
SOFIA
STRATOSPHERIC OBSERVATORY
FOR INFRARED ASTRONOMY
NASA
DLR
N747NA
NASA
850

SOFIA

First Generation Instruments

E.E. Becklin

SOFIA Chief Science Advisor

Asilomar Workshop

June 6, 7, and 8, 2010

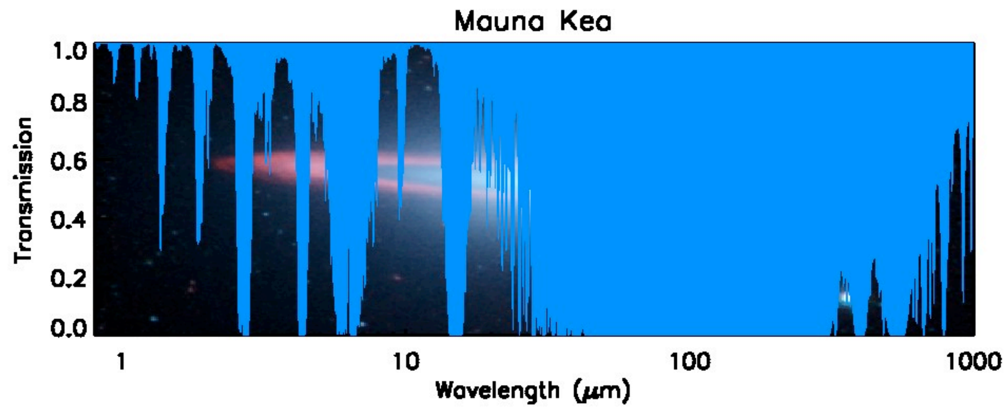
Outline of Material

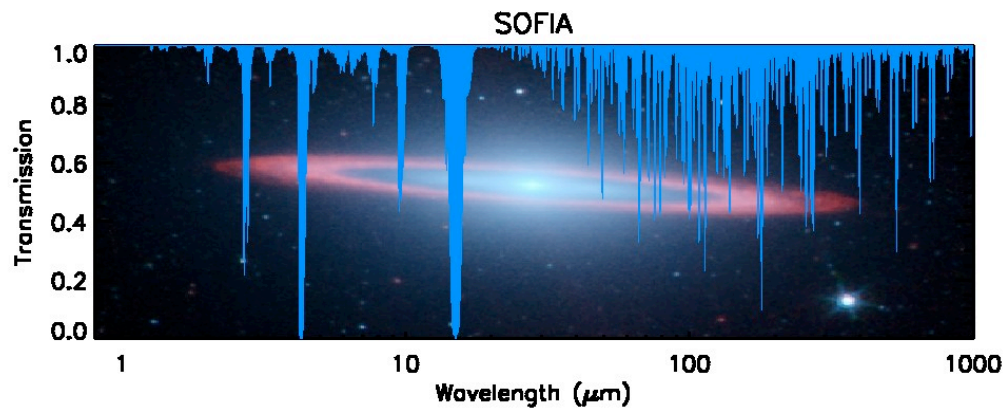
- Overview
- The First Generation Instruments
- Summary and Conclusions

OVERVIEW

Why Instruments on SOFIA

- Infrared transmission in the Stratosphere very good: >80% from 1 to 1000 microns
- Instrumentation: wide complement, rapidly interchangeable, state-of-the art
- Long lifetime
- Outstanding platform to train future Instrumentalists
- Near Space Observatory that comes home after every flight

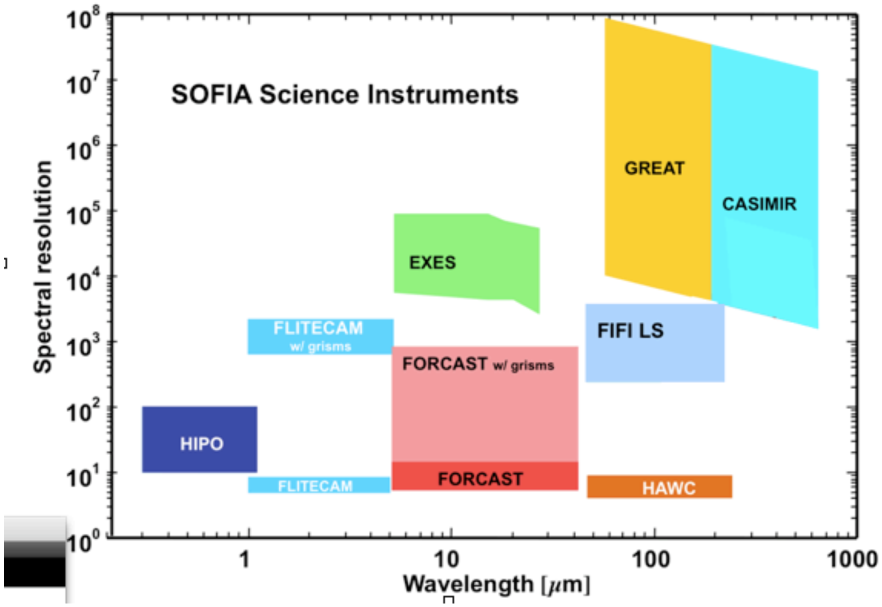




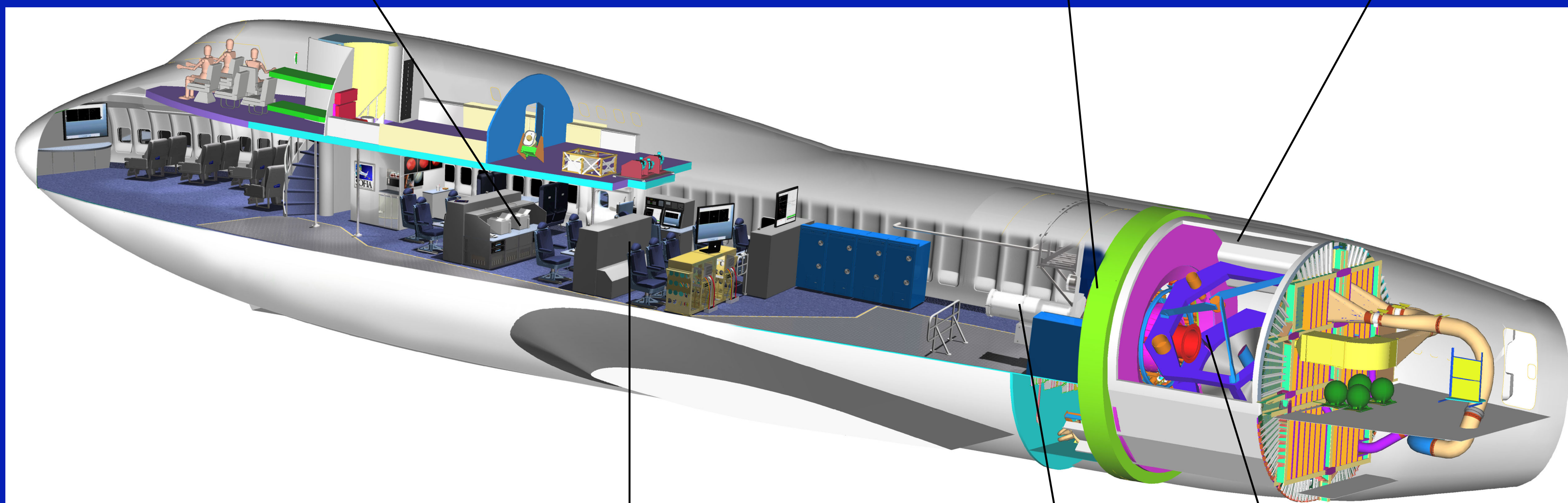
SOFIA's 1st Generation Instrument Complement

As an airborne mission, SOFIA supports a unique, expandable instrument suite

- SOFIA covers the full IR range with imagers and low to high resolution spectrographs
- 2 instruments at Initial Operations; 8 instruments at Full Operations.
- SOFIA will take full advantage of improvements in instrument technology. There will be one new instrument or major upgrade each year.
- Will support both Facility Instruments and PI Class Instruments

