# A Visible Wavelength Astro-Comb for Calibrating HARPS-N

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Photonics and Planets
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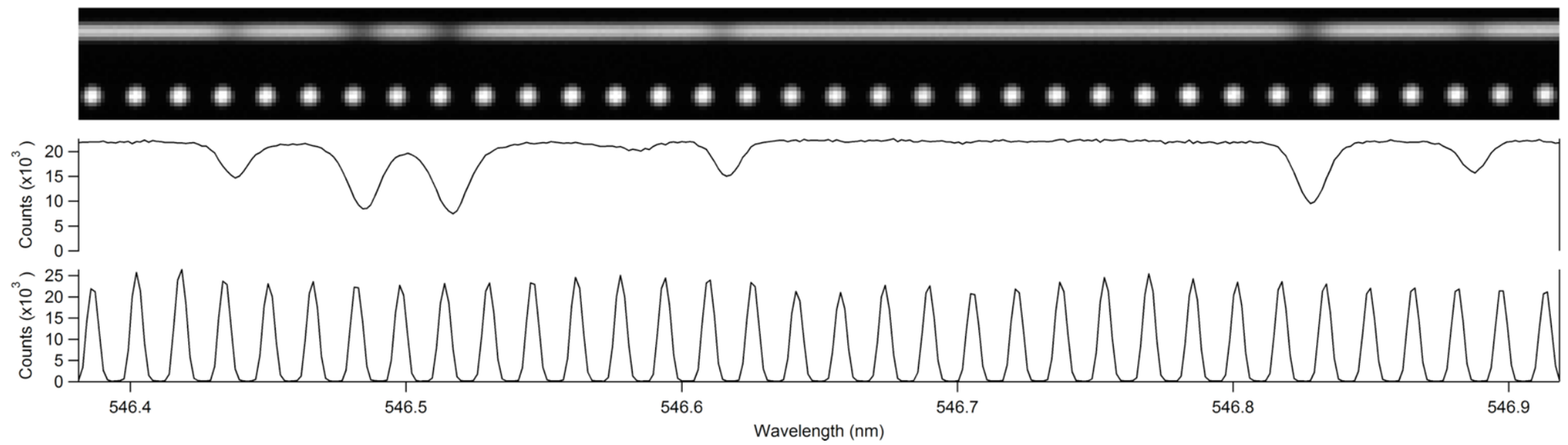
# Calibrator

*What do we need?*

- Dense, evenly spaced lines
  - spacing matched to resolution (line spacing ~ twice resolution)
  - narrow linewidth compared to spectrograph resolution
- Bright source
  - all lines of equal intensity
- Span optical spectrum
- Traceable to fundamental physics
- Operable at telescope

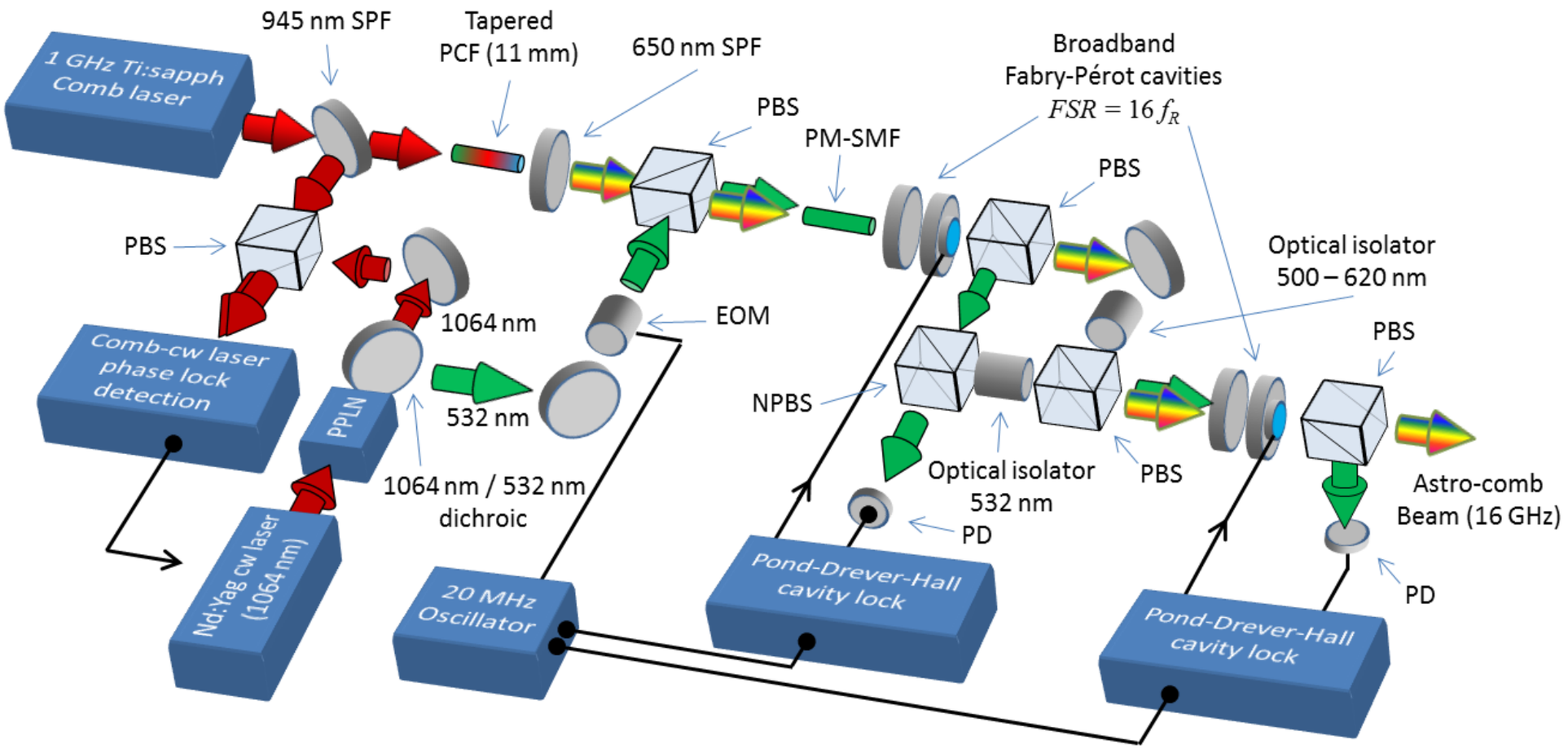
*Raw spectrum from HARPS-N with both asteroid Vesta and astro-comb calibration*



# Components of Laser Frequency Comb Calibrator

1. **Laser frequency comb**
*produces sharp spectral features whose wavelengths are referenced to atomic frequency standards.*
2. **Wavelength shifting element**
*shifts light generated by laser into spectral range desired for spectrograph calibration while preserving coherent properties of light.*
3. **Filter cavity**
*matches spacing of calibration lines to resolution of spectrograph to be calibrated.*

# Astro-comb




Filter out most comb lines with a stabilized Fabry-Perot Cavity to yield line-spacing up to ~100 GHz

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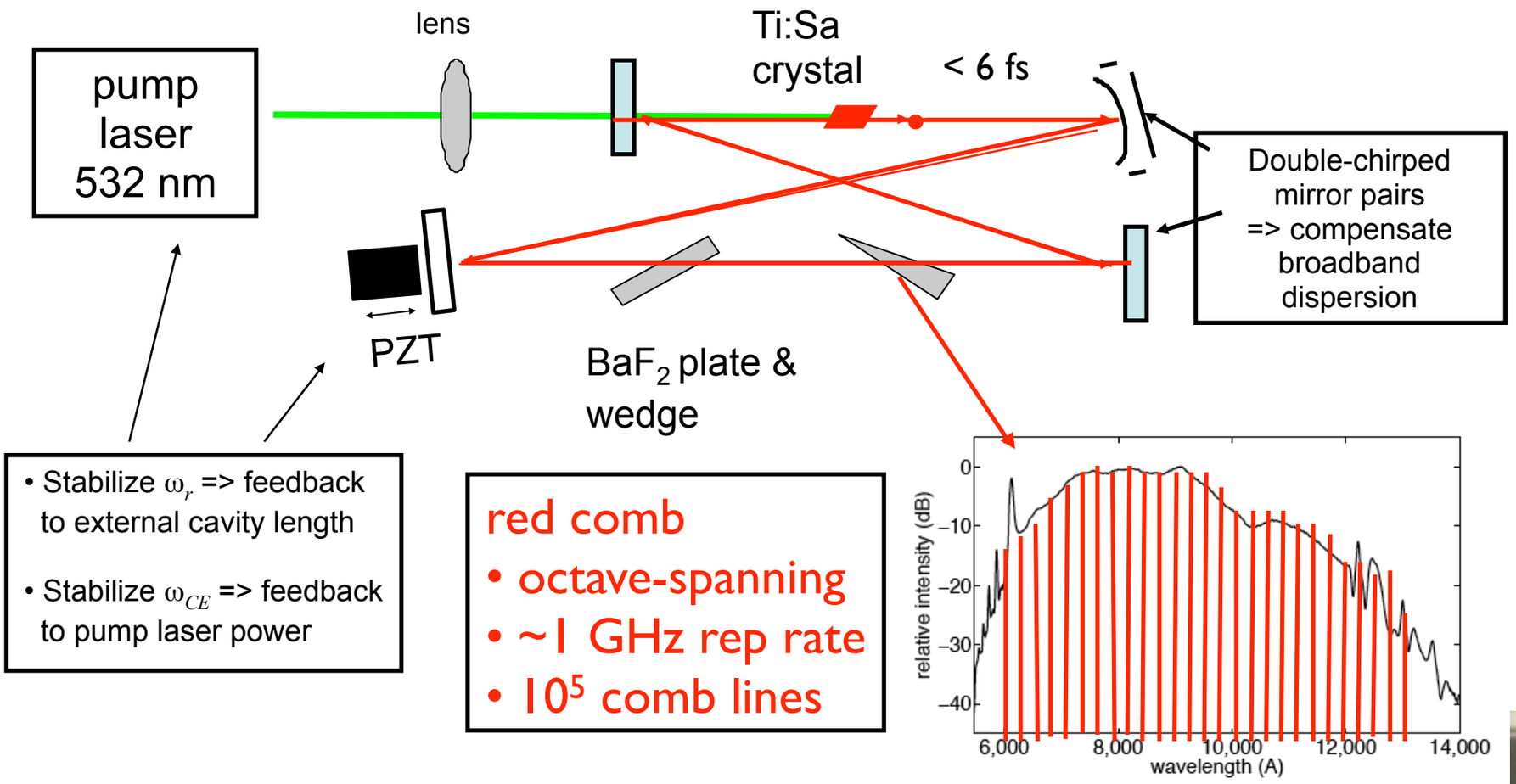
# Femtosecond Ti:Sapphire Laser



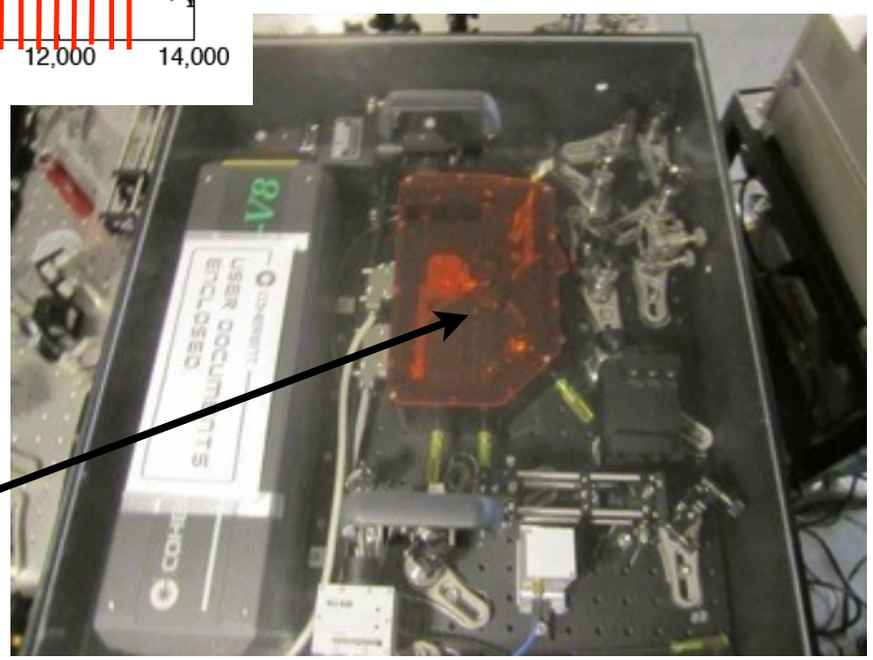

**ν = 1 GHz**

**v = 550 m/s**

**λ = 0.01 A**

Broadband gain, Kerr effect => octave spanning
Kerr-lens mode-locking => stabilize pulsing
Cavity sets $T_{rep}$ ~1 GHz

