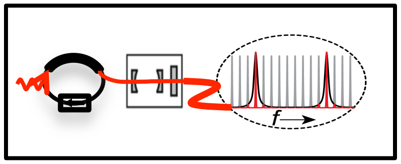
High Precision Spectroscopy from SOFIA?

Steve Osterman

Center for Astrophysics and Space Astronomy
University of Colorado

Scott Diddams (NIST)
Frank Quinlan (NIST)
Gabe Ycas (CU Physics)
John Bally (CU)



CASA
CENTER FOR ASTROPHYSICS
AND SPACE ASTRONOMY

Time & Frequency Division
NIST

Talk Outline

- Why perform NIR Spectroscopy in the NIR?
- How would you perform NIR spectroscopy
- Why perform NIR spectroscopy from SOFIA (what does that extra 25K ft buy you?)
- Strawman instrument description

Why Precision Spectroscopy?

- HARPS, HIRES, etc. have shown the value of high precision spectroscopy for RV planet searches at visible wavelengths
- Visible light RV searches for terrestrial mass planets in habitable zones are limited to solar like stars
- M Dwarfs are promising subjects but are not easily observed at visible wavelengths
- Precision NIR spectroscopy is becoming a reality with advances in laser comb technology, but NIR spectroscopy still contends with atmospheric absorption

Precision NIR RVSpectroscopy would allow us to address:

- What are the detailed dynamics of M/K Stars? Rotation rate? Activity?
- What fraction of M/K stars have planetary systems?
- What are the masses and orbital parameters of these planets?
- How do young stellar and planetary systems originate and evolve?
- What are the physical processes and initial conditions that produce different types of systems?
- Where are potentially habitable planets?

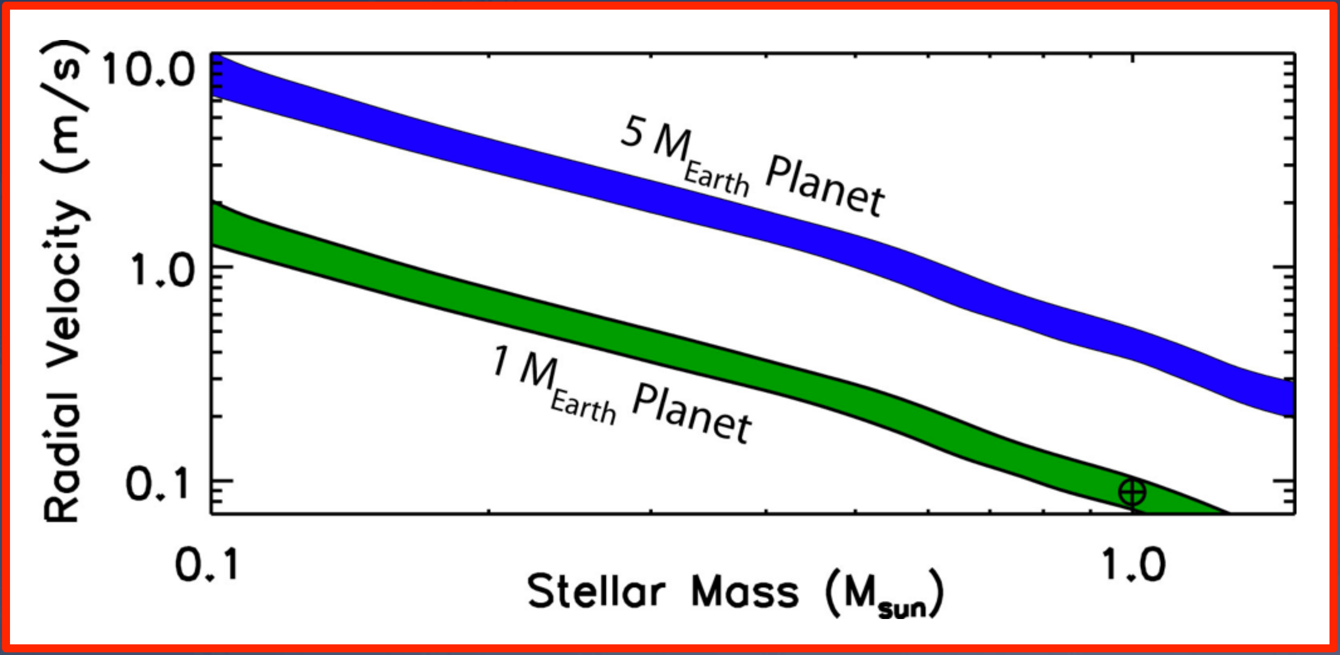
The challenge here is that NIR spectroscopy is limited to tens to hundreds of m/s by the lack of a good calibration source. The laser frequency comb can support sub-m/s precison.

Why would we look for planets around low mass stars, and why in the NIR?

- Larger RV signature for a given planet mass in the habitable zone
- Large number of host stars within 10pc
- Cool stars brighter in the NIR
- No shortage of narrow spectral features

Increased RV signature:

- Low Temperature, Low Mass Host:
  - Habitable zone is closer to the host, increasing RV signature
  - Lower host mass increases RV signature
  - Tighter orbit leads to shorter period (weeks)



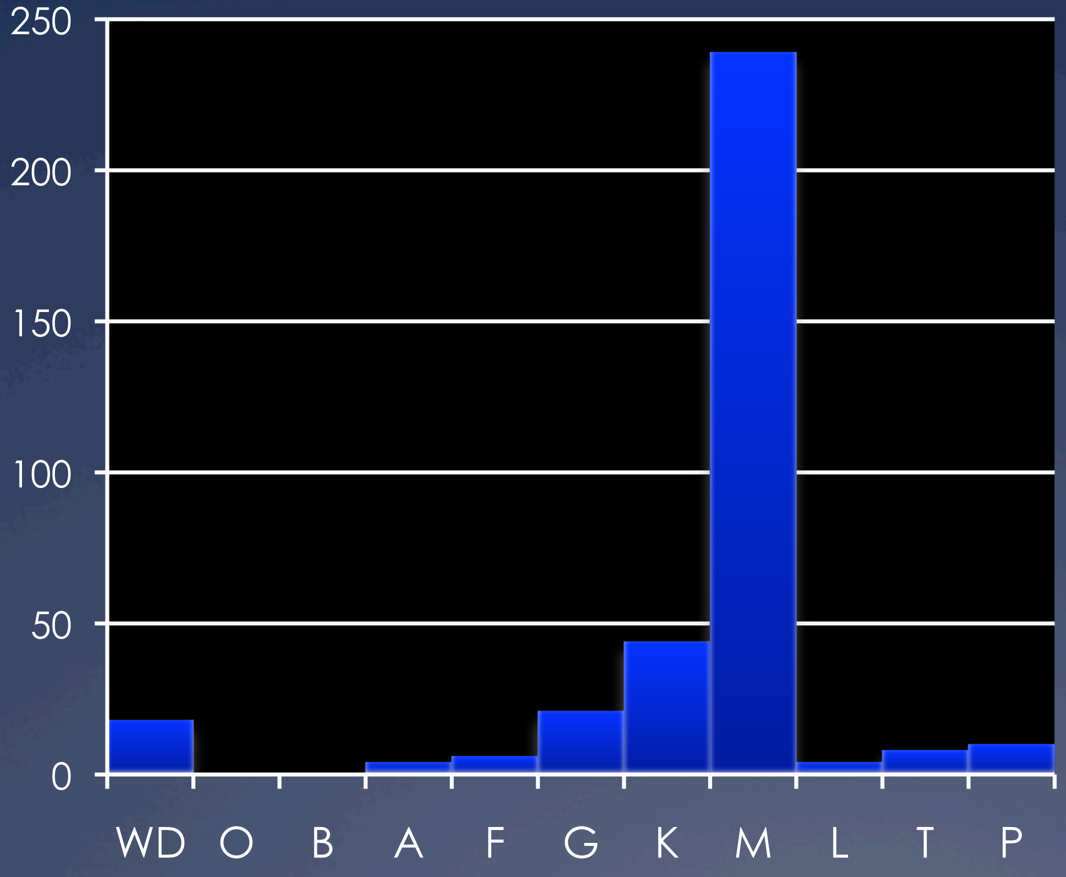
Stellar RV for earth mass planet in the habitable zone. Derived from Kasting (1993, fig. 15).