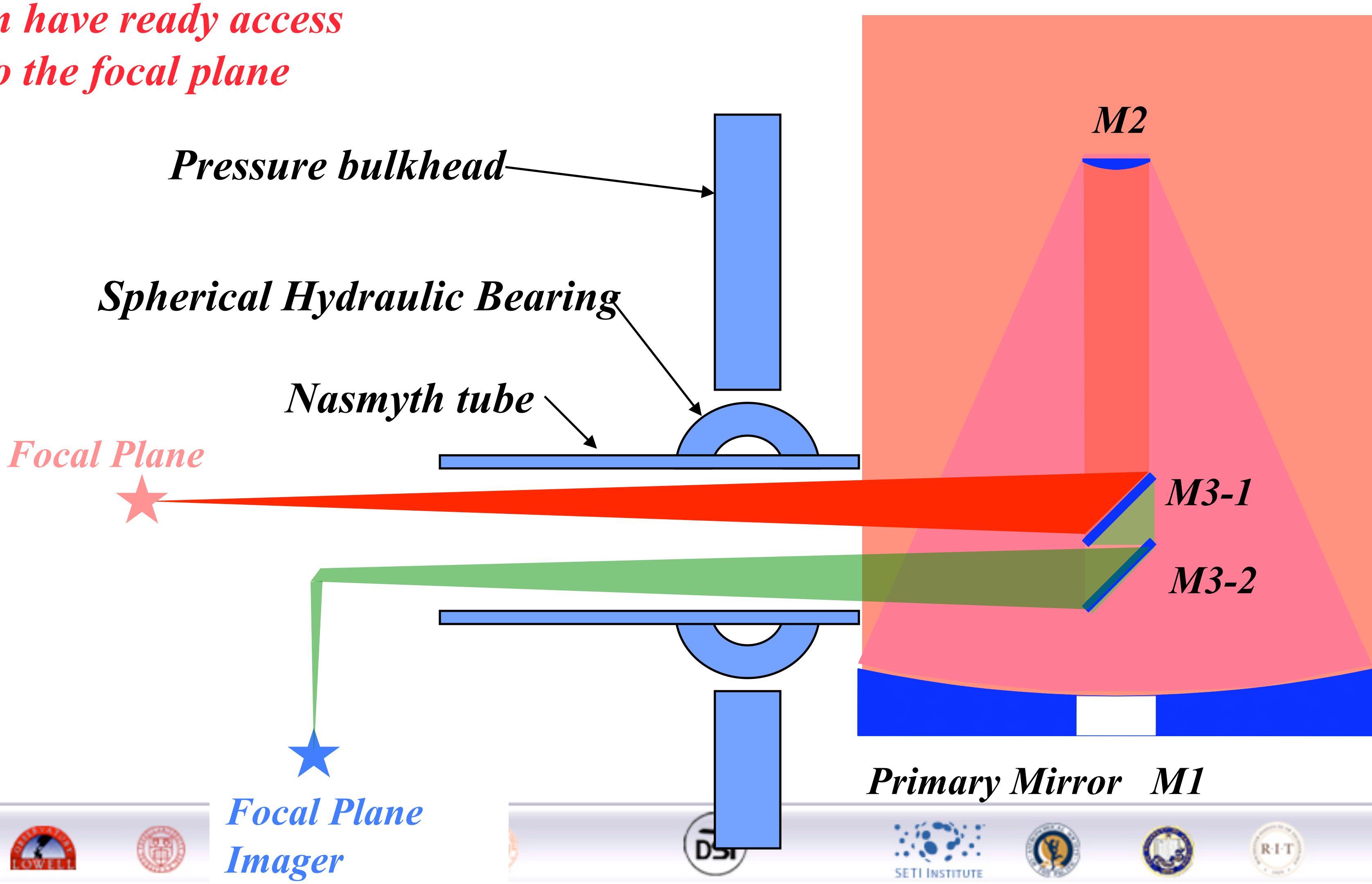


SOFIA — The Observatory

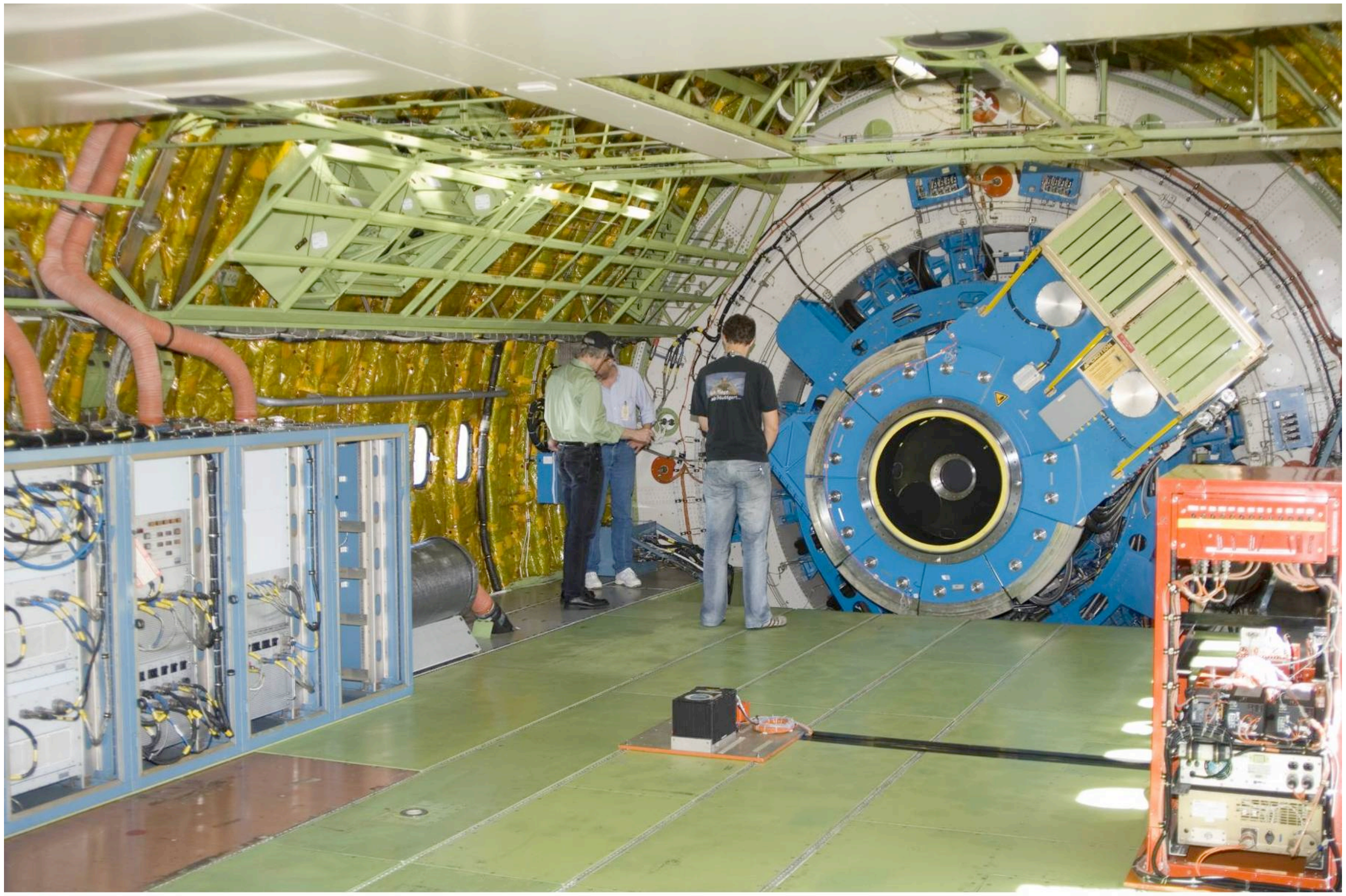


Nasmyth: Optical Layout

Observers in pressurized cabin have ready access to the focal plane



Main Deck, Looking Aft at Instrument Interface

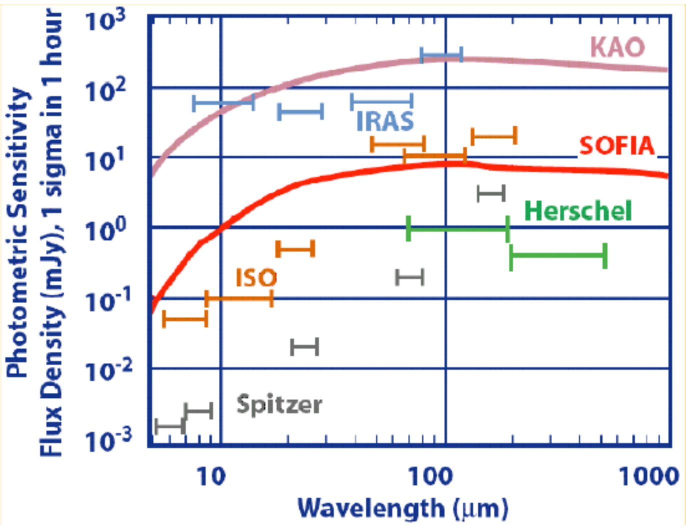


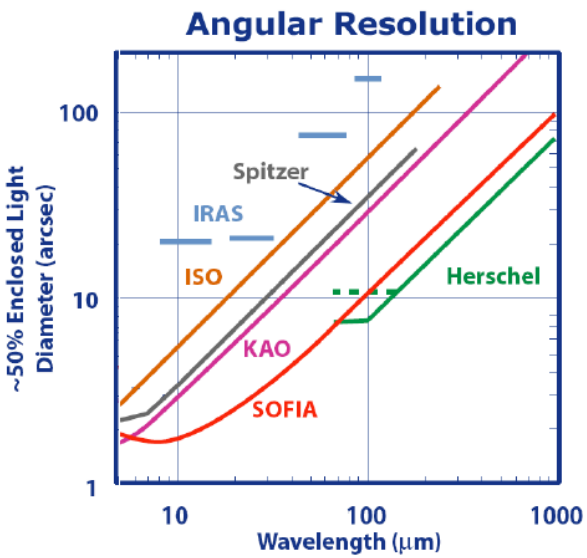
NASA Dryden Flight Research Center Photo Collection
http://www.dfrc.nasa.gov/Gallery/Photo/index.html
NASA Photo: ED07-0078-033 Date: April 25, 2007 Photo By: Tony Landis

Technicians check out the mounting structure of the infrared telescope installed in NASA's Stratospheric Observatory for Infrared Astronomy (SOFIA).

SOFIA in the Palmdale Hanger

Photometric Sensitivity and Angular resolution





SOFIA is as sensitive as ISO

SOFIA is diffraction limited beyond 25 μm (θmin ~ λ/10 in arcseconds) and can produce images three times sharper than those made by Spitzer

