In search of Exo-earths:

Development of next generation extreme precision radial velocity spectrographs

Joe Philip Ninan

On behalf of HPF & NEID Team

ASET Colloquium at TIFR, Mumbai
19/December/2017

#HPF
#NEID

PennState
Eberly College
of Science

Are we alone?

- “There are infinite worlds both like and unlike this world of ours . . . We must believe that in all worlds there are living creatures and plants and other things we see in this world.”

  -Epicurus (ca. 300 BCE)

- “There are countless suns and countless Earths all rotating around their suns in exactly the same way as the seven planets of our system . . . The countless worlds in the universe are no worse and no less inhabited than our Earth”

  Giordano Bruno, (1584)

- Cosmotheoros: Or, Conjectures Concerning the Planetary Worlds (Huygens, 1698)

Outline

- Very brief intro to Exo-planets
- Planets around cool stars
- How to build next generation ultra-stable spectrograph (2 times!)
- Some early results!

Plethora of Exo-planets

2925 EOD Planets
Planets with good orbits listed in the Exoplanet Orbit Database

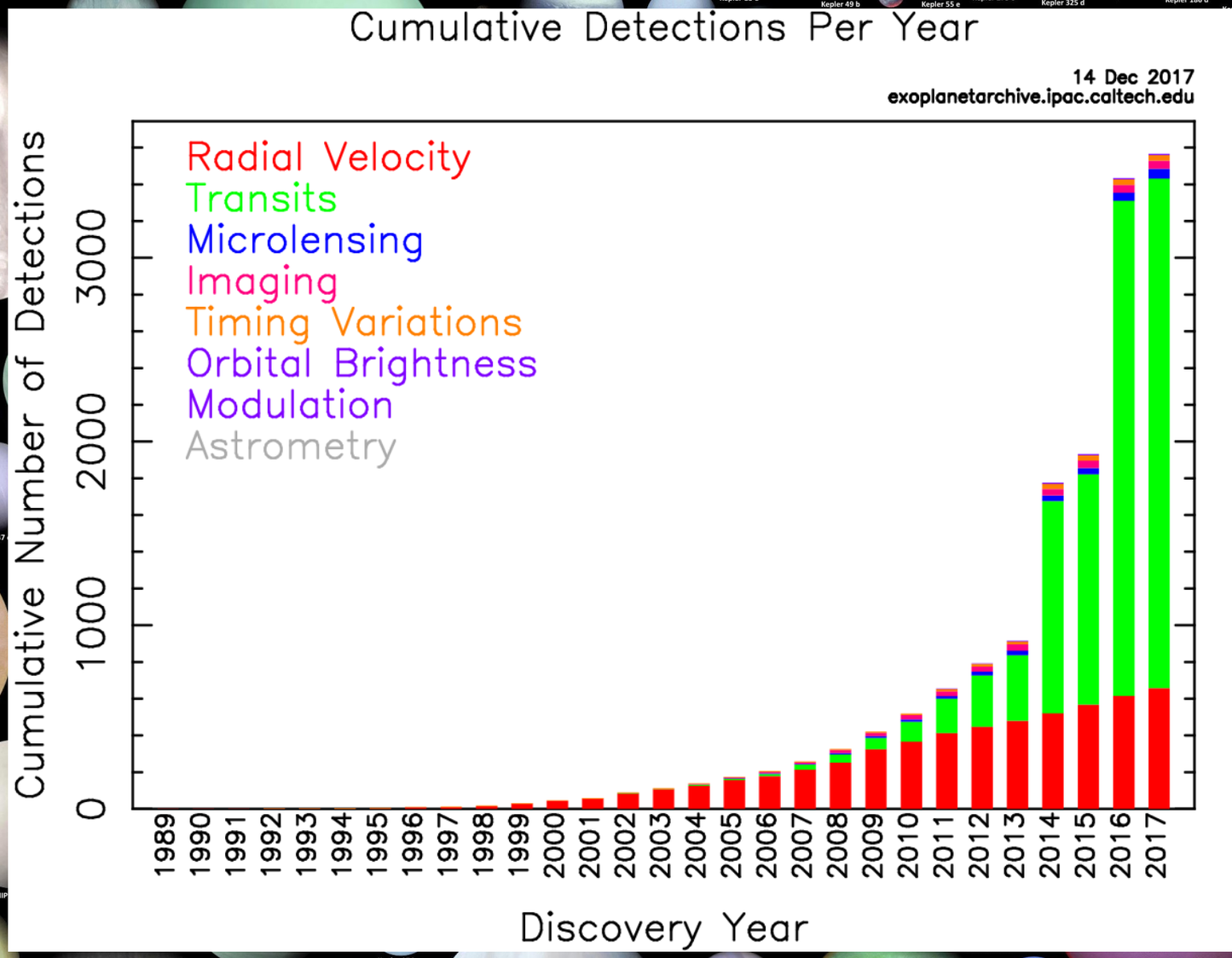
25 Other Planets
Including microlensing and imaged planets

2950 Total Confirmed Planets

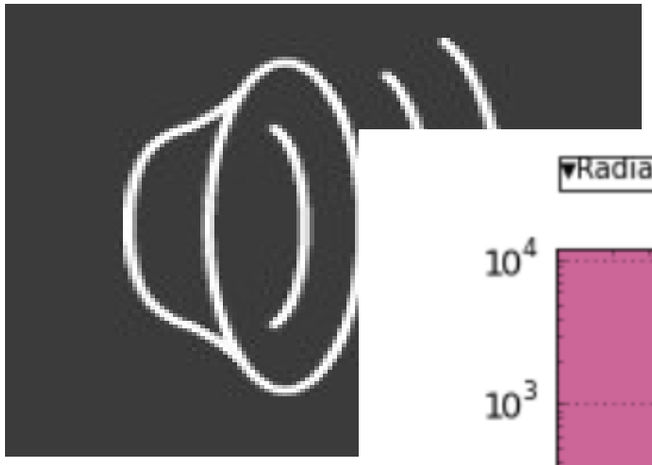
2337 Unconfirmed Kepler Candidates

5287 Total Planets
Confirmed planets + Kepler Candidates

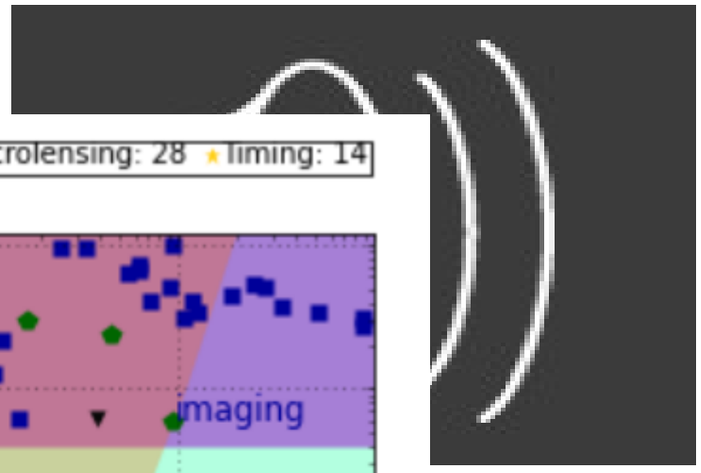
exoplantes.org



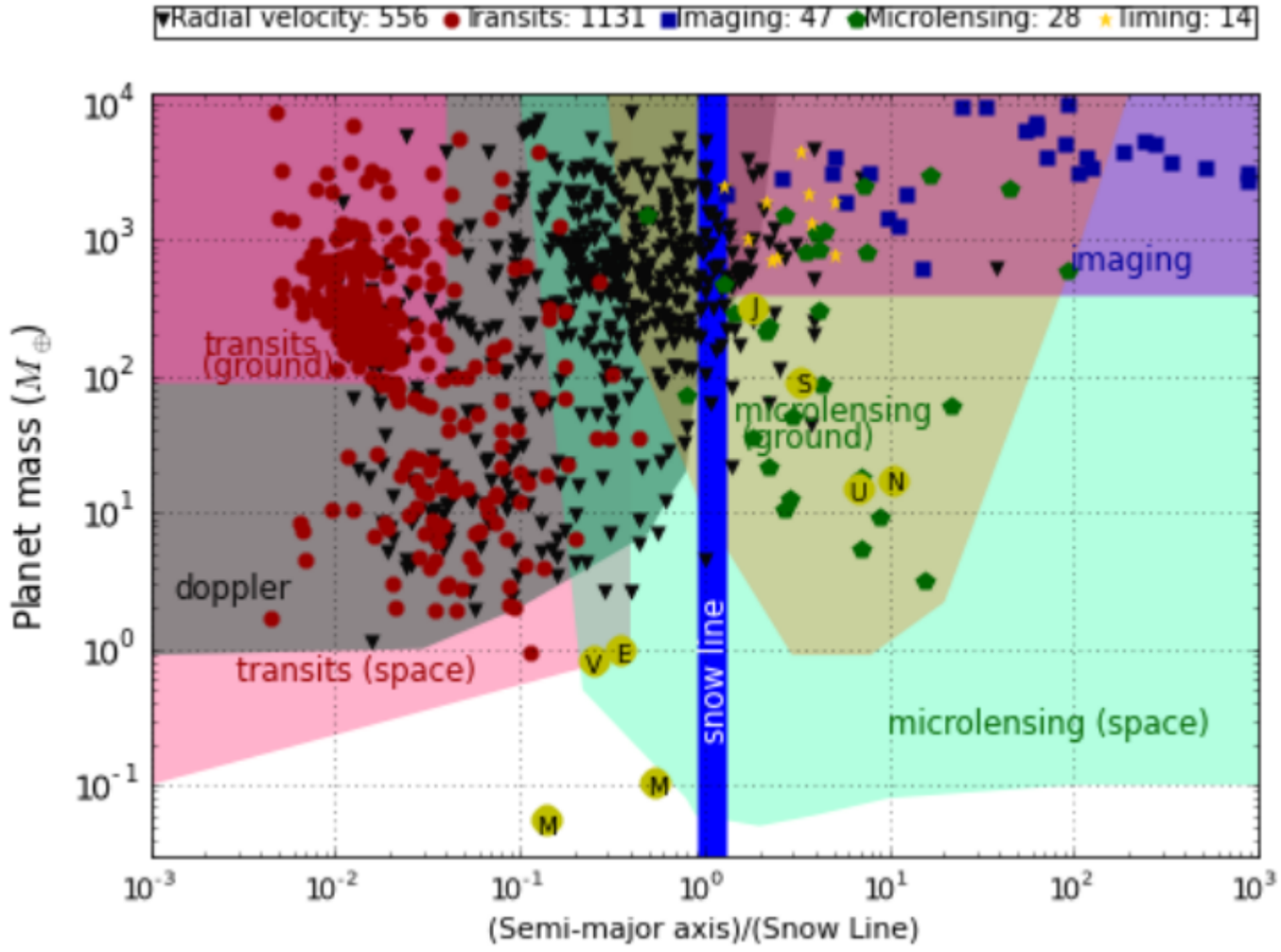
Methods of Detection

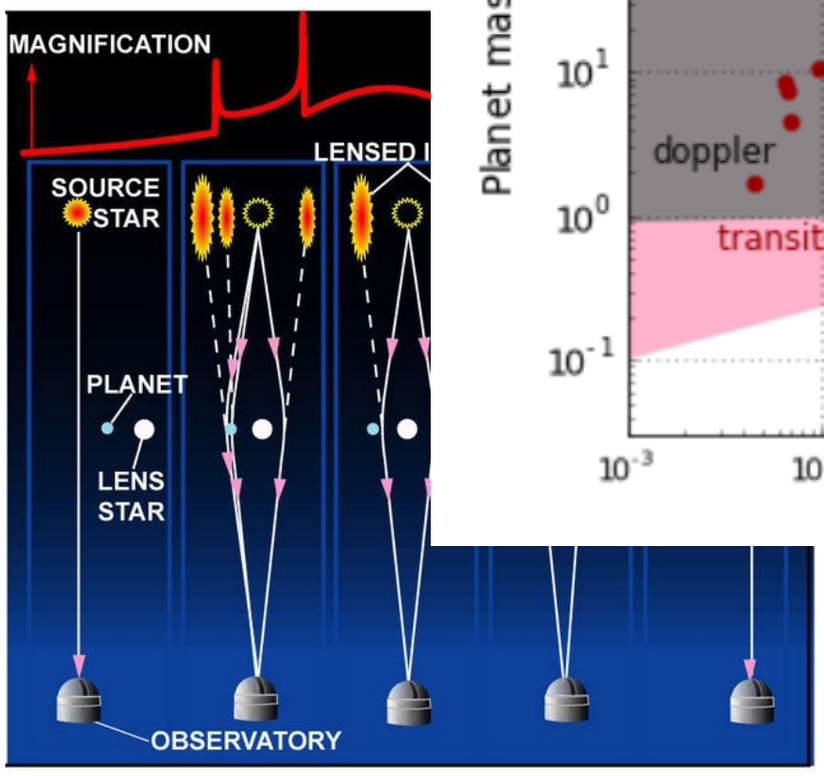


Transit meth

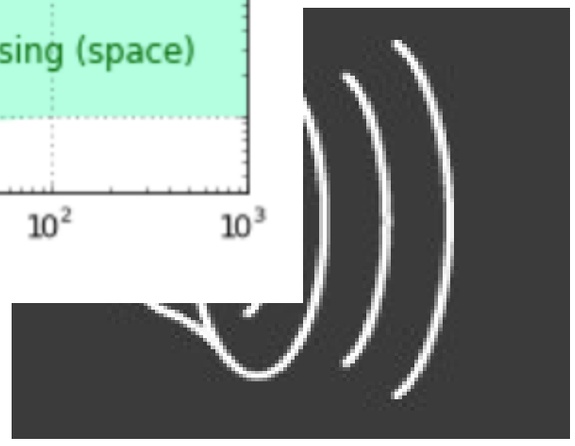


elocity method





Gravitational Lensing method



Direct Imaging method

Habitable Zone

- Exo-earths : Rocky planets like earth around Sun like stars, inside Habitable Zone.