Exo-planets around nearby mature K, M dwarfs

- Most common type of star in the Solar vicinity
  - Most K, M stars are single
  - K and M spectral types:
    - M ~ 0.08 to ~ 0.7 Solar masses
    - L ~ 10^{-4} to 0.16 Solar luminosities

Stellar Mass (M_0)	Planet Mass (m_e)	Lum. (L_0)	Type	$R_{HAB.}$ (AU)	RV (cm/s)	Period (days)
0.10	1.0	8e-4	M8	0.028	168	6
0.21	1.0	7.9e-3	M5	0.089	65	21
0.47	1.0	6.3e-2	M0	0.25	26	67
0.65	1.0	1.6e-1	K5	0.40	18	115
0.78	1.0	4.0e-1	K0	0.63	15	209

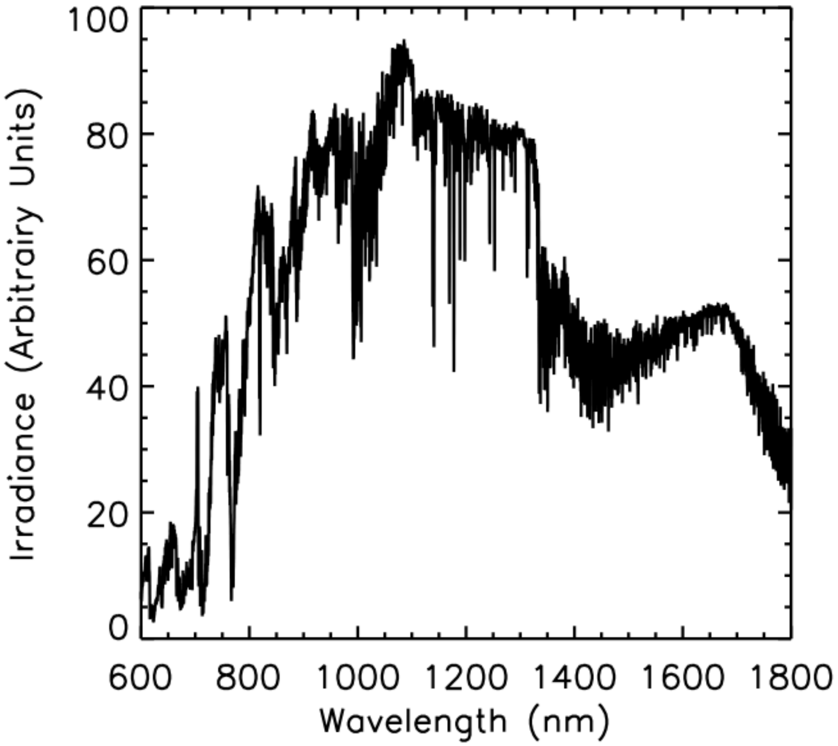
Large number of host stars within 10pc



Data from most recent *RECONS* survey values (Jan 2009) showing predominance of class M stars within 10 pc.

Cool, low mass stars are brighter in the NIR

M6 Model Spectrum

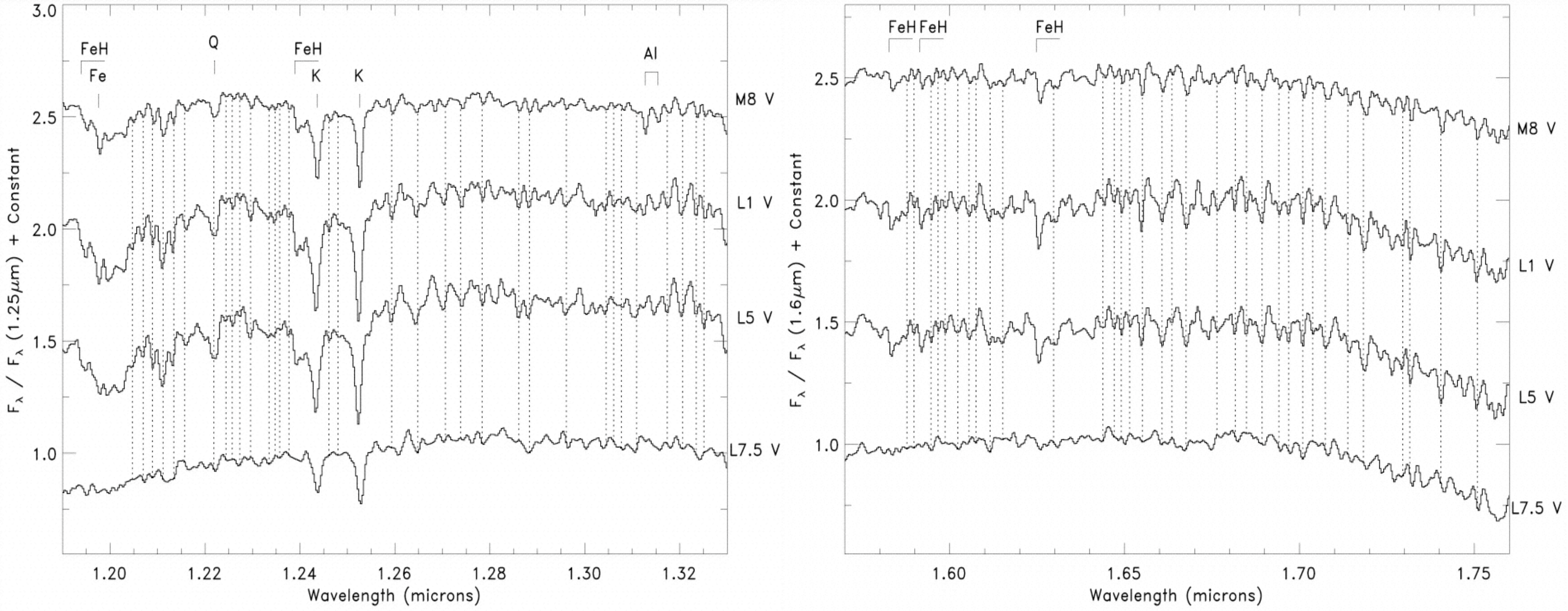


(courtesy of Peng Jiang, 2009)

- Optical RV surveys limited to stars more massive than early M dwarfs (>0.3 Msun)
- Lower mass stars are too faint in visible light for optical RV surveys