FORCAST

FORCAST on SOFIA for First Light

FORCAST: Mid-IR Imager

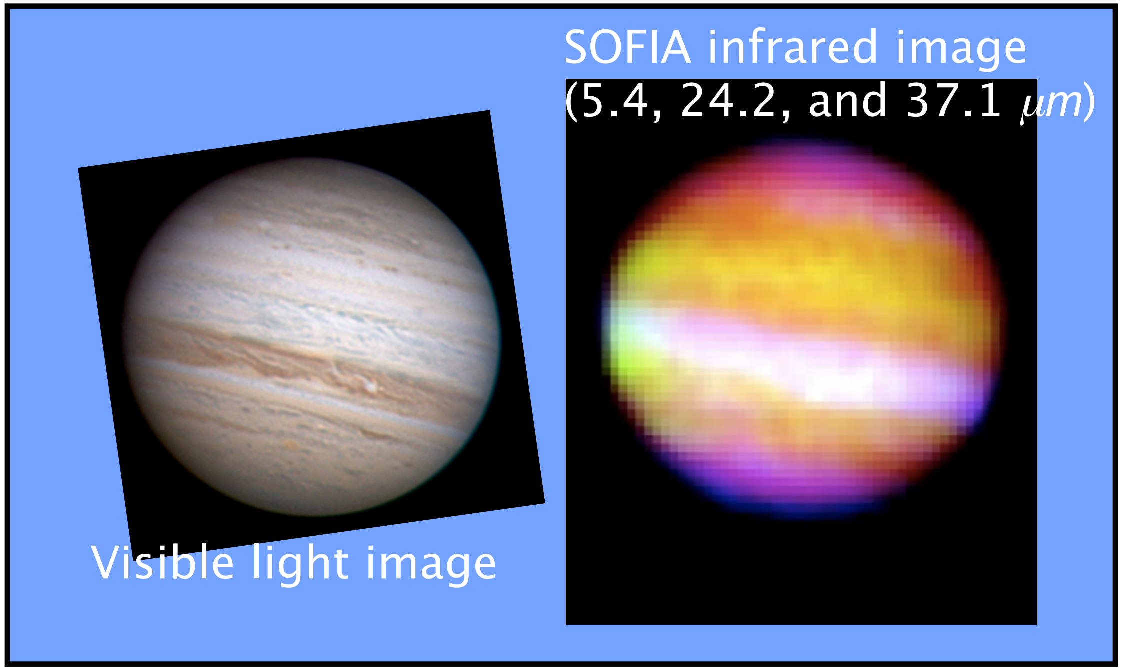
PI: T. Herter (Cornell Univ.)
herter@astrosun.tn.cornell.edu

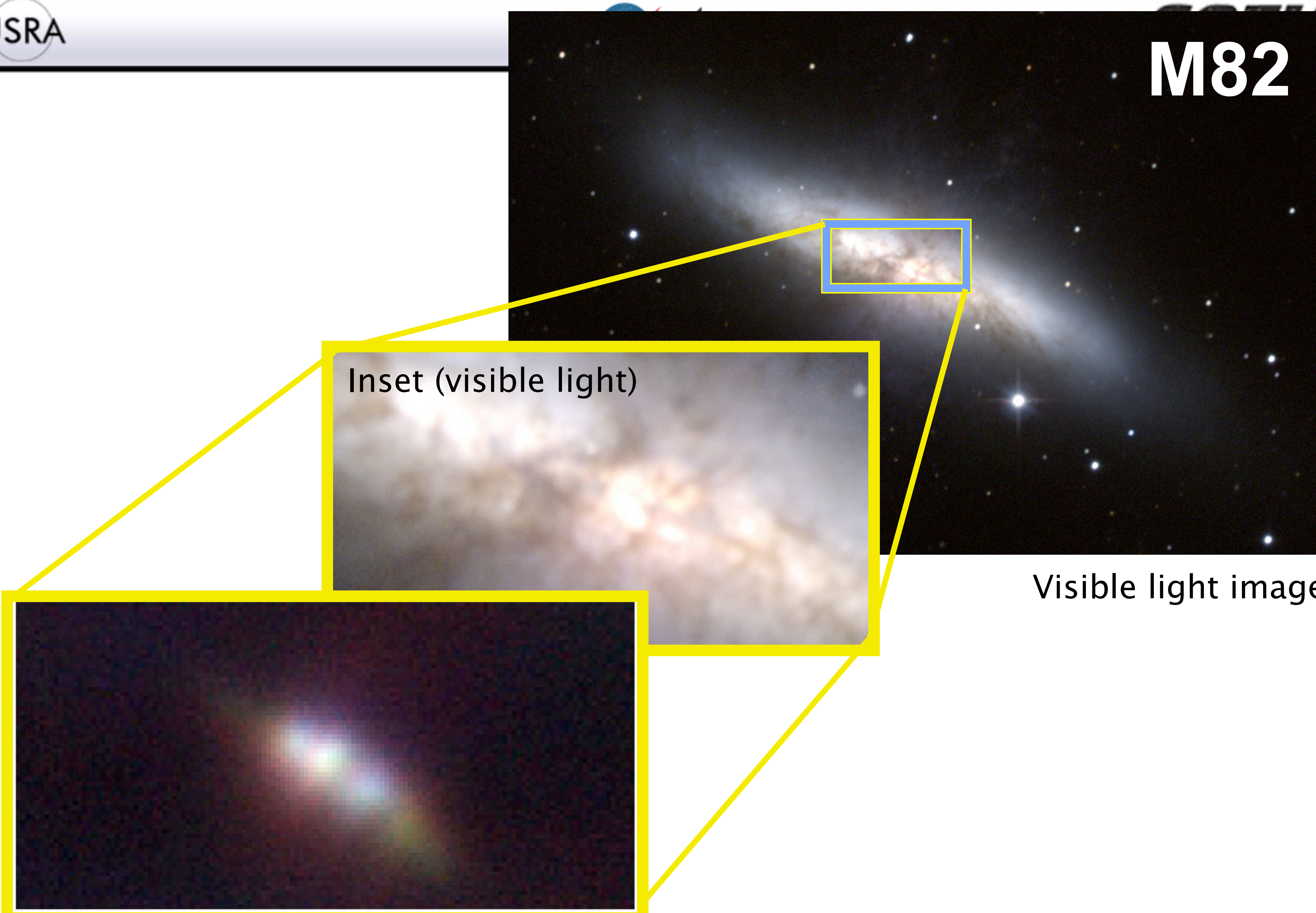
Detectors: Dual channel
256 x 256 arrays;
5 – 25 μm (Si:As)
20 – 40 μm (Si:Sb)
Field of View: 3.2' x 3.2'; 0.75"/pixel
Image size: Lambda/10 arcsec fwhm

Science: Thermal and narrow band imaging

Targets: Circumstellar disks, Galactic Center, Galactic and extragalactic star formation

NB: Diffraction Limited > 15 microns;
Grism upgrade funded (Ennico et al.)


SOFIA infrared image
(5.4, 24.2, and 37.1 μm)
Visible light image



Visible light image

SOFIA infrared image (19.7, 31.5, and 37.1 μm)

FORCAST future and planned upgrades

- Will do Short Science (3 flights this fall)
- Will be part of Basic Science in 2011
- Larger 512x512 array in each channel
- GRISM modes (talk to Kim Ennico and or Terry Herter)

GREAT

GREAT: Heterodyne Spectrometer

PI: R. Guesten, Max-Planck Institut, Bonn
guesten@mpifr-bonn.mpg.de

Detector: dual channel mixer (HEB);
60 – 200 μm (2 – 5 THz)

Field of View: single element

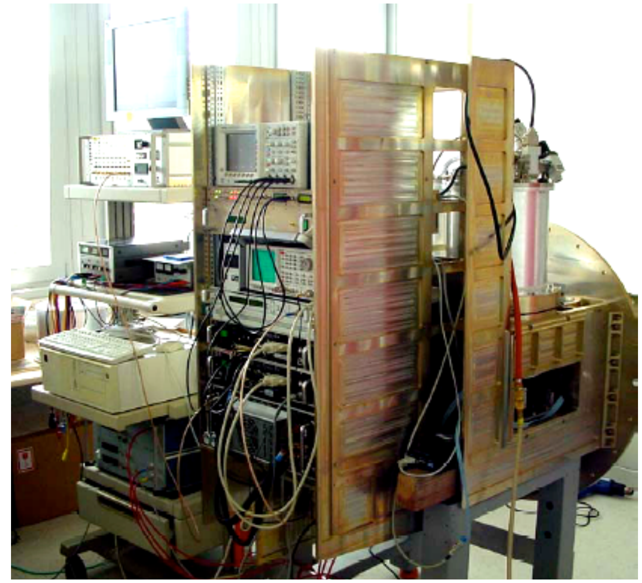
R= 10^6 -> 10^8

Science: Spectroscopy of CII (158 μm), and HD (112 μm)

Targets: Galactic and extragalactic ISM, circumstellar shells

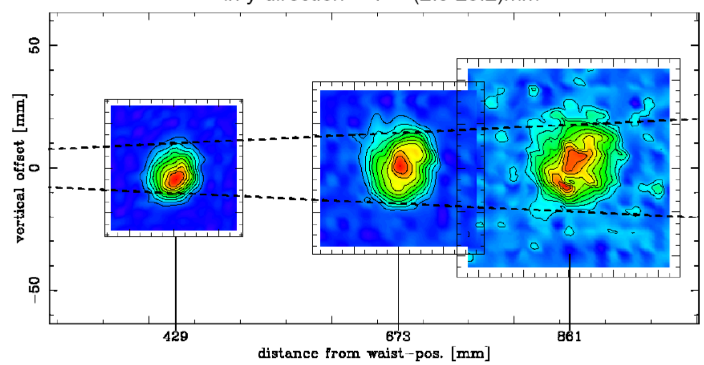
NB: T_S ~ 2500 K at 158 μm

High frequency upgrade at 4.7 THz expected for OI (63 μm).



