SMIRPh

SOFIA Mid-InfraRed Polarimeter

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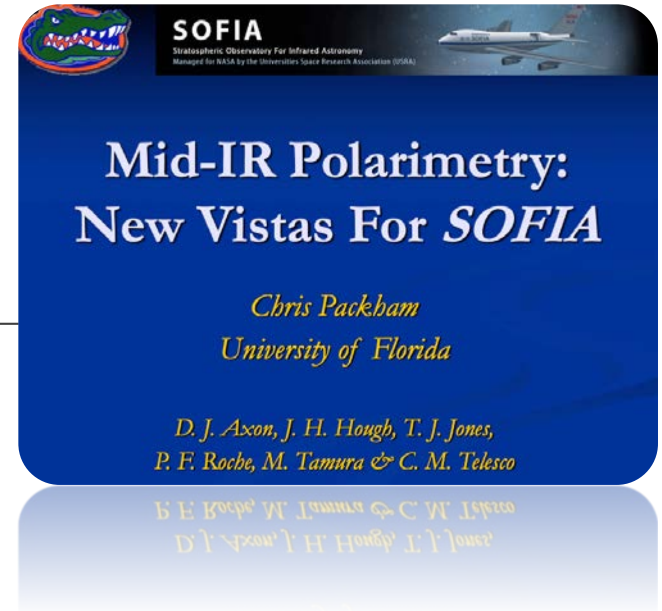
Outline

1. History (& caveats)
2. Science cases
3. Integration to SOFIA
4. Instrument feasibility & status
5. Connection to SOFIA's Science Case Workshop (earlier this month)
6. Conclusions

History (& Caveats)



Originally presented in the 2007 SOFIA 2020 workshop (at Caltech)
- Before SOFIA's 1st light!

A small group lead a science case investigation, technical feasibility, and an early conceptual-level design
- Described in SPIE papers by Packham et al. 2007 (science) & 2008 (design)

Whilst we were interested in continuing work, pressures of other projects meant we did not apply in subsequent instrumentation CfPs

SOFIA has shown itself to be a powerful (and friendly!) polarimetry observatory
- HAWC+ polarimetry is producing excellent results ~50-210 μm
- Ground-based polarimetry covers nicely <14 μm
- Polarimetry 'desert' 14-50 μm remains, and arguably more pronounced with the results from HAWC+

SMIRPh needs updating – welcome input on science & technical aspects, and an understanding from the SOFIA community if there is interest to pursue this
- As noted by Judy detectors are a big concern

IR Advantages

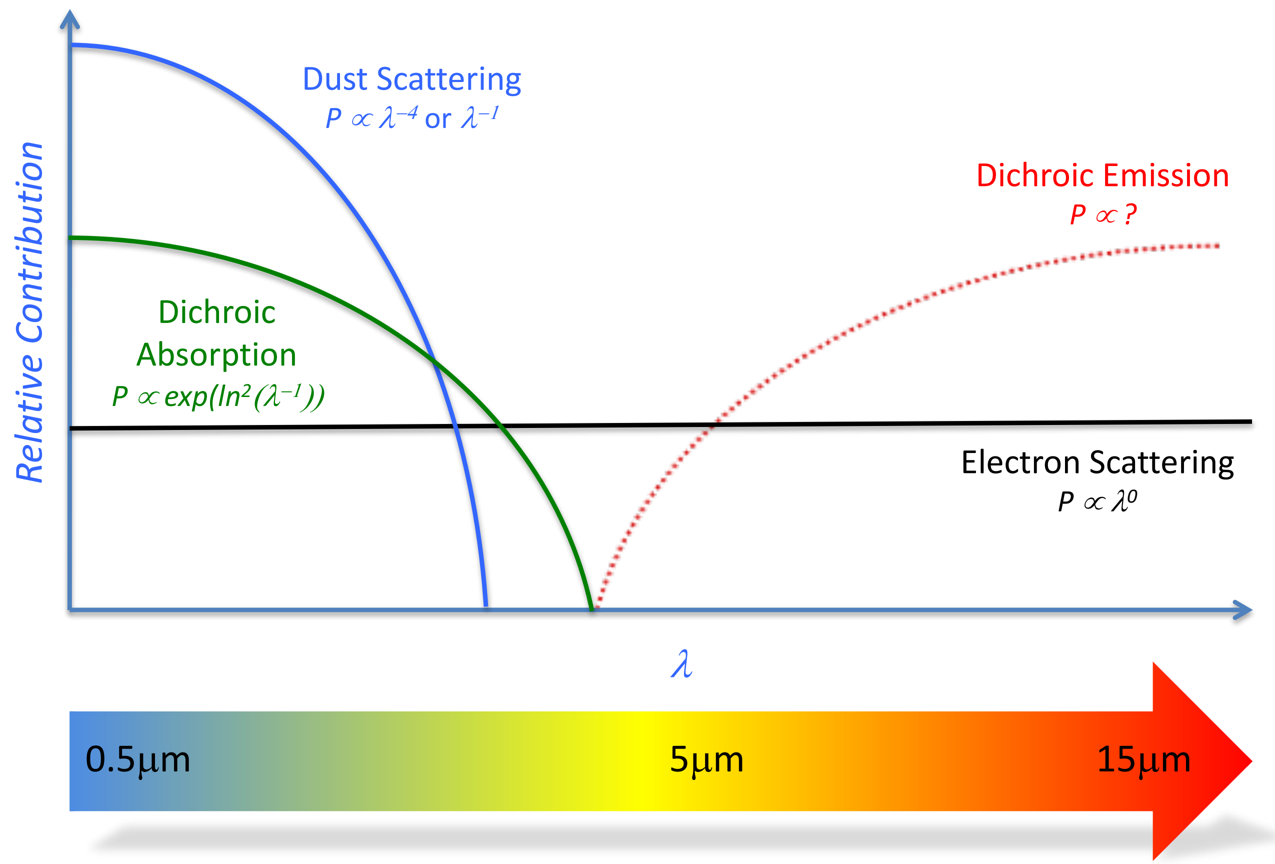
UV, optical, and even NIR have competing polarizing mechanisms

Deeper into the IR the situation is less complicated, but still mechanisms such as dichroic emission, electron scattering, and synchrotron emission could be present

Long baseline coverage is essential to disentangle polarizing mechanisms and/or PAs

Polarization & λ Coverage

(Illustrative only)



Science Cases

1. Solar system
2. Star formation
3. Disks as planetary nurseries
4. Dust grain chemistry
5. AGN and Galaxies

Solar System

Birefringent materials (e.g., silicate absorption bands at 10 and 18 μm)

- Circular polarization of Mercury

Optically active materials (chirality); biosignature of Mars, comets (next slide)

- *Organics on Europa and other sub-surface ocean objects*

Aerosol characteristics in atmospheres of Venus and outer planets (next^2 slide)

Magnetic fields (alignment of dust particles in disks and comets; auroras on giant planets) (next^2 slide)

TABLE 4. Biologically important functional groups and molecular assignments for infrared spectroscopy at STP.