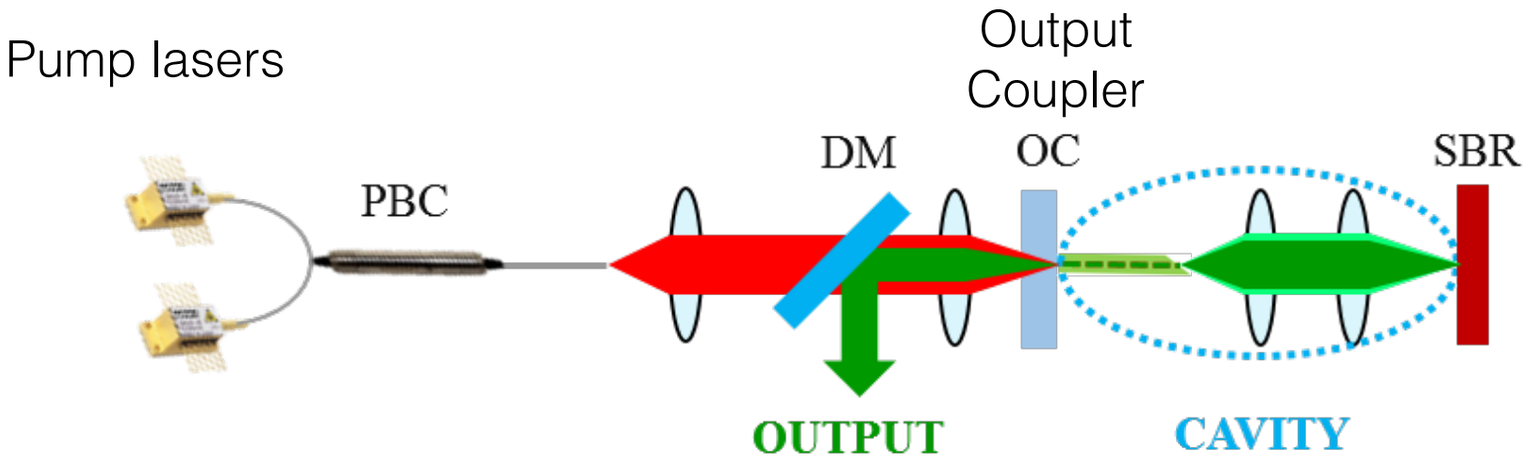
Our laser frequency comb



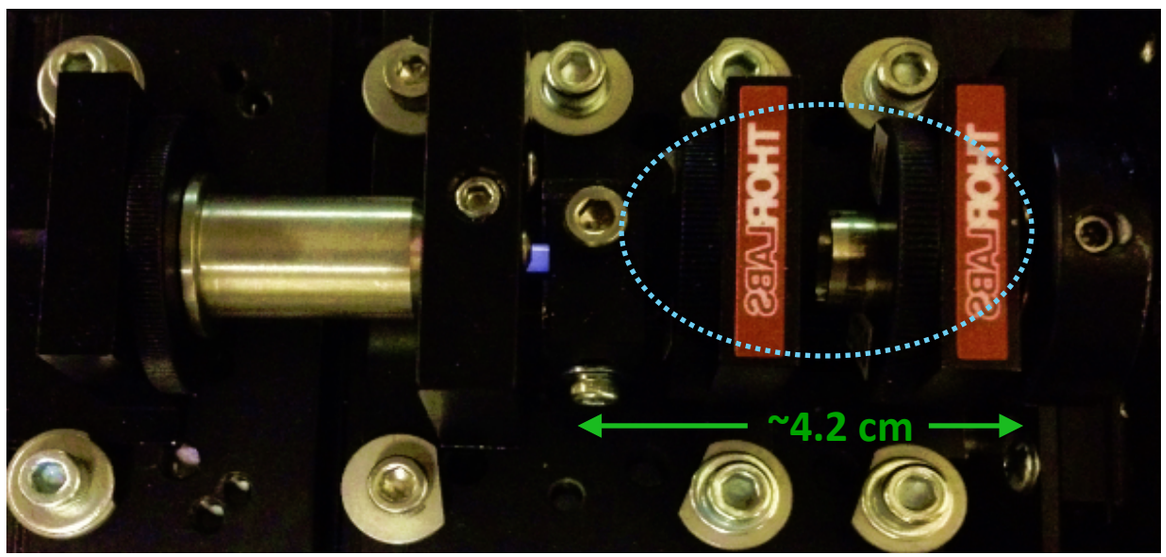
# Automation

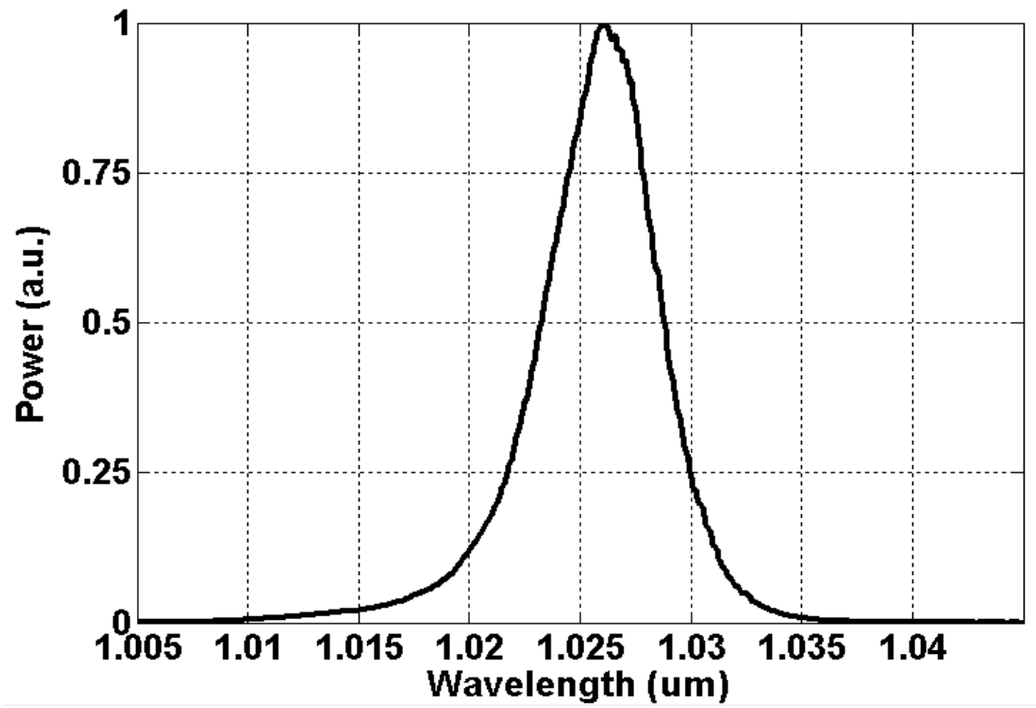
# 3 GHz Fiber Laser

Phosphate glass fiber with $Yb^{3+}$ concentration of 15.2wt.%
46-dB/cm absorption at 976 nm
5.7 dB/cm gain
5-um core diameter and 0.14 N.A.




- 3 GHz repetition rate
- 7 nm bandwidth



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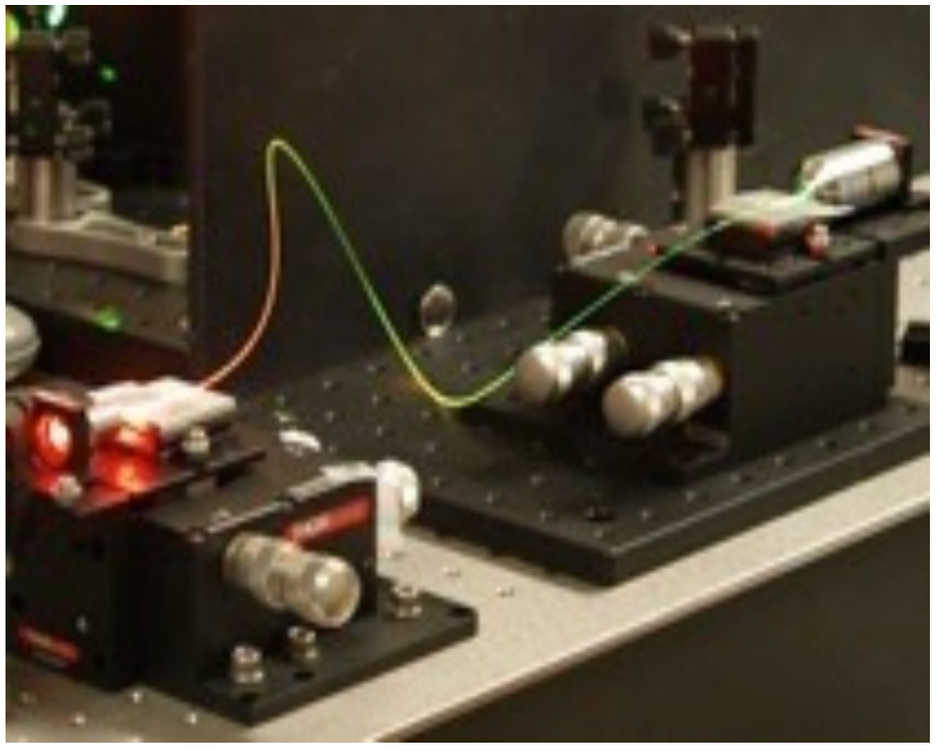
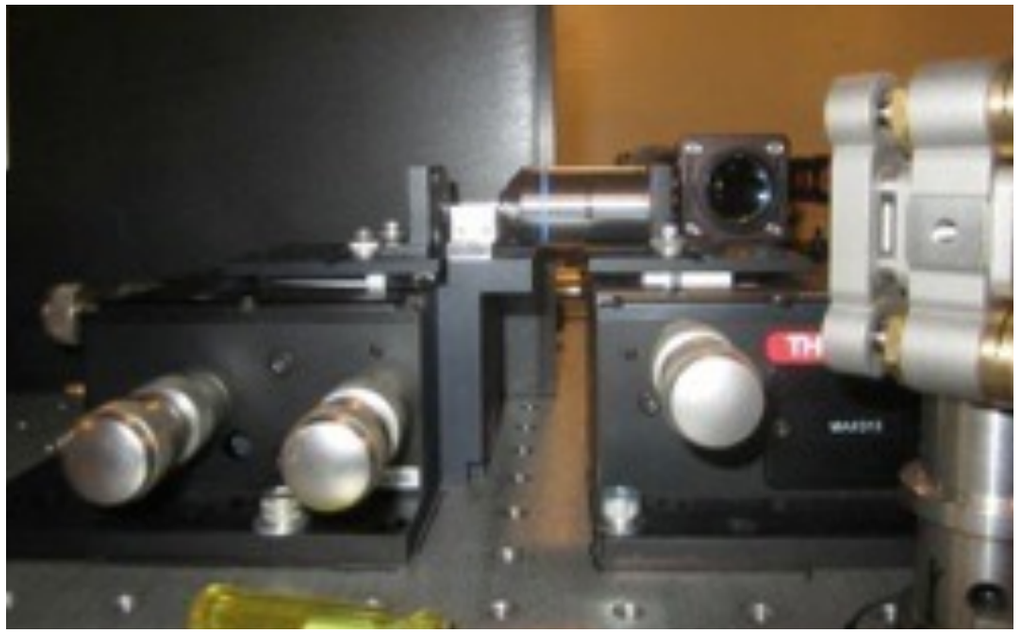
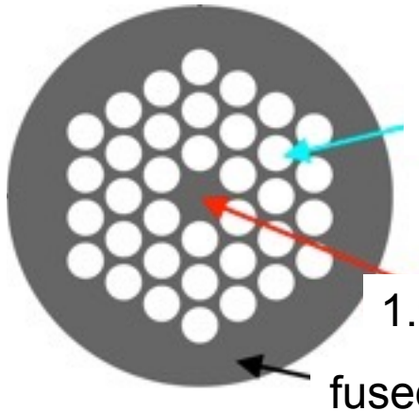
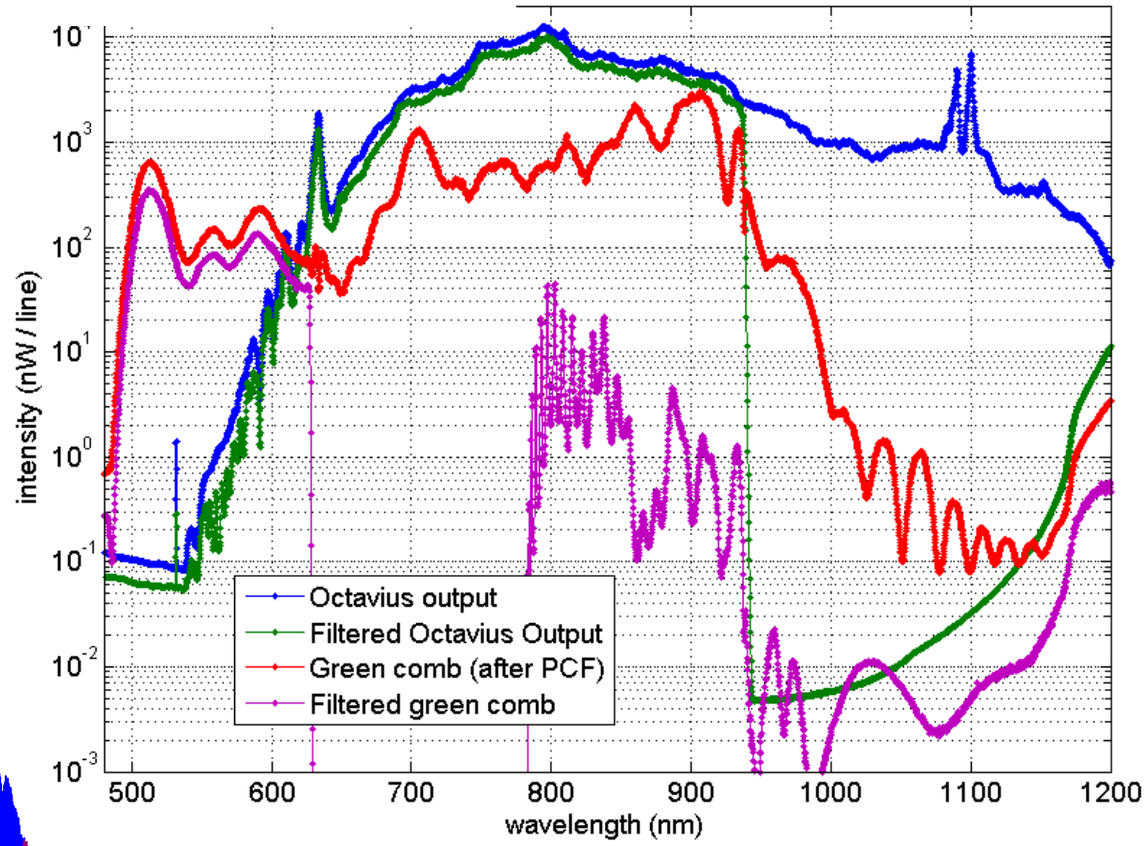
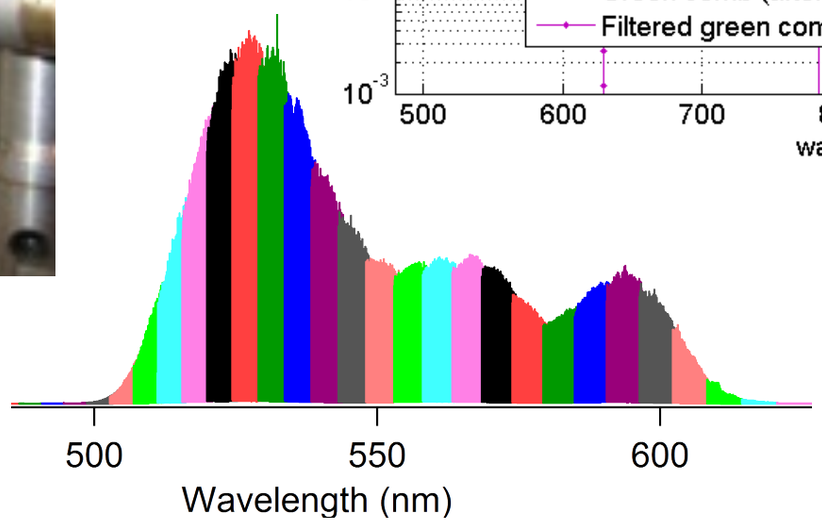
# Photonic Crystal Fiber