Distinct, Narrow Features

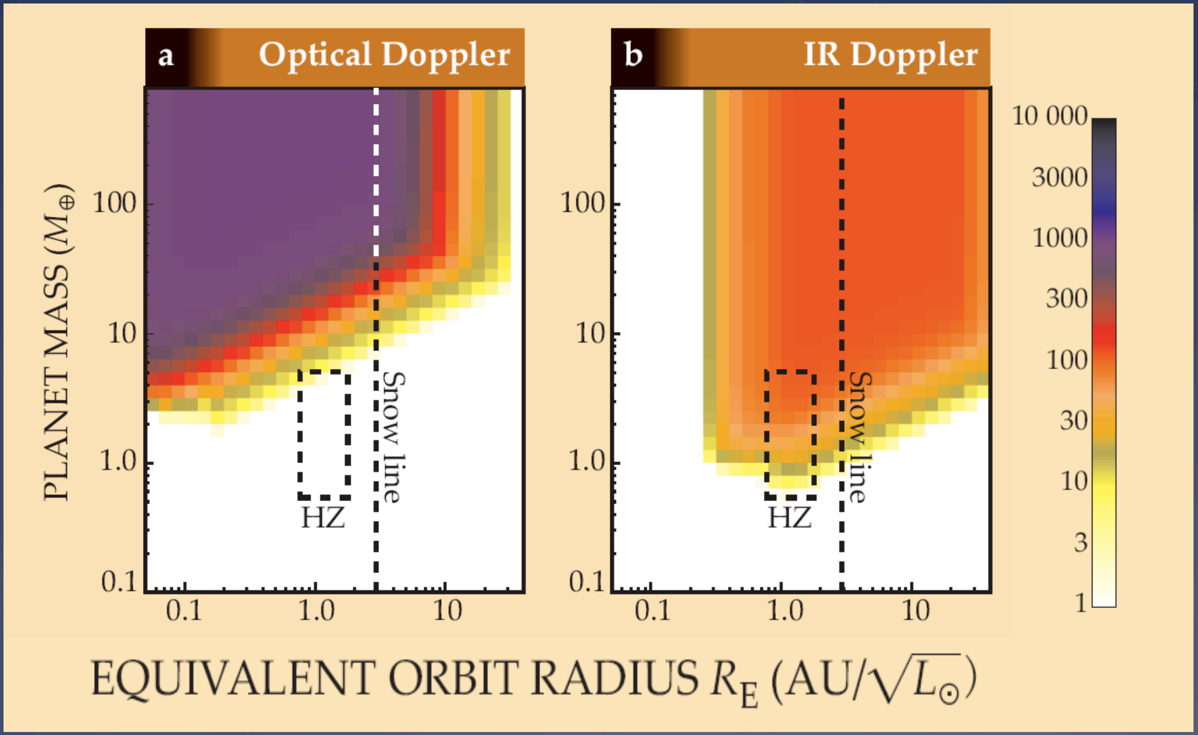
- M and L dwarfs have numerous sharp absorption features in the H and J bands



Fe absorption features in J and H band, from Cushing, 2003

IR Doppler

- Lunine explored the probability of discovery as a function of the radiant equivalent radius and found a distinct advantage for IR Doppler as a tool for probing the habitable zone of nearby stars



From
Lunine, 2009

Testing Planet Migration Theories

- Gas Giants around Solar type form only at r > 2 - 4 AU due to shear -

  Must happen before H_2 is lost to UV photo-ablation

  Gravitational instability t ~ 0 - 3 Myr

  (Requires high surface density disk)

  Core accretion t ~ 2 - 5 Myr

  (Requires 5 - 10 Earth mass rock/ice core)
- Migration follows formation
- In disk migration models, migration occurs in obscured, embedded phase.
- What is the youngest star orbited by a "hot Jupiter"?

By seeing through the dust obscuring young stars, we could constrain time & mechanism of migration

Testing Planet Migration Theories

HH 46/47: a young embedded star at visible and IR wavelengths

NTT [**O**II] Hα [**S**II] = 0.38, 0.65, 0.67 μ**m**
Bally & Reipurth (06 “Birth of Stars & Planets” CUP = BR06)

Spitzer $\mathbf{H_2}$ **PAH** 3.6, 4.5, 8 μ**m**
(Noriega-Crespo 04; BR06)

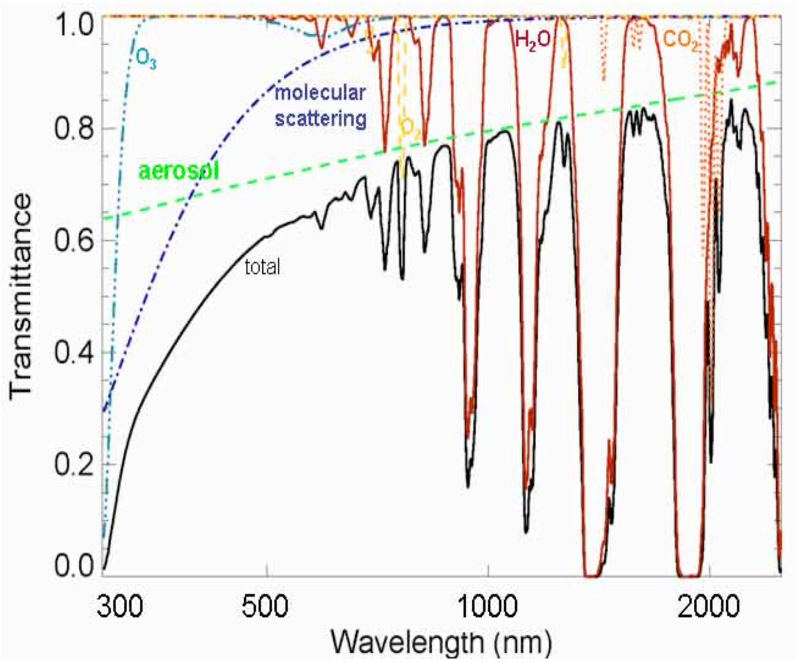
Other projects enabled by high precision NIR spectroscopy

- How common are terrestrial mass planets around low mass stars, and how many reside in the habitable zone?
- How and when do gas giant orbits evolve?
- How common are gas giant planets around post-main sequence red giant?
- Are "Hot Jupiters" Cannibalized by Red Giants? (IRC 10216, R Cor Bor, …)
- How Common are Gas Giant, Brown Dwarfs, and Red Dwarfs Around Massive Super-giants? (Aldebaran, Antares, Betelgeuse, VY Canis Majoris, …)
- Planetary atmospheres
- Stellar rotation and astroseismology
- M and lower mass spectroscopic binaries

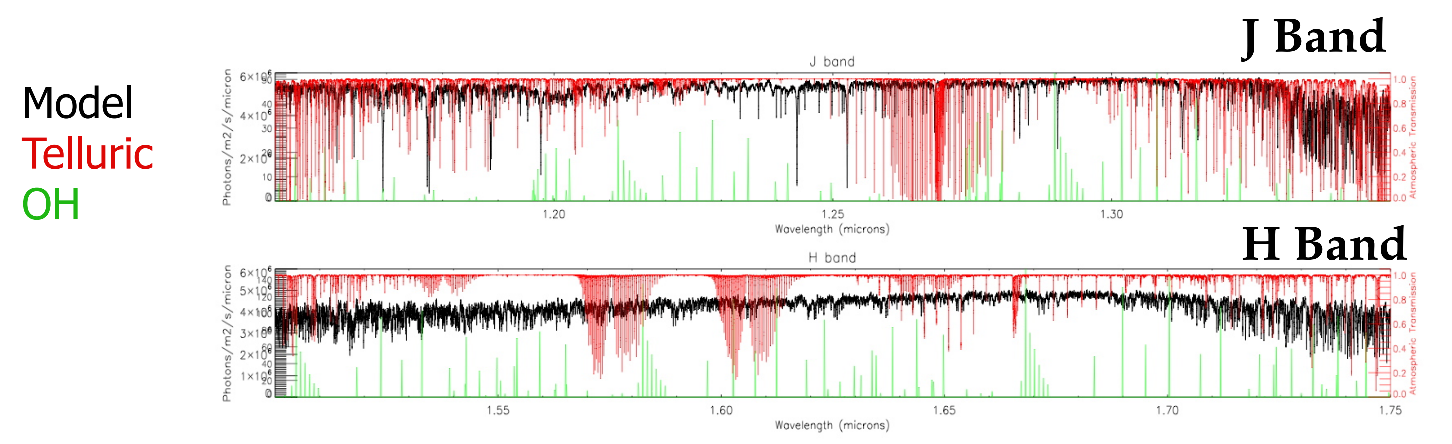
This is not just about finding planets around M stars: By improving RV precision by 2 orders of magnitude we open up an enormous discovery space.

Why not do this from the ground?

