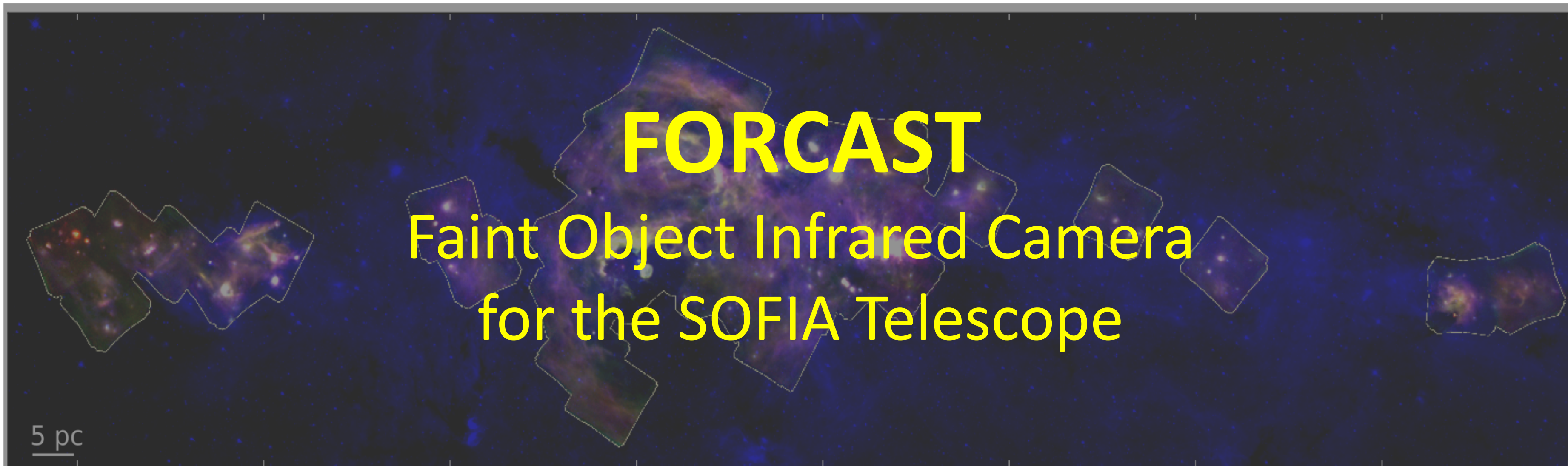
FORCAST

Faint Object Infrared Camera for the SOFIA Telescope



Bernhard Schulz

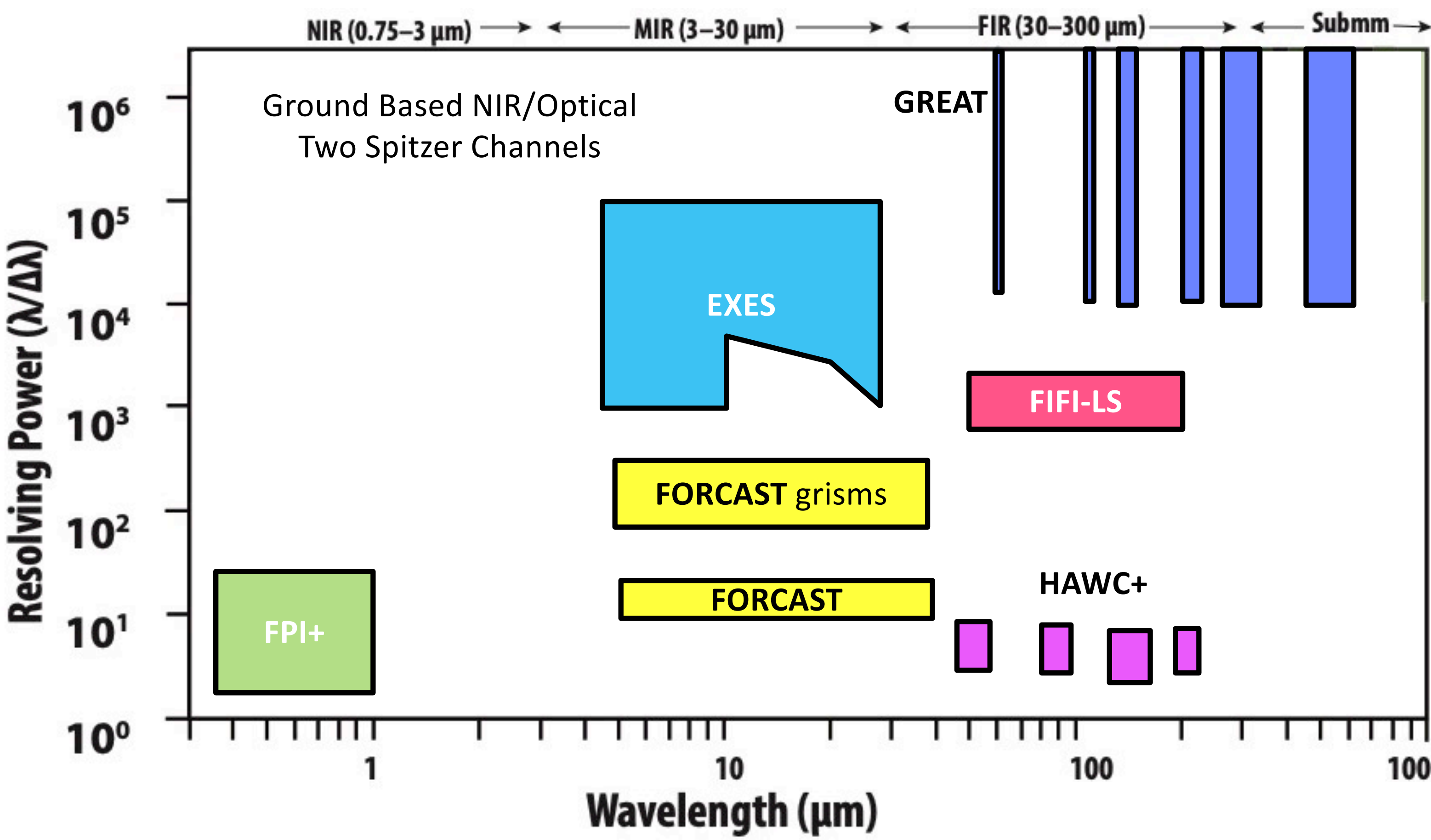
with contributions from

Andrew Helton, Bill Vacca,

Wanggi Lim, Jim de Buizer

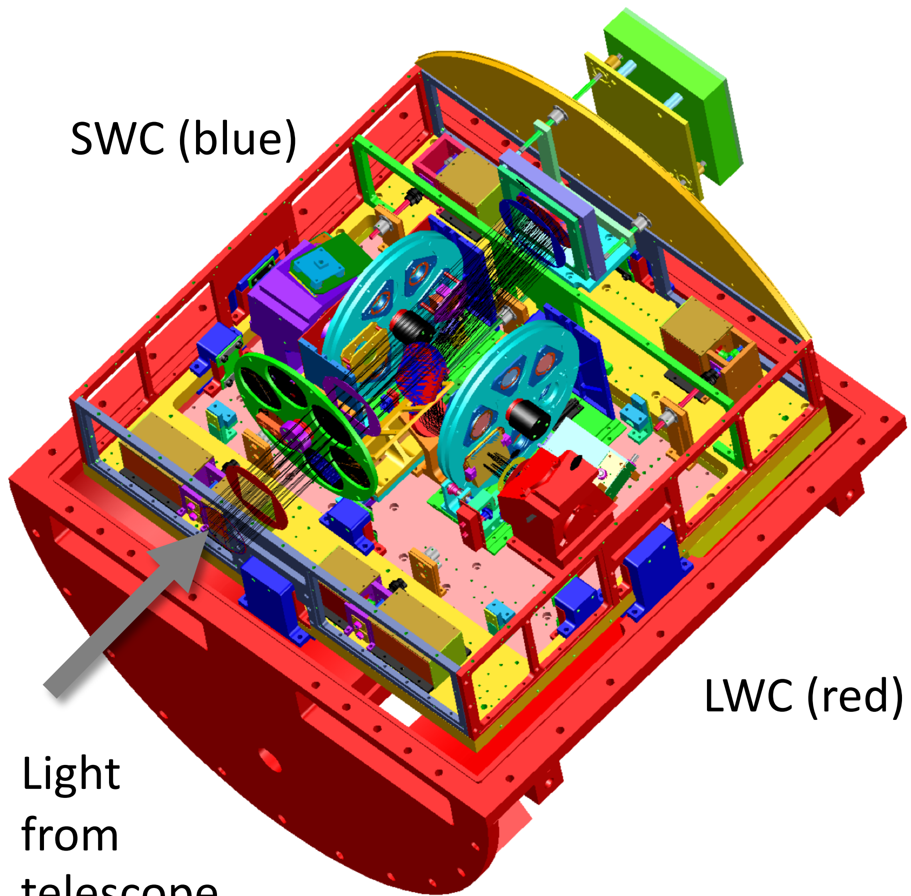
SOFIA Workshop, 8-10 June 2020, DSI Universität Stuttgart

Science Instruments on SOFIA



SOFIA Instruments
EXES
FIFI-LS
FORCAST
FPI+
GREAT
HAWC+

FORCAST (I)

