Stratospheric Observatory For Infrared Astronomy

A Science Vision for SOFIA
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Setting the Stage (1/3)

- For NASA's space missions, Level 1 requirements are sacrosanct (NPR 7120.5E)
  - Level 1 requirements result from years of careful planning, balancing cost, schedule, risk, and science
  - Changes, when they occur, are generally pre-planned descopes to account for changes of costs, schedule, and/or risk
  - Scope increases are seldom allowed
    - Exception: Herschel-HIFI bands 6 & 7 (1.9 THz receivers)
    - At the time 1.9 THz receiver was at TRL 3-4
- Once launched, hardware upgrades of spacecraft or its instruments are not possible
    - Exception: Hubble Space Telescope

Setting the Stage (2/3)

- SOFIA is not a space mission
  - Hardware repairs & updates are in principal possible on a relatively short time scale
  - SOFIA can reinvent itself on a time scale of ~five years
  - Pursuing validation and verification of SOFIA's "Level 1" requirements over many years may not make scientific sense
- SOFIA's current Level 1 requirements are based on decade-old vision
  - What was important then may not be important now
  - Project needs to periodically revisit priorities

Setting the Stage (3/3)

- Computer technology advances make existing SOFIA hardware obsolete
  - Repairs of aging electronic components severely hampered (searches on Ebay!?)
  - Loss of corporate knowledge as key personnel leave project
- SOFIA's new instrumentation and observing modes create new demands on the observatory not envisioned a decade ago
  - E.g. MCCS redesign should be a high priority
  - Adding new instruments requires decommissioning old ones

