DEPARTMENT OF ASTRONOMY AND ASTROPHYSICS

CENTER FOR

Exoplanets & Habitable Worlds

Seeking to discover habitable planets and life beyond the Solar System.

The Era of Exoplanets: Pushing toward Terrestrial Mass Planets in Habitable Zones

Suvrath Mahadevan

The Pennsylvania State University

PENNSTATE

Eberly College of Science

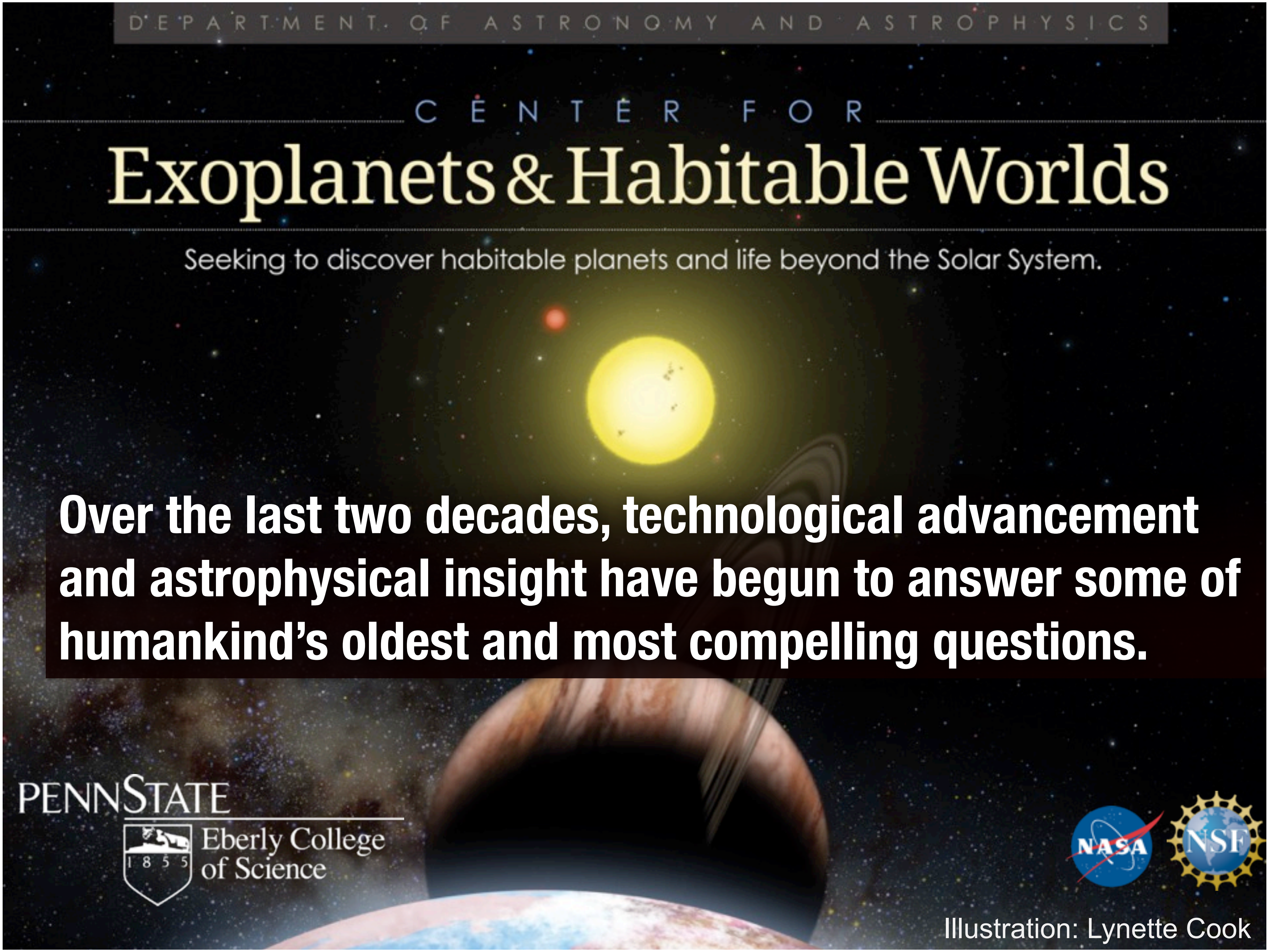
1855

NASA NSF

Illustration: Lynette Cook

There are thousands of exoplanets known today

— more to be discovered, and discovery just the beginning


DEPARTMENT OF ASTRONOMY AND ASTROPHYSICS
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Seeking to discover habitable planets and life beyond the Solar System.
Over the last two decades, technological advancement and astrophysical insight have begun to answer some of humankind's oldest and most compelling questions.
PENNSTATE
1855
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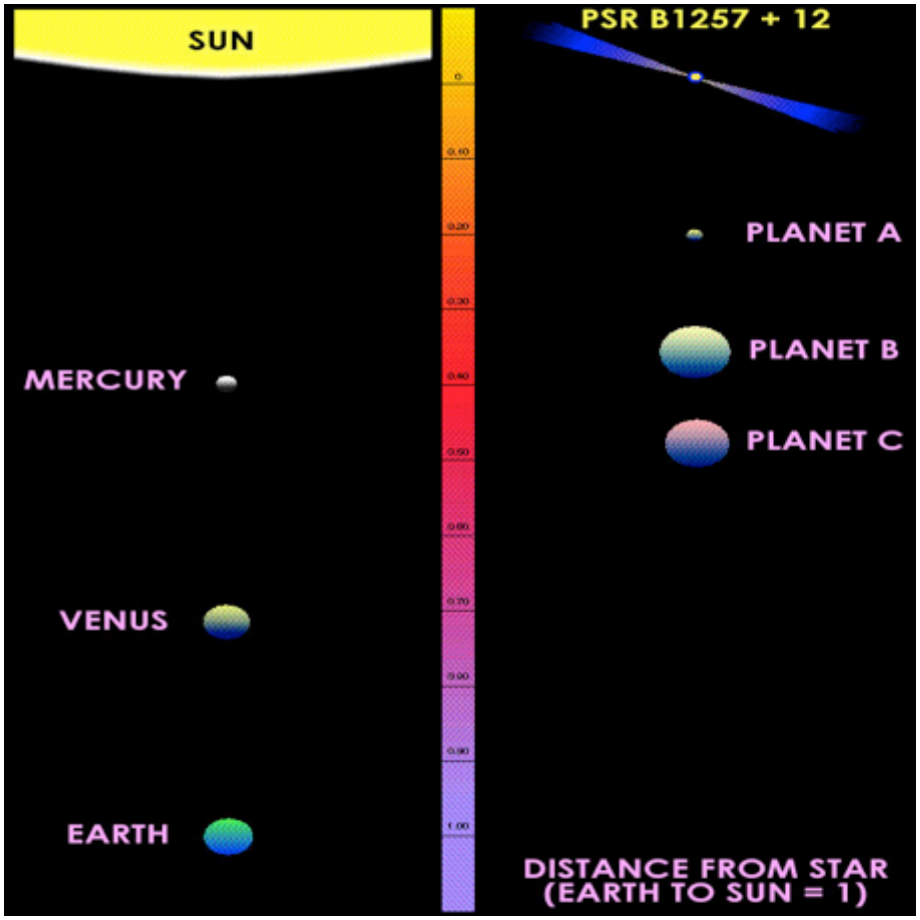
NASA
NSF
Illustration: Lynette Cook

Earth Mass Planets are POSSIBLE to detect



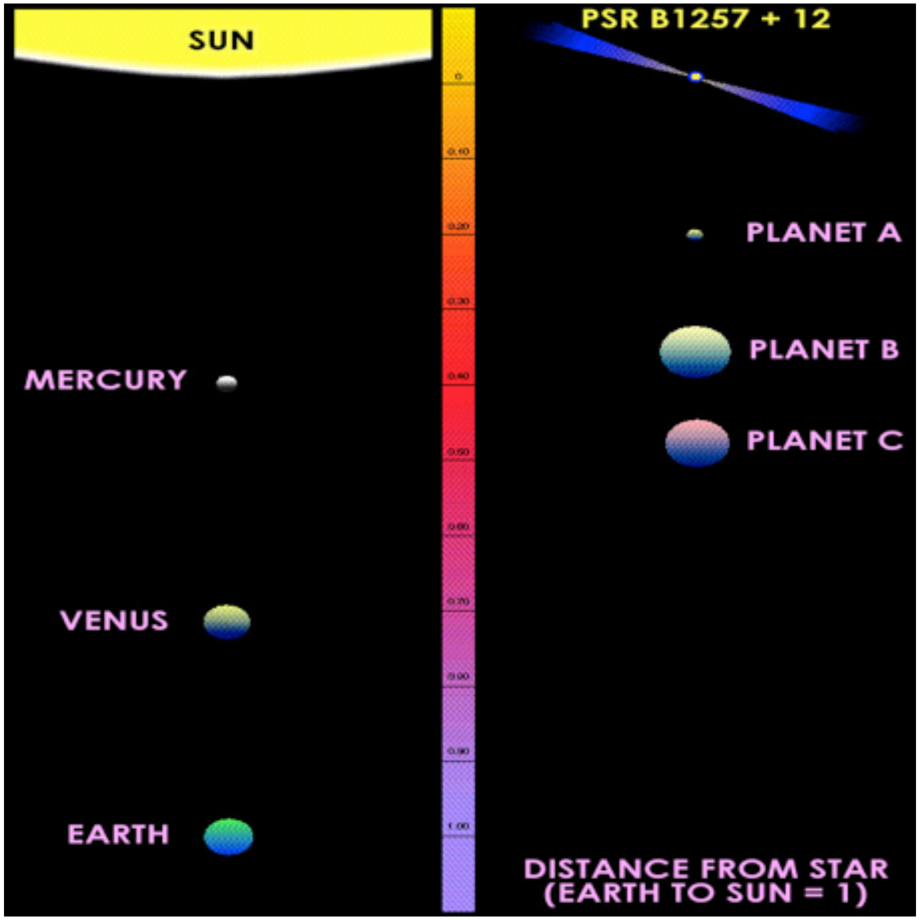
Pulsar Planets: Discovered Alex Wolszczan and Dale Frail (1992) using precise **timing** of pulses. Rare.

Can Measure Time & Frequency VERY precisely and accurately

Latest clocks are at ~ 1part in 10^{18}

We can measures frequency MUCH better than we can measure LENGTH

Earth Mass Planets around Sun-Like Stars ARE hard to detect



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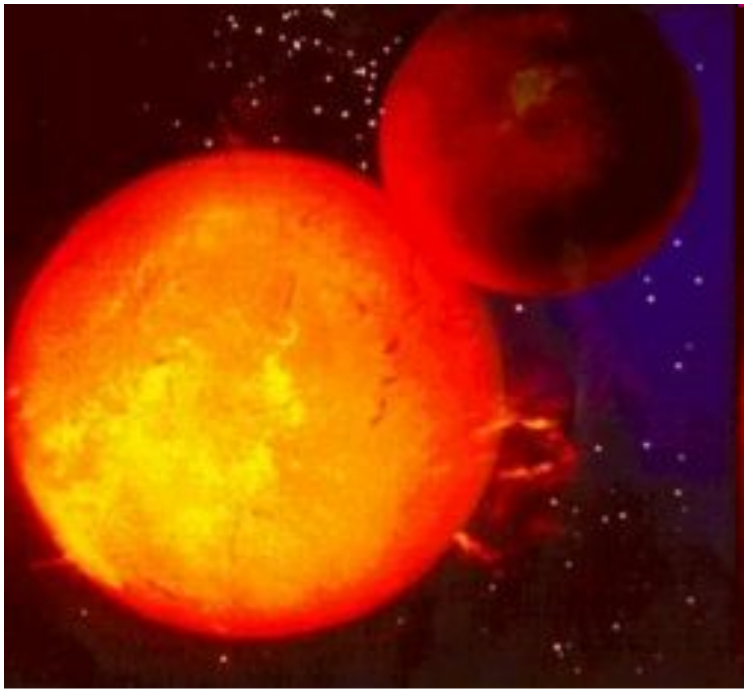
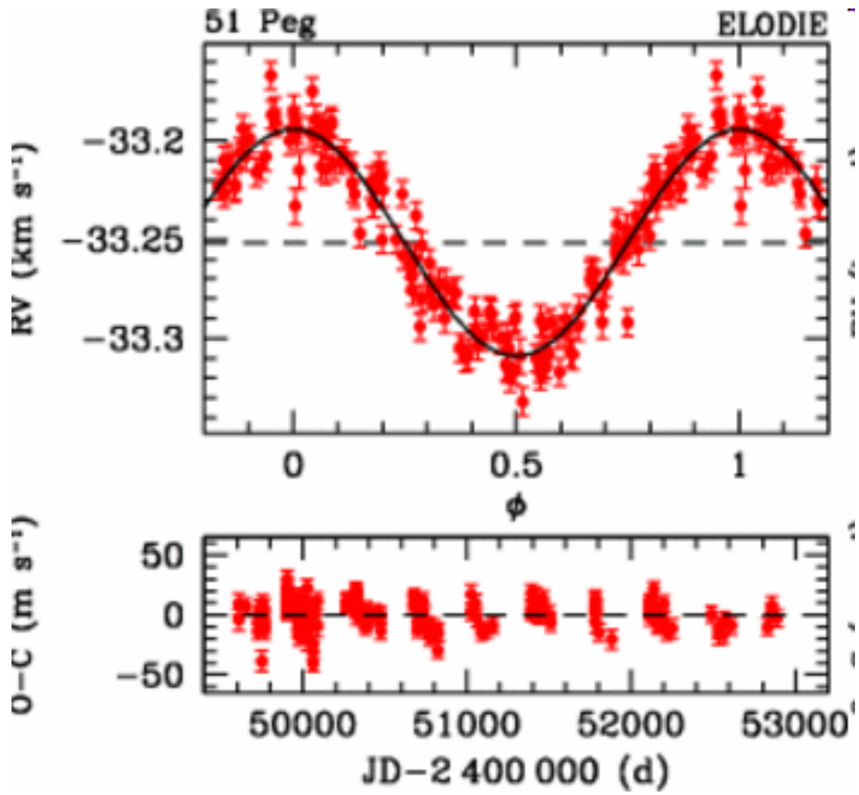
The first Exoplanets discovered



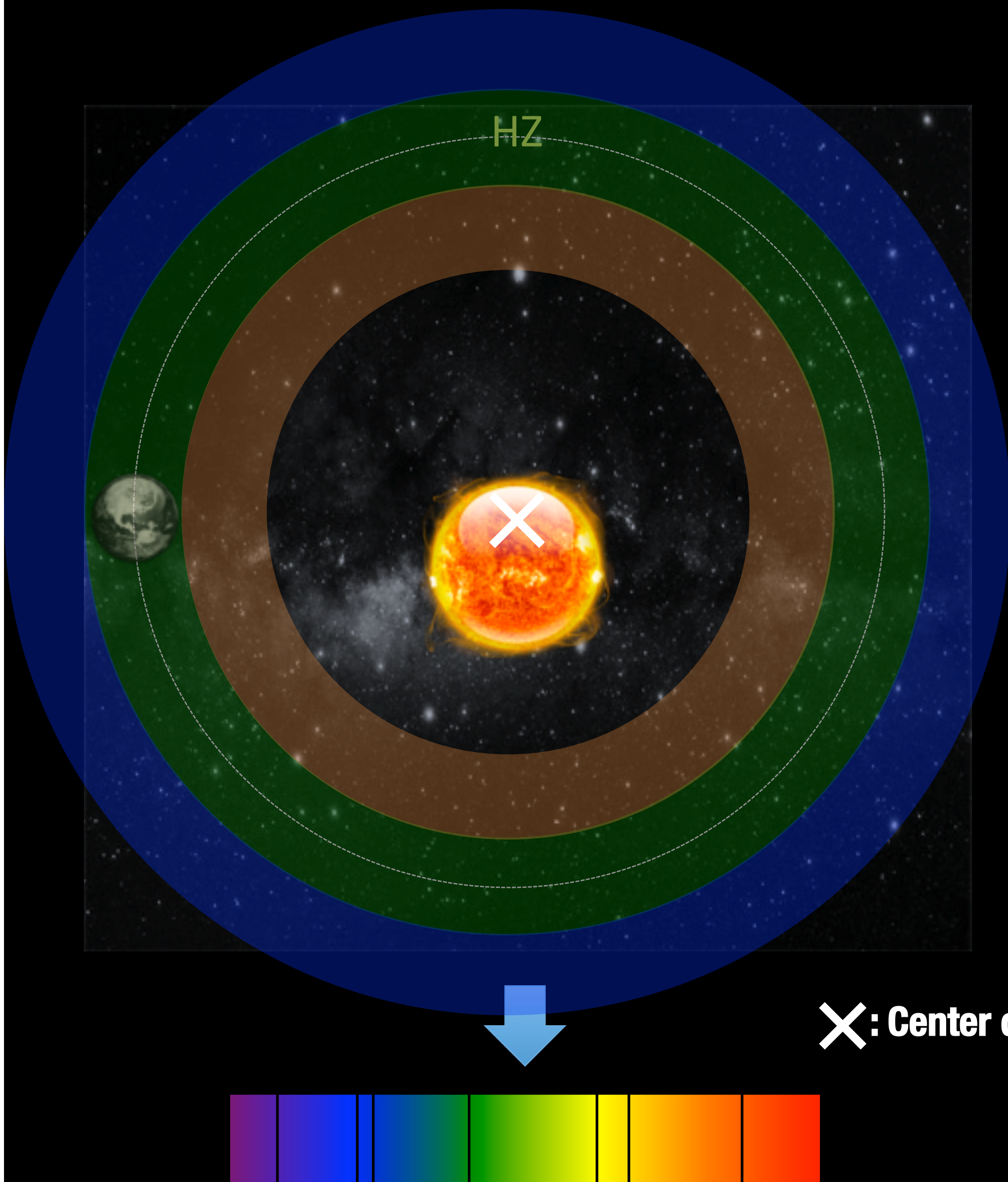


First planets around Sun-like star: Discovered my Michele Mayor and Dider Queloz Geneva, 1994 using spectroscopy and the **radial velocity** technique. A **HOT** Jupiter. 2019 Physics Nobel Prize.

Detection Techniques:

Radial Velocity

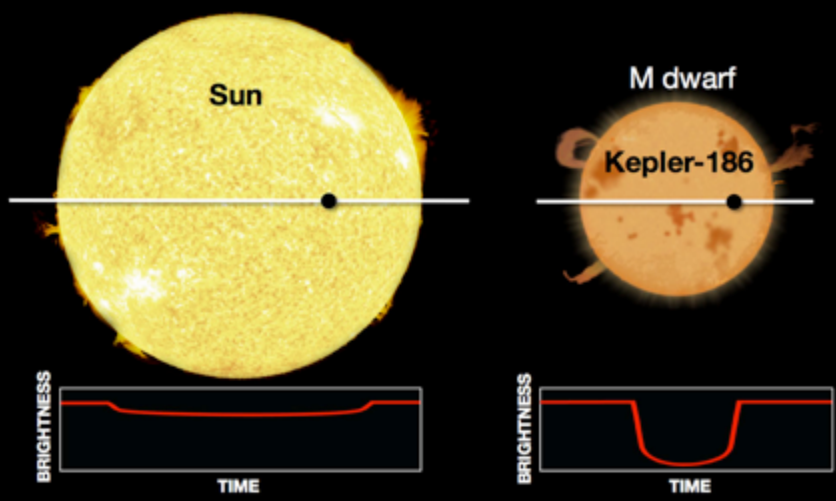
The Earth Introduces a Doppler Radial Velocity shift on the Sun of only 8.9 cm/s in a year.



✕: Center of Mass

~10 cm/s

~1 m/s

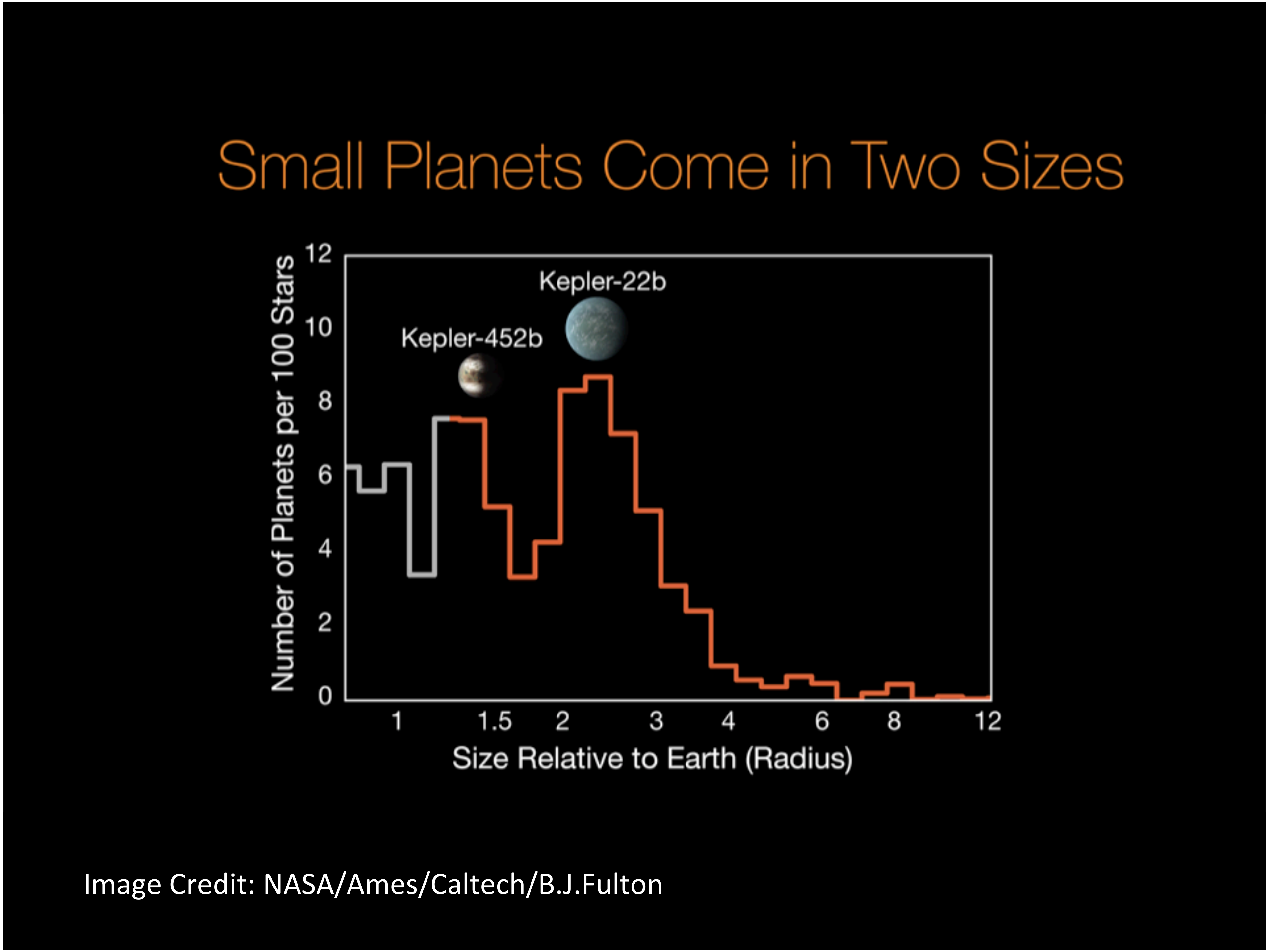


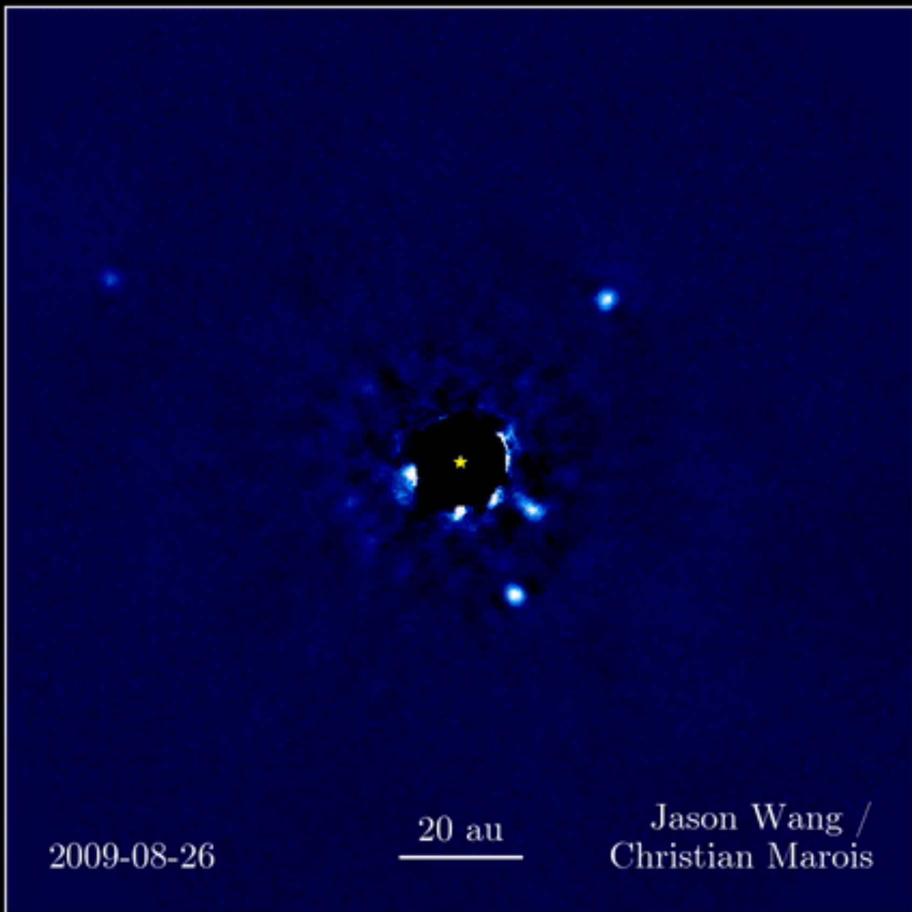
Detection Techniques:

Transits

The Earth around the Sun is an 80ppm signal.

Earth around a late M dwarf is a ~1000ppm signal


Small Planets Come in Two Sizes
Kepler-22b
Kepler-452b
Number of Planets per 100 Stars
0
2
4
6
8
10
12
1
1.5
2
3
4
6
8
12
Size Relative to Earth (Radius)
Image Credit: NASA/Ames/Caltech/B.J.Fulton



HR 8799

Detection Techniques:

Direct Imaging

Can currently image giant planets on long orbits. Pushing to lower contrast levels from space and ground.