Frequency, cm^{-1} (Wavelength, μm)	Functional Groups and Molecular Assignments
25,000 (0.4–0.58)	Carotenoid pigment
16,667 (0.6–0.7)	Chlorophyll-a, -b pigments
10,000 (1.0)	O–H of water of hydration of parent compound (•H_2O)
8000 (1.25)	O–H of water of hydration of parent compound (•H_2O)
6667 (1.5)	O–H of water of hydration of parent compound (•H_2O)
5000 (2.0)	O–H of water of hydration of parent compound (•H_2O)
4878 (2.05)	Amide in proteins, N–H vibration with C–N–H bend
4608 (2.17)	Amide in proteins, N–H fundamental with C–N stretch
4348 (2.3)	C–H and methane
~3500 (2.86)	O–H stretch of hydroxyl groups
~3200 (3.1)	N–H stretch (amide A) of proteins
~2955 (3.38)	C–H stretch (a) –CH_3 in fatty acids
~2930 (3.4)	C–H stretch (a) >CH_2
~2918 (3.43)	C–H stretch (a) of >CH_2 in fatty acids
~2898 (3.45)	C–H stretch, CH in methine group
~2870 (3.48)	C–H stretch (s) of –CH_3
~2850 (3.51)	C–H stretch (s) of >CH_2 in fatty acids
2590–2560 (3.88)	–S–H of thiols
~1740 (5.75)	>C=O stretch of esters
~1715 (5.83)	>C=O stretch of carbonic acid
~1680–1715	>C=O stretch of nucleic acid
~1695 (6.0)	Amide I band components
~1685 (5.93)	Resulting from antiparallel pleated sheets
~1675 (5.97)	Amide I β-turns of proteins
~1655 (6.04)	Amide I of α-helical structures
~1637 (6.11)	Amide I of β-pleated structures
~1550–1520 (6.52)	Amide II
~ 1515 (6.6)	"Tyrosine" specific band
~1468 (6.81)	C–H deformation of >CH_2
~1400 (7.14)	C=O stretch (s) of COO^-
~1310–1240 (7.8)	Amide III of proteins
1304 (7.67)	CH_4, methane
~1250–1220 (8.0)	P=O str >PO_3^-, phosphodeiesters
1240–180 (8.26)	O–S=O stretch of sulfites
~1200–900 (8–11)	C–O, C–C, str of carbohydrates
~1200–900 (8–11)	C–O–H, C–O–C def. of carbohydrates
~1100–1000 (9.52)	P–O, PO_4^{-3} stretch
~1090 (9.17)	P=O stretch (s) >PO_2
~1085 (9.2)	C–O stretch
~1061 (9.4)	C–N and C–C stretch
1140–1080 (9.0)	S–O– stretch of inorganic sulfates
1070–1030 (9.52)	C–S=O of sulfoxides
~1004 (9.96)	Phenylalanine
~852 (11.7)	Tyrosine
~829 (12)	Tyrosine
~785 (12.7)	Cytosine, uracil (ring stretch)

Compiled from *Naumann et al.* (1991), *Naumann et al.* (1996), *Kummerle et al.* (1998), *Smith* (1999), *Choo-Smith et al.* (2001), *Painter et al.* (2001), *Maquelin et al.* (2002), *Dalton et al.* (2003), *Liu et al.* (2005), and *Hand* (2007).

Numerous biologically important lines in the IR, but little known at >12.7 μm

All life on Earth uses left-handed amino acids and right-handed sugars – reason is not known

This handedness is detectable in circular polarization

But tough due to SOFIA photon limits

Hand, K.P., Chyba, C.F., Priscu, J.C., Carlson, R.W. and Nealson, K.H., 2009. Astrobiology and the potential for life on Europa. *Europa*, pp.589-629

Aerosol characteristics of Solar System objects & key observations

From:

Flasar, F.M., Kunde, V.G., Abbas, M.M., Achterberg, R.K., Ade, P., Barucci, A., B’ezard, B., Bjoraker, G.L., Brasunas, J.C., Calcutt, S. and Carlson, R., 2004. Exploring the Saturn system in the thermal infrared: The composite infrared spectrometer. Space Science Reviews, 115(1-4), pp.169-297.

Science objective	CIRS categories: Retrieved physical parameters	Observations
Formation, evolution, and internal structure		
Elemental abundances	He	Nadir occultation point, far-IR maps
	CH_4, NH_3, H_2S	Comp integrations, far- and mid-IR nadir maps, regional nadir maps, limb integrations, limb maps
Isotopic abundances	HD, CH_3D, $^{15}NH_3$, $^{13}CH_4$	" "
Internal heat	Temperatures	Far- and mid-IR nadir maps, regional nadir maps, feature tracks
Atmospheric gas composition		
Disequilibrium species	PH_3, HCP, halides, stratospheric hydrocarbons, new molecules	Comp integrations, limb integrations, limb maps, feature tracks
	Ortho/para ratio	Far-IR nadir maps, regional nadir maps
Condensible gases	NH_3, H_2S	Comp integrations, far-IR and mid-IR nadir maps, feature tracks
External sources (e.g., rings)	Oxygen species: stratospheric H_2O, CO_2, CO	Comp integrations, far-IR nadir maps, regional nadir maps
Clouds/aerosols		
Composition	NH_3, NH_4SH,...	Far- and mid-IR nadir maps, regional nadir maps, limb maps
Microphysical properties	Aerosol/cloud properties	" "
Auroral hot spots		
Spatial and temporal distribution	Temperature and composition gradients	Feature tracks, limb maps, limb integrations, far- and mid-IR nadir maps, regional nadir maps, comp integrations
Spectral properties	New species	Feature tracks, limb integrations, comp integrations
Atmospheric structure		
Temperature, pressure, density	Temperature field	Far- and mid-IR nadir maps, regional nadir maps, limb maps
Circulation		
Zonal jets	Thermal winds	Far- and mid-IR nadir maps, regional nadir maps, limb maps
Meridional motion	Constituent tracers	Comp integrations, far- and mid-IR nadir maps, limb integrations
	Aerosols/diabatic heating and cooling	Far- and mid-IR nadir maps, limb maps
	Potential vorticity (temperature field)	Far- and mid-IR nadir maps, regional nadir maps, limb maps, feature tracks
Waves and vortices	Temperature and comp fields	Far- and mid-IR nadir maps, regional nadir maps, limb maps
Convection	Temperature variance	" "

Cloud Cores to Protostars

Magnetic fields play a crucial role in star formation
- Clearly established that well-ordered magnetic fields often permeate molecular clouds and cloud cores (e.g. Weintraub et al. 2000)

Crucial relatively unexplored problems in star formation is how the magnetic fields ‘evolve’ from cloud cores to protostars

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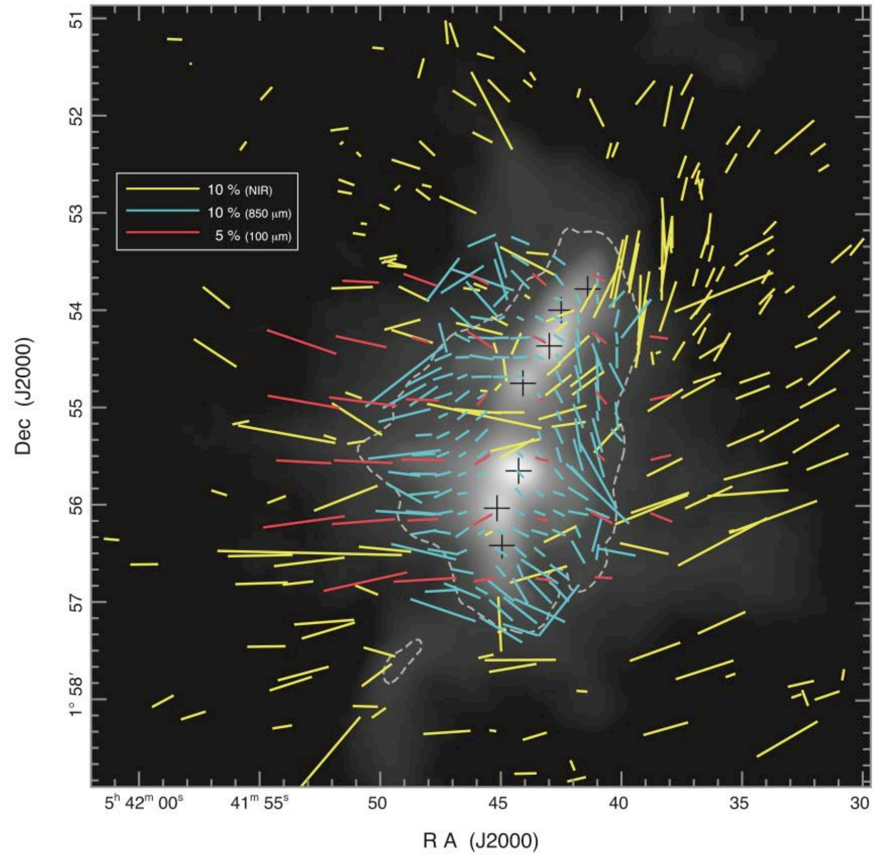
- Transmission polarization at H (yellow), emission polarimetry at 850µm (blue), and at 100 µm (red) of NGC2024
  - Vectors from the emission polarimetry rotated by 90° for comparison with the E-vector of transmission polarization (inferred direction of magnetic field)
  - Background image is 850µm dust continuum intensity map
- Kandori et al. 2007