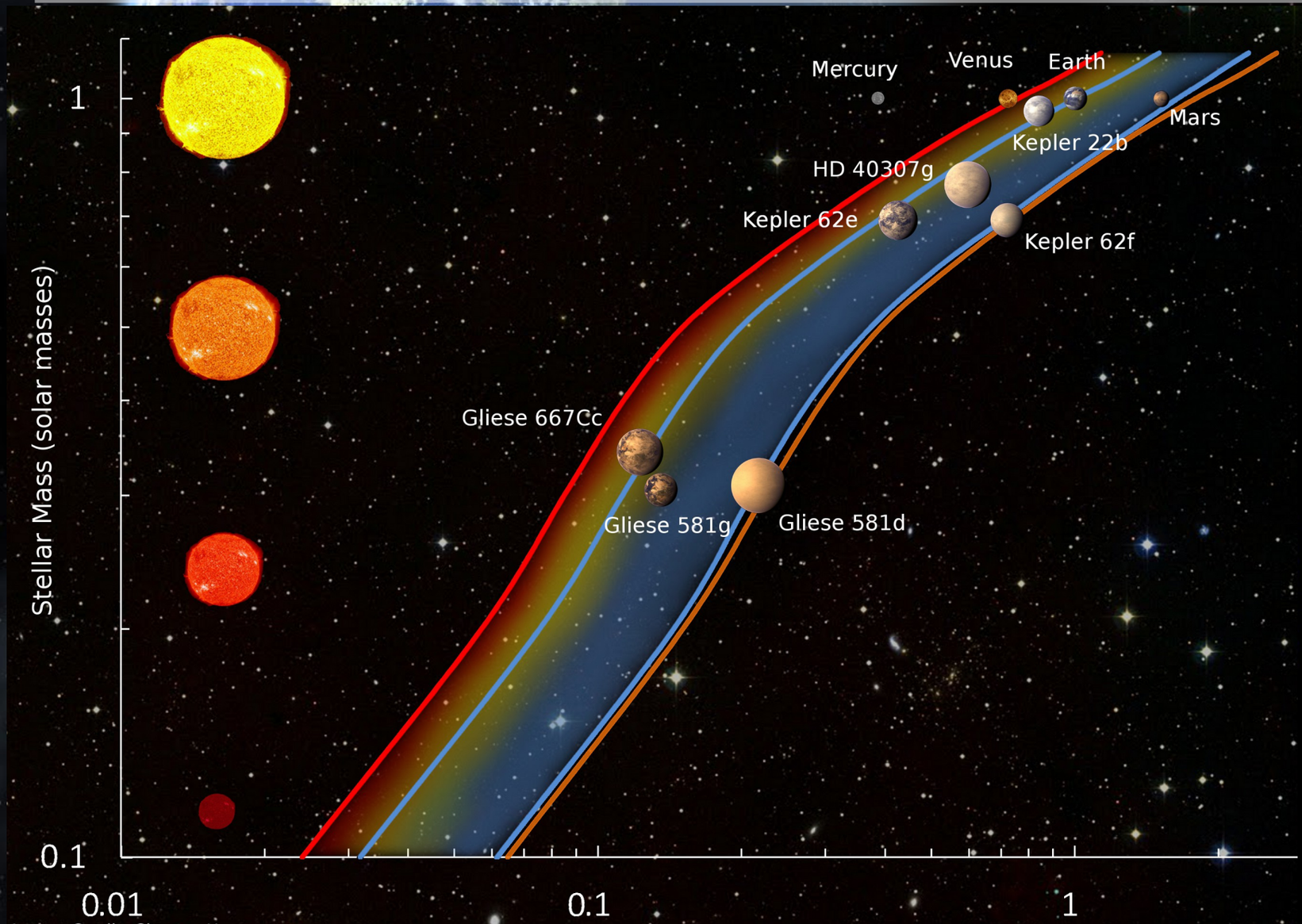
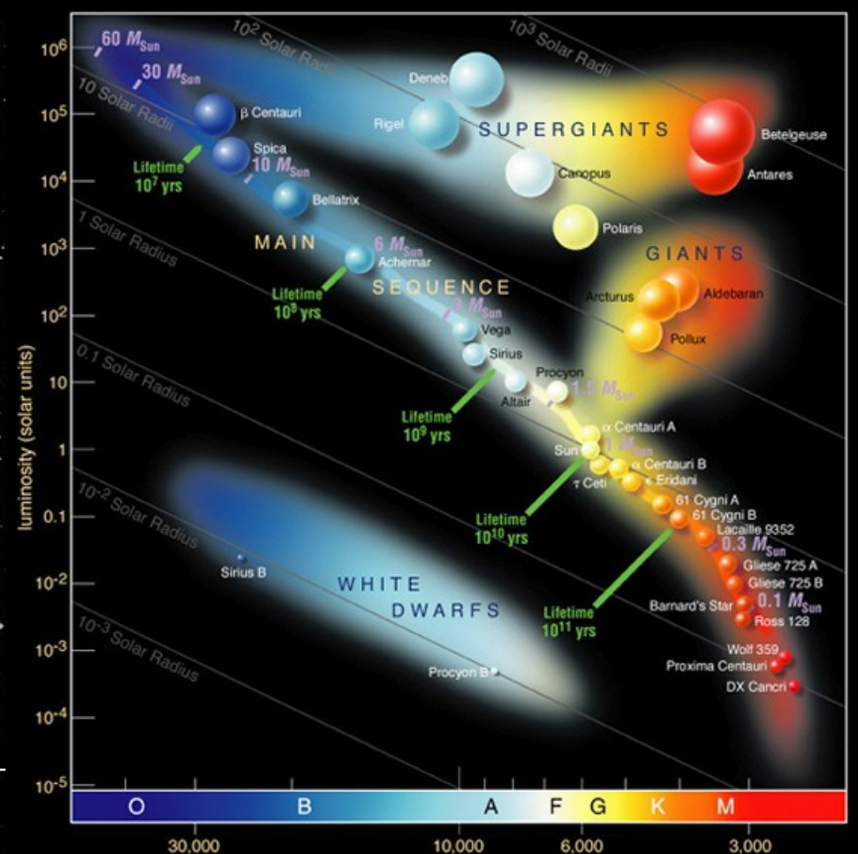


Image Credit: Chester Harman



The Silent Majority :- **M dwarfs**

- 70% of all stars in our galaxy!
- TiO absorption band in blue-green range.
- 0.5 Msun > Mass Range > 0.08 Msun
- Many Trillions of years of life time ~ statistically the likeliest sites for the evolution of life!
- Latest number statistics shows these stars have ~3.5 times more rocky planets than FGK type stars in the same radius.
- 2 times fewer Neptune sized giants

Shields et. al. (2016)

Planetary systems in abundance

- Transit probability ~ 2% in HZ (0.47% for Sun)
- Transit Amplitude ~ 1.3 mmag (0.084 for Sun)
- RV amplitude ~ 2.5 times larger than Sun

$$K = 8.94 \text{ cm s}^{-1} \left(\frac{1 \text{ yr}}{P}\right)^{1/3} \left(\frac{M_p \sin(i)}{M_\oplus}\right) \left(\frac{M_\odot}{M_\star}\right)^{2/3}$$

How ever they have there own challenges!

- High stellar activity and flares.
- Rotation period very close to HZ planet orbit.
- Too faint in optical. Need NIR instrument.

The Habitable Zone Planet Finder

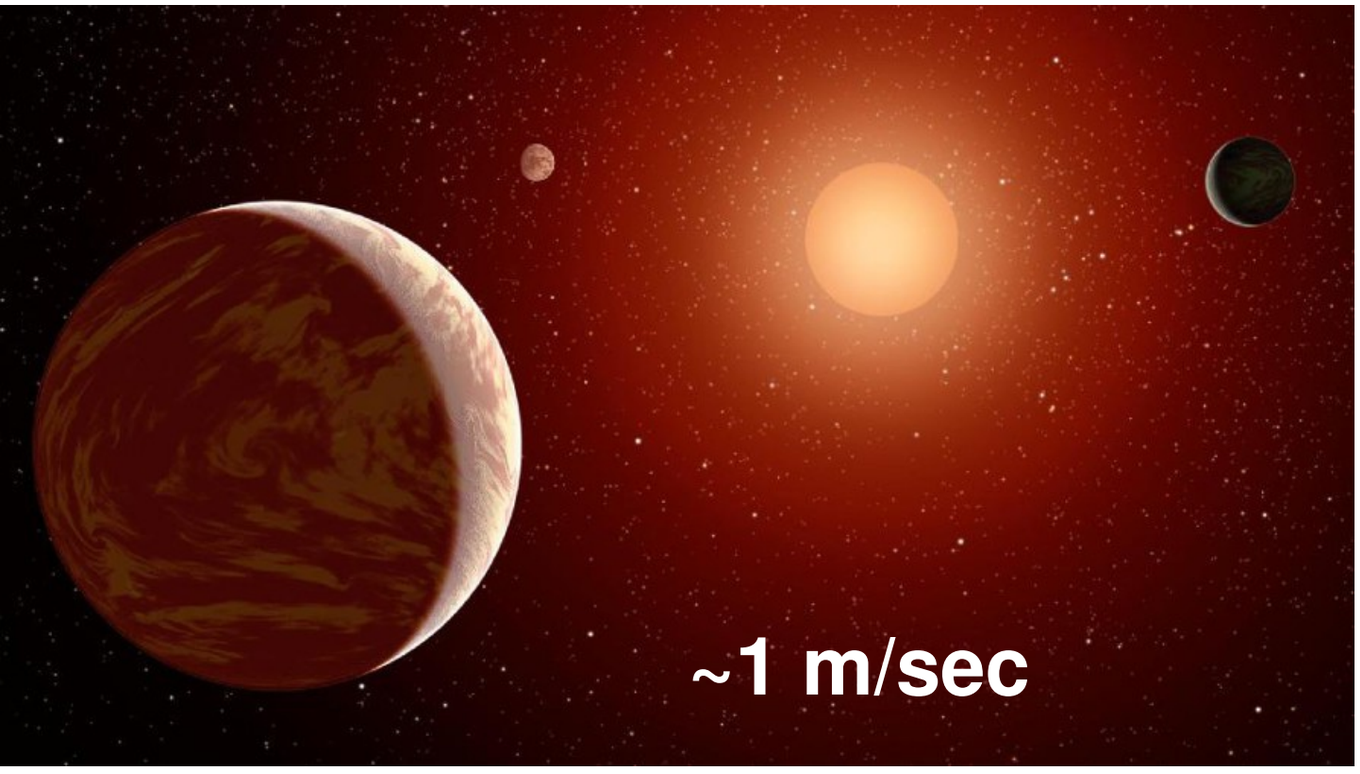
HPF

Near-Infrared for M-dwarfs

NEID

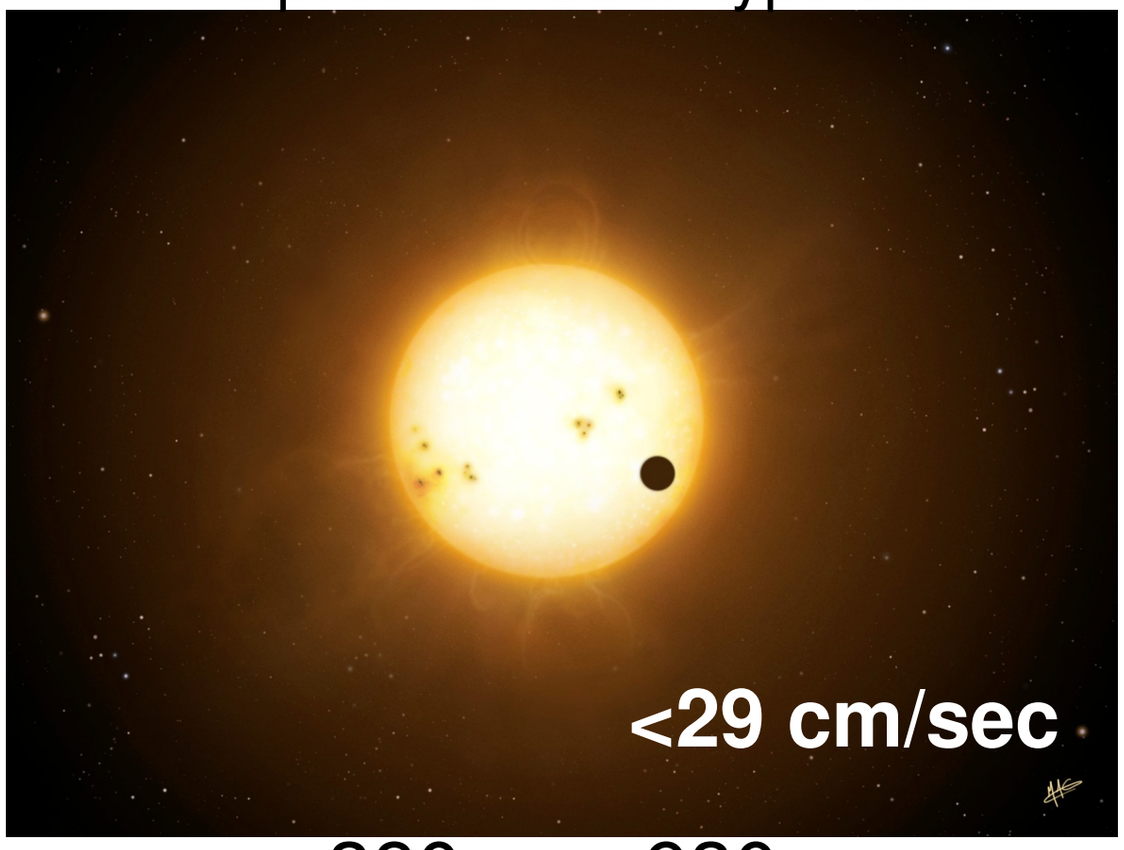
NEID: NN-EXPLORE Exoplanet Investigations with Doppler Spectroscopy