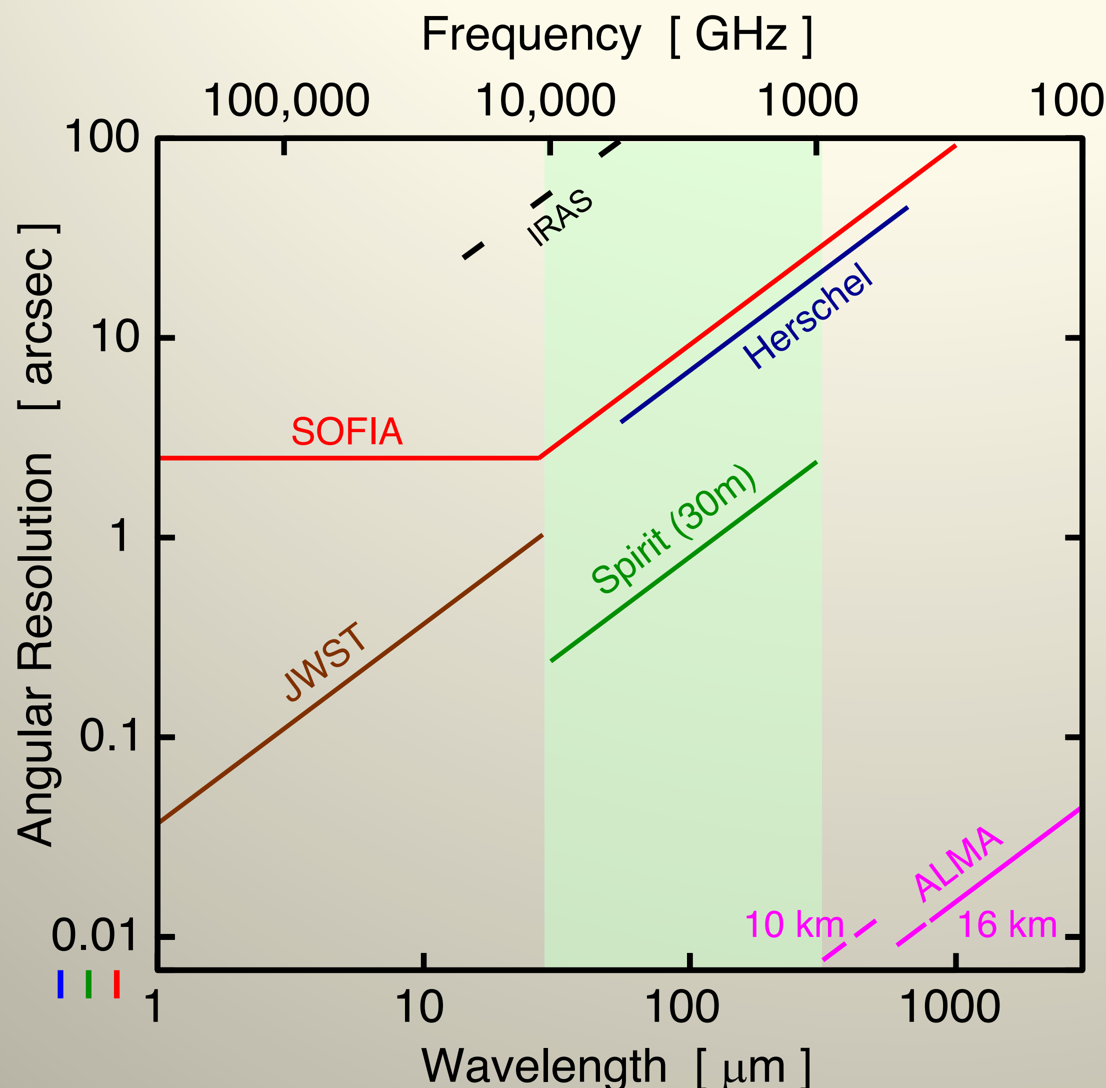
Defining SOFIA's New Vision

- Redefining SOFIA for the next two decades should be a science community effort
  - Input from SOFIA SMO Director and SOFIA Project Scientist is important, but should not be soul source
  - Getting input from community right before SOFIA's Senior Review may be problematic and disruptive
- Current advisory structure is complex
  - SNOPAC (NASA)
  - SOFIA International Summit (NASA/DLR)
  - SOFIA Science Council (USRA)
  - SOFIA Users Group (USRA)
  - GSSWG (DLR)
  - SPOT (NASA)

Hal's Vision for the future SOFIA

- Formulate the most important science accessible to SOFIA based on NASA's vision => "Origins"
- Define how SOFIA can uniquely address this science or uniquely contribute important pieces in synergy with other observatories
  - SOFIA cannot be everything for everyone – it is not a general purpose observatory
  - Must make investments and prioritize efforts to focus on the science themes that SOFIA can do well and can do uniquely => wavelength gap between JWST & ALMA

The Wavelength Gap between JWST and ALMA



JWST will offer unprecedented resolution and sensitivity from long-wavelength (orange-red) visible light to the mid-infrared (0.6 to 28 μm).

ALMA offers ~0.01 arcsecond resolution in its highest frequency bands. Band 10 (planned) will extend to 950 GHz (≈ 320 μm).

SOFIA is the only telescope that currently operates in the 28-320 μm wavelength range.

There is great science potential for observing in ALMA-JWST gap.

Major Far Infrared Science Objectives

- Formation of first stars and galaxies in the early universe
  - How and when did the first stars form? => “First Light”
  - What is the subsequent star formation and metal enhancement history?
  - When and how did re-ionization of the universe occur?
  - What were the seeds of Supermassive Black Holes and how did they grow?
- The physics of the interstellar medium and its life cycle
  - How do stars form out of the interstellar medium?
  - Circulation / enrichment / chemical processes of the interstellar medium
  - Supernova explosions & Nova: enrichment, dust formation,
  - Detailed studies of nearby (resolvable) protostars, star forming regions, “mini-starbursts”, Galactic Center, starbursts => templates
- Formation of new solar systems in protostellar disks
  - How do the disks and their outflows form and evolve?
  - How are planetisimals built up out of interstellar dust?
  - How do terrestrial and Jupiter-type planets form and interact with the disk?
  - What is the chemical state (pre-biotic?) of material that enters into planetary atmospheres?
- Cometary, planetary, and satellite bodies and atmospheres
  - Characterizing and understanding all constituents of the solar system
  - History of our Solar System
  - Finding and analysing pristine material in comets

