Imaging and low-res spectroscopy with SOFIA

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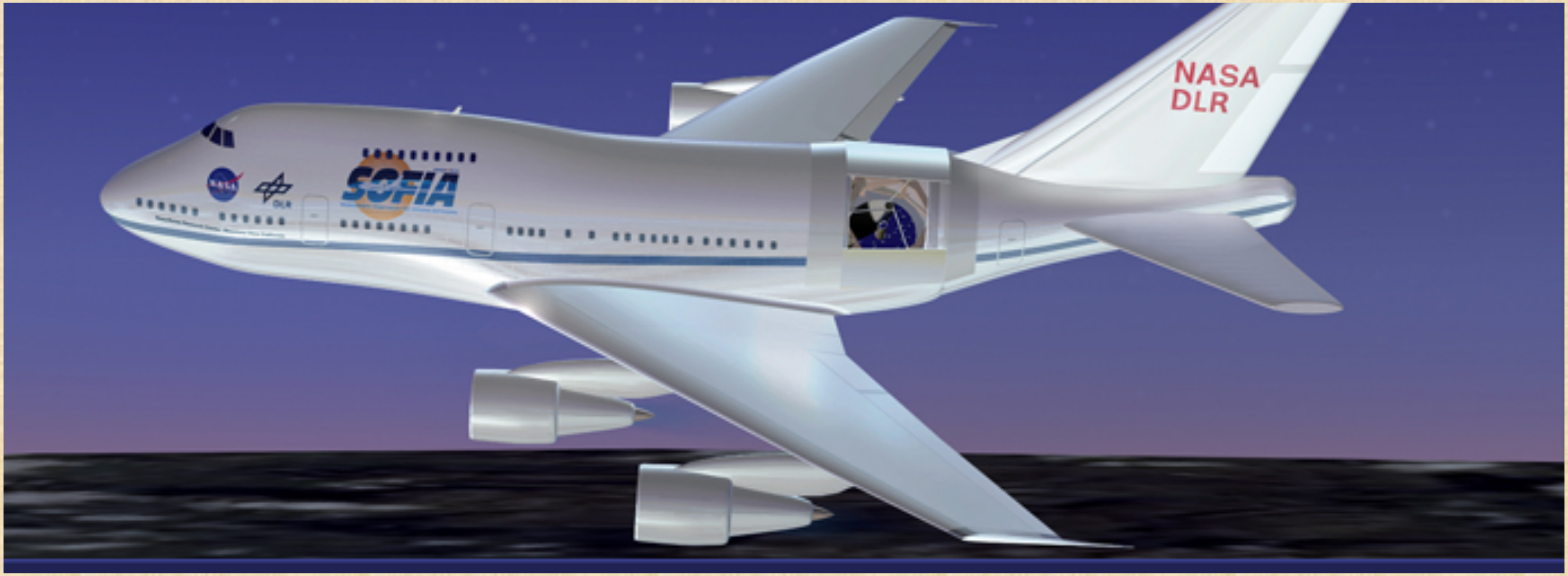


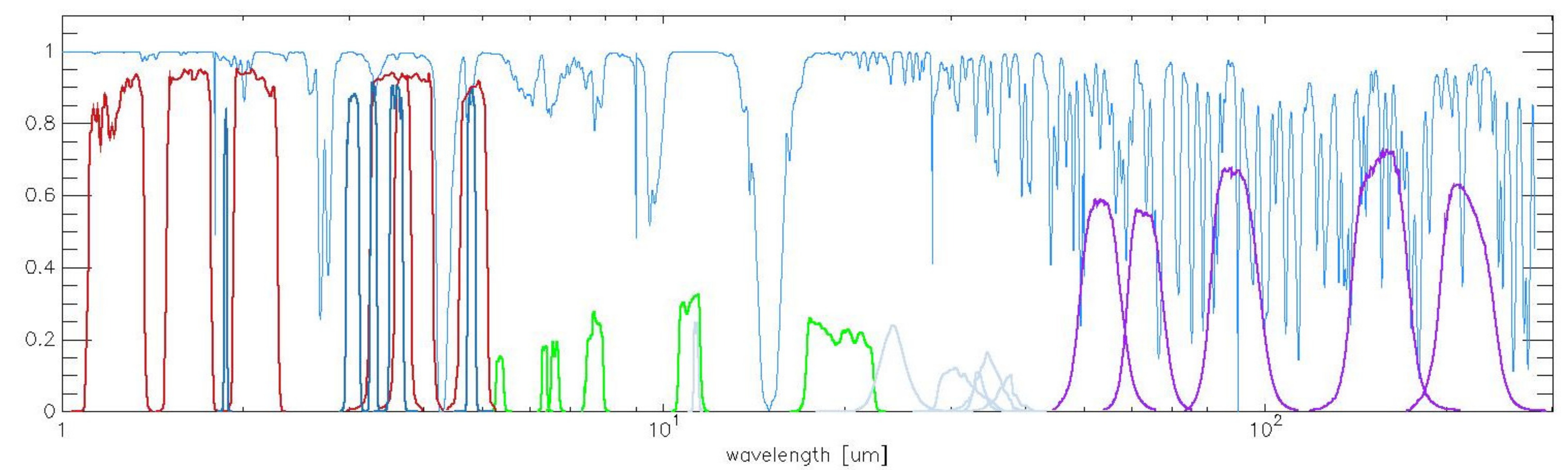
Outline

- Imaging and spectroscopic capabilities
- Observational modes
- Flitecam
- Forcast
- FIFI-LS
- Hawc+

Imaging

Pa α Ice PAH

J H K L M

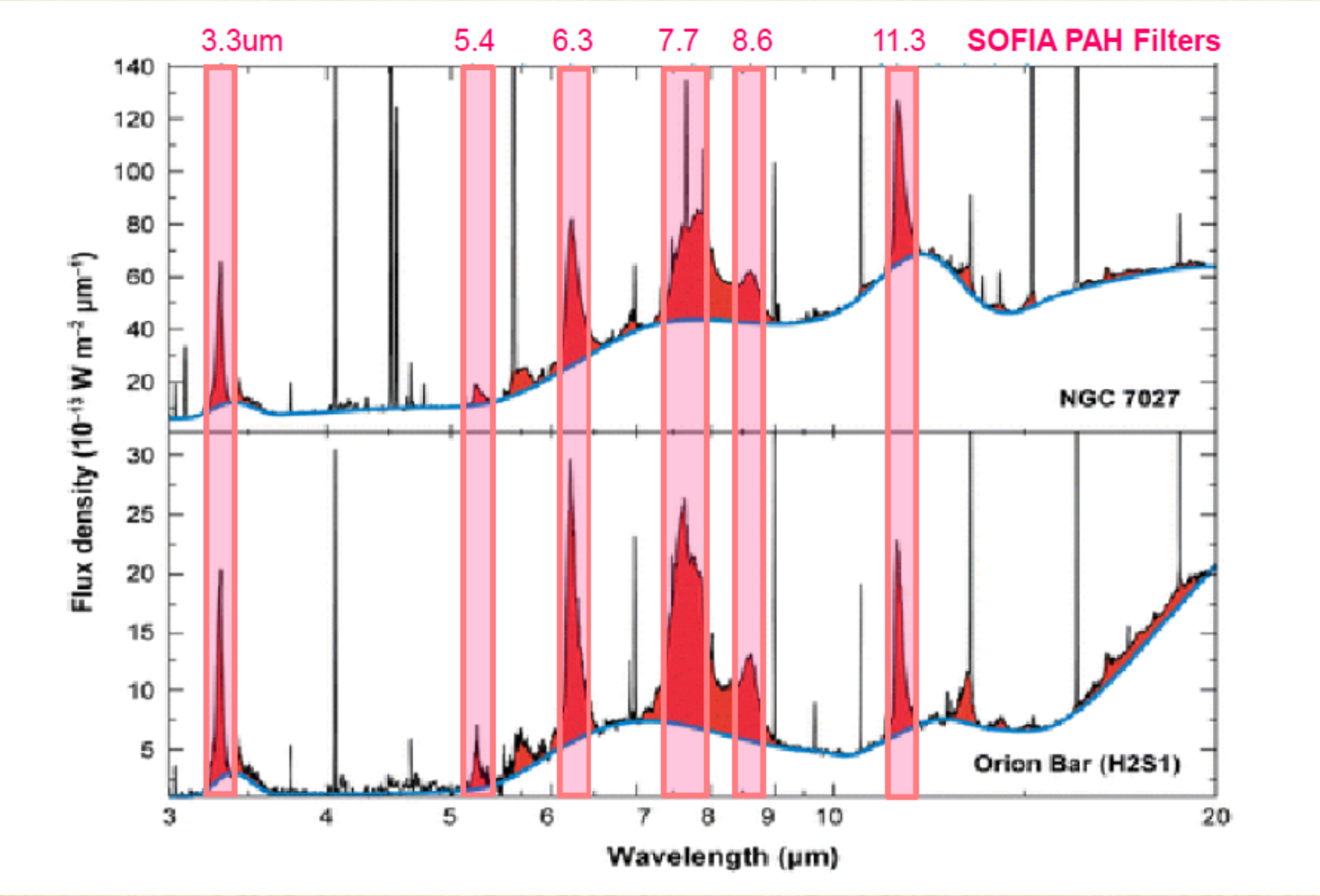


FLITECAM FORCAST HAWC+

2 arrays

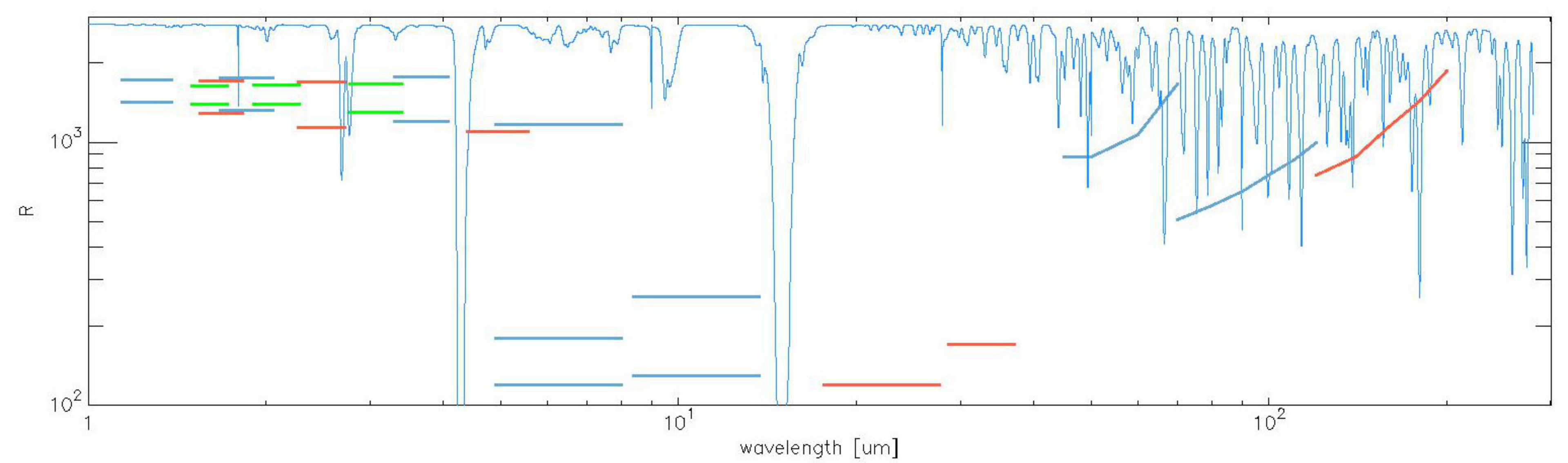
2 arrays (polarization)

