Circumstellar Disks with the Far-Infrared Surveyor

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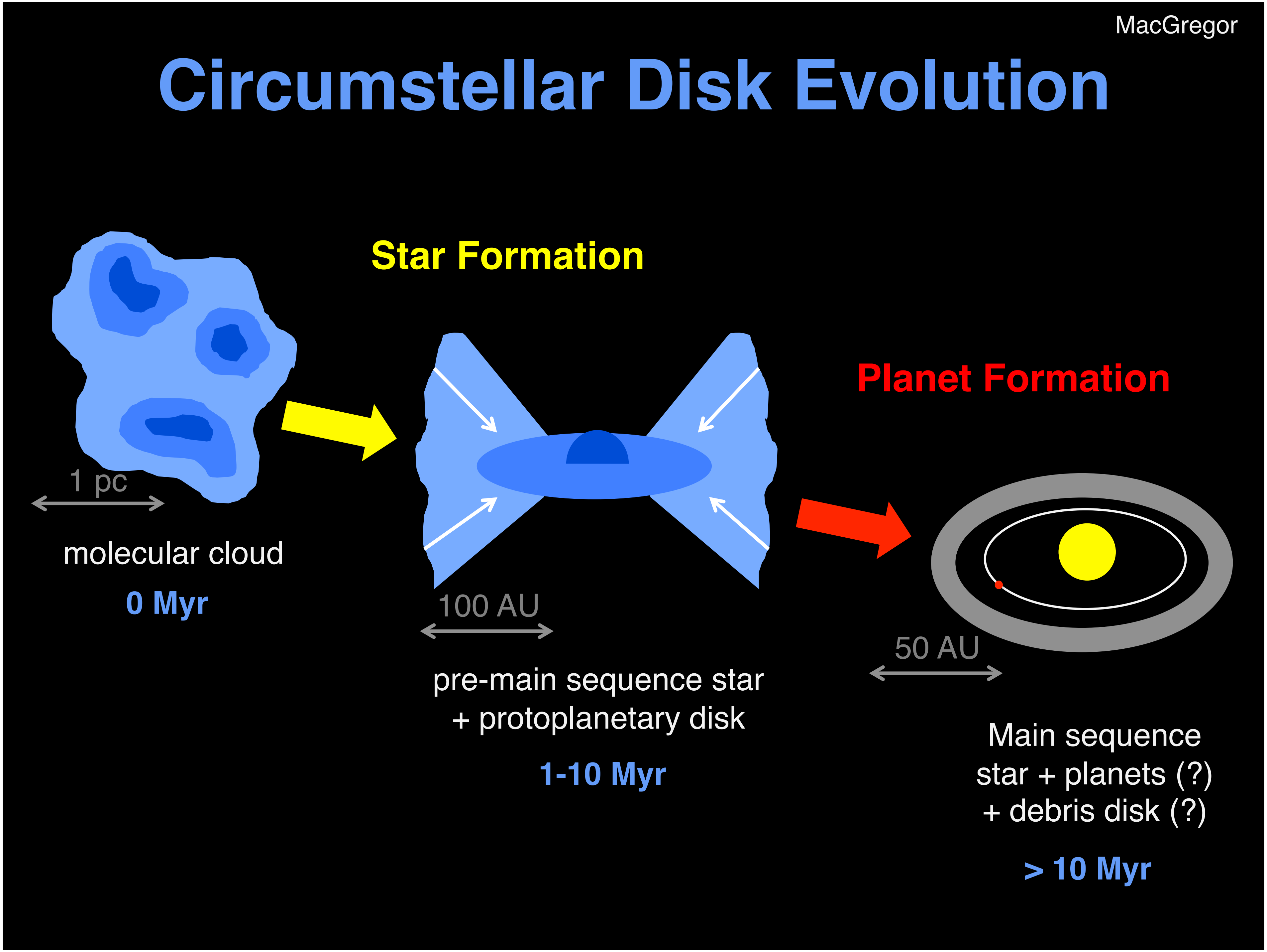
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Circumstellar Disk Evolution
Star Formation
Planet Formation
1 pc
molecular cloud
0 Myr
100 AU
pre-main sequence star
+ protoplanetary disk
1-10 Myr
50 AU
Main sequence
star + planets (?)
+ debris disk (?)
> 10 Myr

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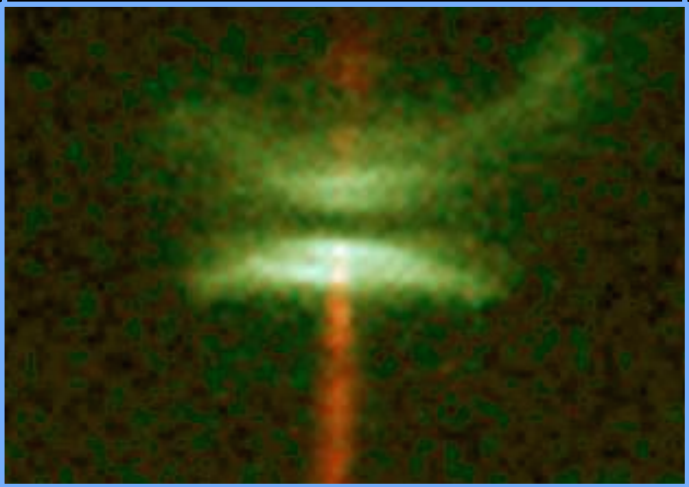
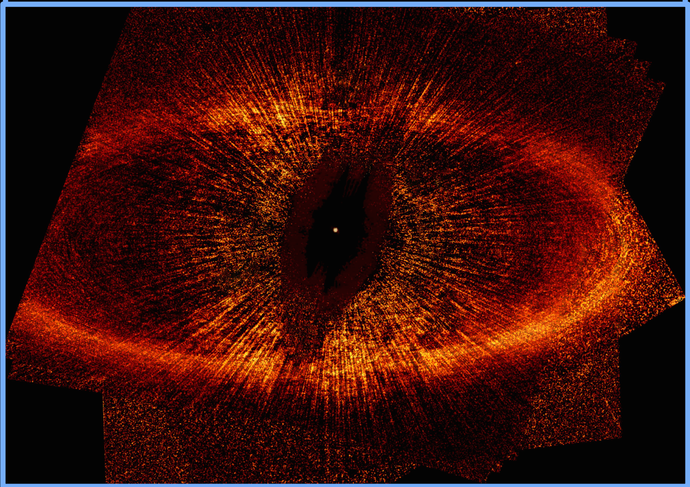
Protoplanetary vs. Debris Disks