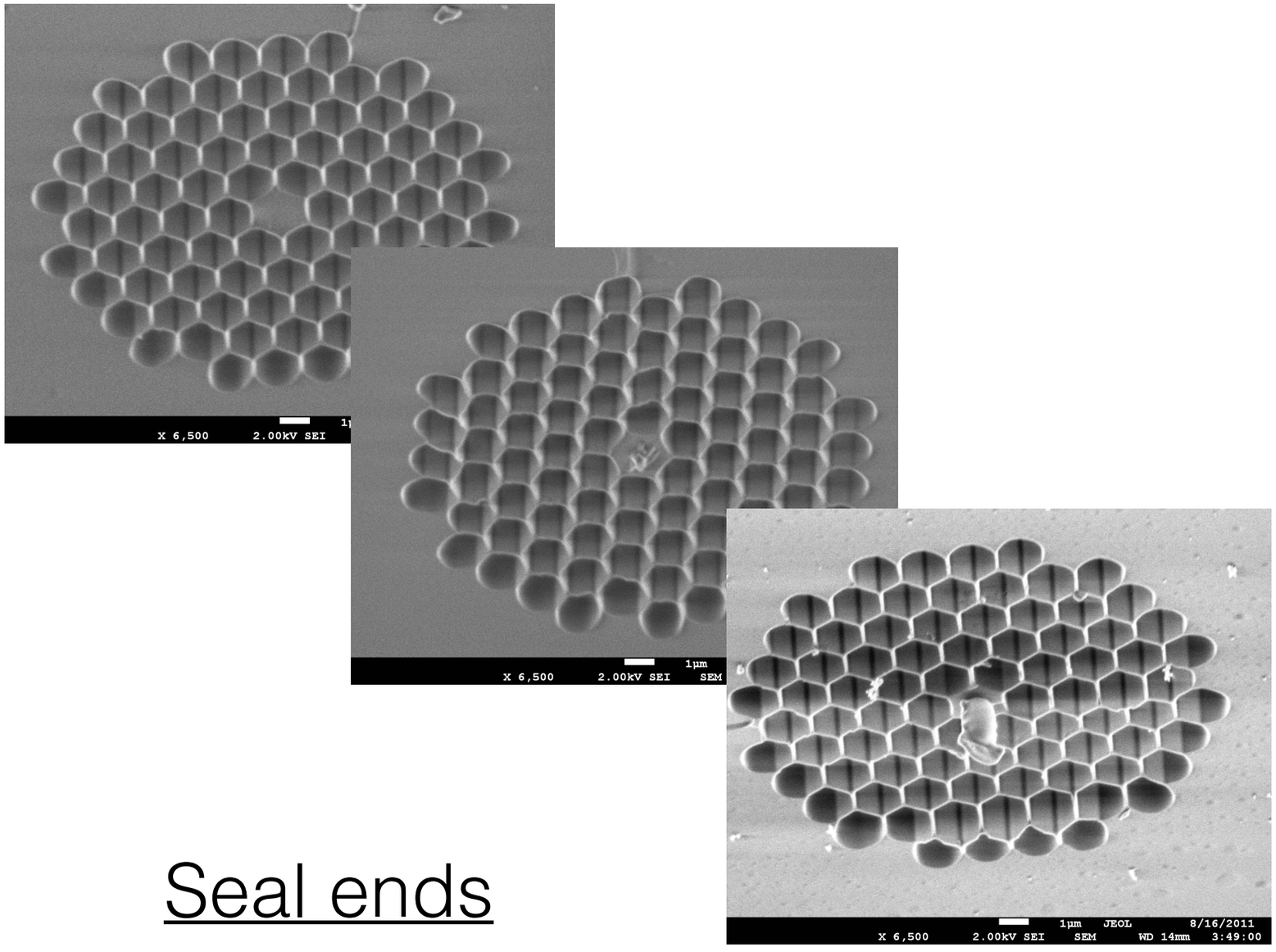




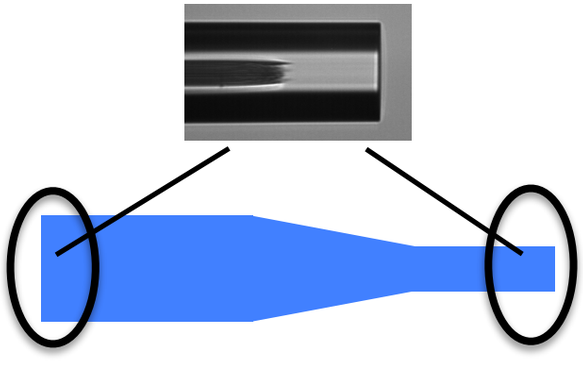



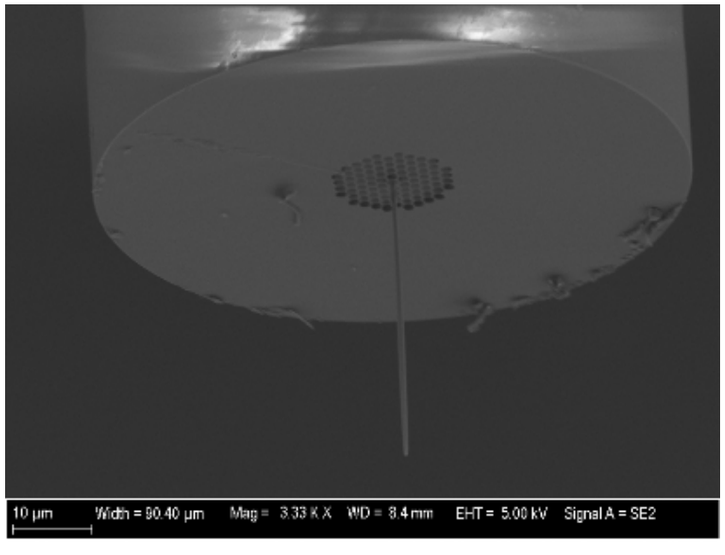
# Dust Accumulation




## Seal ends



## Grow nanowires



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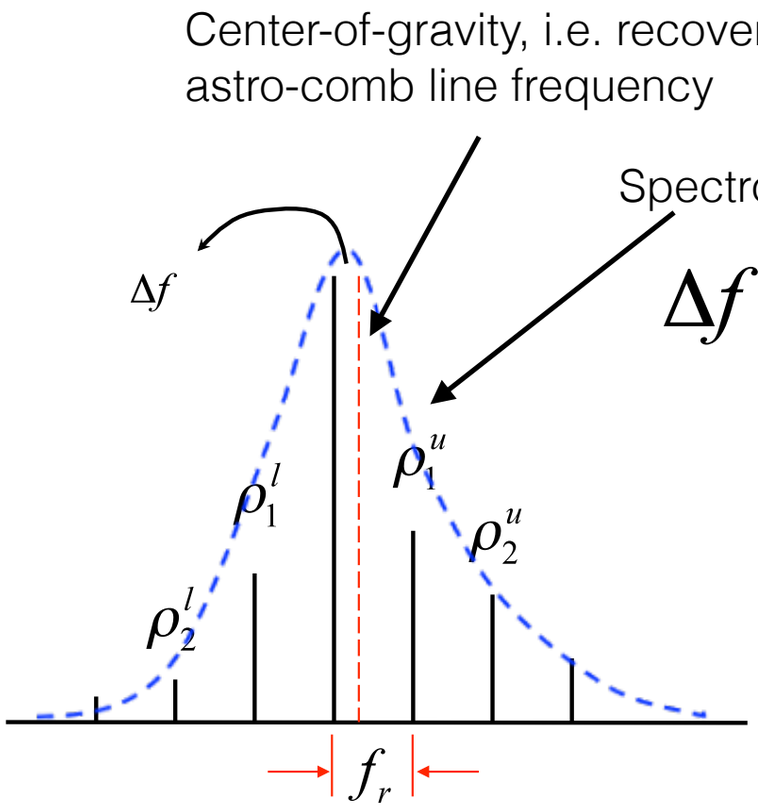
# Filter Cavities

*Filter cavities before or after nonlinear spectral shifting*

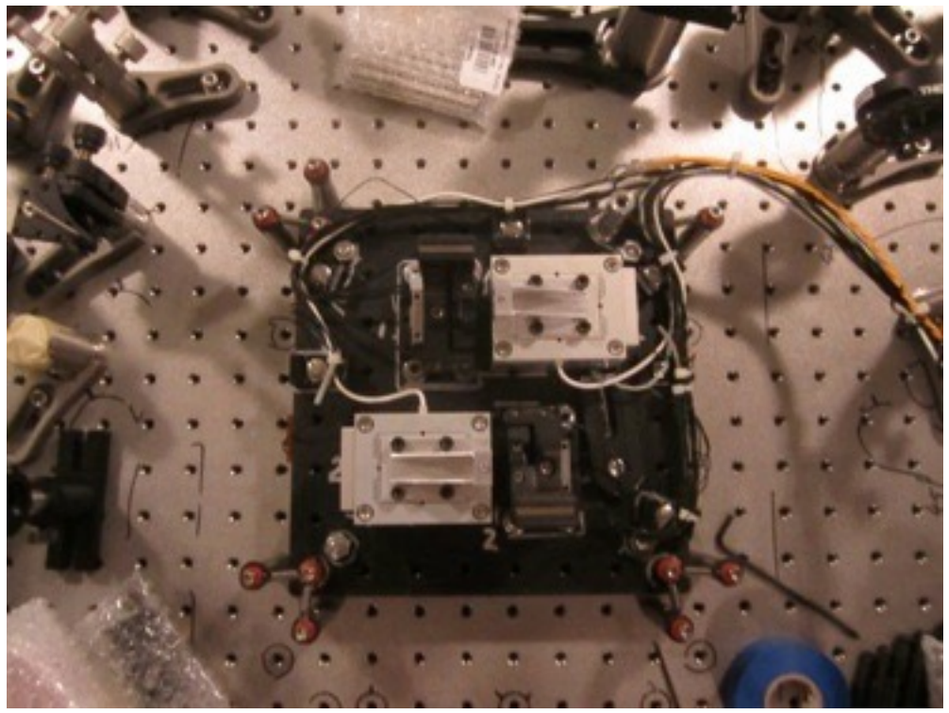
**Before:** nonlinear distortion reduces suppression of undesired laser modes.

**After:** requires broadband filter cavities.



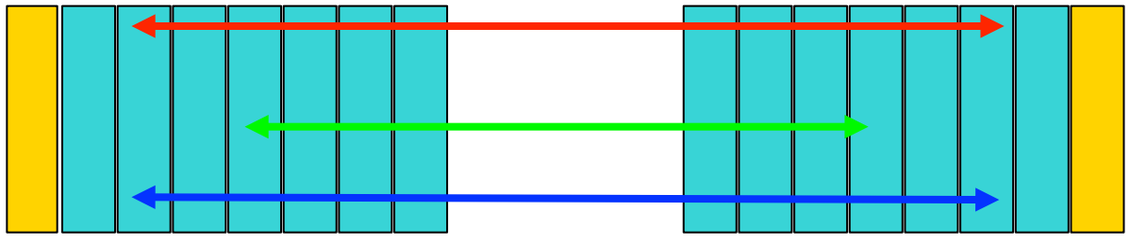

$$\Delta f \approx f_r \sum_{j=1}^{m} j(\rho_j^u - \rho_j^l)$$

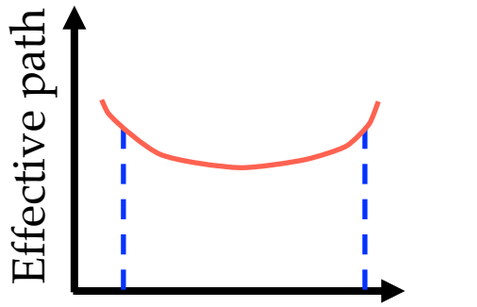
$$\Delta RV = \frac{\Delta f}{\nu_0} c$$