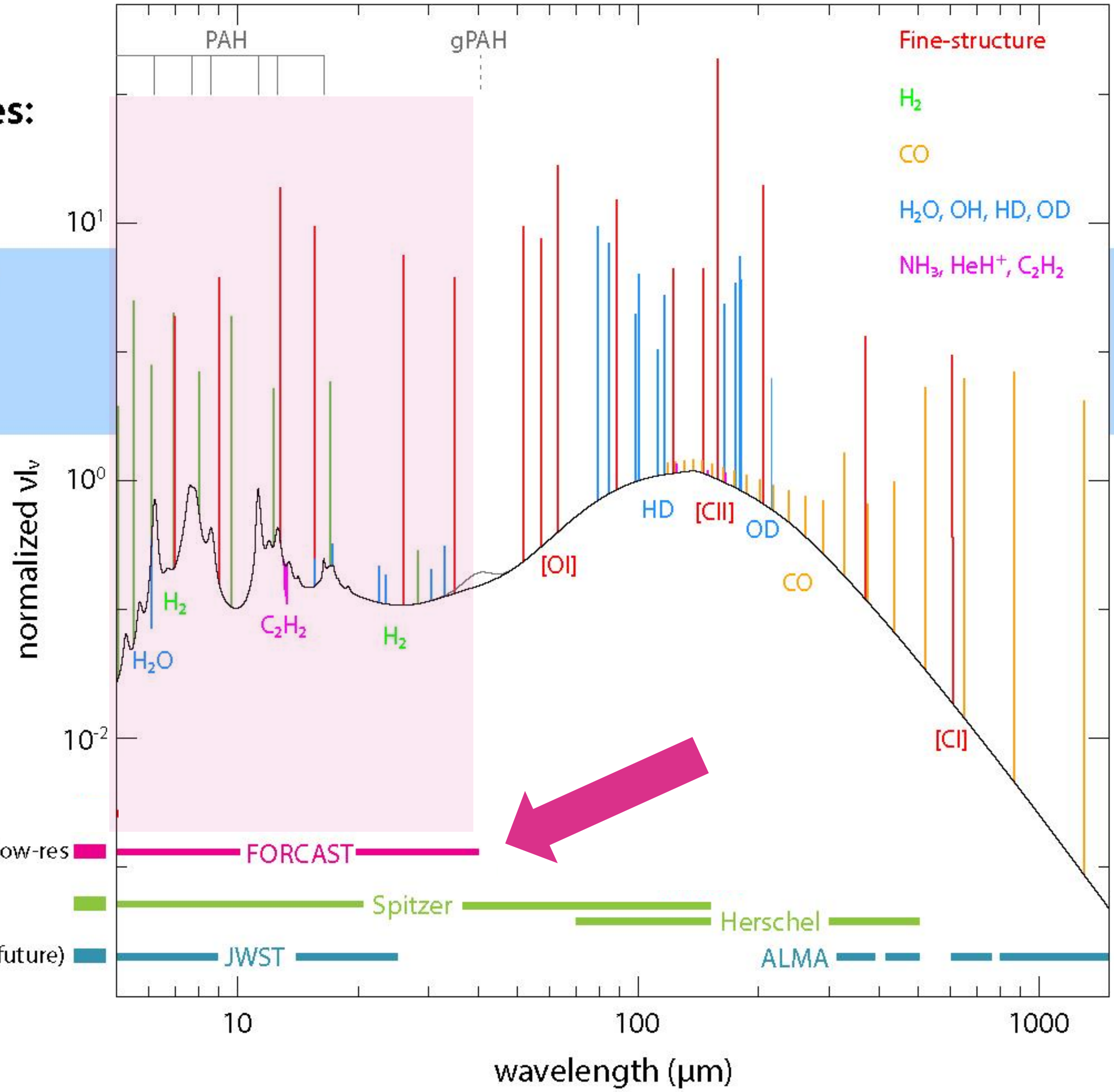


- PI: Terry Herter (Cornell)
- 1st Generation Instrument
- Wide field (3.4' x 3.2' FOV) dual channel camera and spectrograph 5-40 µm
- Two 256x256 arrays with 0.768" pixels
- SWC: Si:As BIB array 5-25 µm
- LWC: Si:Sb BIB array 25-40 µm
- 4 Grisms with 2 long slits provide low resolution (R~70-300) spectroscopy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

SOFIA Covers a Lot of IR Real Estate

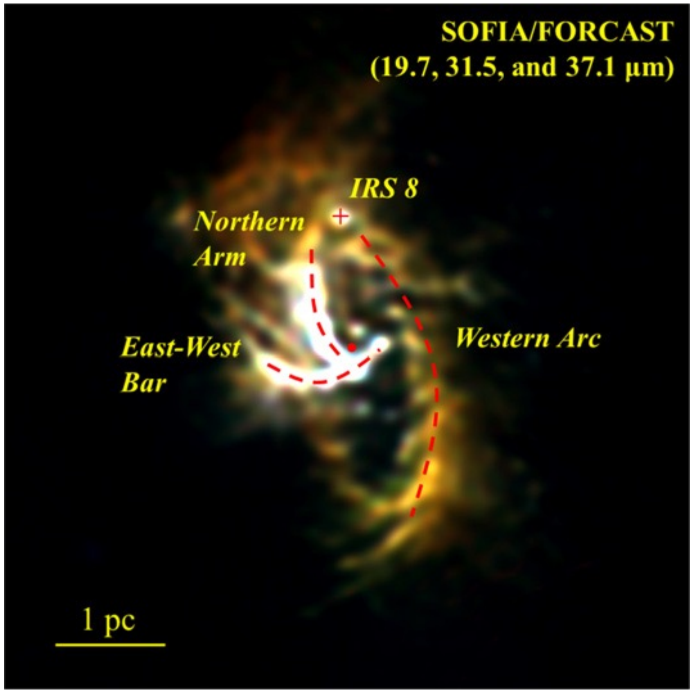
SOFIA measures:

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

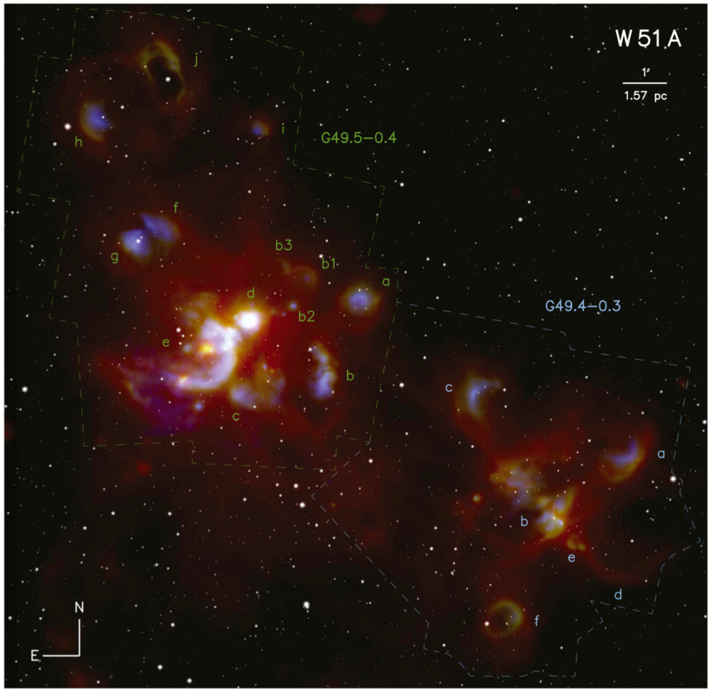


To determine:

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



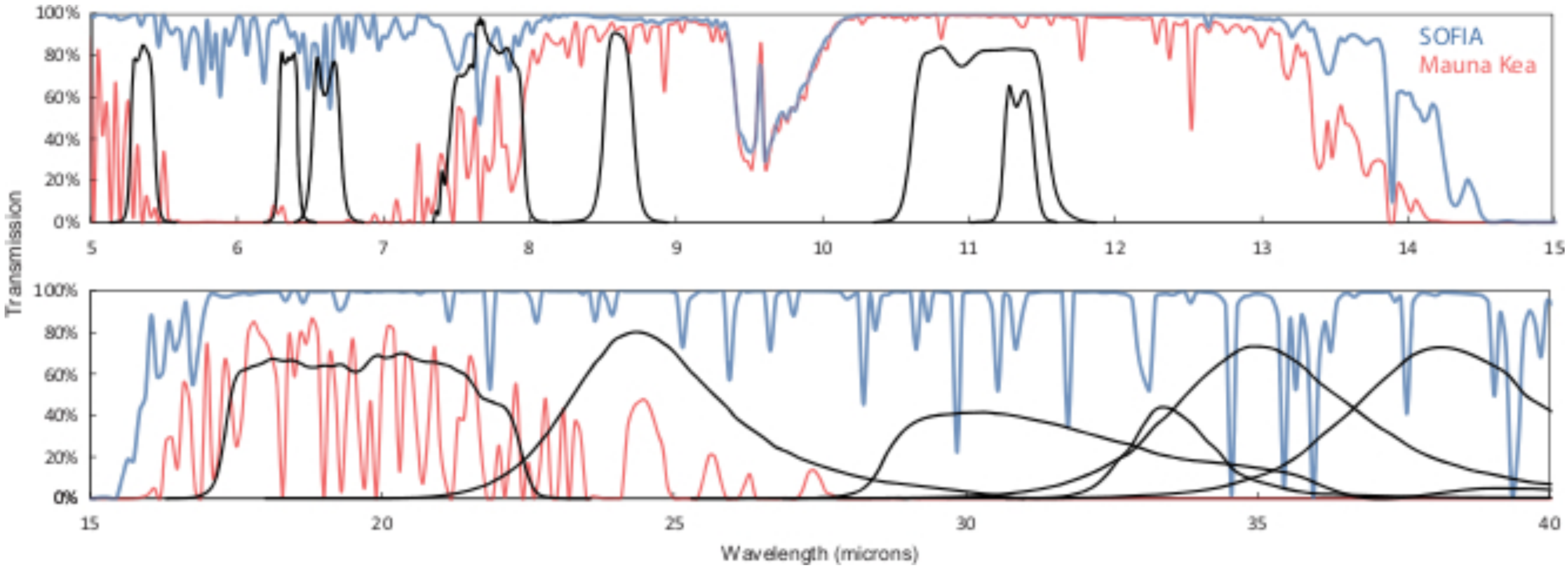
Lau et al., 2013



Lim et al., 2019

IMAGING/PHOTOMETRY

FORCAST Filter Profiles



SOFIA : 41000 ft, 7.3 µm PWV, 45° ZA

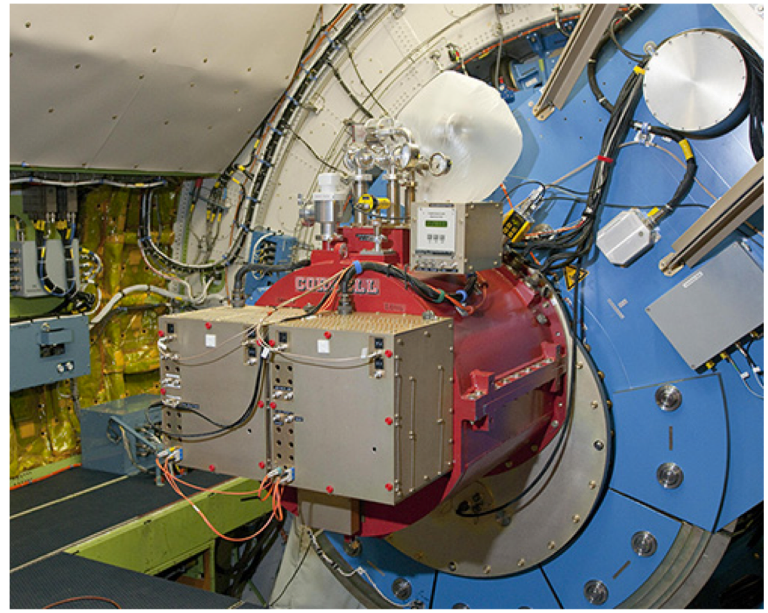
Mauna Kea: 13800 ft, 3.4 mm PWV, 45° ZA

FORCAST (II)

Filter Parameters

SWC Filters		LWC Filters	
λ_{eff} (µm)	$\Delta\lambda$ (µm)	λ_{eff} (µm)	$\Delta\lambda$ (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		

