FORCAST

Faint Object Infrared Camera for the SOFIA Telescope

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with lots of help from

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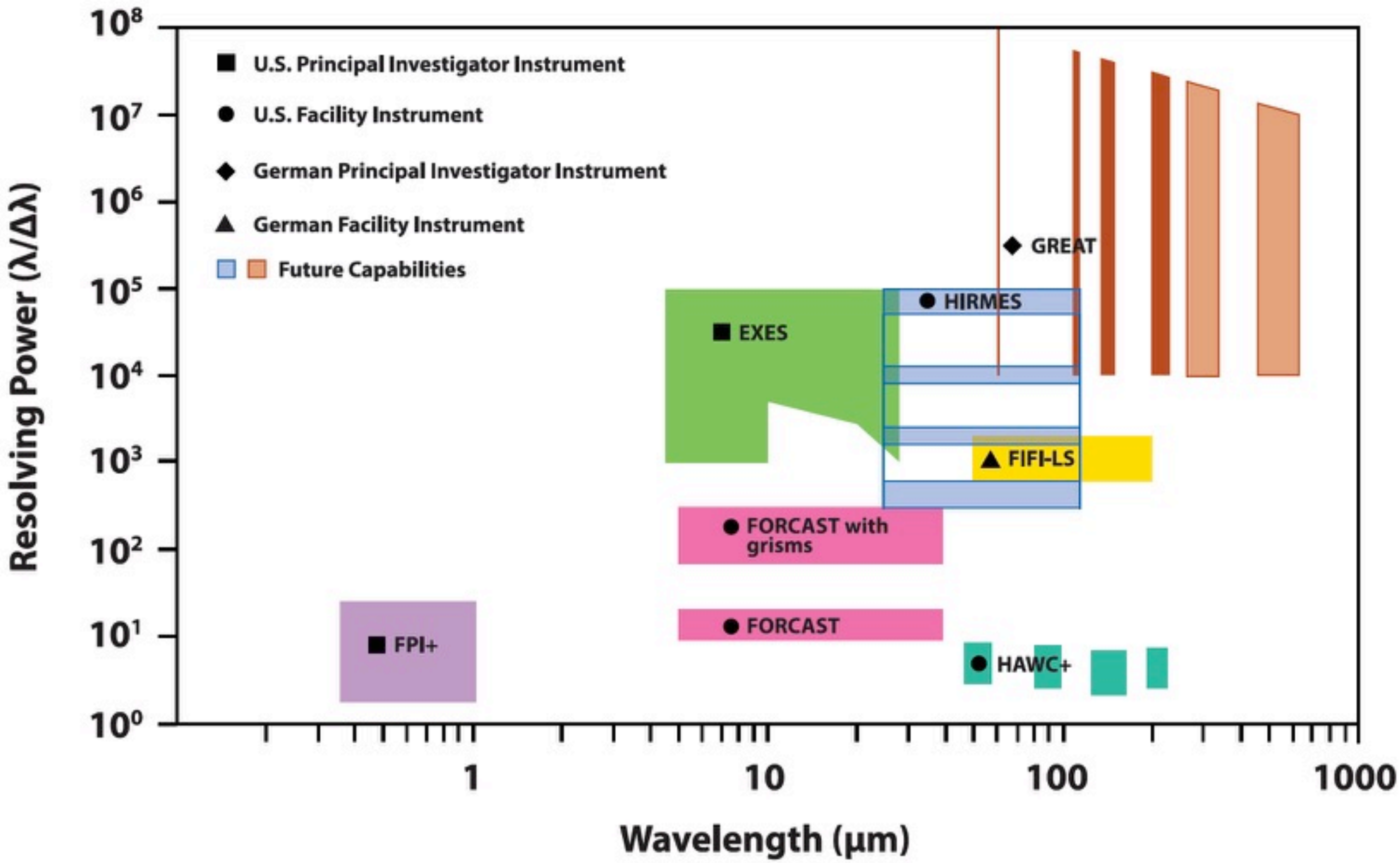
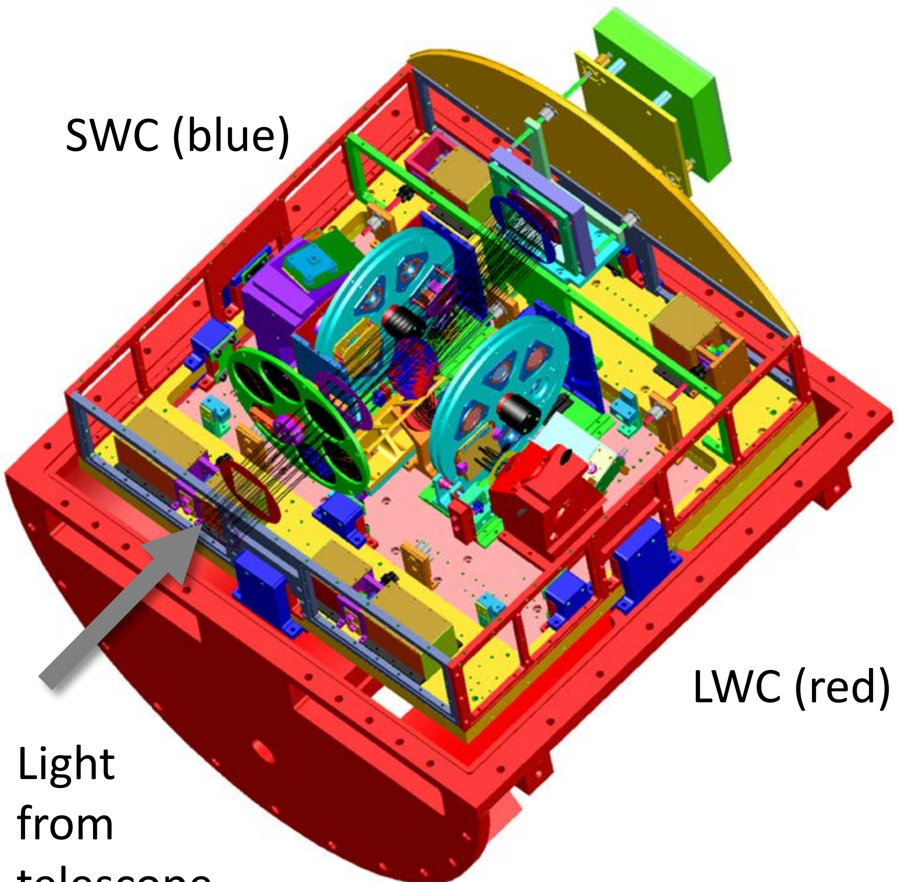
Wanggi Lim, Jim de Buizer

SOFIA Workshop, 2-4 May 2018, DSI Universität Stuttgart

Instrumentation



FORCAST (I)

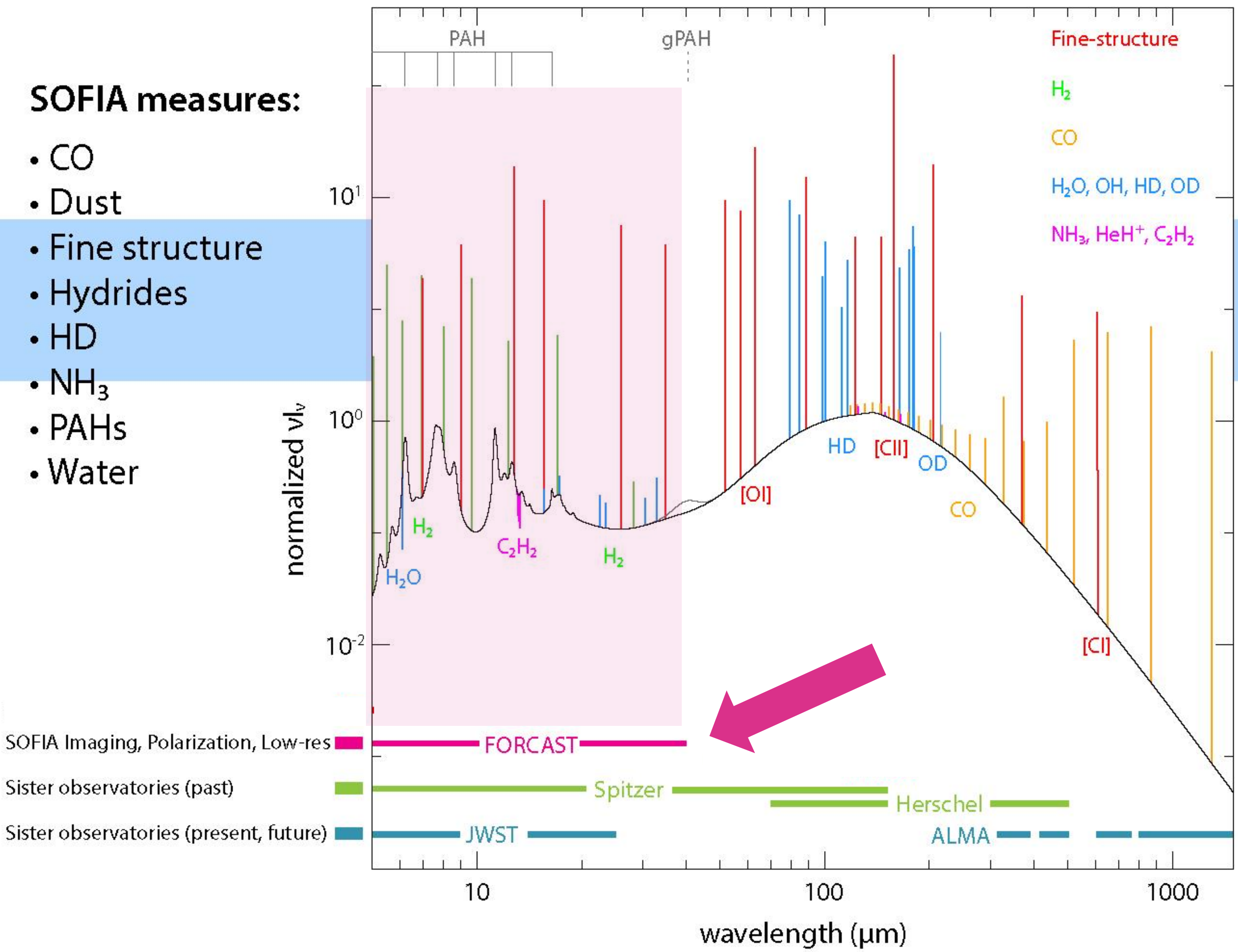


- PI: Terry Herter (Cornell)
- 1st Generation Instrument
- Wide field (3.4' x 3.2' FOV) dual channel camera and spectrograph 5-40 µm
- Two 256x256 arrays with 0.768" pixels
- SWC: Si:As BIB array 5-25 µm
- LWC: Si:Sb BIB array 25-40 µm
- 4 Grisms with 2 long slits provide low resolution (R~70-300) spectroscopy over 5-40 µm

SOFIA Covers a Lot of IR Real Estate

SOFIA measures:

