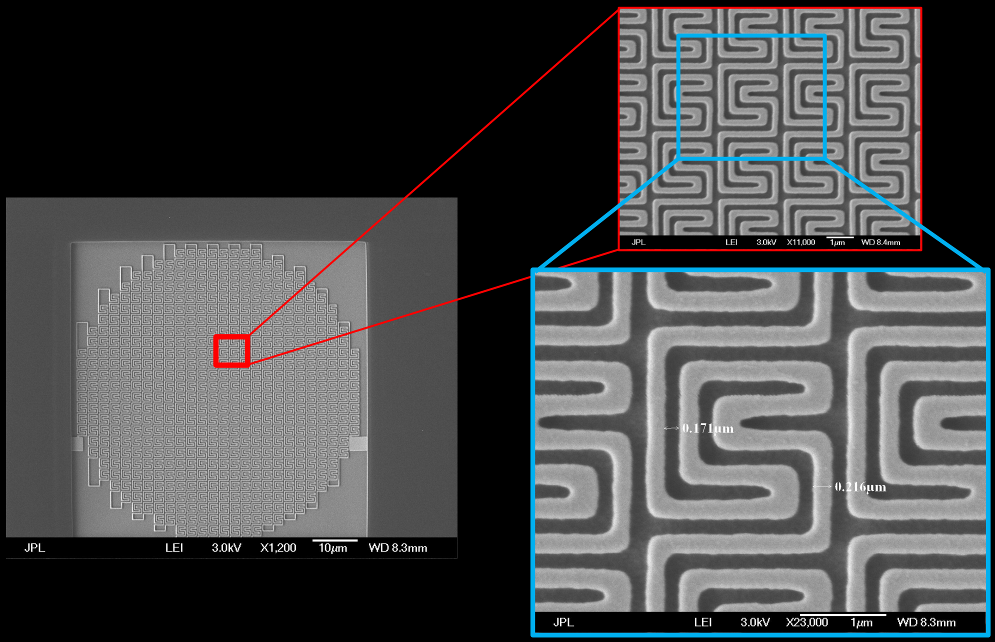
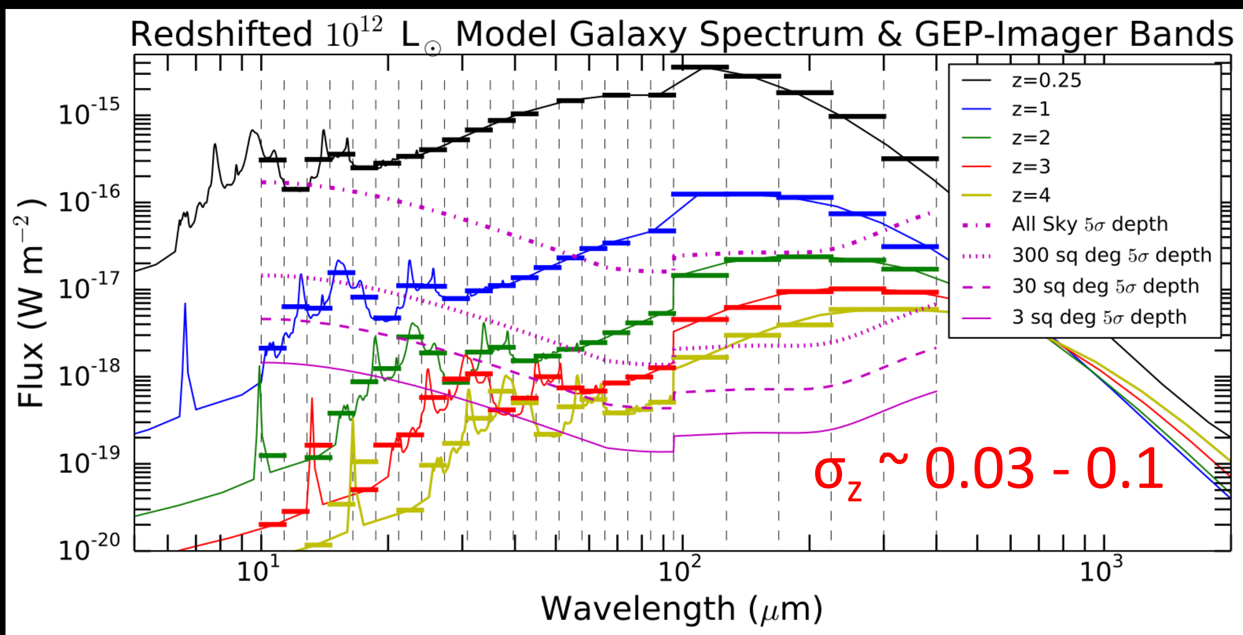
Mid-Infrared Kinetic Inductance Detector and Filter Technology for Low-Resolution Spectral Imaging

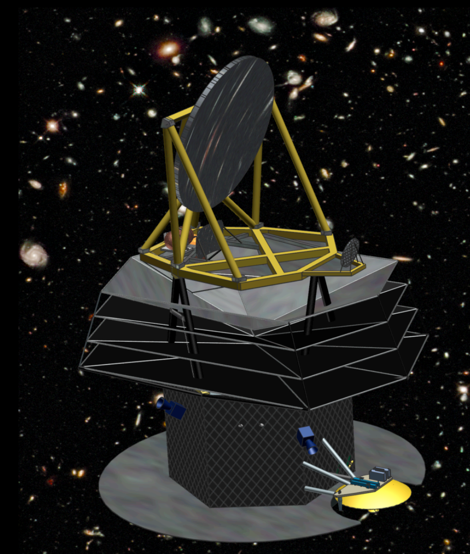


Jason Glenn, NASA Goddard Space Flight Center

July 28, 2020

Background: Galaxy Evolution Probe hyperspectral imager surveys and photometric redshifts

