Debris Disks with Spitzer and beyond

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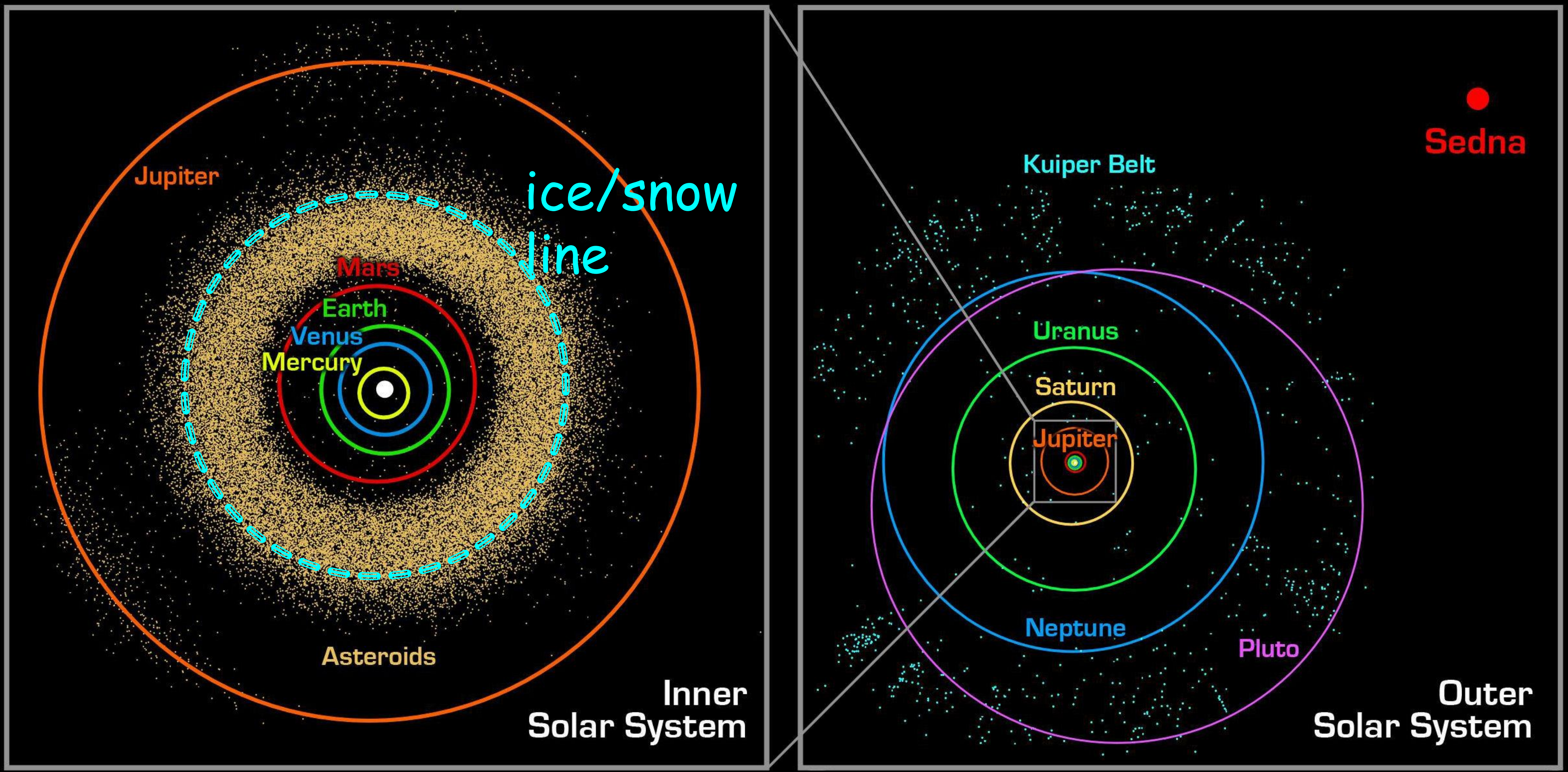
Outline

- Why should we care about debris disks?
- Debris Disk Characteristics based on Spitzer obs.
  - General Disk Behaviour vs. Age
  - Signposts for Planets beyond the Ice Line
  - Other effects that influence disk structure (Challenges of Interpreting Observations)
  - Systems that are sites of high level of dynamical activity in debris disks
- Future Prospects and Conclusions

Why we should care about debris disks?

Solar System's Debris Disk

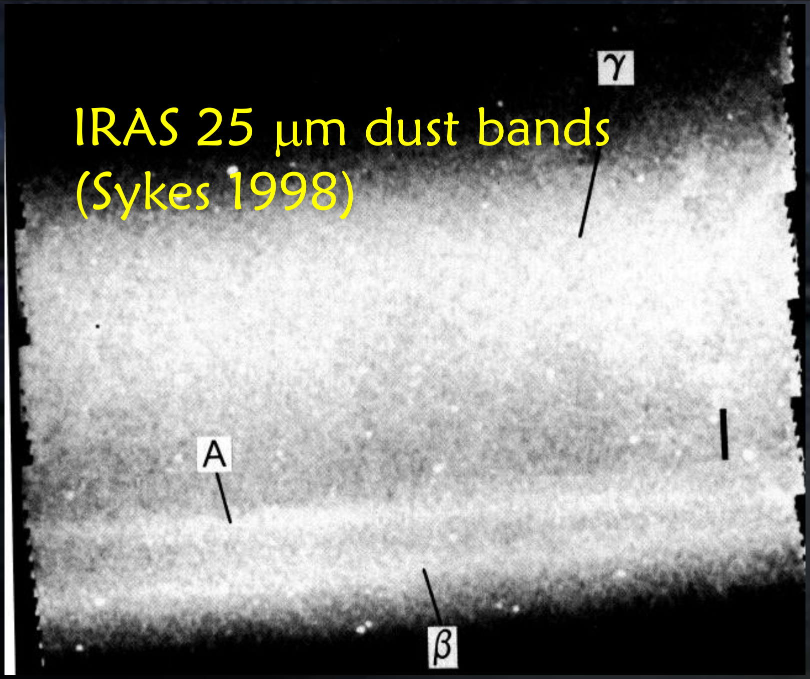
Two leftover planetesimal (minor-body) belts
- Asteroid Belt (2-4 AU): ~100,000 1-km-size bodies
- Kuiper Belt (30-50 AU): large icy bodies



Planetesimals Collide

optical scattered light

infrared thermal emission



- dust particles in the zodi

  radius ~ 10-100 μm in size

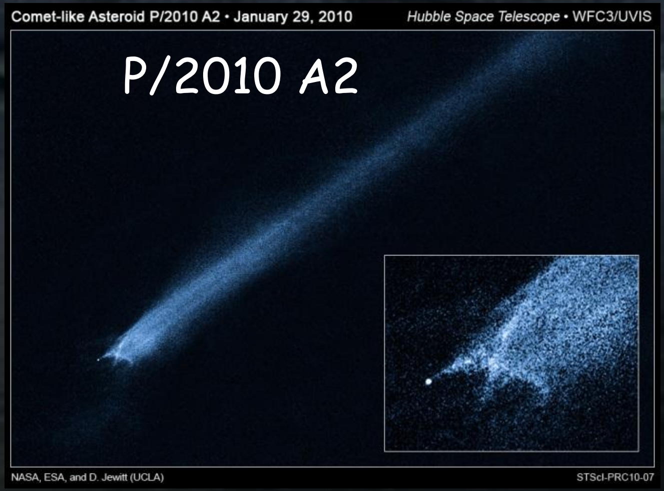
  mass ~ 10^{18-19} g

  density ~ 10^{-7} cm^{-2}

  (Love & Brownlee 1993)

