# The Multifactorial Calibration System

HISPEC

**ExSoCal 2025**

**University of California, Los Angeles**

**15 December 2025**

**Ben Sappey** on behalf of the HISPEC Instrument Team

HEISING-SIMONS FOUNDATION

GORDON AND BETTY MOORE FOUNDATION

Astrobiology Center

Northwestern University

University of California San Diego

W. M. Keck Observatory

Maunakea Island of Hawai'i

California Institute of Technology

University of California Los Angeles

JPL Jet Propulsion Laboratory California Institute of Technology

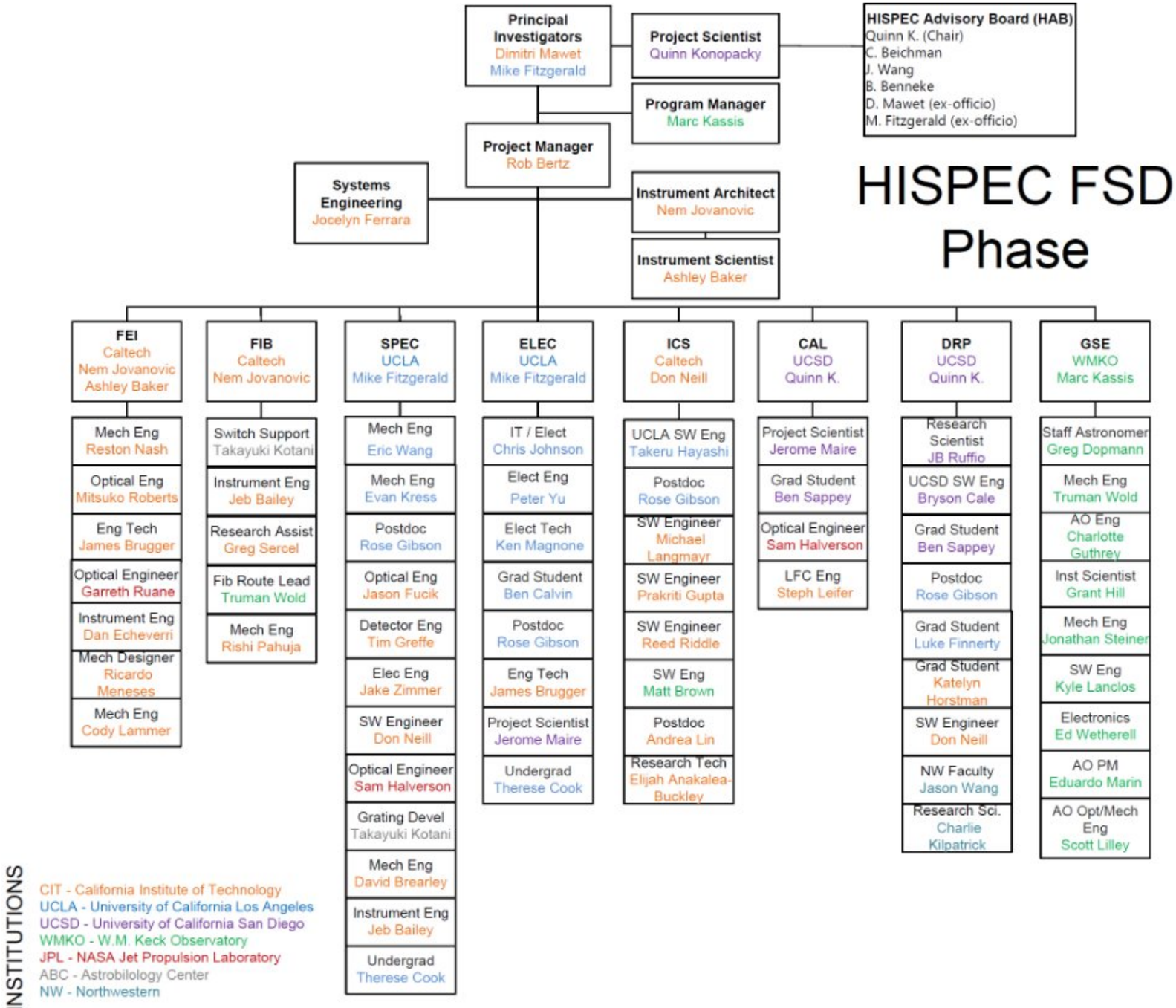
NASA

UC San Diego

SCHOOL OF PHYSICAL SCIENCES

Department of Astronomy and Astrophysics

# HISPEC FSD Phase




INSTITUTIONS

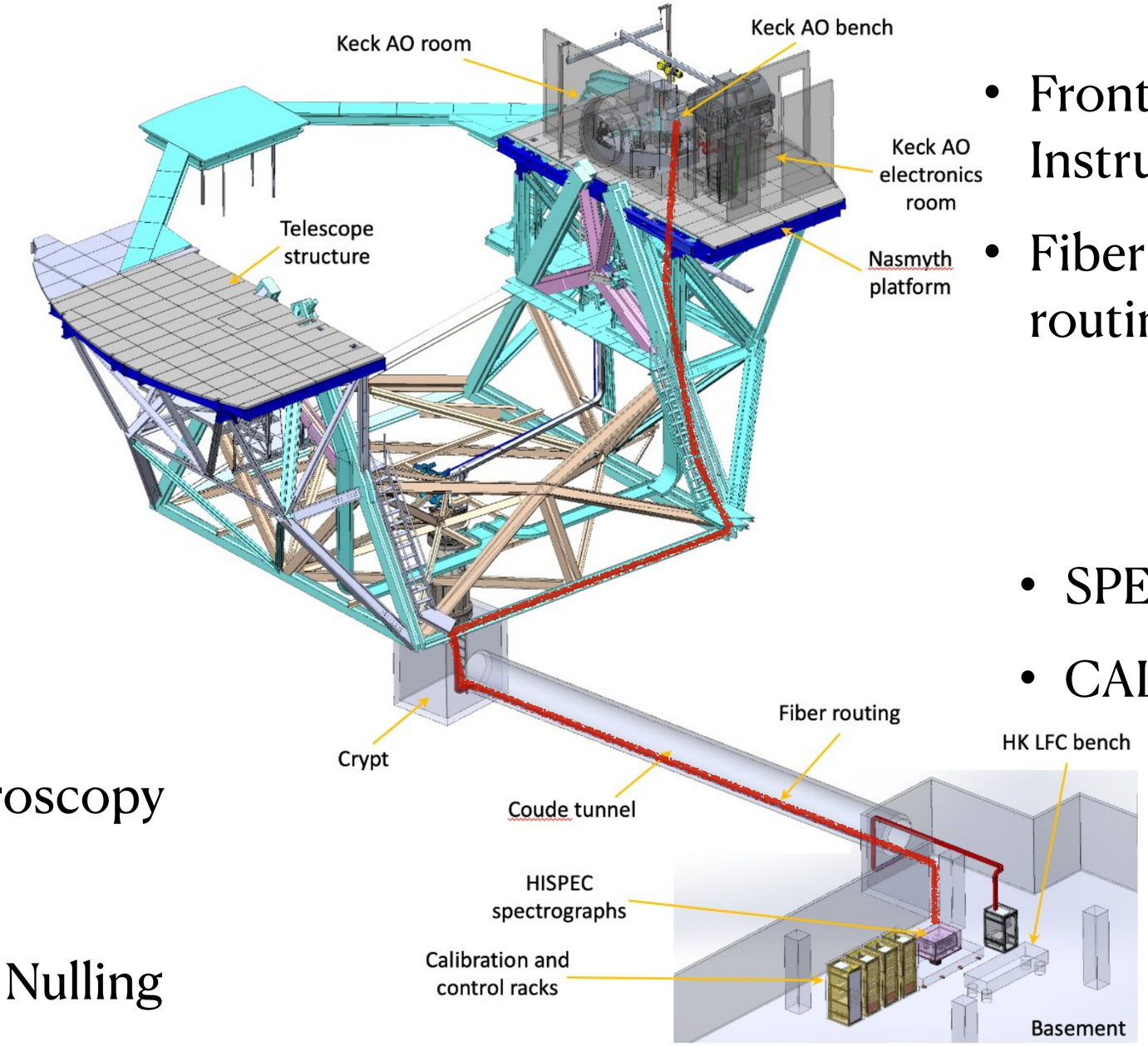
CIT - California Institute of Technology
UCLA - University of California Los Angeles
UCSD - University of California San Diego
WMKO - W.M. Keck Observatory
JPL - NASA Jet Propulsion Laboratory
ABC - Astrobiology Center
NW - Northwestern

# HISPEC Overview

- AO-fed
- Single-Mode Fiber
- y, j, H, K bands simultaneously
- Resolution = >100,000

3 + 1 Exoplanet Science Cases

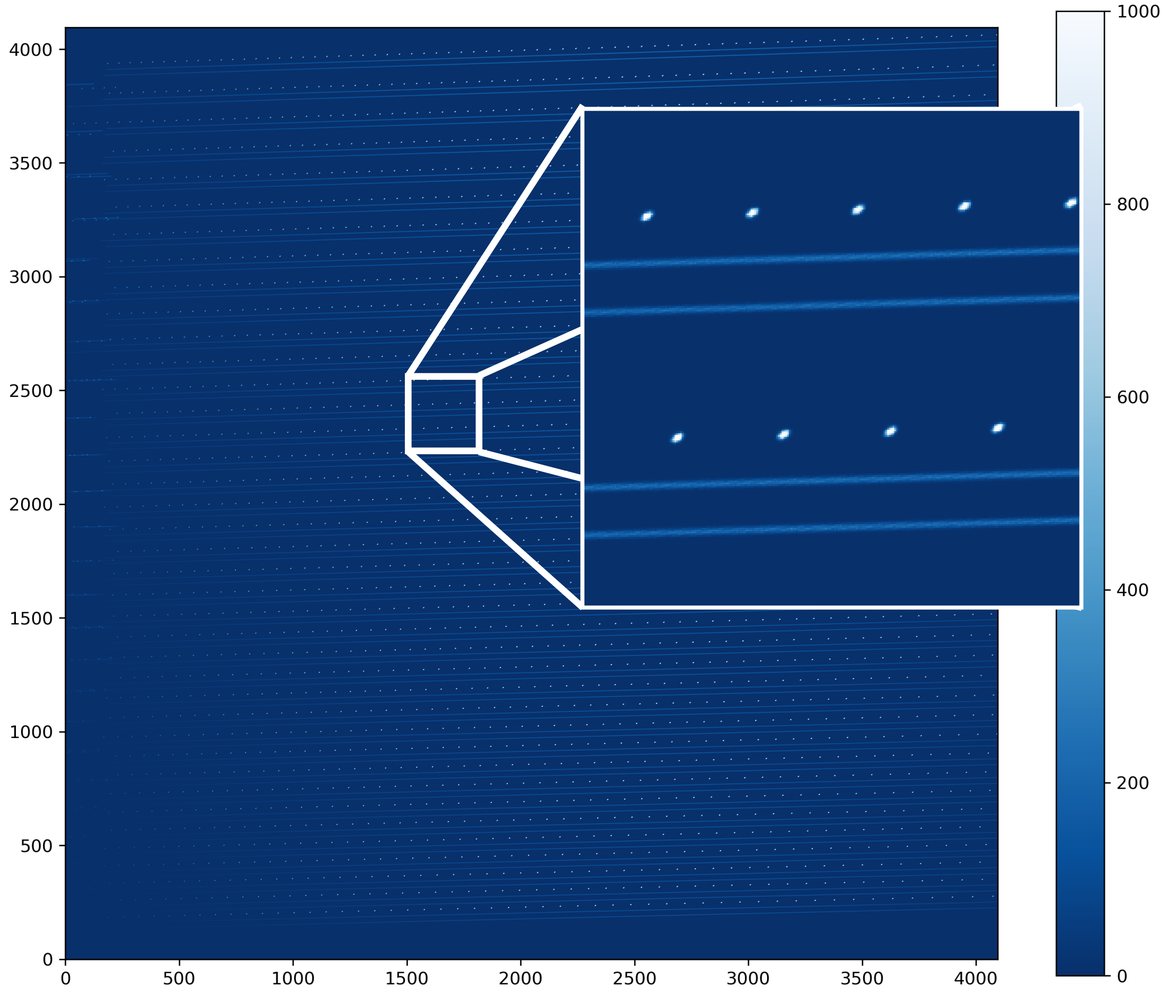
- Transit Spectroscopy
- High-contrast Direct spectroscopy
- PRV
- + Interferometry with Fiber Nulling