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SOFIA lacks sensitivity

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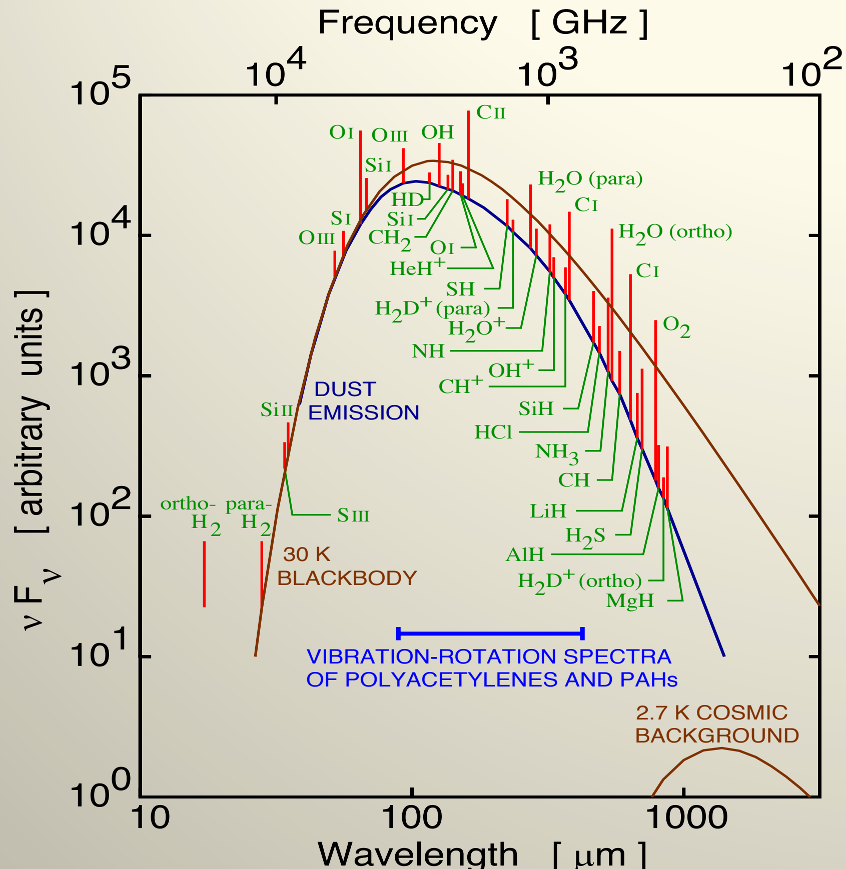
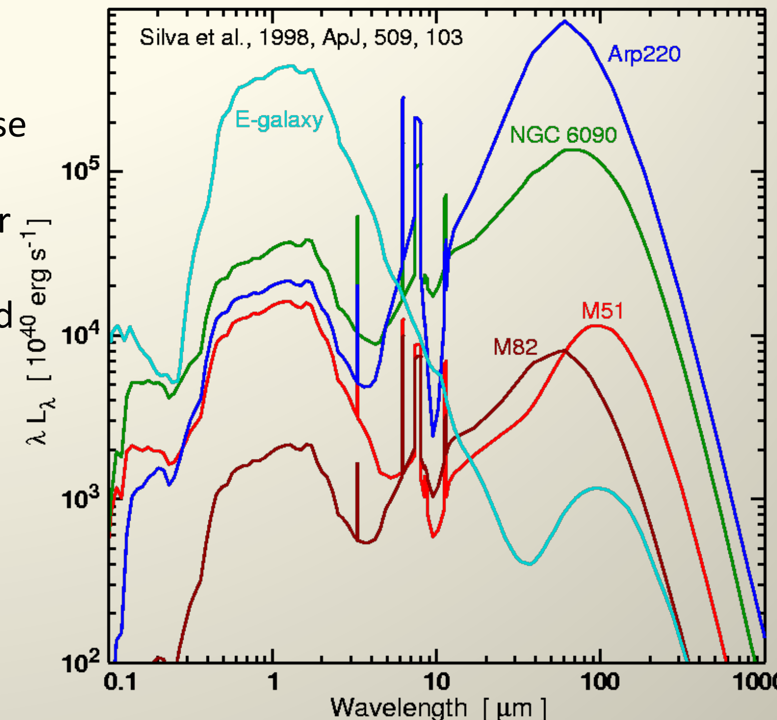
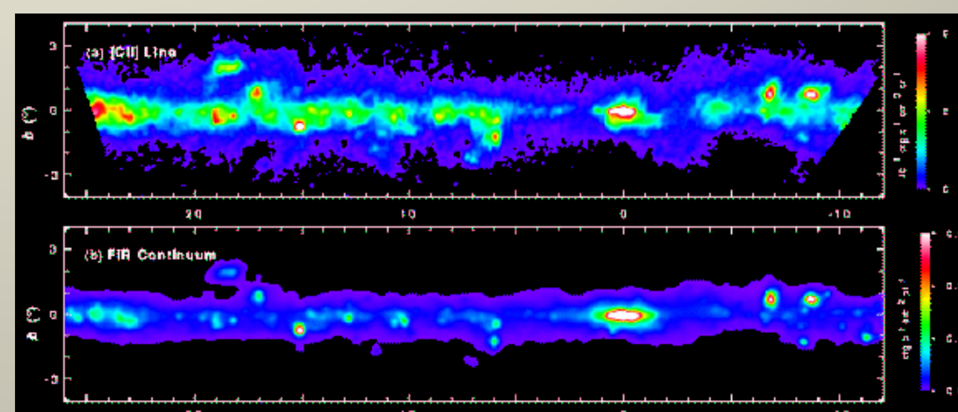
Emission from Star Forming Regions