"to see" in the native language of the Tohono O'odham



807 nm -1279 nm

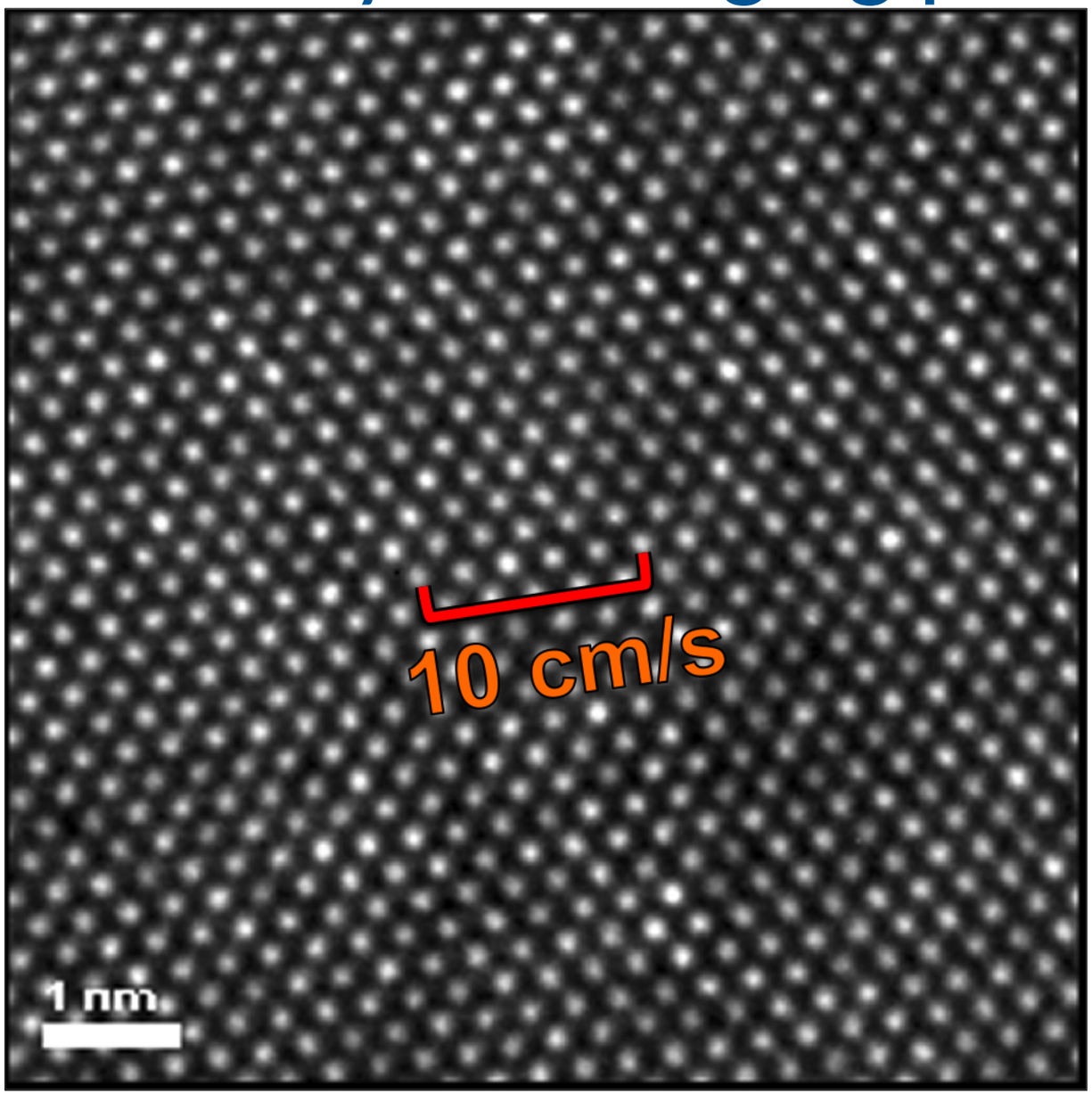
Optical for Solar type stars



380 nm -930 nm

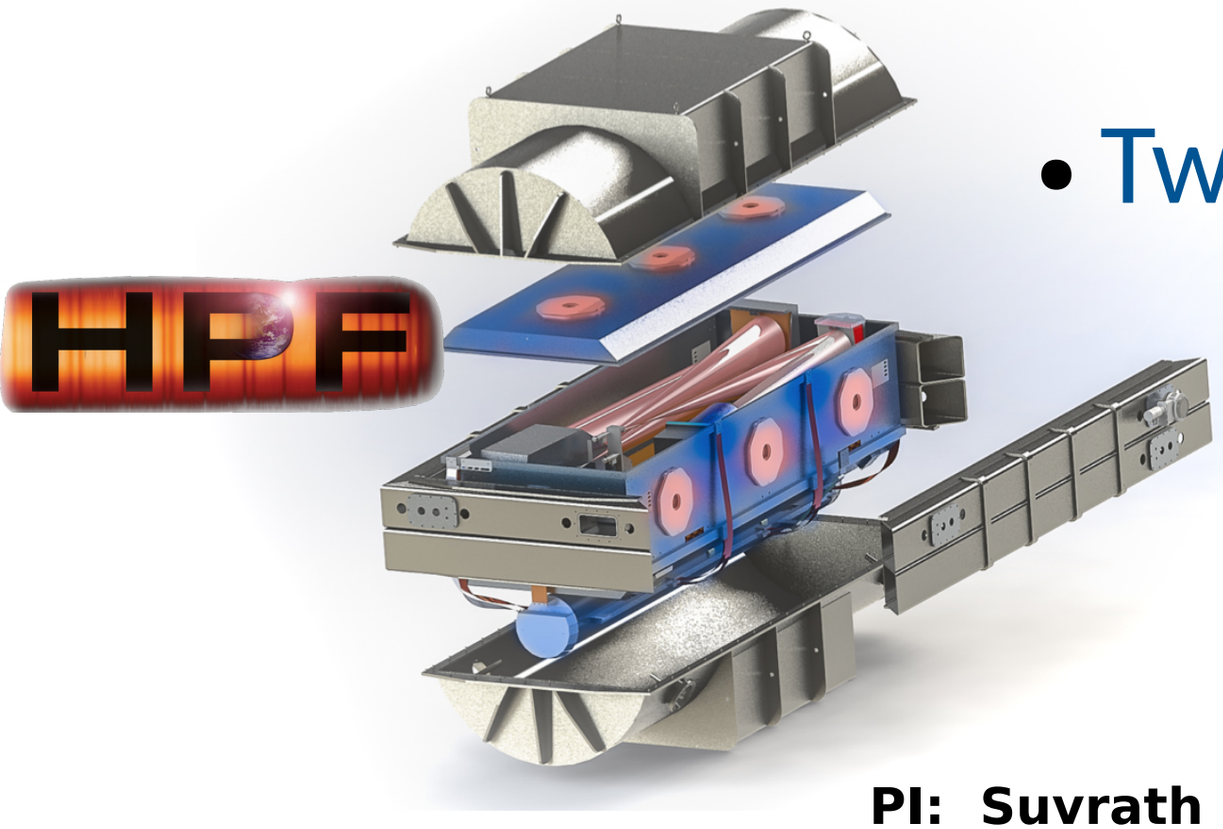
29 cm/sec ~ 1/6000th of a 10 um pixel

- cm/sec is a really challenging problem!

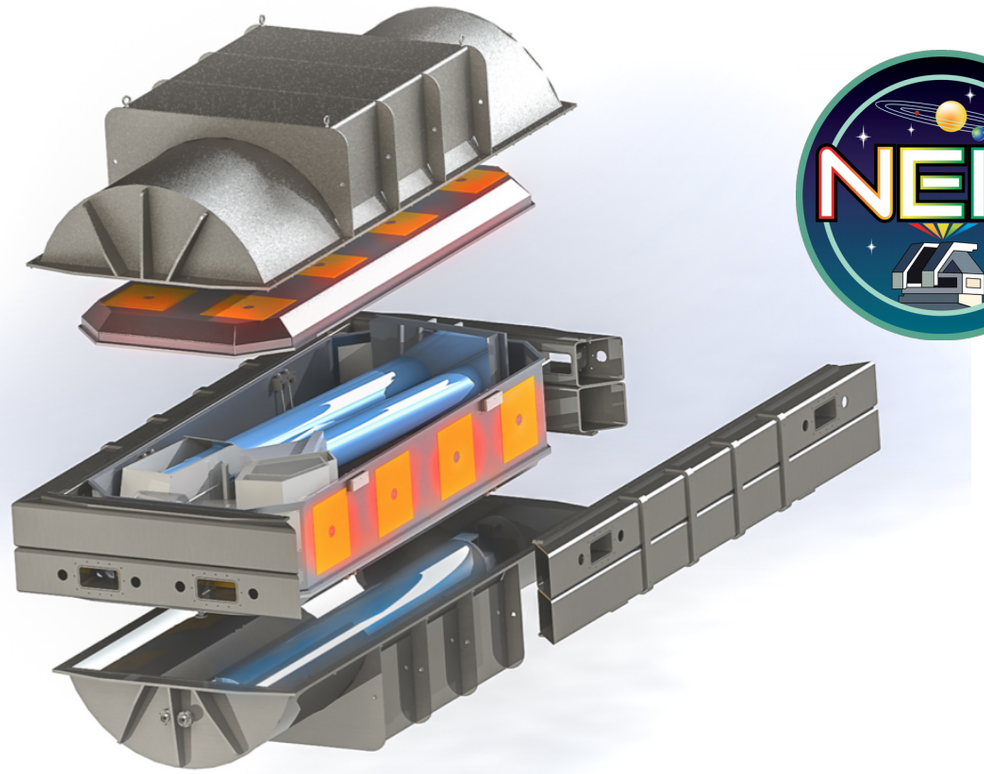


Ki Bun Kin (2012)

How to make an ultra stable spectrograph



- Twice!



PI: Suvrath Mahadevan, PSU

NEID's white pupil optical design

Schwab et. al. SPIE (2016)

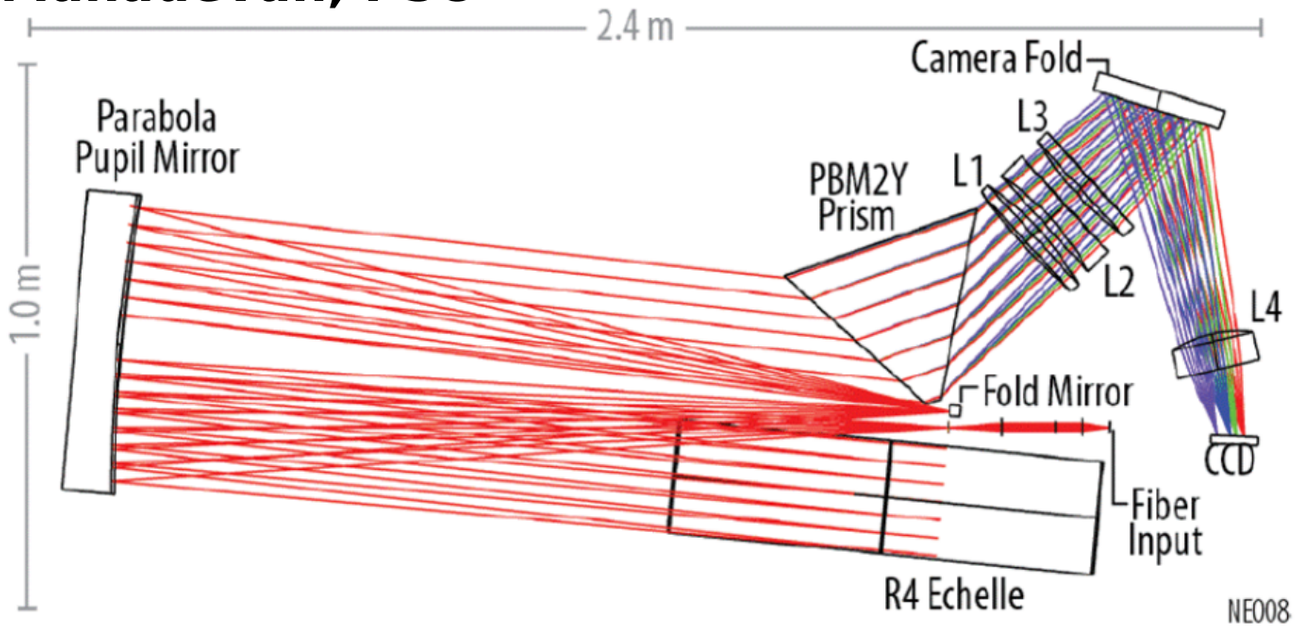
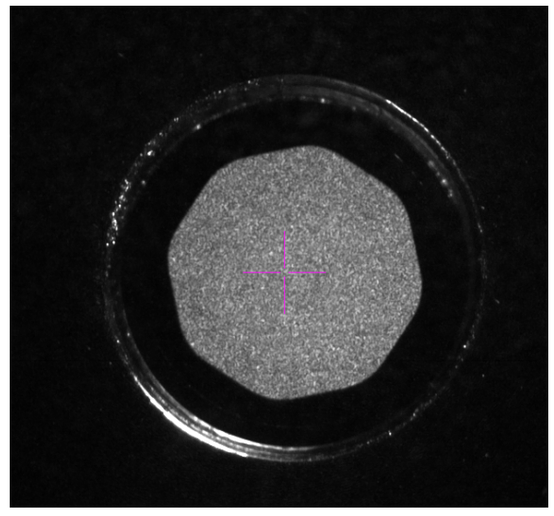


Fig. 2. Optical layout of NEID.

A stable location

- A stable spectrograph needs a stable home!
- Take light from the Alt-Azimuth telescope's focal plane to basement/spectrograph room.



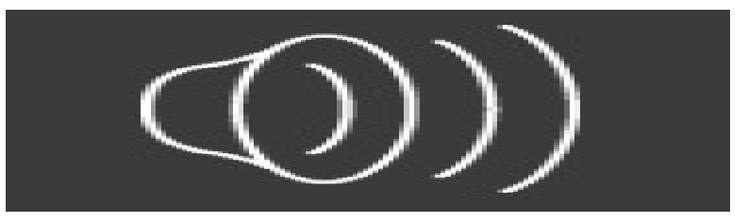
- Appropriate wavelength light guides: Optical fibers!

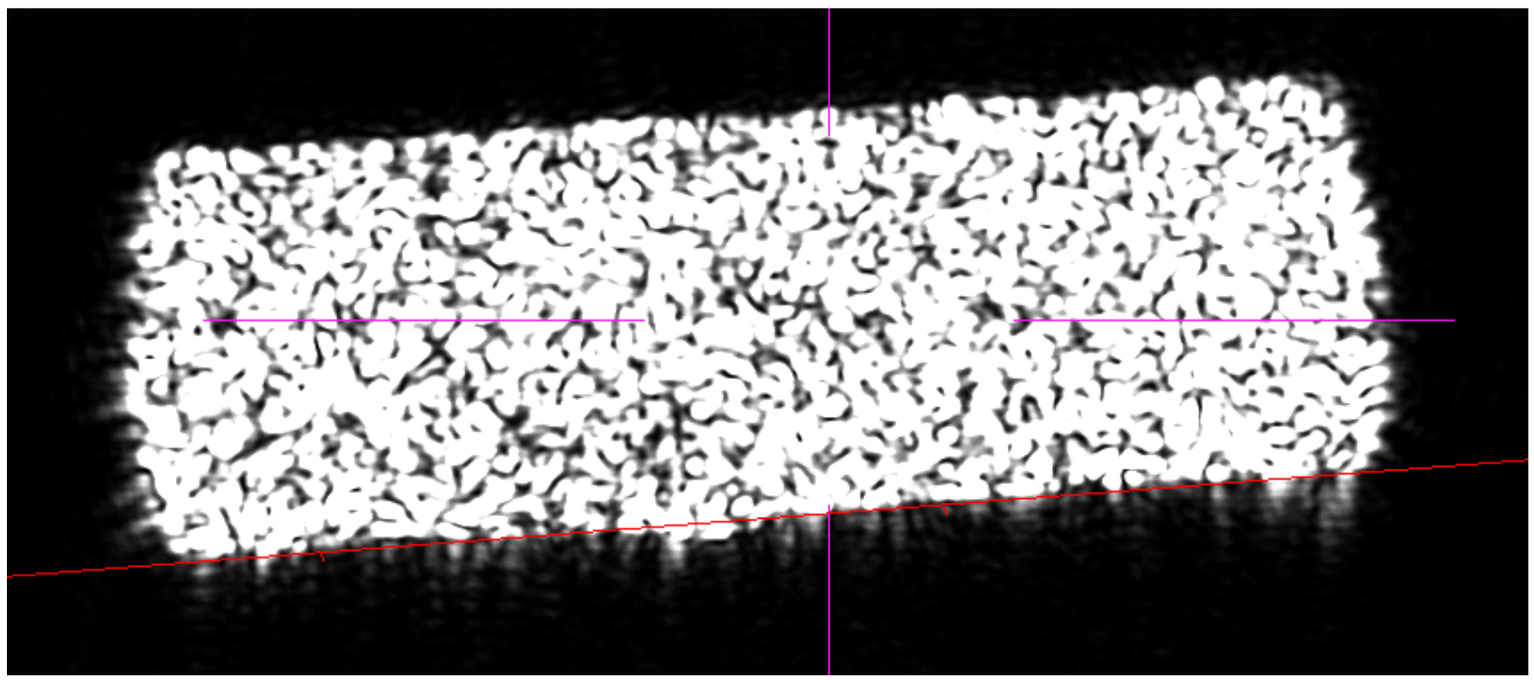
Ramsey et al., (1980)

- Put the slit of the spectrograph at the end of the fiber.

