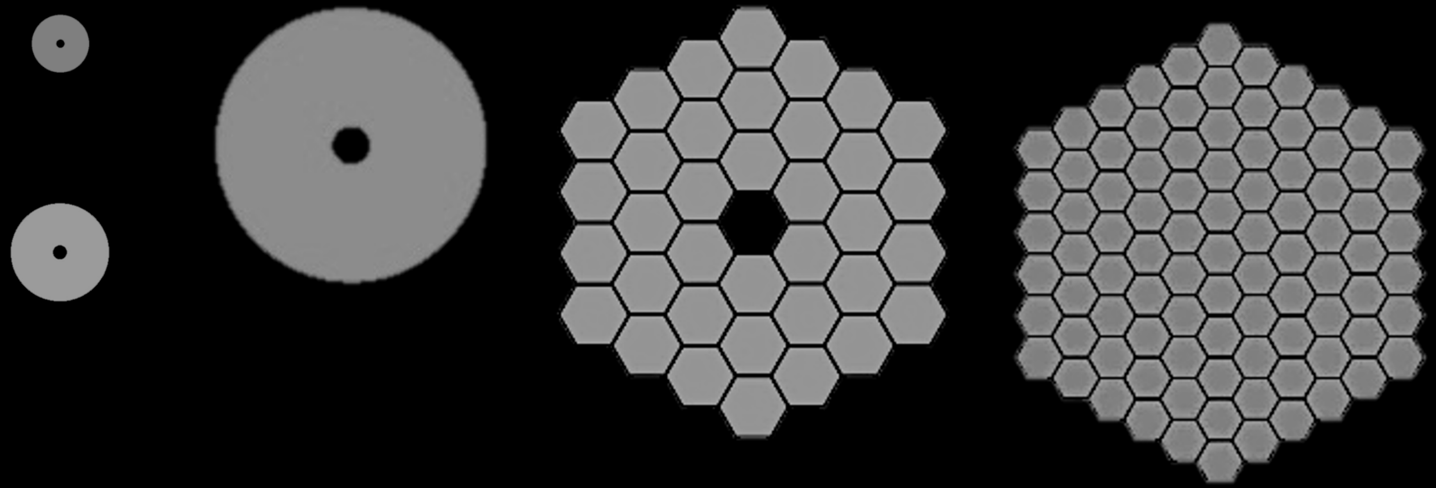
Aperture

Efficiency

Information content



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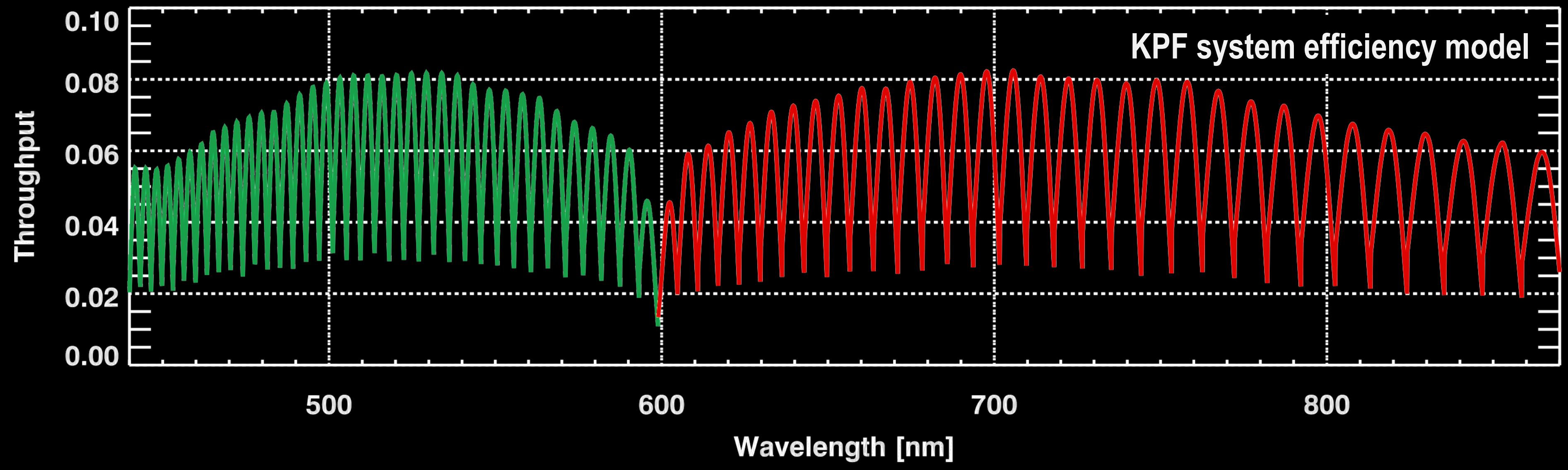

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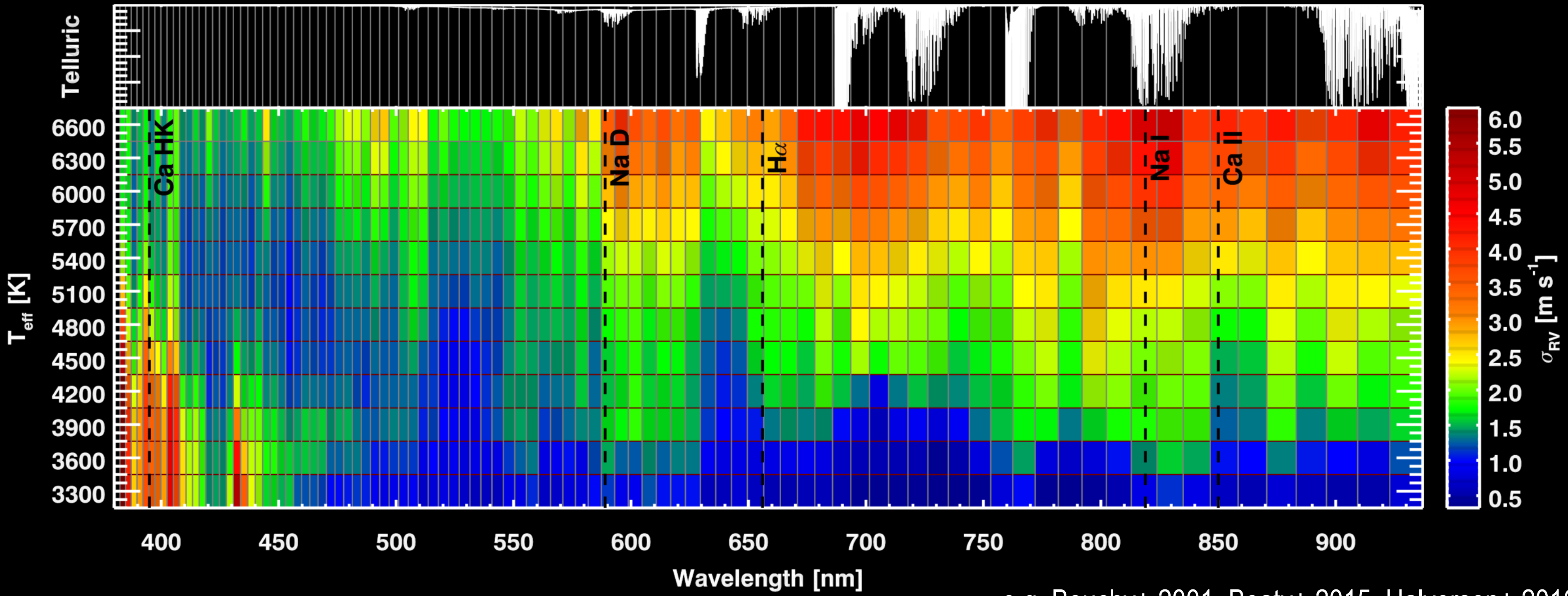

e.g. Bouchy+ 2001, Beaty+ 2015, Halverson+ 2016

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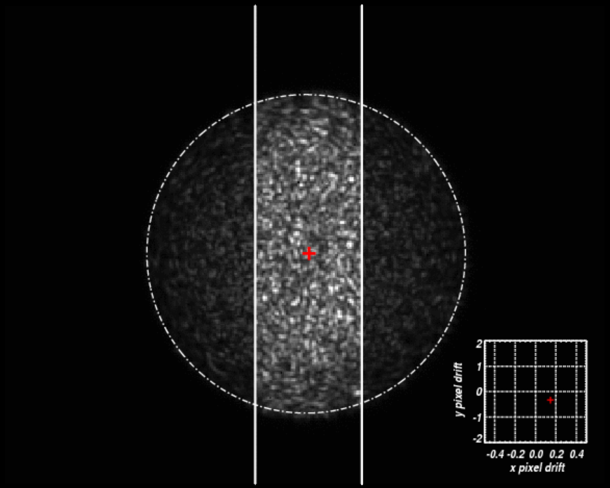
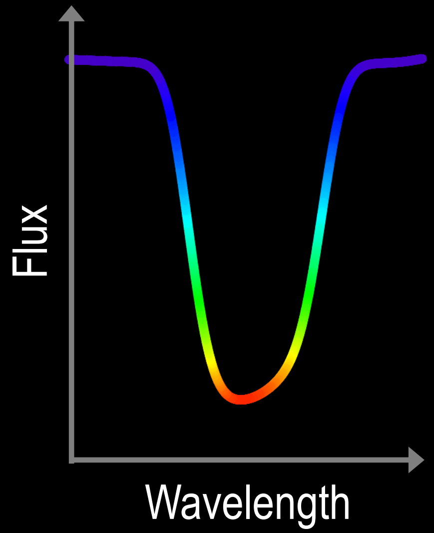
Instrumental stability

Calibration ability

External errors, analysis





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

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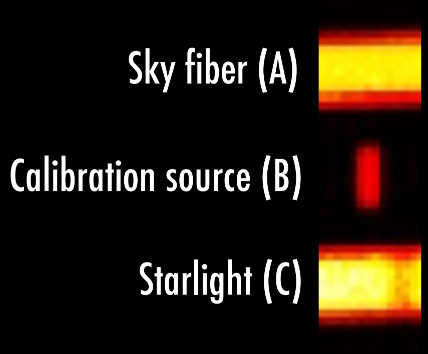