# Filter Cavities

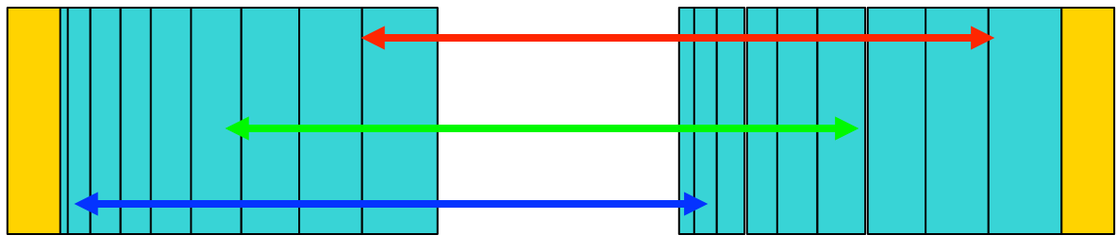
## Bragg-Stack Mirror Pair

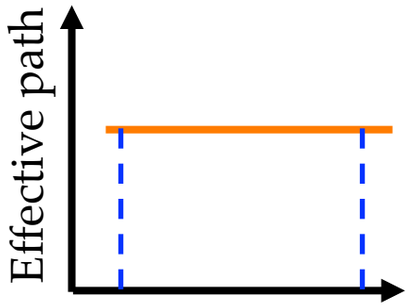


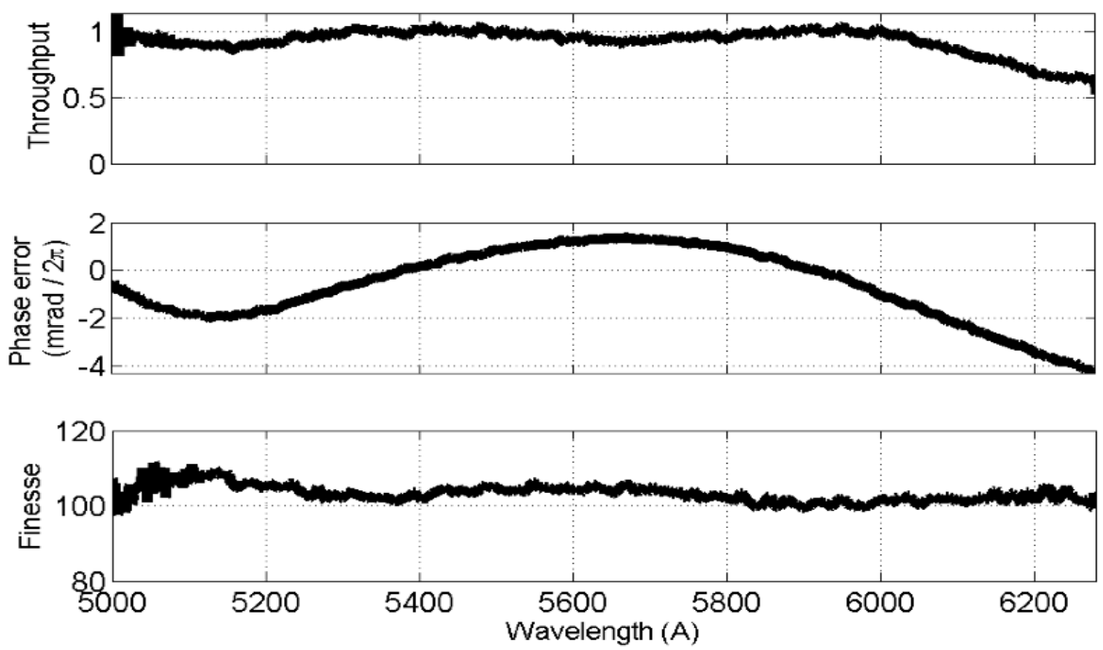



Layers of alternating refractive index

## Complementary-Chirped Mirror Pair

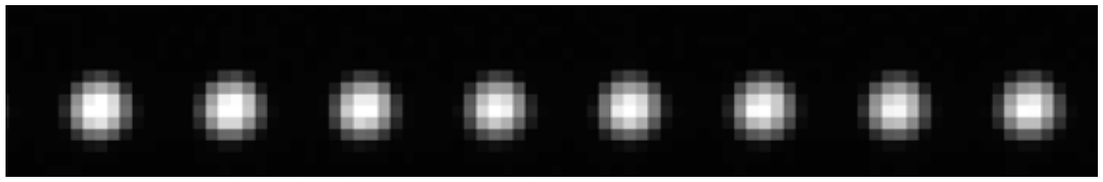




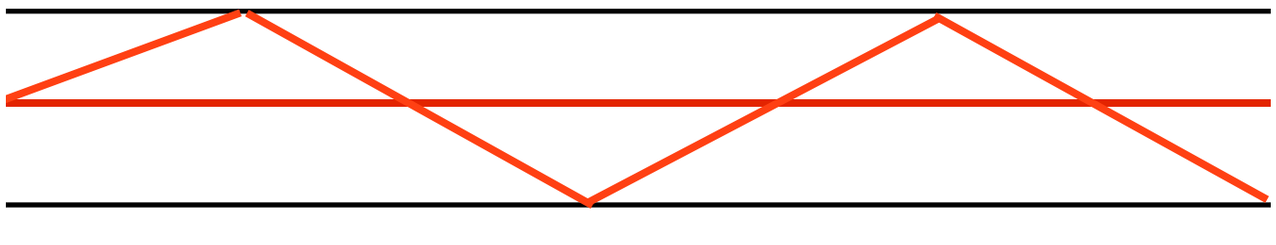



# Speckle

*Astro-comb points are images of the fiber output*



**Multimode fiber**

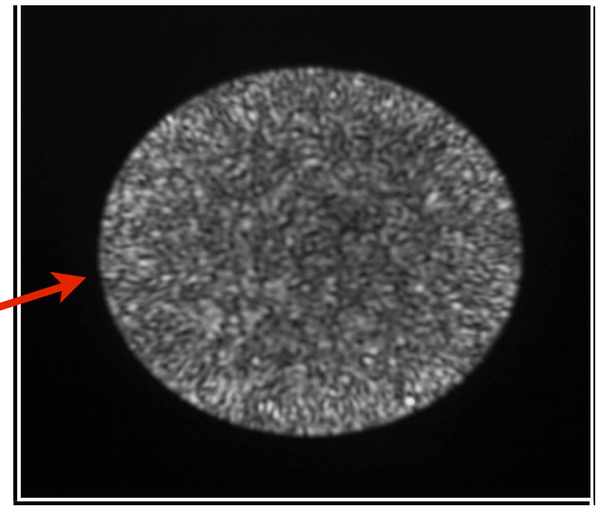


short path

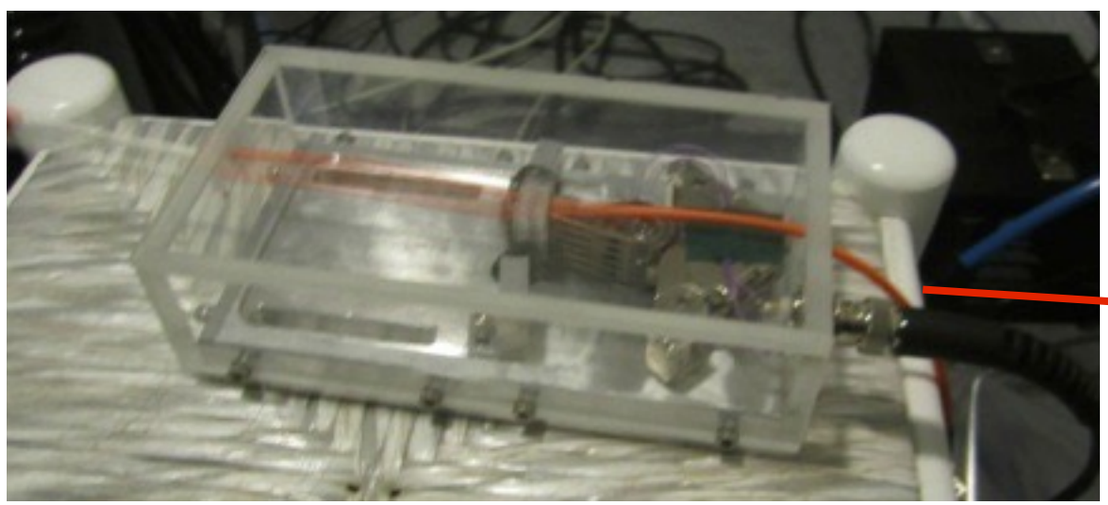
long path

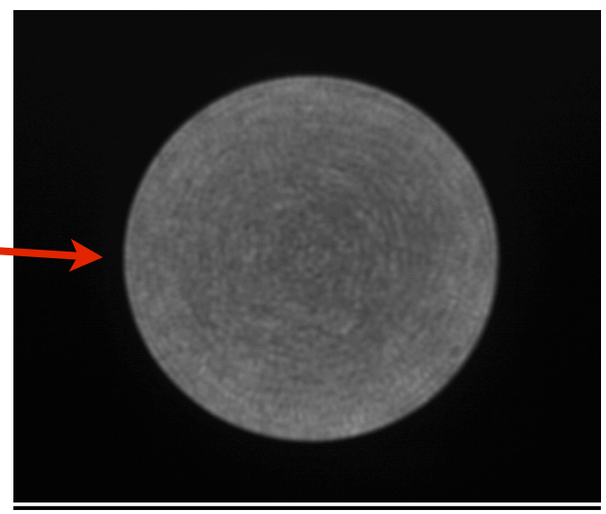
*maximum angle: total internal reflection*