Default filter set



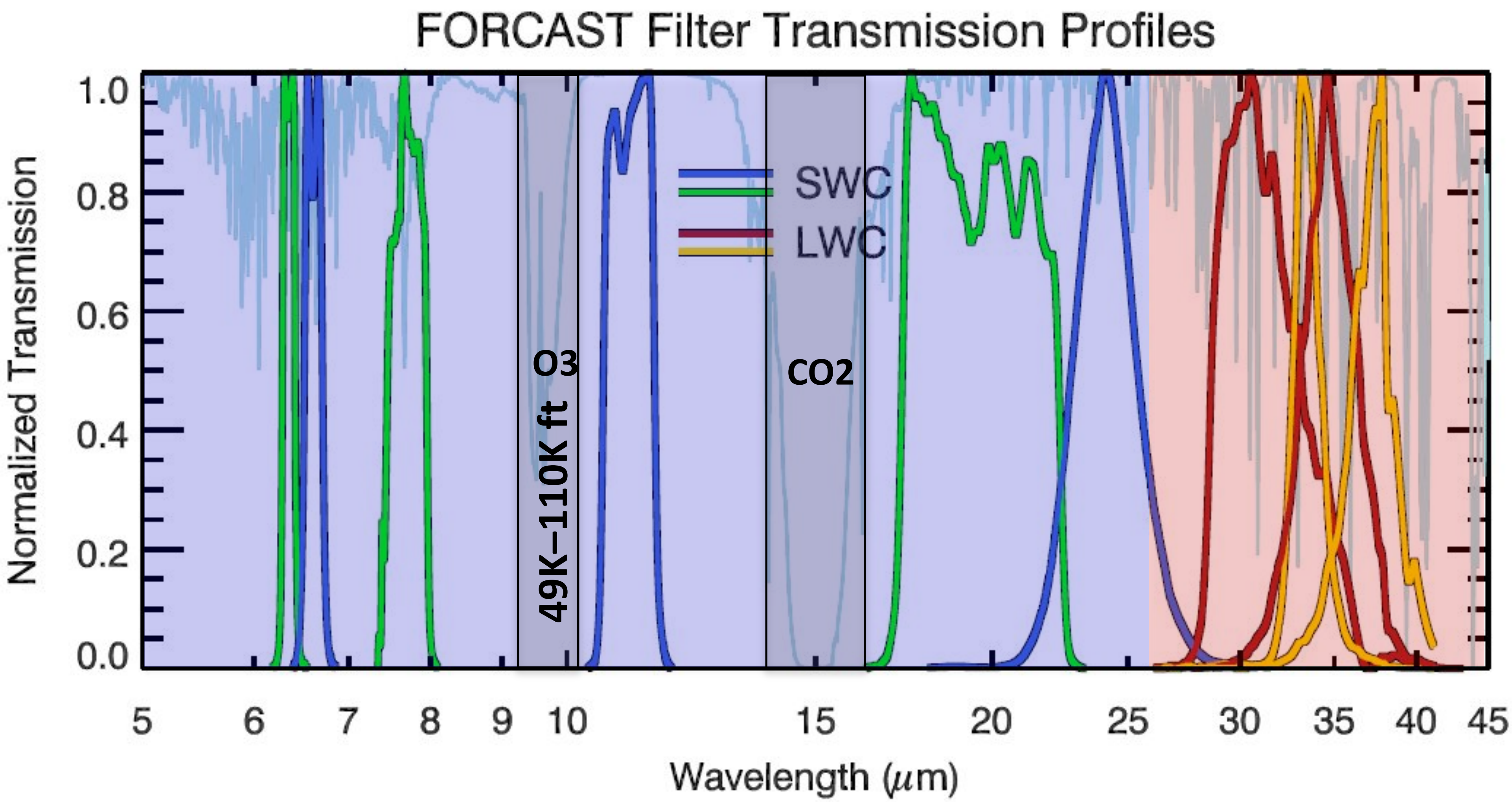
Grism Details

Grism	Coverage (µm)	R ($\lambda/\Delta\lambda$)[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	

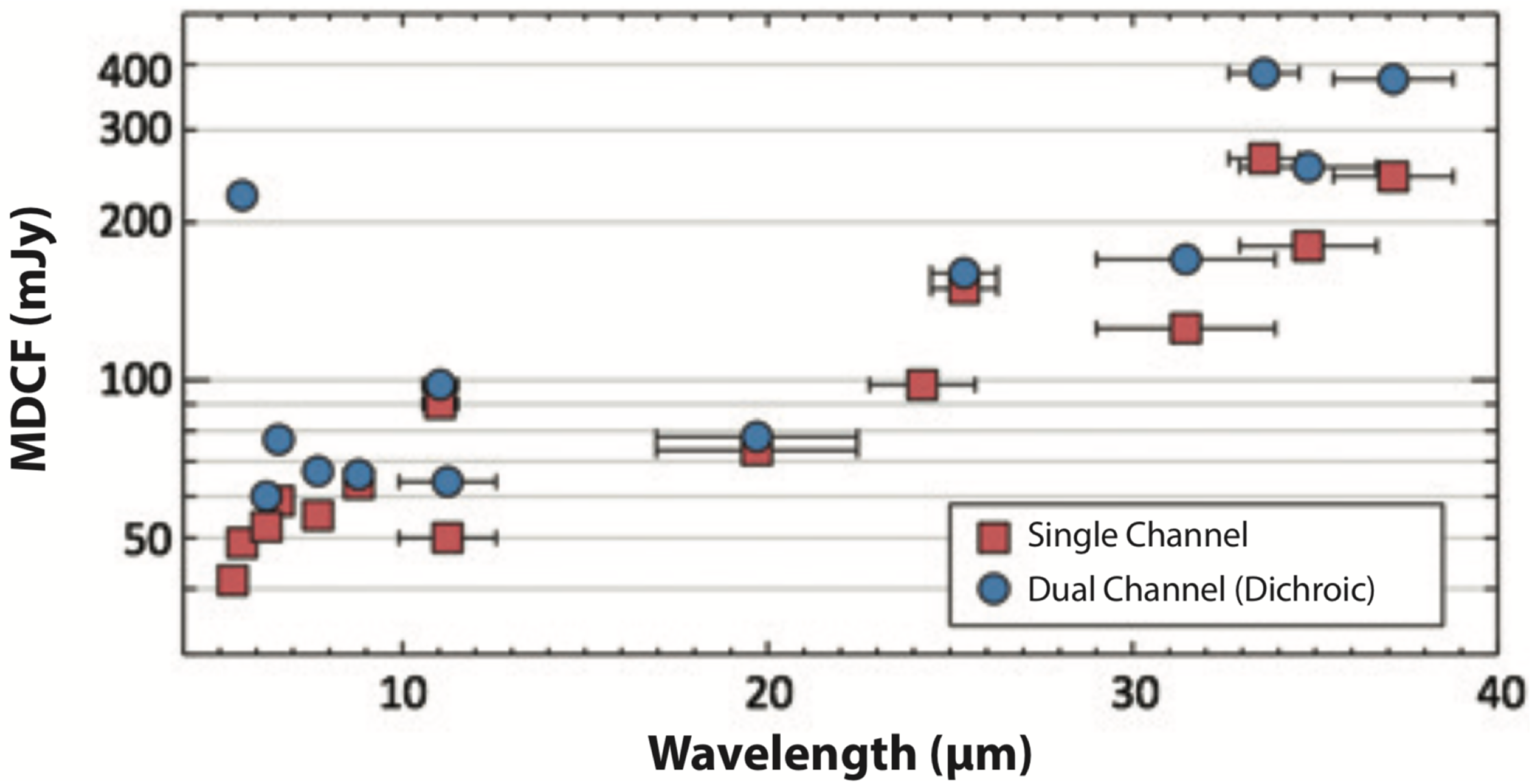
FWHM values for 2 estimates of the telescope jitter, 1.25” and 2.1”

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	

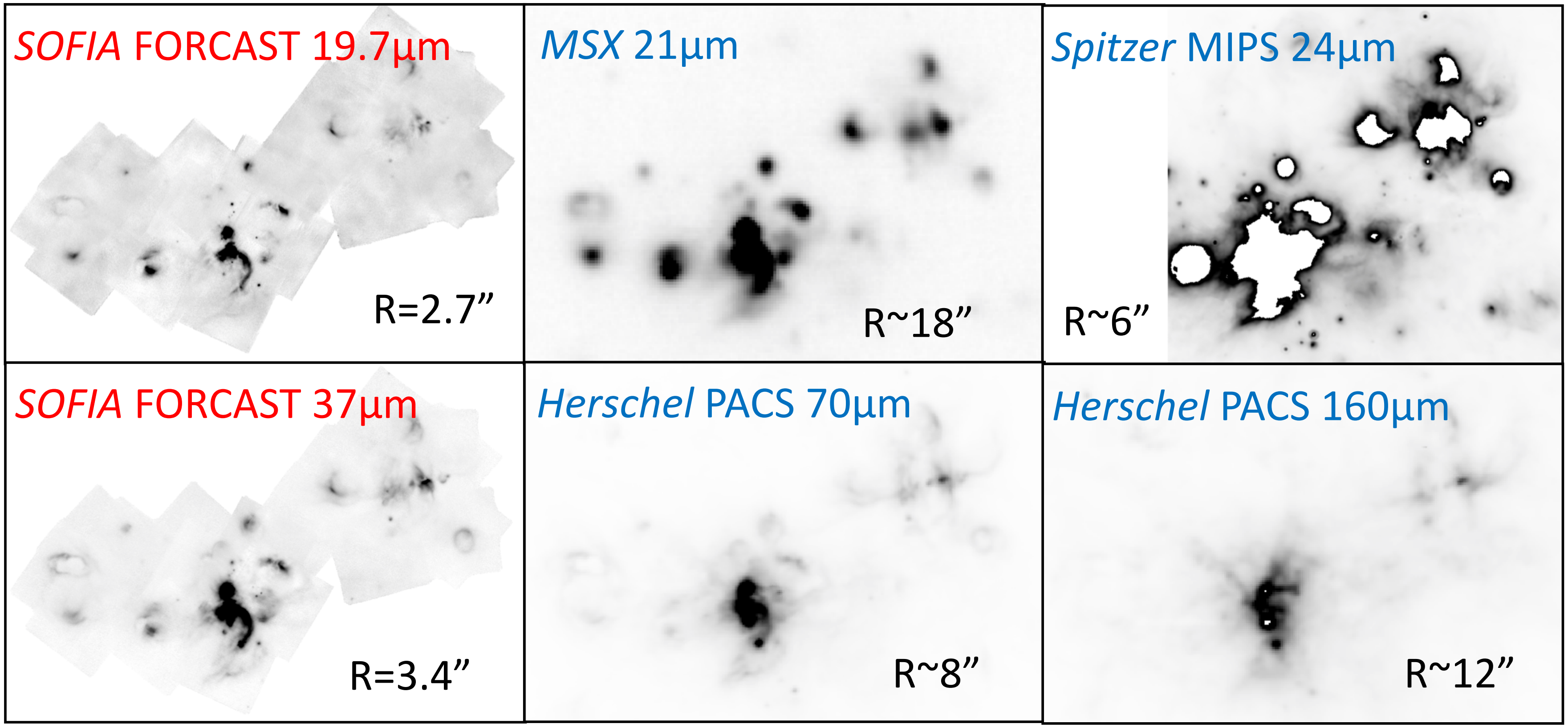
- Dual channel mode allows simultaneous imaging at two wavelengths
- However, there is decreased throughput compared to single channel mode