- Atmosphere opaque between ~1.3 and 1.5 μm and ~1.8-2.0 μm
- Complicated by time varying telluric lines throughout transmission bands

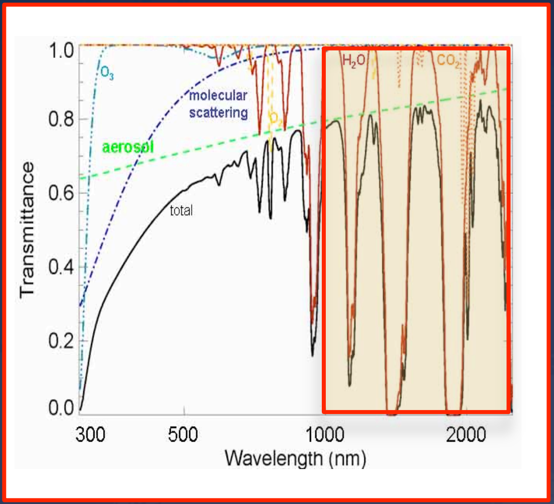


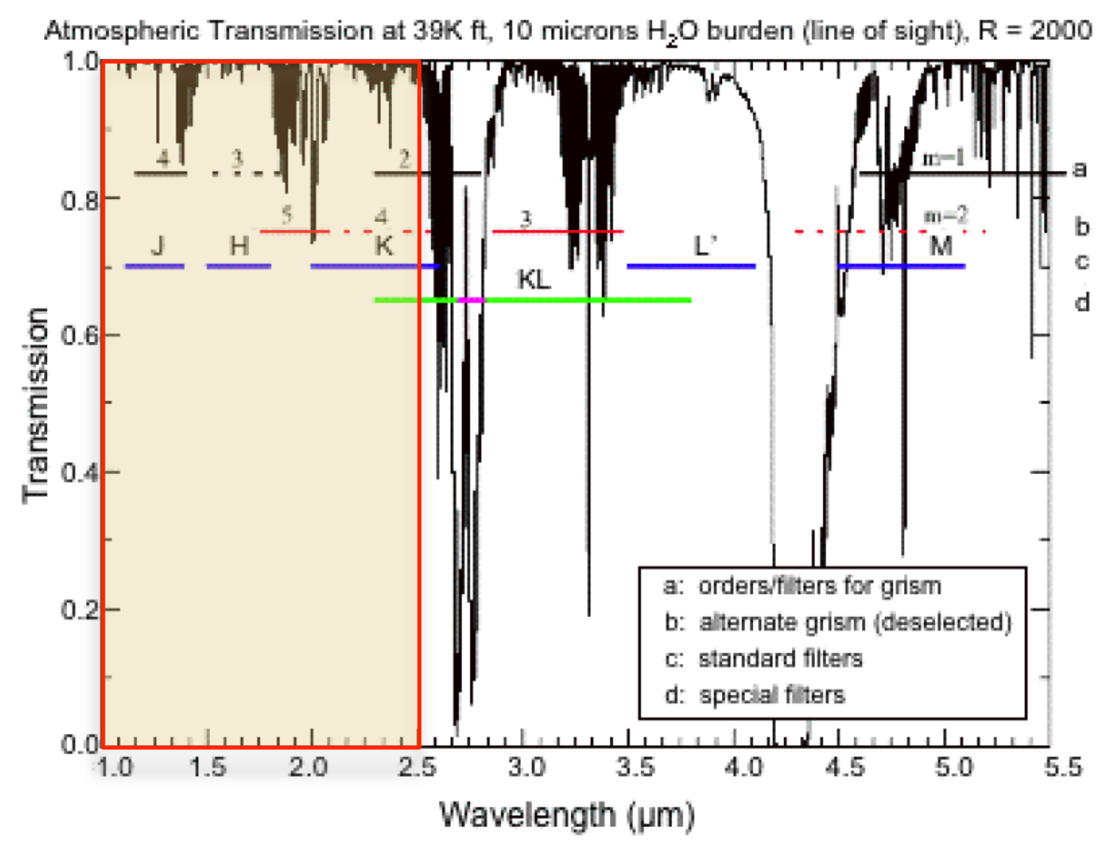
LASP, 2010



From Hugh Jones, April 2009

Transmission at 39K ft -





From FLITECAM Performance Summary (http://www.sofia.usra.edu/Science/instruments/performance/FLITECAM/FLITECAM_TimeEst.pdf)

Strawman instrument: Performance Goals

- 5 m/s precision
- Broad band (1.3-2.0 micron)
- Simultaneous wavelength calibration capability
- Multi-object mode
- 50,000 resolution

Strawman instrument: Requirements

- Spectrograph
  - 50,000 Resolution between 1.3 and 2.0 μm:
    - R2 cross dispersed echelle spectrograph
    - Requires 2Kx2K detector for full coverage
  - Single object and limited multi object capability
    - Requires nominal and adjustable high dispersion cross dispersers
  - 5m/s precision on perfect target:*
    - ~4-7m/s intrinsic RV precision limit at S/N100, M6
    - Maximum 1 m/s contribution from calibration source acceptable
    - The fundamental limit is likely to be the transverse (line of sight) RV knowledge and stability of SOFIA
    - Add fast shutter to control RV content

Strawman instrument: Design

- Cross dispersed Echelle
  - Fiber fed
  - Single object mode:
    - 32 orders on H2 MerCad Telluride chip
    - Each order has 3 cal fibers interspersed between object and sky fiber clusters
  - Multi object mode
    - 4 orders on H2
    - Selectable high(er) dispersion cross disperser on tilt stage
    - Each order has 30 object clusters, 5 sky clusters, 10 calibration fiber sets
  - 12.5GHz comb provides 200-300 bright, evenly spaced reference lines per echelle order
    - At S/N 200 this supports 0.15-0.3m/s RV precision
    - Uniform coverage means that all regions have calibration lines

Introduction to Laser Frequency Combs

- The LFC produces an array of bright, narrow, uniformly spaced lines with the frequency of the n^{th} mode (n^{th} emission line) given by

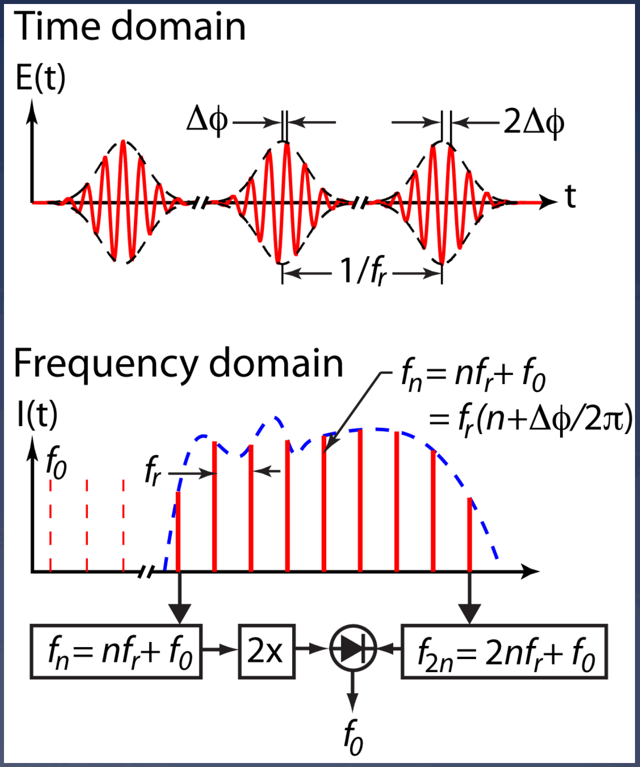
$$f_n = nf_r + f_0$$

f_n is the frequency of the n^{th} mode

f_r is the repetition rate of the laser (~250 MHz to 10 GHz)

