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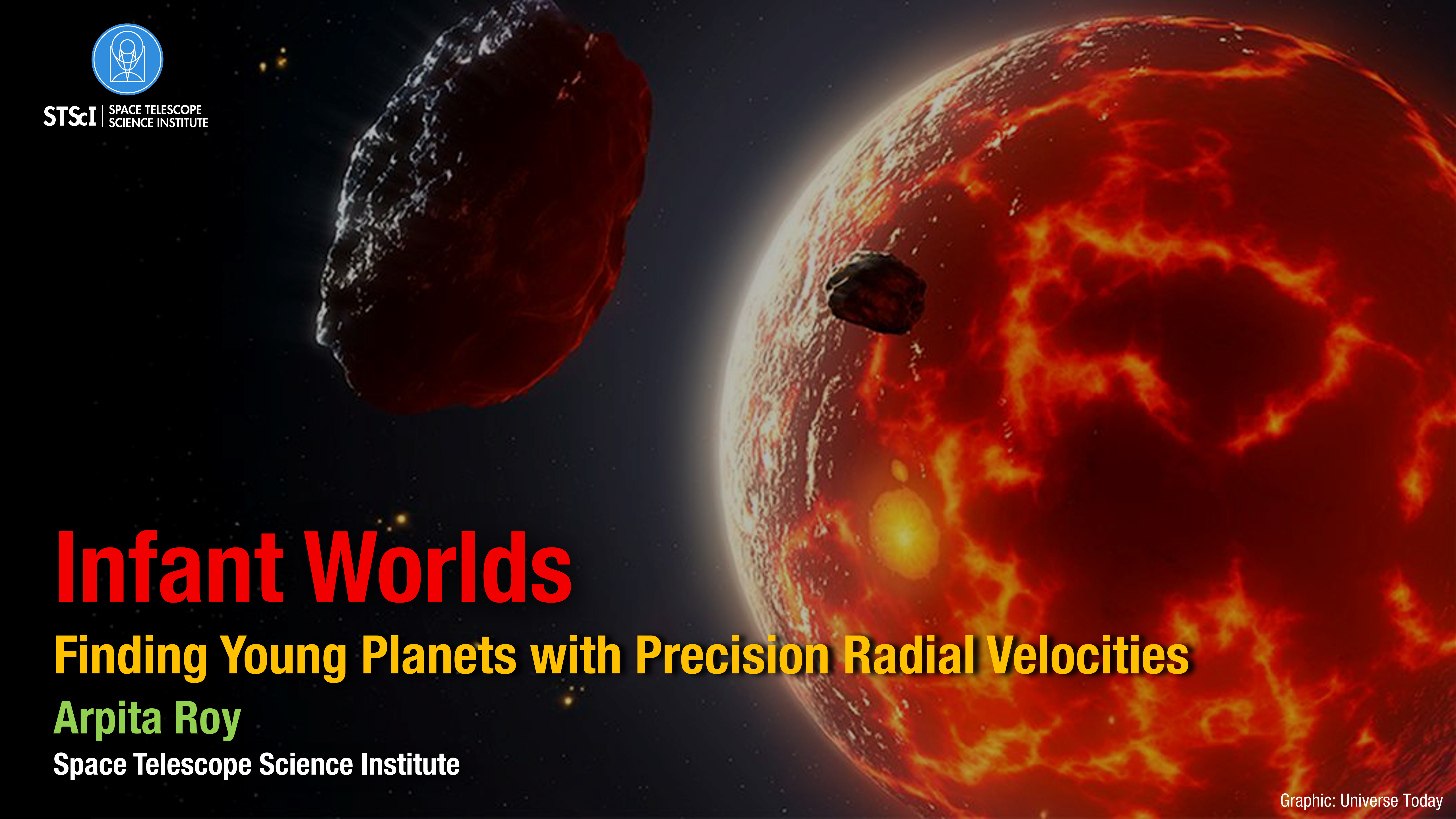


Infant Worlds

Finding Young Planets with Precision Radial Velocities

Arpita Roy

Space Telescope Science Institute

Graphic: Universe Today

About Me

www.arpita.space

Tenure-Track Astronomer
Space Telescope Science Institute

Associate Research Scientist
Johns Hopkins University

— Previously —

Millikan Prize Postdoctoral Fellow
California Institute of Technology

PhD, Astronomy & Astrophysics
Pennsylvania State University

Exoplanet Science

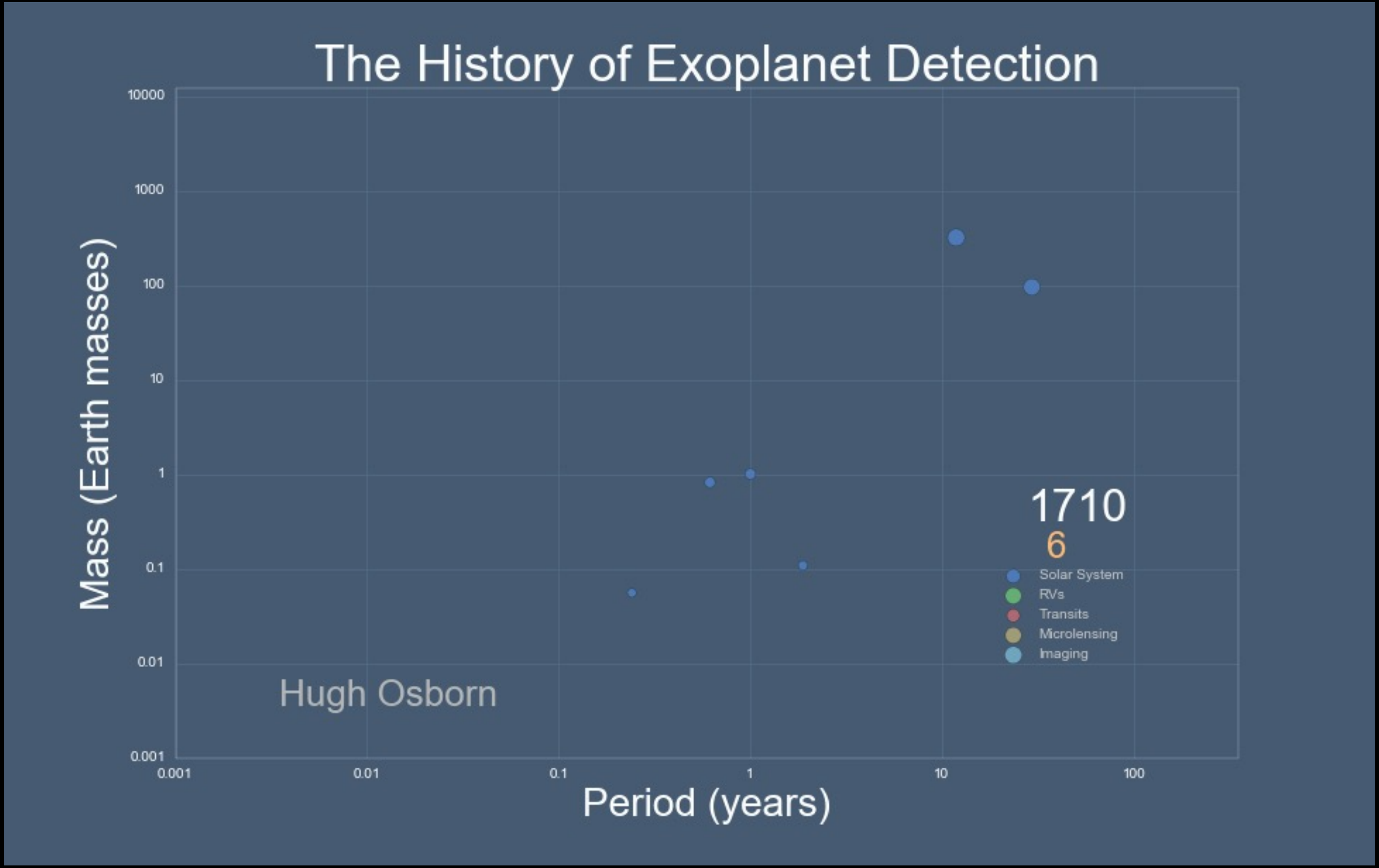
Instrumentation

Data Analysis

*Looking for grad students

Current State of the Field

Exoplanet Discovery Driven By New Technologies



Source: Hugh Osborn, University of Warwick

The Precision Radial Velocity Technique

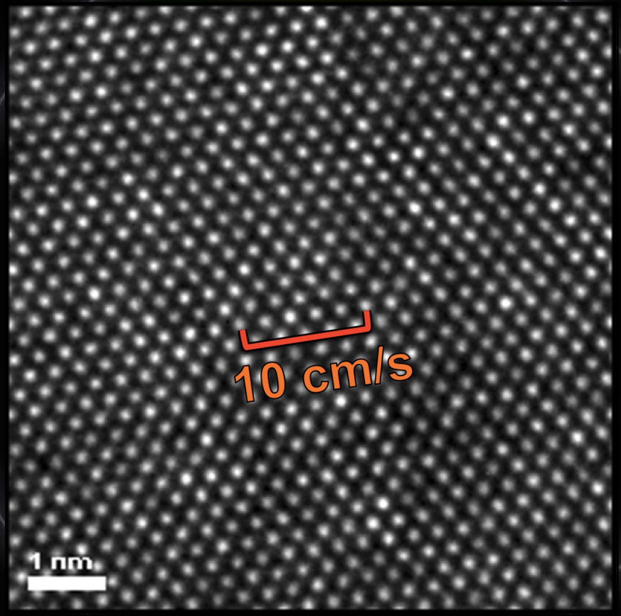
EPRV = Extreme Precision Radial Velocity

Advancing Technology for Exoplanet Detection

Developing Extreme Precision Spectroscopy

Silicon Lattice: High Resolution TEM Image of individual Si atoms.
[Ki Bun Kin, SPIE 2012]