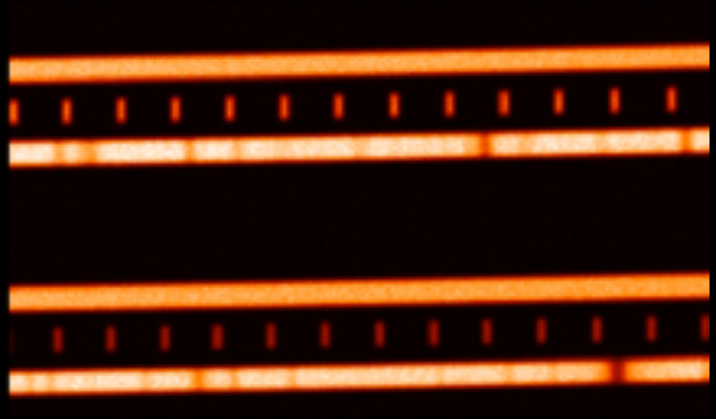

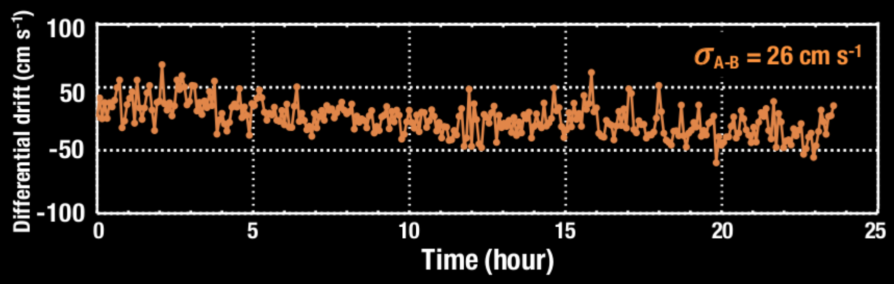

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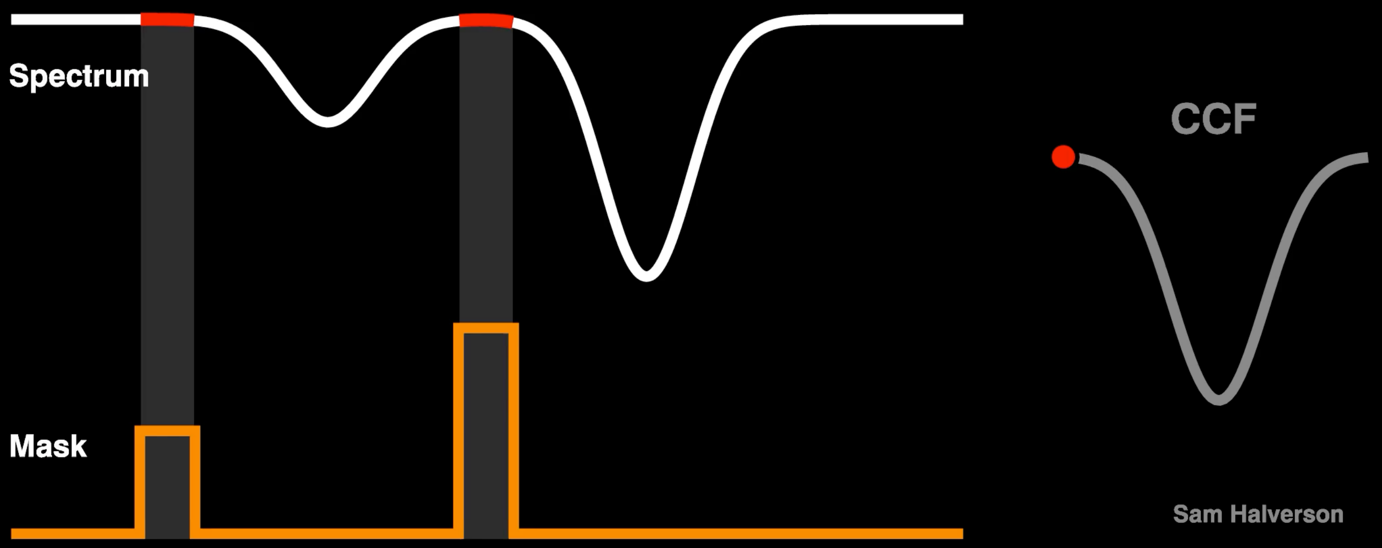

Sam Halverson

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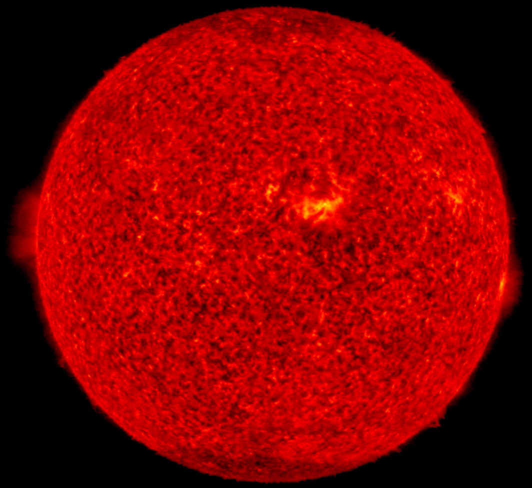
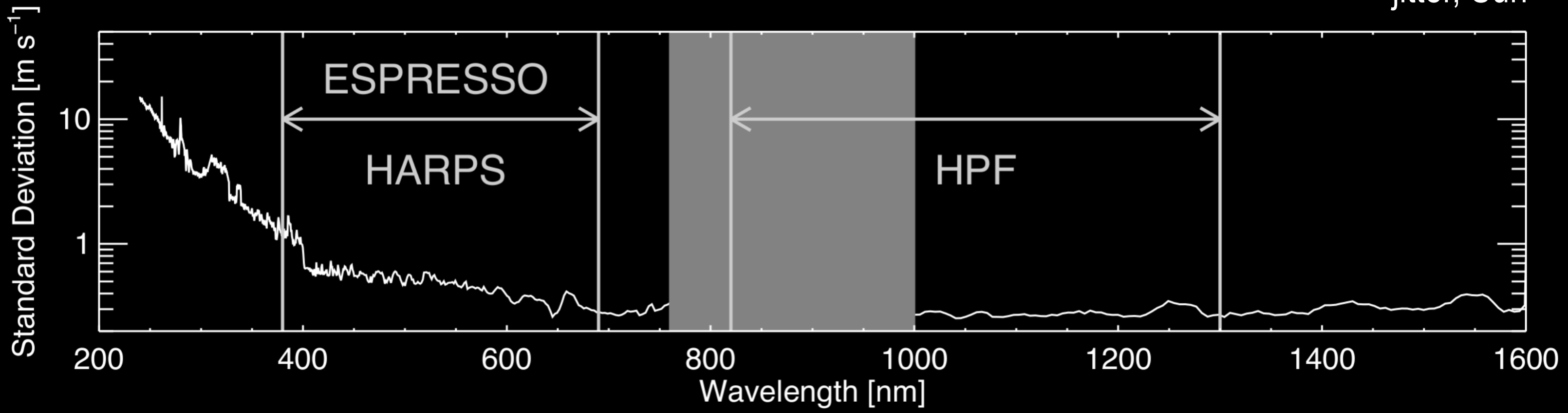


estimated $\sigma_{jitter,\ Sun}$



See suite of other talks on stellar activity studies!

Marchwinski et al. 2015

Deconstructing measurement precision (toy model)

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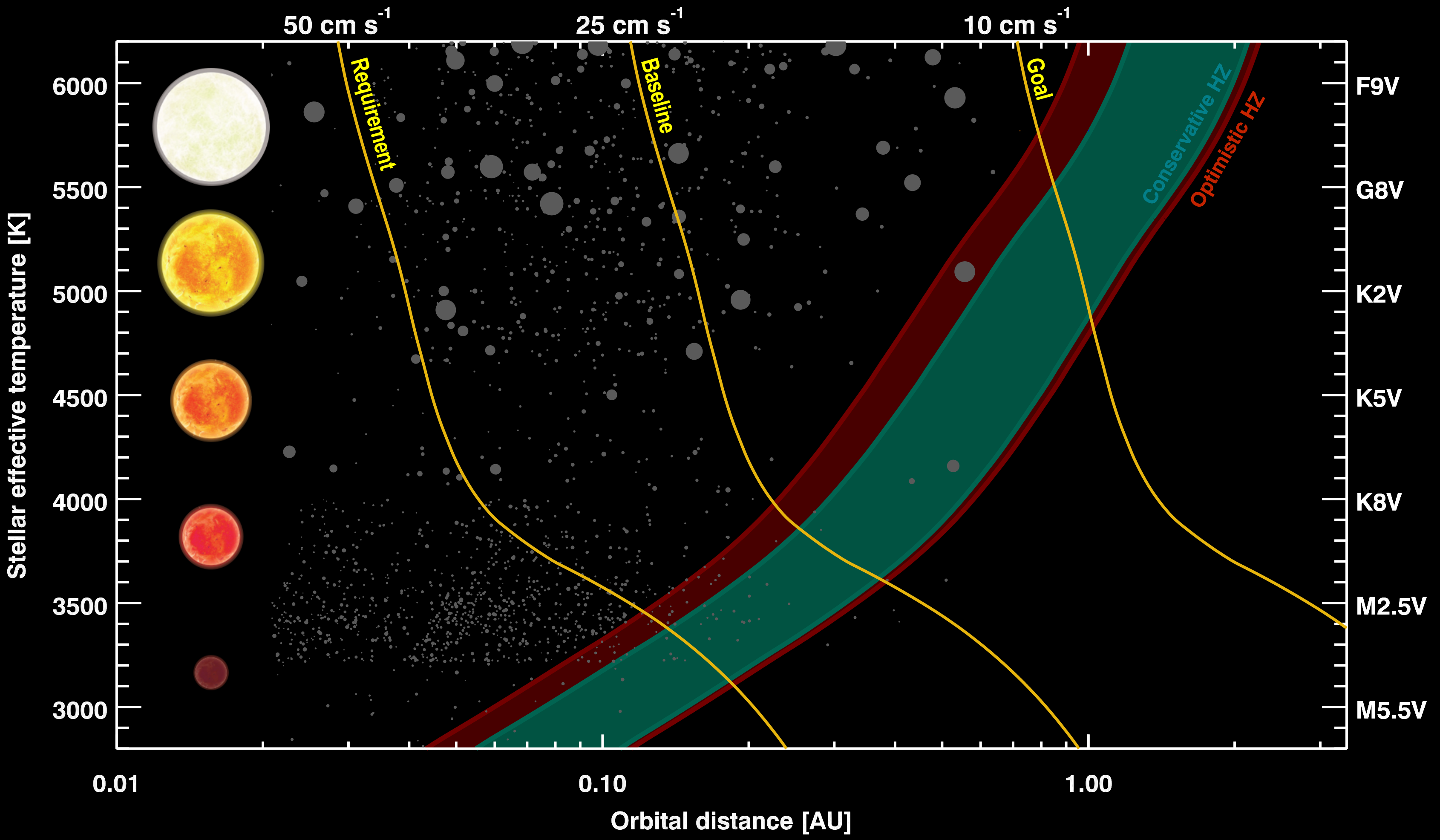
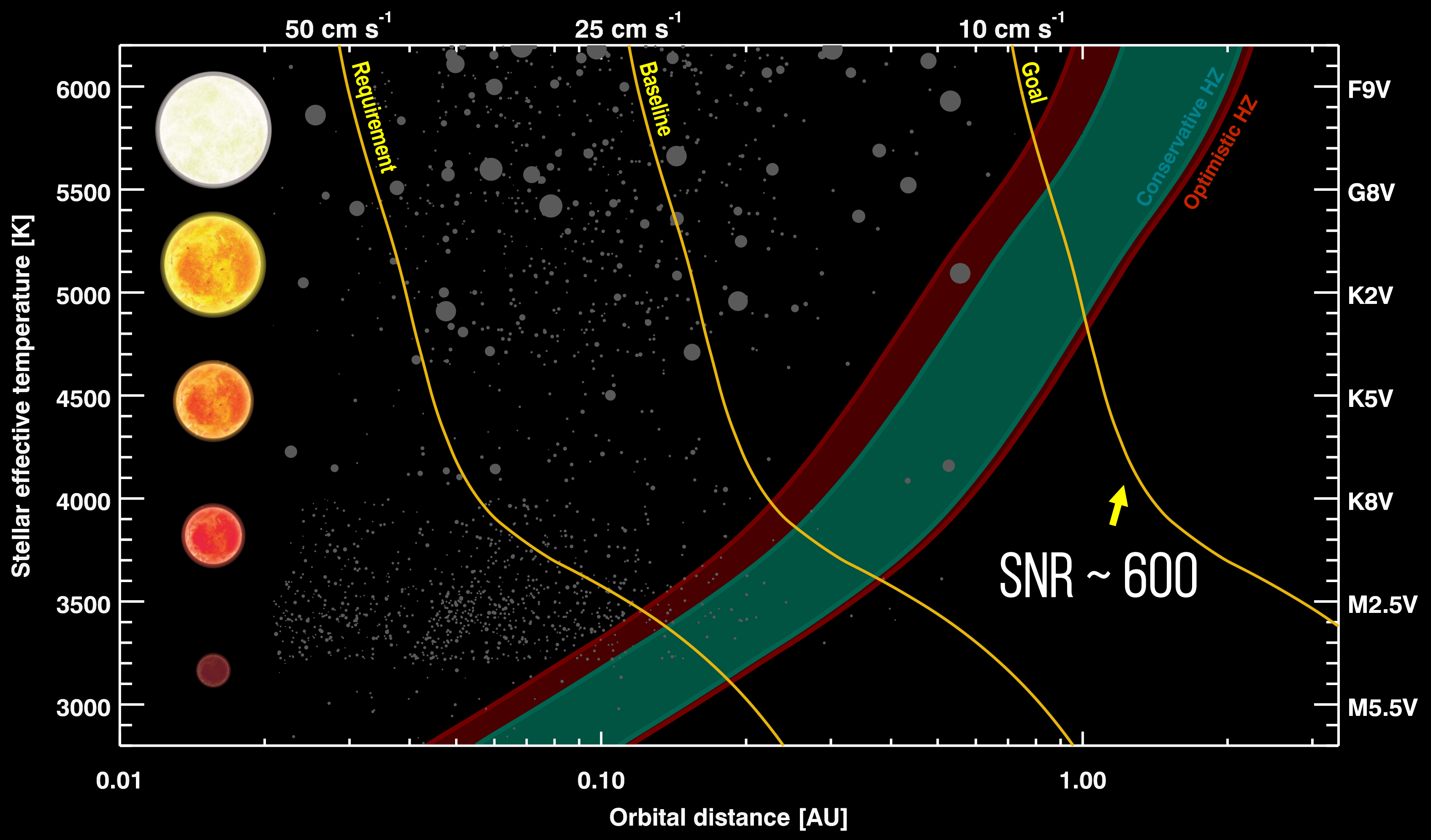
How many photons do you need?