Protoplanetary	Debris
Pre-main sequence stars	Main sequence stars
Gas rich	No (or very little) gas
Accretion onto star	No accretion
Optically thick	Optically thin



HH 30 (Burrows et al., 1996)



Fomalhaut (Kalas et al., 2005)

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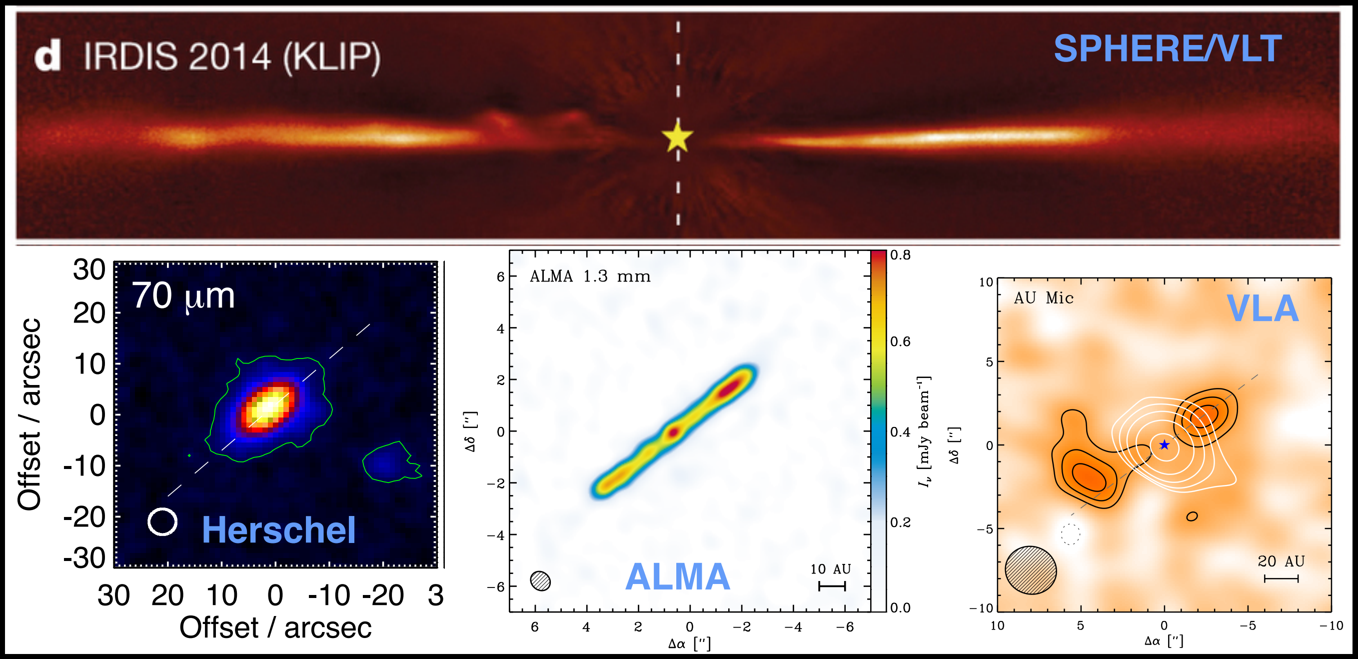
Debris Disks: Observables

First extrasolar debris disk detected as "excess" infrared emission around Vega by the IRAS satellite (Aumann et al., 1984)



Boccaletti et al (2015), Matthews et al. (2015), MacGregor et al. (2013), MacGregor et al. (in prep)

Detected at wavelengths from optical (scattered light) to millimeter and radio (thermal emission)

Key Science Questions

1. How common is our Solar System morphology?
   - What is the occurrence rate of debris disks around FGK stars?
   - How do the characteristics of the host star influence disks?
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2. What can we learn from the structure of debris disks?
   - How do planets affect disk structure?
   - How does disk structure vary with wavelength?