10cm/s corresponds to 1/6,000th of a 10 micron pixel

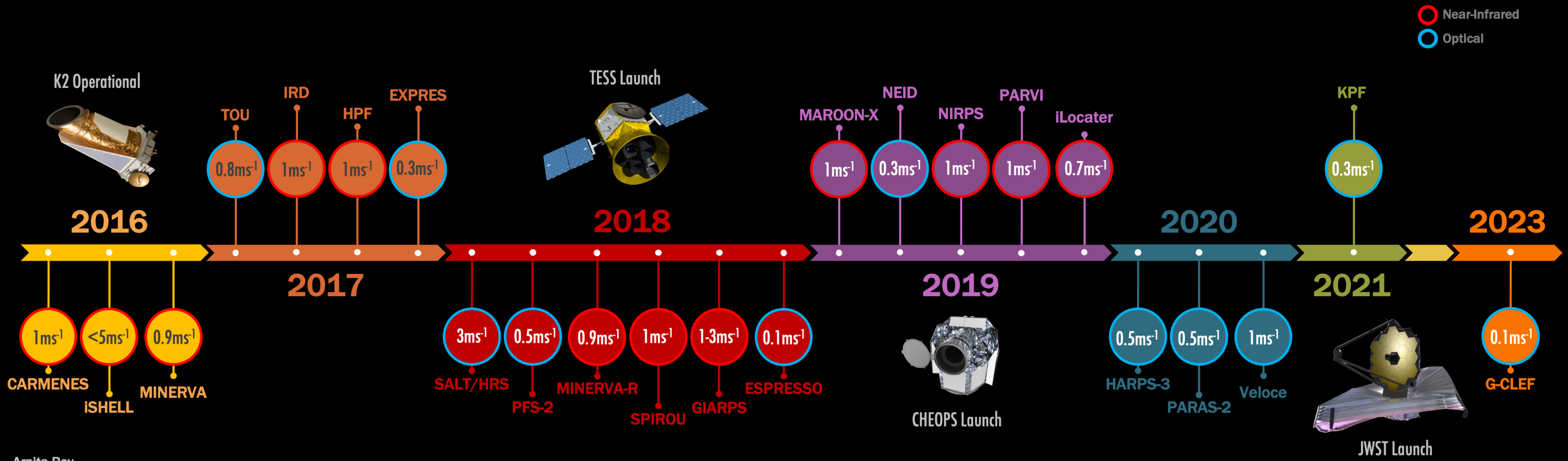


PLANETQUEST
THE SEARCH FOR ANOTHER EARTH

About 800 planets discovered
Source: NASA Exoplanet Exploration

The Precision Radial Velocity Landscape

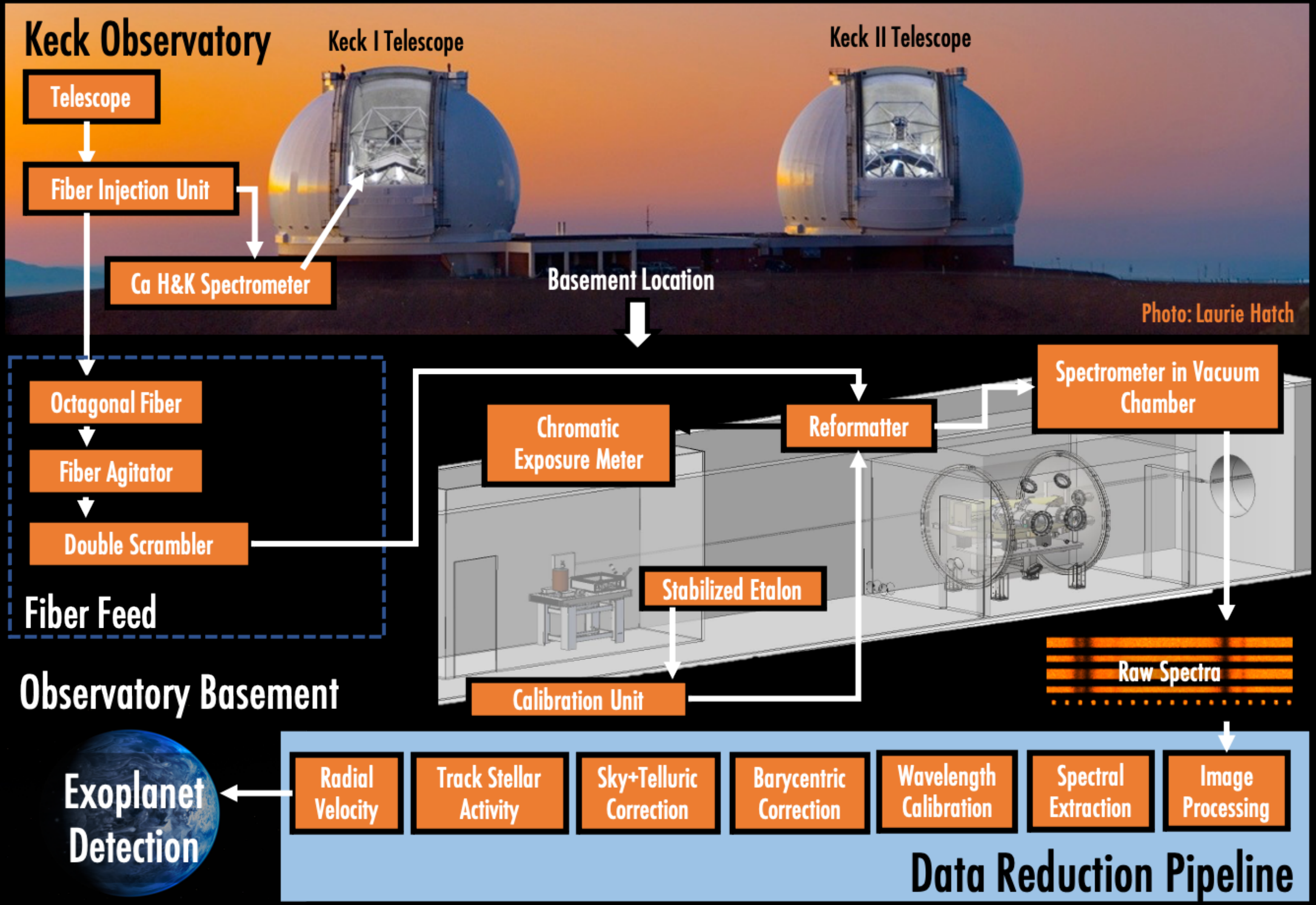
23 New Ground-Based RV Spectrographs



Arpita Roy
From Wright & Robertson 2017

Complex Systems Rather Than Monolithic Instruments

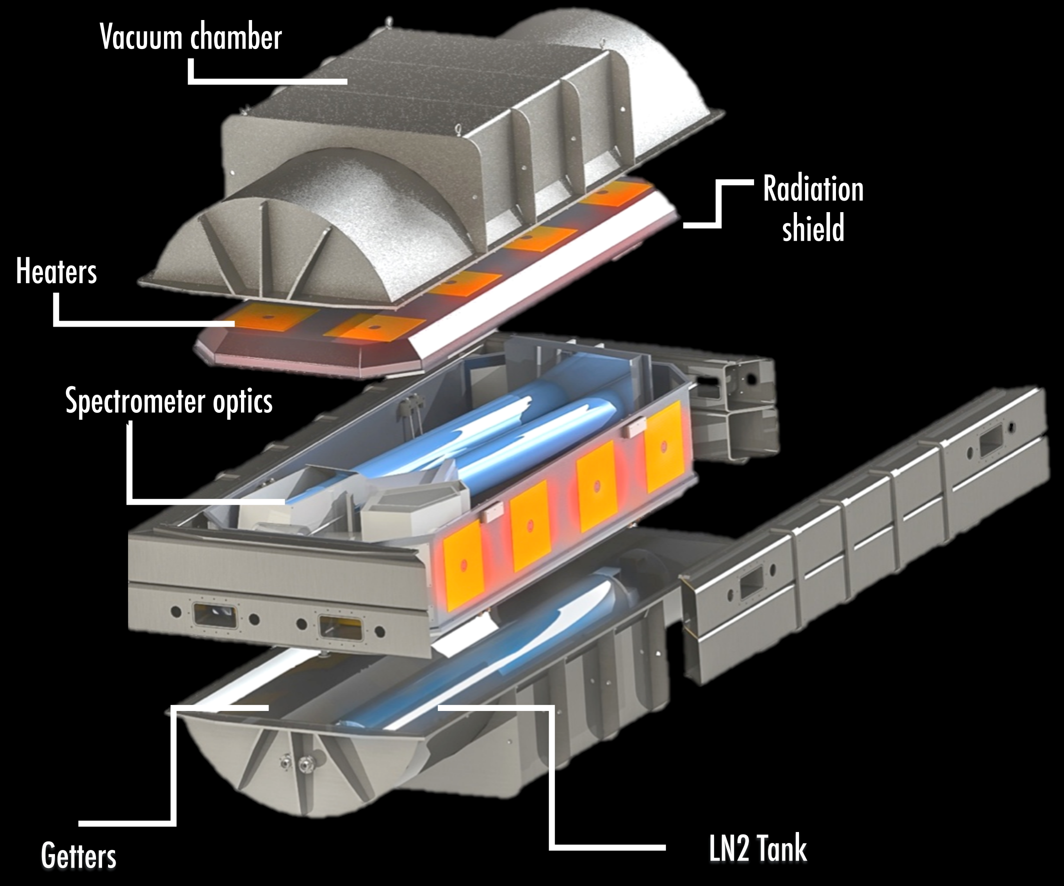
Composed of many subsystems spanning hardware and software, as well as the observatory facility

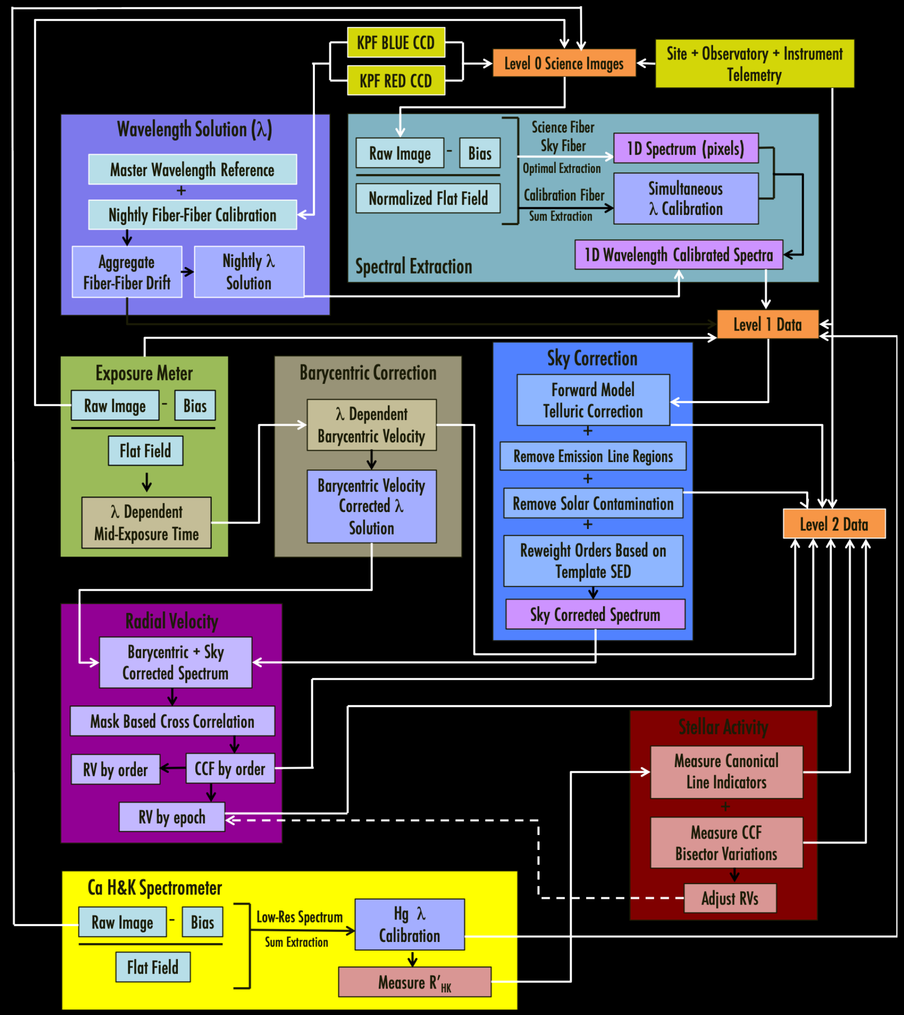


Keck Planet Finder

Philosophy Behind Extreme Precision Systems

Stabilize everything possible in hardware. **Correct** everything possible in software.





* And then don't touch system for 5-10 years (ideally)

Engineering Extreme Precision Systems

Bottom-up systems engineering approach is key to performance estimation

Total NEID instrumental error budget: 26.6 cm/s

25%

Instrument (uncalibratable): 14.7 cm/s (30.6%)

Fiber & illumination: 14.7 cm/s

Calibration source modal noise	2.5 cm/s
Continuum modal noise	2.5 cm/s
Near-field scrambling	3.5 cm/s
Far-field scrambling	5.0 cm/s
Stray light	5.0 cm/s

Detector effects: 7.1 cm/s

Readout thermal change	5.0 cm/s
Charge transfer inefficiency	5.0 cm/s

Barycentric correction: 1.7 cm/s

Algorithms	1.0 cm/s
Exposure midpoint time	1.0 cm/s
Coordinates and proper motion	1.0 cm/s

Reduction pipeline: 10 cm/s

Software algorithms	10 cm/s

Instrument (calibratable): 11.2 cm/s (1.1%)

Thermo-mechanical: 7.8 cm/s

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

Detector effects: 8.1 cm/s

Pixel inhomogeneities	1.0 cm/s
Electronics noise	1.0 cm/s
Stitching error	3.0 cm/s
CCD thermal expansion	2.0 cm/s
Readout thermal change	5.0 cm/s
Charge transfer inefficiency	5.0 cm/s

Calibration source (uncalibratable): 11.5 cm/s (18.7%)

Calibration accuracy: 5.7 cm/s

Stability	4.0 cm/s
Photon noise	4.0 cm/s

External errors (uncalibratable): 18.7 cm/s (49.6%)

Calibration process: 10 cm/s

Software algorithms	10 cm/s

Telescope: 12.2 cm/s

Guiding	scrambling
ADC	6.9 cm/s
Focus	5.0 cm/s
Windshake	8.0 cm/s

Atmospheric effects: 14.1 cm/s

Micro-telluric contamination	10 cm/s
Sky fiber subtraction	10 cm/s

Beyond the era of single dominant sources of error. Need to understand, measure, and manage every possible source of error

Image: Sam Halverson

Delivering Extreme Precision Systems

The Habitable Zone Planet Finder arriving at the 10m Hobby Eberly Telescope in Texas.

It's nerve wracking, but FedEx will even deliver multimillion dollar instruments!

Image: Gudmundur Stefansson

Measuring EPRVs from Spectra

Raw Data from Echelle Spectrograph

Complex Focal Plane Image, Composed of Multiple Fibers and Numerous Echelle Orders

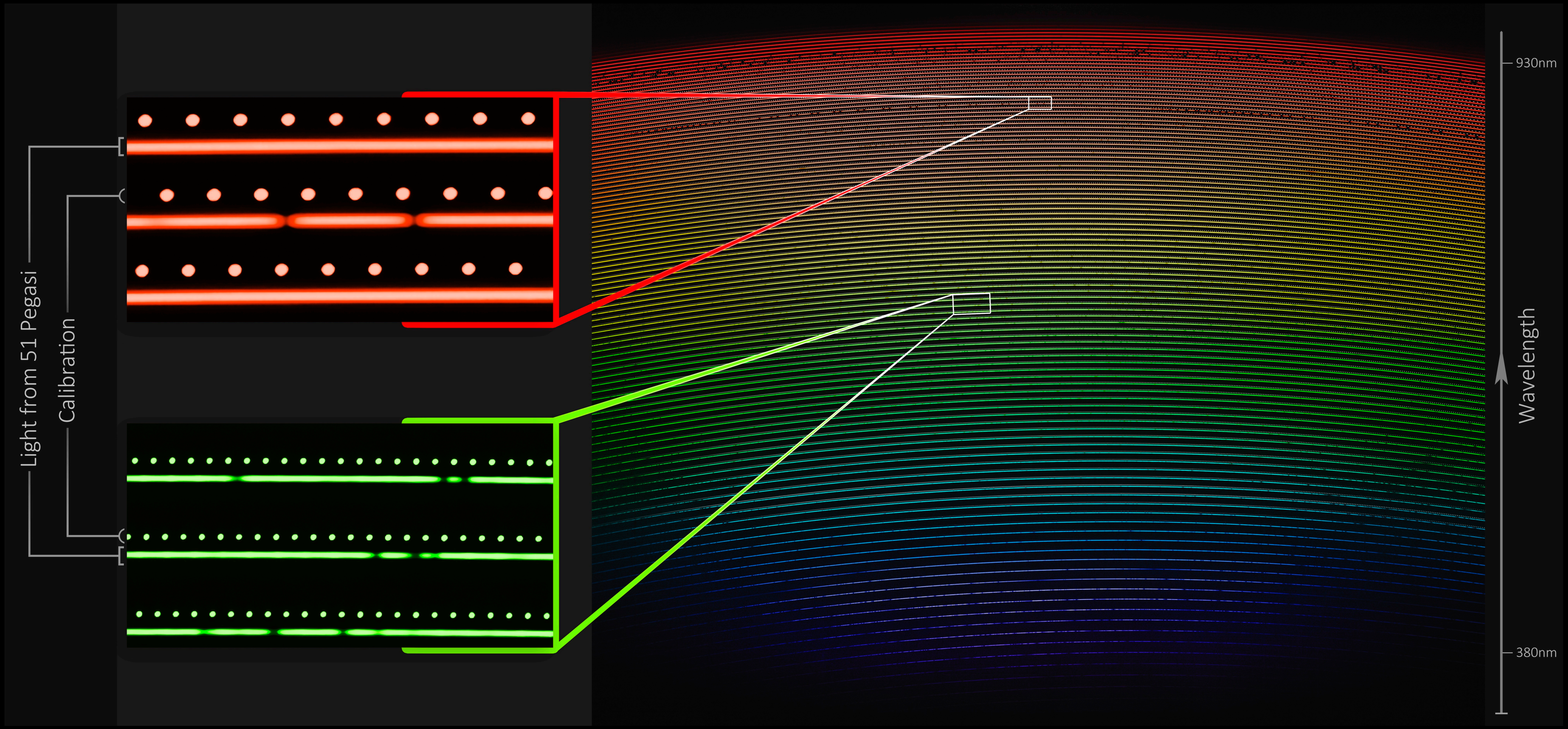
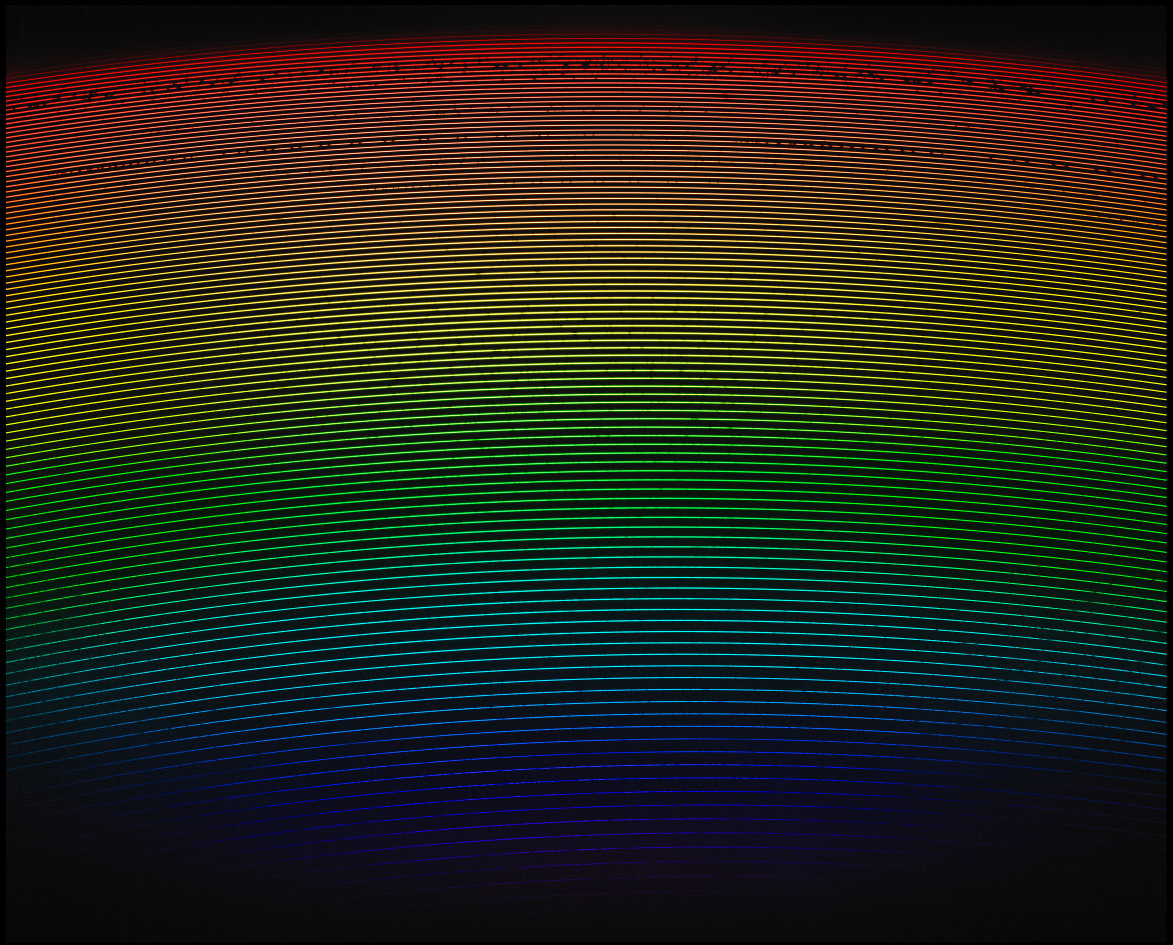