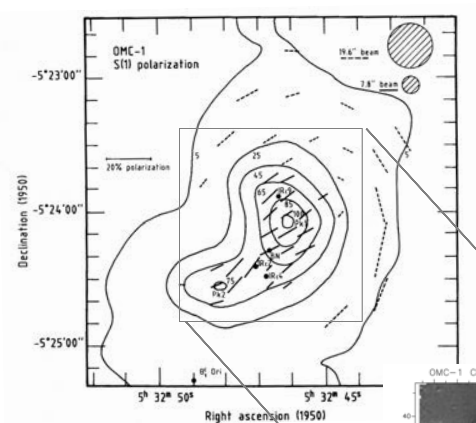


- *All data show a good agreement in outer regions, but correlation significantly breaks down in inner dense region (within the dashed curve)*
- *Indicative of magnetic field twisting from outer to inner regions, potentially affecting the dust collapse?*

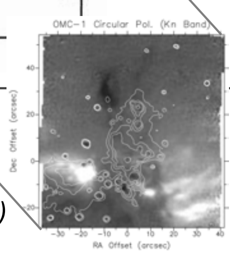
A multi-wavelength full-Stokes view of star formation

Example: OMC-1

1-5 μm **10-40 μm** **50-200 μm** **870 μm**

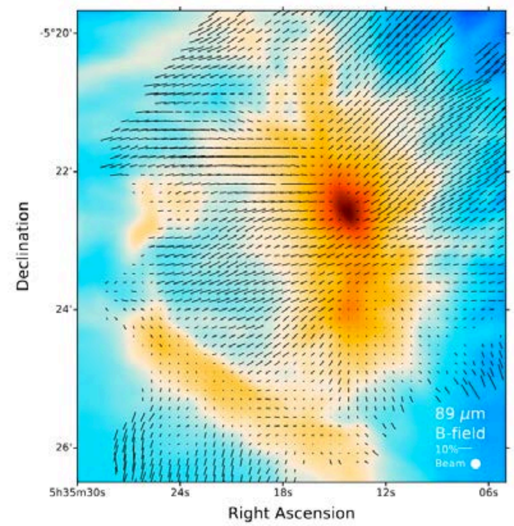


Hough et al. (1986)

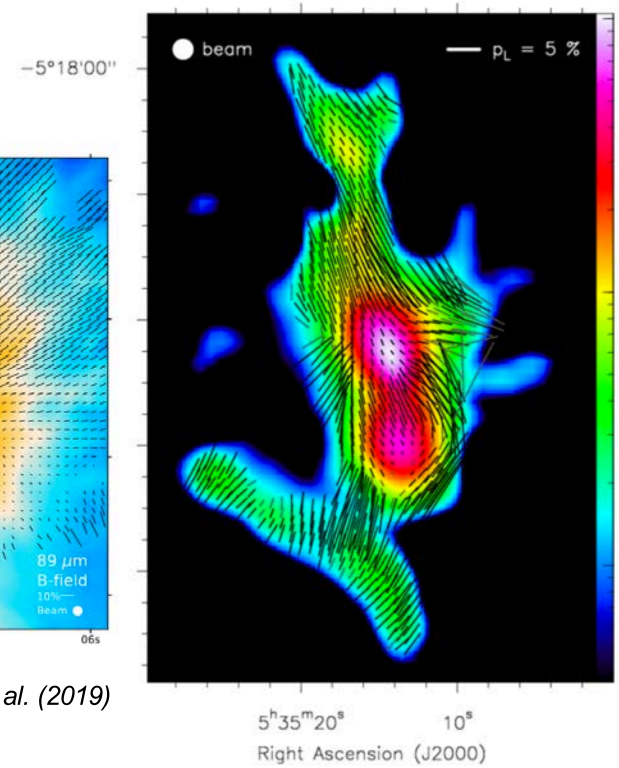


Chrysostomou et al. (2000)

BIG GAP!



Chuss et al. (2019)



Wiesemeier et al. (2014)

Unique constraints

- Dust geometries
- Dust properties (size, shape, composition)
- Magnetic field geometries

Essential to understand

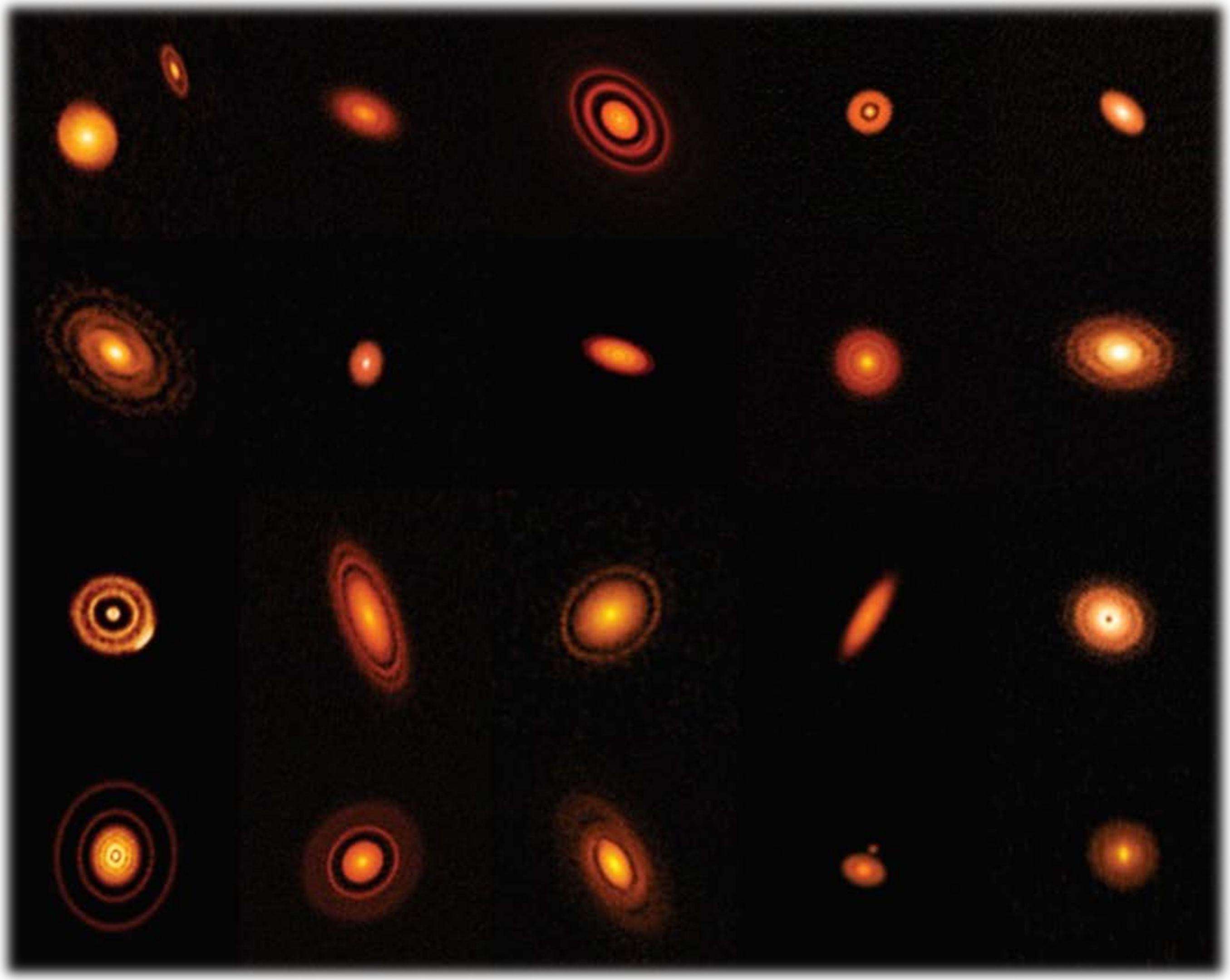
- *Planet formation*
- *Angular momentum evolution*
- *Possibly the origin of homochirality*

Disks

Dust grain chemistry

Could polarimetry can help in the structure determination as well as the chemical composition in the inner (warmer (i.e. mid-IR)) part of the disk

- Building on existing SOFIA successes?