How many photons do you need?



Some (potentially) useful benchmarks

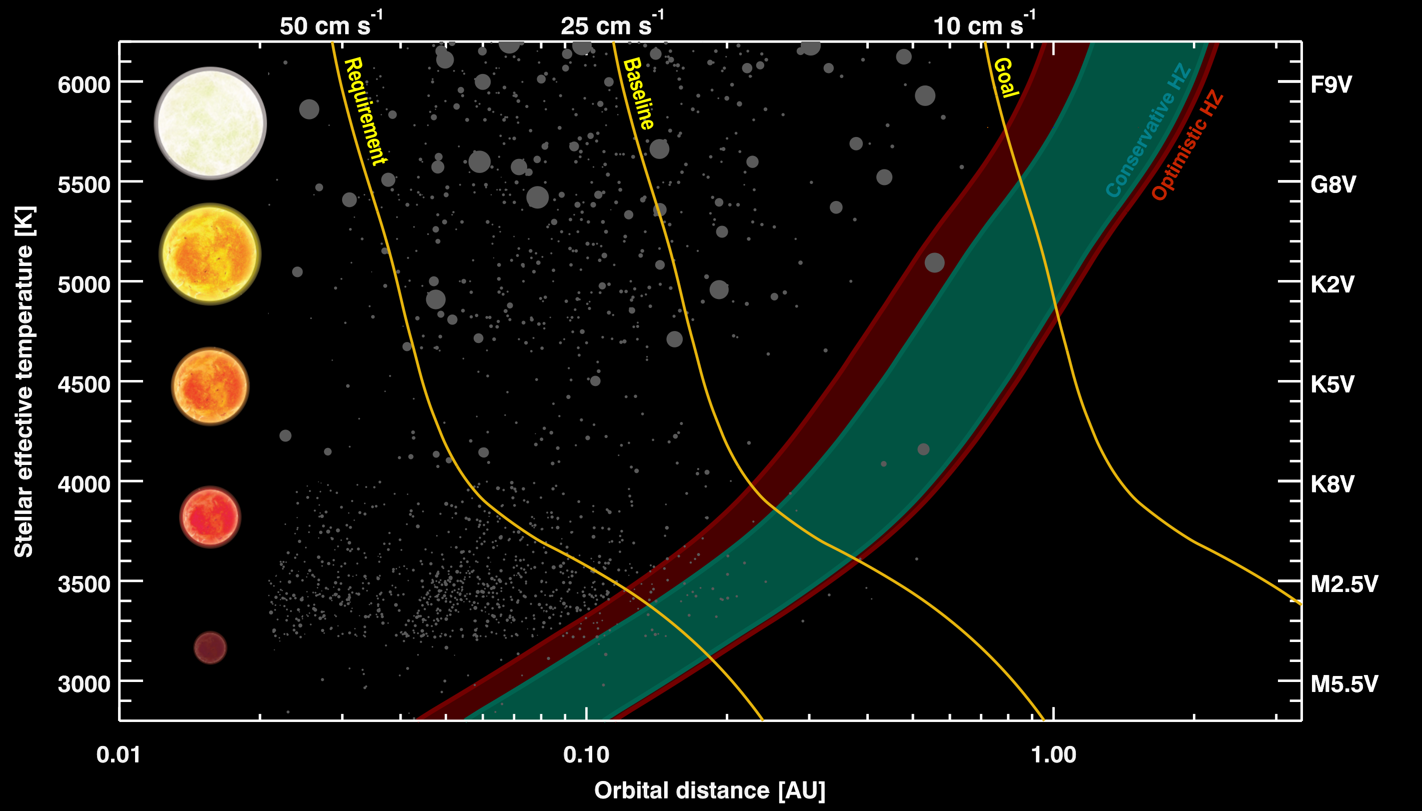
$$\sigma_{photon} \propto SNR^{-1} \propto flux^{-2}$$

Let's assume:

3.5 m telescope

5% flat average efficiency

15 min exposure



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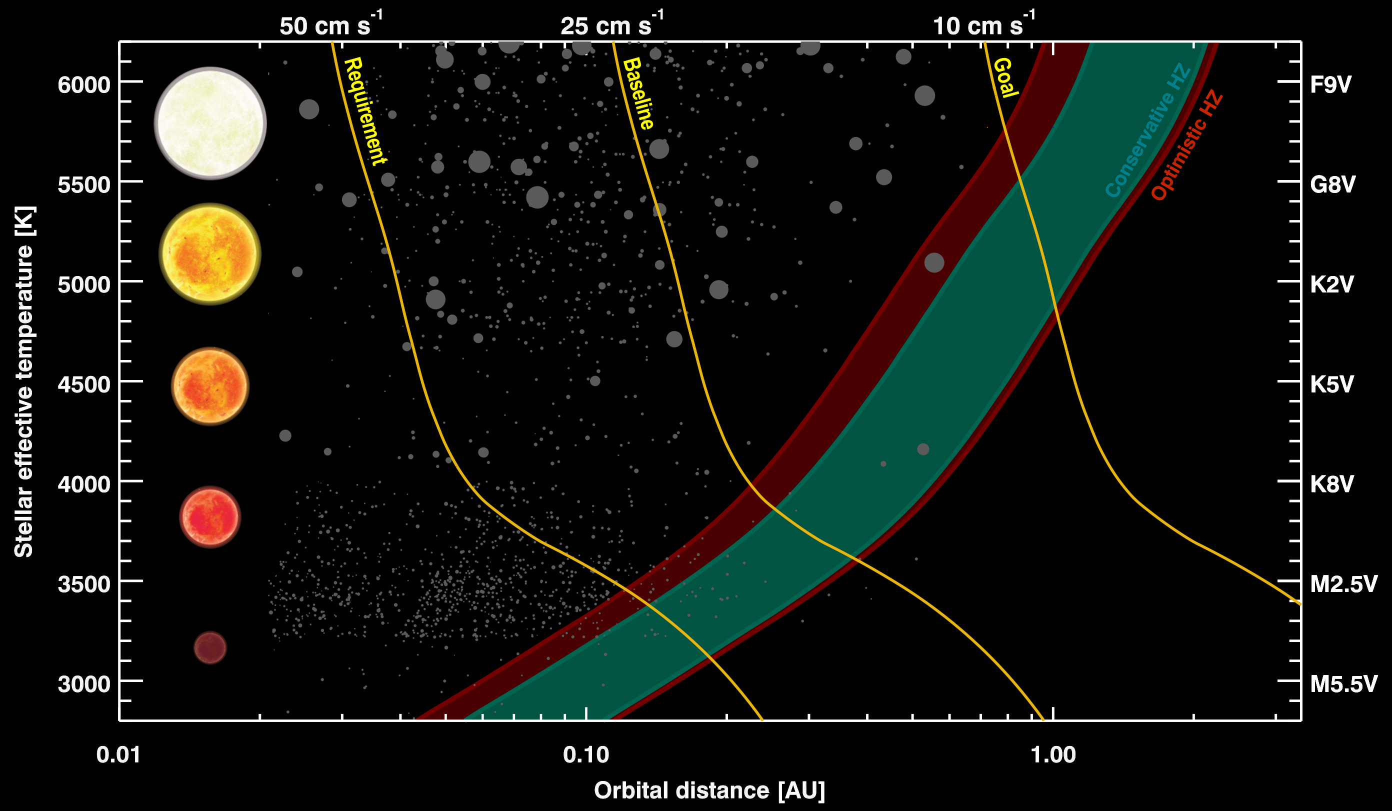

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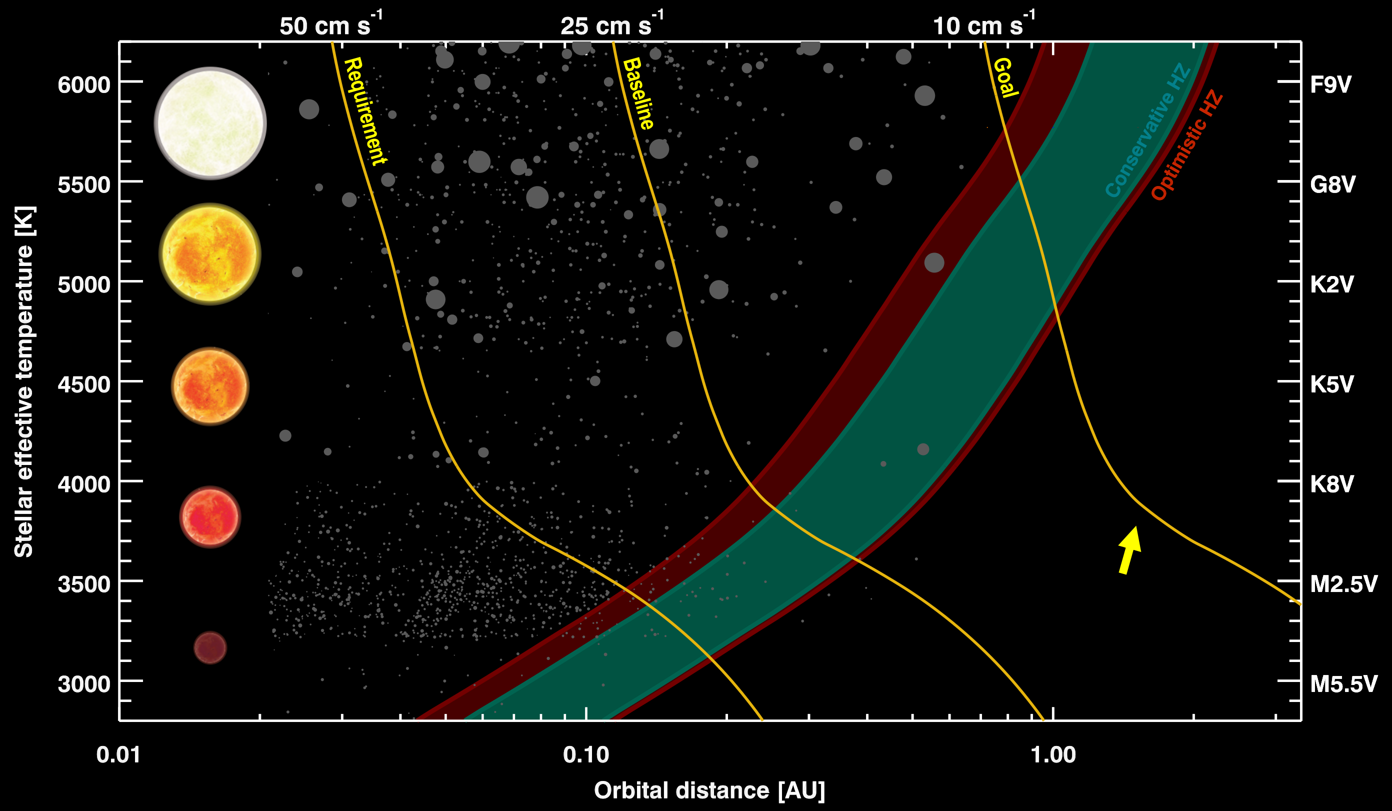
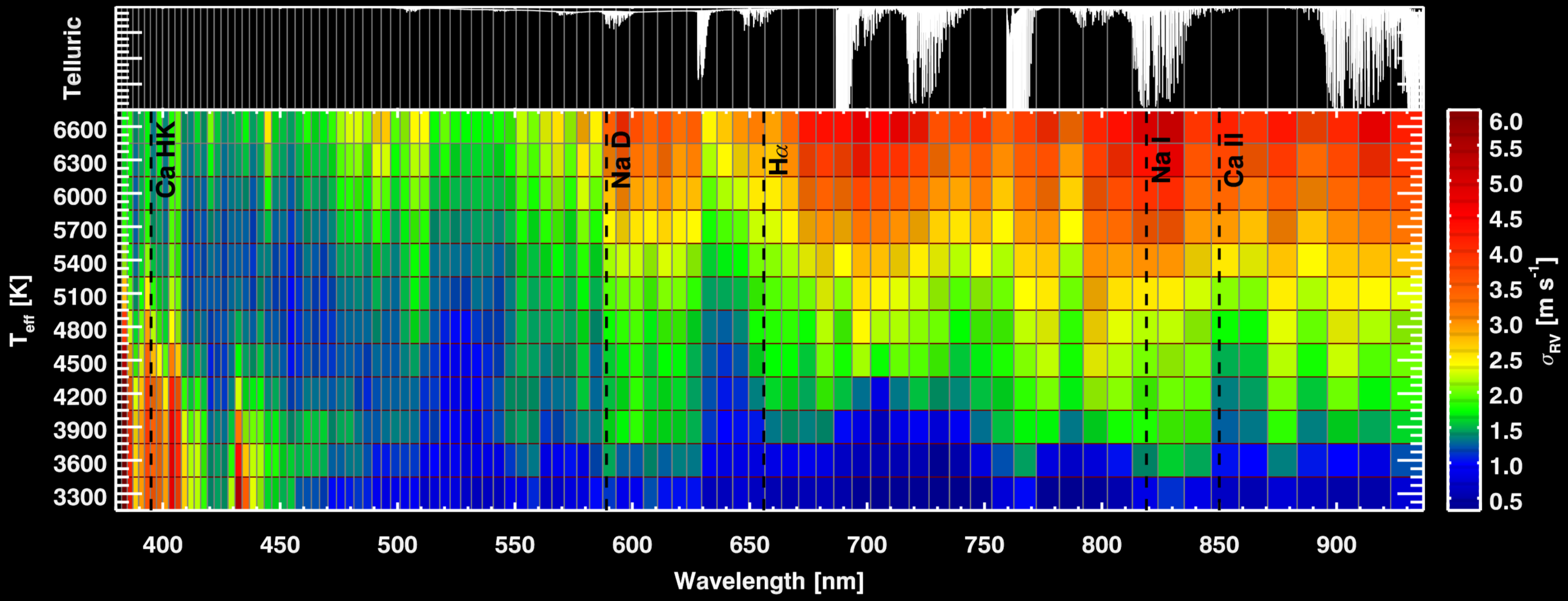