Emission from a star forming region (~70K) with spectral lines imposed on the dust continuum.

Dusty galaxies emit mostly in the Far IR. These wavelengths probe their star formation properties and evolution





C+ at 158 µm, the strongest cooling line in the ISM. BICE Galactic maps of C+ at very low spectral resolution (top) and dust emission (bottom).

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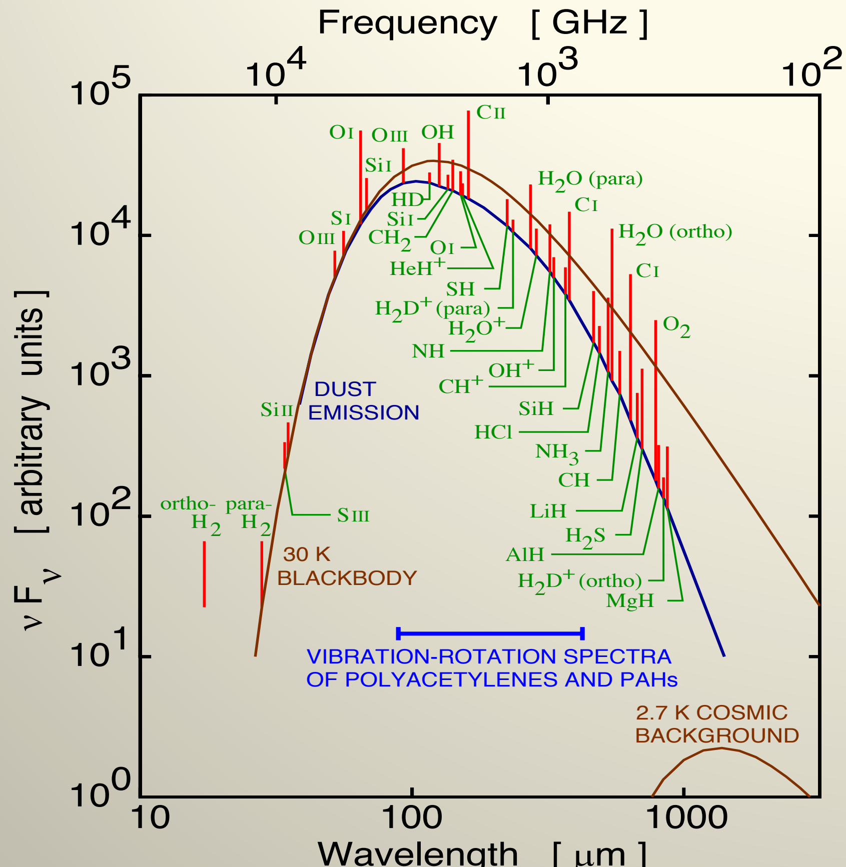