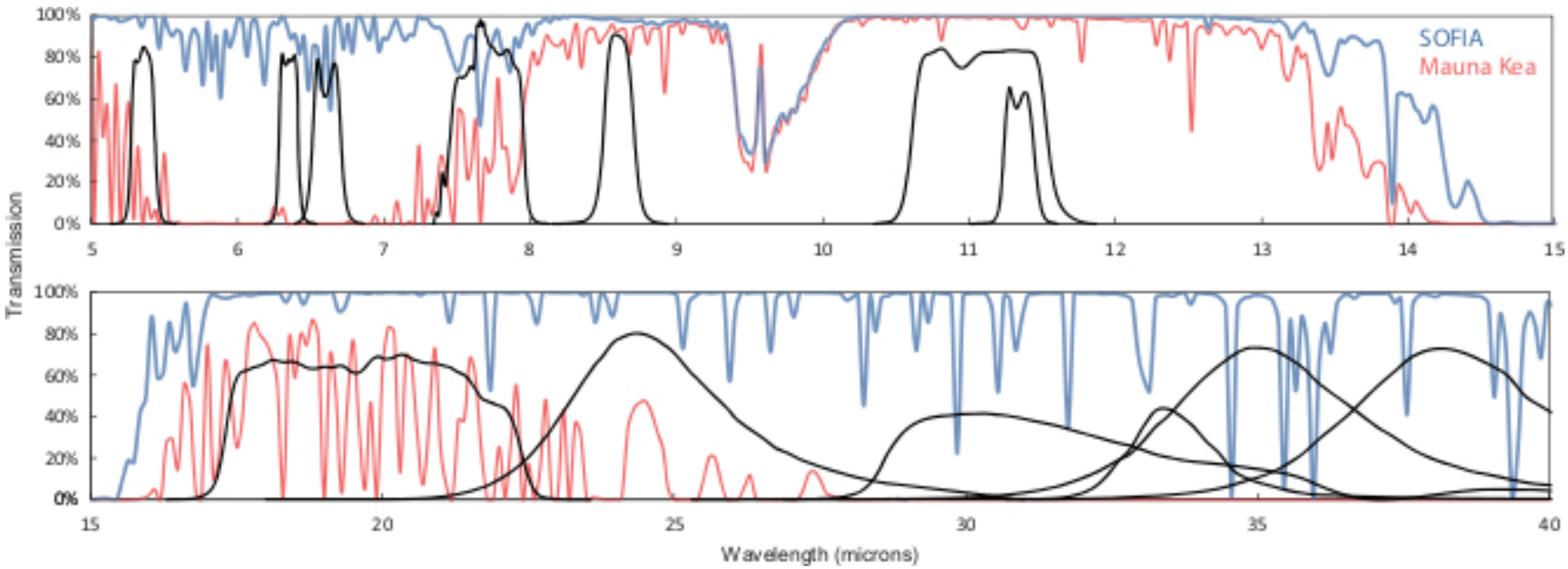
- CO
- Dust
- Fine structure
- Hydrides
- HD
- NH_3
- PAHs
- Water



To determine:

- Age
- Composition
- Density
- Gas Dynamics
- Magnetic fields
- Pressure
- Shocks
- Temperature

FORCAST Filter Profiles

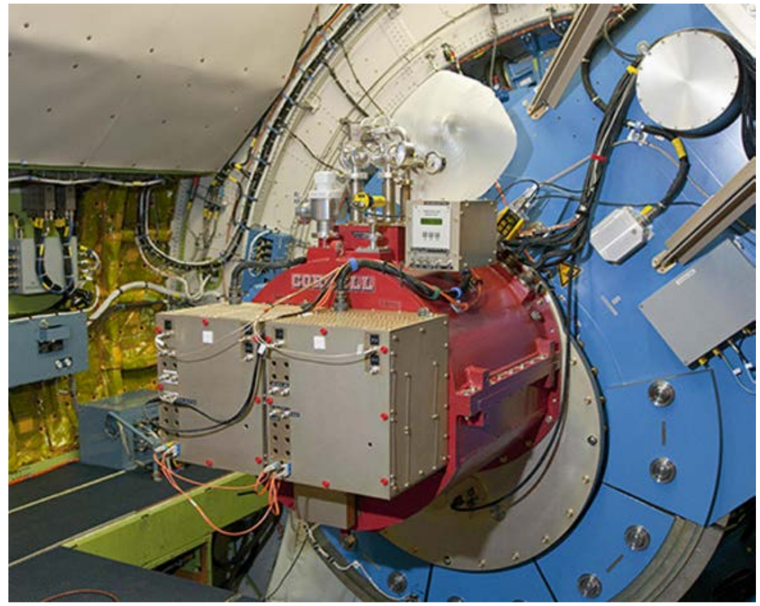


SOFIA : 41000 ft, 7.3 µm PWV, 45° ZA
Mauna Kea: 13800 ft, 3.4 mm PWV, 45° ZA

FORCAST (II)

Filter Parameters

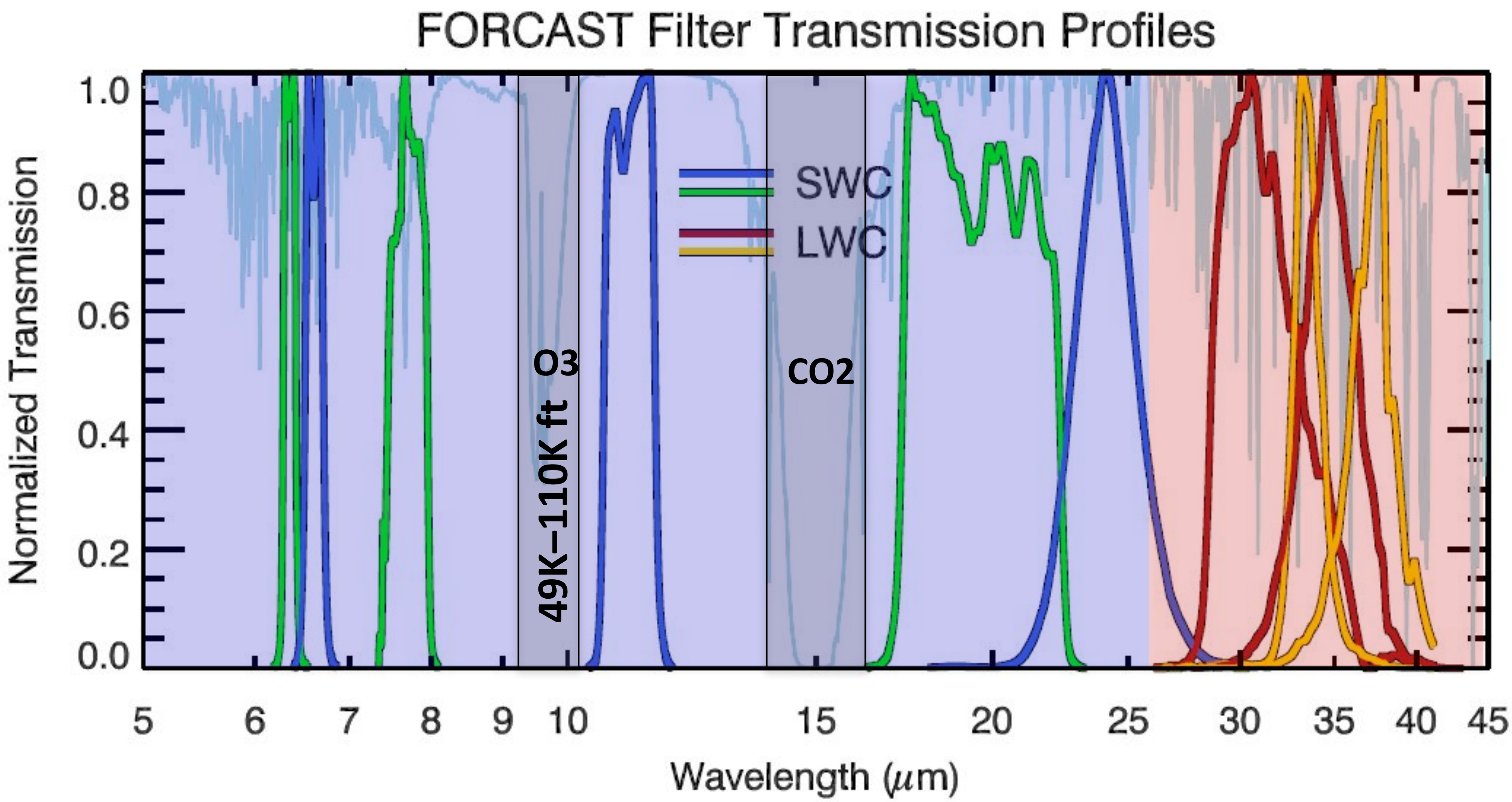
SWC Filters		LWC Filters	
λ_{eff} (µm)	Δλ (µm)	λ_{eff} (µm)	Δλ (µm)
5.4	0.16	24.2	2.9
5.6	0.08	31.5	5.7
6.4	0.14	33.6	1.9
6.6	0.24	34.8	3.8
7.7	0.47	37.1	3.3
8.8	0.41	A subset of these will be chosen each cycle as the nominal set.	
11.1	0.95		
11.2	2.7		
11.3	0.24		
11.8	0.74		
19.7	5.5		
25.4	1.86		



Grism Details

Grism	Coverage (µm)	R (λ/Δλ)[a]
G063	4.9–8.0	120[c]/180
G111	8.4–13.7	130[c]/260
G227	17.6–27.7	110/120
G329	28.7–37.1	160/170[b]

[a] For the 4.7”x191” and the 2.4”x191” slits, respectively.
[b] The resolution of the long, narrow-slit modes is dependent on (and varies slightly with) the in-flight IQ.
In Cycle 7 only low spectral resolution modes will be offered



- The dichroic is designed to transmit light at wavelengths greater than 25 microns, and reflect light less than 25 microns

Table 2: FORCAST Filter Characteristics

Channel	λ_{eff} (μm)	$\Delta\lambda$ (μm)	Imaging FWHM ($''$)		Spectral Features of Note
SWC	6.4	0.14	3.0	3.5	6.3µm PAH feature
	6.6	0.24	2.9	3.5	Continuum reference for PAH
	7.7	0.47	2.7	3.5	7.7µm PAH feature
	11.1	0.95	2.7	3.6	N-band substitute (11.3µm PAH)
	19.7	5.5	2.9	3.8	Q-band sub, Am. Silicate feature
	24.2	2.9	3.3	4.0	24.3µm [Ne V] line
LWC	31.5	5.7	3.4	4.3	
	33.6	1.9	–	4.5	33.5µm [S III] line
	34.8	3.8	3.6	4.5	Crystalline Silicate feature
	37.1	3.3	3.5	4.7	