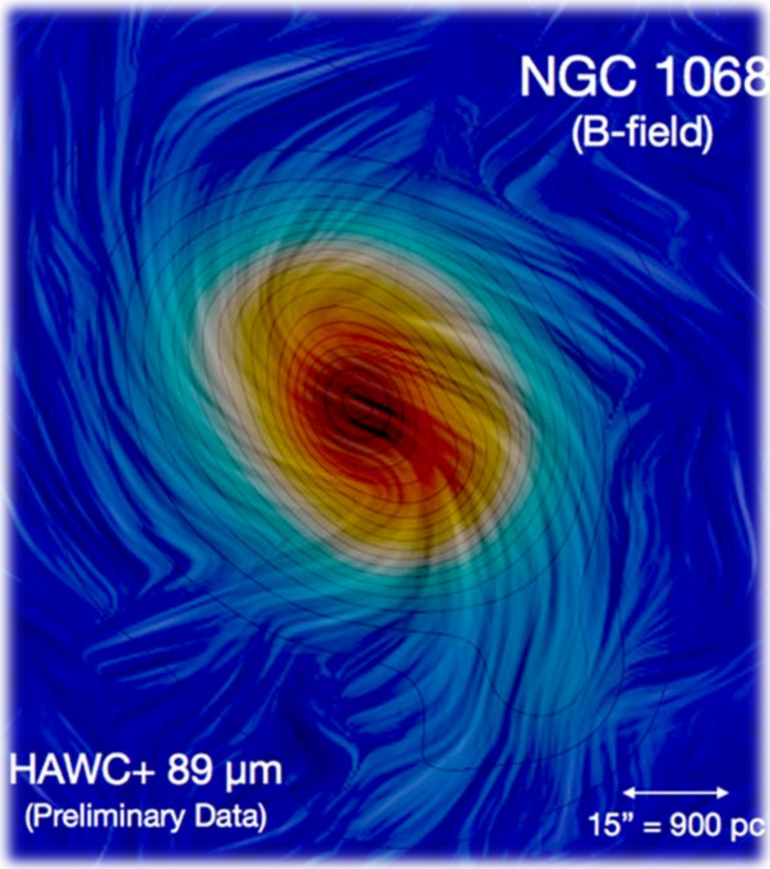


Dust Grain Chemistry

Polarization profile is very sensitive to changes in optical properties associated with crystallinity (Aitken 1996)

- Crystalline silicate grains of the silicate features at 6.8, 9.7, 19, 23.8, 26.7, and 28.4μm
- PAH features at 6.2, 7.7, 8.6, 11.3μm
- These have not been studied (well) as yet

A program of spectropolarimetry of infrared absorption bands would be a unique legacy for SOFIA



AGN & Galaxies

HAWC+ is probing the large-scale magnetic fields of galaxies

Central regions of AGN remain of interest, and the interface between host galaxy and AGN could be probed

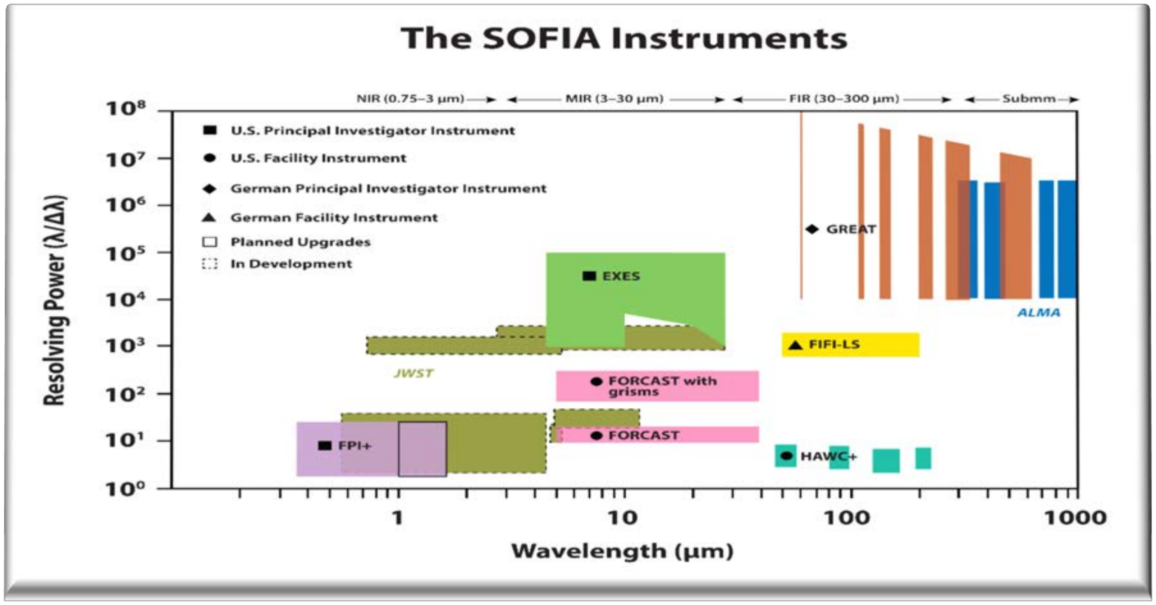
- But spatial resolution is challenged from SOFIA

Connection to ALMA needs to be investigated

- But far superior spatial resolution is crucial for understanding the barely resolved AGN
- There is plenty of experience and knowledge in the SOFIA community to help these considerations

