Characterizing Gas and Dust Debris in Exoplanetary Systems Using SOFIA-HIRMES

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On behalf of the HIRMES Team

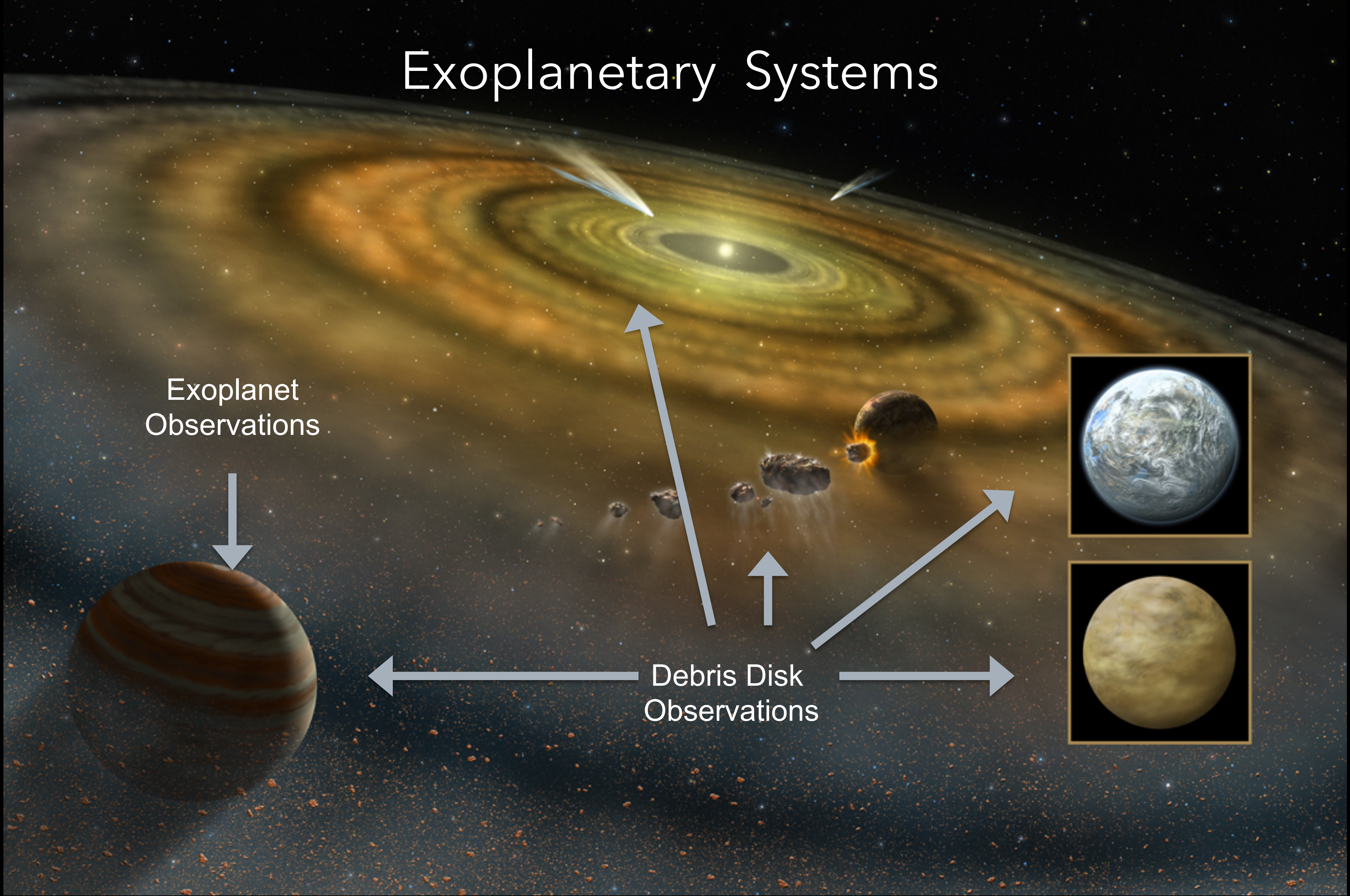
SOFIA Tele-Talk 02-05-2020

HIRMES Talk Schedule

FY2020 HIRMES Tele-Talks		
Instrument Overview	4 December	Matt Greenhouse
Protoplanetary Disks	11 December	Klaus Pontoppidan
Comets	15 January	Stefanie Milam
Deuterium in Giant Planets	29 January	Gordon Bjoraker
Debris Disks	5 February	Christine Chen
Protostellar Outflows	12 February	Dan Watson

The slides for past talks are archived on the SOFIA Tele Talk website

Exoplanetary Systems

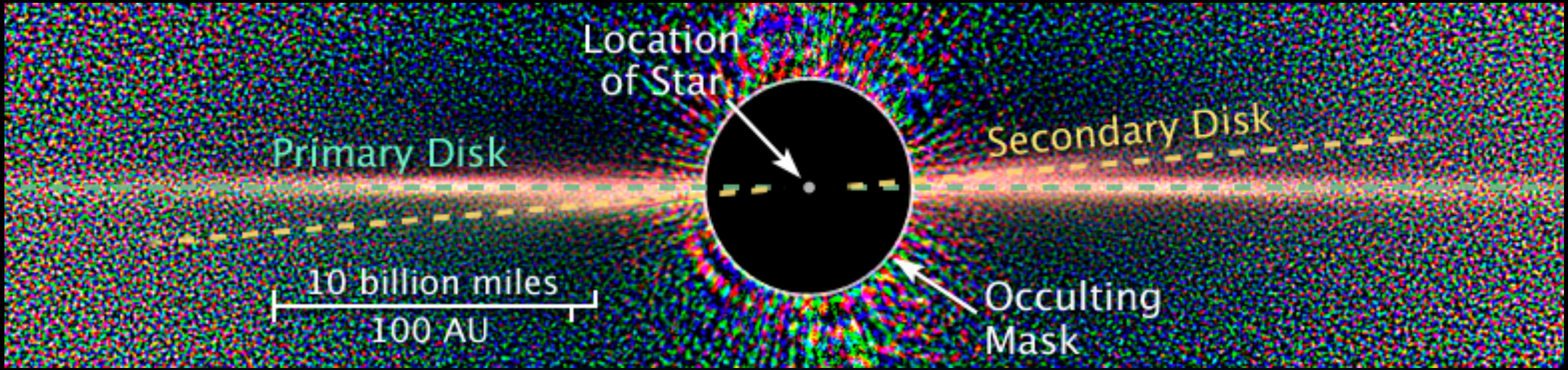


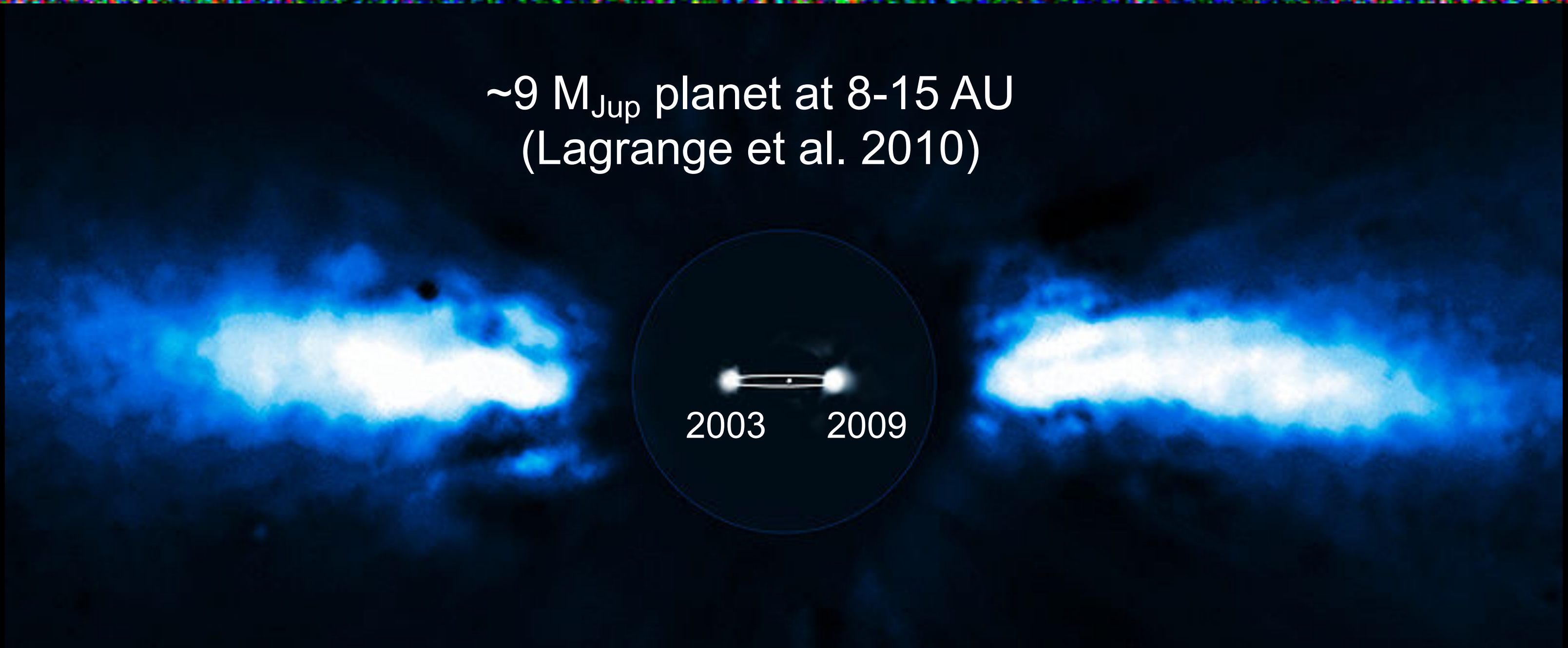
Outline

- The Planet Disk Connection
- HIRMES Legacy Science
  - A Detailed Study of beta Pictoris
  - O I Reconnaissance
  - Water Ice Reconnaissance