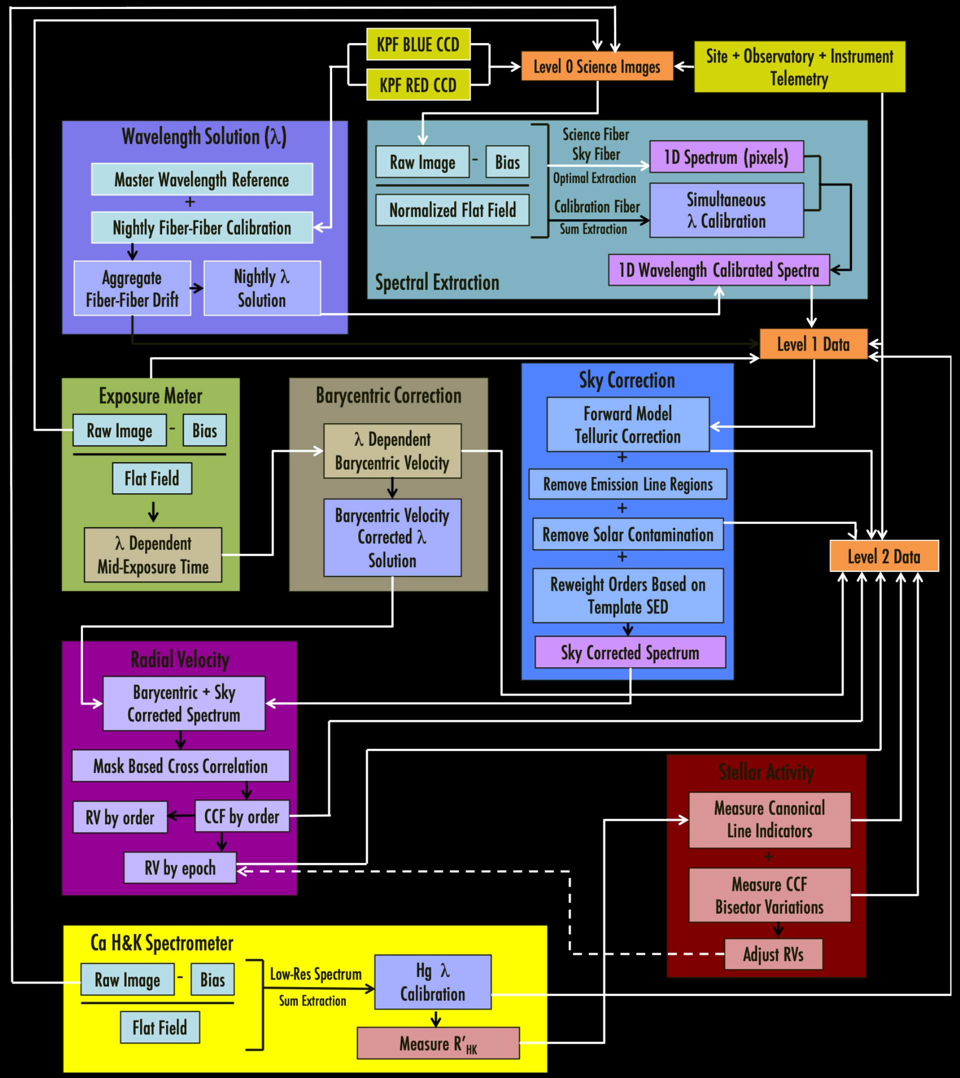
Image: NEID First Light Press Release

Hint: Read it like a book

Processing Raw Data from Echelle Spectrograph

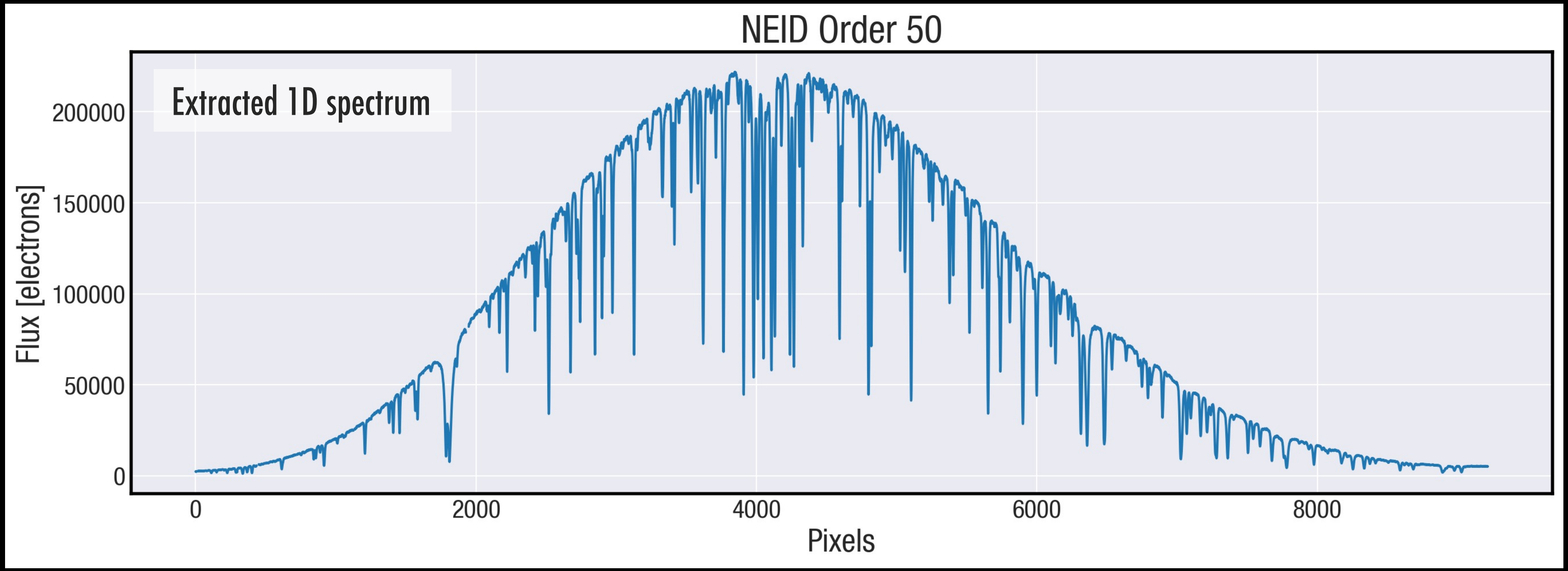
Extreme Precision Pipelines Needed to Preserve Quality of Data Delivered by Hardware





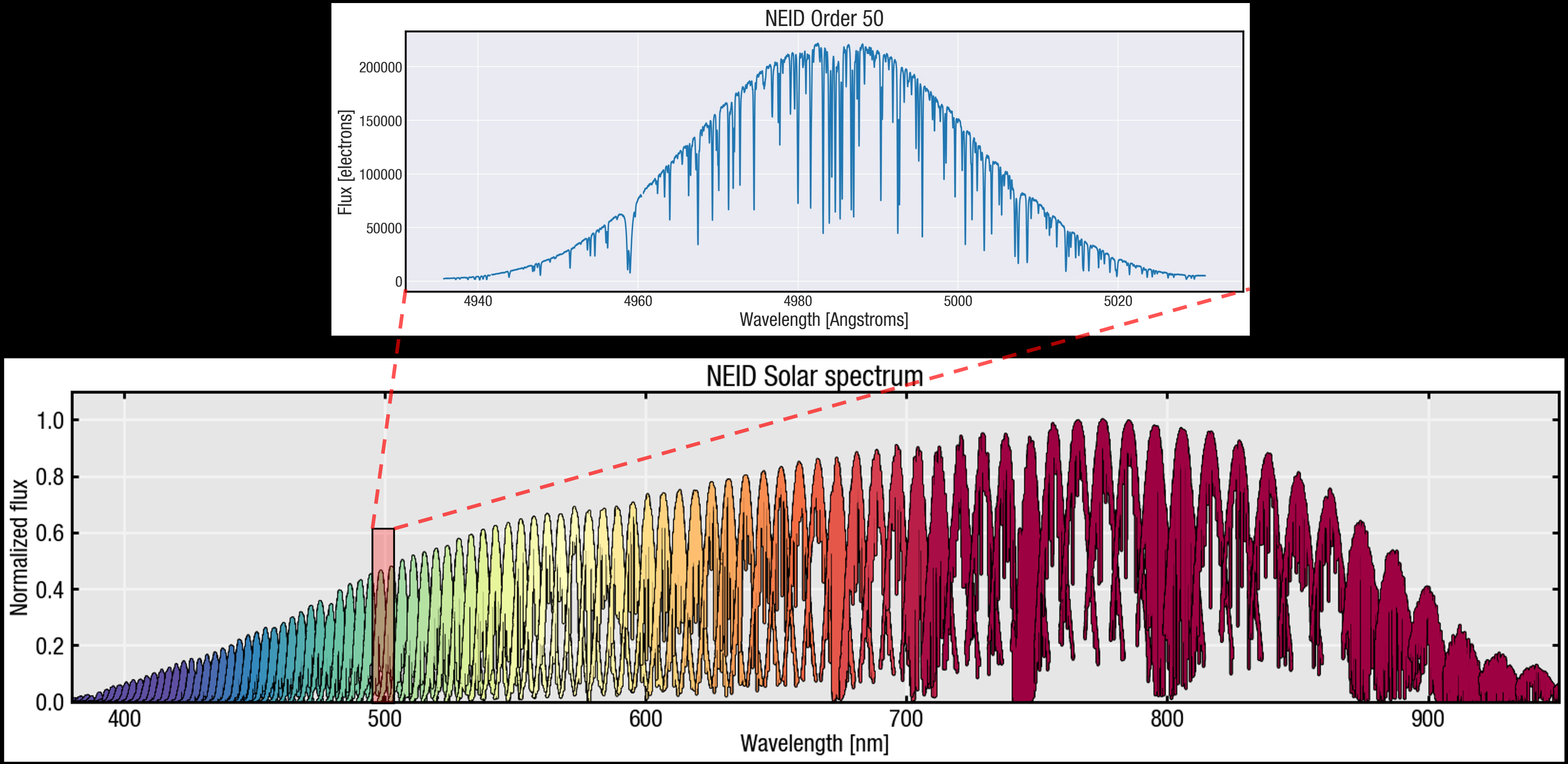
Extract Spectra from Raw 2D Data

Extensive image corrections and sophisticated extraction techniques



Calibrated Spectra from Echelle Spectrograph

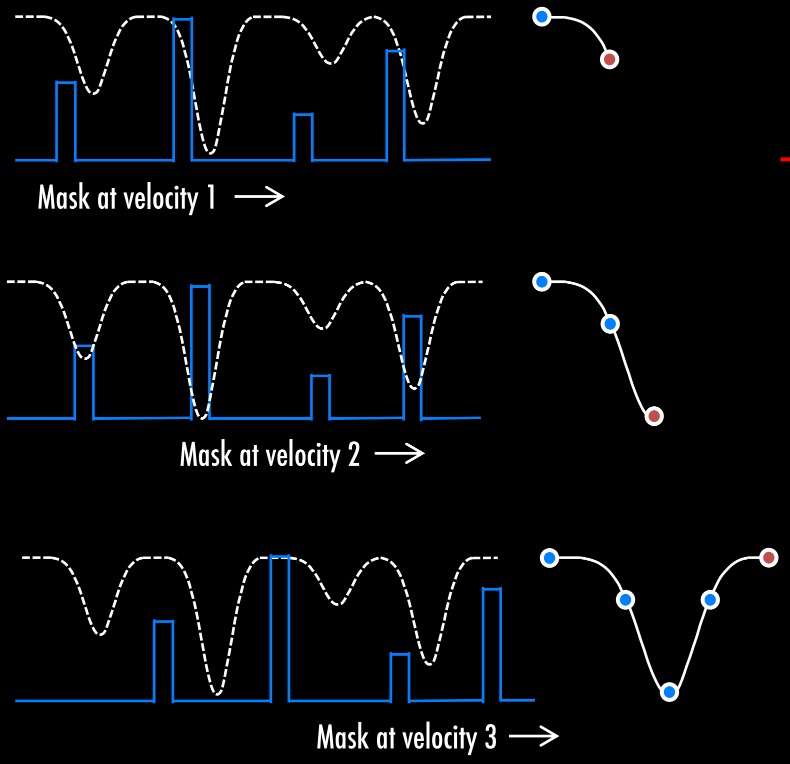
Use wavelength calibrator (eg. laser frequency comb) to assign colors to pixels



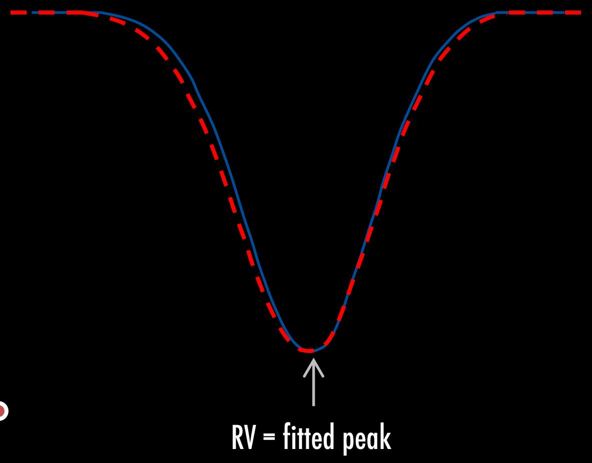
Cross Correlation With a Stellar Mask

True bulk motion causes all stellar lines to move in an identical way [without changing shape]