SOFIA Instrumentation Map

Spectral resolution vs. wavelength



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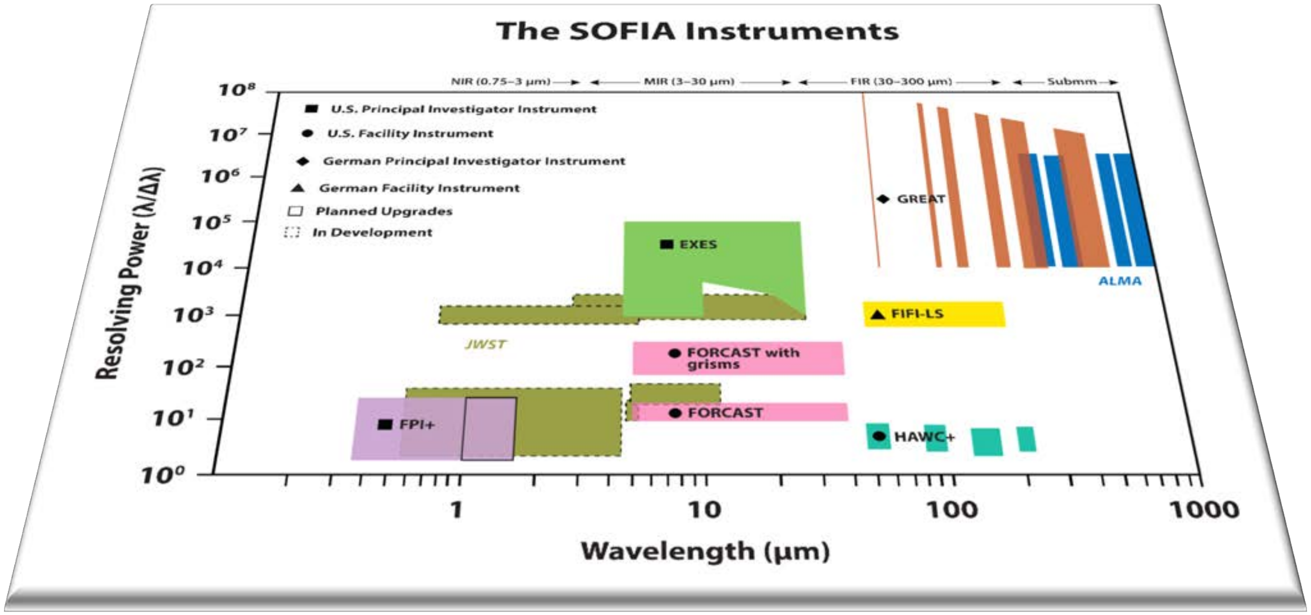
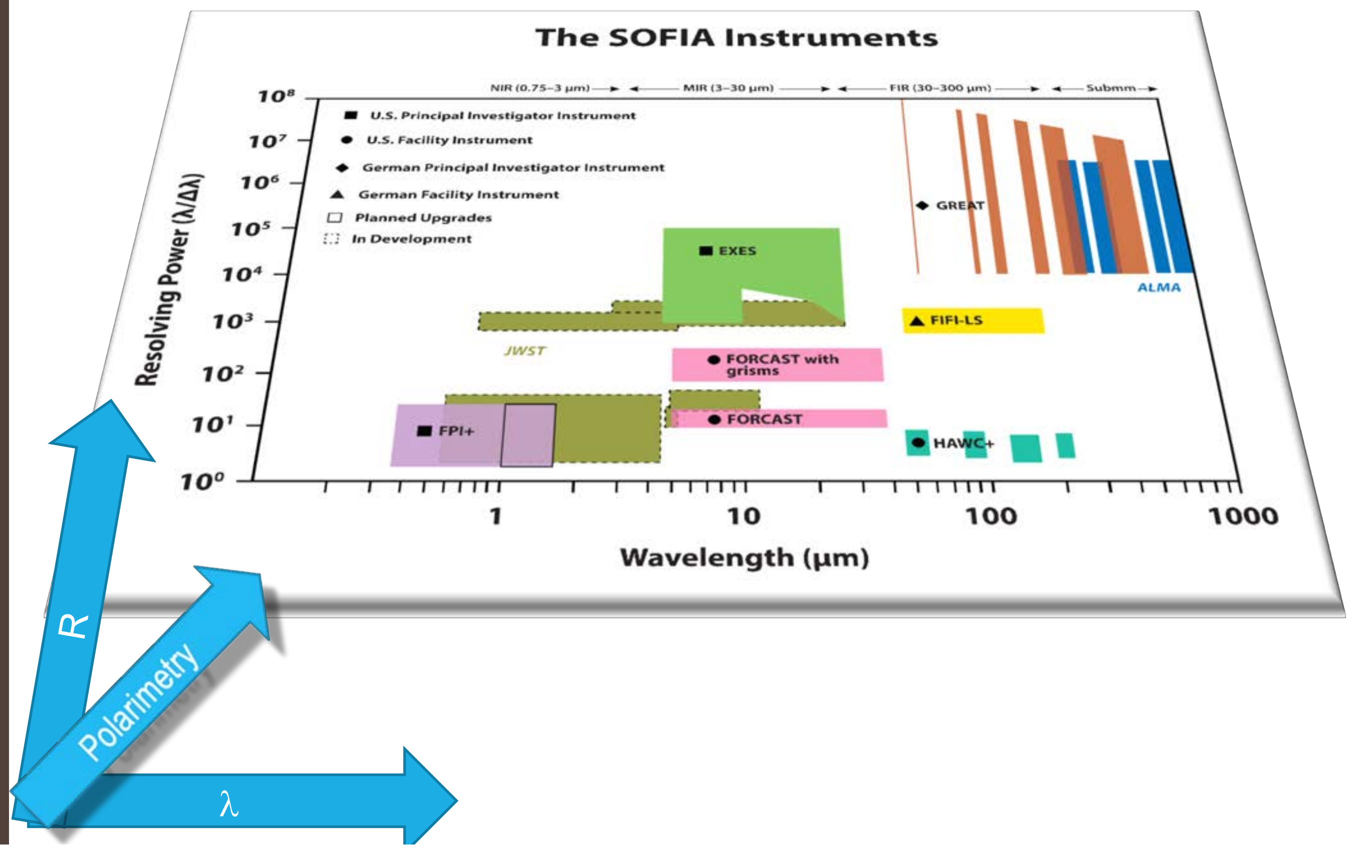