3. What role does atomic and molecular gas play in the evolution of circumstellar disks and planetary systems?
   - How common is gas in debris disks?
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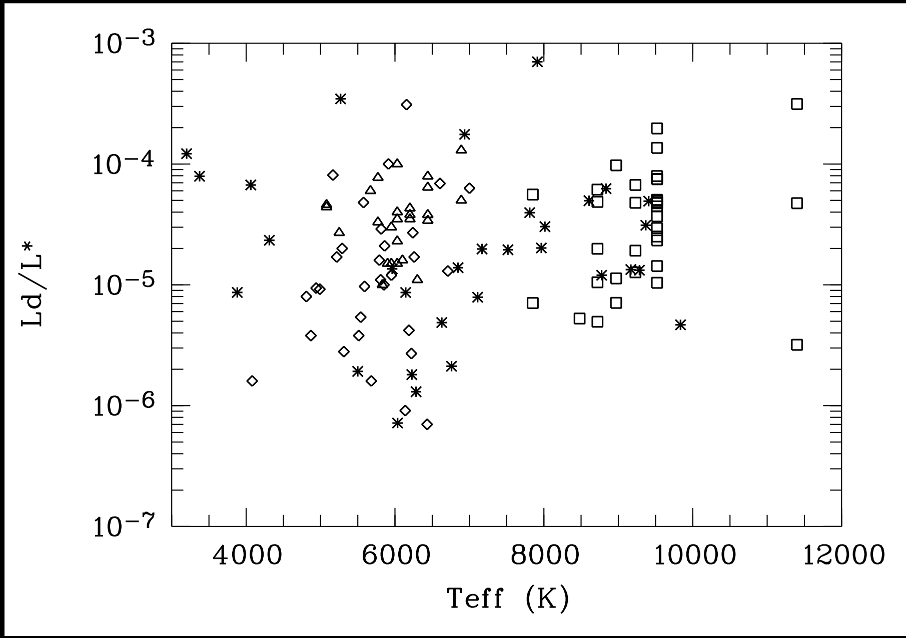
Debris Disk Occurrence Rate

- Want to understand the incidence and correlation of debris disks with stellar properties (age, spectral type, metallicity, stellar/planetary companions)
- By understanding the diversity, we can place our own Solar System in context
- Some progress with previous IRAS, Spitzer, and Herschel surveys



Matthews et al. (2014)
Data: Su et al. (2006), Trilling et al. (2008), Eiroa et al. (2013)

Incidence for FGK stars: 20.2 ± 2%
(Eiroa et al. 2013)

Incidence for A stars: 25%
(Thureau et al. 2013)

Age dependence? Surveys suggest that occurrence for A stars peaks at 10-15 Myr (Hernandez et al. 2007, Currie et al. 2007)

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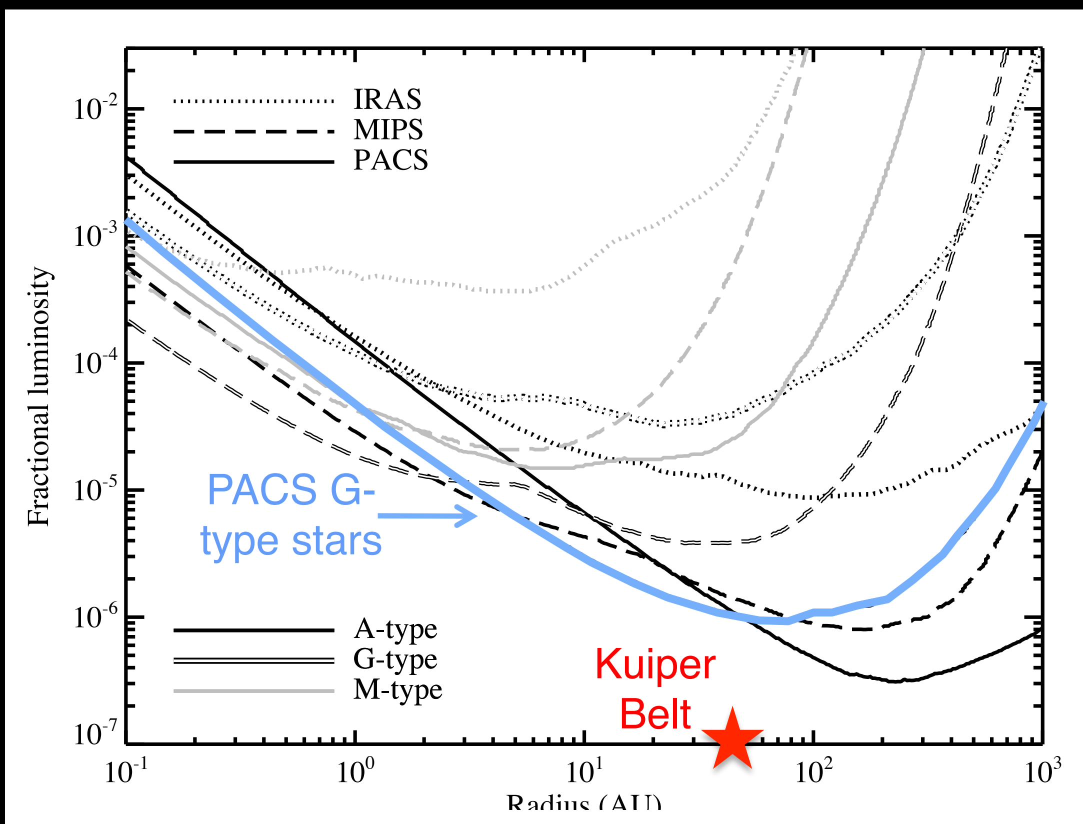
Debris Disk Occurrence Rate

No previous infrared surveys have had the sensitivity necessary to detect our own Kuiper Belt ($L_d/L_* \sim 10^{-7}$)



Matthews et al. (2014)

