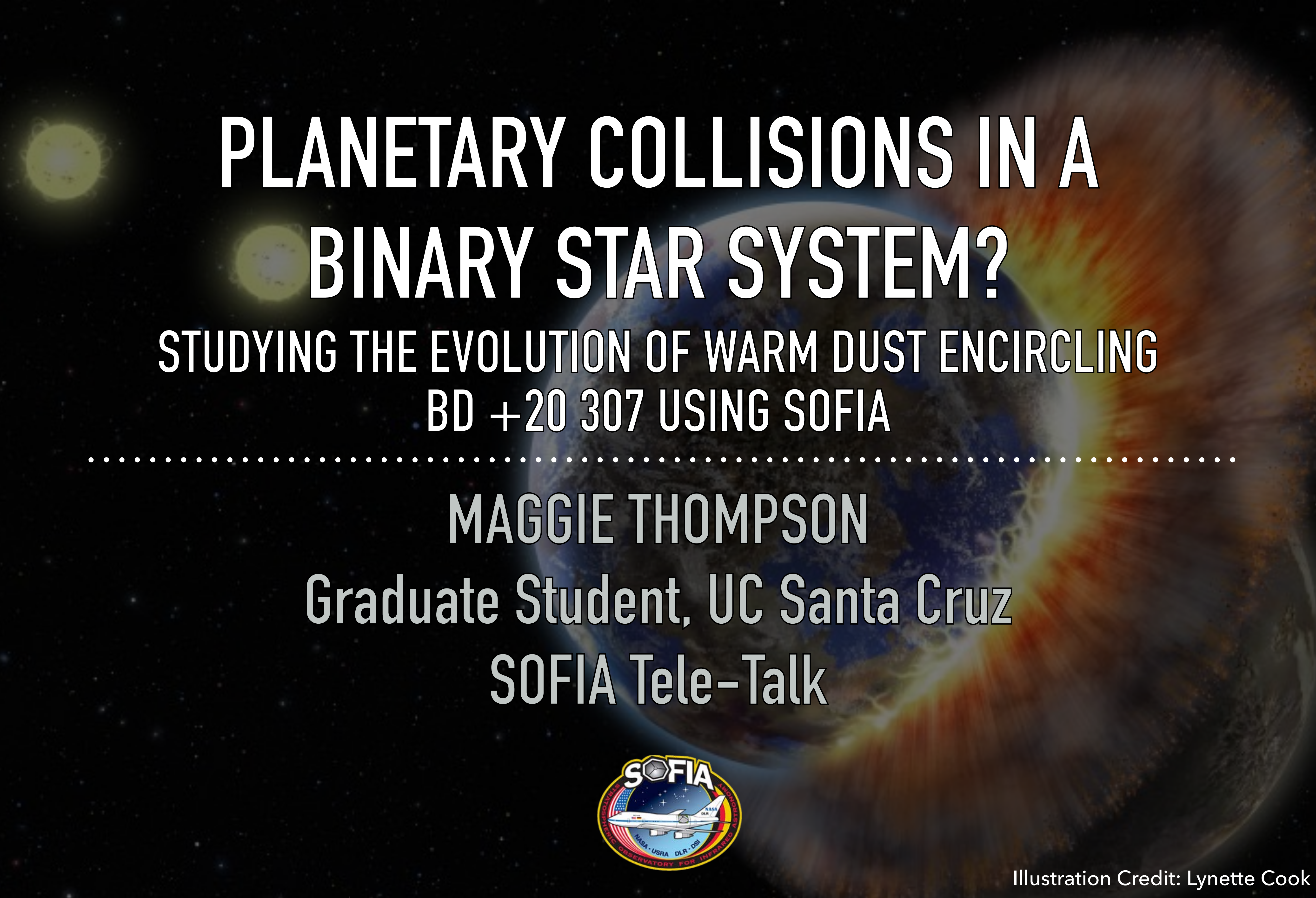

PLANETARY COLLISIONS IN A BINARY STAR SYSTEM?

STUDYING THE EVOLUTION OF WARM DUST ENCIRCLING BD +20 307 USING SOFIA

MAGGIE THOMPSON
Graduate Student, UC Santa Cruz
SOFIA Tele-Talk

Illustration Credit: Lynette Cook

July 17, 2019

COLLABORATORS

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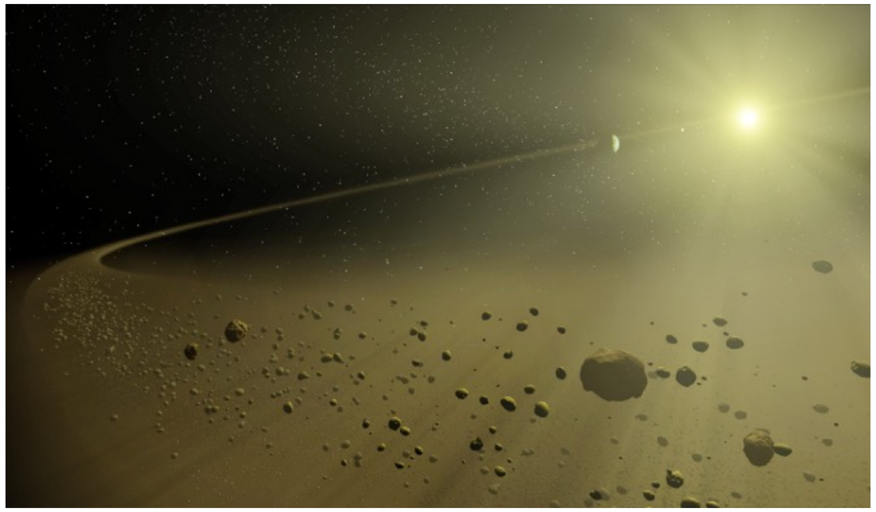
Illustration Credit: Lynette Cook

ROADMAP

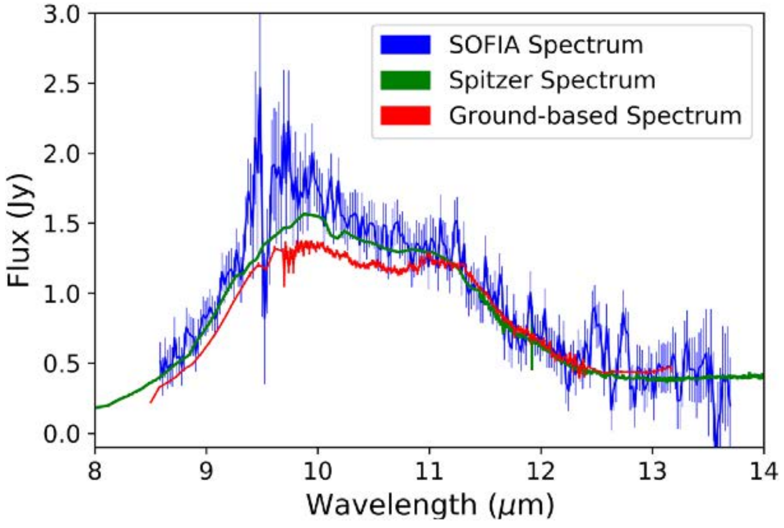
1. What are debris disks? And why is BD +20 307 unusual?



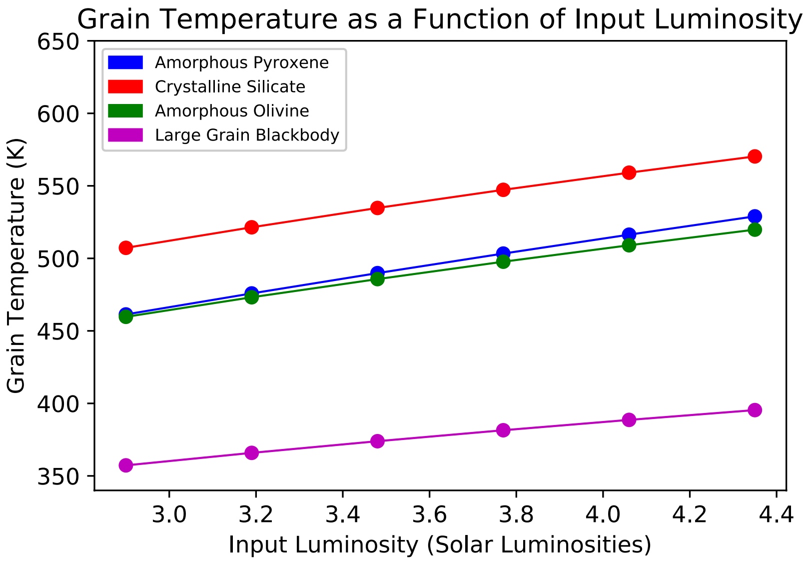
2. Prior observations of BD +20 307

3. SOFIA Observations

4. How BD +20 307's debris disk changed over ~10 years?



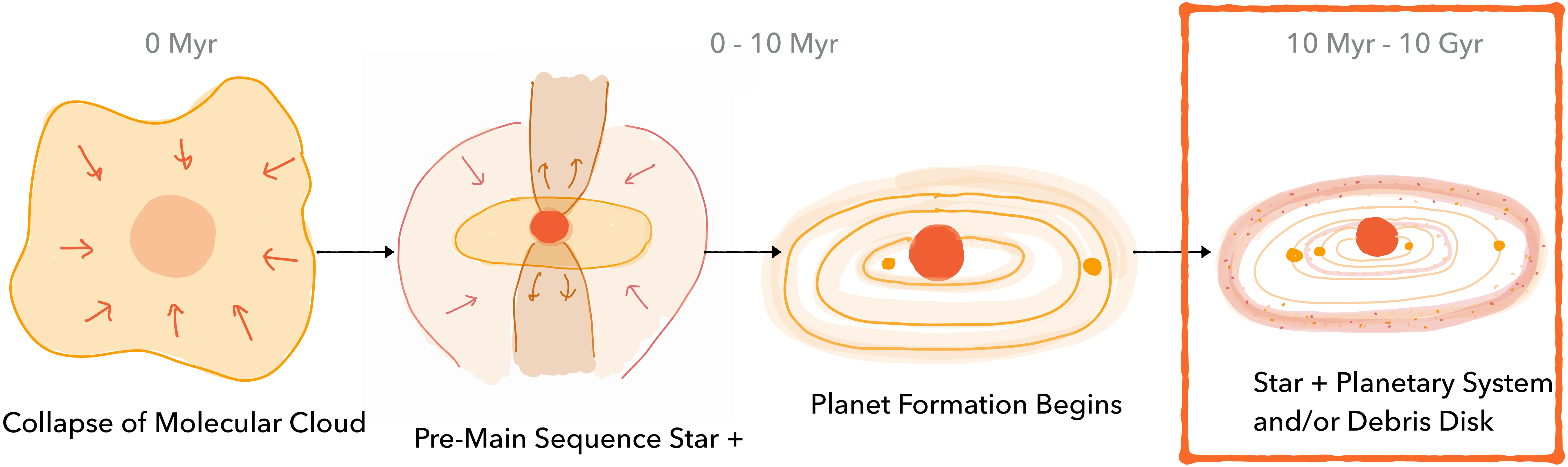
5. What could cause an increase in flux from the debris disk?



6. Future Work & Conclusions

Image Credit: T. Pyle (SSC), JPL-Caltech, NASA; Ethan Tweedie Photography/ W. M. Keck Observatory; Gemini North Observatory (gemini.edu);, JPL-NASA/Caltech; NASA/ Jim Ross; Lynette Cook

1(a). WHAT ARE DEBRIS DISKS?



0 Myr

0 - 10 Myr

10 Myr - 10 Gyr

Collapse of Molecular Cloud

Pre-Main Sequence Star +
Protoplanetary Disk

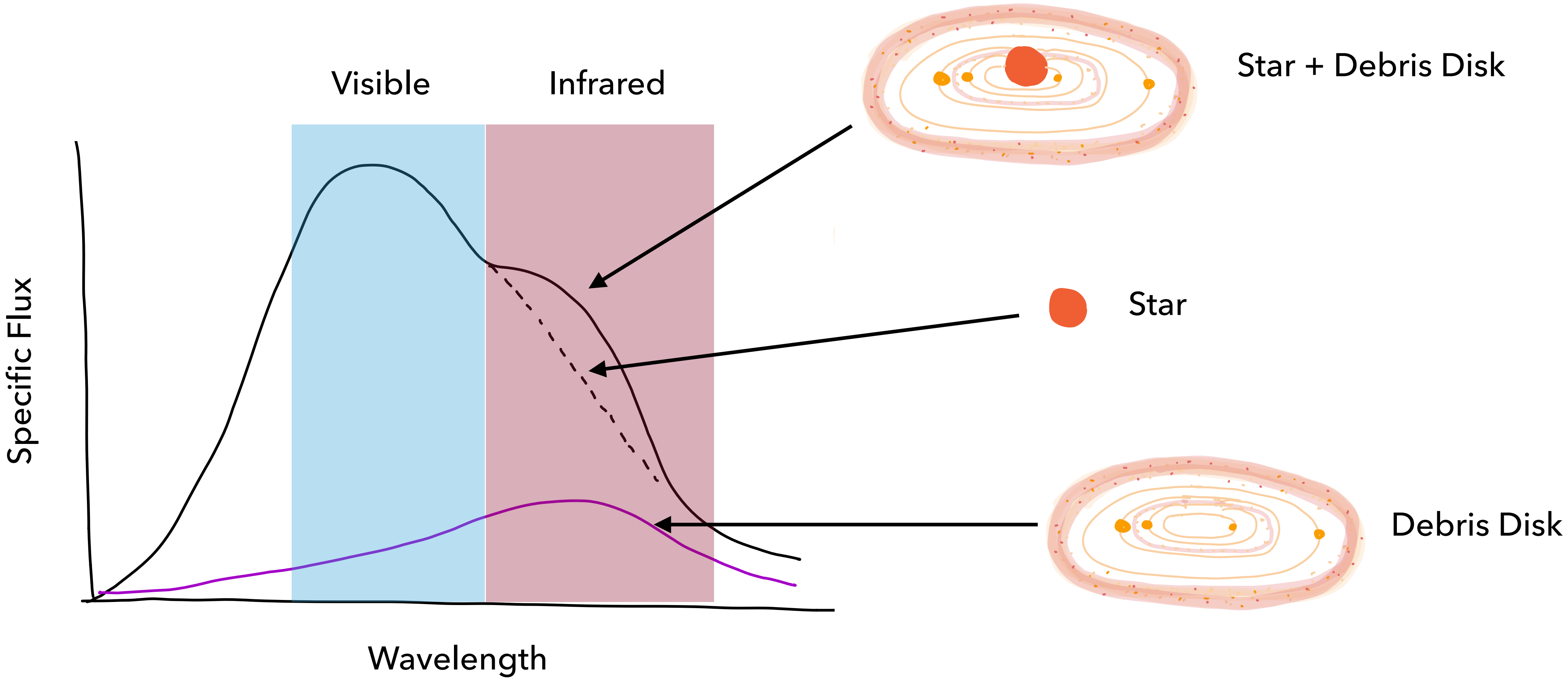
Planet Formation Begins

Star + Planetary System
and/or Debris Disk

- Typical debris disks include leftover planetesimals and secondary dust from planet formation
- Most debris disks contain low-temperature dust (≤ 100 K) orbiting far from host star
    - Debris disk analogs in our Solar System are the Asteroid Belt and Kuiper Belt

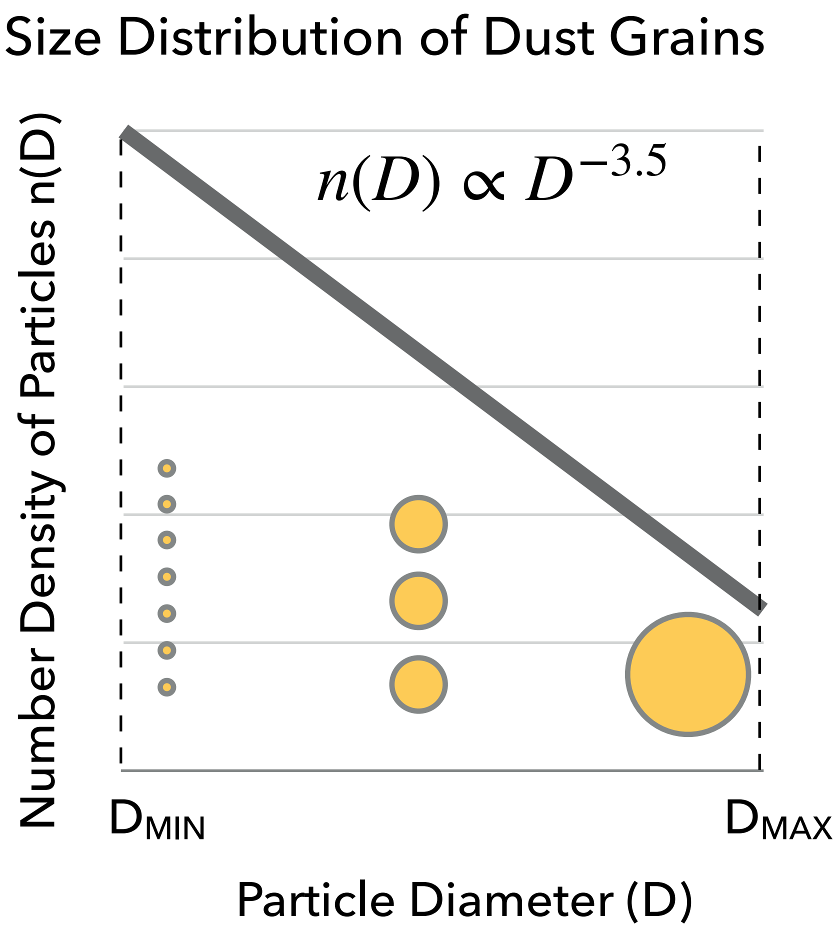
1(b). HOW TO DETECT DEBRIS DISKS?