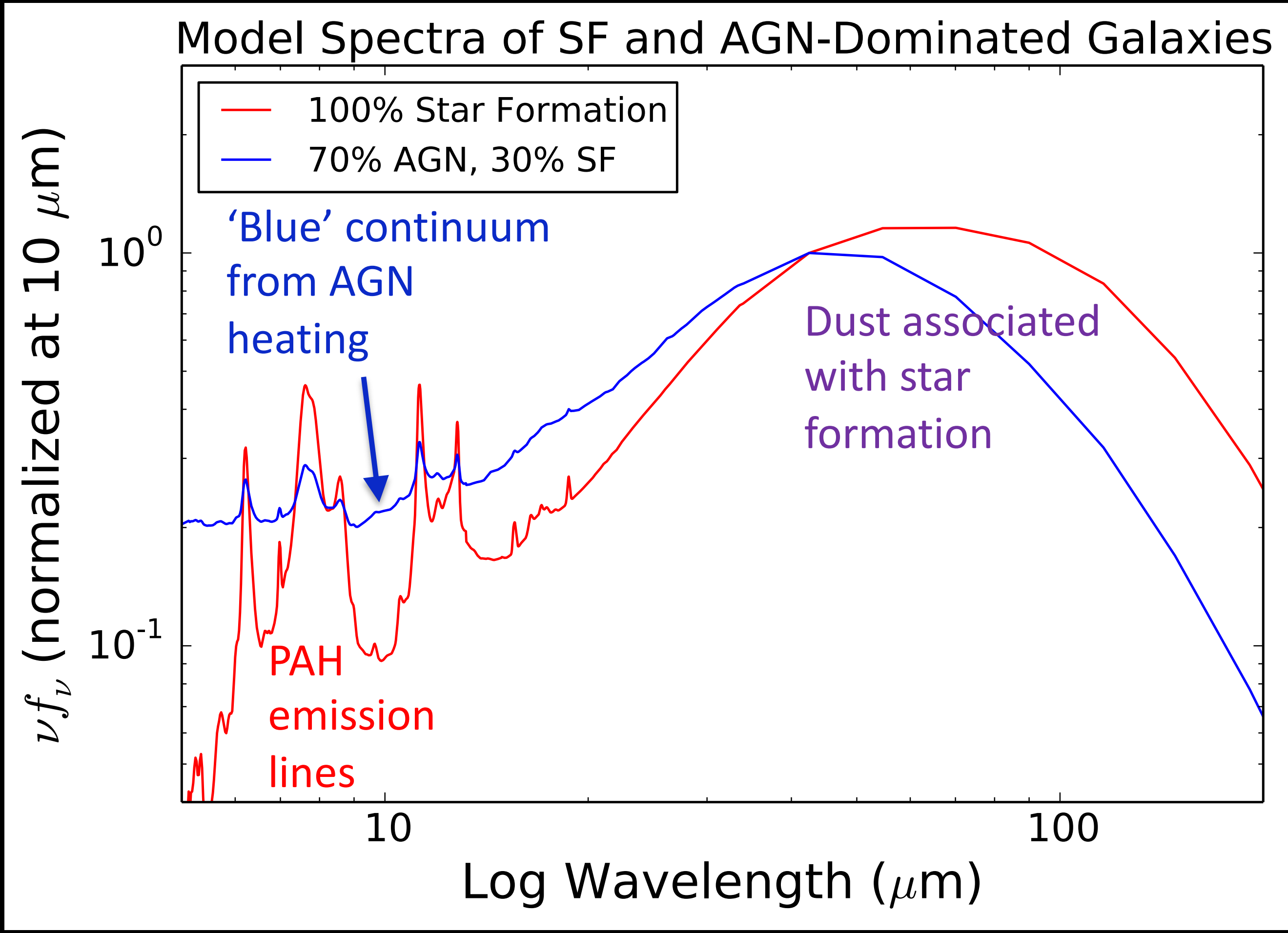




23 mid and far-IR spectral bands to measure the redshifts of millions of star-forming galaxies using the prominent PAH emission lines and silicate absorption.

Mid- / Far-IR Spectra of Active Galaxies

Diagnostics of star formation, radiation fields, obscured AGN



Spectral models from Dale et al. 2014 – *models do not include MIR/FIR atomic fine-structure lines*

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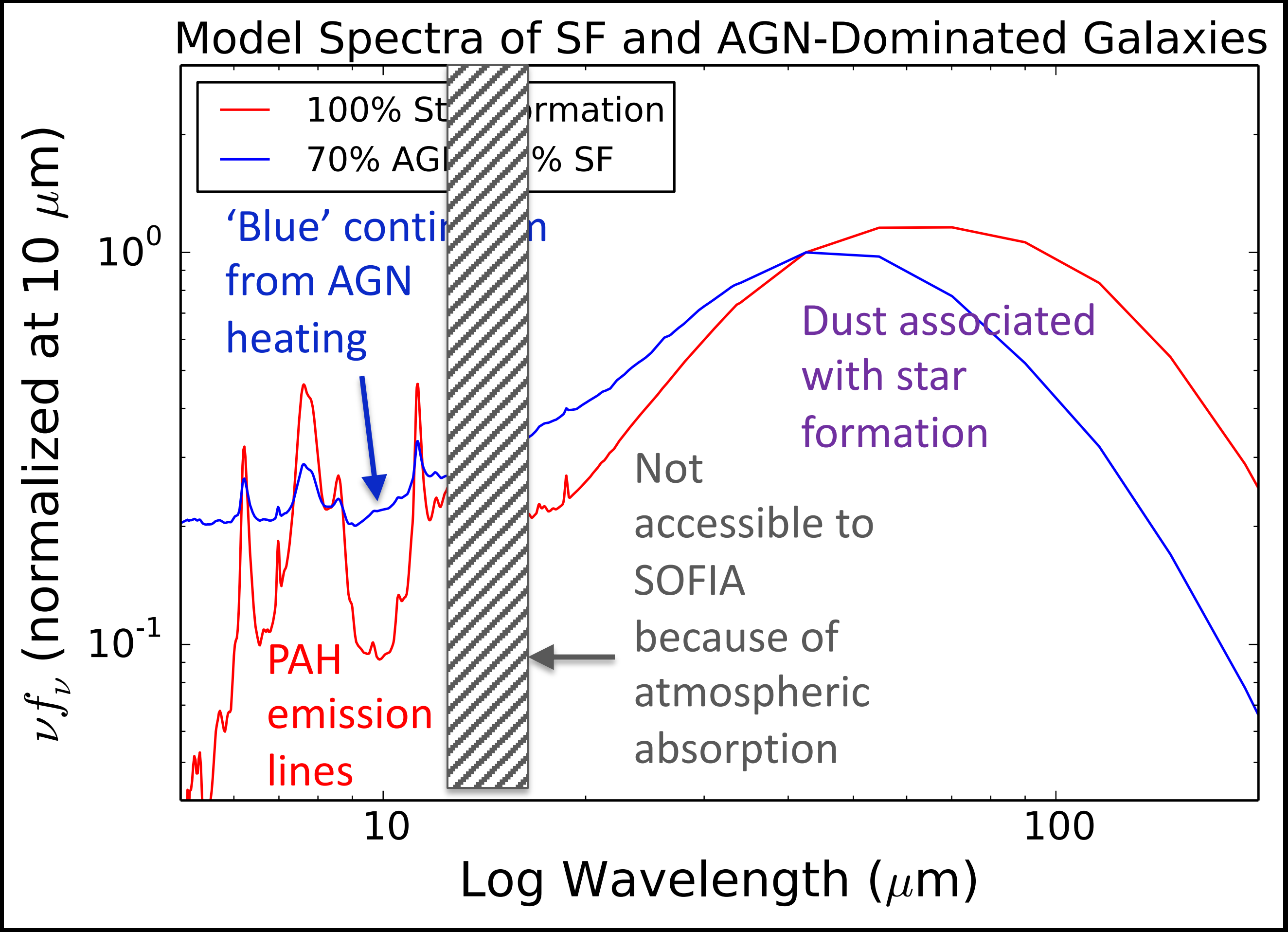