Stability of Optical fiber output

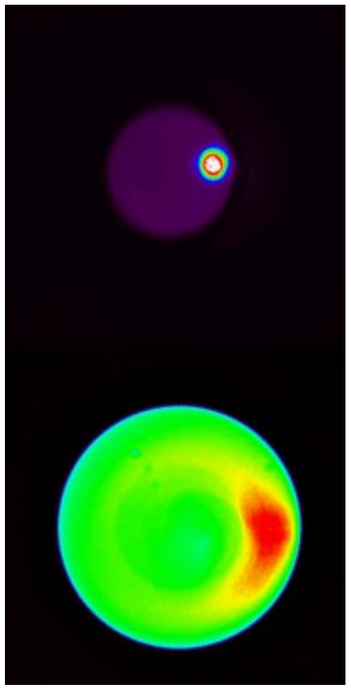
- Model Noise

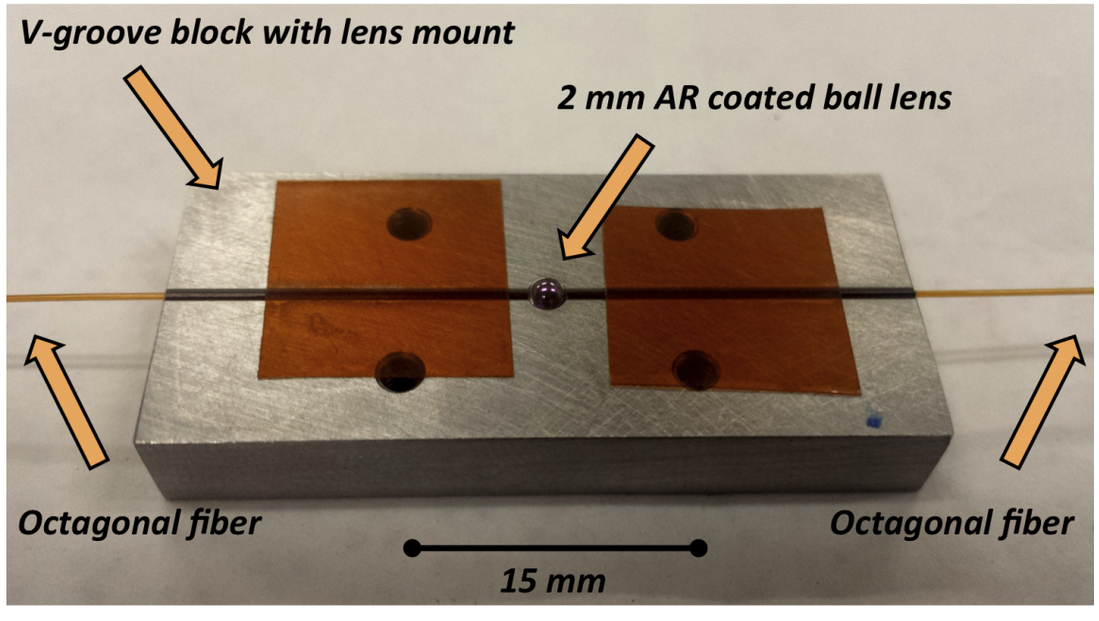


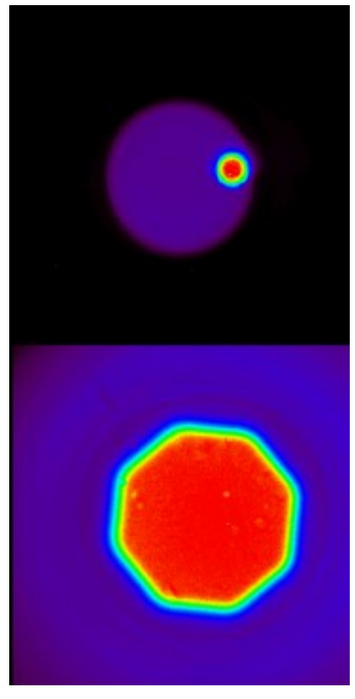


Near & Far field Scrambling

Roy A. (2017 Thesis), McCoy et. al. (2012)







Throw the air out! (ΔP ↓)

- Change in pressure results in change in refractive index of air medium

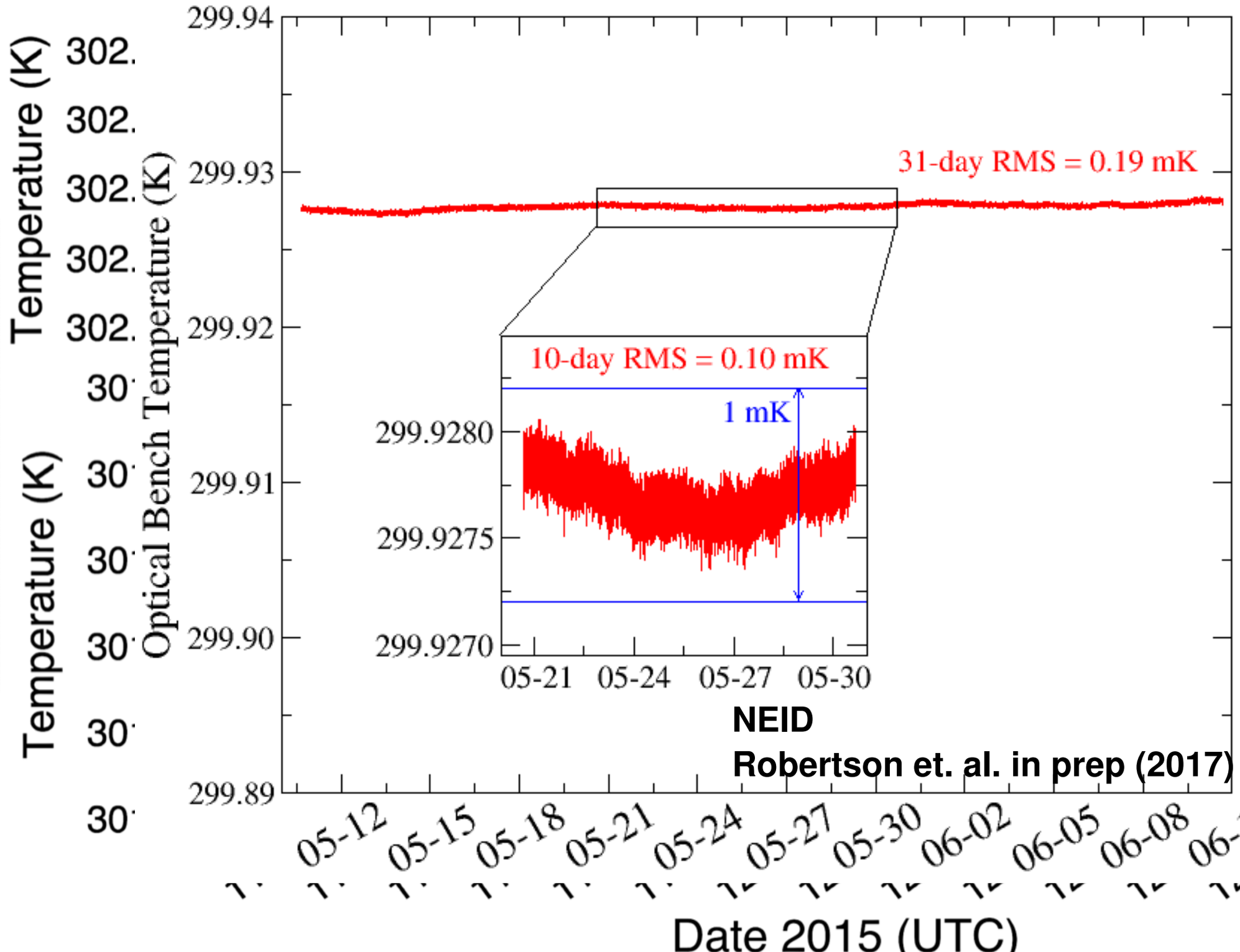
  (3 Torr ~ 300 m/sec)

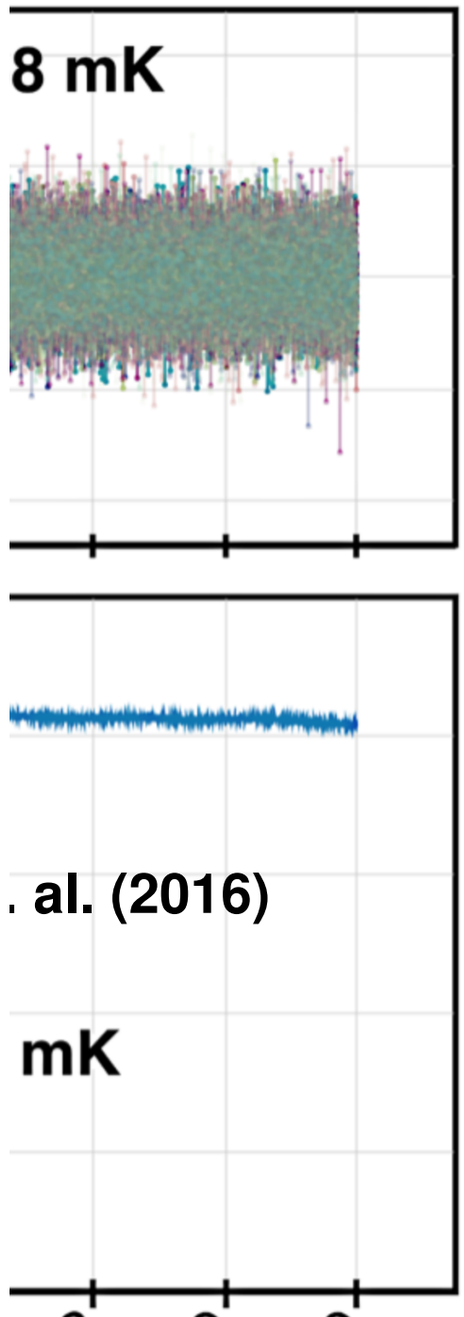
  Just to solve refractive index changes < 10^-3 Torr.
- However, to reduce the thermal coupling between the optical bench from the chamber to be purely radiative. We need P < 10^-7 Torr.

Activated charcoal getter
&
NexTorr Hydrogen getter

Stefansson et. al. (2016)

Control temperature to sub-mK level!





Control temperature to sub-mK level!

- LN2 fill transient control using back pressure regulators and automated timing.
- HPF at 180 K and NEID at 300 K

Stefansson et. al. (2016)

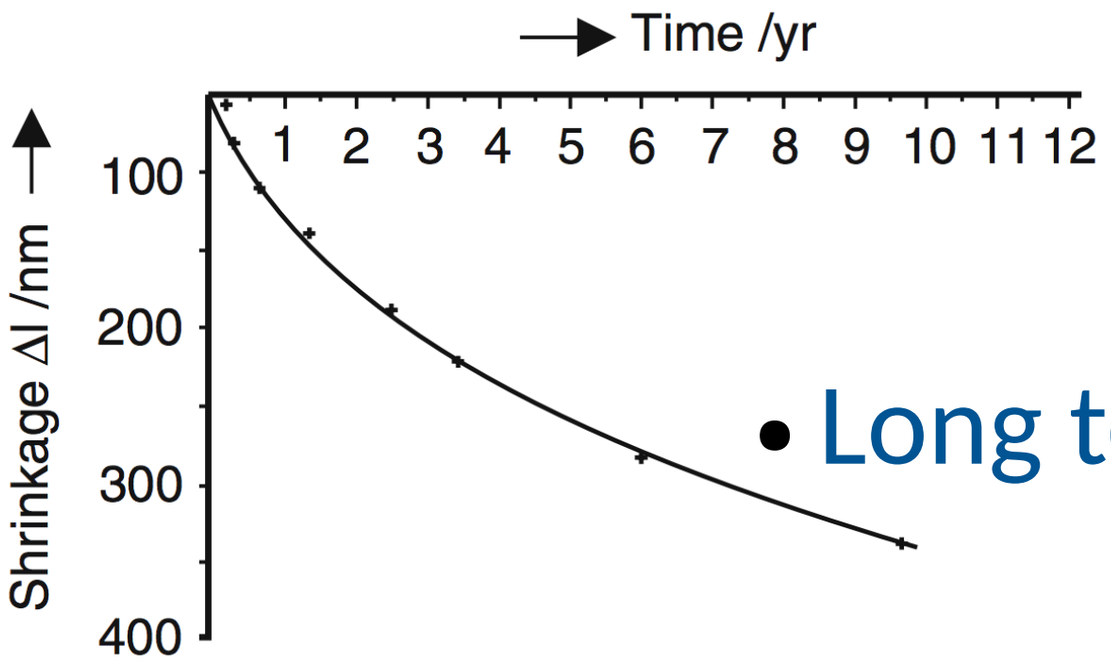
- Steady readout mode of the detector
- Passive enclosure for filtering out high frequency HVAC cycling.
- Public release of SolidWorks models:

  http://bit.ly/HPF_ECS

The Grating's stability

- R4 Echelle Grating (31.6 lines/mm) made of Zerodur Class 0 Extreme(0.2 ppm/K)

  from Newport/Richardson Grating Labs.



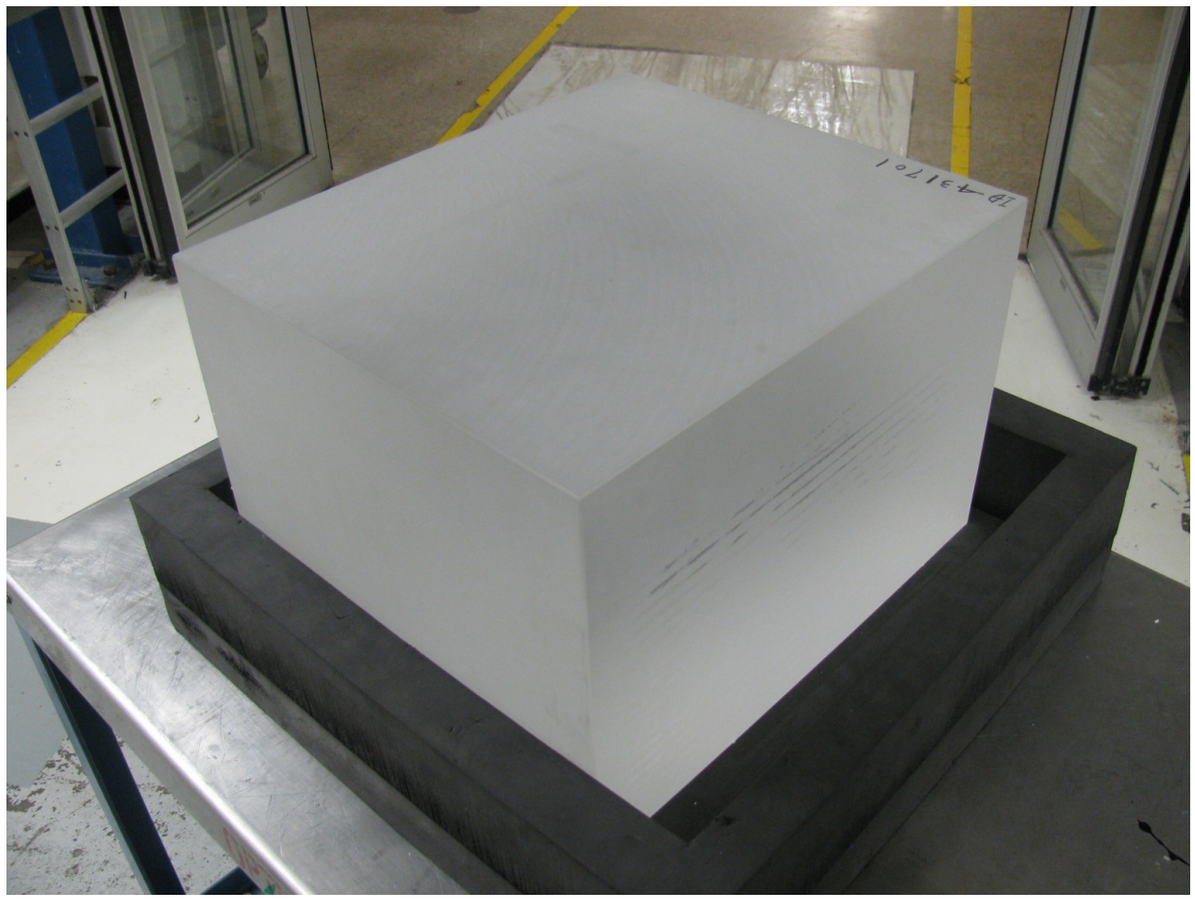
- Long term crystallization of Zerodur!