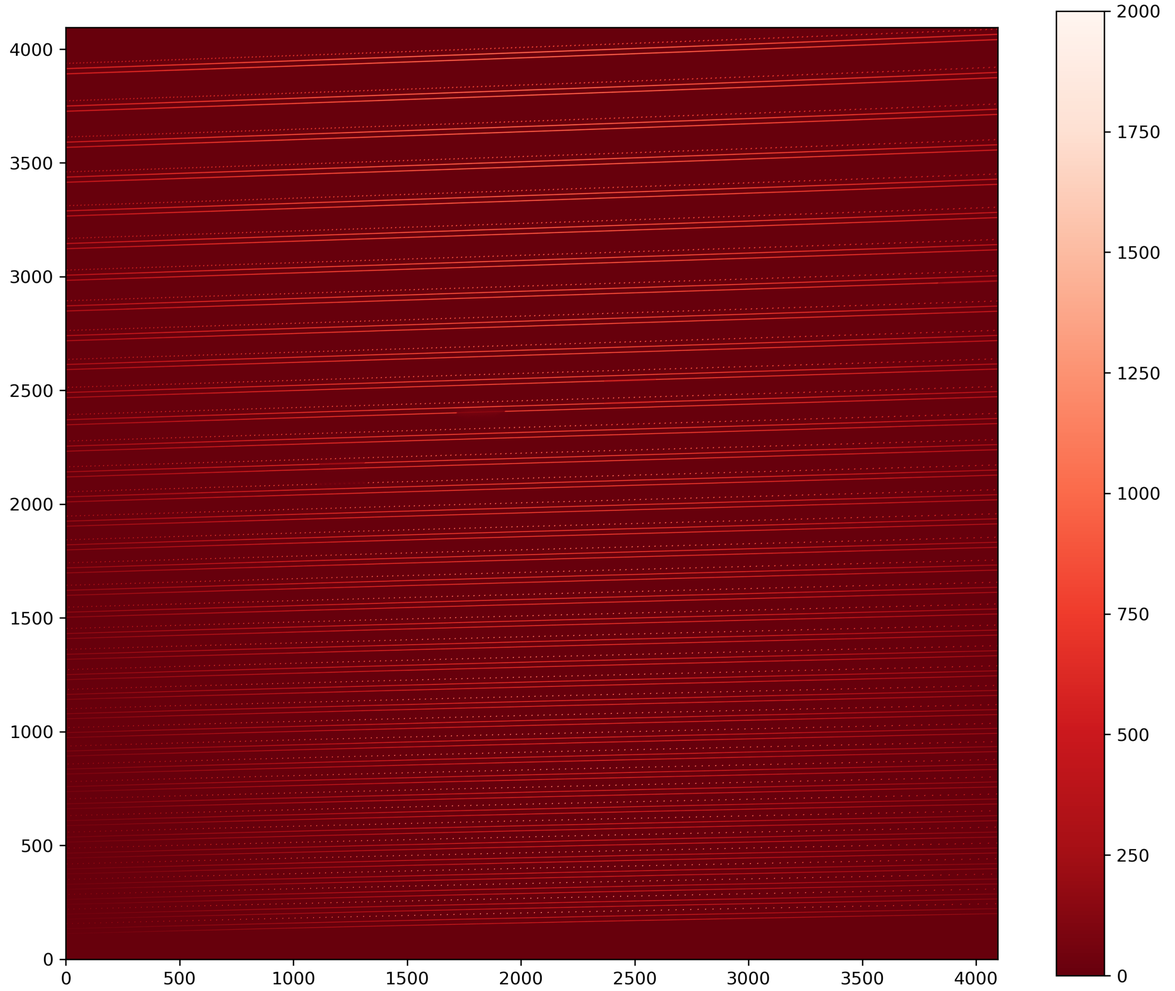



- Front-End Instrument
- Fiber routing

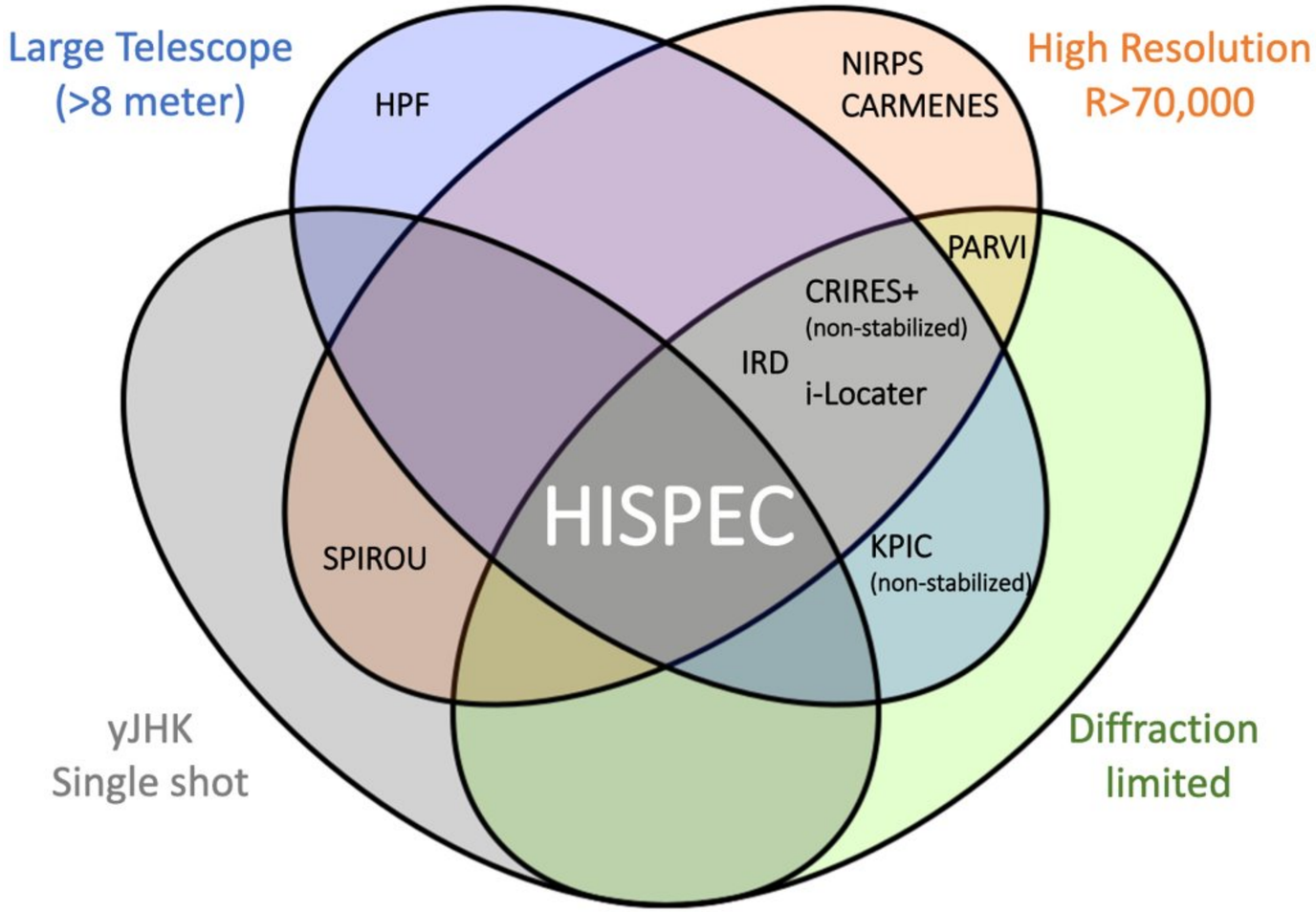
- SPEC
- CAL

# HISPEC Overview



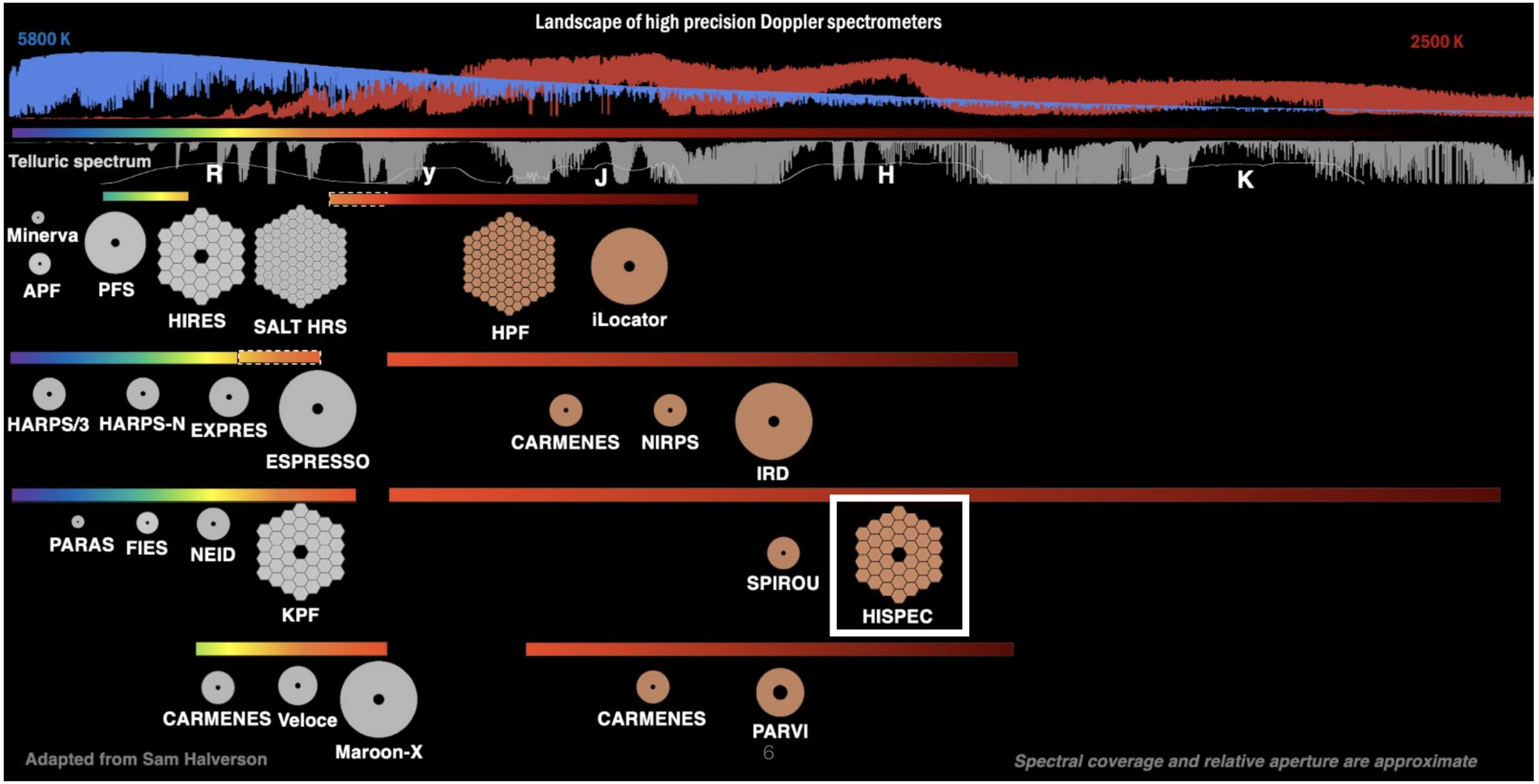



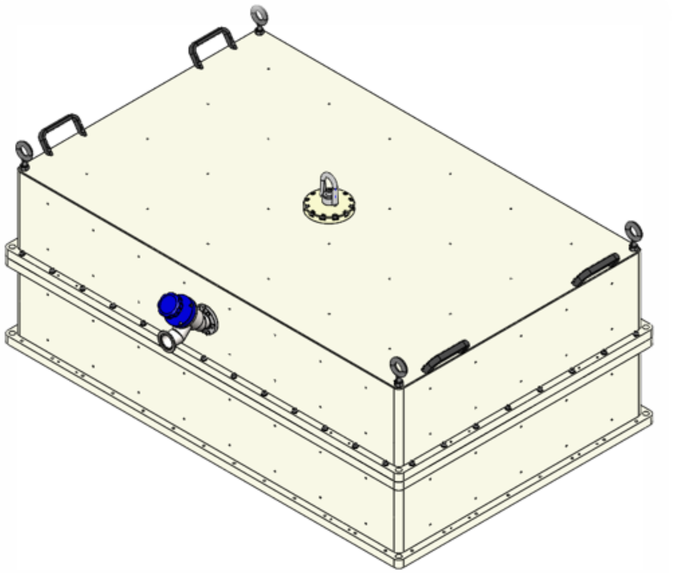
# HISPEC in context with PRV Instruments

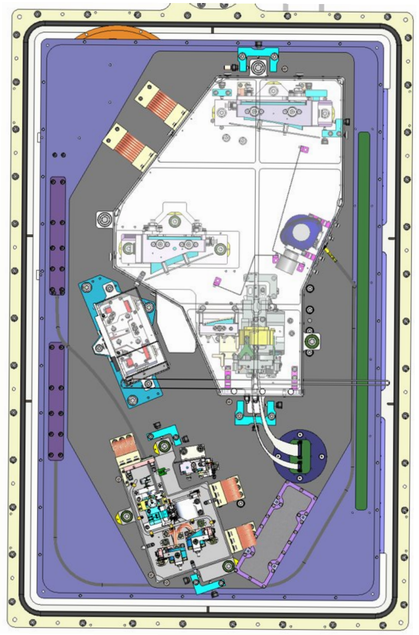


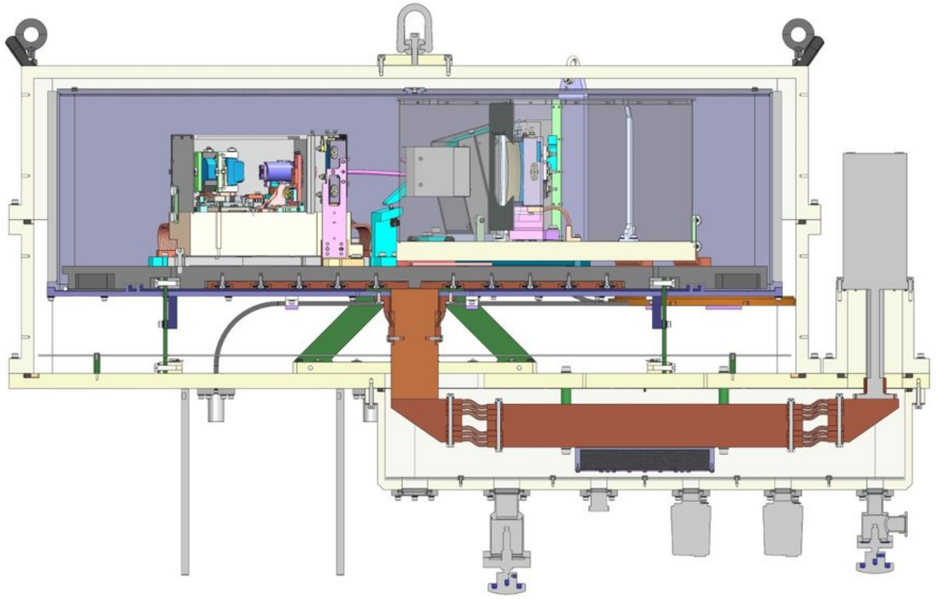
# HISPEC in context with PRV Instruments