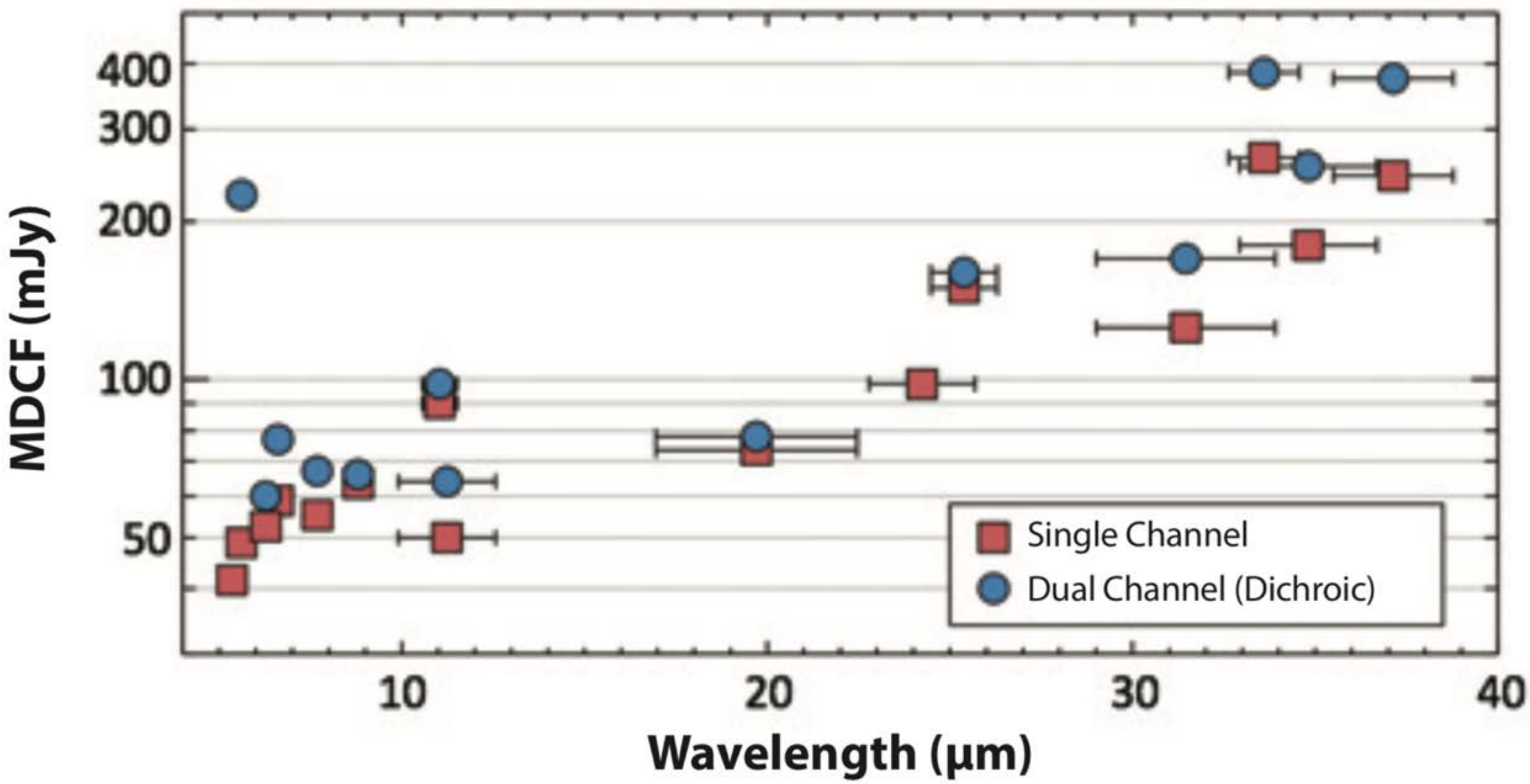
FWHM values for 2 estimates of the telescope jitter, 1.25” and 2.1”

Filters and Dichroic

Channel	λ_{eff} (μm)	$\Delta\lambda$ (μm)	
SWC	6.4	0.14	
	6.6	0.24	~60%
	7.7	0.47	
	11.1	0.95	
	19.7	5.5	~85%
	24.2	2.9	
LWC	31.5	5.7	
	33.6	1.9	~40%
	34.8	3.8	
	37.1	3.3	

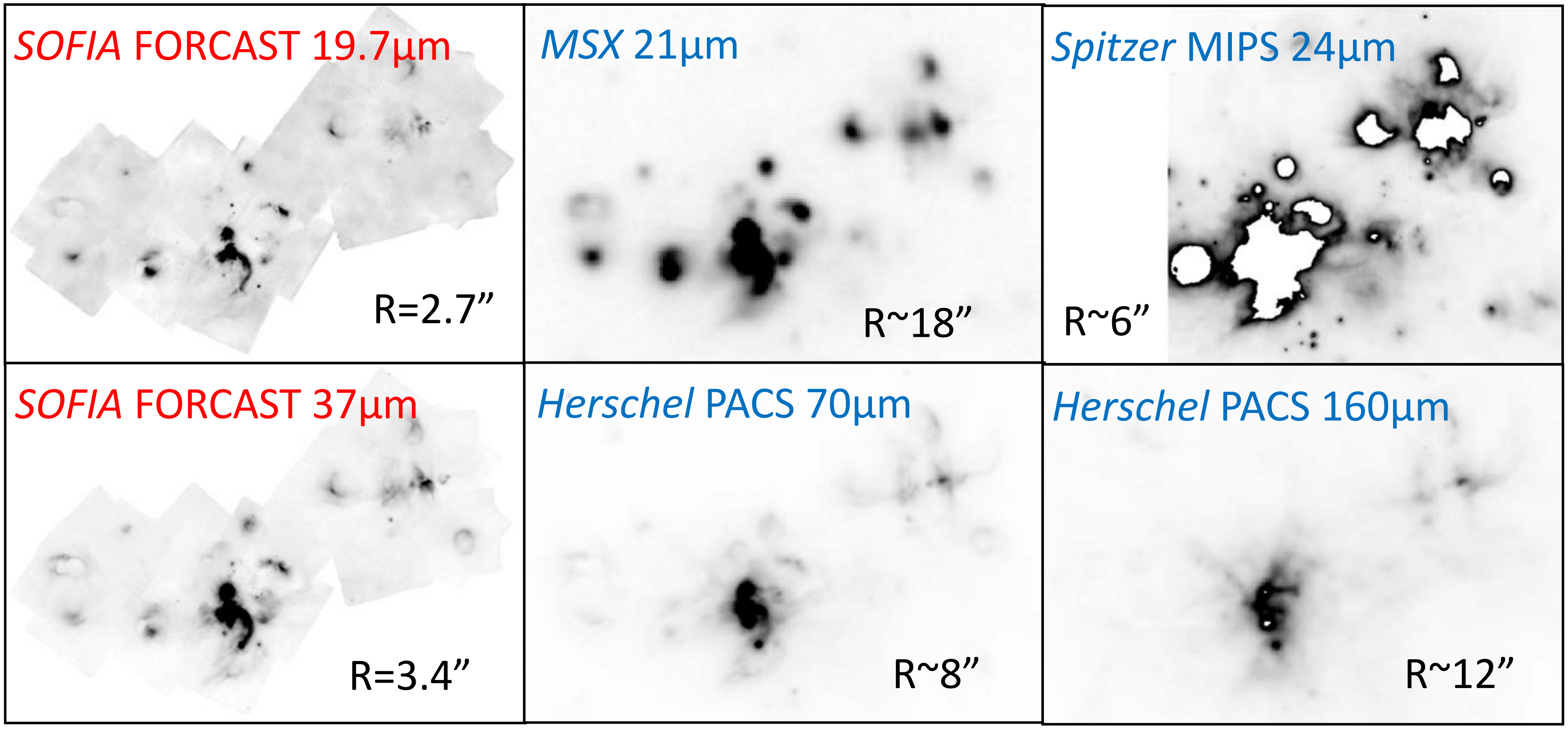
- Dual channel mode allows simultaneous imaging at two wavelengths
- However, there is decreased throughput compared to single channel mode

Imaging Sensitivity



- S/N=4 in 900s, 41000 feet, single channel mode; larger limiting fluxes with dichroic
- Altitude/water vapor affect sensitivity more in the LWC
- In preparing your FORCAST observations, you can use SITE, the online integration time estimator

Spatial Resolution: W51A Maps



Maps provided by Wanggi Lim

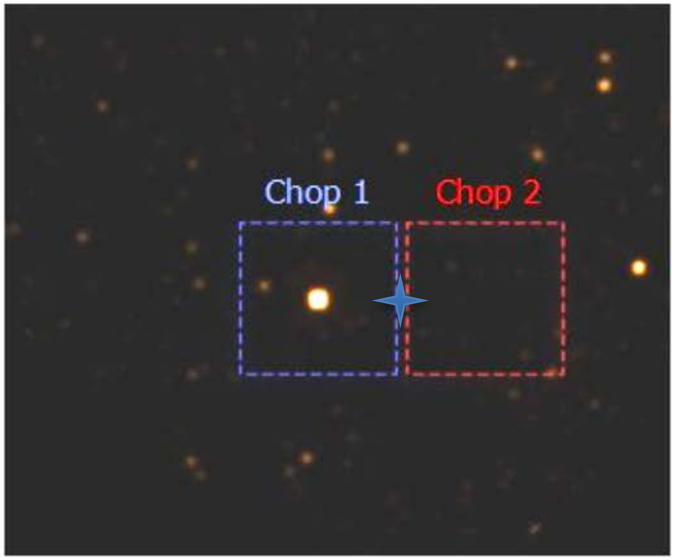
- Highly sensitive space telescopes (e.g.. Spitzer, WISE) are saturated on the W51A main region.
- The 19.7 & 37.1um bands are mostly free from PAH feature and allow to trace the dust continuum.
- SOFIA can chop up to 10 arcmin, allowing it to observe extended bright regions.

Chop/Nod Technique

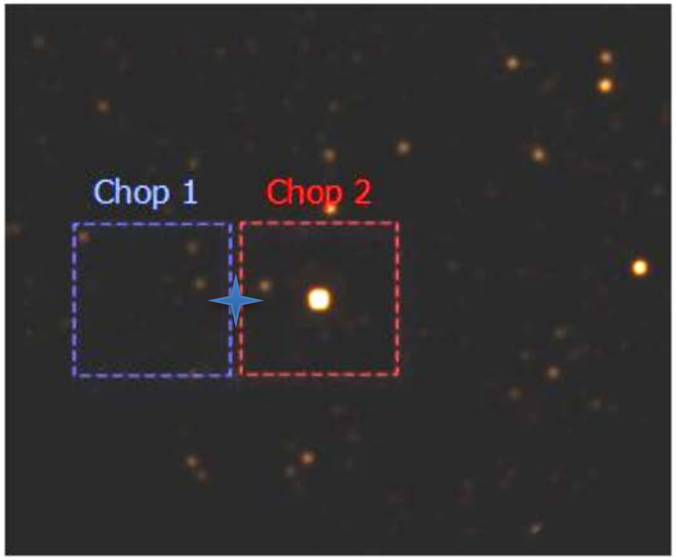
- MIR observations are completely background (sky+telescope+instrument) limited
  - Background can be >10^6 times brighter than most sources
  - Detector wells can fill in 1-100 msec
- MIR background varies rapidly (order of less than a few sec)
- To subtract majority of the background the secondary is tilted between on-source and off-source positions (chopping) at a rapid rate (~few Hz)
- However, chopping introduces small additional offsets (radiative offset) due to the different optical paths for the beams in the two chop positions
- To remove radiative offset, telescope is moved to another position (nodding) and the chop is repeated
  - Nods on a timescale of ~30 sec,
- The two images from the chop positions are subtracted, and the two resulting chop-subtracted images from the two nod positions are subtracted
  - This double-differencing removes all background contributions
- One must ALWAYS chop and nod for FORCAST observations