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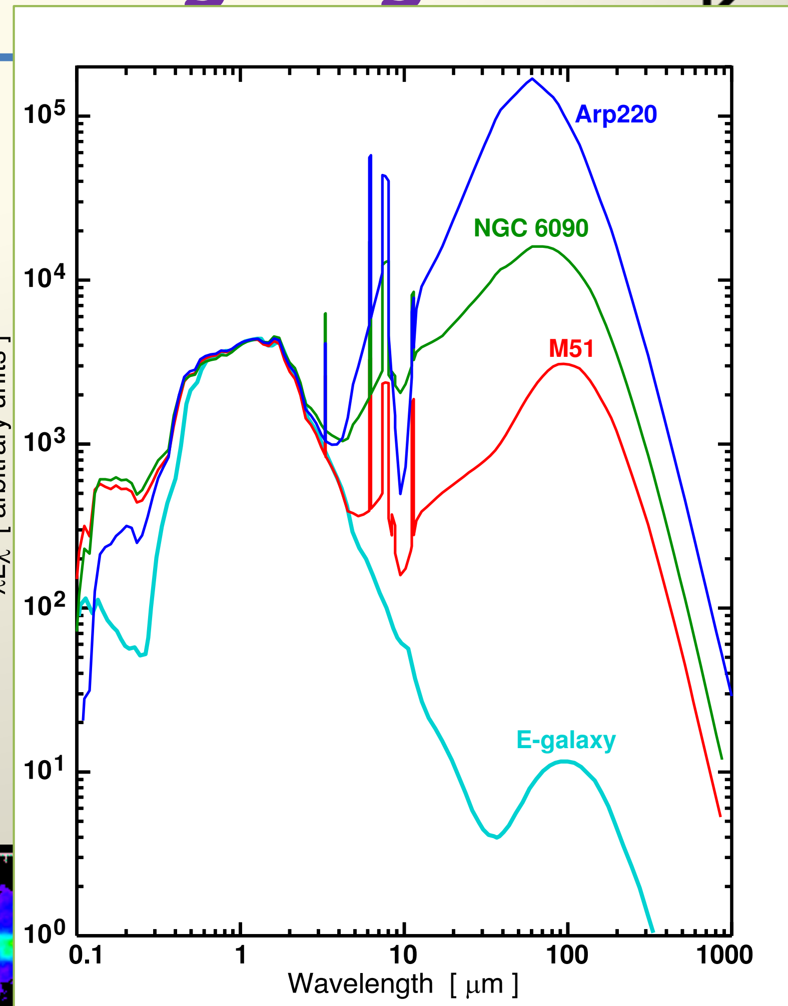

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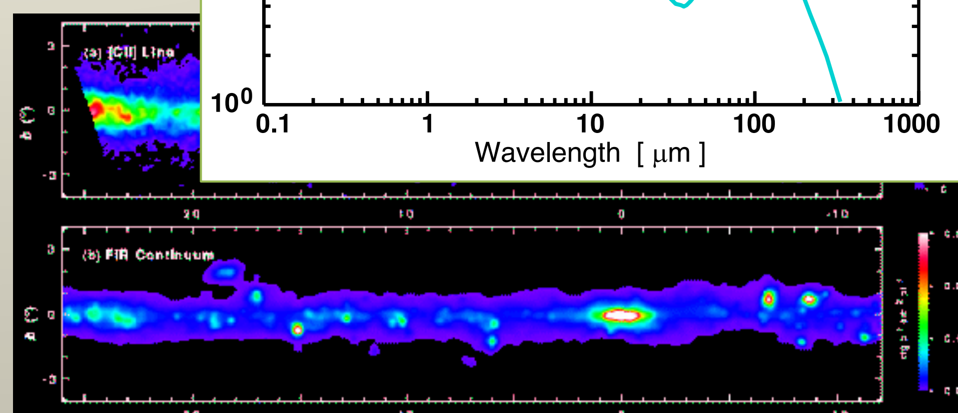

How can the Far IR enhance our Understanding of these Basic Science Themes? (1/2)