## R ≈ 100,000, 0.98 - 2.46 $\mu$m, Fiber Fed (SMF)







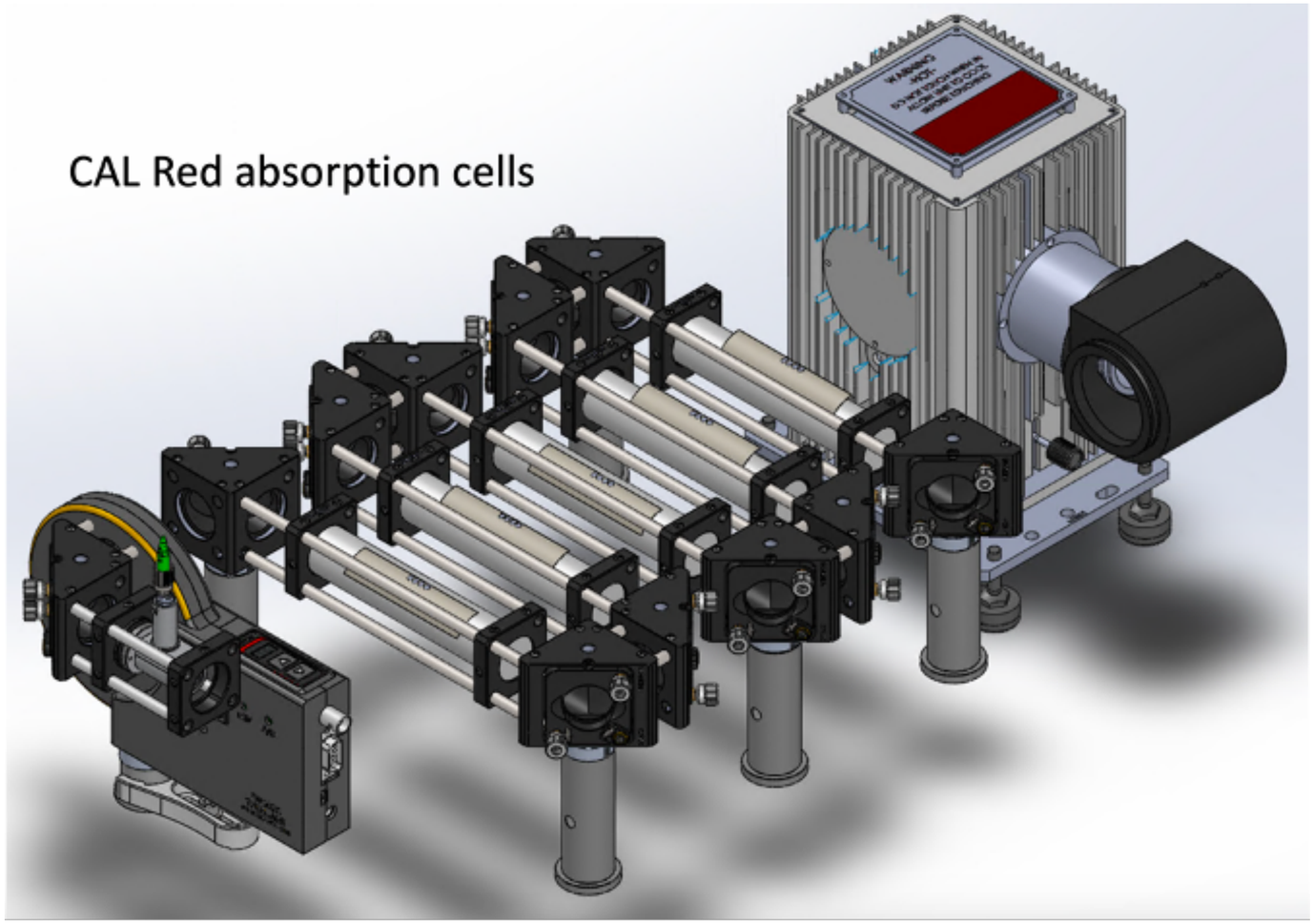


# HISPEC is designed to be —

# stable

# HISPEC is designed to be —

# flexible




# HISPEC is designed to be —

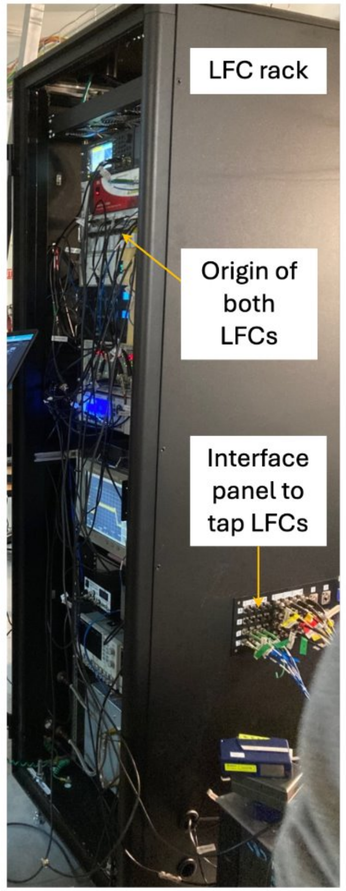
# calibrated (robustly)

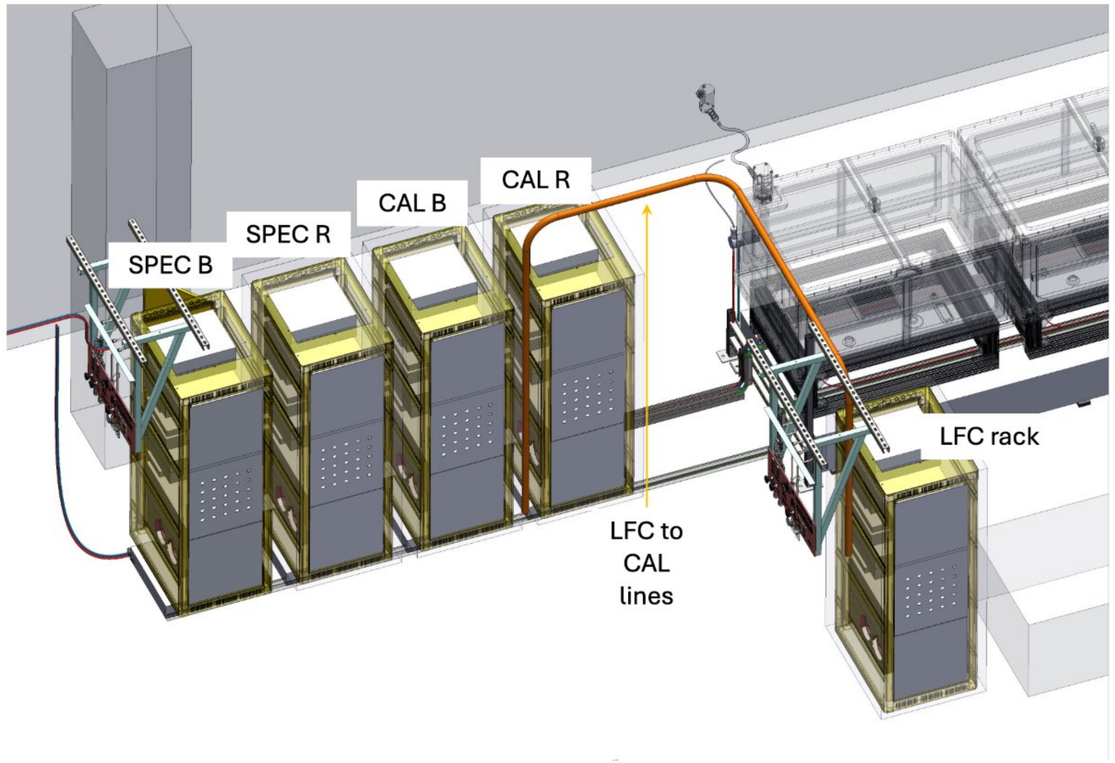
# CAL Overview

# CAL Overview

**CAL will provide**

1. Detector-level calibrations
   - darks
   - flats
2. Instrument-level calibrations
   - Fiber flats/traces
3. Wavelength Solution
   - 30 cm/s *internal* RV precision



# CAL Overview

## BSPEC

- Menlo Systems LFC (0.97 - 1.45 μm)
  - i.e., IR light that KPF does not use
- Etalon
- Hollow Cathode Lamp (Uranium)
- BSPEC Flatfield

## RSPEC

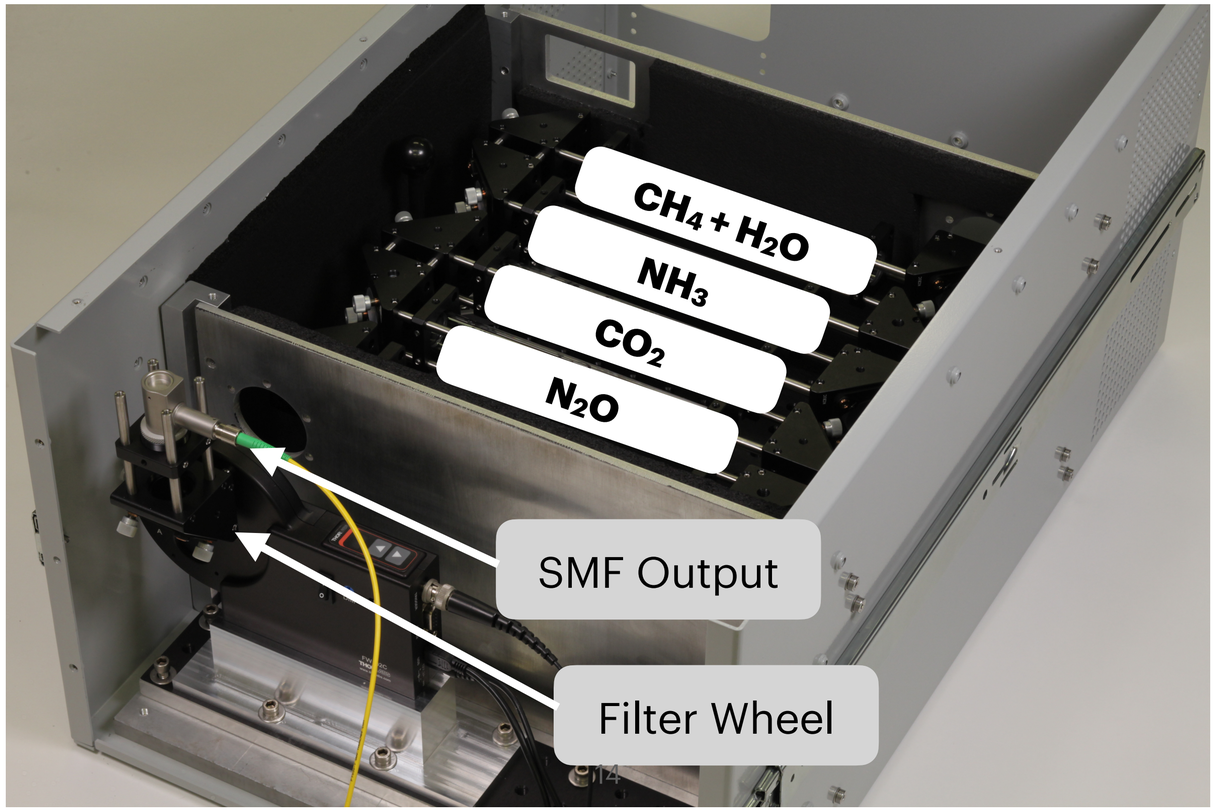
- HK LFC (1.10 - 2.2 μm, → 2.5 μm)
- Etalon
- Gas Cells ($CO_2$, $CH_4$, $NH_3$, $N_2O$)
- RSPEC Flatfield

# Wavelength Calibrators

# Wavelength Calibrators

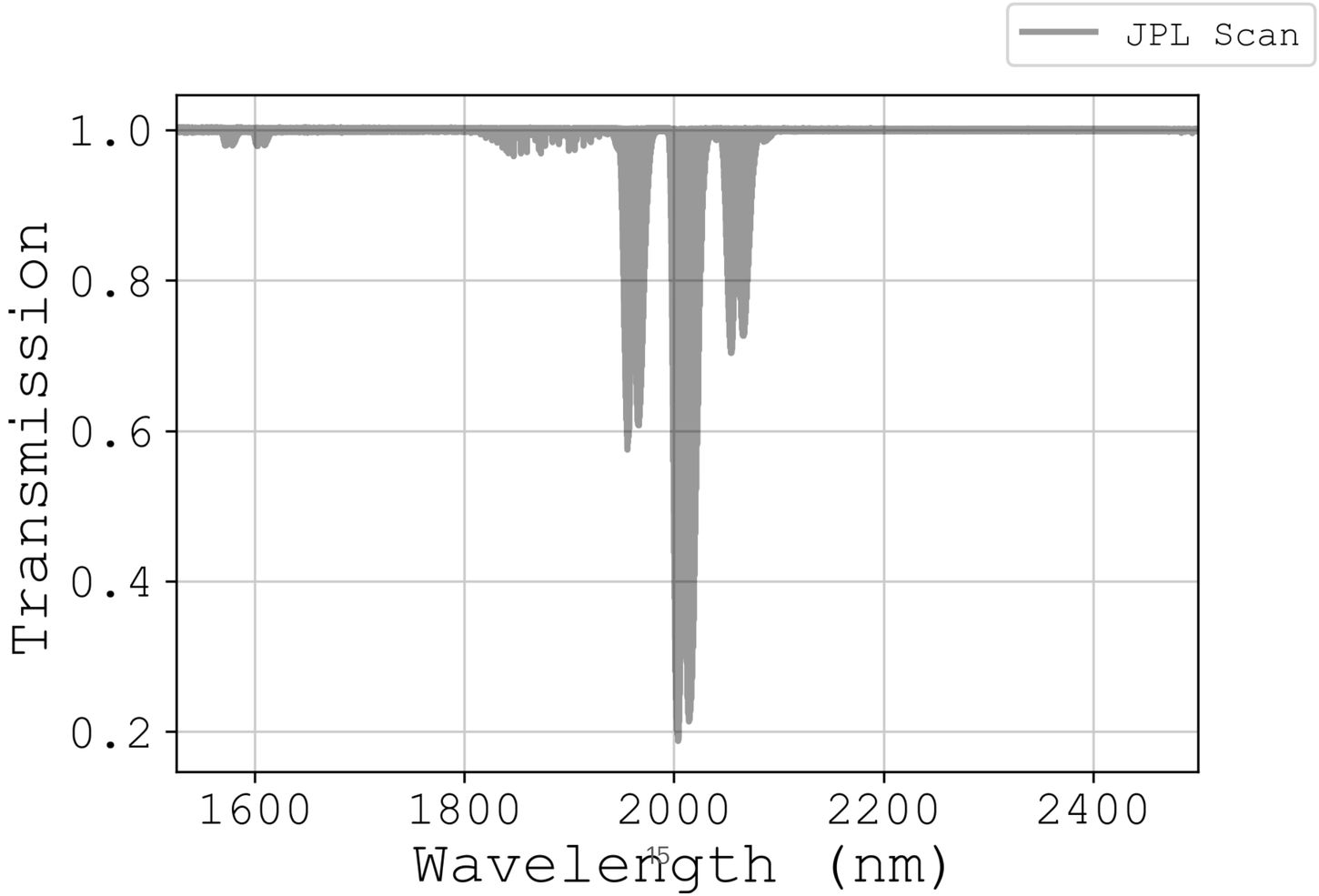
## Gas Cells

Light goes through the gas cells, some gets absorbed, the transmission spectrum is used to calibrate the dispersion axis