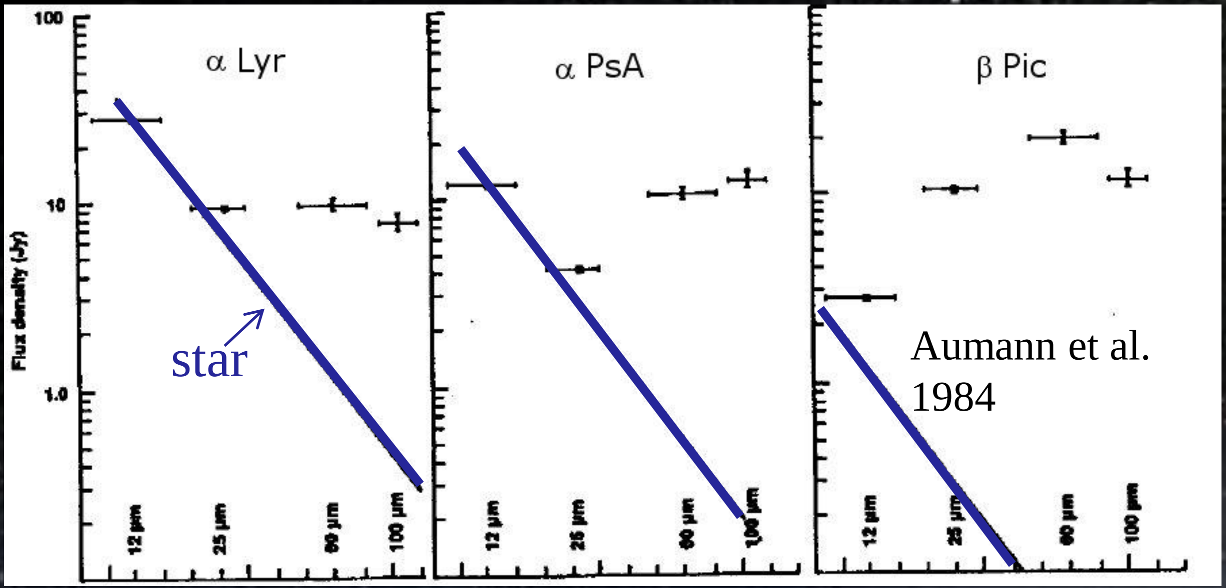
- some dust bands can be associated with the breakup of asteroids 5 and 8 Myr ago (Nesvorný et al. 2002)

- We are witnessing asteroid collisions!!

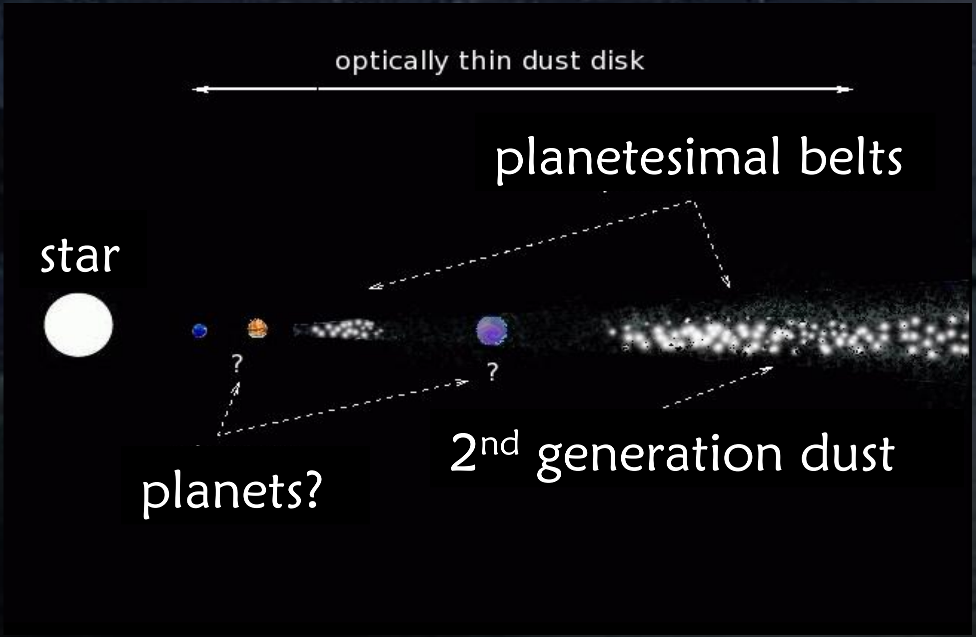


Jewitt et al. 2010, Snodgrass et al. 2010

Discovery of Debris Disks



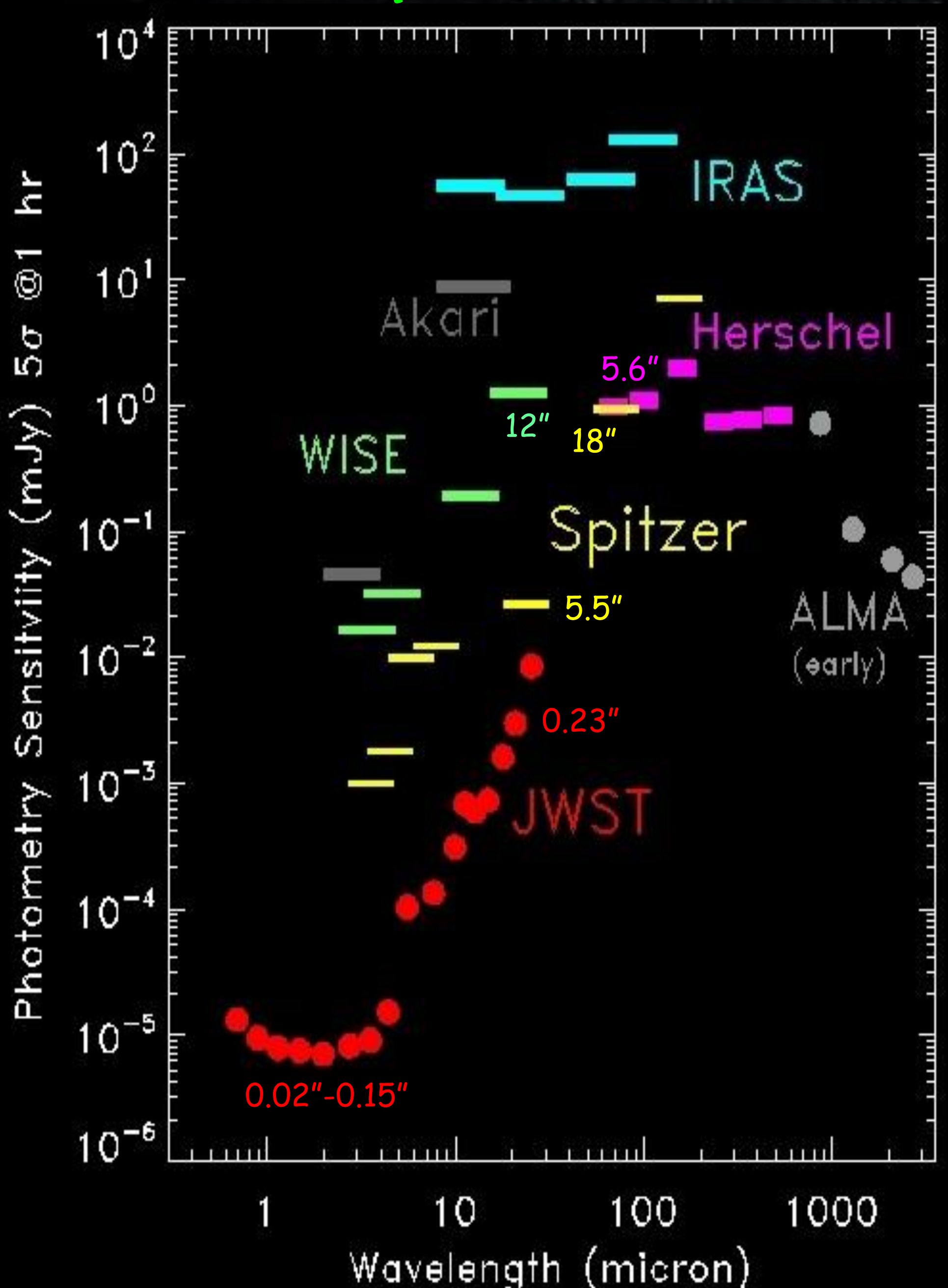
Discovered by IRAS in 1984 as far-IR excesses from systems of particles analogous to enhanced Kuiper belts, 11 years earlier than the discovery in our own Kuiper Belt!



Dust, the observable component in a debris disk, traces the unseen minor bodies in a planetary system

→ the dust properties (i.e., amount, structures) are directly linked to the physical nature of the underlying planetary system.

Modern Space Facilities



- Full sky coverage from all sky survey facilities: IRAS, Akari, and WISE
- Resolved disk structures and new discovery of very cold disks by Herschel
- JWST is not a survey facility for debris disks

Spitzer sensitivity combined with high observational efficiency: photospheres at 24 μm for stars of A0V at 1.1 kpc, G0V at 350 pc, M0V at 150 pc
→ Spitzer provides the means to study various stages of planet formation.