PAHs



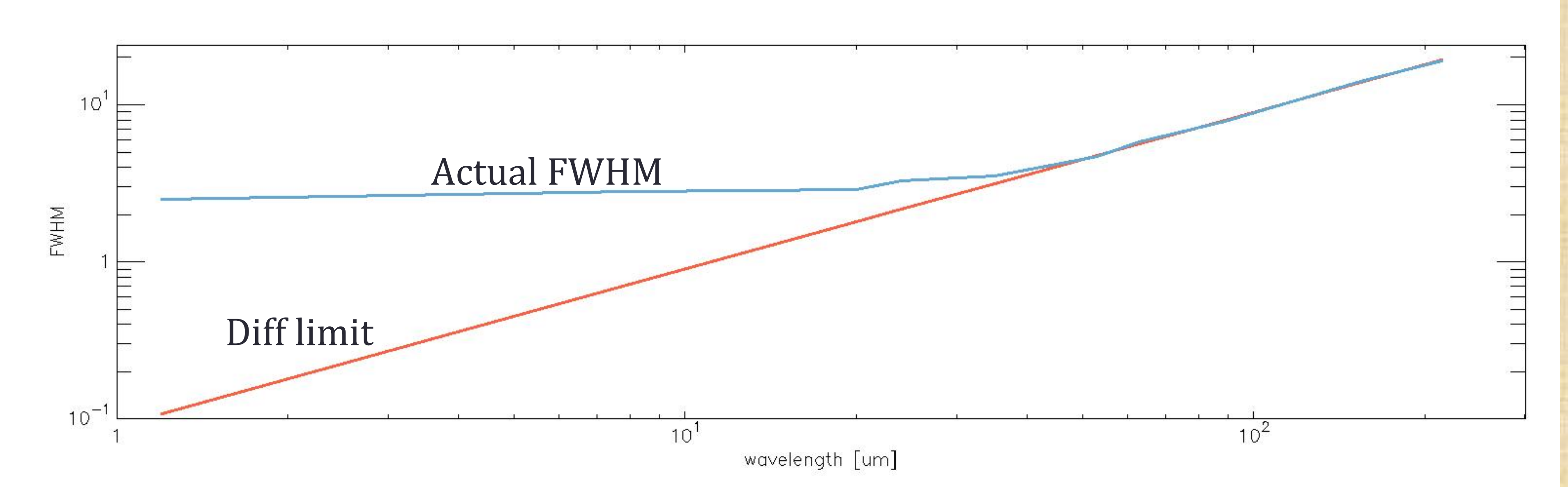
Filter set allows one to map the PAH chemistry

Low-res spectroscopy



FLITECAM	FORCAST	FIFI-LS
• 3 grisms • 3 orders • 2 slits	• 6 grisms • 2 long slits: 2.4” x 191” 4.7” x 191” • 1 short slit: 2.4” x 11.2”	• 2 arrays / 2 gratings • 2 orders for the blue • IFU (5 x 5)

Spatial res - FOV



FLITECAM: 1024x1024
8’ × 8’

FORCAST: 256x256
3.4’ × 3.2’
3.4’ × 3.2’

HAWC+: 64 x 40
2’ .. 6.1’ × 2’.7.. 8’
2’ .. 6.1’ × 2’.7.. 8’

FIFI-LS: 5x5
0.5’ × 0.5’
1’ × 1’

Observational modes

Types of observations

- Staring
- Maps

Techniques

- Chop – Nod
- Asymmetrical chop-nod
- Scan

Chop - nod

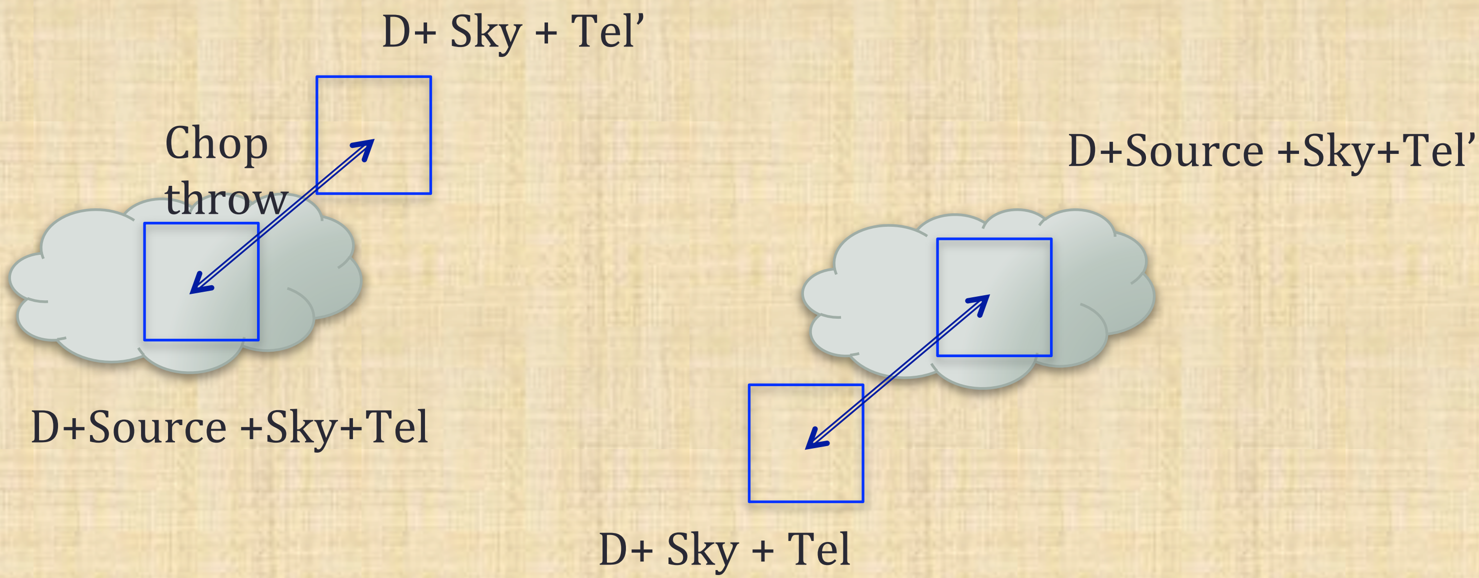
CHOP Modulation (few Hz) between ON and OFF source
Difference eliminates variation of atmosphere and detector response

NOD Every 10', invert ON and OFF optical paths
Sum of the two nods gets rid of different telescope background

CAVEATS

- Chop throw affects optical path (distortions)
- Chopping and nodding add overhead