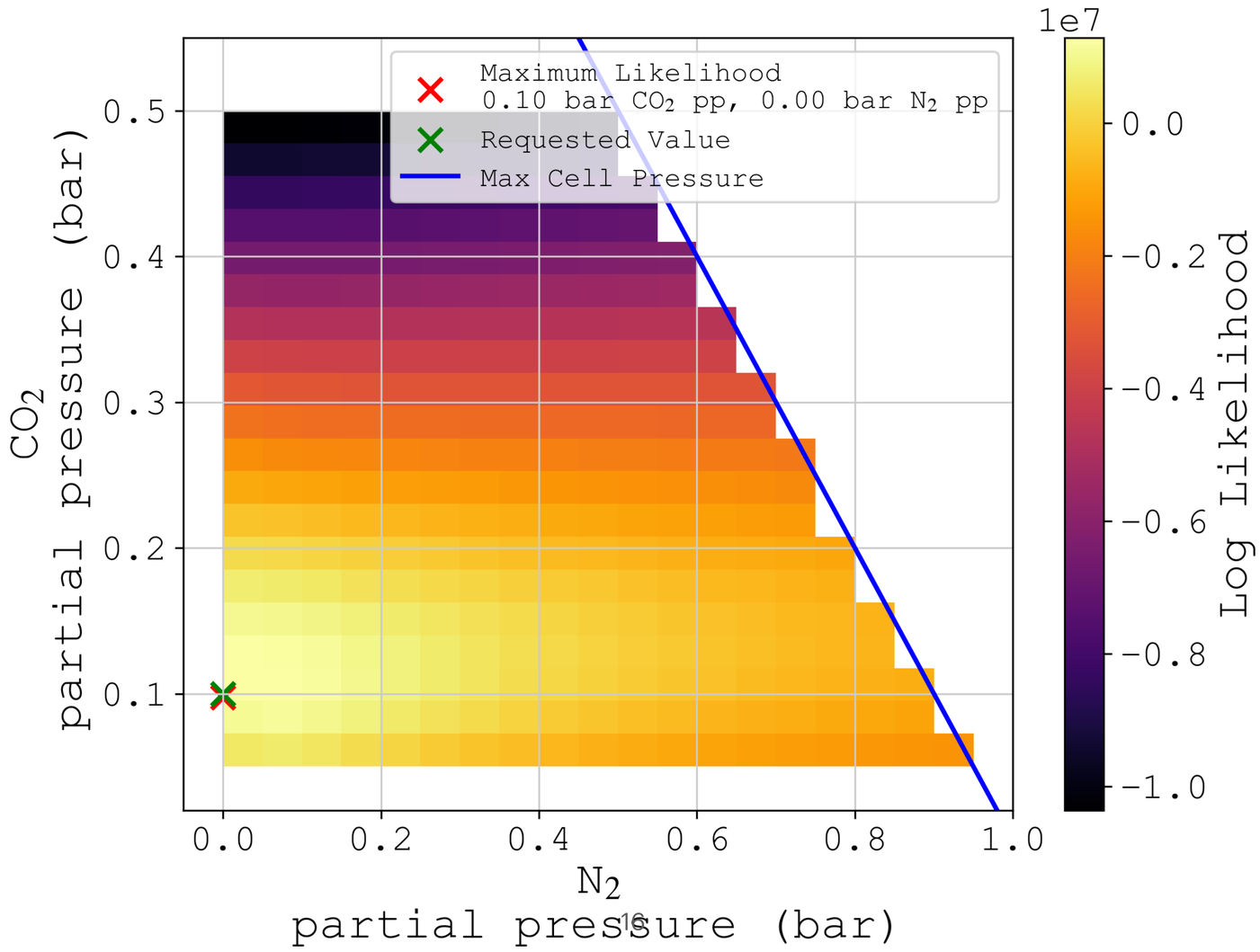
# Wavelength Calibrators

## Gas Cells



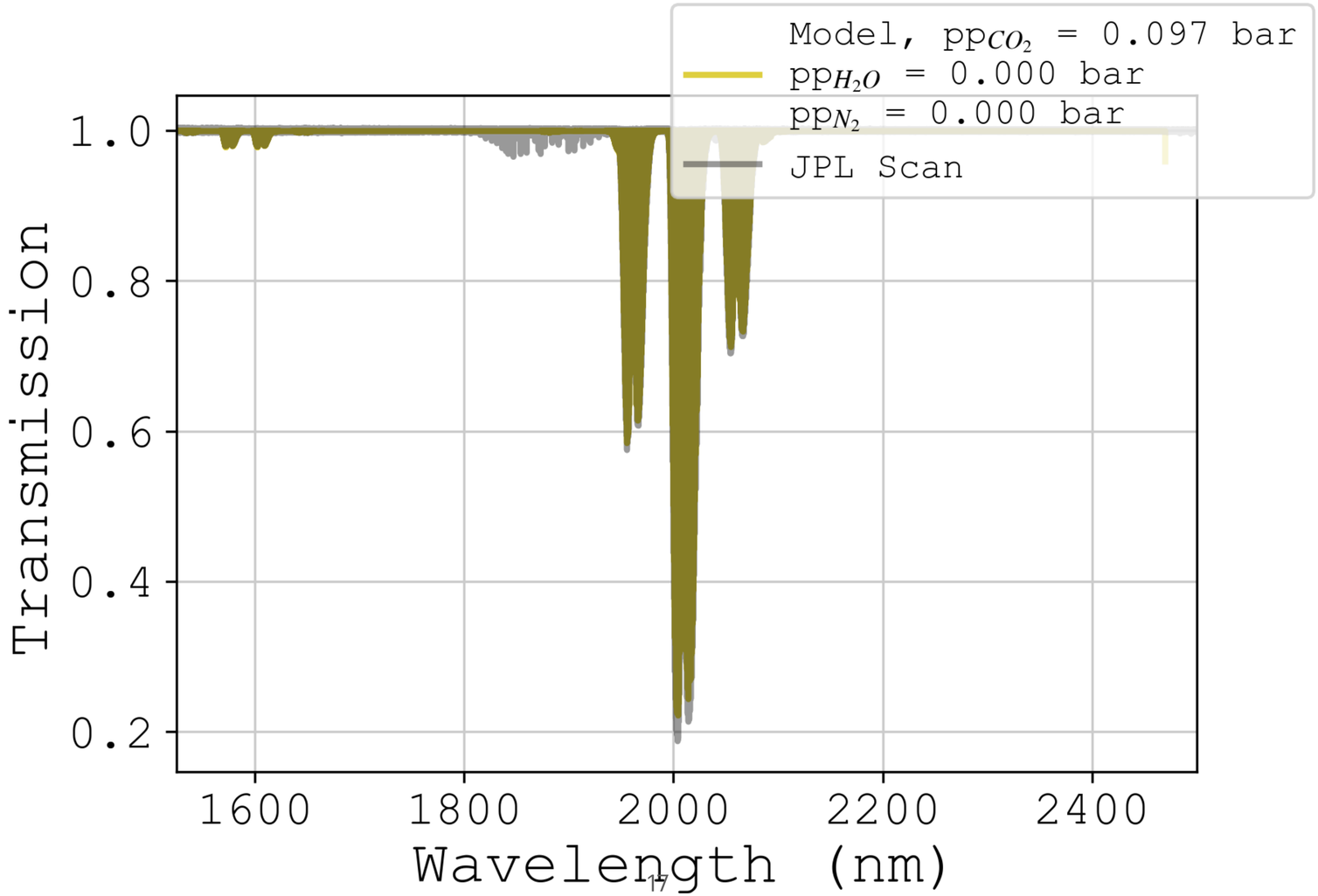
# Wavelength Calibrators

## Gas Cells



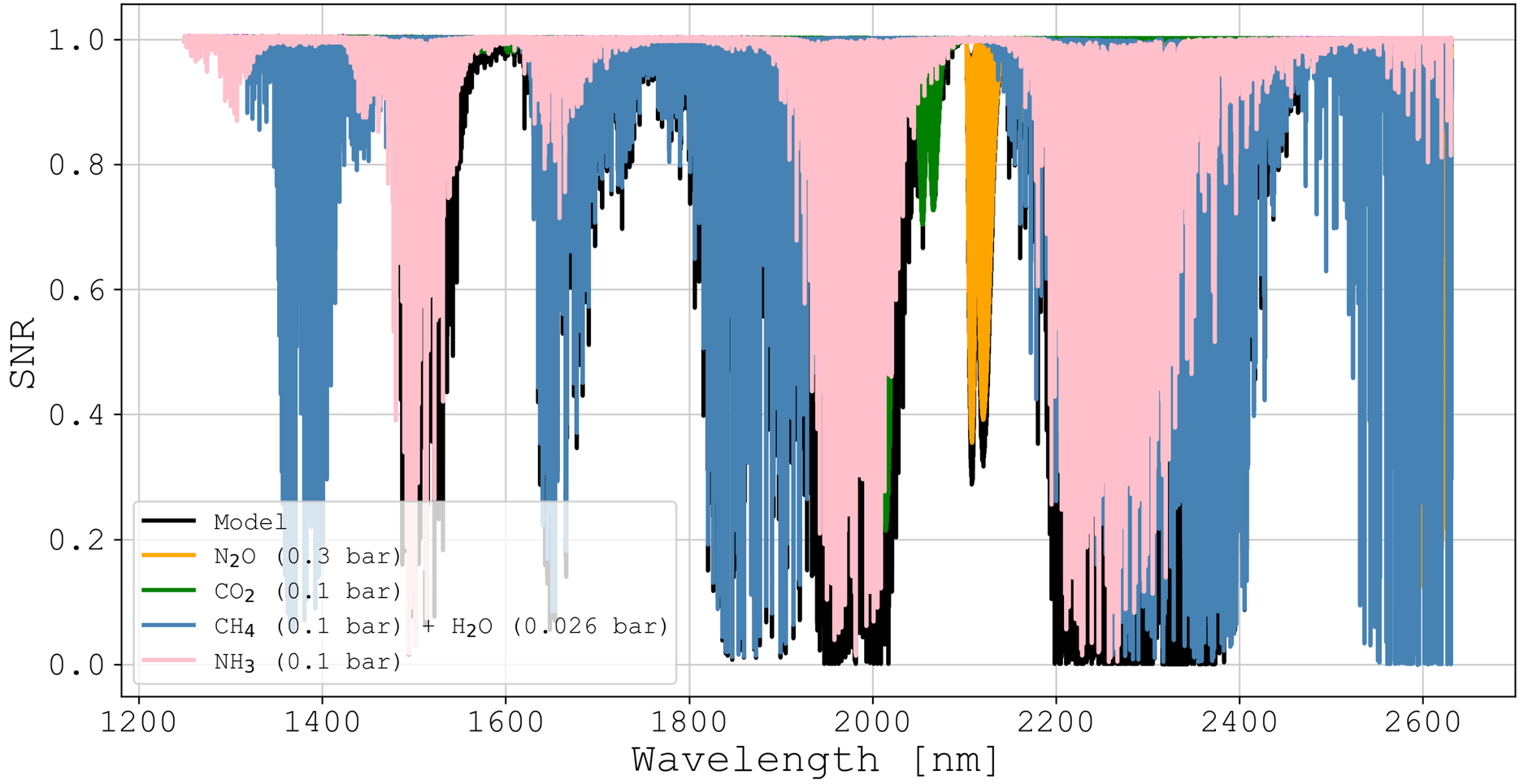
# Wavelength Calibrators

## Gas Cells



# Wavelength Calibrators

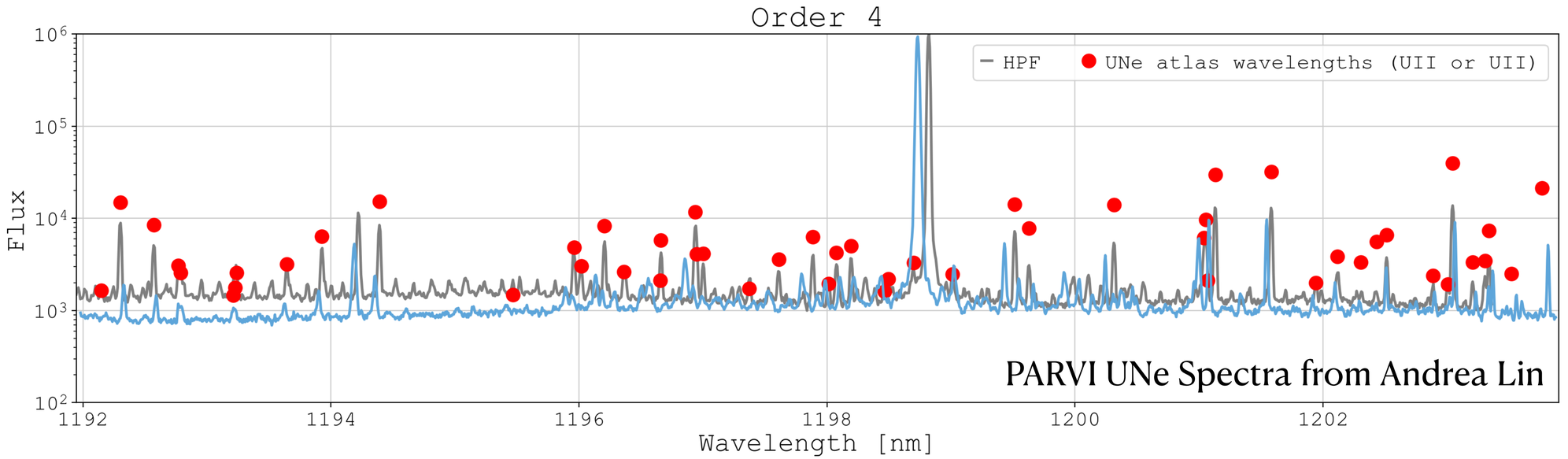
## Gas Cells



# Wavelength Calibrators

## Hollow Cathode Lamp

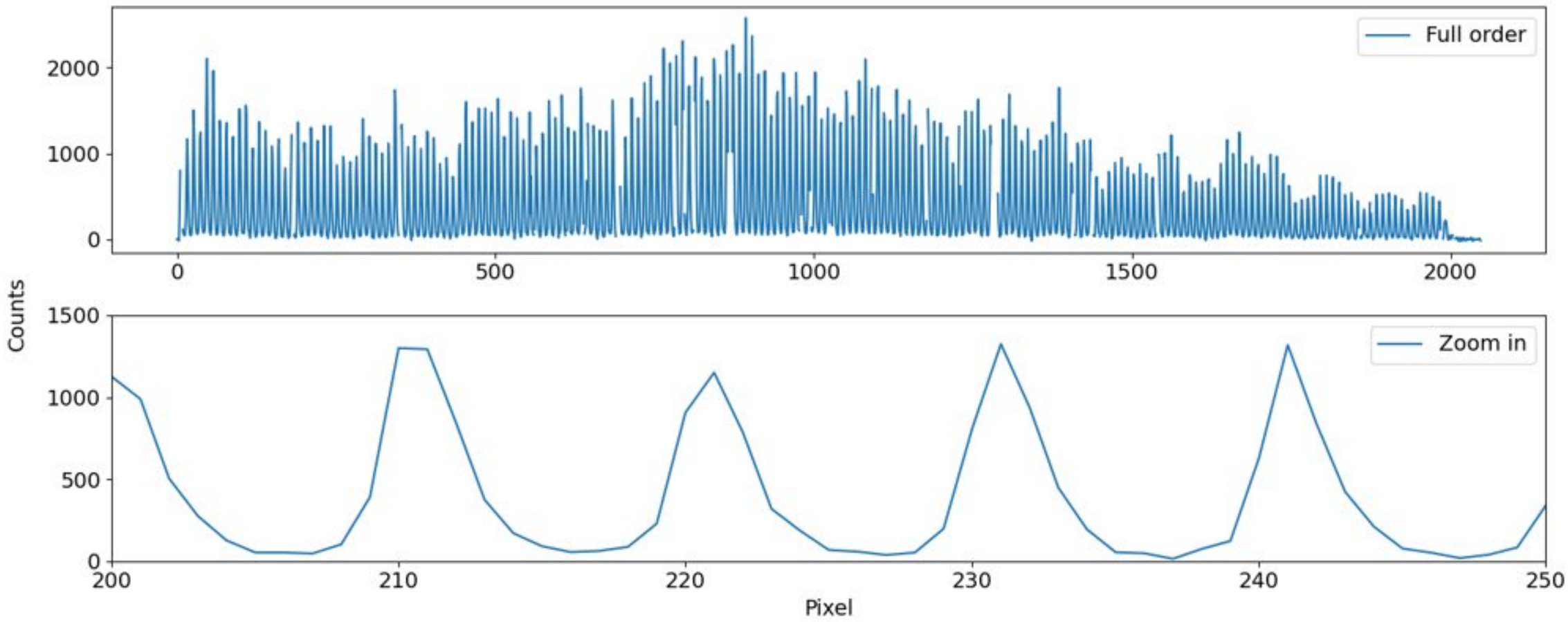
Uranium/neon




- PARVI test showed sufficient flux coupled into SMF
- Sufficient SNR on H2RG in 30s
- Heritage in APOGEE, CRIRES+, and HPF
- Used for calibrating yJ bandpass

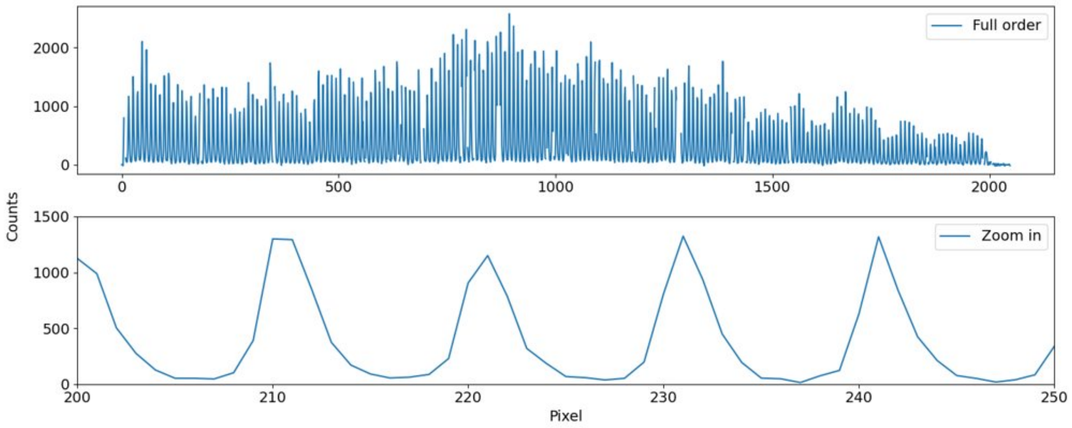
# Wavelength Calibrators

## Laser Frequency Combs



# Wavelength Calibrators

## Laser Frequency Combs




HK comb spectrum, H-band,