Theoretical beam-width @ focal plane: 2.55mm

Measured in x-direction : (2.2 ±0.2)mm
in y-direction : (2.5 ±0.2)mm



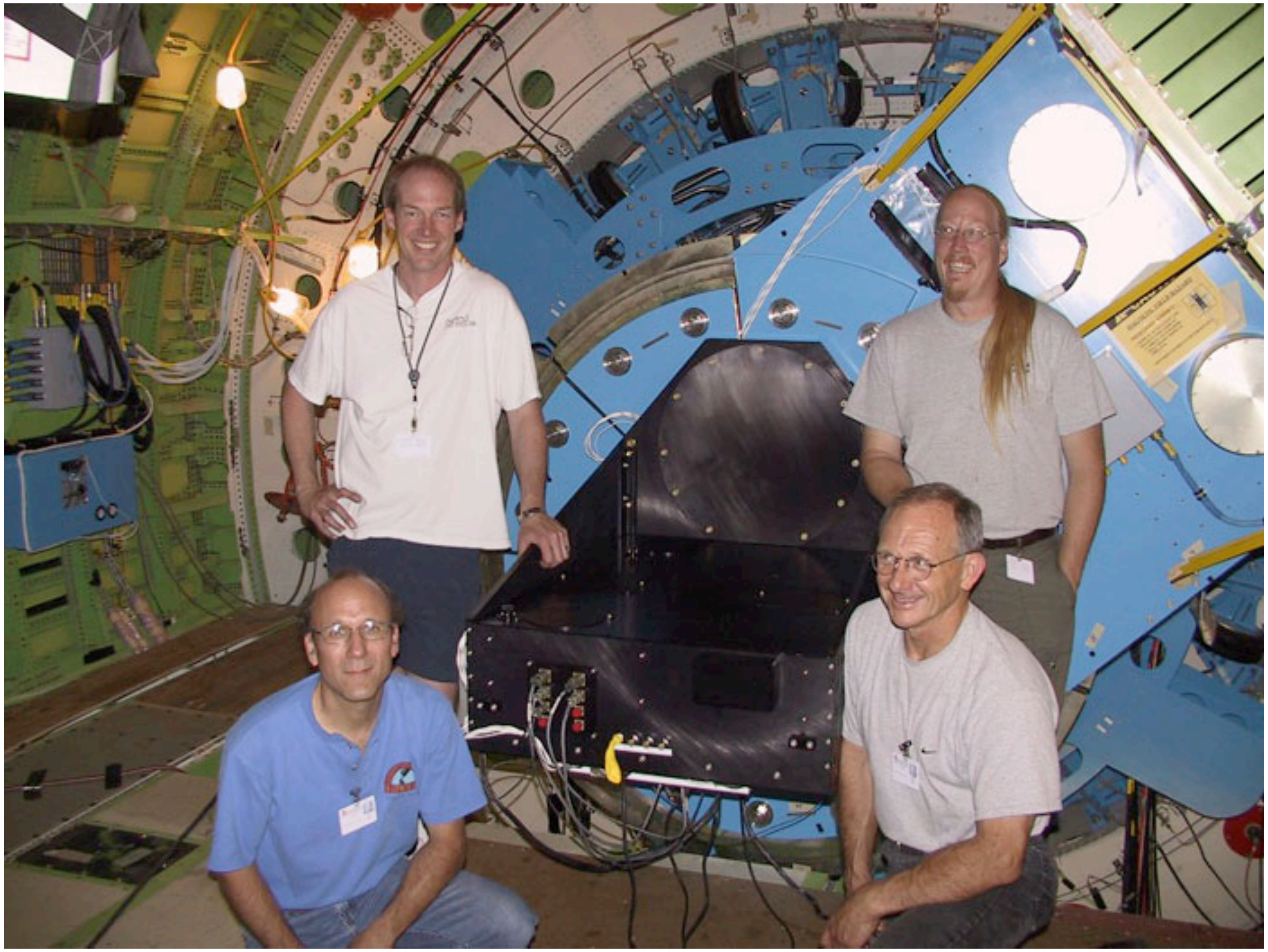
Successful lab demonstration of GREAT in Oct 2005

GREAT Future

- Will do Short Science (3 flights this winter)
- Then will be part of Basic Science in 2011
- Will fly the 4.7 THz (OI line)
- Possible 7 channel array (see poster)

HIPO

HIPO as a Test Instrument



HIGH-SPEED IMAGING PHOTOMETER FOR OCCULTATIONS:

HIPO

- **Dual-channel CCD Occultation photometer**
- **Can co-mount with FLITECAM for additional IR channel**
- **Occultation photometer - up to 50 Hz frame rate**
  - Detectors: Two Marconi CCD47-20, 1024 × 1024 pixels
  - Seeing limited imaging: plate scale 0.33"/pixel, 5.6' FOV
    - **Filters as desired**
    - **Wavelength coverage from ozone cutoff to silicon QE cutoff**
  - Precise Photometry: Very low scintillation noise, stable PSF
  - Mobility: SOFIA allows observations from almost anywhere
- **Test the SOFIA telescope assembly imaging quality**
  - Test Capabilities: Shack-Hartmann, retroreflection

HIPO Spectral Passbands

Wavelength range: **0.3 – 1.1 µm**

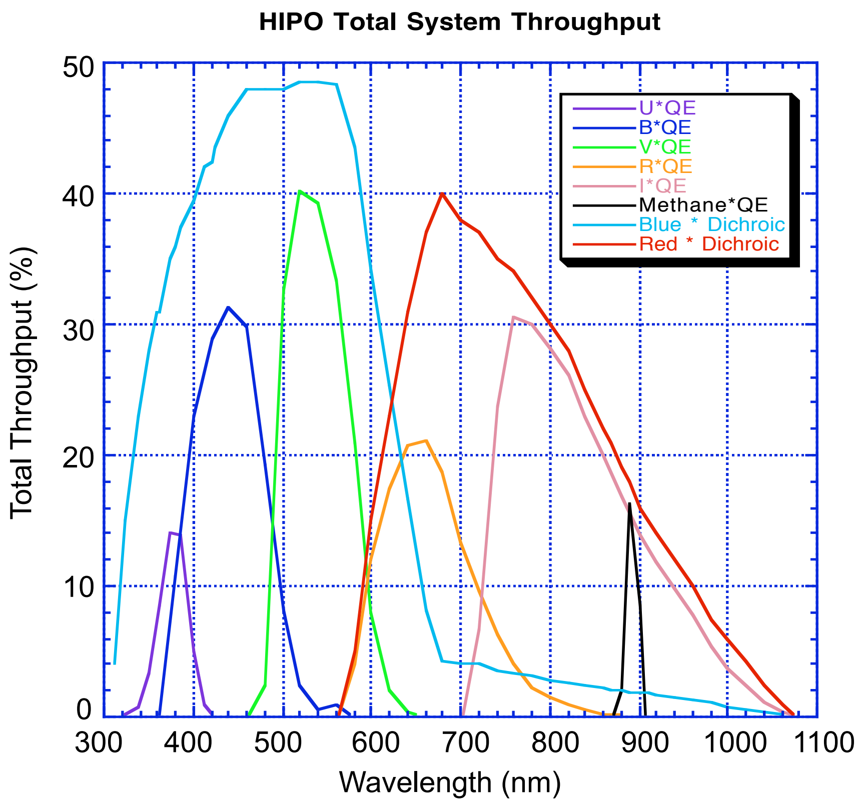
Dual-channel high-speed direct imaging photometer. Modes include:
- Single frames
- Shuttered time series
- Frame transfer time series up to 50 Hz
- Short time series up to 10 KHz

Broadband imaging filters:
- Standard UBVRI passbands

Narrow-band filters at, e.g.:
- Methane filter at 0.89 µm

Dichroic Reflectors:
- HIPO will use a dichroic reflector to separate its channels. The transition wavelength for the first light dichroic has not been determined.

Additional Filters:
- Additional custom filters will be added for specific events



HIPO will include standard Johnson filters at first light that will be used primarily for facility performance testing. Occultation observations will normally be unfiltered for events involving faint stars or will use specialized filters such as the methane filter shown here for events with bright stars. The dichroic response shown here is only an example.

FLITECAM

FLITECAM: Near-IR Imager

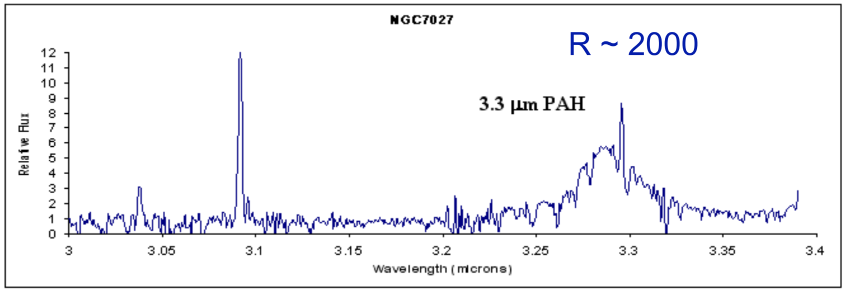
PI: I. McLean (UCLA)
mclean@astro.ucla.edu

Detector: Single 1K x 1K array;
1-5 μm (InSb)

Field of View: 8.2' x 8.2' ;0.5" pixels

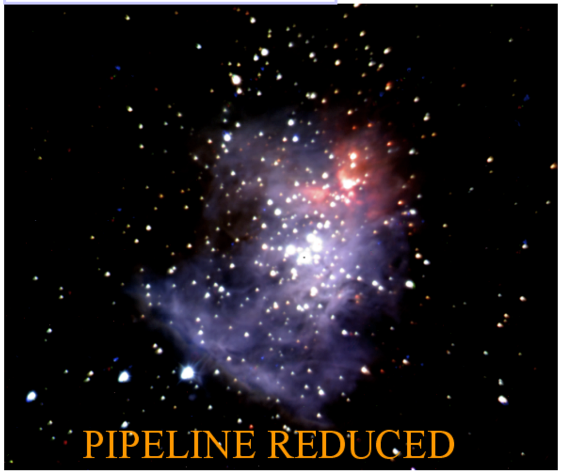
Science: Imaging, Spectroscopy (GRIMS R~2000),
Occultations (with HIPO)

