Grism spectroscopy with FORCAST

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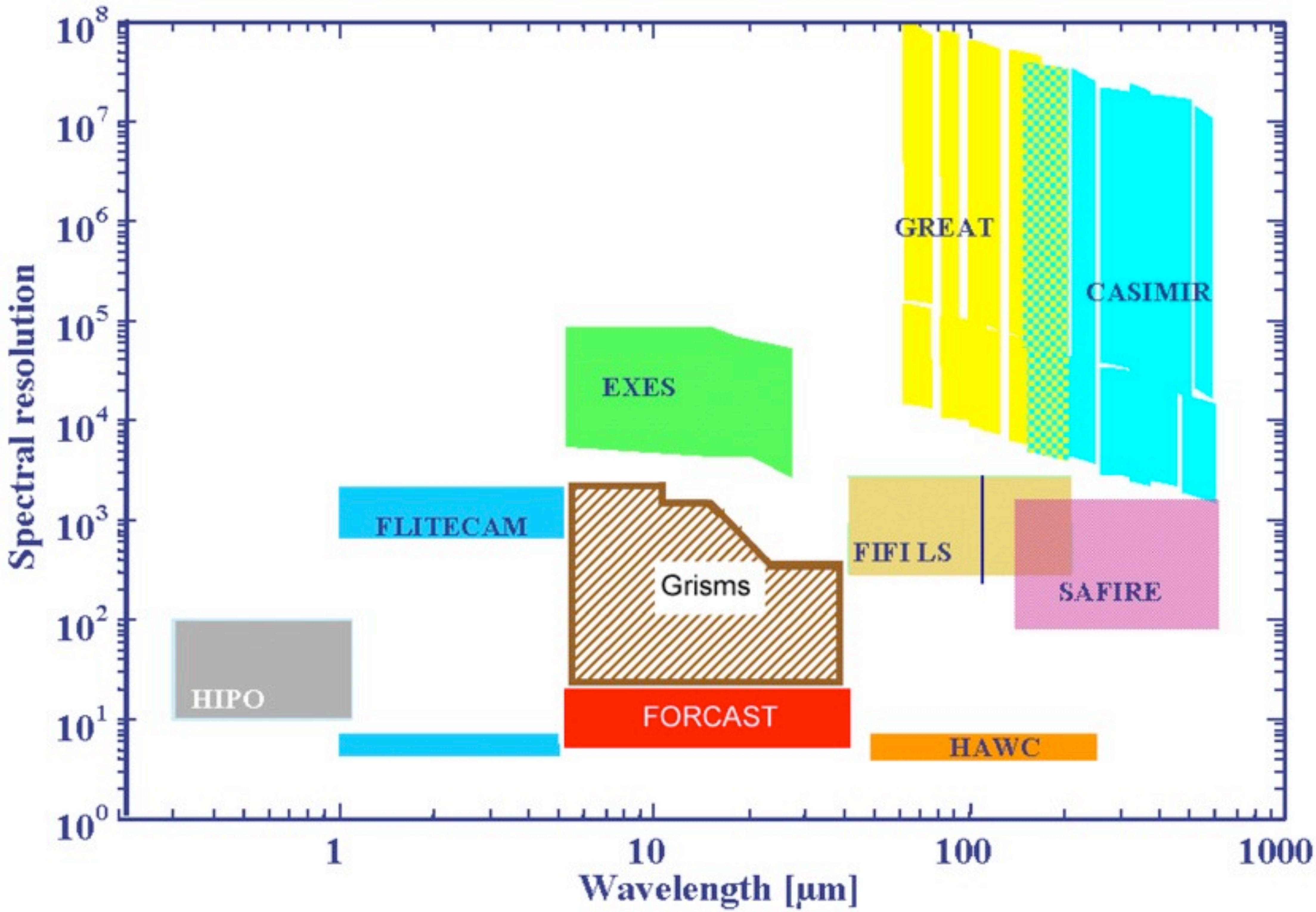
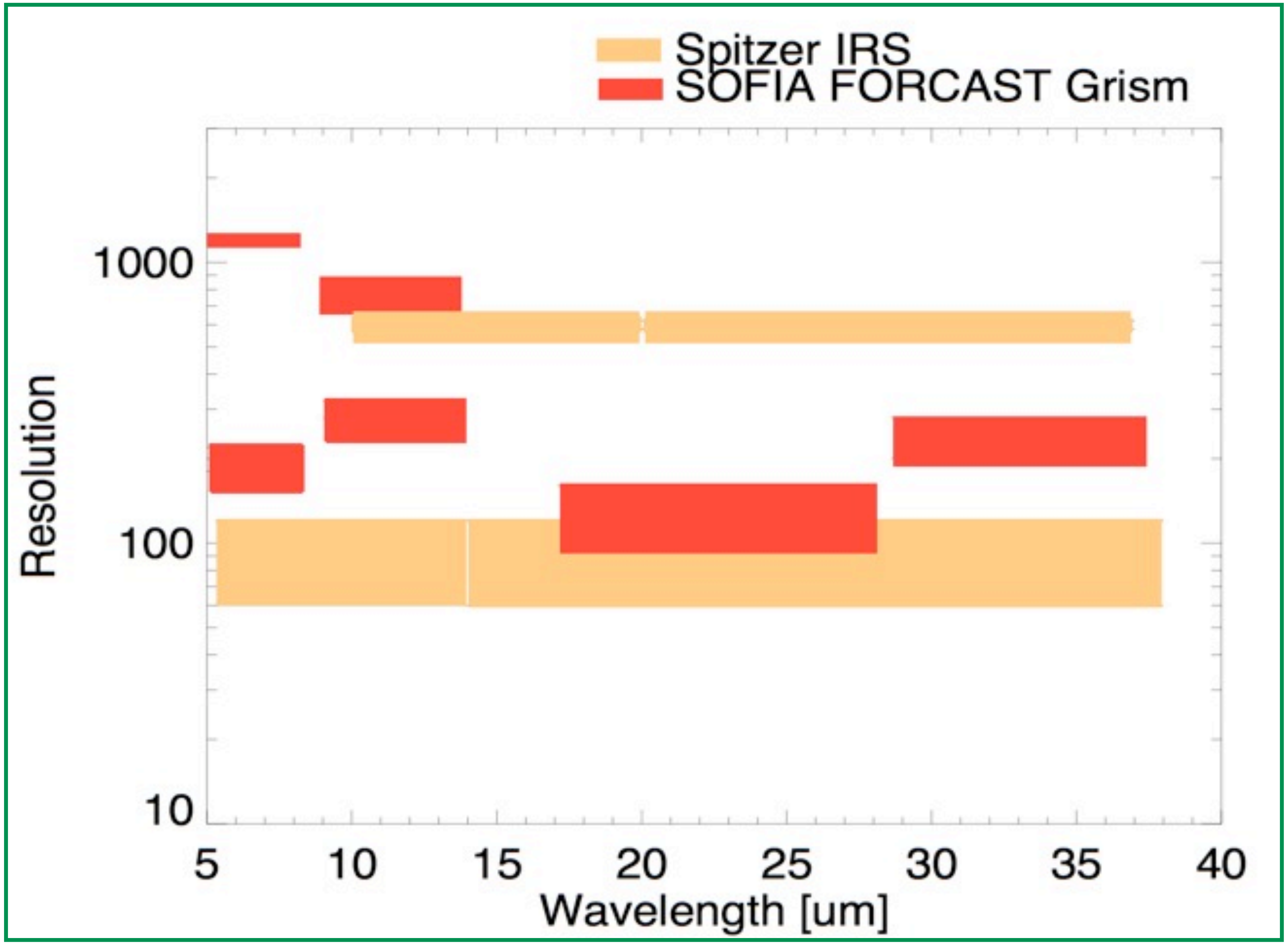
FORCAST grism spectroscopy will fill a current gap in the observational capabilities of SOFIA



FORCAST grism spectroscopy compared to Spitzer



Circumstellar dust

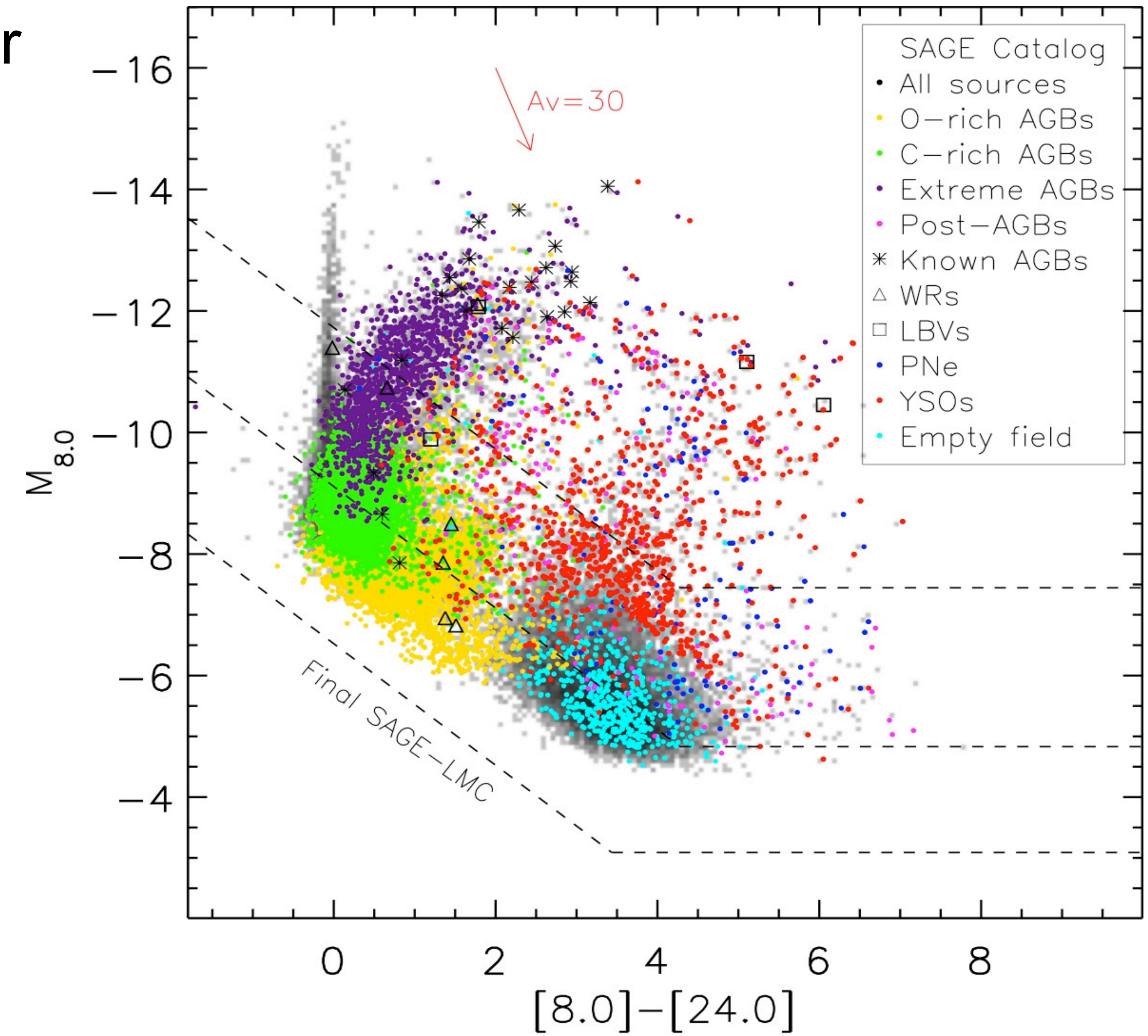


Figure 3-6. *Infrared color-magnitude diagram of stars in the nearby galaxy, the Large Magellanic Cloud, obtained by the SAGE Spitzer Legacy Program (Blum et al. 2006; Meixner et al. 2006). Different classes of objects – indicated by different color symbols –segregate into different parts of this diagram due to differences in dust composition and spectral characteristics, while their distribution reflects intrinsic variations in mass-loss rates. The GAIA mission will provide accurate distances for stars in the Milky Way and this will enable similar color-magnitude diagrams for our own galaxy. The dashed lines indicate the SAGE photometry limits for the LMC and the predicted sensitivity limits (10 σ in 900 sec) for FORCAST in the GRISM mode for these types of objects at 3 and 10 kpc, respectively, in the Milky Way. Figure is courtesy of M. Sewilo & SAGE team.*