Chop - nod



Nod A

Nod B

Difference: Source + Tel – Tel’ Source + Tel’ - Tel

Average: Source

Asymmetric chop - nod

Nod A

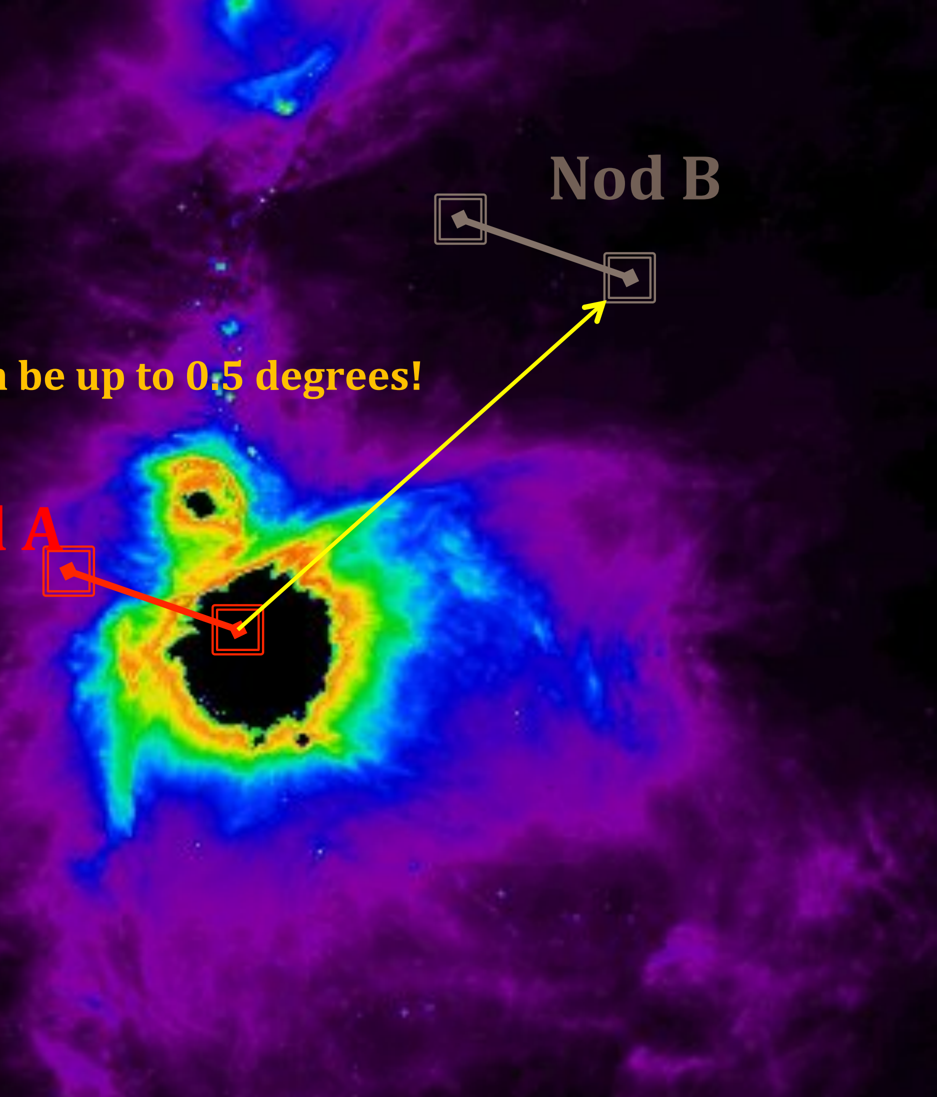
Nod B

Difference: Source + Tel – Tel’ Tel’ - Tel

Sum: Source

SOFIA can chop and nod with very large throws

SOFIA can chop asymmetrically up to 7' and can nod up to 0.5 degrees, allowing imaging in very large/crowded regions



Ground-based O/IR telescopes only chop-nod with throws <30"

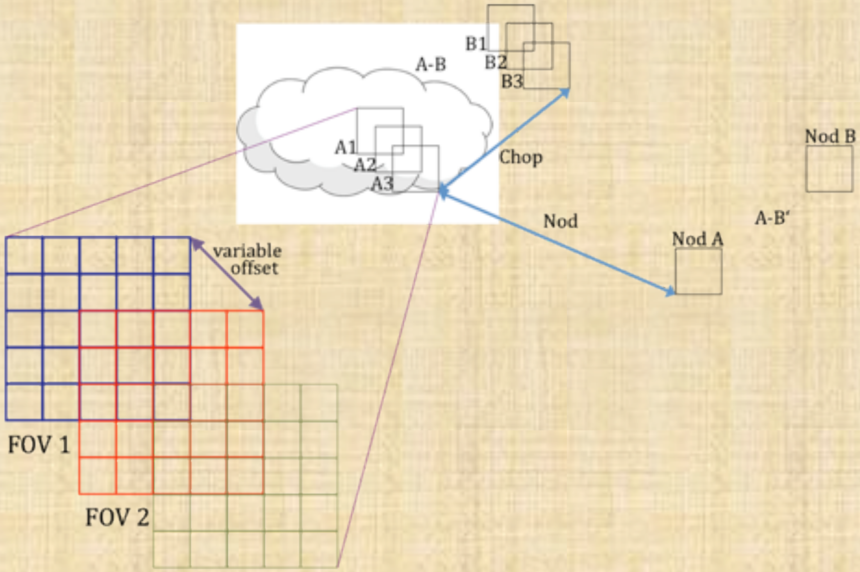
This form of chop-nod (C2NC2) is highly inefficient

However, this form of chop-nod delivers the best image quality

General lesson when preparing observations: Check Spitzer, WISE, MSX, IRAS, or Herschel images to make sure your chop-nod scheme will work!

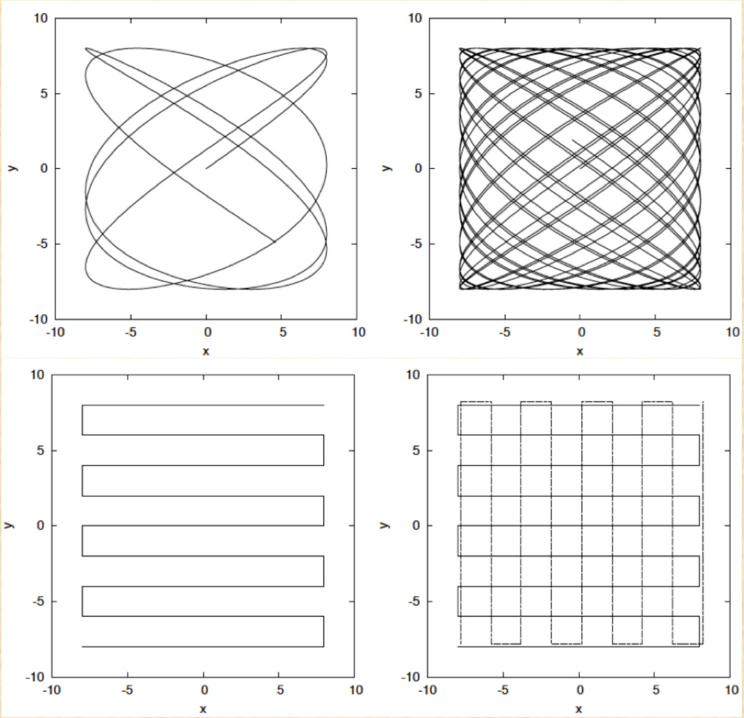
Chop Nod/ Scan Mapping

Asymmetric Chop Nod



FIFI-LS

Scan Mapping



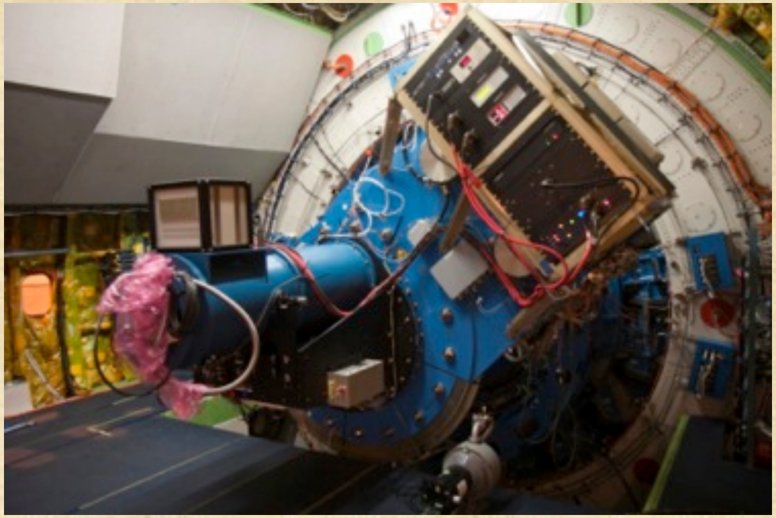
HAWC+

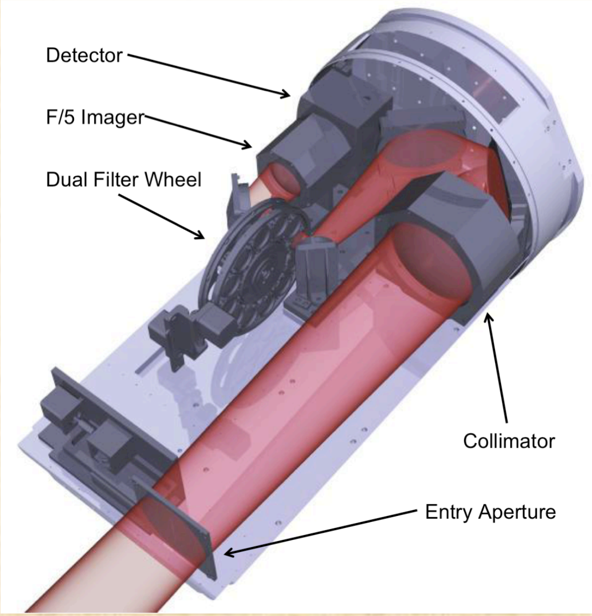
Chop-nod / scan mapping

- Chop/nod can be done in asymmetric mode by using the same OFF nodding to make it more efficient
- When scanning with HAWC+ cover a region with no emission if absolute continuum is required