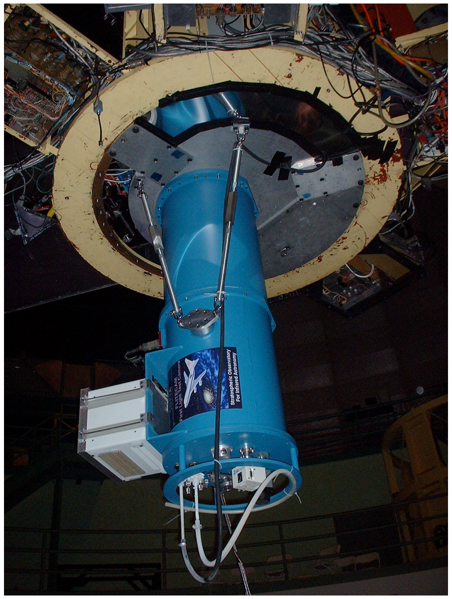
Targets: Galactic, extragalactic



Grism observations from Lick of NGC 7027

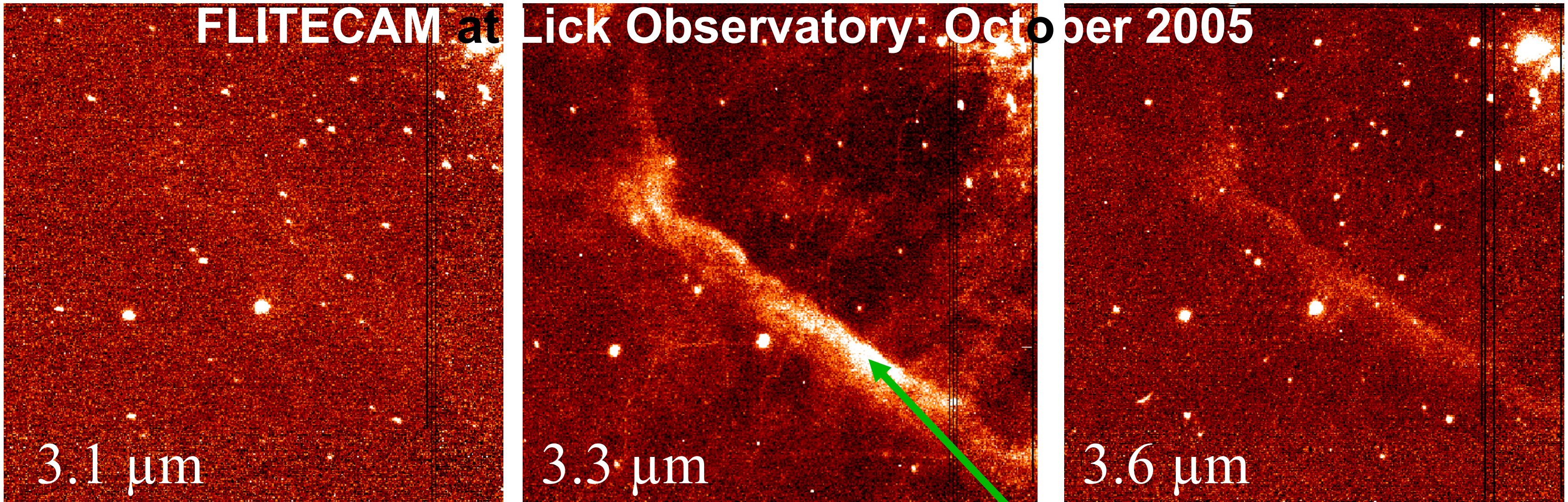
JHK color composite of Orion obtained with FLITECAM on the Lick 3-m telescope.



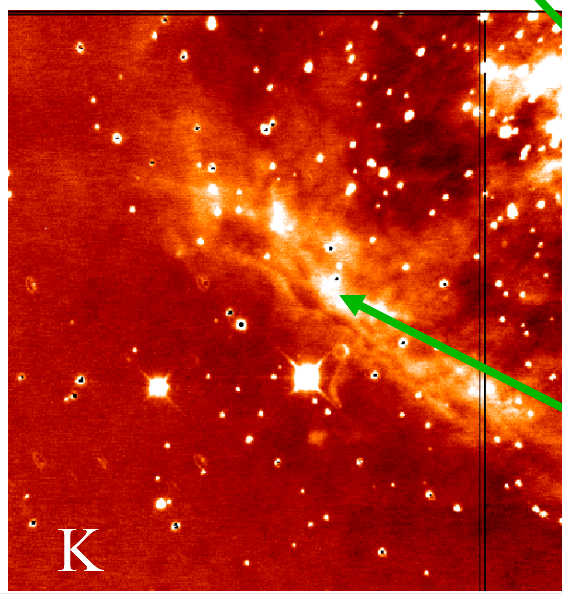


Working/complete FLITECAM instrument at Lick in 2004/5

The Orion Bar



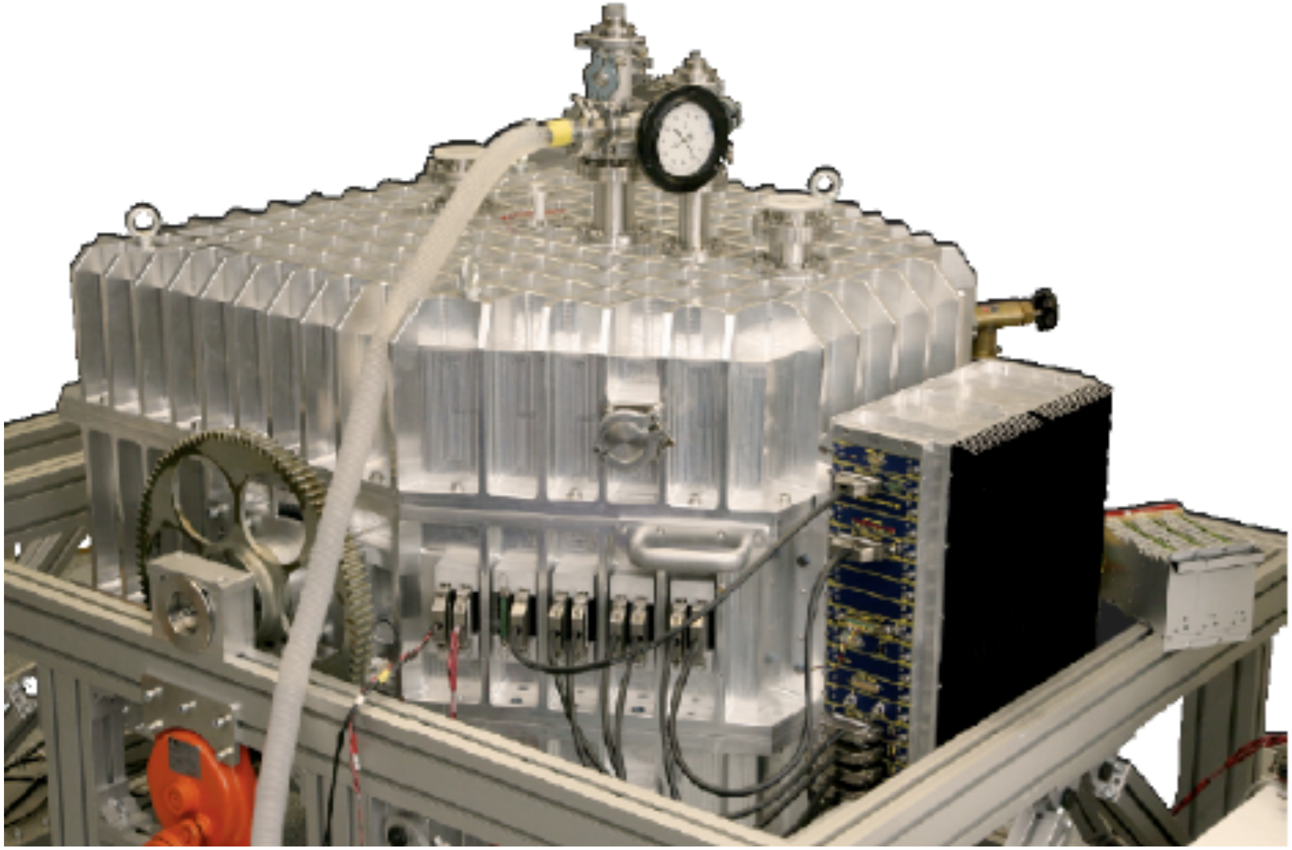
The Orion Nebula: Imaging with narrow band (1%) filters and compared to K-band. Pipeline-processed images *as obtained at the telescope*.



Strong PAH emission at 3.3 microns.

Strong ionized hydrogen emission at 2.17 microns

FIFI-LS



FIFI-LS: Far-IR Spectrometer

PI: A. Poglitsch, Max-Planck Institut, Garching
alpog@mpe.mpg.de

Detectors: Dual channel 16 x 25 arrays;
42 – 110 μm (Ge:Ga)
120 - 210 μm (Ge:Ga stressed)

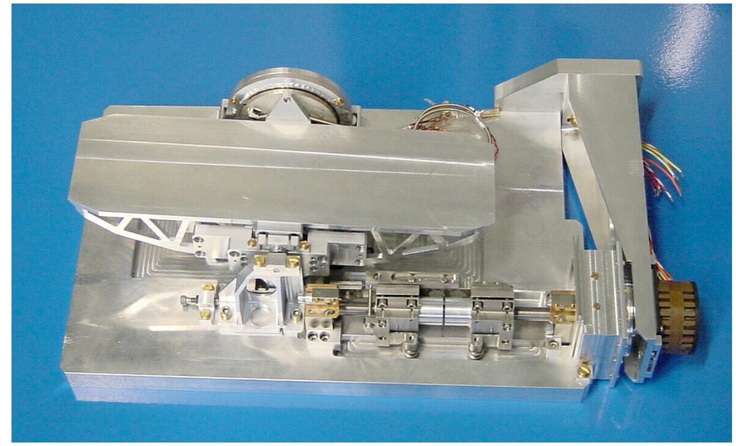
Field of View: 30” x 30” (blue), 60” x 60” (red)

R= 1500 - 6000

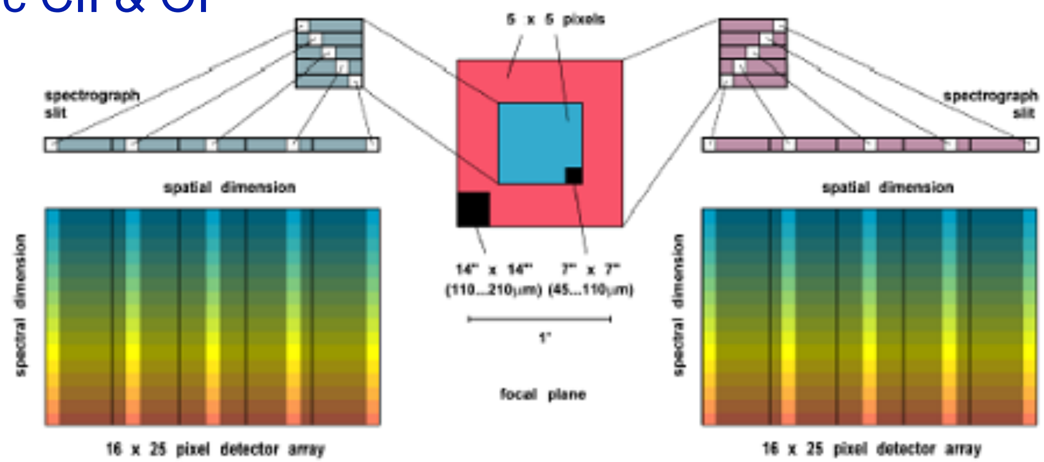
Science: Imaging of extragalactic CII & OI