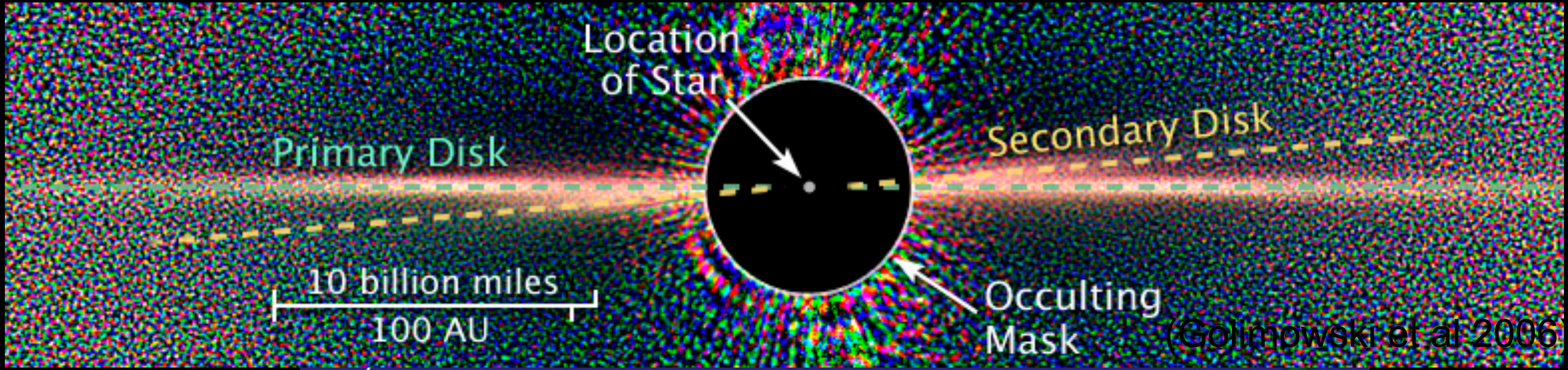
Reconstructing the β Pictoris Planetary System

Extended disk of small grains up to ~1400 AU from the star (Golimowski et al. 2006)



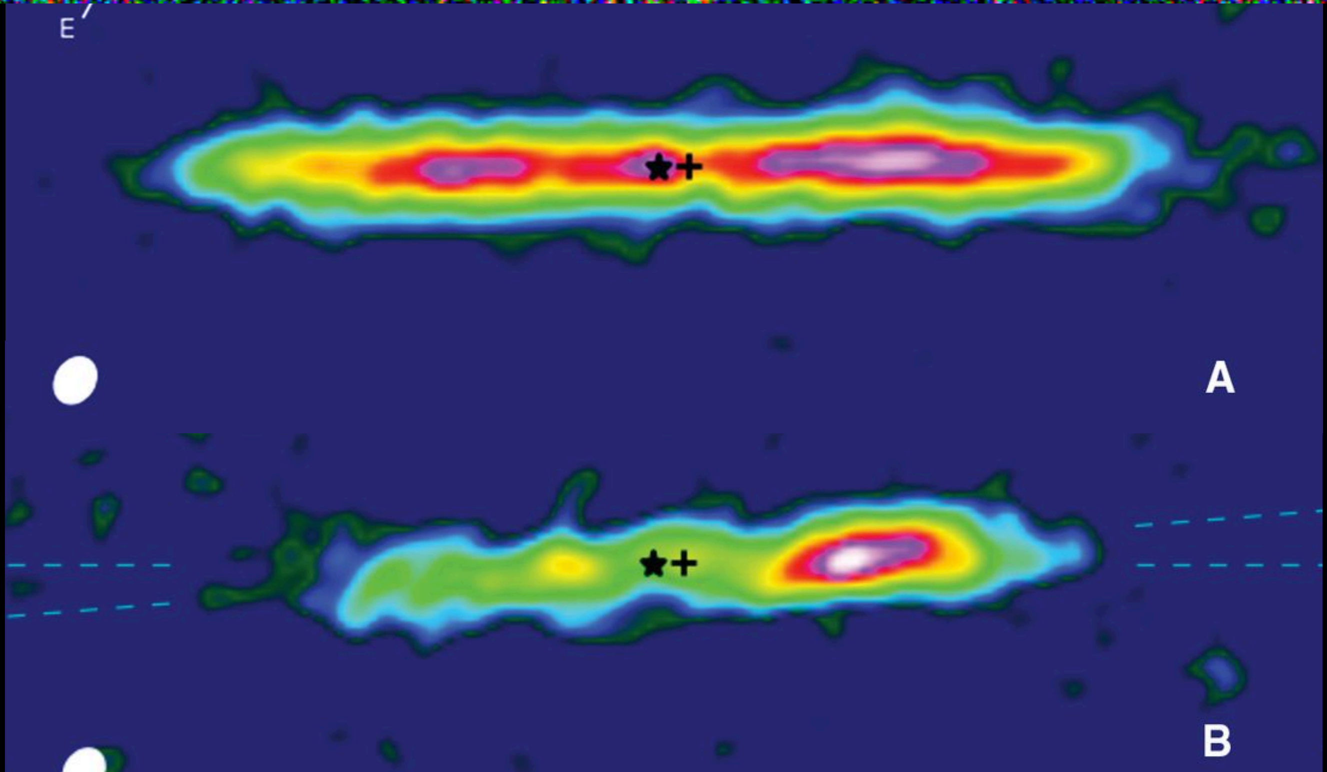


Reconstructing the β Pictoris Planetary System

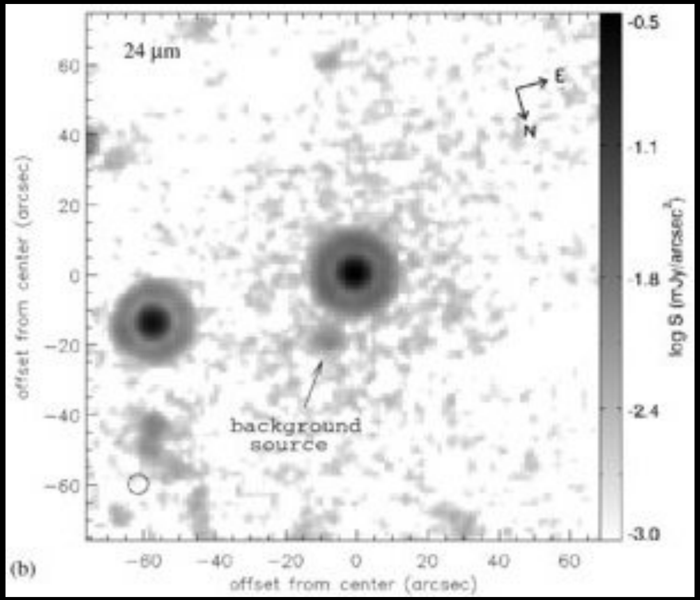


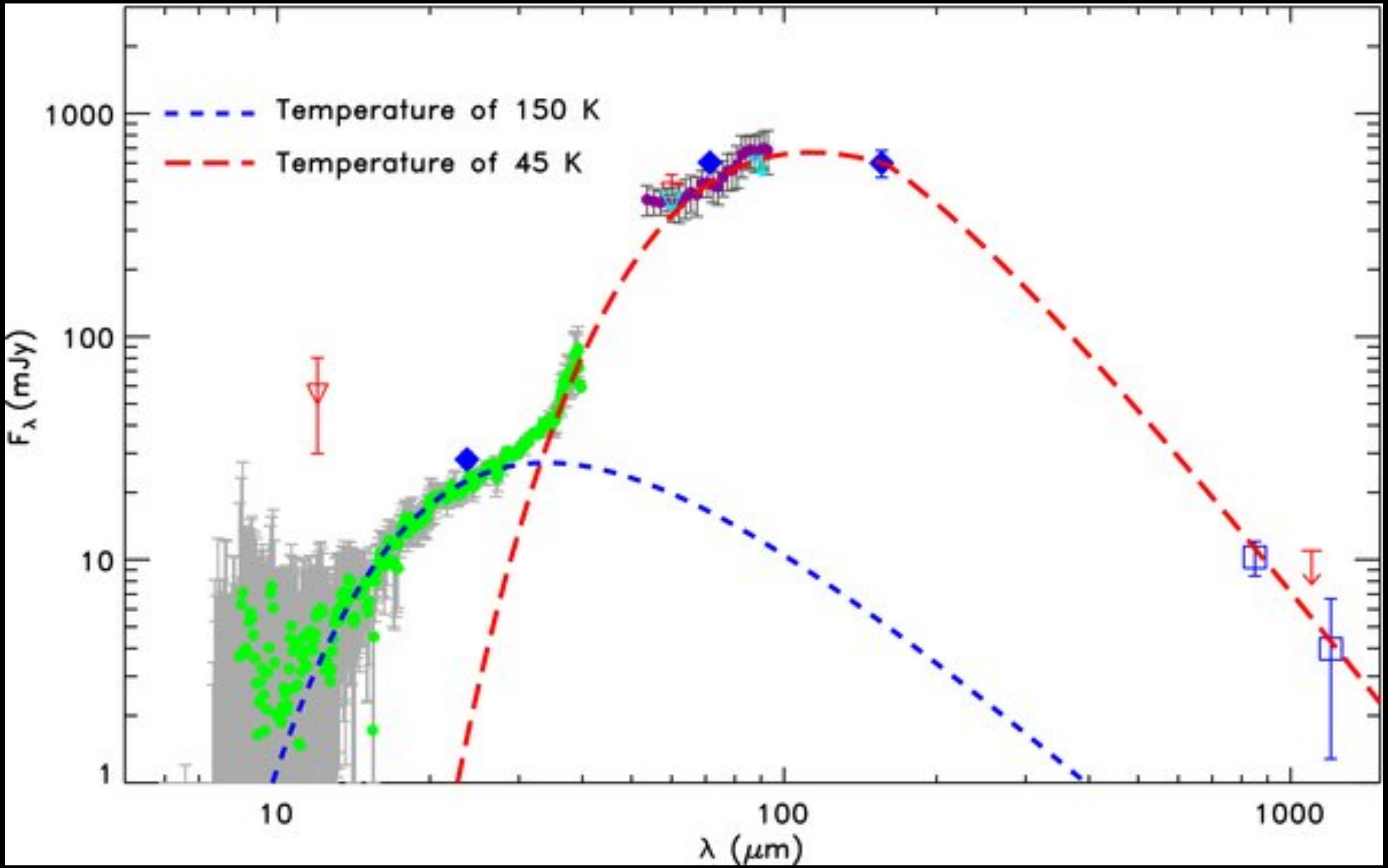
Ring of large grains at 95 AU (Dent et al. 2014)