Life cycle of dust

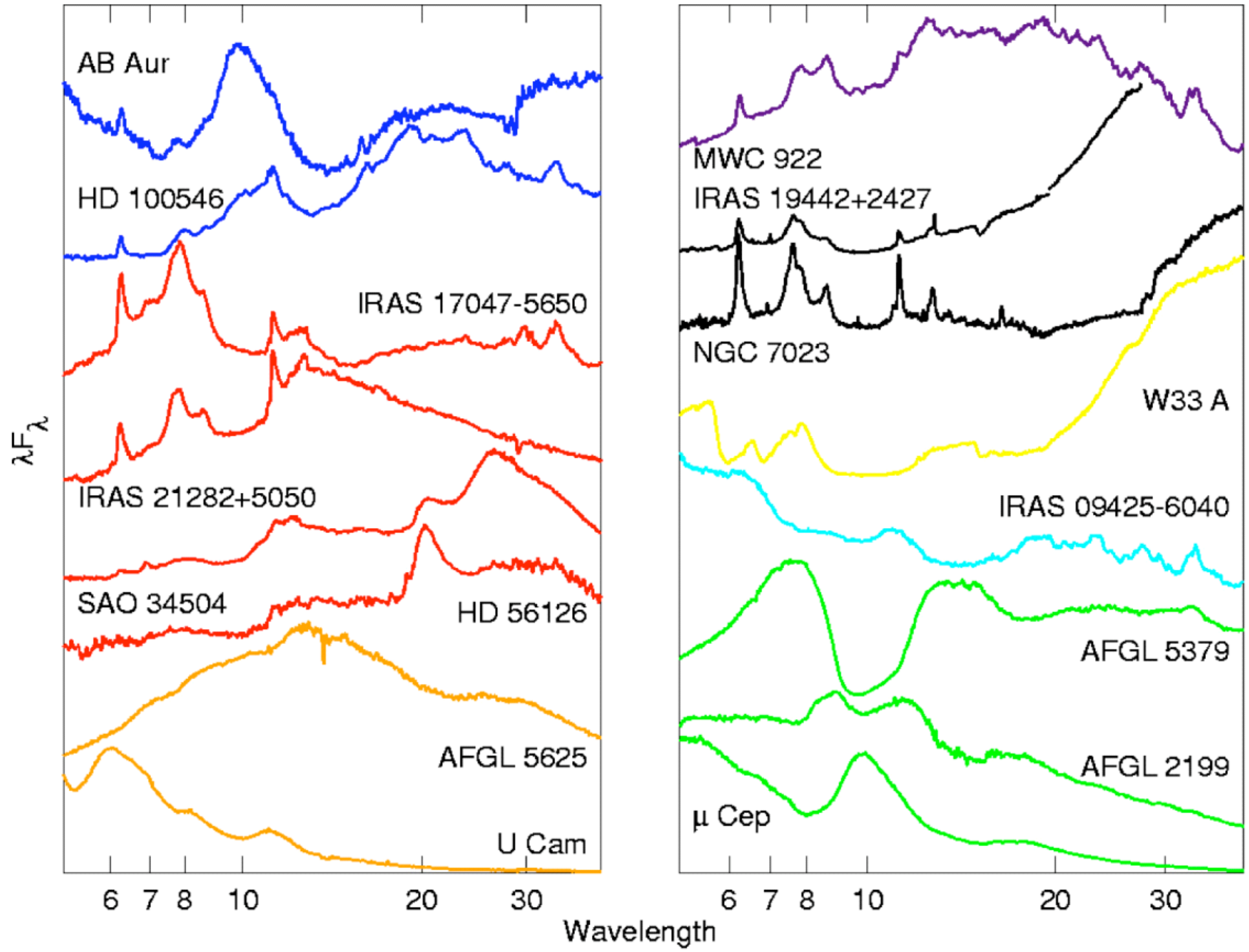
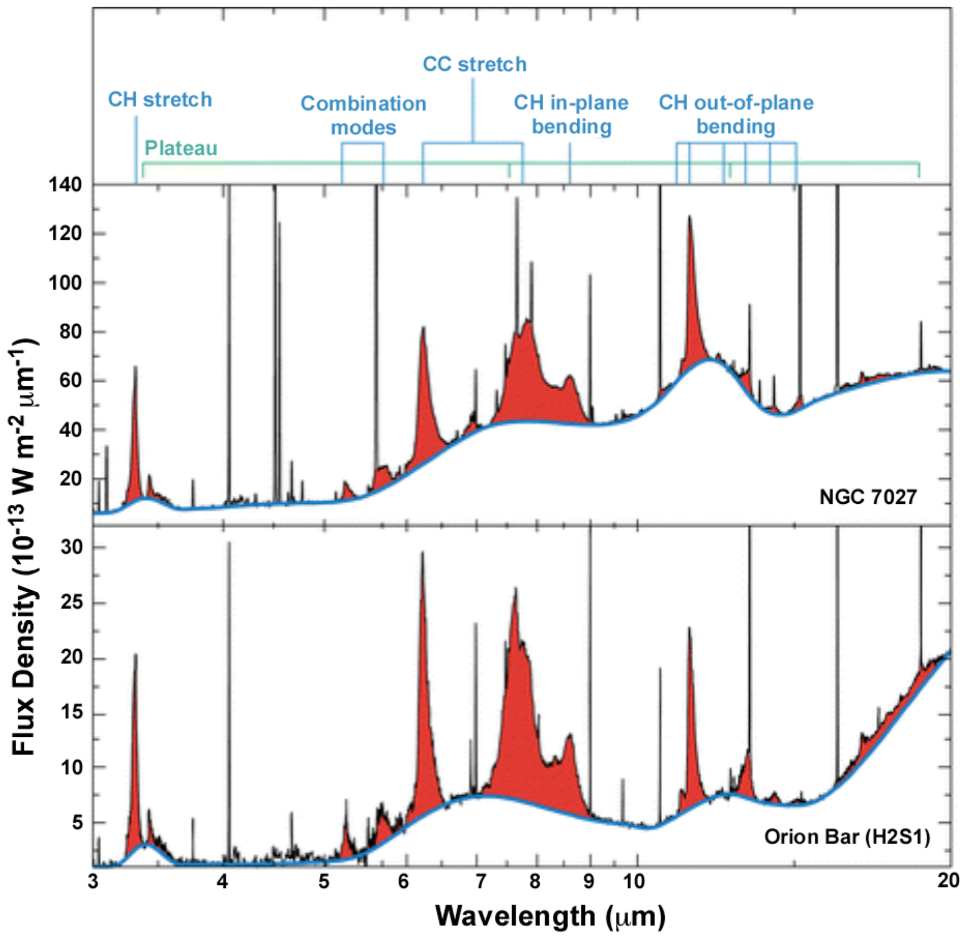


Figure 3-5. *The rich and spectrally diverse stardust revealed by ISO and Spitzer requires systematic study. A selection of ISO SWS spectra of a variety of objects shown here illustrates the rich spectral diversity of the dusty Universe . Key: dark blue: Herbig AeBe; red: post-AGB and PNe; orange: C-rich AGB; green: O-rich AGB; light blue: mixed chemistry AGB; yellow: deeply embedded YSO; black: HII region/reflection nebula; purple: mixed chemistry post-AGB.*



ISM: PDR environmental characteristics

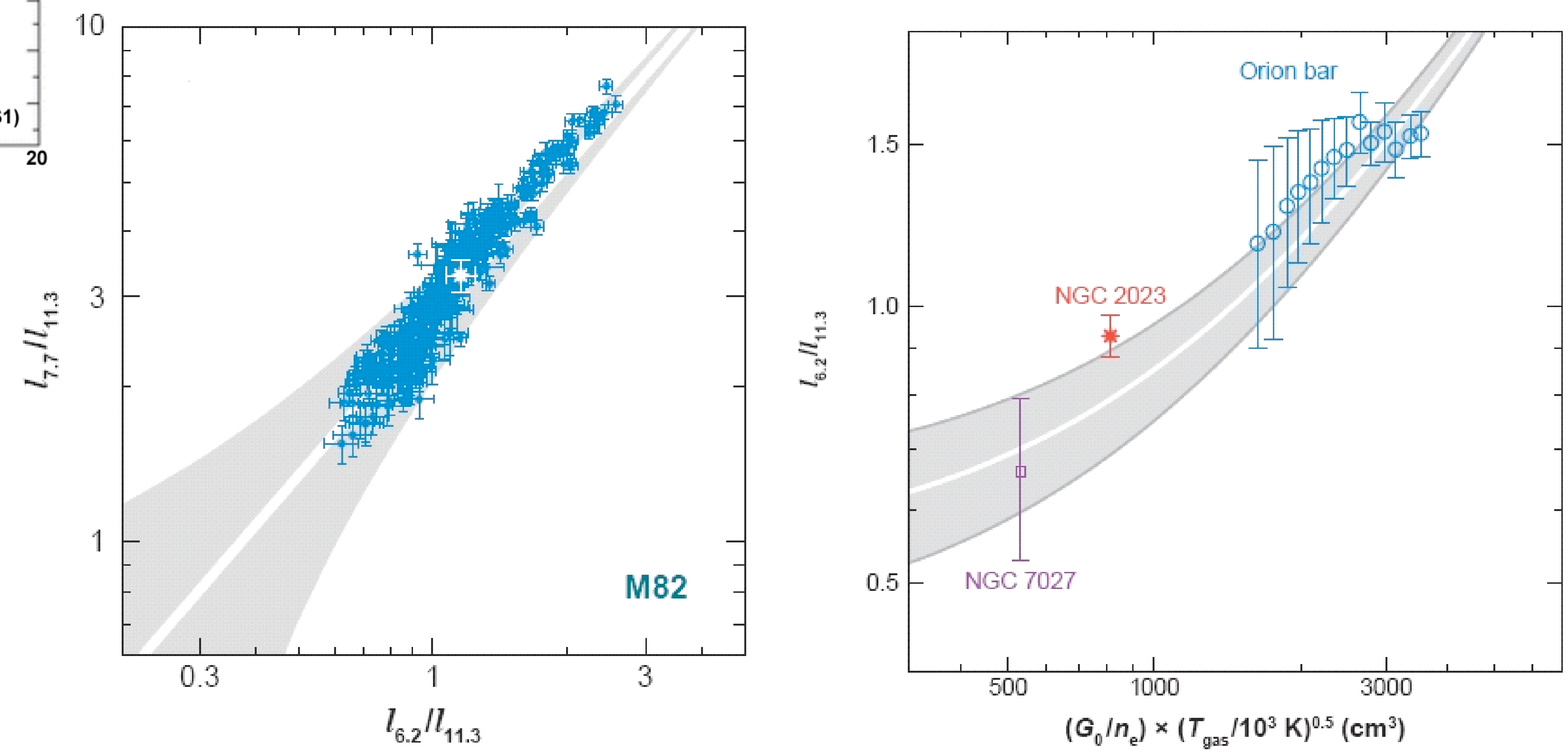
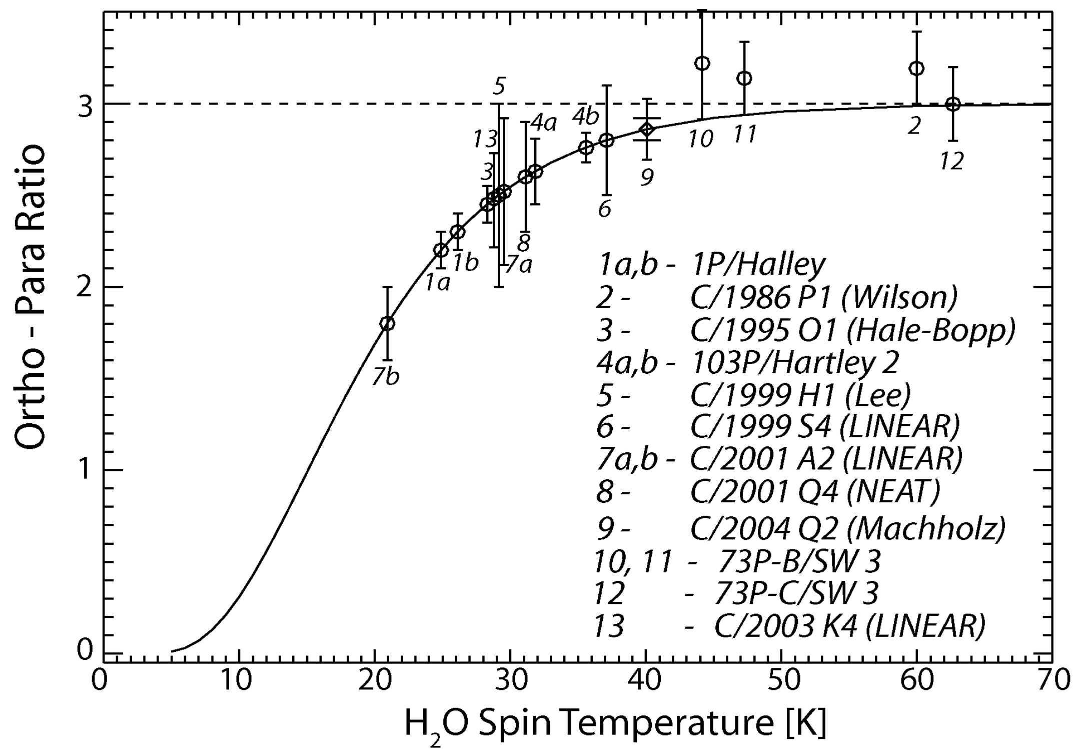


Figure 3-4. *Left panel: Variations in the relative strength of the 6.2, 7.7, and 11.3 μm PAH bands observed in the starburst galaxy, M82 (Galliano et al., 2008). As these data illustrate, the 6.2 and 7.7 μm bands – due to PAH cations – vary relative to the 11.3 μm band – due to neutral PAHs – by a factor of 4 in this data set. Similar variations are observed in many other sources. Right panel: The observed ratio of the 6.2 to 11.3 μm band – a measure of the ionization balance of PAHs is related to the physical conditions in a few well-studied PDRs through the ionization parameter,* $G_o T^{1/2}/n_e$*, a measure of the ionization rate over the recombination rate (Galliano et al. 2008).*

Solar system: comet chemistry and mineralogy



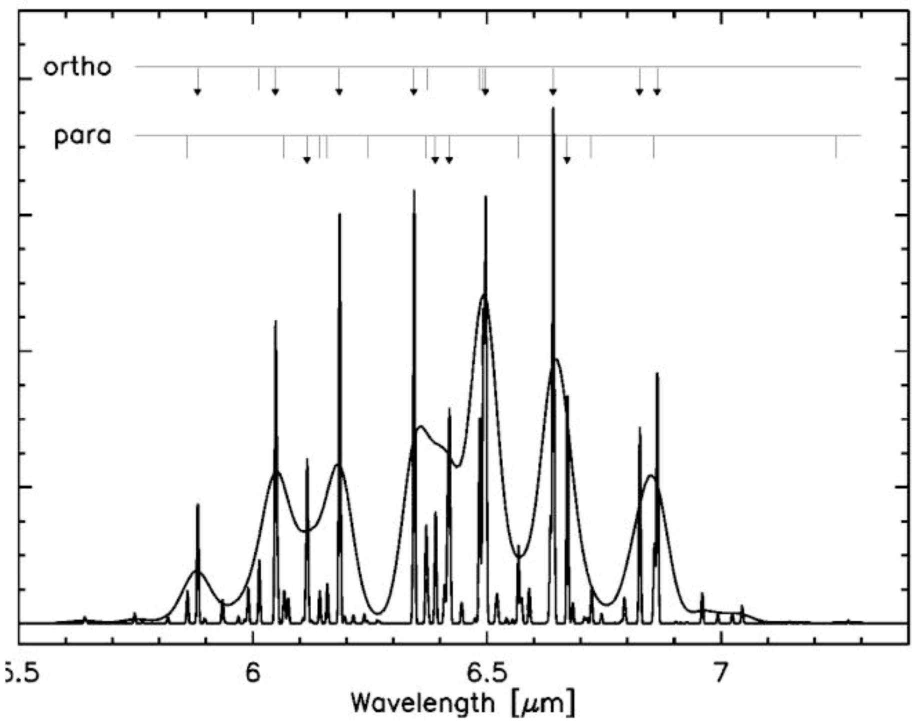


Figure 5-3. *(Left): Ortho-para ratios for H_2O in comets (Bonev et al. 2007) placed on a theoretical curve connecting them to the corresponding formation temperature. (Right): The 6.5 μm H_2O band in comet K4, both fully resolved and also convolved to the resolution of Spitzer (Woodward et al. 2007). Ortho and para lines are indicated. EXES on SOFIA would provide major improvement in the detection limits by resolving lines of each spin isomer, and eliminating spectral confusion from interloping lines.*