Extracted from KPIC, R~35,000
(credit, K. Horstman)

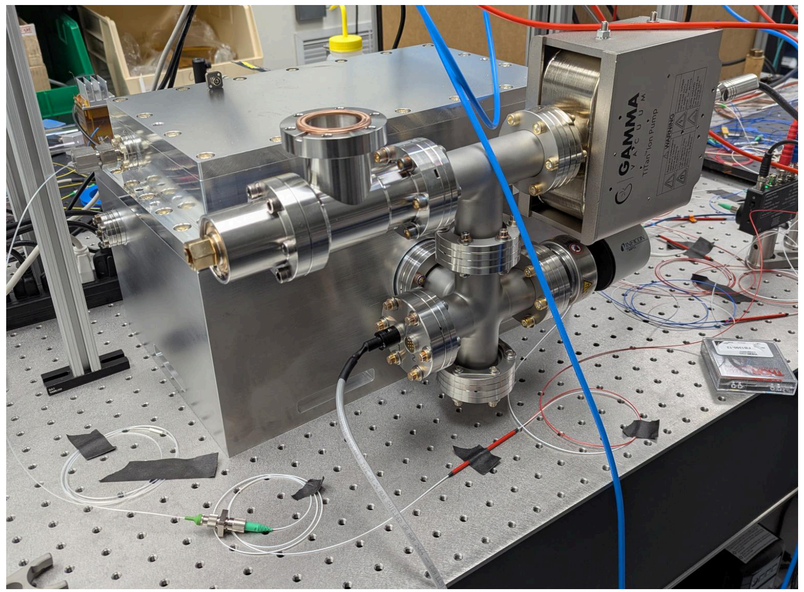
**Description of Comb - Yi et al. 2016, Leifer et al., *in prep*.**

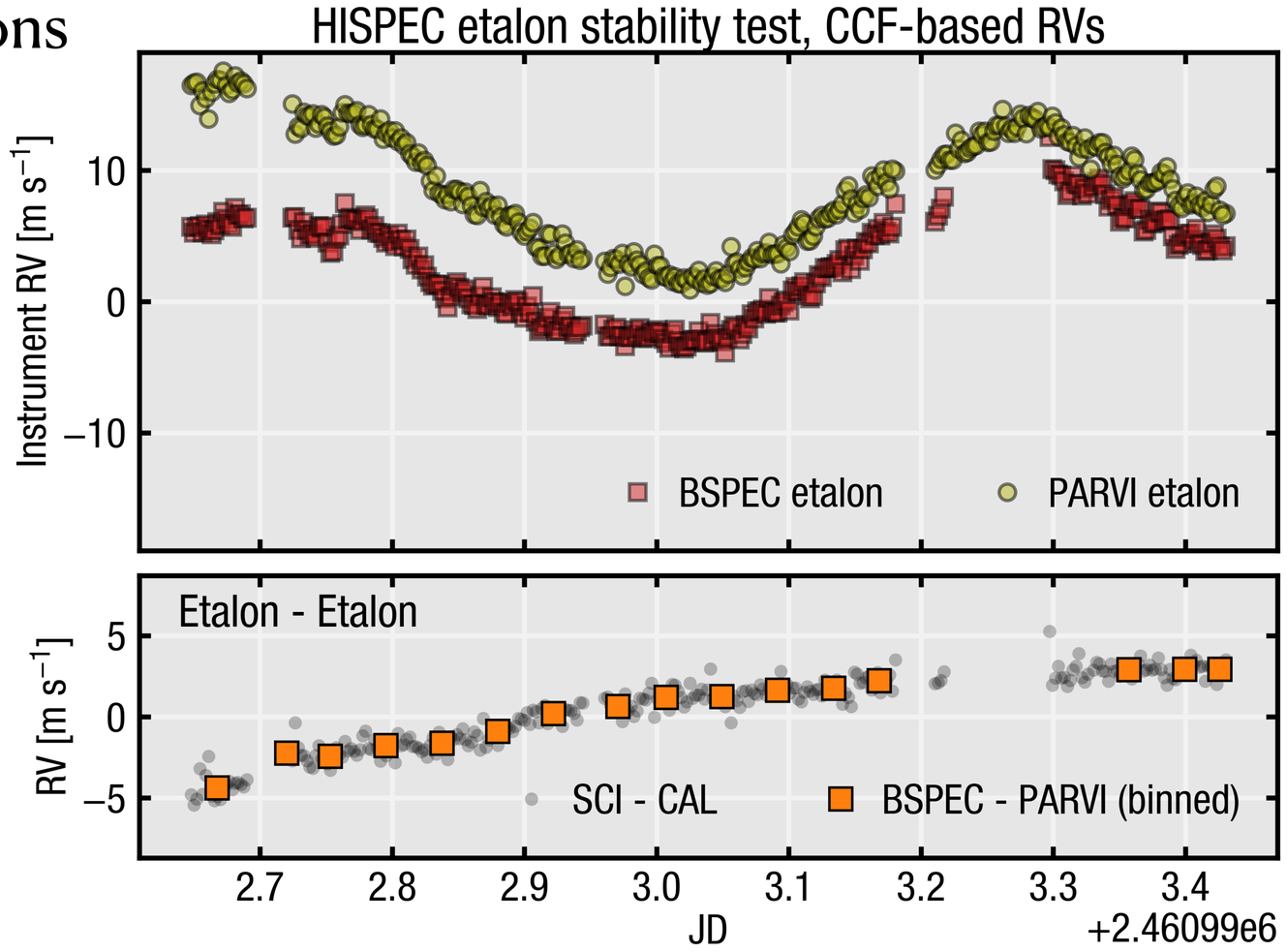
- Mode spacing of 16 GHz, scannable across orders (LSF calibration)
- Operating range: 1.1 — 2.2 μm (→ 2.5 μm)
- An IR flattener is being installed to prepare comb light for NIRSPEC/HISPEC.
- Line spacing locked to GPS-disciplined rubidium clock
- Potential to lock comb to Menlo reference
- Will measure stability relative to Menlo comb (anticipate <10 cm/s stability)

# Wavelength Calibrators

## Etalons

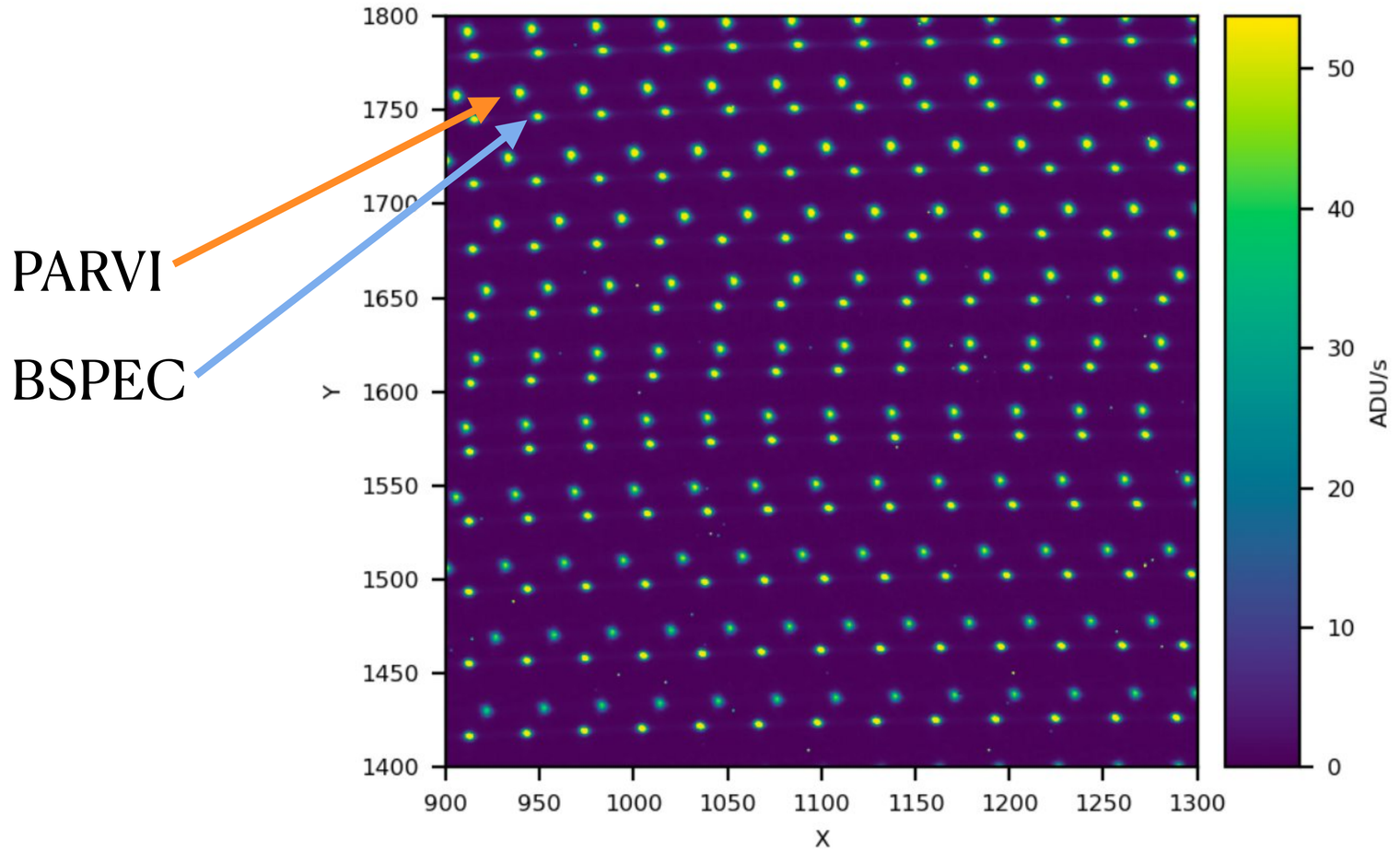
- Stable Laser Systems, yJ and HK etalons
- Broadband IR emitter light source
- <100 nW incident on the cavity