Clump of comets at 50 -60 AU (Dent et al. 2014



Reconstructing the HR 8799 Planetary System



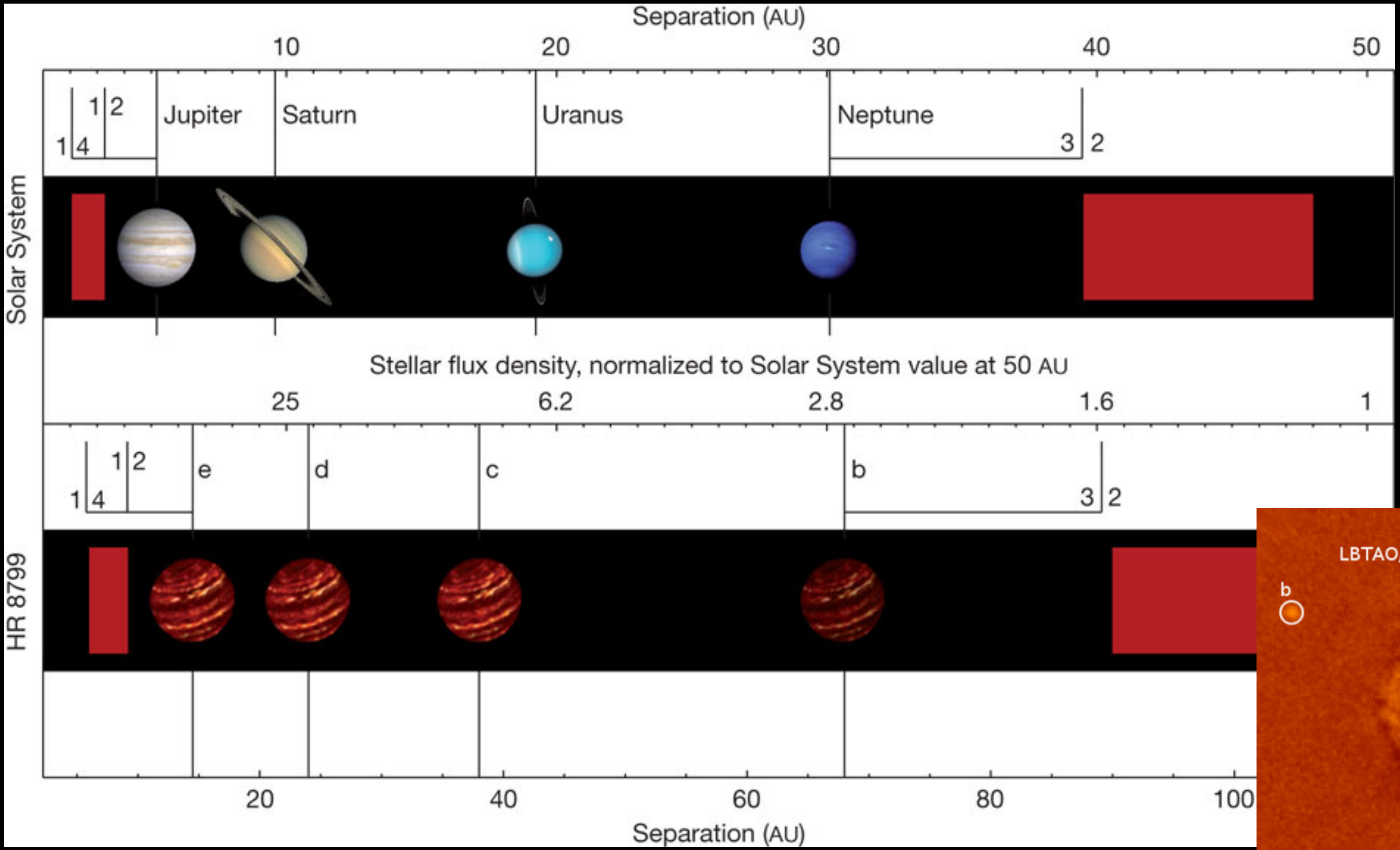


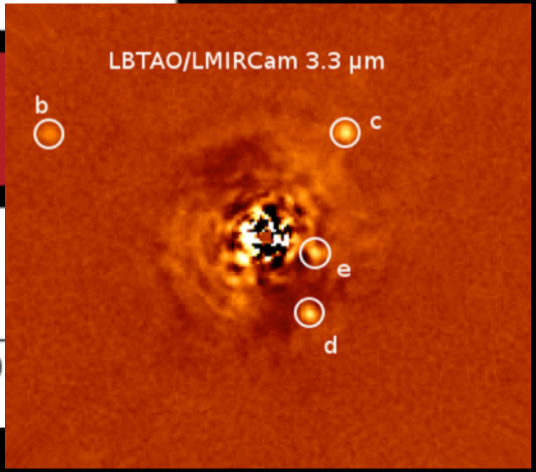
SED fitting suggests that this system has two dust components, analogous to the asteroid and Kuiper belts in our Solar System

Su et al. (2009)

Reconstructing the HR 8799 Planetary System

(Marois et al. 2010)





(Skemer et al. 2012)

Spectral Energy Distribution analysis shows two dust populations which may be separated by planets