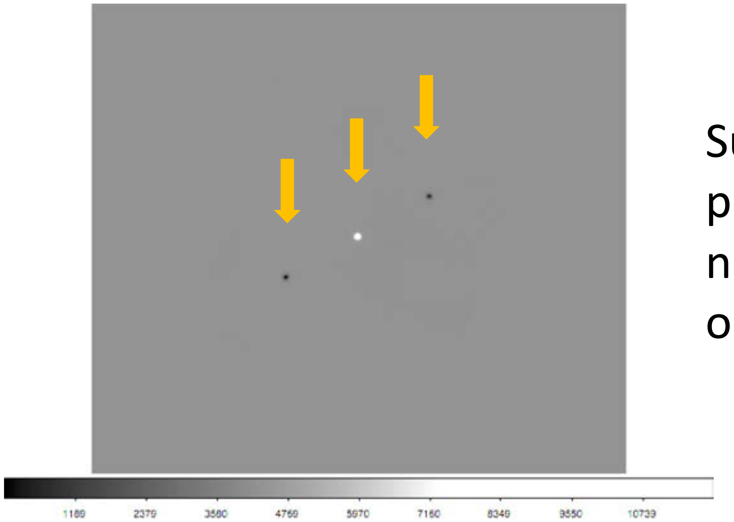
Nod_Match_Chop (Symmetric Chop) Mode

Nod A



Nod B



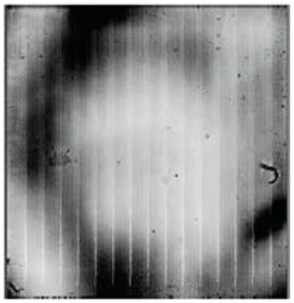


Subtracted image provides positive and negative images of the object

Nod_Perp_Chop (Symmetric Chop) Mode

Chop 1 | Chop 2 | Chop 1 – Chop 2

Nod A



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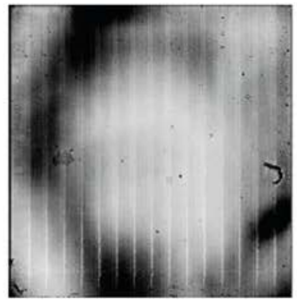

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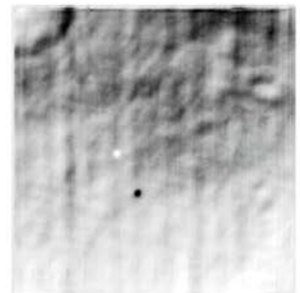
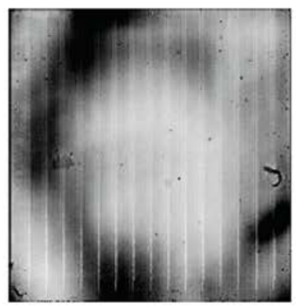


Nod B

–



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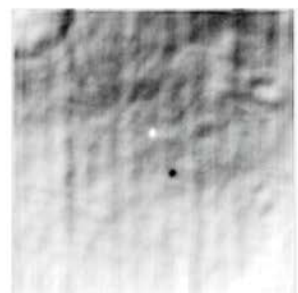
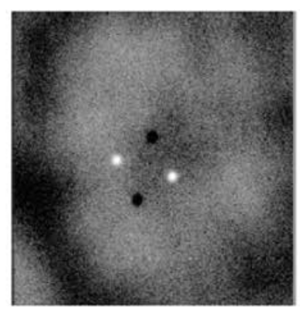


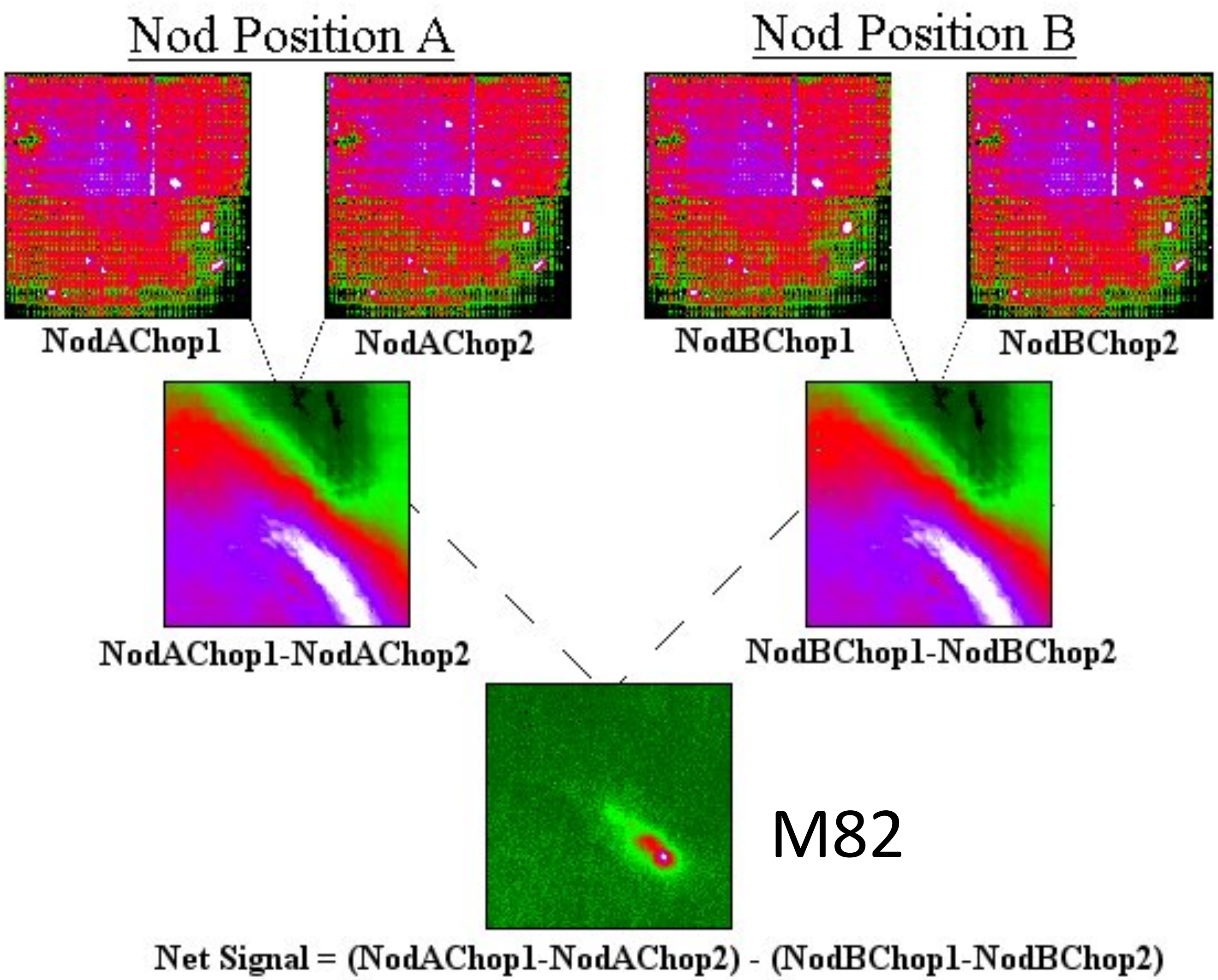
Subtracted backgrounds from sky, telescope, instrument, but still including radiative offset.

Sky+Telescope+Instrument

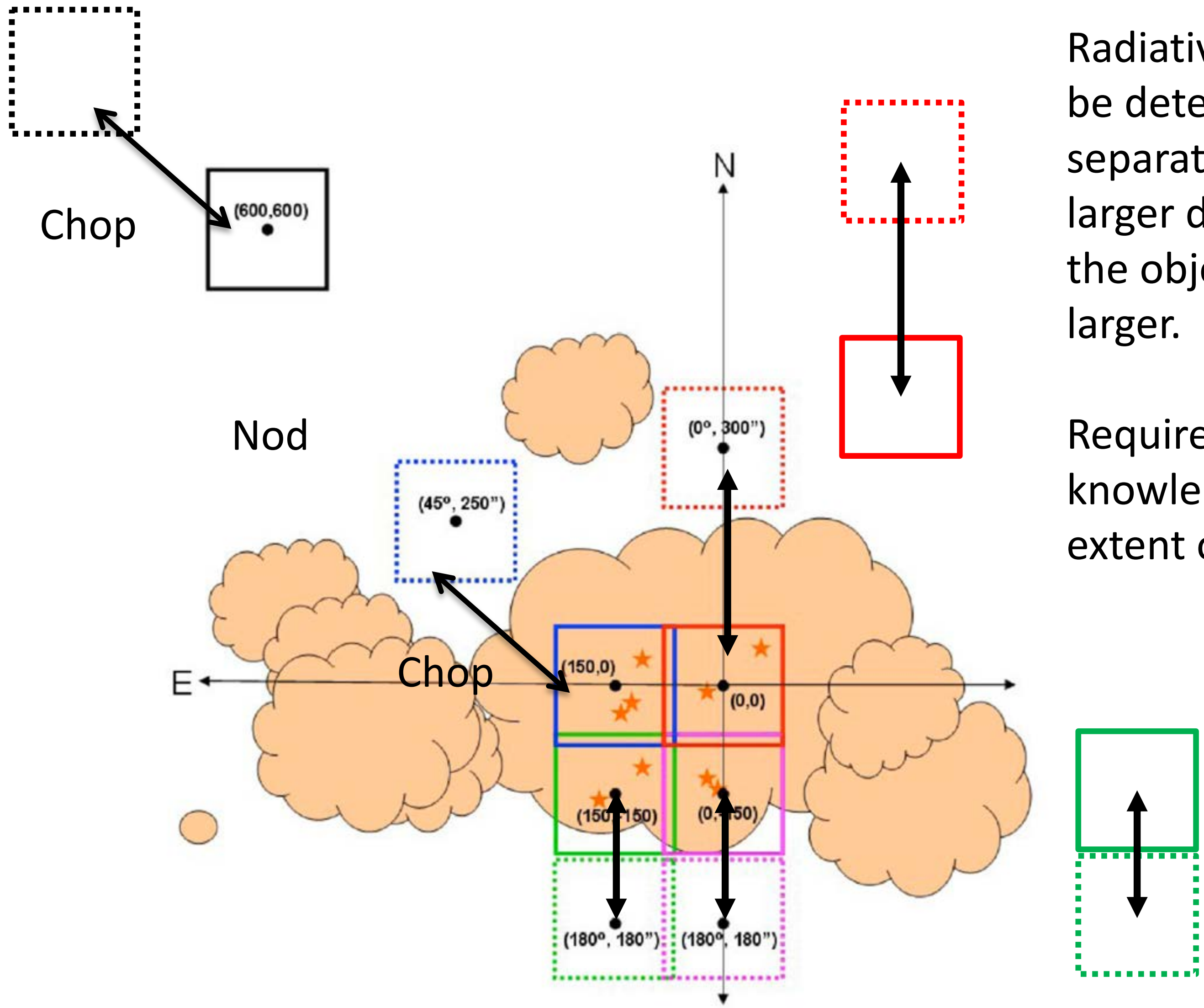
Nod A (chop 1 – chop2) – Nod B (chop 1 – chop 2) =



Now also radiative offset removed.