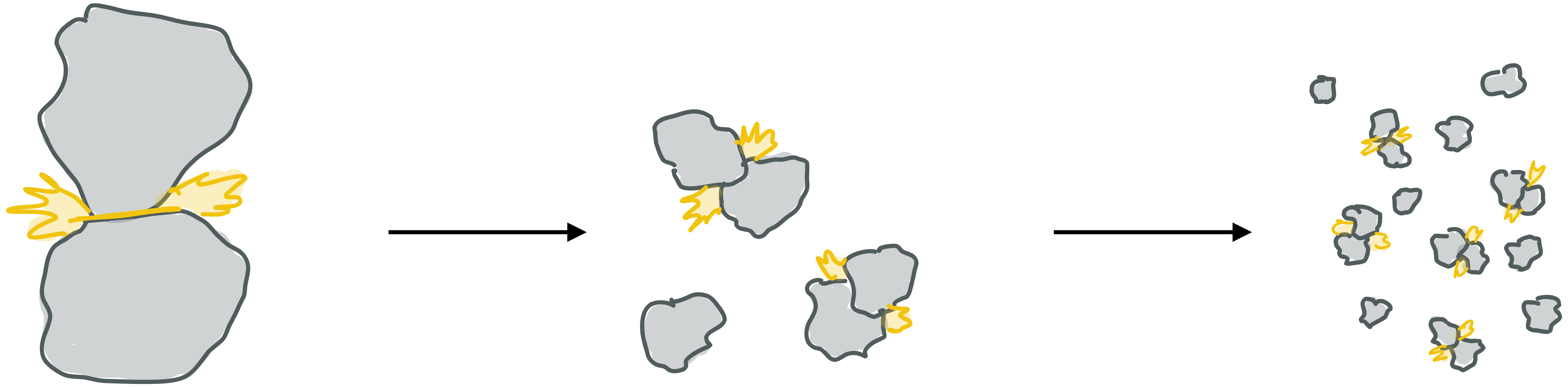
- Observable infrared excess over the photospheric emission from a main sequence star (Vega Phenomenon)
- Amount of dust is measured by the luminosity fraction: $L_{IR}/L_{\star}$



1(c). HOW TO EXPLAIN THE EVOLUTION OF MOST DEBRIS DISKS?

- **Collisional cascade**: process in which larger planetesimals in the disk collide and are continually broken up into smaller objects
- Once objects break apart to small enough sizes they will be removed either by radiation pressure pushing particles out of the system or Poynting Robertson drag pulling them into star
- In a collisional cascade, small debris disks with warm dust do not last for very long because of these removal mechanisms





Adapted from Mark Wyatt DG13

1(d). WHY LOOK FOR TIME VARIABILITY IN DEBRIS DISKS?

- **Collisional cascade model is an over-simplification**; in reality, collisions are stochastic and planetesimal strengths vary depending on grain composition, size distributions etc.

- **Collisional cascade can proceed differently for different systems**: some dust disappears rapidly over time while other disks show extreme variability

- **Debris disk variability gives us a unique window into planetary-scale collisions** that may be common in late stages of planet formation

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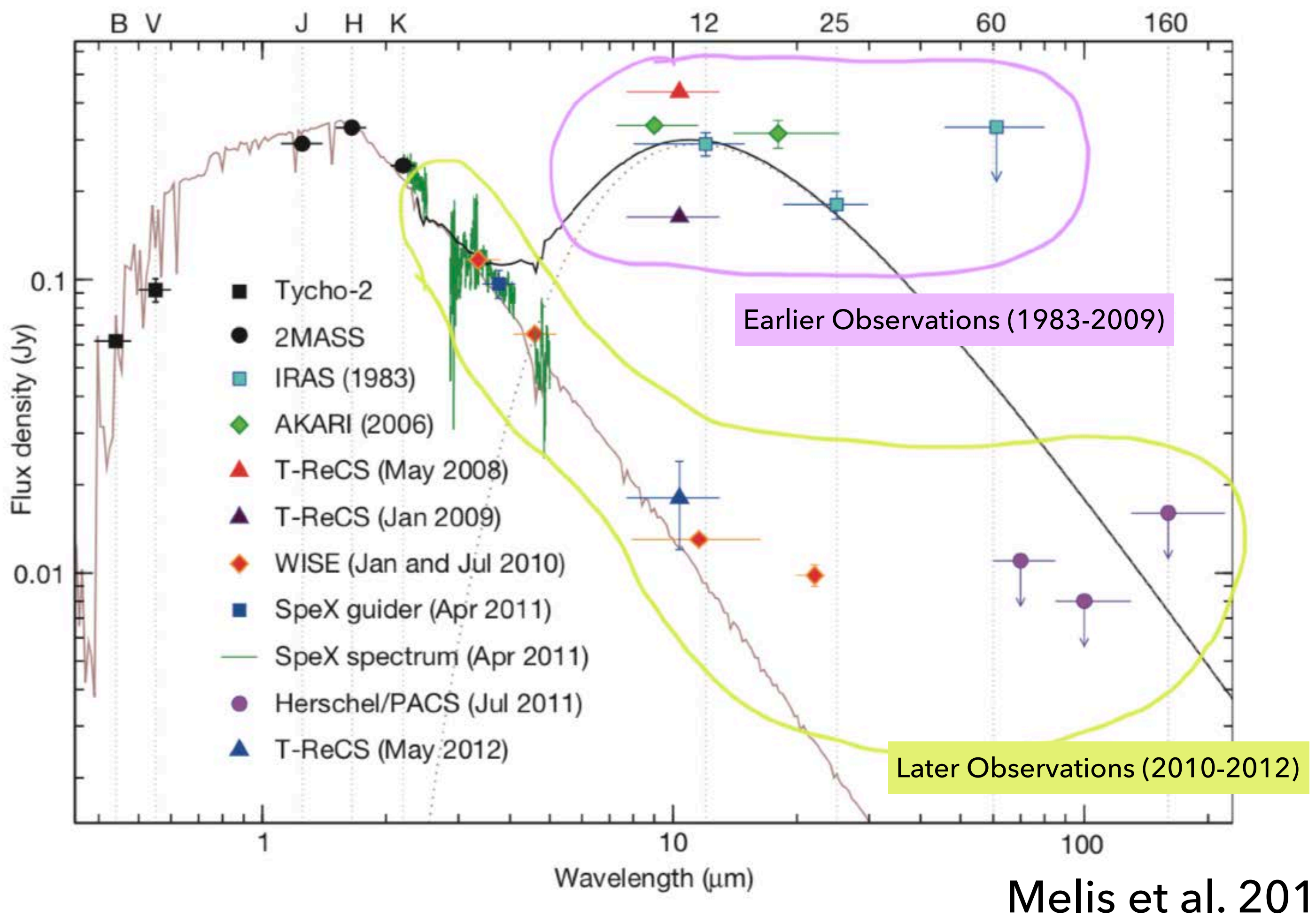
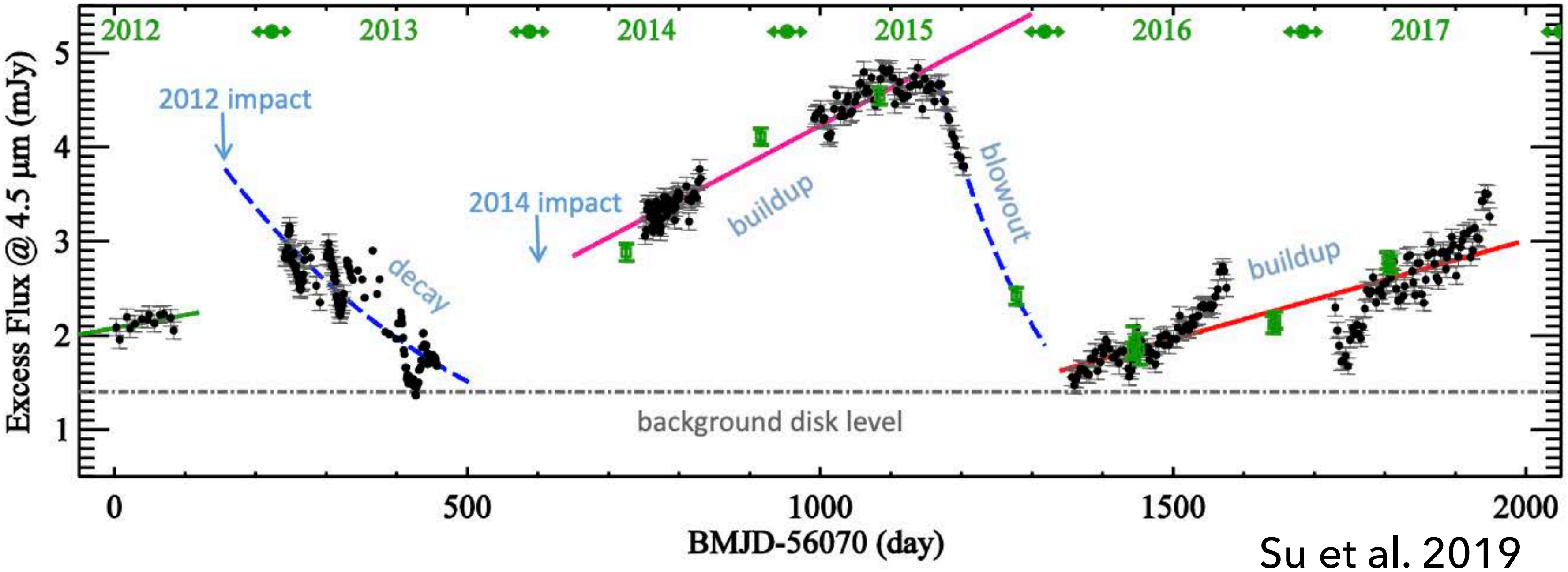


Melis et al. 2012

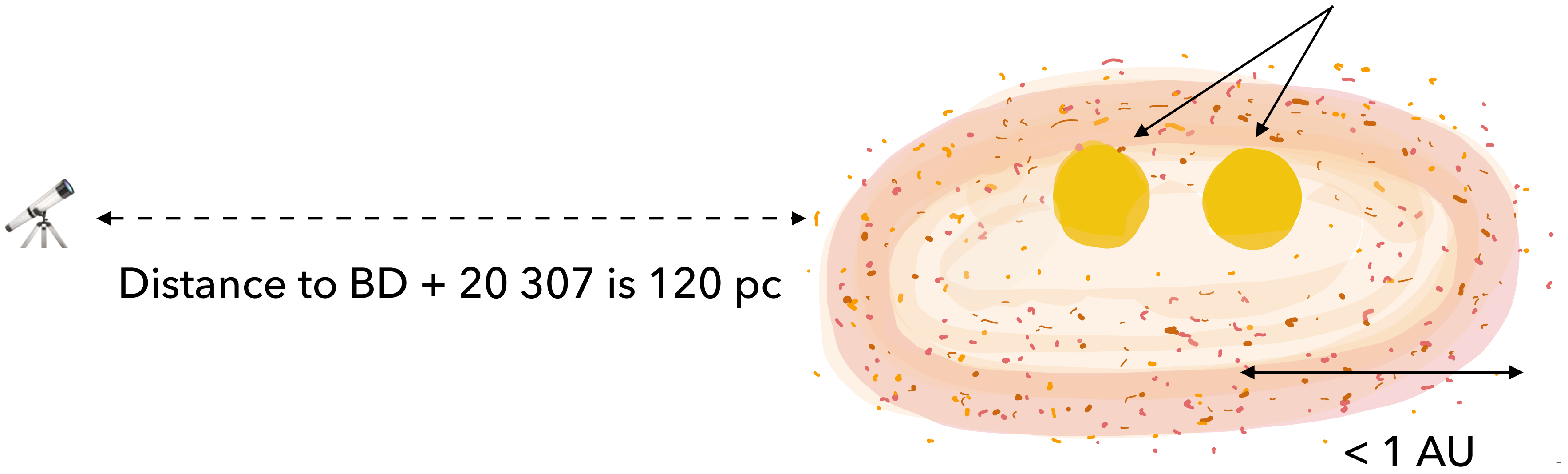
ID8



Su et al. 2019

1(d). WHAT IS BD +20 307 AND WHY IS IT UNUSUAL?

- There exists a small set of known stars with unusually warm, dusty debris disks that can give insight into final configurations of planetary systems (e.g., η Corvi, HD 69830, HD 72905, and **BD +20 307**) (Wyatt et al. 2007)



Nearly identical F-type dwarf stars on 3.4-day period

Distance to BD + 20 307 is 120 pc

< 1 AU

Infrared Excess:

$$L_{IR}/L_{\star} = 0.032$$

- A prime example is BD + 20 307 (tidally-locked F-type binary)
  - Dustiest system known for its age (≥ 1Gyr)
  - All dust is contained within 1 AU of the system
  - Changes in dust’s composition observable on short timescales

1(e). PROJECT GOALS:

Main Question: Has the dust around BD + 20 307 changed significantly over the course of a decade? If so, in what way?

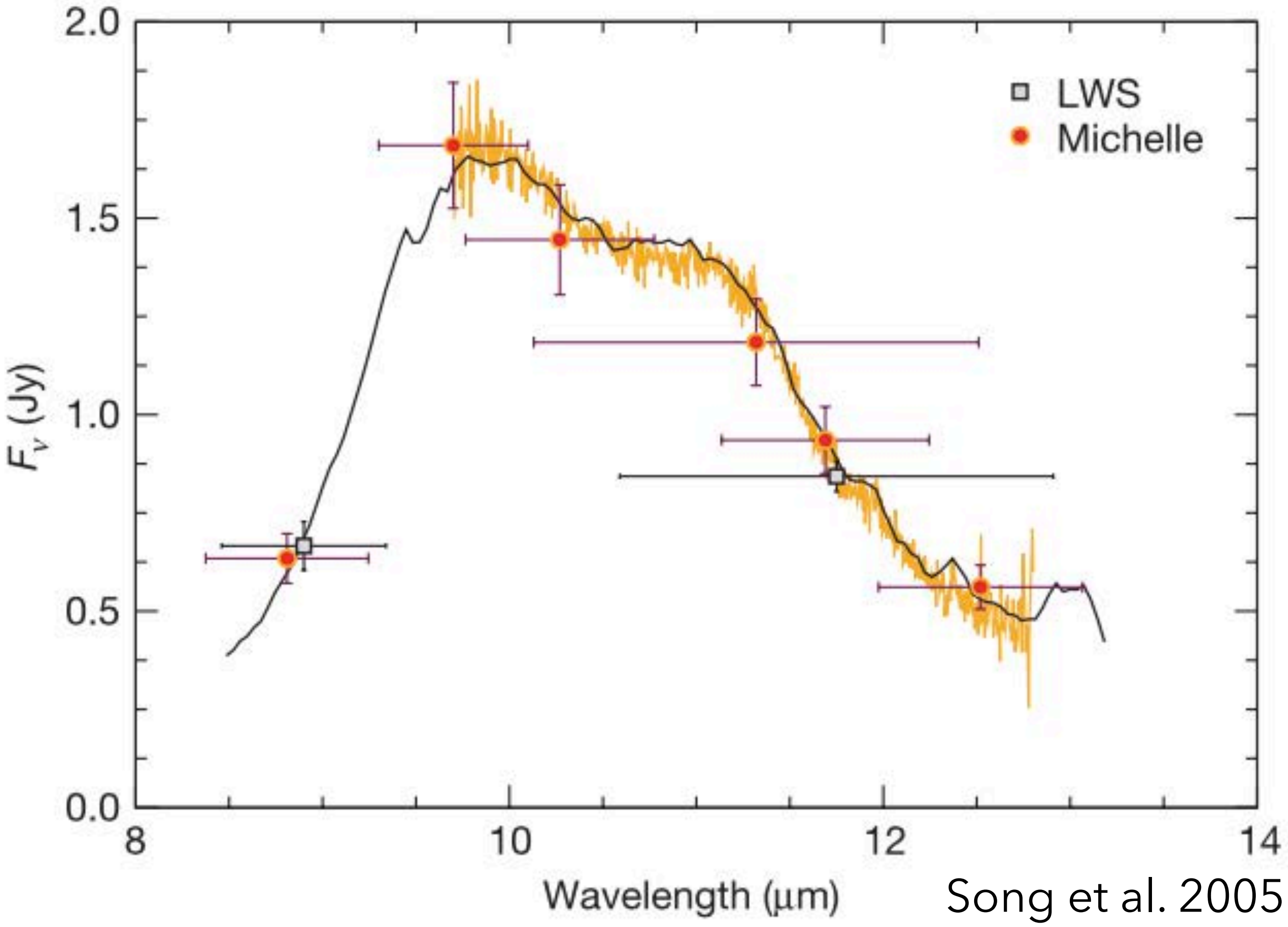
- Analyze new infrared spectroscopy and photometry data from SOFIA
- Compare recent data to previous infrared spectra to detect differences in BD +20 307's debris disk over short timescales
- Discuss possible mechanisms to explain differences over a decade
- Increase general understanding of behavior of planetary systems around binary stars