# Wavelength Calibrators

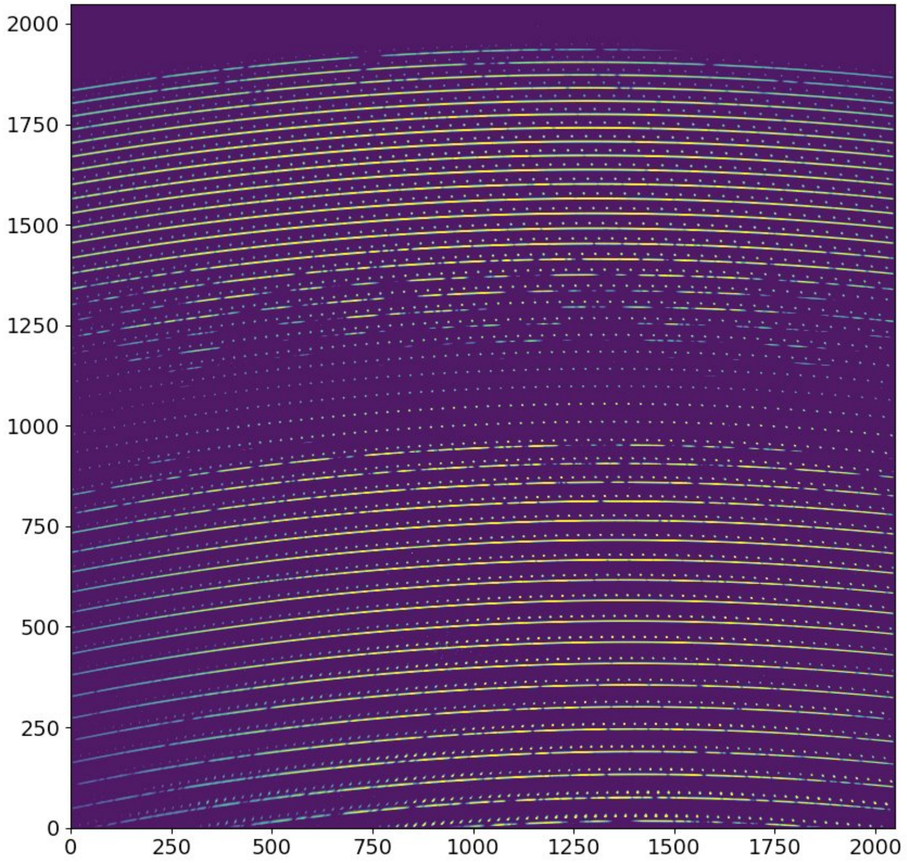
## Etalons



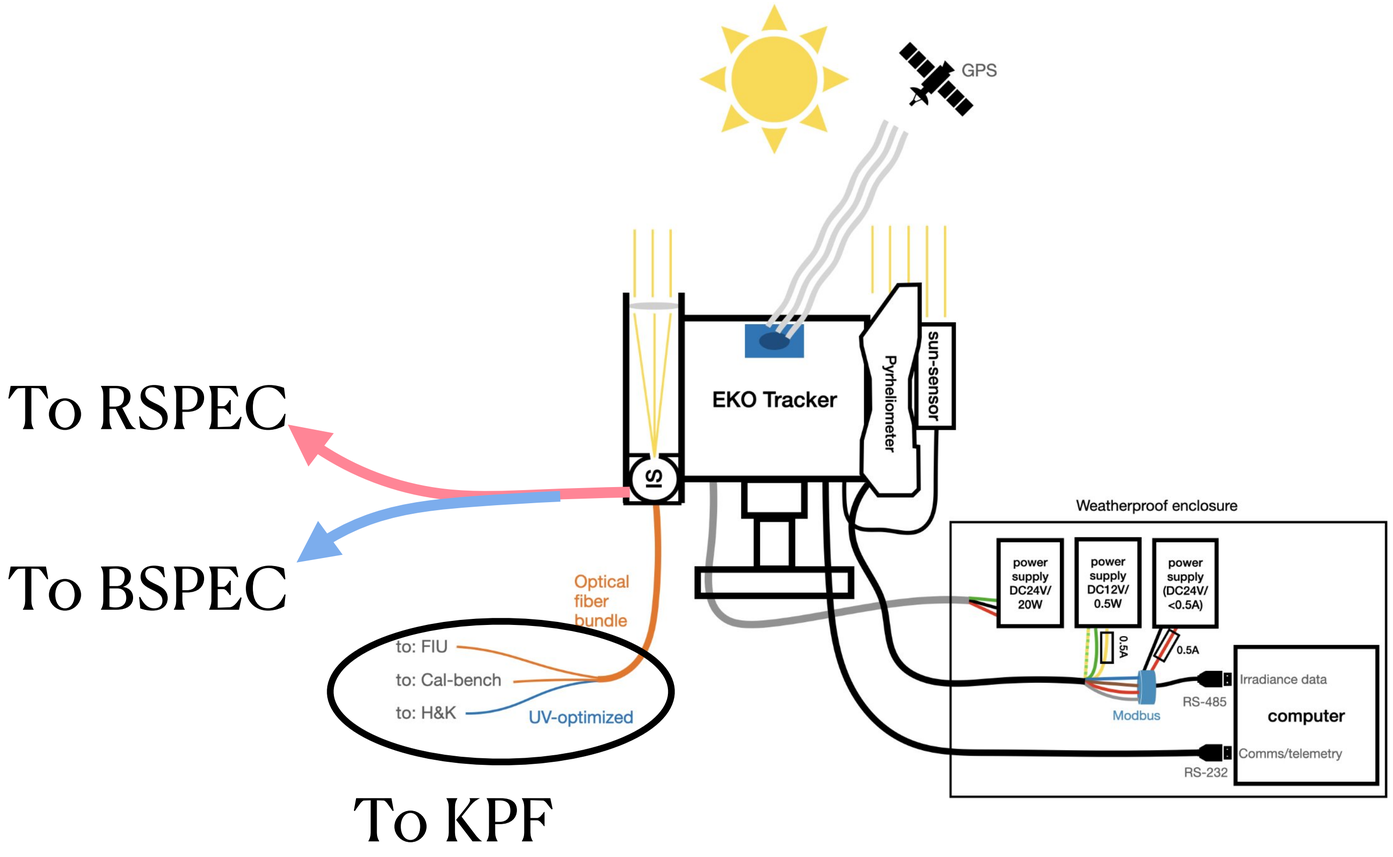
# Solar Collector

# Solar Collector

## Sharing is Caring




2D Solar Image with PARVI



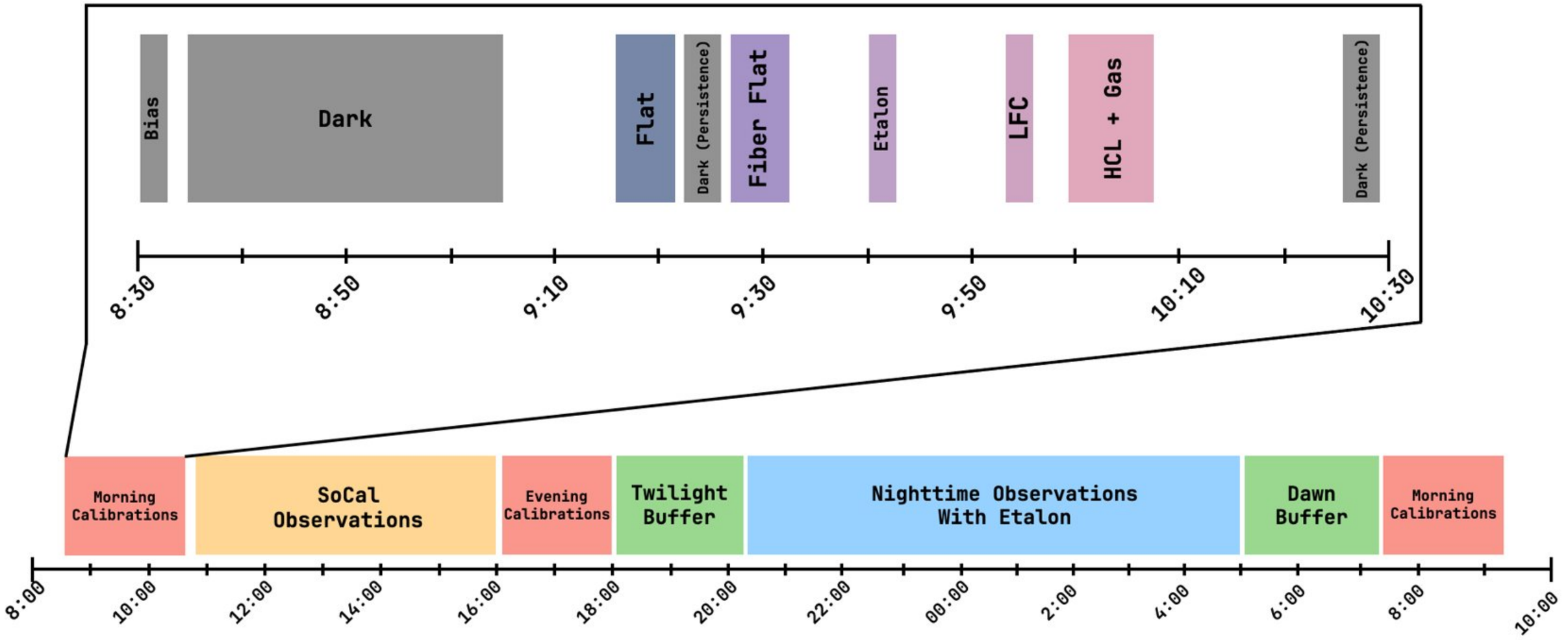
# Conclusion - We are testing CAL with PARVI