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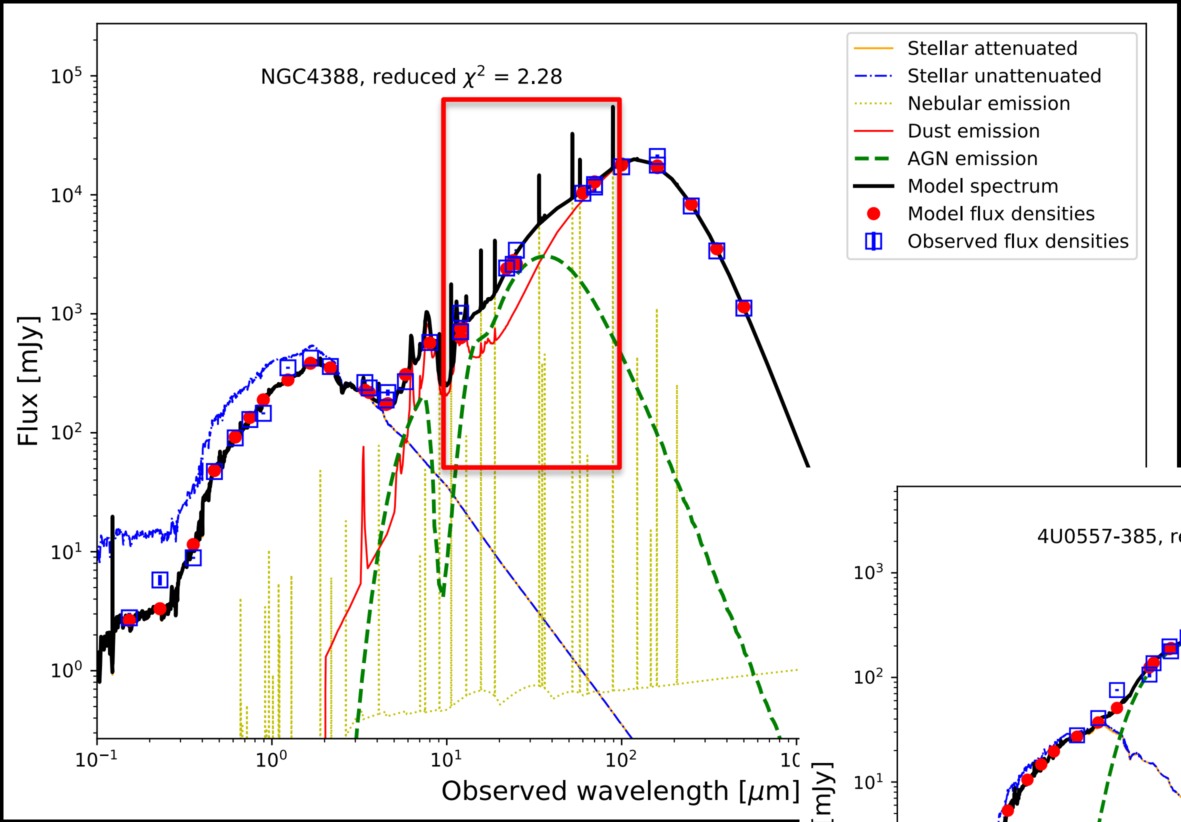
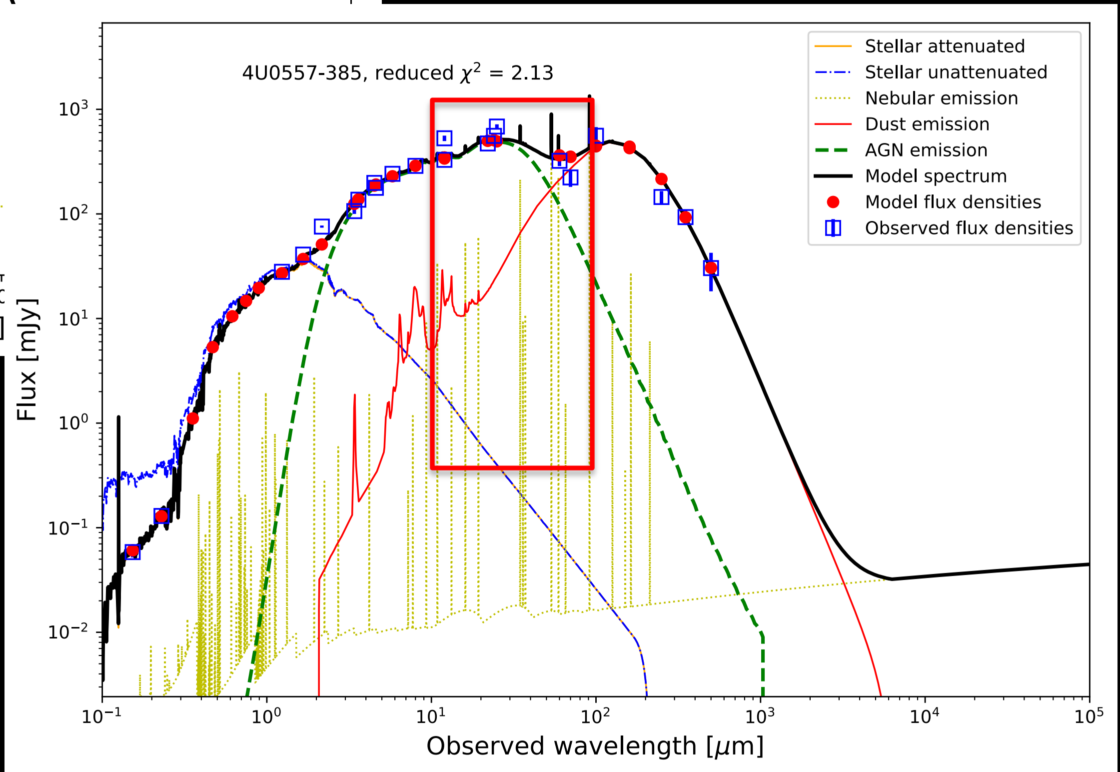
Mid-IR Spectra of Galaxies Are Very Sensitive to SF and AGN



Smith et al. (in prep)