Illustration Credit: Lynette Cook

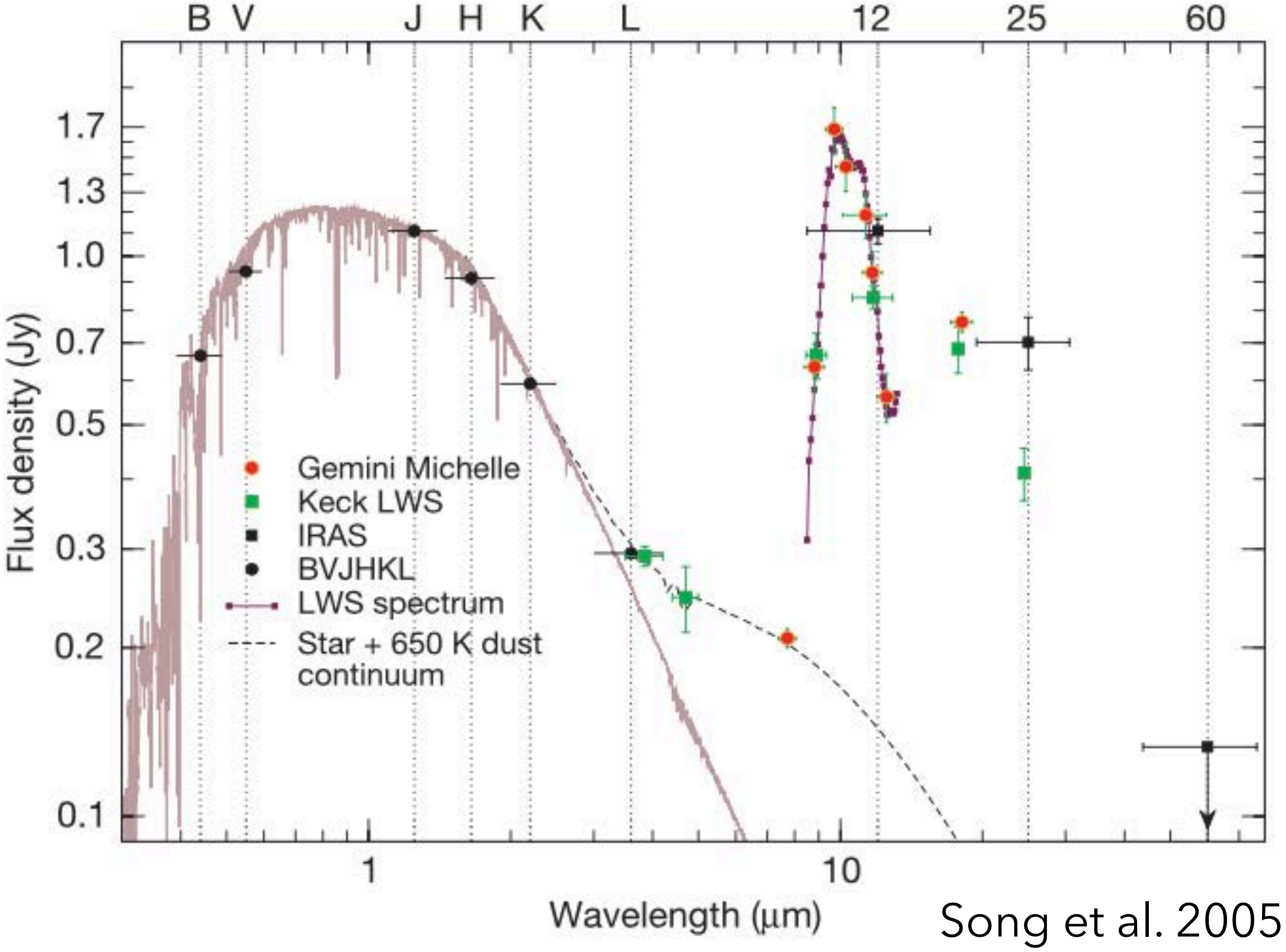
2(a). PRIOR OBSERVATIONS FROM GROUND

Keck and Gemini (2004-2005)

- Infrared spectrum of BD + 20 307 shows peaks at 10 μm and 11.3 μm indicative of amorphous silicates and crystalline silicates, respectively
- Infrared excess of BD + 20 307 produces 3-25 μm flux densities much larger than expected from the star alone



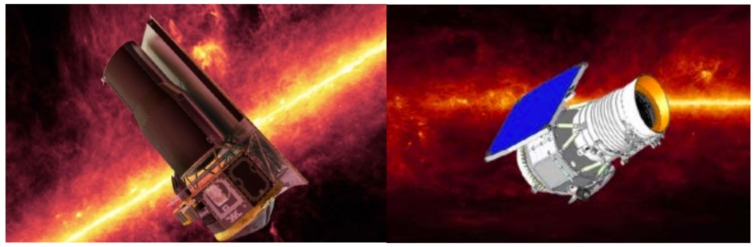
Song et al. 2005



Song et al. 2005

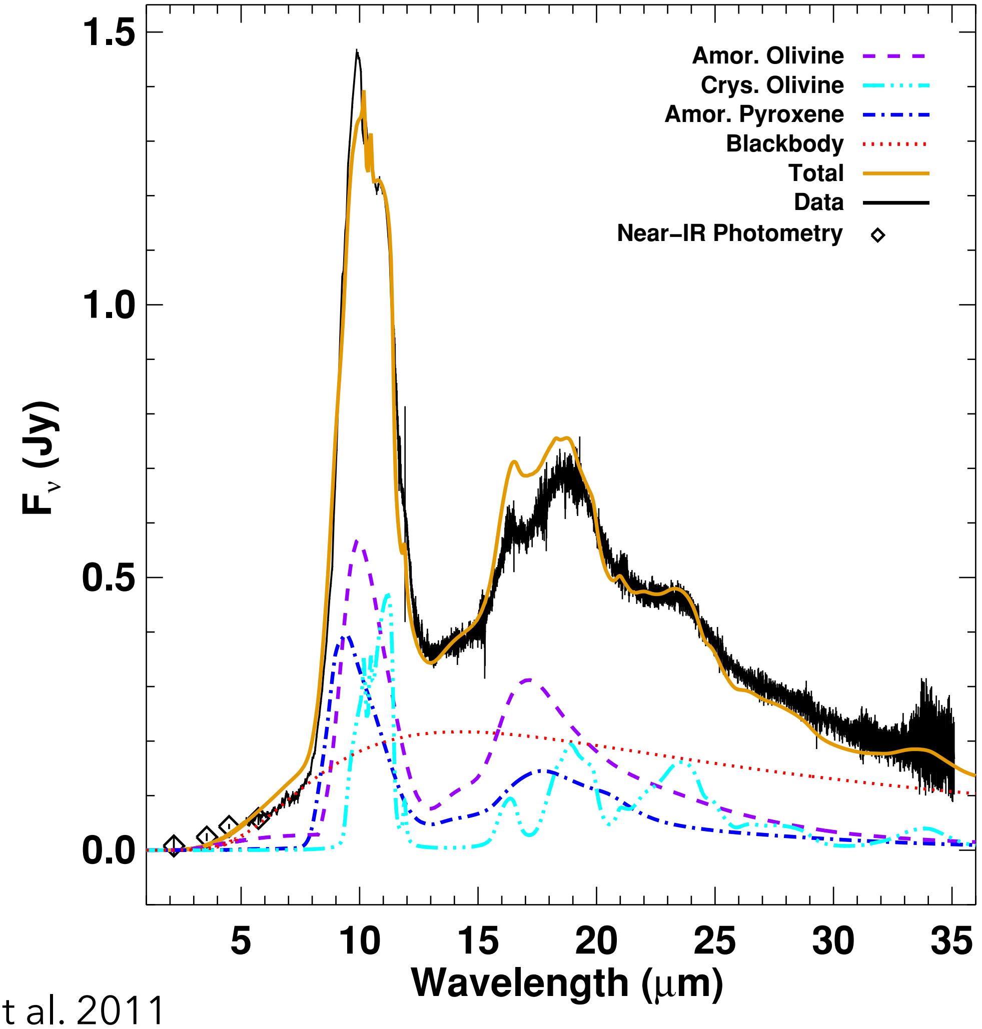
Image Credit: Ethan Tweedie Photography/ W. M. Keck Observatory; Gemini North Observatory (gemini.edu)

2(b). PRIOR OBSERVATIONS FROM SPACE

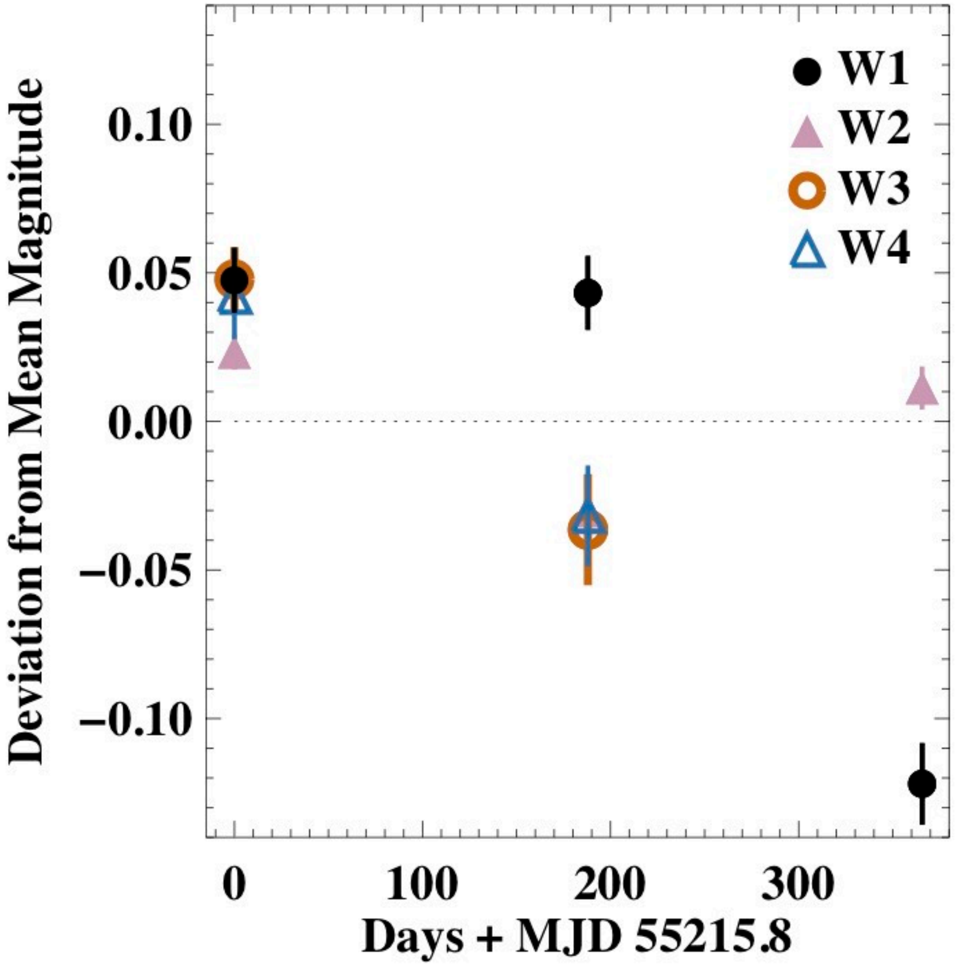


Spitzer (2005-2007) and WISE (2010-2011):

- All of the dust around BD +20 307 is located within 1 AU
- Collisional cascade of a planetesimal belt cannot explain the large amount of observed dust over BD +20 307's life
- **Dust at this flux level cannot last over system's age so it must be transient**



Weinberger et al. 2011



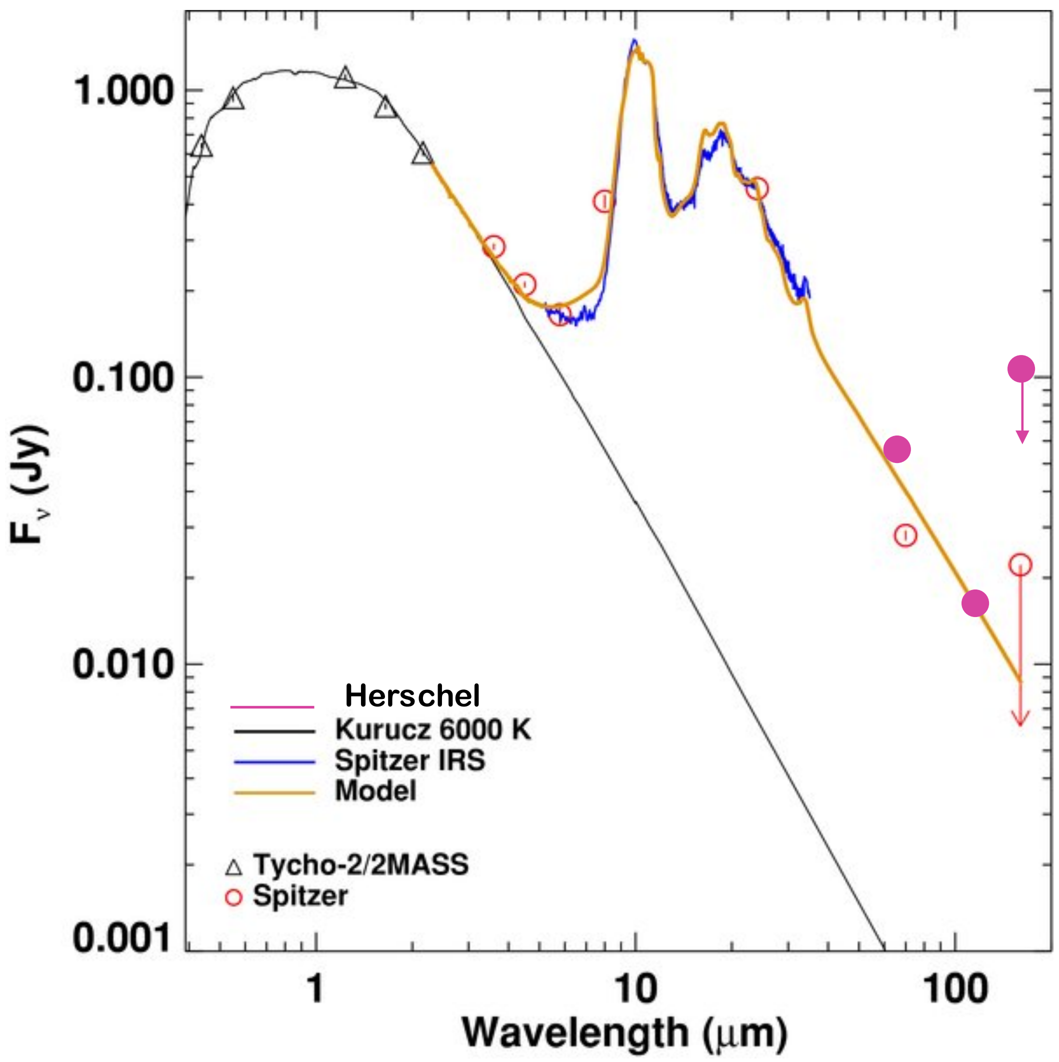
Thompson et al. 2019 & Meng et al. 2012

Image Credit: JPL-NASA/CalTech

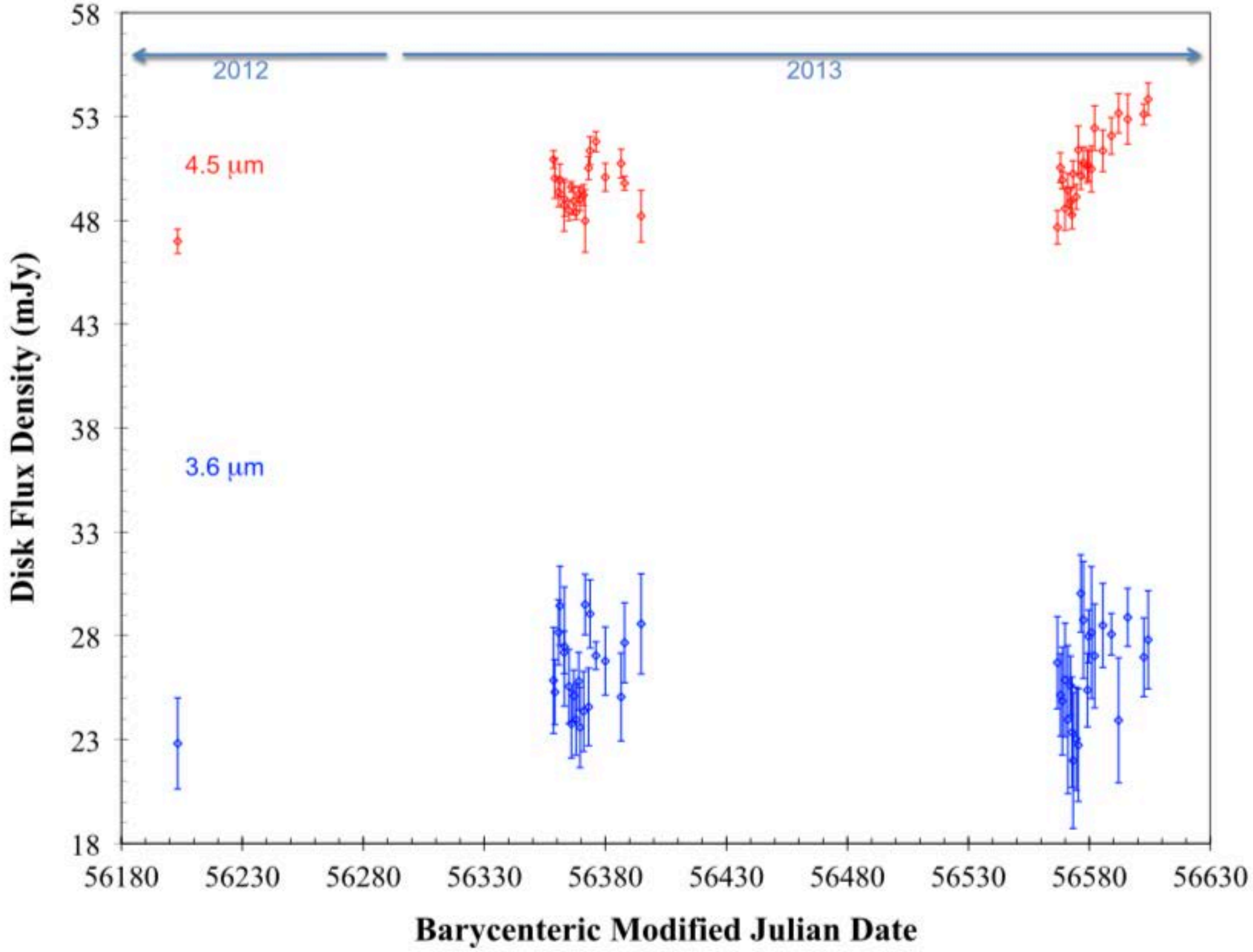
2(c). PRIOR OBSERVATIONS FROM SPACE

Herschel (2011-2012) and Spitzer (2012-2013)

- No additional cold dust is needed to fit the IR excess (T_{dust} ~ 400 K)
- Disk flux increased slightly at 4.5 μm but not at 3.6 μm from 2012 to 2013



Weinberger et al. 2011 & Vican et al. 2016



Meng et al. 2015

3(a). SOFIA OBSERVATIONS

- Instrument: Faint Object Infrared Camera and Spectrograph (FORCAST), a dual-channel mid-IR camera and spectrograph (5-40 microns)
  - Data obtained during two nights in February 2015 and covered 8-14 μm
  - Noted high noise between ~9.4-10 μm due to Earth’s ozone