1.0 m s^{-1} -> V of ~11.2
0.1 m s^{-1} -> V of ~6.2

The *quality* of the photons matters, too

Weighted stellar information content as function of wavelength and spectral type



The quality factor '*Q*' is a measure of weighted slopes of spectrum: $\sigma_{photon} \propto Q^{-1}$

e.g. Bouchy+ 2001, Beaty+ 2015, Halverson+ 2016

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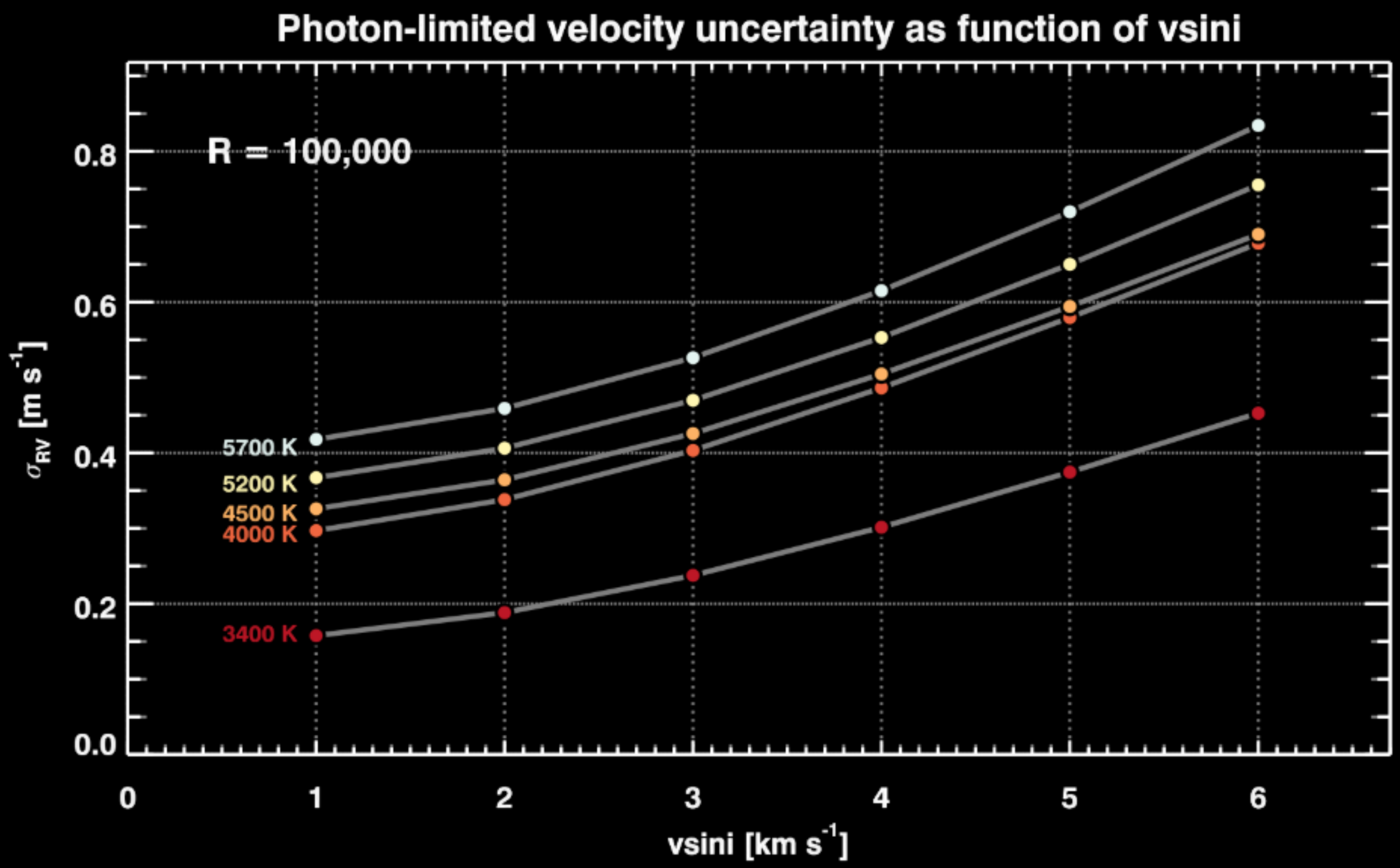

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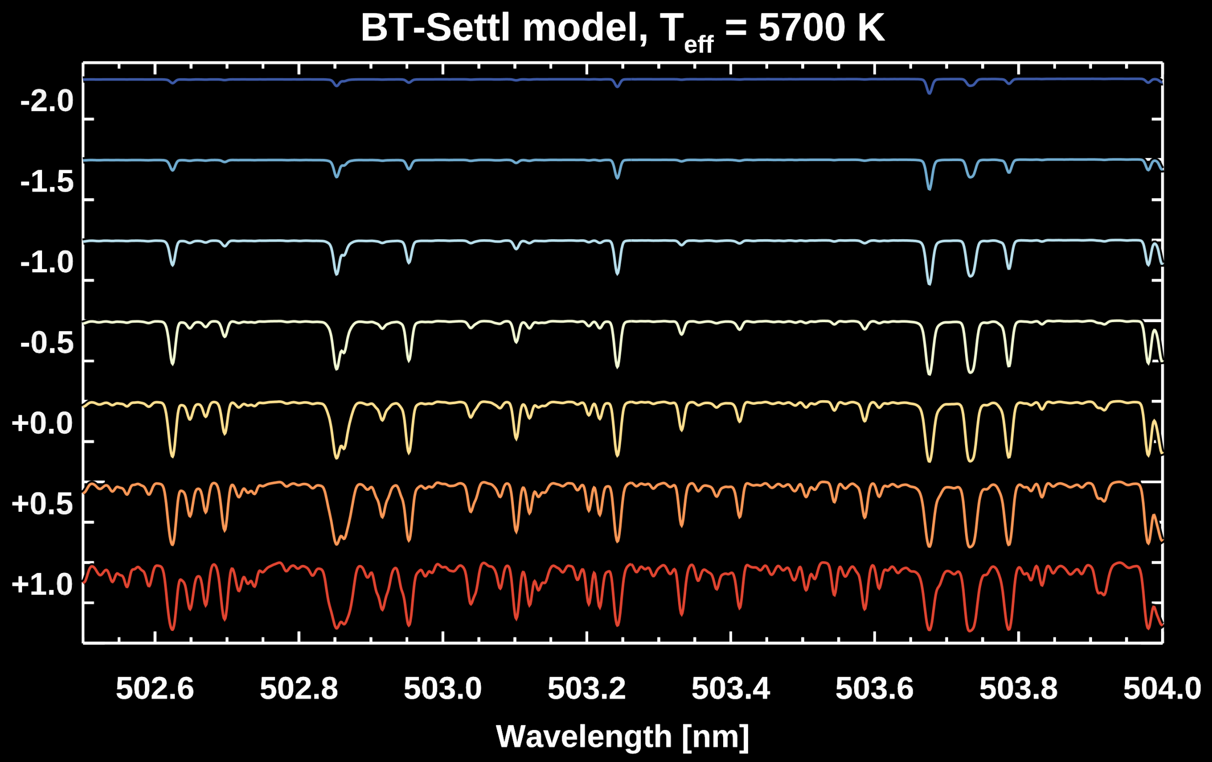
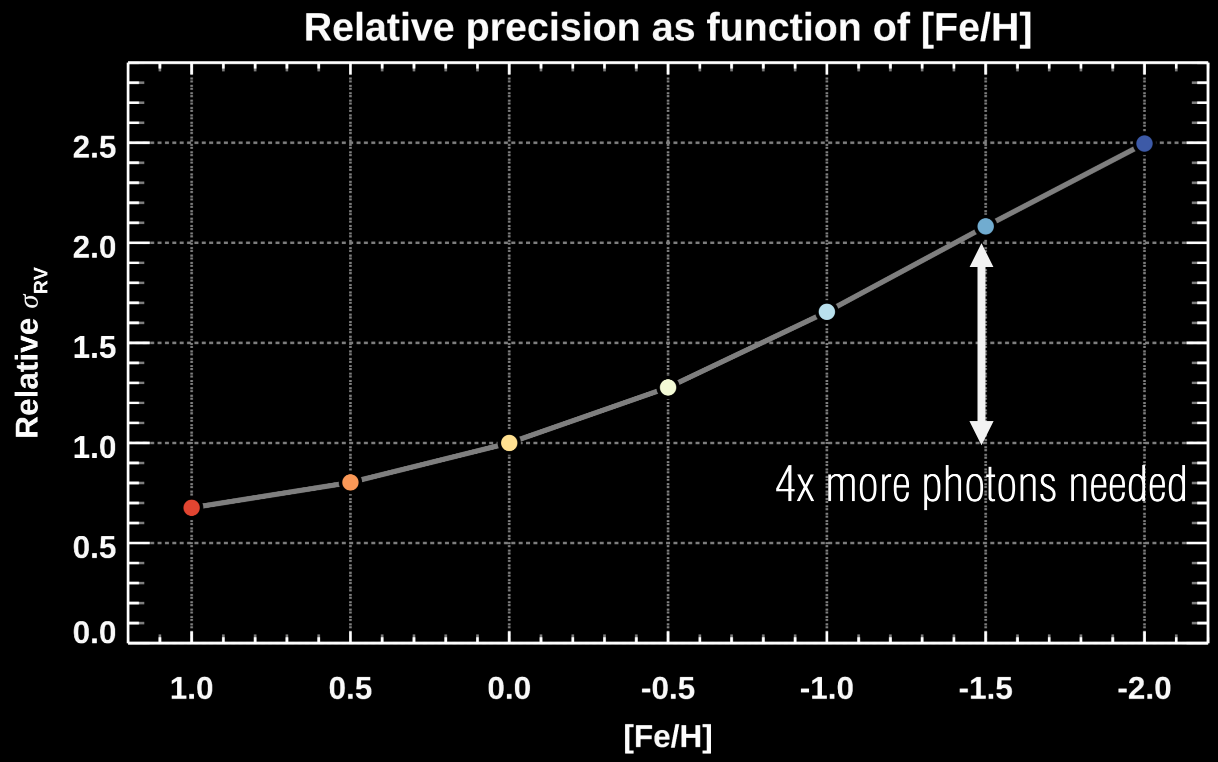
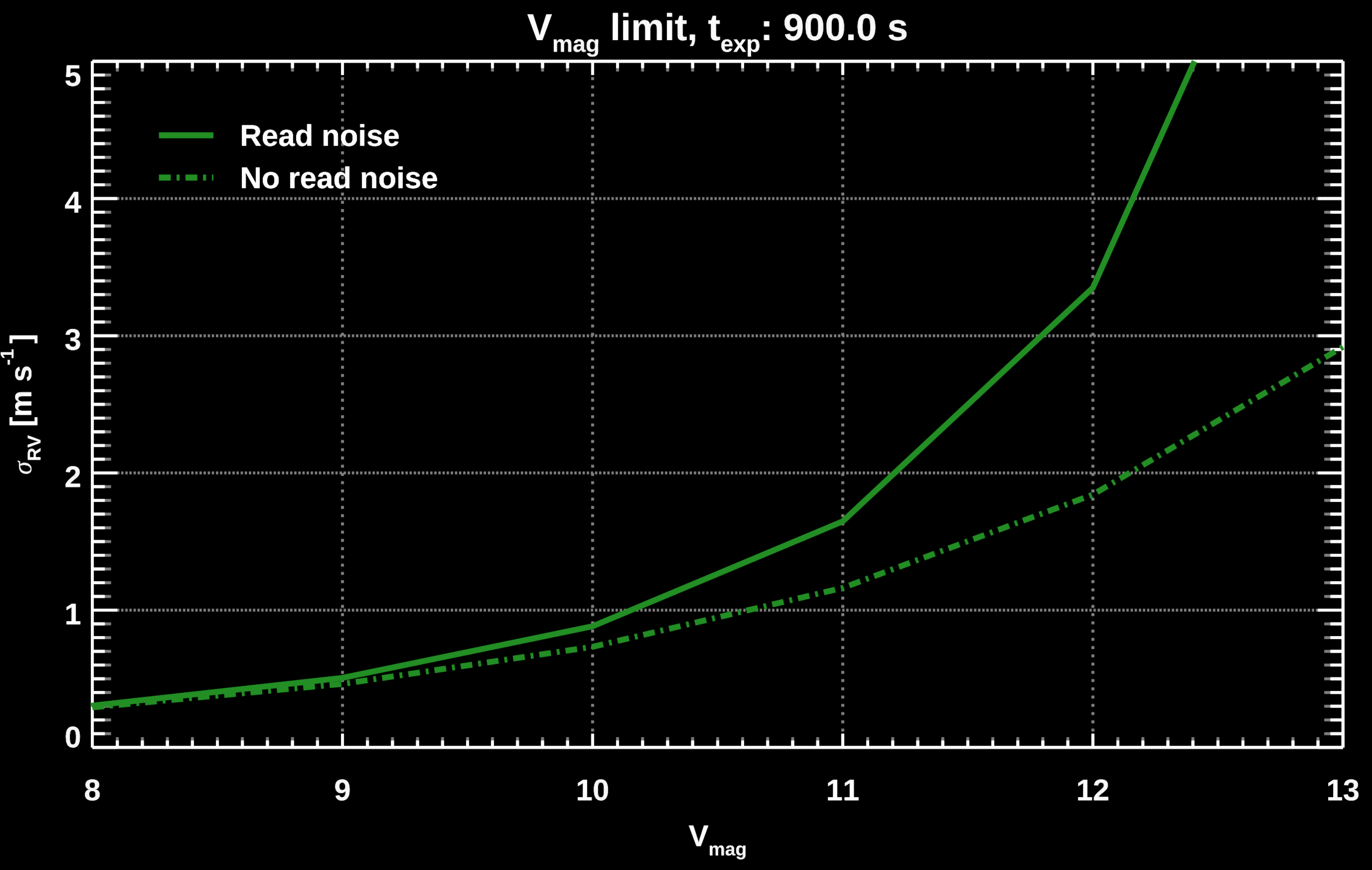