The cross disperser

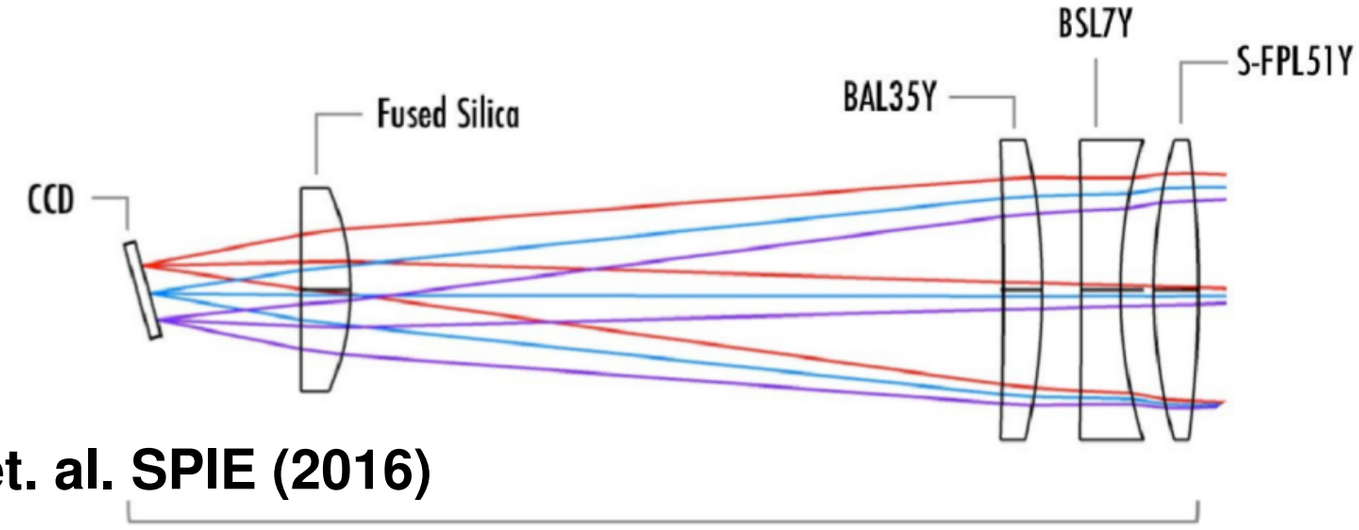
- VPH (Volume-Phase Holographic Grating) in HPF

- A huge prism in NEID!

- Polishing and wavefront correction by Zygo



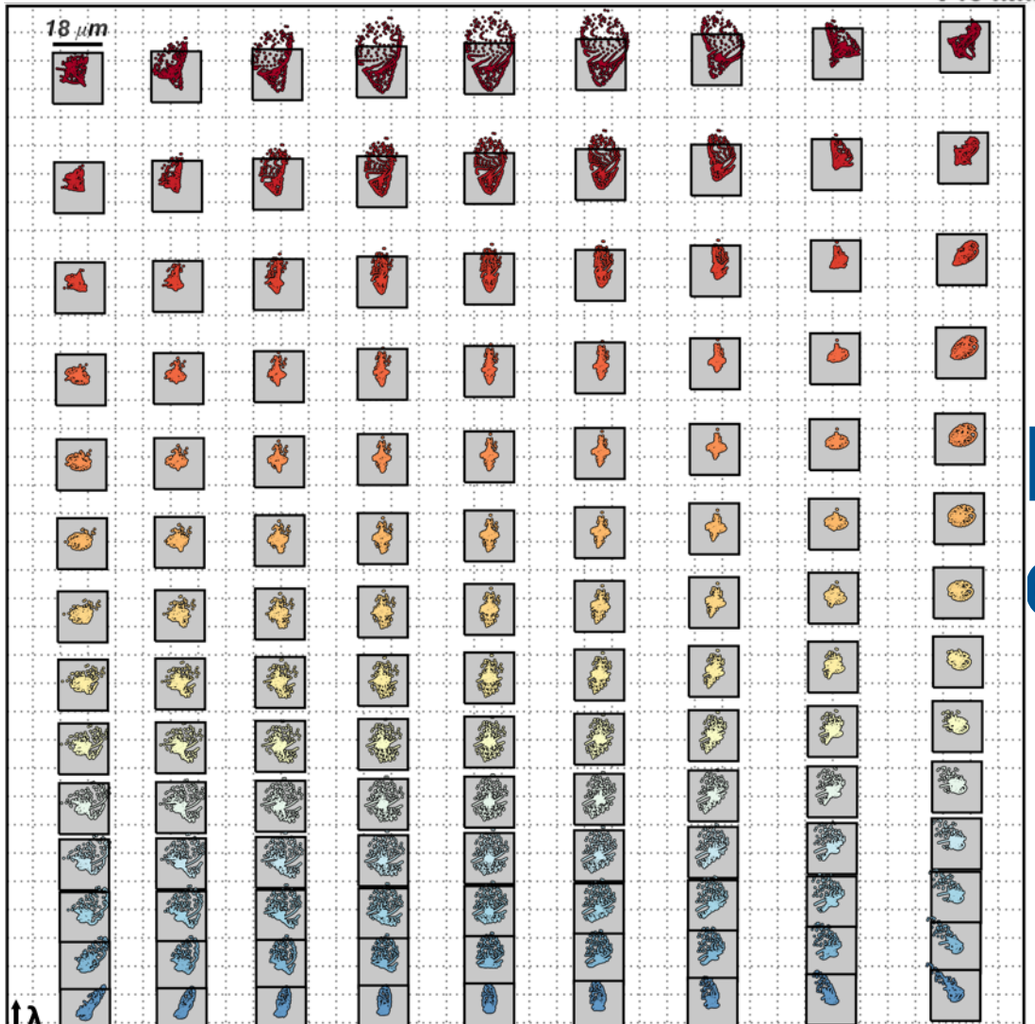
The Camera



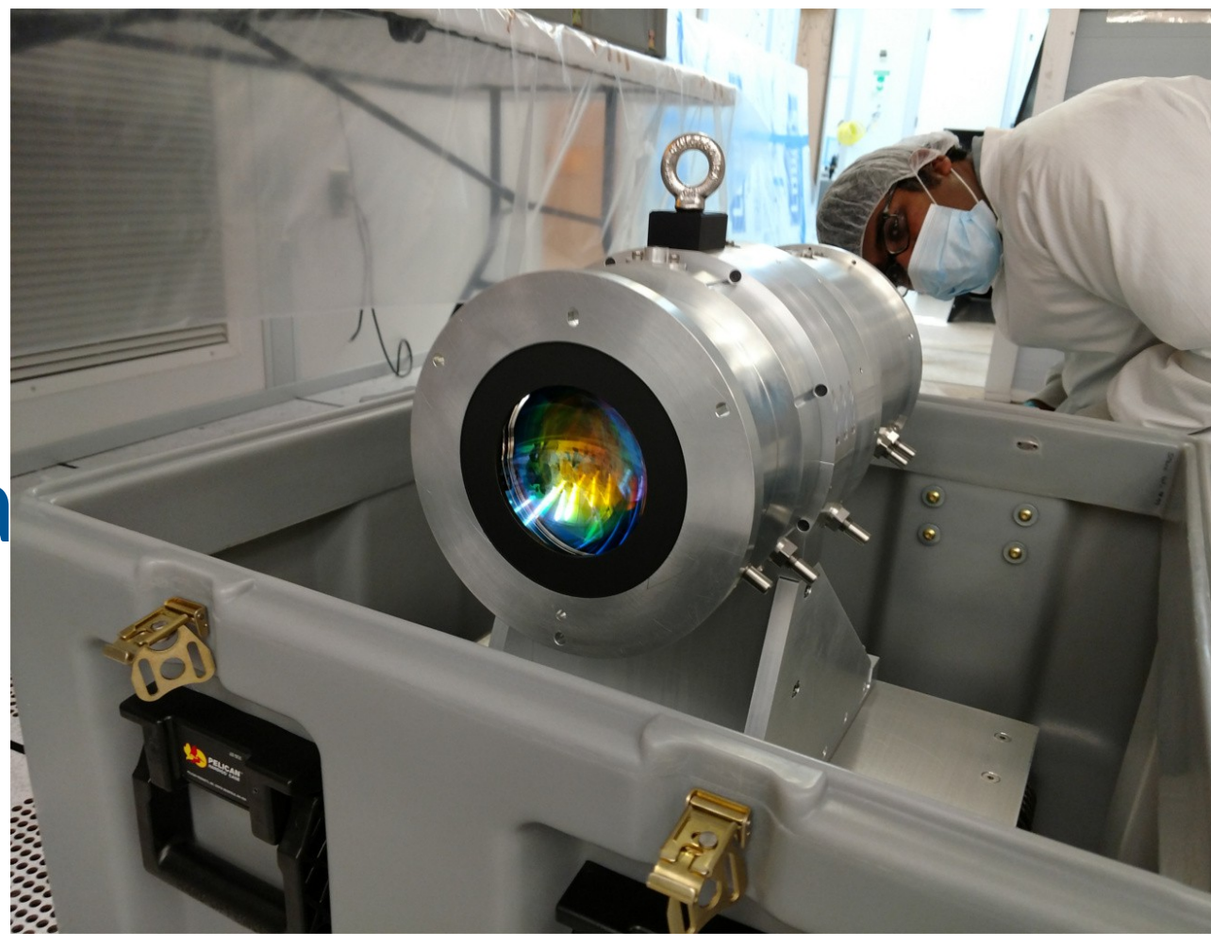
Schwab et. al. SPIE (2016)

- NEID's elegant Camera design avoiding cylindrical lens

HPF focal plane image quality

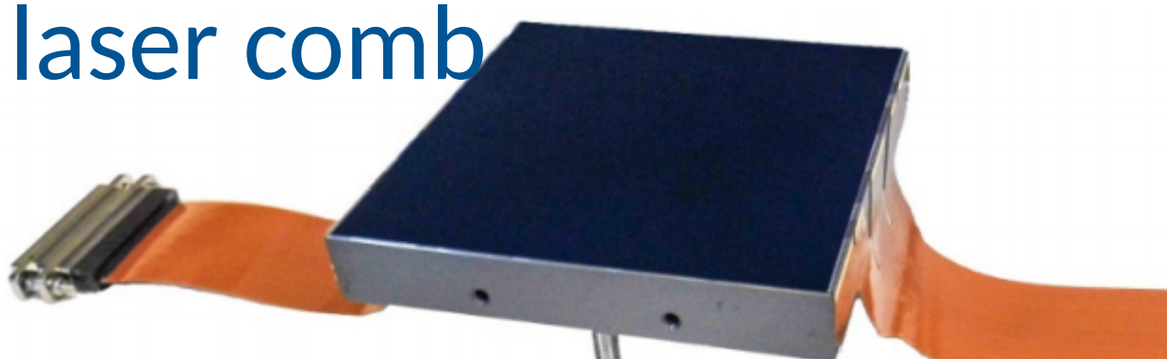


HPF's camera



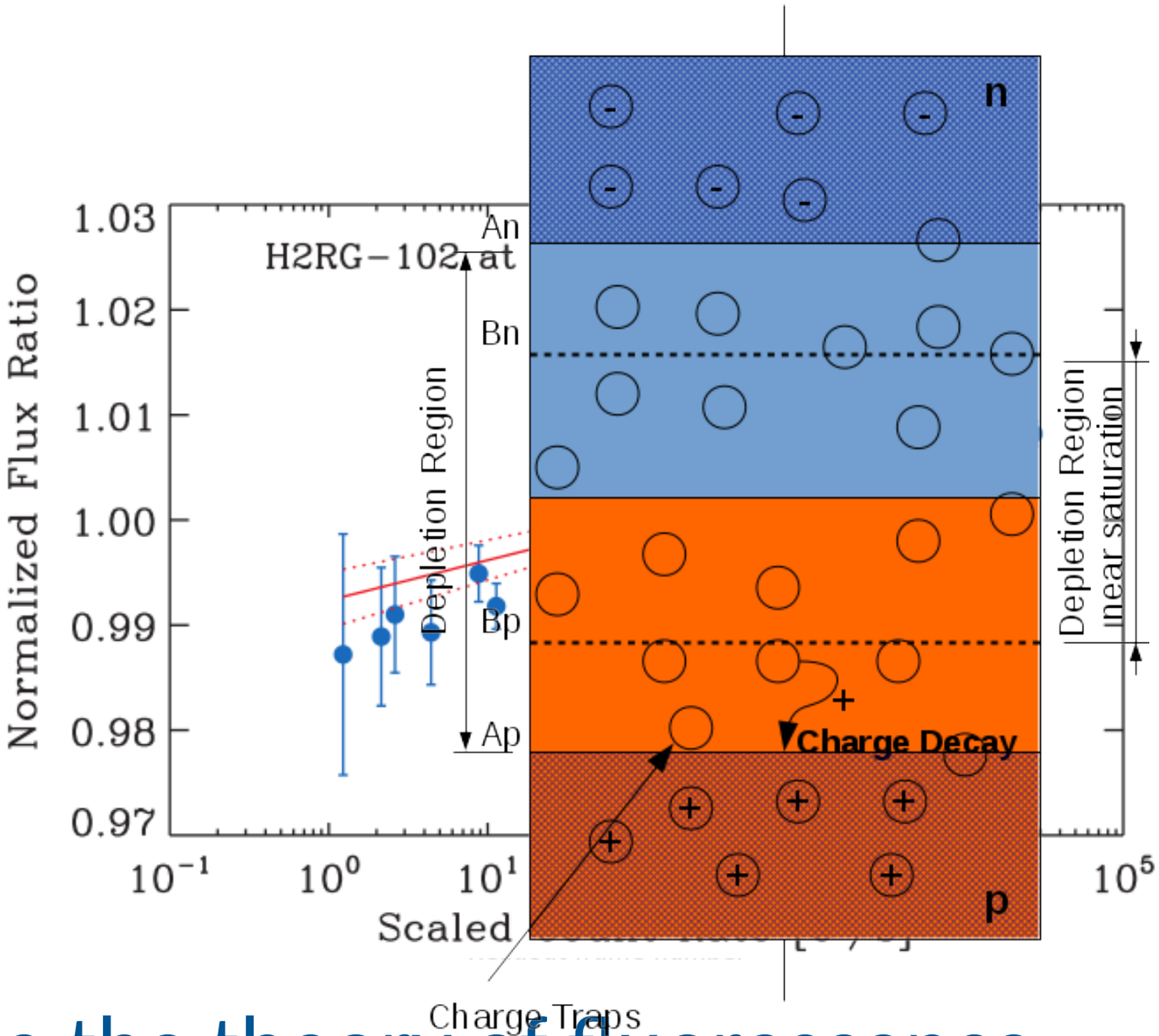
The Detector

- HPF used 2kx2k H2RG (Teledyne), with a 1.7 micron cut-off
  - (Hence, 180 K operating temperature would suffice)
- NEID uses a back illuminated 9216 x 9232 e2v CCD.
- Read out periodically to keep thermal gradients stable and avoid wrapping.
- Pixel stitching errors and sensitivity profiles matter for cm/sec precision!
  - Calibration planned using laser comb