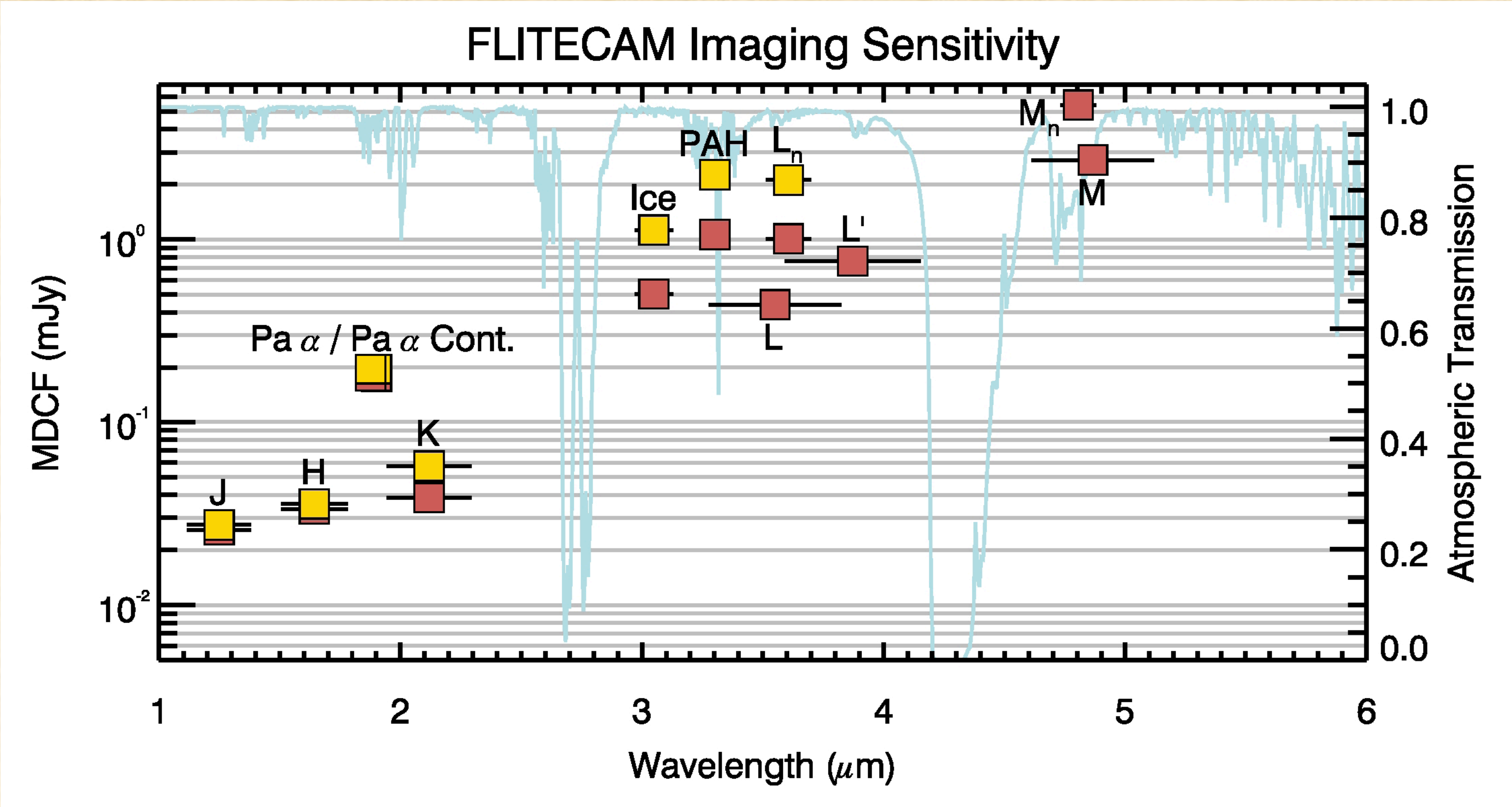
FLITECAM

- FLITECAM – **F**irst **L**ight **I**nfrared **TE**st **CAM**era
- P.I. Ian McLean (UCLA)
  - Near-IR (1.0-5.5 µm) camera
    - 1024 x 1024 InSb Array
    - 8' x 8' FOV with 0.475" square pixels
  - Grism Spectrometer
    - 2' slit length
    - Dual width, 2" and 1" – R ~ 850 and 1700 respectively





FLITECAM



J,H ~ 17.5 mags K ~ 17 (SNR = 4, 900 s)

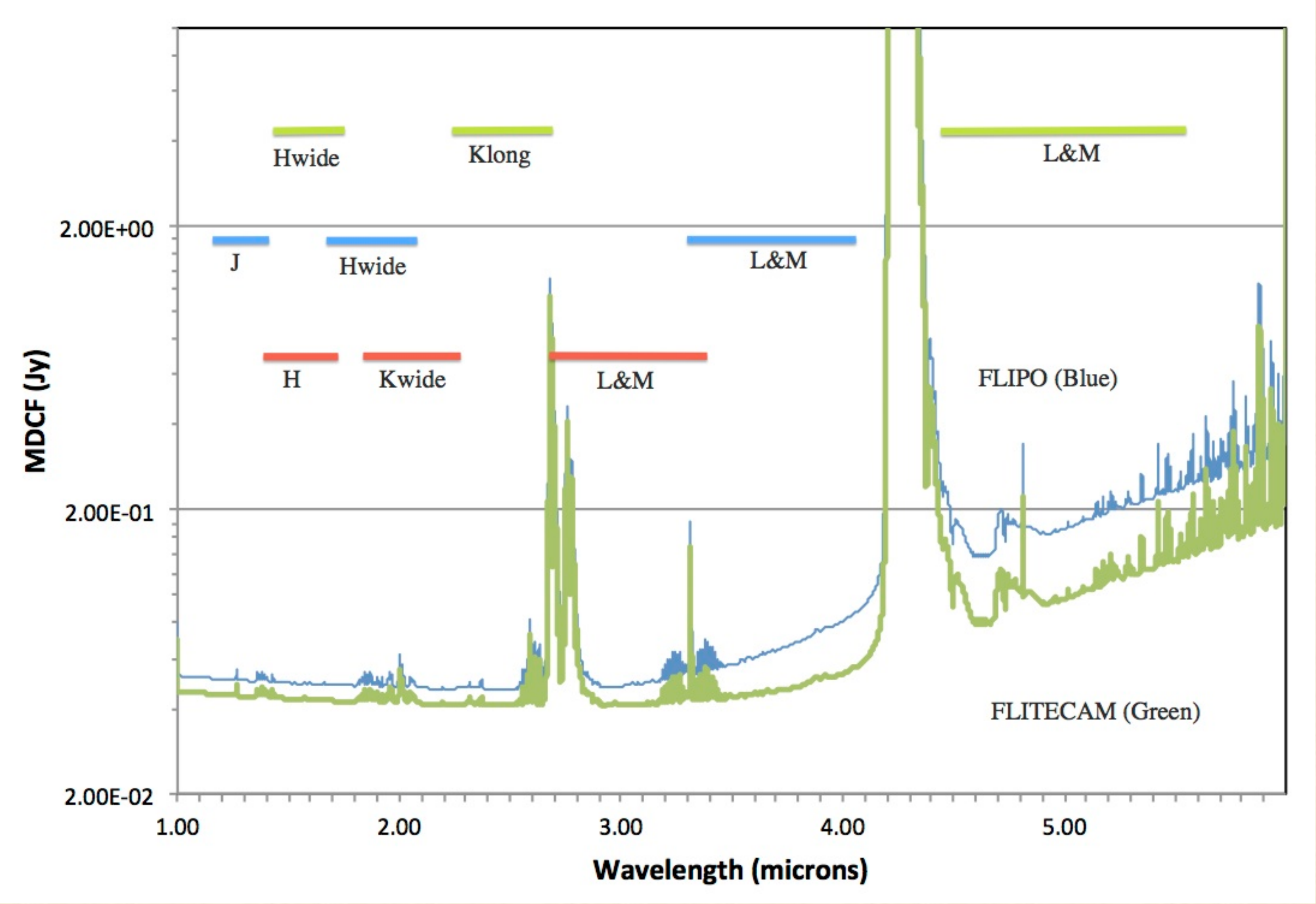
FLITECAM

Grism	Coverage (µm)	Resolution (WS/NS; R=λ/Δλ)	Features of Interest
FLT_B3_J	1.14-1.39	1425/1720	**O I**, **C I**, Fe II
FLT_C4_H	1.50-1.72	1400/1640	Mg I, Fe II
FLT_A3_Hw	1.55-1.83	1290/1710	Mg I, Fe II
FLT_B2_Hw	1.68-2.05	1320/1750	**He II**, Fe II
FLT_C3_Kw	1.91-2.28	1390/1650	Fe II, Na I
FLT_A2_KL	2.27-2.72	1140/1690	
FLT_C2_LM	2.78-3.40	1300/1670	Aromatics
FLT_B1_LM	3.30-4.07	1200/1780	Aromatics + Aliphatics
FLT_A1_LM	4.40-5.53	-/-	

Low Res: Δv ~ 210 – 260 km/s

High Res: Δv ~ 170 – 180 km/s

FLITECAM

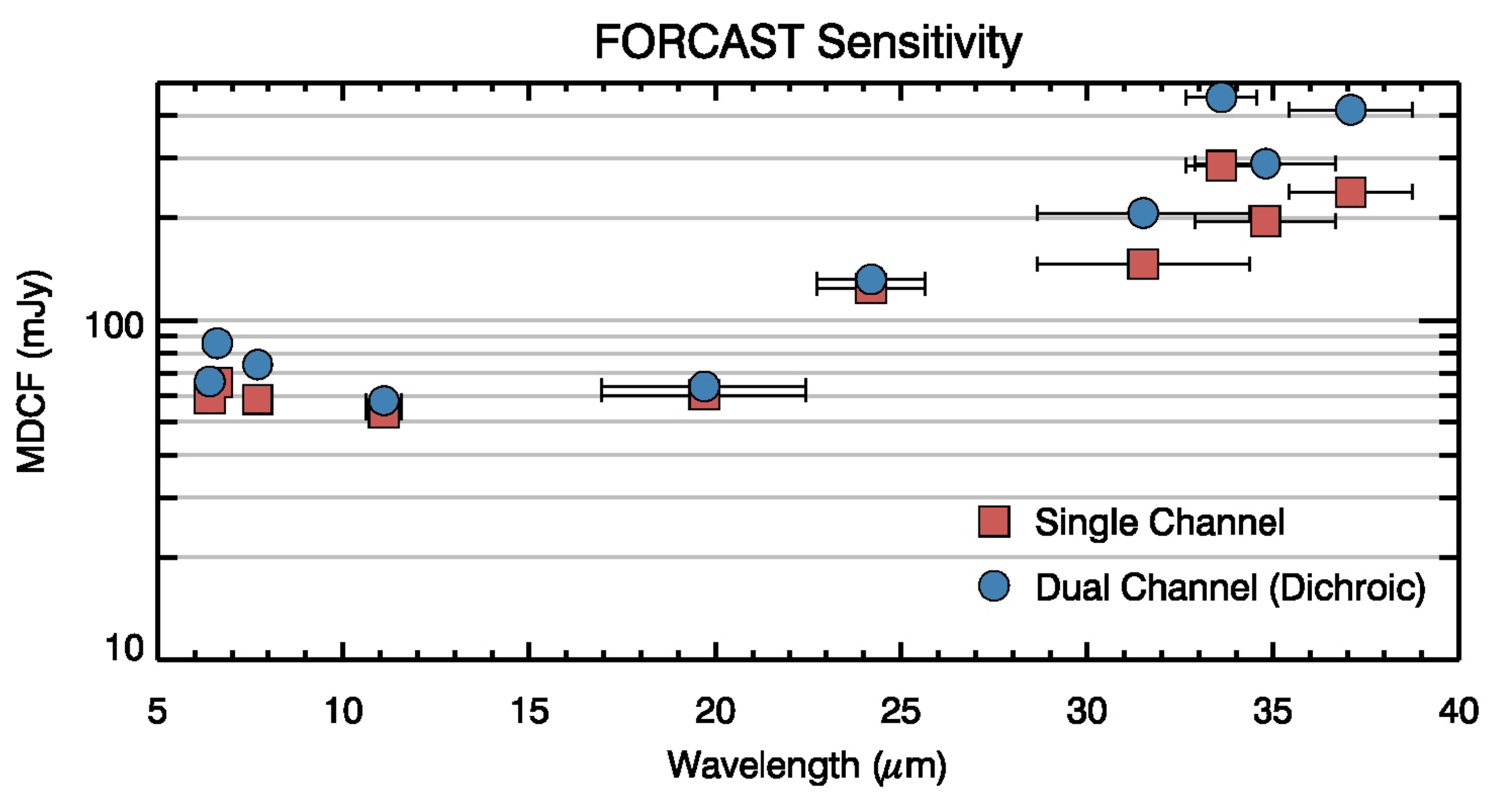


SNR = 4 in 900s

FORCAST

- FORCAST - **F**aint **O**bject infra**R**ed **CA**mera for the **S**OFIA **T**elescope
- Imaging - P.I. Terry Herter (Cornell)
  - Dual Channel, mid-IR (5-40 μm) camera
    - Short Wave Camera (SWC) – Si:As BiB Array – $\lambda < 25$ μm
    - Long Wave Camera (LWC) – Si:Sb BiB Array – $\lambda > 25$ μm
    - 3.4' x 3.2' FOV with 0.768" square pixels
- Spectroscopy – P.I. Luke Keller (Ithaca College)
  - Grism Spectroscopy
    - Low Resolution from 5-40 μm at R ~ 200