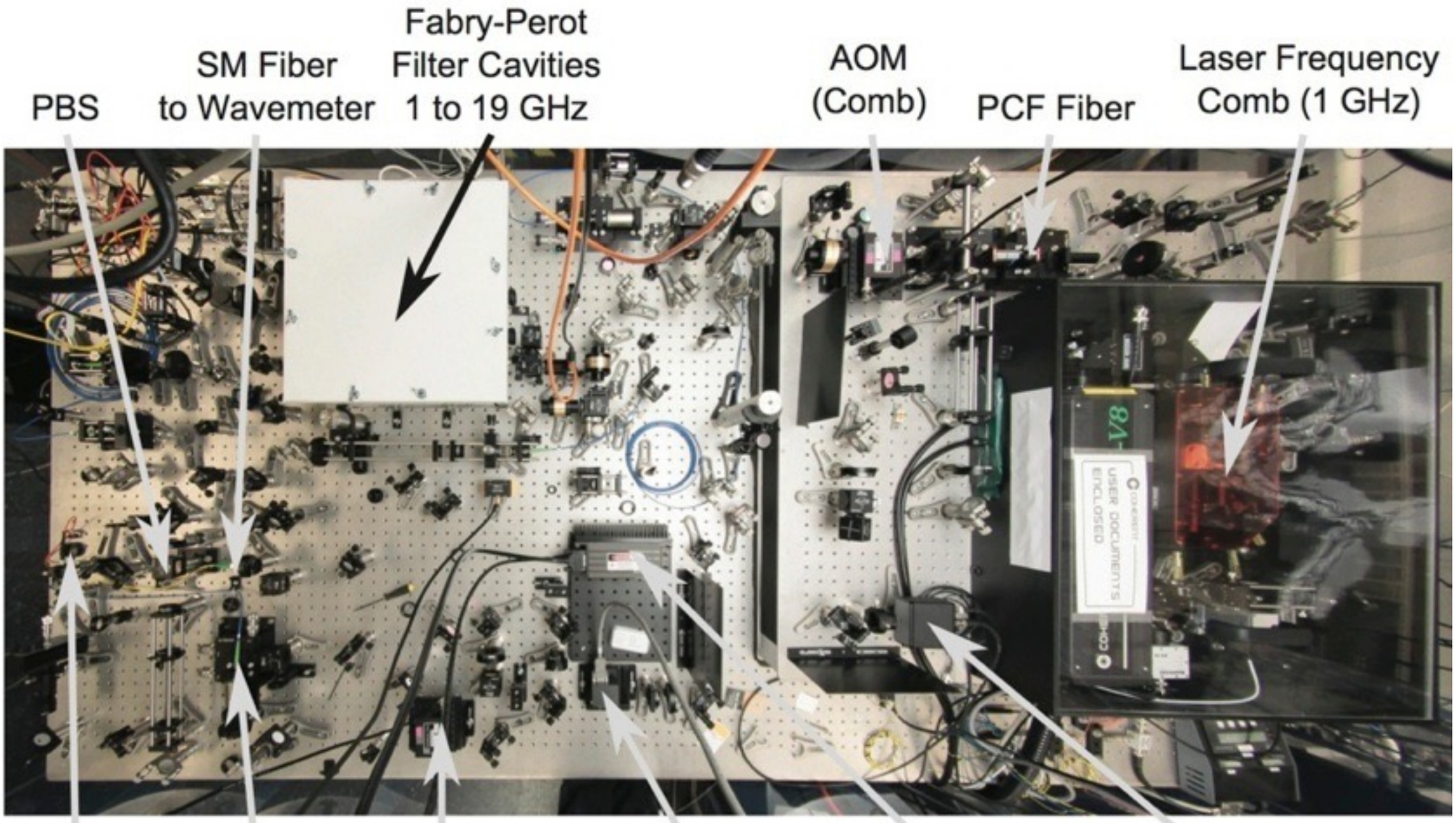
*paths interfere with coherent light*



**Fiber shaker (hard disk head)**

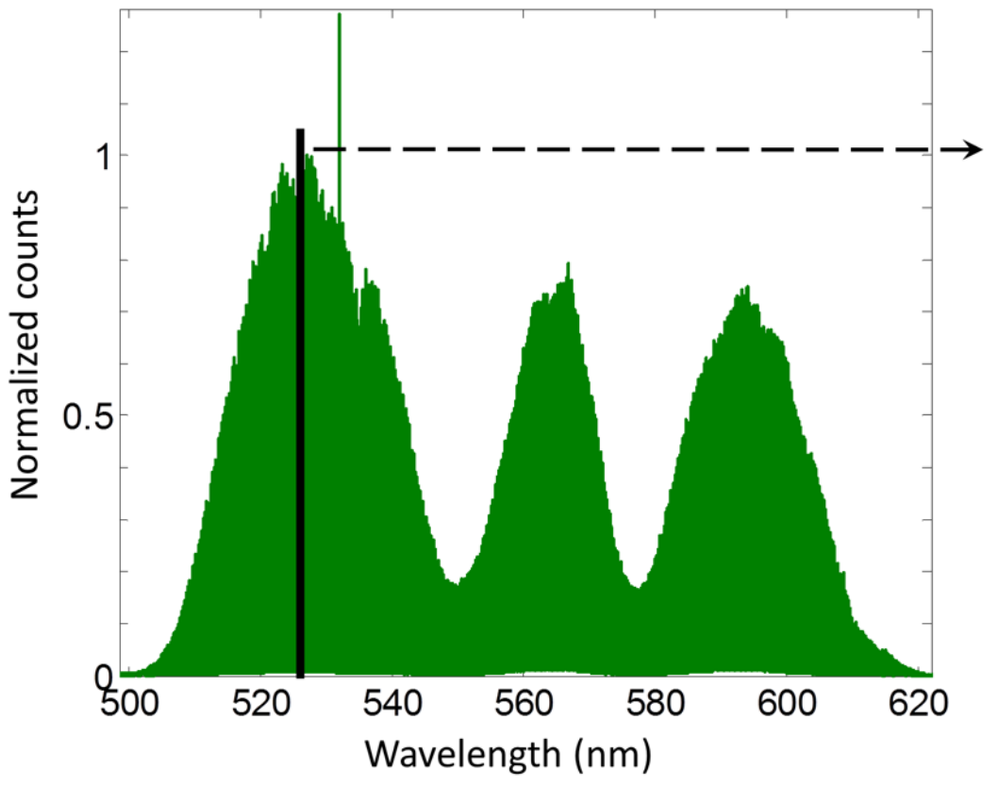




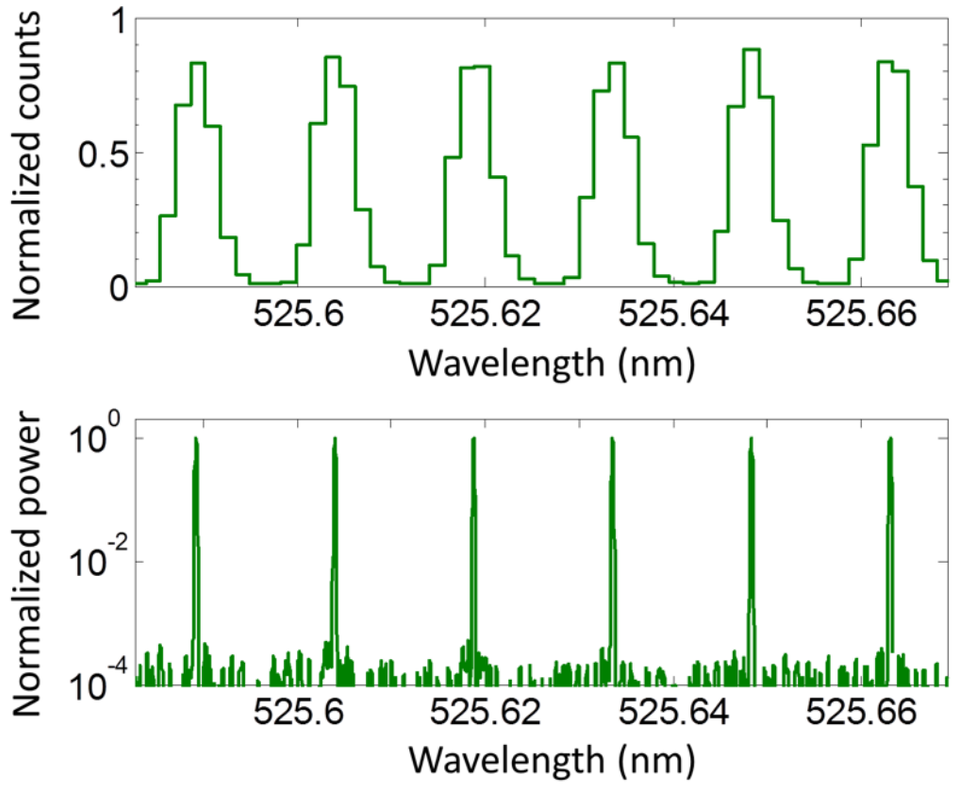

PBS
SM Fiber to Wavemeter
Fabry-Perot Filter Cavities 1 to 19 GHz
AOM (Comb)
PCF Fiber
Laser Frequency Comb (1 GHz)
MM Fiber to FTS
PM-SM Fiber to FTS
AOM (Reference)
Doubling Crystal 1064 to 532 nm
Reference Laser (1064 nm)
Reference to Comb Phase Lock (1064 nm)