Herschel DUNES
average sensitivity: $\sim 10^{-6}$
(133 FGK stars within 20 pc)

Herschel DEBRIS
median sensitivity: 2×10^{-5}
(446 A through M nearby stars)

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System Morphology: Inner Belts

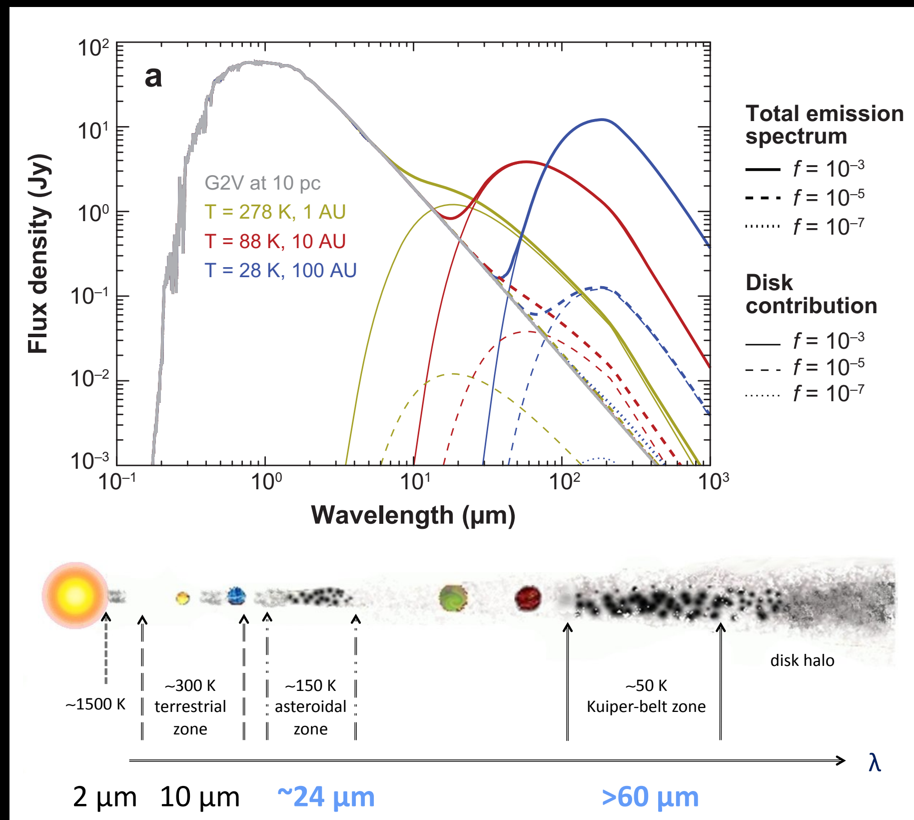
Solar System morphology:

1) warm asteroid belt in the terrestrial planet zone (0.5-3 AU)
2) cold Kuiper Belt (40-48 AU)

How common is this morphology in other systems?

Observations at different wavelengths probe multiple regions of a disk

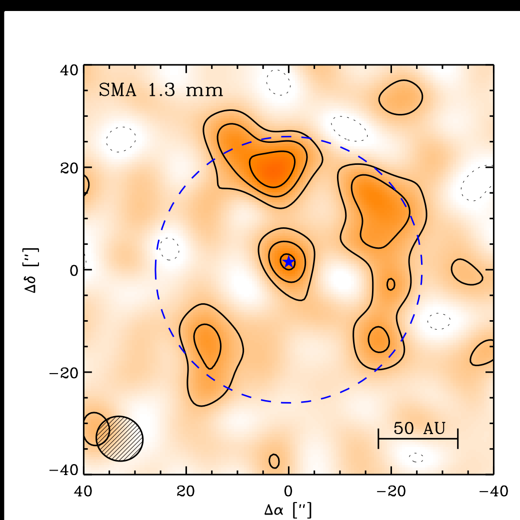
Shorter wavelengths probe components closer into star



Wyatt et al. (2008), Matthews et al. (2014)