FORCAST

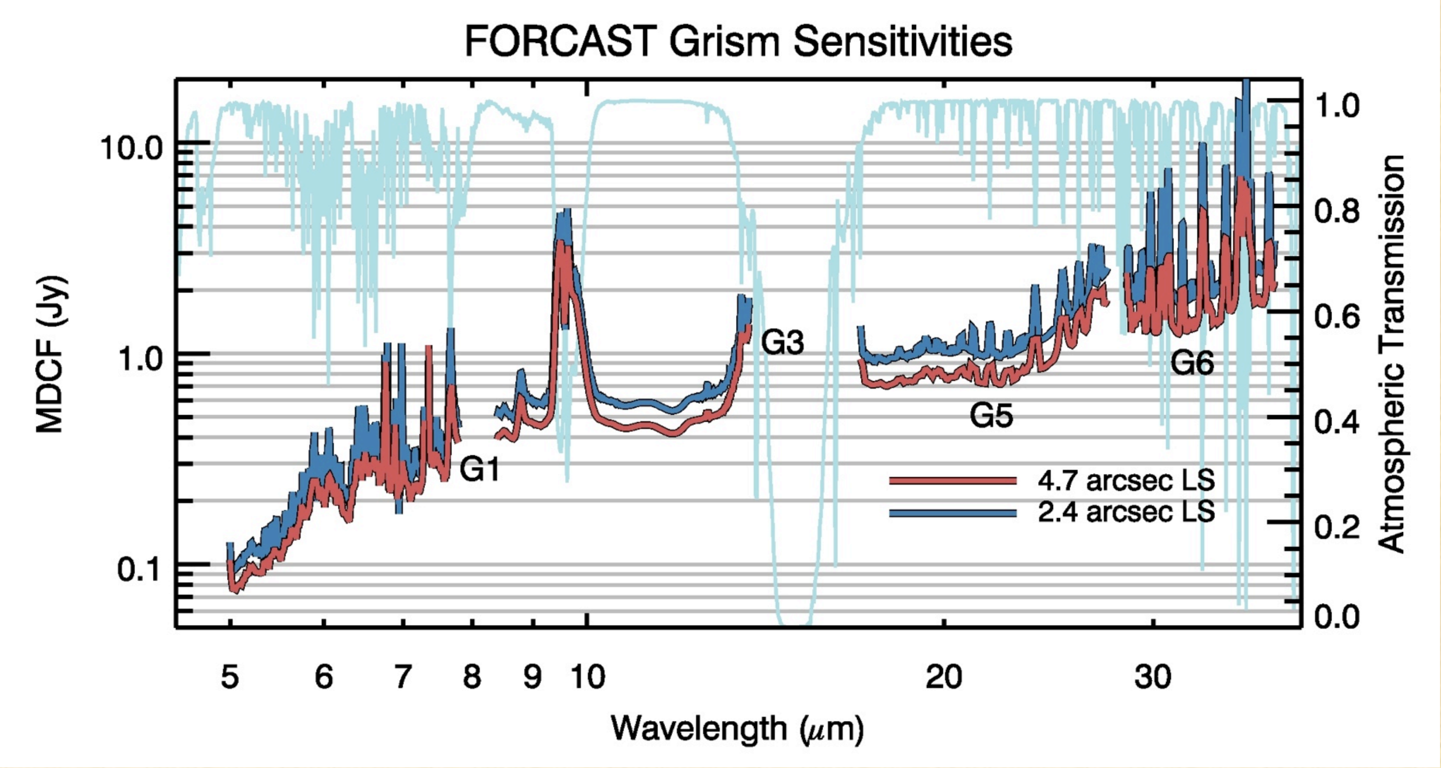


SNR = 4   in 900s

FORCAST

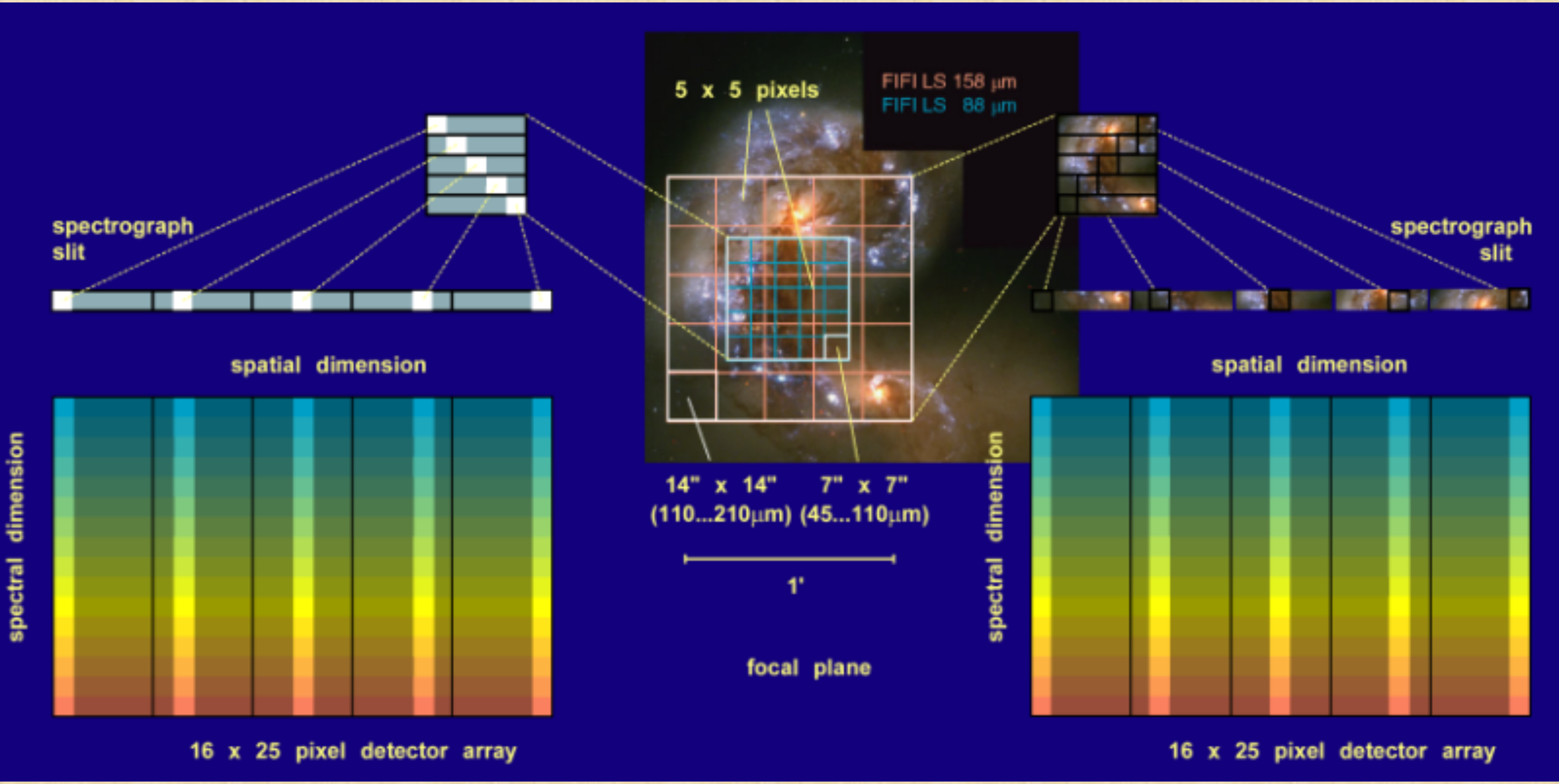
Grism	Coverage (μm)	Resolution (WS/NS) ($R=\lambda/\Delta\lambda$)	Resolution (WS/NS) (Δv [km/s])	Features of Interest
FOR_G063	4.9-8.0	90/180	3000/1670	[Mg V]; [Mg VII]; [Ne VI]; [Ar II] PAHs
FOR_G111	8.4-13.7	150/300	2000/1000	[Ar III]; [S IV]; [Ne II] PAHs, Silicates, SiC
FOR_G227	17.6-27.7	70/140	4290/2140	[S III]; [Ne V]; [O IV] Silicates
FOR_G329	28.7-37.1	110/220	2730/1360	[S III]; [Ne III]

FORCAST



SNR = 4 in 900s

FIFI-LS


5 x 5 pixels
FIFI LS 158 μm
FIFI LS 88 μm
spectrograph slit
spectrograph slit
spatial dimension
spatial dimension
spectral dimension
spectral dimension
14" x 14"
(110...210μm)
7" x 7"
(45...110μm)
1'
focal plane
16 x 25 pixel detector array
16 x 25 pixel detector array