Success of Spitzer Cryogenic Mission

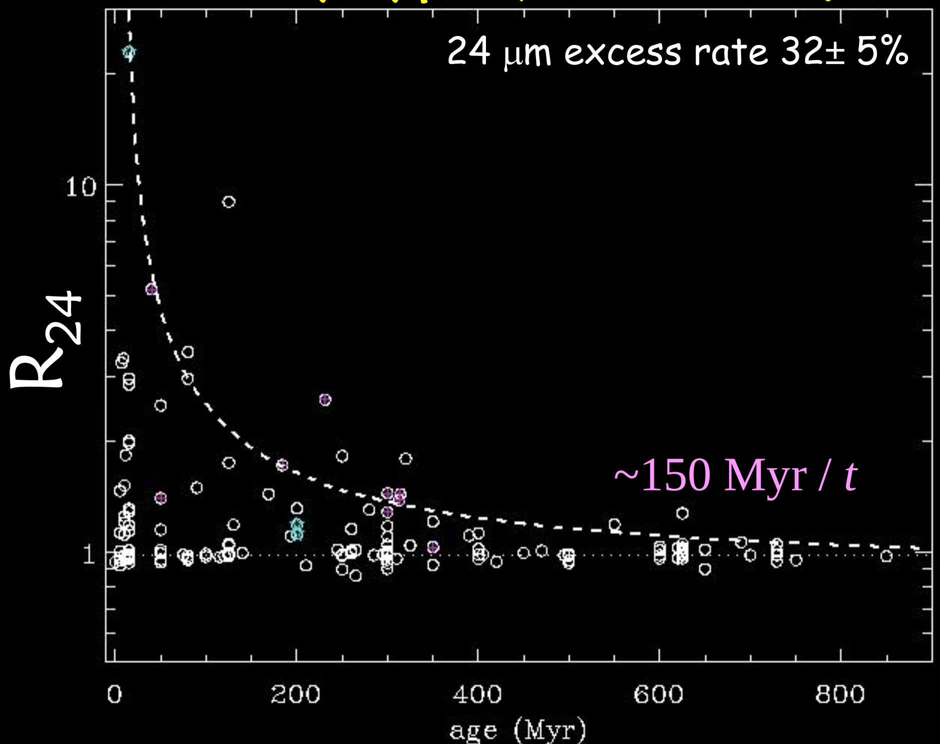
~200 papers published in debris disk topics so far

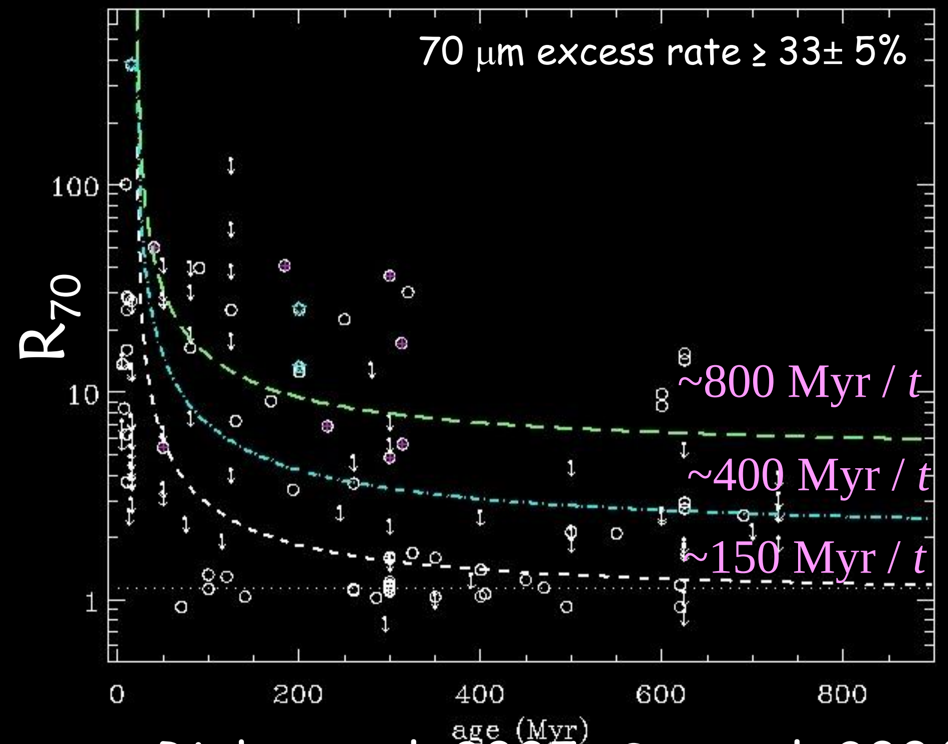
- Excess incidence: A-stars (Rieke et al. 2005, Su et al. 2006), solar-like stars (Beichman et al. 2005, Bryden et al. 2006, Moor et al. 2006, Trilling et al. 2008, Meyer et al. 2008, Hillenbrand et al. 2008, Carpenter et al. 2008, 2009, Moor et al. 2011), M-type stars (Gautier et al. 2007, Plavchan et al. 2011);
- Stellar Clusters/Associations (a few Myr to ~600 Myr) (Young et al. 2004, Gorlova et al. 2004, Chen et al. 2005, Stauffer et al. 2005, Gorlova et al. 2006, Carpenter et al. 2006, Sicilia-Aguilar et al. 2006; Hernandez et al. 2006, 2007, 2008, 2009, 2010, Gorlova et al. 2007, Siegler et al. 2007, Currie et al. 2007, 2008, Cieza et al. 2008, Gautier et al. 2008, Rebull et al. 2008, Gaspar et al. 2009, Balog et al. 2009, Stauffer et al. 2010, Sierchio et al. 2010, Smith et al. 2011).
- Binarity (Trilling et al. 2007), Metallicity (Beichman et al. 2006), RV-planet host stars (Bryden et al. 2006, Moro-Martin et al. 2007, Kospal et al. 2009, Bryden et al. 2009, Dodson-Robinson et al. 2011), Rotation/X-rays (Chen et al. 2005, Rebull et al. 2008, Stauffer et al. 2009), Galactic Thick Disk Population (Sheehan et al. 2010) … and many more.
- Individual Resolved Disks (Stapefeldt et al. 2004, Su et al. 2005, Su et al. 2008, Backman et al. 2009, Su et al. 2009).