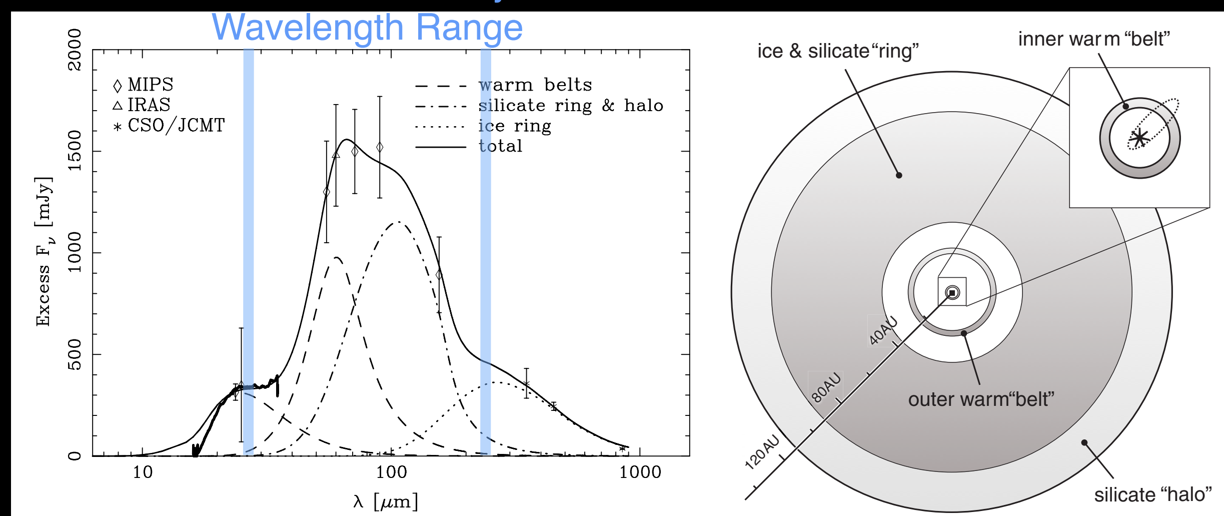
An Example: Epsilon Eridani

- Star: K2V, 3.22 pc, 400-800 Myr
- Infrared and millimeter imaging reveals an outer dust belt at ~64 AU
- Spitzer IRAC (3.6-7.9 μm) and MIPS (24, 70, 160 μm) reveal excess emission attributable to two inner dust belts with the closest at ~3 AU
- Could planets be responsible for maintaining this architecture?



MacGregor et al. (2015b)

Far-Infrared Surveyor Wavelength Range

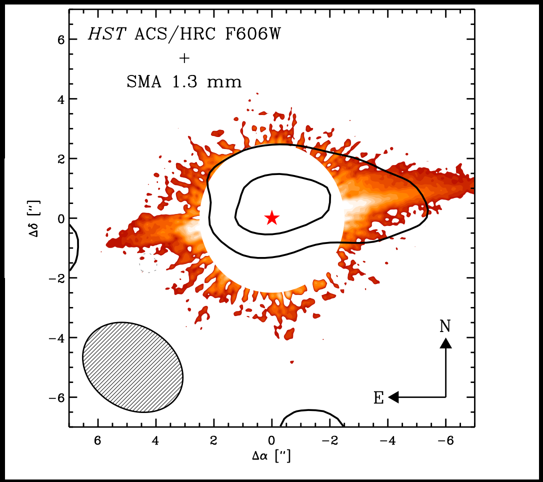


Backman et al. (2009)

Debris Disk Structure

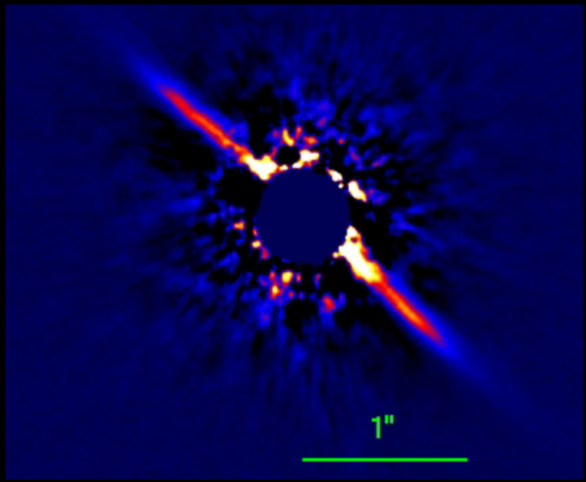
- Planets orbiting a star can gravitationally perturb an outer debris belt
- Variety of structure: warps, clumps, brightness asymmetries, central offsets, sharp edges, etc.
- Alternative way to probe for wide separation planets that are difficult to detect via transits or RV techniques

HD 15115



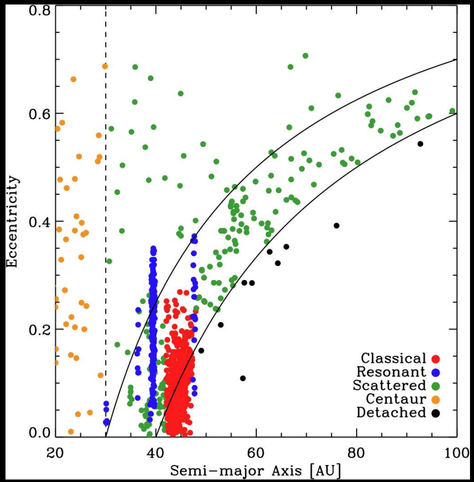
MacGregor et al. (2015a)
Kalas et al. (2007)

HD 32297



Currie et al. (2012)