Solar system: planetary atmospheres

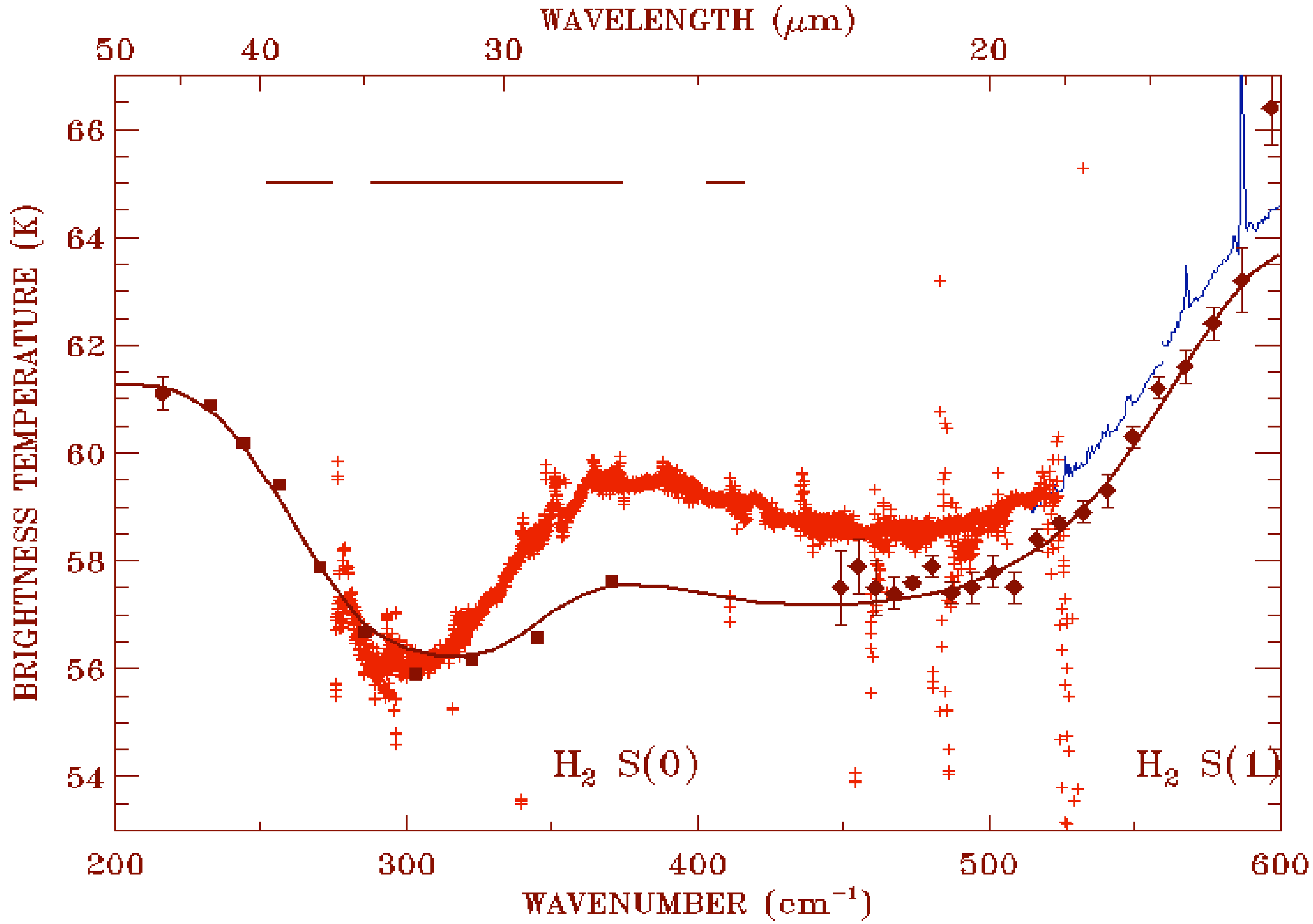
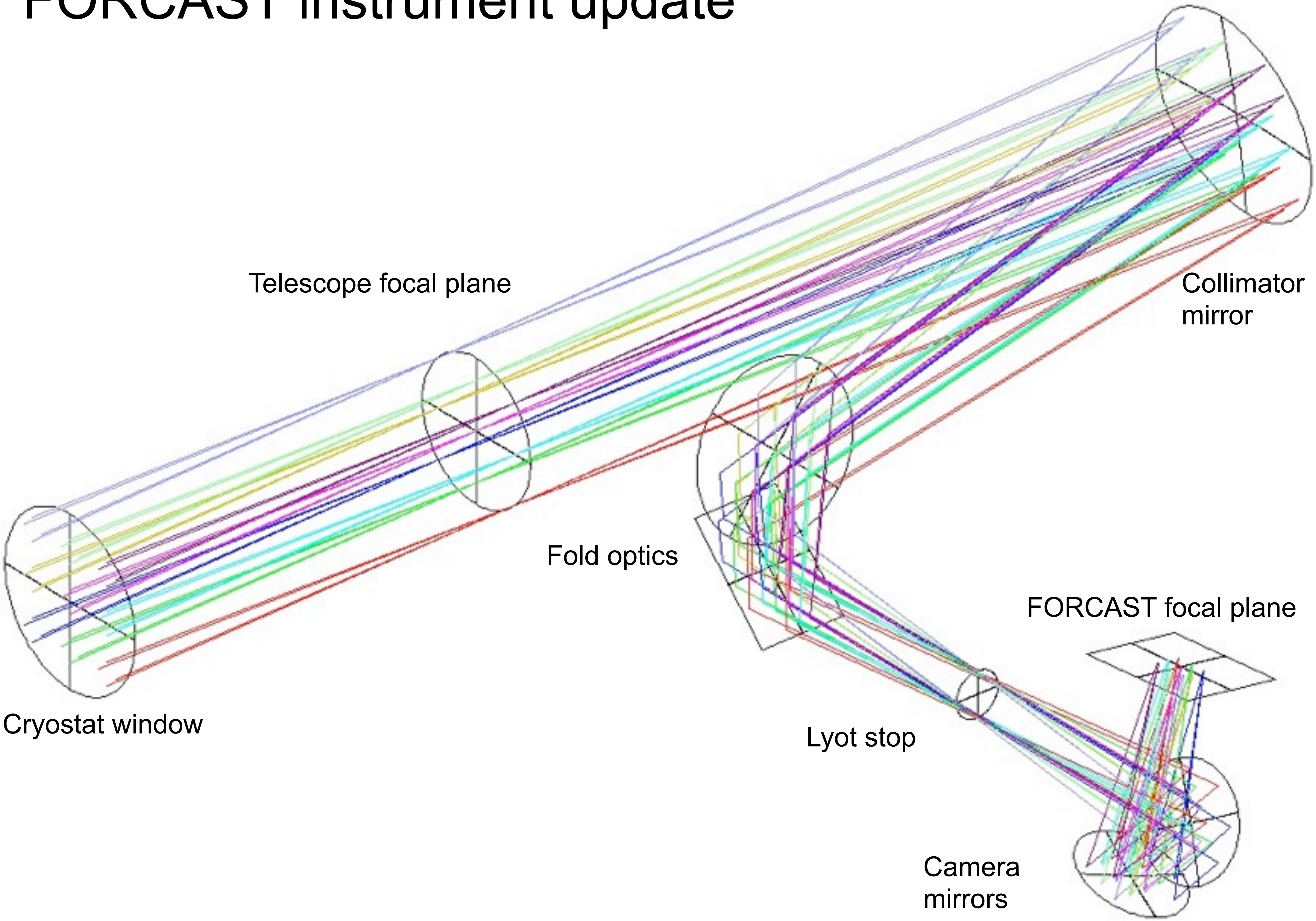
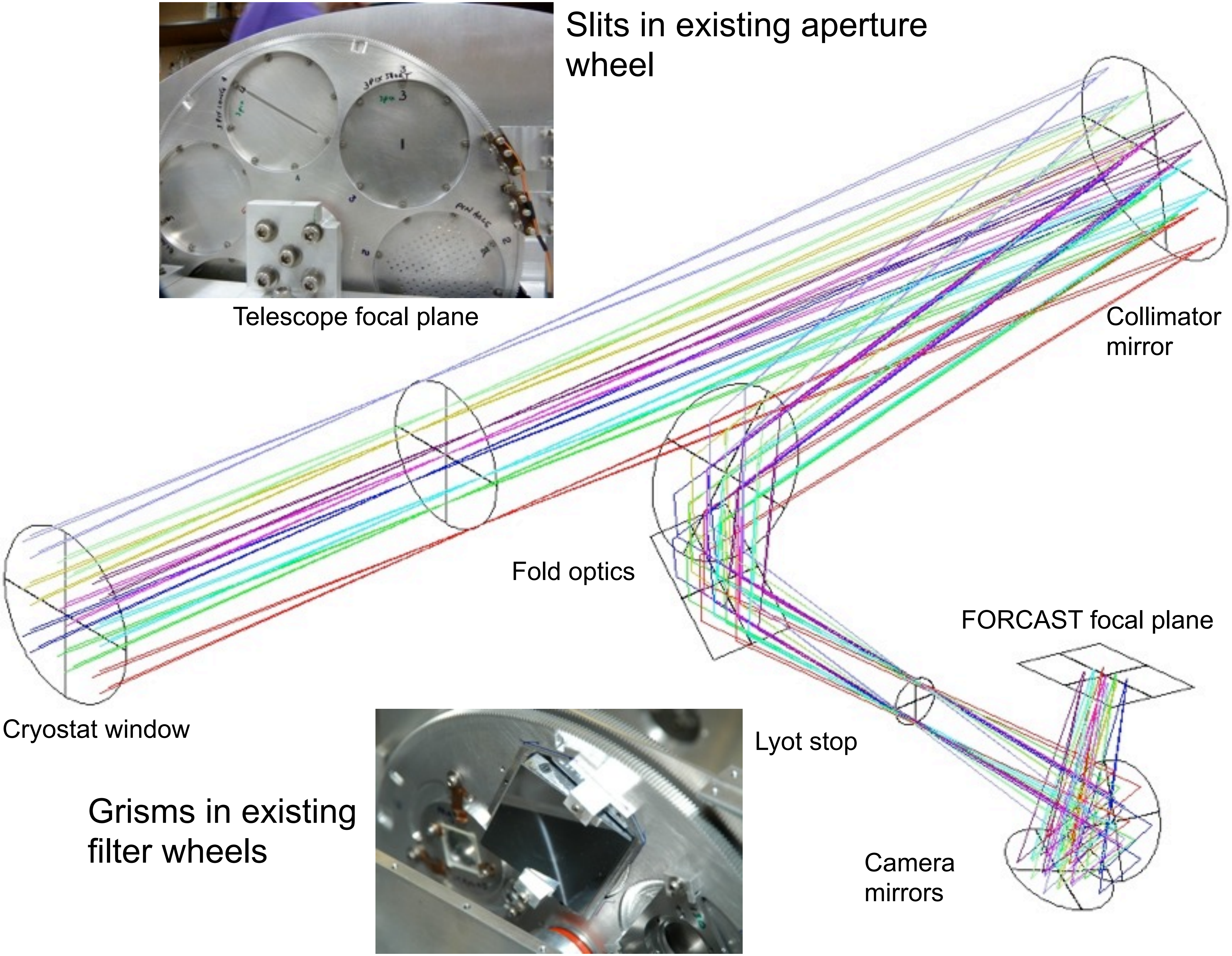


Figure 5-6. *Spectrum of Neptune in the difficult and important mid-IR region unique to SOFIA. The locations of the emission cores of the broad H_2 collision-induced S(0) and S(1) rotational lines are also indicated. Spitzer IRS LH spectral data are red crosses, and SH spectra are the blue lines. A model fitting ground-based data from the 1980s (Orton et al. 1987, diamonds) plus ISO LWS (filled circle) and SWS (filled boxes) data are also shown. Spectral ranges covered by SOFIA FORCAST's 38.0, 30.0, and 24.4 μm broadband filters are shown schematically at the upper left.*