Late Stages of Planet Formation

Terrestrial Planet Formation

Giant Impacts including Moon Formation and Late Patina

30-100 Myr

Formation of km-sized bodies

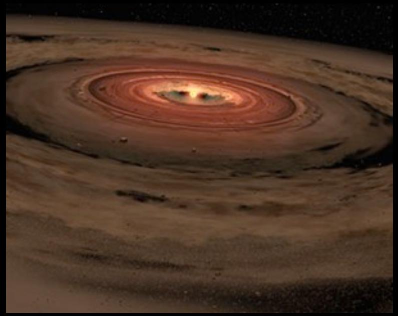
~few Myr

Oligarchic Growth

time

1-3 Myr

Core Formation

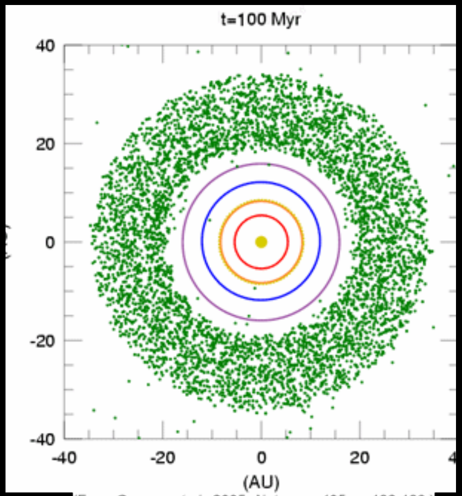


10-30 M

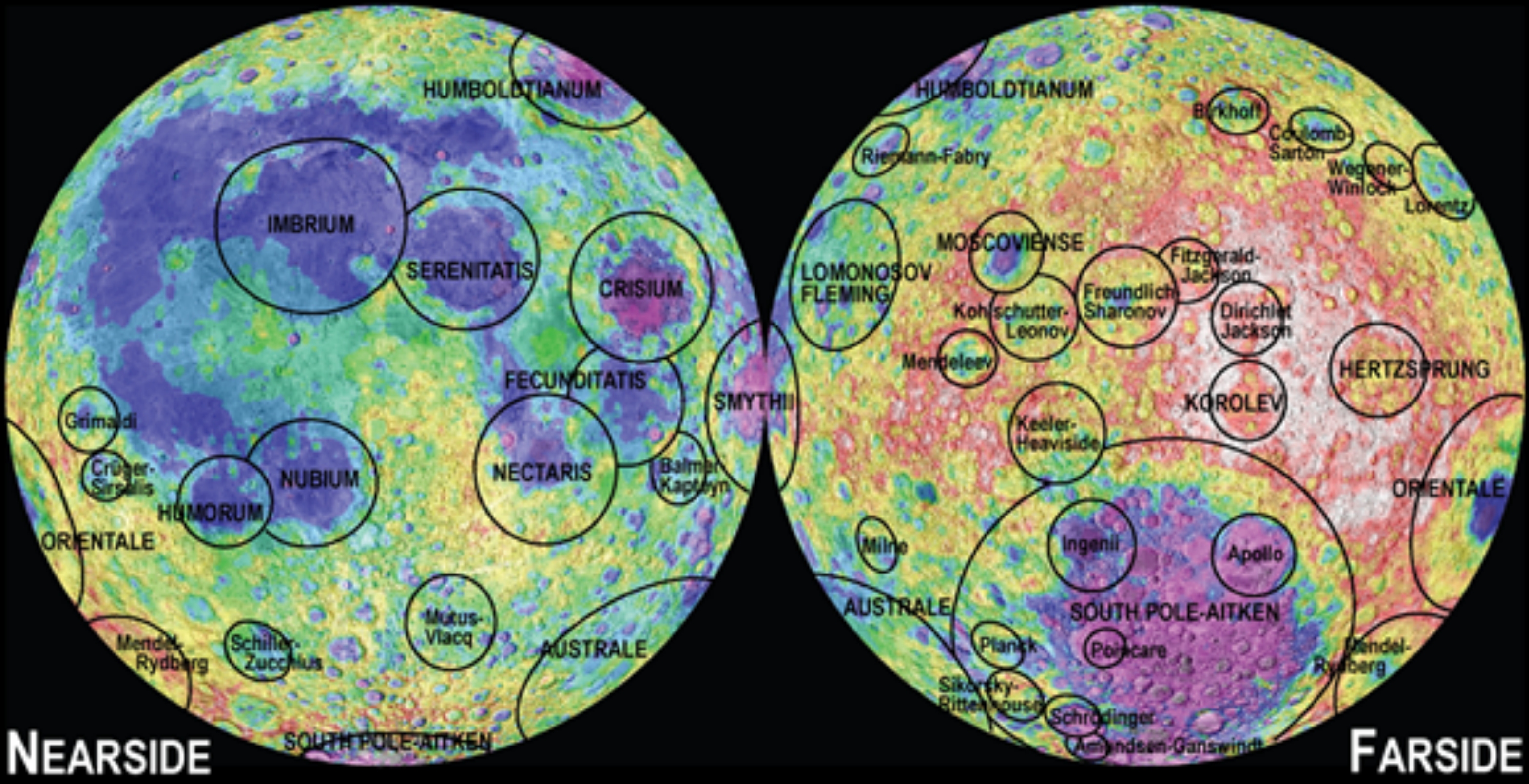
Envelope Accretion

Giant Planet Formation

Stochastic Processes: Giant Planet Formation and Migration in Our Solar System

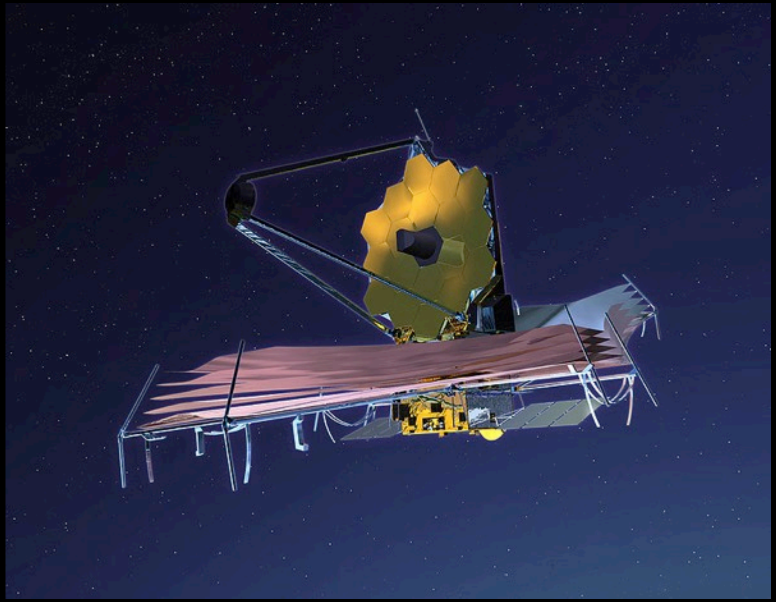


(From Gomes, *et al.*, 2005, *Nature*, v. 435, p. 466-469.)



- The moon and terrestrial planets were resurfaced during a short period (20-200 Myr) of intense impact cratering 3.85 Ga called the Late Heavy Bombardment (LHB)
- Apollo collected lunar impact melts suggest that the planetary impactors had a composition similar to asteroids
- Size distribution of main belt asteroids is virtually identical to that inferred for lunar highlands
- Formation and subsequent migration of giant planets may have caused orbital instabilities of asteroids as gravitational resonances swept through the asteroid belt, scattering asteroids into the terrestrial planets.

Tracing Thermal Emission from Dust and Gas…



ALMA

- Spatially resolved imaging of planetesimal birth rings
- Discovery of CO gas toward 17 dusty, young systems and C I toward a smaller subset

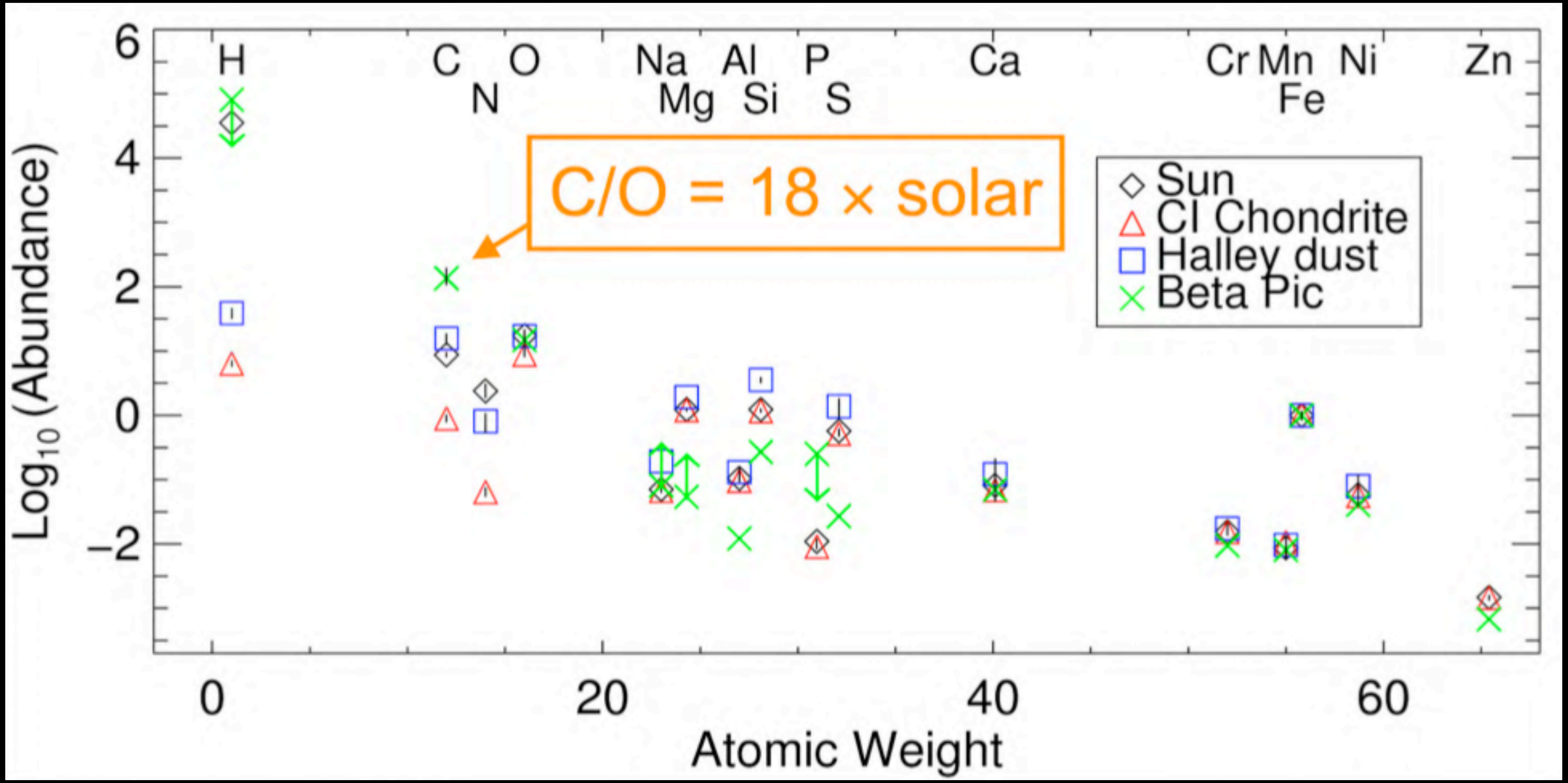
HIRMES

- Will enable **low resolution (R~600)** spectroscopic characterization (25-122 μm) encompassing water ice
- Will enable **high resolution (R~100,000)** spectroscopic characterization (25-122 μm) encompassing O I, H_2O, OH

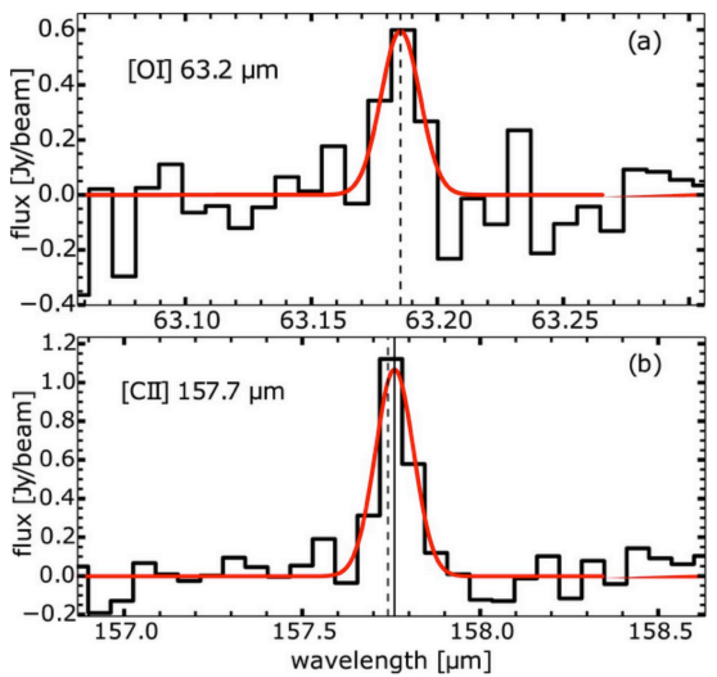
JWST

- Will enable spatially resolved mid-infrared imaging
- Will enable spatially resolved near- and mid-infrared (R~3,000, 1-28 μm) spectroscopy of silicates and fine structure lines

β Pictoris: Previous Observations of Gas



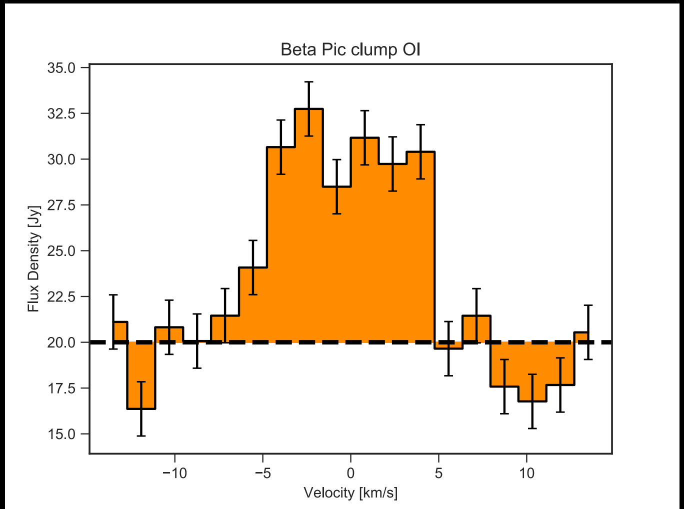
Roberge et al. (2006)