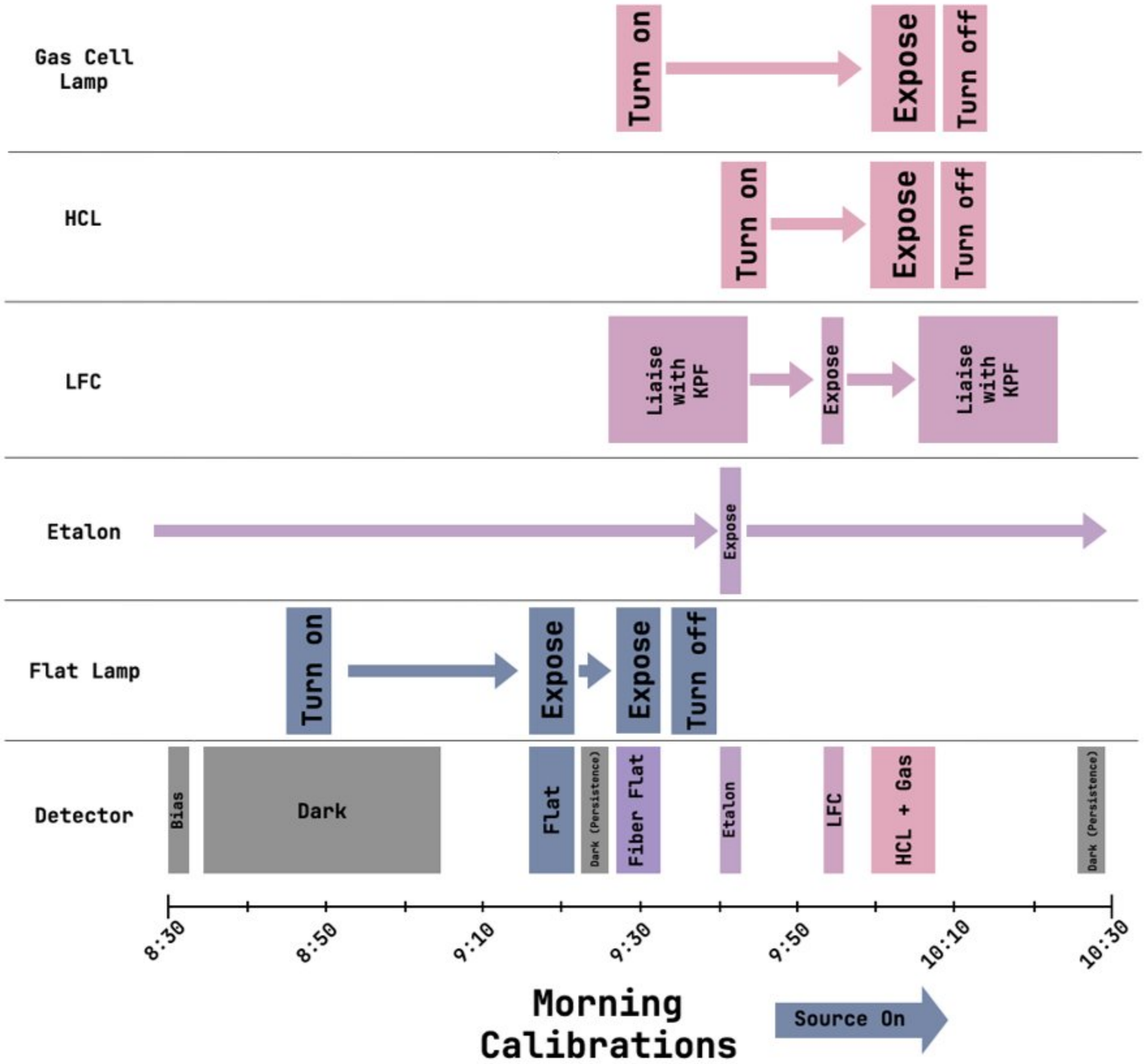


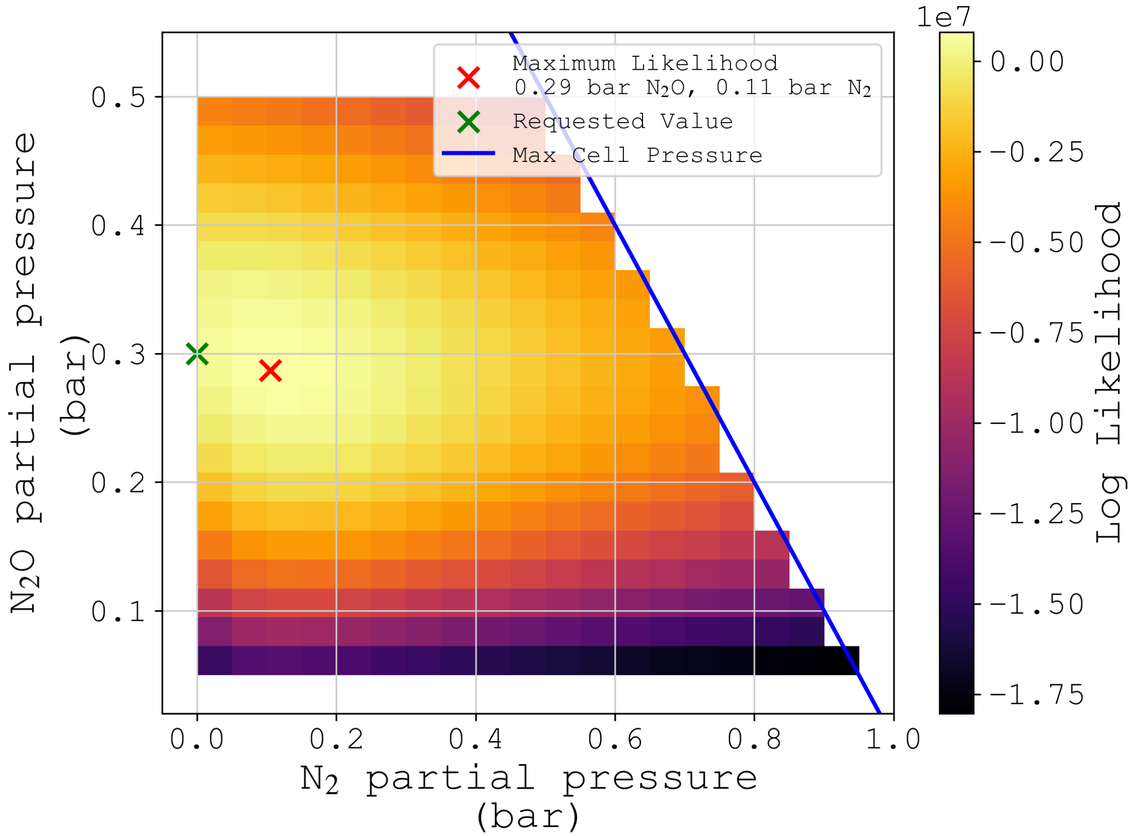
- SMF spectrographs provide a lot of flexibility and stability for calibration
- Wavelength solutions are determined from every available calibration source
    - The best available is used for data reduction
- Etalon subsystem is stable to PARVI instrument drift floor

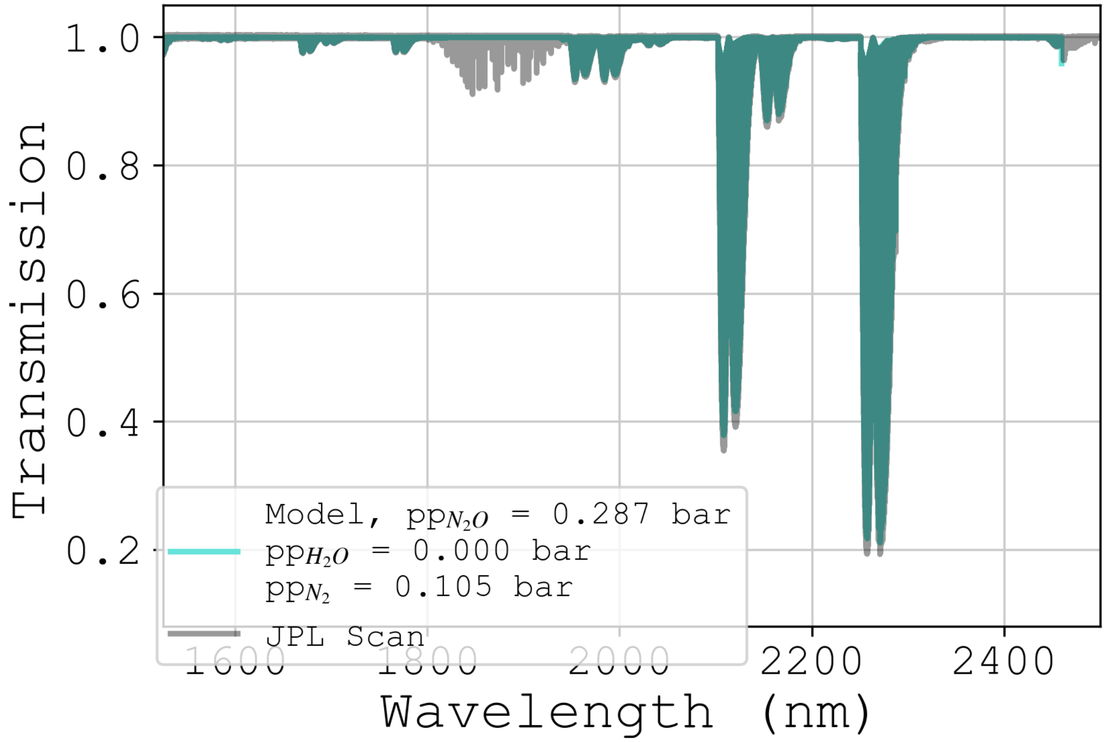
# Backup Slides

# A Day in the Life of HISPEC

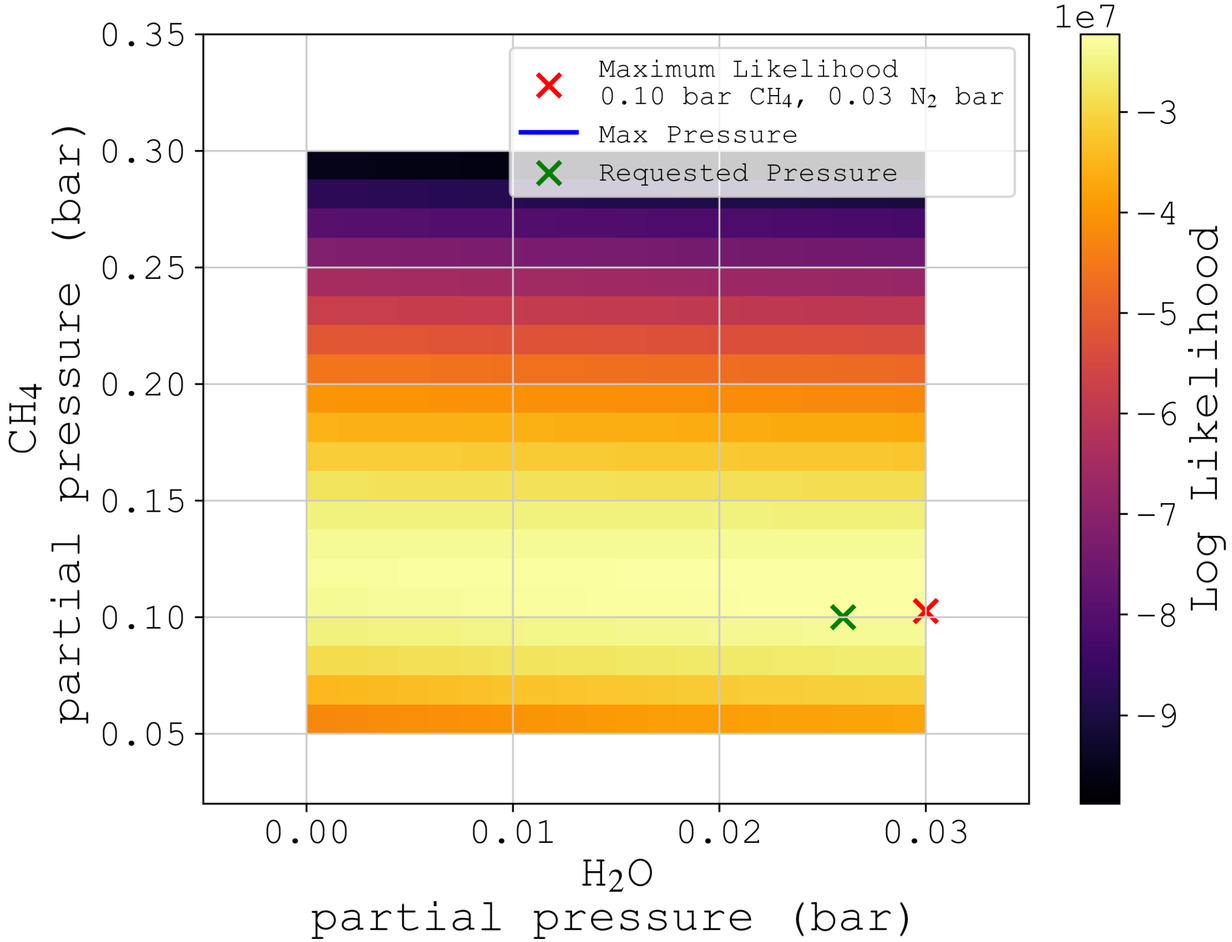

Bias
Dark
Flat
Dark (Persistence)
Fiber Flat
Etalon
LFC
HCL + Gas
Dark (Persistence)
8:30
8:50
9:10
9:30
9:50
10:10
10:30
Morning Calibrations
SoCal Observations
Evening Calibrations
Twilight Buffer
Nighttime Observations With Etalon
Dawn Buffer
Morning Calibrations
8:00
10:00
12:00
14:00
16:00
18:00
20:00
22:00
00:00
2:00
4:00
6:00
8:00
10:00

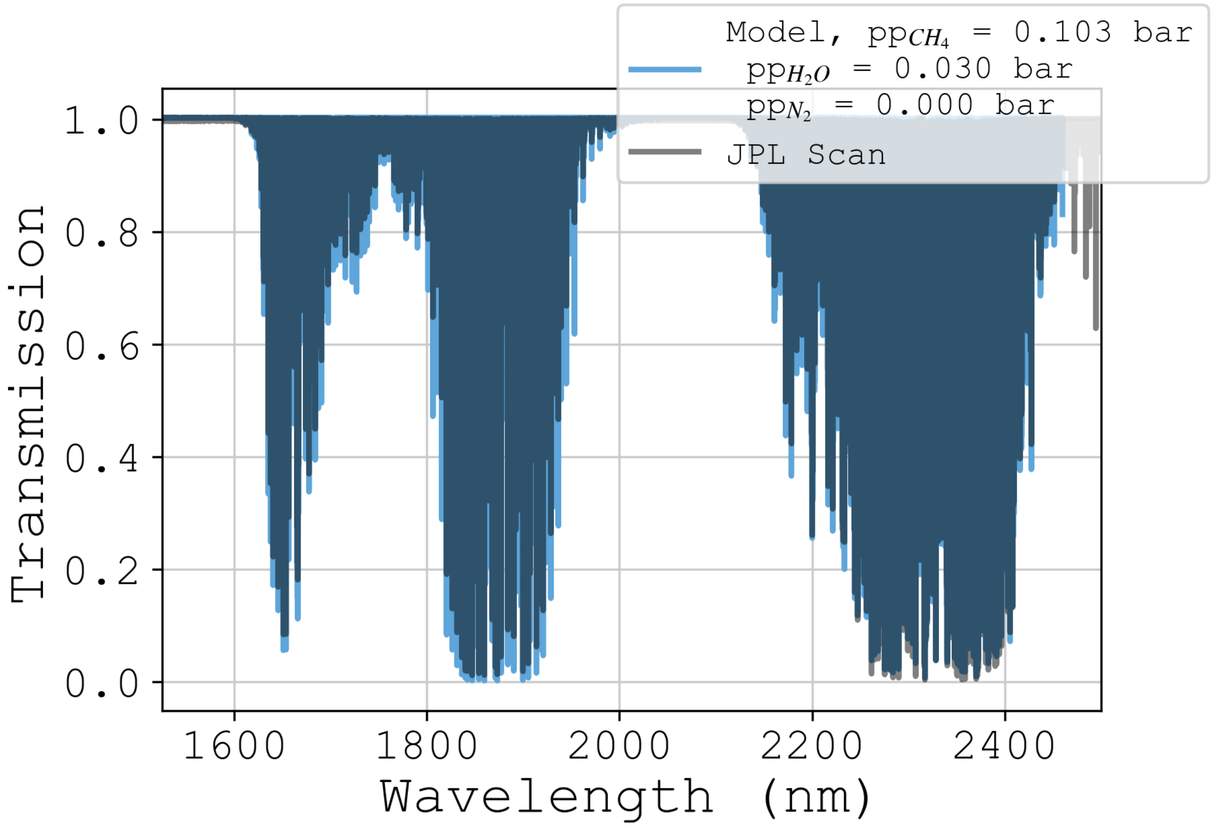

Gas Cell Lamp
Turn on
Expose
Turn off
HCL
Turn on
Expose
Turn off
LFC
Liaise with KPF
Expose
Liaise with KPF
Etalon
Expose
Flat Lamp
Turn on
Expose
Expose
Turn off
Detector
Bias
Dark
Flat
Dark (Persistence)
Fiber Flat
Etalon
LFC
HCL + Gas
Dark (Persistence)
8:30
8:50
9:10
9:30
9:50
10:10
10:30
Morning Calibrations
Source On