Cross-correlation with Weighted Mask



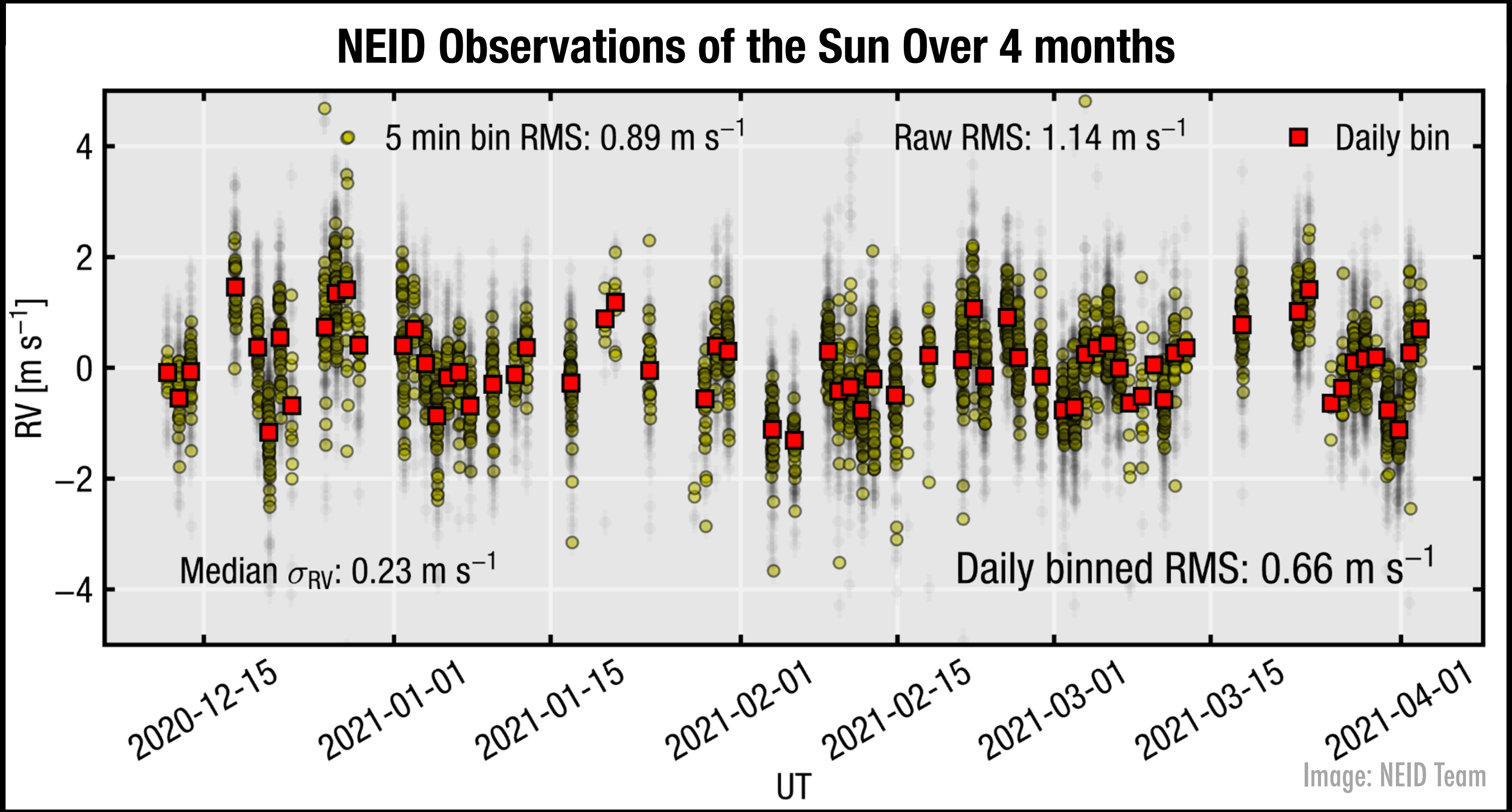
Measuring Radial Velocity Via Gaussian Fitting



- Pick best areas, rich in RV information and clean from tellurics
- Works well for FGK stars with well defined lines and continuum
- Mask can evolve over time as the data stream lengthens
- Very hard for M dwarfs due to lack of clean lines and poor synthetic models

Verifying Precision On Sky

NEID observes the Sun every day, in addition to a set of "standard stars" at night



- We first verify precision internally using multiple calibration sources
- The Sun provides daily high signal-to-noise, high cadence data, stars provide full system checks
- Allows us to track both short term (minutes) to long term (years) precision
- For a perfectly quiet star, the scatter in this data would show the instrument noise floor

Verifying Precision On Sky

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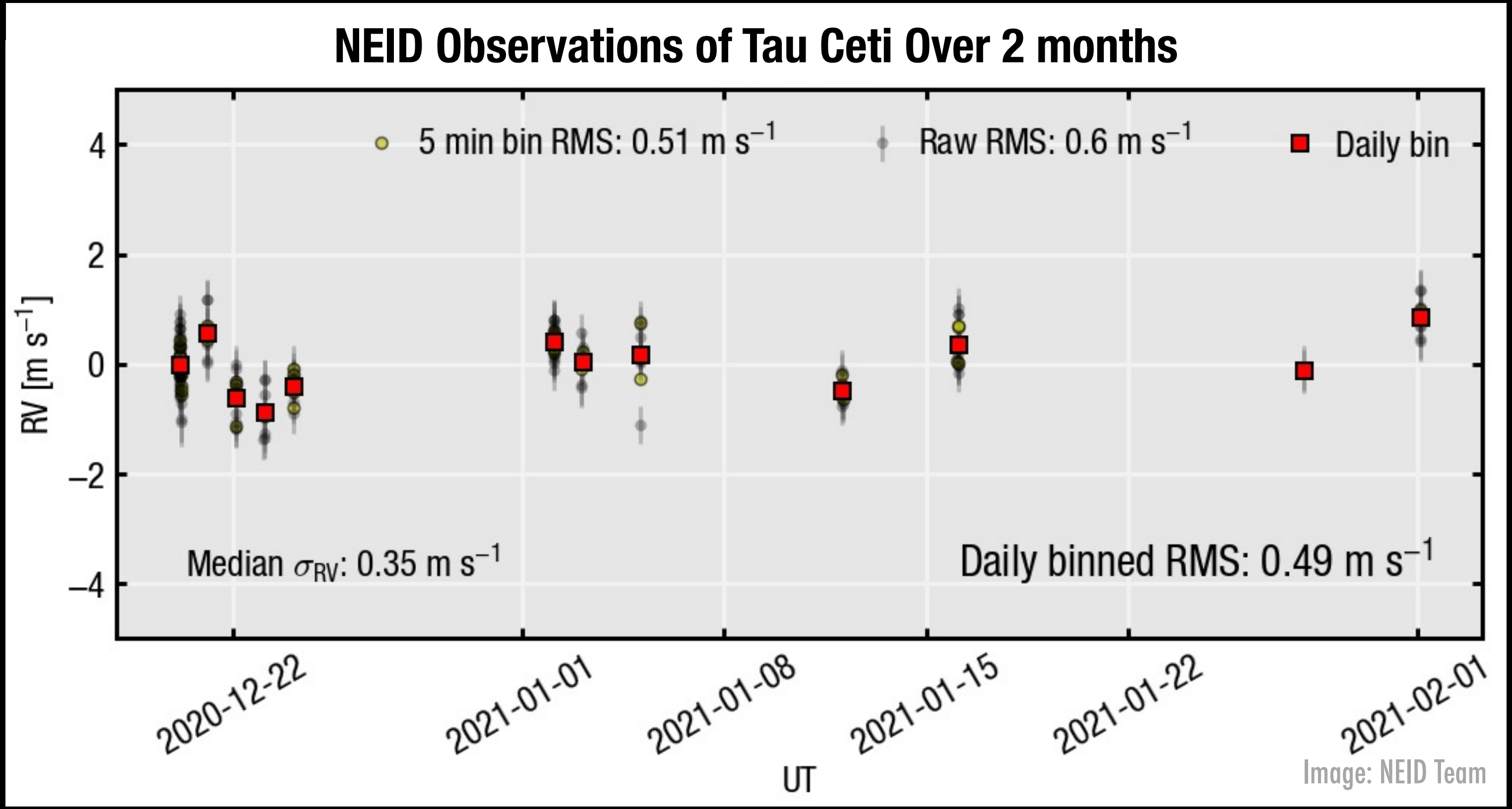

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Delivering Extreme Precision Systems

The WIYN telescope observing stars and feeding light into the NEID spectrograph

Good News: These instruments are achieving their predicted precisions on sky!

Image: NOIRLab

Delivering Extreme Precision Systems

The WIYN telescope observing stars and feeding light into the NEID spectrograph

Good News: These instruments are achieving their predicted precisions on sky!

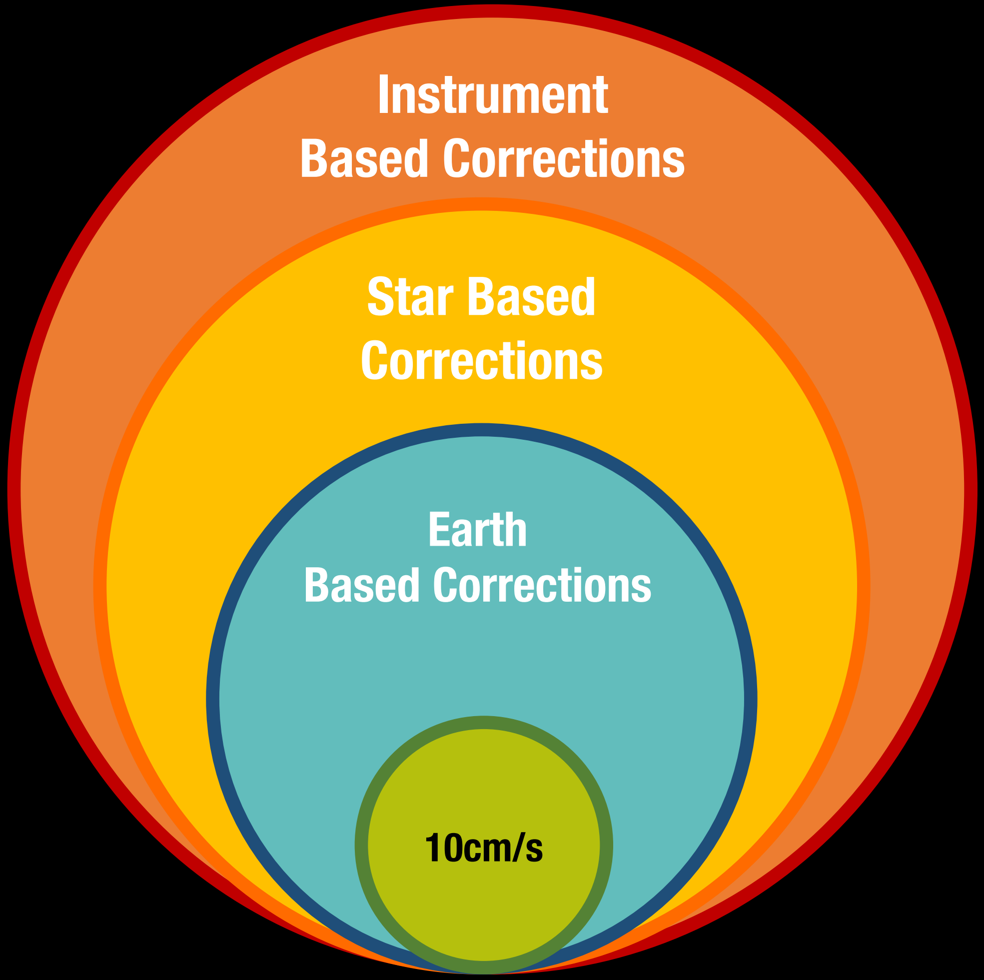
Bad News: Now we are limited by noise from the star that is not well-understood at this level.

Image: NOIRLab

Real Stars, Real Problems

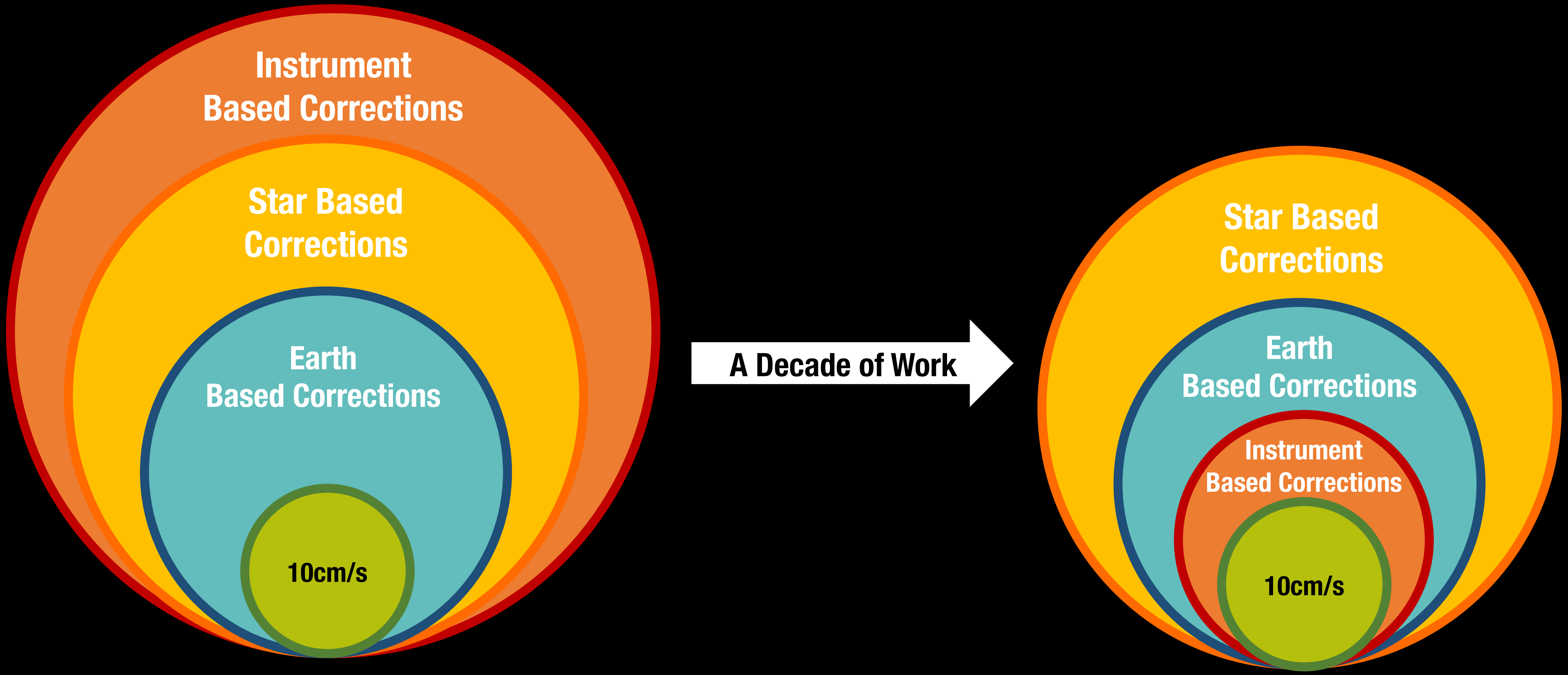
*aka Stellar Activity

Limitations to Radial Velocity Precision



In the decades since the first discovery of a planet with RV, we used to be instrument limited.