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

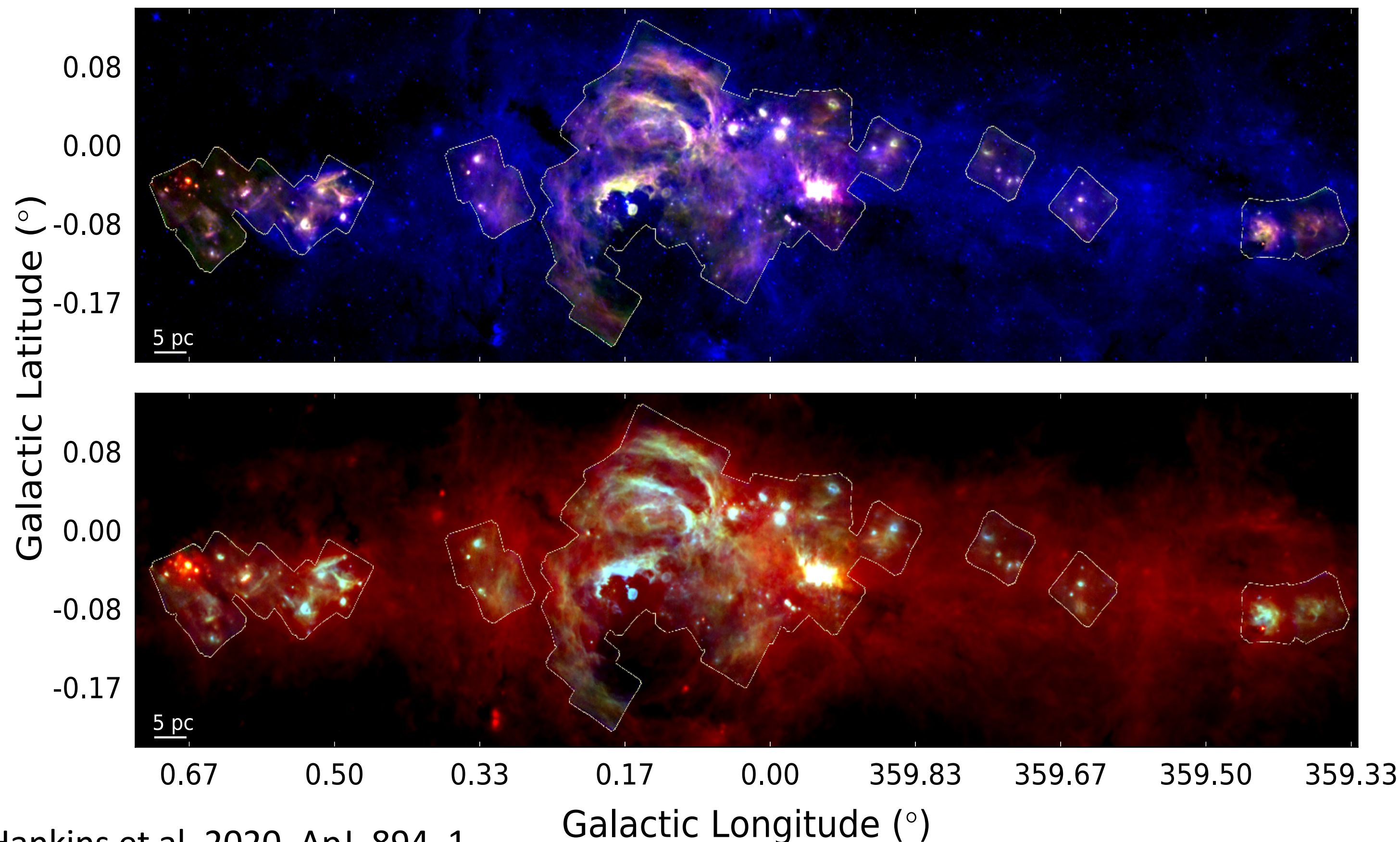
Spatial Resolution: W51A Maps



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.

The Central Galaxy with FORCAST



Hankins et al. 2020, ApJ, 894, 1

The SOFIA/FORCAST mosaics of the inner Galaxy provides crucial complementary information to other infrared surveys. Top: A false-color map of the region using Spitzer/IRAC 8 µm (blue), SOFIA/FORCAST 25 µm (green), and 37 µm (red). Bottom: A second false-color map of the survey region using SOFIA/FORCAST 25 µm (blue), 37 µm (green), and Herschel/PACS 70 µm (red) highlighting the longer wavelength (cooler dust) context. Both figures show an outline of the SOFIA/FORCAST survey footprint in white.

The SOFIA Cycle 7 Legacy Program 07_0189 (PI: Hankins) used FORCAST to complete the picture of the mid-infrared emission (MIR) from this region at 25 and 37 µm by filling in all bright regions that were too bright for Spitzer.

The data showcase many interesting regions and features, including structures in the Arched Filaments and Sickle H II regions, and signs of embedded star formation in Sgr B2 and Sgr C.

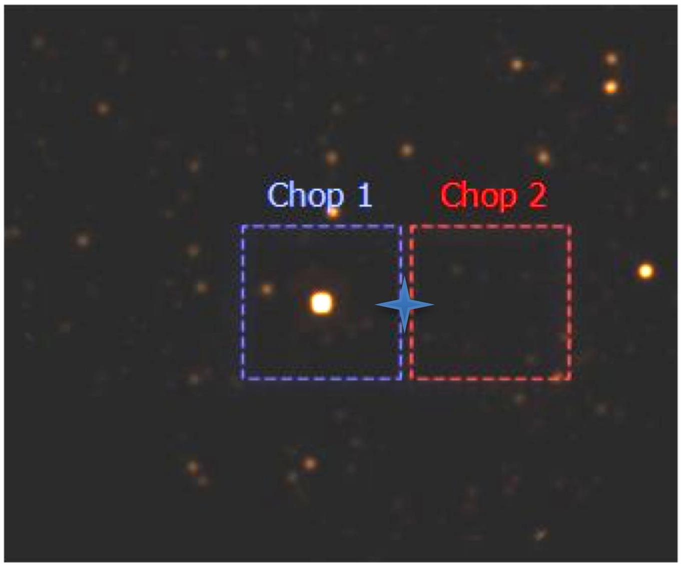
The complete dataset is publicly available in IRSA.

Chop/Nod Technique

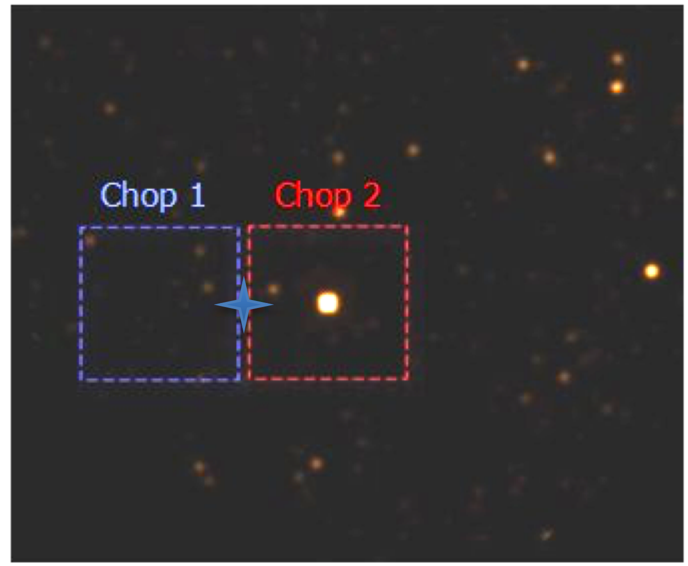
- MIR observations are completely background (sky+telescope+instrument) limited
  - Background can be >10^6 times brighter than most sources
  - Detector wells can fill in 1-100 msec
- MIR background varies rapidly (order of less than a few sec)
- To subtract majority of the background the secondary 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

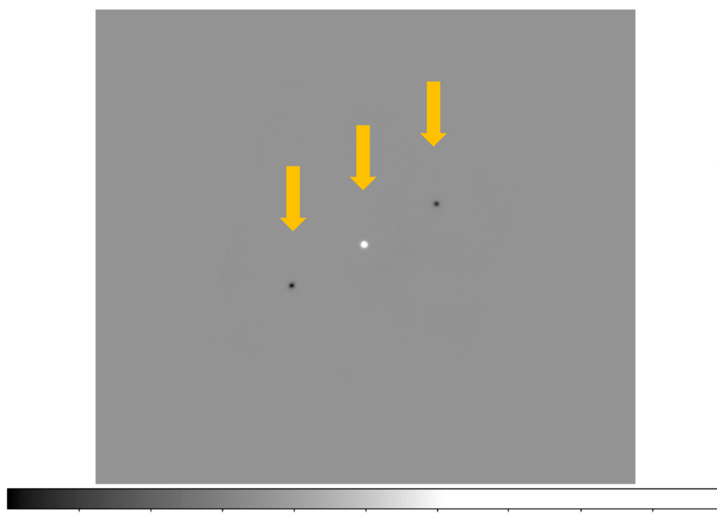
Nod_Match_Chop (Symmetric Chop) Mode

Nod A



Nod B





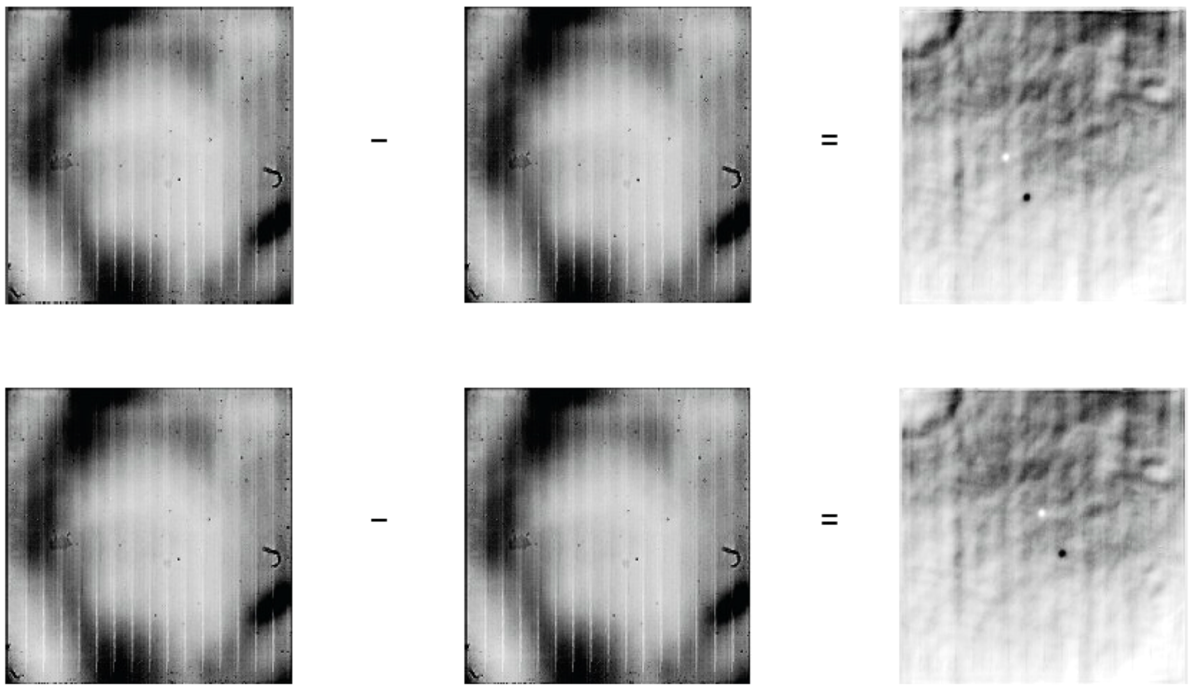
Subtracted image provides positive and negative images of the object