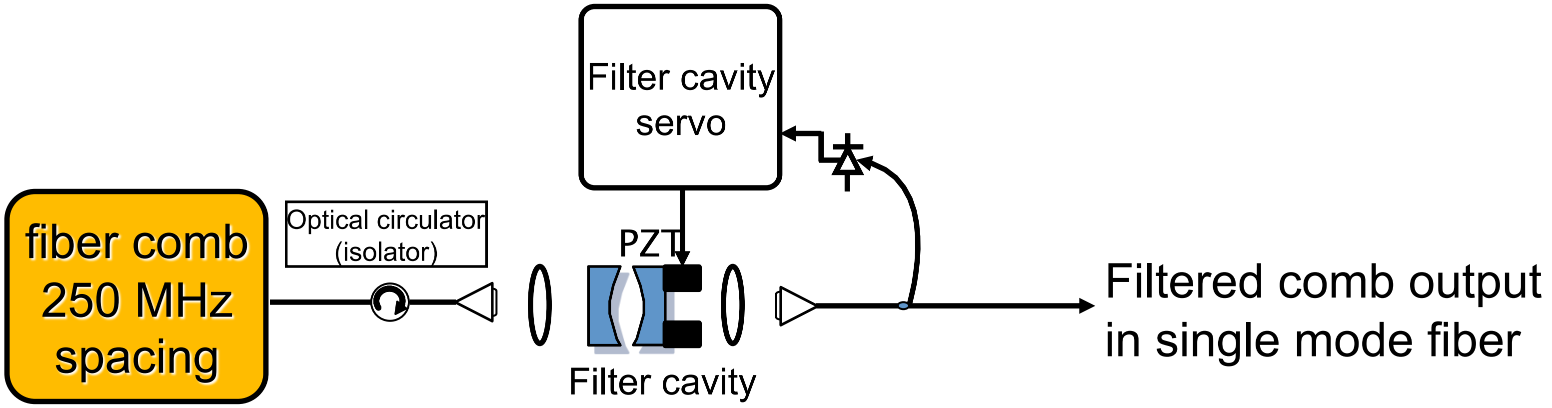
f_0 is the carrier offset frequency ($< f_r$)

- This relation is <u>exact</u> (measured to 10^{-19}).
- A Fabry Pérot cavity is used to increase mode spacing to a level suitable for astronomical spectrographs.

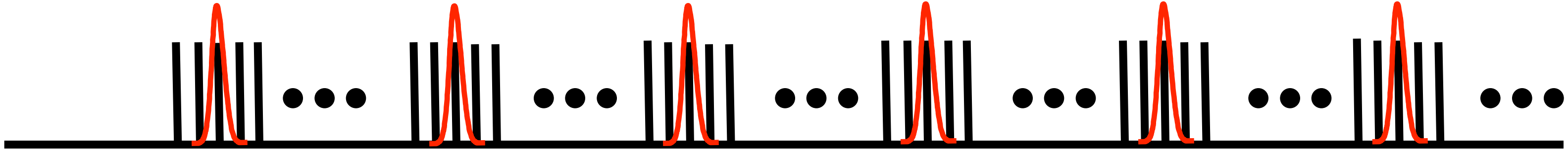


The comb spectrum is the Fourier transform of a pulse train with the group and phase velocities offset by $\Delta\phi$. f_0 and f_r are RF and easily stabilized to high precision.

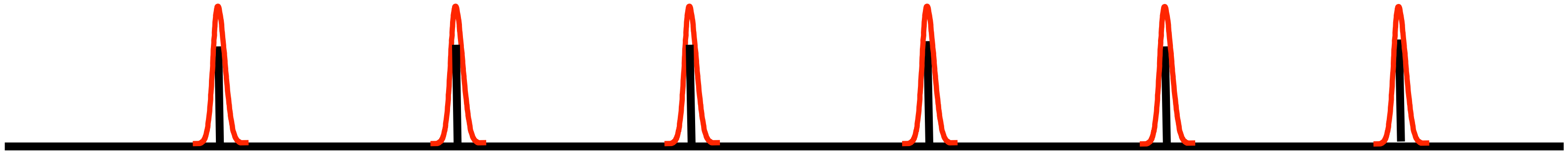
1.55 μ m Er:Fiber+filter cavity setup



Original 250 MHz comb &
filter cavity transmission

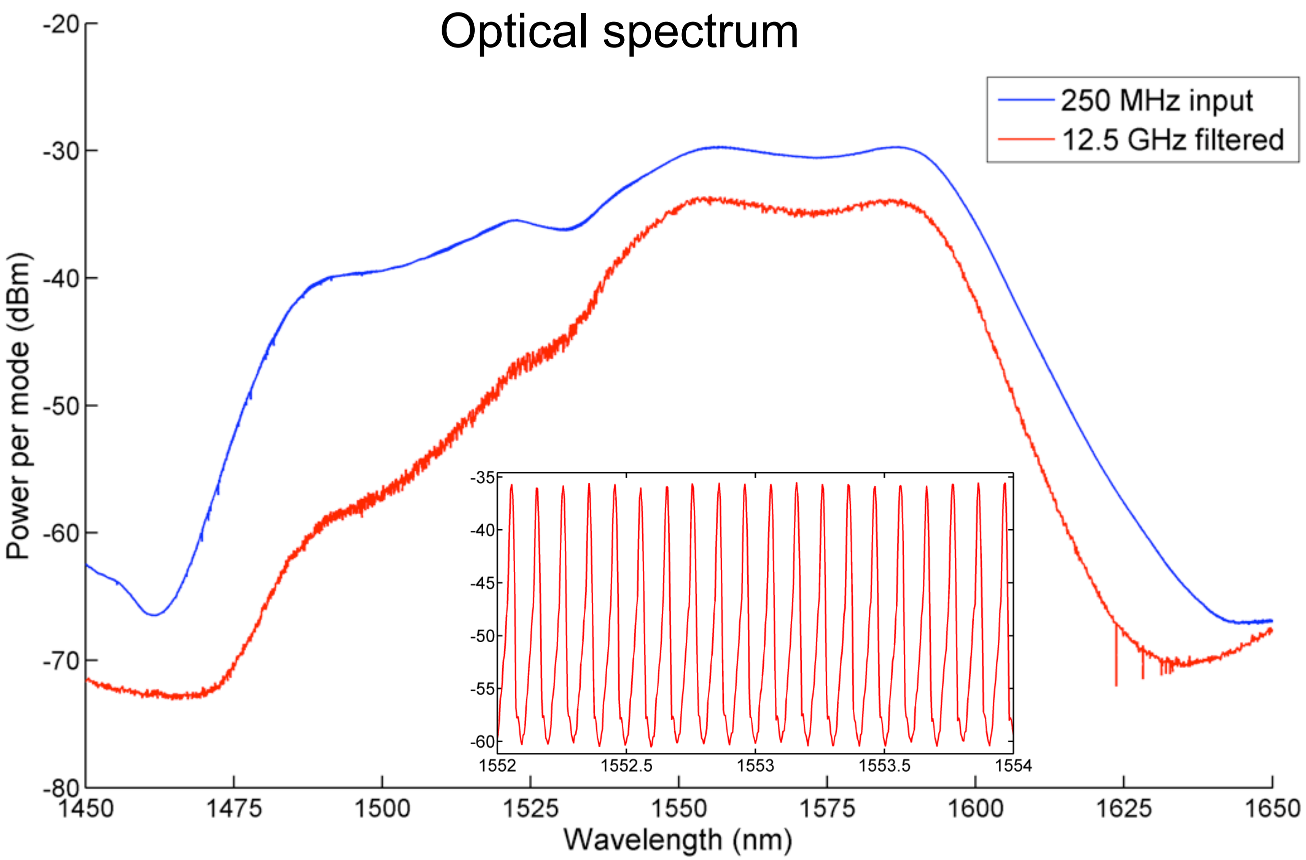


Filtered 12.5 GHz comb (0.1nm, or λ/Δλ =15,500 at 1.55μm)



Filter cavity selects one mode of every 50 to generate 12.5 GHz-spaced comb.