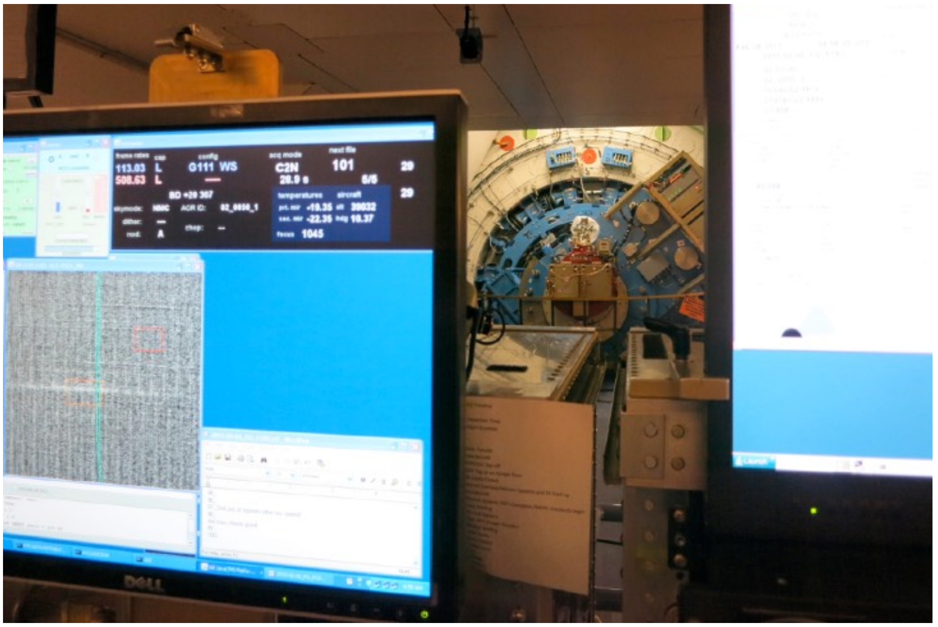
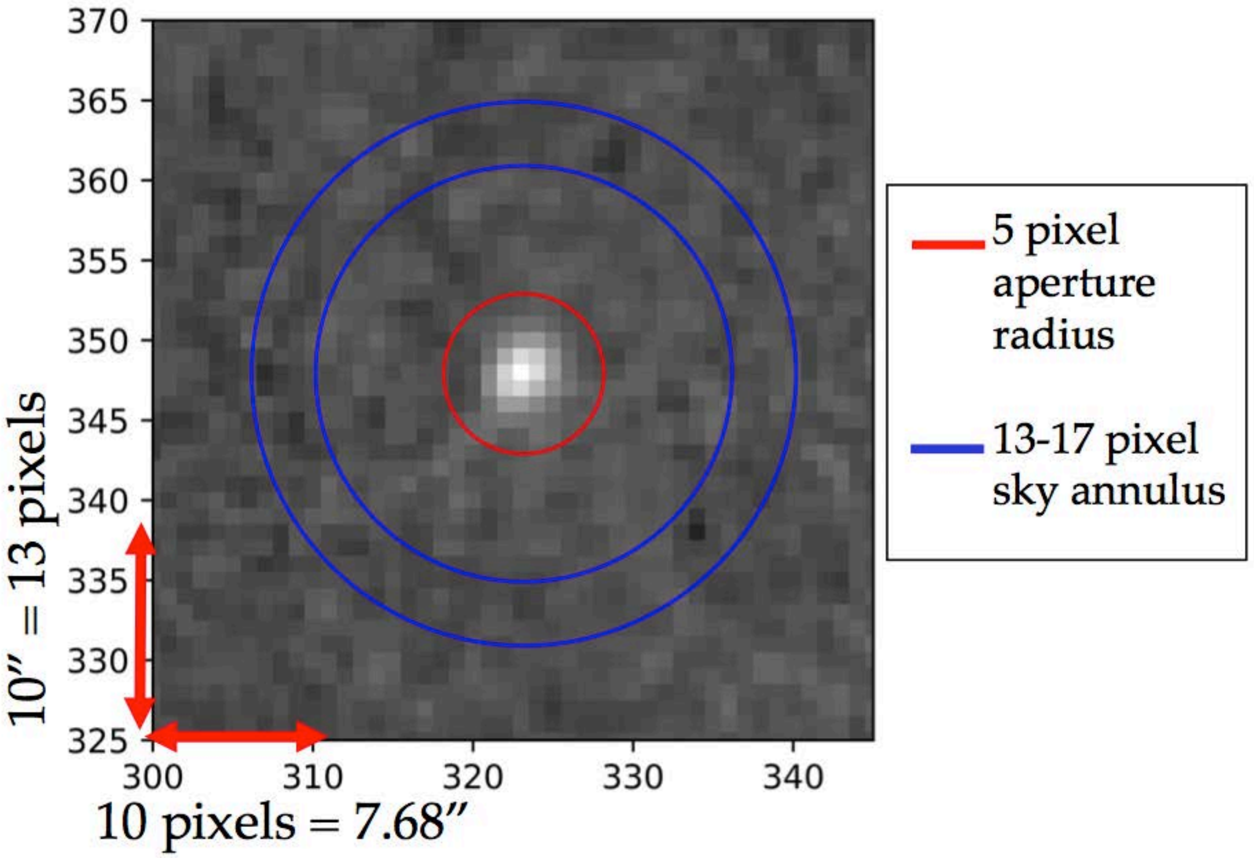
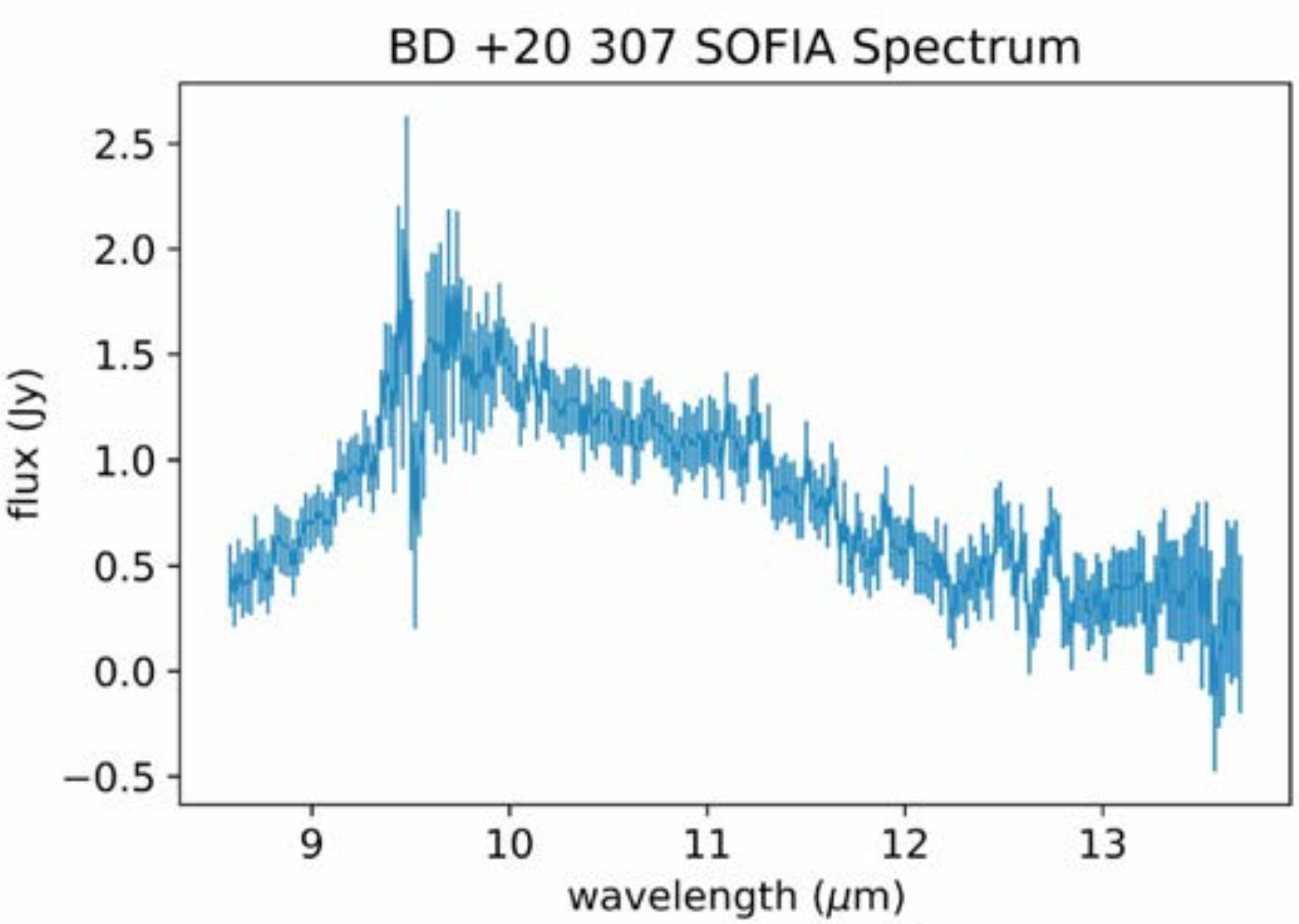



Image Credit: A. J. Weinberger; NASA/ Jim Ross

3(b). SOFIA DATA ANALYSIS

- Average 11 μm SOFIA spectra
- Photometric calibration and normalization of SOFIA spectra
- Model stellar flux for photosphere subtraction
- Determine proper uncertainty of SOFIA spectra

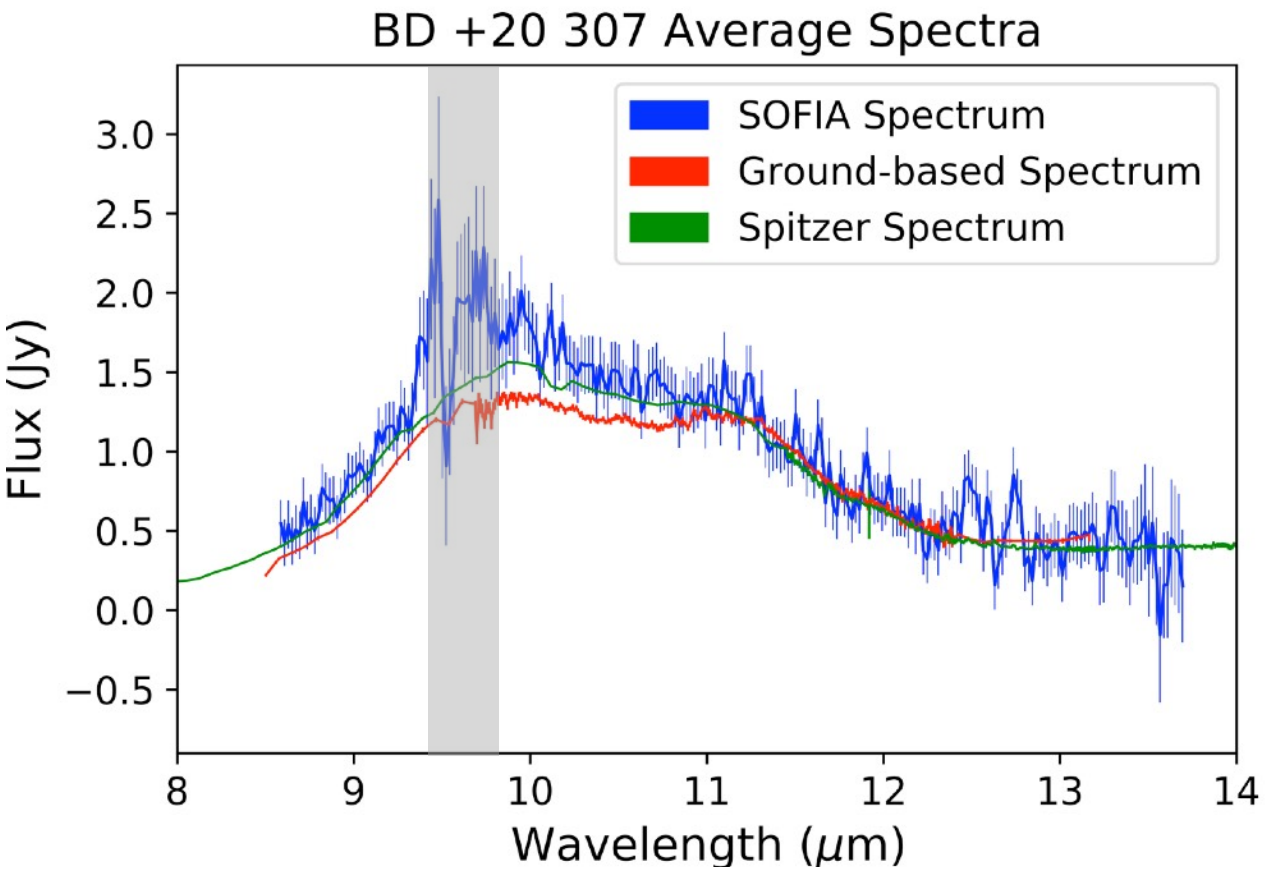


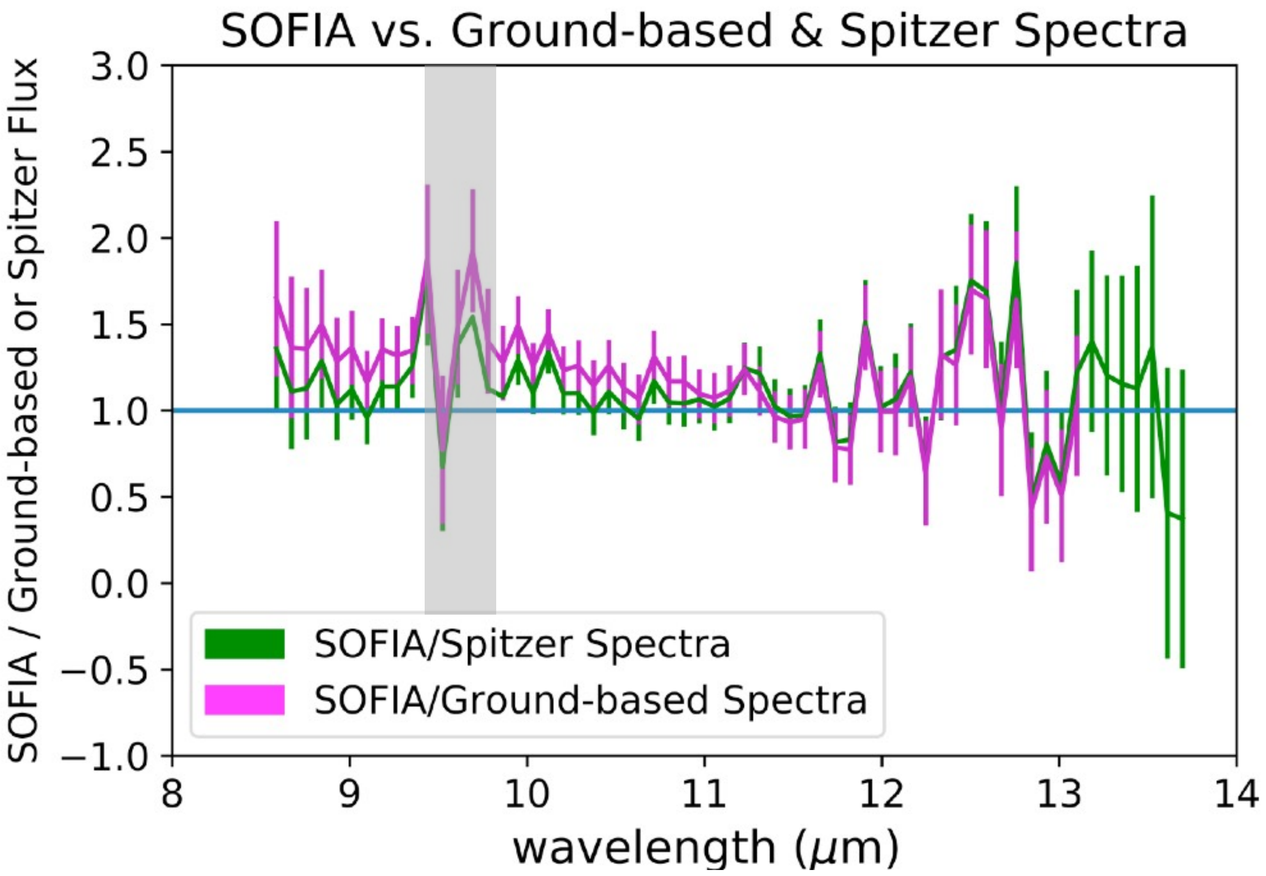


Thompson et al. 2019

4(a). RESULTS: INCREASE IN DISK FLUX OVER ALL WAVELENGTHS

- From ~8.8 - 12.5 μm BD +20 307's disk flux has increased by **10 ± 2 %** over 8 years between Spitzer and SOFIA observations and **29 ± 6 %** over ~10 years between Keck/Gemini and SOFIA observations
- *~9.4 - 9.9 μm (gray shaded regions) is where telluric ozone absorption adds noise to spectrum