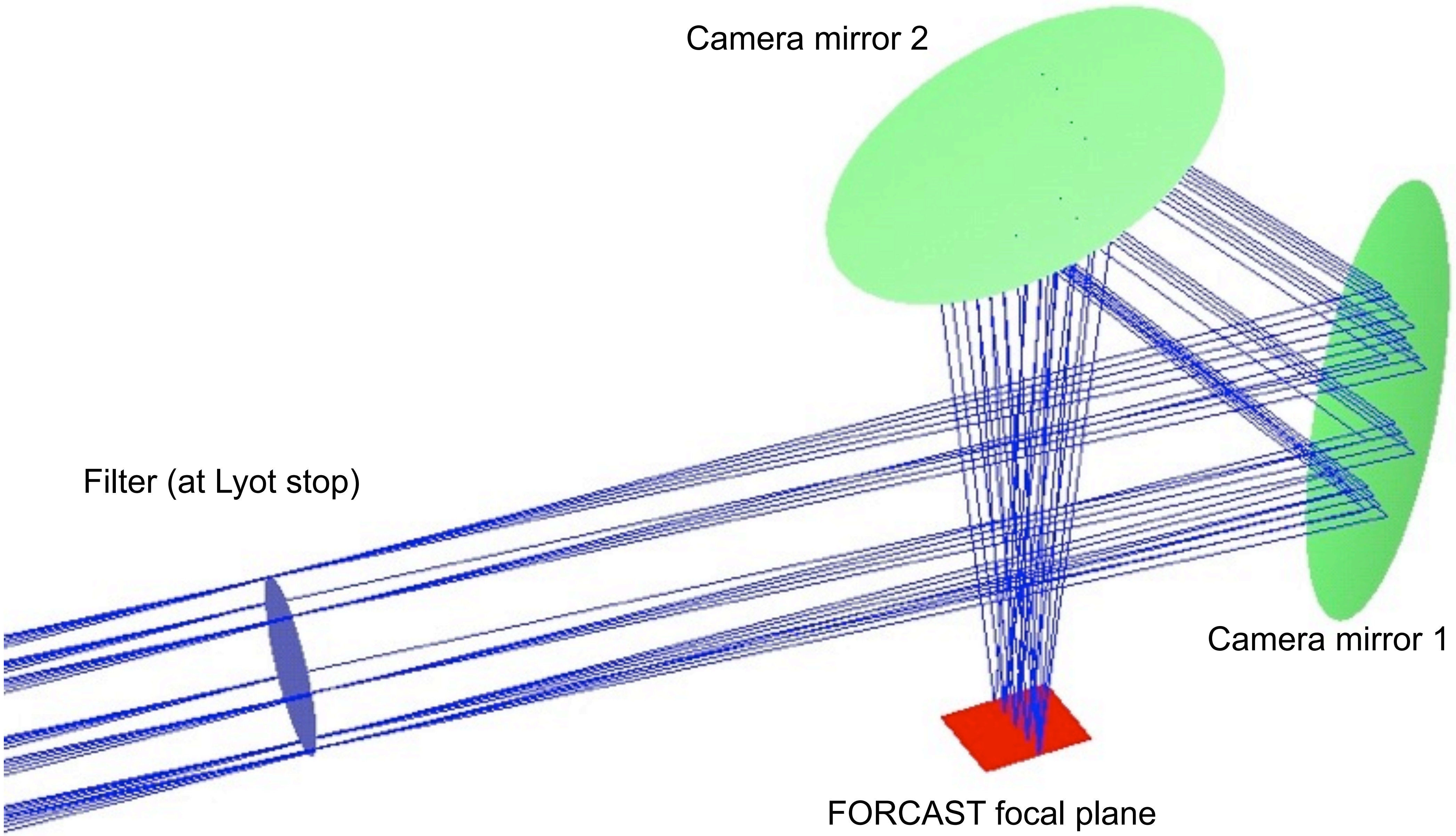
ITHACA PHYSICS

FORCAST instrument update

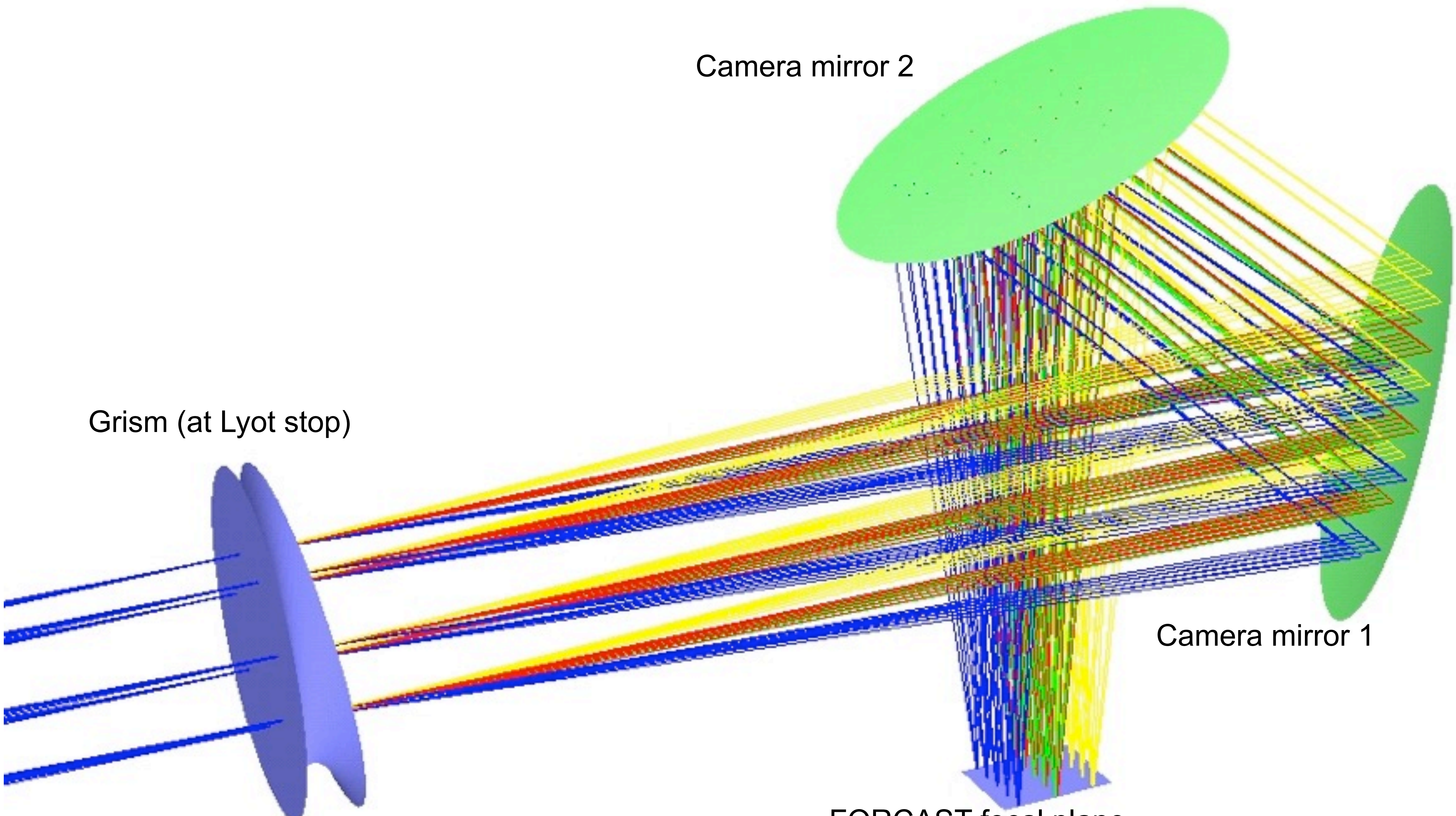


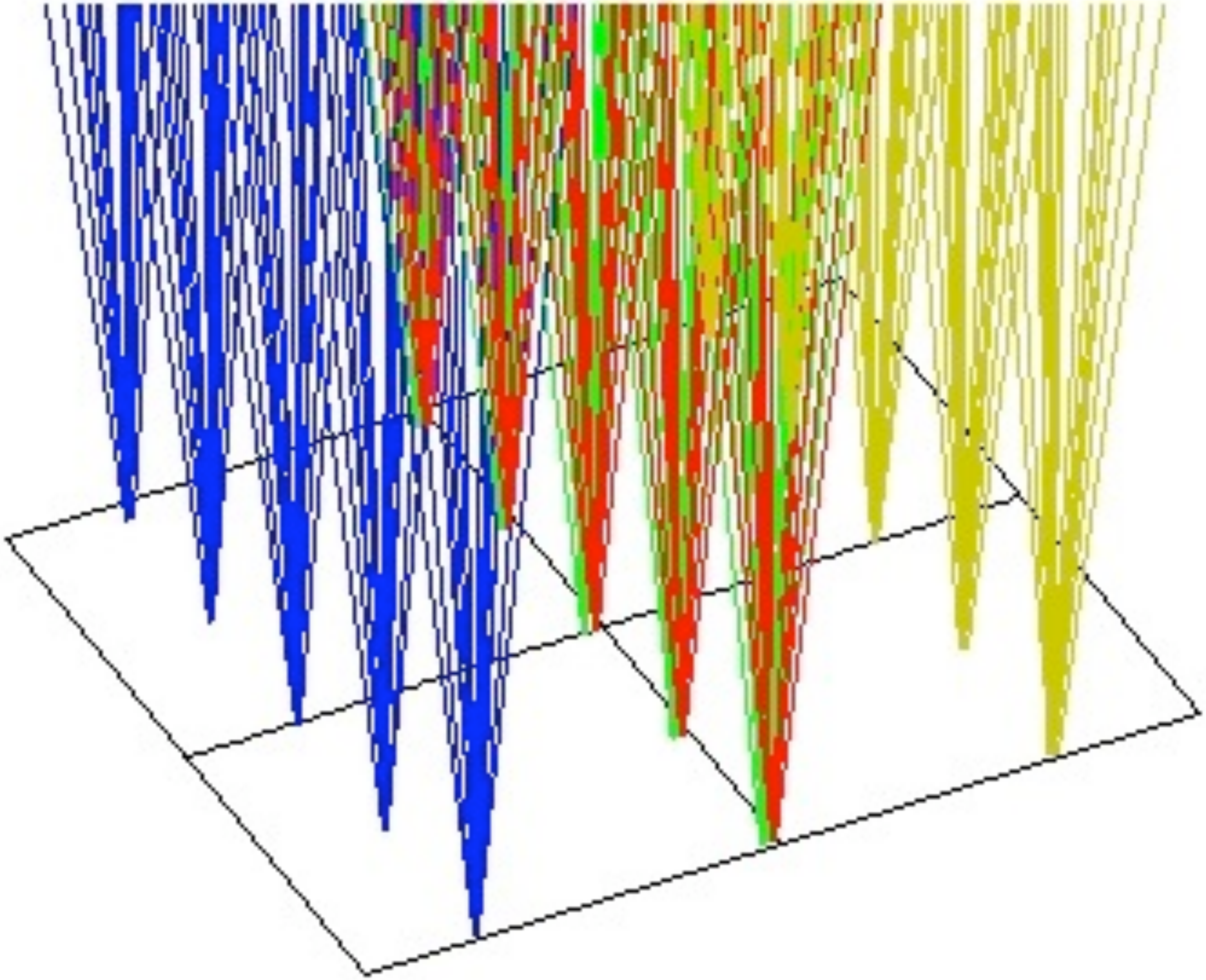

Slits in existing aperture wheel
Telescope focal plane
Collimator mirror
Fold optics
FORCAST focal plane
Cryostat window
Lyot stop
Grisms in existing filter wheels
Camera mirrors

FORCAST instrument update: pupil (with imaging filter), camera, and focal plane



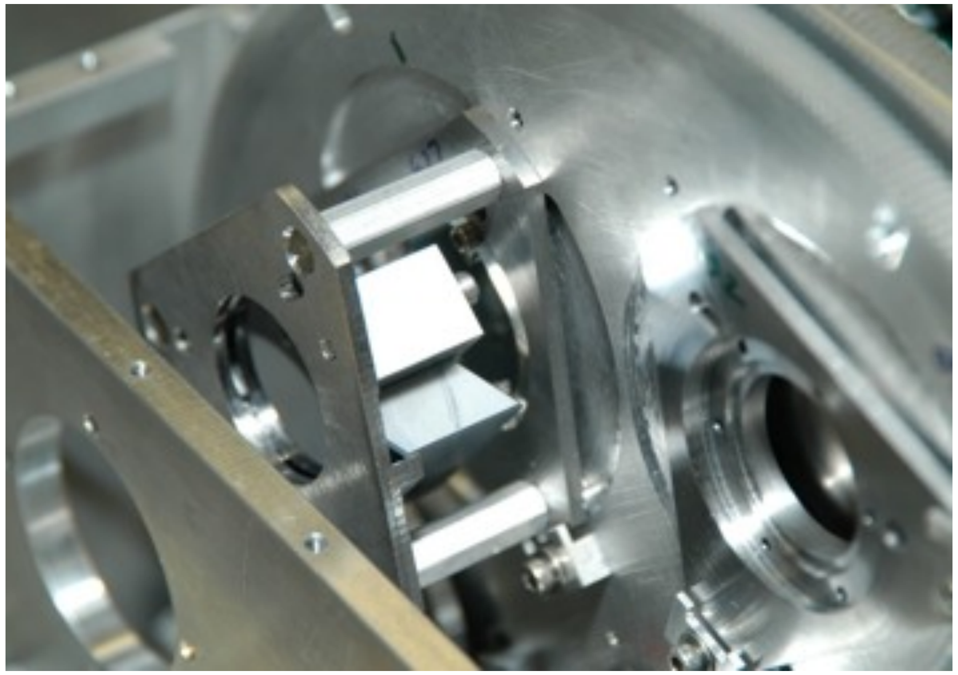
FORCAST instrument update: imaging pupil (with grism), camera, and focal plane



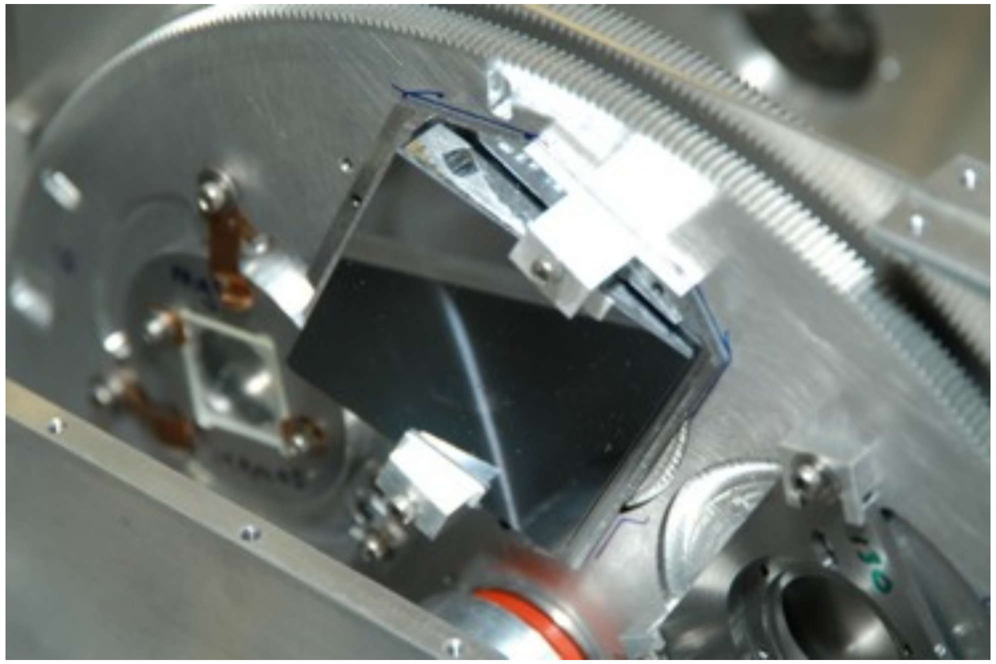


FORCAST focal plane with grism raytrace

FORCAST Grism hardware is finished and testing of all grism modes in FORCAST is done

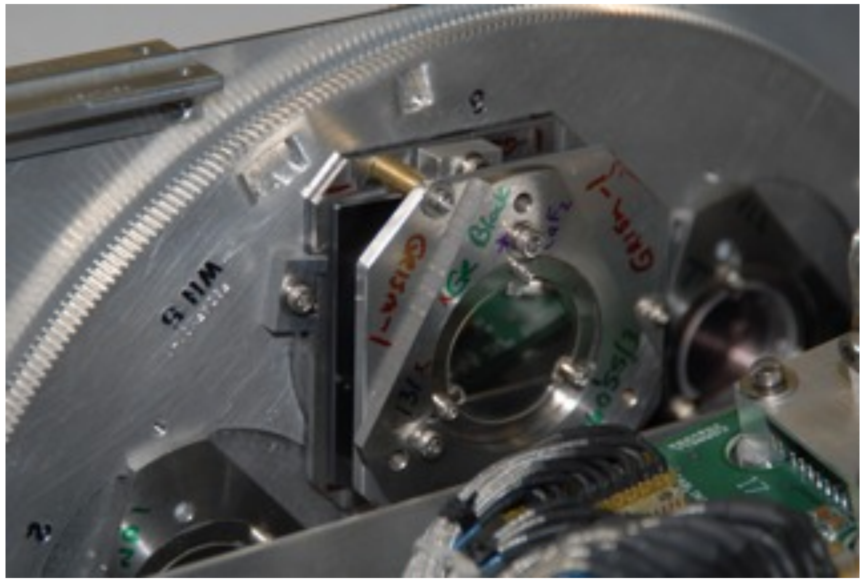


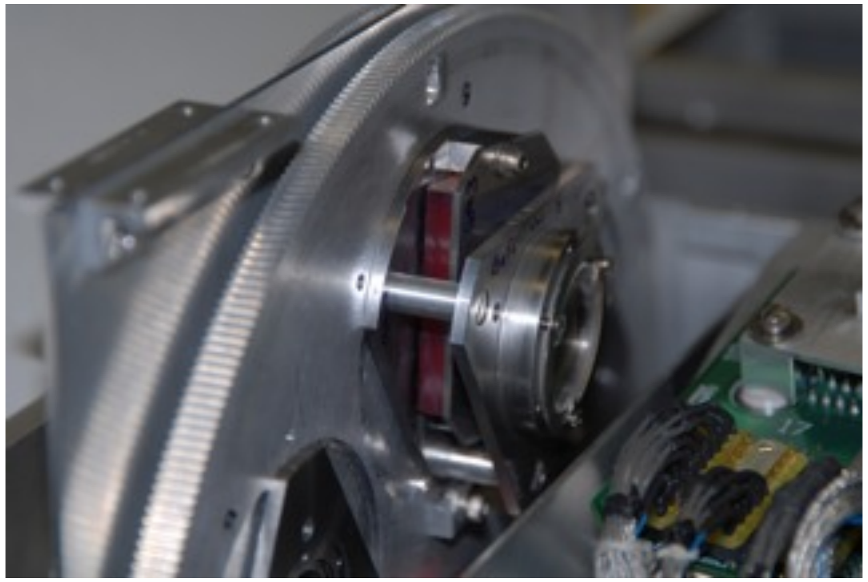
4.9 - 7.8 μm grism in FORCAST short-wavelength filter wheel