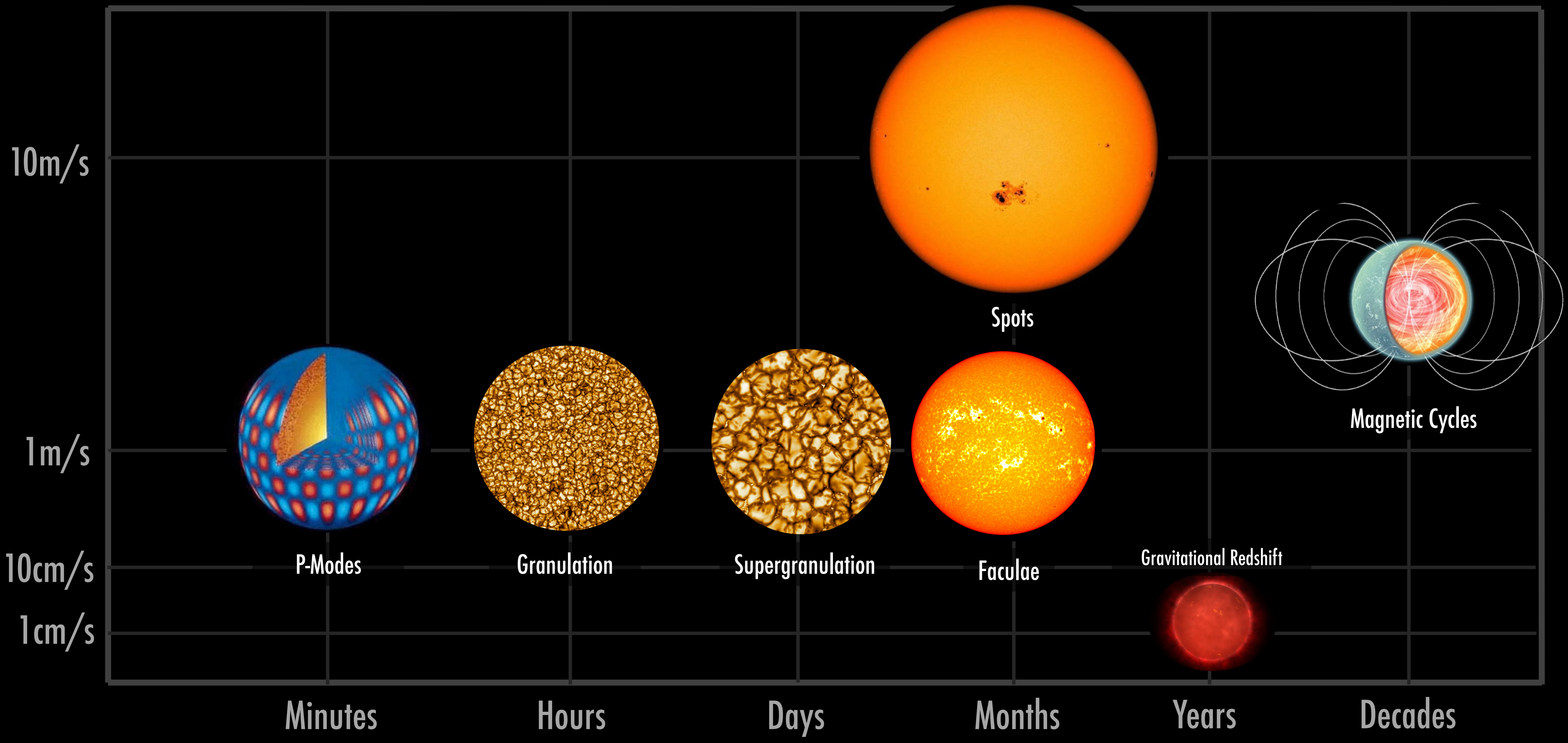
Limitations to Radial Velocity Precision



With a new generation of instruments coming online, we are now limited by stellar activity.

Stellar Activity Signals in Radial Velocity Measurements

*Sun-like Stars



Stellar Activity Signals in Radial Velocity Measurements

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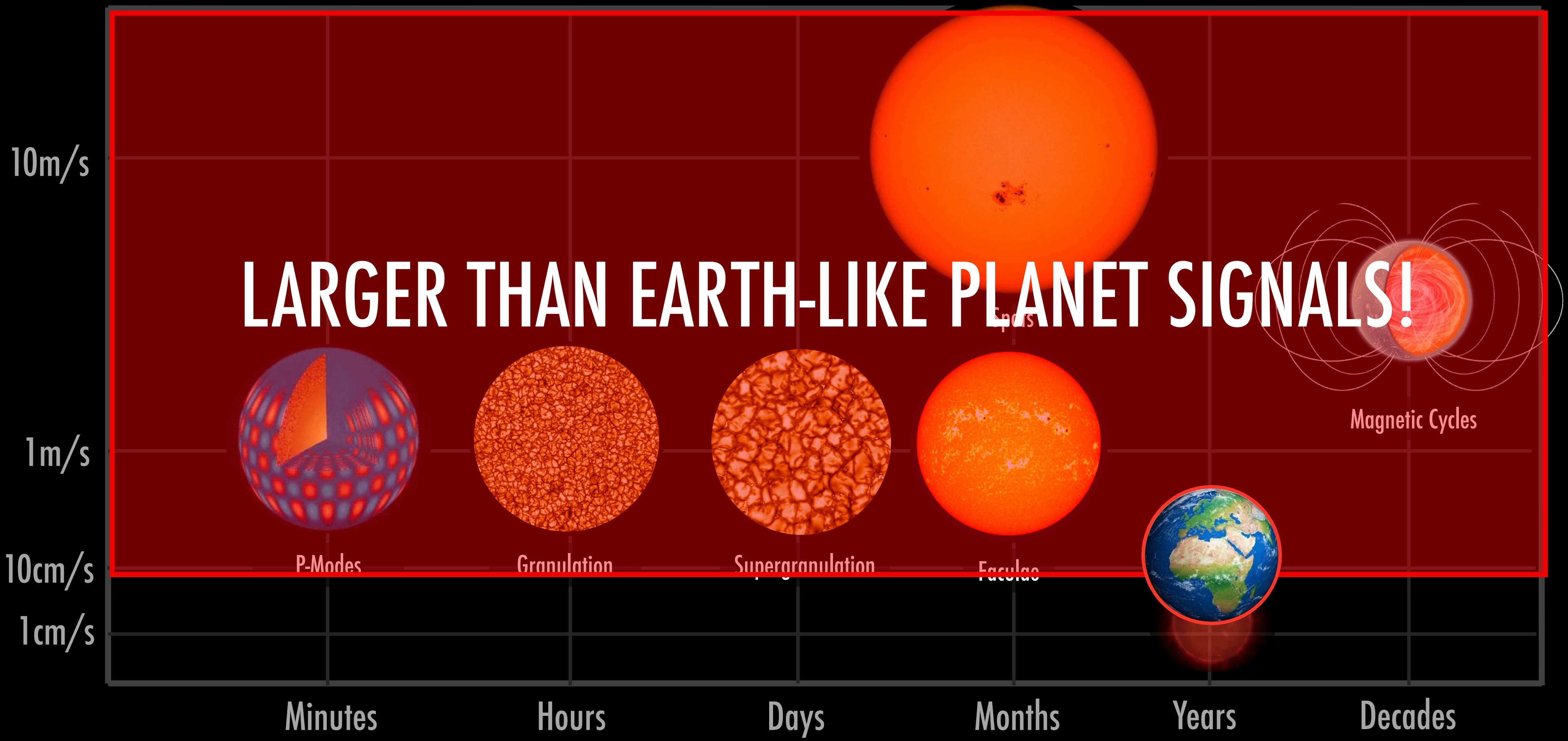
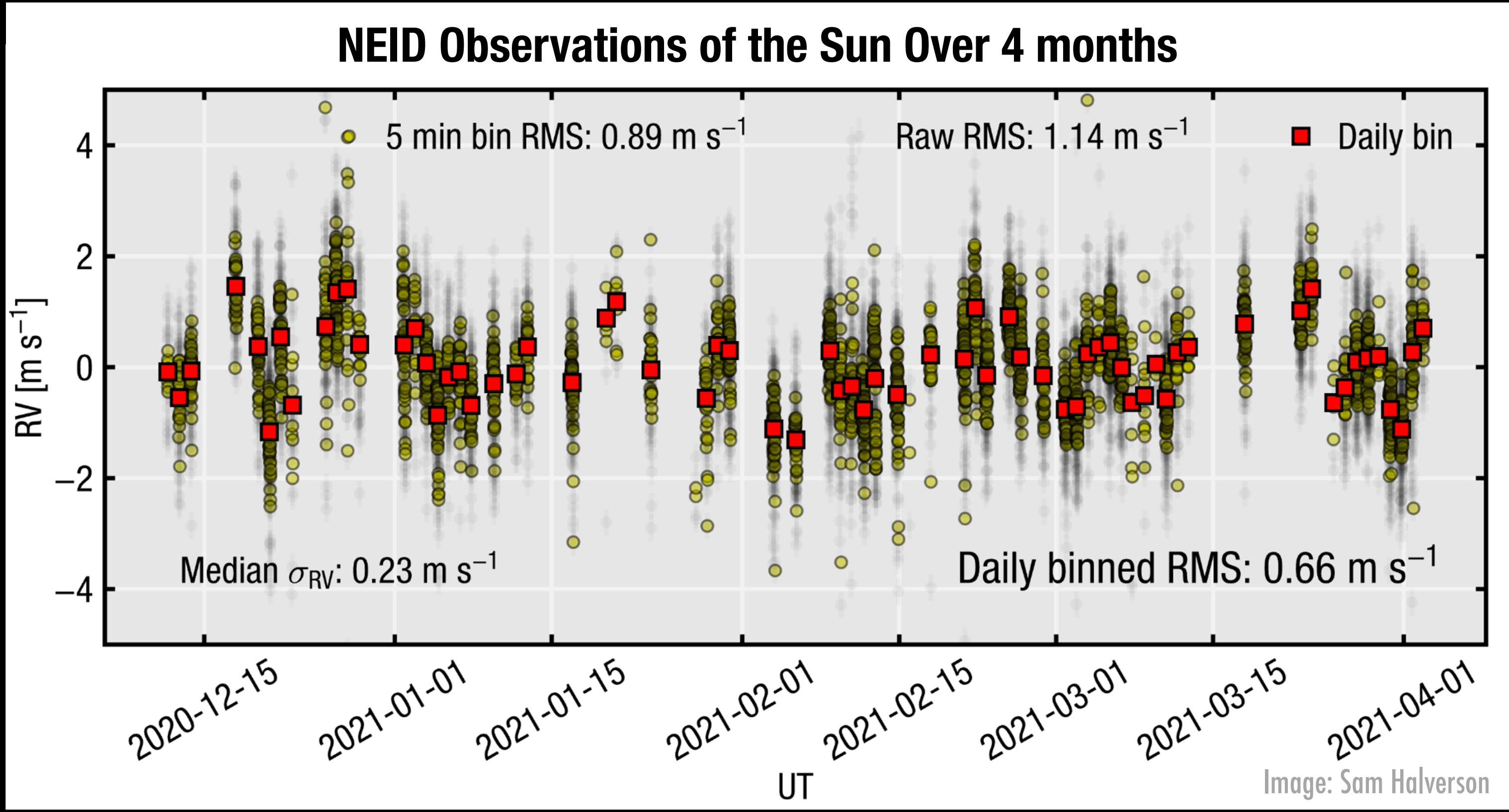
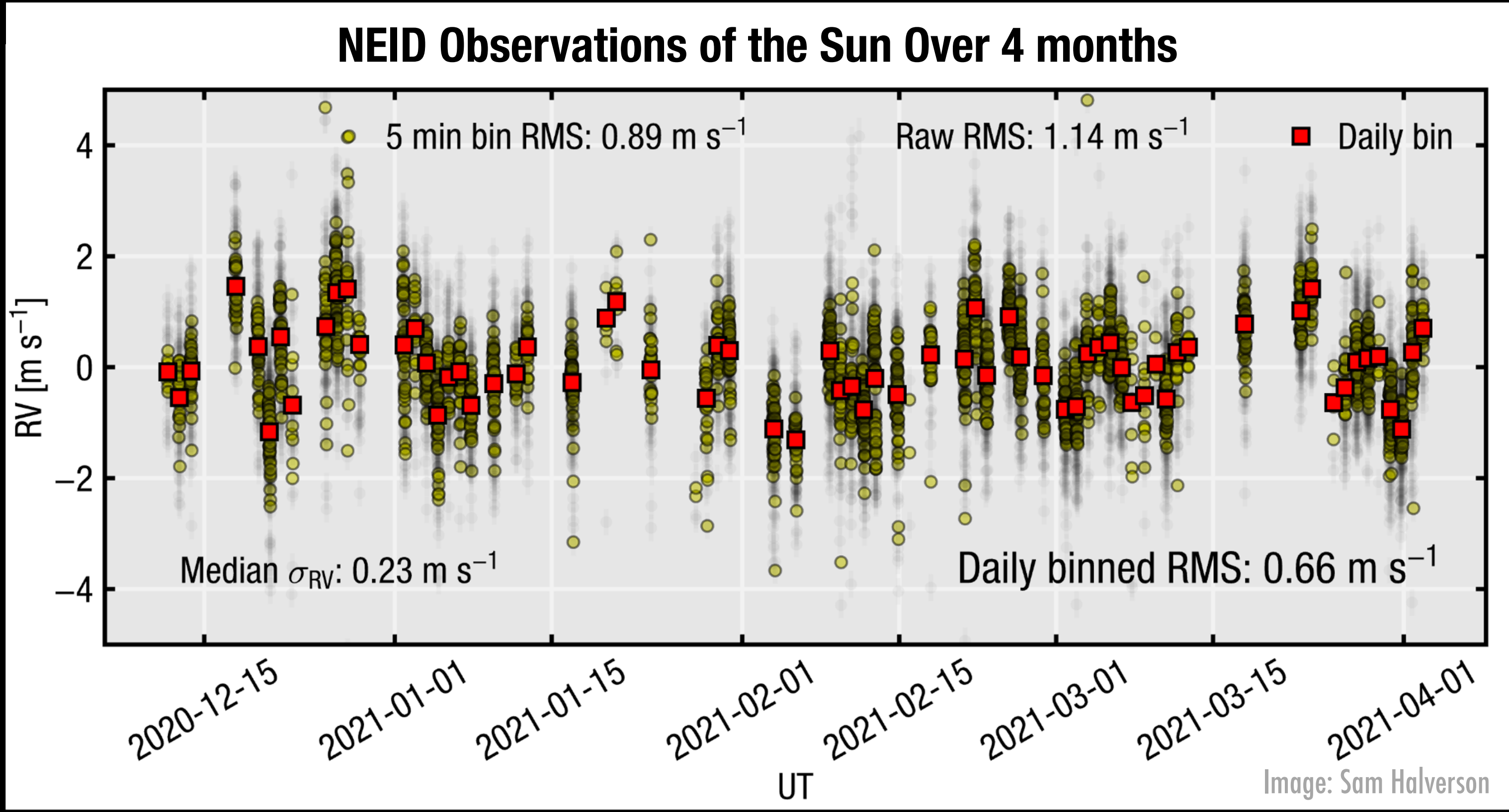


Practices to Combat Stellar Activity Limitations



- Typically RV surveys target "quiet" stars that have lower levels of activity
- Observe for long enough to average over p-mode oscillations
- Avoid periods contaminated by stellar activity when looking for planets