Nod_Perp_Chop (Symmetric Chop) Mode

Chop 1 | Chop 2 | Chop 1 – Chop 2

Nod A – =

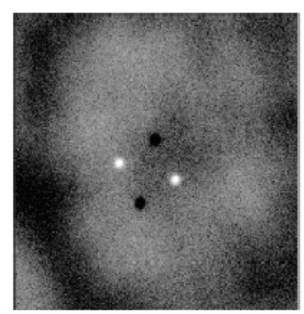
Nod B – =



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

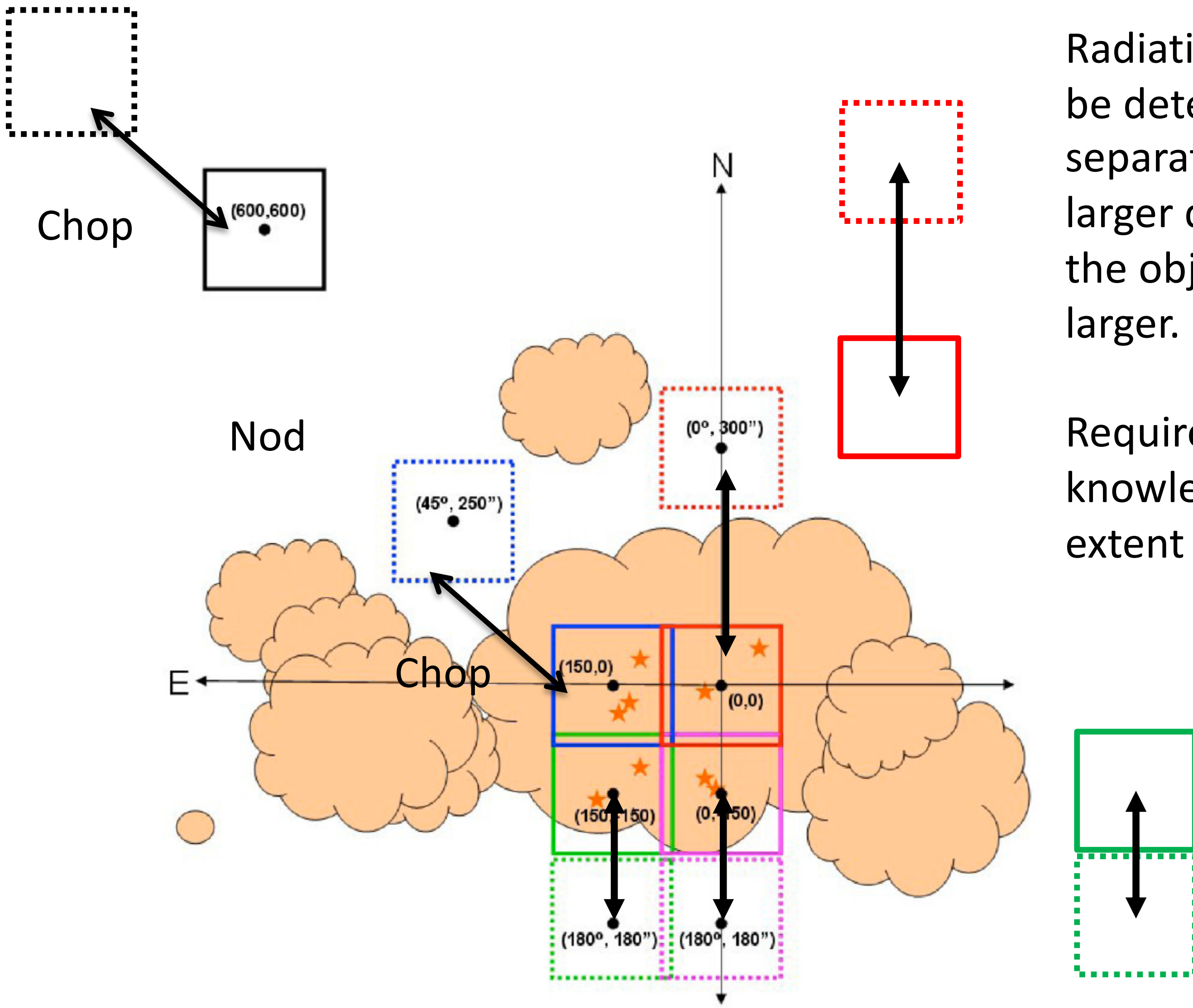
Sky+Telescope+Instrument

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



Now also radiative offset removed.

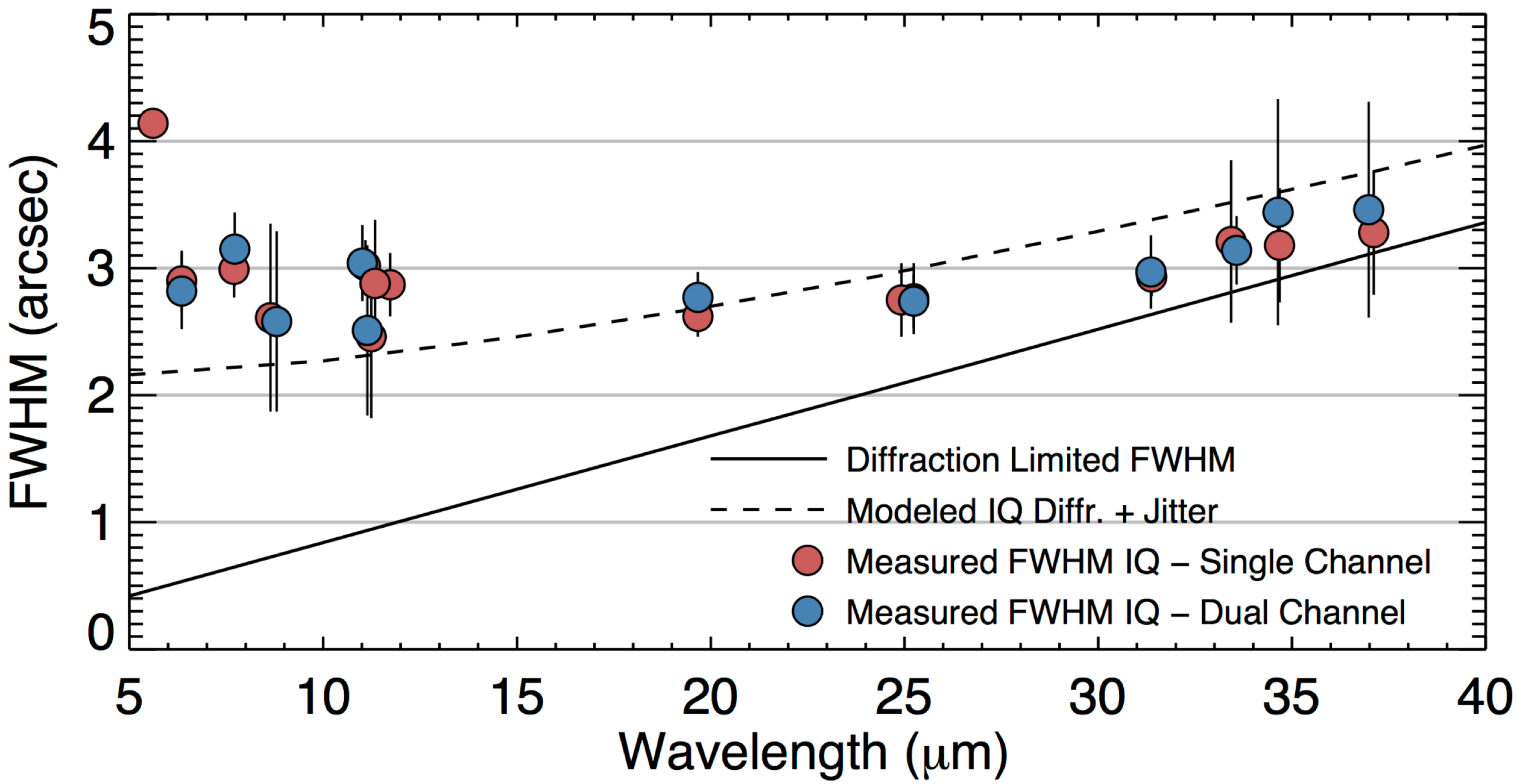
C2NC2 (Asymmetric Chop) Mode



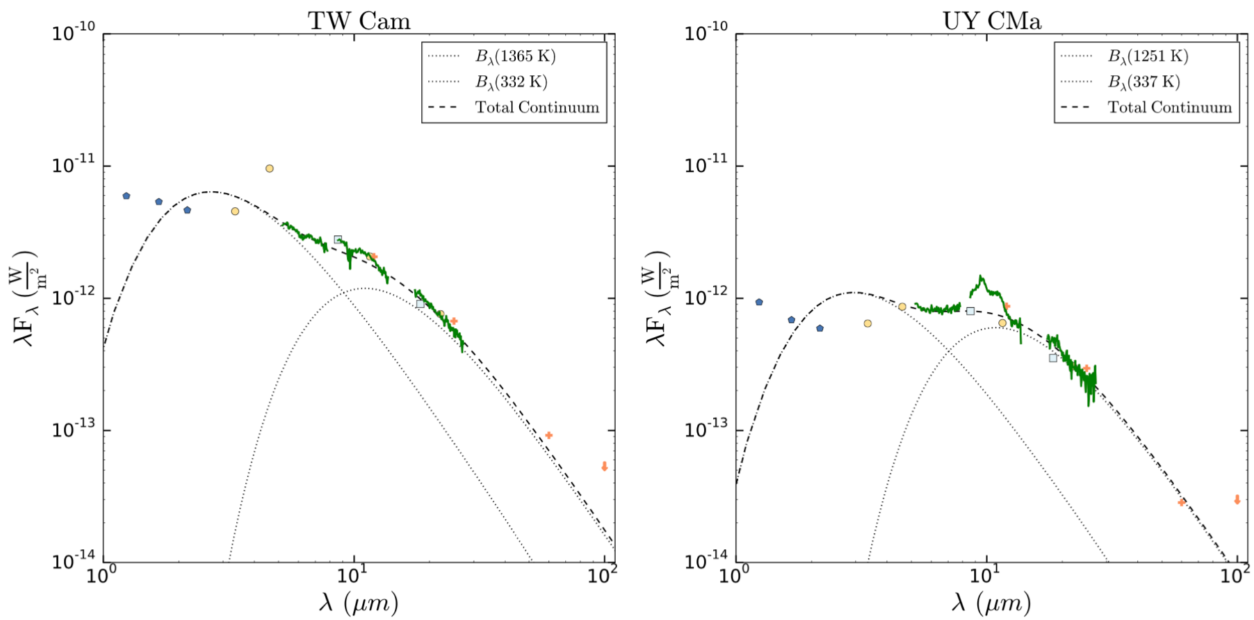
Radiative offset can be determined in separate nod cycle at larger distance from the object if that is larger.