SOFIA Instrumentation Map

Spectral resolution vs. wavelength vs. polarimetry capability



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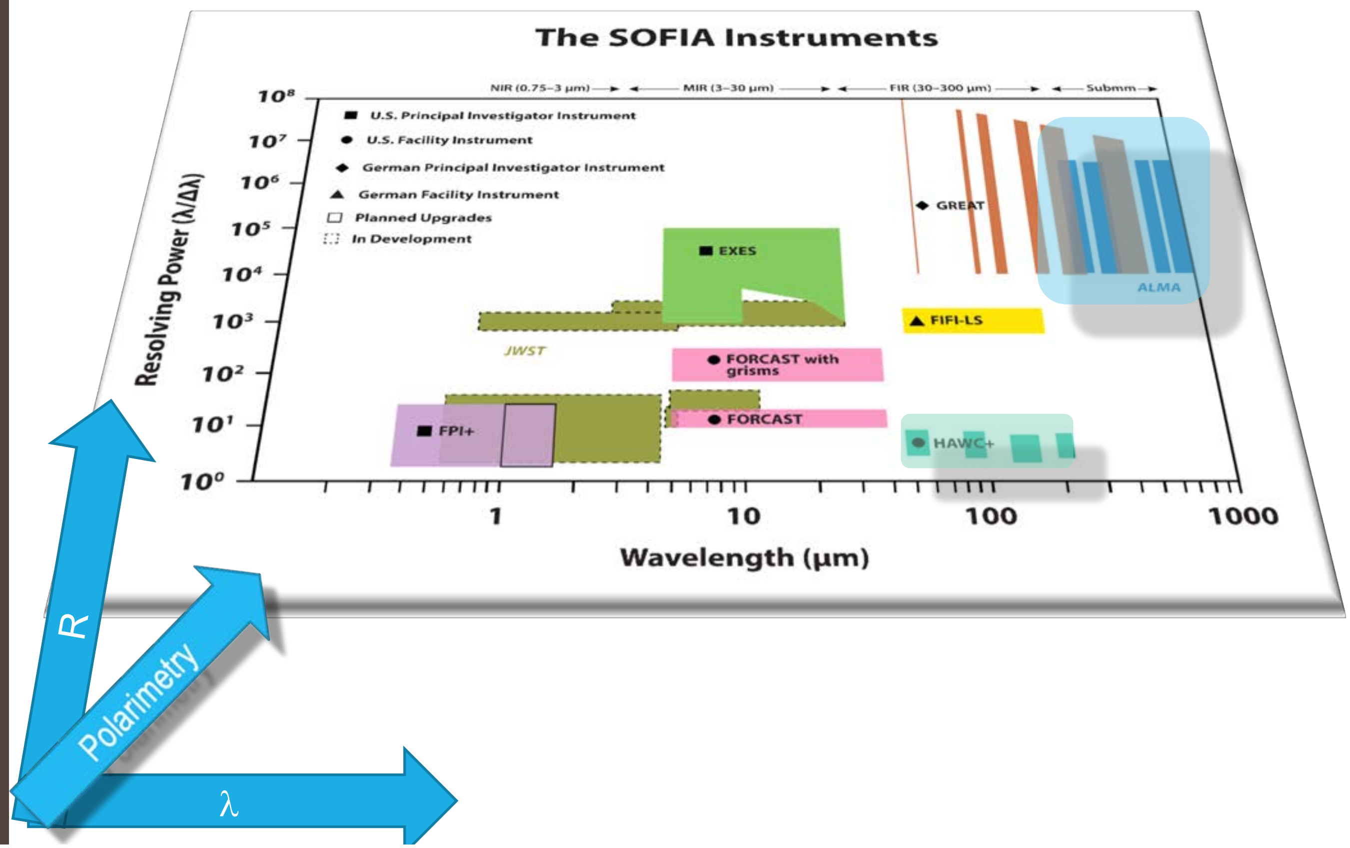
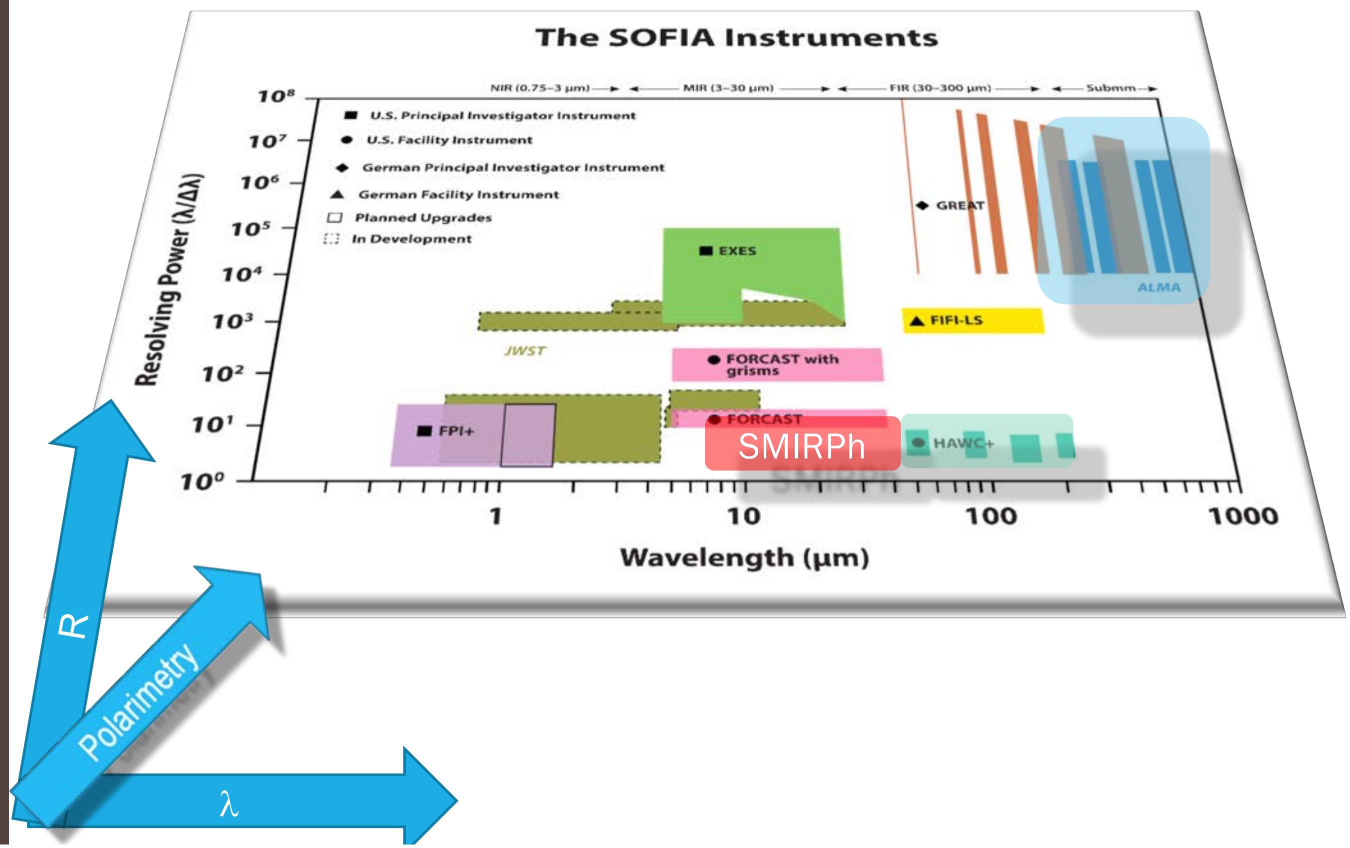


SOFIA Instrumentation Map

Spectral resolution vs. wavelength vs. polarimetry capability

With the addition of SMIRPh, continuous polarimetric coverage from MIR-mm wavelengths would be afforded