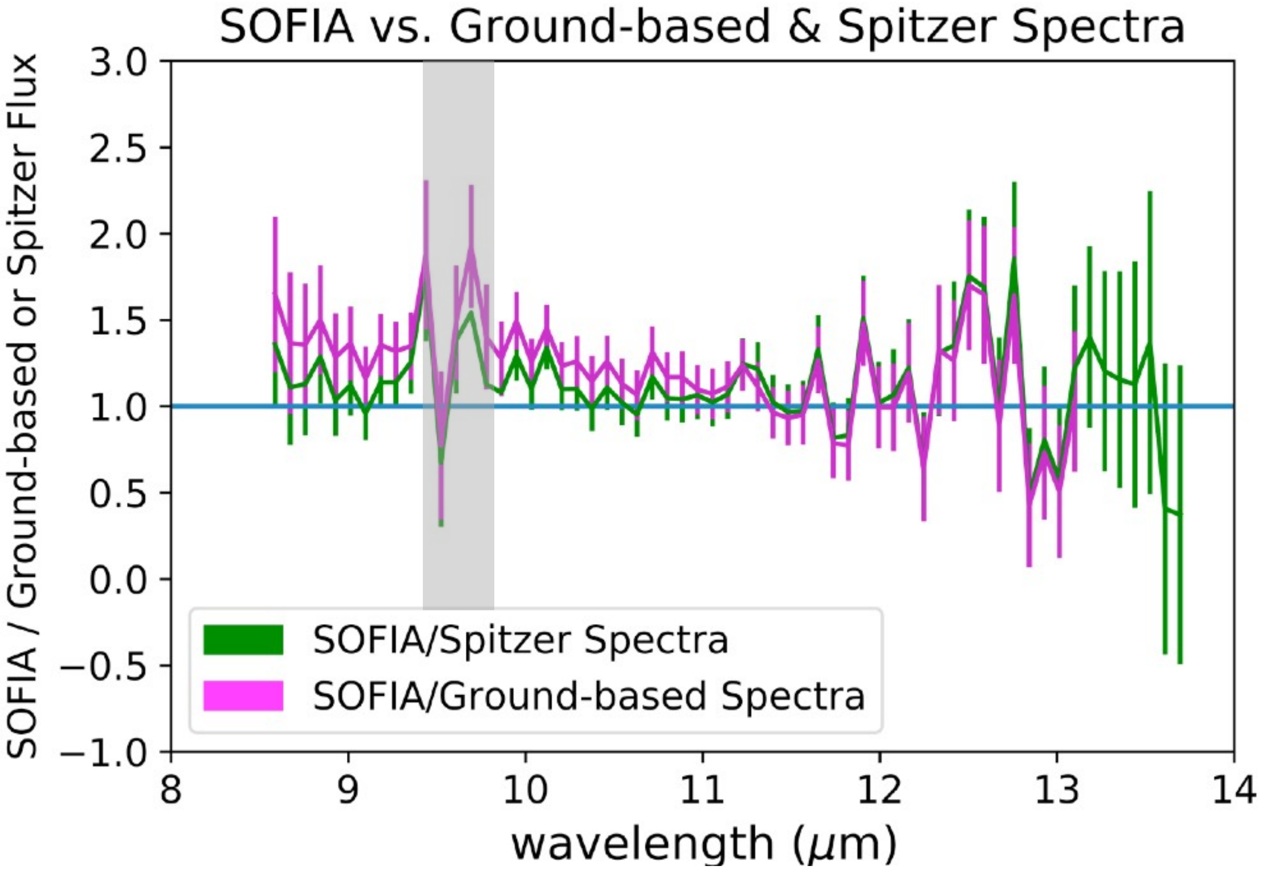


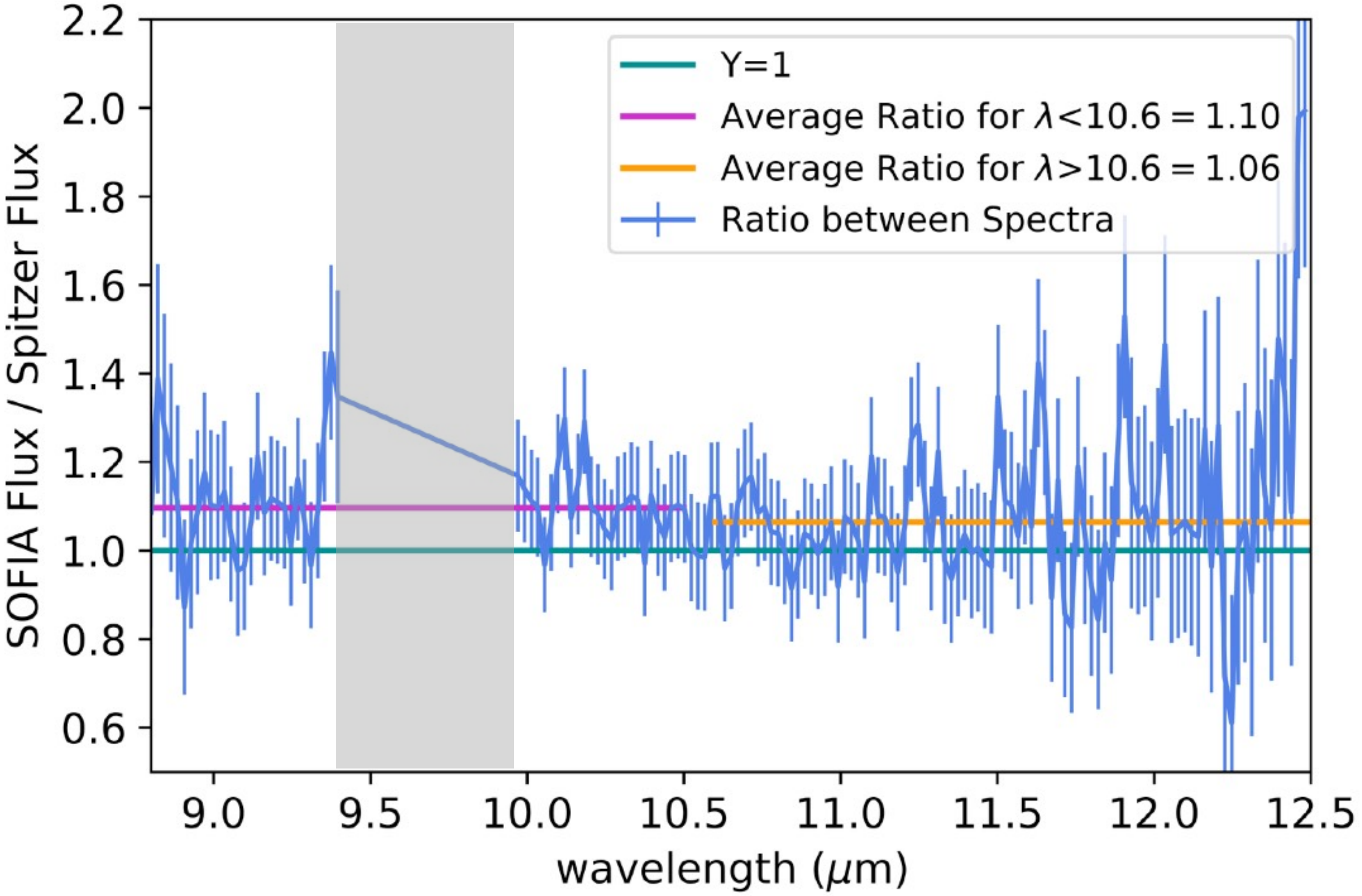
Thompson et al. 2019

4(b). RESULTS: SUGGESTIVE INCREASE IN FLUX AT SHORTER WAVELENGTHS (< 10.6 μm)

- 10.6 μm distinguishes between spectral peaks due to crystalline and amorphous grains
- Data suggests that there is a larger increase in flux at shorter wavelengths (< 10.6 μm) but due to uncertainties in the data not definitive

$$\left(\frac{F_{<10.6\mu m}}{F_{>10.6\mu m}}\right)_{SOFIA} = 1.77 \pm 0.52 \quad \text{vs.} \quad \left(\frac{F_{<10.6\mu m}}{F_{>10.6\mu m}}\right)_{Spitzer} = 1.67 \pm 0.01$$

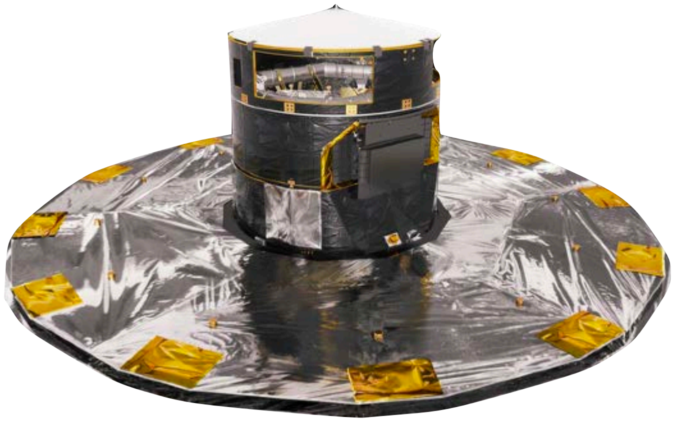




Thompson et al. 2019

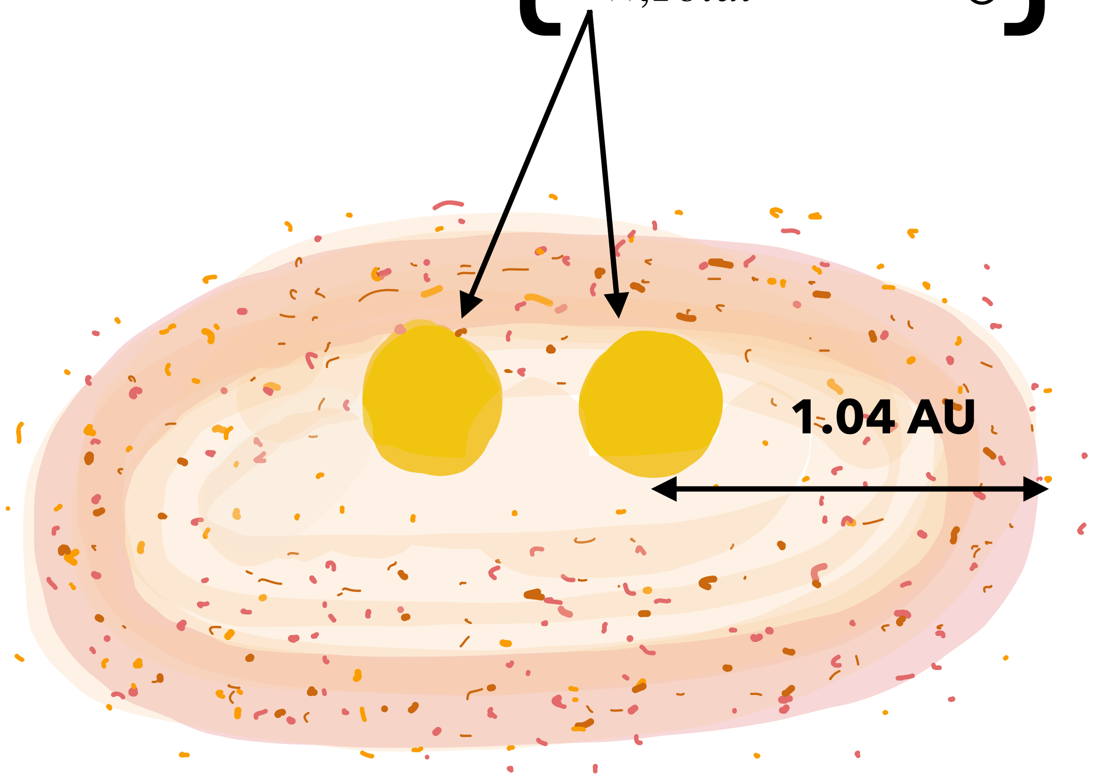
4(c). RESULTS: RE-COMPUTED DEBRIS DISK PARAMETERS

- Updated stellar luminosity from ***Gaia*** = 2.9 $L_\odot$ (Updated parallax measurement of 8.3 mas)
- Assume each star contributes half the luminosity and has T_{eff} = 5900 K, [Fe/H] = -0.43, age ≈ 1 Gyr
- Total stellar mass = 1.9 $M_\odot$
- Dust is located at 1.04 AU



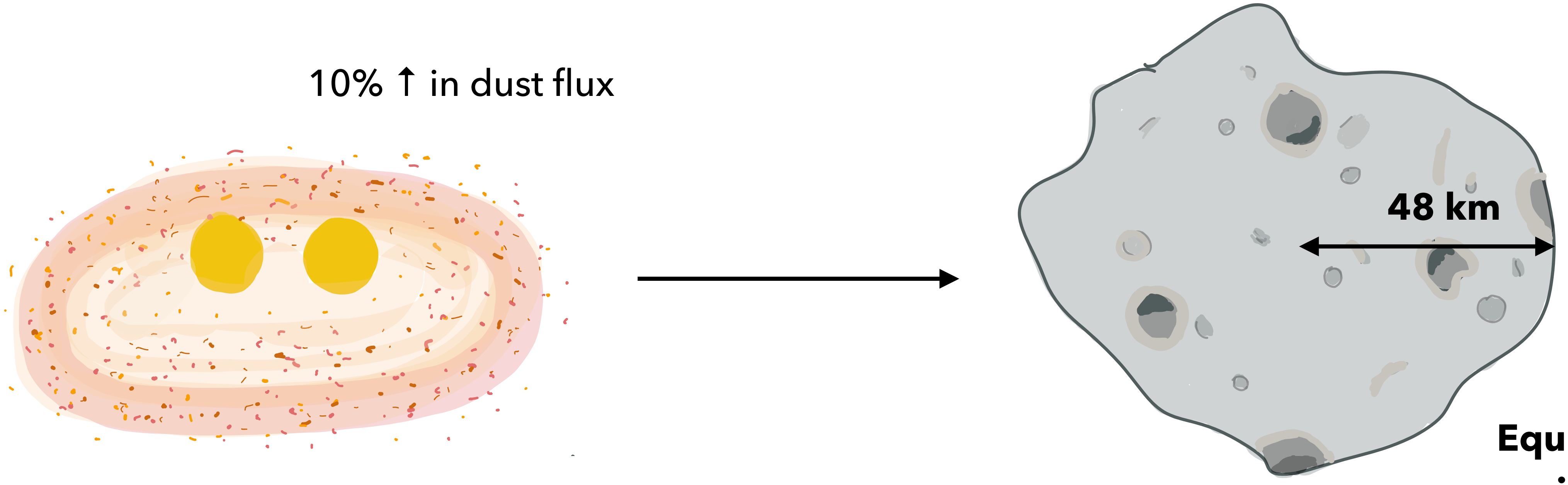
Gaia DR2; Gaia Collaboration et al. 2018

$$\left\{\begin{matrix} M_{\star,Total} = 1.9 M_\odot \\ L_{\star,Total} = 2.9 L_\odot \end{matrix}\right\}$$



5(a). POSSIBLE EXPLANATIONS FOR FLUX INCREASE: INCREASE IN NUMBER OF DUST GRAINS

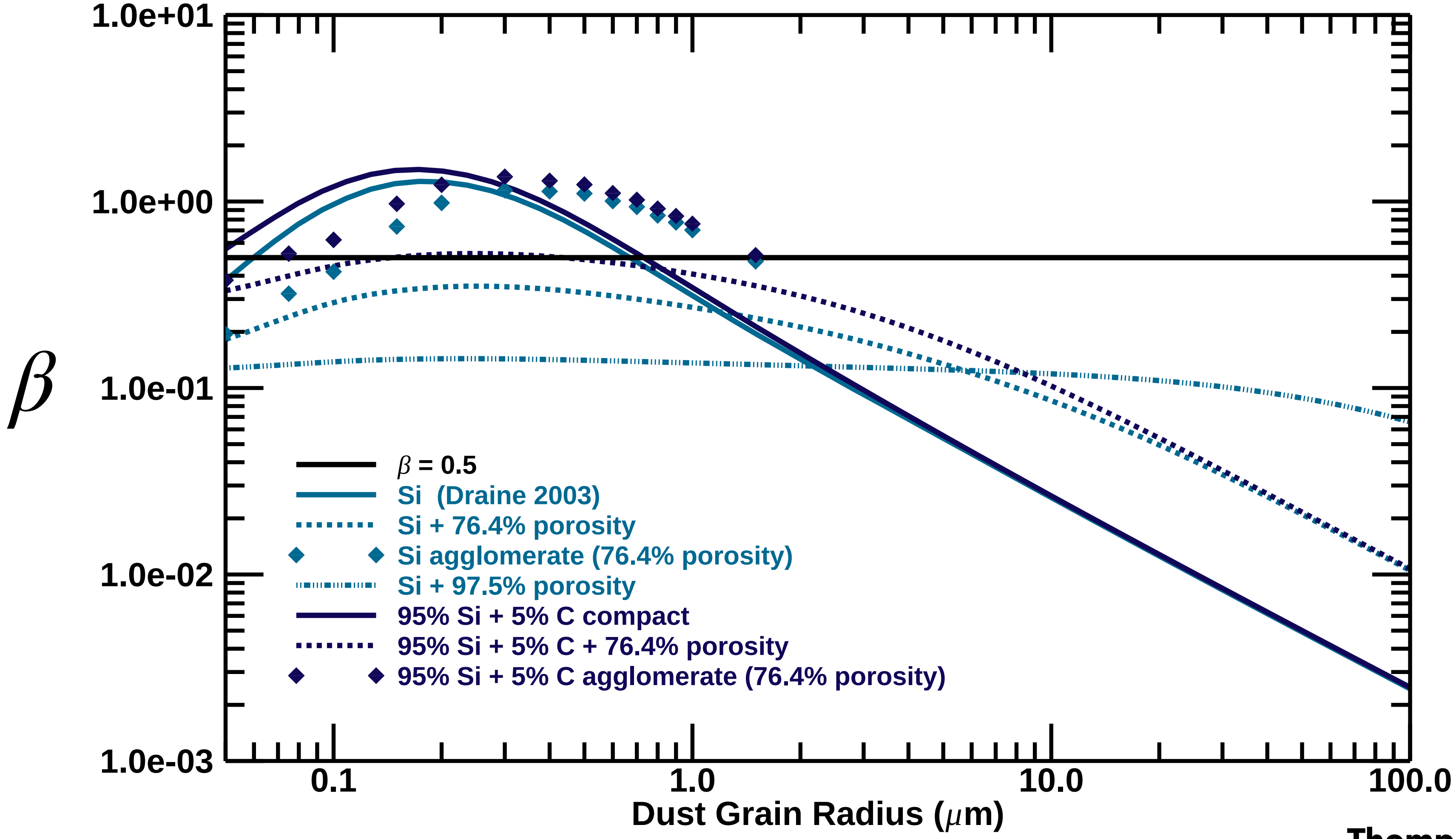
- Assuming disk is optically thin and all dust grains have same size (0.5 μm) and opacity, to get a 10% increase in luminosity between Spitzer and SOFIA observations would need to introduce **9x10^{32}** more grains
- Combining all of these additional dust grains into one spherical object makes a **48 km** radius body
- *Note: this number of additional dust grains is a *lower limit* because of optically thin disk assumption



Equivalent to 9x10^{32} grains each 0.5 μm in size

5(b). POSSIBLE EXPLANATIONS FOR FLUX INCREASE: RELAXING STEADY-STATE COLLISIONAL CASCADE ASSUMPTIONS (1)

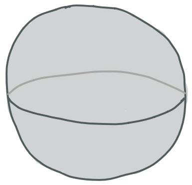
- β is the ratio between radiation pressure pushing grains out and gravity from host stars pulling them in $(\beta = \frac{F_{Radiation\ Pressure}}{F_{Gravity}})$
- For a given dust grain composition, there is a characteristic blowout size, which is denoted by where a given curve intersects the $\beta = 0.5$ line below which grains will be ejected from the system



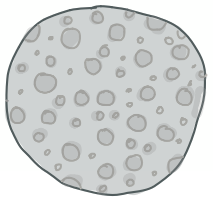
Dust Grain Compositions & Shapes:

Pure Astro-Silicate Grains

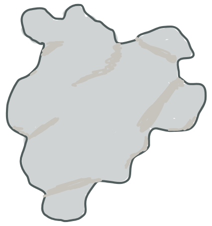
Astro-Silicate Amorphous Carbon Mixture Grains



Compact Spheres



Porous Spheres



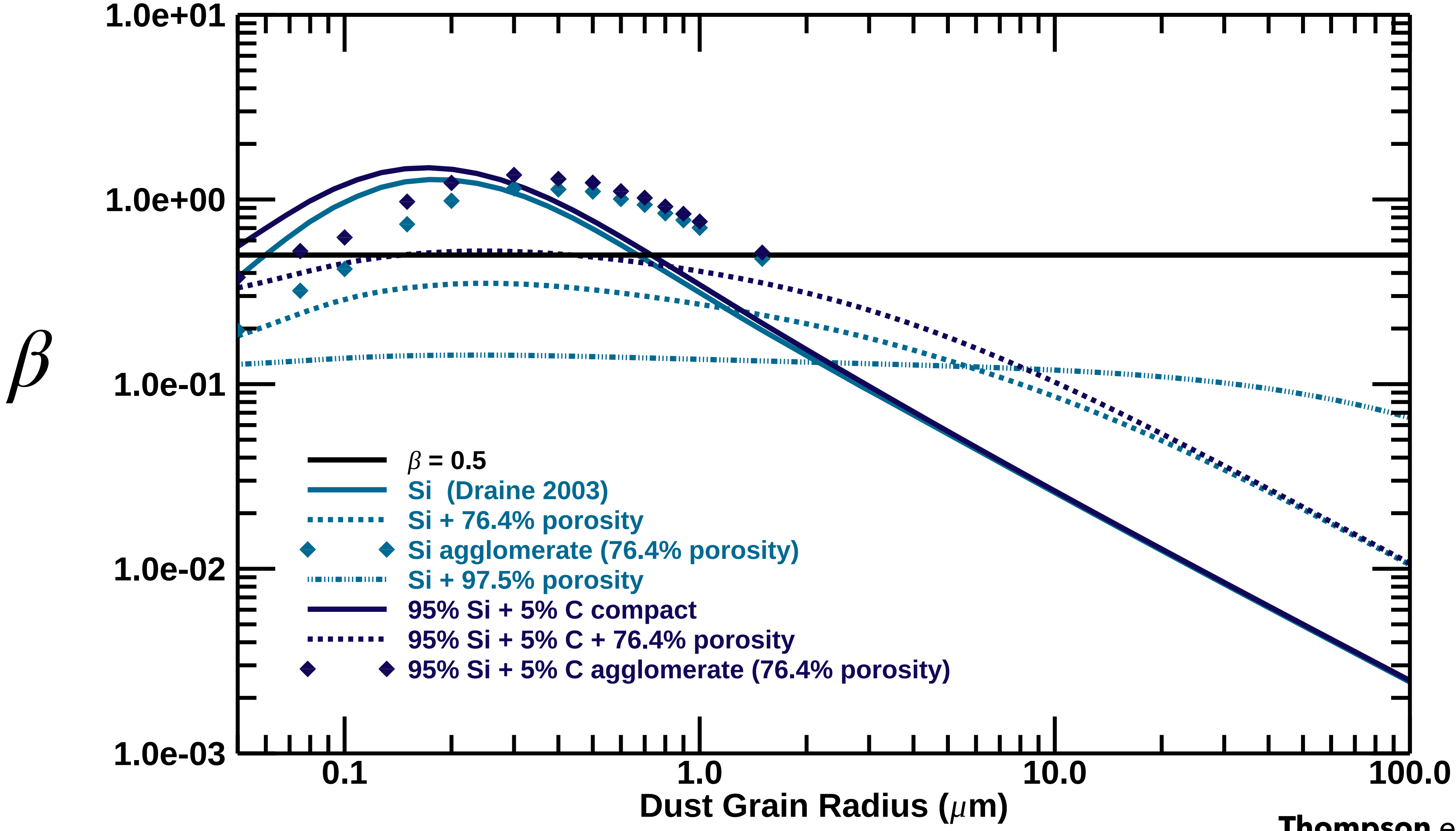
Agglomerated Debris Particles

Thompson et al. 2019 & See Arnold et al. 2019

5(b). POSSIBLE EXPLANATIONS FOR FLUX INCREASE: RELAXING STEADY-STATE COLLISIONAL CASCADE ASSUMPTIONS (2)

- In the case of BD +20 307, very small grains can survive in the disk, and they can be effective at breaking up larger grains and launching avalanches that may happen stochastically over time

- Can add complexity to collisional cascade models by varying planetesimal strength due to different dust grain compositions, thermal histories and size distributions

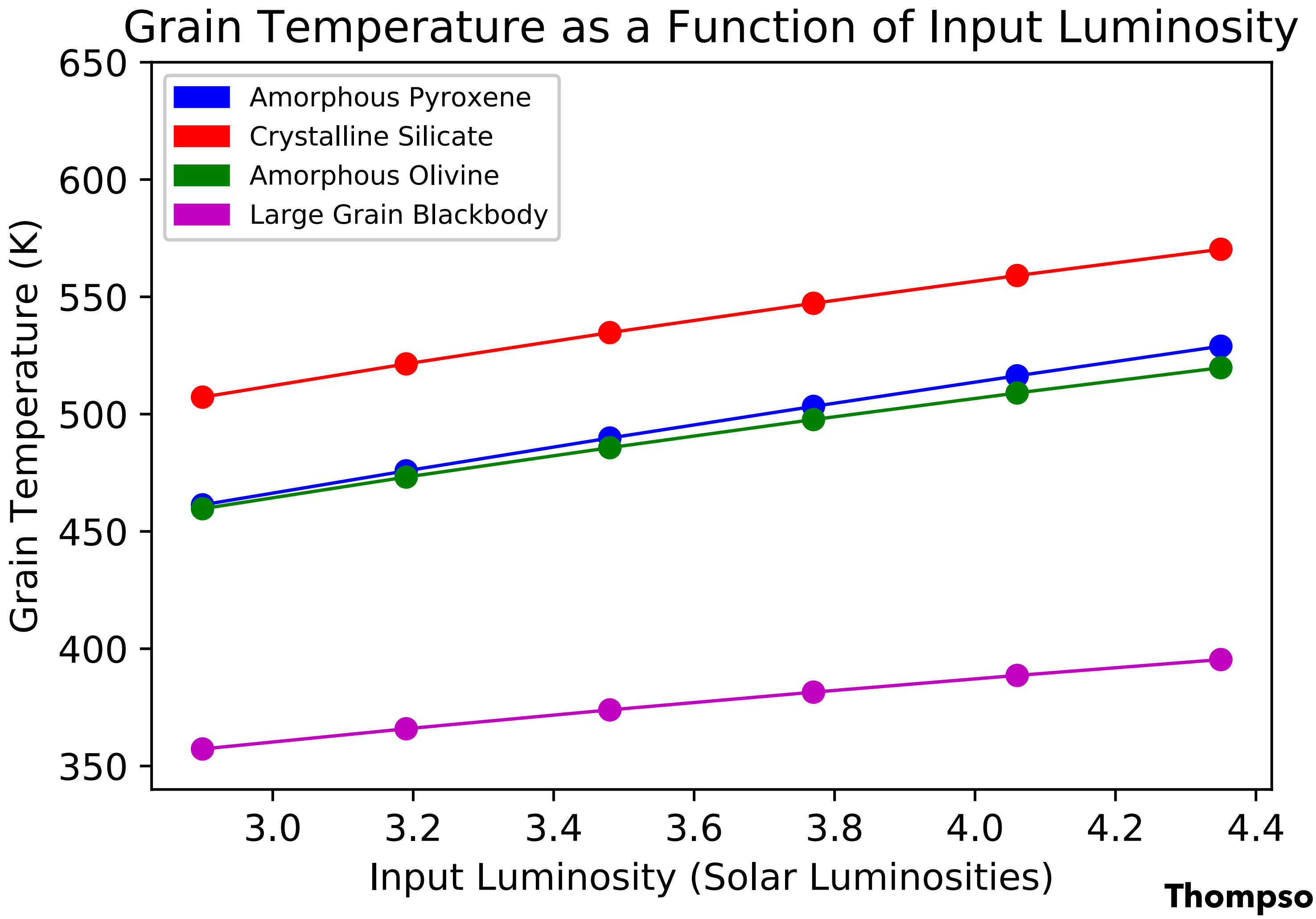


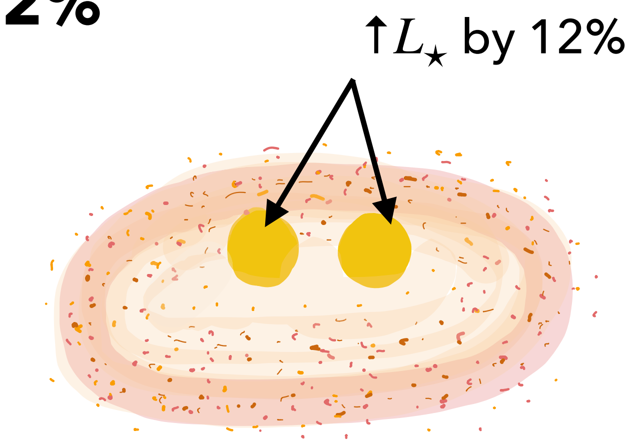
$$\beta = \frac{F_{Radiation\ Pressure}}{F_{Gravity}}$$

Thompson et al. 2019 & See Arnold et al. 2019

5(c). POSSIBLE EXPLANATIONS FOR FLUX INCREASE: INCREASING TEMPERATURE OF THE DUST (1)

- One way to increase the dust temperature is by increasing the stellar flux at wavelengths where dust absorbs strongly (UV-visible)
- To increase dust flux by 10% would need to increase dust temperature by ~3.5% which corresponds to a **stellar luminosity increase of 12%**





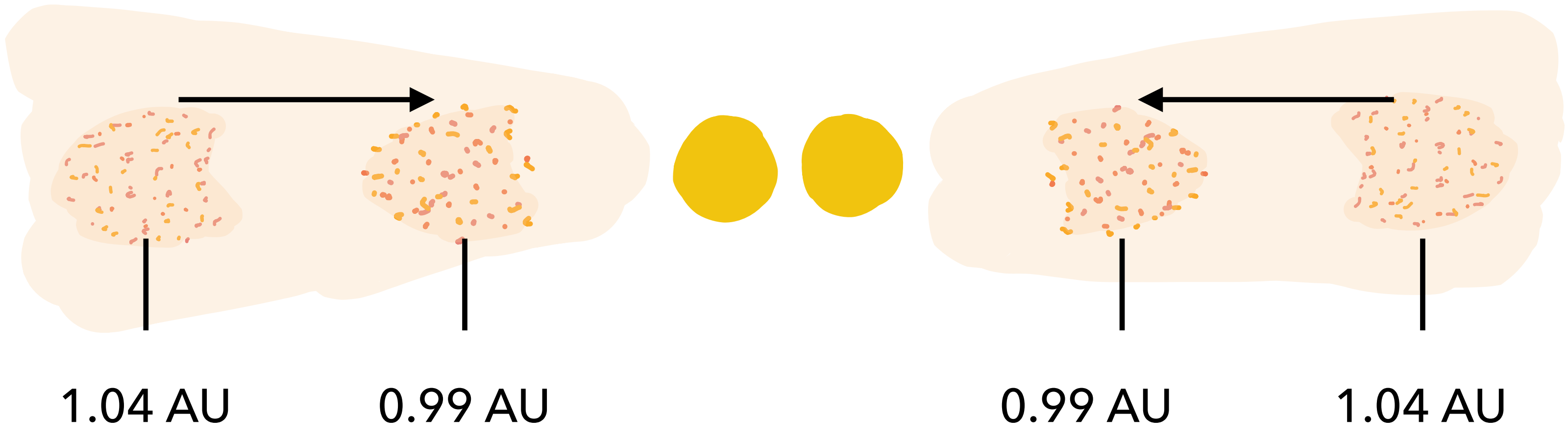
Increasing stellar luminosity by 12% causes dust temperatures to increase:

- Amorphous Pyroxene: 461 → 478 K
- Crystalline Silicate: 507 K → 524 K
- Amorphous Olivine: 459 K → 475 K

Thompson et al. 2019

5(c). POSSIBLE EXPLANATIONS FOR FLUX INCREASE: INCREASING TEMPERATURE OF THE DUST (2)

- Another way to increase the dust temperature is by moving the dust grains closer to the binary stars
- To increase the dust flux by 10% requires **moving the dust in by ~5% from 1.04 to 0.99 AU** which increases dust temperature by ~15 K
- Change in temperatures is similar among different grain compositions, so spectrum shape does not change much by such a temperature increase (< 2%) at short (<10.6 μm) relative to long (>10.6 μm) wavelengths
- Stellar wind induced by enhanced X-ray activity of a tidally-locked spectroscopic binary system could reduce timescale to drag dust in a few tenths of an AU to ~10 years, comparable to time between our observations

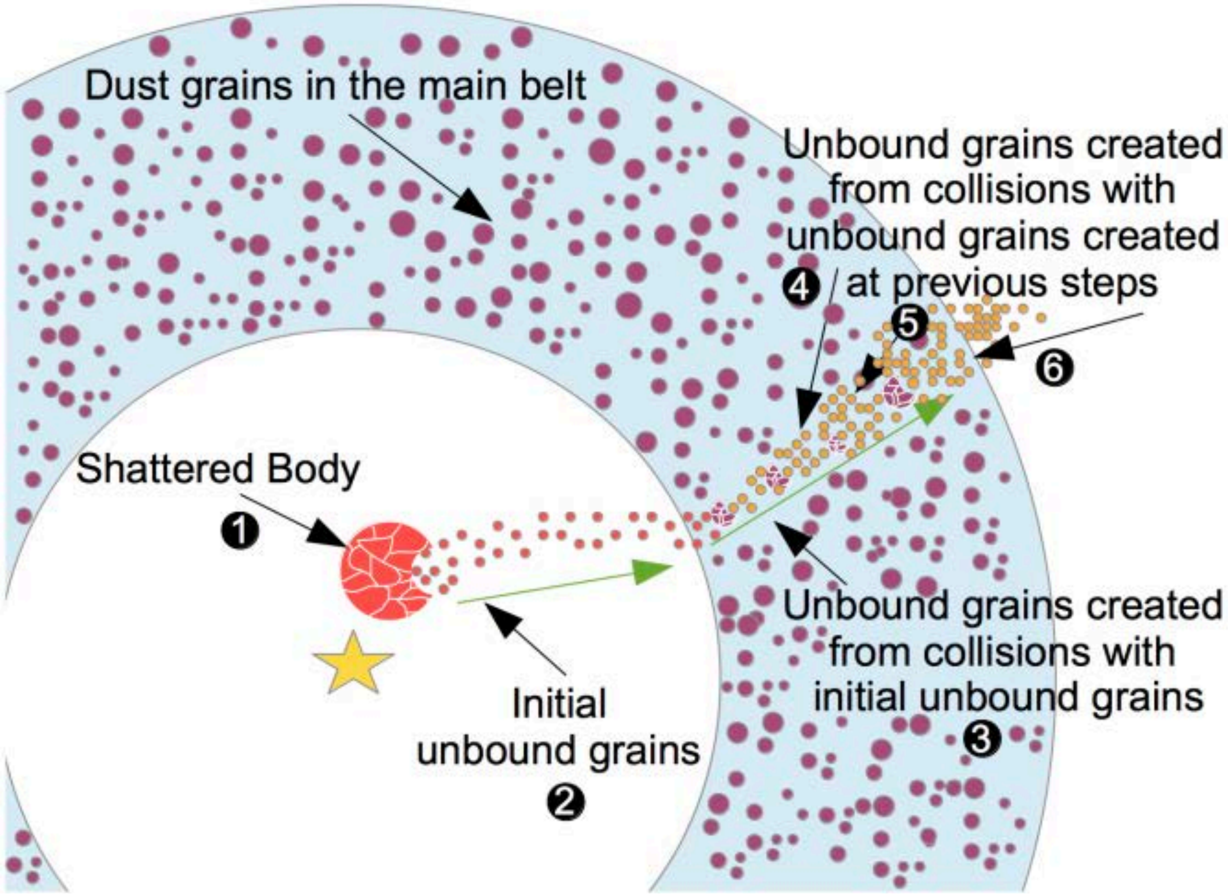


5(d). POSSIBLE EXPLANATIONS FOR FLUX INCREASE: CHANGE IN DISK SURFACE AREA VISIBLE TO OBSERVER

- To account for increased disk flux, it is possible that **disk's surface area visible to the observer increased either by production of more dust grains or a change in the optical depth**

- Total number of grains would need to increase by ~same fraction as the increase in flux

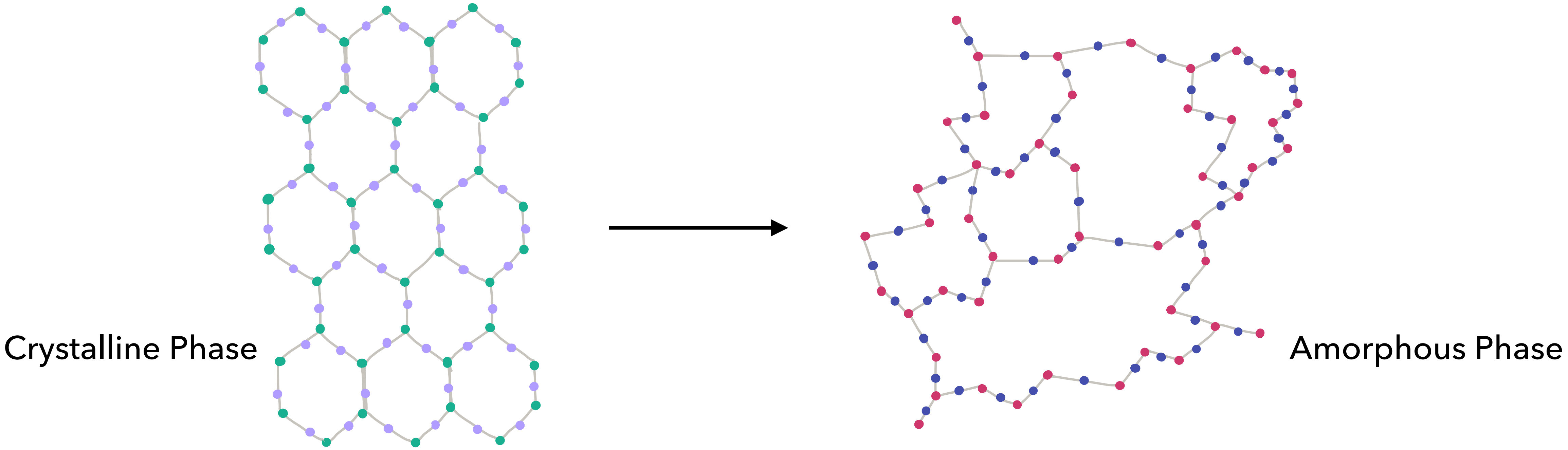
- Similar to "avalanche" type events considered in Grigorieva et al. 2007 and Thebault & Kral 2018 in which breakup of a large planetesimal happens in background of pre-existing disk of small particles, which triggers more collisions that increase the amount of small dust grains