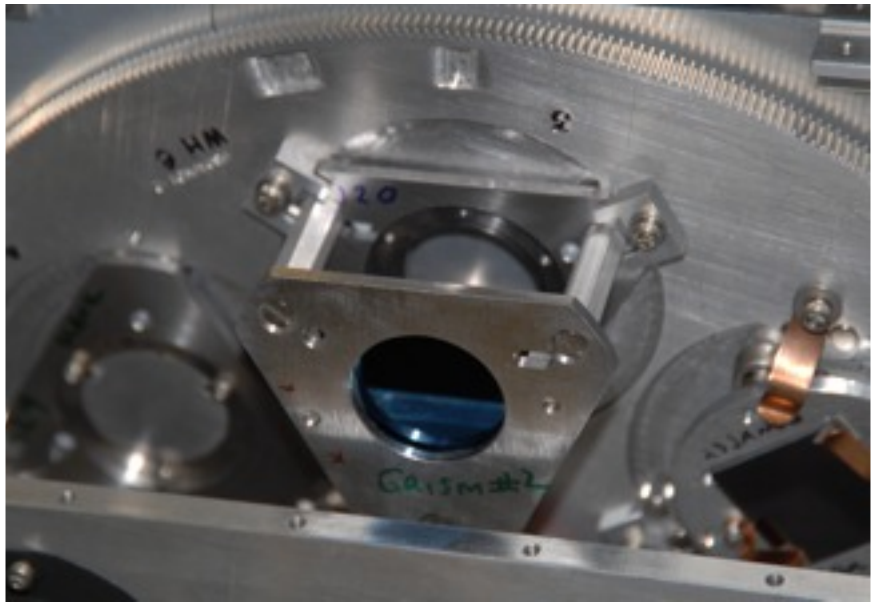


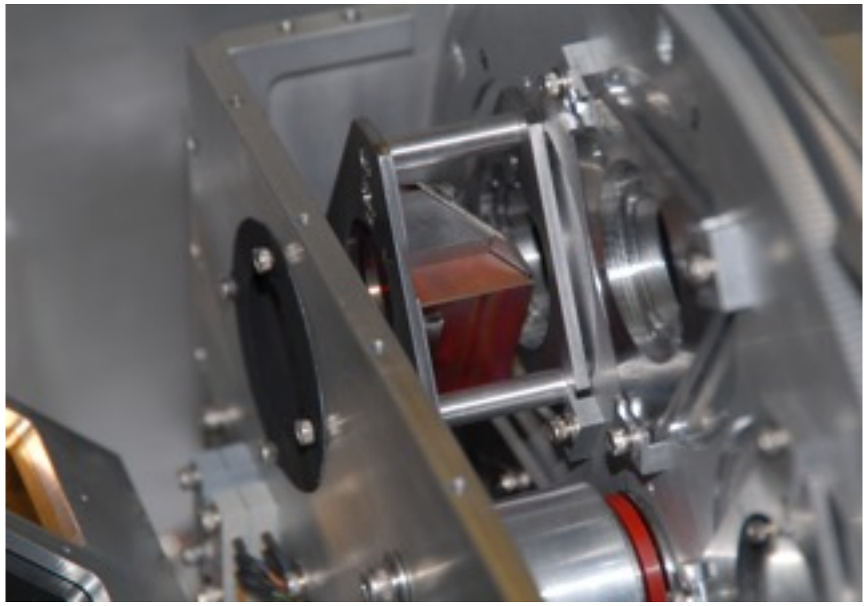
17 - 28 μm grism in FORCAST long-wavelength filter wheel

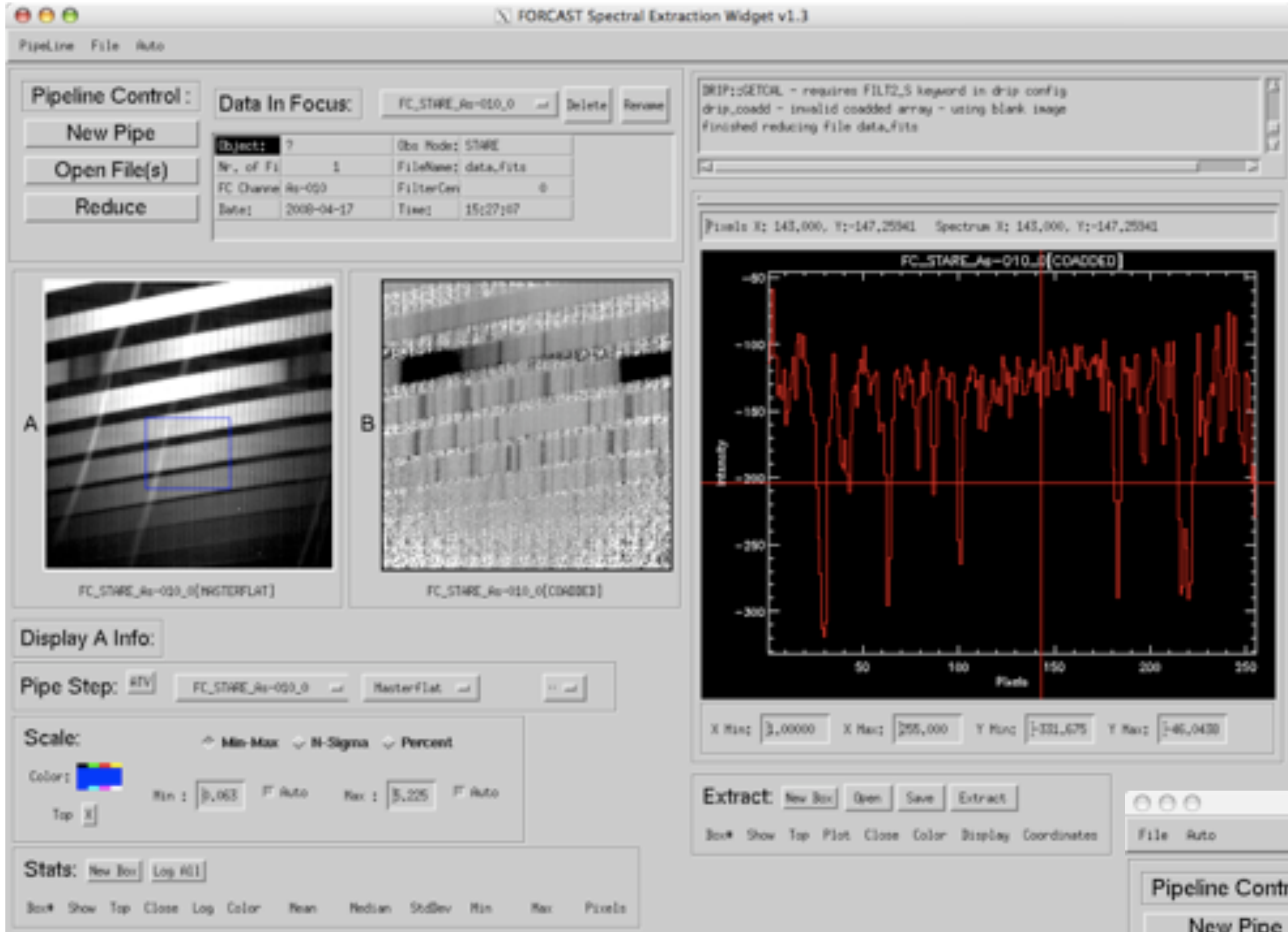
FORCAST Grism hardware



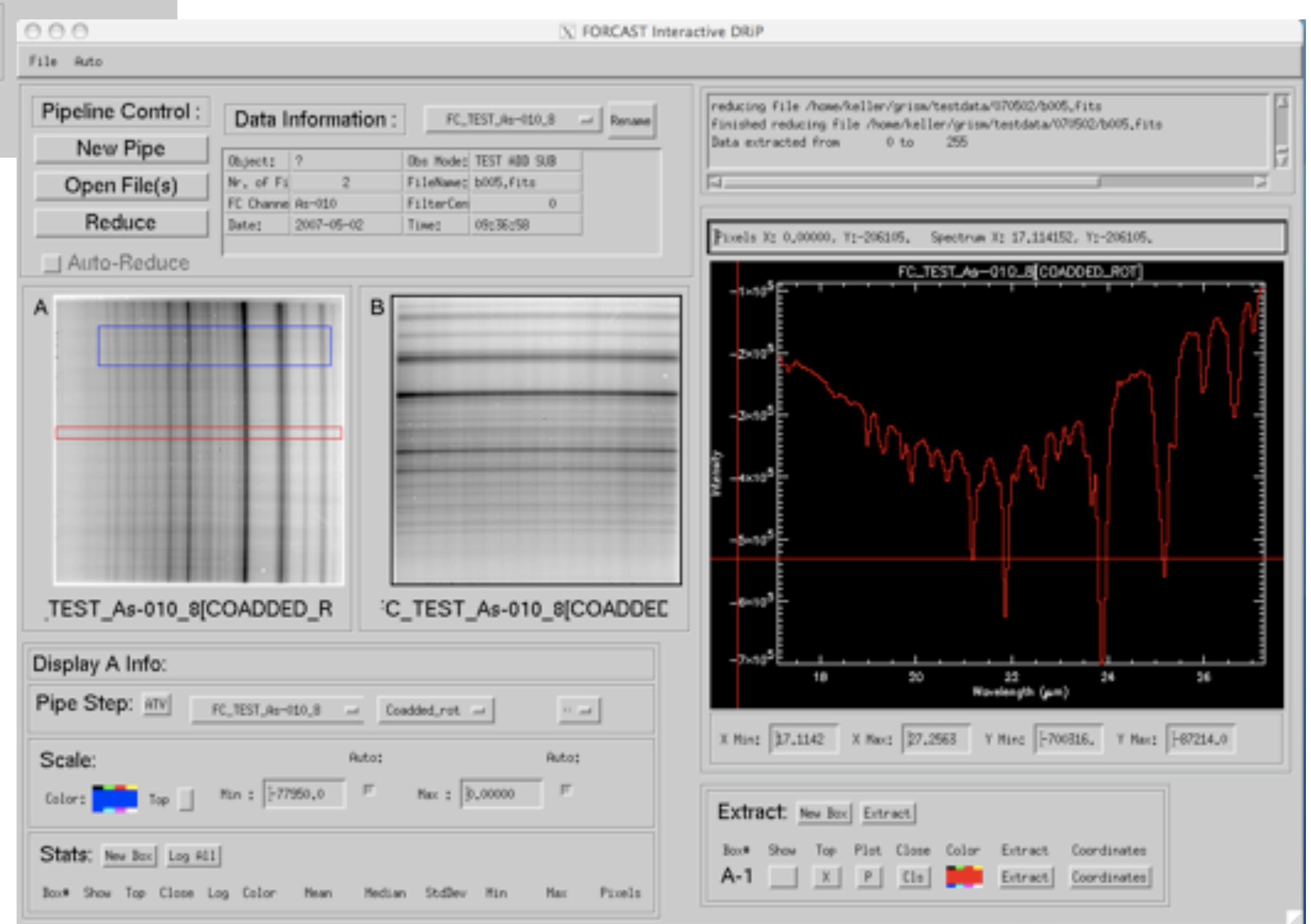




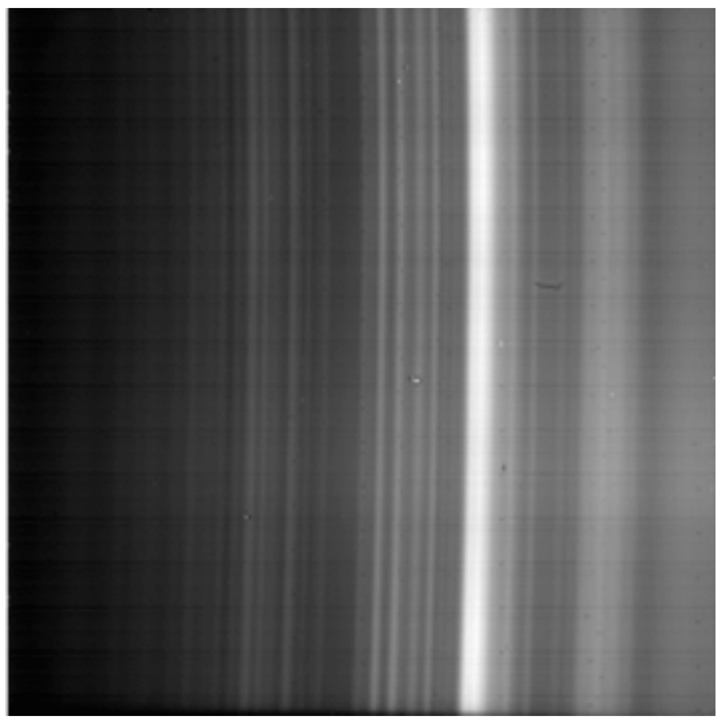


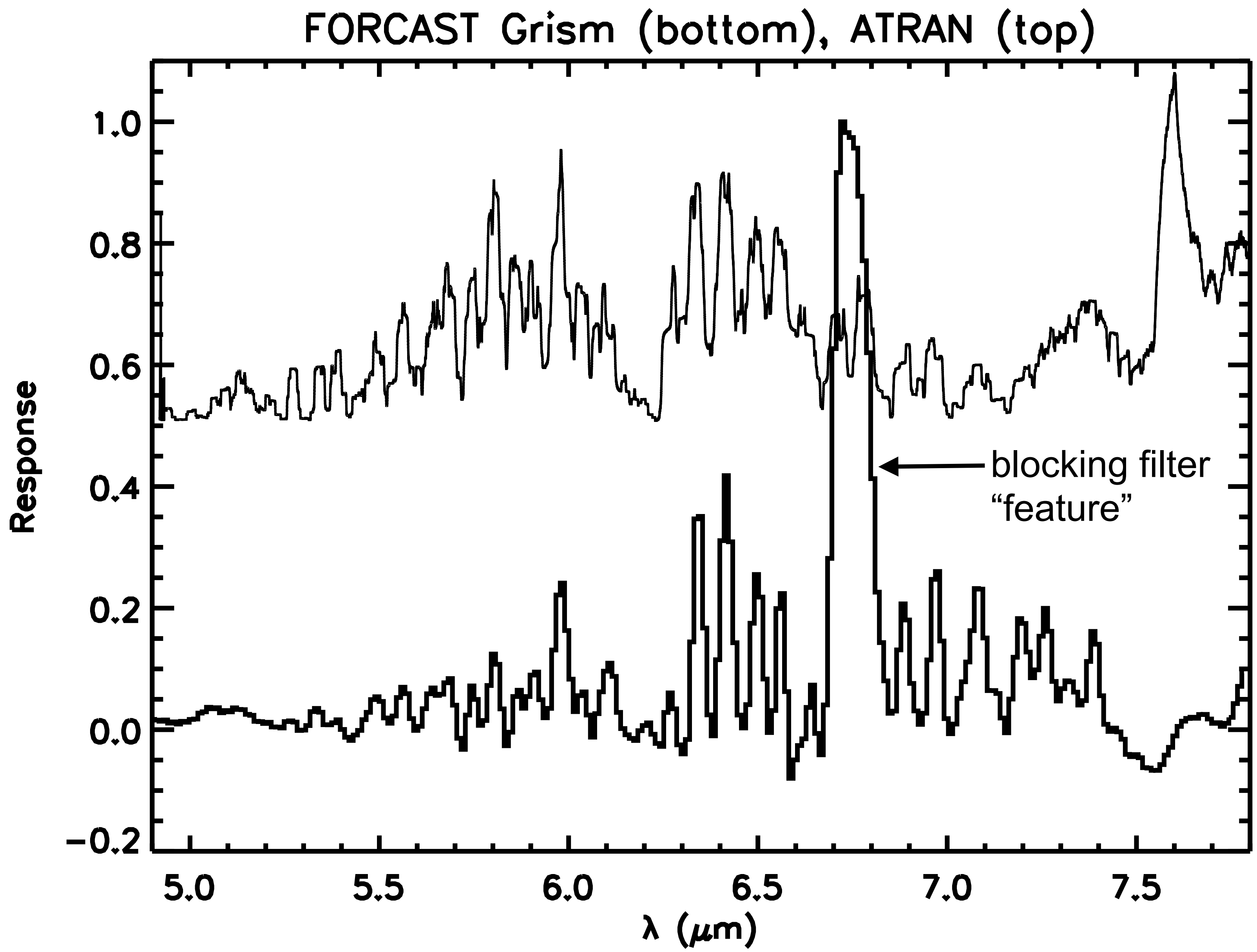


Data reduction and analysis software are finished and testing is under way



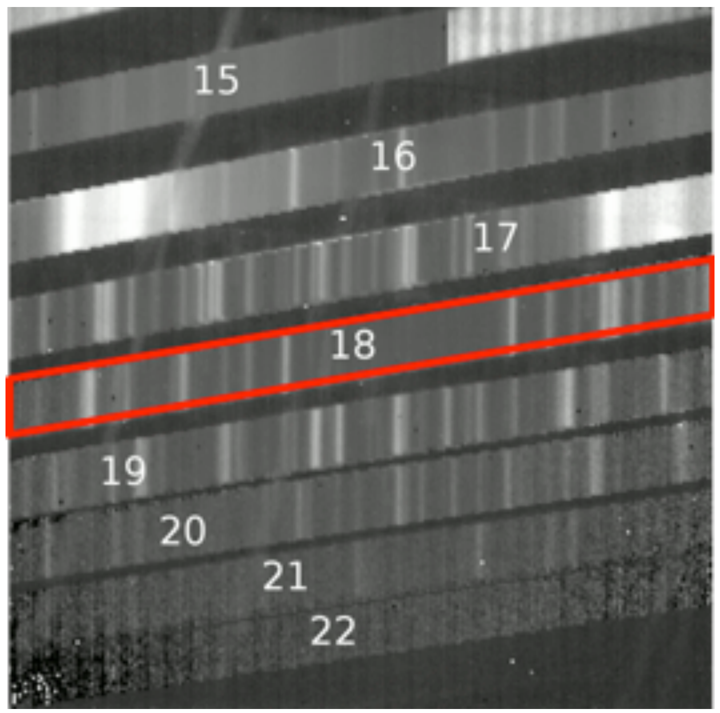
Lab test results for Grism 1 (in FORCAST): 4.9-7.8 μm, R=200
(Water vapor in emission against a 77K background)