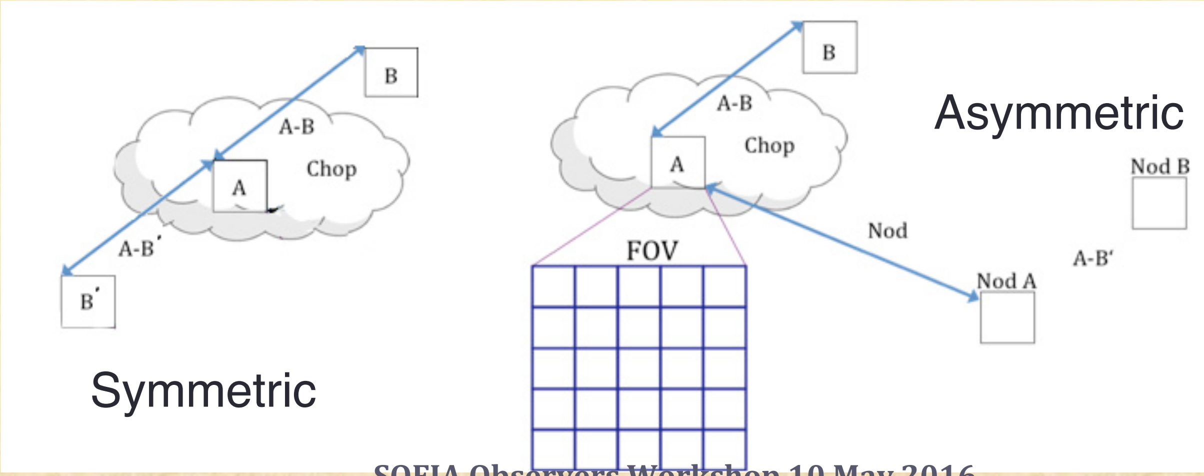
FIFI-LS

- **Symmetric Chop**
  With matched nod -> symmetric off-positions
  Max chop throw $\theta < 5'$ for $\lambda<120\mu m$ & $\theta < 4'$ for $\lambda < 63\mu m$
  Overhead: 170% (assumes long integration times)

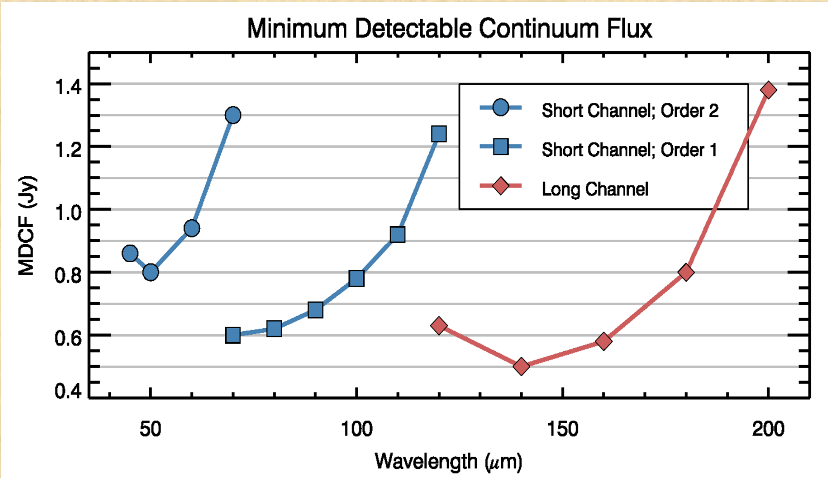
- **Asymmetric Chop**
  Needs reference position
  Overhead: 430% (assumes long integration times)

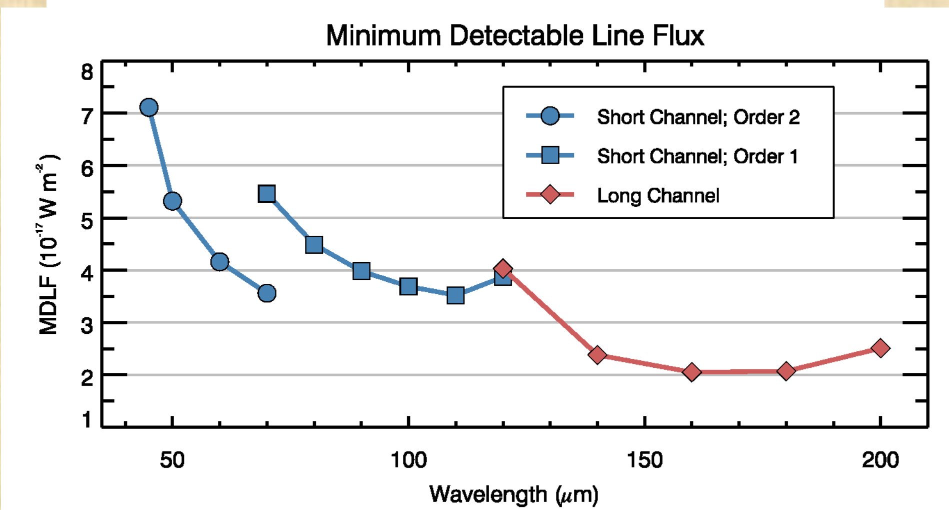
- **Bright Object**
  Asymmetric chop with two on-positions per nod-cycle
  Overhead: 500% (assumes $t_{on} \approx 5s$)

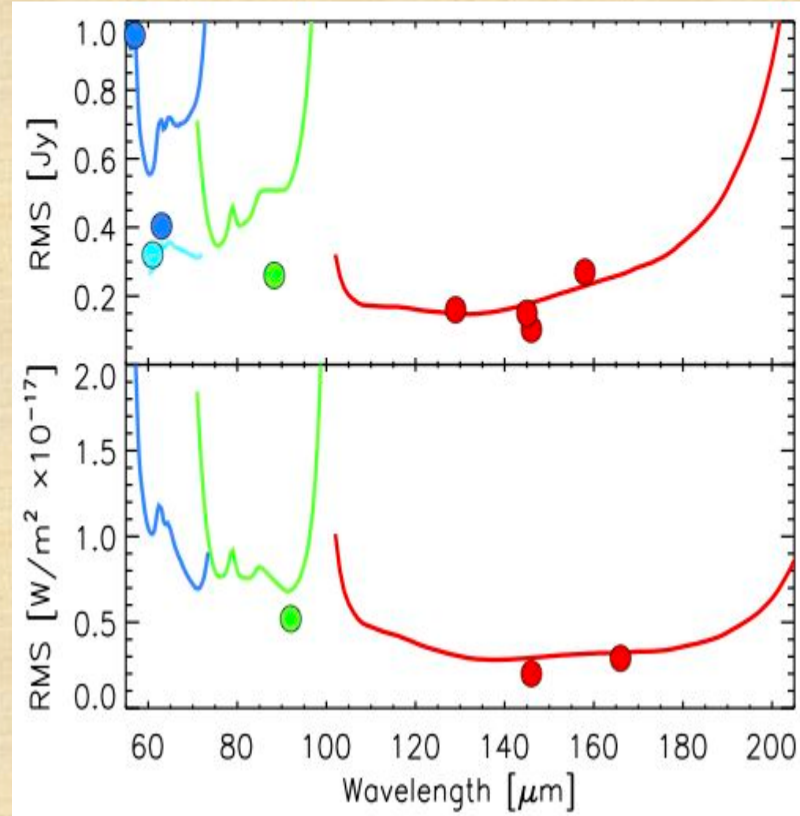
- **Spectral Scan** Several microns wide spectral features



FIFI-LS vs PACS







PACS 1σ sensitivity in 400 s

FIFI-LS 4σ sensitivity in 900 s

FIFI-LS vs PACS

There are several differences with PACS:

- Two independent grisms for the two channels. So, two wavelength ranges can be observed at the same time
- Blue and red arrays have different pixel sizes, better sampling the PSF
- Asymmetric chop allows for large chop throws
- K-mirror enables the alignment of the FOV
- Fast mapping capability (telescope can move fast)
- Blue wavelength ranges starts at 51μm allowing the measurement of the [OIII] 52μm line (impossible with Herschel)

Rotation angle

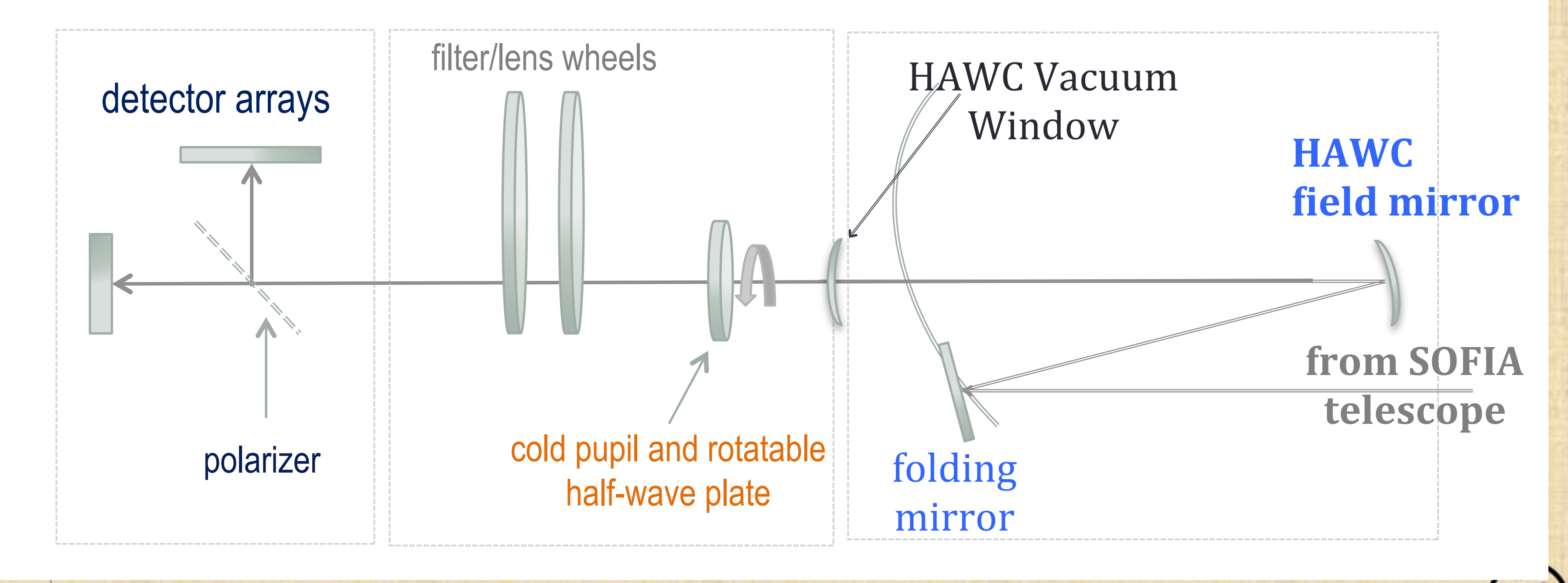
- SOFIA does not have an instrument rotator.
- FORCAST and FLITECAM do not have a field rotator
- FIFI-LS has a field rotator (K-mirror)
- The rotation of the field is not known a priori but only when the flight is planned.