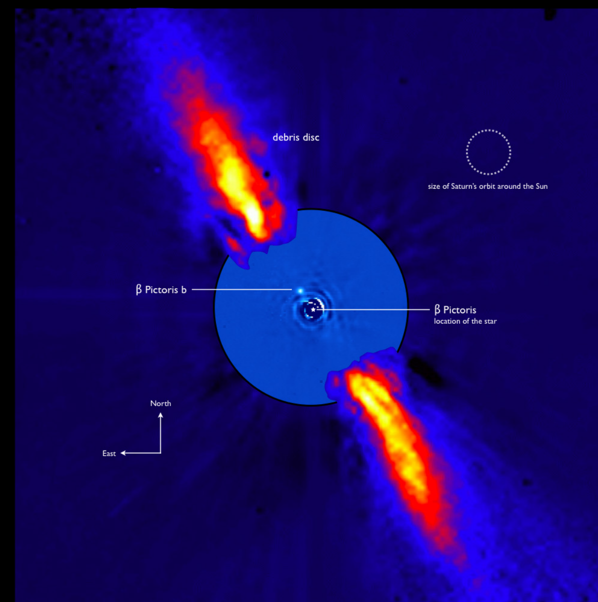
Kuiper Belt



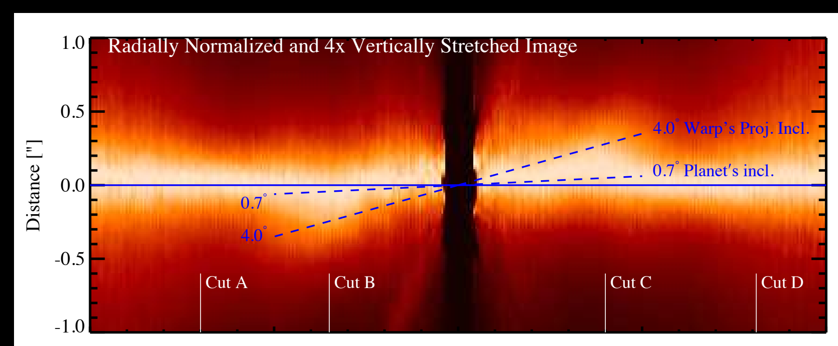
Jewitt et al. (2009)

An Example: β Pictoris

- Star: A6V, 19.4 pc, 21 Myr-old
- Well-studied debris belt at ~85 AU (Dent et al. 2014)
- Secondary disk of scattered light inclined by about 4° (Ahmic et al. 2009; Apai & Schneider 2009)
- Planet discovered by direct imaging using the VLT in 2008 (Lagrange et al. 2008)
- Orbital radius of 8 – 9 AU, orbital period of 17 – 20 yrs
- Given properties of β Pic b, secular perturbations from the planet could produce the observed warp



Lagrange et al. (2008)



Apai & Schneider (2015)

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Wavelength Dependent Structure