Targets: Extragalactic imaging

NB: Imaging array is 5 x 5 pixels



Grating drive & support optics integration with flight cryostat in 2006



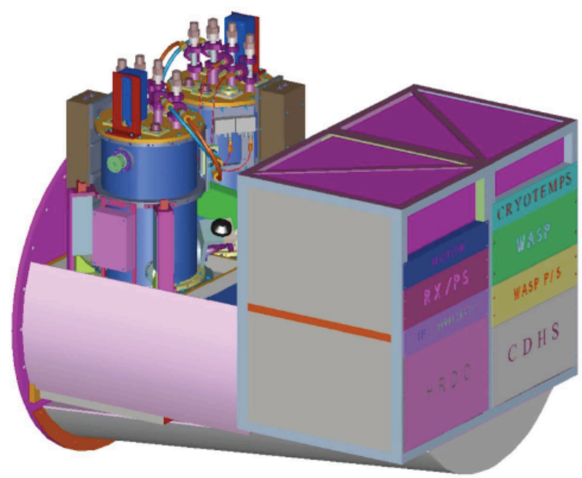
On sky orientation of ‘blue’ and ‘red’ channels

FIFI-LS Current Status

- All components complete on Red Side
- Blue side will be finished this year
- Instrument will be moved to Stuttgart for Testing later in the year.
- Testing will be done under direction of Alfred Krabbe
- Will become a Facility Instrument with both German and US users. (Modification of EOOP which allowed US use of instrument)

CASIMIR

Jonas Zmuidzinas: Caltech, PI



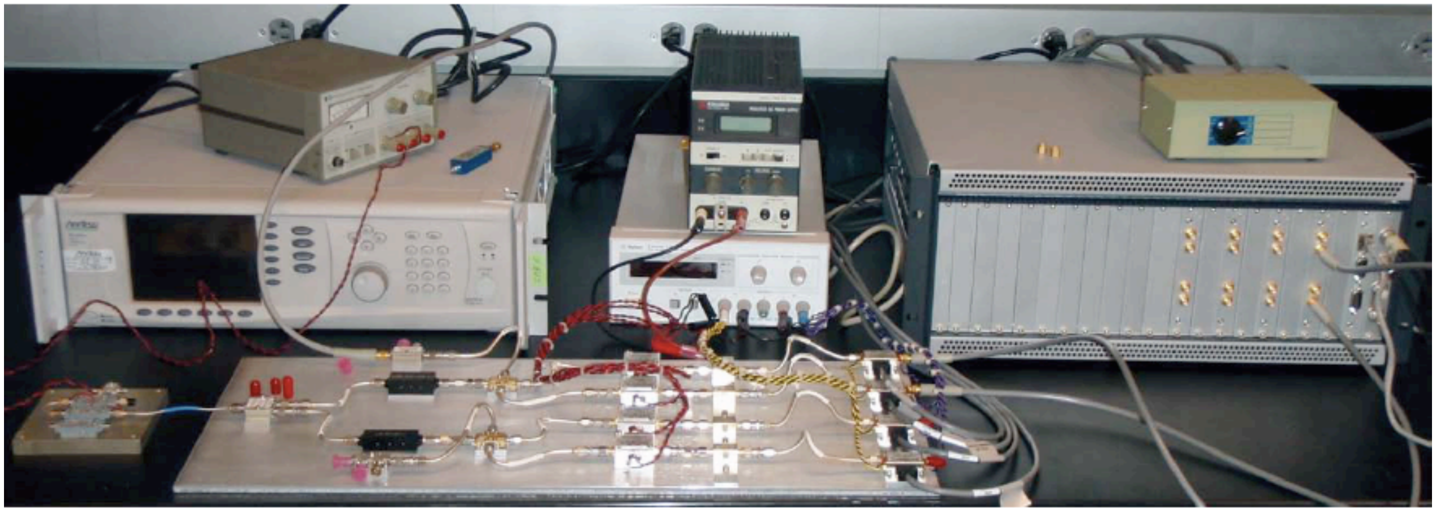
CASIMIR

Overview

- High resolution heterodyne spectrometer
- 500 – 1500 GHz, 5 bands
  - 550 GHz, 750 GHz, 1.0 THz, 1.2 THz, 1.4 THz
- Single pixel, single polarization per band
  - Four bands available per flight
- Advanced SIS mixers
  - DSB T_{rx} < 3 $h\nu/k$ for ν < 1THz; 6 $h\nu/k$ for ν > 1THz
- 4–8 GHz IF bandwidth

FFT Digital Spectrometer

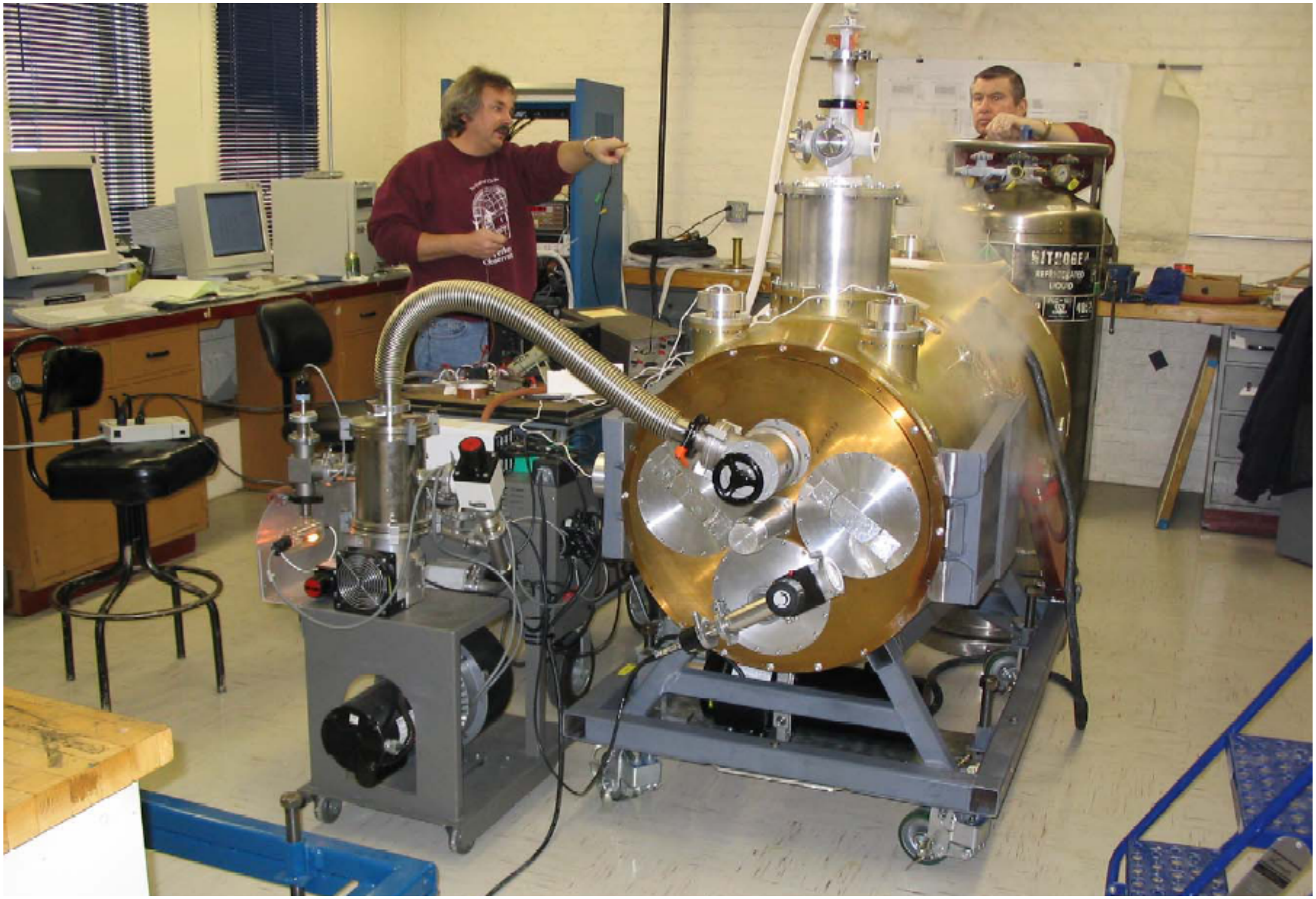
- Total 16 GHz with 250 kHz channel width (4 GHz for each of four mixers)
- Initial half (8 GHz) delivered in May 2009, remainder in March 2010
- IF system designed – IQ mixer downconverter – prototype in use in lab
- Astronomical demonstration at CSO in October 2009
- Flight IF processor on order, delivery expected in March 2010
- Further astronomical tests of complete system in 2010