# Results

## Full Spectrum

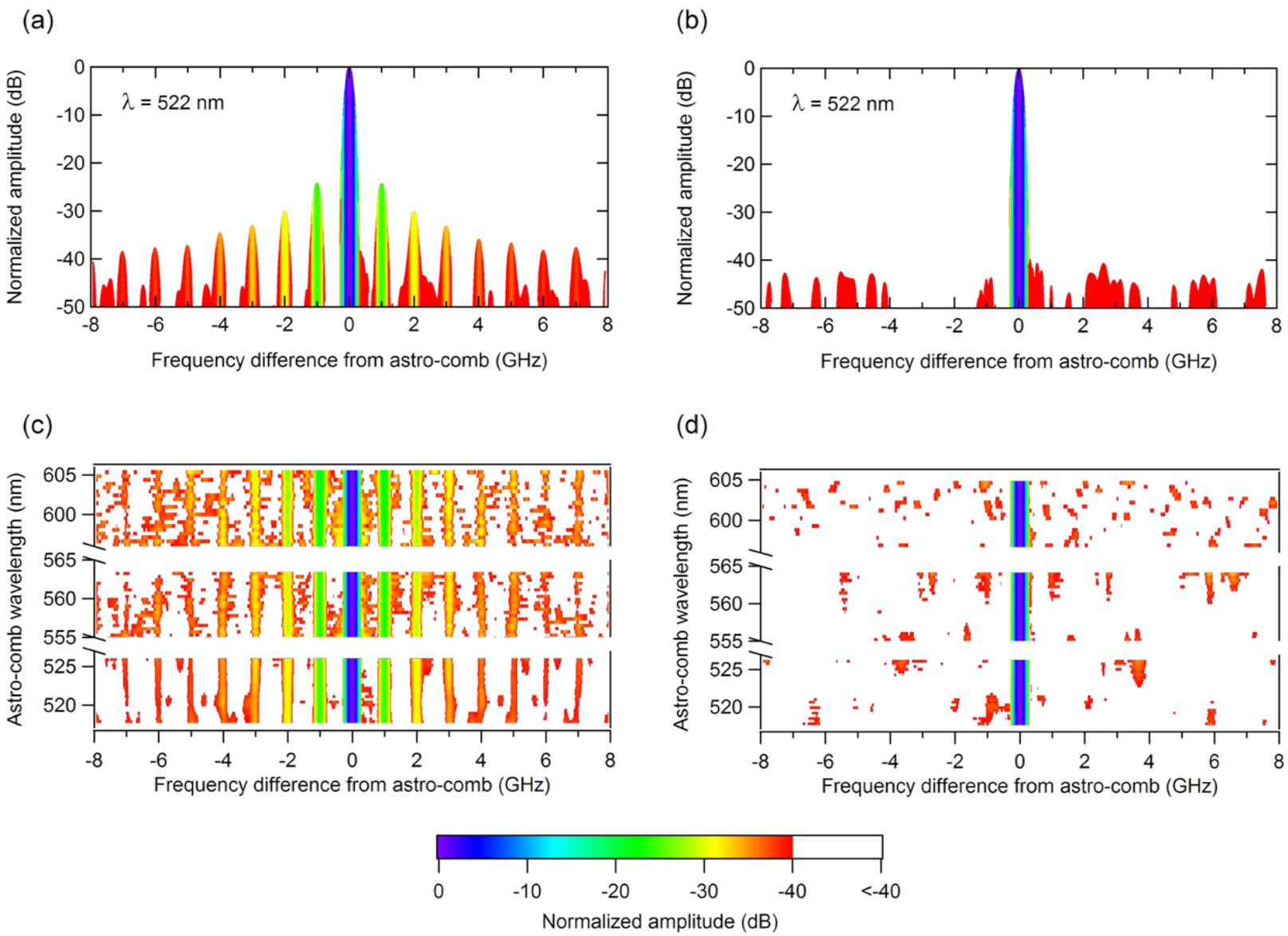



## HARPS-N Resolution




## FTS Spectrum

# Suppression of Unwanted Lines



# Getting Ready

## Late December 2012

# Getting Ready

Late December


early January

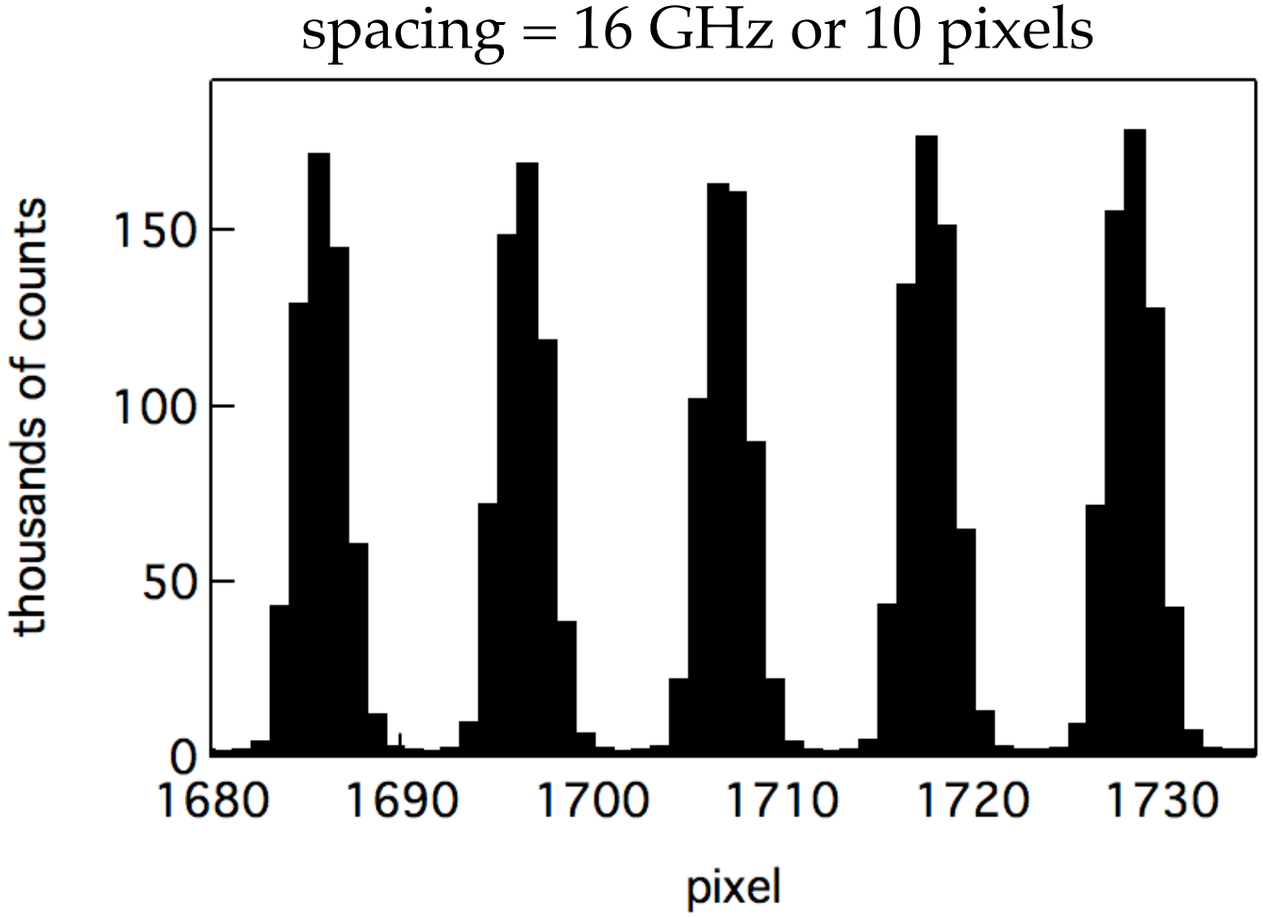
# System Arrives at Telescope

# Four days later...

# Operational

# How well can we calibrate?

$$\delta\nu = A\frac{\mathrm{FWHM}}{S/N \times \sqrt{n}}$$




$A \approx 0.5$

FWHM ≈ 5.6 GHz

$(S/N)_{20\ s} \approx 350$

$n \approx 3$ pixels

$\Delta\nu \approx 4.3$ MHz or 2.3 m/s *for one peak*

~350 peaks/order: 12 cm/s *in each order*

ν = 1 GHz

v = 550 m/s

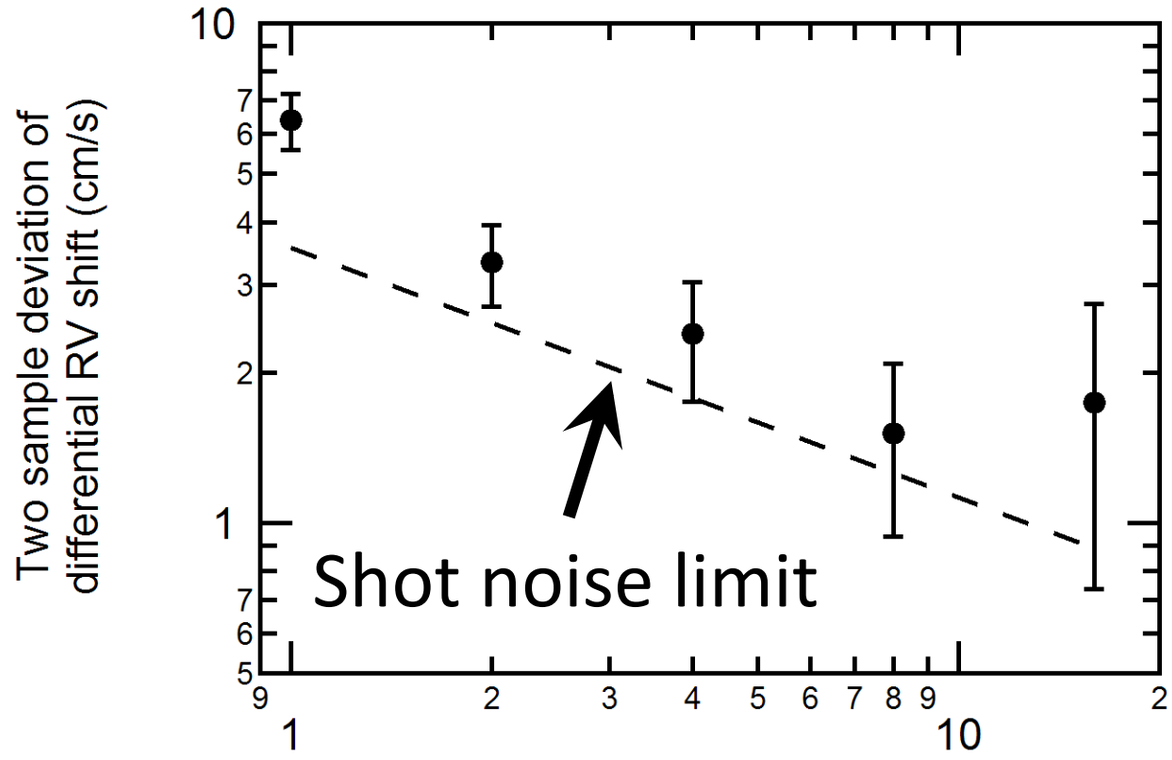
λ = 0.01 A

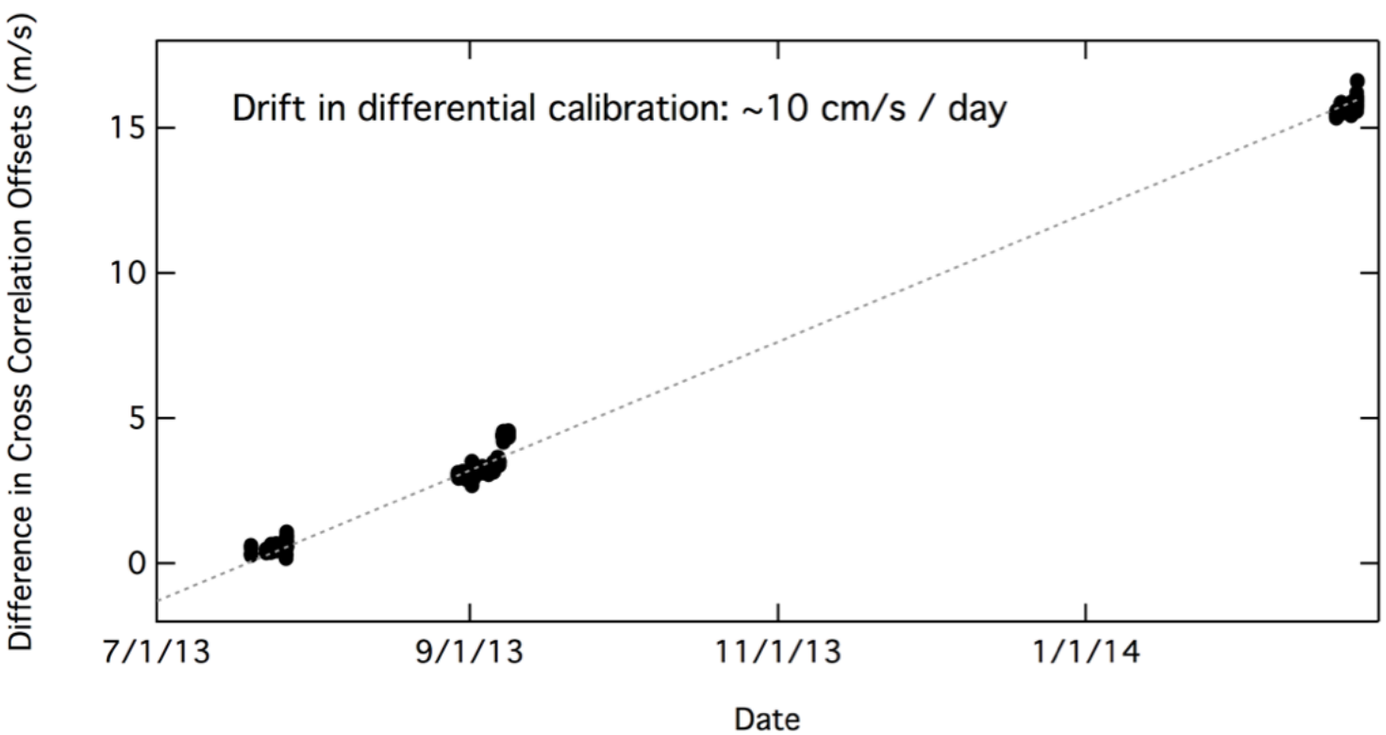
0.63 pixels

9 μm

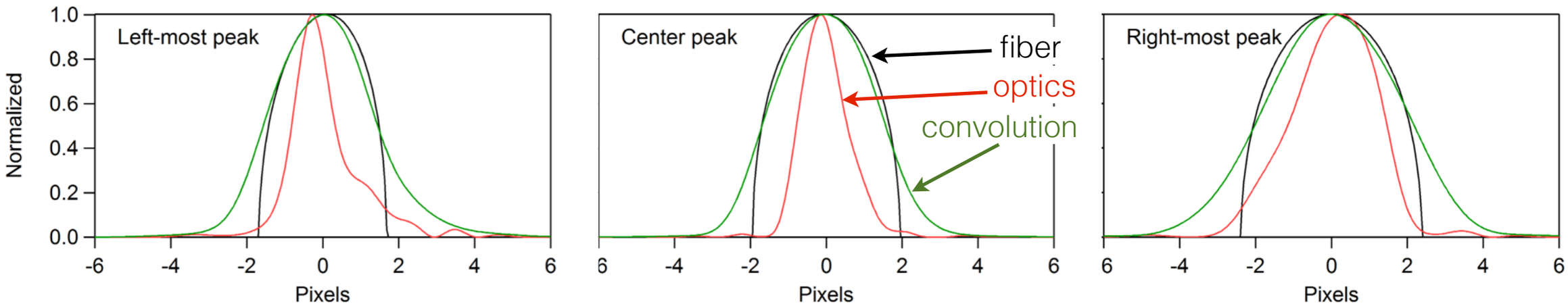
# Comb Calibration Sensitivity

- Feed comb light into both “science” and “calibration” fibers
- Comb gives <5 cm/s calibration per exposure
- Needs bright star with many exposures



# Studying HARPS-N Line Profile



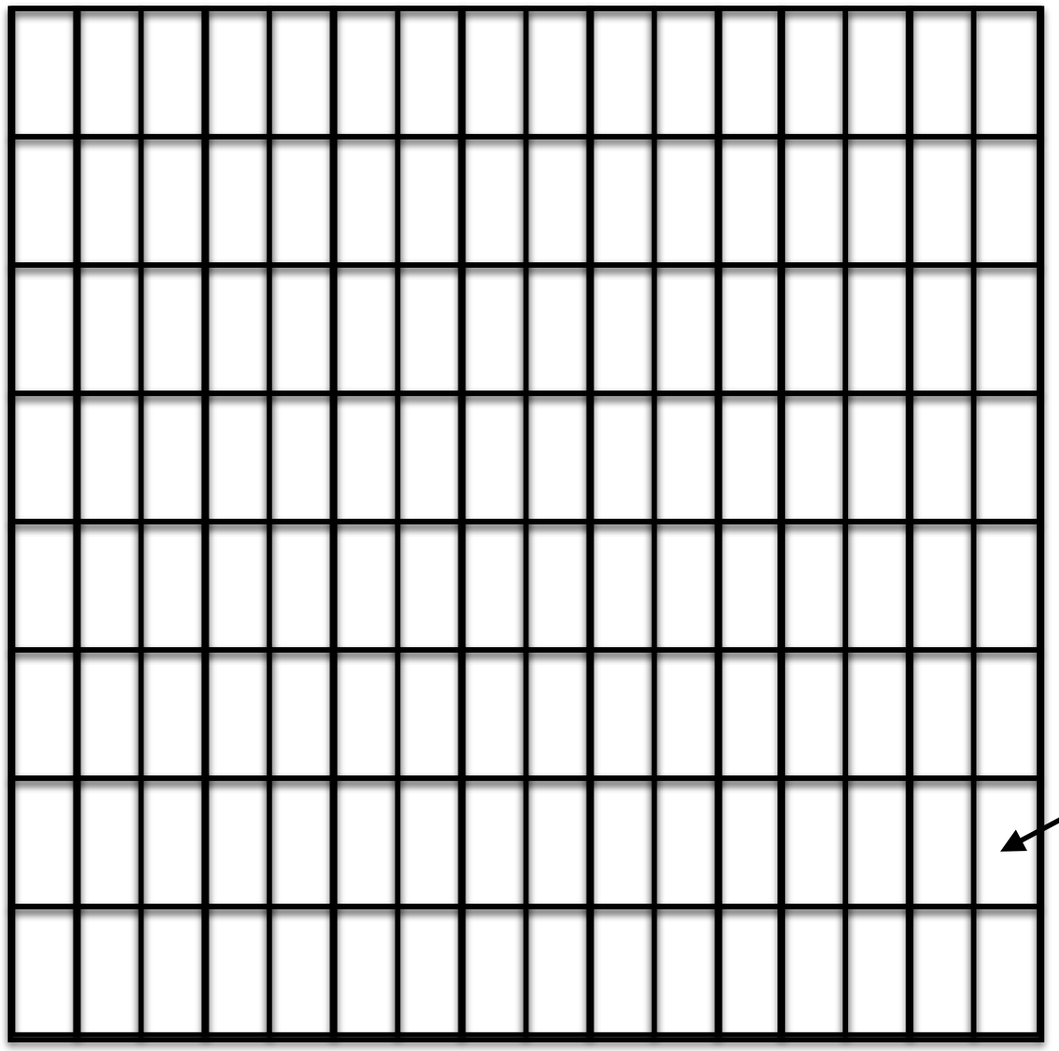

*skewed right*

*skewed left*

- Comb enables mapping of instrument line profile
- use line profile to forward model stellar line shapes
- Monitor drift in centroids of lines

# CCD Mask Errors

**CCD:**



**CCD masks**

**256×512 px**

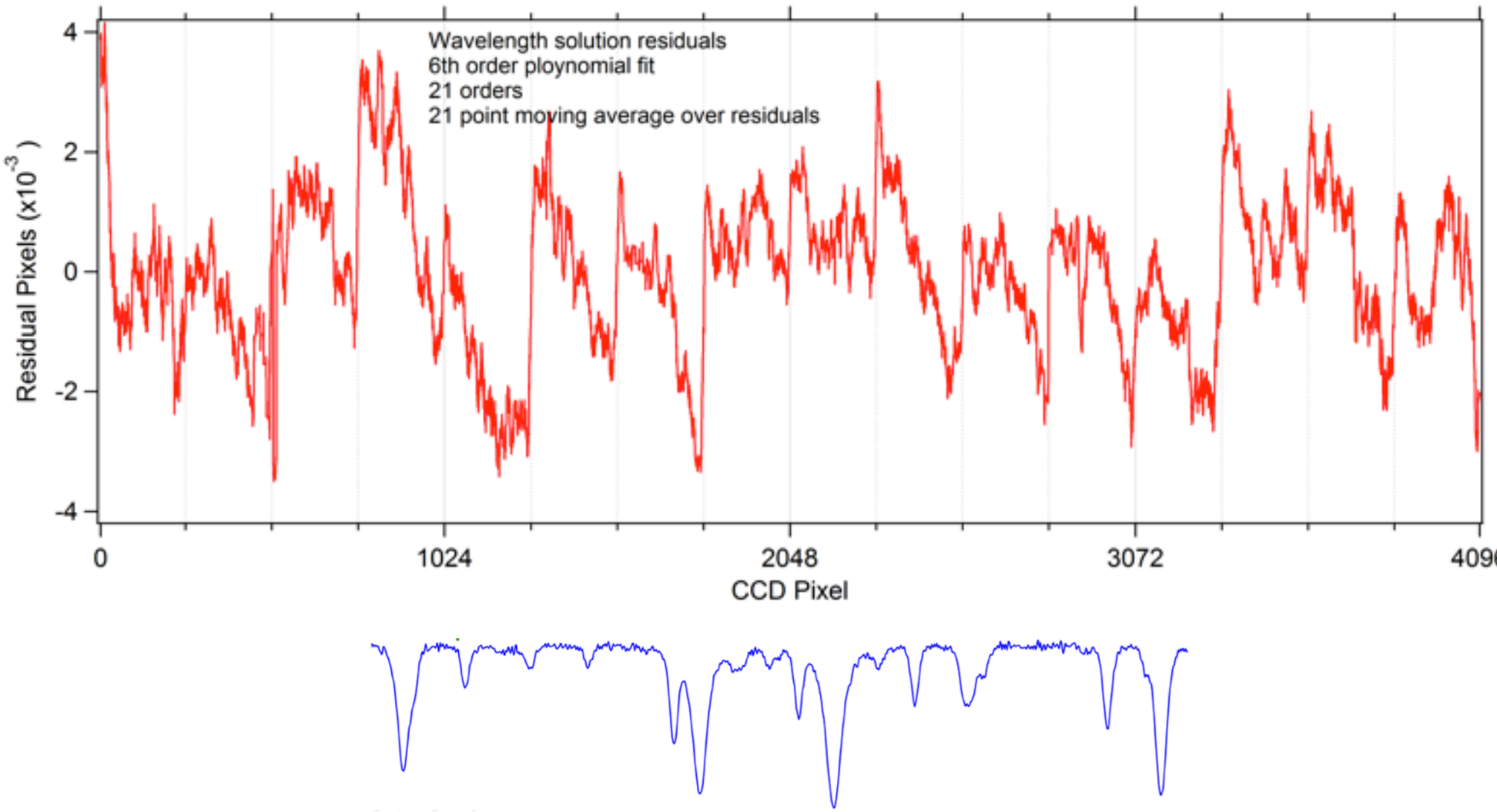
CCD electrodes are written with 256x512 mask which is moved across CCD wafer.