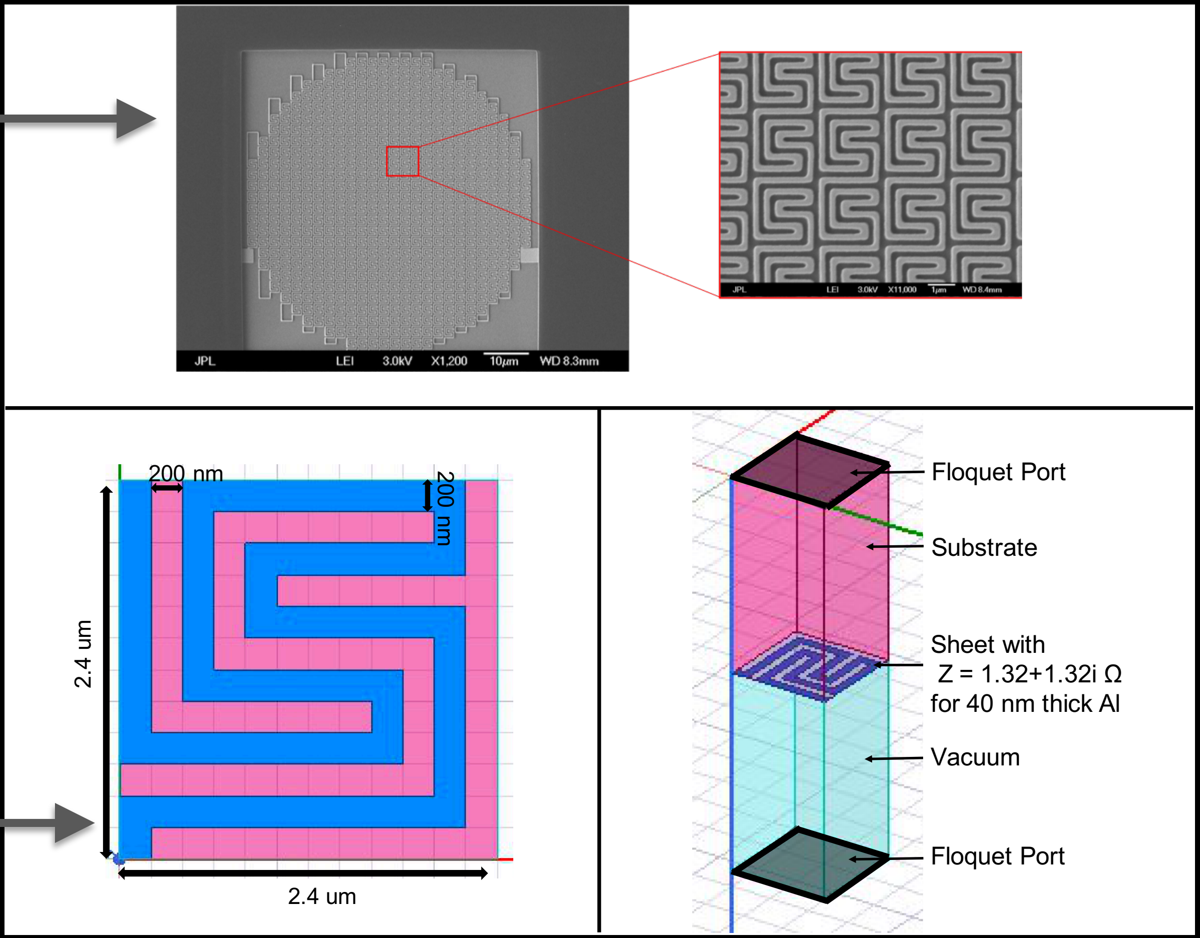


Low-Volume, All-Aluminum 10 µm KIDs

Single polarization architecture

This inductor (absorber) is coupled to an interdigitated capacitor to form a micro-resonator. The pixel pitch is ~300 µm, with the size dominated by the IDC.

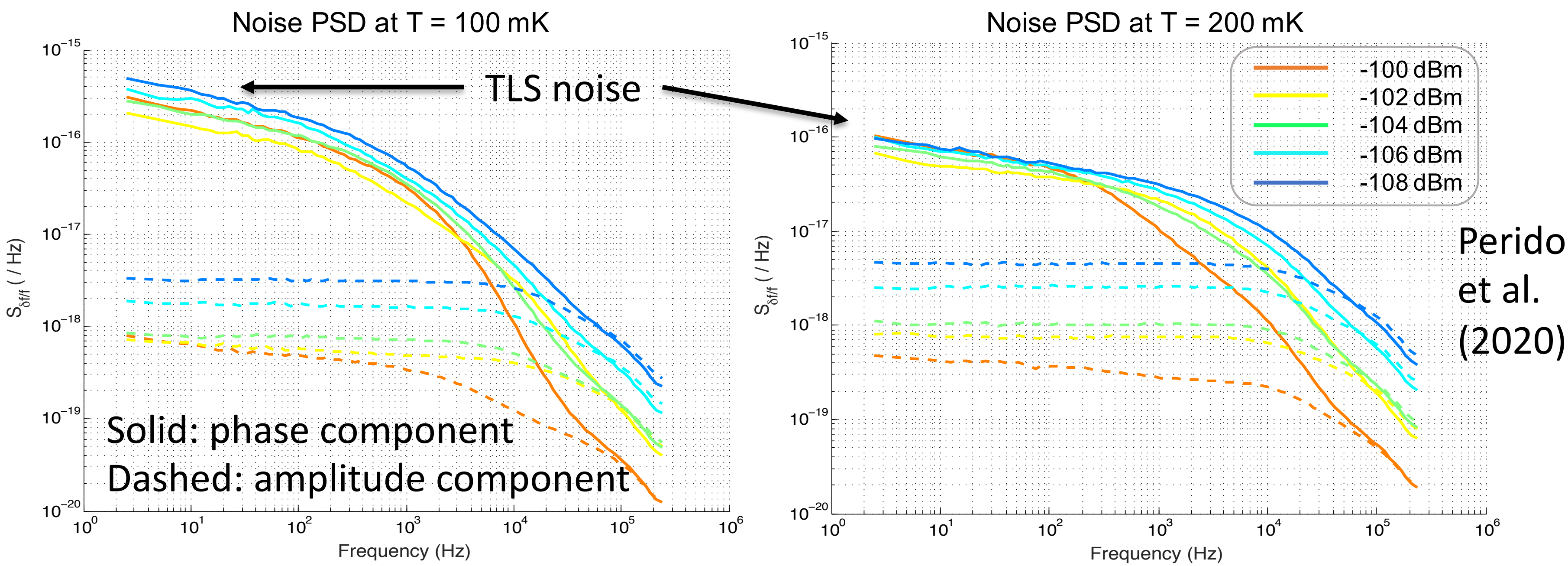
Unit cell and simulation set-up.



Simulations predict broad absorption with 70% @ peak.

Noise and Sensitivities

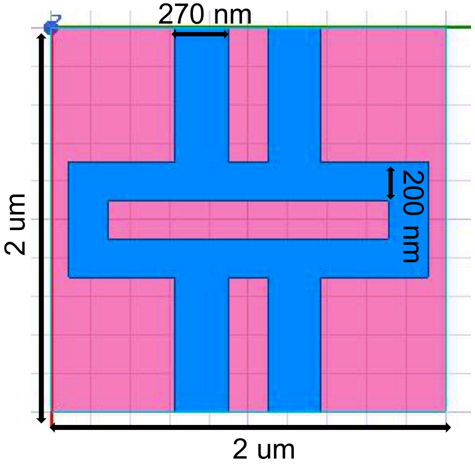
Single polarization architecture



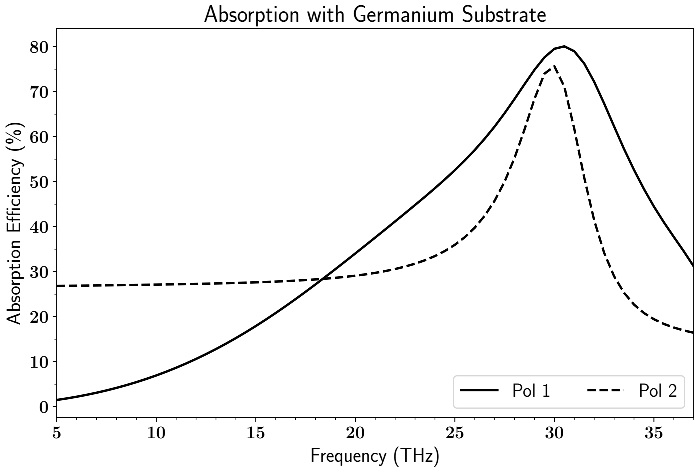
- Still need responsivity measurements.
- **Previously achieved NEPs of 1x10^{-17} W Hz$^{-1/2}$ @ 350 µm -->** more sensitive than we will need for an LVF instrument for SOFIA (Glenn et al. 2016).
- We expect these devices to be > 10x more sensitive: smaller volumes, τ_{qp} = 1 ms (Fyhrie et al. 2019, Hailey-Dunsheath et al. submitted).