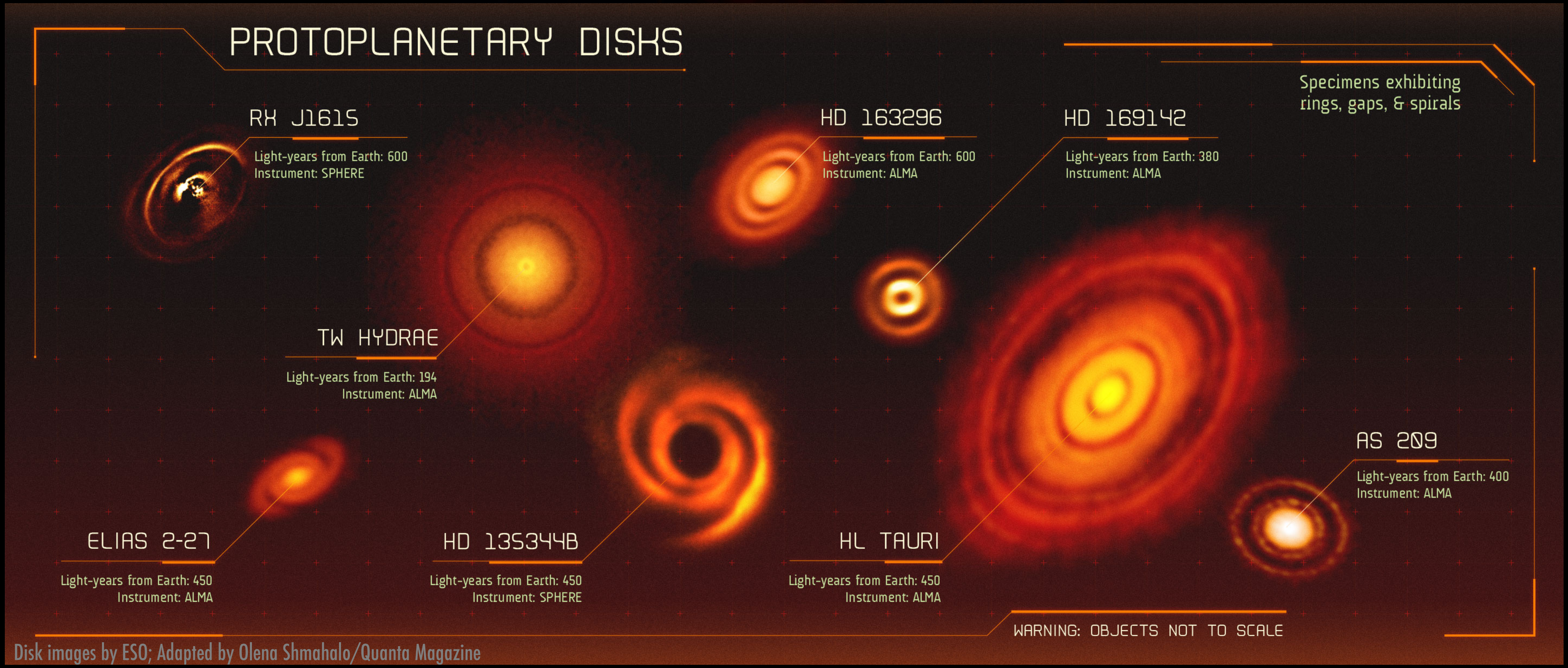
Practices to Combat Stellar Activity Limitations



- Typically RV surveys target "quiet" stars that have lower levels of activity → activity is variable, cause biased target selection
- Observe for long enough to average over p-mode oscillations → difficult to balance p-mode times with photon collection time
- Avoid periods contaminated by stellar activity when looking for planets → interesting parameter space made inaccessible

Young Stars, More Problems

Planetary Nurseries Around Young Stars



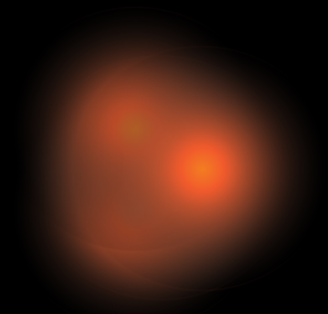
Planets are formed in the circumstellar disks around young stars.

These disks of gas and dust are slowly etched by new planets as they gather up more material.

These young systems are undergoing tumultuous violent changes, and we are still learning about these complex environments.

Gaps In Planet Formation Theory

The Existence of Hot Jupiters Is A Puzzle



The first exoplanets discovered were Hot Jupiters.

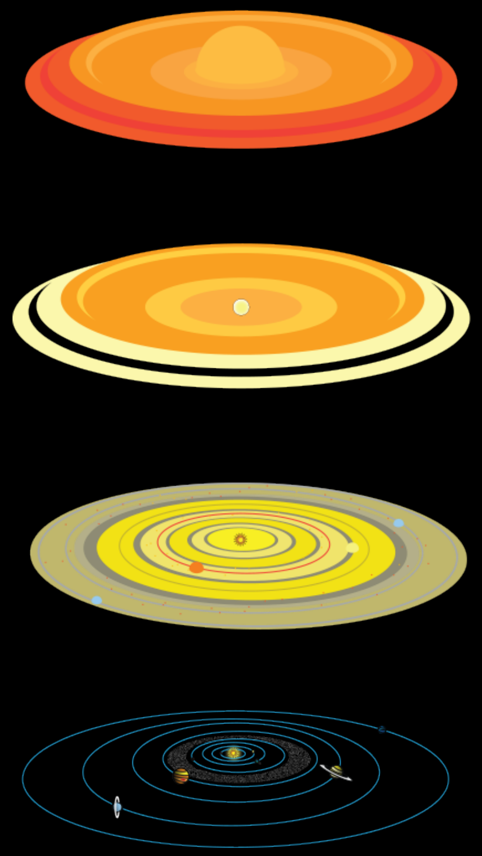
- They still represent a large fraction of all exoplanets discovered (10-15%)

These are not as common as smaller planets.

- They have an estimated occurrence rate of about 1% [Wright et. al. 2012]
- But continue to be discovered in growing numbers due to observing biases

But Hot Jupiters pose a real challenge to planet formation theory.

- Classical theories cannot explain the presence of such large planets so close to the parent star



Gaps In Planet Formation Theory

Several Ideas Have Been Put Forward To Explain This Population

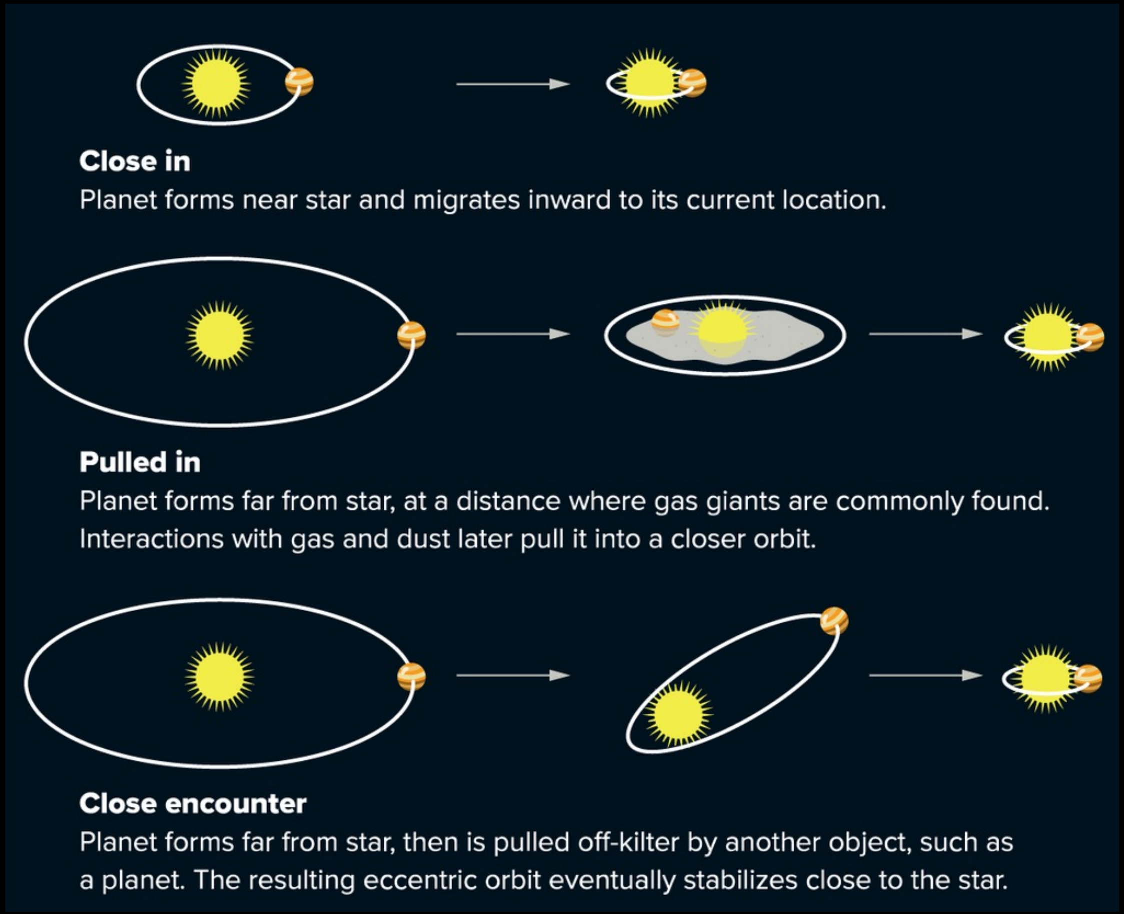


Image: Dawson & Johnson 2018

In situ formation

- Forms in the vicinity of the host star and remains in close orbit
- Not compatible with Solar nebula theory since not enough material
- Cannot explain misalignments, high eccentricities, and lack of companions suggesting more violent, dynamic migration pathway

Disk Migration

- Planet migrates inwards as the result of angular momentum exchange between the gas giant and the disc

Dynamical Interaction

- Planet is sent to a highly eccentric orbit following a strong perturbation (planet-planet scattering), or secular interactions
- Being close enough to the star at periastron, tidal forces exerted by the star act to circularize the planet's orbit.

None of the theories can individually explain the ensemble of properties observed for the mature giant planet population.

Gaps In Planet Formation Theory

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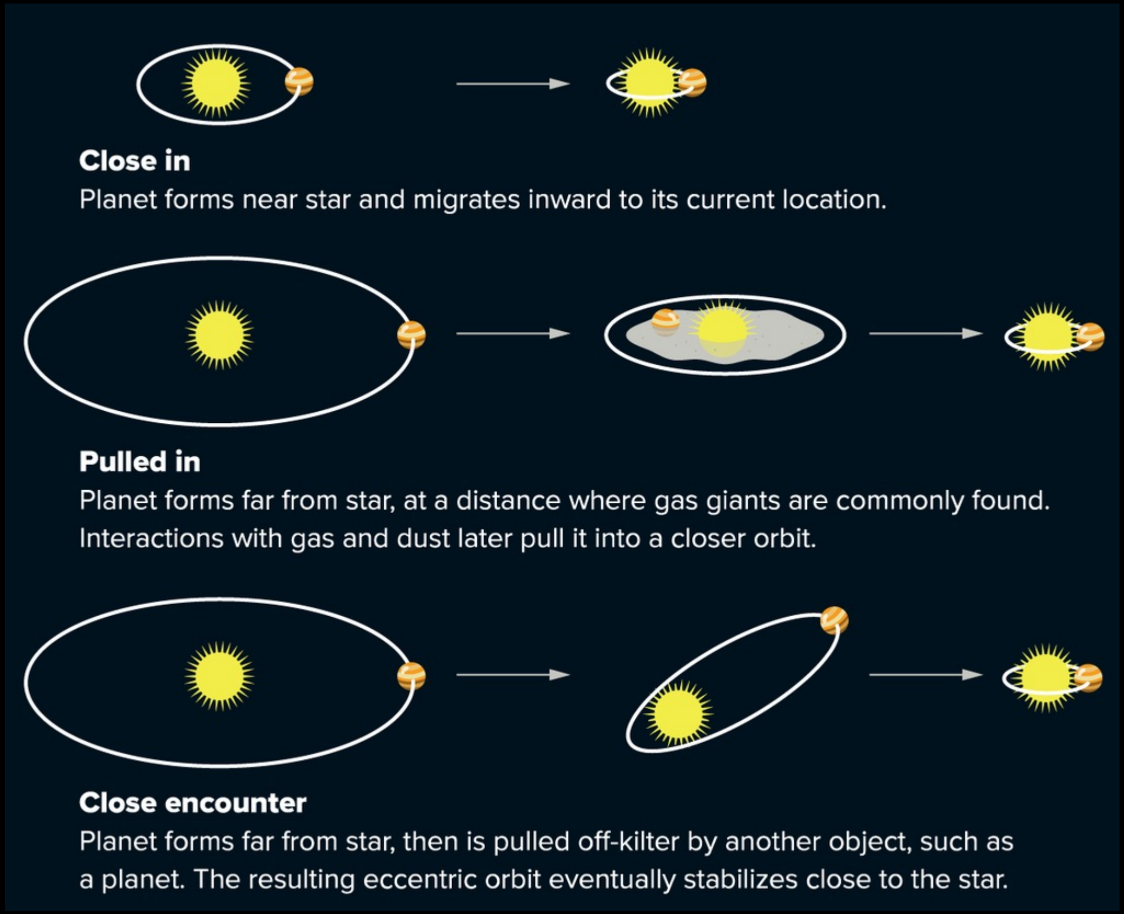

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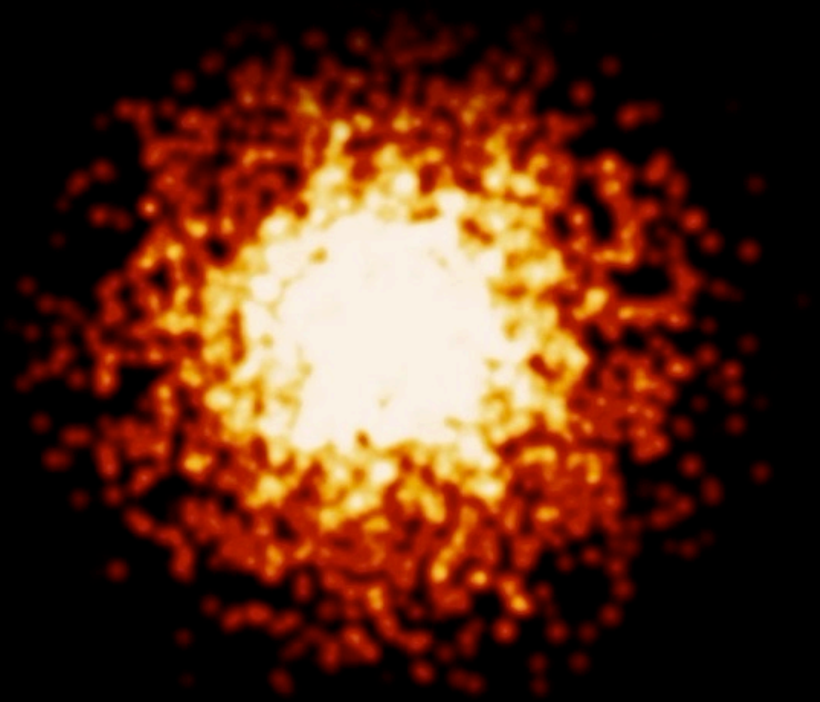
Observing young systems is key to resolving this puzzle.