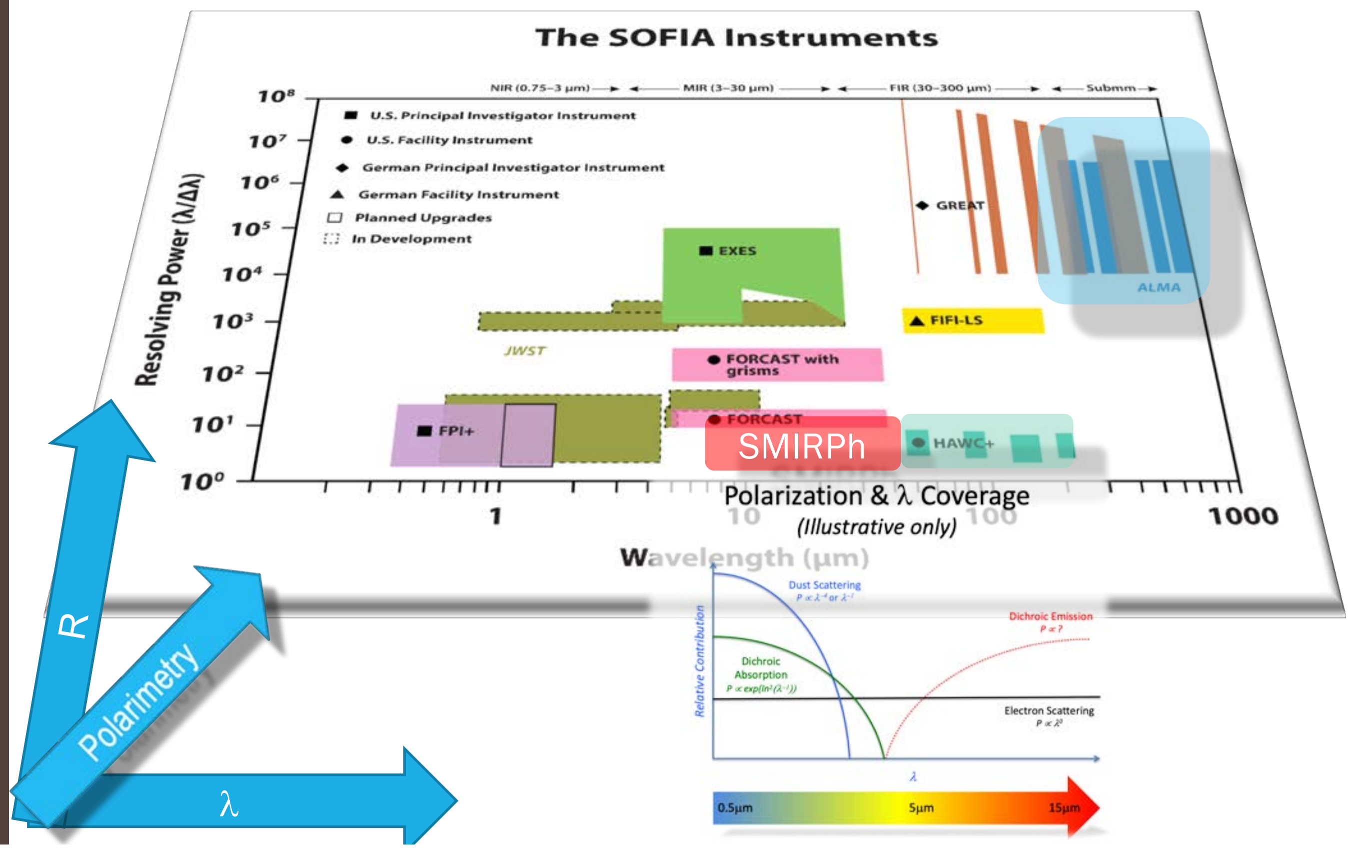


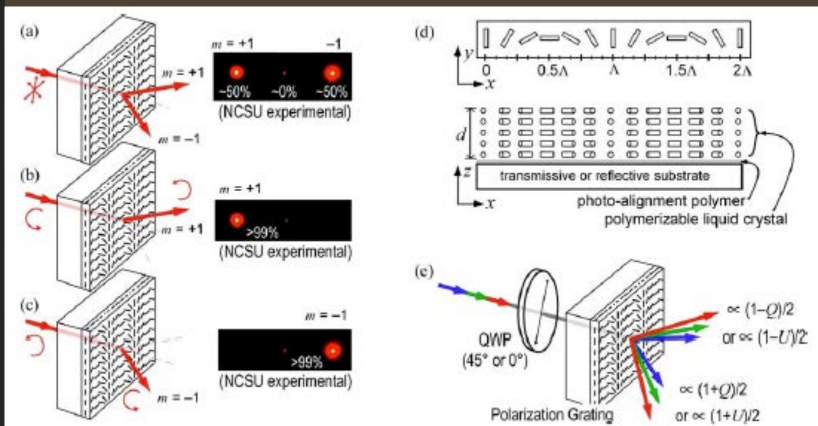
SOFIA Instrumentation Map

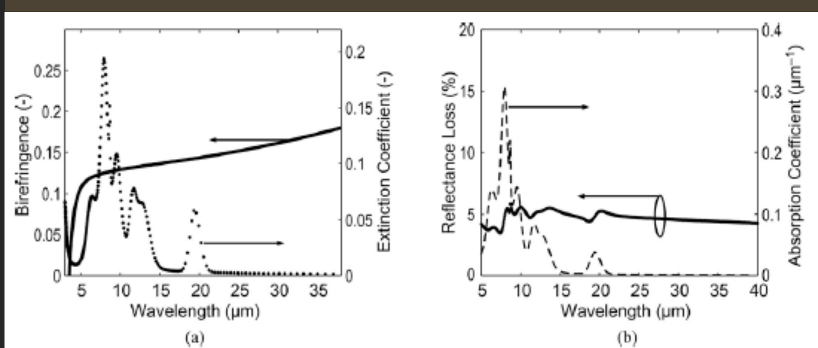
Spectral resolution vs. wavelength vs. polarimetry capability

Reminder of the importance of wavelength coverage

SMIRPh would be highly complementary to HAWC+







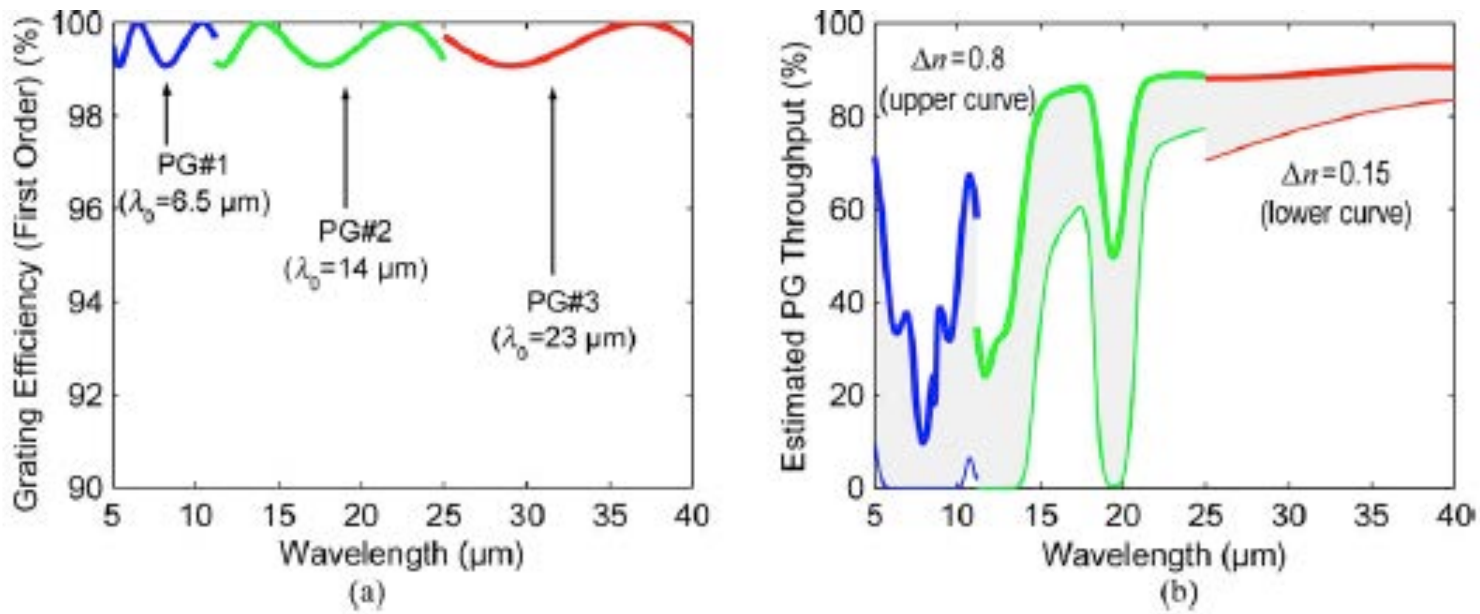
Key Polarimetric Component

Polarization gratings seem to be the unique polarimetric component that operates at the appropriate wavelengths

- Packham et al. 2010

CanariCam is currently the only 8-14 (~20) μm dual-beam polarimeter

- No dual-beam material available at longer λλ (to my knowledge)
- Also very challenging to AR coat a crystal for large bandwidths