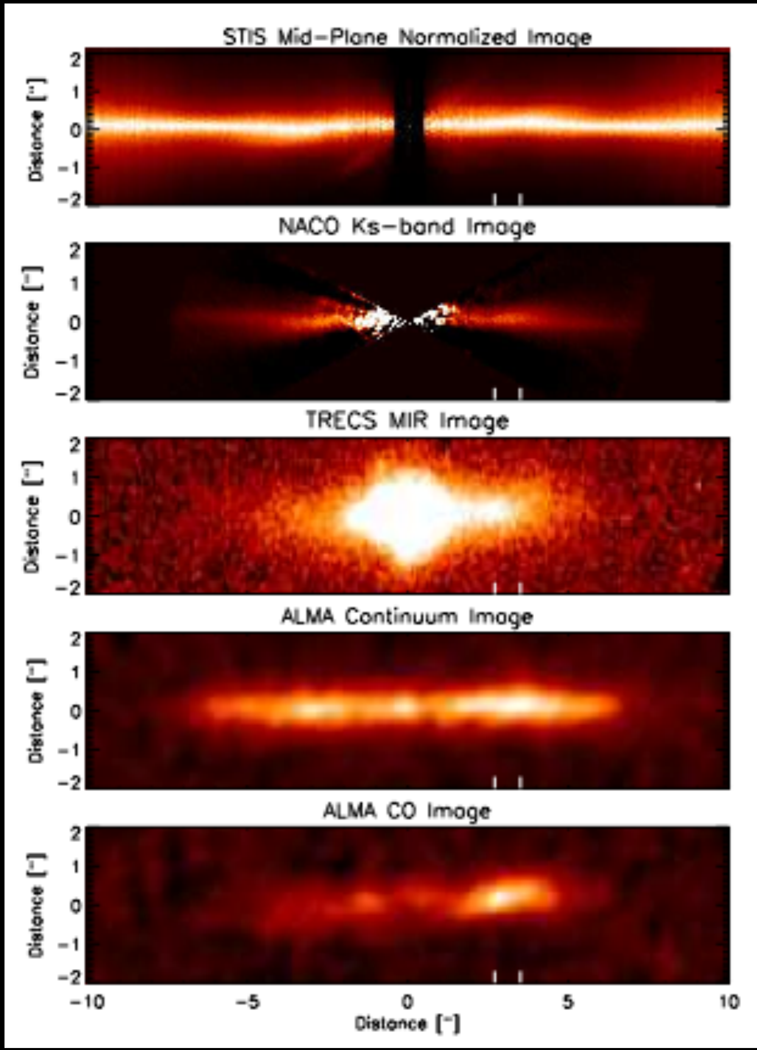
575.2 nm

2.18 µm

8.7-24.6 µm

870 µm

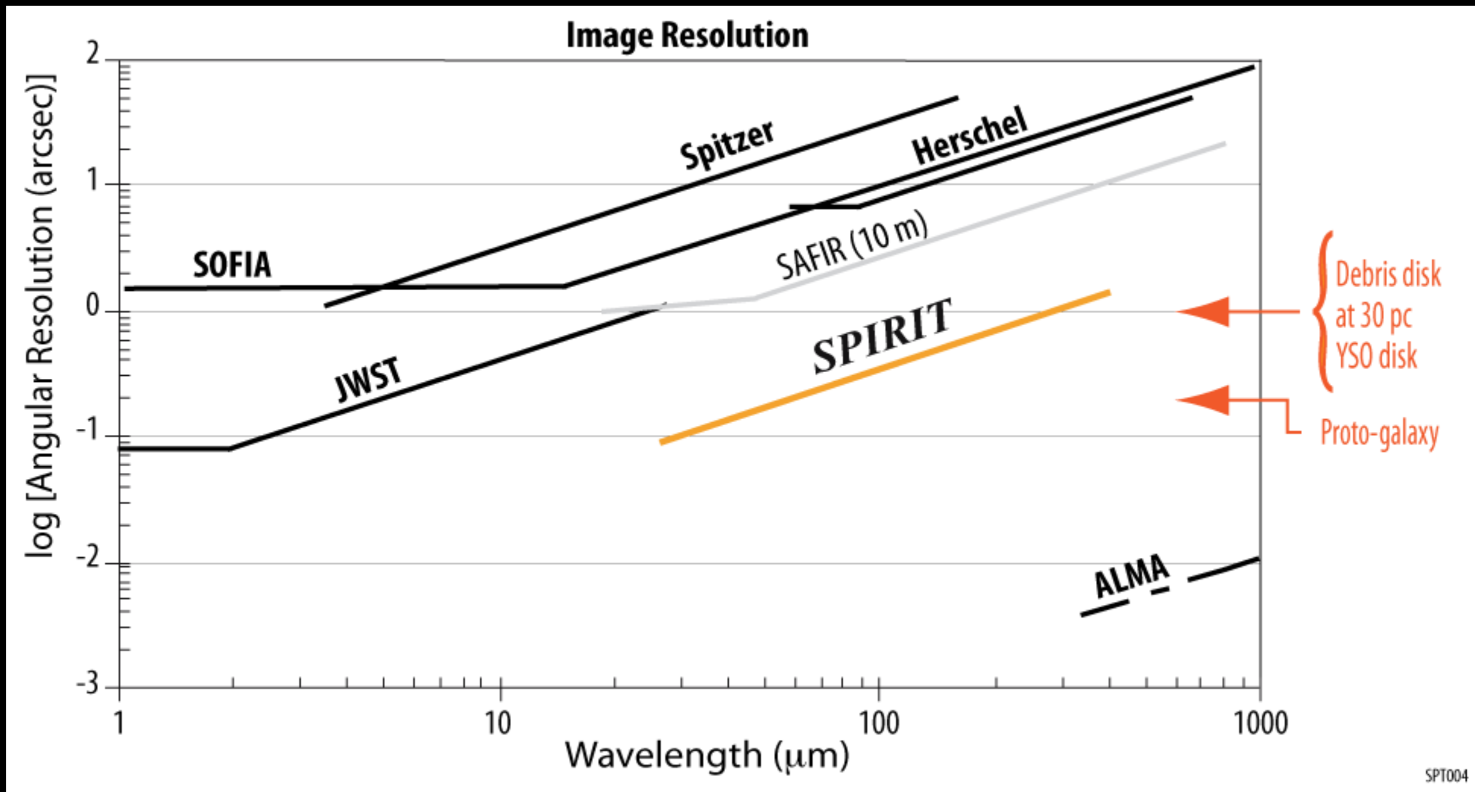
870 µm



Apai & Schneider (2015), Lagrange et al. (2012), Li et al. (2012), Dent et al. (2014)

- NE-SW asymmetry seen at all wavelengths
- Warp visible in the optical and near-infrared
- New Herschel/HIFI observations show higher abundance of C II gas in the SW (Cataldi et al. 2013)
- Mid-IR observations suggest smaller grains in SW wing (Telesco et al. 2005; Li et al. 2012)
- Axisymmetric warp likely due to planetary perturbations
- What about asymmetric features? Possible recent collision?

The Role of Far-IR Observations



What resolution is required to resolve structure?

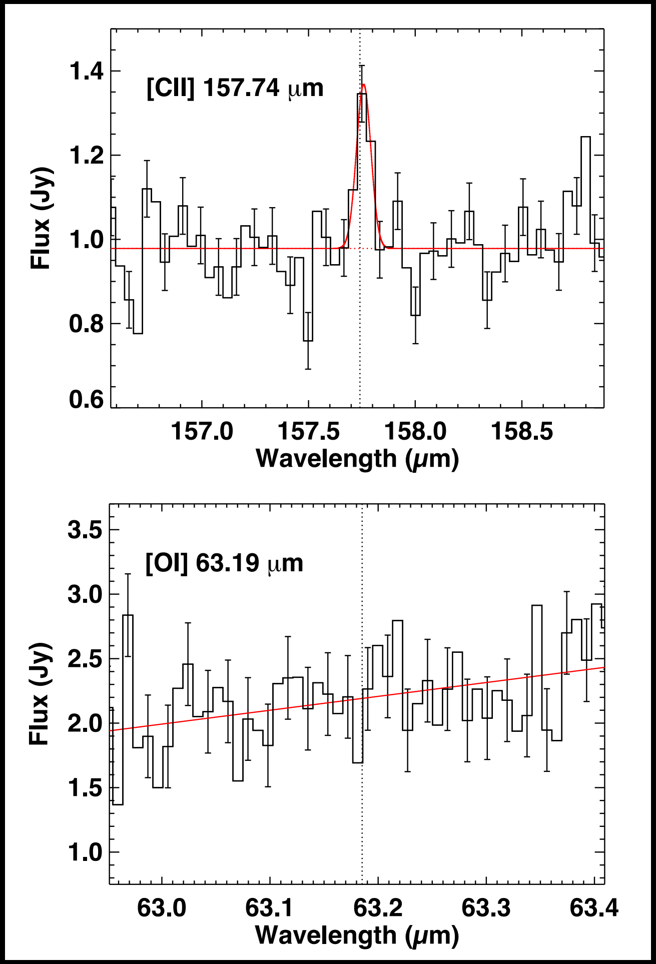
At a distance of 10 pc –
Asteroid Belt: 1 arcsec diameter
Kuiper Belt: 10 arcsec diameter

Plot: Leisawitz & Rinehart (2012)

Gas in Circumstellar Disks

- Growing number of debris disks with detections of atomic and molecular gas: β Pictoris, 49 Ceti, HD 32297
- Gas appears to be secondary in β Pictoris and 49 Ceti (comets)
- New window on disk structure (velocity information), planetesimal composition and protoplanetary disk dispersal

Far-IR observations can target higher CO transitions, HCN, CII, OI, etc.