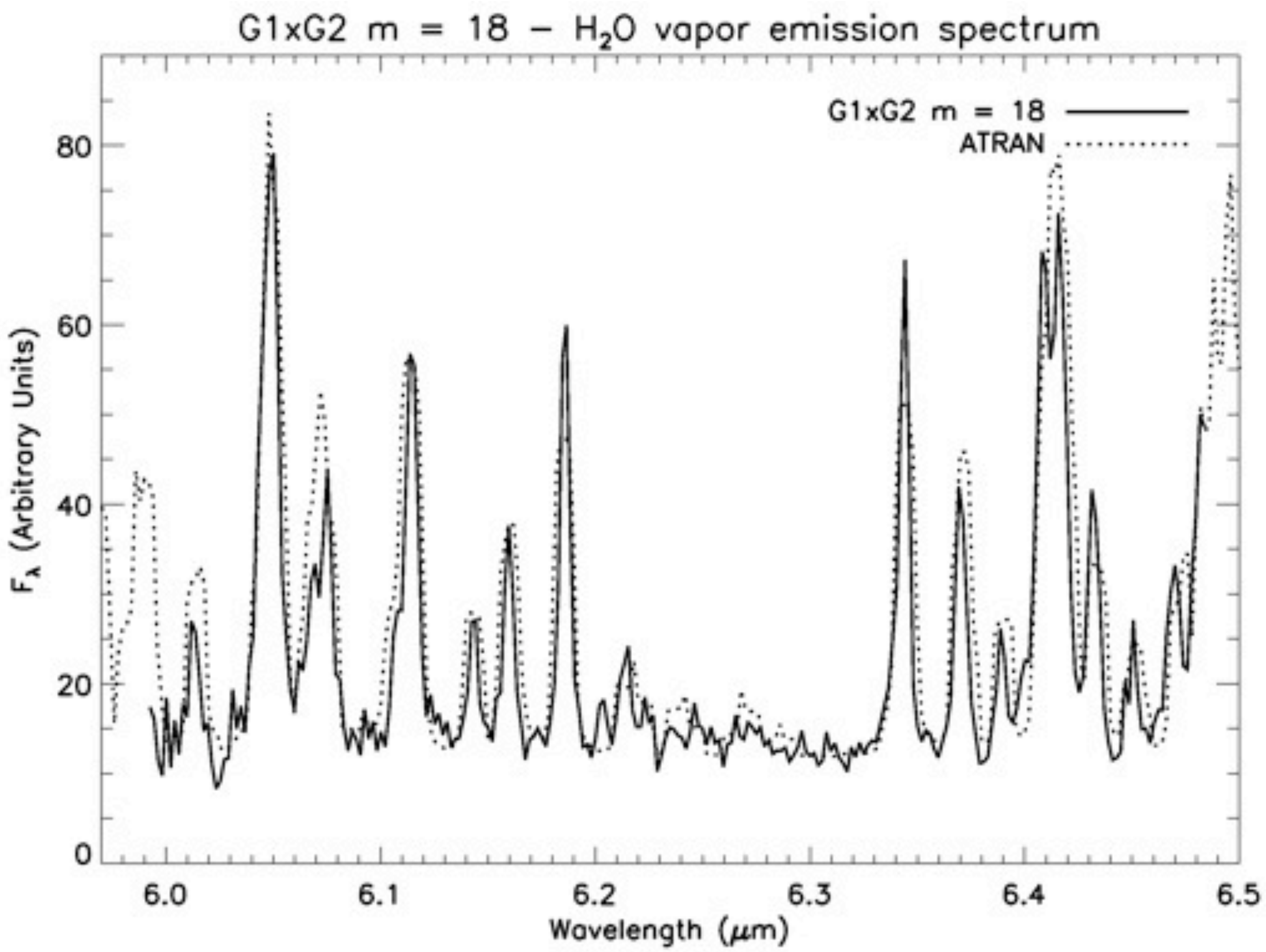




SOFIA Community Task Force tele-talk (5 October 2010)

Lab test results for Grism 1 (in FORCAST): 4.9-7.8 μm, R=1200
(Water vapor in emission against a 77K background)

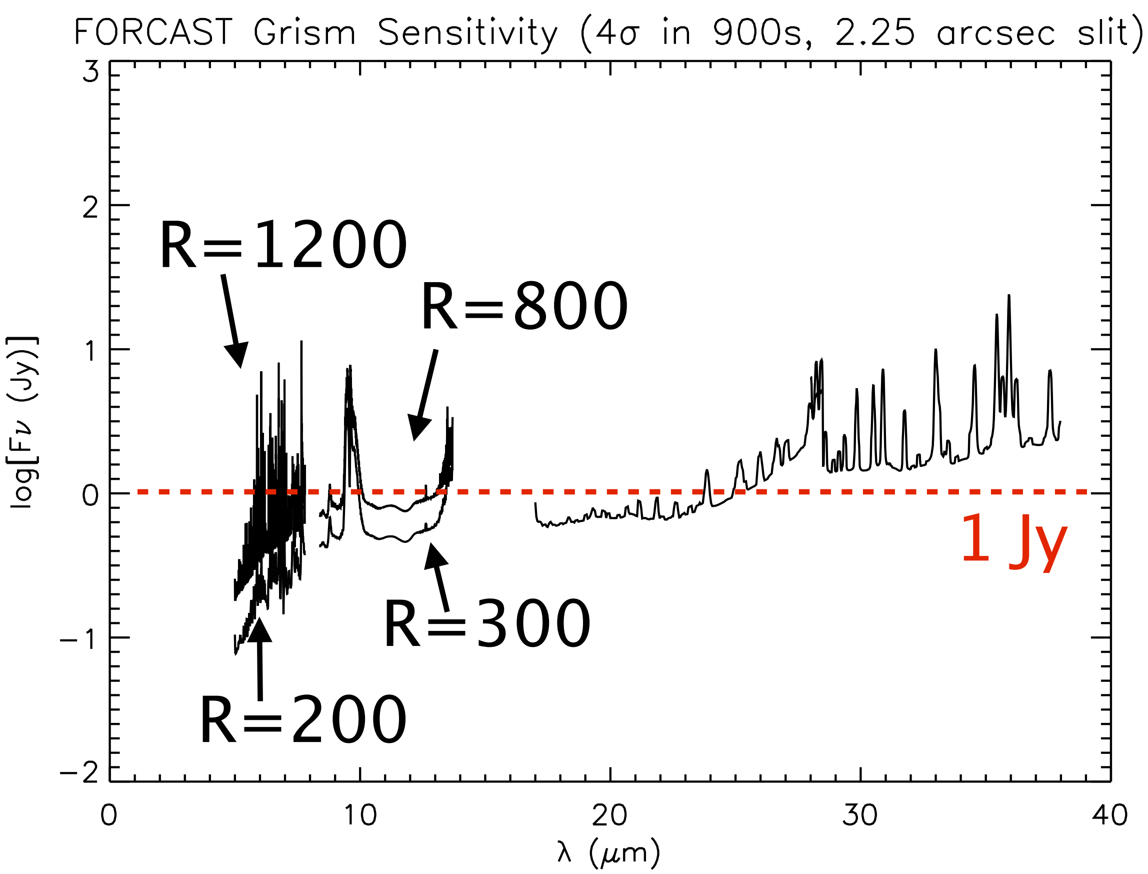


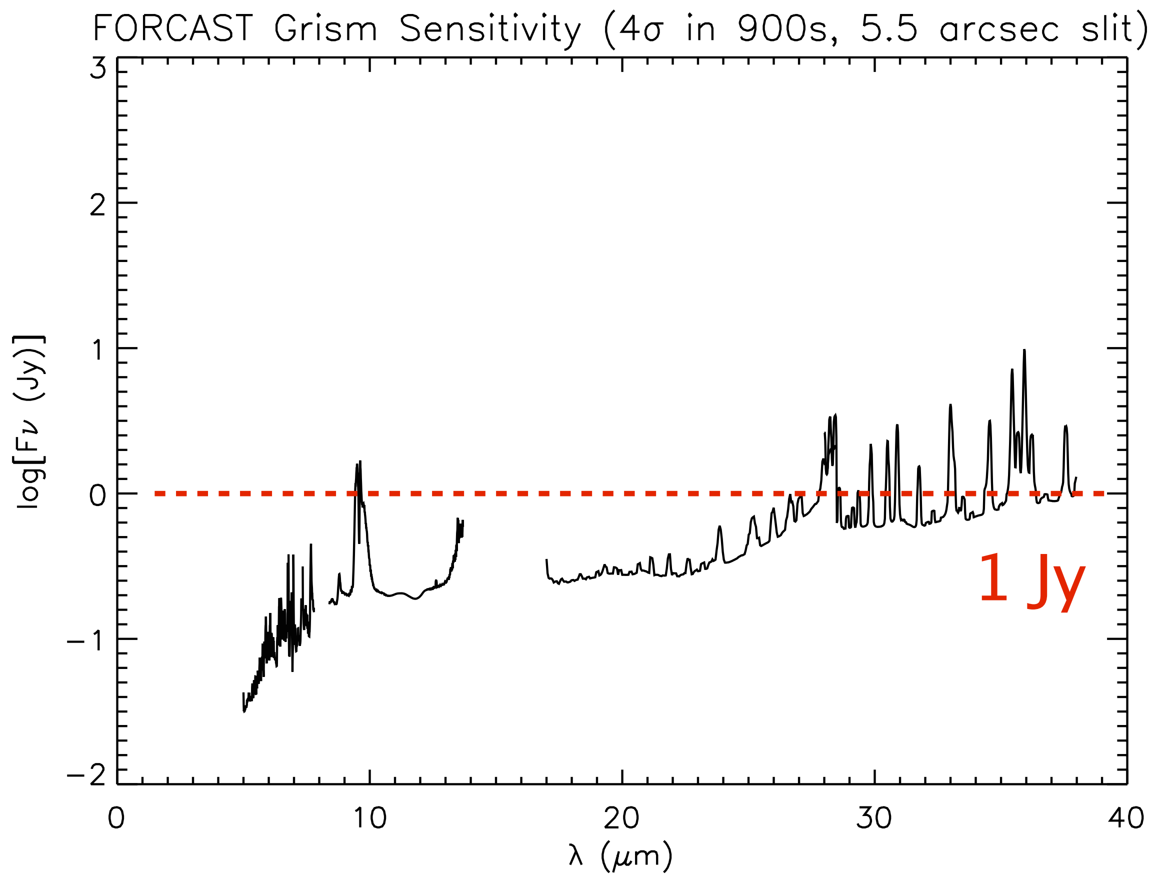


FORCAST spectroscopy Observing Modes

Mode	λ range (μm)	R	Entrance slits
G5-8	4.9 - 7.8	200	2.25”x192”
		100	5.5”x192”
G5-8XD	4.9 - 7.8	1200	2.25”x11.25”
G8-13	8.4 - 13.7	300	2.25”x192”
		150	5.5”x192”
G8-13XD	8.4 - 13.7	800	2.25”x11.25”
G17-28	17-28.5	140	2.25”x192”
		70	5.5”x192”
G28-38	28 - 38	250	2.25”x192”
		125	5.5”x192”

Estimated Point Source Sensitivity





Strategies & Challenges

- No dual-channel observations in Cycle 1, but using opposite FORCAST channel for target acquisition to save time is possible.

- The slit position angles are fixed (cannot rotate), but the field WILL rotate a few degrees per line-of-sight "rewind" on a cadence that depends on the aircraft heading (e.g. position of source in the sky).

- Spectrophotometric calibration will use observations of stars interleaved with primary observations.