Sun-like System

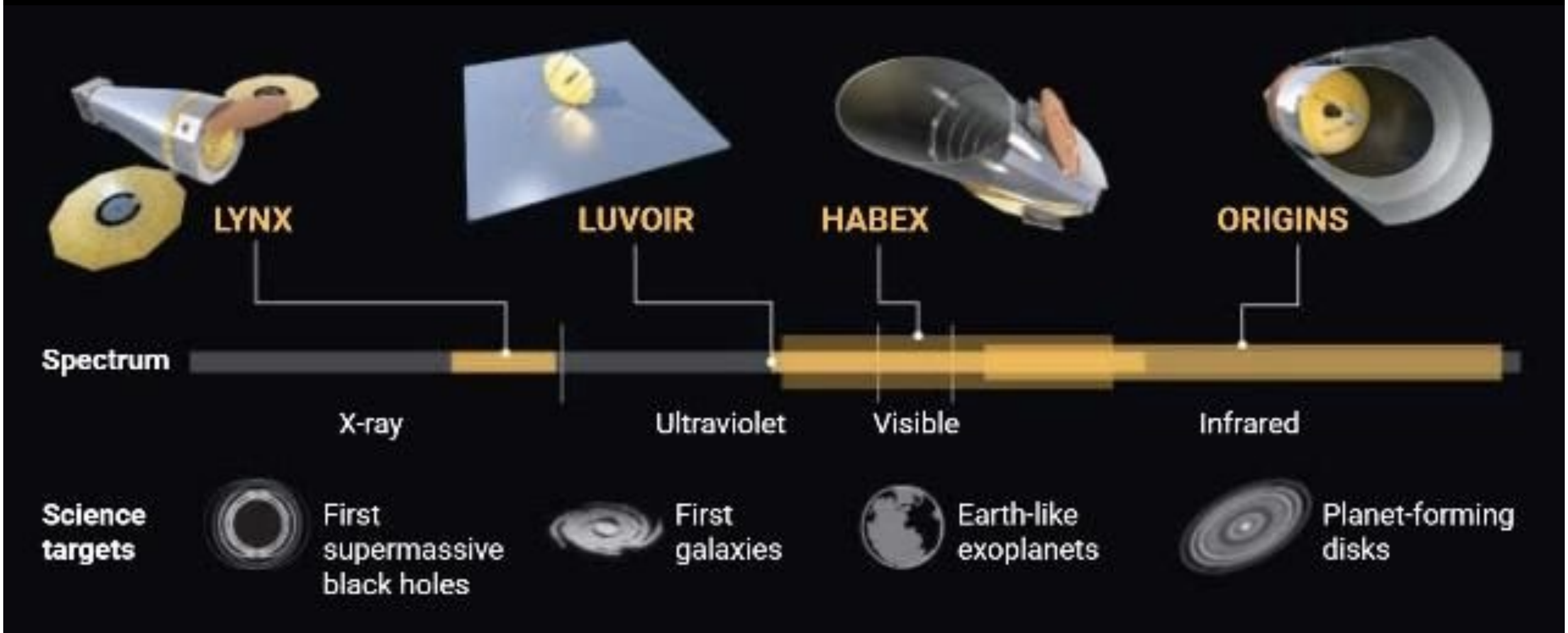
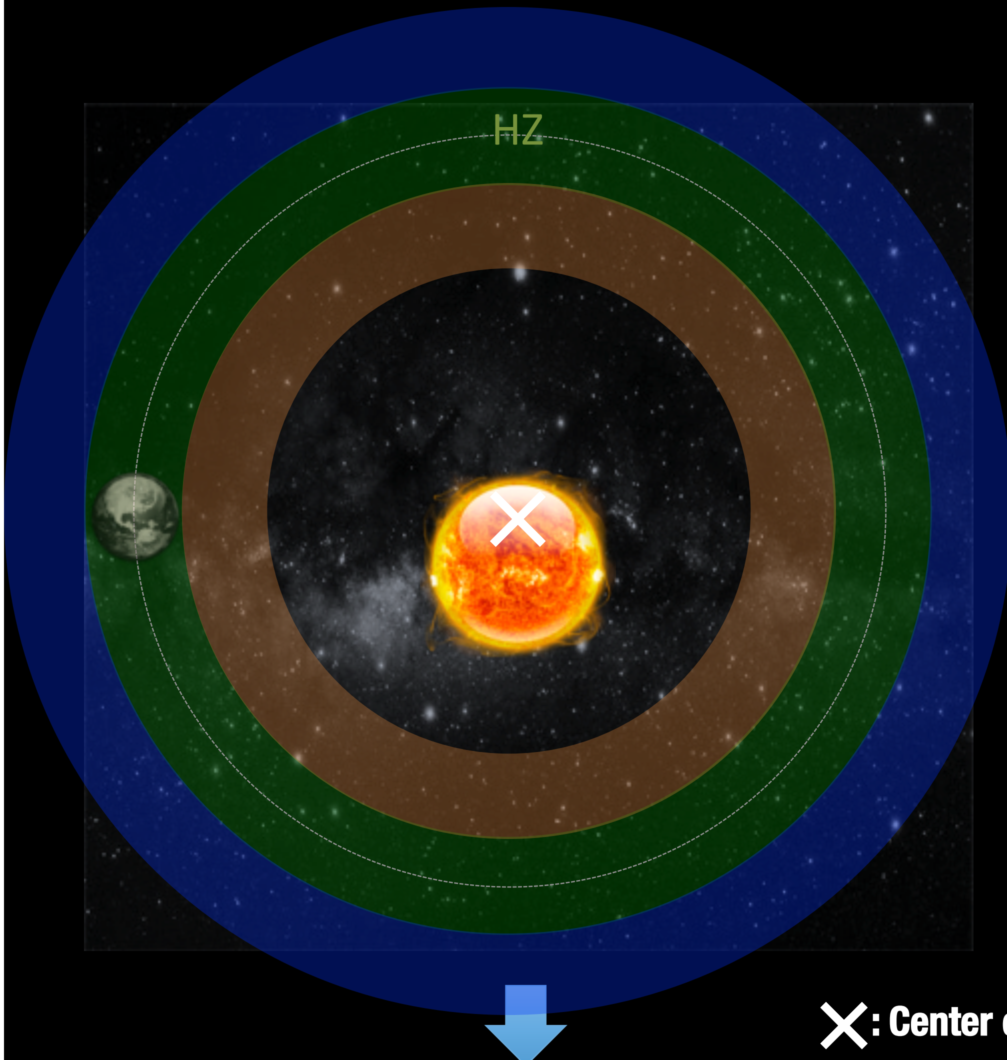


Image Credit: NASA

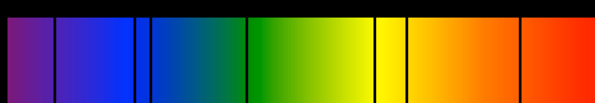


Detection Techniques:

Radial Velocity

The Earth Introduces a Doppler Radial Velocity shift on the Sun of only 8.9 cm/s in a year.

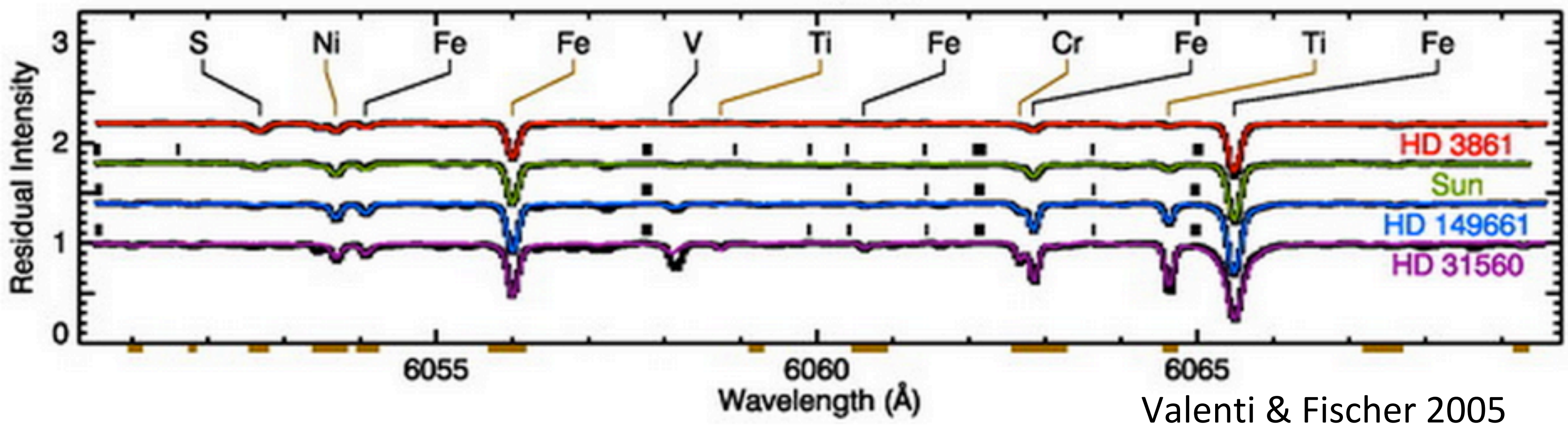
X: Center of Mass



~10 cm/s

~1 m/s

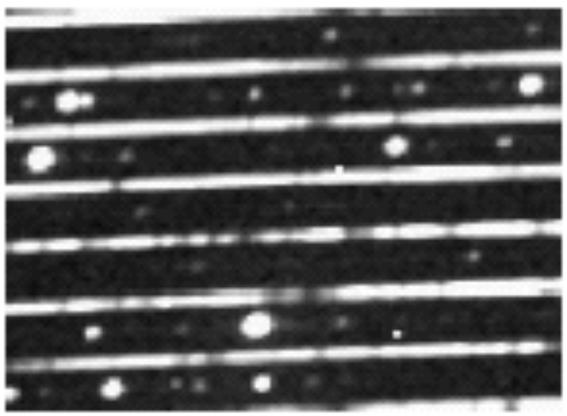
Starlight Dispersed



Valenti & Fischer 2005

Two Main Techniques

Simultaneous reference



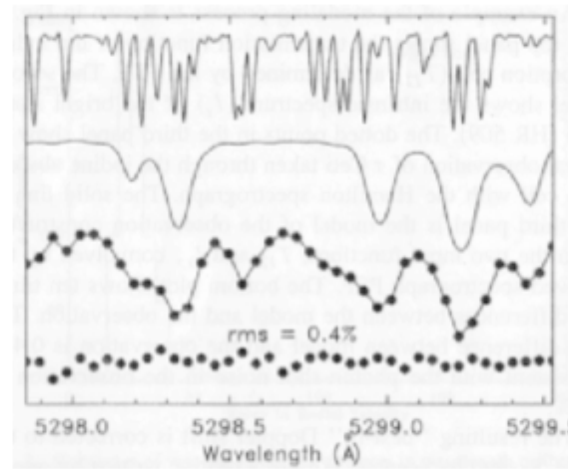
No differential changes allowed between fibers

Needs Fibers & calibration fiber

Wide wavelength range

REQUIRES instrument stability

Self reference (iodine cell)



Instrument profile may change as long as star and iodine affected identically

Suitable for any/slit spectrographs

Restricted range (~500-620nm)

REQUIRES 'de-convolution'

Other Techniques

Externally Dispersed Interferometry

Technique to tap into information content in spectral lines using a interferometer in series with a grating (Erskine et al. 2007, van Eyken et al. 2010))

Used to discover HD102195b (Ge et al. 2006)

Heterodyne Spectroscopy:

Potentially very precise but very poor signal-to-noise properties in the optical

Ongoing work in collaboration with NIST to do this for the Sun.

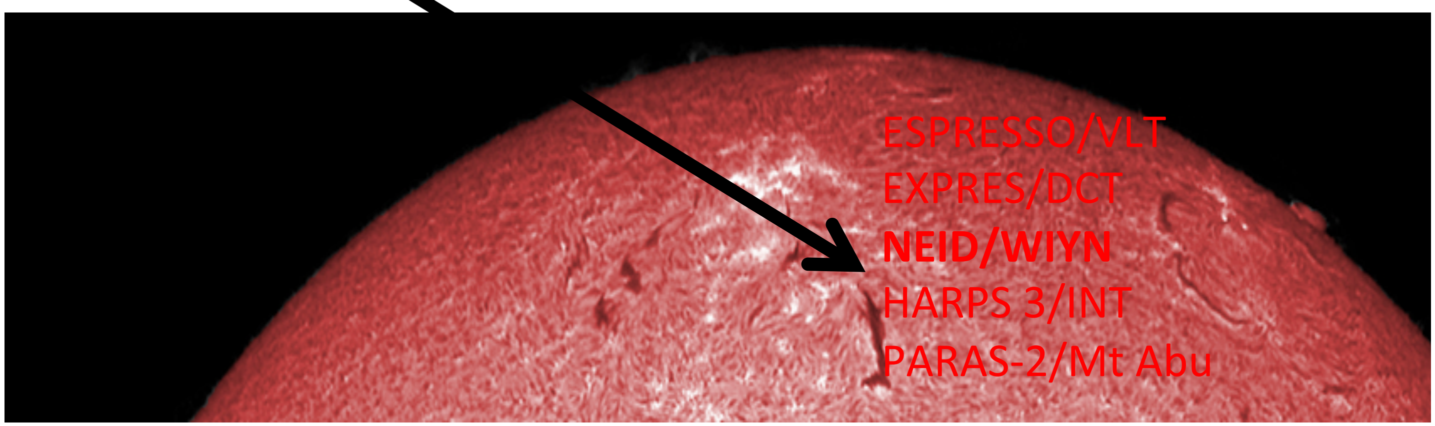
Simultaneous Reference Technique

Griffin 1967 ~ km/s

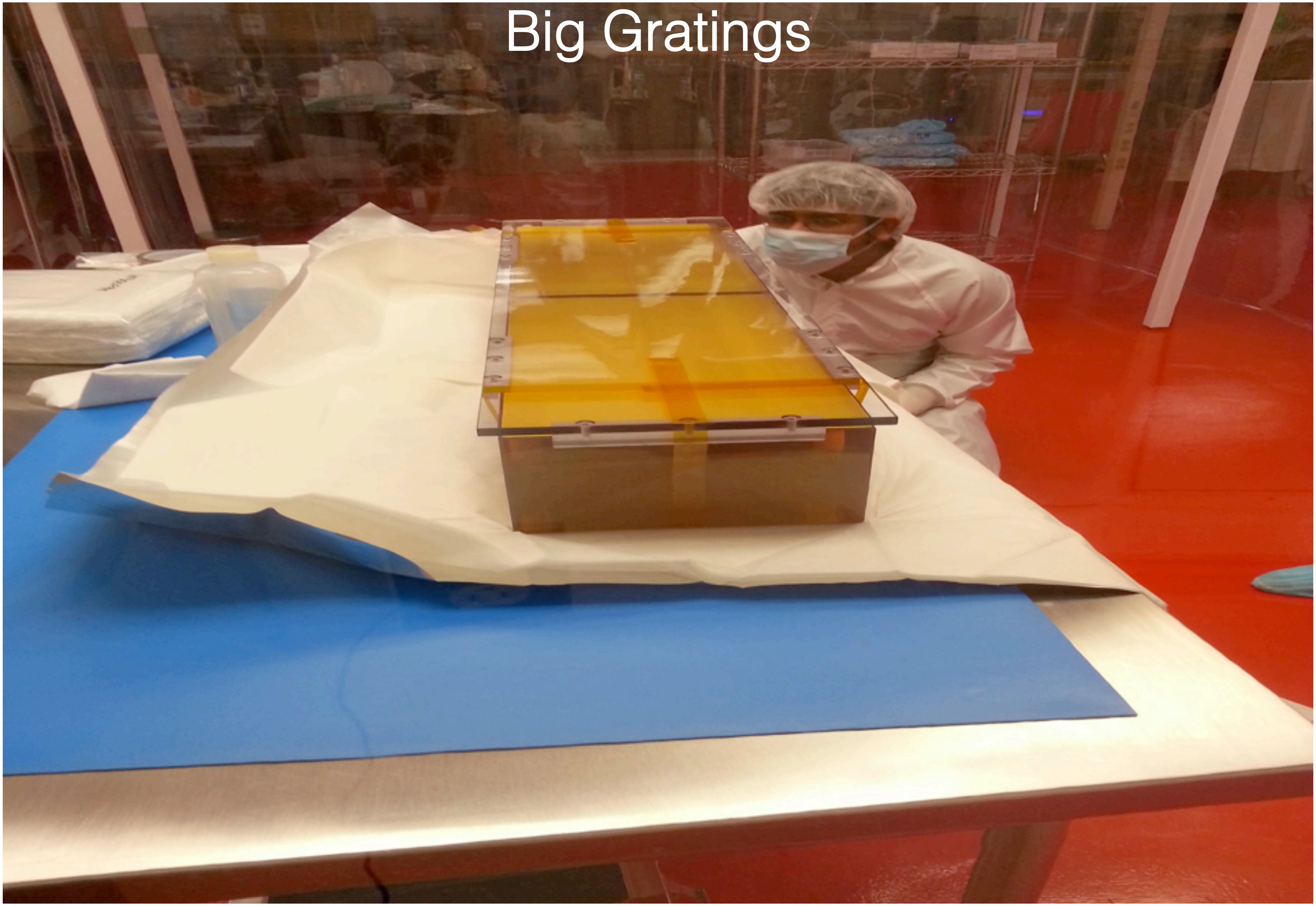
CORAVEL 1979 ~300 m/
s

CORALIE/ELODIE1990 ~5-10 m/s

HARPS 2000s~1 m/s

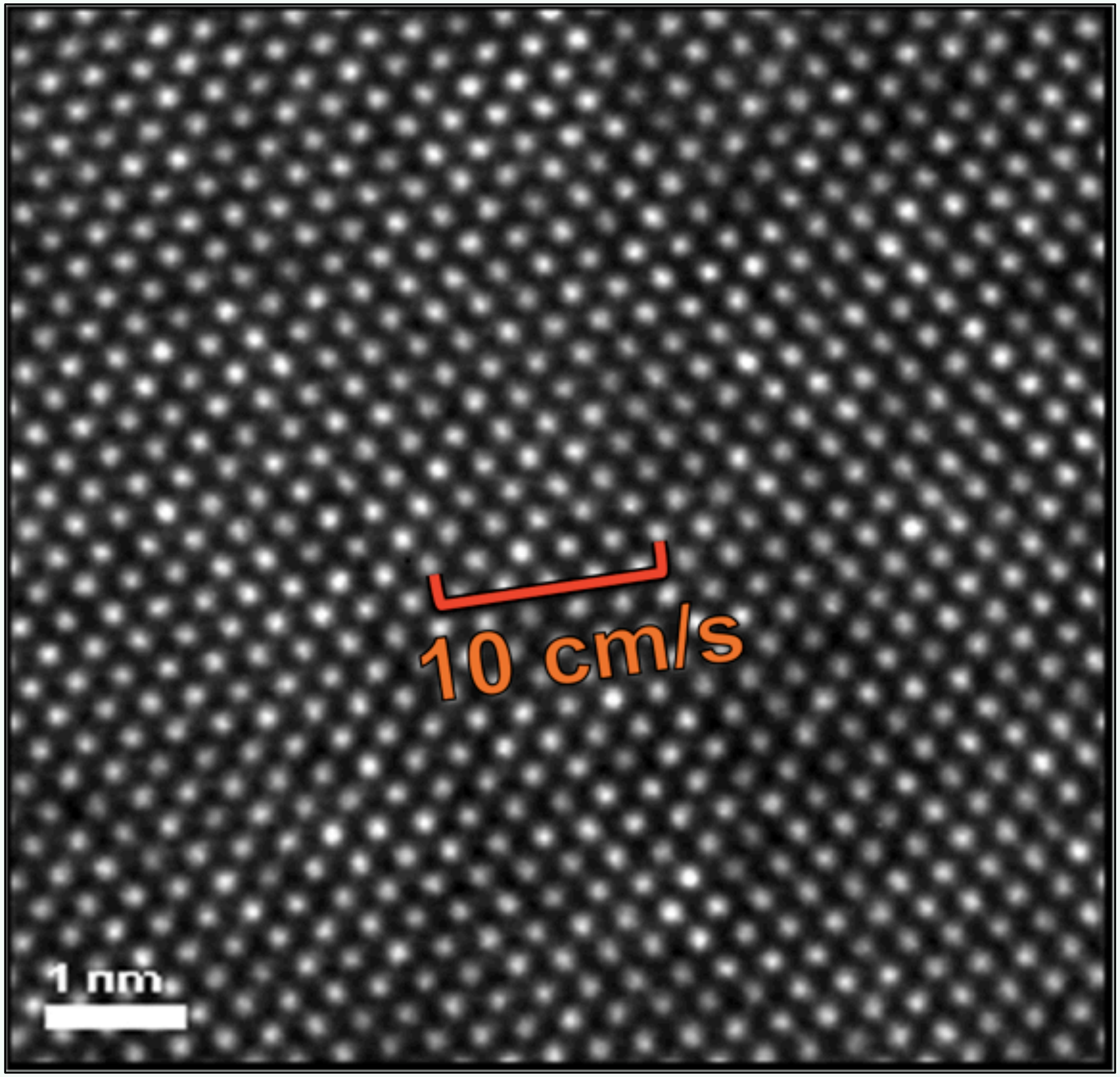


Big Gratings



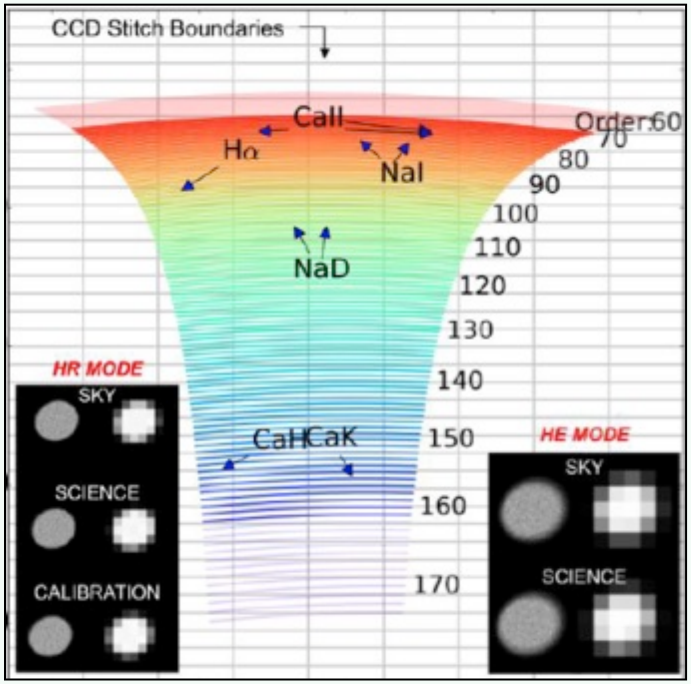
Extreme Precision Doppler Measurements are HARD!

What does 10 cm/s velocity shift look like?

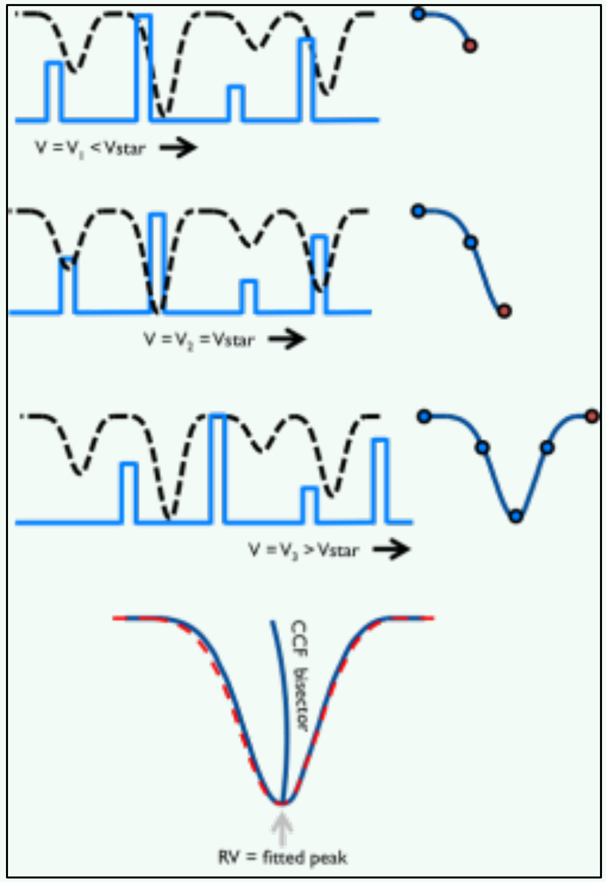


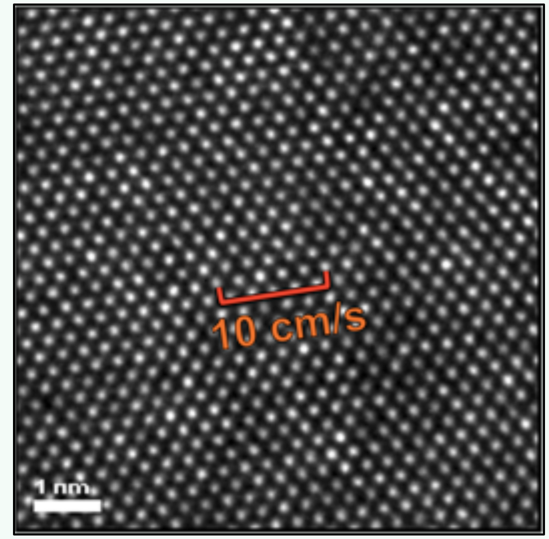
1/1000th of a pixel

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



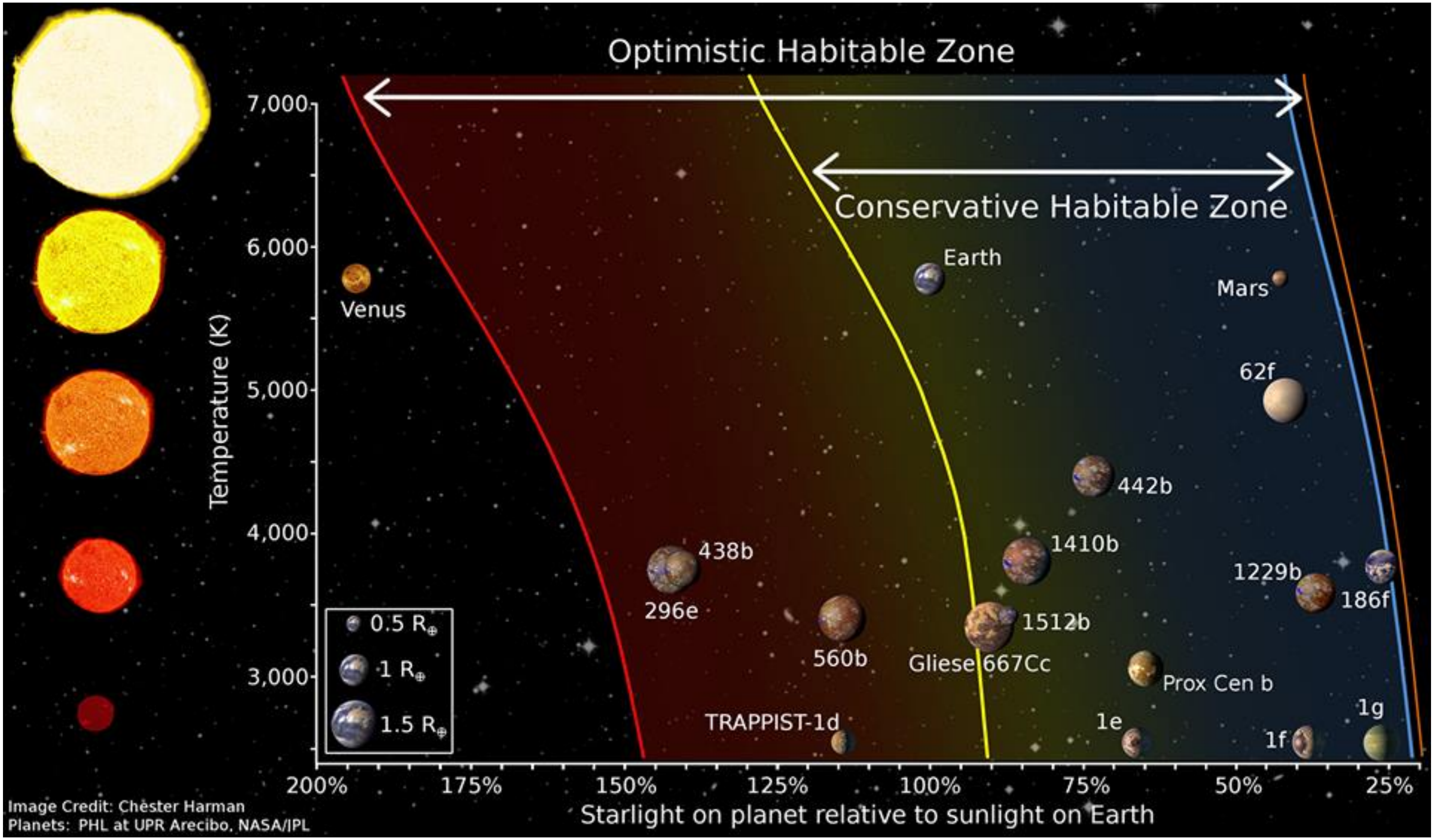
NEID 9k x 9k CCD with
10 micron pixels.
Echelle spectral orders
from 60 to 170 are shown.