HPF's H2RG Detector

- Up-the-ramp readout. (Cosmic Ray fix)
- Bias fluctuations
- Non-linearity
- Reciprocity Failure
- Persistence
  - Trying to model using the theory of fluorescence decay



Ninan et. al. SPIE (2018b)

Overview of the Error Budget

Total NEID instrumental error budget: 27.0 cm/s

Instrument (uncalibratable): 15.1 cm/s (30.6%)

Fiber & illumination: 8.7 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
Polarization	2.0 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

25%

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

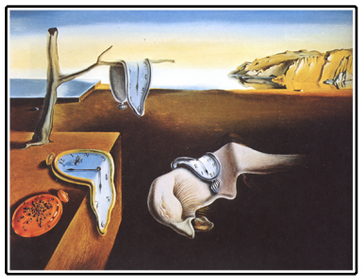
Guiding	scrambling
ADC	6.9 cm/s
Focus	5.0 cm/s
Windshake	8.0 cm/s

Atmospheric effects: 14.1 cm/s

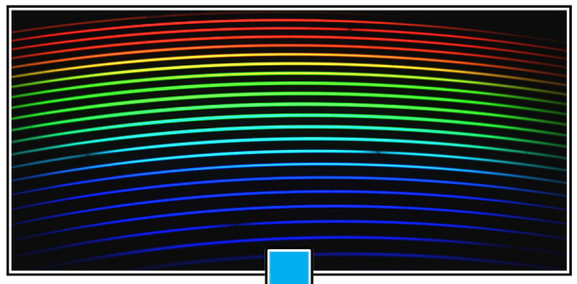
Micro-telluric contamination	10 cm/s
Sky fiber subtraction	10 cm/s

Halverson et. al. (2016)

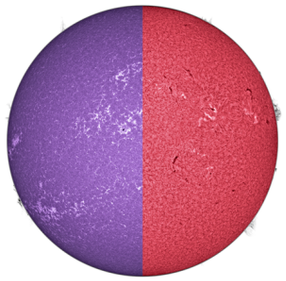
Algorithmic Challenges



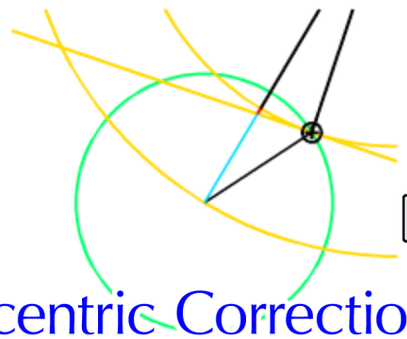
Detector Persistence



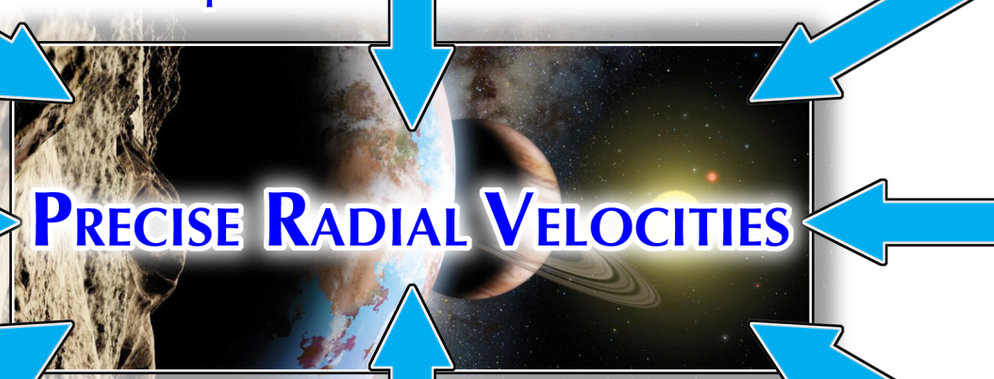
Spectral Extraction

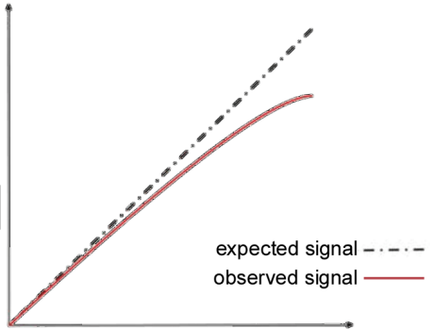


Stellar Activity

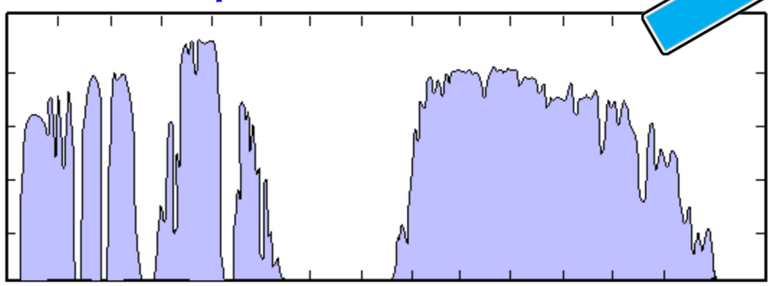


Barycentric Correction & Exposure Times

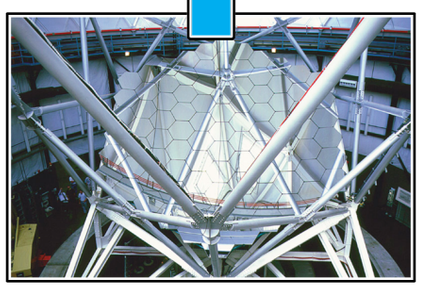




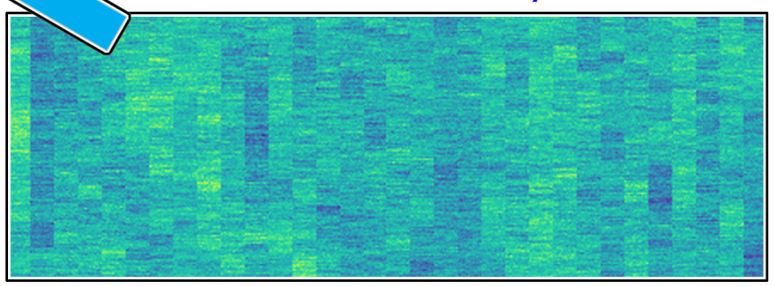
Non-Linearity



Tellurics



Modeling Telescope Flux Variations

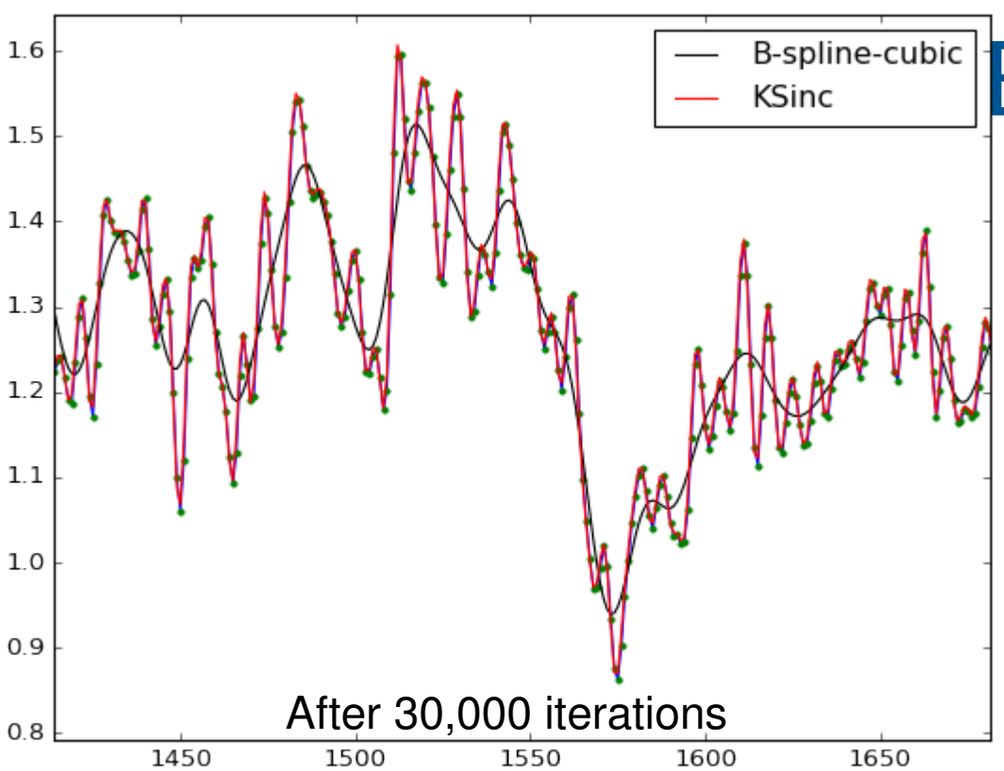


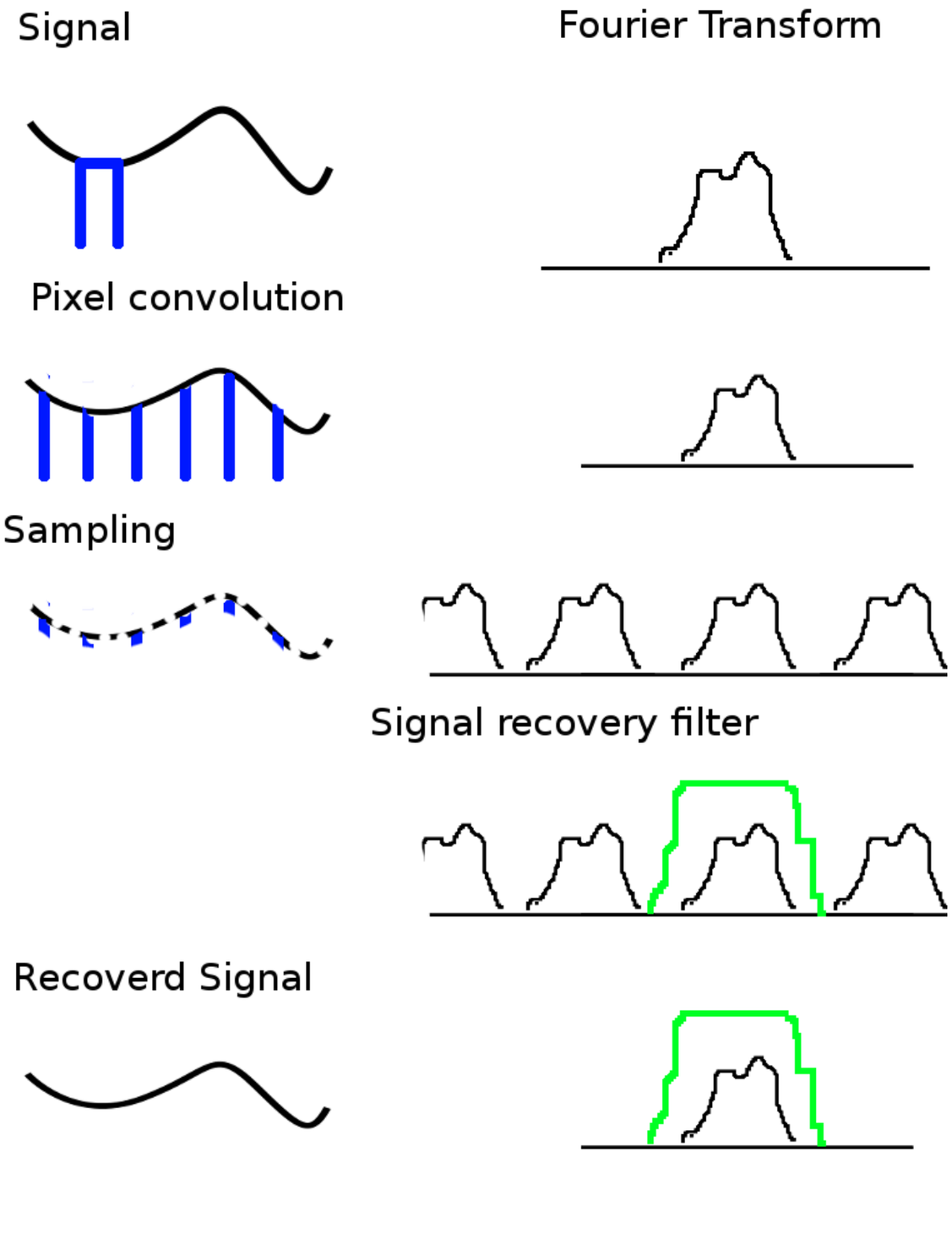
Bias Variations

Ninan et. al. (under prep)