Dual Polarization Architecture

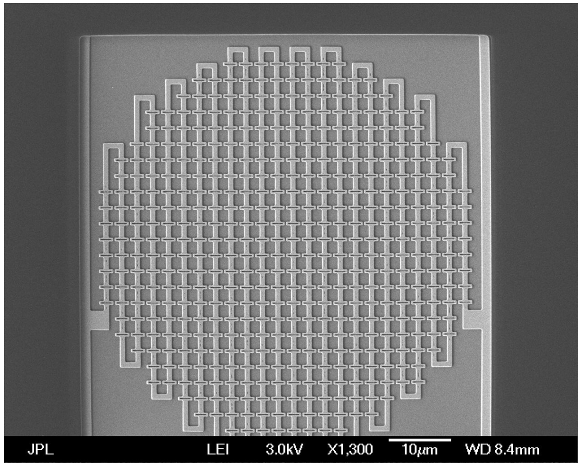
Unit Cell



Simulated Absorption



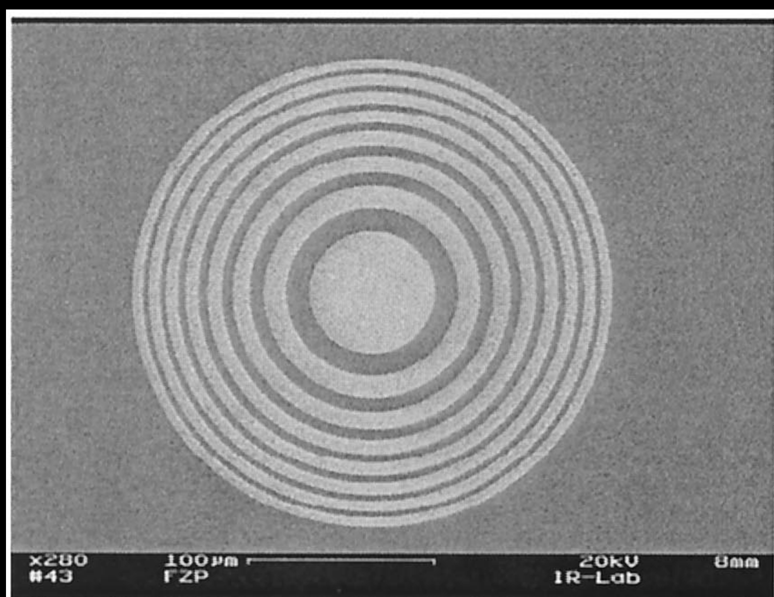
Absorber Photograph



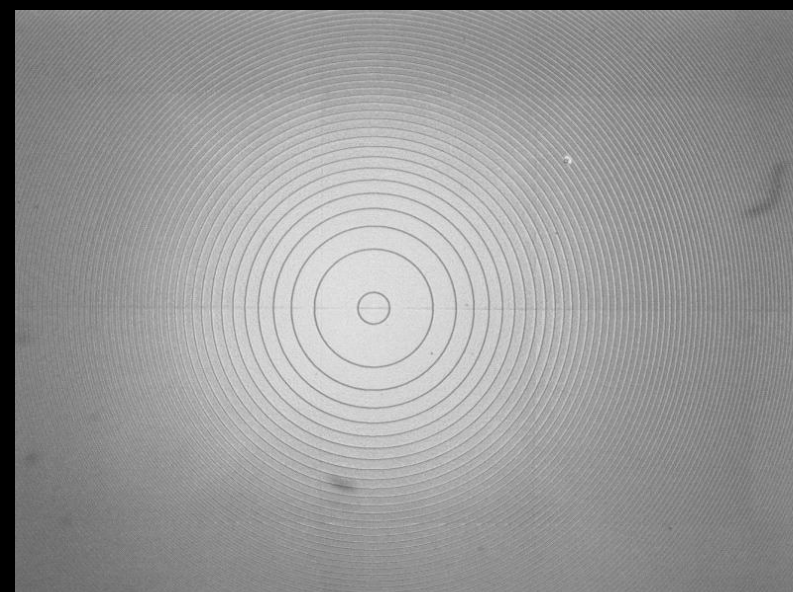
Germanium substrate to avoid Si 14 – 17 µm absorption features. (Central plot shows mesh + substrate performance, not dielectric substrate losses, but the wafers are 500 µm thick and won't have substantial loss from 10 to 20 µm.)

Next Steps for Mid-IR KIDs

1. Optical coupling: Fresnel plate lenses, then Fresnel lenses if needed
2. 30 µm implementation
3. Fabricate on Ge substrate for 10 to 20 µm (Si for $\lambda > 20$ µm).



2D Fresnel plate lenses demonstrated for 10 µm by Gonzalez et al. (2004)



3D Fresnel lenses (Wilson et al. 2005)

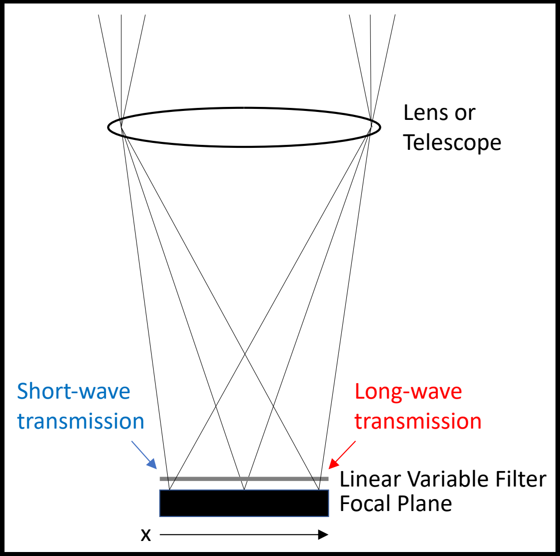
Spectrometer Architecture Comparison

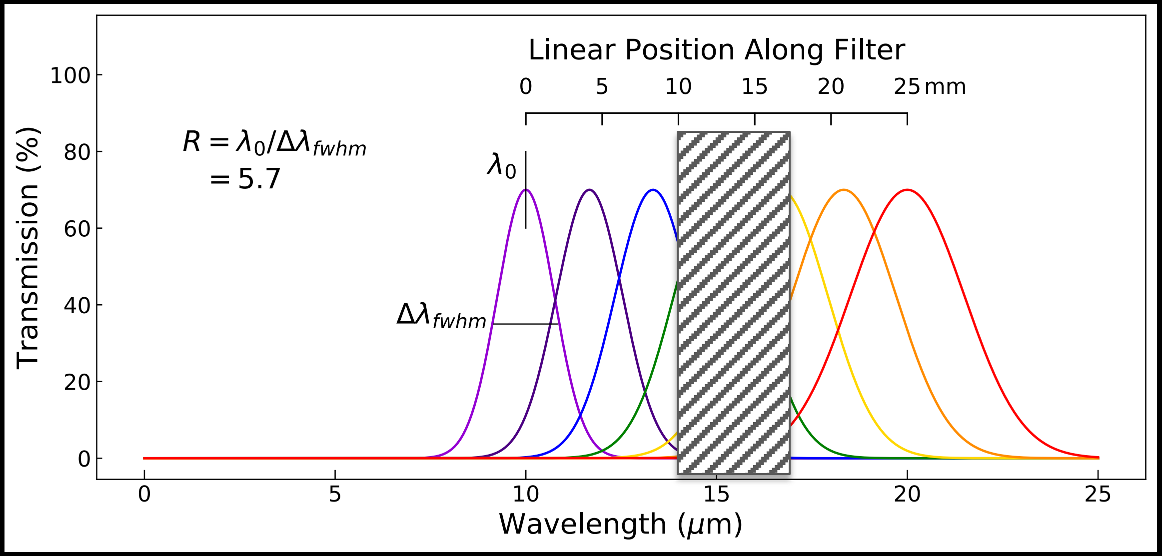
Tailored to SOFIA (and over-simplified – apologies!)