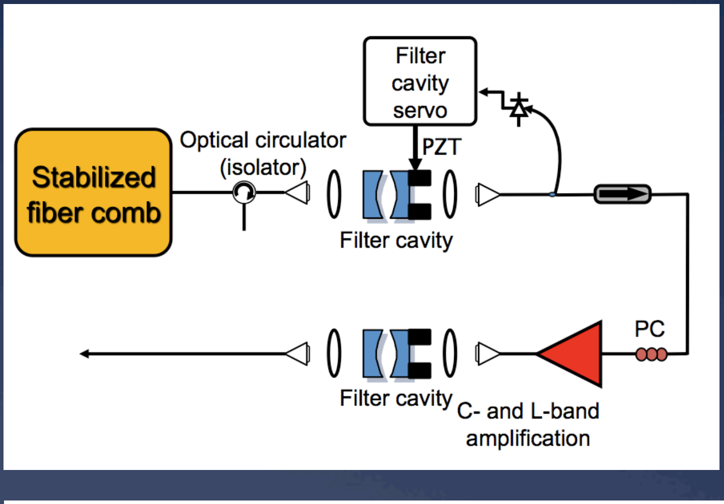
Single filter cavity performance

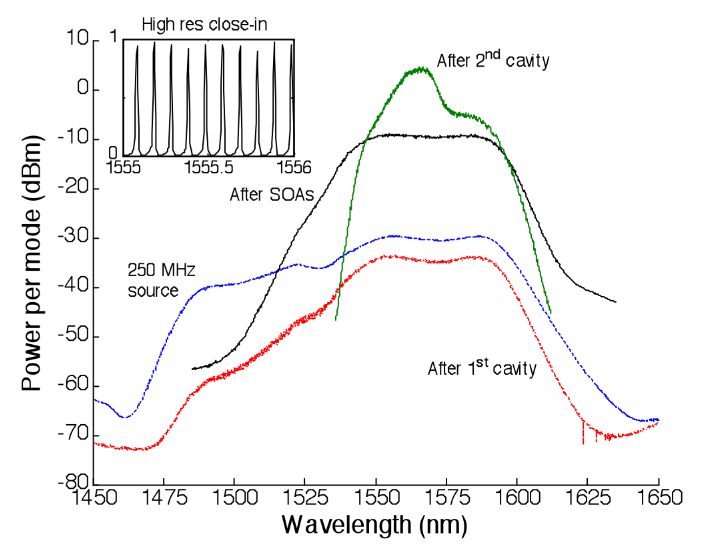


Loss per mode at center of spectrum ~4 dB. Greater loss in the wings is due to filter cavity dispersion.

Mode Filtering and Spectrograph Feed

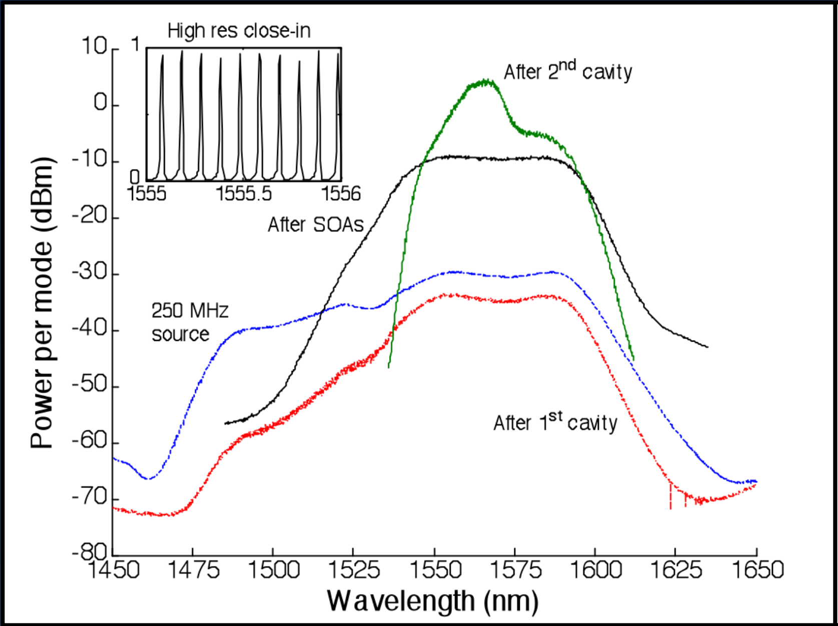
- At f_r = 250MHz, mode spacing is too narrow to support a $\lambda/\Delta\lambda$=50,000 instrument. The comb spectrum will be filtered to 12.5GHz before being fed to the spectrometer (at 1.6 μm this provides one mode per 0.11 nm).
- Second filter increases intermode suppression.
- Comb output is very bright (~.1mW per mode) enabling rapid calibrations and use of an integrating sphere for comb-to-spectrograph coupling.
- Post filter nonlinear broadening increases band pass to 1300-1800nm