Maximum Likelihood
0.29 bar N₂O, 0.11 bar N₂
Requested Value
Max Cell Pressure
N₂O partial pressure (bar)
N₂ partial pressure (bar)
1e7
Log Likelihood
0.00
−0.25
−0.50
−0.75
−1.00
−1.25
−1.50
−1.75
0.0
0.2
0.4
0.6
0.8
1.0
0.1
0.2
0.3
0.4
0.5

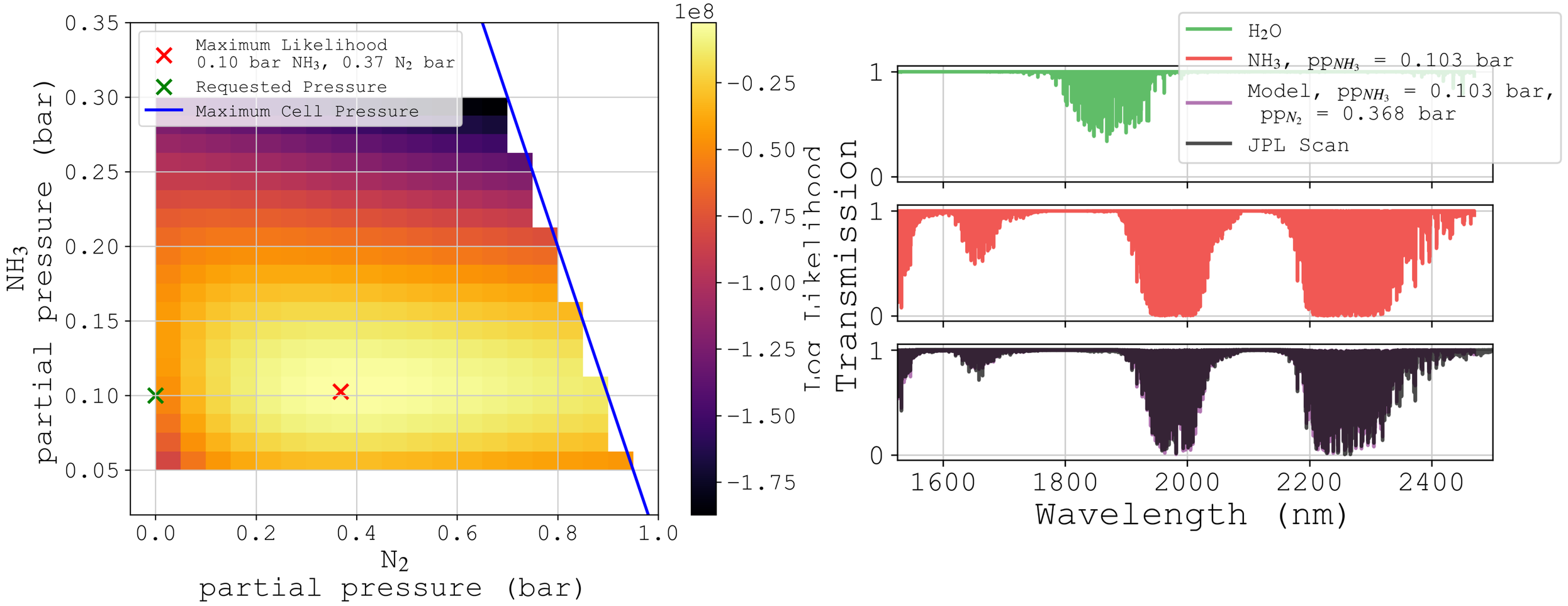

Transmission
Wavelength (nm)
Model, pp$_{N_2O}$ = 0.287 bar
pp$_{H_2O}$ = 0.000 bar
pp$_{N_2}$ = 0.105 bar
JPL Scan
1600
1800
2000
2200
2400
0.2
0.4
0.6
0.8
1.0

# N2O


Maximum Likelihood
0.10 bar CH4, 0.03 N2 bar
Max Pressure
Requested Pressure
CH4
partial pressure (bar)
H2O
partial pressure (bar)
Log Likelihood
1e7


Model, pp$_{CH_4}$ = 0.103 bar
pp$_{H_2O}$ = 0.030 bar
pp$_{N_2}$ = 0.000 bar
JPL Scan
Transmission
Wavelength (nm)

# CH4 + H2O


Maximum Likelihood
0.10 bar NH3, 0.37 N2 bar
Requested Pressure
Maximum Cell Pressure
NH3 partial pressure (bar)
N2 partial pressure (bar)
1e8
Log Likelihood
H2O
NH3, ppNH3 = 0.103 bar
Model, ppNH3 = 0.103 bar, ppN2 = 0.368 bar
JPL Scan
Transmission
Wavelength (nm)

NH3

# Etalon Specifications

## Specifications Shared Between Etalons

- Free Spectral Range = 30±1 GHz
- Finesse = 40 ± 5
- Transmission >50%
- FC/APC
- Wedged Substrate: 60 arcmin to the 1st ghost
- Cavity Drift <20 kHz/day best effort

## yJ Design Specifications

| | | |
|---|---|---|
| 950 -1550 nm | Fiber Type : OFS ClearLite 980 16 Optical Fiber | Test Wavelength 1319nm |

## HK Design Specifications

| | | |
|---|---|---|
| 1450-2500 nm | Fiber Type: LVF ZBLAN – 5.5/125 | Test Wavelength 1550 nm |

# HISPEC Top Level Requirements

| | Specification | Note |
|---|---|---|
| **Wavelength range** | 0.98-2.46 microns | Simultaneous y J H K |
| **Resolving power** | 100,000 | On average |
| **Sampling** | >2.5 pix | Over 80% of the range |
| **Instrument stability** | 30 cm/s (fiber to fiber) | Excluding atmosphere |
| **Architecture** | Fiber-fed diffraction-limited | Single-mode fibers |
| **Point source sensitivity** | 15 mag | S/N=30 per resel (4 hr) |
| **Calibration** | Etalon, LFC | LFC separately funded |
| **Mode 1** | Single-object on-axis | PRV, transits |
| **Mode 2** | Single-object off-axis | Direct spectroscopy of spatially resolved off-axis companions |
| **Mode 3** | Fiber nulling | High contrast detection/characterization within diffraction limit |

# State Tracking

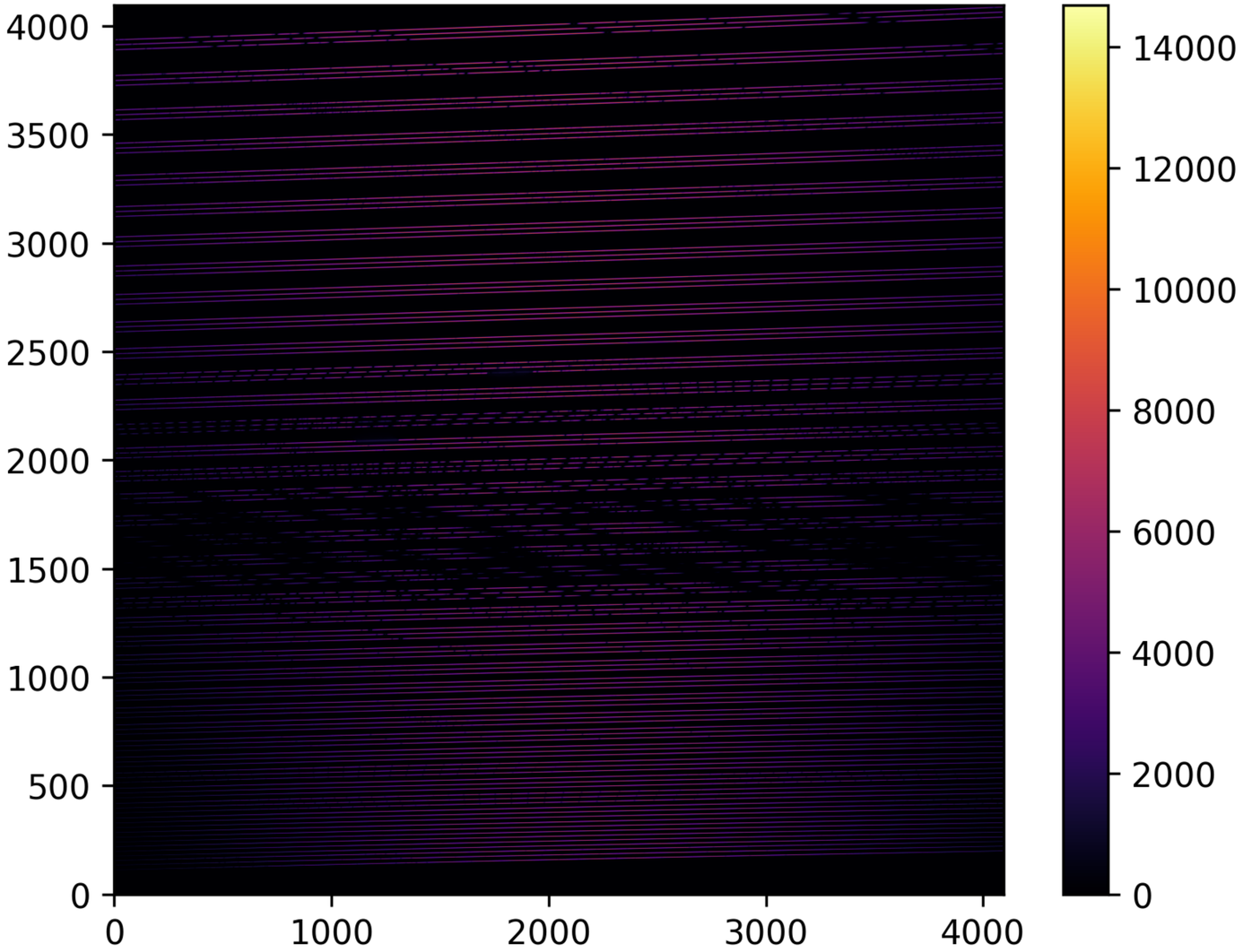
## All Fibers Simultaneously, No FEI

| | | | | | | |
|---|---|---|---|---|---|---|
| **CAL box** | Narcissus Mirror | Flat Lamp | Flat Lamp | Etalon | LFC | Gas + HCL |
| **CAL Flatfield Switch** | Narcissus Mirror<br>State I | Flatfield<br>State II | Narcissus Mirror<br>State I | Narcissus Mirror<br>State I | Narcissus Mirror<br>State I | Narcissus Mirror<br>State I |
| **CAL switch Input** | Narcissus Mirror<br>State V | Narcissus Mirror<br>State V | FS(R/B)-Flat<br>State IV | CAL-Etalon<br>State III | CAL-LFC<br>State II | CAL-Gas<br>CAL-HCL<br>State I |
| **CAL switch Output** | MS(R/B) | MS(R/B) | MSR(R/B) | MSR (R/B) | MSR (R/B) | MSR (R/B) |
| **Main switch input** | Calibration<br>State II | Calibration<br>State II | Calibration<br>State II | Calibration<br>State II | Calibration<br>State II | Calibration<br>State II |
| **Main switch output** | Splitter in | Splitter in | Splitter in | Splitter in | Splitter in | Splitter in |
| **Fiber 1** | Dark | Det-flat | Fib-flat | Etalon | LFC | HCL+Gas |
| **Fiber 2** | Dark | Det-flat | Fib-flat | Etalon | LFC | HCL+Gas |
| **Fiber 3** | Dark | Det-flat | Fib-flat | Etalon | LFC | HCL+Gas |
| | Dark | Detector Flat | Fiber Flat | Etalon | LFC | HCL+Gas |

# Full FEI Calibration

| CAL box | Flat Lamp | Flat Lamp | Flat Lamp | Etalon | Etalon | Etalon | LFC | LFC | LFC | HCL + Gas | HCL + Gas | HCL + Gas |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CAL Flatfield Switch | Narcissus Mirror State I | Narcissus Mirror State I | Narcissus Mirror State I | Narcissus Mirror State I | Narcissus Mirror State I | Narcissus Mirror State I | Narcissus Mirror State I | Narcissus Mirror State I | Narcissus Mirror State I | Narcissus Mirror State I | Narcissus Mirror State I | Narcissus Mirror State I |
| CAL switch Input | FS(R/B)-Flat State IX | FS(R/B)-Flat State IX | FS(R/B)-Flat State IX | CAL-Etalon State VIII | CAL-Etalon State VIII | CAL-Etalon State VIII | CAL-LFC State VII | CAL-LFC State VII | CAL-LFC State VII | CAL-Gas CAL-HCL State VI | CAL-Gas CAL-HCL State VI | CAL-Gas CAL-HCL State VI |
| CAL switch Output | Keck AO/FEI | Keck AO/FEI | Keck AO/FEI | Keck AO/FEI | Keck AO/FEI | Keck AO/FEI | Keck AO/FEI | Keck AO/FEI | Keck AO/FEI | Keck AO/FEI | Keck AO/FEI | Keck AO/FEI |
| FEI Injection | Fiber 1 | Fiber 2 | Fiber 3 | Fiber 1 | Fiber 2 | Fiber 3 | Fiber 1 | Fiber 2 | Fiber 3 | Fiber 1 | Fiber 2 | Fiber 3 |
| Main switch input | Speckle State IV | Science State IV | Background State IV | Speckle State IV | Science State IV | Background State IV | Speckle State IV | Science State IV | Background State IV | Speckle State IV | Science State IV | Background State IV |
| Main switch output | Slit | Slit | Slit | Slit | Slit | Slit | Slit | Slit | Slit | Slit | Slit | Slit |
| **Fiber 1** | Fib-flat | | | Etalon | | | LFC | | | HCL + Gas | | |
| **Fiber 2** | | Fib-flat | | | Etalon | | | LFC | | | HCL + Gas | |
| **Fiber 3** | | | Fib-flat | | | Etalon | | | LFC | | | HCL + Gas |
| | Fiber Flat Fiber 1 | Fiber Flat Fiber 2 | Fiber Flat Fiber 3 | Etalon Fiber 1 | Etalon Fiber 2 | Etalon Fiber 3 | LFC Fiber 1 | LFC Fiber 2 | LFC Fiber 3 | HCL+Gas Fiber 1 | HCL+Gas Fiber 2 | HCL+Gas Fiber 3 |

# Simulated Data with PyEchelle




The Dreaded Telluric Spectrum

# PARVI Etalon