Keep in mind faint limits, read noise



Applications that require lots of photons

Pushing the limits of low-mass planet discovery

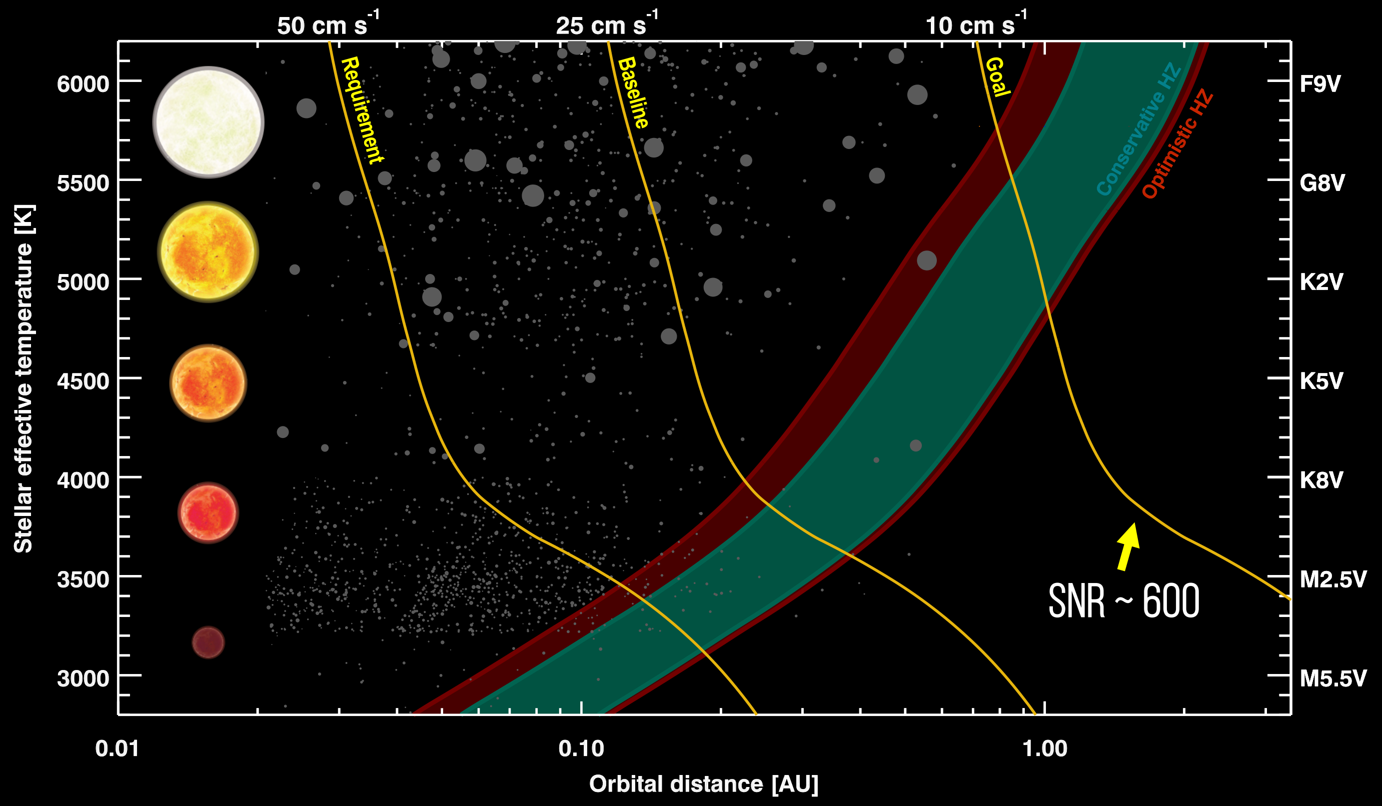
- Highest precision measurements require photons, instrumental stability, broad bandwidth

Ultra-high cadence, precise measurements

- RM measurements are often photon-starved
- Asteroseismology requires exquisite time sampling

Transiting planet characterization

- Follow-up known *Kepler* and TESS stretches the limits of 3-4m telescopes.



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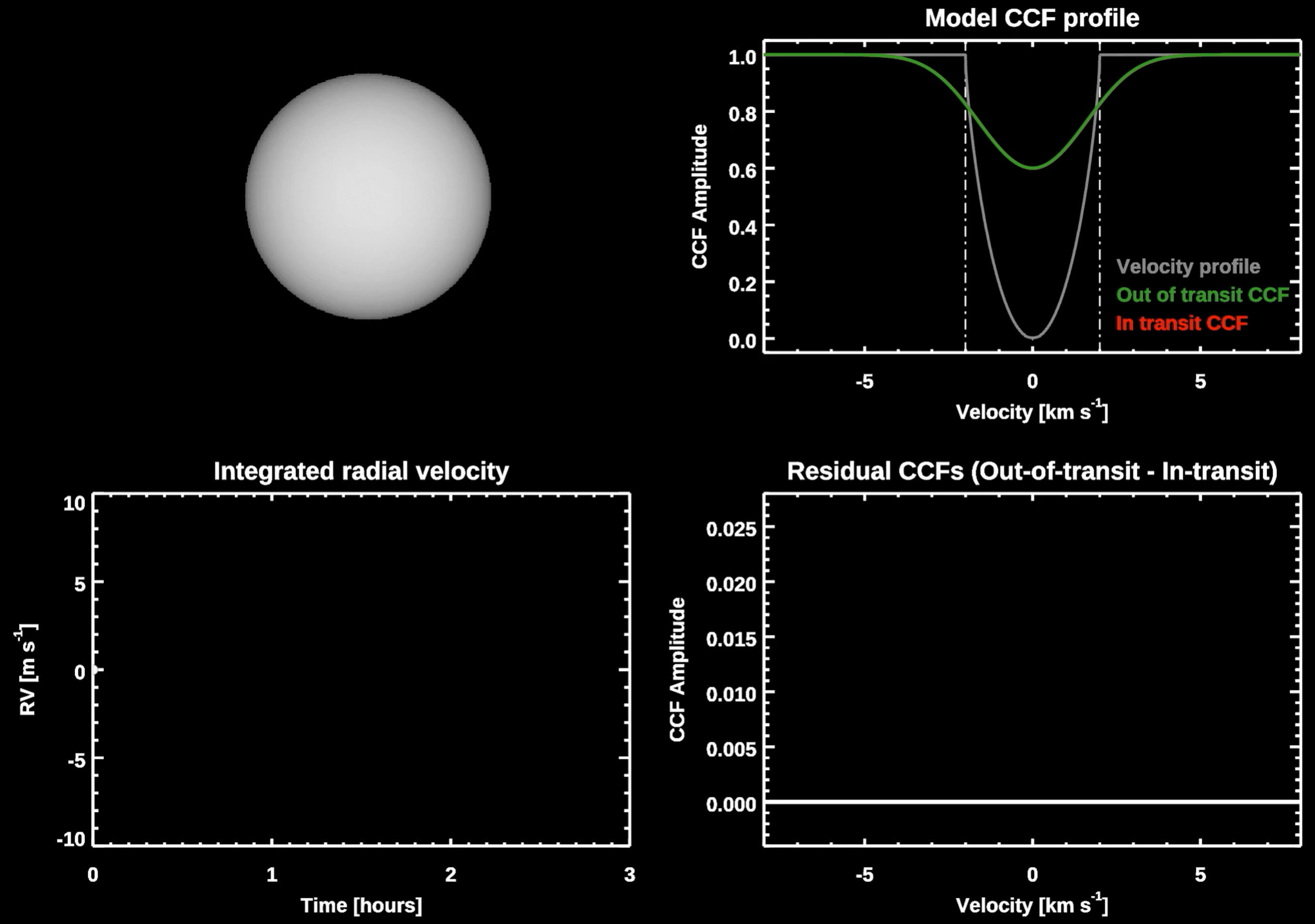