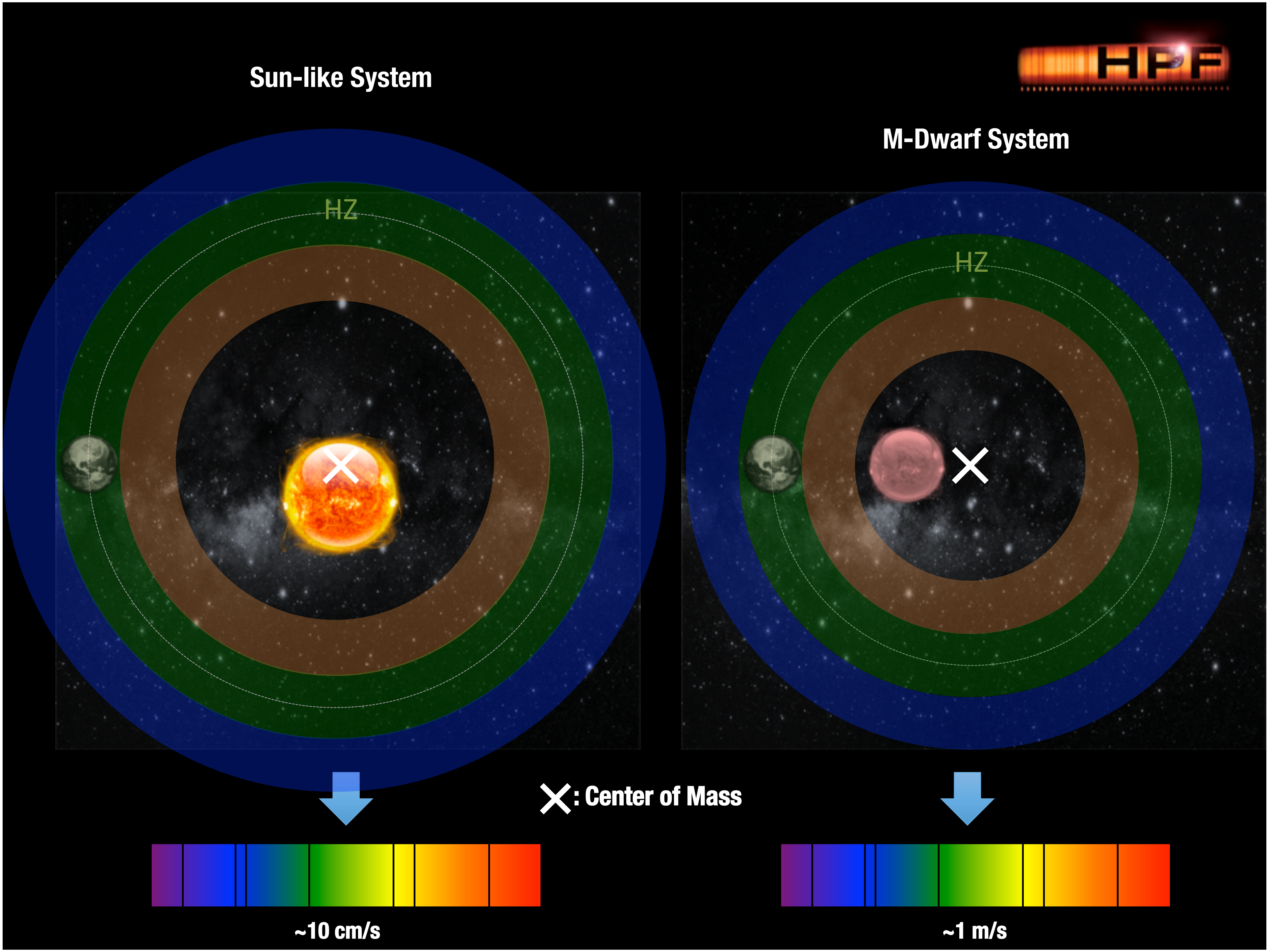


Silicon Lattice: High
Resolution TEM Image of
individual Si atoms.
Ki Bun Kin, SPIE 2012

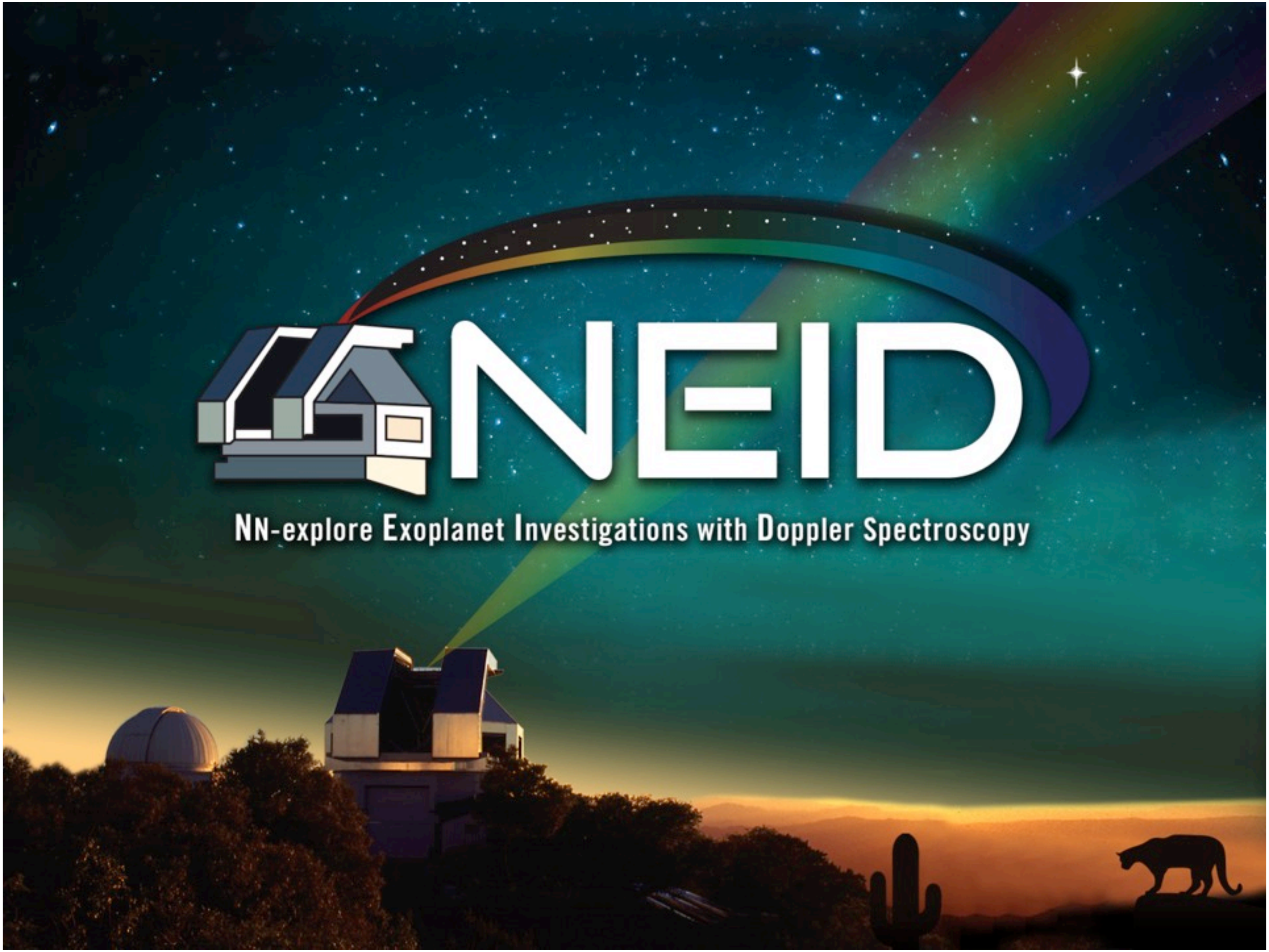
The Habitable Zone



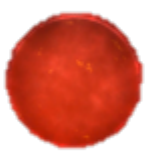
Koparappu et al. 2013

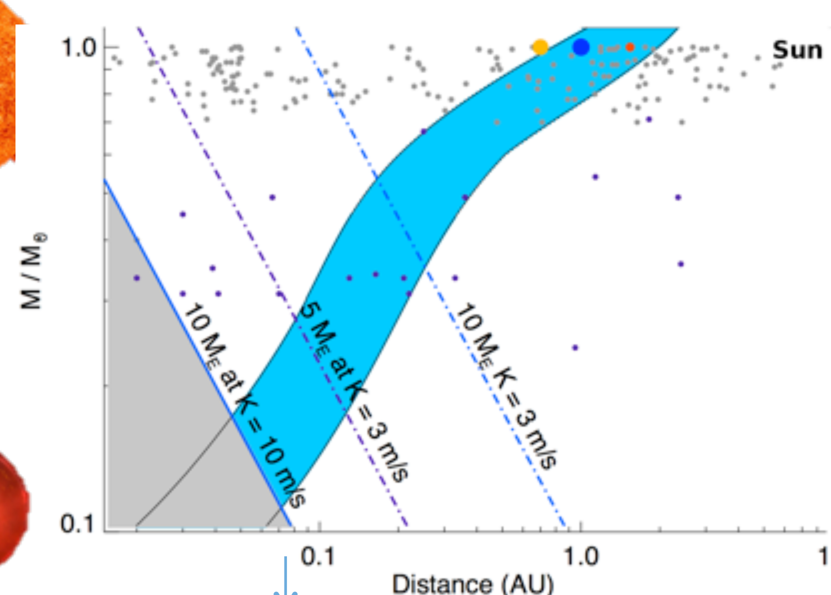

Sun-like System
HPF
M-Dwarf System
HZ
HZ
: Center of Mass
~10 cm/s
~1 m/s

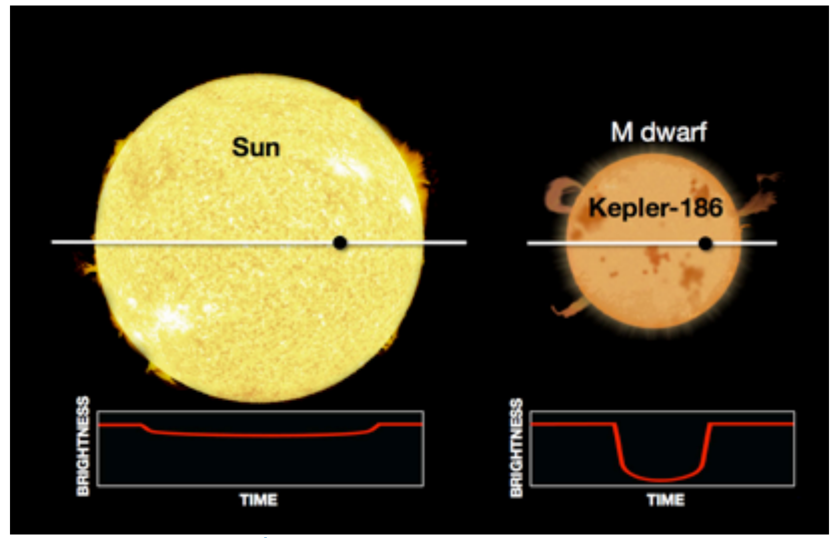
Habitable Zone Planet Finder (HPF)


NEID
NN-explore Exoplanet Investigations with Doppler Spectroscopy

What Can Spectroscopy Give Us?







<u>Radial Velocity</u>

<u>Transit</u>

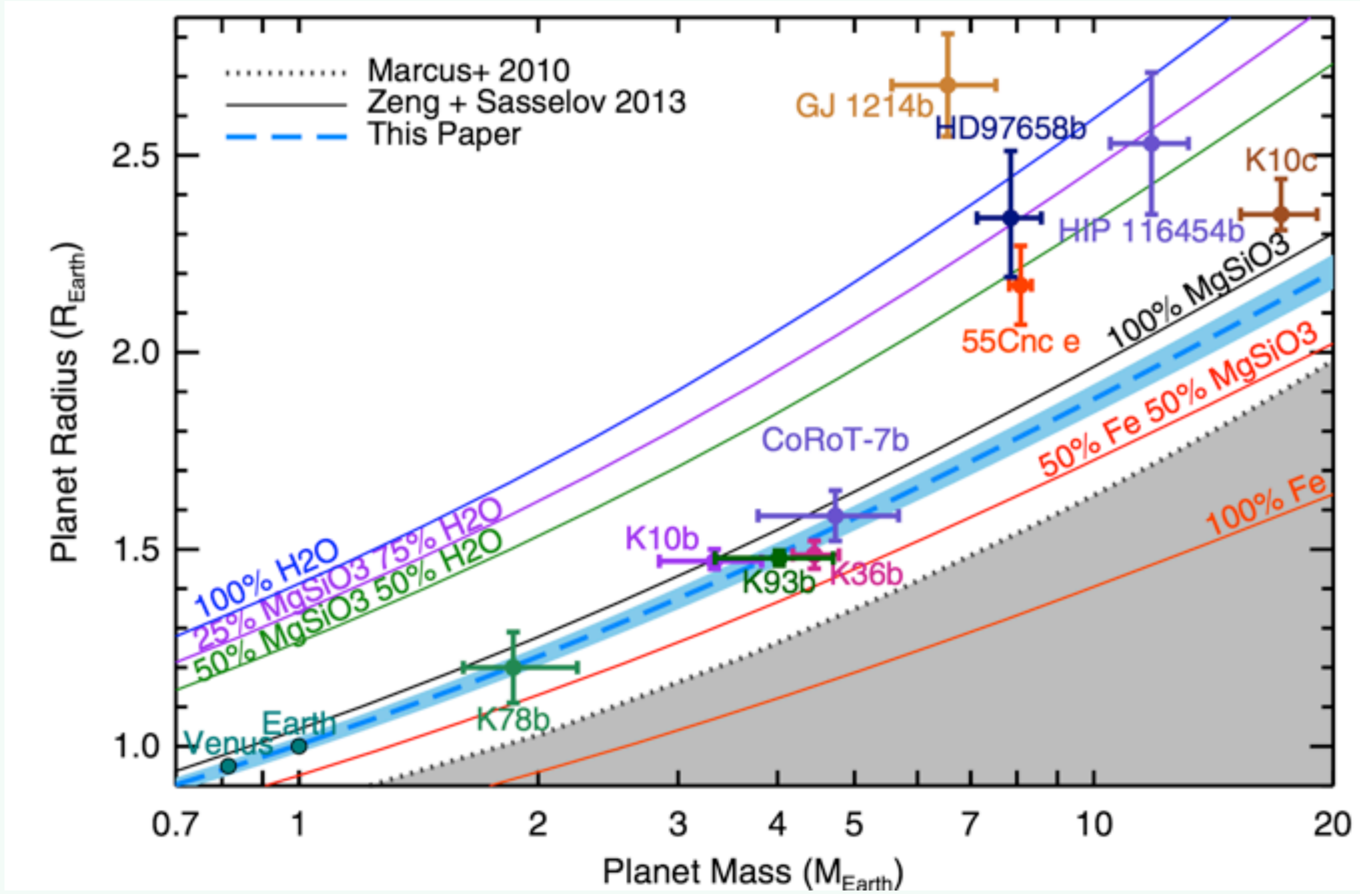
Planet Mass

Radius

Density

Science: The Need for sub-m/s RV

- Very precise planet masses needed to constrain composition/ formation models.
- TESS will provide transiting planets around bright stars, but precision RV resources are lacking.
- Other questions: multiplicity, obliquity, dynamics, etc. Answerable with RVs.

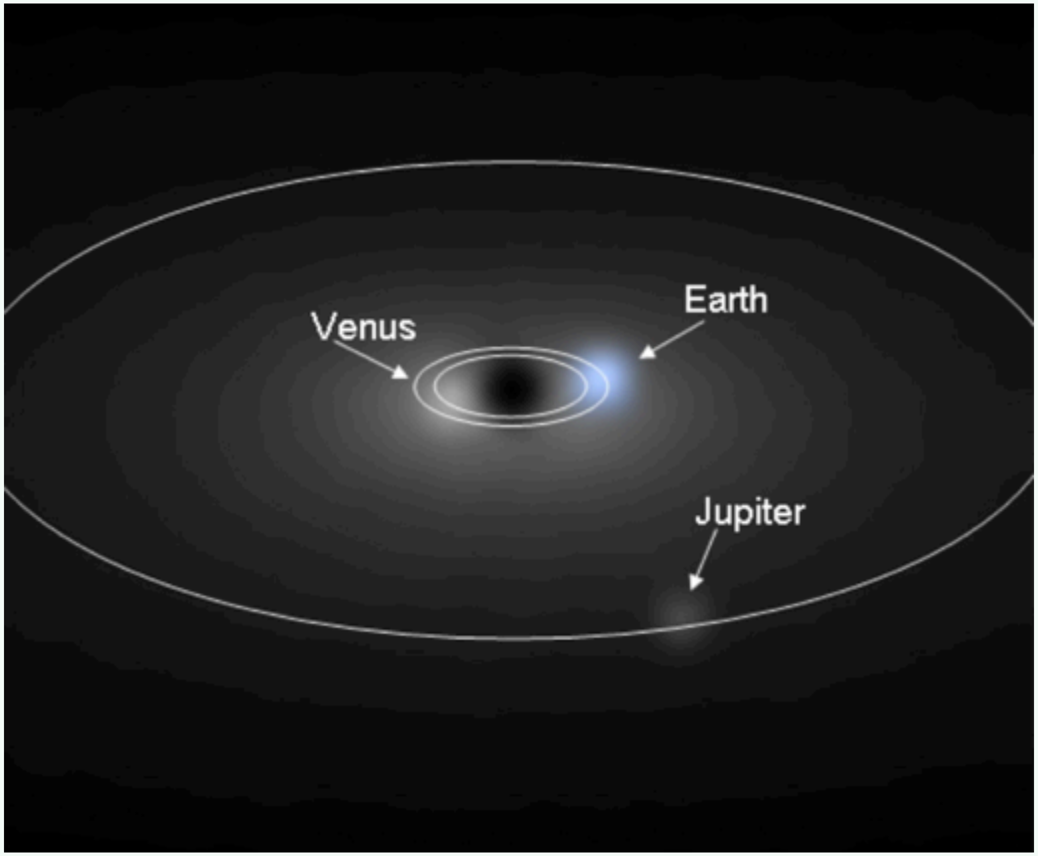


Dressing et al. 2015

Extreme precision RV follow-up is a *requirement* for the success of TESS!

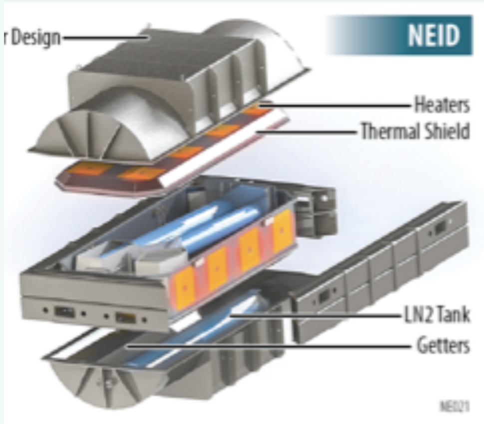
Science: The Need for sub-m/s RV

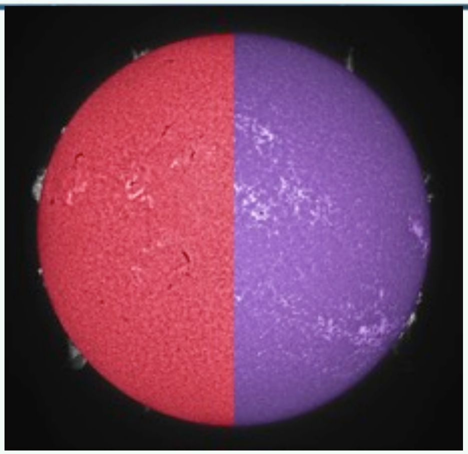
- Earth-mass planets in the HZ have 10-30 cm/s RV amplitudes, requiring observations on 100s of nights at <<50 cm/s precision.
- **These planets represent the top targets for future imaging missions!**
- Knowing whether we have the ability to discover such planets could drive the design of future flagship missions derived from concepts like LUVOIR and HabEX.



Simulated image of the solar system as viewed by a future space-based LUVOIR imager.

So What Do We Need?