Thebault & Kral 2018

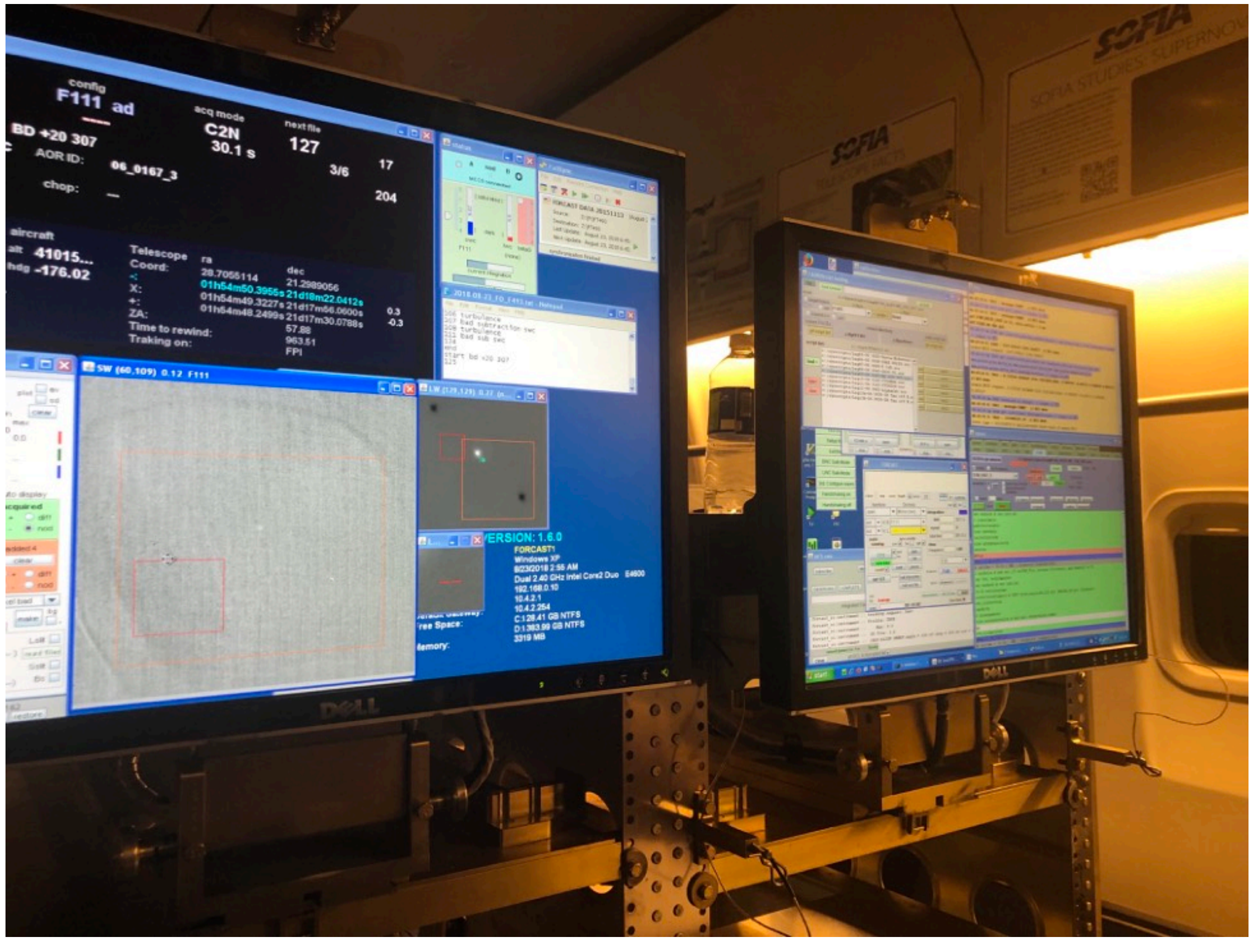
5(e). POSSIBLE EXPLANATIONS FOR FLUX INCREASE AT SHORTER WAVELENGTHS: CONVERTING FROM CRYSTALLINE TO AMORPHOUS PHASES

- The possible greater increase in flux at shorter (<10.6 μm) wavelengths suggests that the dust's silicate composition may have evolved during this short timescale
- Catastrophic collision can subject bodies to extremely high temperatures and pressures; if temperatures are high enough that grains reach their melting temperatures and they cool at a fast enough rate, then they can be quenched into a glass
- Conversion from crystalline to amorphous phase via *collisions* seems plausible and could explain the greater increase in flux at shorter wavelengths



6(a). RECENT SOFIA OBSERVATIONS

- In August and September of 2018, SOFIA's FORCAST re-observed BD +20 307 at both short (~11 μm) and **long (~23 μm) wavelengths**
- Guest observer on August 23 flight; 9 hours 51 minutes crisscrossing through western part of the U.S.



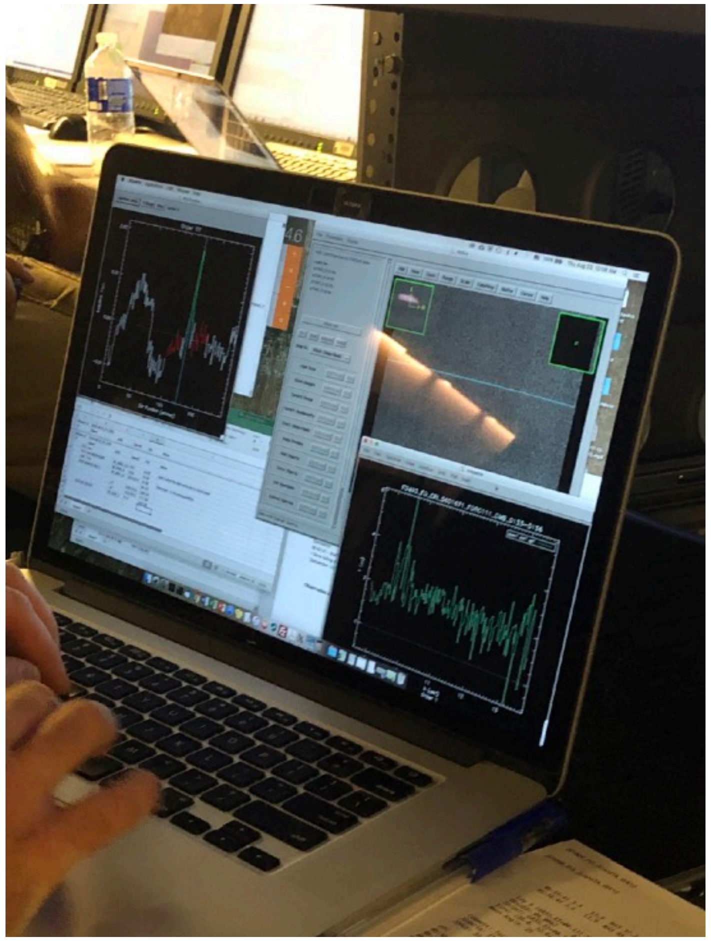
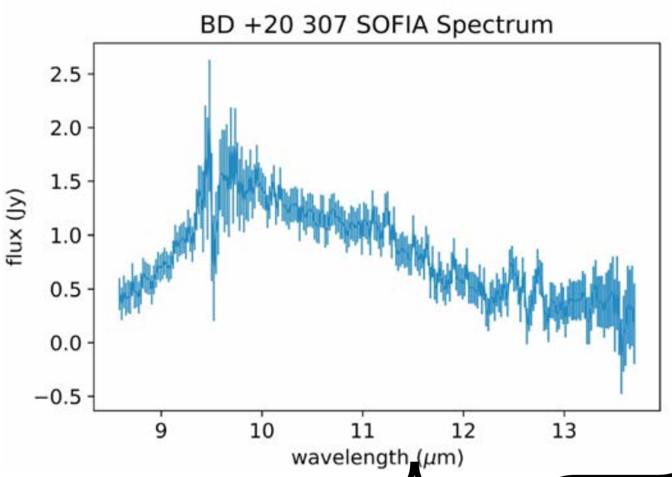


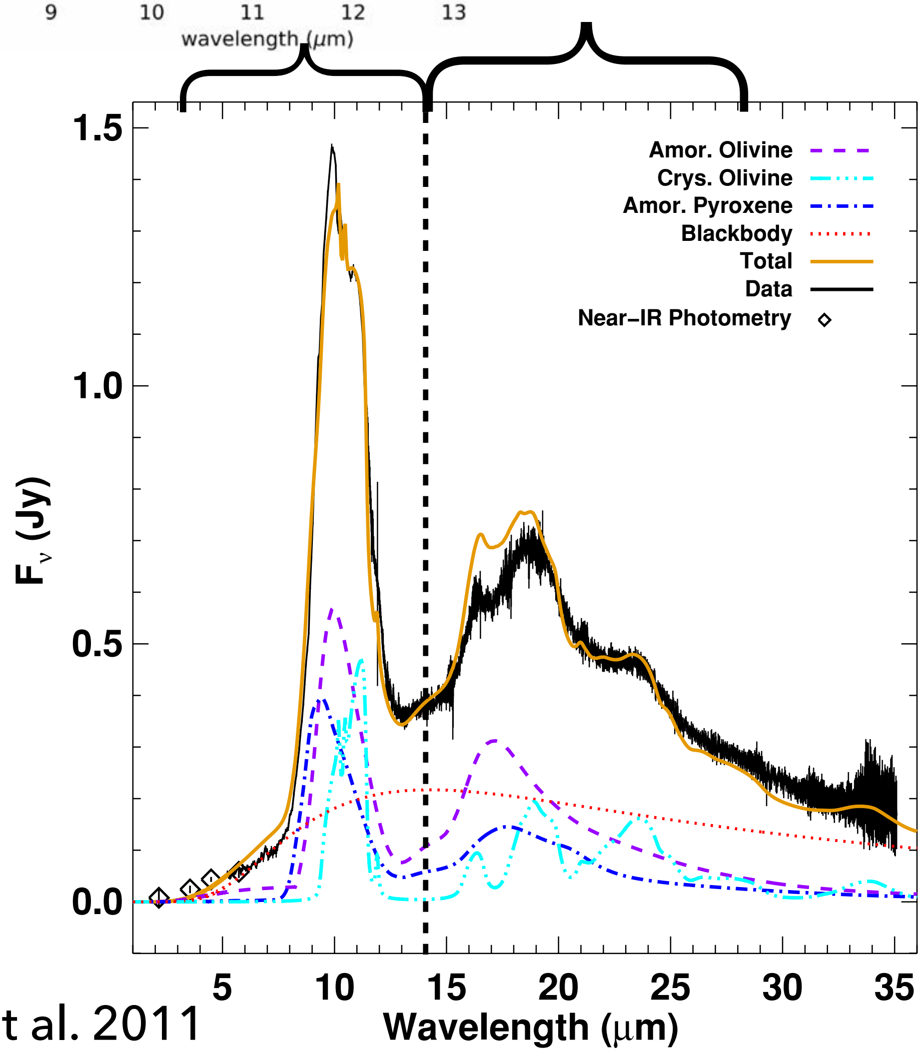
Image Credit: M. A. Thompson

6(b). FUTURE BD +20 307 DATA ANALYSIS

- ✓ New SOFIA observations covering longer wavelengths (~20 μm), giving a complete dataset of mid-IR spectroscopy and photometry for BD +20 307 over 14 years
- Obtaining longer wavelength data with SOFIA is essential because it is where the spectrum is more sensitive to changes in dust composition and grain size
- Fit composition models of the dust grains to wider wavelength range (as in Weinberger et al. 2011)



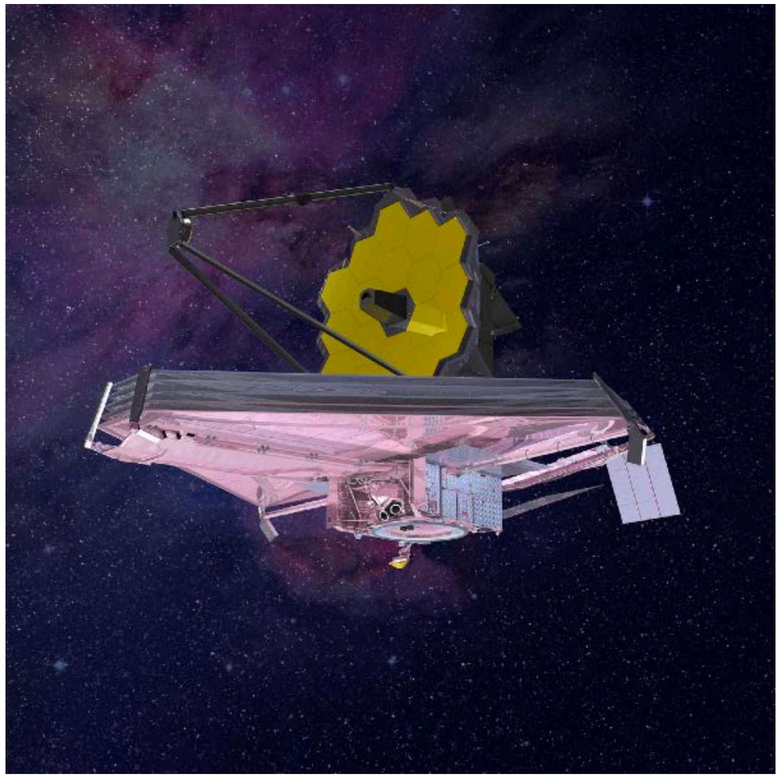
Analysis in progress…
stay tuned



Weinberger et al. 2011

6(c). FUTURE OBSERVATIONS WITH JWST'S MIRI

- In addition to analyzing BD +20 307 with SOFIA, JWST's MIRI (5-28 μm) instrument is suitable for follow-up observations
- JWST slated to launch in 2021; observing BD +20 307 with MIRI will allow us to continue our consistent monitoring of BD +20 307's dusty debris disk over last ~20 years



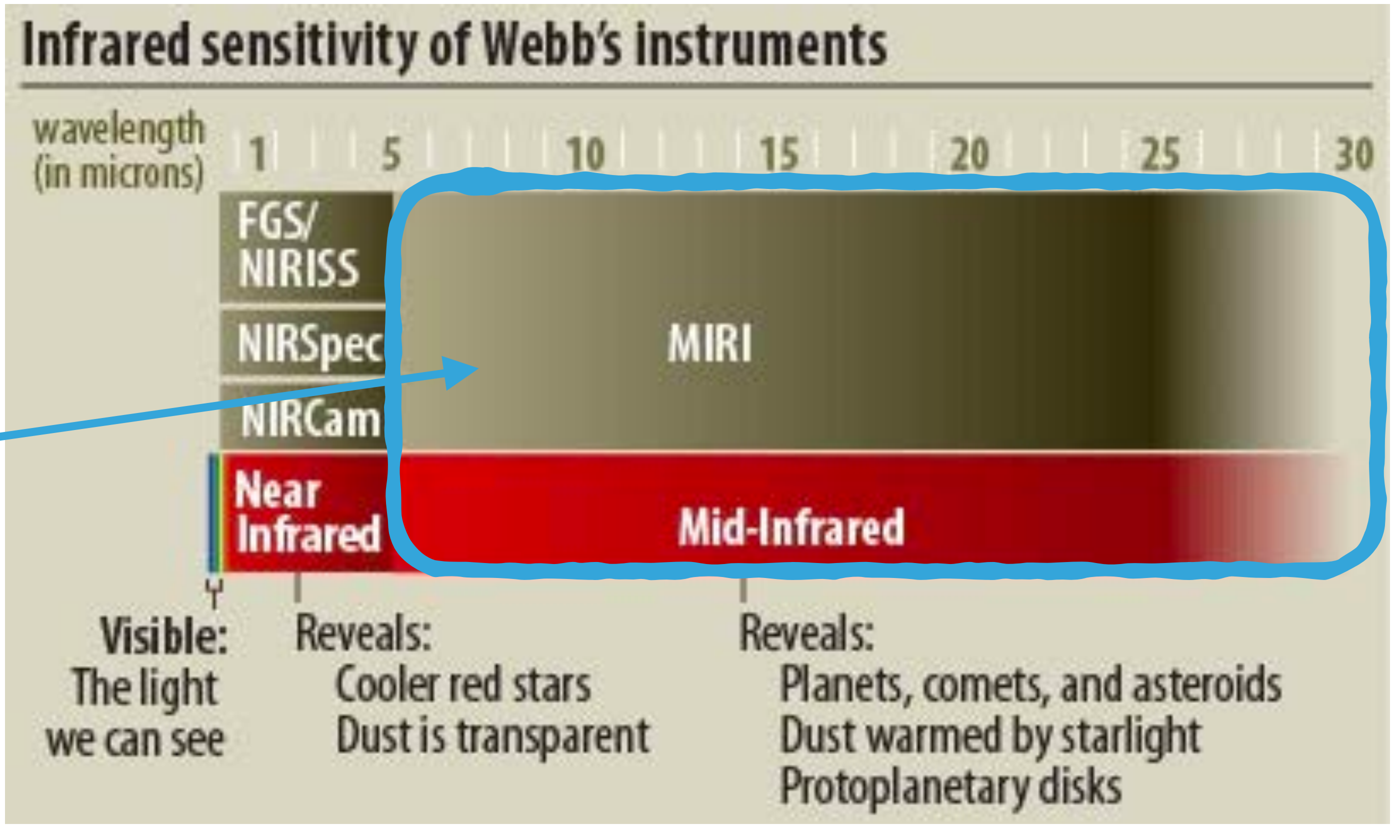
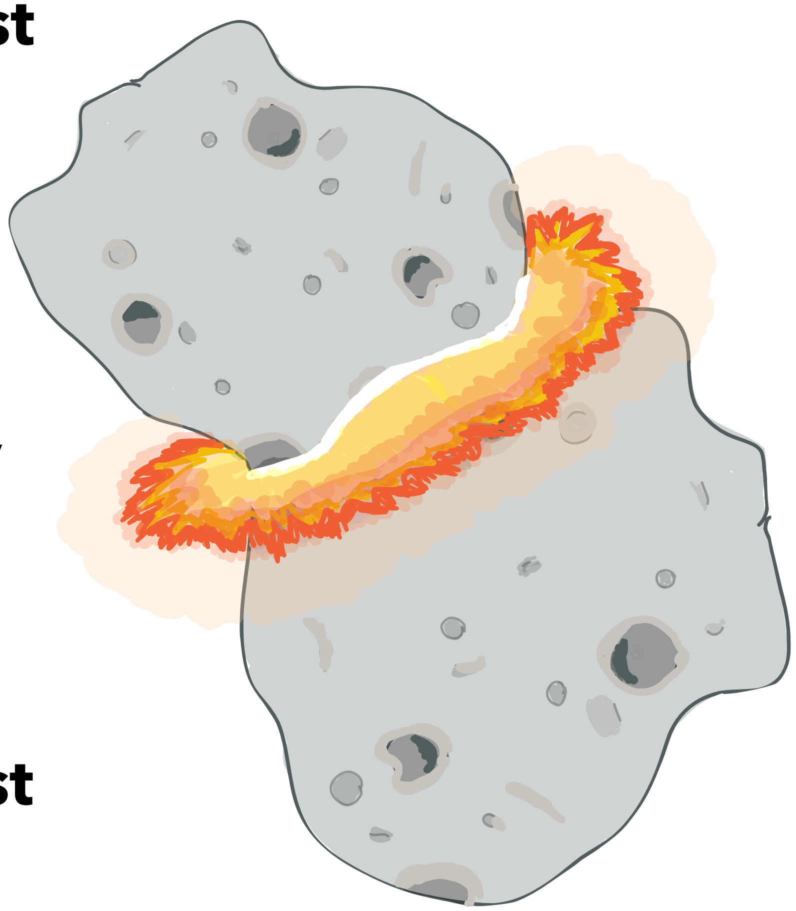