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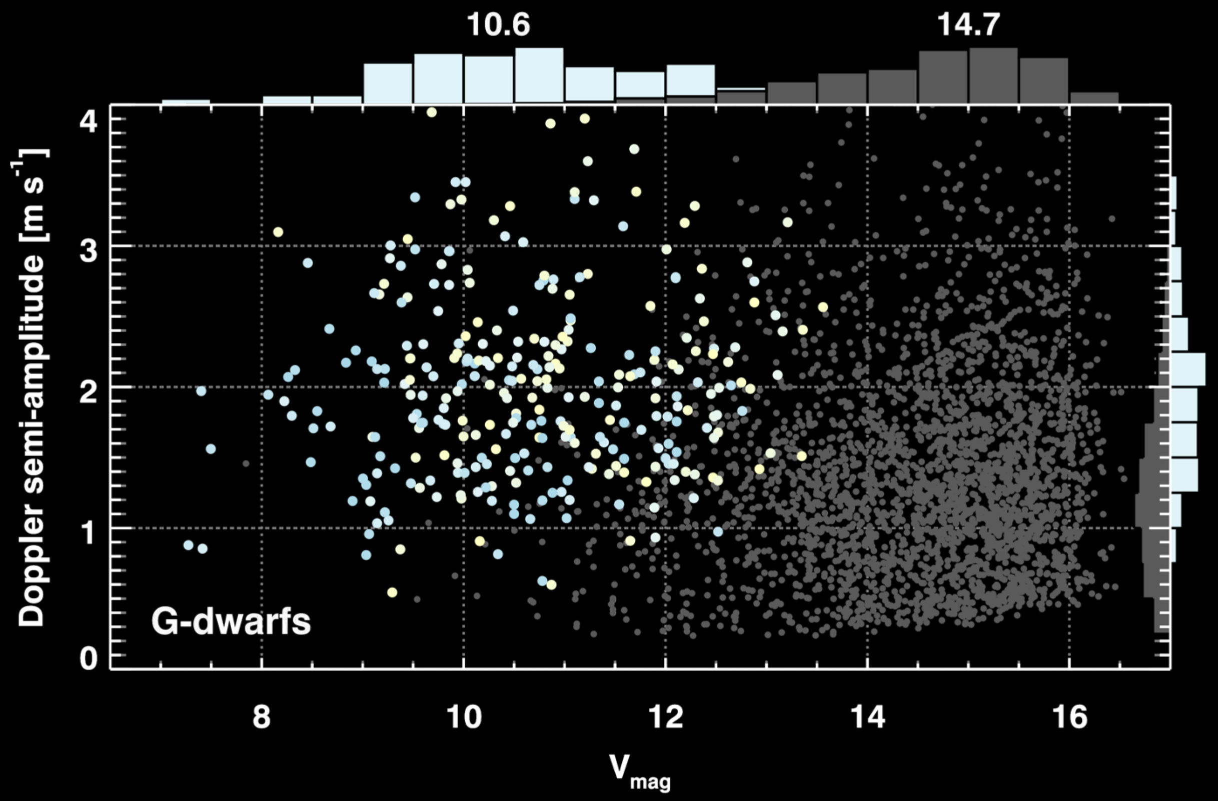

Deconstructing measurement precision (toy model)

σ_{RV}

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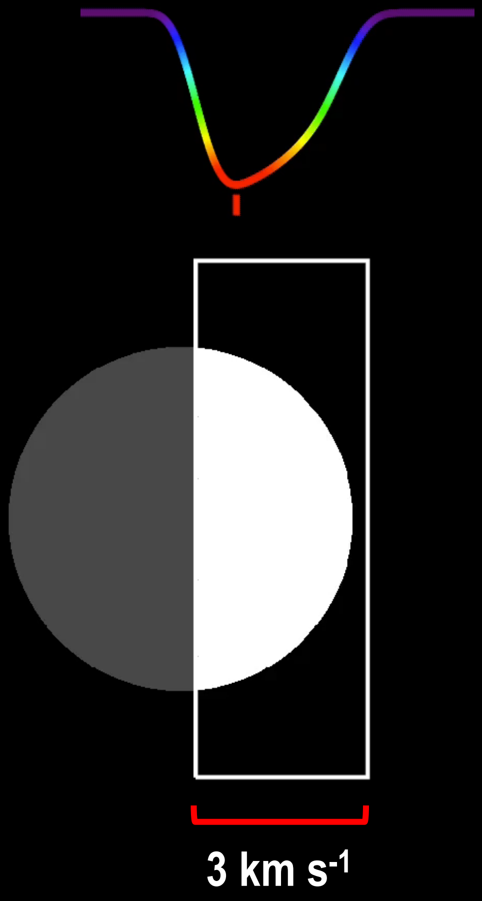
How stable does my instrument illumination have to be?

Spectrometer line profile
'Spectral' domain

Entrance slit
'Spatial' domain



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

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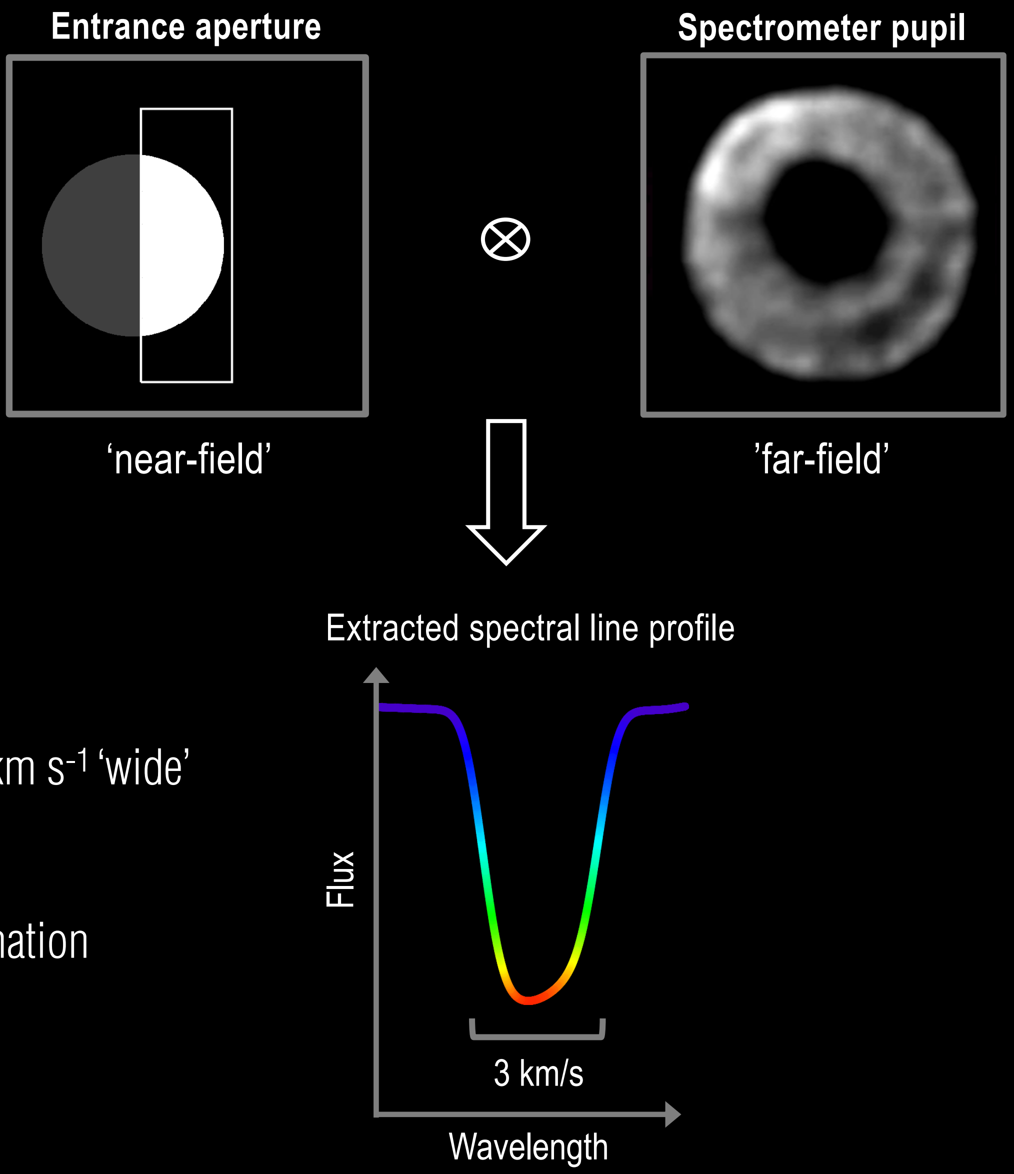
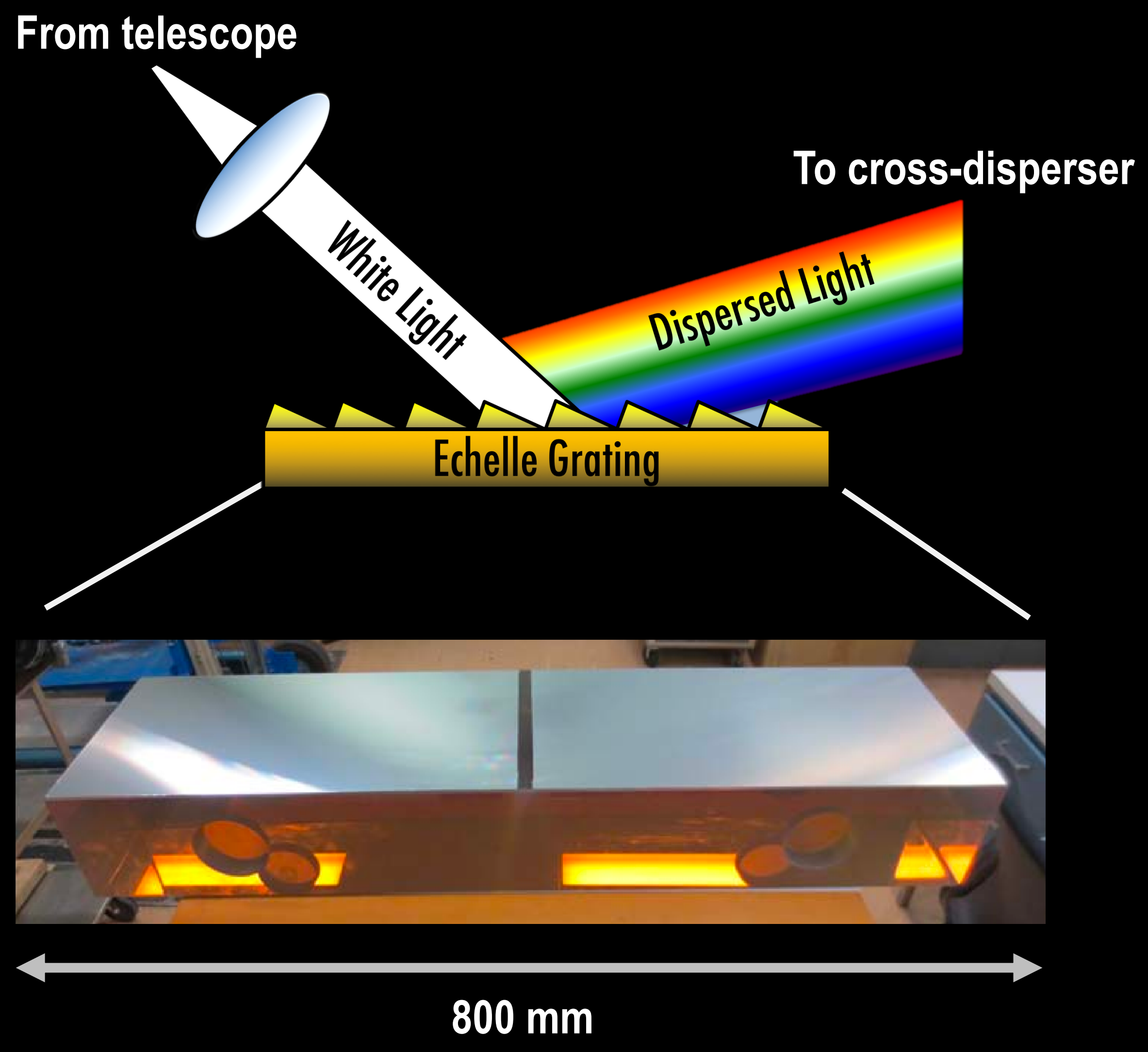


R~100,000 line spread function is ~3 km s^{-1} 'wide' in velocity.