Nod Position A
Nod Position B
NodAChop1
NodAChop2
NodBChop1
NodBChop2
NodAChop1-NodAChop2
NodBChop1-NodBChop2
M82
Net Signal = (NodAChop1-NodAChop2) - (NodBChop1-NodBChop2)

C2NC2 (Asymmetric Chop) Mode



Radiative offset can be determined in separate nod cycle at larger distance from the object if that is larger.

Requires prior knowledge about extent of that object.

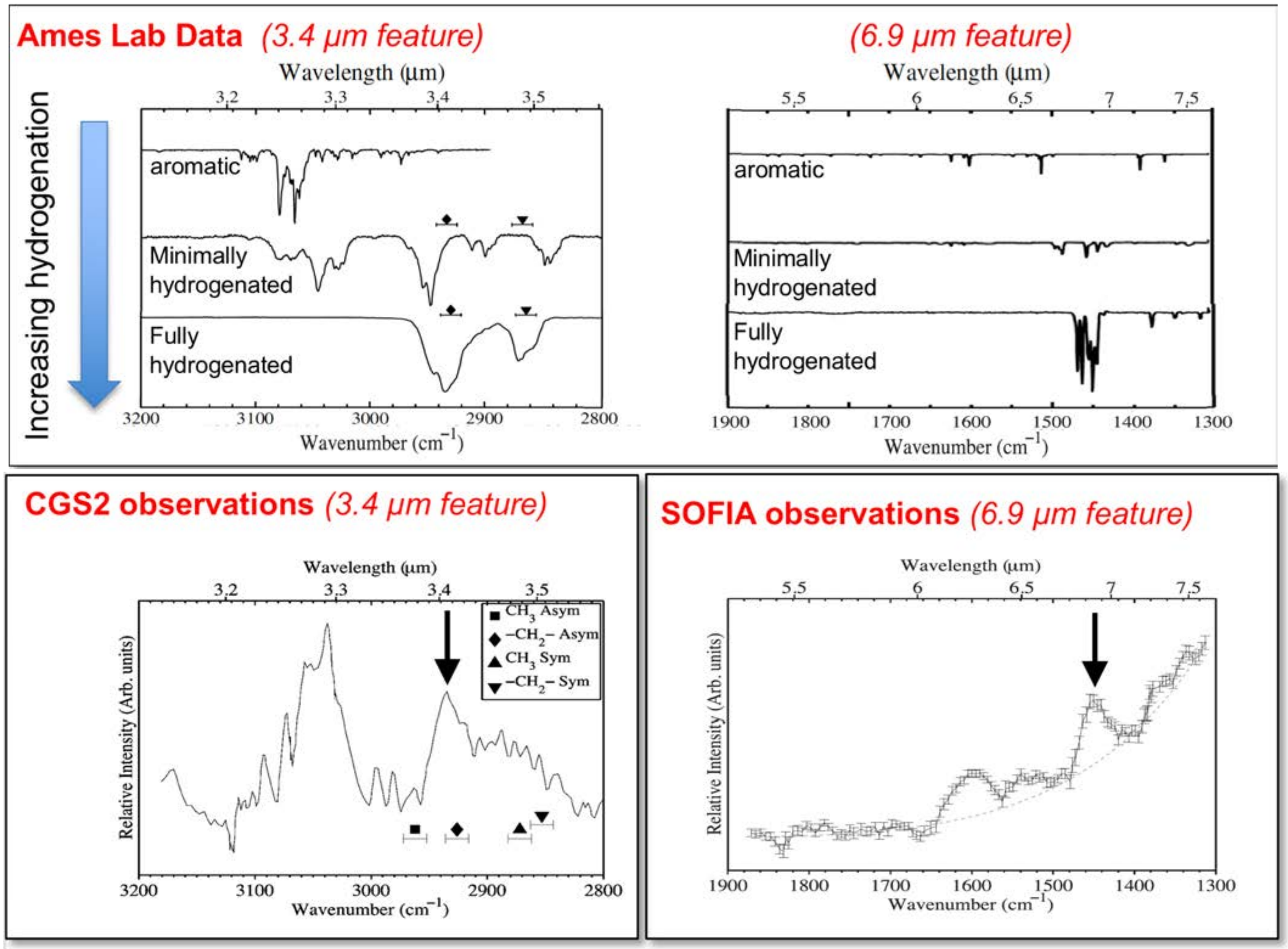
FORCAST Grisms and Slits

Grism	Wavelength	Slit	Resolving Power
Long Slit Spectroscopy in the Short Wavelength Camera			
G1	4.7-7.8 µm	2.4”x192”	200
		4.7” x192”	100
G3	8.4-13.7 µm	2.4” x192”	300
		4.7” x192”	150
Long Slit Spectroscopy in the Long Wavelength Camera			
G5	17.6-27.7µm	2.4”x192”	140
		4.7” x192”	70
G6	28.7-37.1µm	2.4” x192”	220

Notes:

- Grism spectroscopy available only in single-channel mode
- There is NO field de-rotator, so orientation of slit on sky is dependent on flight plan

Testing PAH Theory



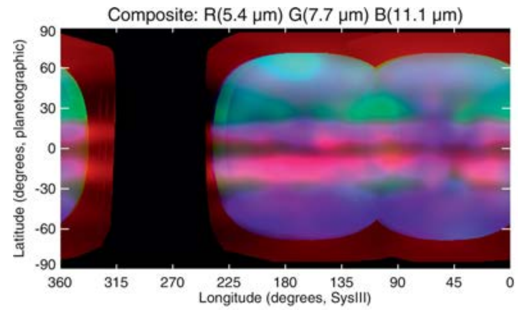
- Testing H_n-PAH hypothesis
- Highly hydrogenated PAHs as source for 3.4 µm feature requires presence of methylene (-CH2-) scissoring modes at 6.9 µm.
- High hydrogenation affects both the lifetime and chemistry of the PAHs.

Materese+2017

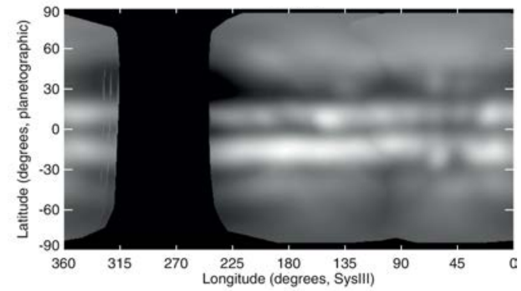
The interpretation of this astronomical data would not have been possible without lab data.

FORCAST – Planetary Atmospheres

"Jupiter's Para-H_2 Distribution from SOFIA/FORCAST and Voyager/IRIS 17-37 μm Spectroscopy", Fletcher+2017



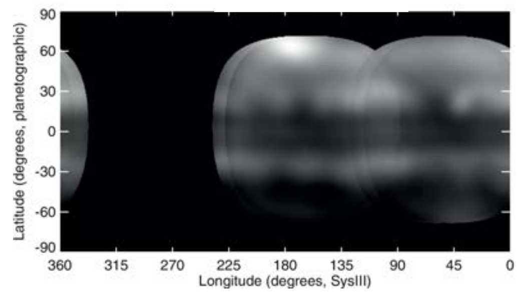
5.4 μm



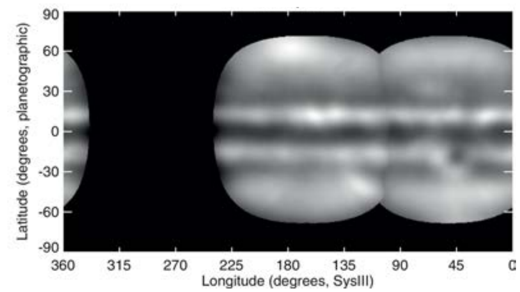
Atmospheric Composition:

- 5.4 μm – radiance
- 7.7 μm – methane
- 11.1 μm – ammonia and ethane

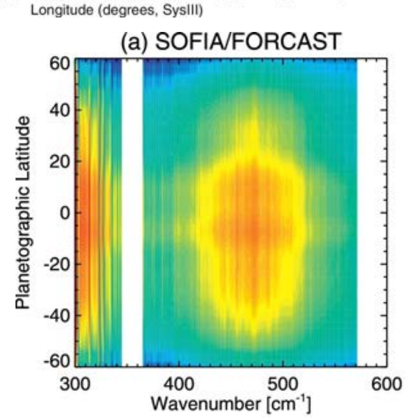
7.7 μm

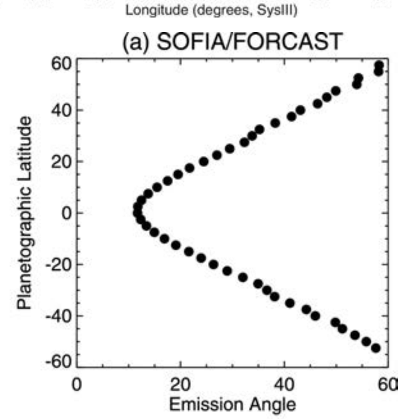


11.1 μm



Slitscan mapping from 5-35 μm allow tracing of S(0) and S(1) transitions of para-H_2, revealing vertical mixing within the upper atmosphere.