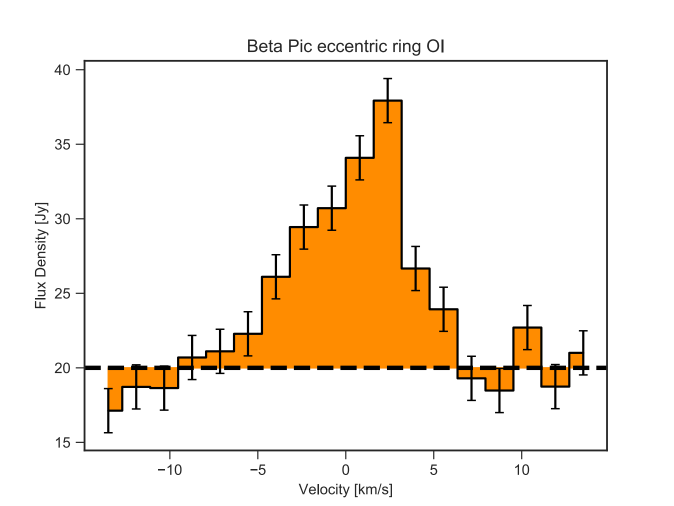


Brandeker et al. (2016)

- In addition to CO, 15 atoms have been detected in absorption and/or emission
- If the gas is produced as part of the collisional cascade, then the gas abundance may reflect the underlying parent body abundance

β Pictoris: Tracing Gas Kinematics using HIRMES





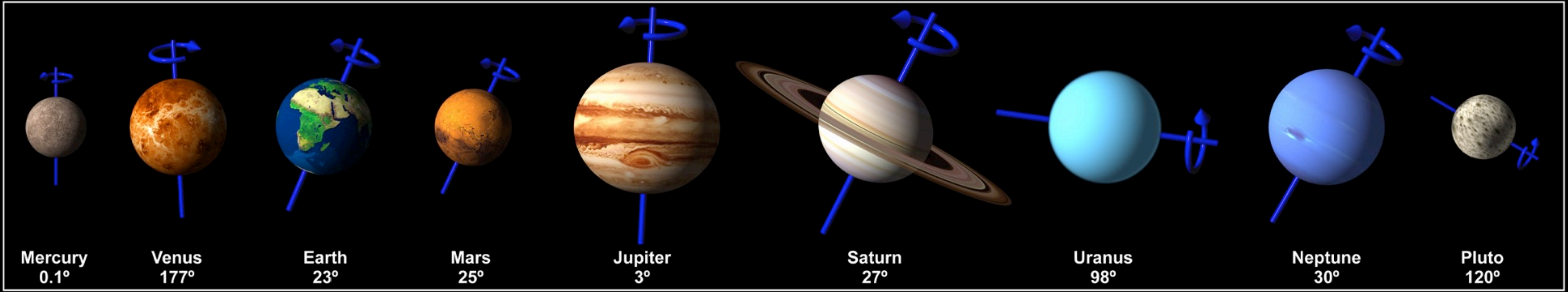
What is the origin of the ALMA gas clump (observed in CO and C I)?

1. An unseen second planet in the system is trapping icy parent bodies into a mean motion resonance that facilitates collisions, liberating icy particles.

2. A giant collision

The shape of the O I line profile may be able to distinguish between these two possibilities.

Giant Collisions in the Outer Solar System



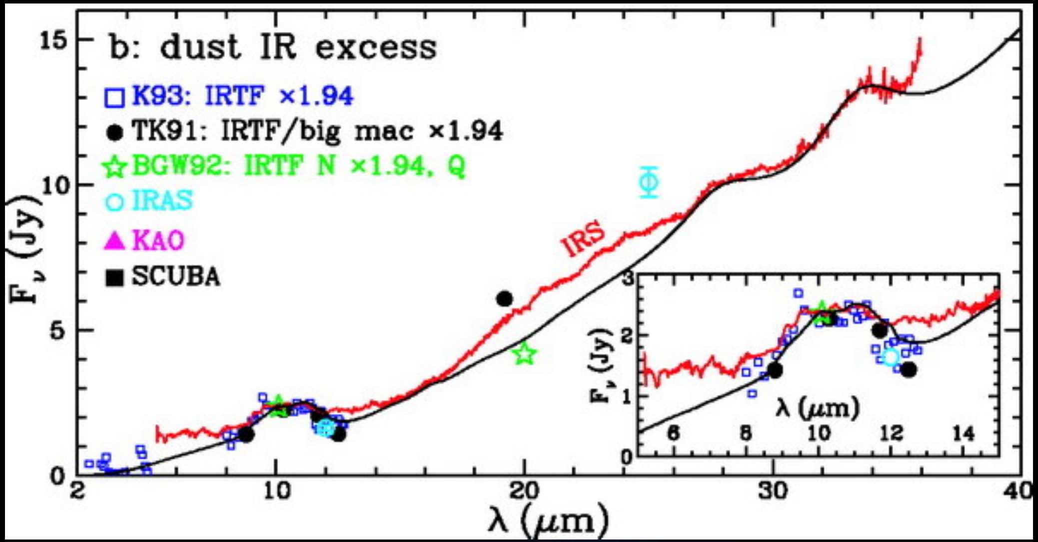
Obliquity of the Nine Planets

- Reproducing the the obliquities of Uranus and Neptune is challenging for simulations of Solar System formation
- N-body numerical simulations suggest that Uranus and Neptune's obliquities and mass ratio could have been produced by giant collisions, assuming 5-10 planetary embryos with initial masses of ~3-6 $M_{\oplus}$ (Izidoro et al. 2015)

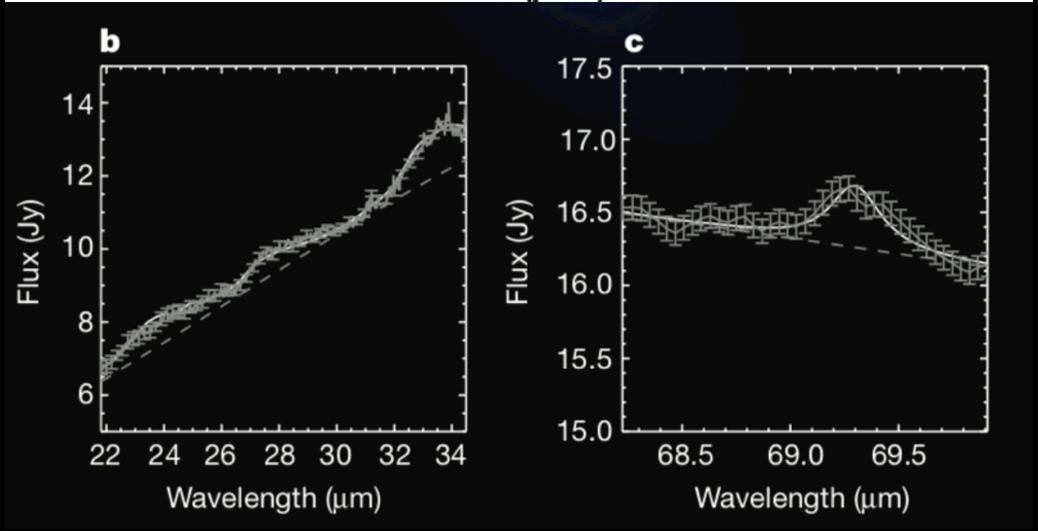
β Pictoris: Previous Solid-State Spectroscopy

- Spitzer IRS detected 10, 20, and 30 μm silicate emission features, modeled assuming amorphous cometary and crystalline olivine fluffy aggregate (P=0.90)
- Herschel PACS detected the 69 μm forsterite feature. It's peak position suggests that the material is Mg-rich (x=0.01±0.001)
- No ice features have been detected to date

Chen et al. (2007)

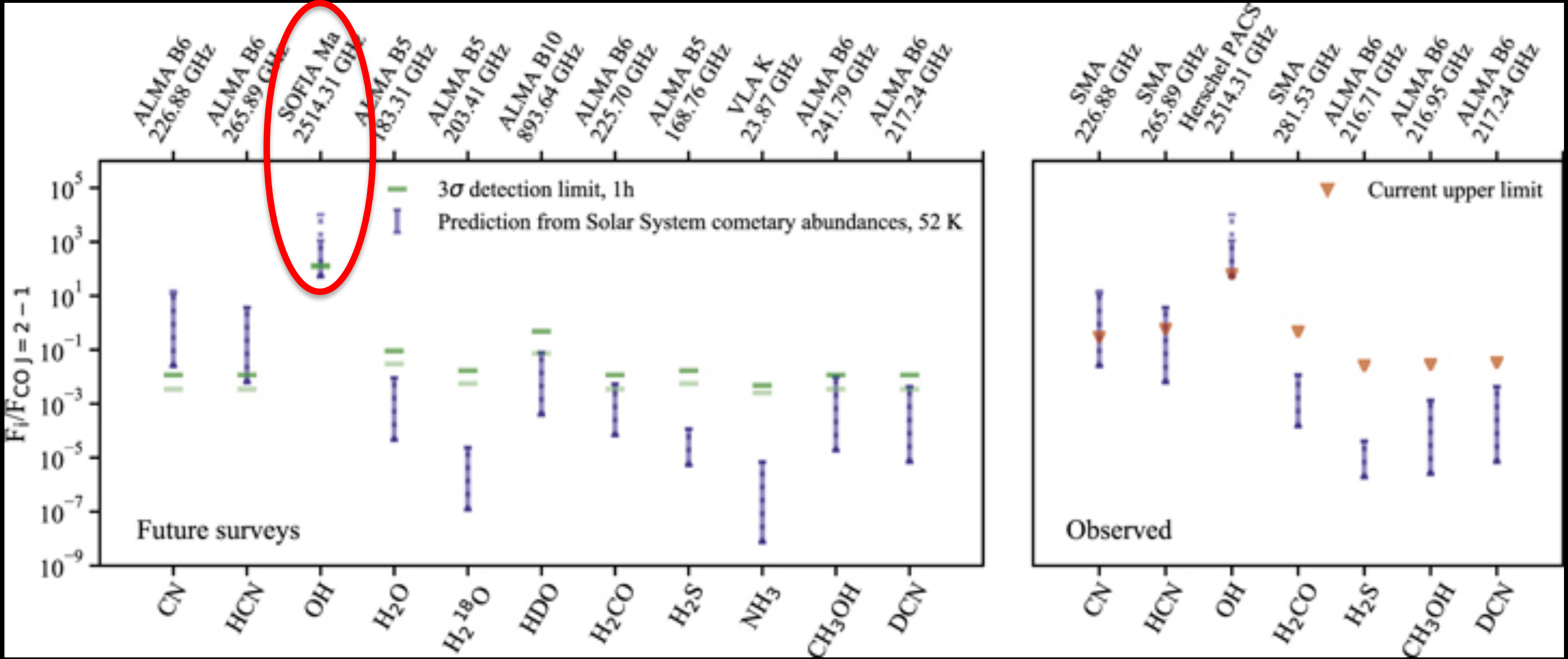


De Vries et al. (2012)