Roberge et al. (2013)

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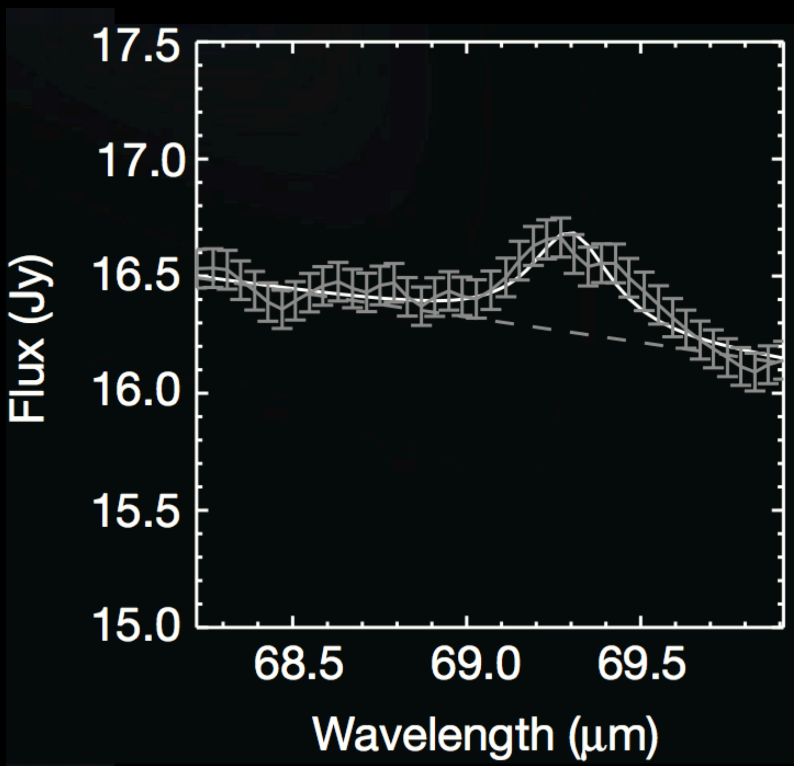
Dust Compositions



de Vries et al. (2012)

- Herschel PACS detection of the 69 μm olivine feature in the spectrum of β Pictoris
- Indicates that cold dust between 15 – 45 AU is Magnesium rich and makes up 3.6% of total dust mass
- Similar crystalline olivine abundances in β Pictoris and Solar System comets
- Can infer grain crystallization and size from shape of the emission feature

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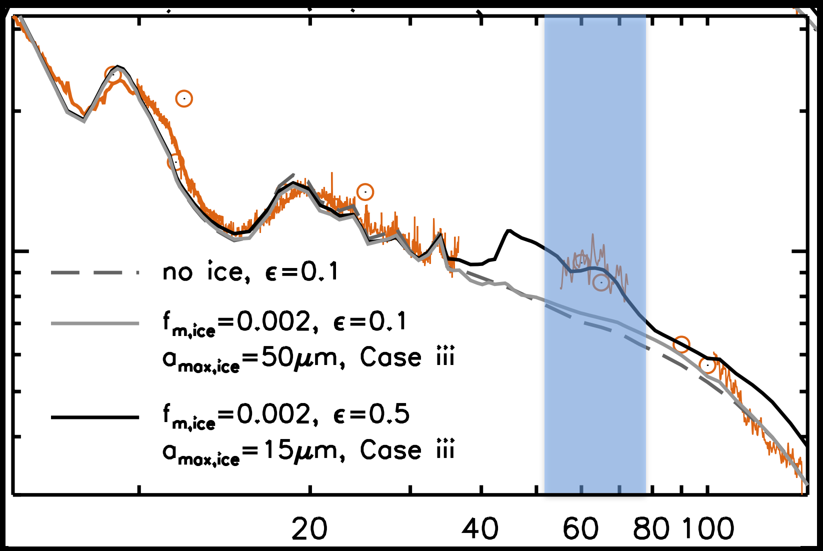
Water in Circumstellar Disks

- Water ice may play an important role in forming planetesimals by
  - Helping grains stick together (Ormel et al. 2011; Kuroiwa & Sirono 2011)
  - Increasing the dust to gas mass ratio at the snowline and inducing the accumulation of grains at this location (Kretke & Lin 2007)
- Herschel detected ice around T-Tauri star GQ Lup at 63 μm
  - Consistent with models of ice-enhanced grain growth



McClure et al. (2012)

Far-IR observations of water and water ice can only be done with space telescopes like the Far-Infrared Surveyor

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Instrument Requirements?

Wavelength Range
24 – 250 μm

Continuum Sensitivity
10-100 μJy

Angular Resolution
<1 arcsec

Survey Capabilities?
Yes

Spectral Resolution
>1000 (10^5 – 10^6)

Spectral Line Sensitivity
10^{-19} W/m^2