HAWC

Al Harper: Univ. of Chicago, PI

HAWC



HAWC Spectral Passbands

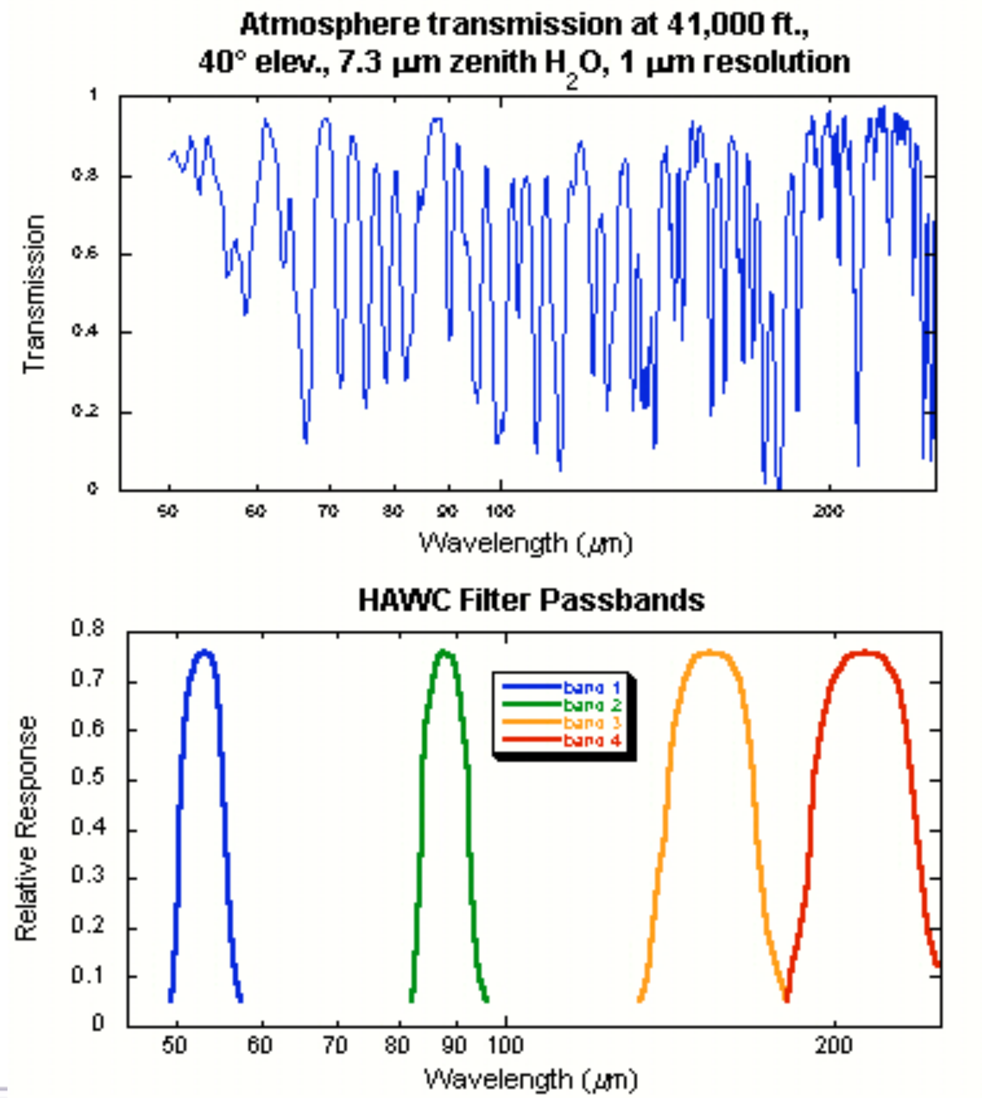
Wavelength range: **50 - 240 μm**

Four bandpass filters:

Band No.	λ_o	R = $\lambda_o/\Delta\lambda$
1:	58 μm	10
2:	88 μm	10
3:	155 μm	6.7
4:	215 μm	5

Each passband is observed separately; time to change passbands is roughly 2 minutes.

Reimaging optics provide match to diffraction limit in each passband (data on page 3).



HAWC Angular Resolution

SOFIA

Beam size shown is the instrument FWHM size for nominal operating conditions

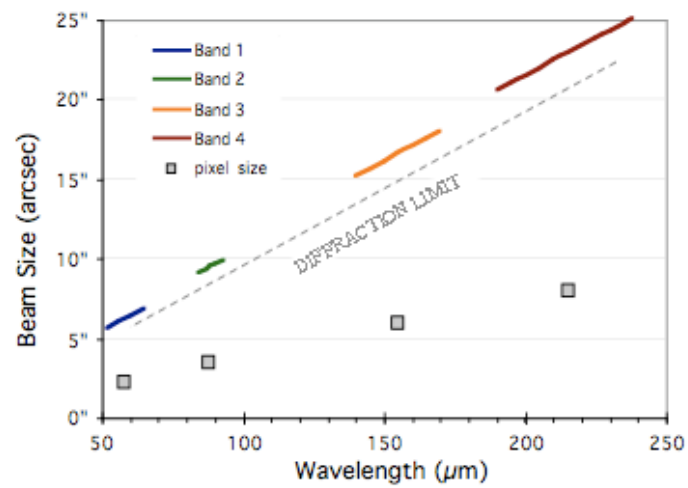
Format: 12 x 32 pixel array

2.25" pixel: ▪ — λ 58 μm — FOV: 27" x 72"

3.5" pixel: ▪ — λ 88 μm — FOV: 42" x 112"

6.0" pixel: ▪ — λ 155 μm — FOV: 72" x 192"

8.0" pixel: ▪ — λ 215 μm — FOV: 96" x 256"



Notes:

(1) Angular resolution shown is the root sum square of the pixel size and the diffraction limit.

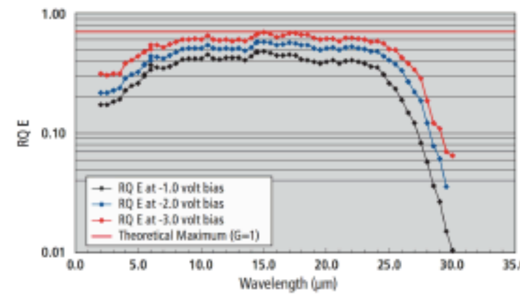
(2) SOFIA and all first light focal-plane instruments are now in development. All sensitivity and resolution data are preliminary, and based on anticipated performance of the observatory and the instruments. Actual performance of the SOFIA telescope and instrument combination will be established after flight operations begin. Telescope performance is expected to be upgraded during the first two years, and instrument performance may be upgraded, or additional modes or capabilities may be added.

PERFORMANCE ESTIMATES GIVEN HERE ARE BASED ON DATA SUPPLIED BY THE INSTRUMENT TEAMS. A POINT OF CONTACT FOR EACH INSTRUMENT IS PROVIDED.

EXES

Matthew Richter: UC Davis PI
Support from NASA Ames and U Texas

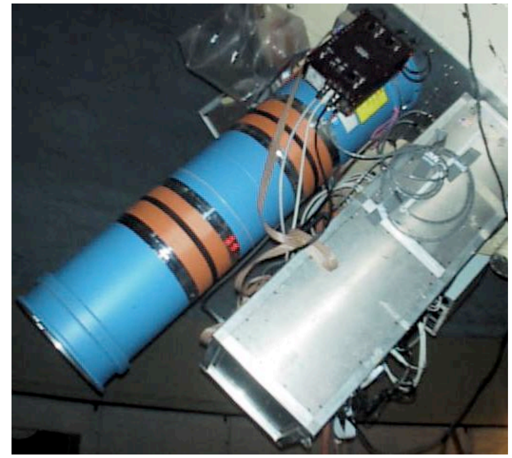
- EXES is a PI instrument optimized for high spectral resolution in mid-IR
  - High resolution mode:
    - cross-dispersed with R = 50,000 to 110,000 depending on slit width
    - single setting coverage of ~0.8% with 10-20” long slit or ~4% with 3-5” long slit
  - Other spectral modes
    - R ~ 10,000 to 20,000
    - R ~ 2000 to 4000
  - imaging for slit-positioning and pupil
- Wavelength range set by detector and science
  - shortest wavelength (~4.5 μm): CO Δv=1
  - longest wavelength (~28.3 μm): H_2 J=2-0
    - detector sensitivity likely under 10% for H_2



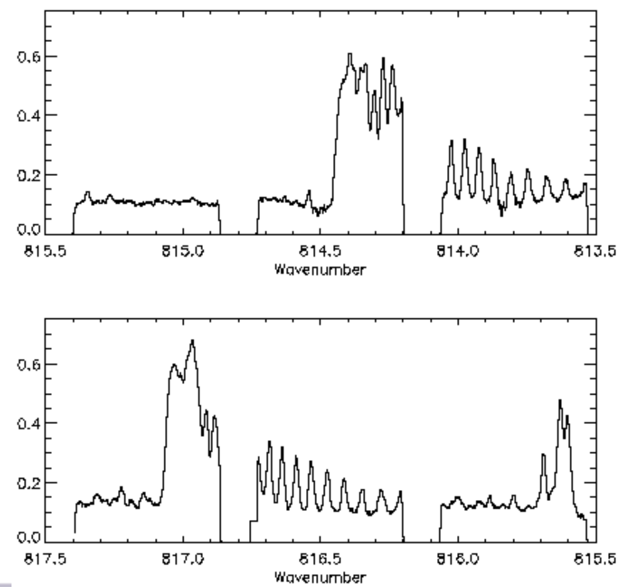
Spectral response of a device similar to EXES’s detector

Ground Based Prototype TEXES

- Many successful telescope runs at McDonald, IRTF and Gemini
  - Testbed for EXES
  - Similar gratings and optics
  - All modes work
  - Achieved R=100,000 at 10 mm
  - Data reduction pipeline
- Some preliminary results from McDonald 2.7 meter
  - H_2O emission from VY CMa
  - Mg I emission and H_2O and OH absorption in Arcturus
  - C_2H_6 emission from Jupiter's stratosphere