10 cm s^{-1} PSF stability requires illumination stability of **1 part in 30,000.**

How stable does my instrument temperature have to be?



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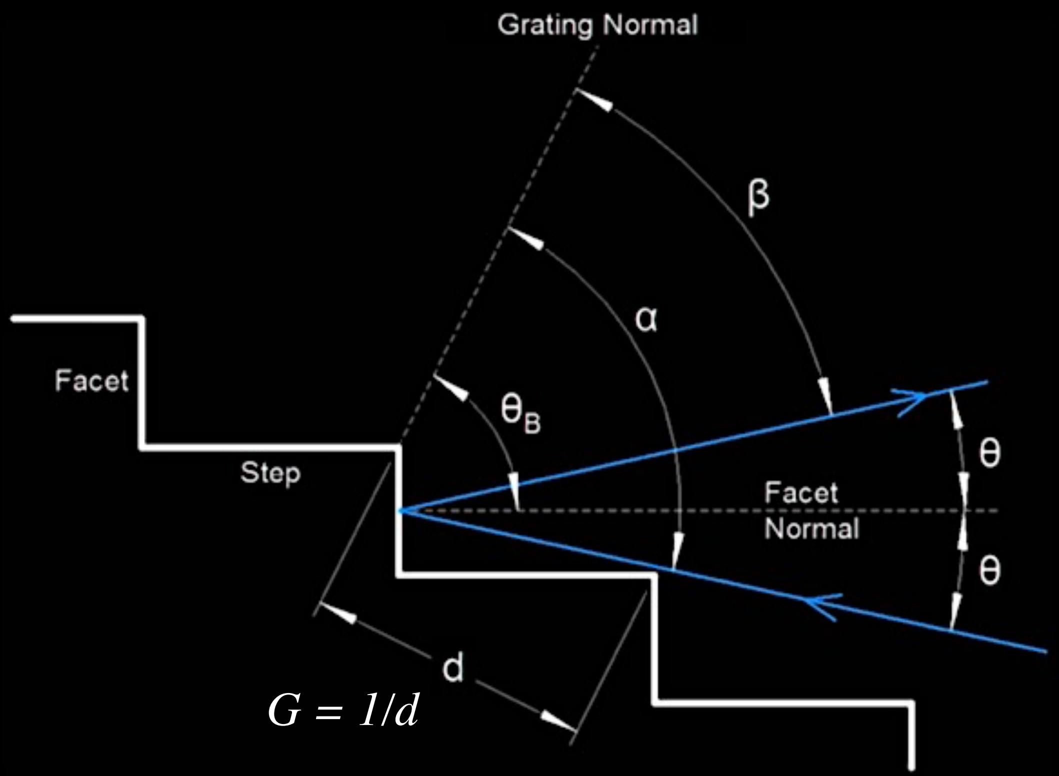

$$m\lambda G = 2\sin\theta_{\mathrm{B}}\cos\theta$$

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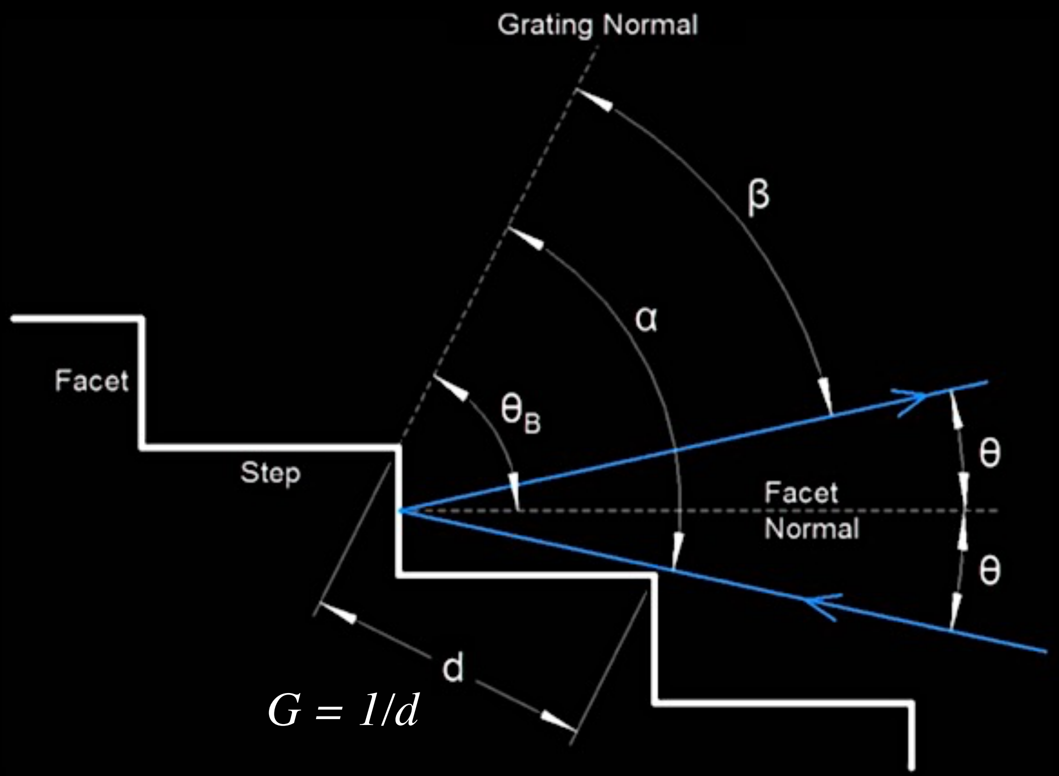
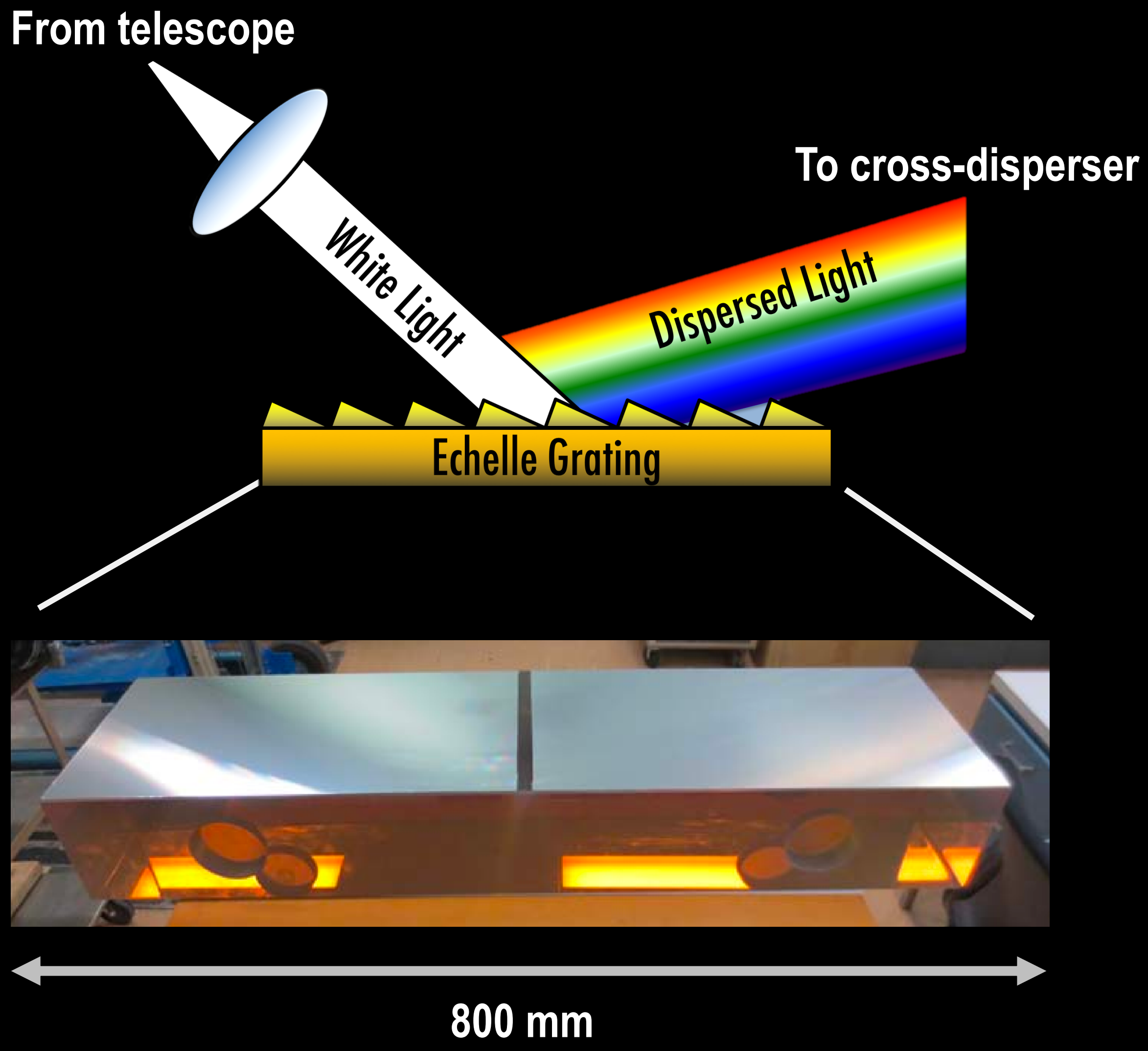


$$m\lambda G = 2\sin\theta_{\mathrm{B}}\cos\theta$$

Depends on grating length

How stable does my instrument temperature have to be?



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

$\Delta T = 10$ mK

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

Deconstructing measurement precision (toy model)

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

TOTAL ERROR: 30 CM S^{-1}

% INSTRUMENTAL ERROR CORRECTED BY CALIBRATION: 90

FIBER & ILLUMINATION: 14 CM S^{-1}	INSTRUMENTAL: 20 CM S^{-1}	COMPUTATION: 18 CM S^{-1}	DETECTOR EFFECTS: 7 CM S^{-1}	EXTERNAL SOURCES: 18 CM S^{-1}
Modal noise (star + cal.)	Therm. stability (bench)	Barycentric corrections	Pixel center offsets	Telescope & FIU guiding
Near + far-field scrambling	Therm. stability (gratings)	Calibration process	Pixel inhomogeneities	ADC variation
Stray light + ghosts	Therm. stability (camera)	Reduction and software	Charge transfer efficiency	Focus variation
Fiber-fiber contamination	Vibrational stability		CCD thermal expansion	Fiber injection angle
Polarization variation	Pressure stability		Readout thermal change	Micro-tellurics
FRD (star + calibration)	Zerodur phase change		Brighter-fatter effect	Scattered sunlight

A variety of errors can be traced with a simultaneous calibration source

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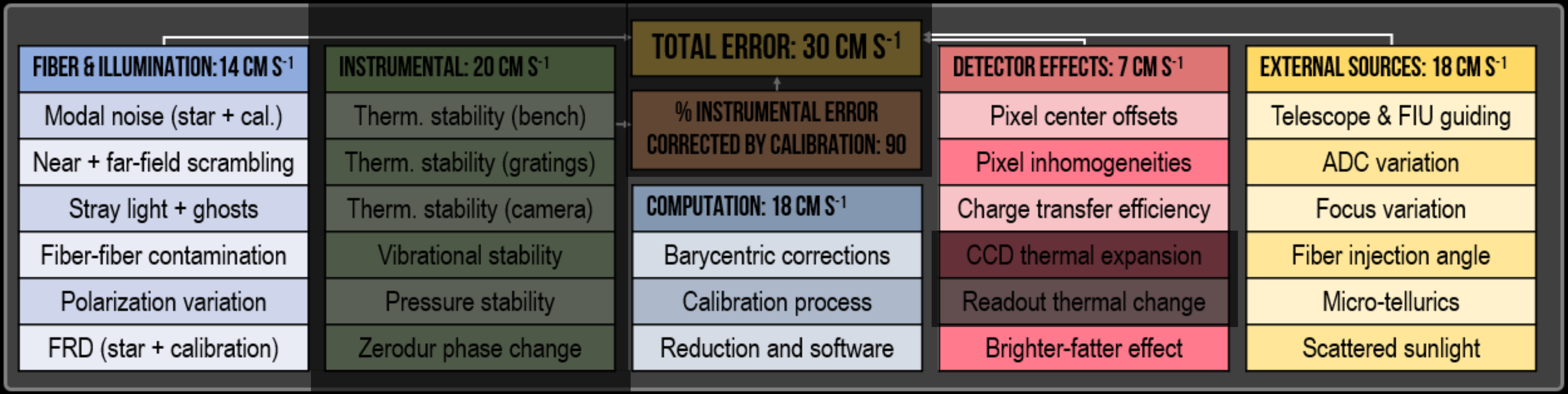
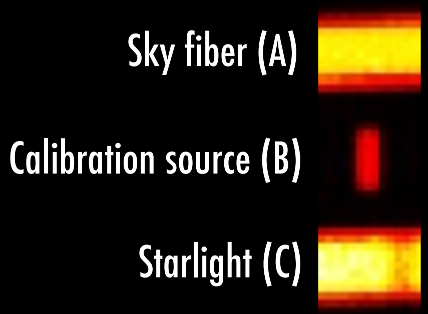
Sky fiber (A)