General Comments

- Dust continuum emission peaks in the Far IR/submm at cosmological redshifts $0 < z < 5$
- Many important diagnostic molecular & fine structure lines not available from ground (HD, H_2O/HDO, OH, other hydrids, fs-lines, bending modes of hot complex molecules, high-J CO)
- Far IR/submm atmospheric "windows" do not permit access to all needed diagnostic lines at any given redshift z
- 8 – 12μm PAH features shift into Far IR window beyond $z > 2.5$

Stars, Disks, and Planets

- Structure and characterization of circumstellar disks before, during and after planet-forming stages
- Detection and mapping of large (pre-biotic?) molecules
- Other science: jets and outflows including dust-producing evolved stars, structure and kinematics of molecular clouds and Galactic Center region

How can the Far IR enhance our Understanding of these Basic Science Themes? (2/2)

Star Formation Activity within nearby Galaxies (1 kpc spatial resolution or better)

- Properties of the interstellar medium (ISM) as a function of location (temperature, density, metallicity, UV radiation hardness and density).
- Star formation rate (SFR) from characteristic Far IR radiation as a function of location (spiral arms, nuclear starburst, etc...) and of local ISM conditions
- Influence of neighboring galaxies on SFR and ISM properties.

Star Formation History

- Population III stars form via H_2 cooling (lowest rotational transitions) of metal-less clouds at cosmological redshifts $10<z<20$.
- PAH features and fs diagnostic lines can be used out to reionization epoch to
  - Disentangle radiation due to accretion onto supermassive black holes versus extreme star formation activity
  - Study metallicity history of the universe

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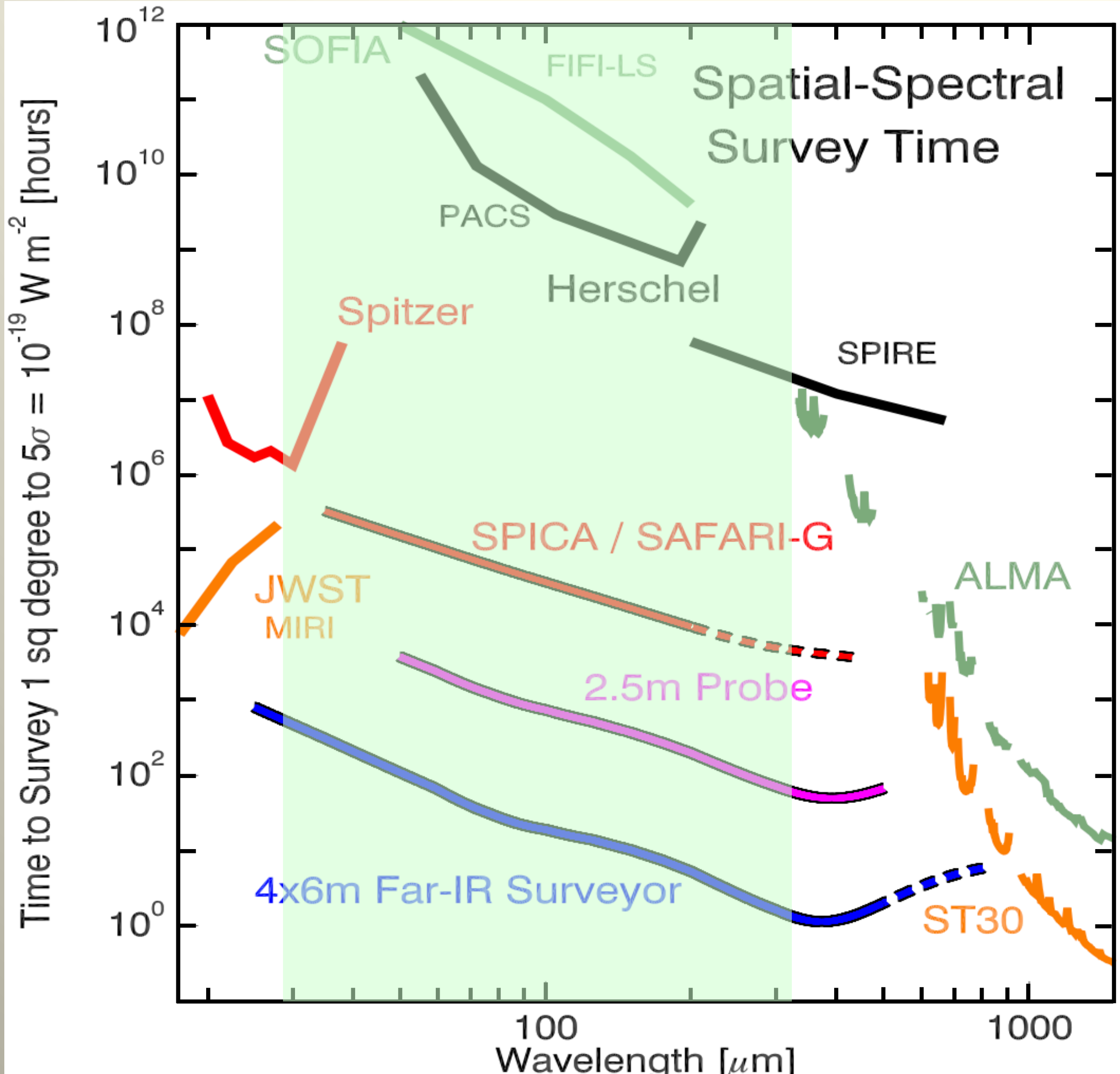