Disk Emission with Age

Early-type Debris Disks vs. Age

~160 Early-type (late B to A) Stars





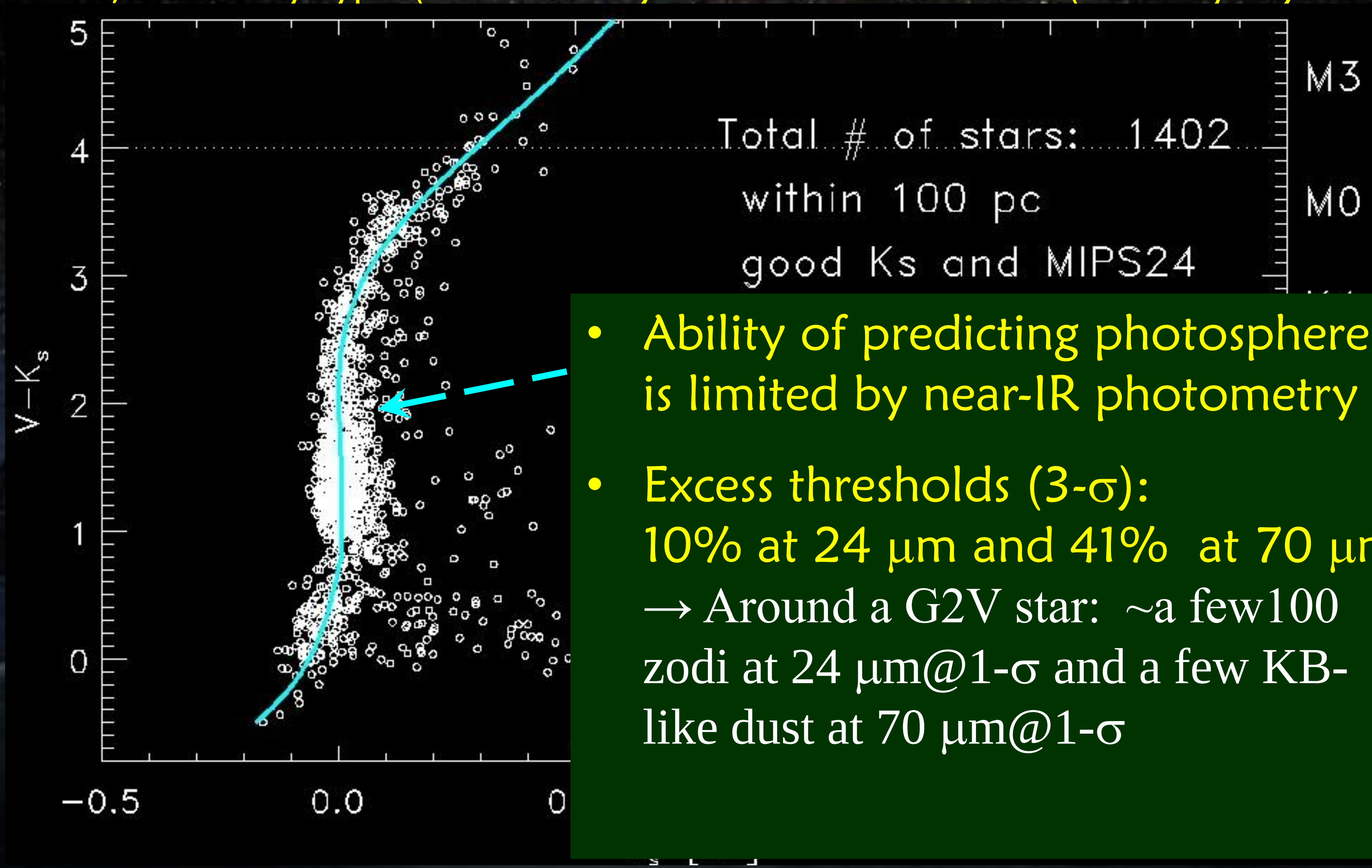
Rieke et al. 2005, Su et al. 2006

- Slow decay at 70 μm is consistent with planet formation theory
- Similar decay behavior seen around solar-like Stars at 24 μm (Meyer et al. 2008, Trilling et al. 2009, Carpenter et al. 2009), but inconclusive at 70 μm due to age uncertainty and many non-detections.

Spitzer Debris Disk Measurements

~3000 stars measured at 24 and/or 70 μm (pointed obs.)

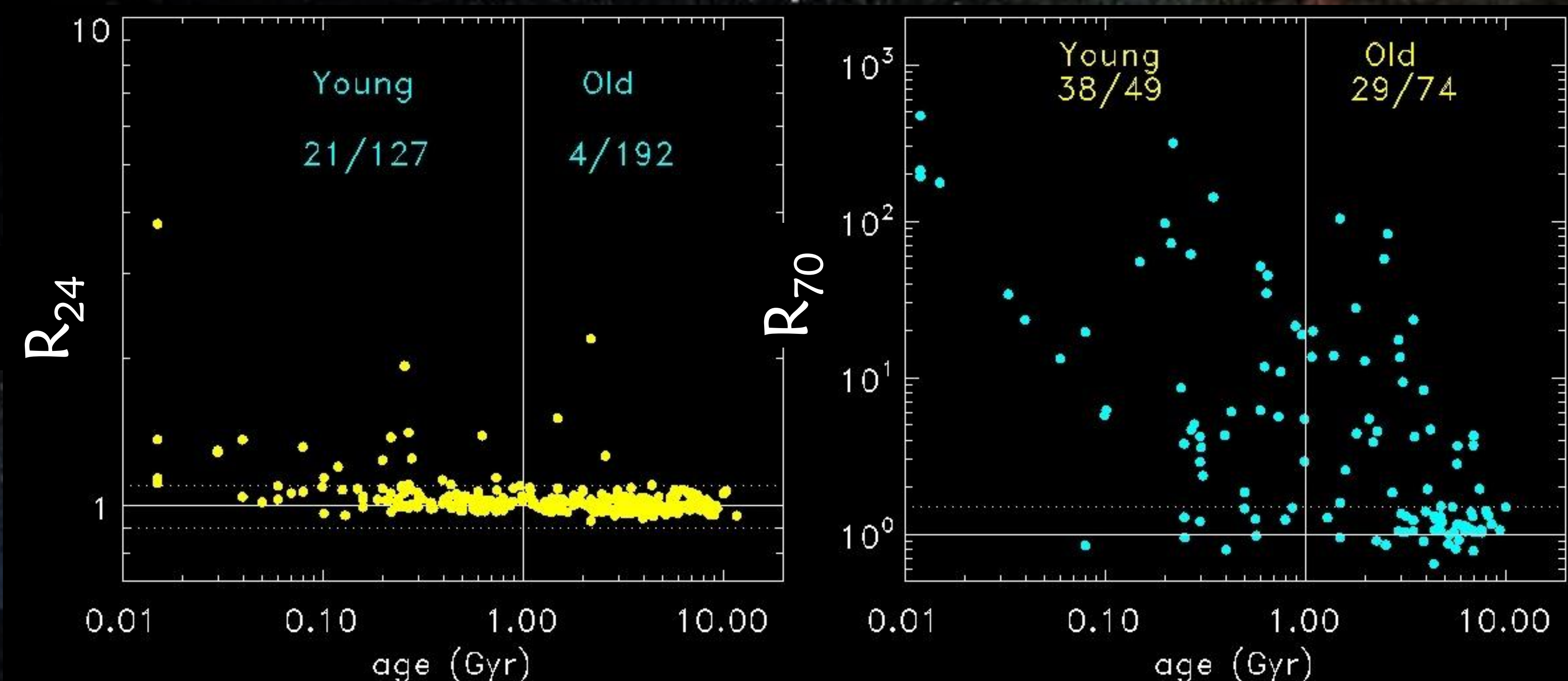
~1/3 of early-type (late B to F3) and the rest solar-like (F4-early M)



- Ability of predicting photospheres is limited by near-IR photometry
- Excess thresholds (3-σ): 10% at 24 μm and 41% at 70 μm → Around a G2V star: ~a few100 zodi at 24 μm@1-σ and a few KB-like dust at 70 μm@1-σ

Funded by NASA-ADP programs, and Spitzer GO7 warm mission program

Solar-like Debris Disks vs. Age



based on good detections only S/N > 3

- Amount of Excesses generally decays with stellar age
- At 24 μm, 16.5±3.6% for age <1 Gry, but 2.1±1.0% afterwards
- At 70 μm, 77.6±12.6% for age <1 Gry, but 39.2±5.9% afw.
- Non-detections need special cares to fold in for comparison.

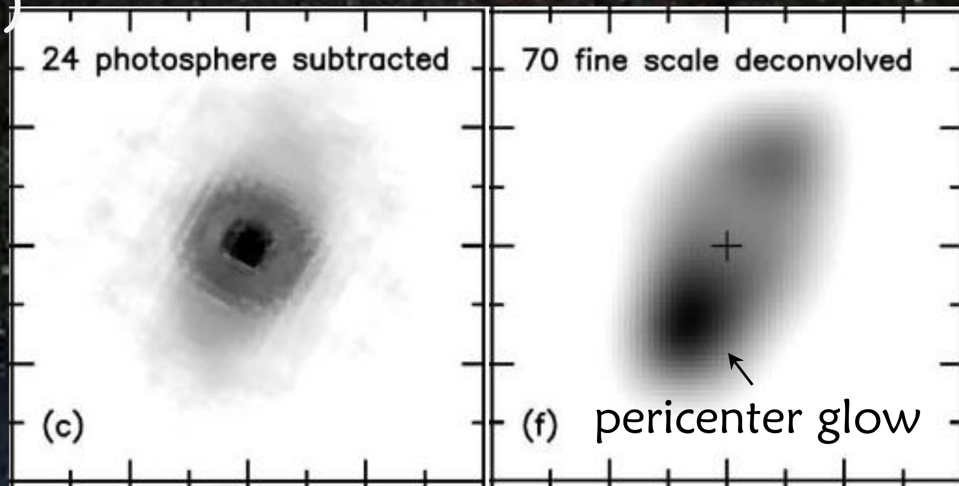
Signposts for planets beyond the ice line

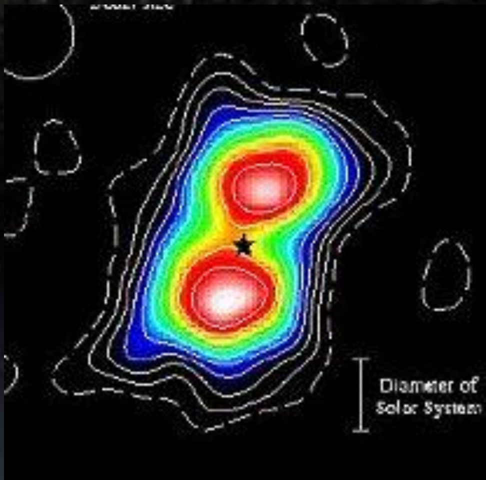
Inner vs. Outer Zones in Debris Disks

Illustration | MIPS 24 μm | MIPS 70 μm | SCUBA 850 μm

Fomalhaut (A3V)