CCD mask errors are 2-3 millipixel offsets at each mask boundary.

How well is the mask positioned? Can we see systematic errors at mask boundaries?

*Look for these errors at HARPS-N.*

# CCD Mask Errors



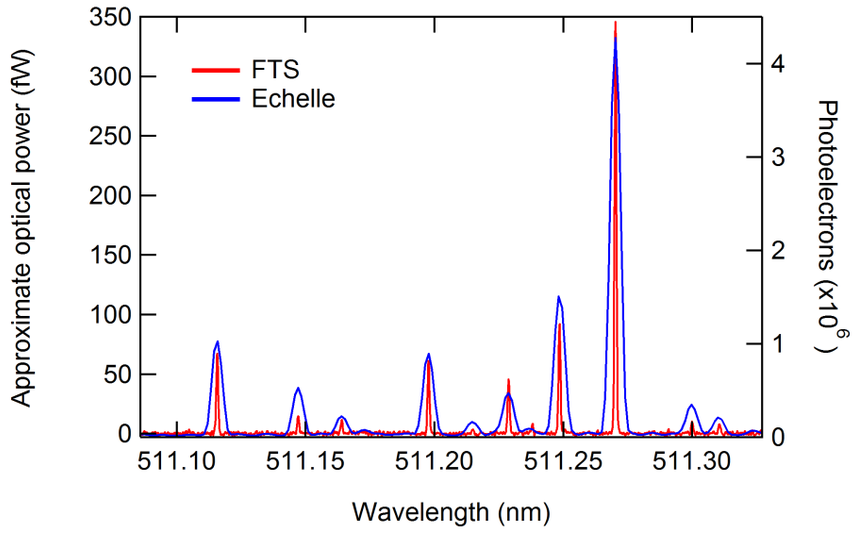

CCD mask errors are 2-3 millipixel offsets at each mask boundary.

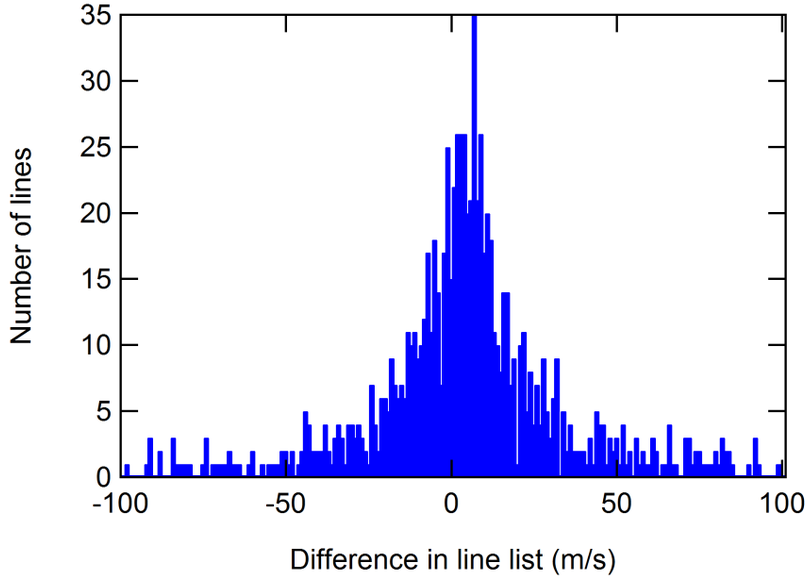
As Earth moves during the year absorption line shift by ~ 30 pixels.

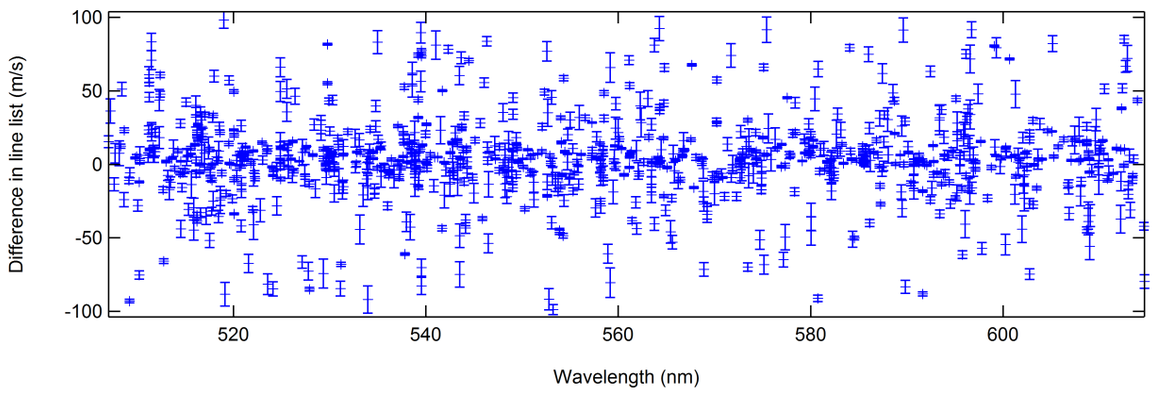
If absorption line crosses a mask boundary, line center will have systematic error.

*Can we develop a correction for these systematic errors?*

# Thorium Lamp Tests



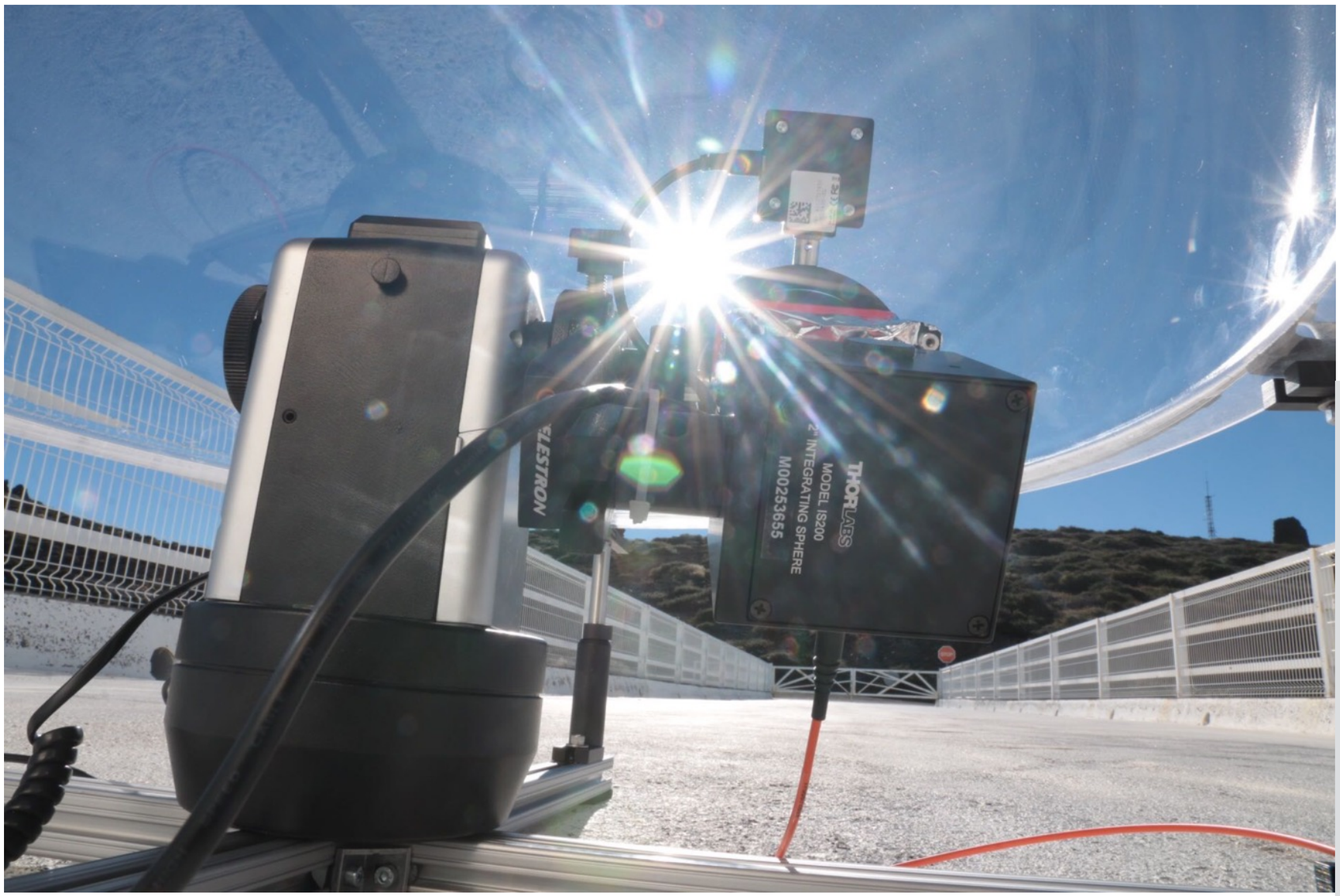




Christophe applies an overall correction based on shifts in Ar lines for aging of lamp.

Can we confirm these corrections and perhaps understand the physics of these shifts?

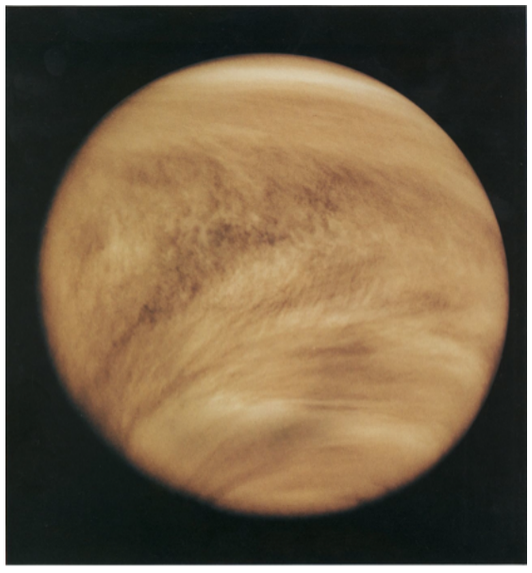
*Can we improve Th lamp corrections or provide astro-comb correction to them?*

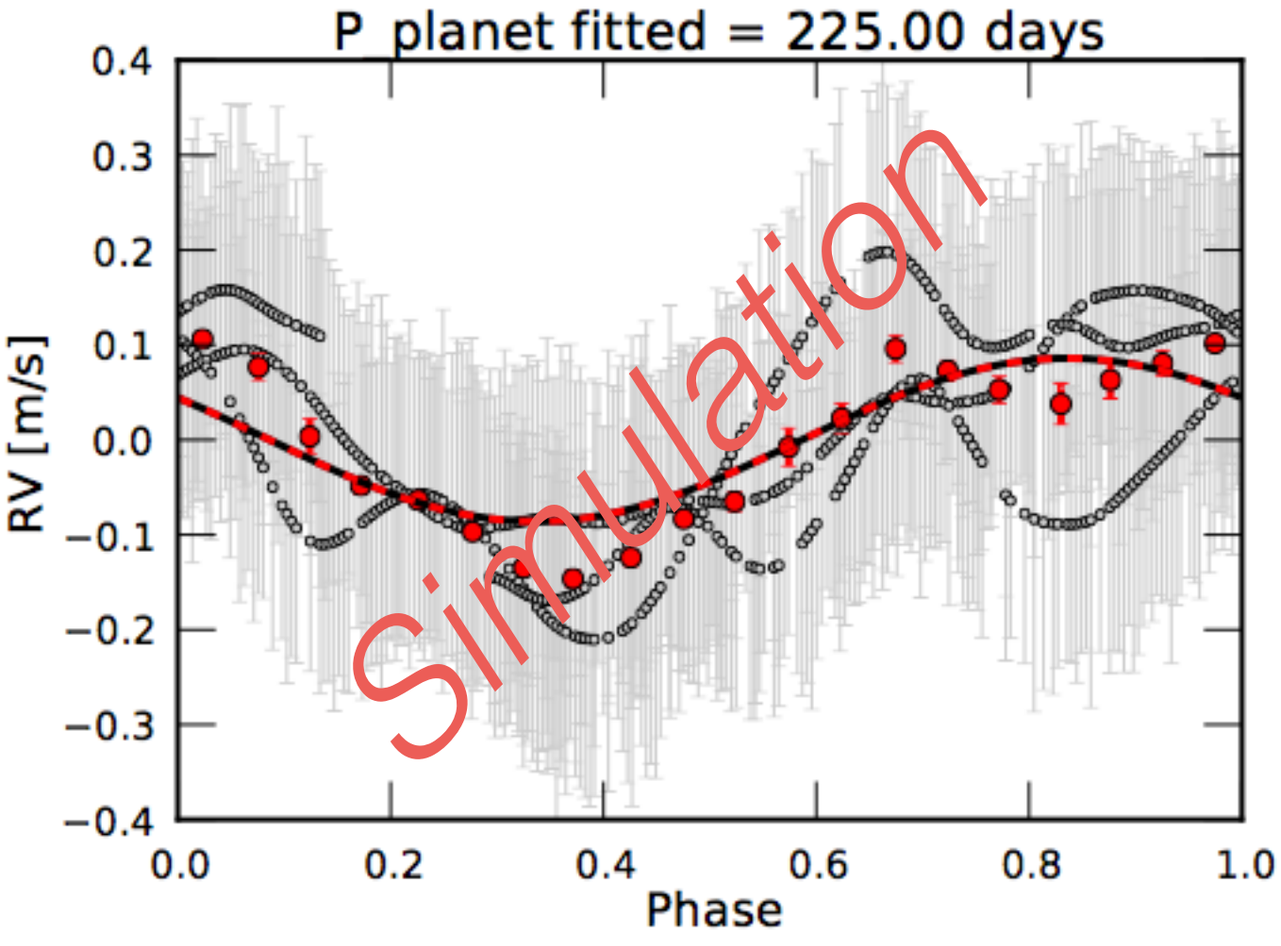
# Solar Telescope




- Tracking mount
- 3 inch lens
- UV filter
- Iris for checking guiding
- Integrating sphere
- Solarization resistant 300 um fiber output
- Feed HARPS-N calibration unit (CU)