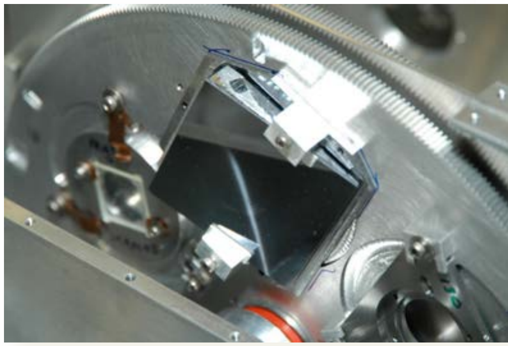


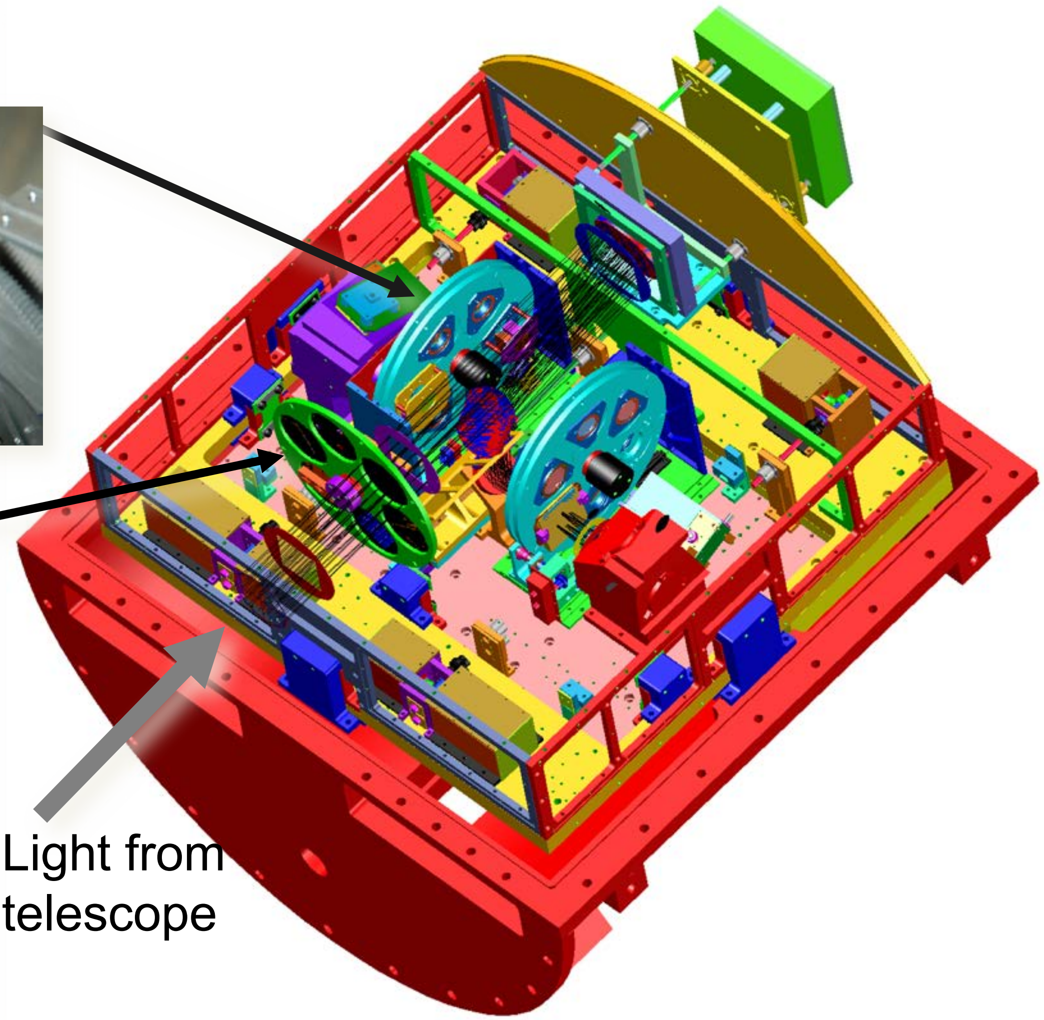


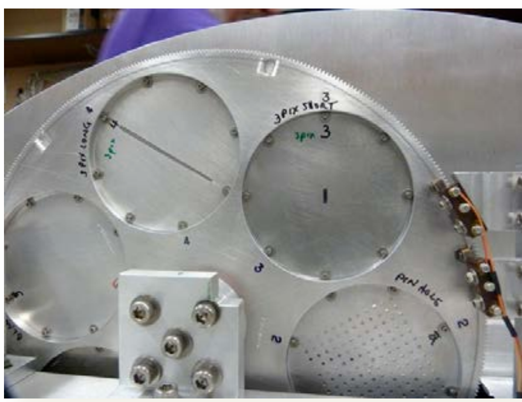
33.3 μm 16.7 μm

FORCAST grism design overview: layout

Grisms in existing imaging filter wheels

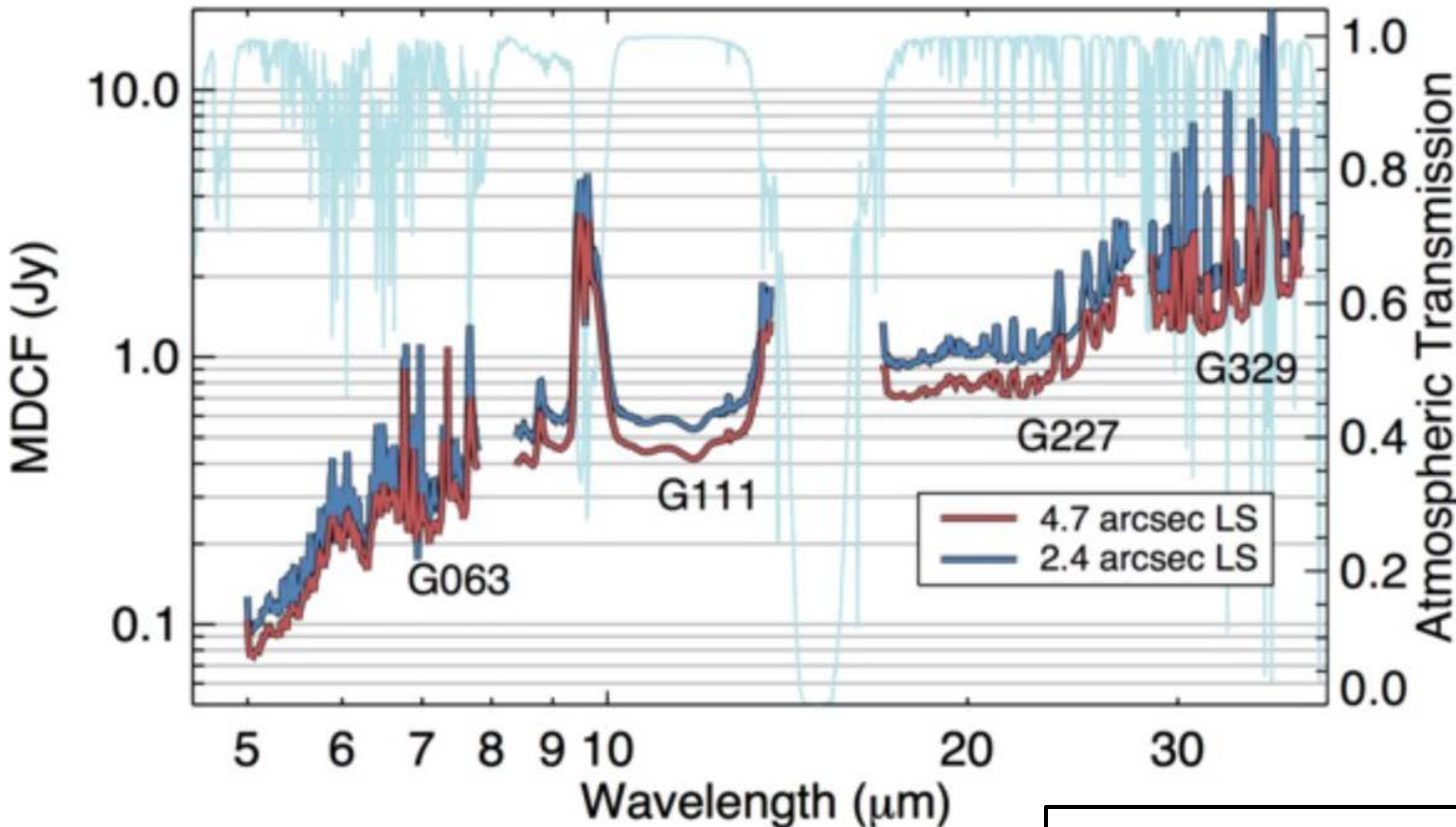






Slits in existing aperture wheel

FORCAST Grism Sensitivities



Cross Dispersed spectroscopy not offered!

- S/N=4 in 900s at 41000 feet (7μm water vapor)

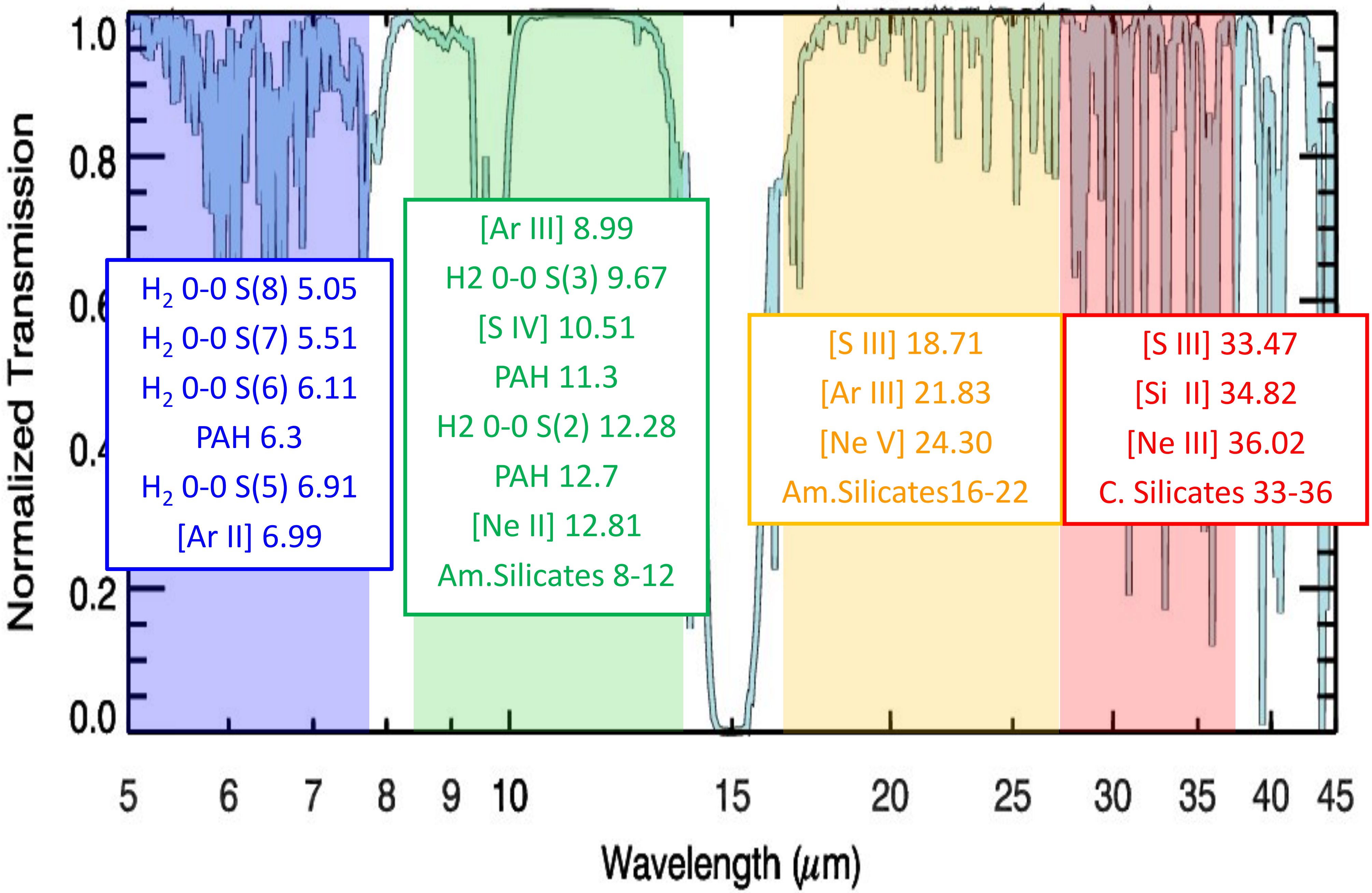
Long Slit Point Source Sensitivities

Table 5-5.