Requires prior knowledge about extent of that object.

FORCAST Spatial Resolution



Scintillation of the residual atmosphere, turbulence in the boundary layer at the telescope door and the rest vibrations of the telescope limit the achievable spatial resolution.

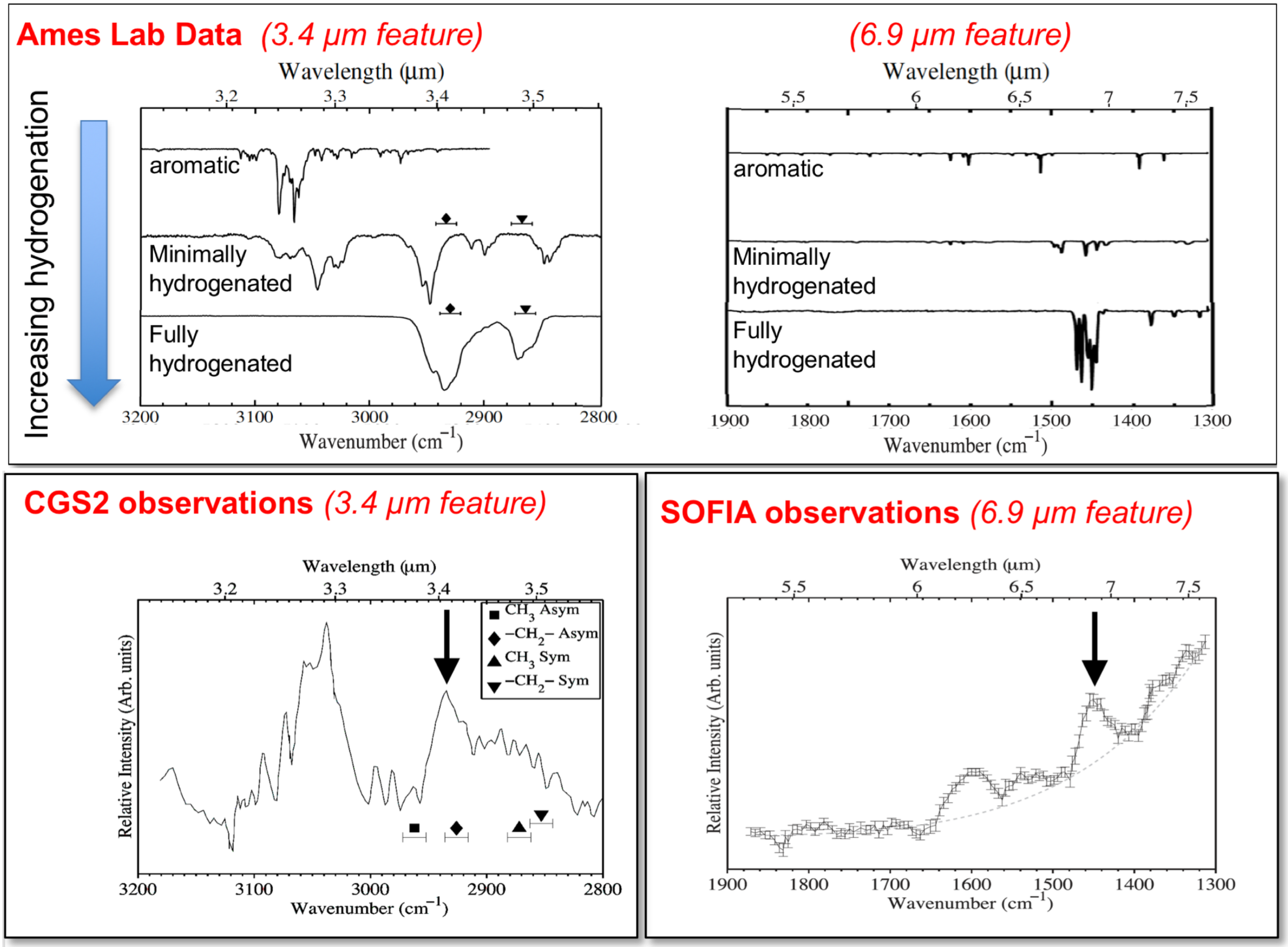


Arneson+2017

Data from: FORCAST, 2MASS. MSX, AKARI, WISE, IRAS, Herschel, Planck

GRISM SPECTROSCOPY

Testing PAH Theory



Materese+2017

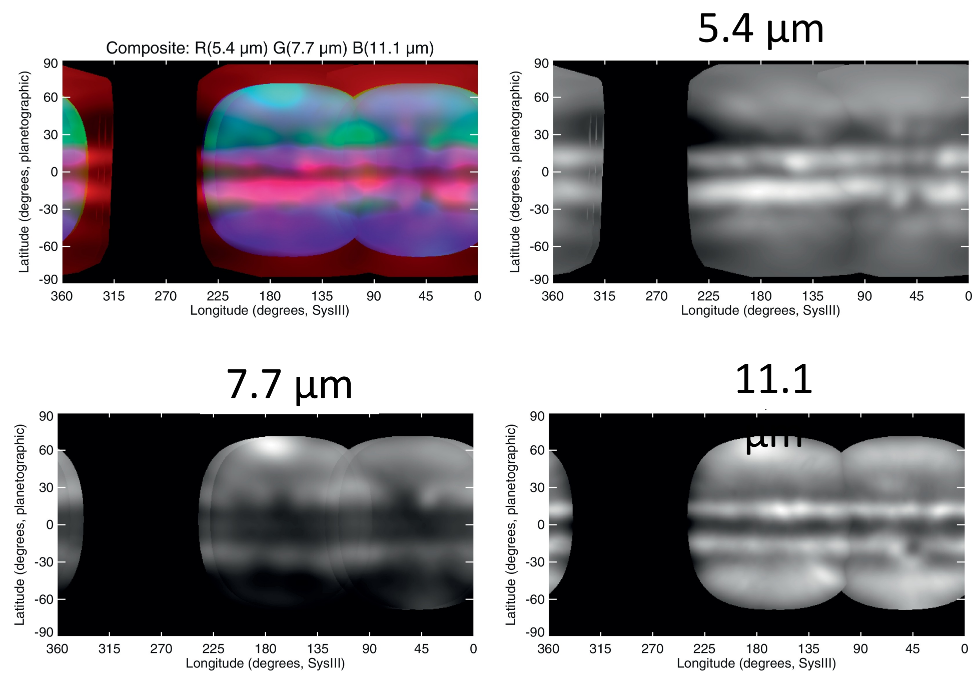
- Testing H_n-PAH hypothesis
- Highly hydrogenated PAHs as source for 3.4 µm feature requires presence of methylene (-CH2-) scissoring modes at 6.9 µm.
- High hydrogenation affects both the lifetime and chemistry of the PAHs.

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

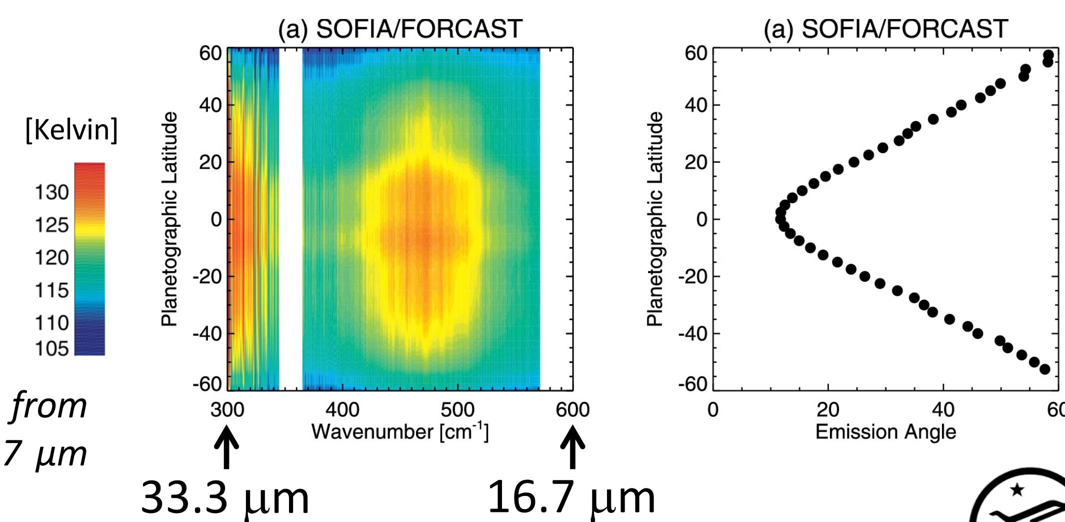
FORCAST – Planetary Atmospheres

Contextual imaging of Jupiter in three filter bands. Filter bands show:

- 5.4 µm – radiance attenuated by 1-4 bar cloud opacity
- 7.7 µm – stratospheric methane emission near 10 mbar
- 11.1 µm – 500mbar temperatures, ammonia, and ethane at higher emission angles



Brightness temperature spectra for different planetary latitudes. Slit scan mapping at 5-35 µm allowed tracing of S(0) and S(1) transitions of para-H_2 in the upper troposphere, and showed a gradient from equator to pole with increasing abundance towards the pole.