Calibration source (B)

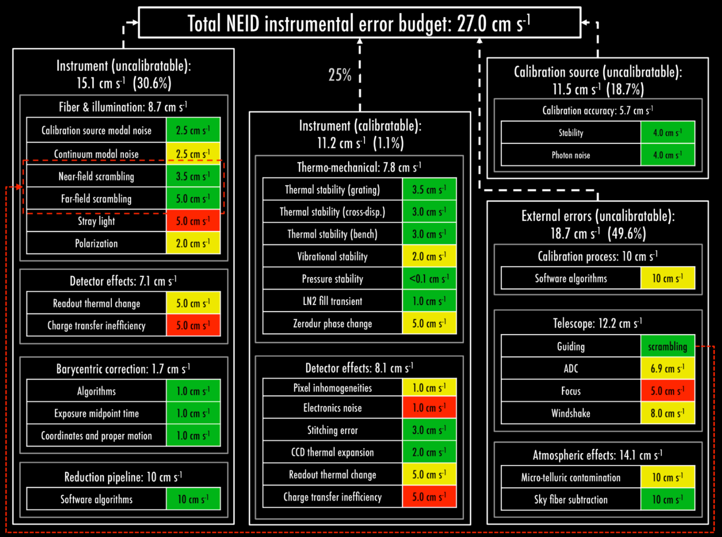
Starlight (C)

…while others are not, and rely on intrinsic stability

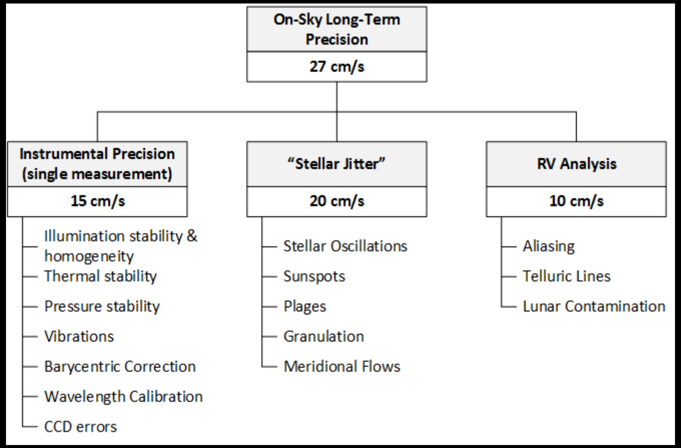




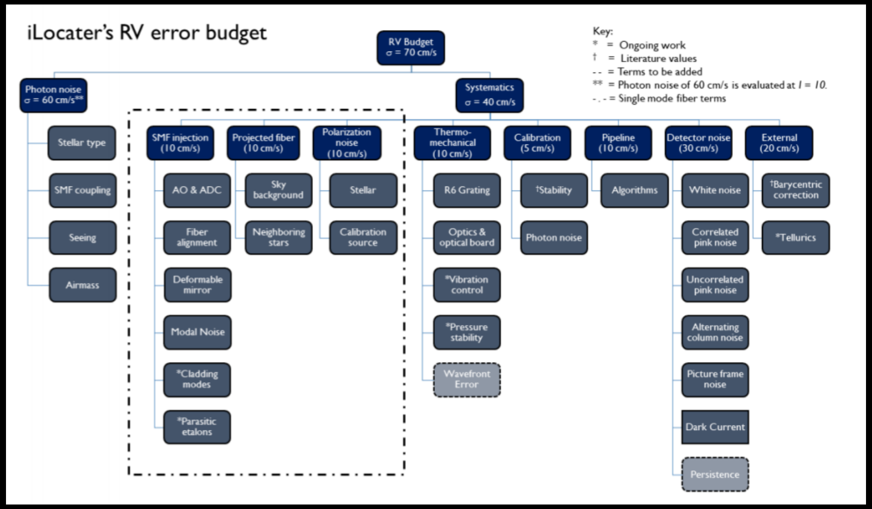
Other examples of PRV error budgets



Halverson et al. 2016



Blackman et al. 2020



Bechter et al. 2018

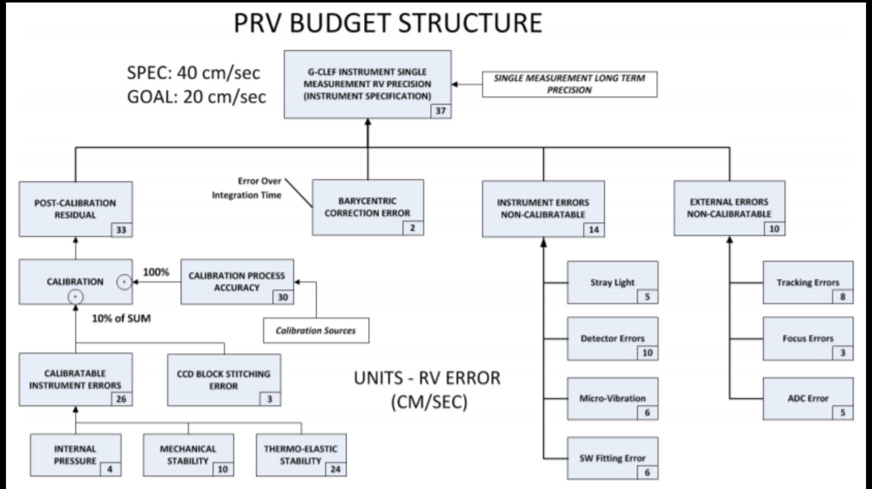
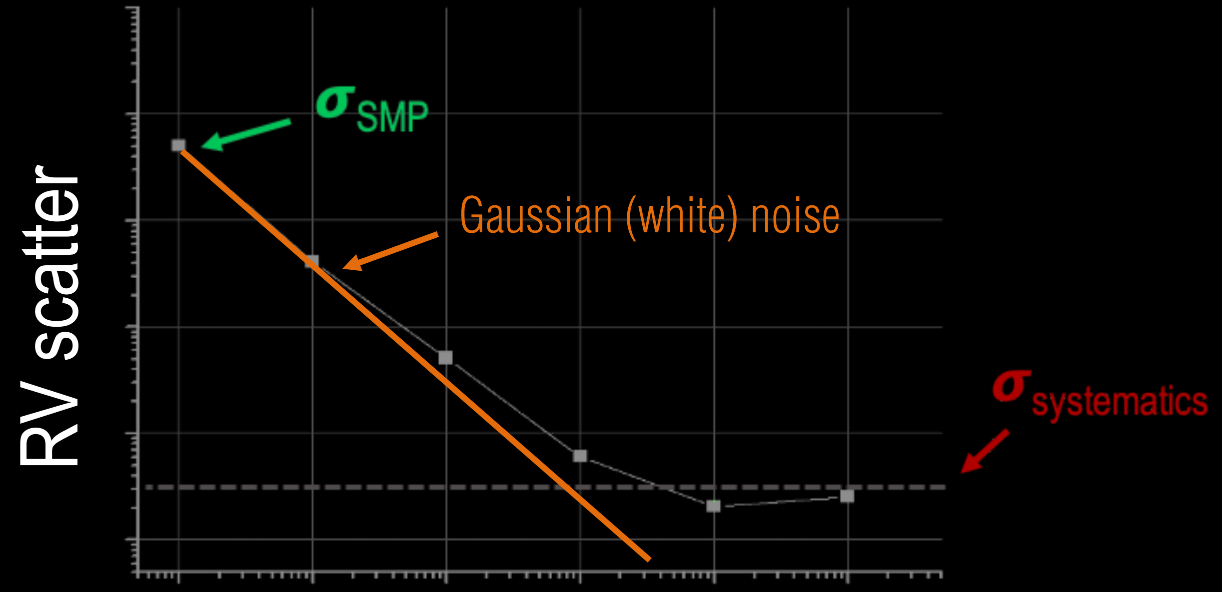


Figure 4. PRV Error Budget Top Level Structure

Podgorski et al. 2012

One final note on combining errors

Each error has behavior – not all are 'random' distributions that can be RSS'd



Number of bins

Only true if all errors are random!

$$\sigma_{RV} \sim (\sigma_a^2 + \sigma_b^2 + \sigma_c^2 + \ldots)^{0.5}$$

Takeaways

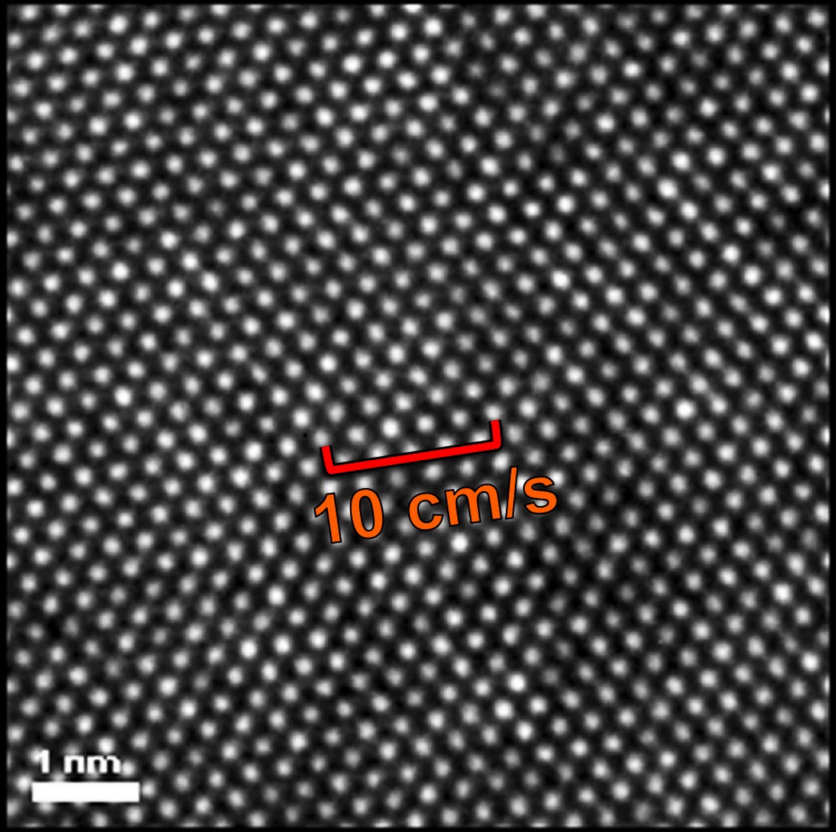
- Estimating errors is hard!

- Always be aware of the symphony of instrumentation and software pieces that work together to deliver a final RV measurement, and think about how each piece behaves.

- Remain cognizant of how many photons you need to achieve your science, and the ‘quality’ of the photons you’re collecting.

- Empirically assessing measurement performance is a complicated task, and requires some level of prediction (assembling an error budget), and testing (in-lab and on-sky measurements).

- Identifying the ‘tall tent poles’ is a top priority for the next decade!



TEM image of silicon wafer lattice (typical CCD)

Jet Propulsion Laboratory
California Institute of Technology

jpl.nasa.gov

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