Architecture	Advantages	Disadvantages	Comments
Heterodyne Receiver	Ultra-high $\mathcal{R}$	Limited mapping speed	Ex: GREAT
Diffraction Grating	Moderate or high spectral $\mathcal{R}$, dispersion of background	Limited mapping speed (higher with IFU / long slits)	Ex: EXES, FIFI-LS, HIRMES
Fourier Transform	Moderate to high spectral $\mathcal{R}$, limited mapping capability	Limited field of view, no reduction of background	Ex: Herschel SPIRE
Fabry-Perot	High $\mathcal{R}$, limited mapping capability	Limited field of view	Ex: HIRMES
Linear-Variable Filter	***Rapid hyperspectral mapping, extremely compact and simple***	Limited $\mathcal{R}$ and dispersion of background	Suited to extended objects

Linear-Variable Filter Spectrometer

Simple! Compact!

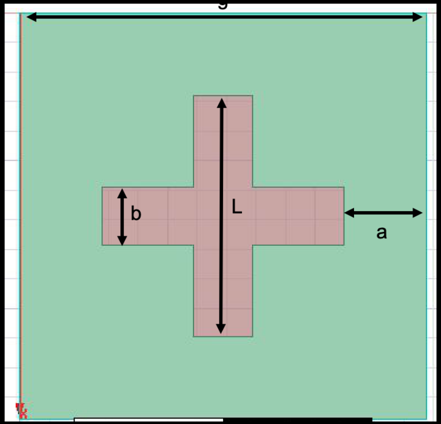




- Viavi Solutions is starting a design study aimed for 10 – 16 and 16– 26 µm for GEP.
- Perhaps 8.5 – 13.5 µm and 17 – 27 µm or slightly wider (metal mesh) would be appropriate for SOFIA.

Metal-Mesh Linear-Variable Filter Concept

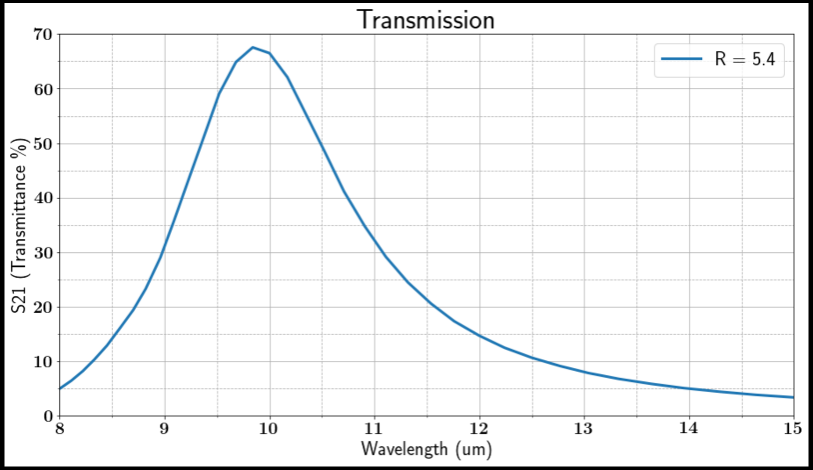
Simple fall-back solution from dielectric filters.

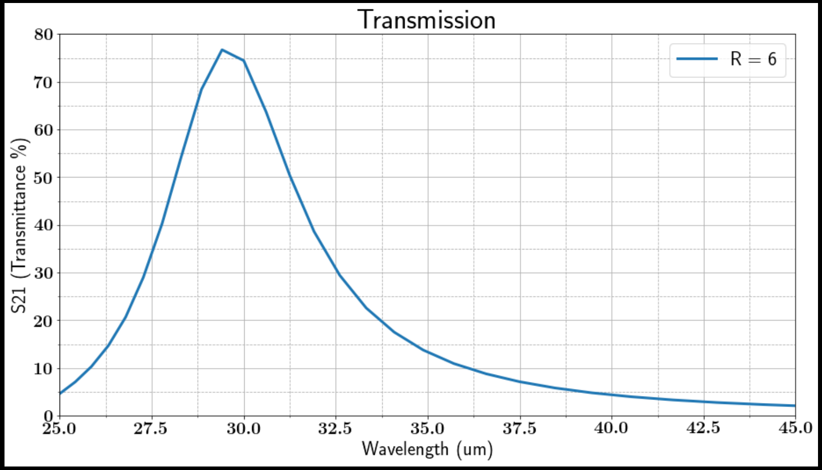


Top Left: Unit cell of bandpass filter. Pink – wafer substrate. Green – gold film.

Bottom: Ansys HFSS simulated transmission profiles. Stacked filters and smaller features can increase $\mathcal{R}$.

GEP would require Ge for 14 – 17 µm because of absorption, but SOFIA would not.





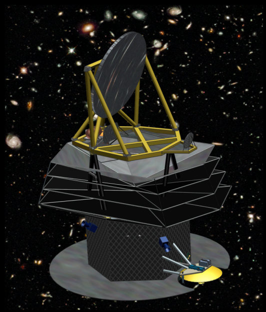
Notional SOFIA Mid- / Far-IR Hyperspectral Imager