Long Slit Point Source Sensitivities							
		4.7" Slit			2.4" Slit		
Grism	λ (μm)	R = (λ/Δλ)	MDCF (mJy)	MDLF (W m^{-2})	R= (λ/Δλ)	MDCF (mJy)	MDLF (W m^{-2})
FOR_G063	5.1	120	79	2.3E-16	180	98	2.9E-16
FOR_G063	6.4	120	219	5.2E-16	180	268	6.3E-16
FOR_G063	7.7	120	496	5.2E-16	180	724	6.3E-16
FOR_G111	8.6	130	419	4.9E-16	300	532	6.2E-16
FOR_G111	11.0	130	449	4.1E-16	300	575	5.2E-16
FOR_G111	13.2	130	593	4.5E-16	300	764	5.8E-16
FOR_G227	17.8	110	715	8.6E-16	140	936	1.1E-15
FOR_G227	22.8	110	834	7.9E-16	140	989	9.3E-16
FOR_G227	27.2	110	1979	1.6E-15	140	2586	2.0E-15
FOR_G329	28.9	160	1365	6.5E-16	220[a]	1899	9.0E-16
FOR_G329	34.1	160	1408	5.6E-16	220[a]	1994	8.0E-16
FOR_G329	37.0	160	1763	5.6E-16	220[a]	2439	8.0E-16

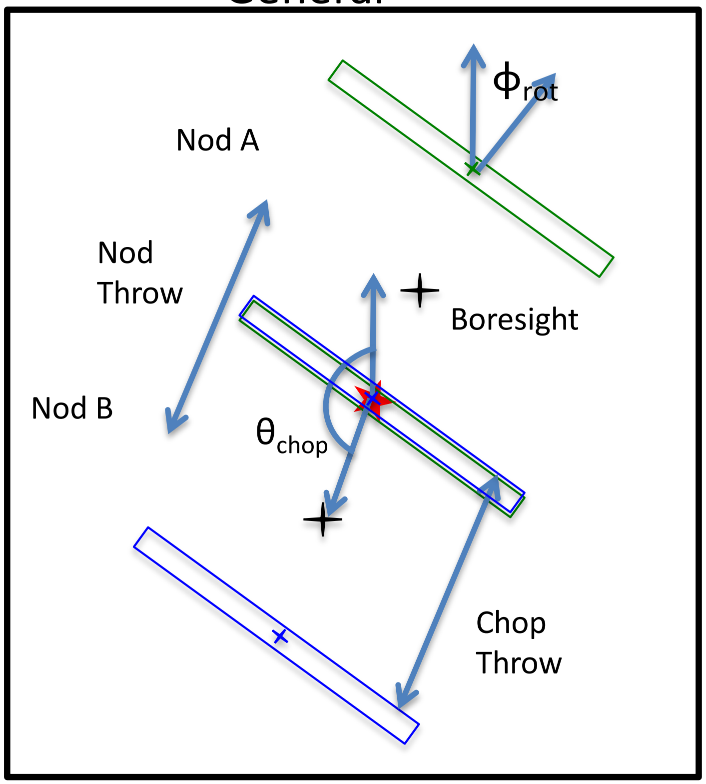
[a] The 2.4 arcsec long slit mode for G329 will not be available during Cycle 6.