High Instrumental RV precision

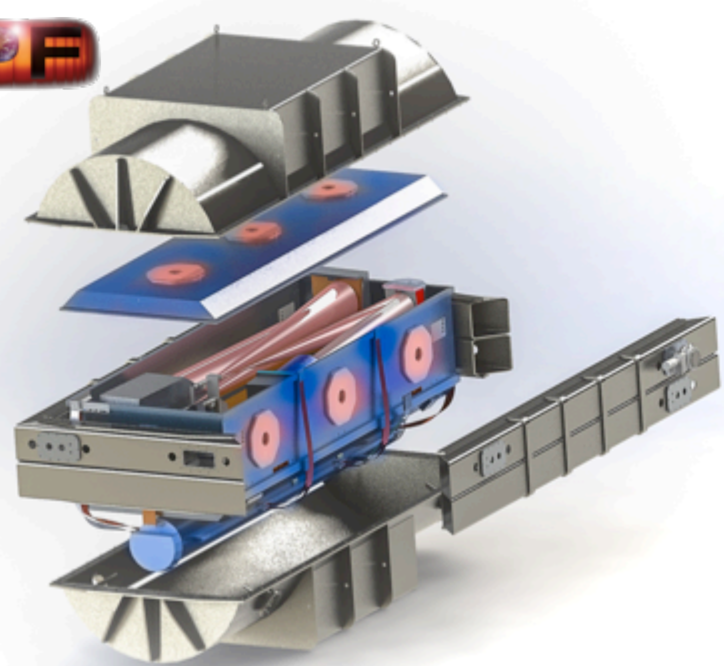
Understanding Stellar Activity

Significant Observing Time, over epochs

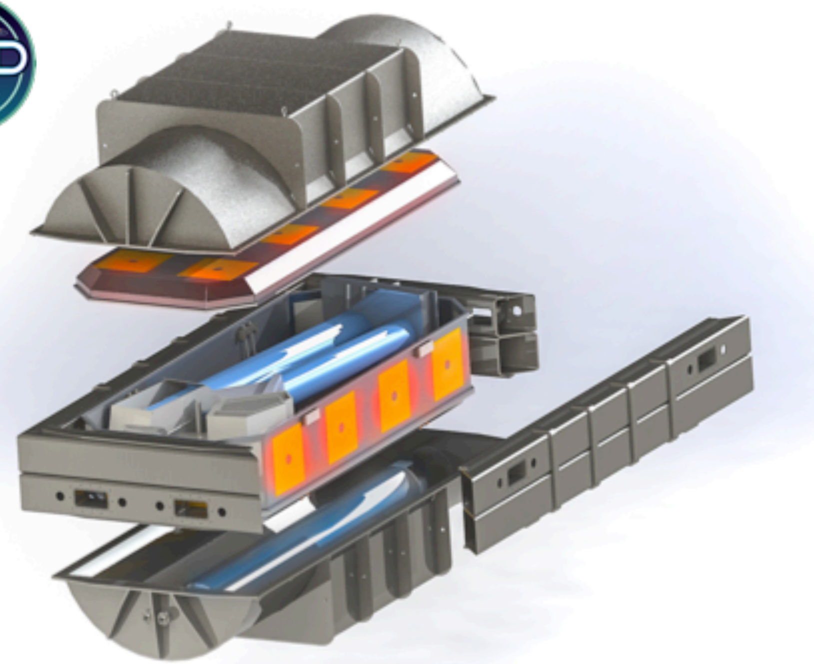
NEID HPF

HPF and NEID: next generation fiber-fed ultra-stabilized spectrographs

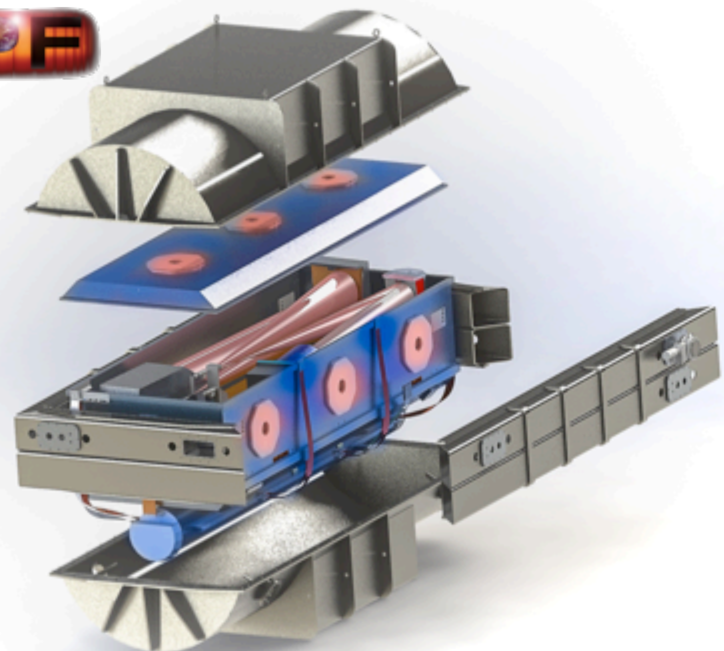
HPF

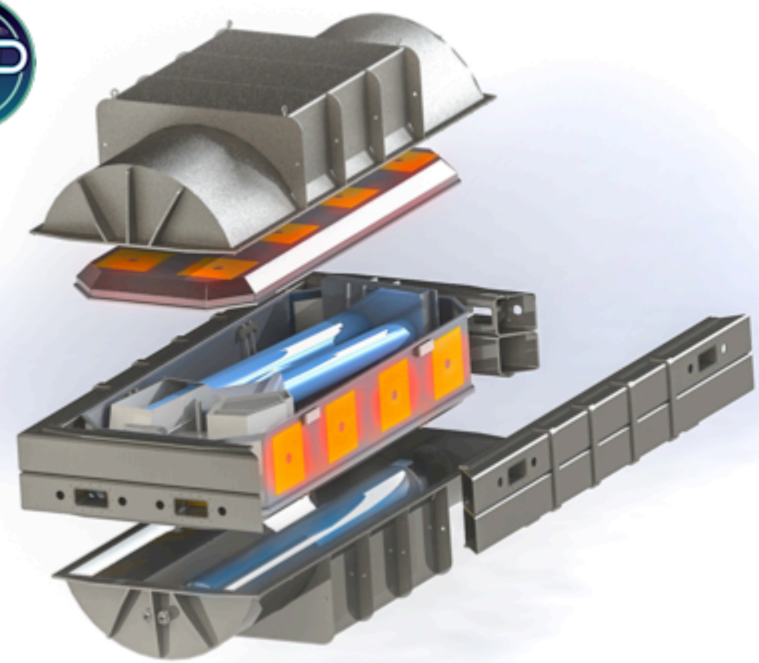


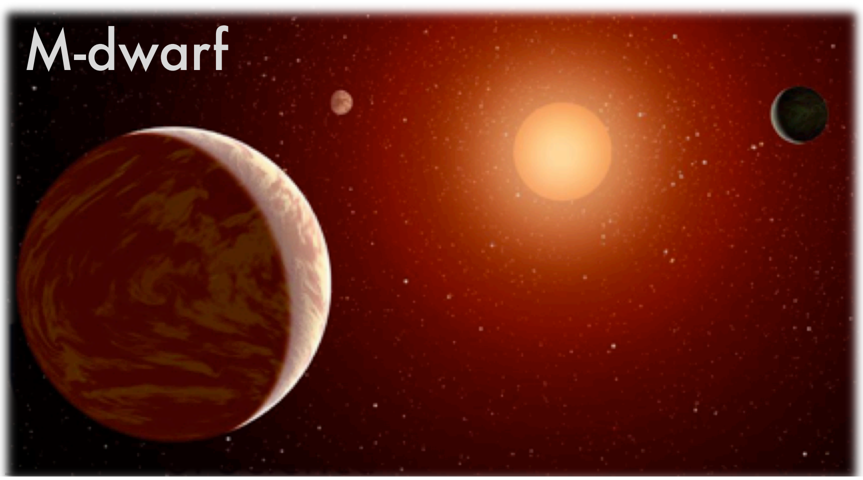
NEID

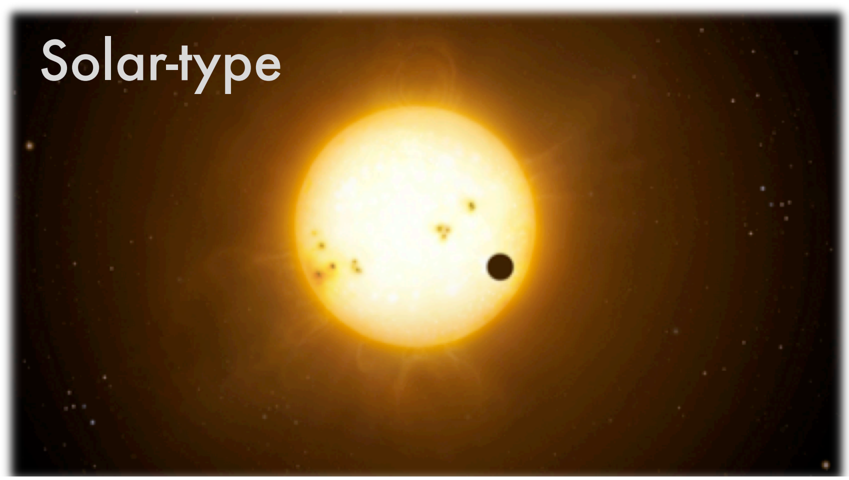


The wavelength bandpass is optimized for the instruments' science goals









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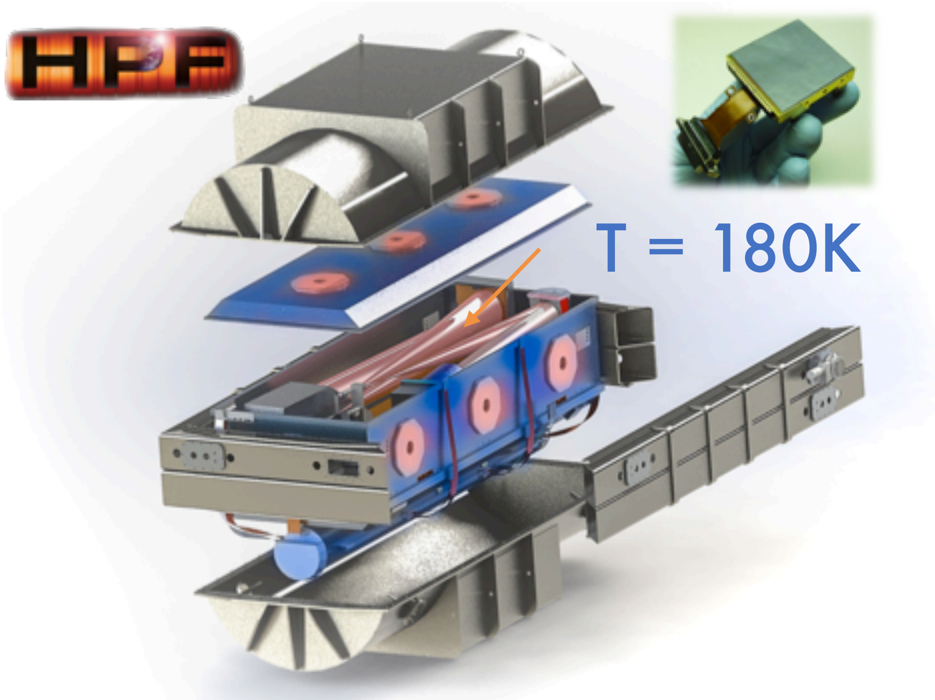
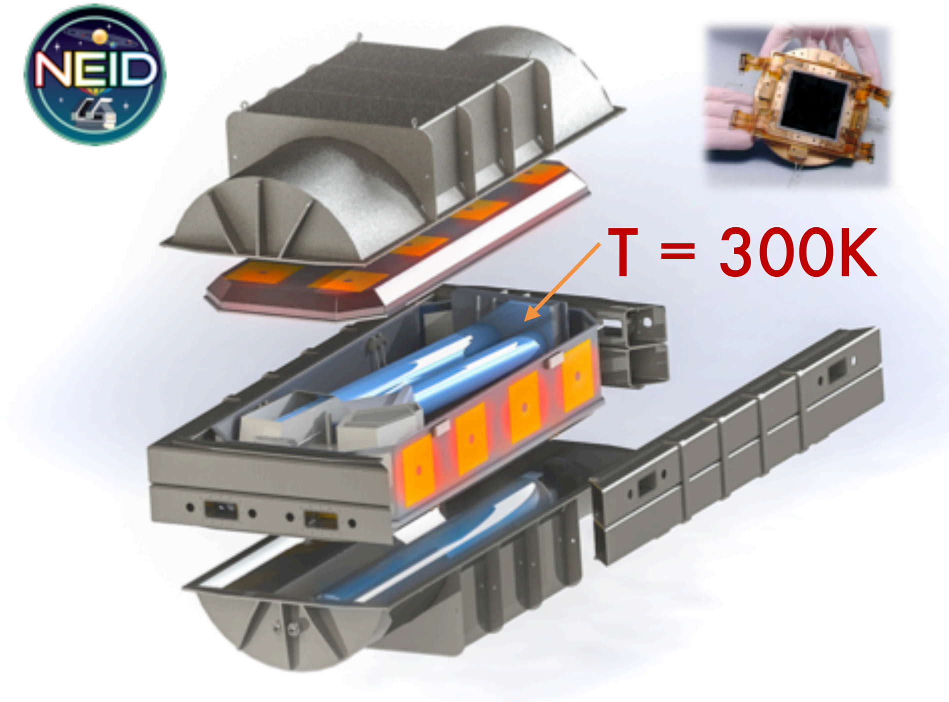
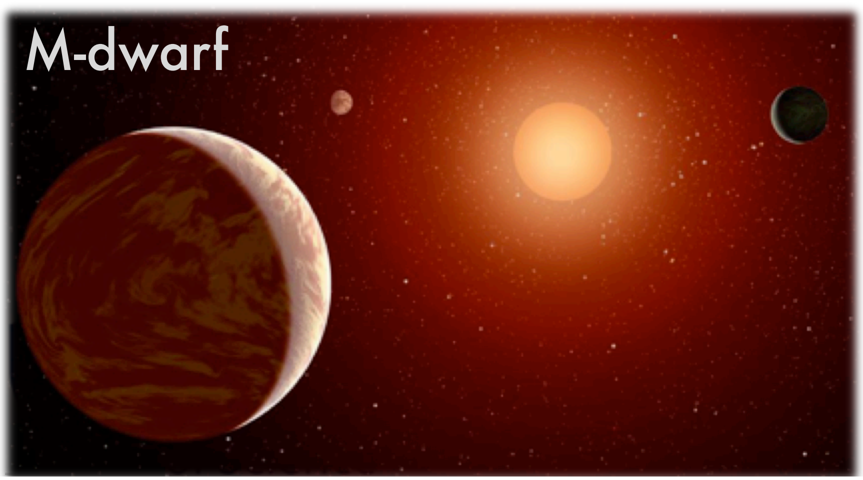
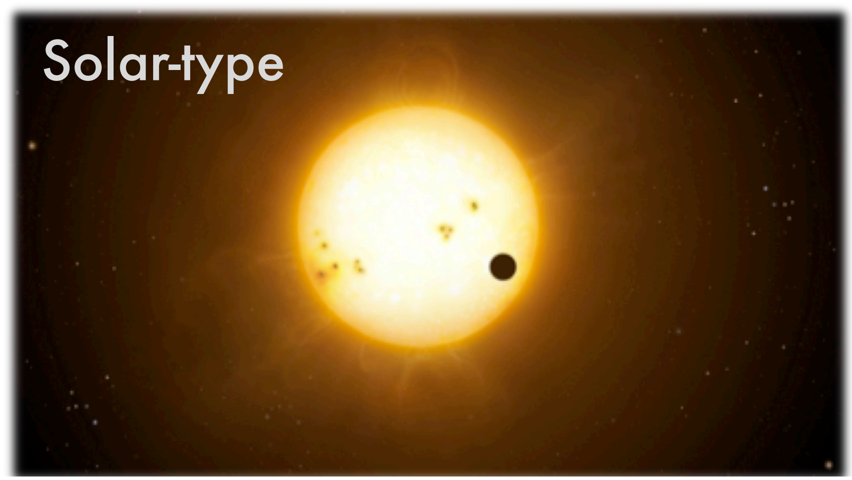
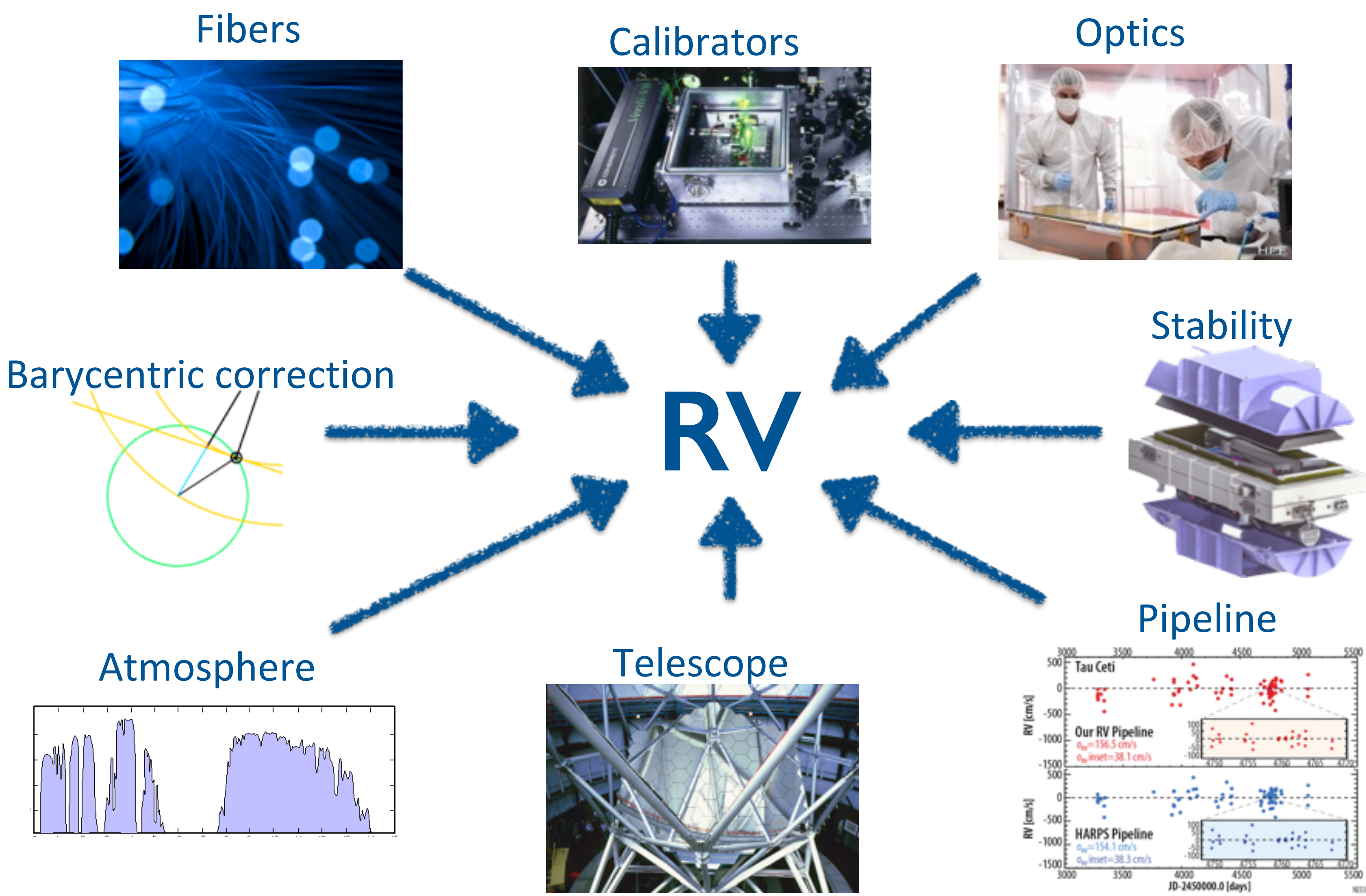








Achieving high instrumental RV precision is a multifaceted problem



Need not just a spectrometer-need a precision RV System

Advanced Environmental Control System

Laser combs, Etalon, Lamps

White Pupil Spectrometer

High Performance Detector

RV

Telescope Port System

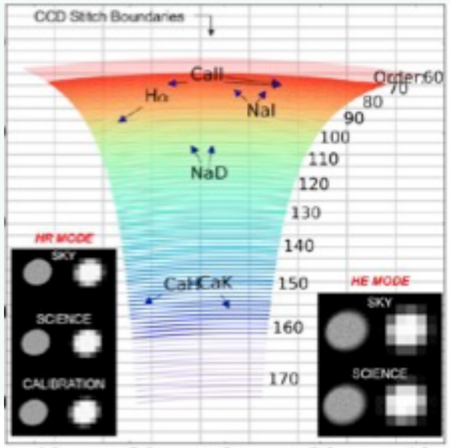
Unsliced high scrambling fiber feed

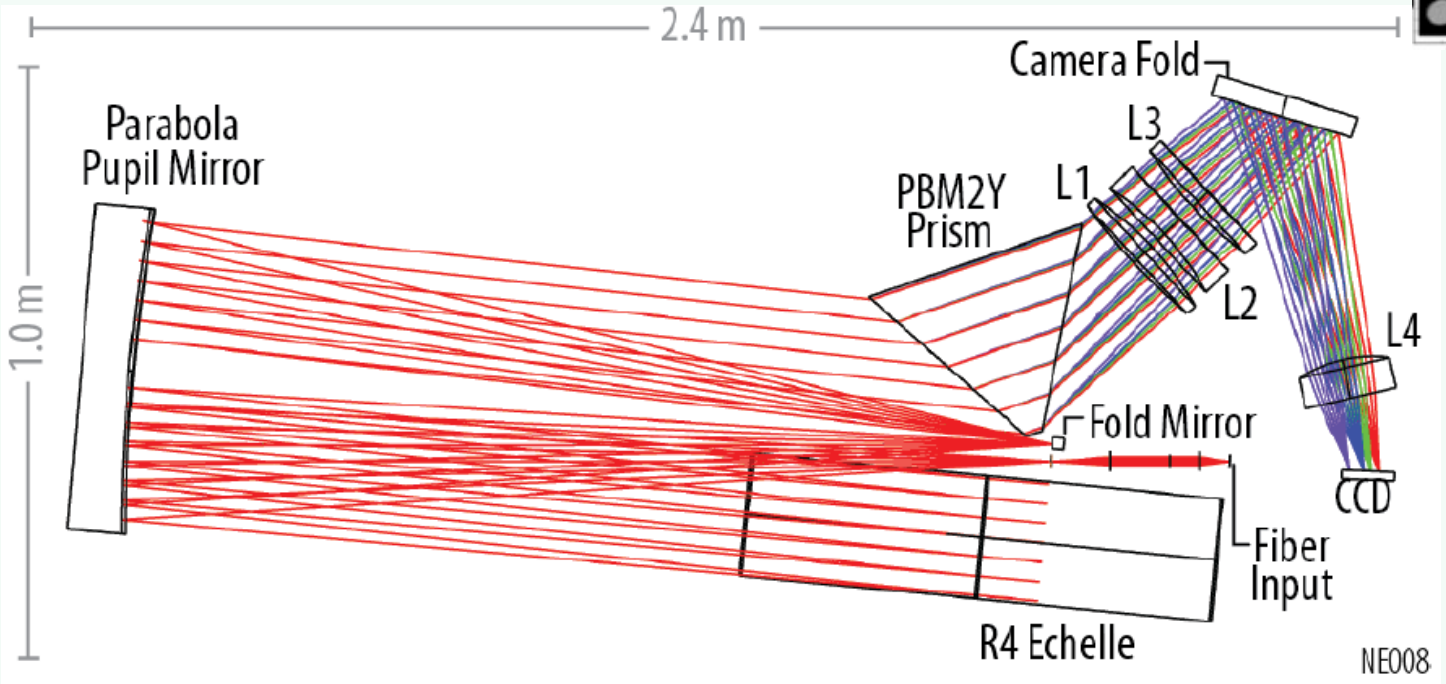
Data Reduction Pipeline

Chromatic Exposure Meter

NEID Optical Design

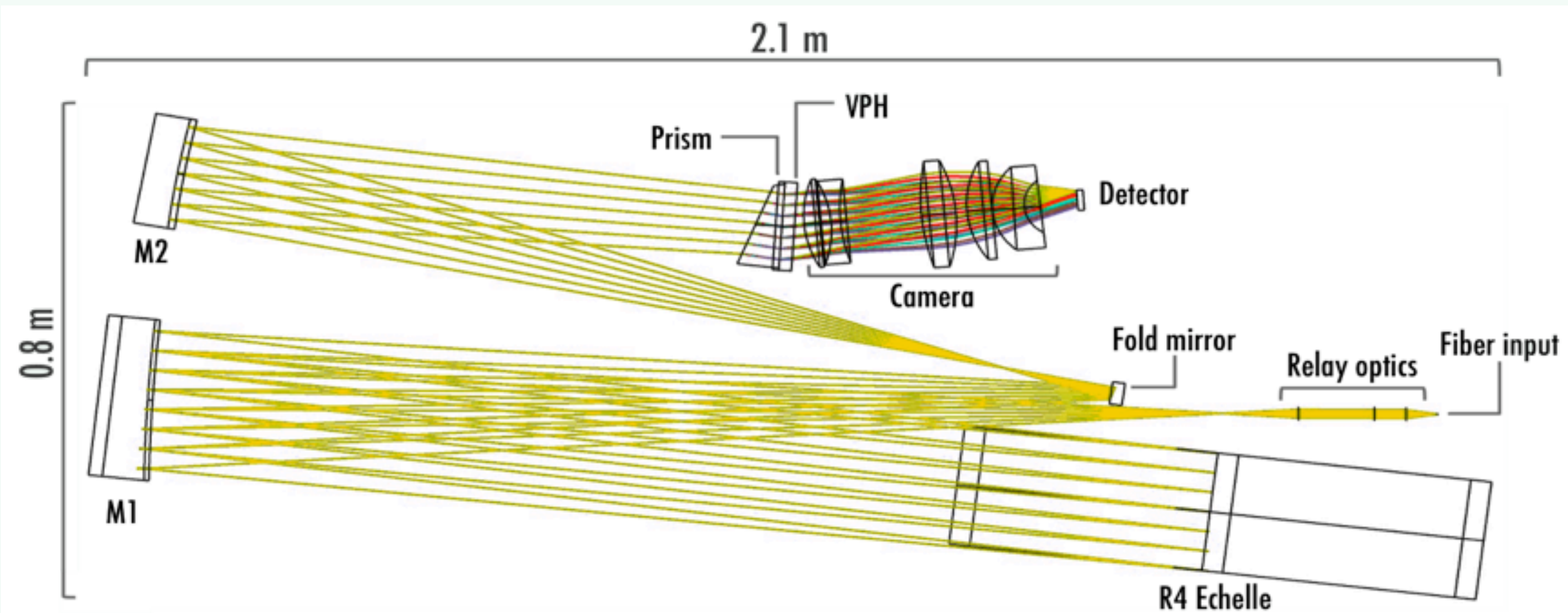
Spectral Resolution, R~120,000, Spanning 380-930nm