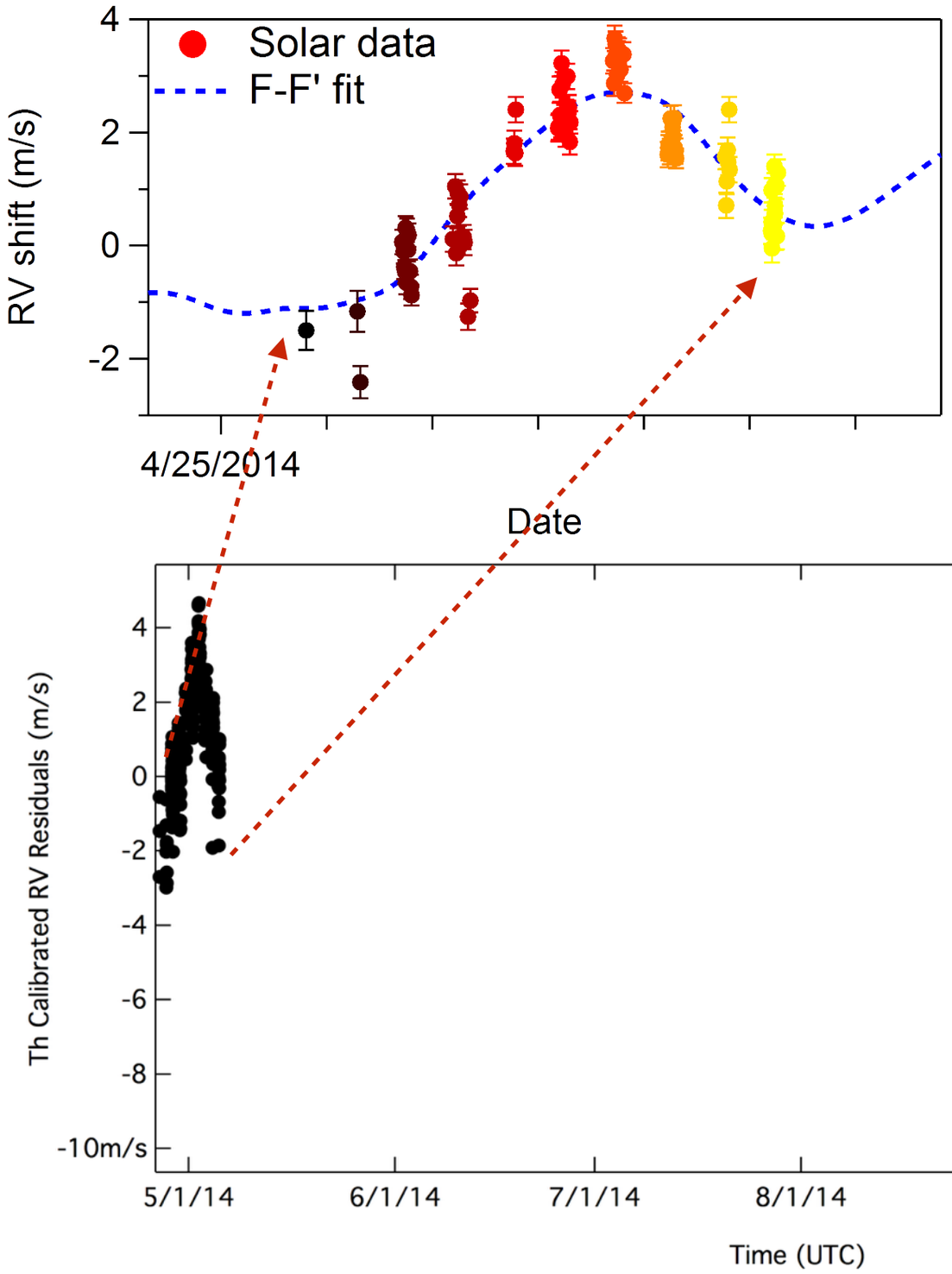
# Solar Radial Velocity





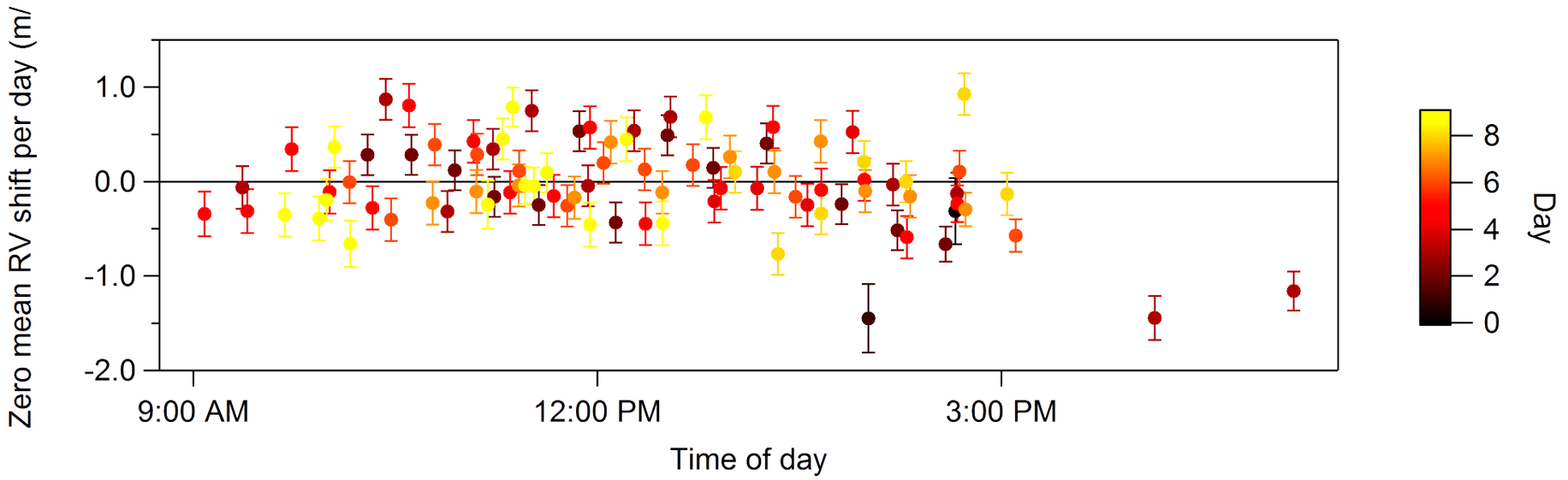

- Search for Venus in signals from Sun.
- We require 10 cm/s (0.3 ppb).
- We will learn about stellar (solar) jitter.

# Barycentric-Corrected RVs



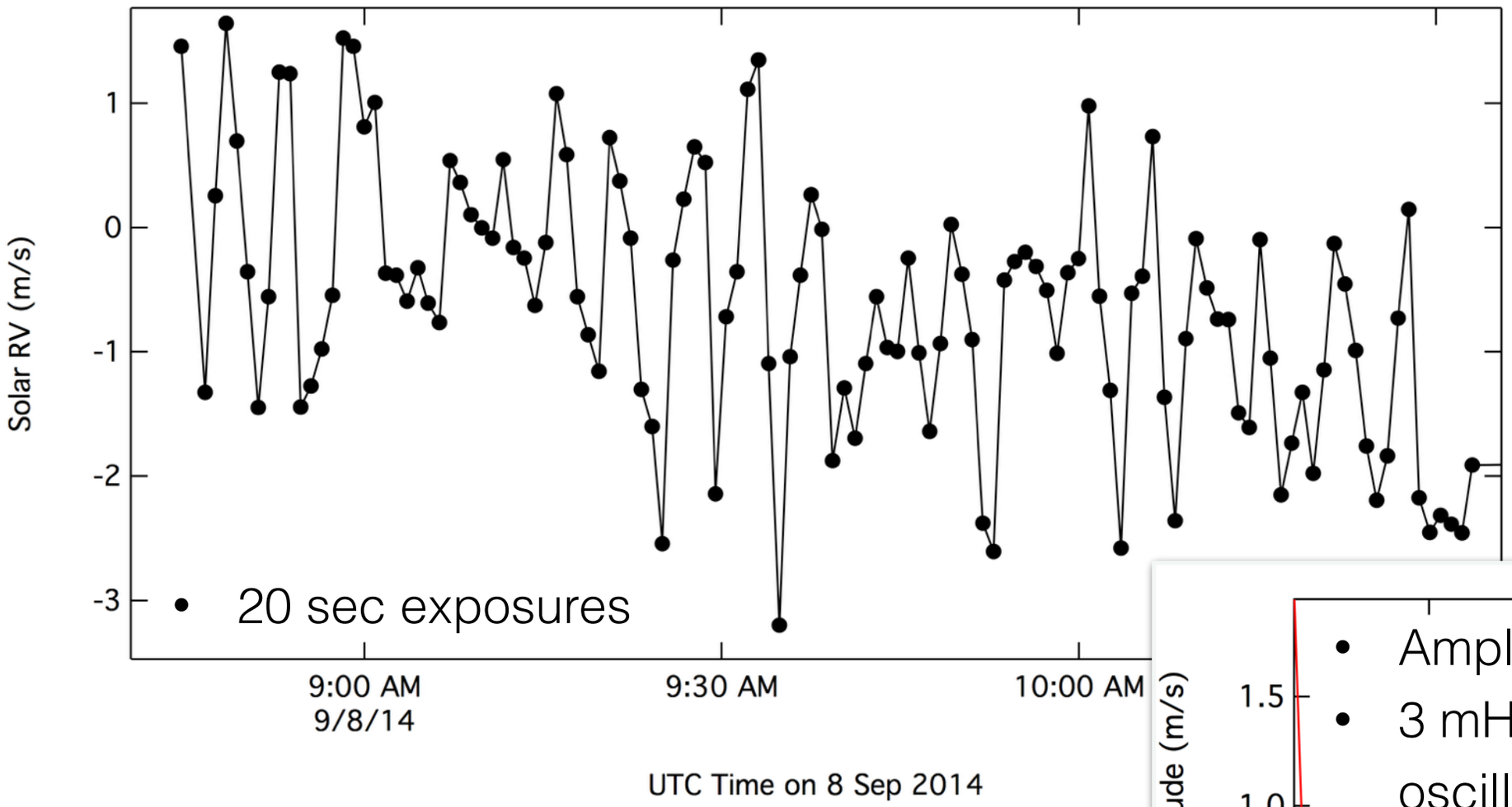

- Subtract expected velocity (from JPL *Horizons* ephemeris).
- Dominated by rotation of Earth changing projection of velocity.

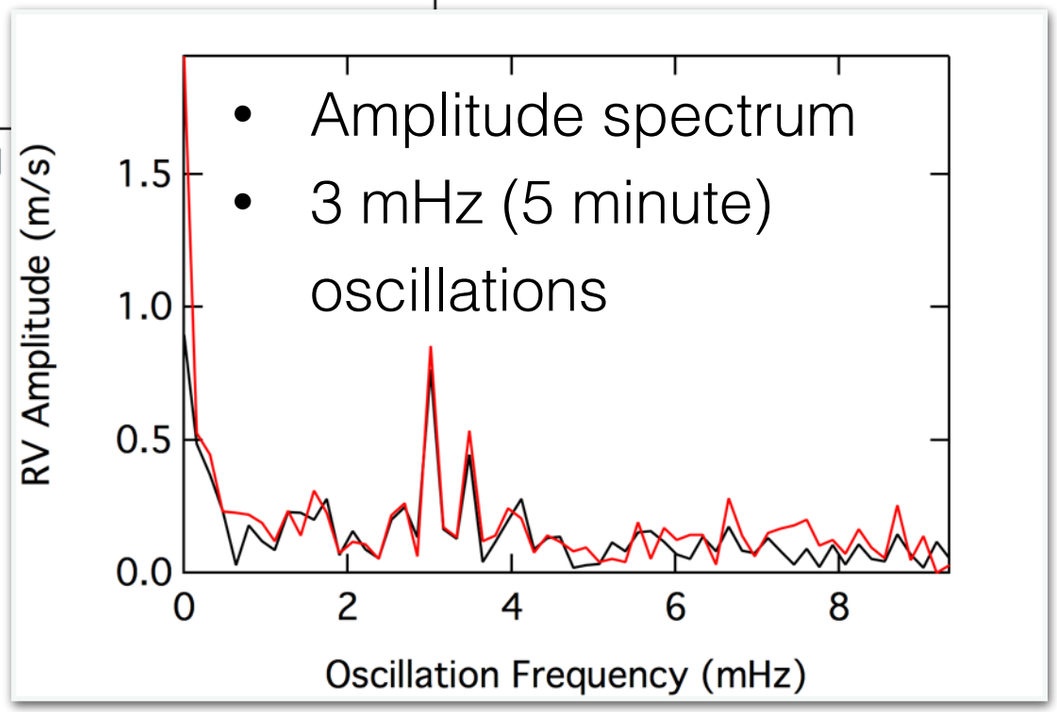
# Daily Residuals




- Residuals during each day are at the 30 cm/s level (1 ppb).
- Errors from fit to sunspots are also at 30 cm/s level.
- Long term stability? (*We return in 4 weeks to test.*)
- Absolute accuracy? (*Work in progress.*)

# Short Cadence Exposures



# Thanks!