HAWC+

- Two detector arrays (64×40 pixels) simultaneously measure both components of linear polarization. Components are ***Reflected*** and ***Transmitted*** off a polarizing wire grid.

- Five different passbands from 50 – 250 μm. Each passband is diffraction limited with a plate scale that Nyquist samples the beams

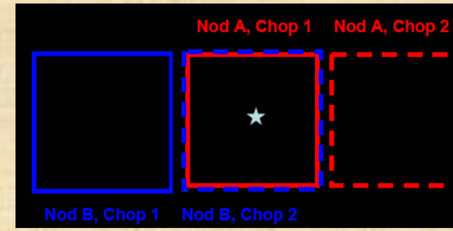
- Rotatable half-wave plates are used to rotate the plane of polarization. HWPs are matched to each passband.



Observing mode

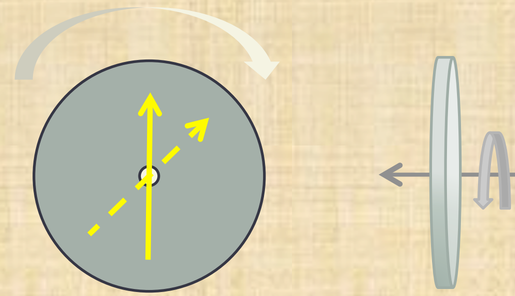
1) Chop-Nod

- Nod parallel to chop, symmetric only
- Chop amp. 2–8 arcmin, freq. 5–20 Hz



2) Rotate Half-waveplate (HWP)

- Step in 4–8 positions/angles (0°-180°)
- Repeat chop-nod sequence at each HWP angle

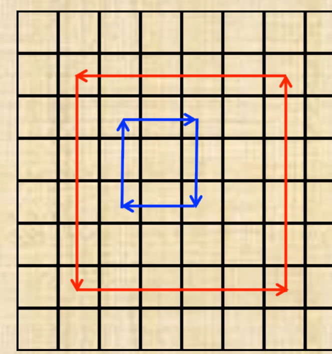


3) Dithering

- Repeat Chop-Nod and HWP sequences at all dither positions

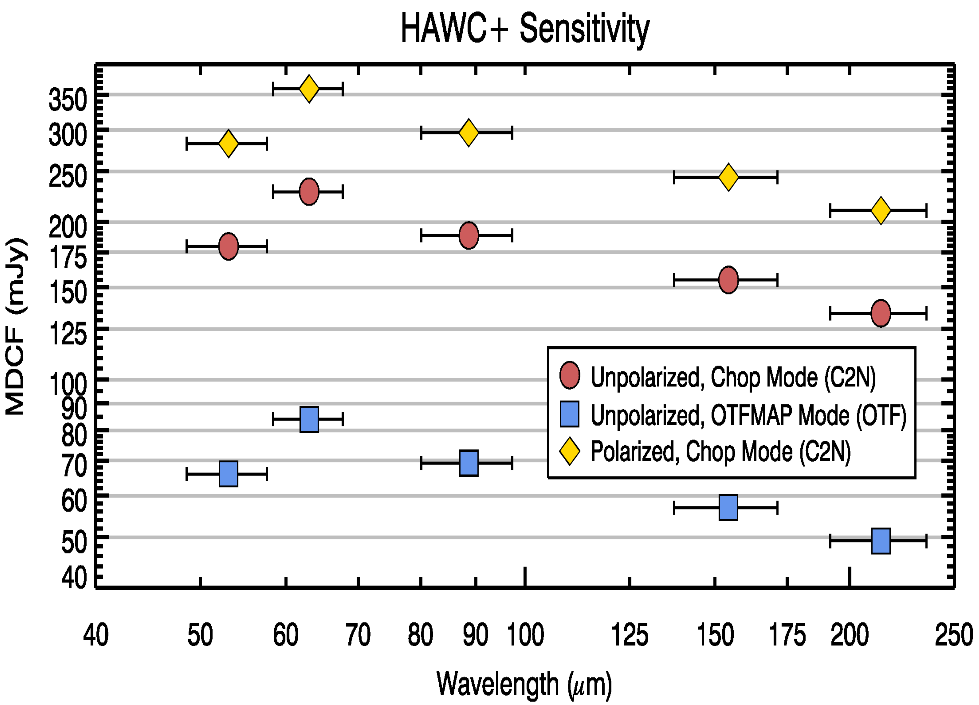
4) Mapping

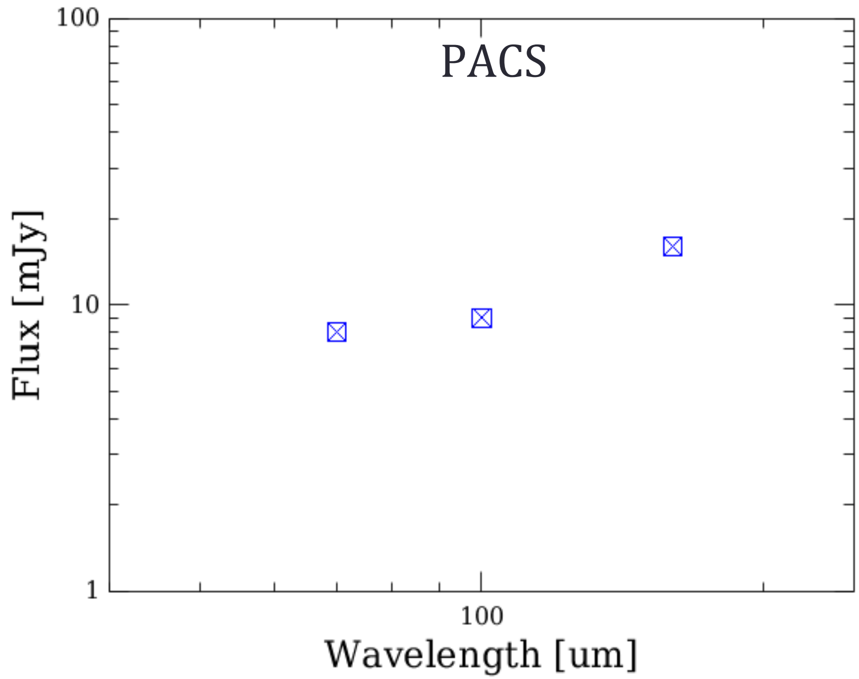
- Repeat Dither, HWP, and Chop-Nod sequences at all map positions



Polarimetry requires at least 4 separate photometric measurements. (1 chop-nod) × (4 HWP) × (4 dithers) ~ 15–30 minutes minimum observing time.

HAWC+ vs PACS





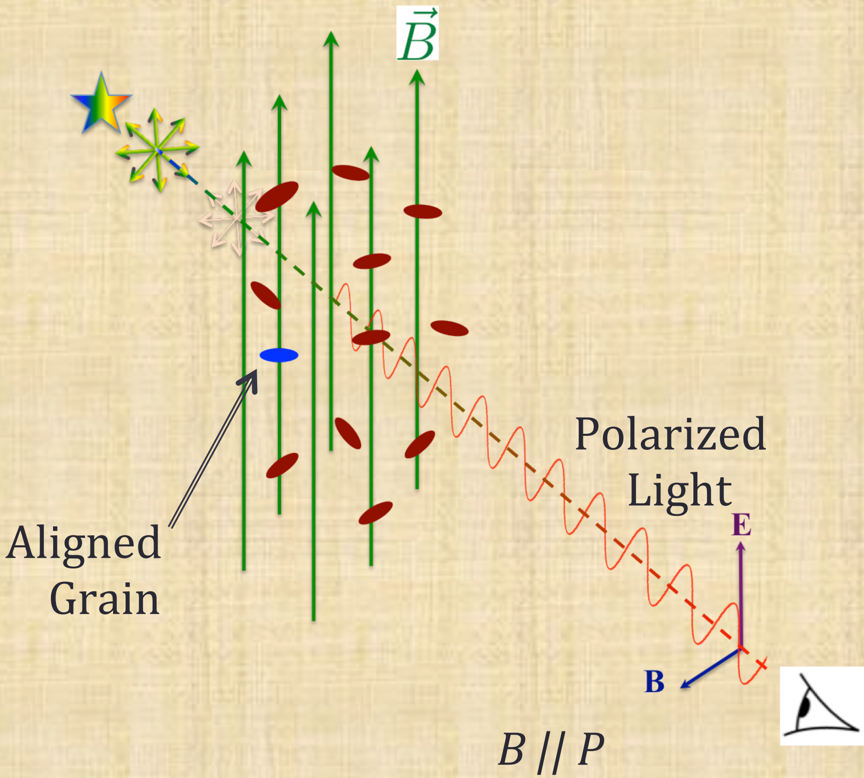
Less sensitive than PACS but still competitive in scan mode, even for extra-galactic sources.