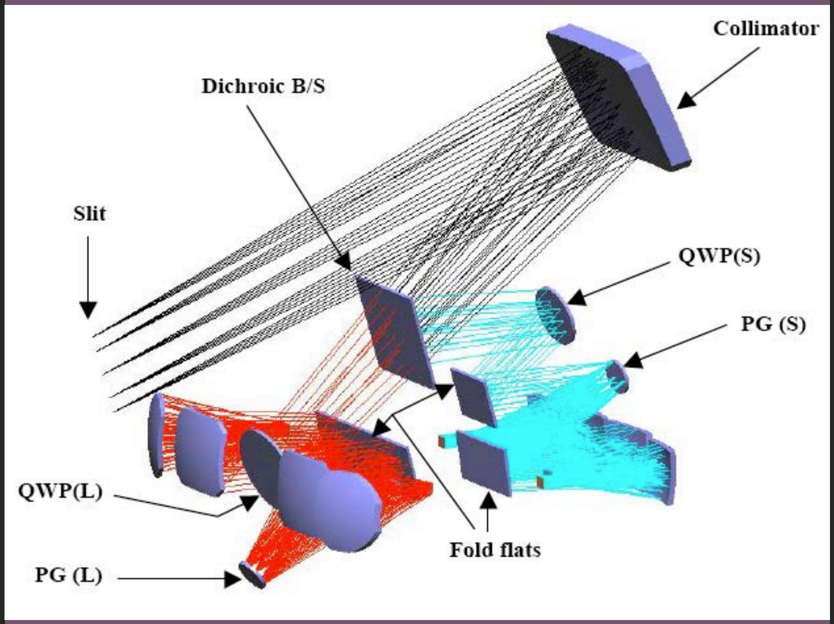
Optimized PG Designs

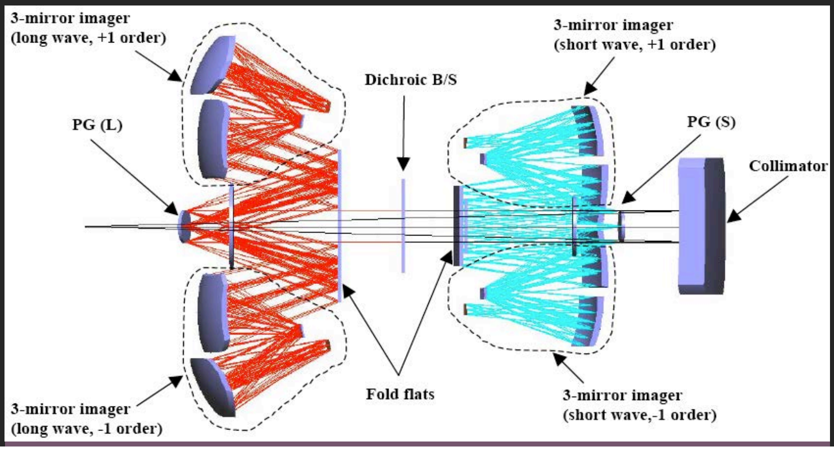
VERY HIGH THROUGHPUT
& EFFICIENCY

SMIRPh Design Requirements

All requirements met in our initial design

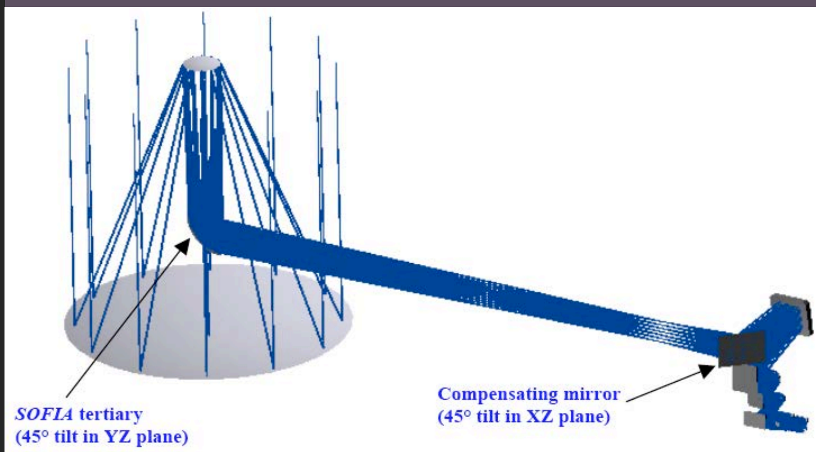
1. Two spectral bands are required, spanning 5-25µm and 25-40µm, henceforth the blue and red arms respectively
   a. The 5-25µm array is based-lined around Raytheon's Aquarius array, a 1024^2 Si:As based detector
   b. The 25-40µm array is base-lined to be the same pixel size and number as the Aquarius, likely a Si:Sb array
2. If possible, simultaneous observations in the red and blue arm with a minimal transition in wavelength space between the arms
3. The optics must be diffraction limited at all wavelengths >15µm, the shortest wavelength at which *SOFIA* is expected to deliver diffraction-limited observations
4. The plate scale is set to Nyquist sample the shortest wavelength at which *SOFIA* is expected to deliver diffraction-limited observations
   a. In the blue arm, this is at λ=15µm, resulting in a plate scale of 0.62" per pixel
   b. In the red arm, this is at λ=25µm, resulting in a plate scale of 1.03" per pixel
5. Instrument must be a dual-beam polarimeter to maximize efficiency and minimize spurious polarization due to variable sky transmission, emission and image quality
   a. Images in orthogonally polarized beams must be of indistinguishable image quality to ensure minimal instrumental polarization
6. Instrumental polarization must be low (<1%)
7. Imaging- and spectro-polarimetry should be available, with [total flux] imaging available as a goal
8. Spectroscopic resolution optimized to disperse entire wavelength window on each array
9. The system should be an all reflective design, as far as possible, to minimize chromatic aberrations
10. Optics must be readily able to be fabricated
11. The instrument must conform to the *SOFIA* space envelope

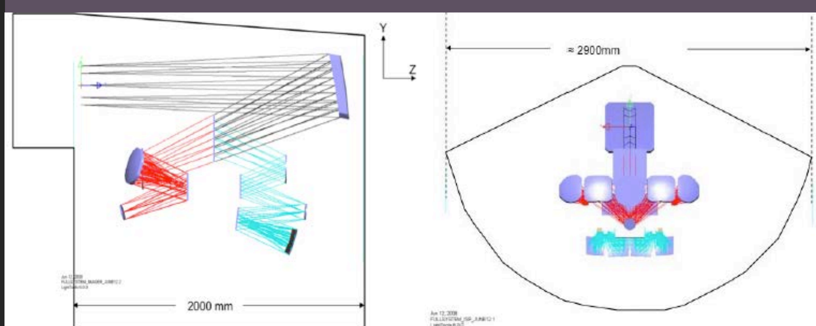




Initial Design Output

Space Envelope Complience





SMIPh Status

All SMIRPh work was done >12 years ago, needs to be updated

- Both scientifically and technically
- Detectors remain my own personal biggest concern, but Judy's presentation gives me hope

In the past years SOFIA has shown itself to be an excellent polarimetry tool

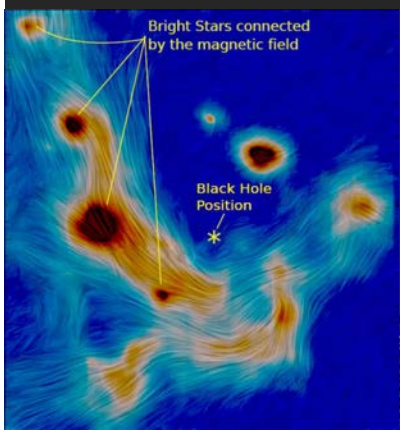
- The breadth of wavelength space could be very interesting for SOFIA

I am interested to know if both the SOFIA community and the Observatory are interested to 'reanimate' this work

Quick note about UTSA

- *We are located very close to South West Research Institute (SwRI)*
  - *For example New Horizons and Juno*
  - *Many faculty cross-listed and close collaboration, with several joint projects in progress*
  - *SwRI is lead institute for SCORPIO for Gemini South*
  - *World-leading instrumentation capabilities, could easily envision SMIRPh with UTSA-SwRI*

SOFIA's Science Case Workshop



1. Disk masses and structures important
   1. Polarimetry can help in the structure determination as well as the chemical composition in the inner (warmer (i.e. mid-IR)) part of the disk
2. ISM diagnostics
   1. Dust grain chemistry and polarimetry is highly effective
3. Solid bodies, ices, and minerals
   1. Broad solid-state ice and mineral features in the mid- and far-IR (i.e. Ceres)
4. Star formation
5. Magnetic fields in dusty regions
   1. HAWC+ supported by broader λ range, disentangling polarizing mechanisms, better 3D tomography, at higher spatial resolution
   2. Builds on an existing SOFIA strength
6. Stars, novae, and SN
   1. Mid-IR dust –polarimetry is highly sensitive for dust grain chemistry
7. Galaxies
   1. Mid- to far-IR polarimetry for magnetic fields
8. Galactic Center
   1. Excellent probe and examine the magnetic field
9. Solar system
   1. Comet work for SMIRPh could be especially exciting

Conclusions

SMIRPh & HAWC+

An excellent synergy

Would help to establish SOFIA as a unique polarimetric observatory & legacy

We invite comments, collaborations, input

Workshop 1 Themes

Science Case	Capability
Disk Masses	HD line at 112 μm
ISM/disk diagnostics	High-res MIR/FIR spectroscopy (hydrides, Si II, H_2O)
Disk/Solar System Ices + solids	Med-res MIR spectroscopy (ice features)
Star Formation/ISM	High-res FIR spectral imaging (C II, O I, O III…)
Galaxies/Star Formation B-field	MIR and FIR polarimetry
Stars/Novae/Supernovae	Monitoring/Photometry/Imaging
Galaxies ISM	Med-res spectroscopy (C II, O I, O III…)
Galactic Center	Imaging, spectroscopy, polarimetry
Solar System/Comets gas	Med-res and High-res spectroscopy, imaging