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

FORCAST Grisms and Slits

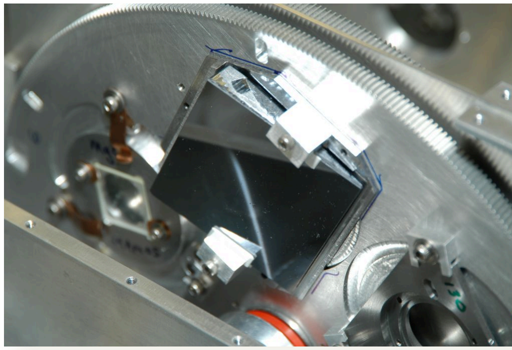
Grism	Wavelength	Slit	Resolution
Long Slit Spectroscopy in the Short Wavelength Camera			
FOR_G063	4.9 - 8.0 μm	2.4” x 192”	180
		4.7” x 192”	120
FOR_G111	8.4 – 13.7 μm	2.4” x 192”	260
		4.7” x 192”	130
Long Slit Spectroscopy in the Long Wavelength Camera			
FOR_G227	17.6 – 27.7 μm	2.4” x 192”	120
		4.7” x 192”	110
FOR_G329	28.7 – 37.1 μm	2.4” x 192”	170
		4.7” x 192”	160

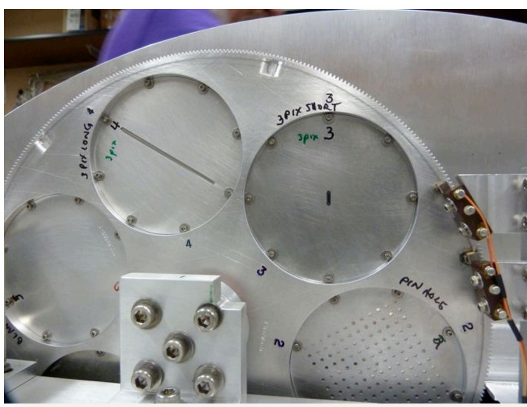
Notes:

- 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

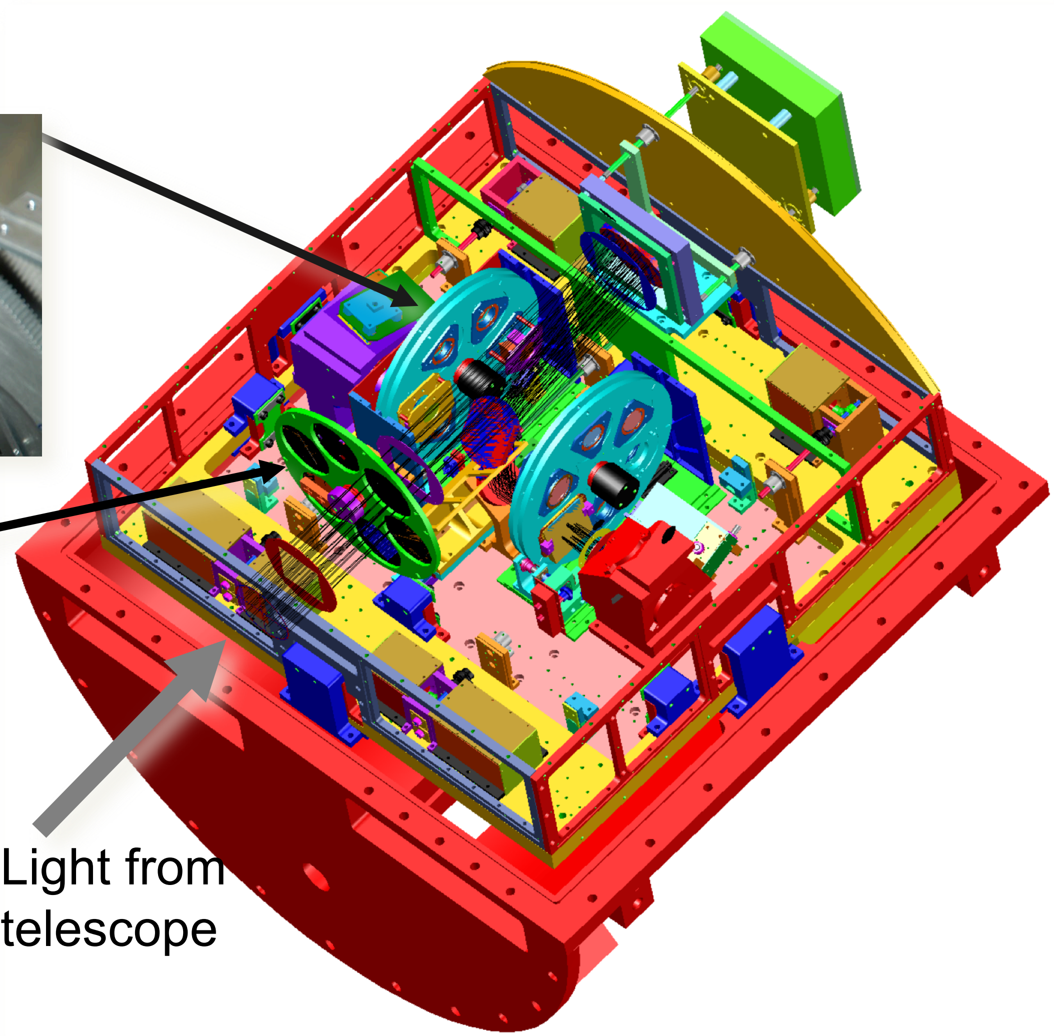
FORCAST grism design overview: layout

Grisms in existing imaging filter wheels

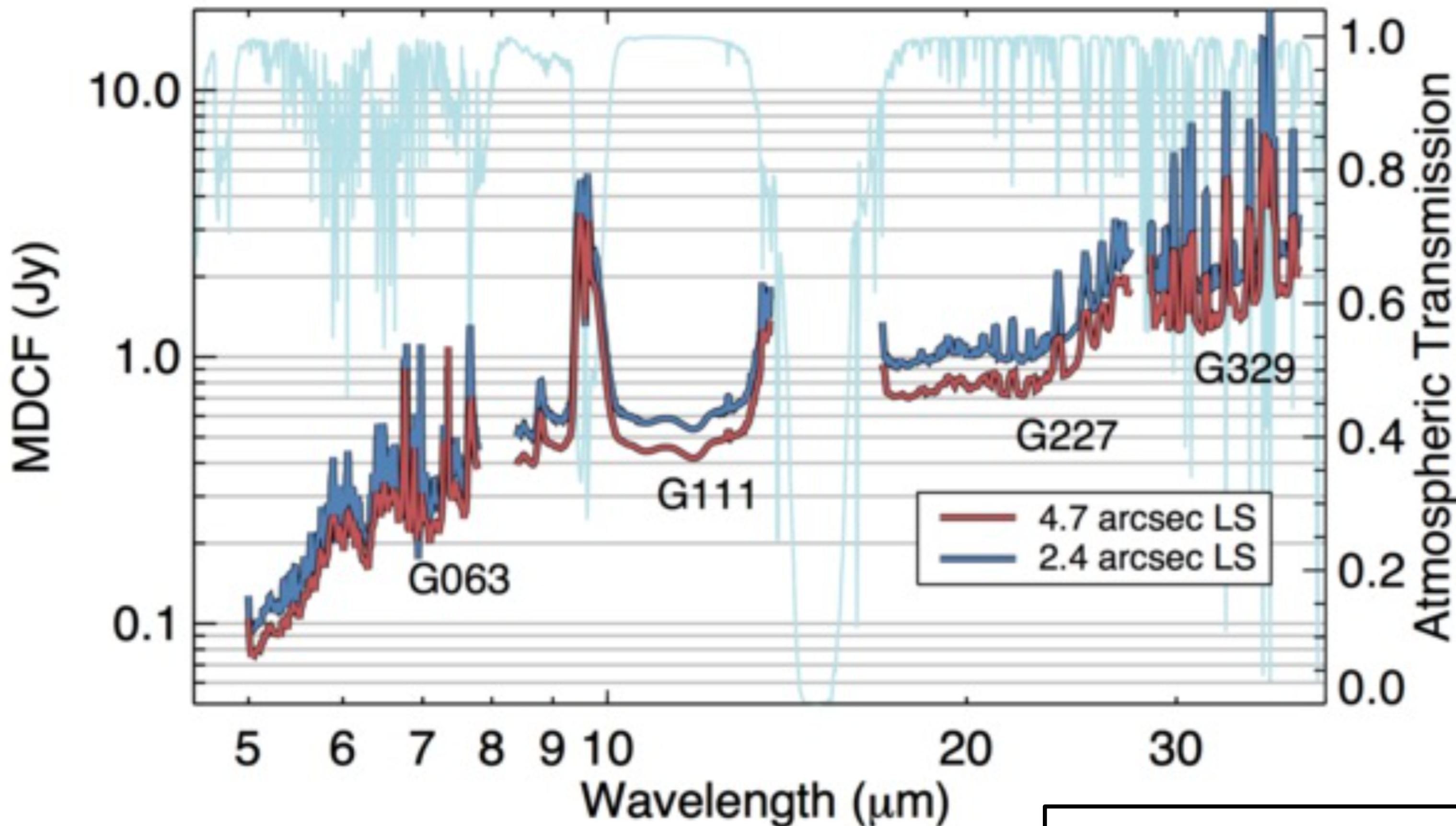




Slits in existing aperture wheel



FORCAST Grism Sensitivities



Cross Dispersed spectroscopy not offered!