7.7 pc

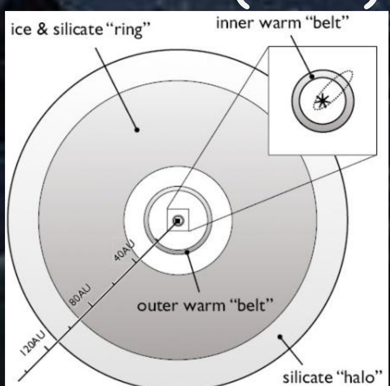




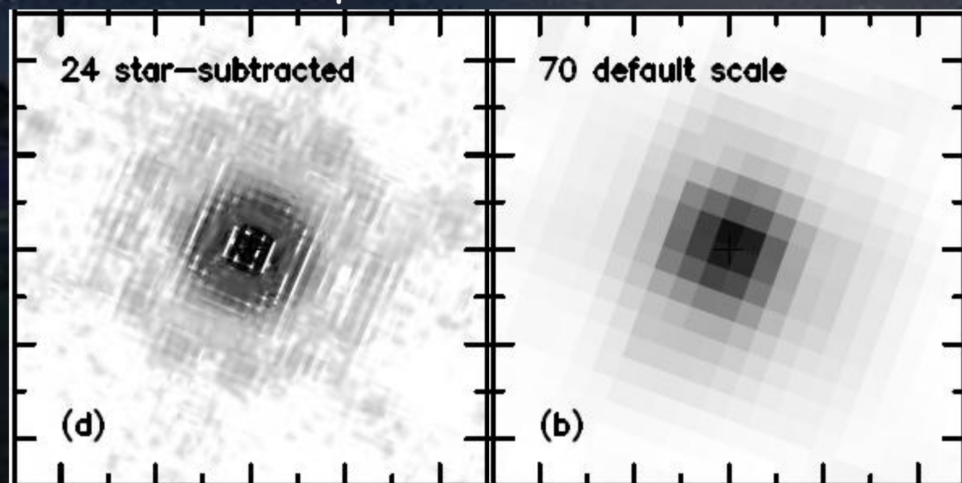
Stapelfeldt et al. 2004

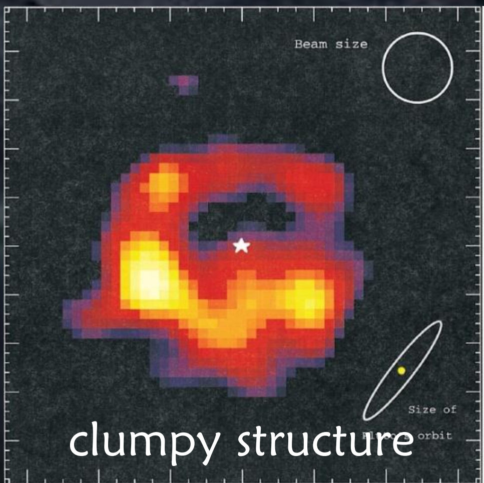
Holland et al. 1998

ε Eridani (K2V)



3.2 pc





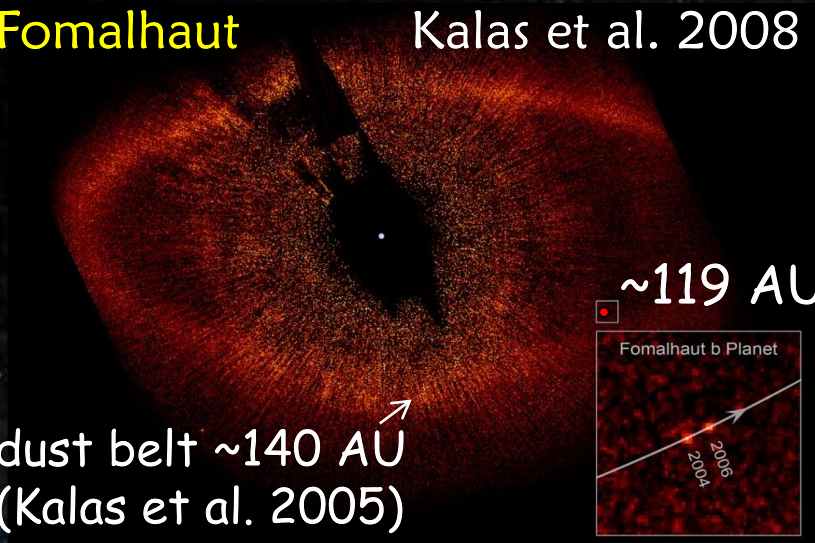
Backman et al. 2009

Greaves et al. 1998

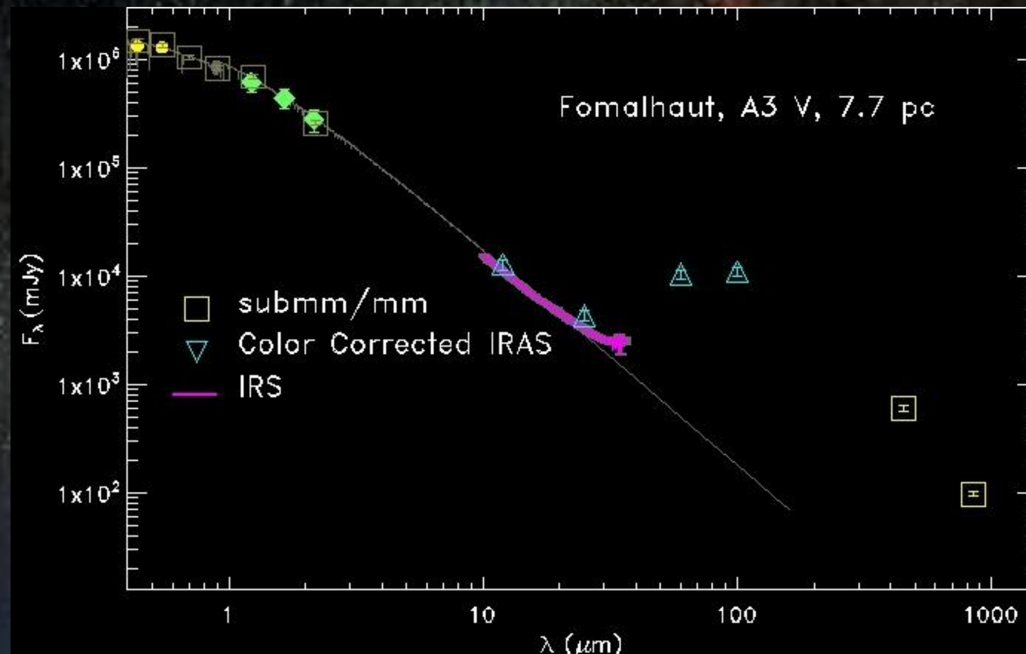
All images are in the same orientation and angular size.