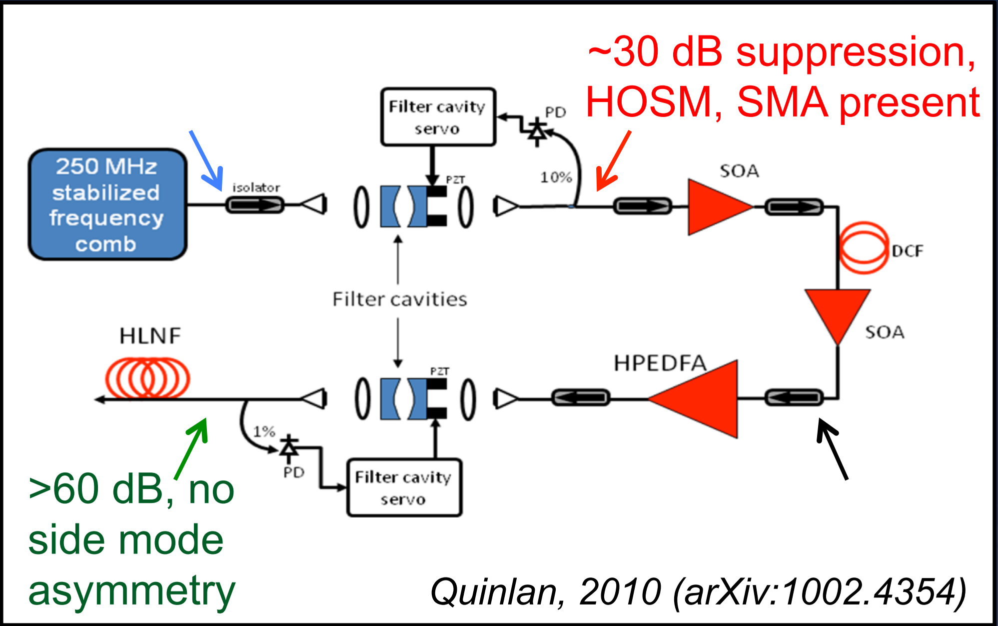




Double filter configuration

second filter cavity increases spur suppression





~30 dB suppression, HOSM, SMA present

>60 dB, no side mode asymmetry

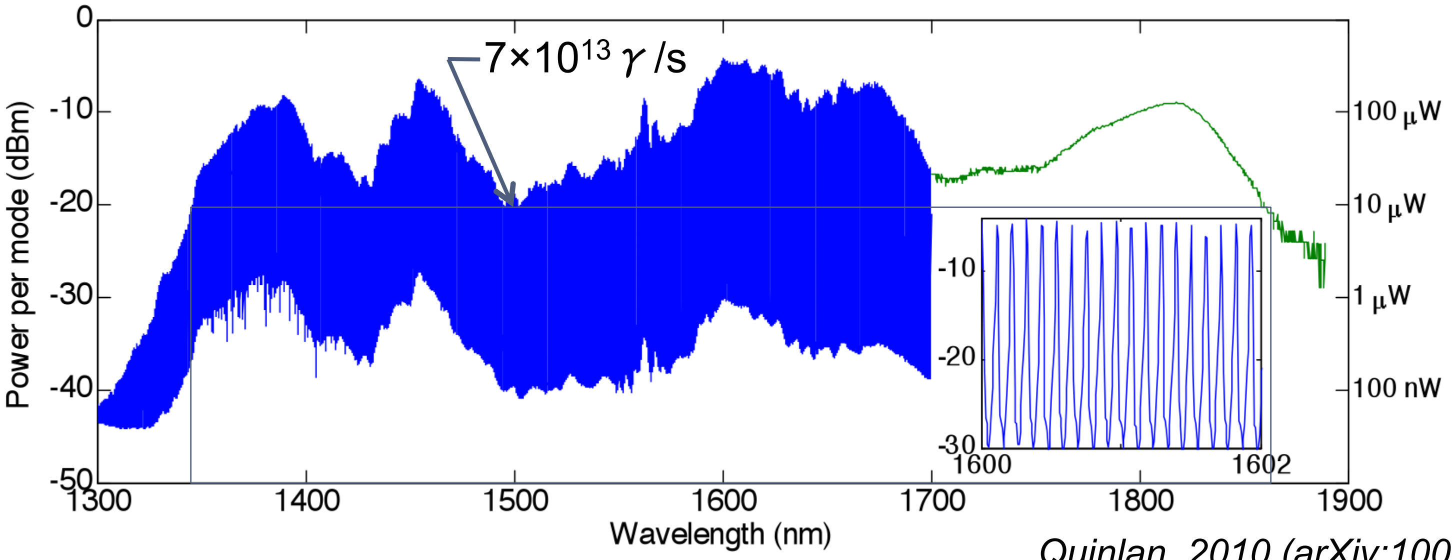
Quinlan, 2010 (arXiv:1002.4354)

Current performance:

- >34dB suppression single cavity, m=50 filter ratio (12.5GHz/250MHz)
- 70nm single cavity coverage (1530-1600nm, defined as >10% of maximum transmission)
- Second cavity in series eliminates HOSM, SMA. >60dB suppression, ~45nm coverage at >0.1mW/mode ($8\times10^{14}\,\gamma$ /sec/mode),

Double filter configuration

HNLF yields >400nm coverage at 12.5 GHz



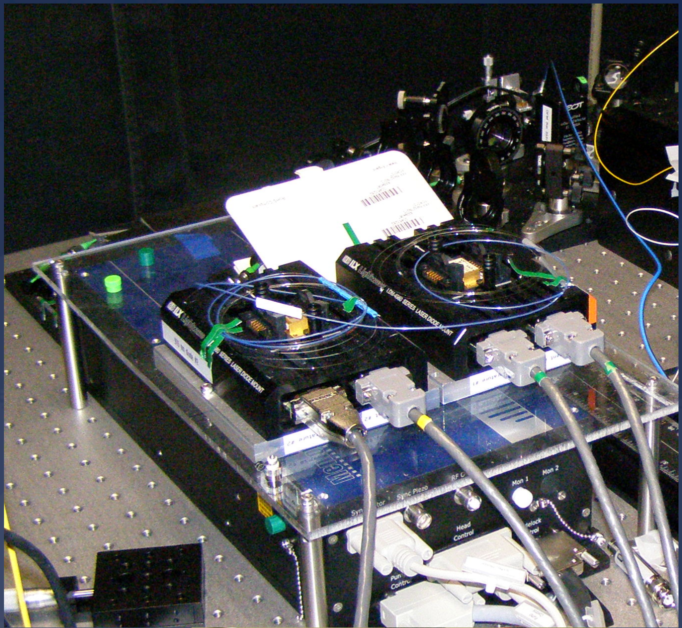
Quinlan, 2010 (arXiv:1002.4354)

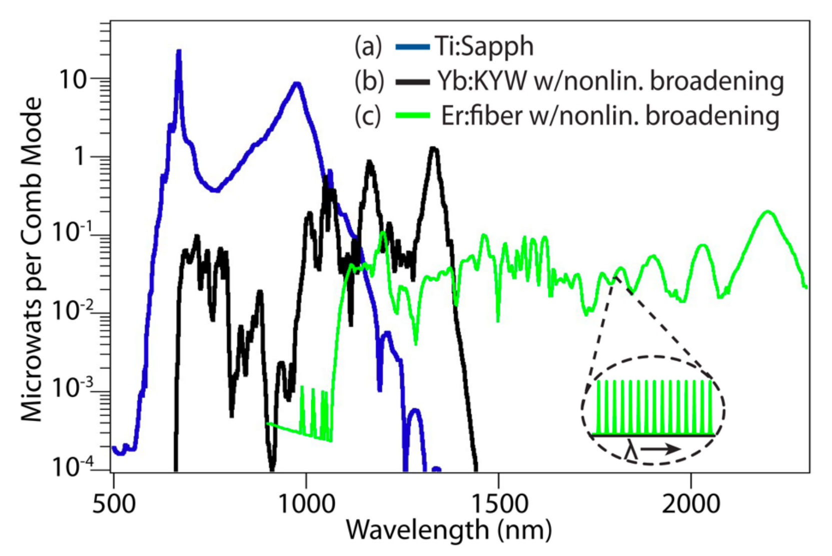
Broadend comb performance:

- 20-40dB side mode supression at 12.5GHz (tested up to 1700nm)
- ~1350 – 1850 nm coverage at > 10 μ W/mode
- Line width ~350kHz, dominated by frequency lock noise (GPSDO)