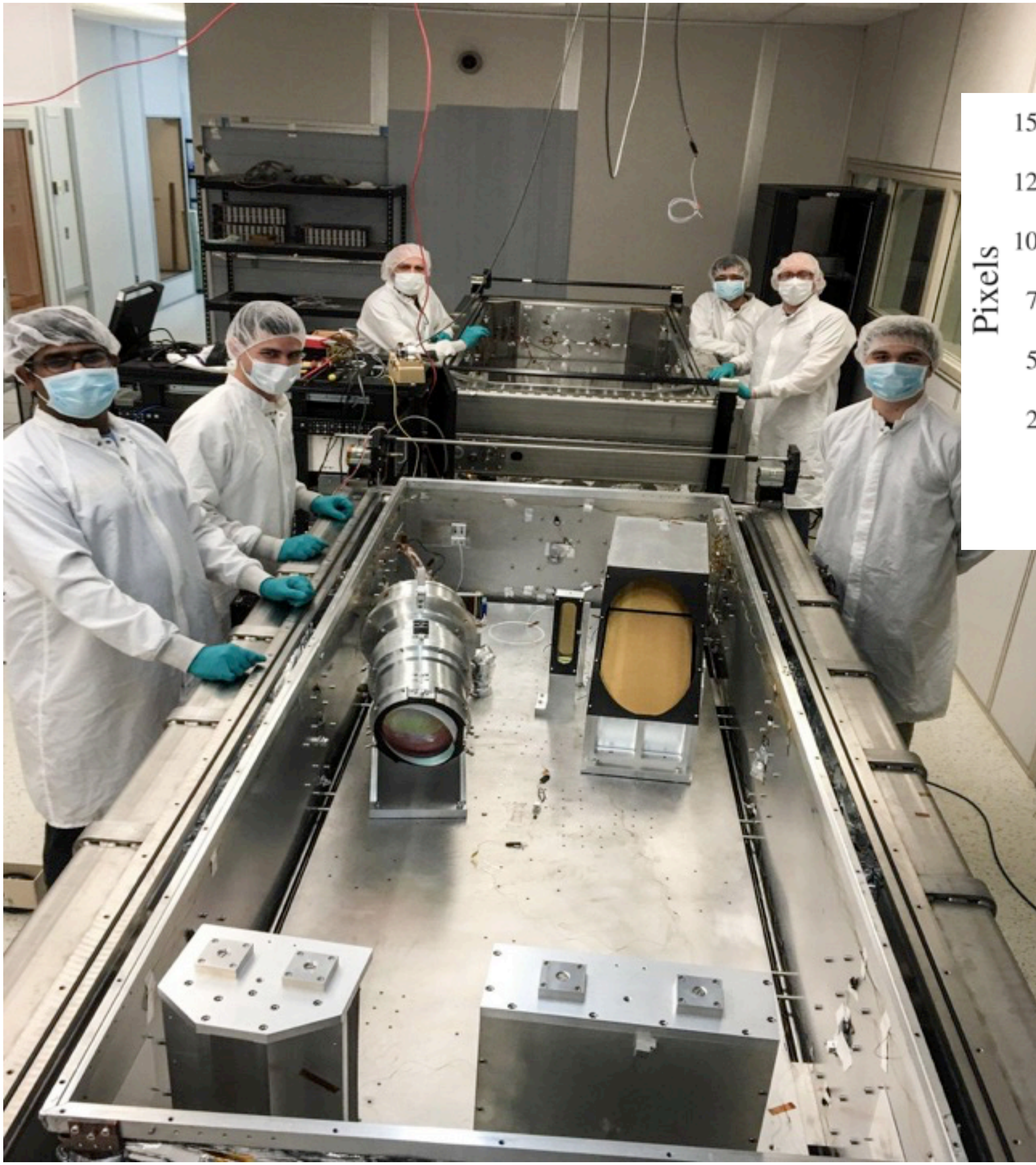


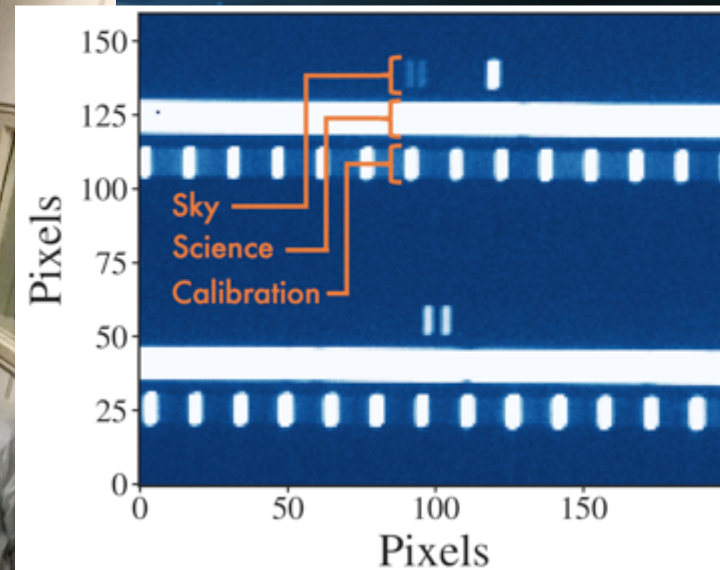


HPF Optical Design

Spectral Resolution, R~55,000, Spanning z, Y, J bands in the NIR

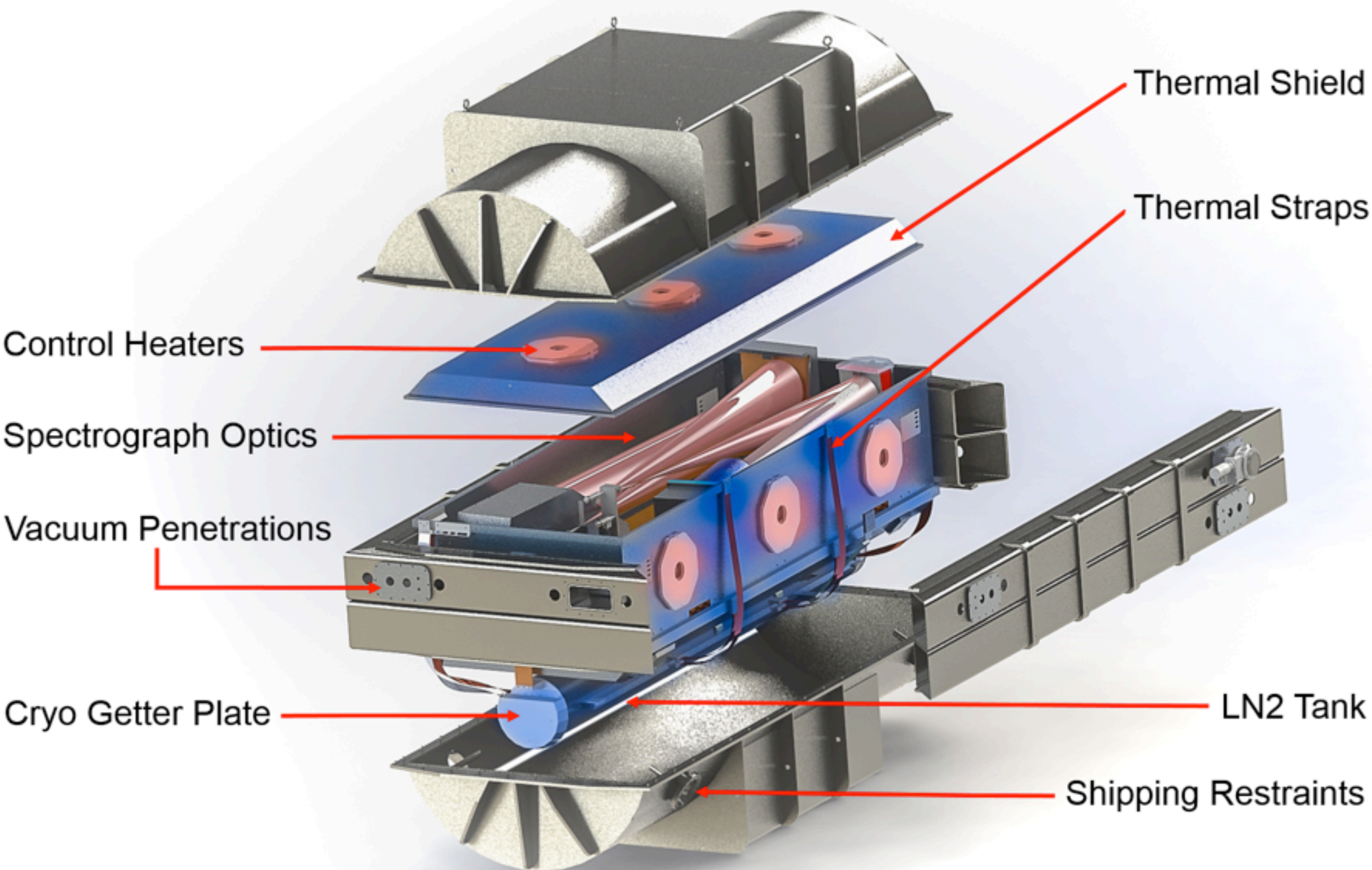






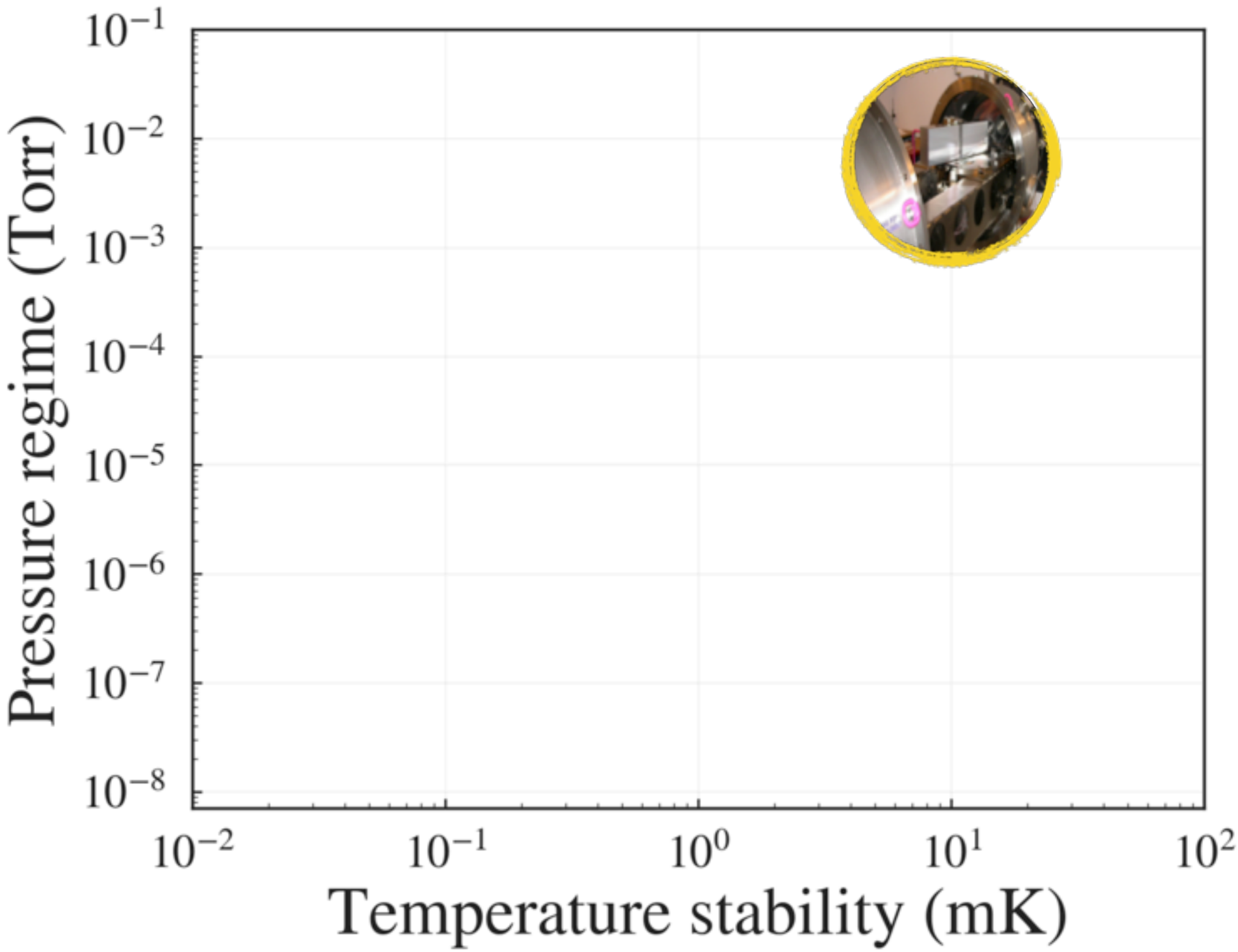
Considerable Effort Focused on minimizing Instrument Drift and ensuring the fibers track each other very closely

The vacuum chamber is essential to create a stable environment



Stefansson et al. 2016, Hearty et al. 2014

Pushing towards 10cm/s requires sub-milli-Kelvin instrument stability and high-quality vacuum chambers



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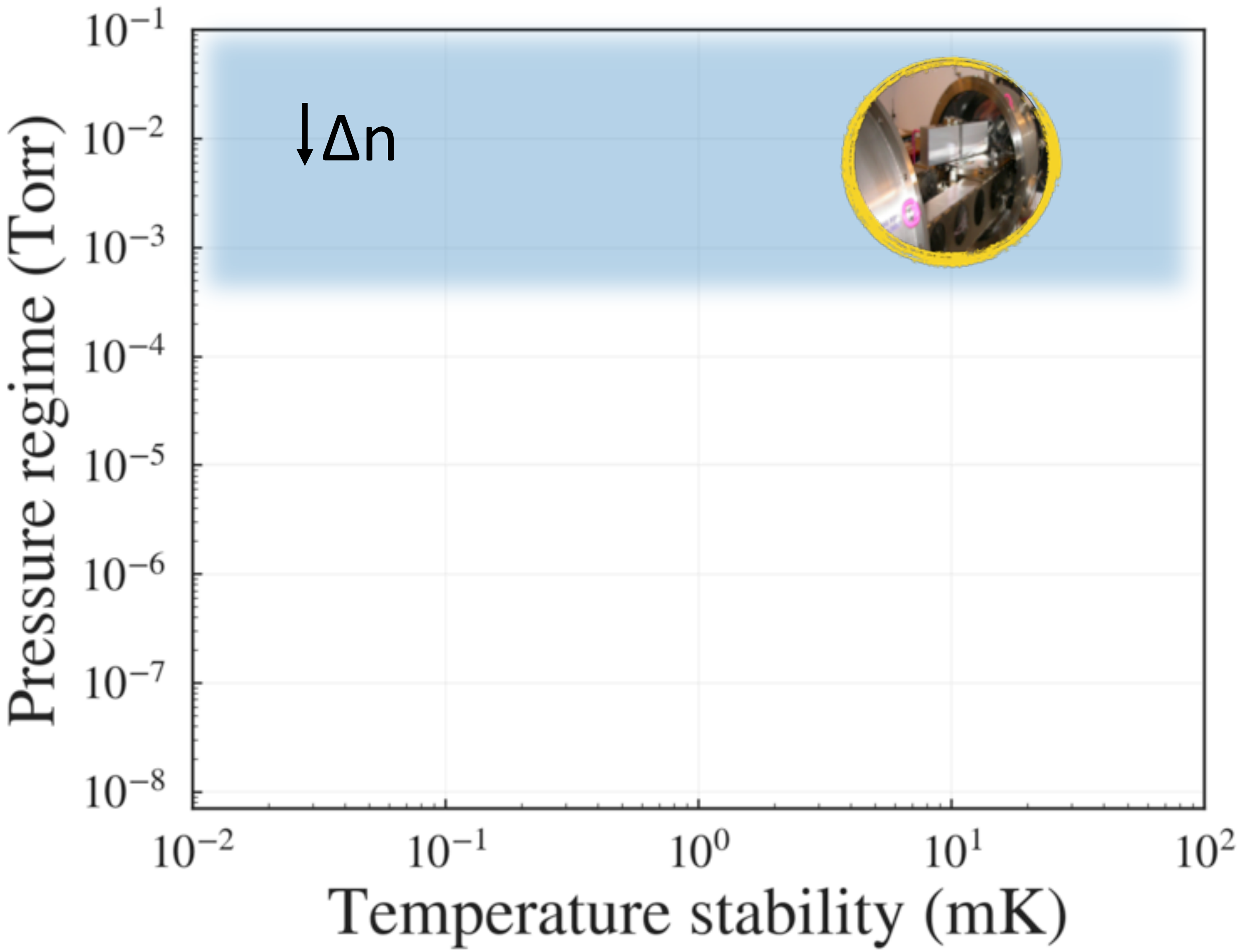

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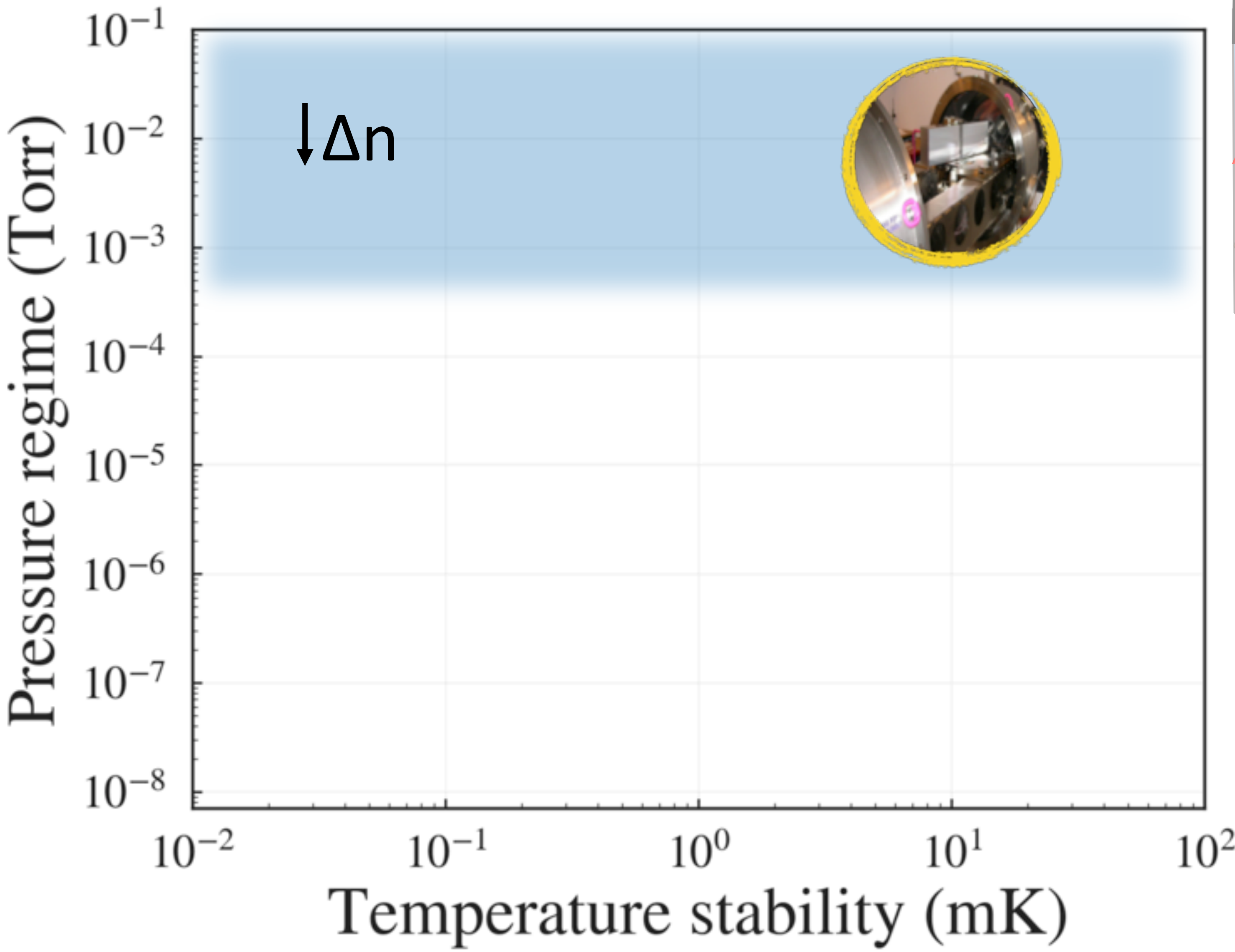

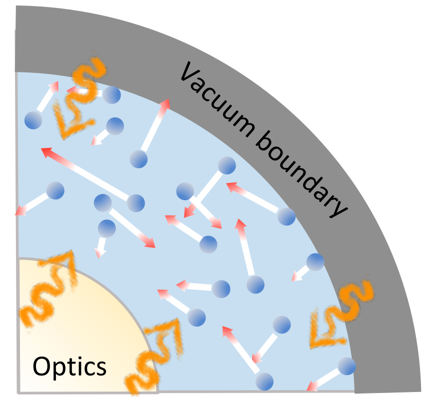

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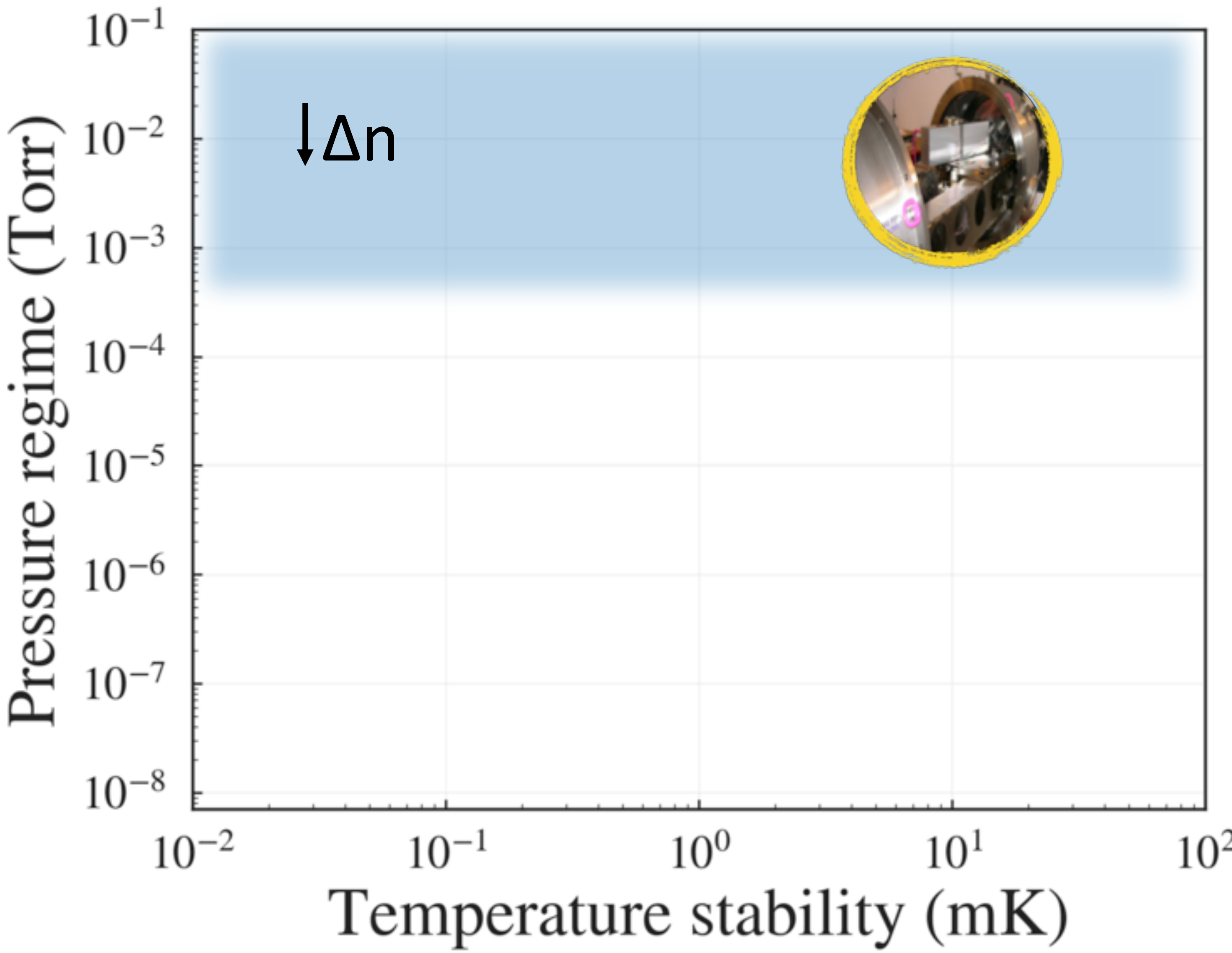

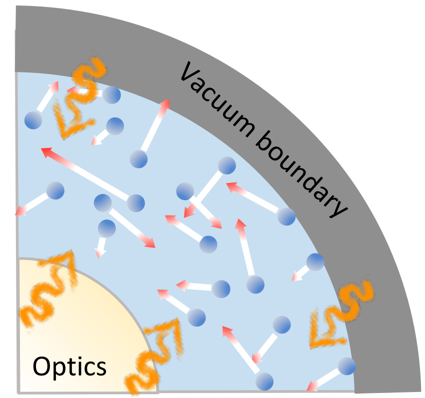

Convection
Radiation

NEID HPF

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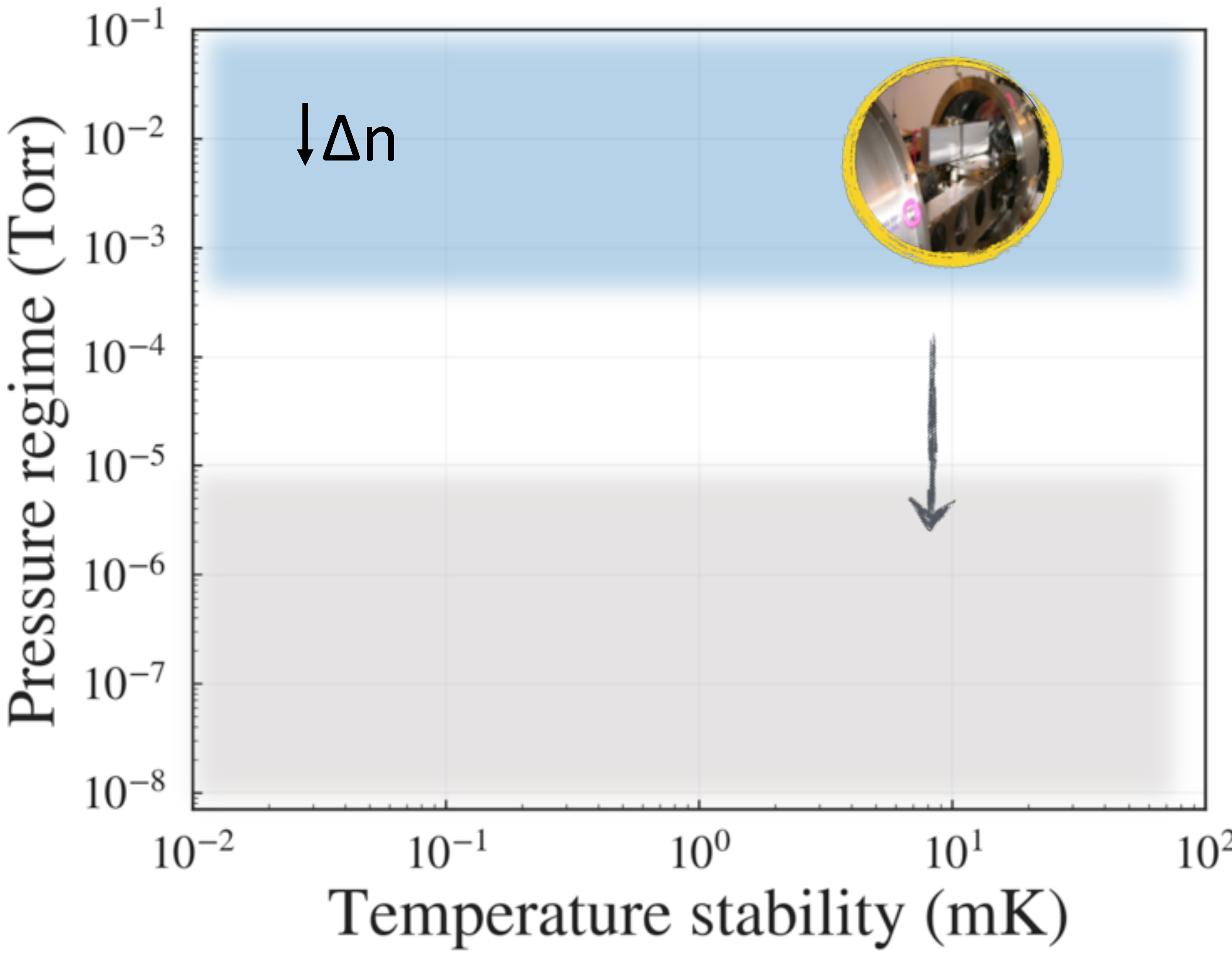
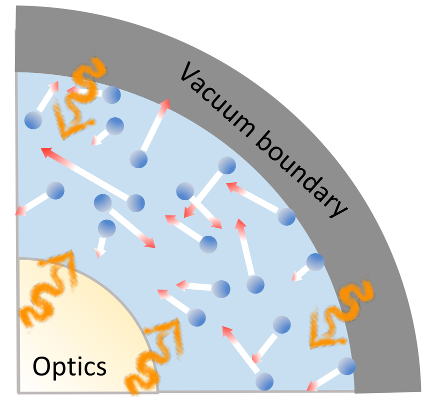
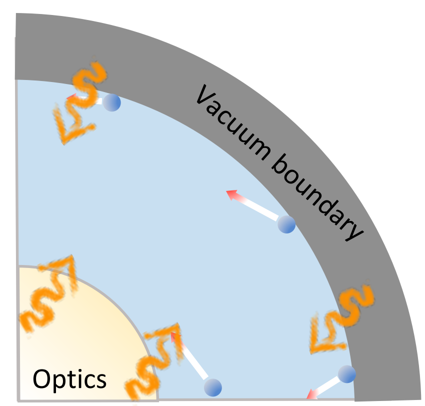