Might catch planet migration in action.

Young Planets Are Great Targets For Direct Detection

Young planets are molten, fiery worlds – this means they are bright in the infrared with light of their own



PLANETQUEST
THE SEARCH FOR ANOTHER EARTH

Large forming planets, well-separated from their stars, are ideal candidates for current direct detection instruments

About 50 planets discovered
Source: NASA Exoplanet Exploration

Young Stars Are Not Easy Targets For Radial Velocity

Early-type Stars Are Historically Excluded from RV Surveys

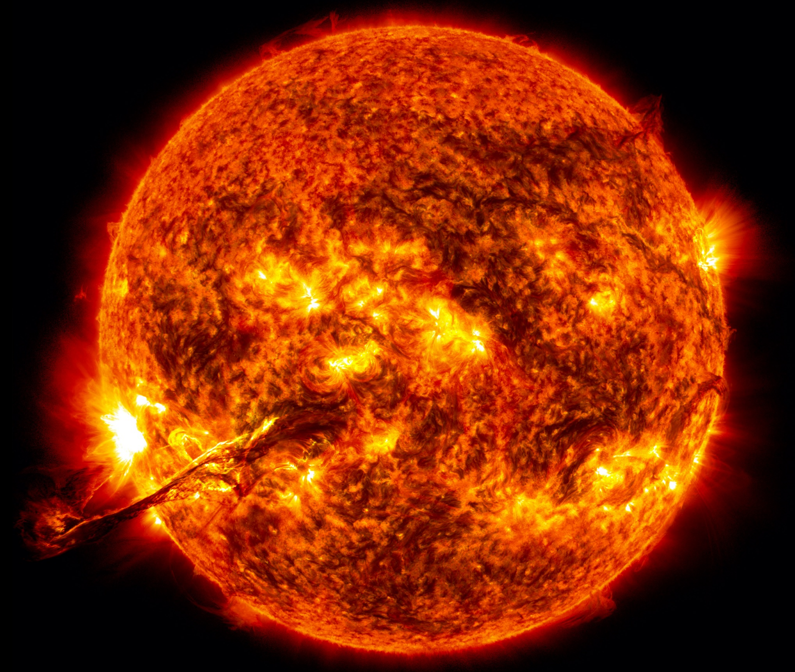
Young stars are generally fast rotators

- Radial velocity information content is tied to the slopes of spectral lines
- High vsin(i) decreases the precision achievable with high-resolution spectra
- Typical expectations of Gaussian lines can break down

Young stars are more active

- High stellar induced jitter, can reach up to a few km/s
- Primarily caused by surface brightness features (spots, faculae, plage), linked to complex internal processes and a strong magnetic field.
- Can completely mask exoplanet signatures, preventing their discovery

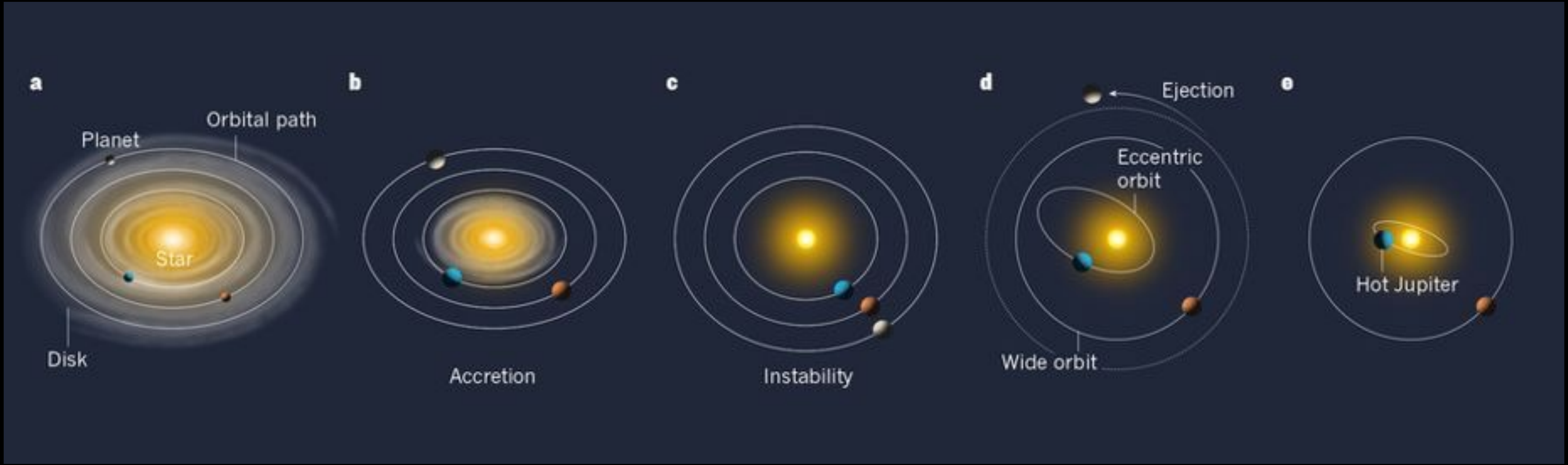
Several false positive detections have been reported around young stars in the past.



Coronal Mass Ejection on the Sun
Source: NASA Goddard Media Studios

Why Should We Still Target Young Systems with Radial Velocity?

Distinguishing Between Planet Formation Theories



Different migration pathways operate on different characteristic timescales

- These can be observationally distinguished by measuring the frequency of gas giants over time
- Disk migration happens early, while the gas disk persists (10 Myr)
- Dynamical mechanisms typically occur later (10-10^4 Myr)

In combination with direct imaging, this would reveal giant planet occurrence rates across age and separation

Leveraging Exquisite Spectroscopy

Delivering Extreme Precision Systems

The WIYN telescope observing stars and feeding light into the NEID spectrograph

Good News: These instruments are achieving their predicted precisions on sky!

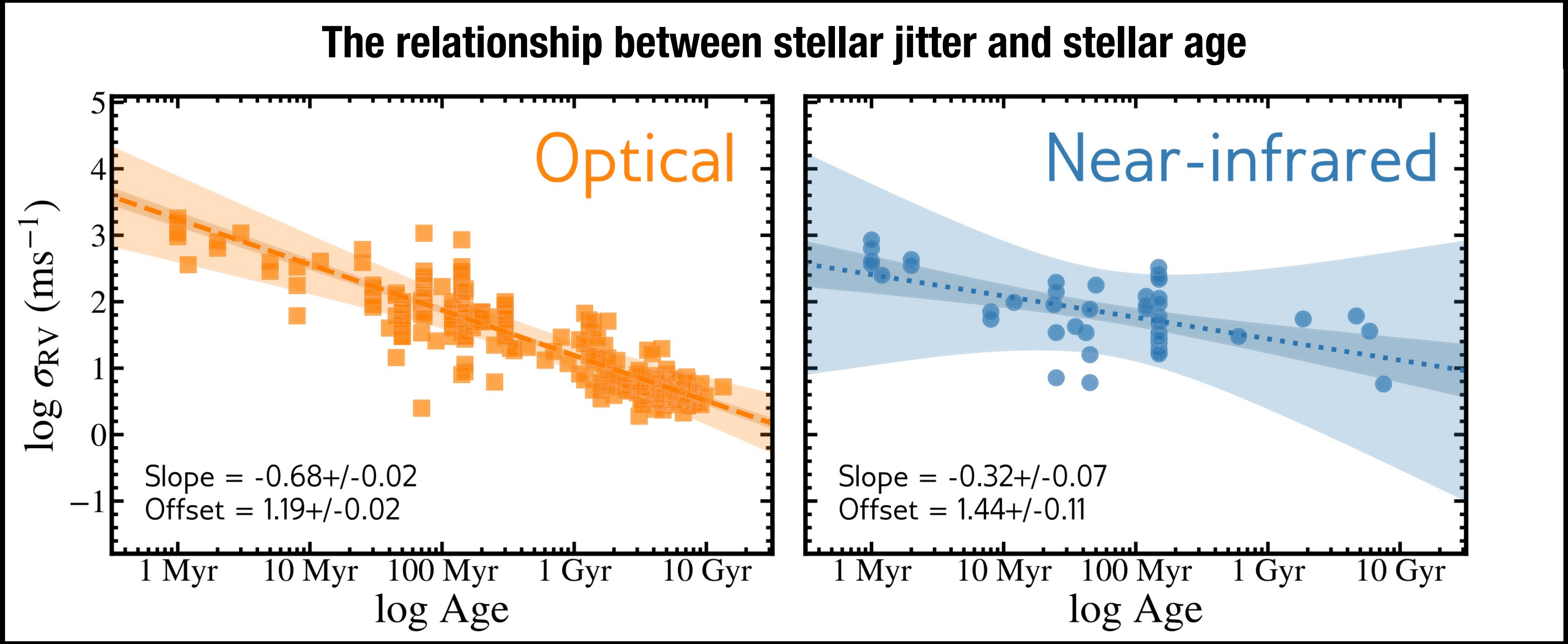
~~Bad News: Now we are limited by noise from the star that is not well-understood at this level.~~

Good News: We now have high-fidelity spectra that allows characterization of stellar activity as signals rather than noise.

Image: NOIRLab

Going to the Near Infrared

Stellar jitter is systematically reduced by a factor of two at young and intermediate ages



RV variability due to starspot coverage is expected to diminish over a star's lifetime as the star spins down and its magnetic field weakens

Jitter decays in a qualitatively similar manner in the NIR as has been seen in the optical

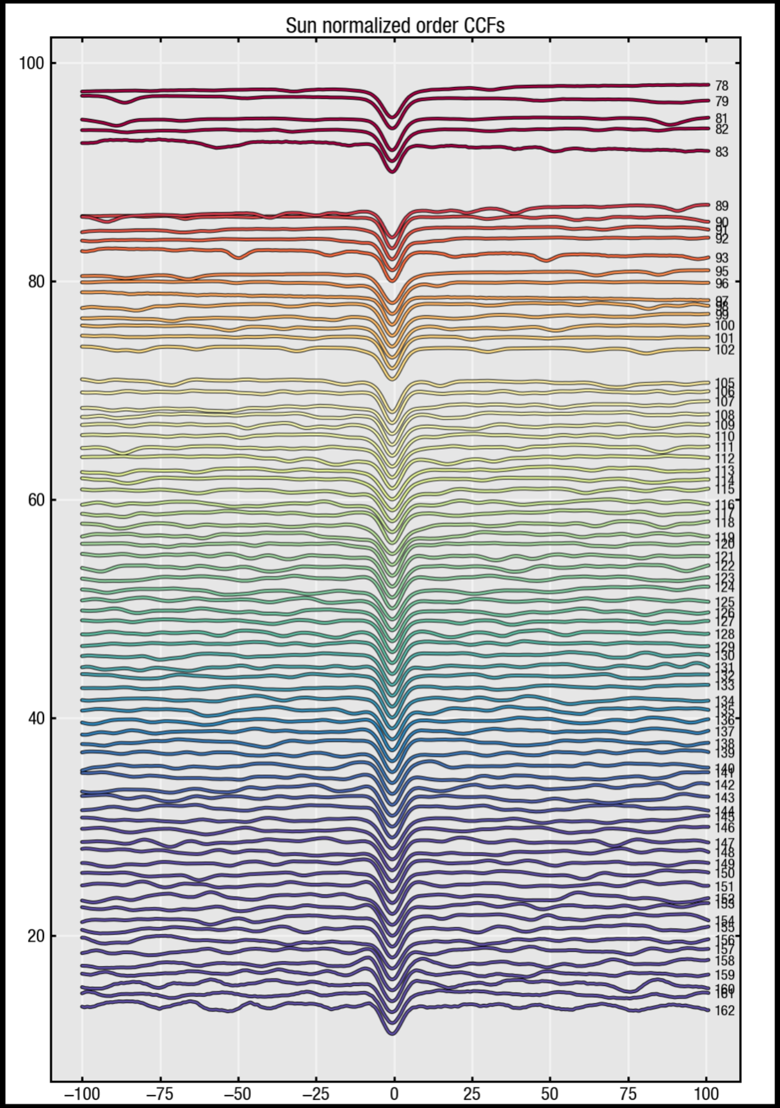
Lower jitter in the NIR reflects the reduced starspot-to-photosphere contrast at longer wavelengths

*Large scatter in the NIR relation likely driven by the comparably small number of measurements

Source: Tran et al. 2021

Examine Chromatic Radial Velocities

NEID's broad spectral grasp allows us to look at detailed wavelength-dependent behaviors



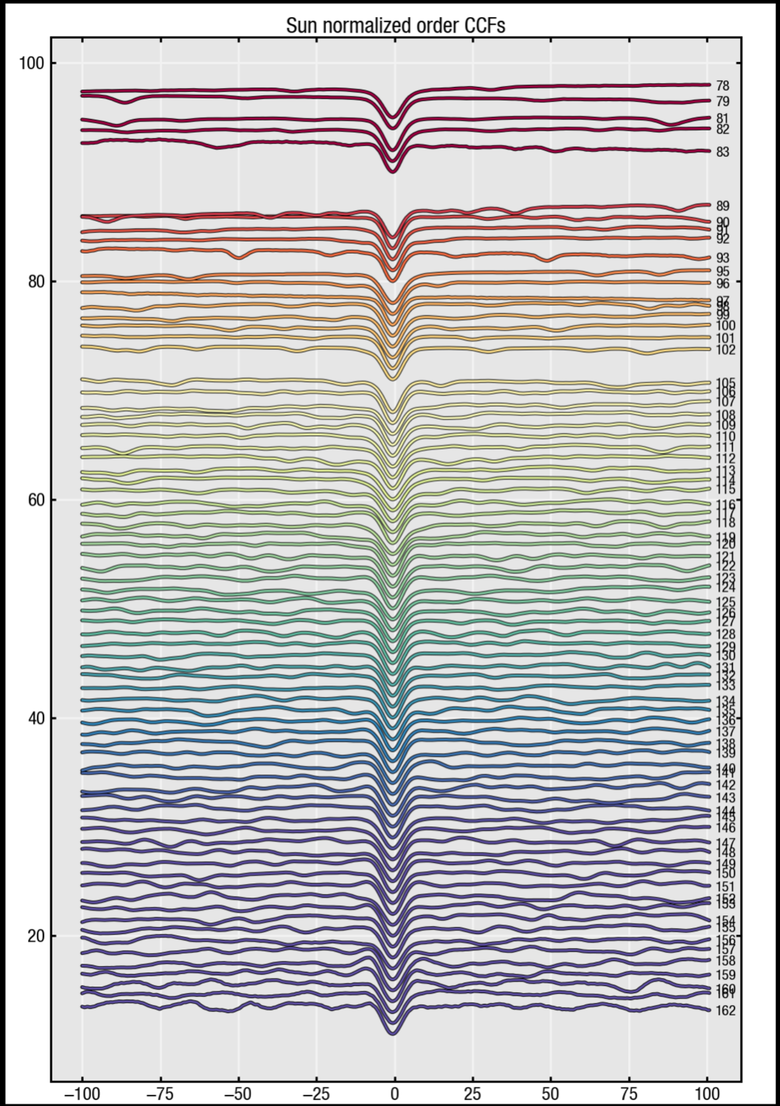
Activity manifests differently across wavelength, while bulk motion is achromatic

Instruments like NEID (380-930nm) offer chromatic leverage against stellar activity

Image: Sam Halverson

Examine Chromatic Radial Velocities

NEID's broad spectral grasp allows us to look at detailed wavelength-dependent behaviors



Activity manifests differently across wavelength, while bulk motion is achromatic

In fact, the majority of <u>individual</u> NEID orders are comparable in precision (1m/s) to the <u>cumulative</u> precision on last generation instruments.