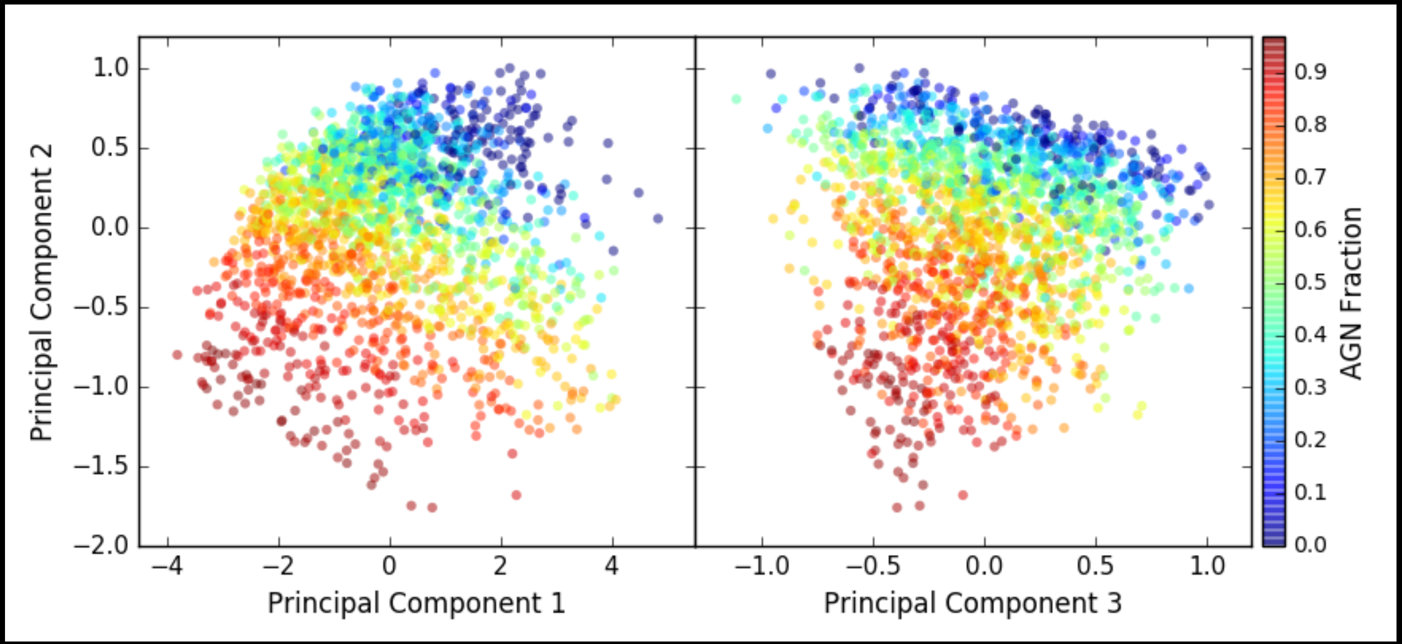
Instrument Parameter	Technology	Comments
Waveband: 8.5 – 13.5 μm Resolution: $\mathscr{R} \geq 8$ ($\mathscr{R}$ = 20 ideally?)	KIDs & dielectric or metal mesh LVF	TESs could work also[a]
Waveband: 17 – 27 μm Resolution: $\mathscr{R} \geq 8$	KIDs & dielectric or metal mesh LVF	TES also[a] Retain $\mathscr{R}$ for PAHs for very bright z ~ 1 galaxies
Waveband: 27 – 370 μm Resolution: $\mathscr{R} = 3$	KIDs & 10 Cardiff bandpass filters	TESs also
Pixel sizes: 300 μm x 300 μm FOV: from 2′ x 2′ to ~8′ x 8′	100 x 100 array of KIDs	Focal plane ~30 mm on a side
Angular resolution: $\geq 1.25''$ @ 10 μm	Set by detector size	Diffraction limit: ~1″ @ 10 μm
Rapid hyperspectral scans	Scanning mirror?	

[a]Could use Si:As and Si:SB for $\lambda < 40$ μm if restricted to this waveband; otherwise two detector technologies would be required (not recommended).

Extra Slides

Disentangling Star-Formation and SMBH-Accretion Rates



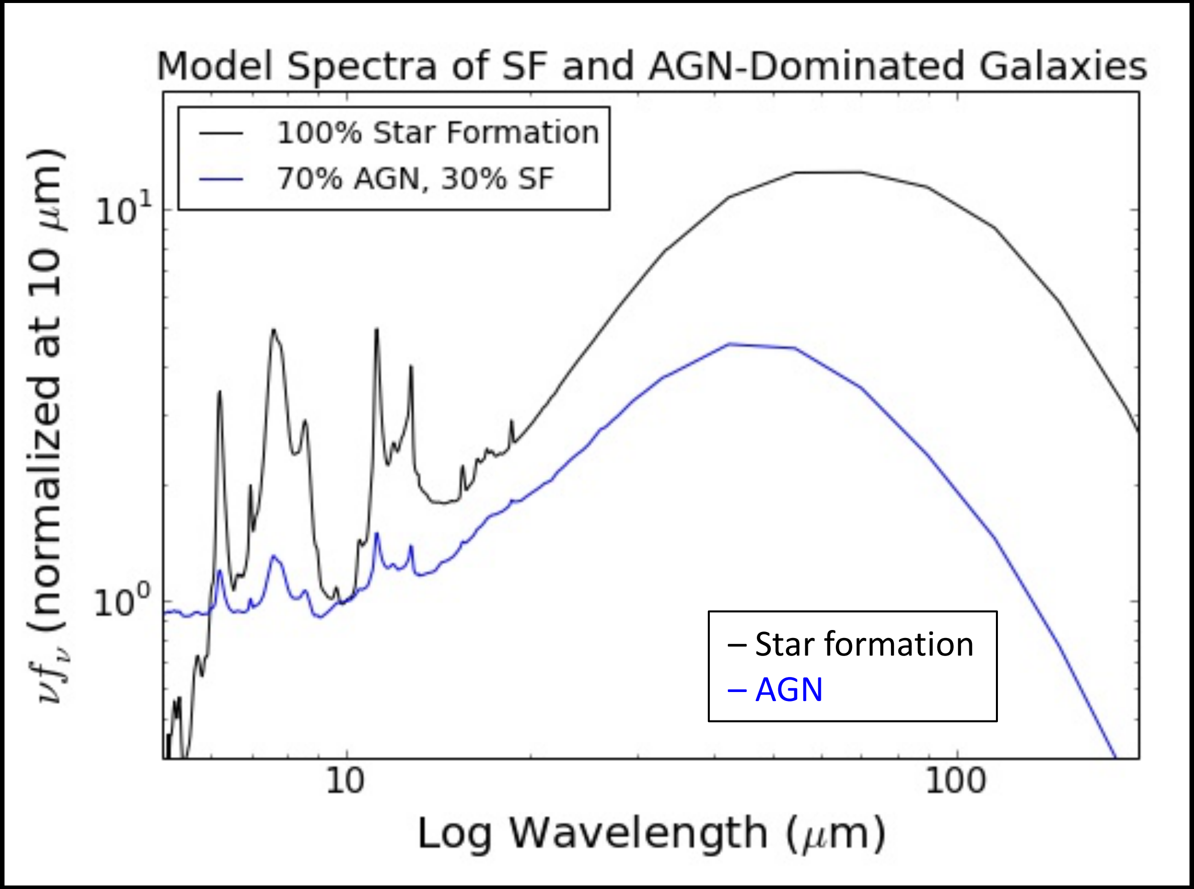


Jeremy Darling

Star formation & AGN can be separated with $\mathcal{R}$ = 8 mid/far-IR bands (plot for GEP). AGN indicators:

- ➢ Warm dust dominant ('blue' mid-IR spectrum)
- ➢ Low PAH-to-continuum ratio

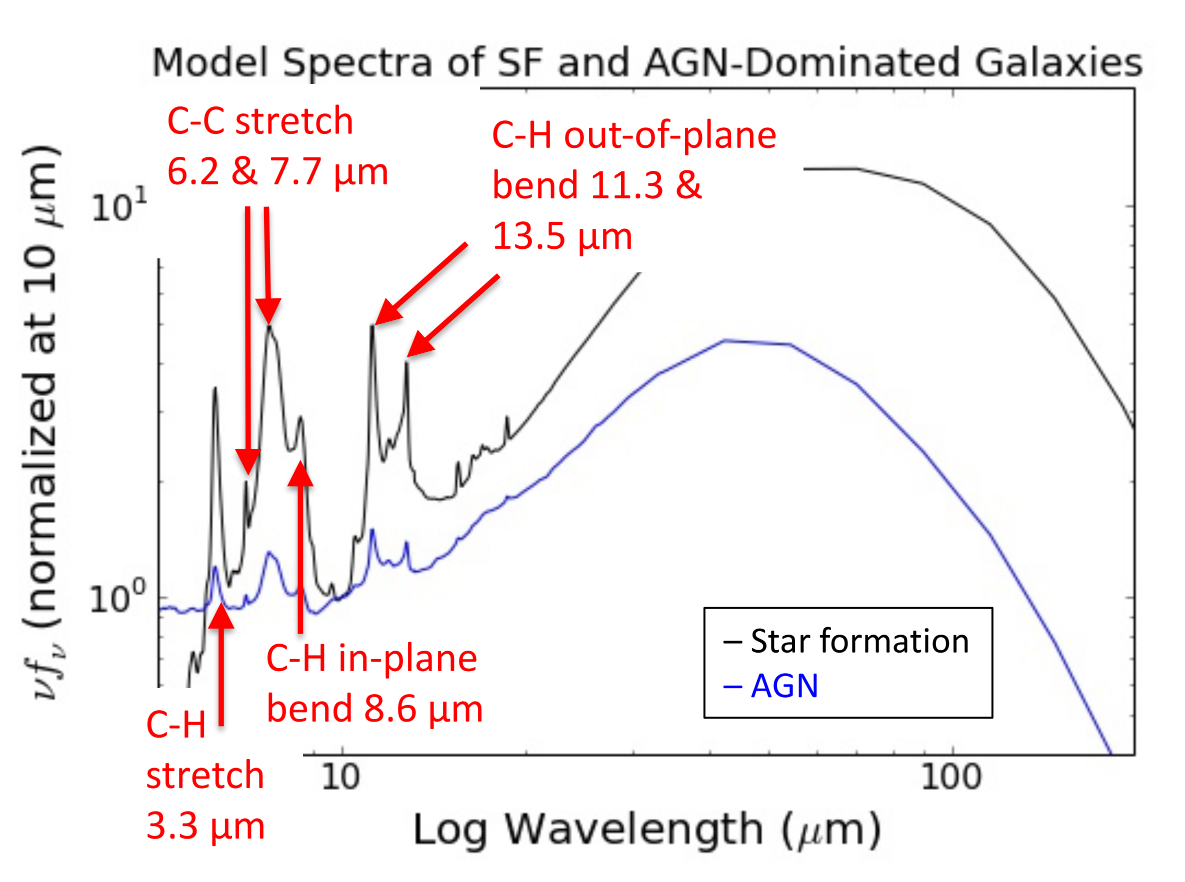
Diagnostics from PAH Lines



- PAHs carry 5-10% of IR luminosity
- 6.2, 7.7, 11.3 μm luminosities correlate with SFRs with similar scatter to H recombination lines (Shipley et al. 2016)
- PAH-derived SFRs depend on gas-phase metallicity
- PAH lines swamped by mid-IR AGN continuum

Molecular Bending-Mode Origins of PAH Emission Lines

Transient heating by UV photons



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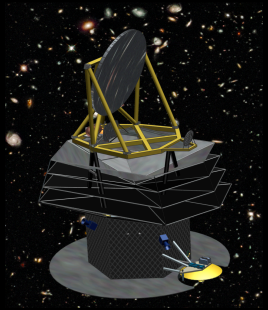
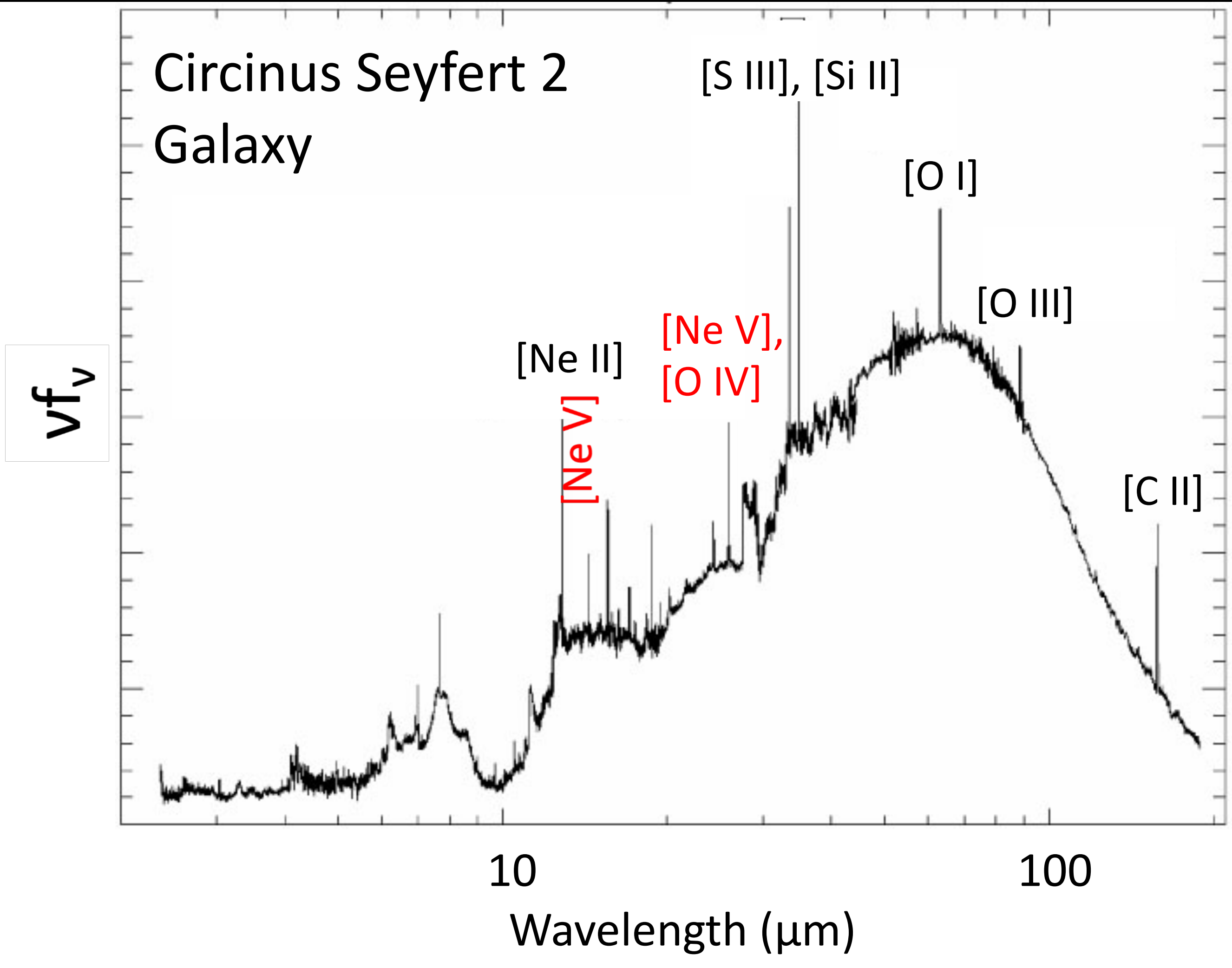
FIR Fine-Structure Lines





Adapted from Moorwood 1999