Rectification and 1D Extraction

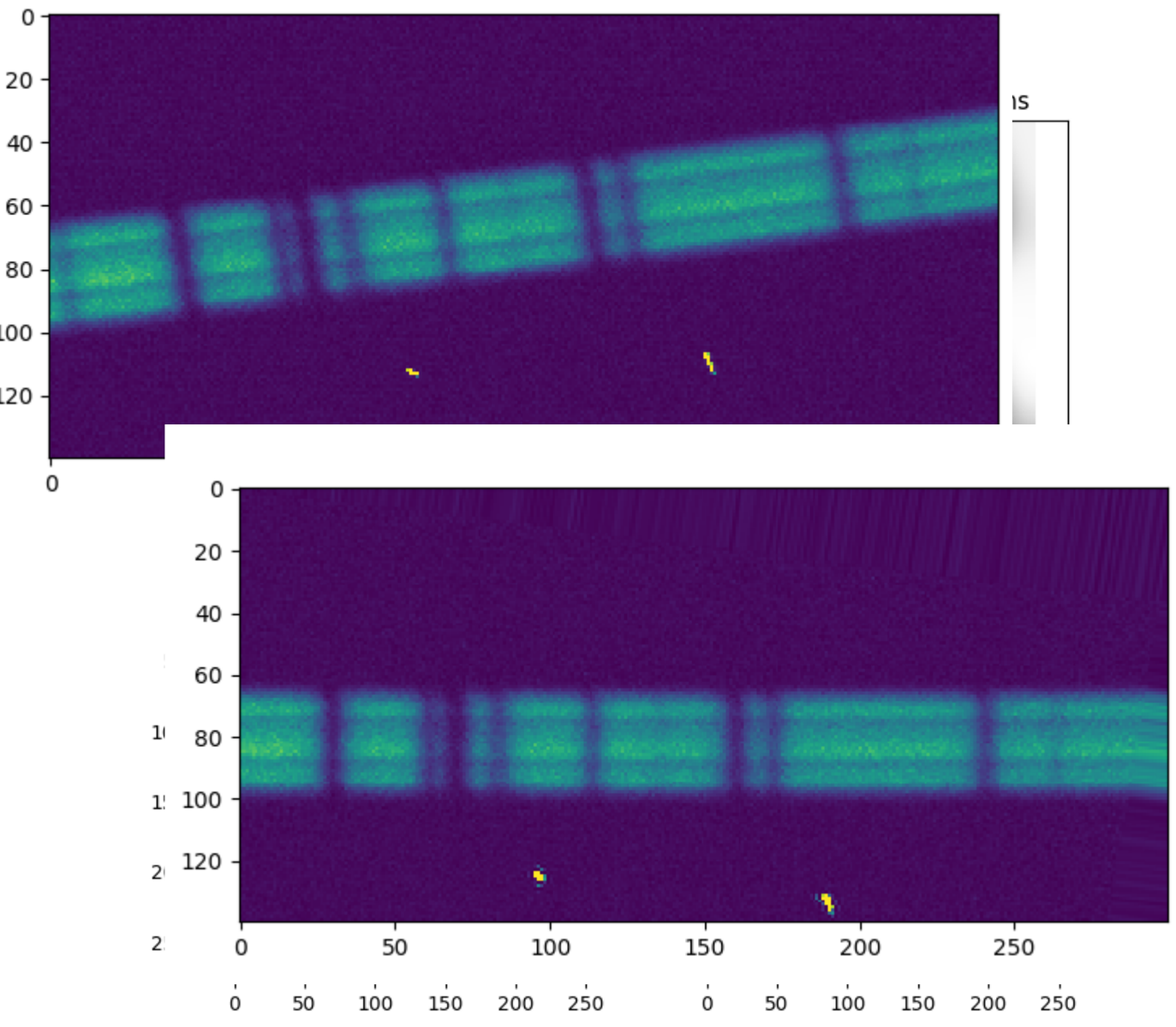
- All echelle spectra hav needs rectification.
- RV information is in slc
- Any finite order Interp information lose.
- Banc





Rectification and 1D Extraction

- Extend the concept to higher dimension



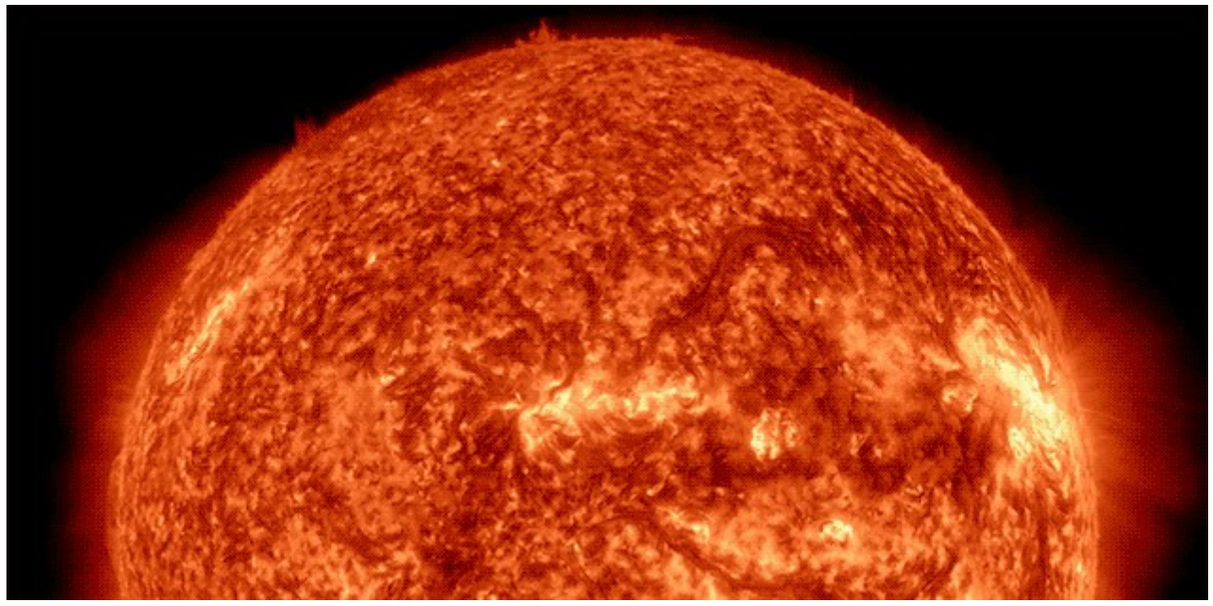
After rectification, we extract the spectrum to a 1D spectrum using optimal extraction algorithm.

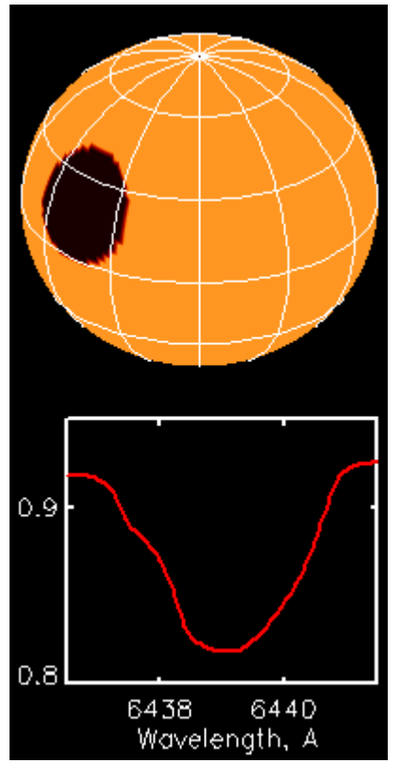
This new Band-limited rectification method is still in its infancy stage.

We are also using more robust polynomial clipping algorithm for rectification and extraction.

Stellar Activity: The biggest challenge

- The biggest challenge we now face is stellar jitter.
- We heavily rely on the spatial and temporal averaging to get a stable RV.



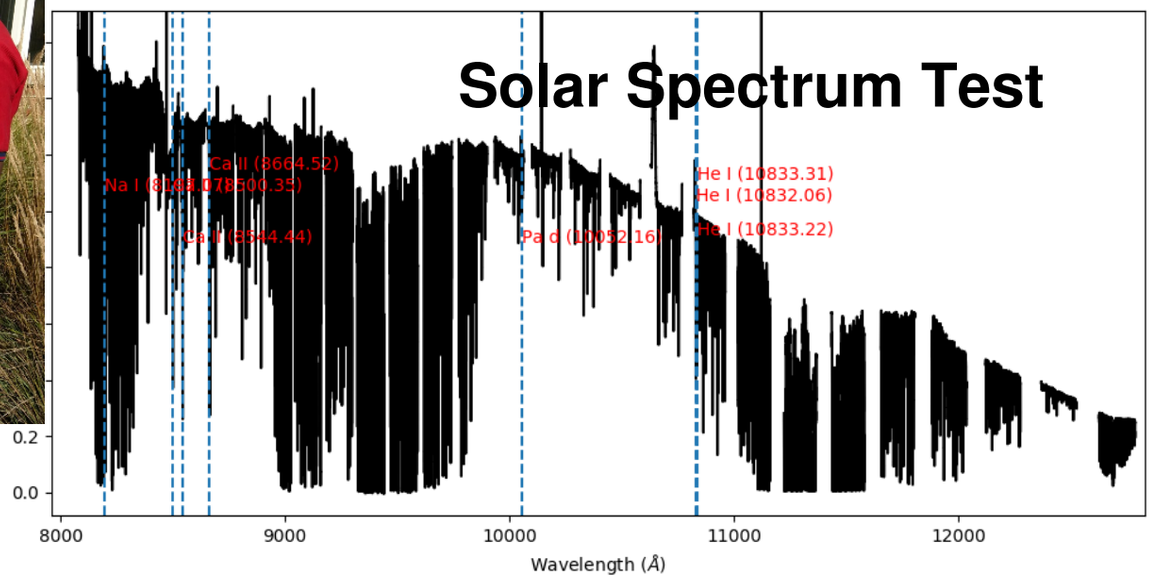


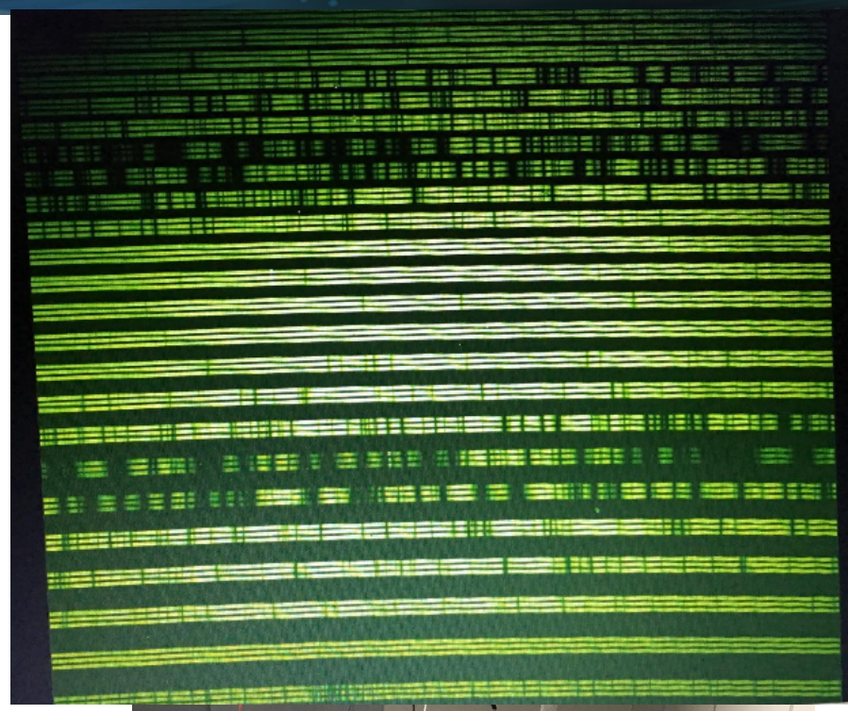
- Convection flows in km/sec;
- acoustic modes (p-modes) in m/sec (several minutes timescale)
- Granulation flows, suppression due to strong magnetic fields regions, etc.
- Lots of work on stellar activity indicators and statistical modeling.

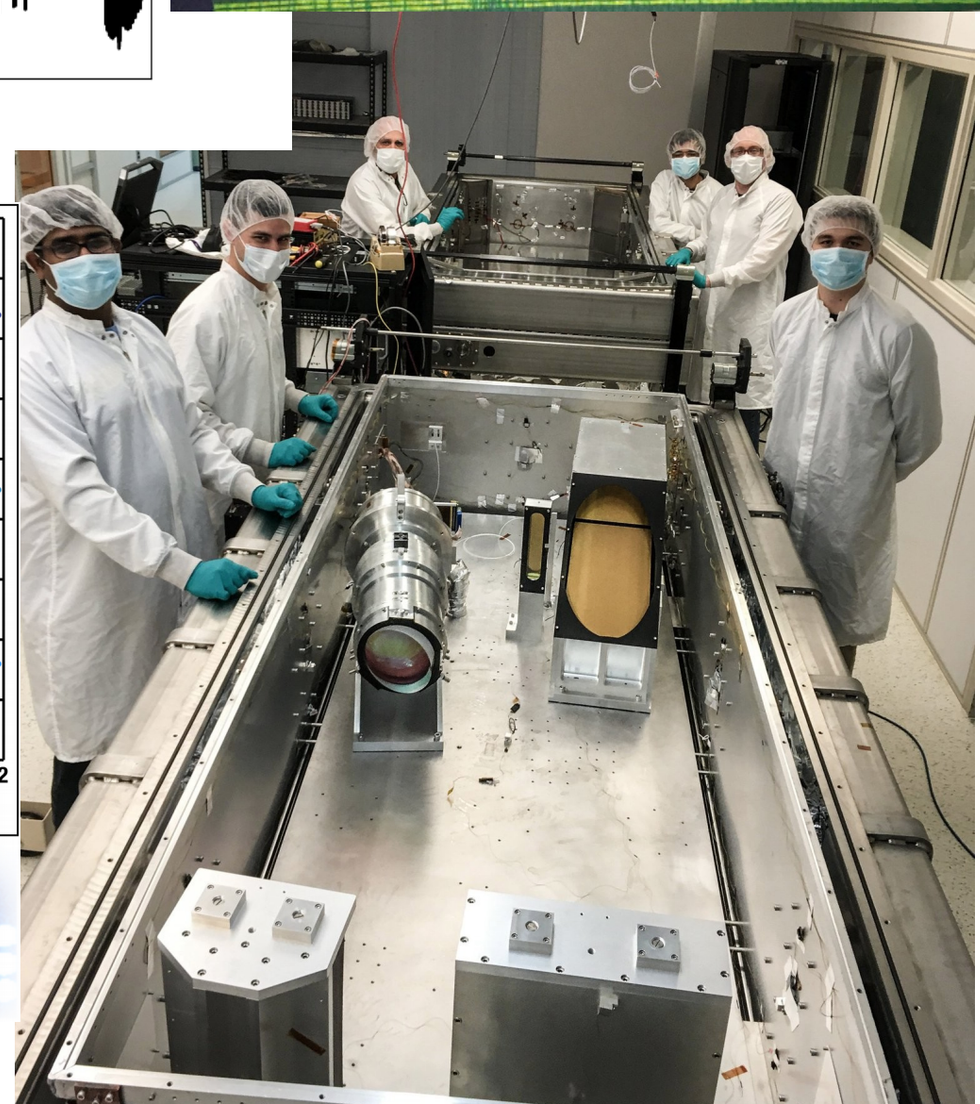
The final magic of Radial velocity estimation!

- CCF Mask method
  - Cross Correlation with a weighted rectangular pulse mask for handpicked spectral lines
  - Not optimal for late type stars like M-dwarfs
- Least Square method
  - Least Square fitting of a template spectrum
- Segmented Least Square Method
  - Weighted Segmented Least Square fitting of a template spectrum. Weights optimized to reduce stellar activity signals.