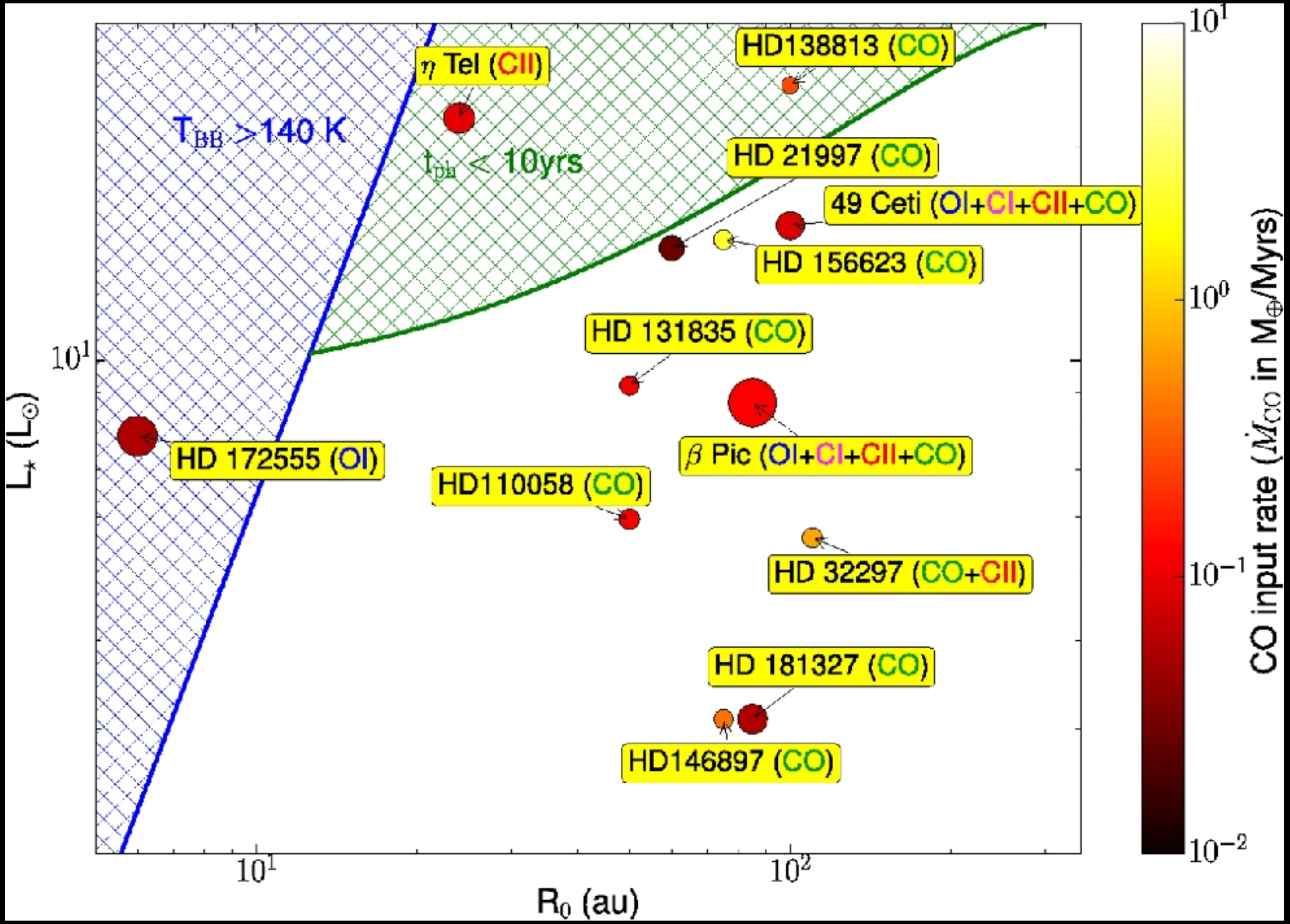
β Pictoris: Constraining OH Abundance

Matra et al. (2018)



- If the extrasolar Kuiper belt around β Pictoris has Solar System comet-like abundances, then HIRMES is expected to detect OH

O I Reconnaissance: Background



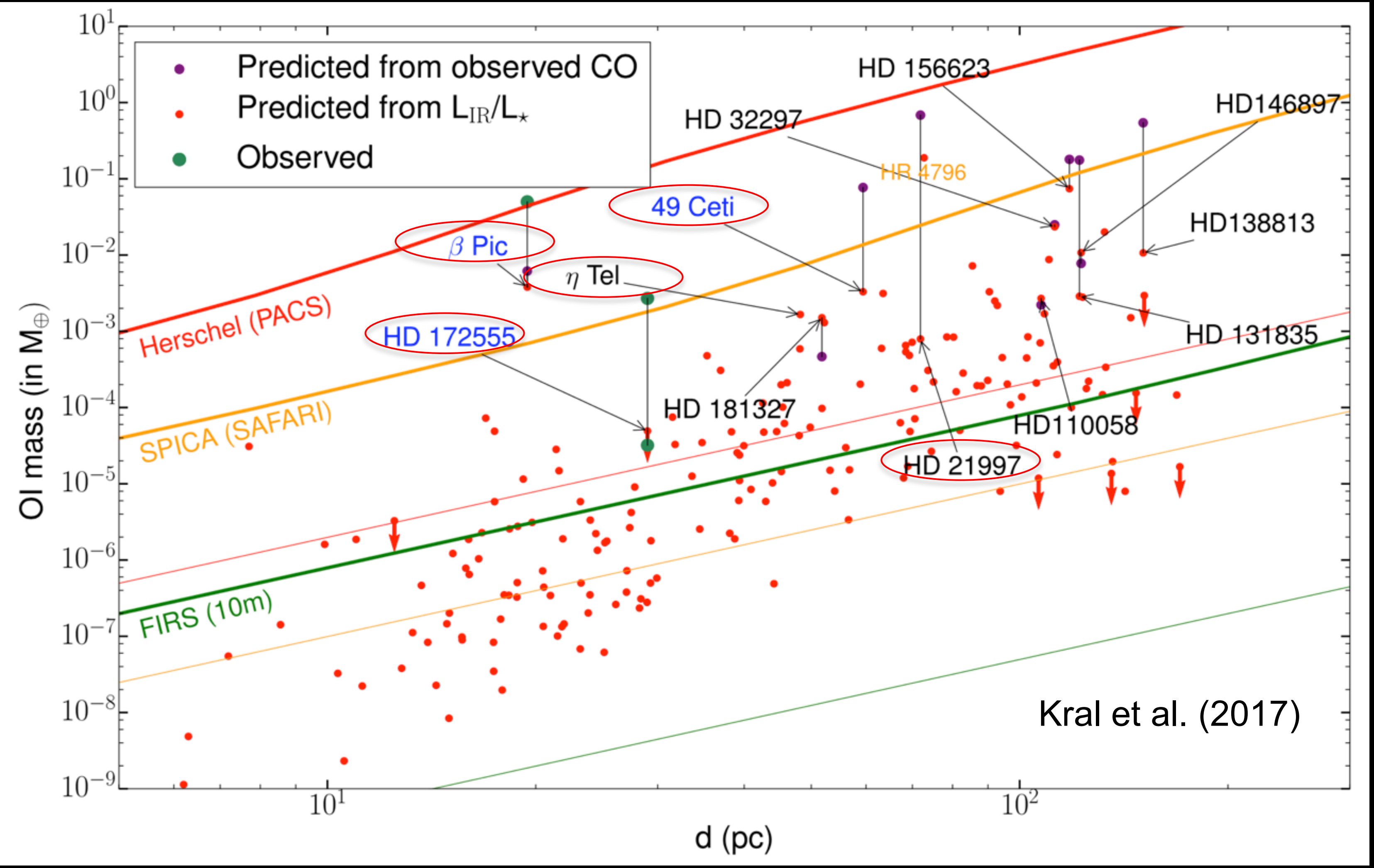
Kral et al. (2017)

Herschel and ALMA together have detected O I, C II, CO, and/or C I toward a growing number of debris disks.

The majority of them (1) have dust distances beyond the snow line and (2) are around low luminosity stars that photo-dissociate CO on timescales longer than 10 year.

O I Reconnaissance: Expected Emission

If the gas in these systems is released from comet-like bodies (with 10% CO compared to Solar System comets), then O I should be detected for the brightest and nearest systems.



O I Reconnaissance: C/O Ratios

What is the composition of the gas and the underlying parent bodies?