Stars + Planets by direct imaging + Debris Disk

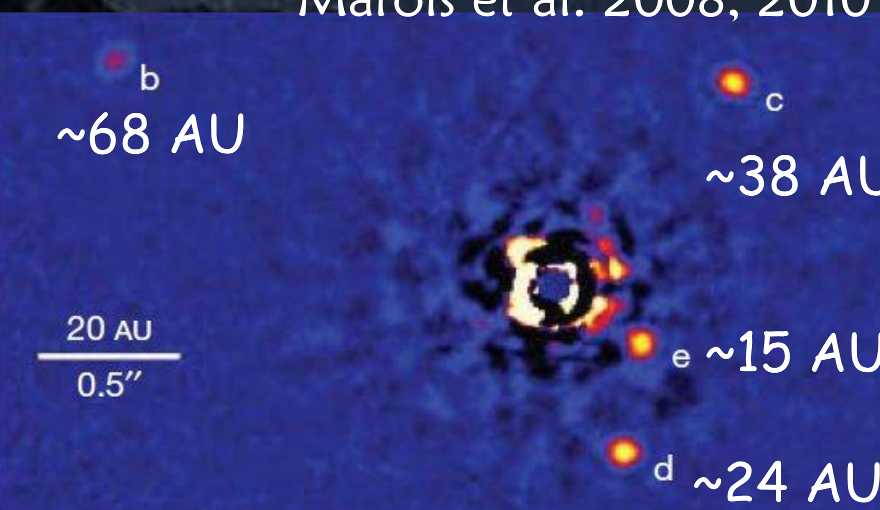
Fomalhaut   Kalas et al. 2008

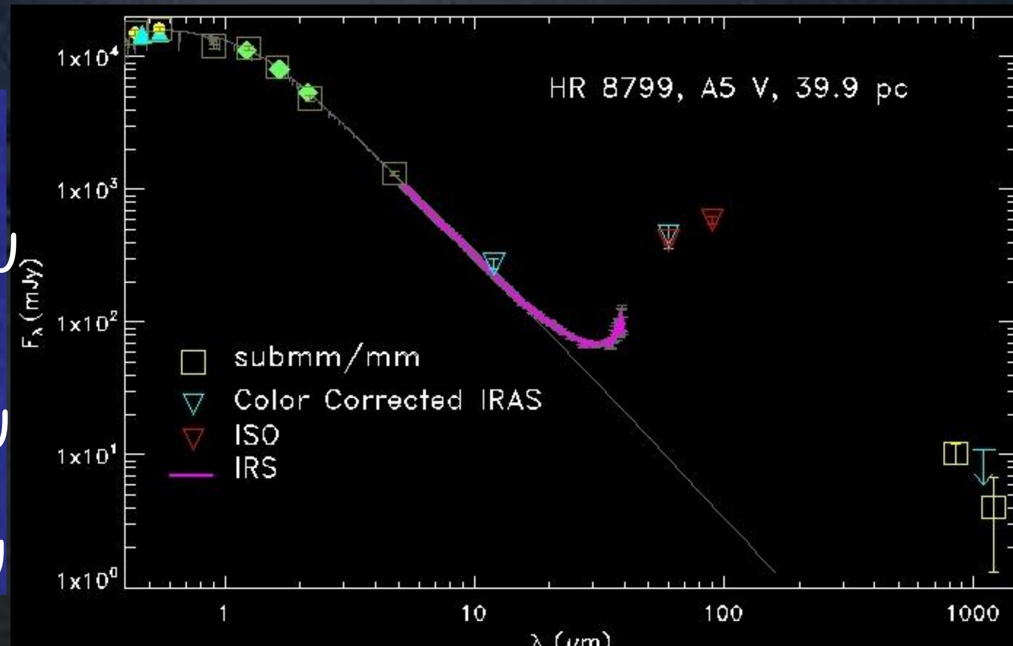


No planet >2 M_J between ~13-40 AU
Kenworthy et al. 2009



HR 8799   Marois et al. 2008, 2010

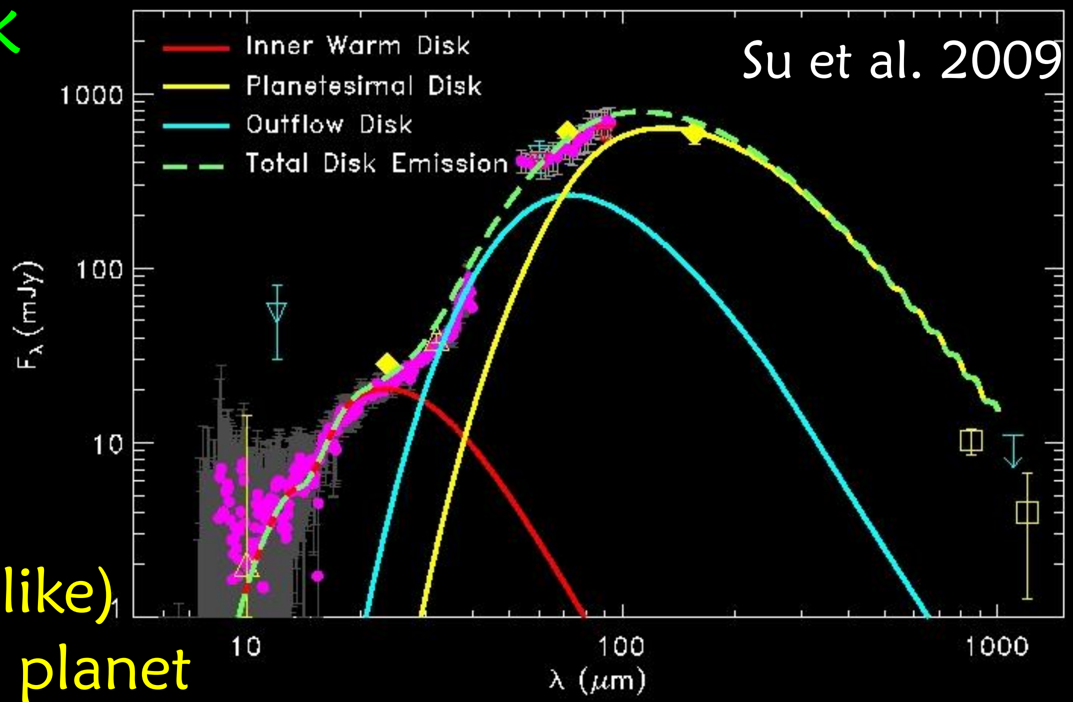


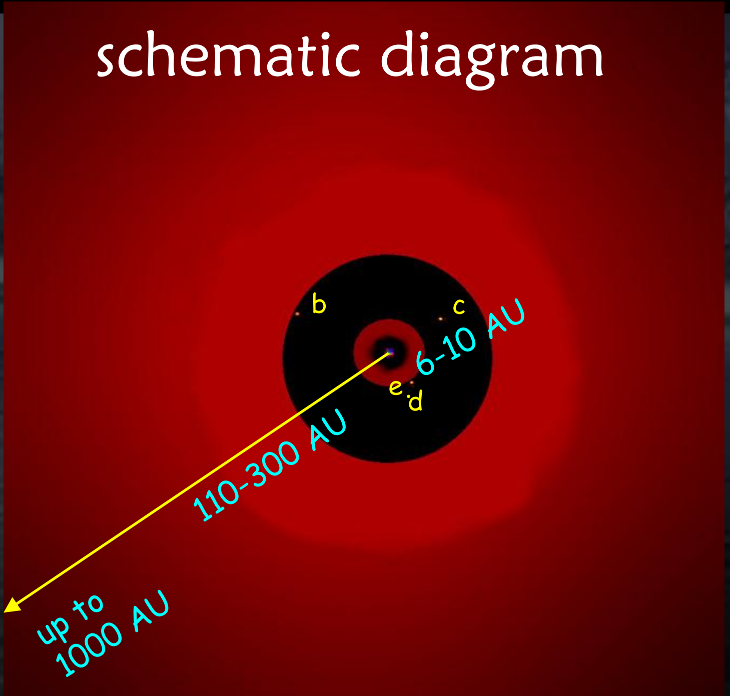


HR 8799 Debris Disk

Combining resolved images and detailed SED modeling:

- Disk is viewed nearly face-on with $i < 25°$.
- Three Component Disk:
  - inner warm (asteroid-like) belt ~6-10 AU (inside planet e)
  - outer cold (Kuiper-belt-like) planetesimal disk ~110-300 AU (outside planet b)
  - extended disk halo extended up to 1000 AU, composed of fine dust grains





Signposts for Planets beyond the Ice Line

Detailed Excess SEDs:

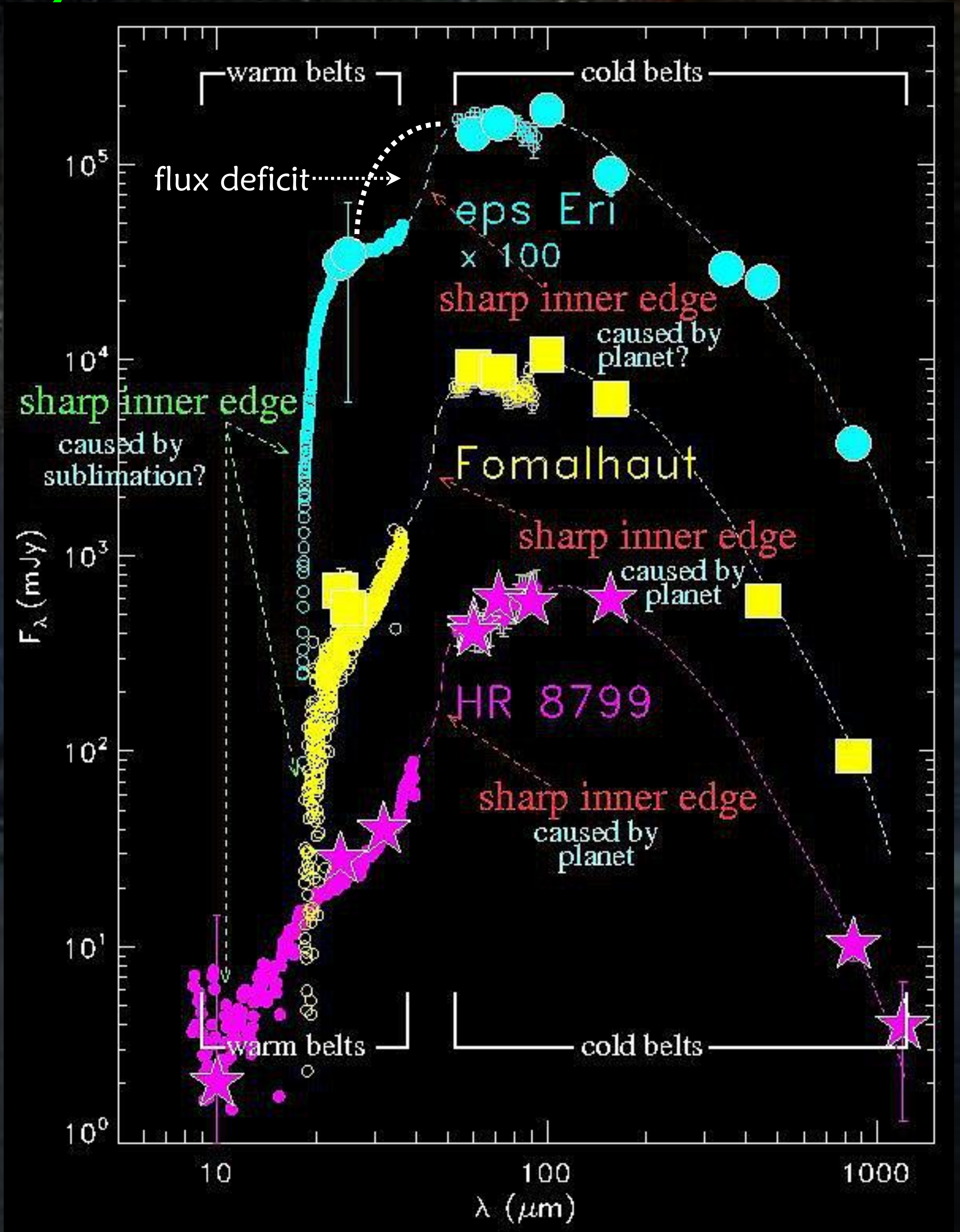
Symbols: observations

pink: HR8799; yellow: Fomalhaut;

cyan: ε Eri

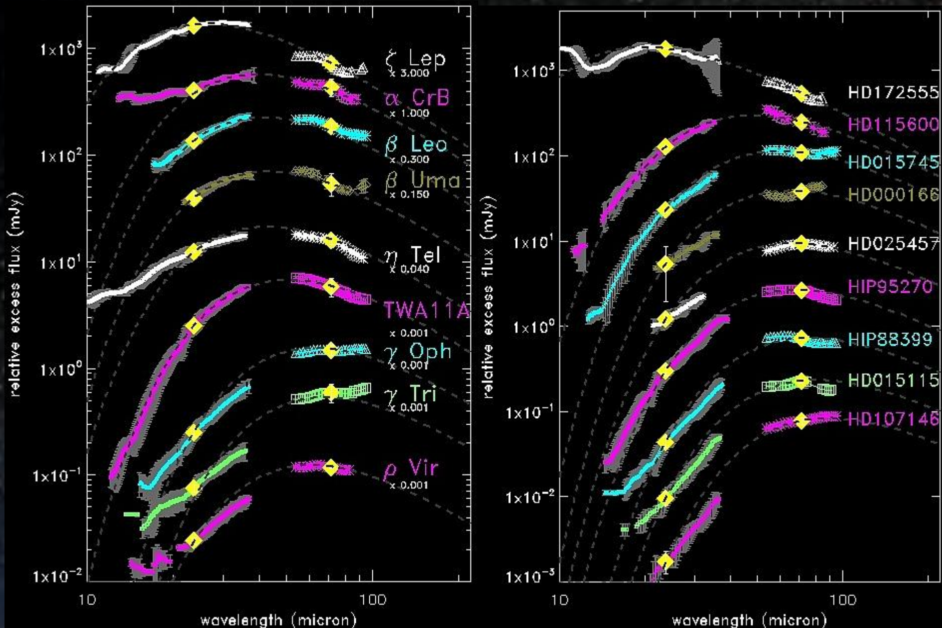
Two Sharp SED features:

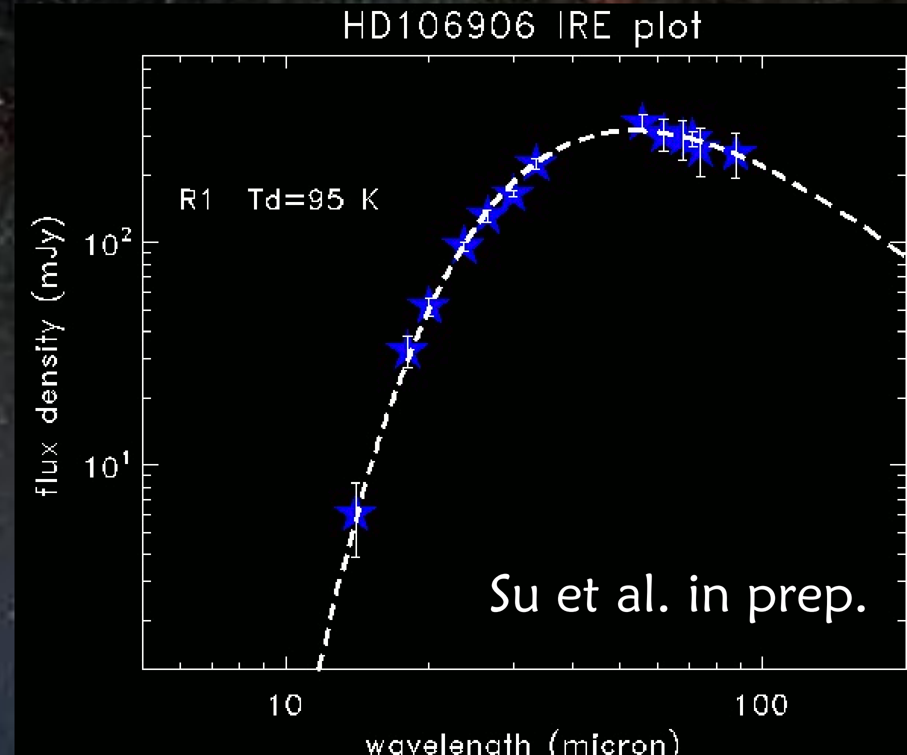
- inner disk edges of warm belt maintained by terrestrial planets? or ice sublimation?
- inner disk edges of cold belt maintained by giant planets (direct imaging in HR8799 and Fomalhaut)



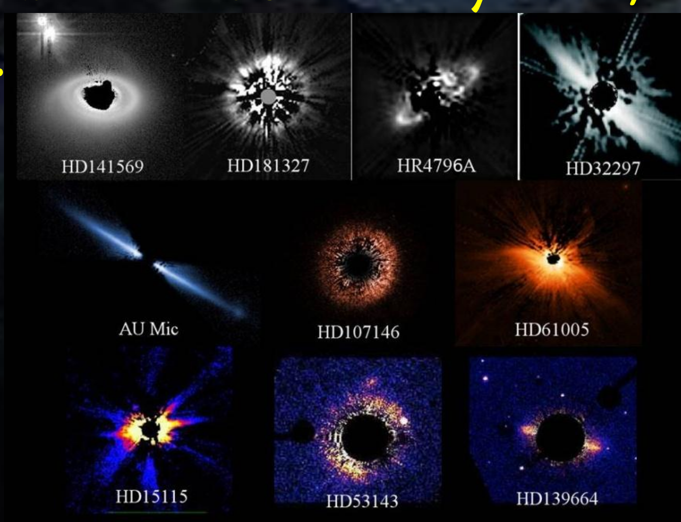
Signposts for Planets beyond the Ice Line

A sample of ~60 disks





~12 disks are resolved by HST/ submm.