Convection
Radiation



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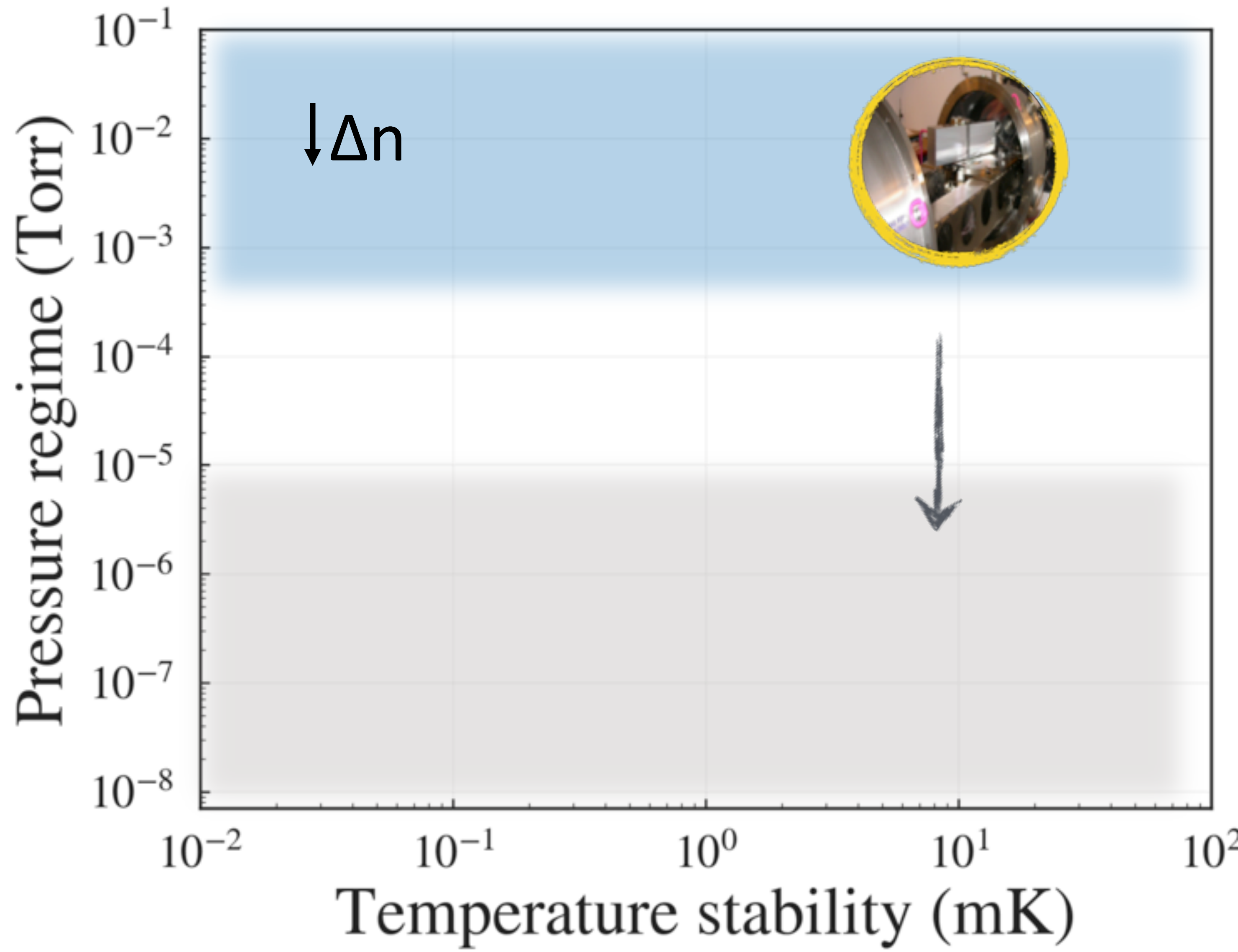
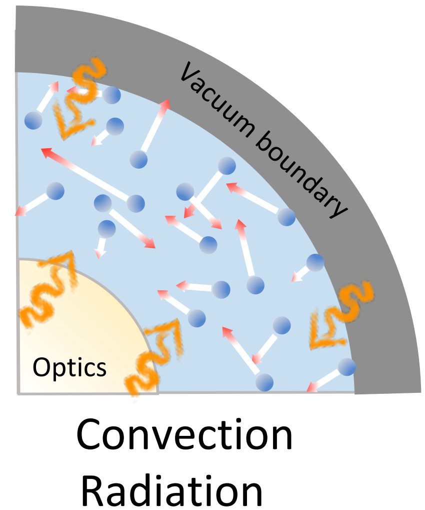
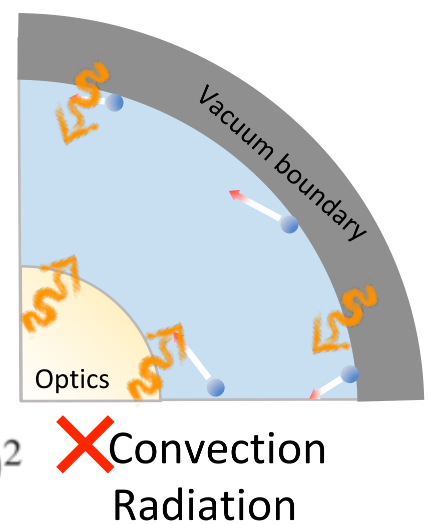
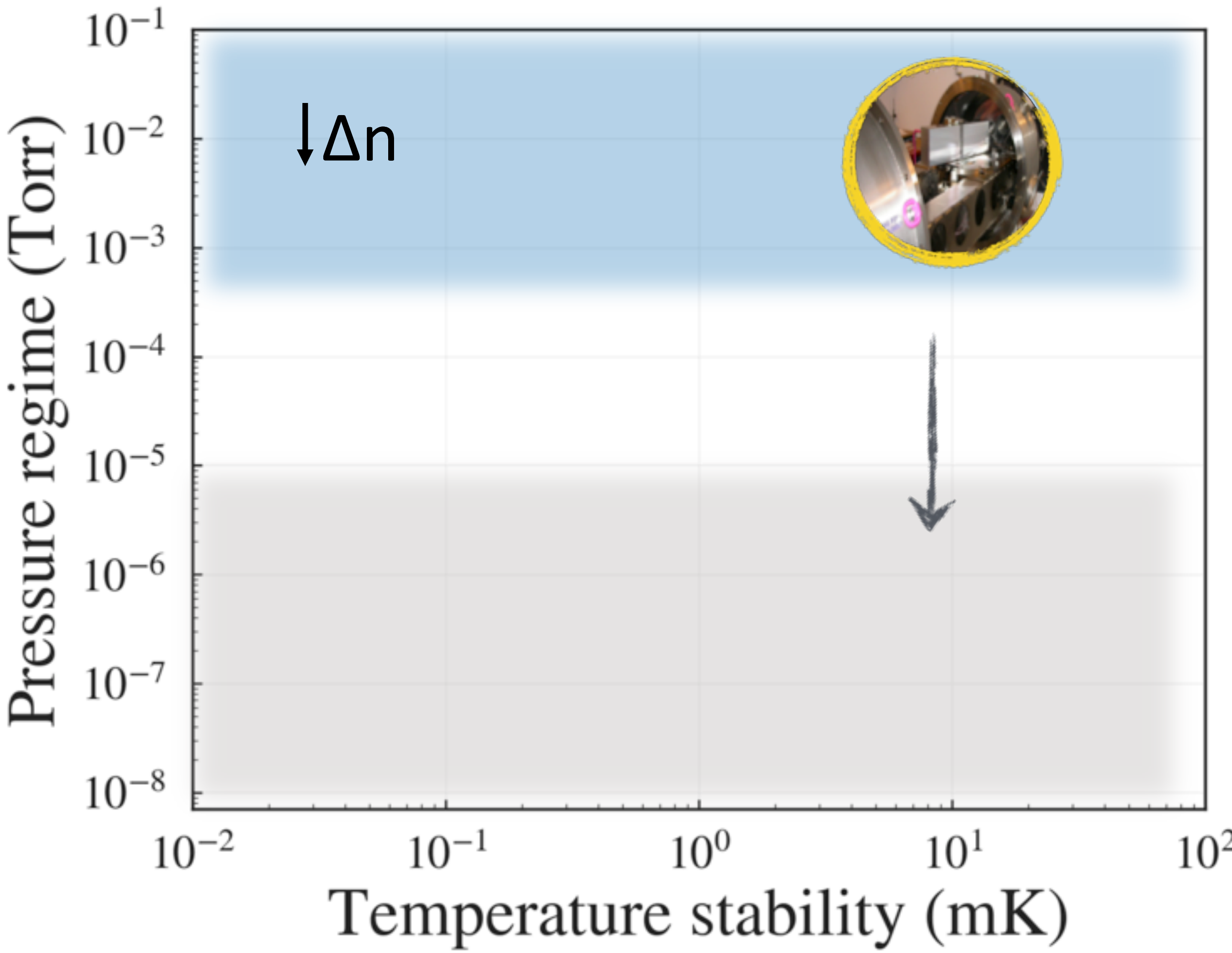
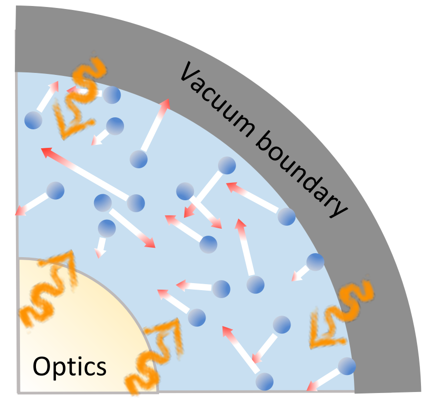




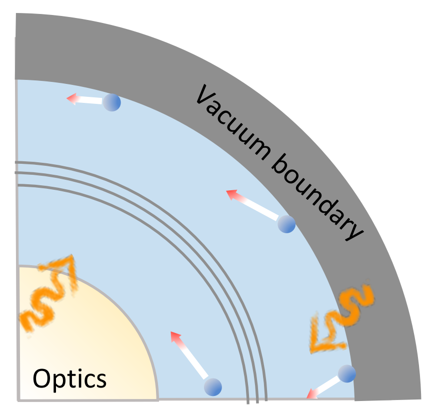


Pushing towards 10cm/s requires sub-milli-Kelvin instrument stability and high-quality vacuum chambers



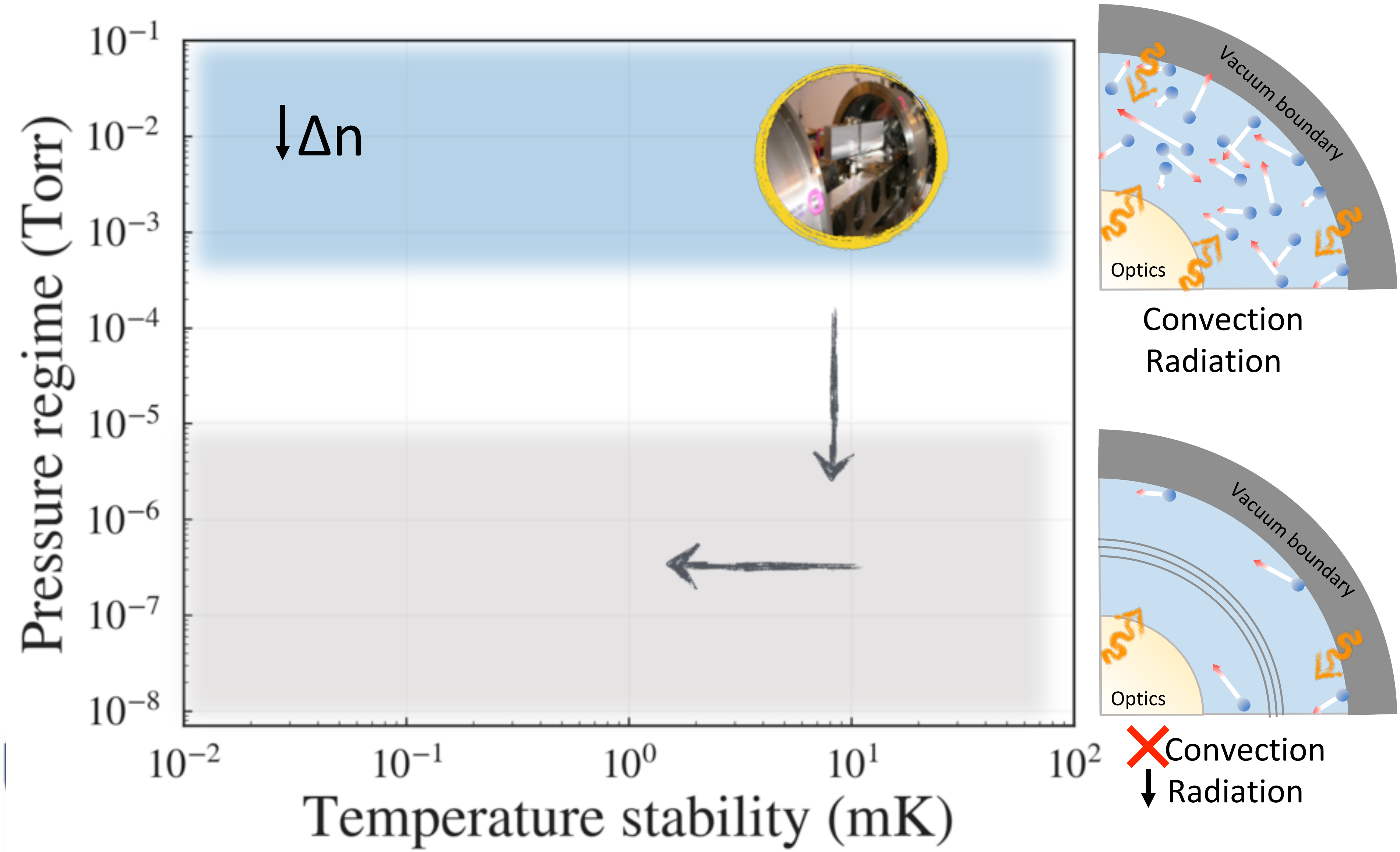


Convection
Radiation

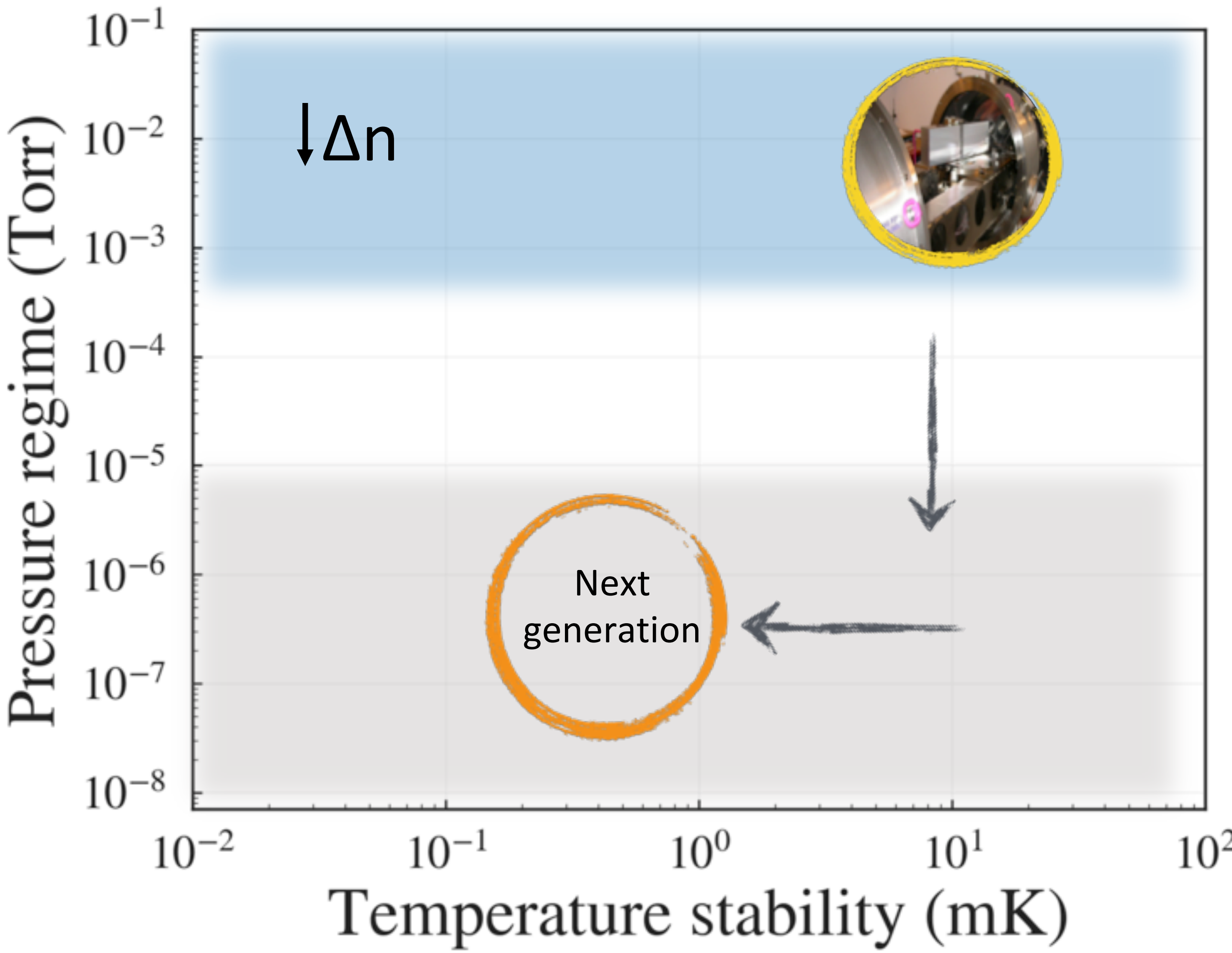


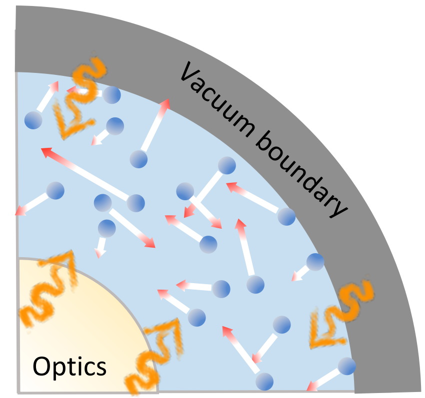
❌Convection
↓ Radiation

Pushing towards 10cm/s requires sub-milli-Kelvin instrument stability and high-quality vacuum chambers

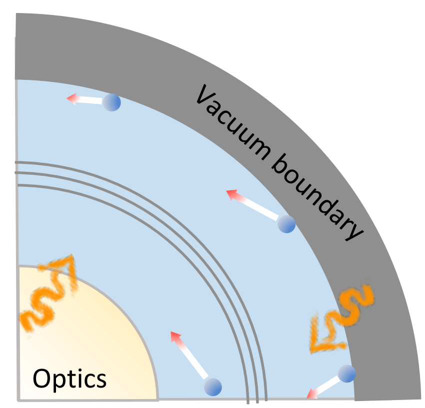


Pushing towards 10cm/s requires sub-milli-Kelvin instrument stability and high-quality vacuum chambers



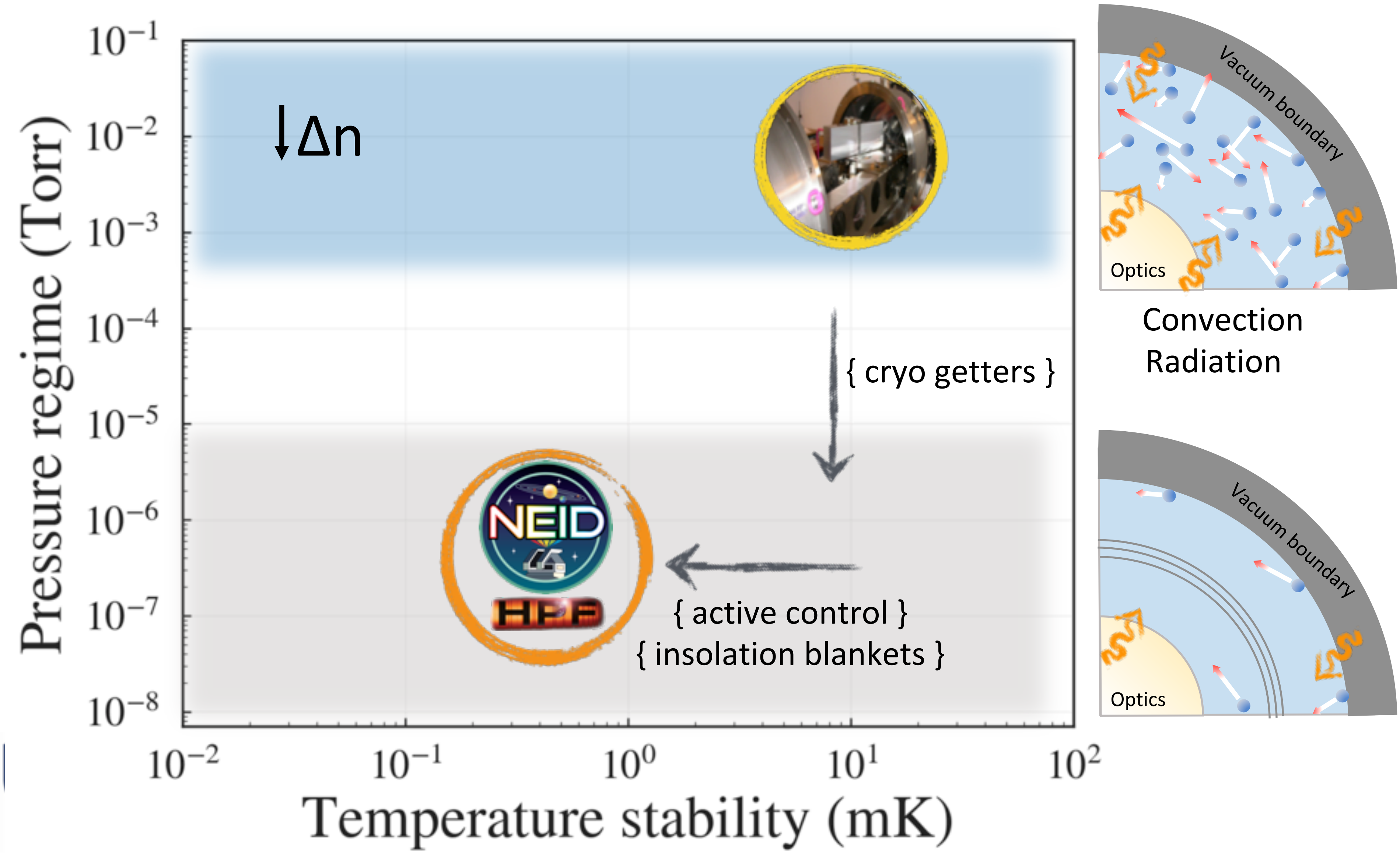


Convection
Radiation

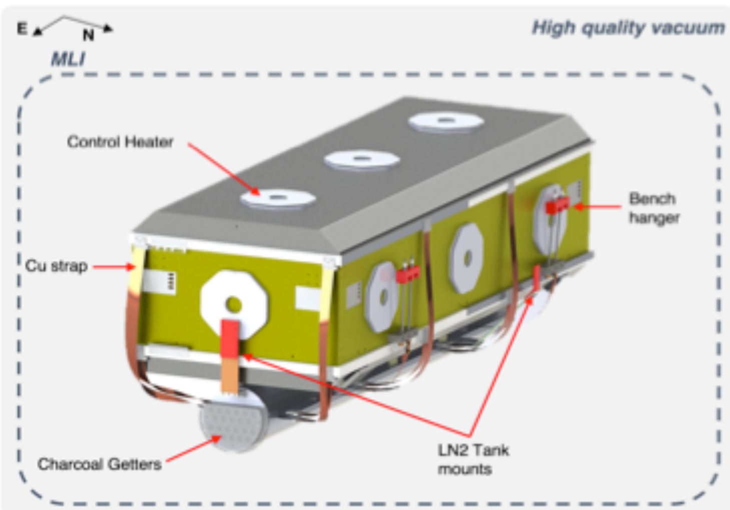


✗ Convection
↓ Radiation

Pushing towards 10cm/s requires sub-milli-Kelvin instrument stability and high-quality vacuum chambers