Spectroscopic sensitivities plotted as spectral survey time in the IR and submillimeter.

The Far IR Surveyor concept has a 4 × 6m off-axis telescope, equipped with R=500 grating spectrometers with 100 beams (at each wavelength) and 1:1.5 instantaneous bandwidth. Detectors are assumed to operate with NEP = 2×10^{-20} WHz$^{-1/2}$. The SPICA / SAFARI-G curve refers to the new SPICA configuration: a 2.5m telescope with a suite of R=300 grating spectrometer modules with 4 spatial beams, and detectors with NEP=2×10^{-19} WHz$^{-1/2}$. Advances in instrumentation on a 2.5m facility could improve SPICA substantially - the 2.5m probe assumes R=500 grating spectrometers with 15 beams per band, and detector NEP of 4×10^{-20} WHz$^{-1/2}$, a sensitivity demonstrated in the lab.

From: Bradford, et al. 2016, "A Probe-Class Opportunity for Far-IR Space Astrophysics"

Where is SOFIA's "Sweet Spot"?

- To obtain highest possible sensitivity, you must cool optics and all detector-visible support structures to 4K
- With SOFIA's warm optics (2.5m; 30-300µm; 220K)
  - 220K black body peaks at ~15µm
  - Normalized to optical/near-IR wavelengths scales by factor 75 (1.3 inch; 400nm-4µm; 17,000K)
  - Optics, support structure, atmosphere contribute to background
    - Chop between target & empty sky
    - Subtract two large numbers for signal
    - Number statistics limit theoretical sensitivity

Where is SOFIA's "Sweet Spot"?

- Alternatively, reduce background radiation $F_\nu \Delta\nu$ by reducing bandwidth $\Delta\nu$ => high resolution spectroscopy
  - e.g. GREAT (heterodyne), EXES, HIRMES
  - Detailed studies of emission and absorption lines
- SIAG (Science Instrument Advisory Group) report ranking SOFIA instruments (except GREAT, HAWC+)

Rank	Name	Science Instrument
1	FIFI-LS	Field-Imaging Far-Infrared Line Spectrometer
2	FORCAST	Faint Object InfraRed Camera for the SOFIA Telescope
2	EXES	Echelon-cross-Echelle Spectrograph
4	FLITECAM	First-Light Infrared Test Experiment Camera
5	HIPO	High-Speed Imaging Photometer for Occultations

Future of Far IR Science?

- For the science community, SOFIA currently provides the only access to the Far IR in the near future
- SOFIA successor could be lighter-than-air autonomous steerable vehicle (sensitivity is still an issue)
- For a future space-based cryogenic Far IR observatory in the far future, I note
  - Far-IR is not militarily or commercially useful
  - Must conceive, develop, build & test detectors and read-out electronics: very little is "off the shelf"
  - Must have a facility that uses detectors in order to develop them
  - Must have a cadre of interested Far IR scientists and engineers


http://www.sofia.usra.edu