C/O ratio critical for understanding nature of volatiles available to form terrestrial planets

C measured from ALMA CO & neutral carbon detections

Need neutral oxygen, water vapor, and/or OH detections to complete the picture

Targets with detected OI emission become candidates for detailed studies

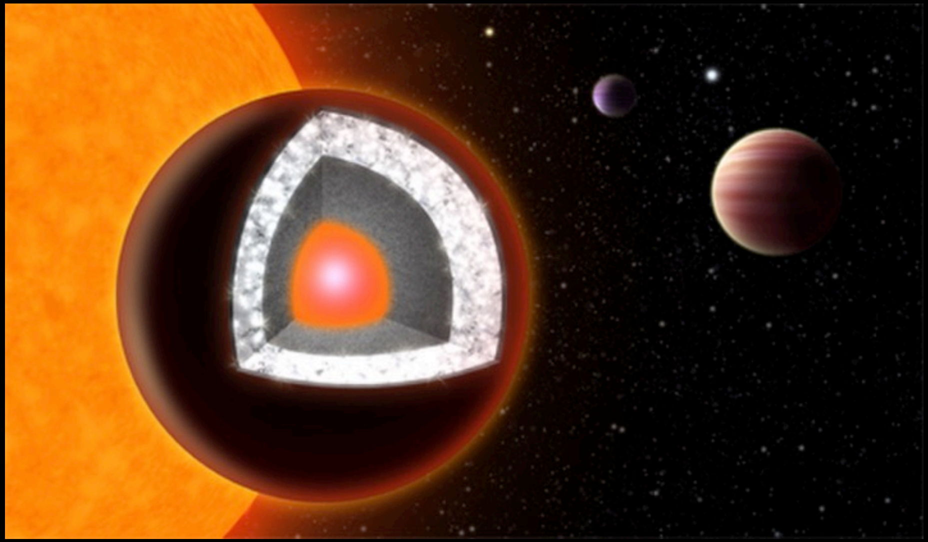


Illustration of 55 Cancri e – an extremely hot planet that may have a surface of graphite surrounding a thick layer of diamond, below which is a layer of silicon-based minerals and a molten iron core at the center (H. Giguere, Space.com)

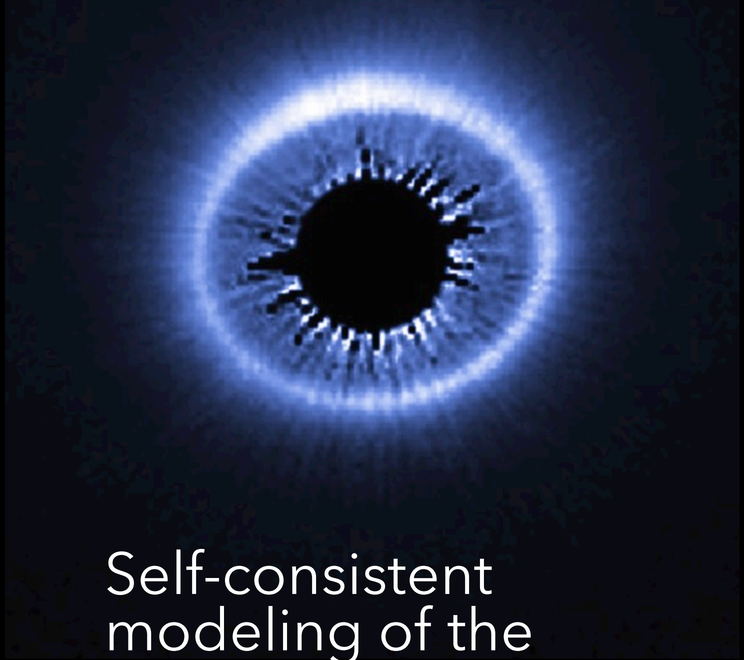
Do carbon planets exist?

Water Ice Reconnaissance: Background

Bockelee-Morvan et al. 2018

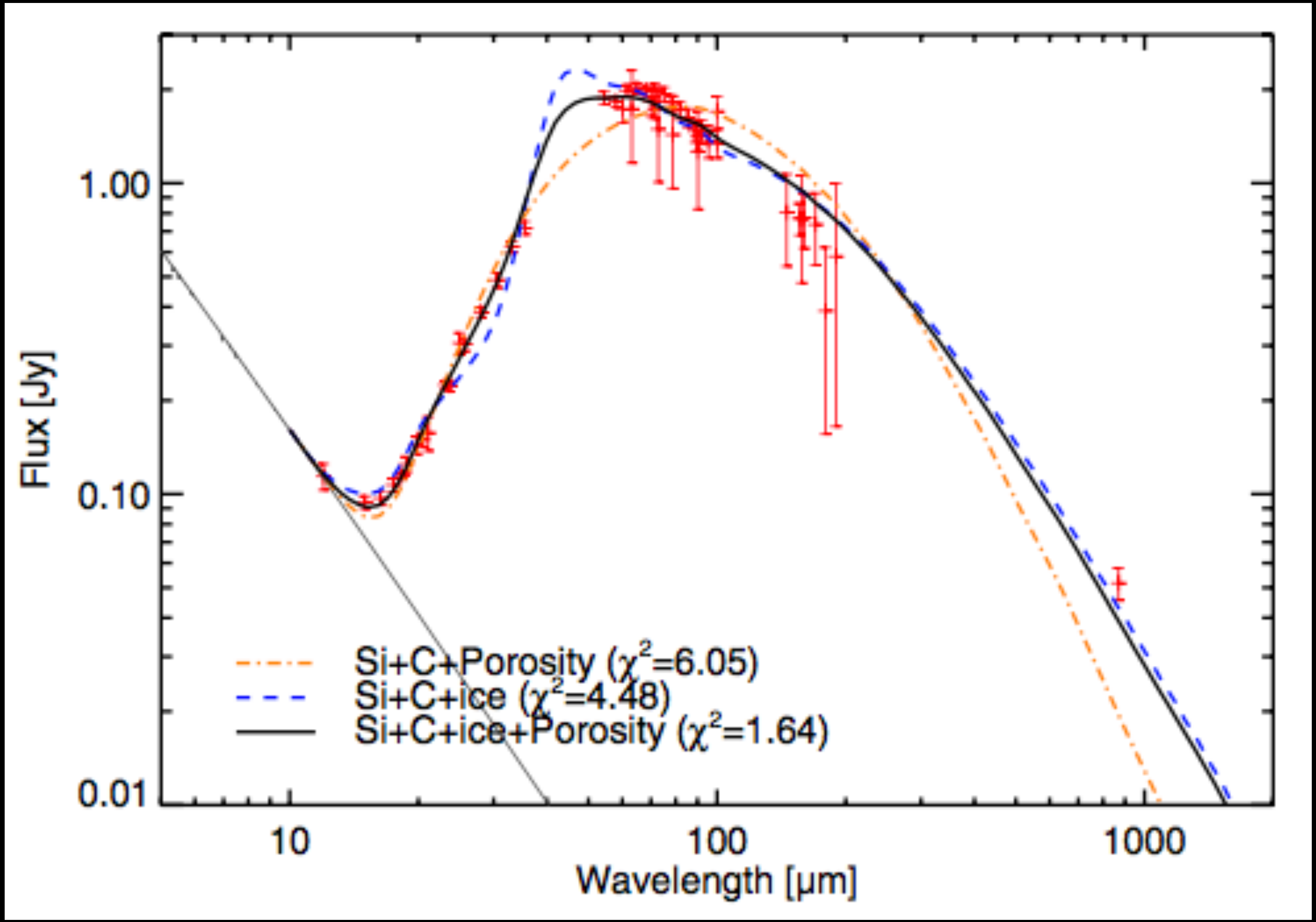
- Planetesimals located beyond the snowline are expected to be analogous to solar system comets
- H_2O is the most abundant volatile species in comets but is not yet detected in any debris disks
- Water ice measurements are needed to refine estimates of the parent body C/O ratio

Water Ice Reconnaissance: A Possible Spitzer Detection



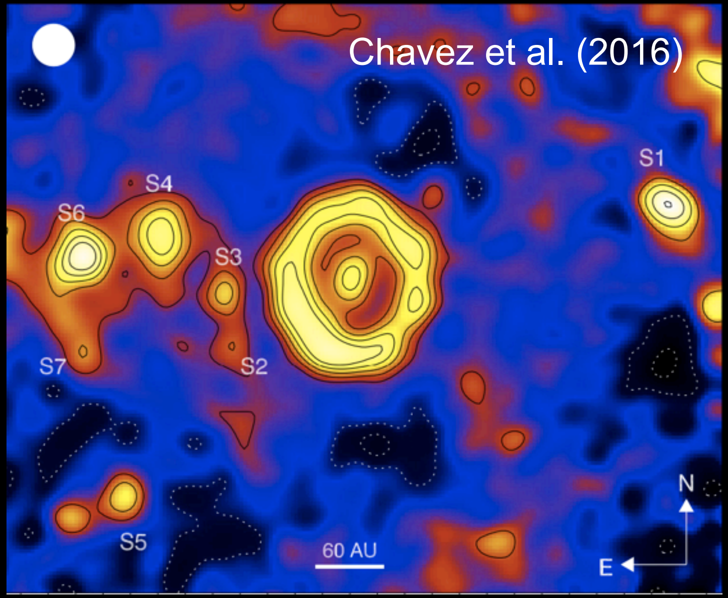
Stark et al. 2014

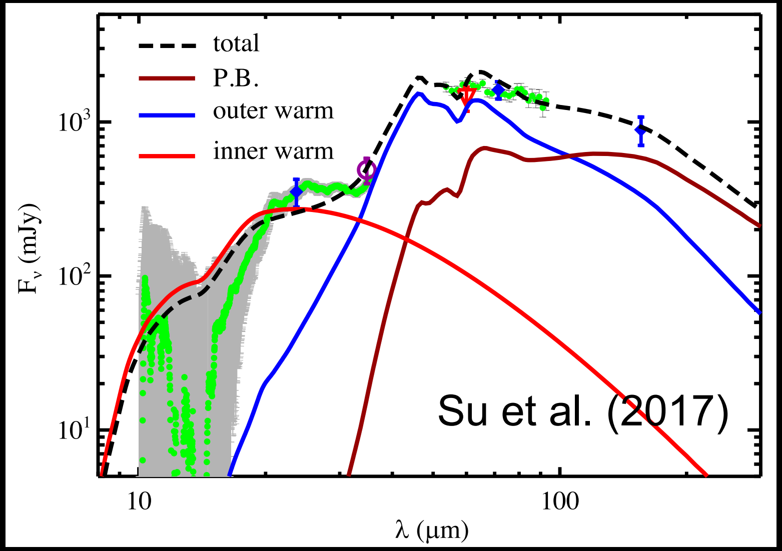
Self-consistent modeling of the scattered light images and thermal SED toward HD 181327 indicates emission from water ice at 63 μm