Path to spectra of astronomical targets in flight (2011 - 2012 activities):

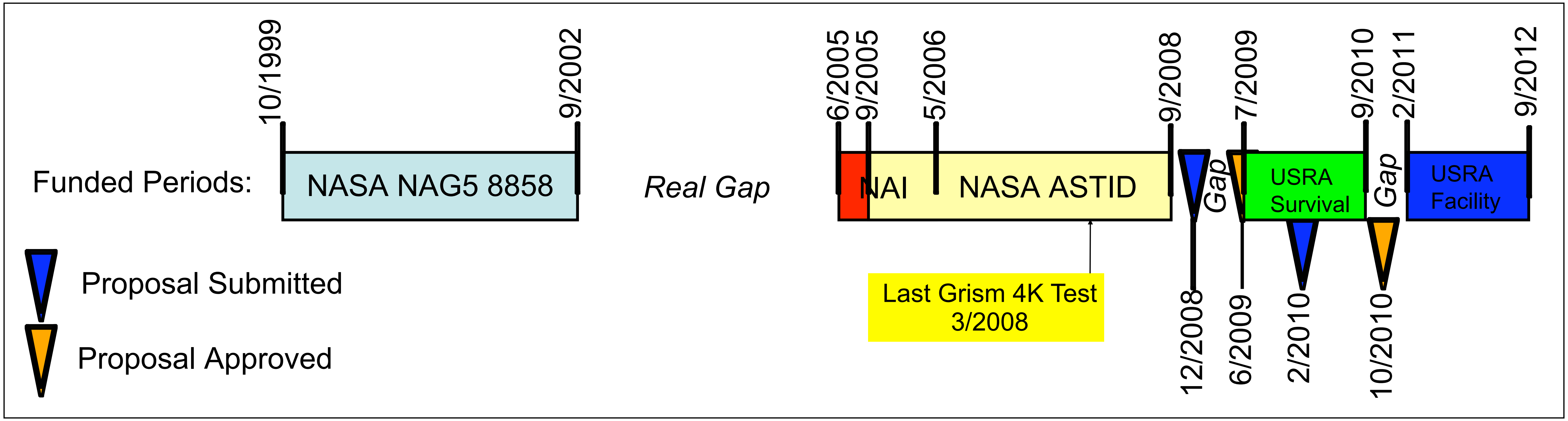
1. **Complete in-flight characterization of FORCAST grsim spectroscopy as a Facility-class mode**
    1. **Install all six grisms in FORCAST and repeat lab testing and verification (DONE)**
    2. **Edit FORCAST data acquisition software initialization files to include grism modes (on-going during Fall 2011)**
    3. **Test and verification on the sky from the ground: Requires FORCAST hardware configuration change,** G3 and G4 modes only (8-13 microns), centering and keeping targets in slits, using FORCAST dual camera to check target positioning, exercise quick look and pipeline software on aircraft, observe flux calibration sources and apply initial flux calibration to verify methods, characterize PSF as function of wavelength and slit position. **(During commissioning line-ops in Summer 2012)**
    4. **In-flight test and verification (**repeat of ground-based test/verification for all grism modes, **Summer 2012)**
2. **Work out details of spectrophotometric flux-calibration (**on-going before, during, and after ground-based test/verification)
3. **Pipeline data processing and support of post-processed grism mode data in the SOFIA data archive:** exercise existing software and make improvements identified in test/verification on ground and in flight **(on-going before, during, and after on-aircraft test/verification)**
4. **Science verification of all 6 FORCAST grism spectroscopy modes, including routine operation of FORCAST in the grism mode as a facility instrument, documentation:** Grism team conduct first science observations (shared risk, Cycle 1) after commissioning.

FORCAST Grism Publications

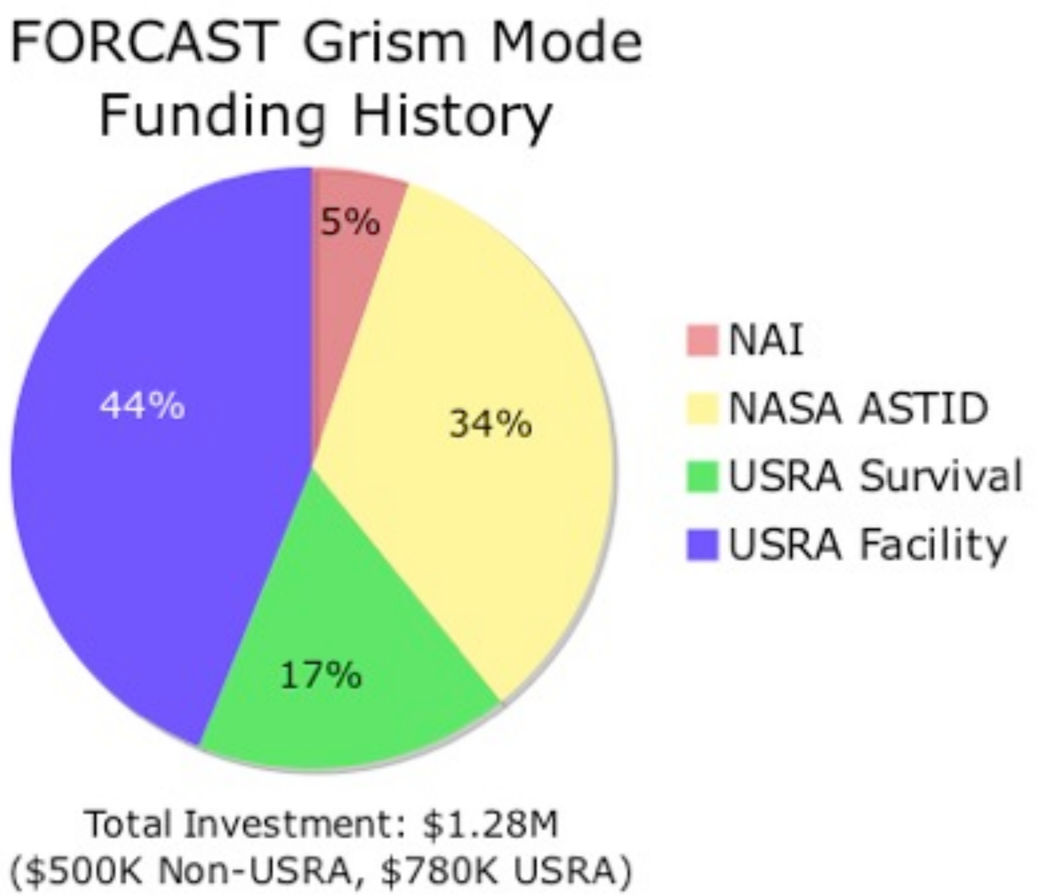
1. Keller, et al. "Protostars and Planets V," Proceedings, No. 1286., p.8481. (2005), Hawaii, October 2005.
2. Ennico, et. al. AAS Meeting 207, #129.02; Vol. 37, p.1376 (2005), Washington, DC, January 2006.
3. Mar et al, SPIE 6269.184-192 (2006), Orlando, Florida, May 2006.
4. Ennico et al, SPIE 6269.57-66 (2006), Orlando, Florida, May 2006.
5. Adams, et al. SPIE 6269.34-44 (2006), Orlando, Florida, May 2006.
6. Keller, et al. "SOFIA 2020 Vision Meeting", Caltech, December 2007.
7. Ennico, et al. AAS Meeting 211, #11.14; Vol. 39, p.746 (2007), UT Austin, January 2008.
8. Deen, et al. SPIE 7014:7014-23 (2008), Marseilles, France, June 2008
9. Keller et al. SPIE, San Diego, CA, USA, June 2010
10. Deen et al. SPIE, San Diego, CA, USA, June 2010

Thanks

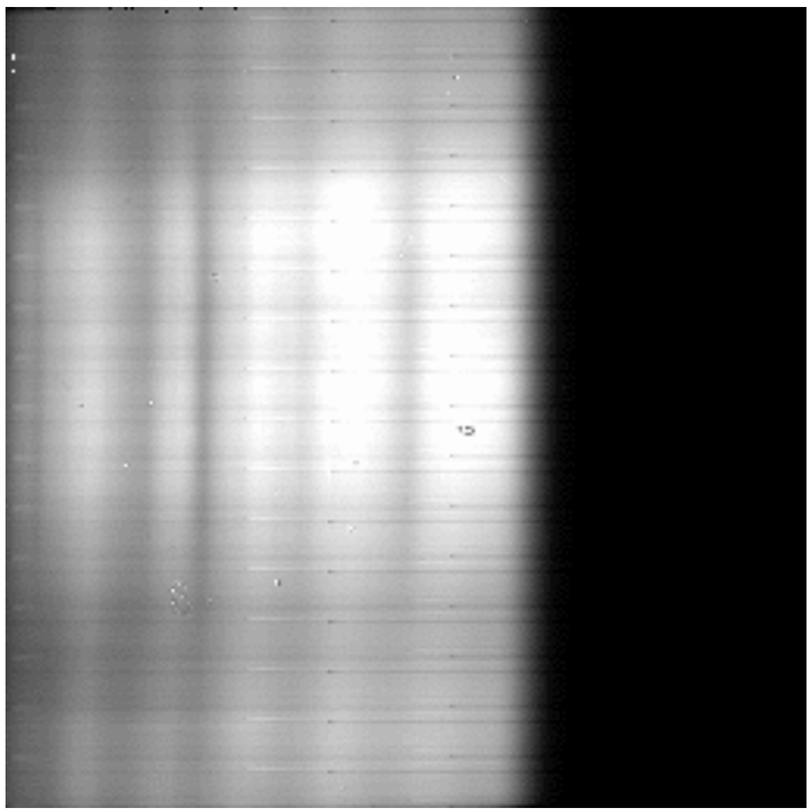
Questions & Comments: Luke Keller (lkeller@ithaca.edu)

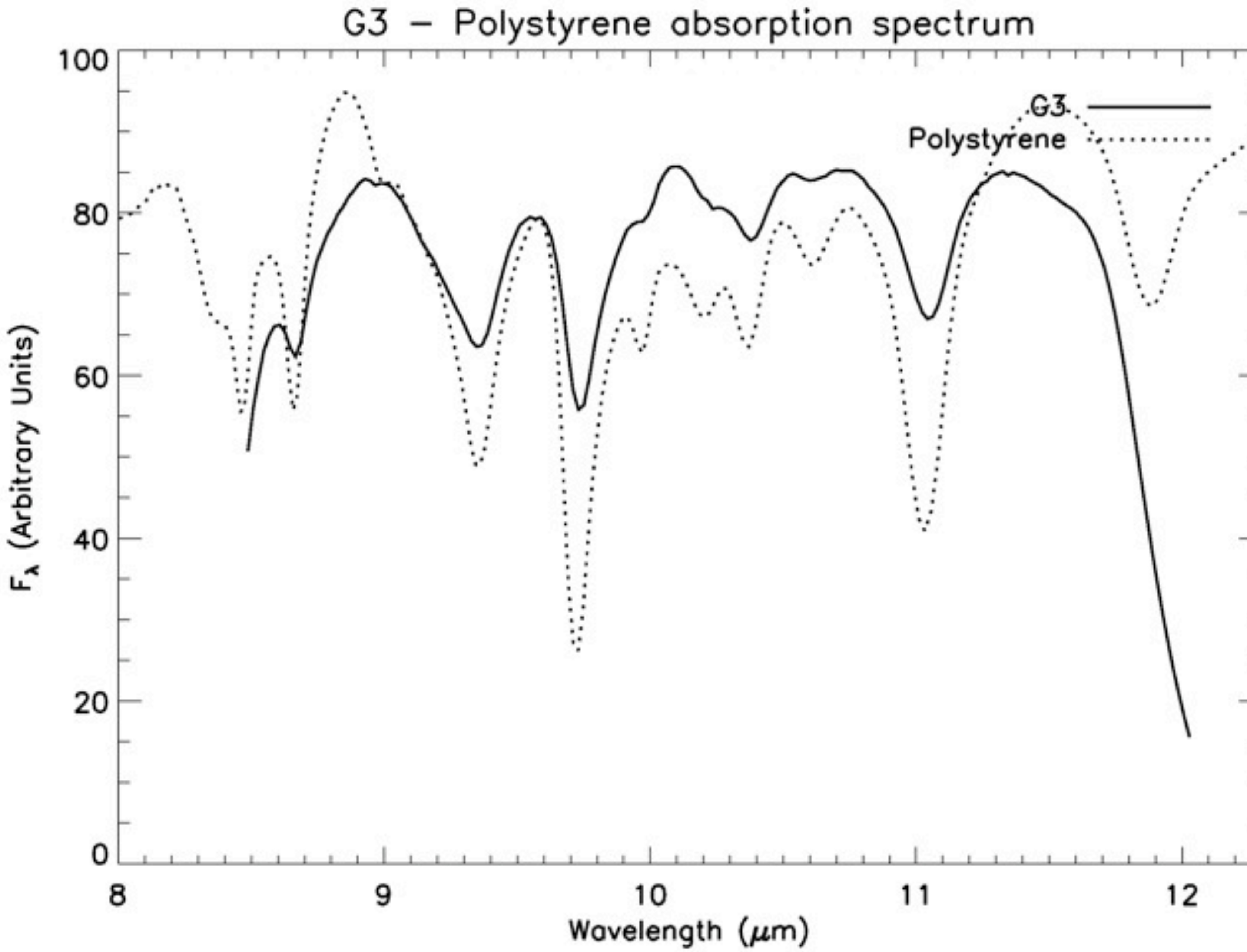


The team is grateful to NASA and USRA for awarding grants that kept the grism project alive (“Survival Mode” 7/2009-9/2010) and for funding the final push in 2011-2012 for the Facility-Class mid-IR grism spectroscopy mode.



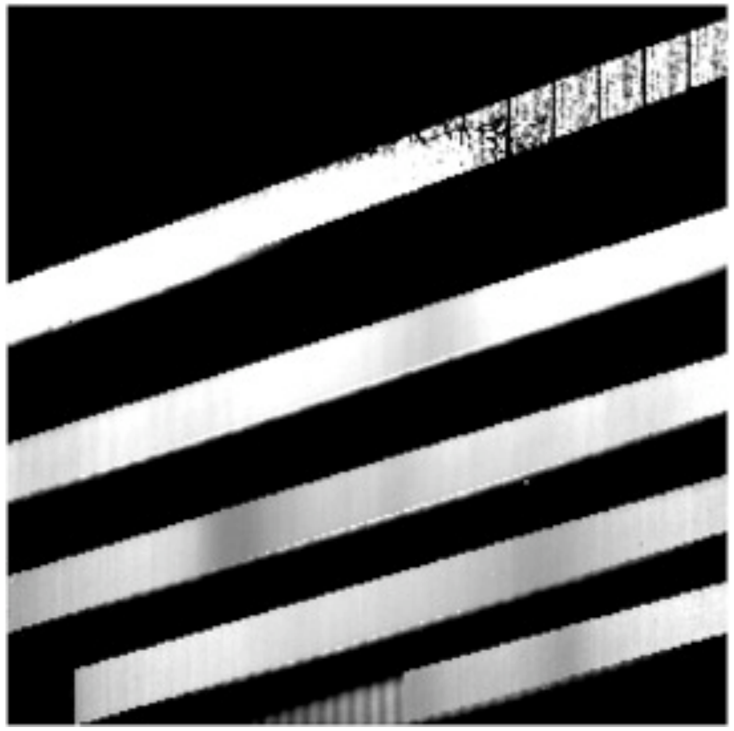
Lab test results for Grism 3 (in FORCAST): 8.4-13.7 μm