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

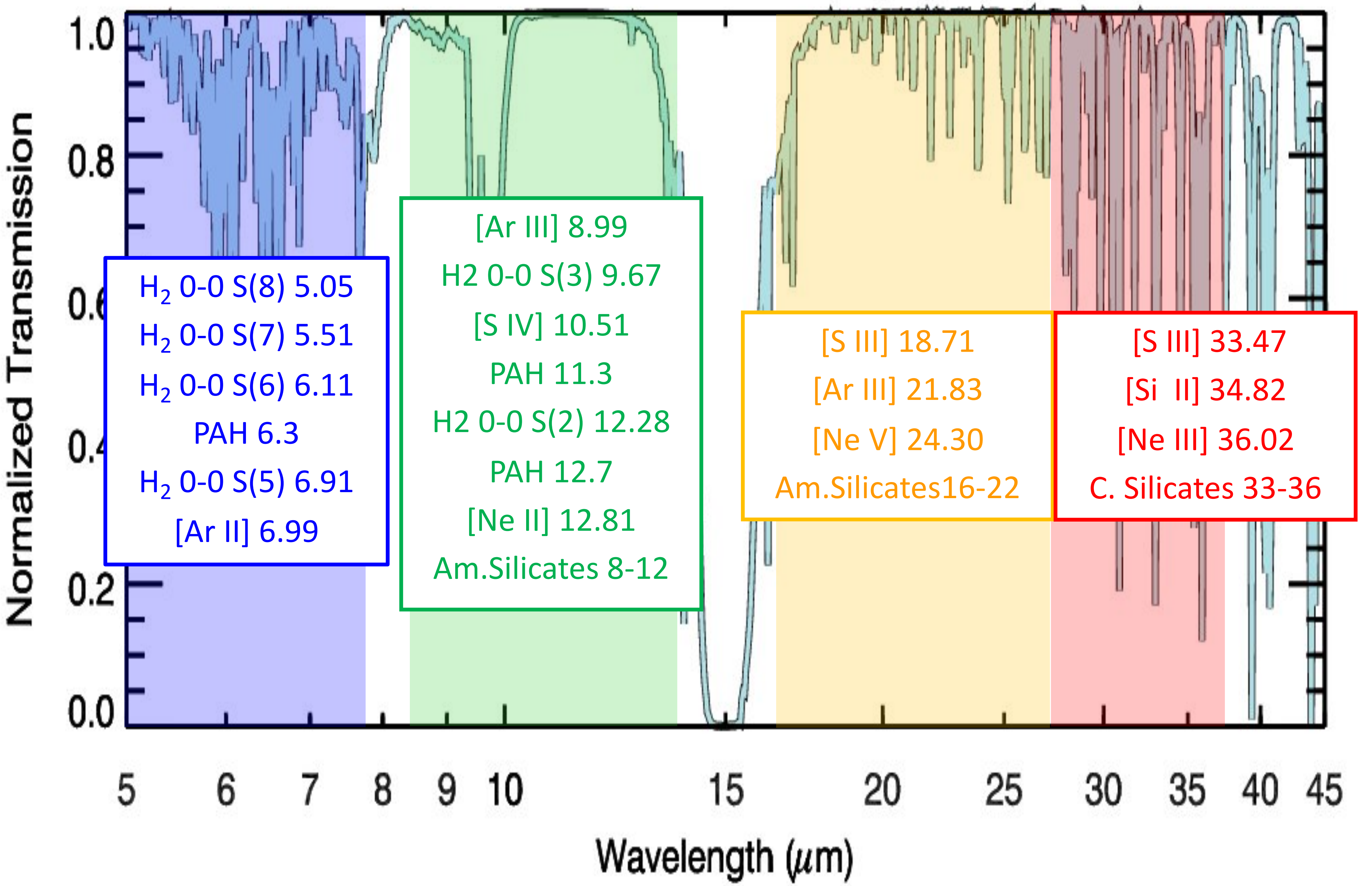
Long Slit Point Source Sensitivities

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

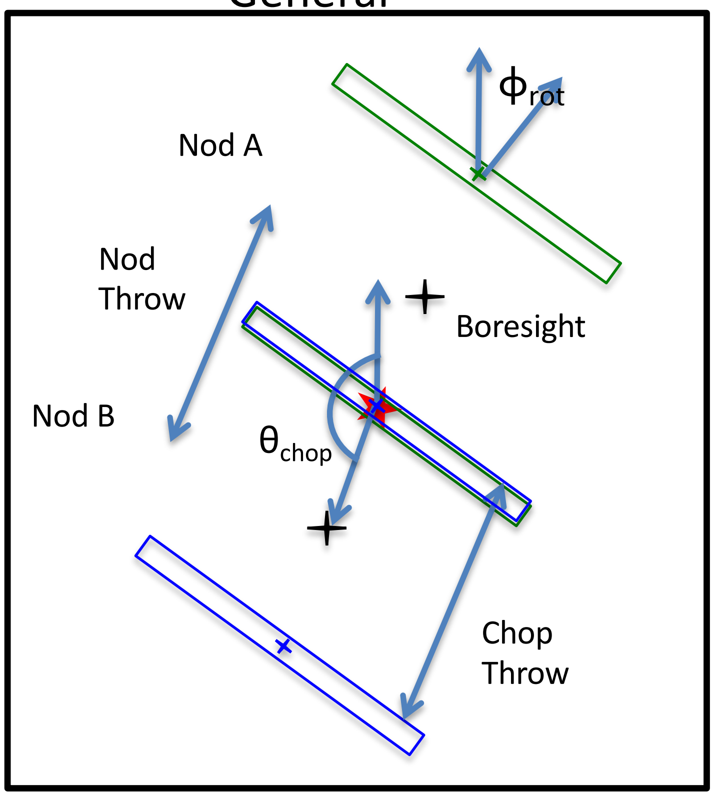
[a] The 2.4 arcsec long slit mode for G329 will not be available during Cycle 6.

Spectral Features of Interest

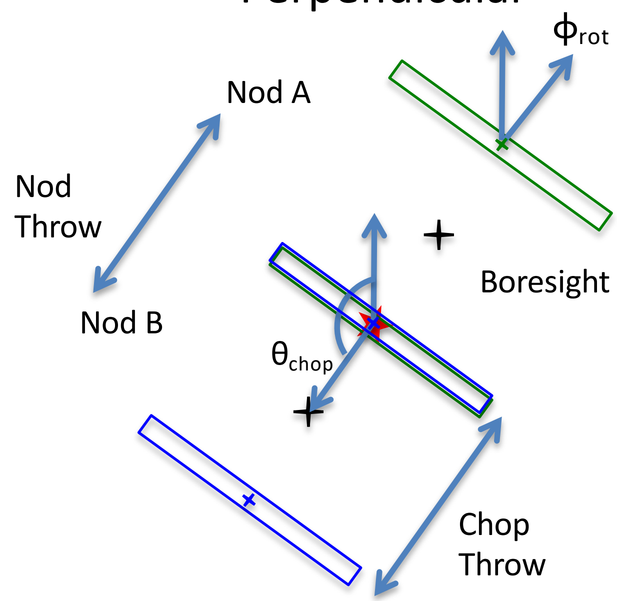


Grism Observing Modes: NMC

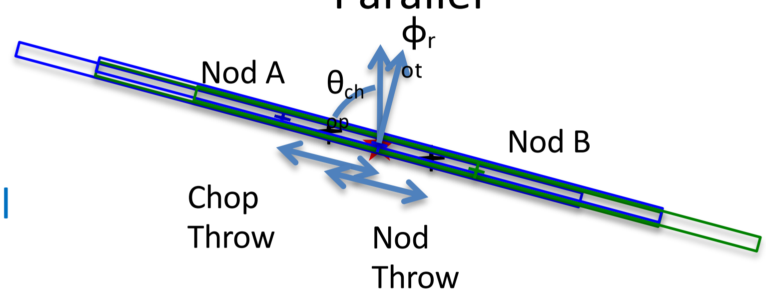
General



Perpendicular

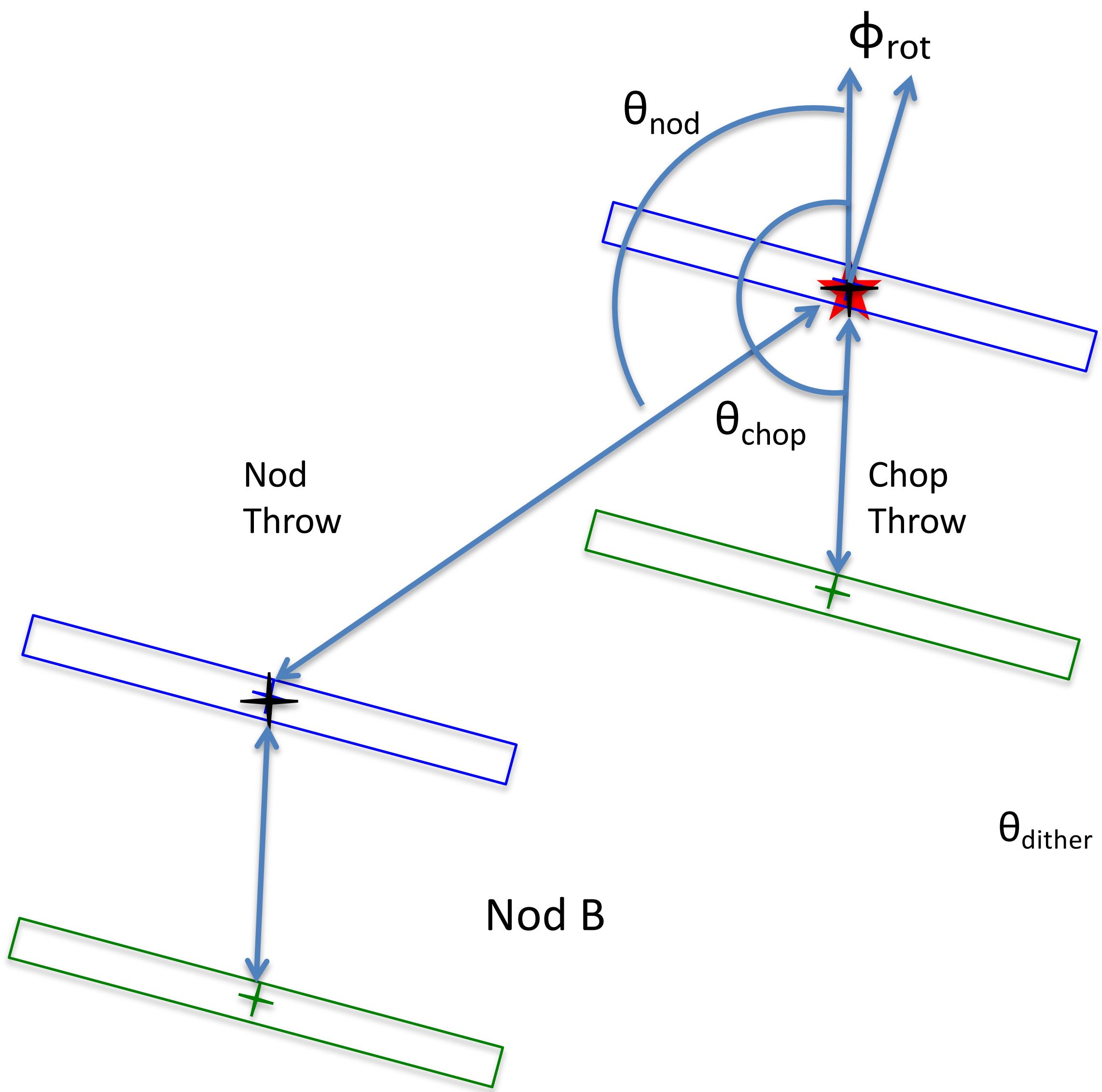


Parallel



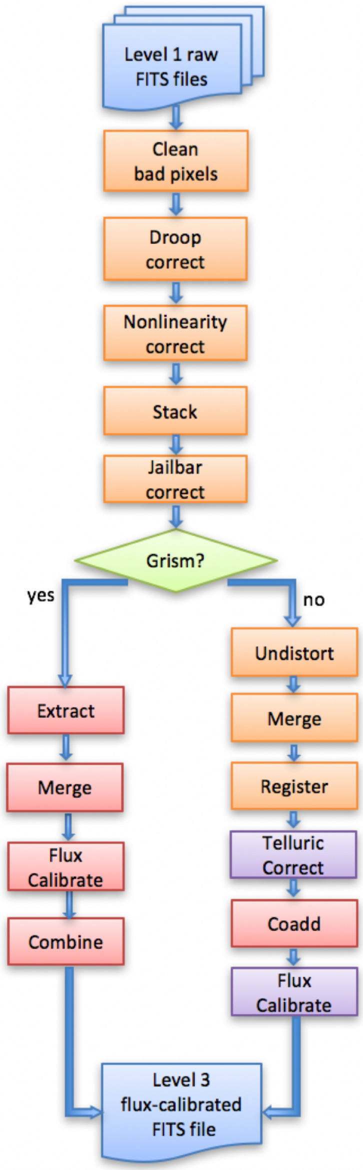
We don’t usually chop or nod along the slit, because extracted spectra don’t match in flux levels. Almost all grism spectroscopy is done in NMC or C2NC2 mode.

Grism Observing Modes: C2NC2



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

Data Reduction Steps



- Depending on the type of observation (photometry or spectroscopy), different procedures are performed after the Jailbar correction.
- Orange boxes indicate steps that use algorithms from the DRIP package.
- Red boxes indicate steps that use FSpextool algorithms.
- Purple boxes use algorithms from the PipeCal package.

- For more information see the *"FORCAST Guest Observer (GO) Data Handbook"* https://sofia.usra.edu/sites/default/files/USpot_DCS_DPS/Documents/FORCAST_GO_HAndbook_RevC.pdf

More Information

SOFIA Information for Researchers Website

www.sofia.usra.edu

SOFIA Help Desk

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