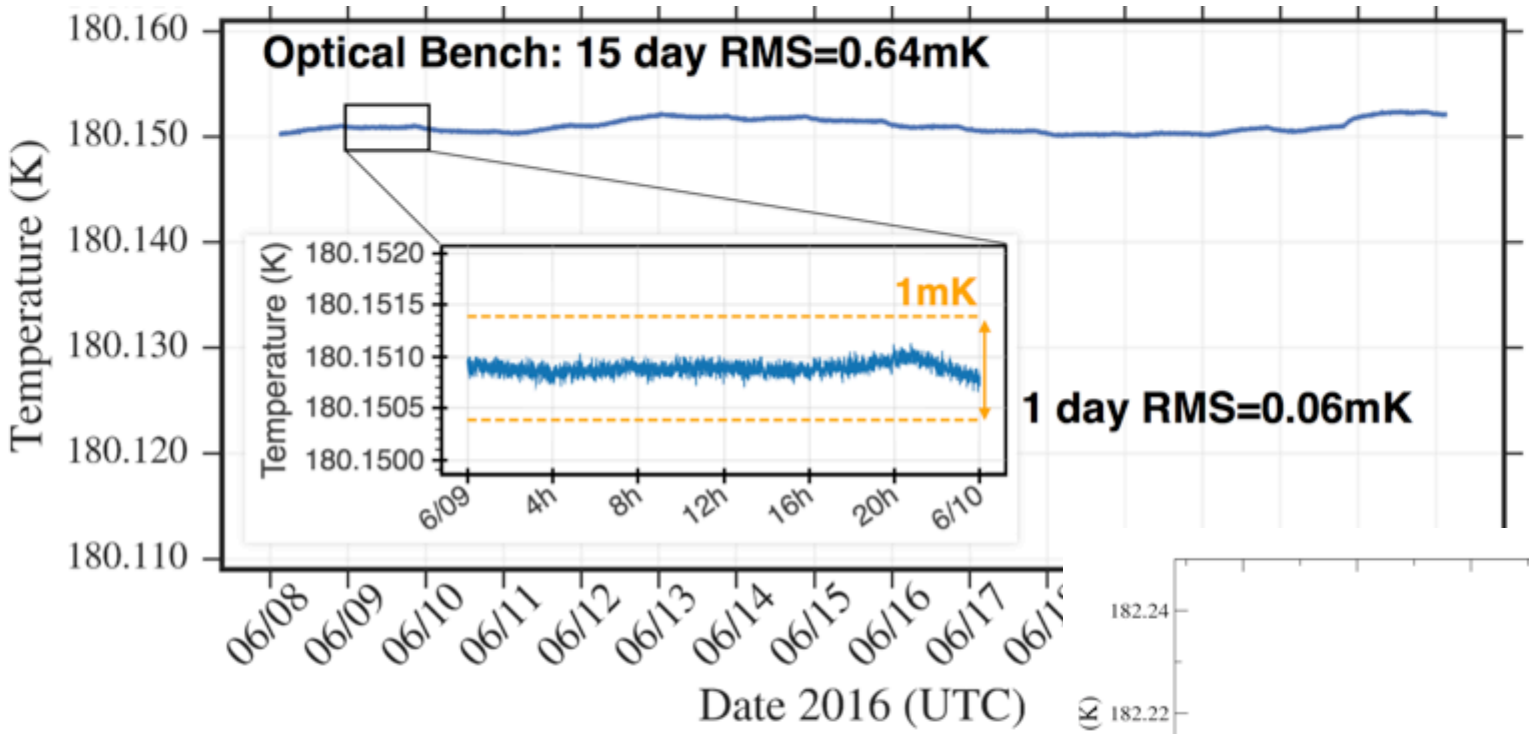


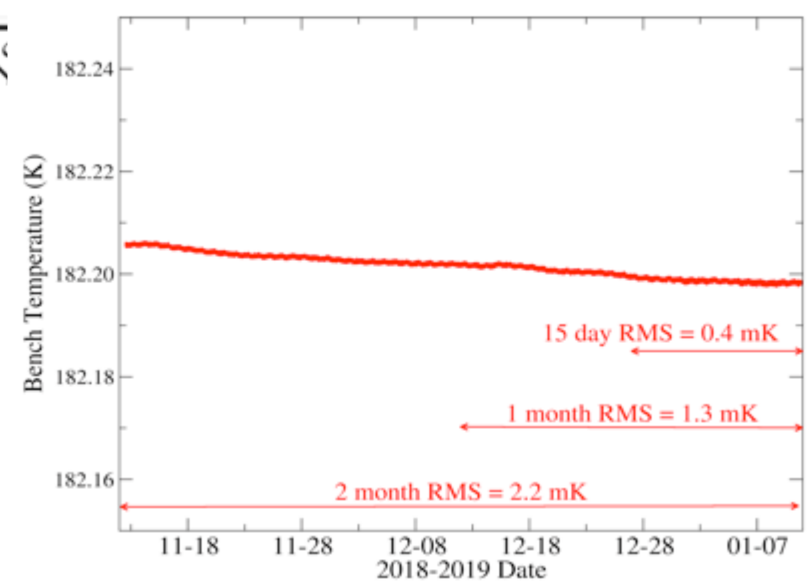
A temperature controlled radiation shield surrounds the optics to create a long-term stable black-body cavity



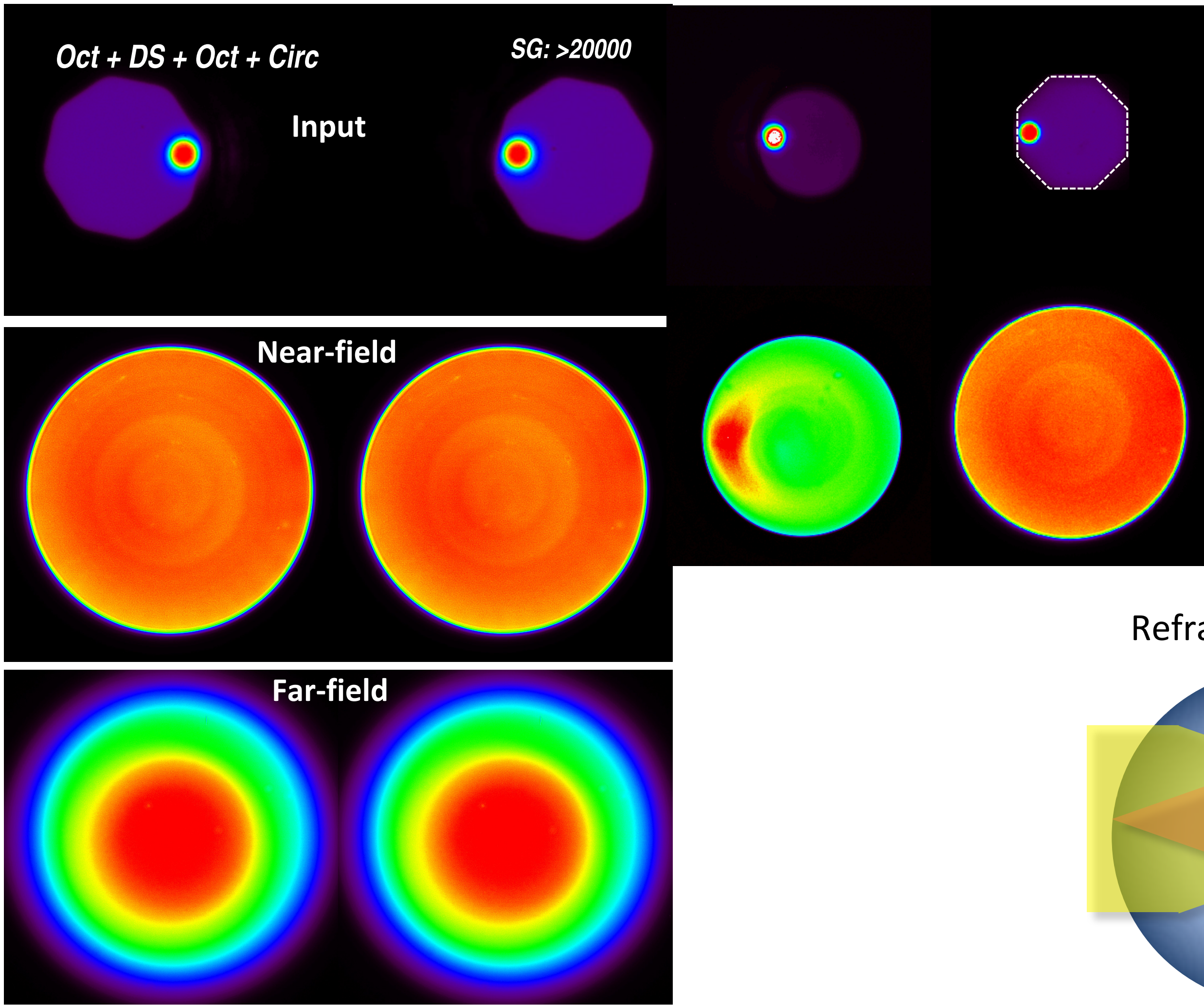
Stefansson et al. 2016, Hearty et al. 2014

The HPF and NEID have demonstrated long-term stable control at the 1mK temperature level and $<10^{-6}$ Torr pressure level

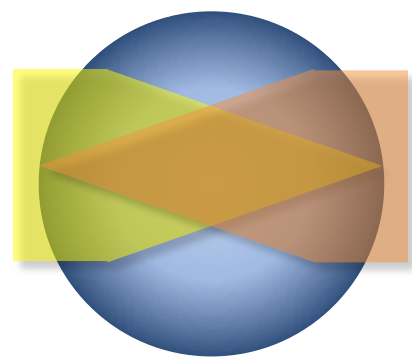




Precision RV System: Scrambling

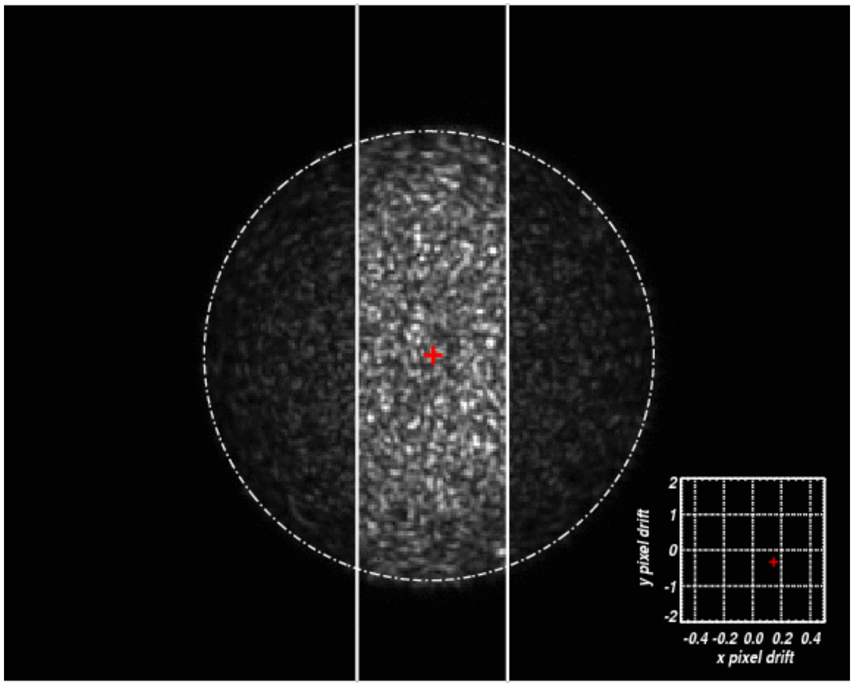


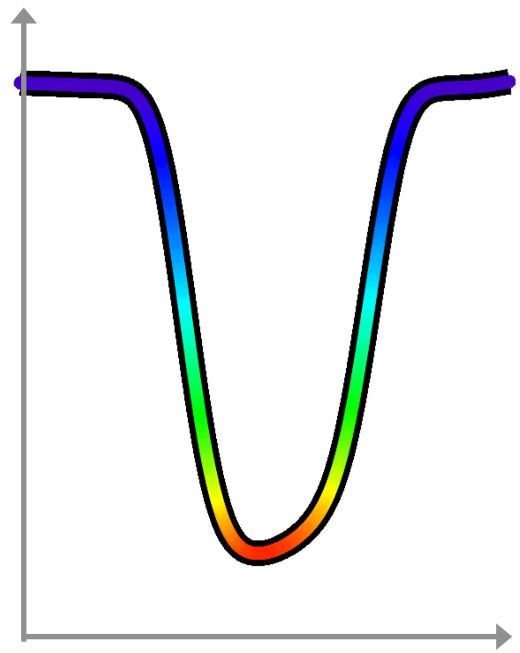
Use of octagonal fibers to enhance scrambling properties, coupled with a 'double scrambler' (Hunter & Ramsey 1992) that inverts the near and far fields of a pair of fibers to provide additional scrambling



Has to be combined with excellent guiding of stellar image on fiber- better than 0.05''

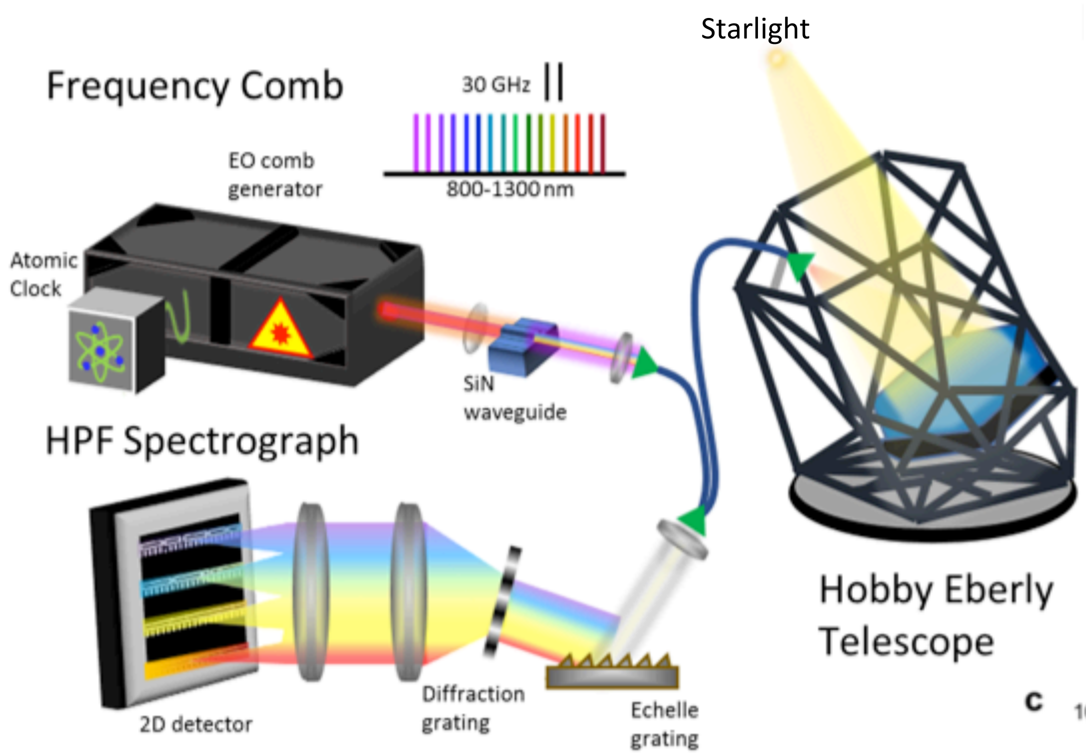
Precision RV System: Modal Noise

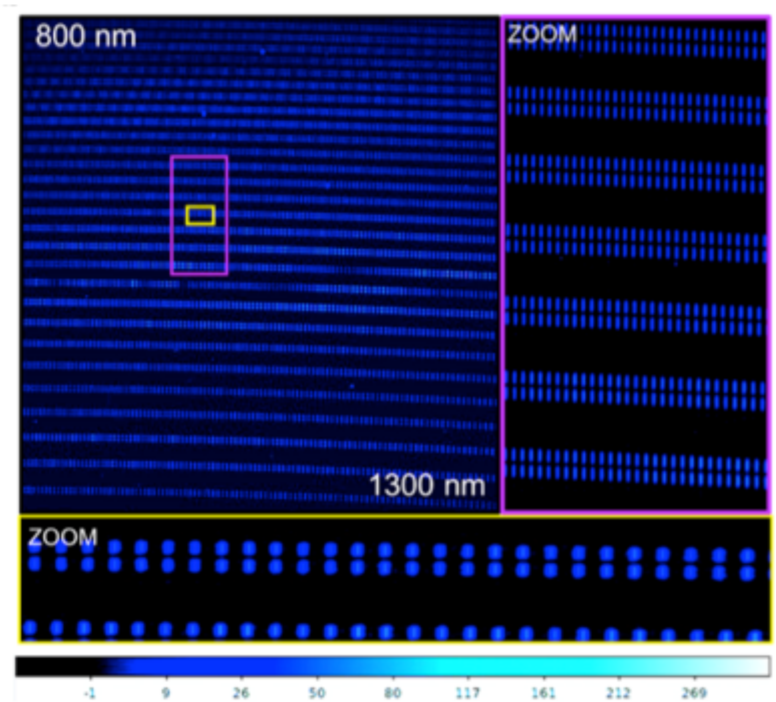


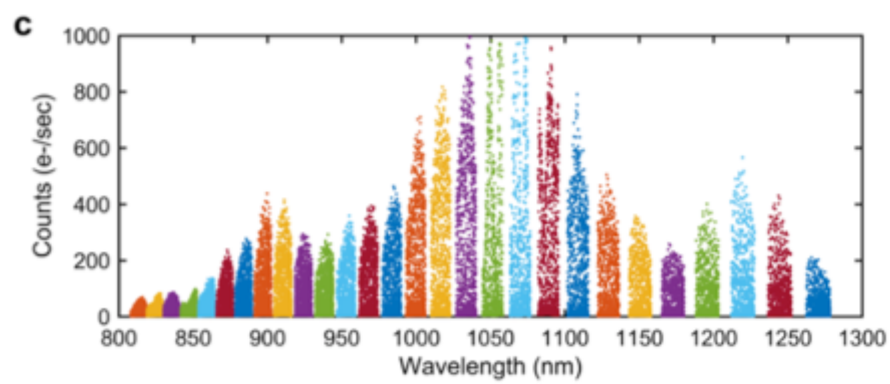


Optical Fibers are waveguides- finite TE and TM modes propagating in waveguide can lead to 'modal noise' − need to agitate fibers to mix modes.

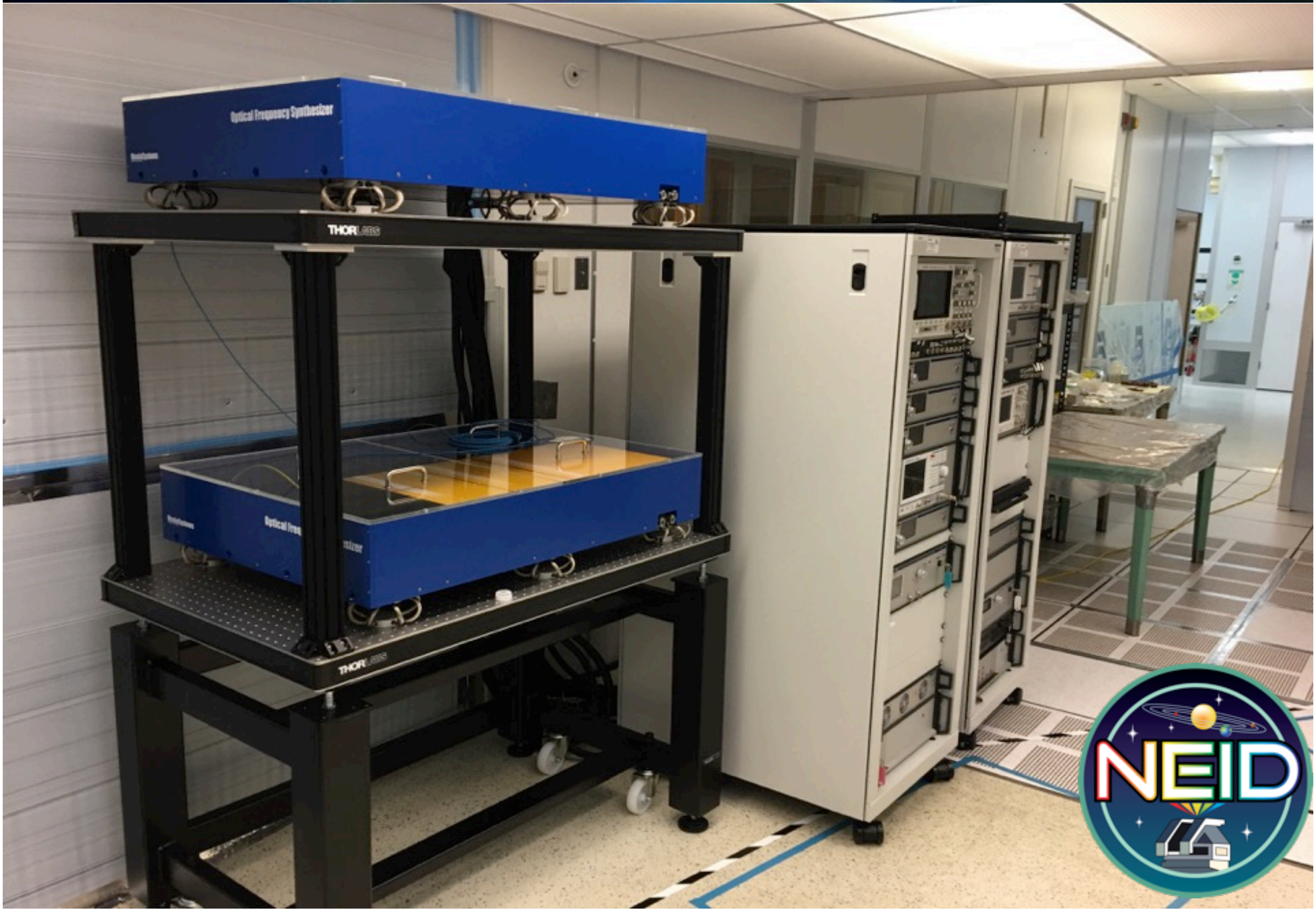
Both HPF and NEID use state-of-the-art Frequency Stabilized Laser Combs for cm/s calibration stability

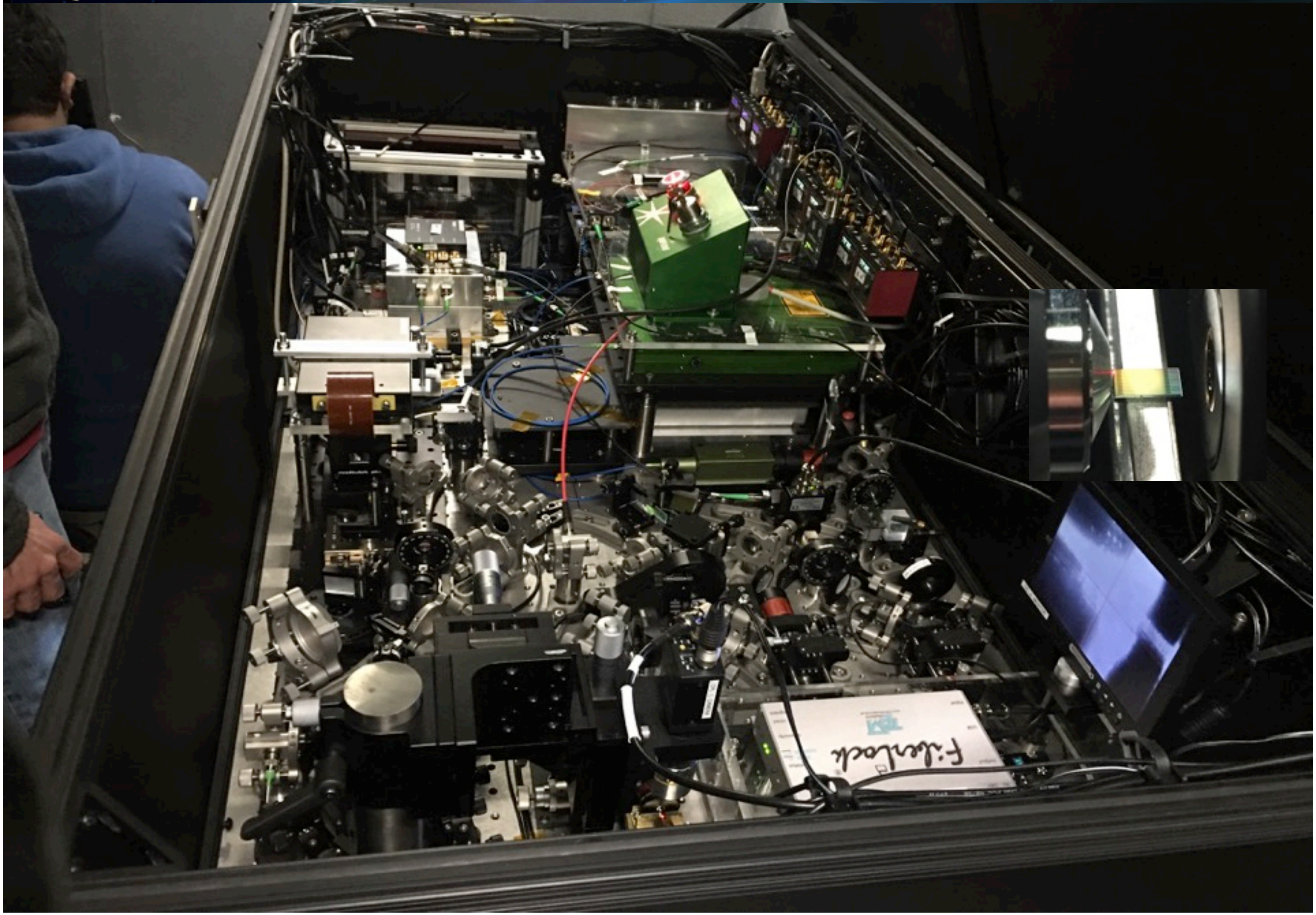






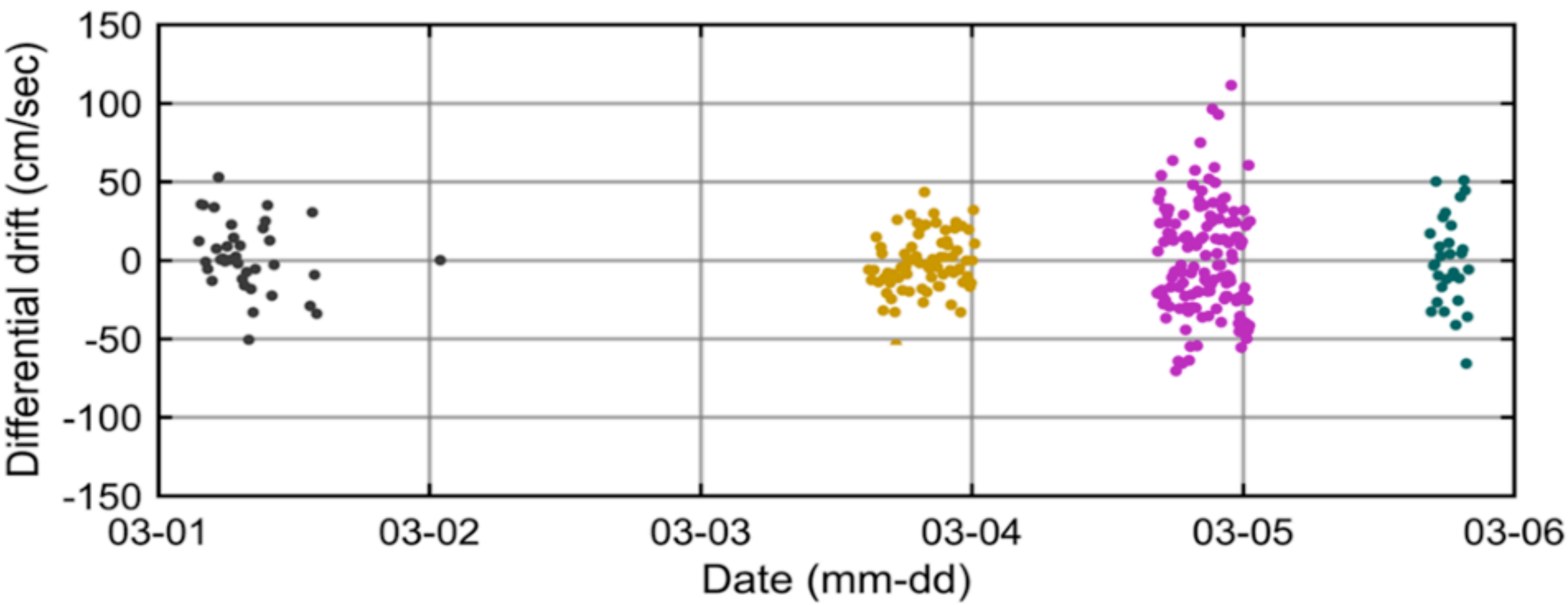
NEID HPF



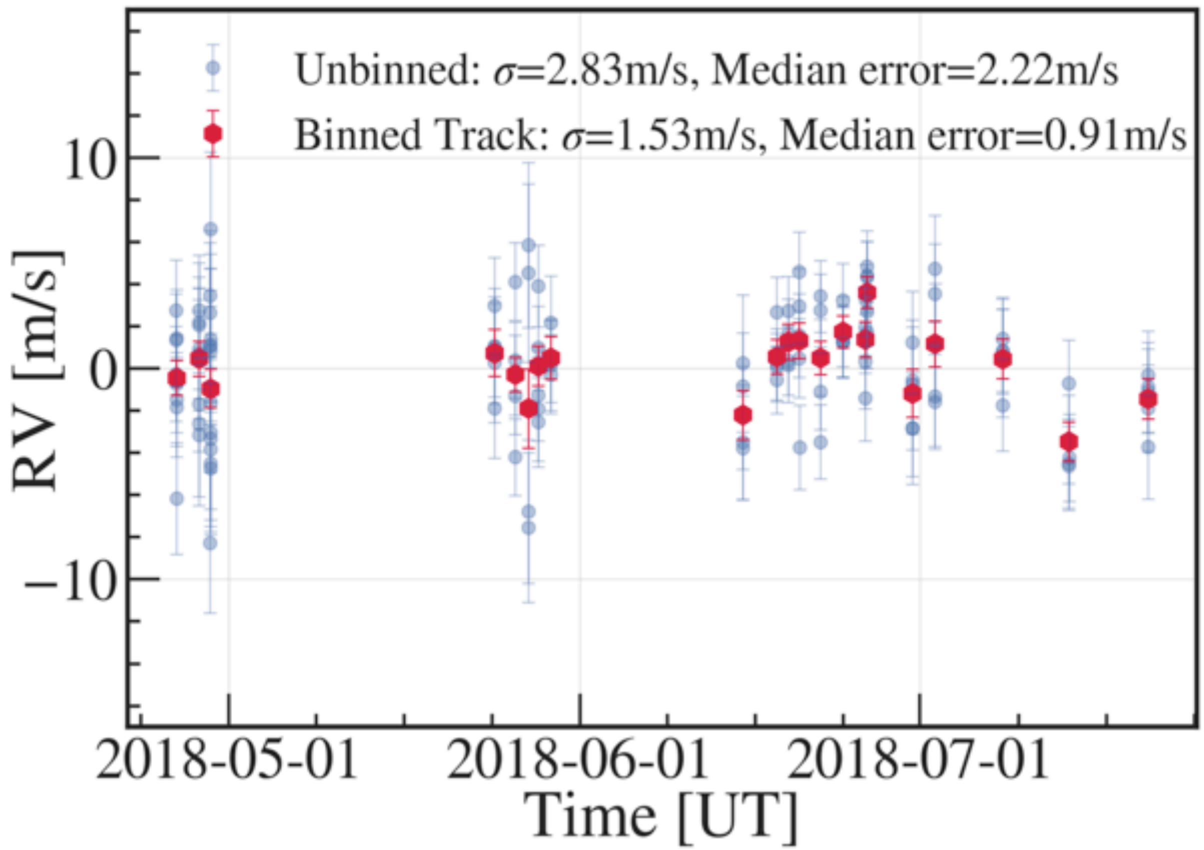

Fiberlock

Laser Comb Stability: The two fibers track each other over many days to a precision of 20cm/s (in near-infrared, with H2RG)