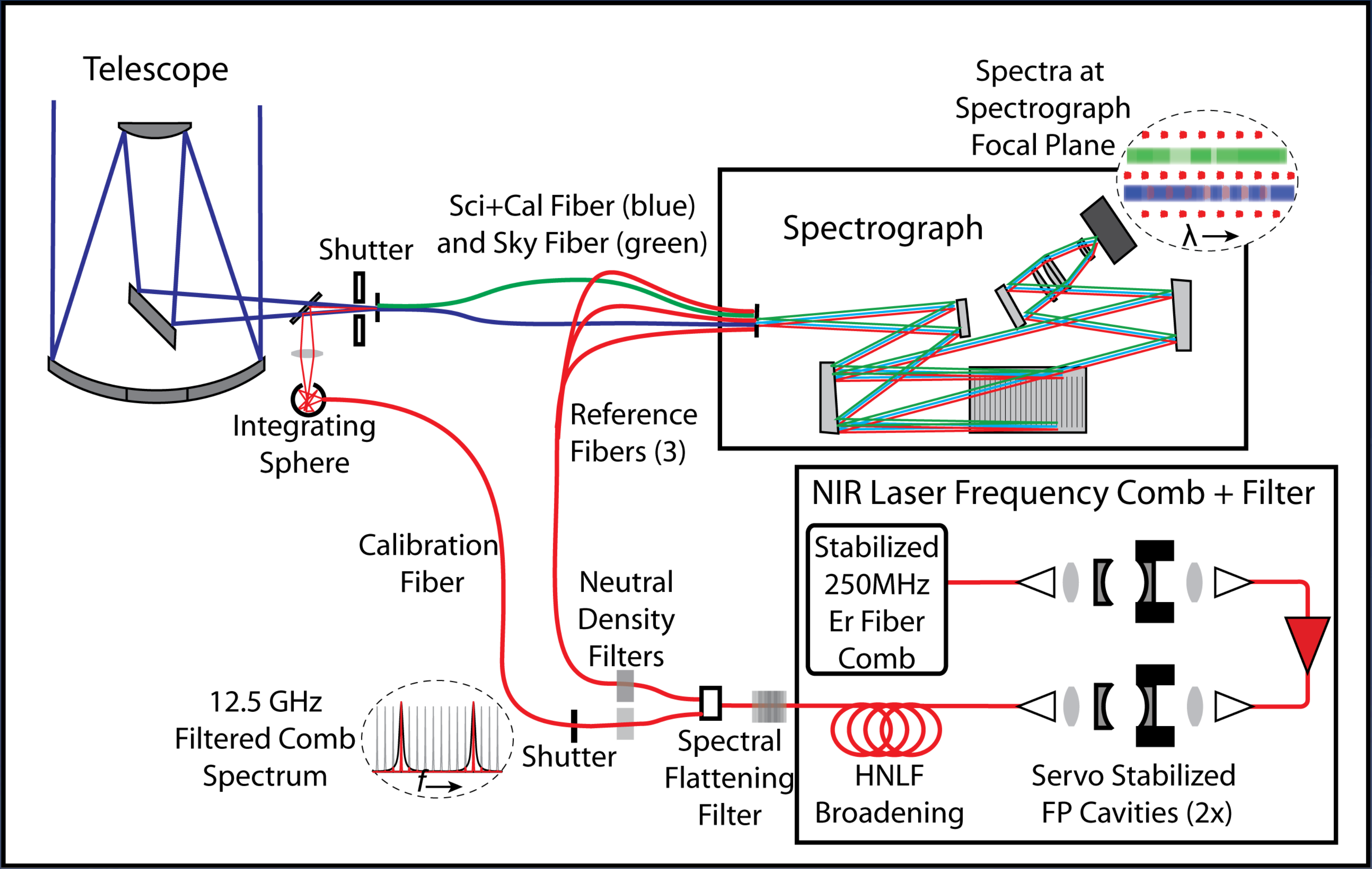
Fiber laser advantages

- Low power requirement
- Compact
- ‘Flight heritage’
- Very stable operation (several days operation without loss of lock)
- Monolithic FP cavities increase stability, reduce footprint , weight

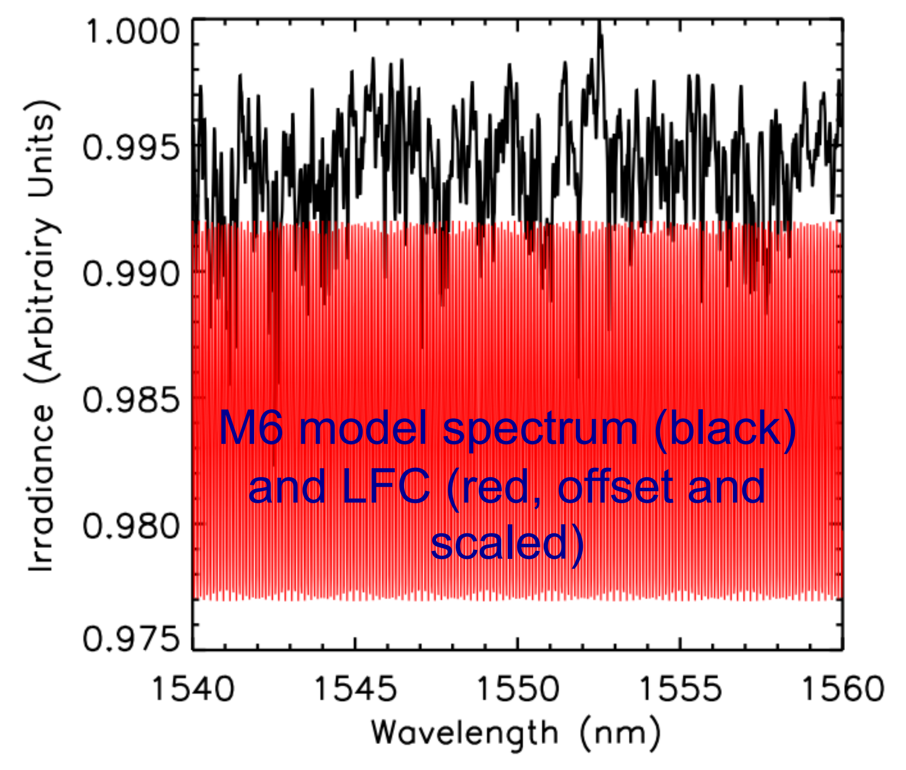




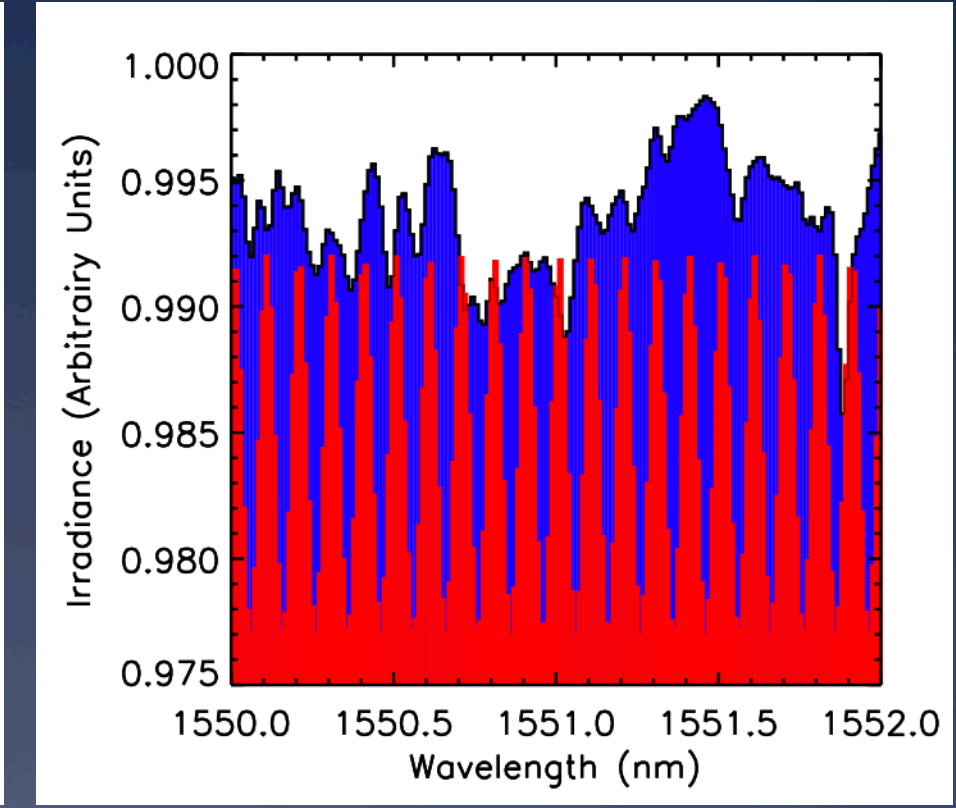
End to End Block Diagram



Frequency Comb: Single order and narrow band simulations



M6 model spectrum (black) and LFC (red, offset and scaled)



- Fiber fed, 55K Res. Spectrograph
- 1.3-2.0 μm band pass single object
- 0.064-.132 μm band pass multi object

- 212-320 comb lines/order
- S/N limited by detector
- 0.15-0.3m/s RV comb precision

Future Plans: IRTF and NIST

- April, 2010: Test comb at NIST/Gaithersburg
  - High resolution FTS with 10^5 dynamic range will allow detailed study of side mode suppression across full band
  - Provide linearity and LSF data for FTS
- August, 2010: Transport comb to IRTF for testing with CSHELL instrument
  - Test comb in parallel with absorption cell
  - Characterized CSHEL stability
  - Observation of RV standard
- IRTF Semester 2010B: Follow-up observations

Summary – what we get

- Broad-band, high-precision, NIR spectroscopy is possible
- Could be packaged for SOFIA – resulting in unique coverage, reduced telluric imprint
- Would open up new lines of enquiry
- Critical technologies all in place, but not all with adequate TRL

The End