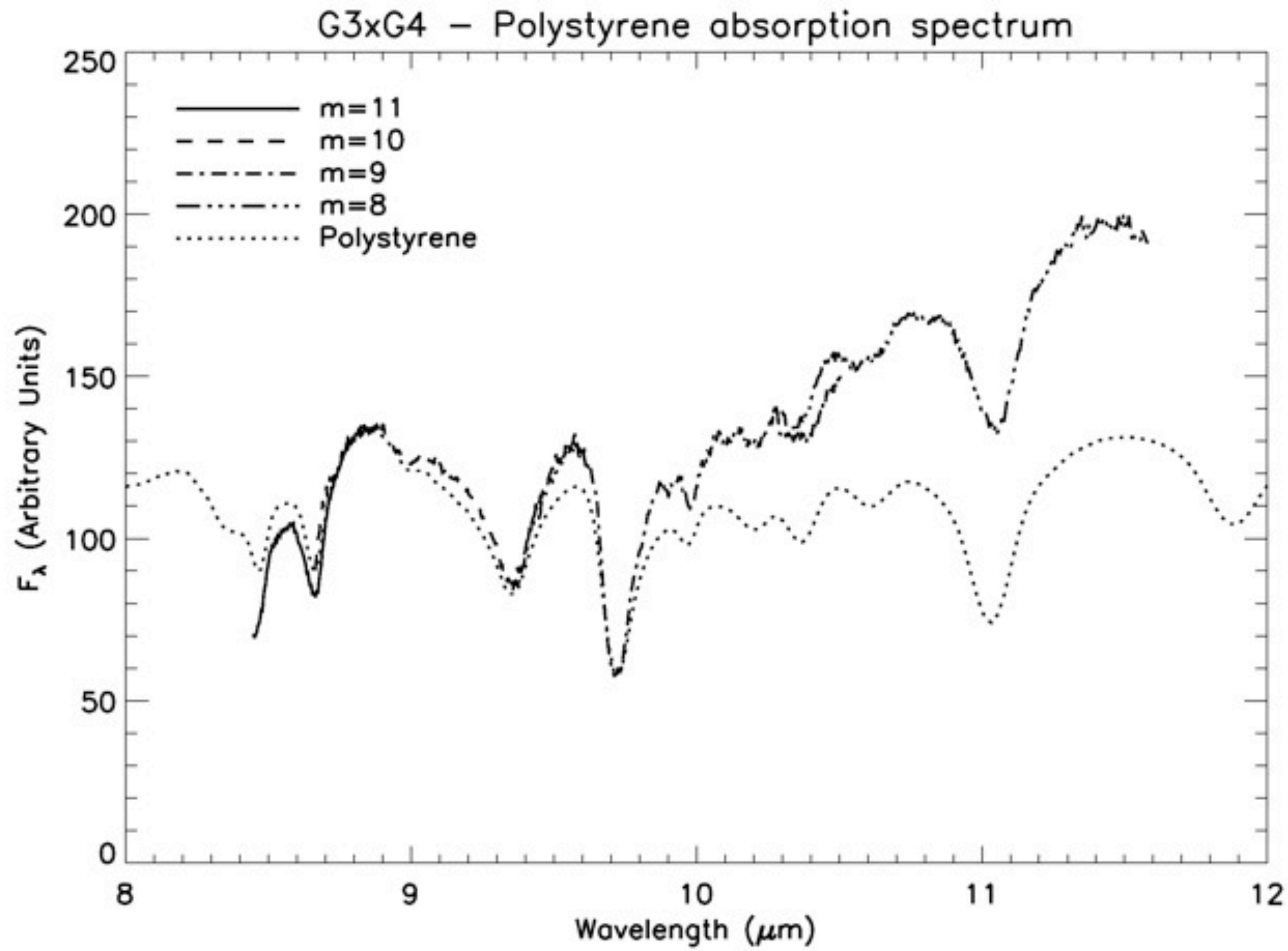




Data with old blocking filter. New filter extends to 13.7 microns.

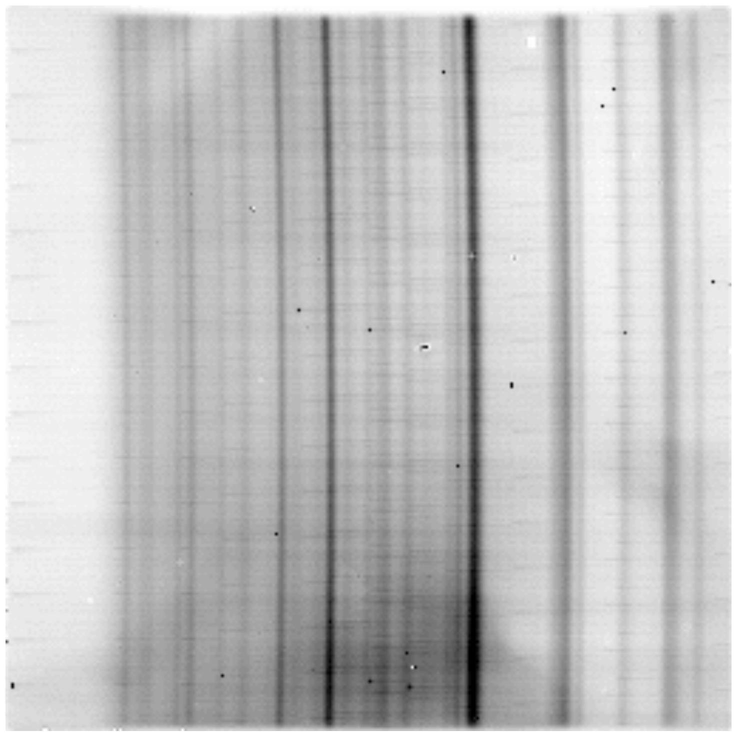
Lab test results for G3xG4 (in FORCAST): 8.4-13.7 μm

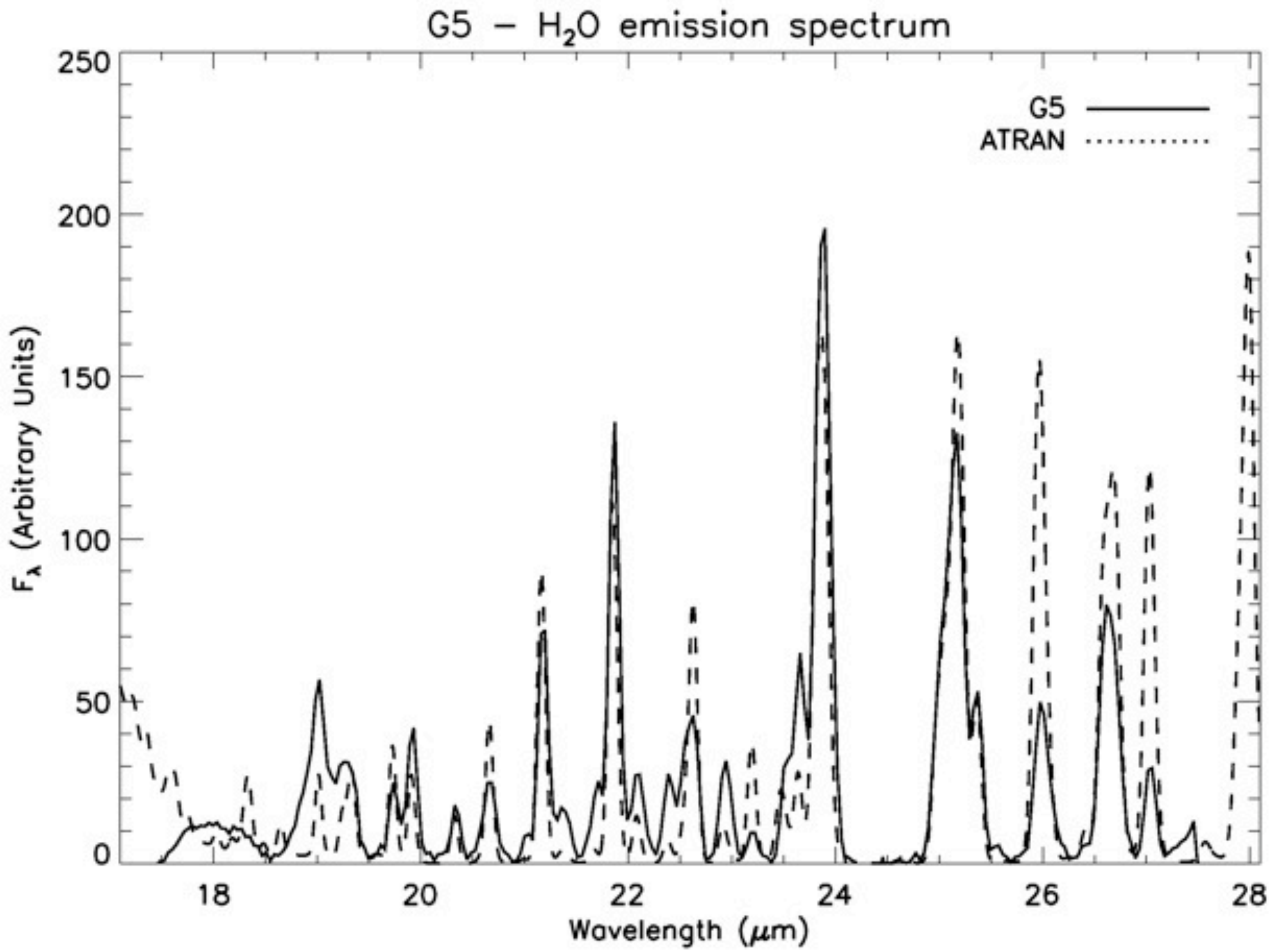




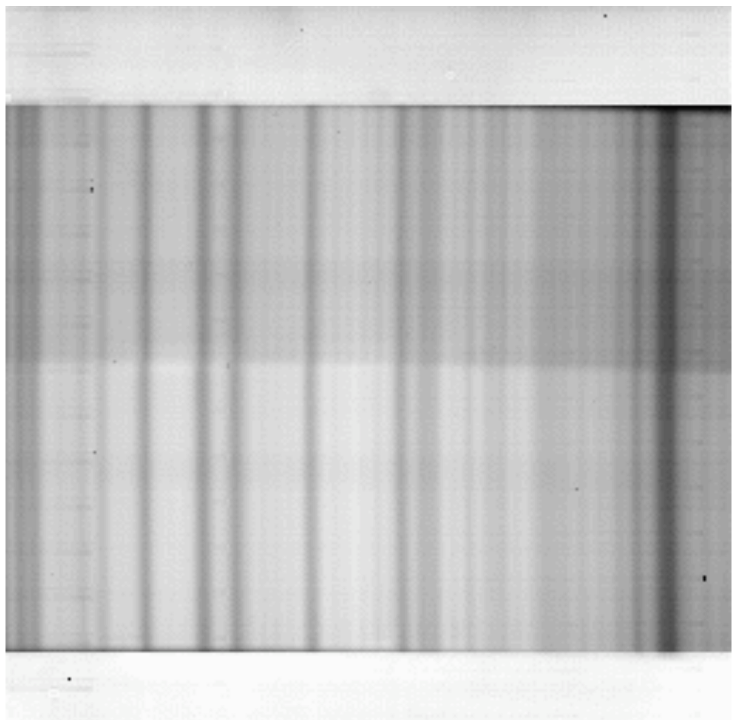
Data with old blocking filter. New filter extends to 13.7 microns.

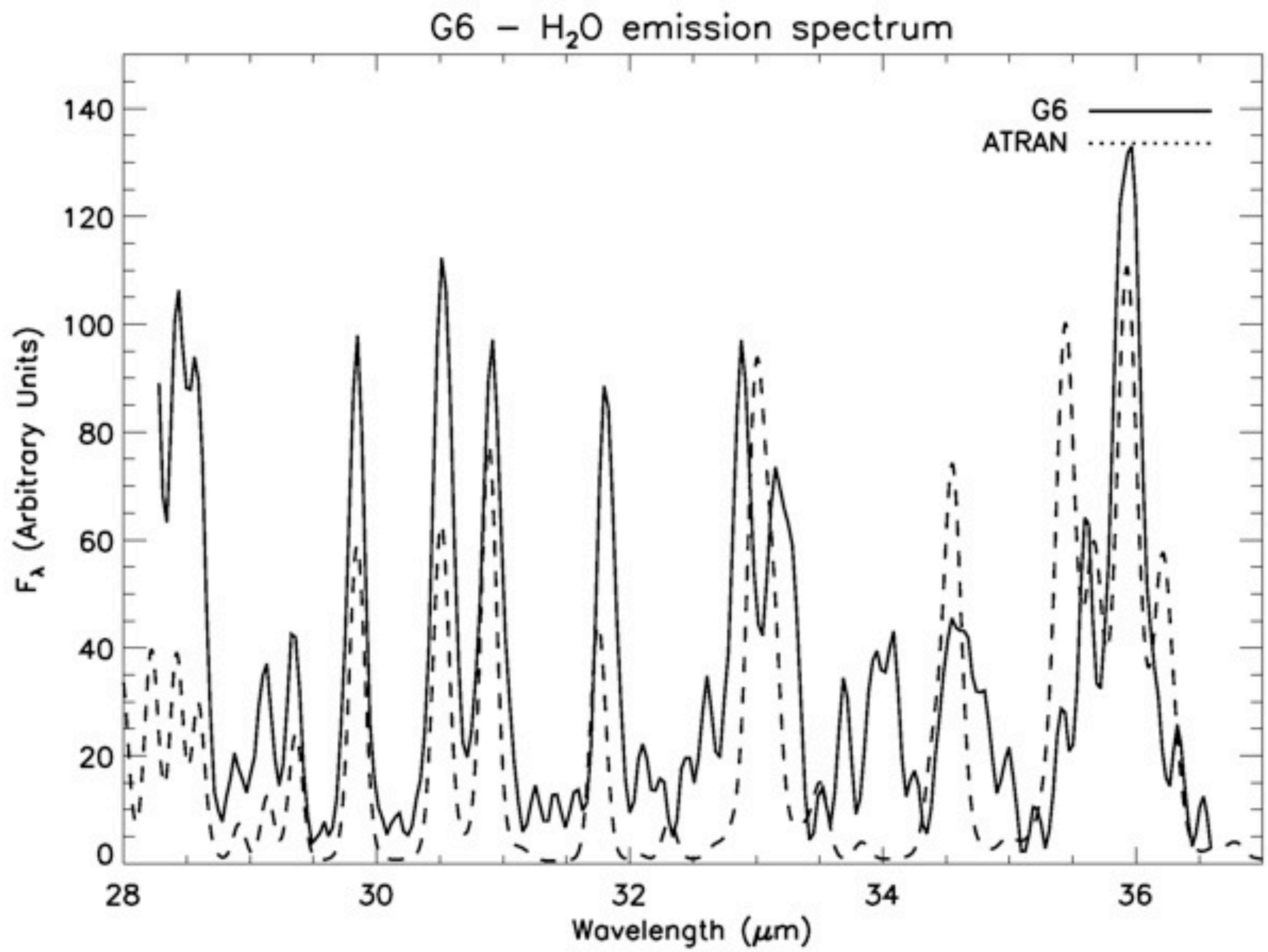
Lab test results for Grism 5 (in FORCAST): 18-28 μm





Lab test results for Grism 6 (in FORCAST): 28-37 μm





Science motivation for FORCAST grism spectroscopy

One of the great strengths of SOFIA is the breadth of capabilities it offers including high resolution spectroscopy over a broad range of wavelengths. The capabilities added by the grism suite include R~100 and R~1200 spectroscopy from 5 to 13 μm and R~150 spectroscopy from 18 to 38 μm. ***These complement the capabilities of recent, current, and future space infrared observatories.*** Examples of science enabled by FORCAST grism spectroscopy:

The evolution of refractory grains from their formation to their incorporation in protoplanetary bodies and solar system bodies (most notably comets)

Spatial distribution and physical characteristics of large molecules like the polycyclic aromatic hydrocarbons (PAH's) in Galaxtic and extra-galactic ISM, protoplanetary disks (the brightest disks tend to the be closer and more extended)

The FORCAST grism modes, together with FIFI-LS, can study interstellar ices in both absorption and emission to give us a handle on the icy material while ALMA and EXES examine the gaseous side of the interplay between the two states. In protoplanetary disks, the information provided by grism spectroscopy, in concert with the longer wavelength instruments, will allow us to follow the chemical state of the icy solid material as these systems evolve and, through studies of comets, to observe this material within more mature planetary disks.

FORCAST grism spectroscopy exemplifies the utility of SOFIA in bridging other infrared observatories and offering higher spatial and spectral resolution than current infrared space observatories. Hershel, for example, does not cover the FORCAST wavelength range for imaging or spectroscopy and JWST will not offer imaging or spectroscopy beyond 28 mm. FORCAST grism spectroscopy will span this gap enabling more and richer scientific investigations.