C_2H_6 in Jupiter

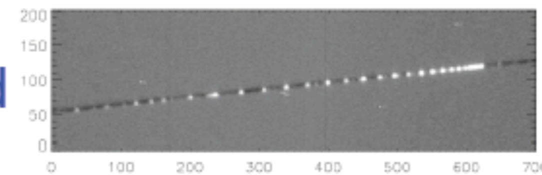


Lab Results with EXES at NASA Ames

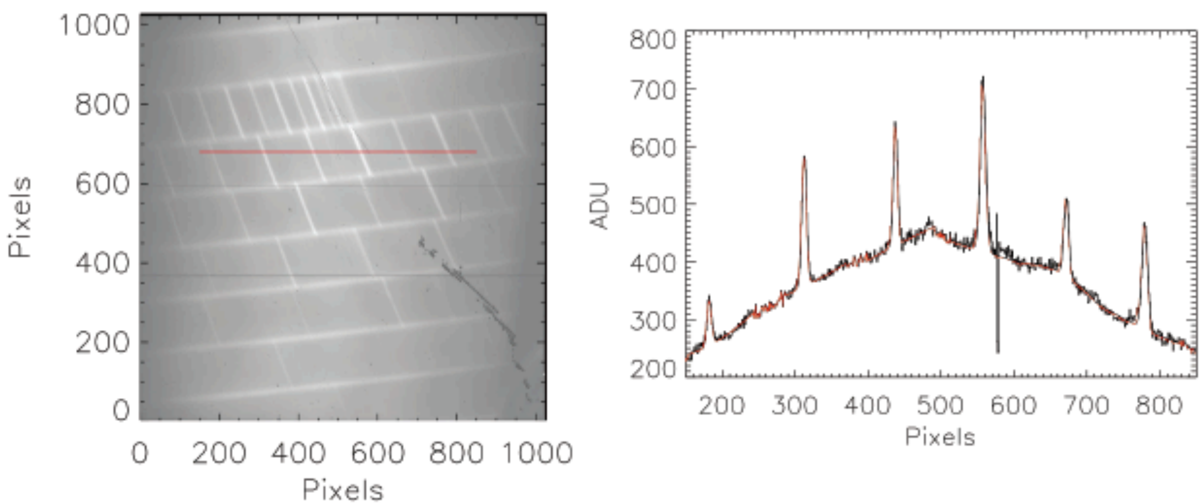
- Spectral resolution at 13.7 μm
  - medium resolution diffraction limited
  - high resolution astigmatic

    R=65,000 at circle of least confusion.

    R=110,000 at best spectral focus
    - most likely cause is cam/coll mirror



C_2H_2 Q-branch in emission from gas cell in medium resolution mode. Spots agree with diffraction convolved with pinhole



C_2H_2 Q-branch in emission from gas cell at best spectral focus. Used Gaussian fit to rows in red to determine spectral resolution

EXES Future Plans

- Will use on the IRTF this coming year
- Working with Ames to obtain a better 1024 detector

Summary and Conclusions

Summary and Conclusions

- SOFIA works as an “Observatory” in the Thermal Infrared.
- We have 8 first Generation Instruments that cover both spectroscopy and imaging.
- Results presented in the SOFIA Science Vision in 2009 and the 2020 Workshop in Dec 2007 showed that advanced instrumentation will be important for SOFIA.
- This workshop is the start of how we get 2nd Generation instruments and upgrades.

How to self organize on New Instruments

- There are poster boards around the Lecture Hall.
- Groups can self organize to produce a plan for a new instrument or upgrade.
- The results can be shown in 10 min presentations to the meeting during Tom Roellig’s talk late on Tuesday afternoon (~4:30)

Back-up

Instrument/ Location	PI	Instrument Type
HIPO/Lowell	Dunham	.3-1.1 μm High Speed Occultation Camera
FLITECAM**/ UCLA	McLean	1-5.5 μm Infrared Camera and IR channel for HIPO
FORCAST**/ Cornell	Herter	Faint Object Infrared Camera. Simultaneous Dual channel observations (5-25 μm & 25-40 μm)
GREAT/MPI-Bonn	Güsten	Hi resolution ($R> 10^6$) Heterodyne Spectrometer 3 bands - 1.6-1.9 THz; 2.4-2.7 THz; 4.7 THz
FIFI-LS**/ MPI Garching	Poglitsch	Dual Channel (42-110 μm ; 100-210 μm) Grating Spectrometer
HAWC**/ UChicago	Harper	High Angular resolution 4 channel Camera @ 50 μm, 100 μm, 160 μm, 200 μm
CASIMIR/ Caltech	Zmuidzinas	Hi resolution ($R\sim 10^6$) Heterodyne Spectrometer 500-2000 GHz
EXES/UT,UC	Richter	5-28 μm-High resolution grating spectrometer (R>100,000)
Davis, Ames		

** Facility Instruments

SOFIA and Spitzer

- SOFIA will become operational after Spitzer runs out of cryogens. The science impact of not being contemporary is small: Spitzer is a high sensitivity imaging and low resolution spectroscopy mission. SOFIA is a high spectral and high angular resolution mission.
- As it now stands, the two observatories are very complementary and now that Spitzer has run out of cryogens, SOFIA will be the only observatory working in the 28 to 60 micron region for over 10 years: Comets, Supernovae, Variable AGN, other discoveries.

SOFIA and Herschel

* SOFIA will now start after Herschel
- Joint calibration work is on going
- For the years of overlap, SOFIA will be only program
  - with 25 to 60 micron capability
  - with high resolution spectroscopy in the 60 to 150 micron region
- When cryogens run out in Herschel in early 2013. SOFIA will be only NASA mission in 25 to 600 micron region for many years
  - Important follow-up
  - Advanced instrumentation will give unique capabilities to SOFIA: Polarization, Heterodyne Arrays, Heterodyne Spectroscopy at 28 microns (ground state of molecular hydrogen), and other interesting astrophysics lines
- Both missions are critically important and complementary

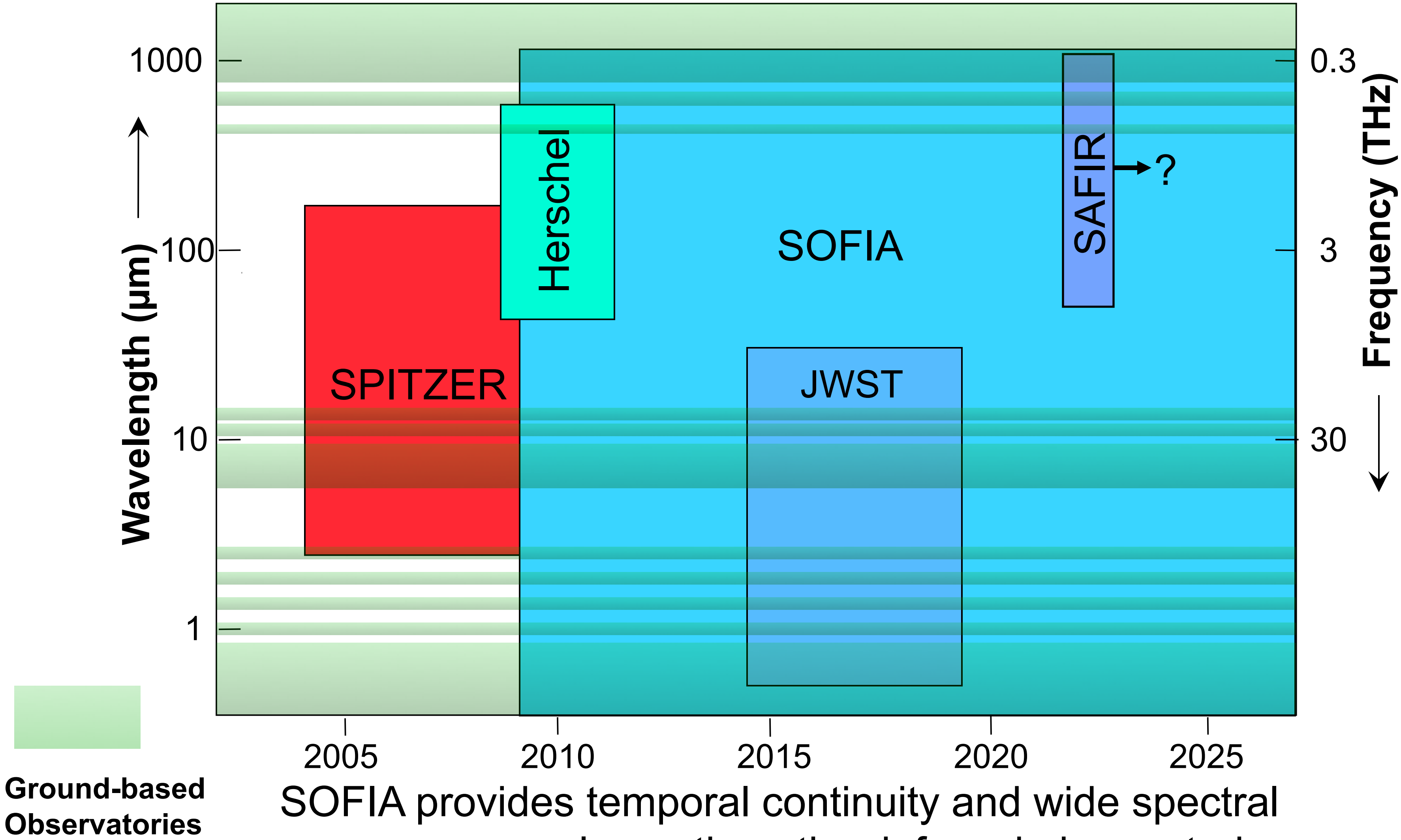
SOFIA and JWST

- SOFIA is very complementary to JWST
- Before JWST is deployed and after Spitzer cryogens run out , SOFIA is only mission with 5 to 8 micron capabilities
  - important organic signatures
- After JWST is launched SOFIA is the only mission to give complementary observation beyond 28 microns and high resolution spectroscopy in 5 to 28 micron region

SOFIA and WISE

- WISE is a very sensitive all sky survey in the 3.3 to 23 micron region which launched in Dec 09.
- SOFIA can provide a number of important follow up observations.
  - Very red sources seen only at 23 microns can be followed up at 38 microns with FORCAST on SOFIA and spectra can be obtained with EXES on SOFIA for the brightest 23 micron sources not seen by IRAS.
  - Nearby cold Brown Dwarfs discovered by WISE can be followed up with the FLITECAM GRISM and EXES.

Infrared Space Observatories



SOFIA provides temporal continuity and wide spectral coverage, complementing other infrared observatories.

SOFIA First Generation Spectroscopy