Polarization

Polarization by Extinction

polarization of background starlight

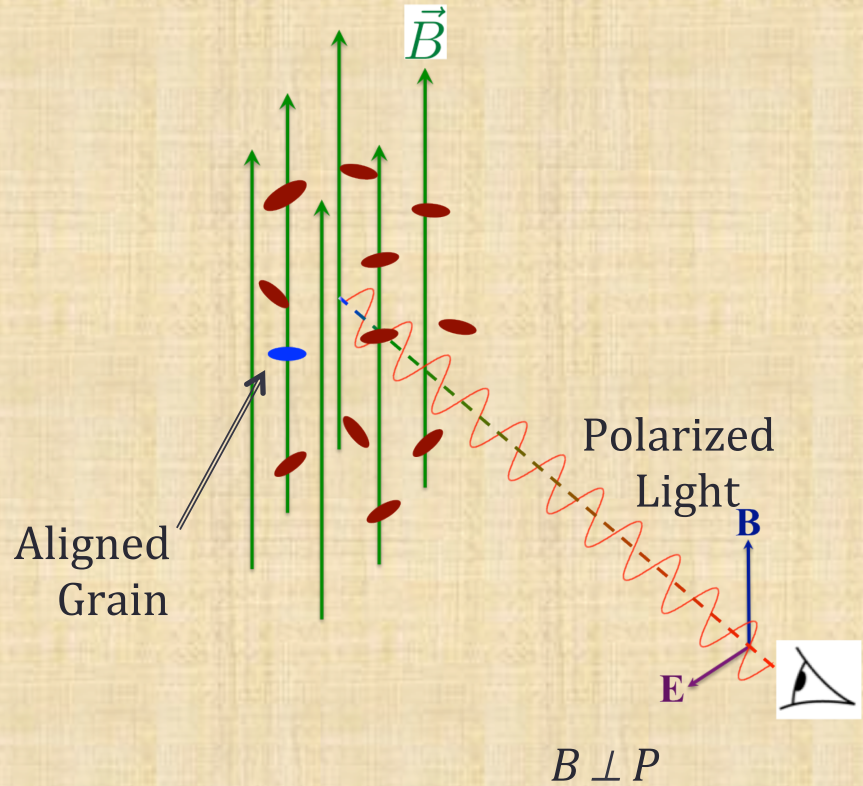
wavelengths ~ NUV – optical – NIR



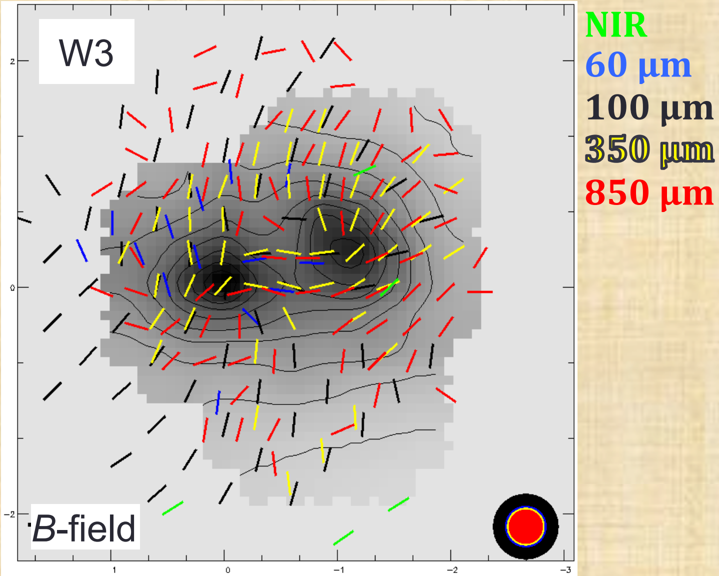
Polarization by Emission

polarization of thermal emission

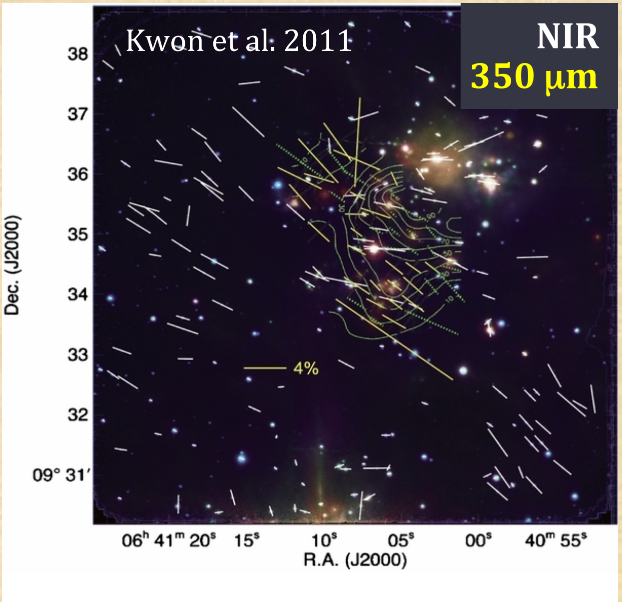
wavelengths ~ FIR – mm



Multi-wavelength Polarimetry



Schleuning et al. 2000; Dotson et al. 2010



- Different wavelengths trace different types/temperatures of dust and hence different regions of clouds.
  - Optical data traces diffuse ISM, FIR/mm traces denser parts of cloud and cores. Do they yield same B-field orientation? How does existence of cloud alter mean Galactic field?
  - Short FIR wavelengths trace dust and *B*-field close to warm cores
  - Long FIR wavelengths trace dust and *B*-field in cooler cloud edges

Planning with Herschel/Planck

- **Beware flux in your reference beams**

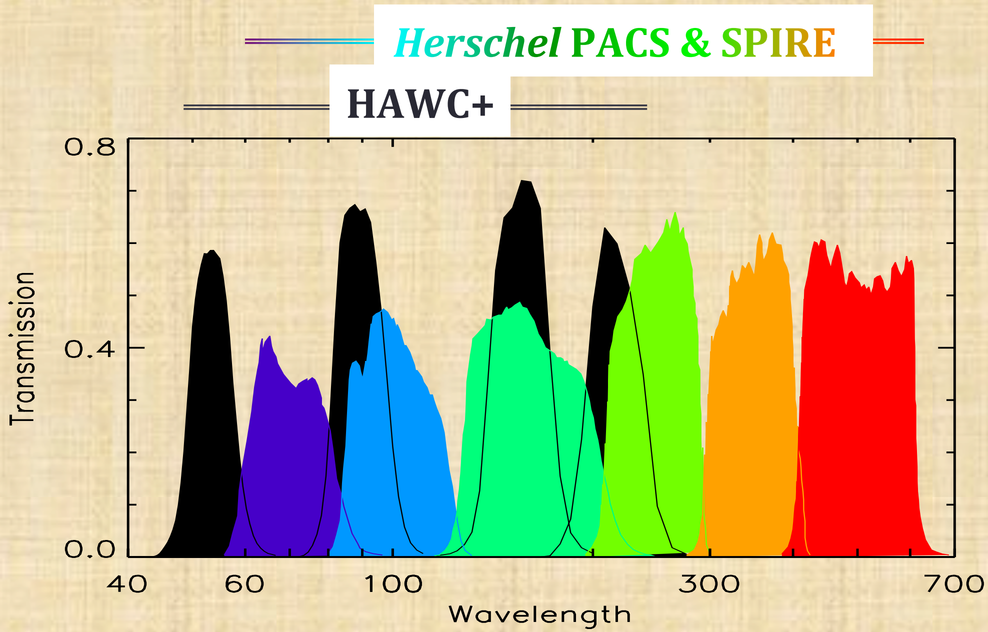
- Total Intensity:
  - even if reference flux cannot be avoided, it always subtracts from source flux
  - There exist many large-scale maps in FIR for planning to avoid reference flux (e.g. IRAS, *Herschel*, *Spitzer*)

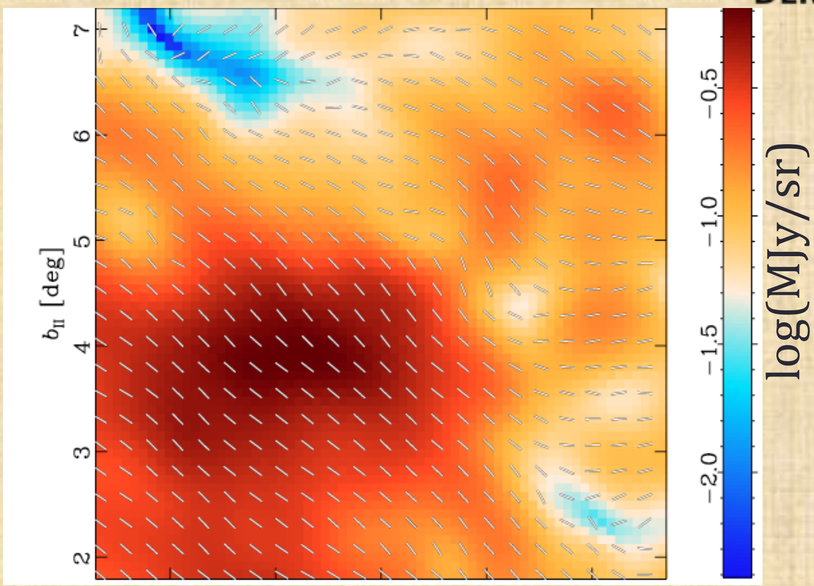
- Polarized Intensity:
  - polarization angle differences between reference and source can lead to subtraction *or addition* (Schleuning+ 1997, PASP, 109, 307; Novak+ 1997, ApJ, 487, 320)

    – There are no large-scale FIR polarization maps. Maybe some combo. FIR intensity surveys and *Planck* 850 μm data

    – Best solution: find the dimmest total intensity region possible, use larger chop throws, repeat measurement w/ different reference region

Planning with Herschel/Planck





Polarized intensity and *B*-orientation

- HAWC bandwidths are narrow
  - λ/Δλ ~ 5 – 6.
- Herschel bandwidths are wider
  - λ/Δλ ~ 3.

- Planck at 850 μm
  - published data plotted at 1 degree resolution for *B*-vectors
  - native resolution ~ 5 arcmin
- Herschel bandwidths are wider
  - λ/Δλ ~ 3.

Summary

- SOFIA's covers the 1-250 μm range with imaging and spectroscopy
- SOFIA can chop and nod with very large throws and map in a fast way large region of sky
- SOFIA offers unparalleled spatial resolution between 28 and 65 μm
- SOFIA imaging bands covers wavelengths most critical for SED modeling and are well suited for mapping PAH chemistry
- SOFIA imaging and spectroscopy in the far-IR (50-250 μm) is competitive with Herschel.
- FIFI-LS is an improved version of PACS with fast mapping capabilities and extended wavelength range.
- HAWC+ samples the far-IR with bands narrower than Herschel's ones and makes possible polarimetry in the far-IR.