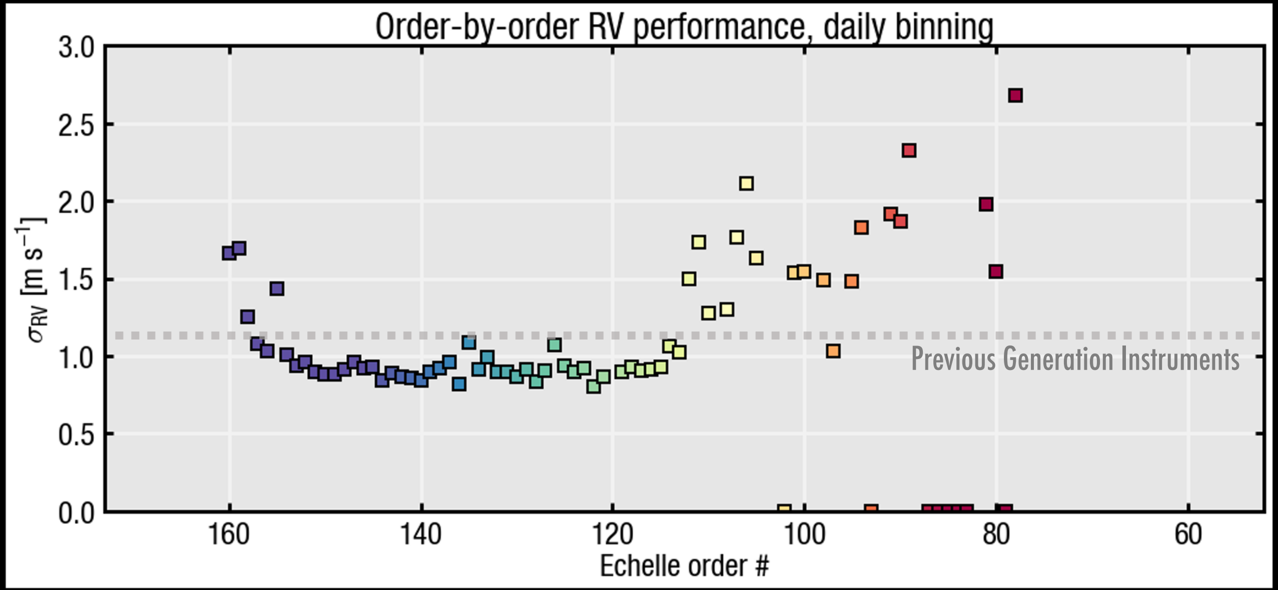
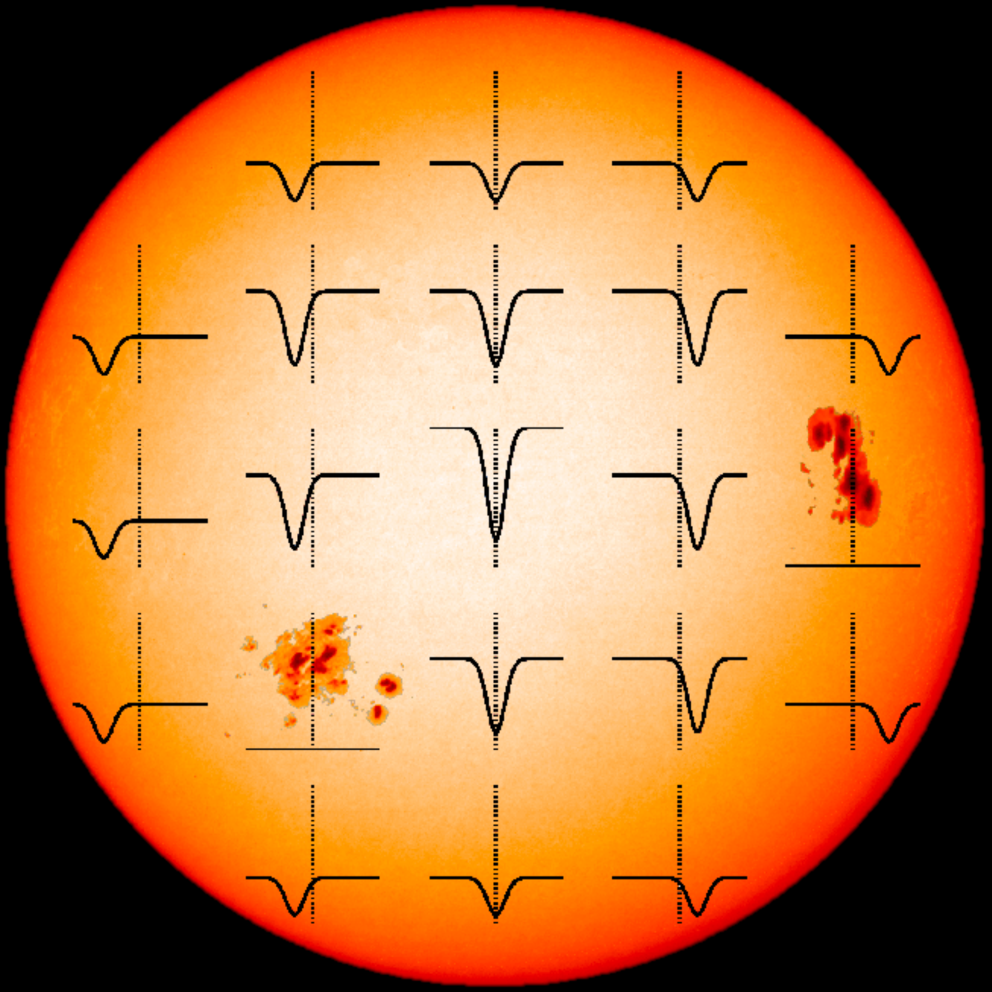


Image: Sam Halverson

A New Paradigm in Activity Indicators

Stabilized instruments allow interpretation of line shape variation as a direct manifestation of stellar physics



Can connect line shape metrics to the stellar atmosphere

Example:

What lines correlate with Ca H&K variability?

Are these from a certain species?

How is it related to depth in the atmosphere?

Rethink activity indicators

Numerous lines that respond to different flavors of stellar activity in different ways

Could imagine making custom line lists for different types of activity

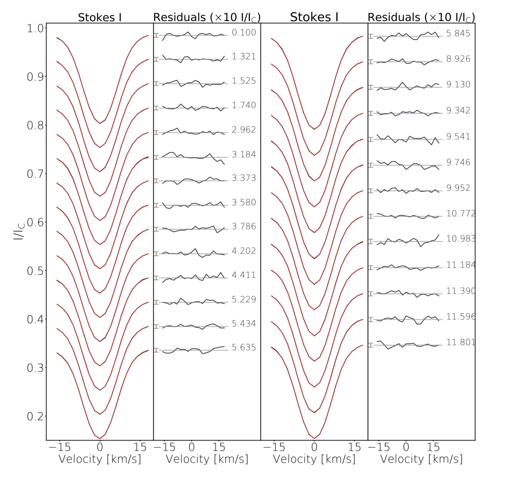
Conversely, don't use activity sensitive lines for planet hunting

Studying active stars helps refine correction techniques for quiet stars

Image: Dumusque et al. 2018, 2019

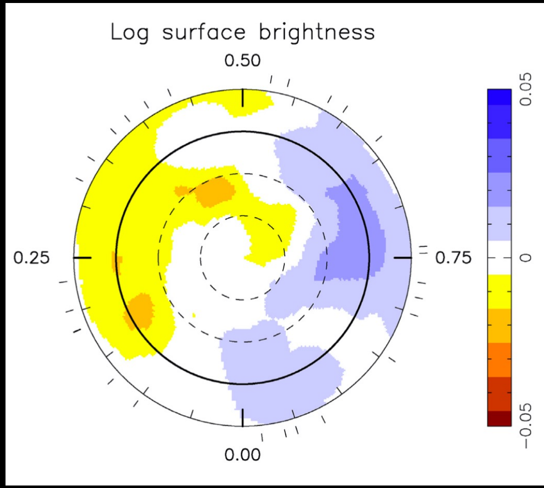
Beyond Typical RV Analysis Techniques

Use additional information about star from easily detected, strong magnetic fields



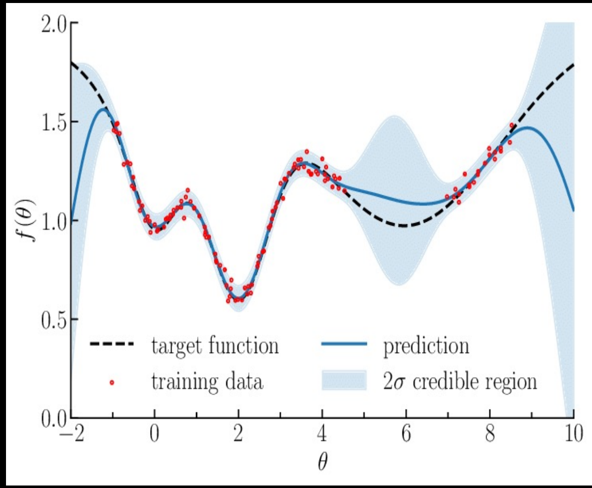
Spectropolarimetry

Can separate spectra into different polarization states which gives different line profiles based on custom masks. Look for Zeeman signatures and measure magnetic field strengths.



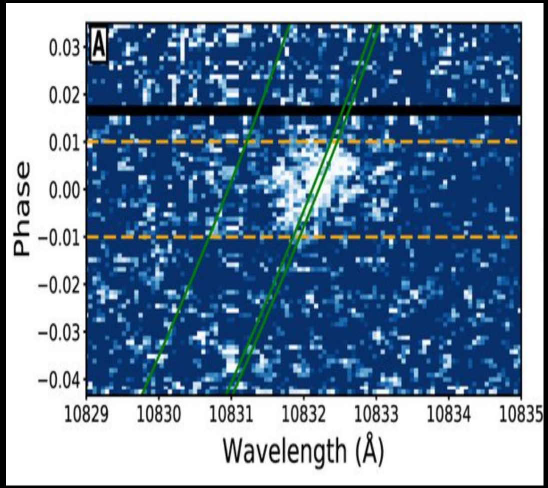
Doppler Imaging

Allows reconstruction of surface topology of the large-scale magnetic fields, allowing one to filter RV curves from the modelled activity, and also to constrain the underlying dynamo processes.



Gaussian Process Regression

Flexible modeling for stellar activity, should be constrained with physical knowledge of the system. Works best with strong magnetic signatures as in young stars.



Spectral Features

Certain spectral lines are good tracers of formation phenomenon. For example, helium has been used to study oblating atmospheres, and H-alpha for accreting planets.

Image: Dumusque et al. 2018, 2019

Young Planet Discoveries

The Young Field of Young Planets with RV

Only A Few Planets Discovered And Almost None With Well-Constrained Bulk Density

Only about 3 young planet-hosting stars found from RV searches

- CI Tau b [Johns-Krull et al. 2016; Flagg et al. 2019], V830 Tau b [Donati et al. 2015, 2016, 2017], and TAP 26 b [Yu et al. 2017b]
- Recently, however, the existence of both V830 Tau b and CI Tau b has been challenged [Damasso et al. 2020, Donati et al. 2020]

Few more with RV derived from spectropolarimetry and in combination with transits

[Donati et al. 2016; Yu et al. 2017 and Deleuil et al. 2012; Alsubai et al. 2017]

The Young Field of Young Planets with RV

Only A Few Planets Discovered And Almost None With Well-Constrained Bulk Density

Multiple promising surveys underway

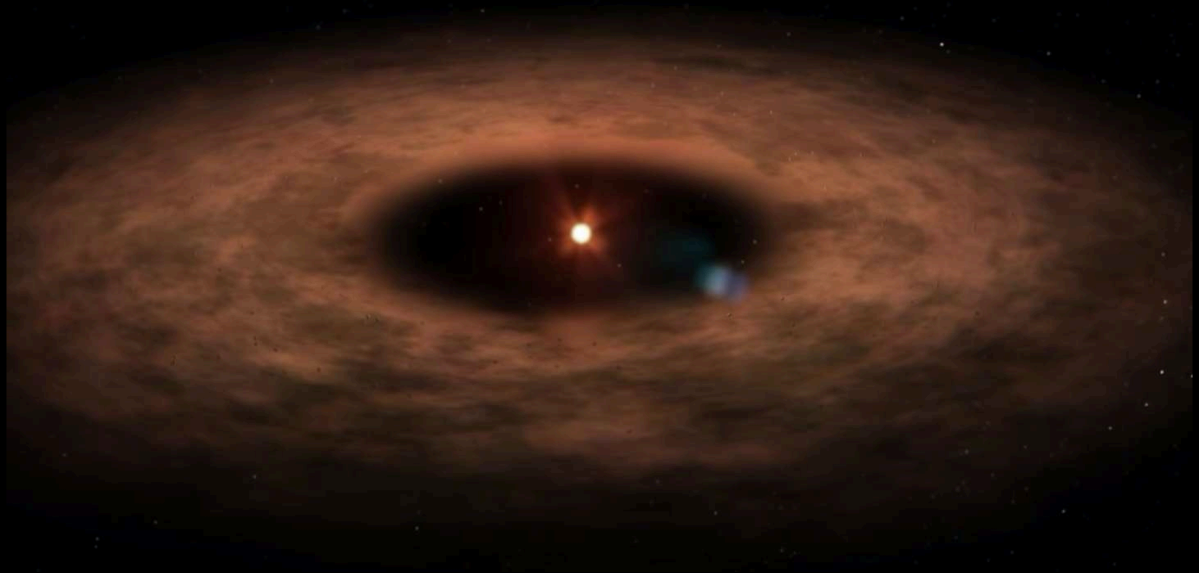
- HARPS Young Nearby Stars Survey, Sophie Young Nearby Stars Survey
- Habitable Zone Planet Finder Epoch of Giant Planet Migration Program

Examples of individual efforts at activity characterization

- NN-EXPLORE EPRV Foundation [Funding + Research Network Management)
- NEID GO Programs

The Young Field of Young Planets with RV

Au Mic – A Case Study in Planet Formation



AU Microscopii is an active, nearby, pre-main sequence star located in the ~22 Myr old Beta Pic moving group

- Hosts a resolved edge-on debris disc at distances ranging that offers an excellent framework to study planet formation and evolution
- A close-in transiting Neptune-sized planet was newly detected around AU Mic from photometric observations collected with TESS and Spitzer space missions [Plavchan et al. 2020]

AU Mic b is the best transiting pre-main sequence target for a velocimetric mass measurement

- Star is bright, and planet is close to star
- However, activity signatures at about 115m/s so previously only upper limit on mass [Plavchan et al. 2020]
- SPIRou observations – going to the NIR, spectropolarimetry, Gaussian Process Regression, Zeeman Doppler Imaging
- Refine mass and constrain bulk density with 3.9-sigma detection of planet

CLOSING THOUGHT

New Fields Need New Researchers!