Image Credit: NASA

6(d). TAKE–HOME POINTS

- **Comparing SOFIA observations to data taken ~10 years earlier by Spitzer, Keck and Gemini, we detect a significant 10% increase in BD +20 307's dust flux between ~8.8-12.5 μm**

- **Suggested change in the shape of the spectrum with dust flux potentially increasing more at shorter (<10.6 μm) compared to longer wavelengths (>10.6 μm)**



- **Steady-state collisional cascade alone cannot explain these variations in BD +20 307's debris disk, particularly the *increase* in dust flux, over such short timescales**

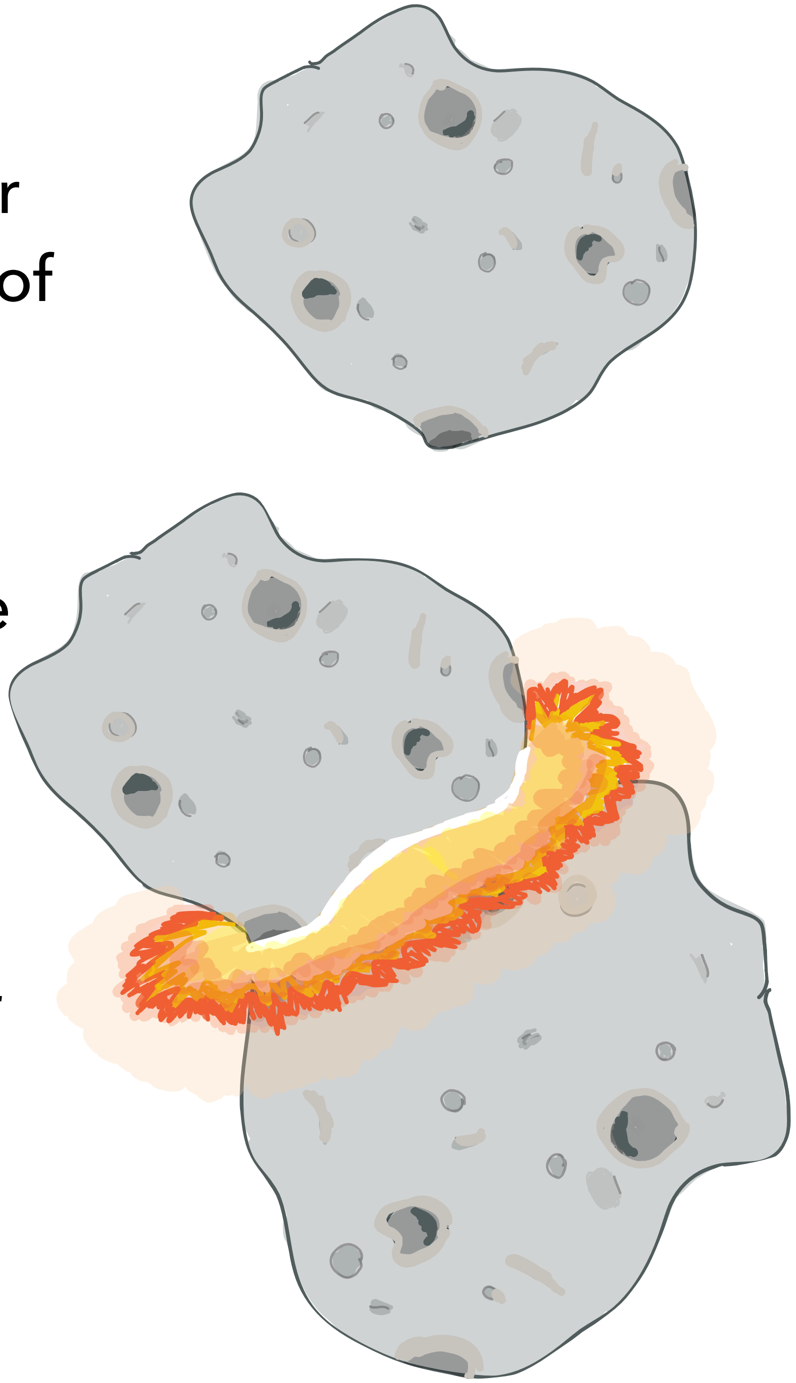
- **A catastrophic collision between planetary-scale bodies is still the most likely origin for the system's extreme dust**

6(e). CURRENT GRADUATE RESEARCH: METEORITE OUTGASSING EXPERIMENTS (1)

- When analyzing debris disks outside those in our own Solar System, we idealize the objects within those disks in terms of their compositions, shapes and sizes

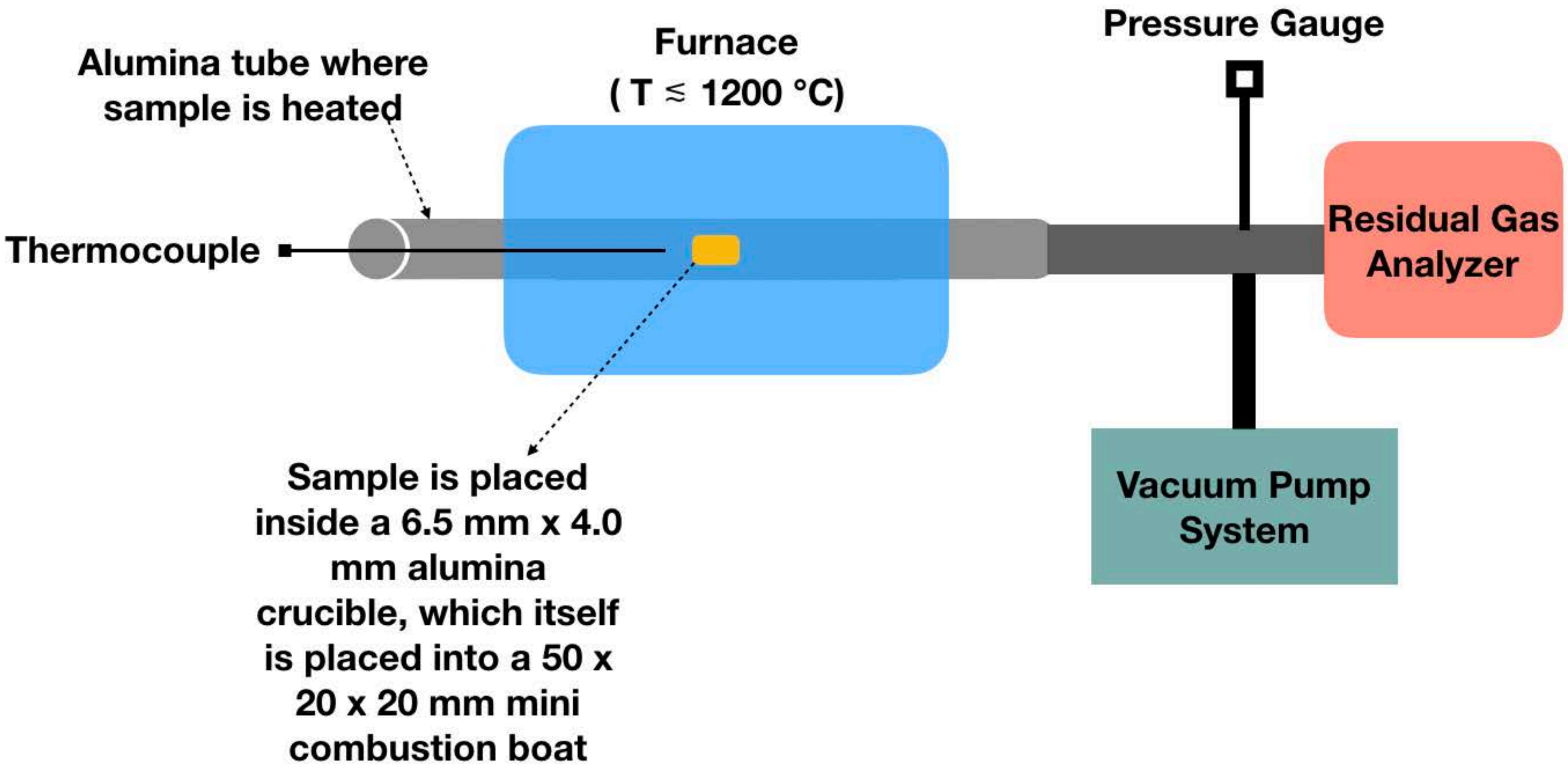
- However, as evidenced by meteorites found on Earth and asteroids and comets in our Solar System, these objects are extremely complex

- Understanding how meteorites evolve during thermal heating events will help us better understand the resulting environments from planetesimal collisions and the types of initial outgassed atmospheres expected for terrestrial-size planets



6(e). CURRENT GRADUATE RESEARCH: METEORITE OUTGASSING EXPERIMENTS (2)

- Currently conducting heating experiments with various chondritic meteorite samples to measure the composition of outgassed volatiles (e.g., H_2O, CO_2, CH_4, N) as a function of temperature (25 - 1200 °C) and time
- Heat powdered meteorite samples in an enclosed vacuum system and measure the resulting abundances of outgassed volatiles using a mass spectrometer



Alumina tube where sample is heated

Furnace (T ≲ 1200 °C)

Pressure Gauge

Thermocouple

Residual Gas Analyzer

Vacuum Pump System

Sample is placed inside a 6.5 mm x 4.0 mm alumina crucible, which itself is placed into a 50 x 20 x 20 mm mini combustion boat

Thompson et al. 2019b (in prep)

6(d). TAKE-HOME POINTS

- **Comparing SOFIA observations to data taken ~10 years earlier by Spitzer, Keck and Gemini, we detect a significant 10% increase in BD +20 307's dust flux between ~8.8-12.5 μm**
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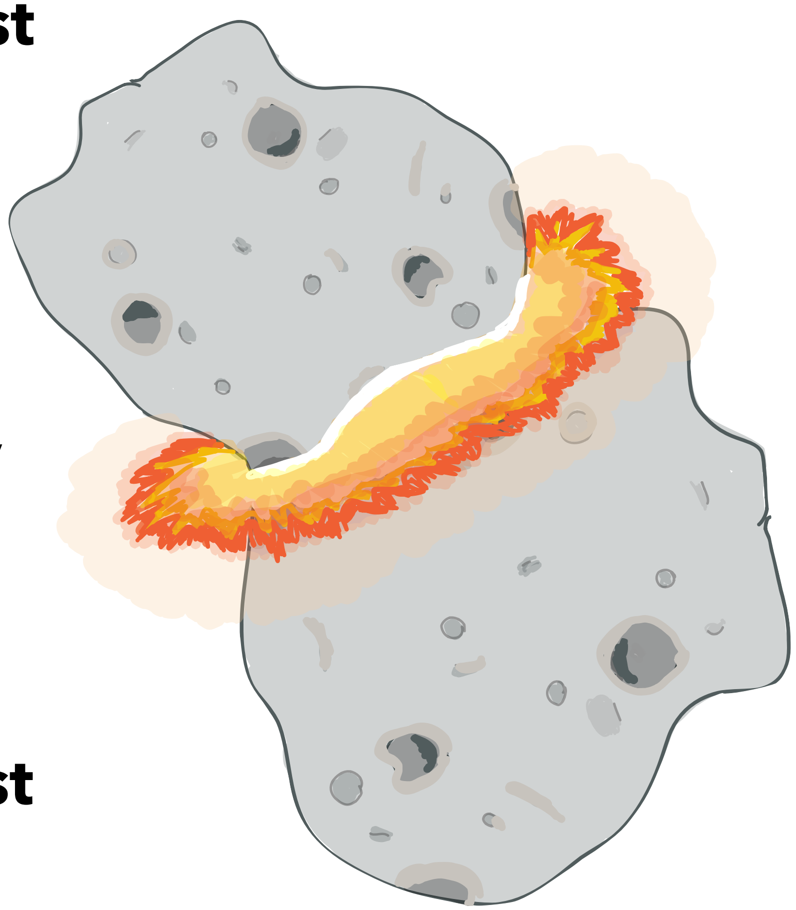


7 (EXTRA). STELLAR ACTIVITY OF BD +20 307?

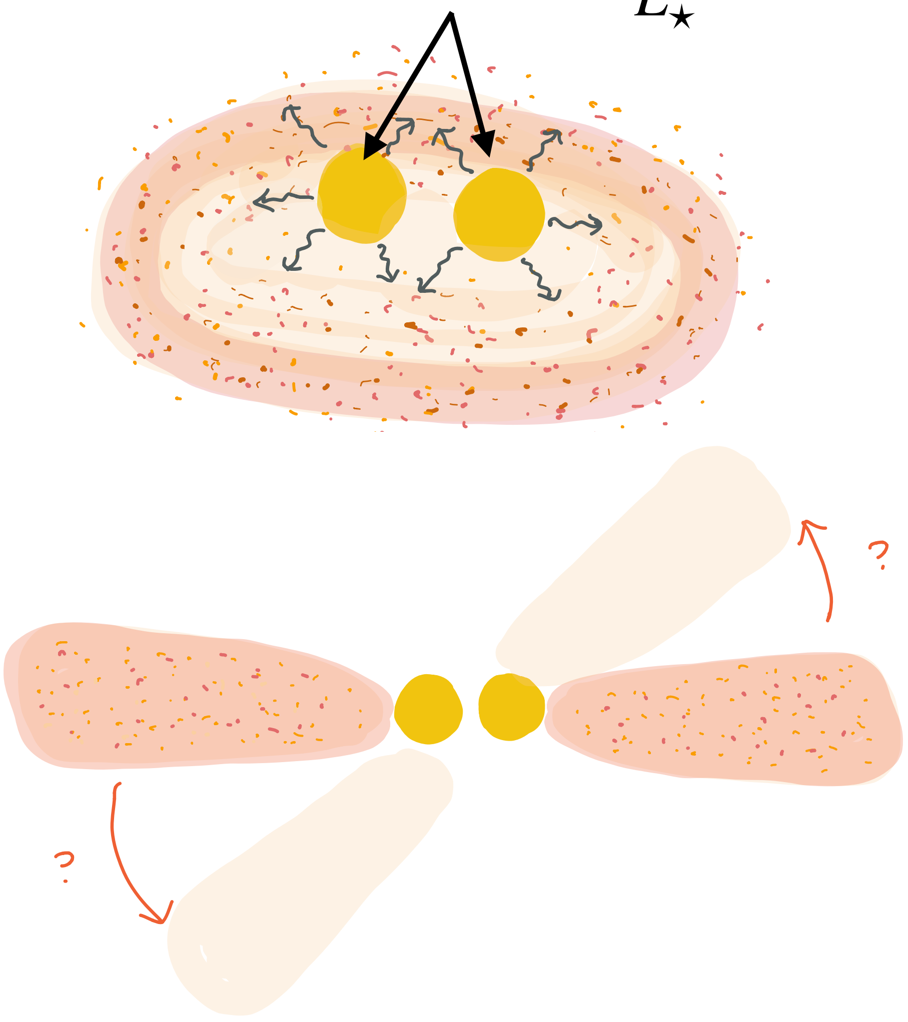
- F-type binary stars can be variable, and their activity is believed to decrease with age

- BD +20 307 is not known for certain to be variable, but once *Gaia* gathers all its data, can check for stellar variability of BD +20 307

- Zuckerman et al. 2008 found BD +20 307's X-ray flux from 0.5-2.0 keV to be: $1.1 \times 10^{-13} erg\ cm^{-2}\ s^{-1}$ which alone cannot cause a ~10% increase in stellar luminosity

- If disk is misaligned with respect to the stellar orbital plane and is precessing on short timescales (~years), dust may heat up when exposed to stellar hotspots

- For Sun-like stars, X-ray activity and winds are likely correlated, so if BD +20 307 has enhanced X-ray activity that may produce a significant stellar wind



F-type binary stars

Fractional X-ray luminosity is $\frac{L_X}{L_\star} = 1.6 \times 10^{-5}$