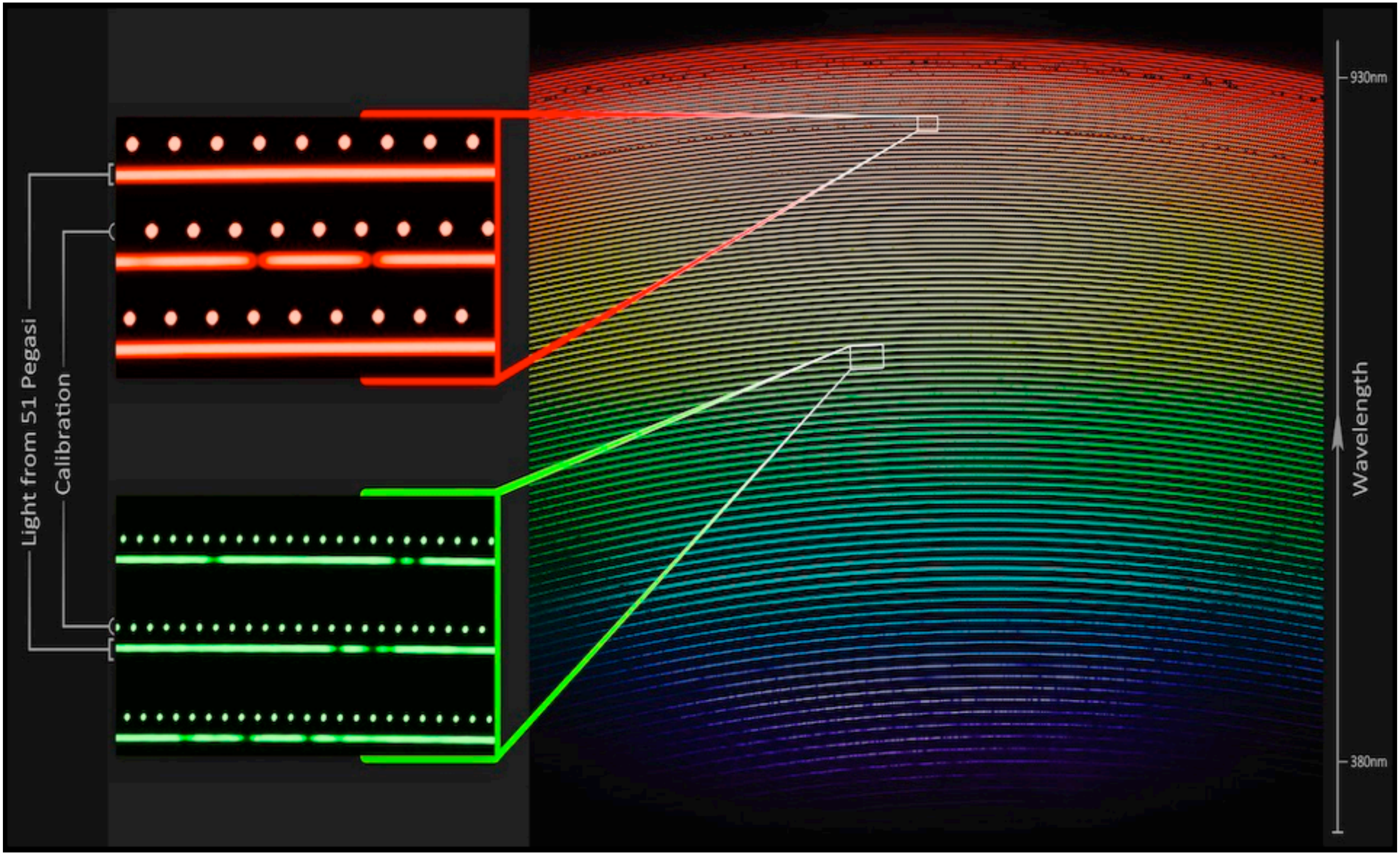
Has been running for almost two years, operating almost continuously and in continuous use as a calibrator for HPF!



HPF: Highest Precision NIR RVs Reported



Barnards Star (GJ 699) , 1.53 m/s – Metcalf et al. 2019

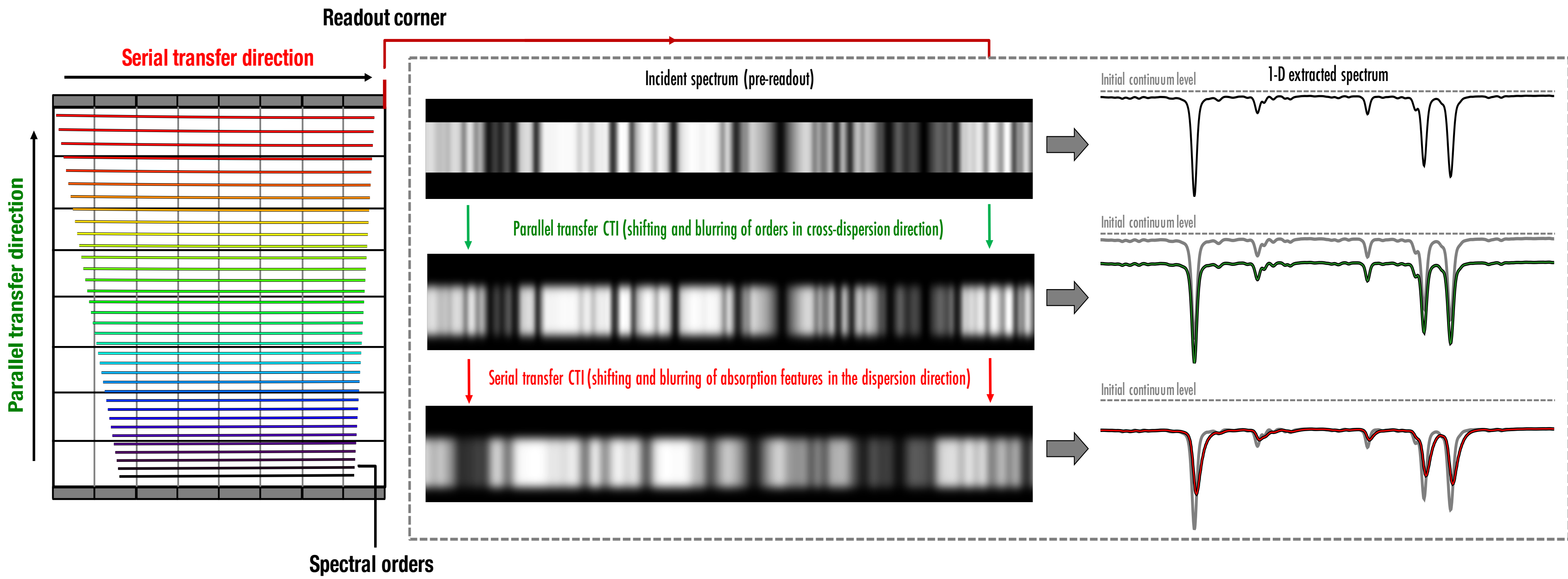


NEID First Light Image

Detectors

Charge transfer (*in)* efficiency. Bouchy 2009, Blake 2017, Halverson 2018

Want CCDs with CTI > 0.999999 (six 9s)

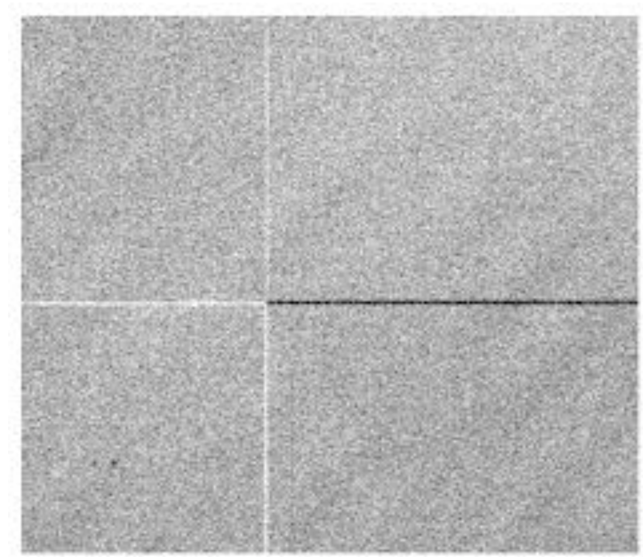


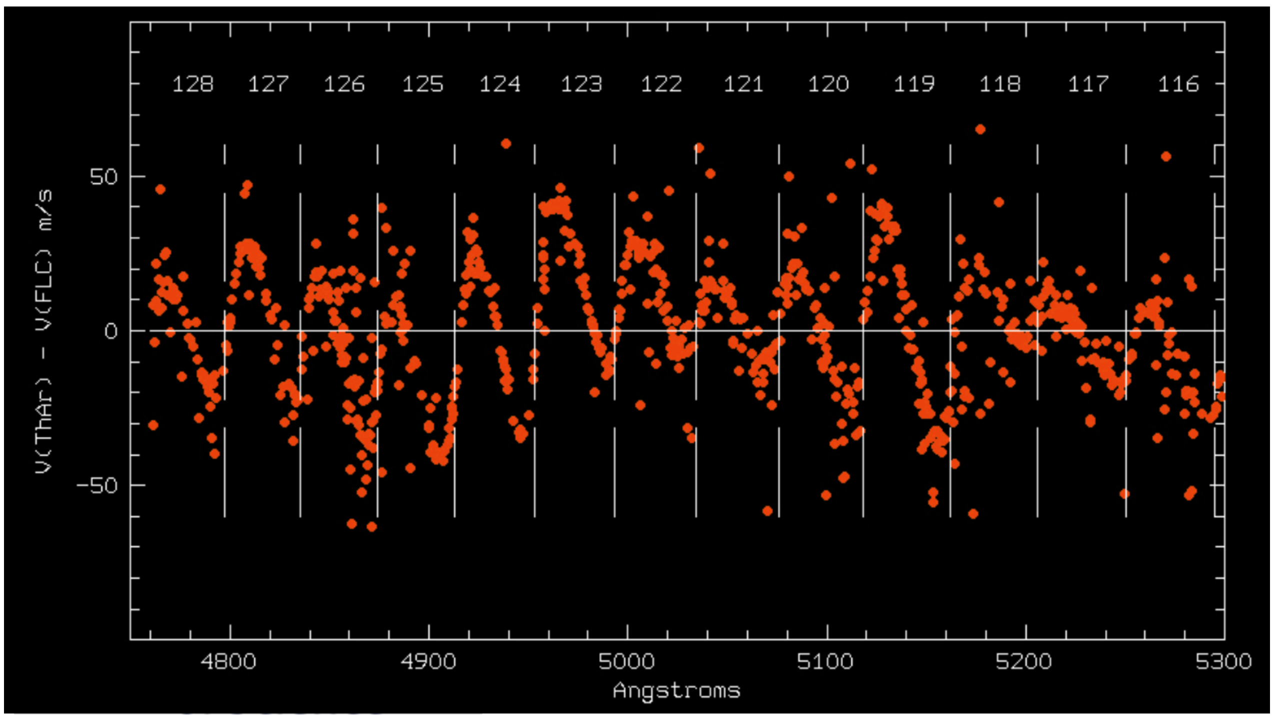
Detectors

CCD stich boundaries

Molaro 2013, Coffinet et al. 2019

1 year RV signals on many stars perfectly correlated with Earth's barycentric correction! Removing lines crossing stick boundaries diminishes signal – Dumusque et al. 2015



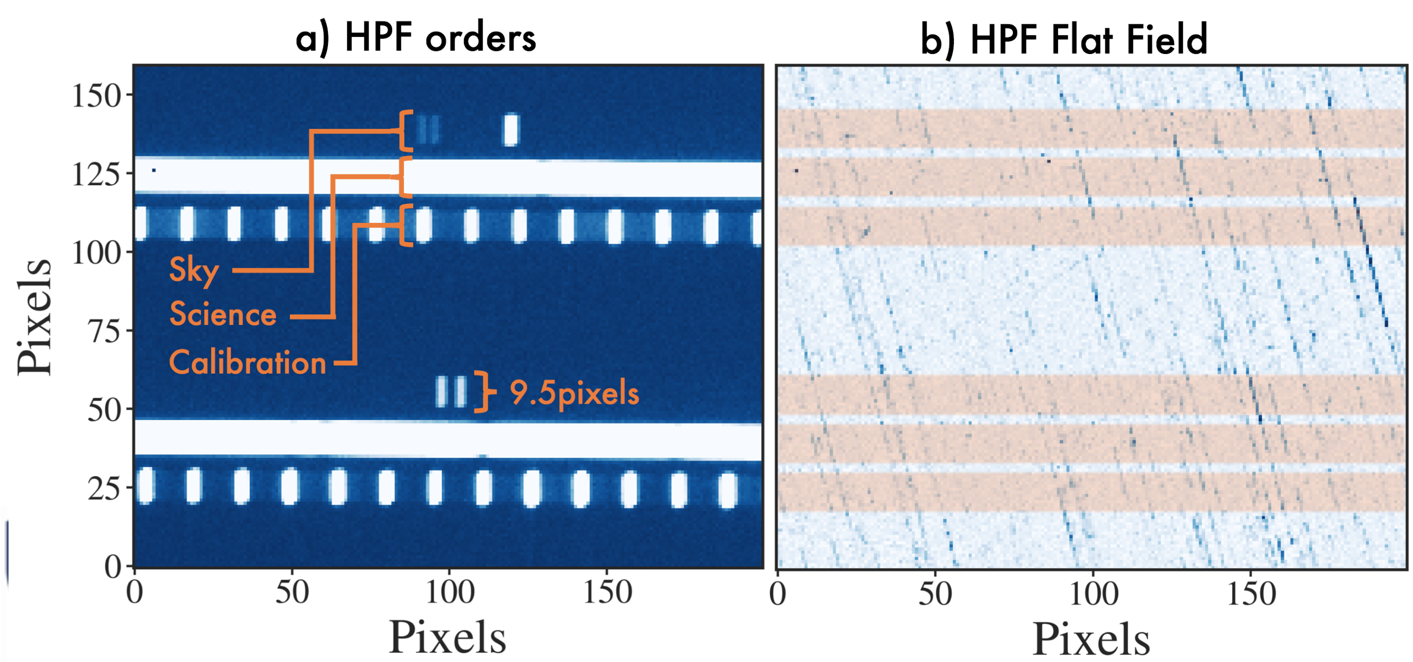


Detectors

CrossHatching in NIR Detectors

Ninan et al. 2019

Crystalline Defects in the HgCdTe material during the growth of the detector layer.
Sub-pixel QE changes. Don't flat field out accurately

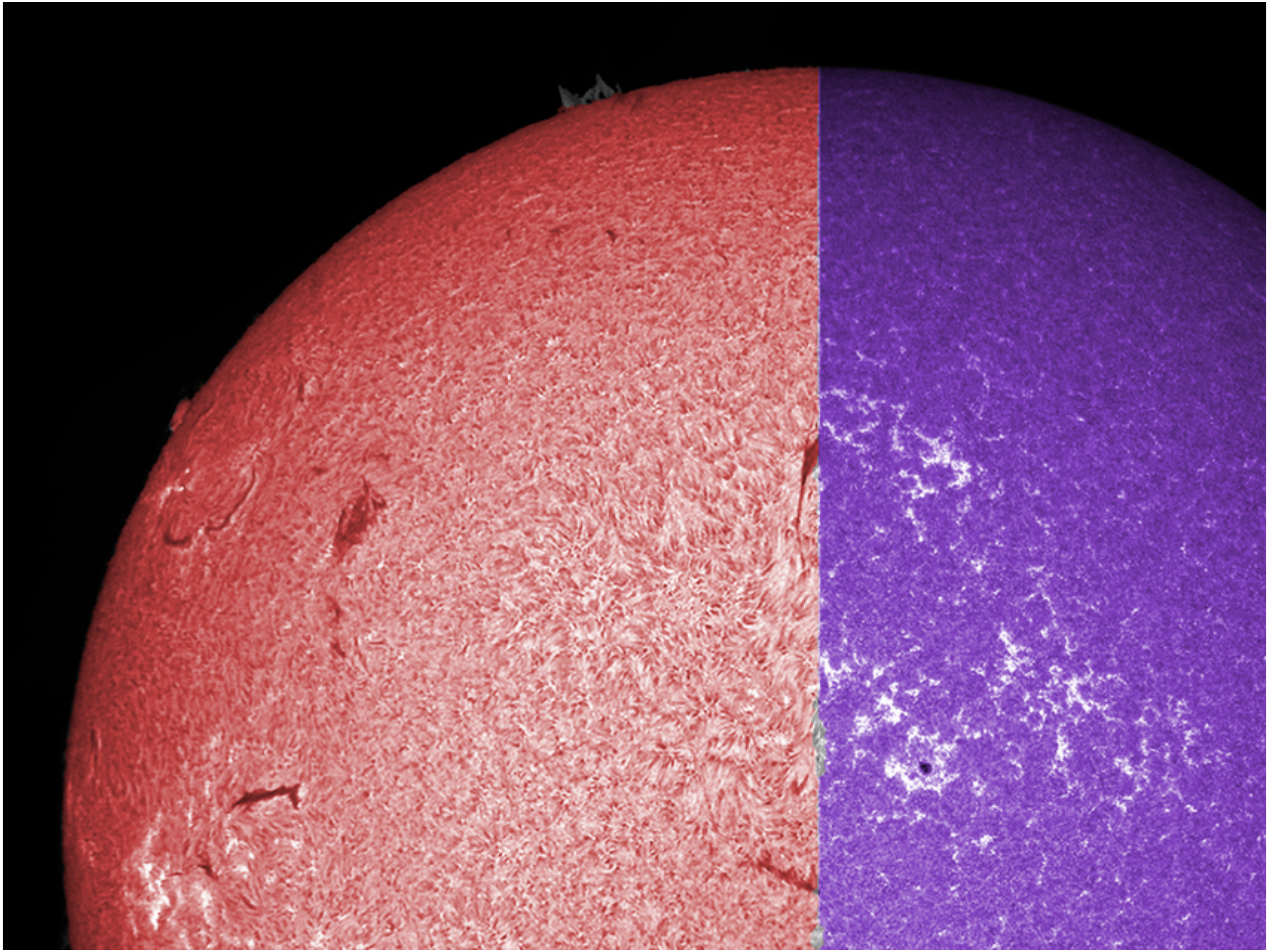


Detectors

Temperature change in Detectors

At 10cm/s (a few nm on the detector) reading out the
CCD can warp the active surface enough to be a detectable RV change!

Very New Territory!
Have to employ special clocking schemes to even out the power dissipation during the Reset-Integrate-Readout cycle



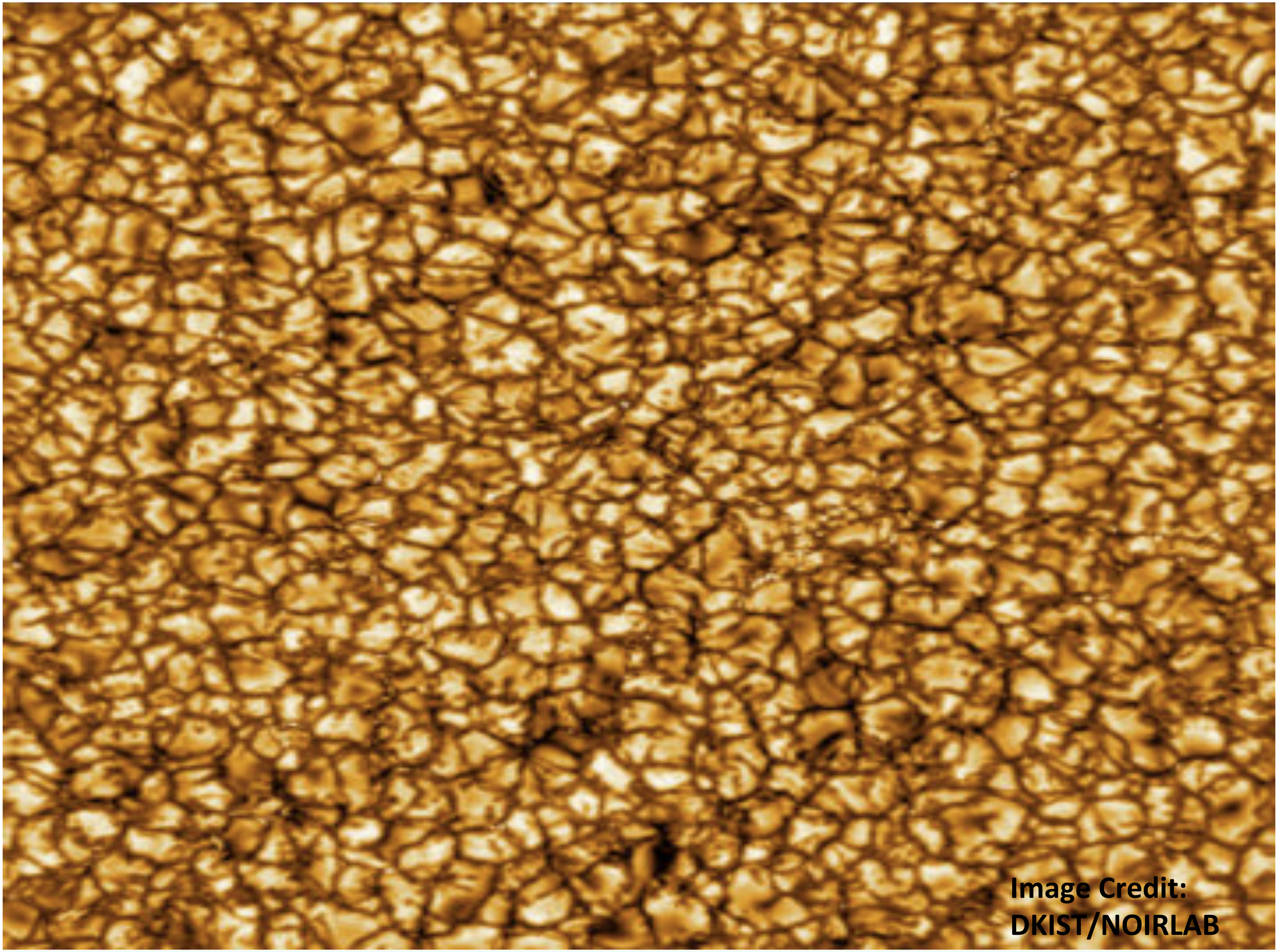


Image Credit:
DKIST/NOIRLAB

Summary

- **Teams** build Complex Instruments
- 10 cm/s is within reach from an instrumental perspective − **but almost everything has to be just right**. Improvements needed in key area like detectors, calibrators.
- Have to understand systematic errors very well.
- Stellar Activity, and mitigation mechanisms a major area where progress is needed. Can need a scary number of RV observations…
- Lots of 'chicken and egg' problems- instrument precision/stellar activity, detector calibration/laser comb.