Spectral Features of Interest

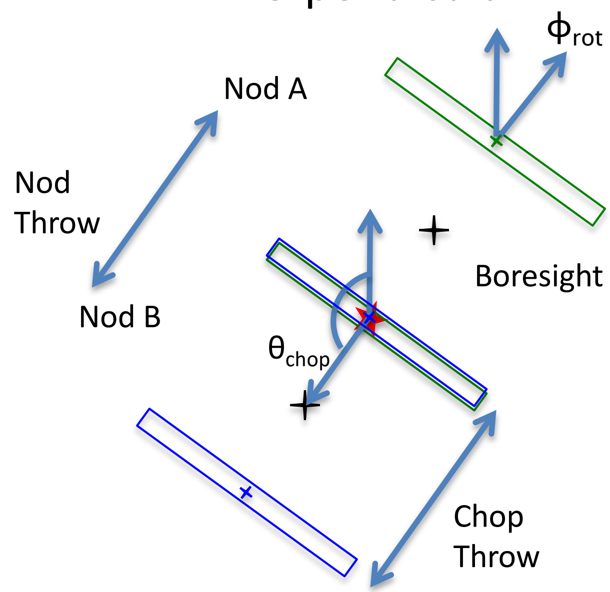


Grism Observing Modes: NMC

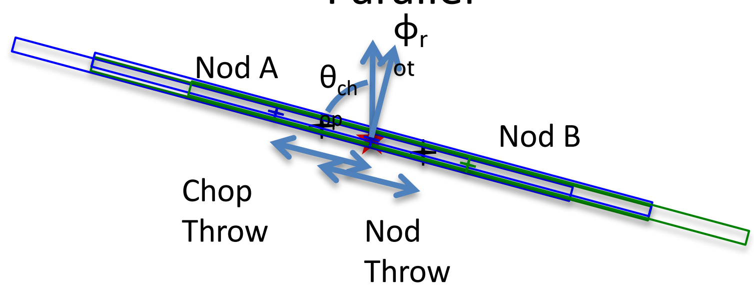
General



Perpendicular

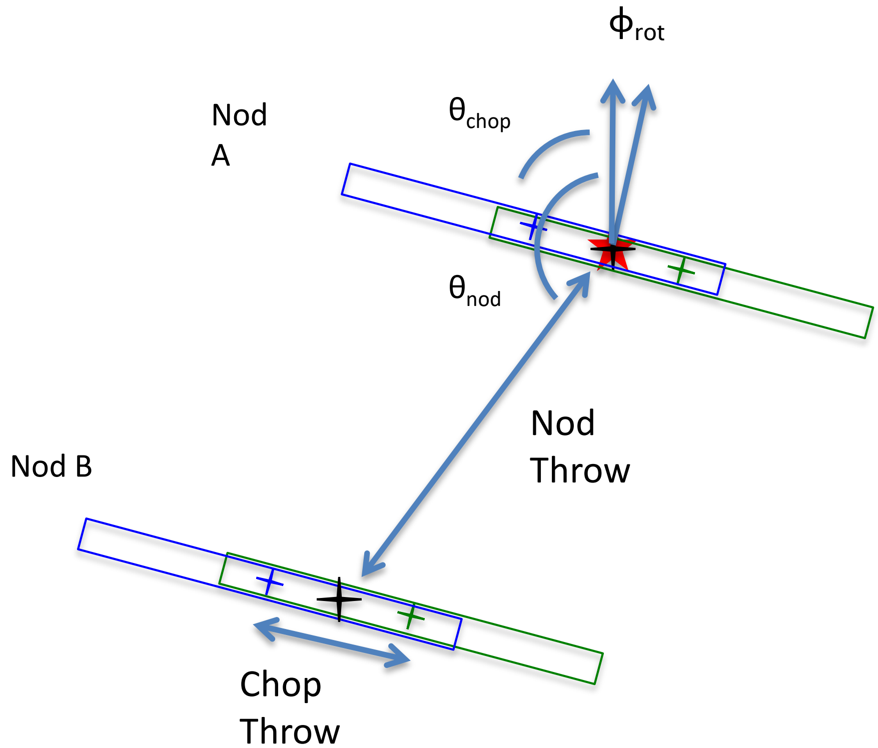


Parallel

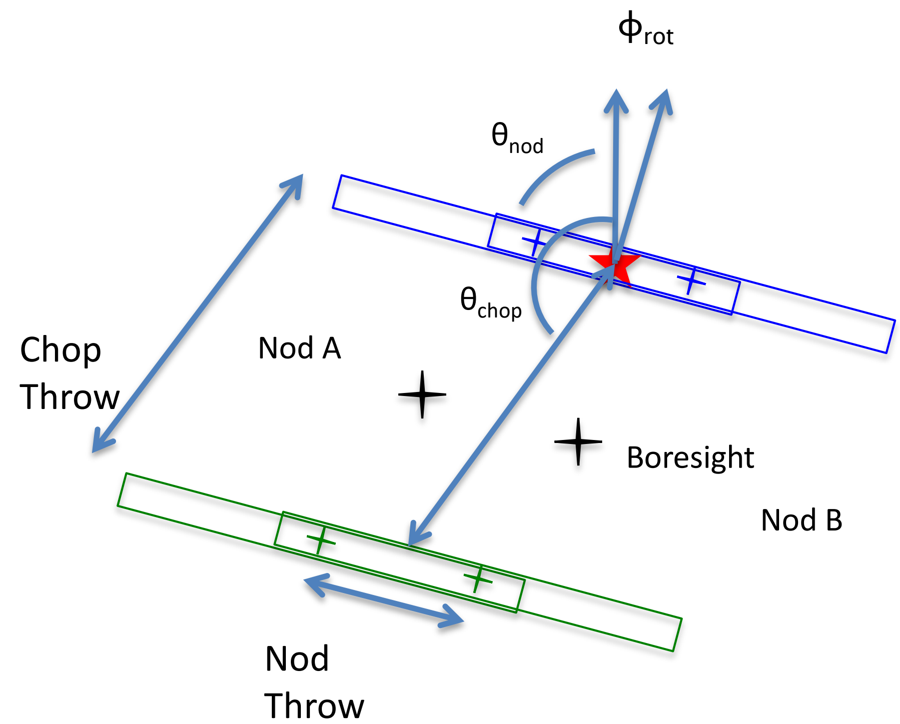


Grism Observing Modes: CAS, NAS

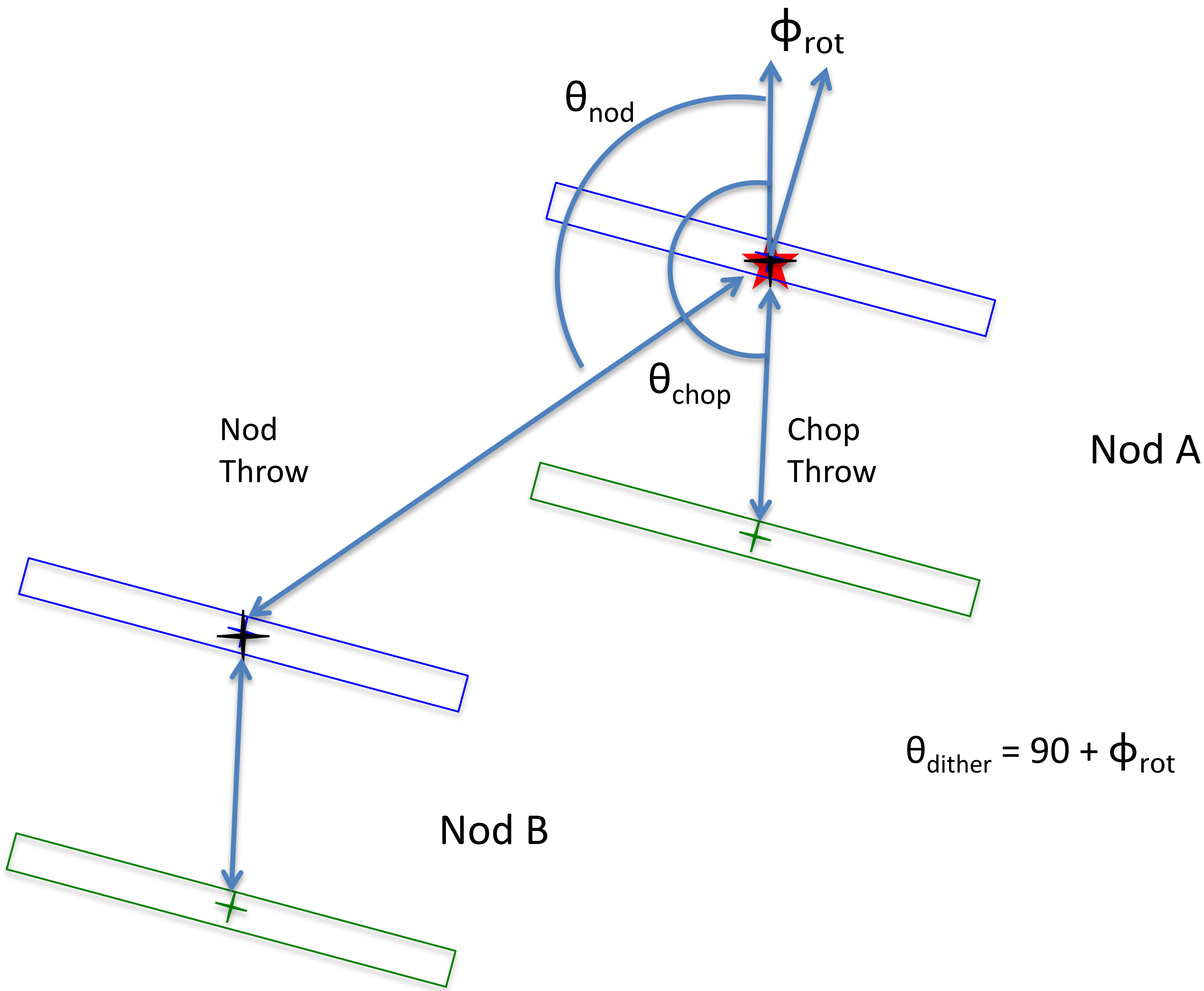
Chop_Along_Slit



Nod_Along_Slit



Grism Observing Modes: C2NC2



$\theta_{dither} = 90 + \phi_{rot}$

Data Reduction Steps

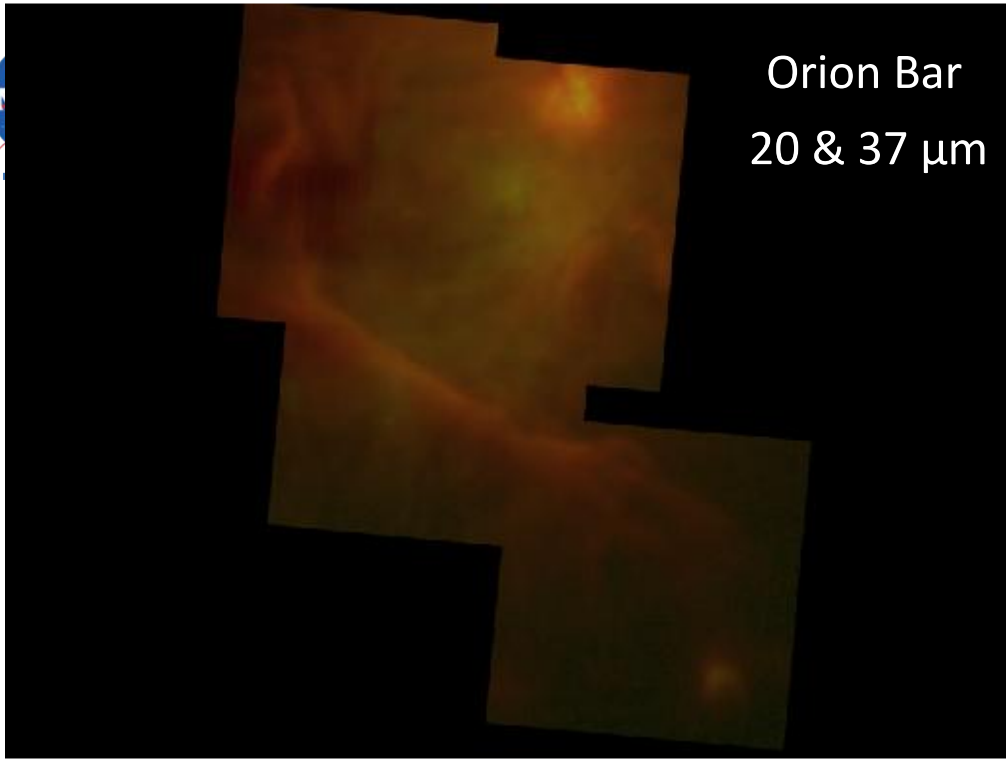
Imaging pipeline:

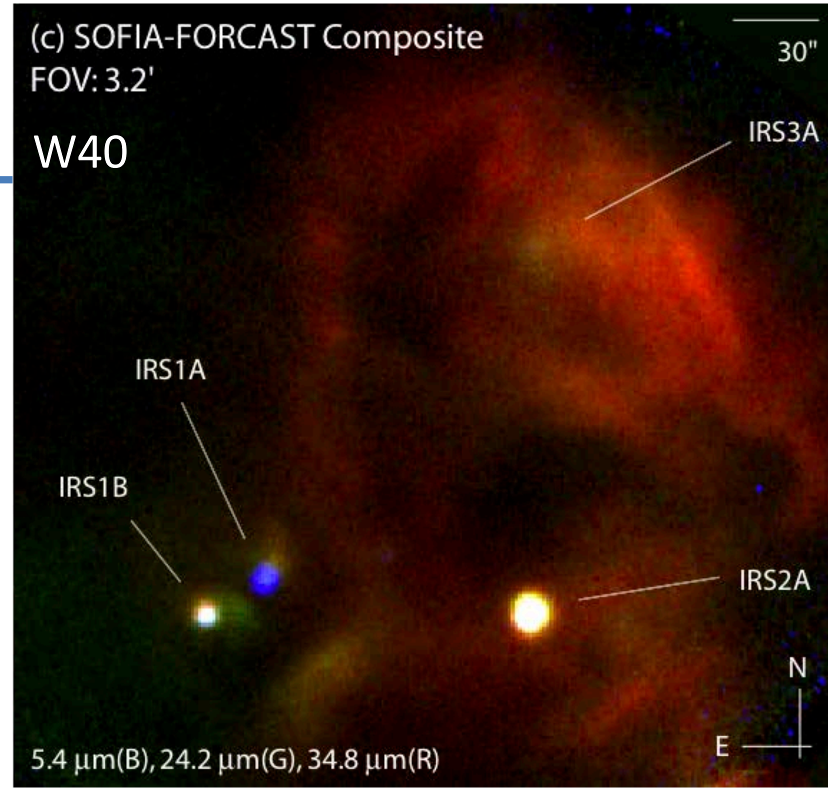
clean: remove bad pixels
linearize: detector non-linearity correction
~~***flatfield***: not applied!~~
stack: background subtraction using chop/nod sets
jailbar: remove pattern noise

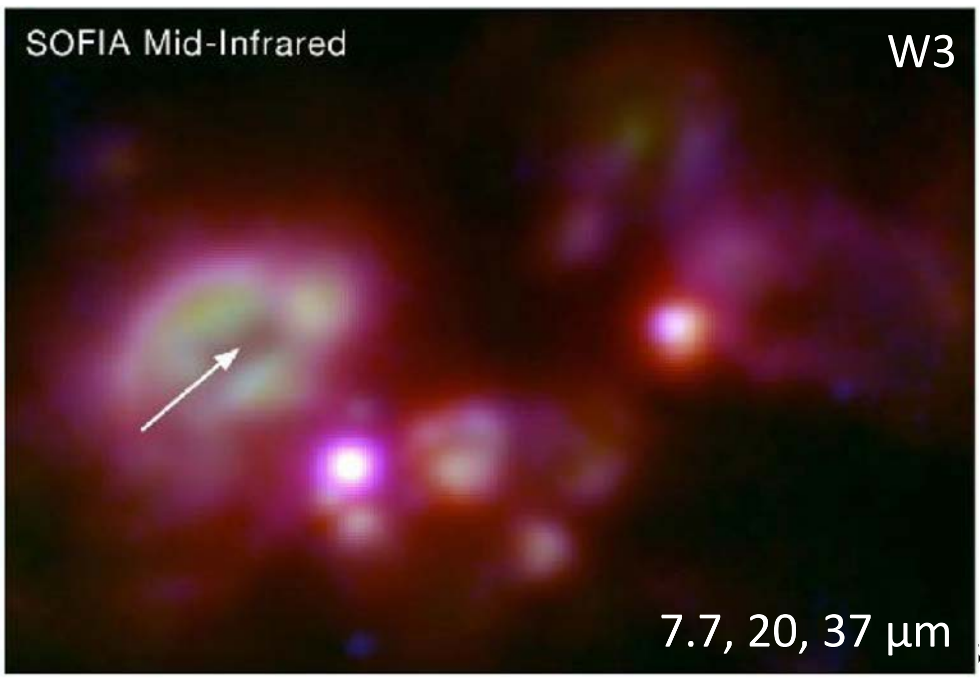
Additional pipeline steps for grism spectroscopy

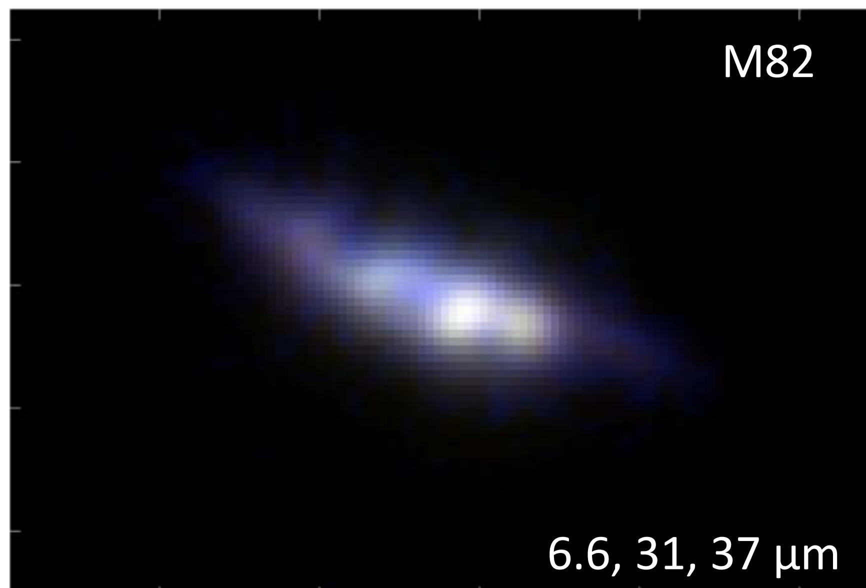
spectral extraction: (optimal or sum columns)
~~***defringe***: not applied!~~
wavecal: apply pre-determined polynomial fit to telluric/nebular lines
telluric*: using observed telluric spectra, pwv data, and ATRAN models
fluxcal: using observed spectra of flux calibration stars
save: extracted and calibrated spectra, any specified intermediate data set

* Telluric spectrum removal may not always be optimized as an automatic pipeline step. This will depend on the frequency and quality of telluric standard star observations during the flight.


Orion Bar
20 & 37 µm


(c) SOFIA-FORCAST Composite
FOV: 3.2'
30"
W40
IRS3A
IRS1A
IRS1B
IRS2A
N
E
5.4 µm(B), 24.2 µm(G), 34.8 µm(R)


SOFIA Mid-Infrared
W3
7.7, 20, 37 µm


M82
6.6, 31, 37 µm

More Information

SOFIA Information for Researchers Website

www.sofia.usra.edu

SOFIA Help Desk

sofia_help@sofia.usra.edu