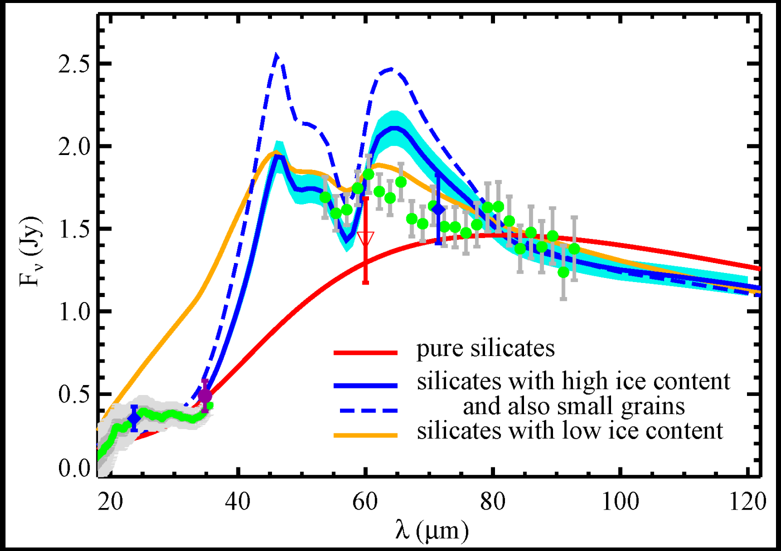


Lebreton et al. 2012

Water Ice Reconnaissance: ε Eridani, A Case Study

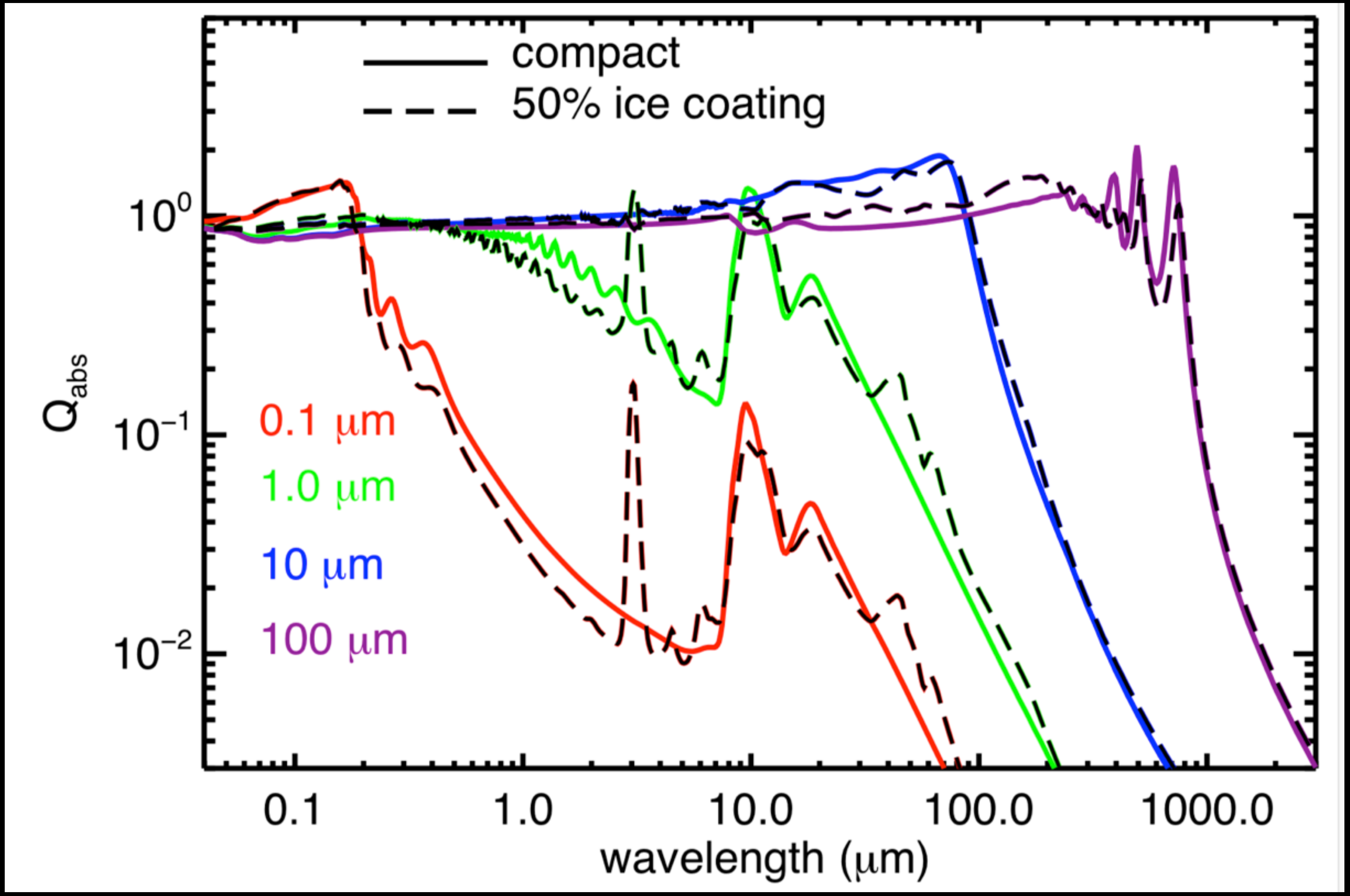






- HIRMES will provide sensitive observations of the 43 and 47 μm crystalline and amorphous water ice features
- Details of the feature shape provide constraints on the presence of minor species and the temperature of the ice

Water Ice Reconnaissance: Detectability



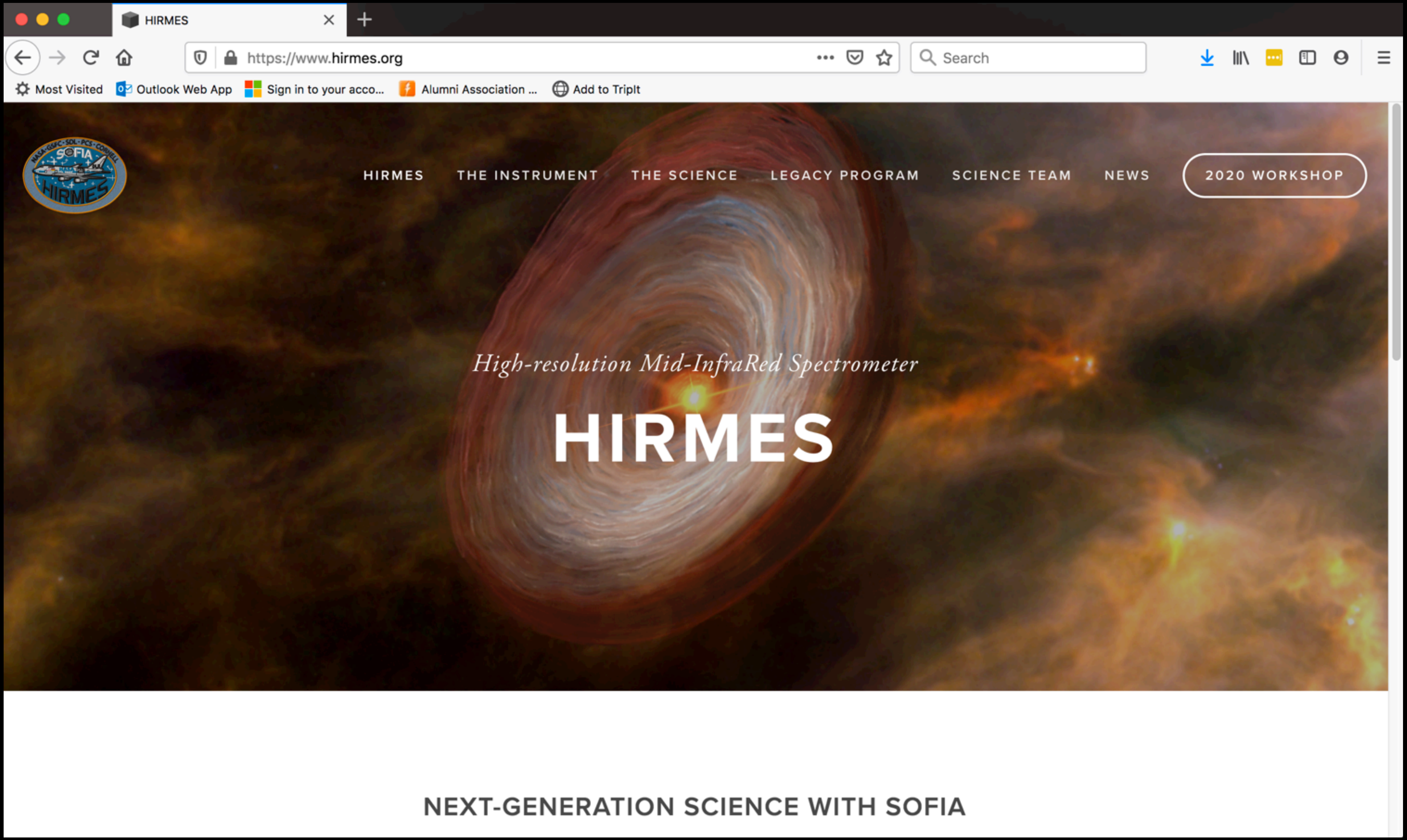
Kate Su, private communication

Only small (<10 μm), warm water ice coated grains will produce sufficiently strong features to be detected with HIRMES

Legacy Science Program: Debris Disks

- Deep Dive Target: β Pic
  - Exoplanetary system (one directly imaged planet) with bright dust and gas emission
- O I Reconnaissance
  - Herschel/PACS surveyed ~40 young, main sequence stars and discovered emission toward β Pic and HD 172555
  - Since that time, ALMA came on-line and discovered CO toward ~15 sources, many of which are ScoCen members not previously searched using Herschel/PACS
  - Search for [O I] 63.2 μm emission
- Water Ice Reconnaissance
  - Expected to be a major constituent of cold, outer belts
  - Some hints of broad 63 μm feature from Herschel/PACS but no definitive detections
  - Search for 42 and 47 μm crystalline and amorphous water ice emission

For Information About HIRMES



Preparing for SOFIA-HIRMES Science
The missing link between JWST and Herschel
• Science talks illustrating the full range of HIRMES' potential
• The HIRMES Instrument, status, and capabilities
• The HIRMES Legacy Science Program
• HIRMES synergies with other missions
June 22-24, 2020
Johns Hopkins University
Space Telescope Science Institute
For more information, visit
https://www.hirmes.org/2020-workshop