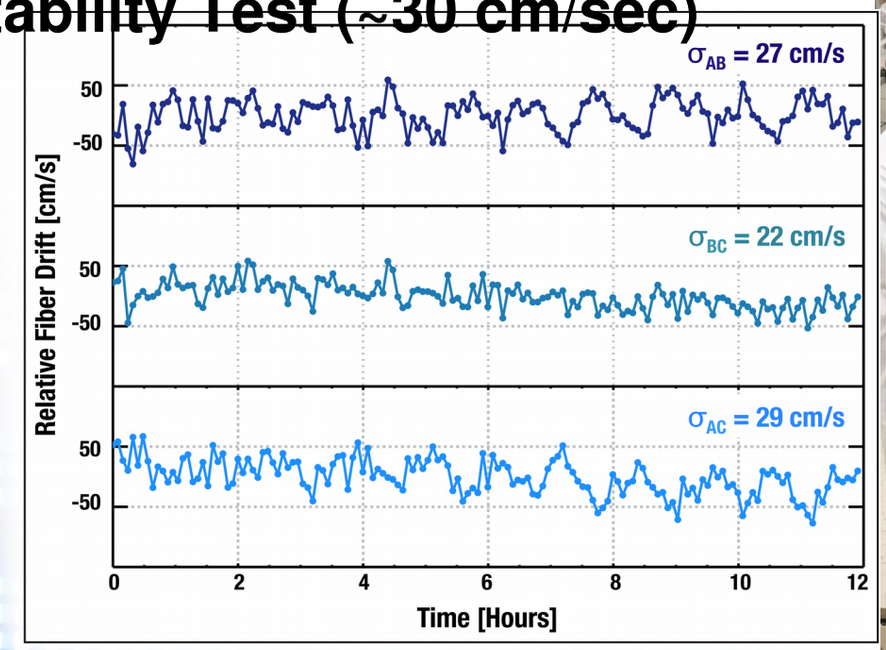
HPF's Lab Tests





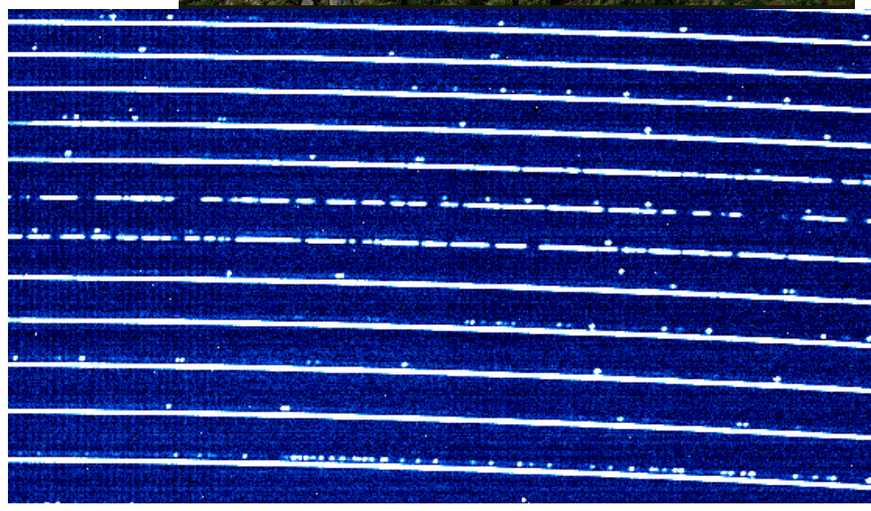


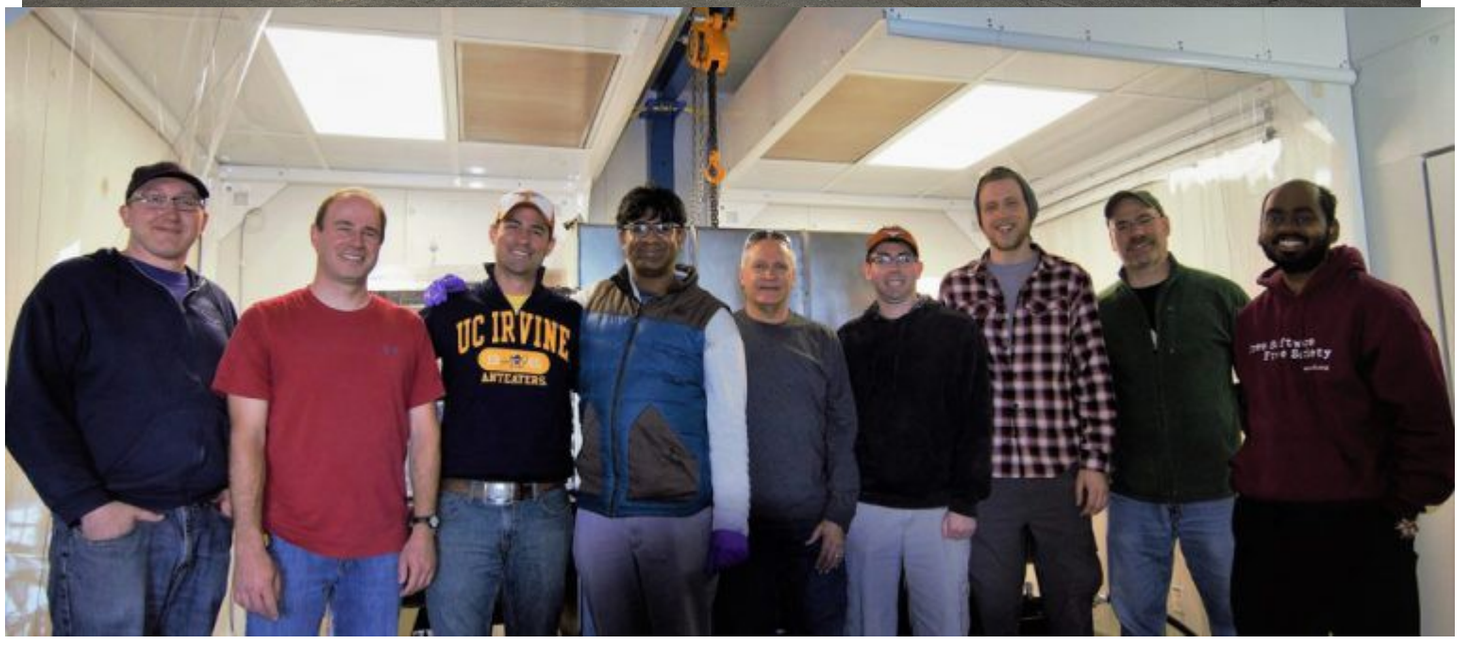
FFP Super K Spectrum Stability Test (~30 cm/sec)



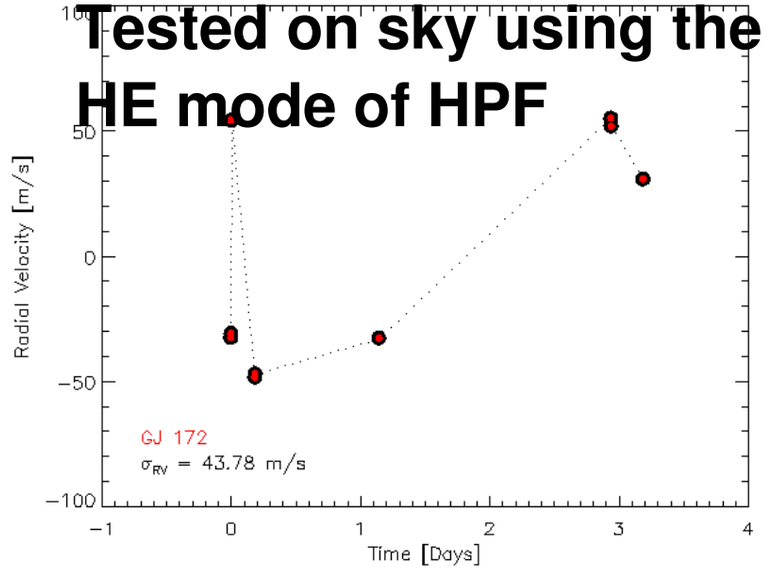
Ninan et. al. @ AAS (2018a)

HPF Commissioning @ 10 m HET

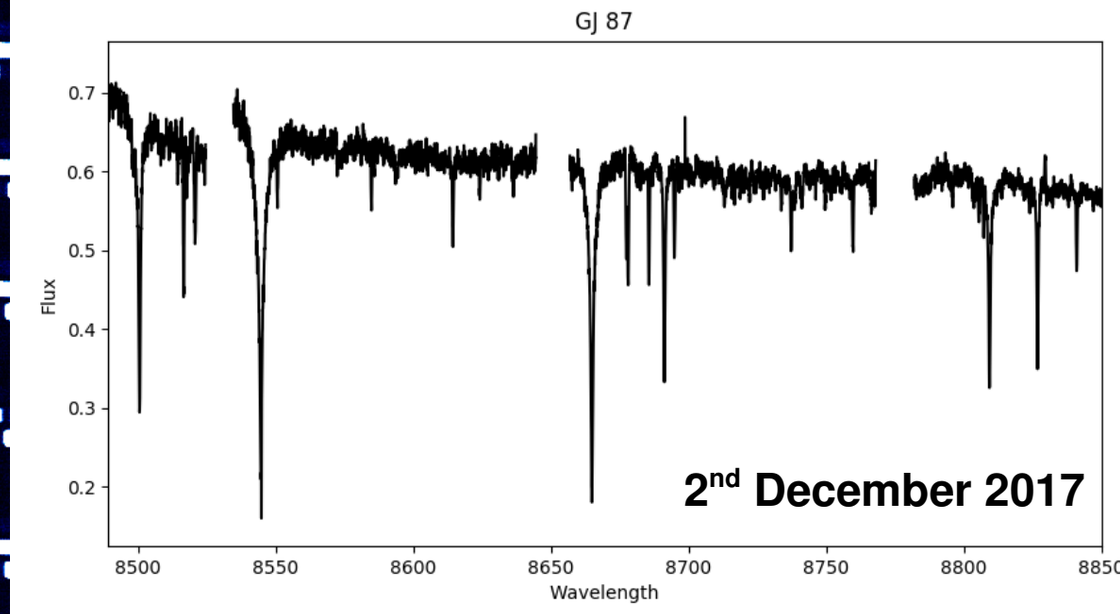




Tested on sky using the HE mode of HPF



HPF First Light on 30th Nov 2017 UT



Instrument has now stabilized !

Stay tuned for first RV stability estimates in the upcoming AAS January 8th 2018

Many more key aspects I skipped...

- The Control Software System

  TIMS: Python-Twisted based asynchronous general instrument control system. **Bender et. al. (2016)**
- The Frequency Comb

  Replacement for hollow cathode lamps for wavelength calibration.
- Calibration Bench
- Telluric Correction
- Solar scattered light correction
- Grating scattered light correction
- Target acquisition inside HPF fiber at HET telescope.
- Large amount of simulations at each stage!
- …

Building these instruments wouldn't be possible without a talented team

Suvrath Mahadevan (PI)
Fred Hearty (PM)
Jason Wright (PS)
Andy Monson (SE)
Chad Bender (IS)
Paul Robertson
Joe Ninan
Kyle Kaplan
Larry Ramsey
Eric Levy
Tyler Anderson
Arpita Roy
Guðmundur Stefánsson
Shubham Kanodia
Scott Blakeslee
Sharon Wang
Eric Ford
Fabienne Bastien
Thomas Beatty
Rebekah Dawson

Cullen Blake (IS)
Sam Halverson

Michael McElwain (IS)
Qian Gong
Ravi Kopparapu

Scott Diddams
Ryan Terrien

Christian Schwab (OS)

Abhijit Chakraborty

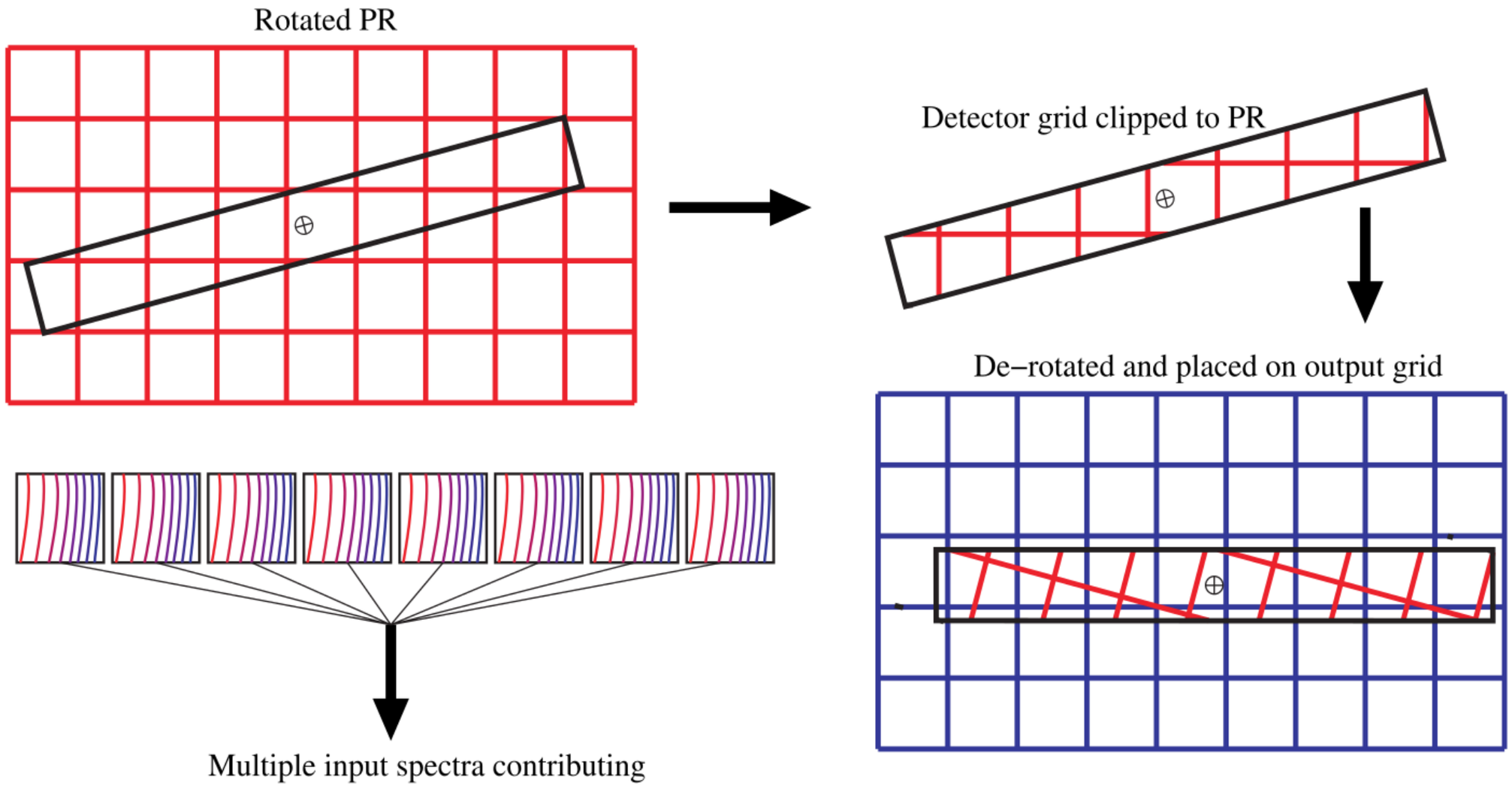
Subset of the NEID Team

Thank you!

Questions

PennState
Eberly College
of Science

Polygonal Clipping : Area weighted Linear interpolation



(Smith+, 2007)

PennState
Eberly College
of Science