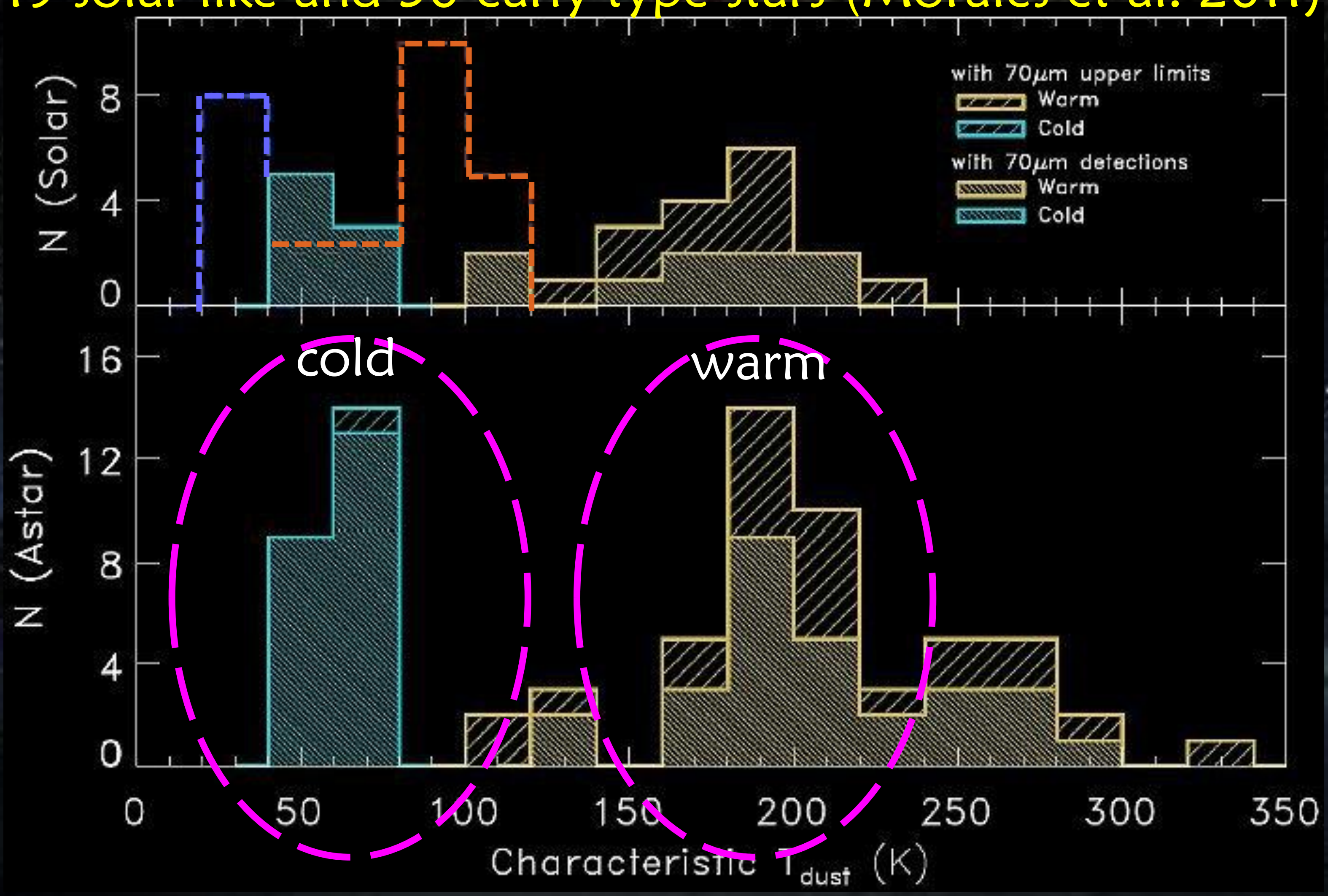
- ~50% are single-component, narrow-belt-like
- ~25% are HR8799-like

(See poster by Bailey et al.)

Other effects that influence disk structure

Similar Dust Temperature Distribution

Stars selected based on 24 μm excesses with ages <1 Gyr :
19 solar-like and 50 early-type stars (Morales et al. 2011)

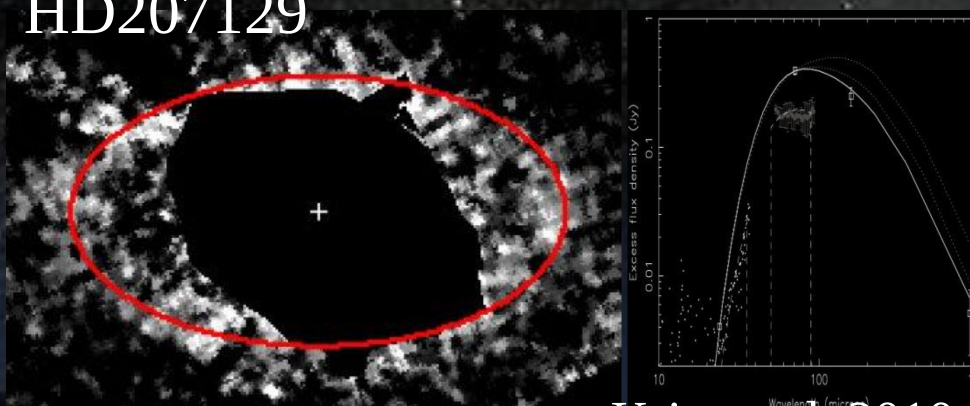


Is ice sublimation responsible?

Particle Size Distribution

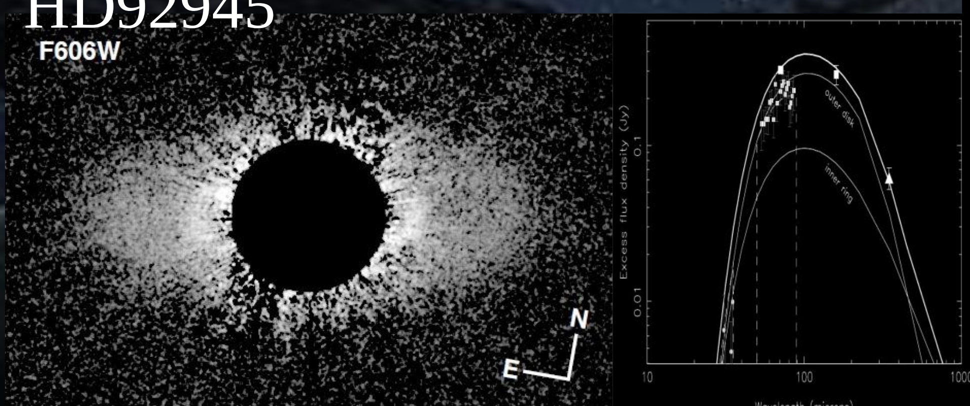
HST resolve images required a steeper ($a^{-3.7}$) power law size distribution to fit infrared SEDs

HD207129



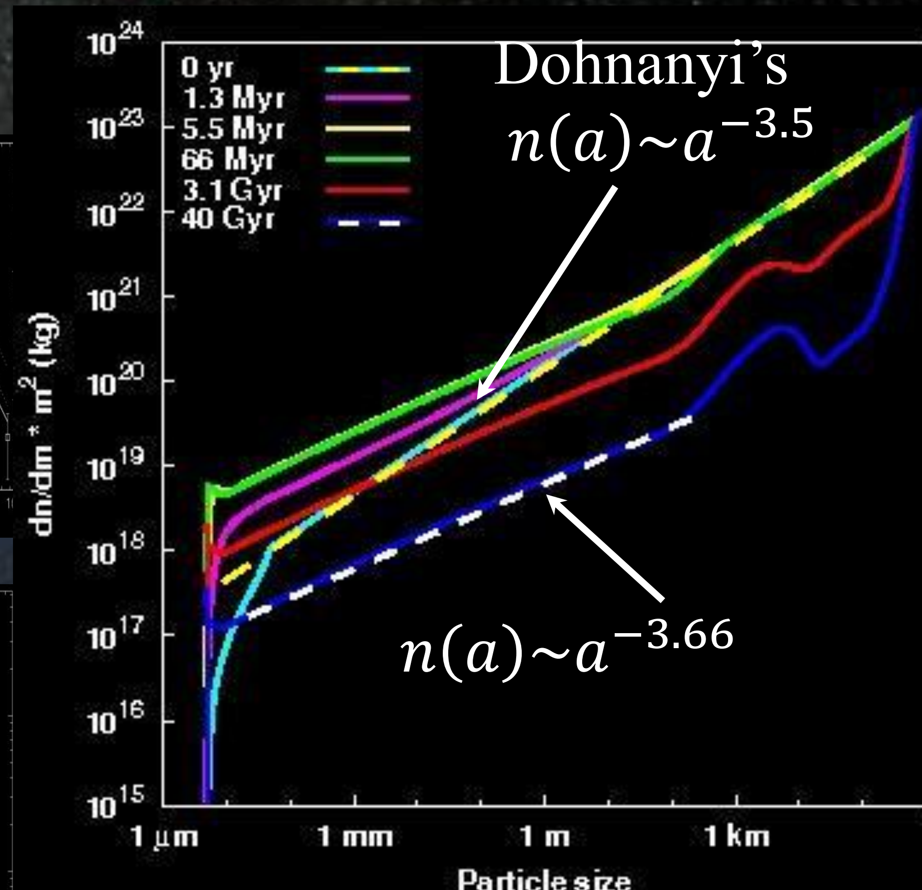
Krist et al. 2010

HD92945



Golimowski et al. 2011

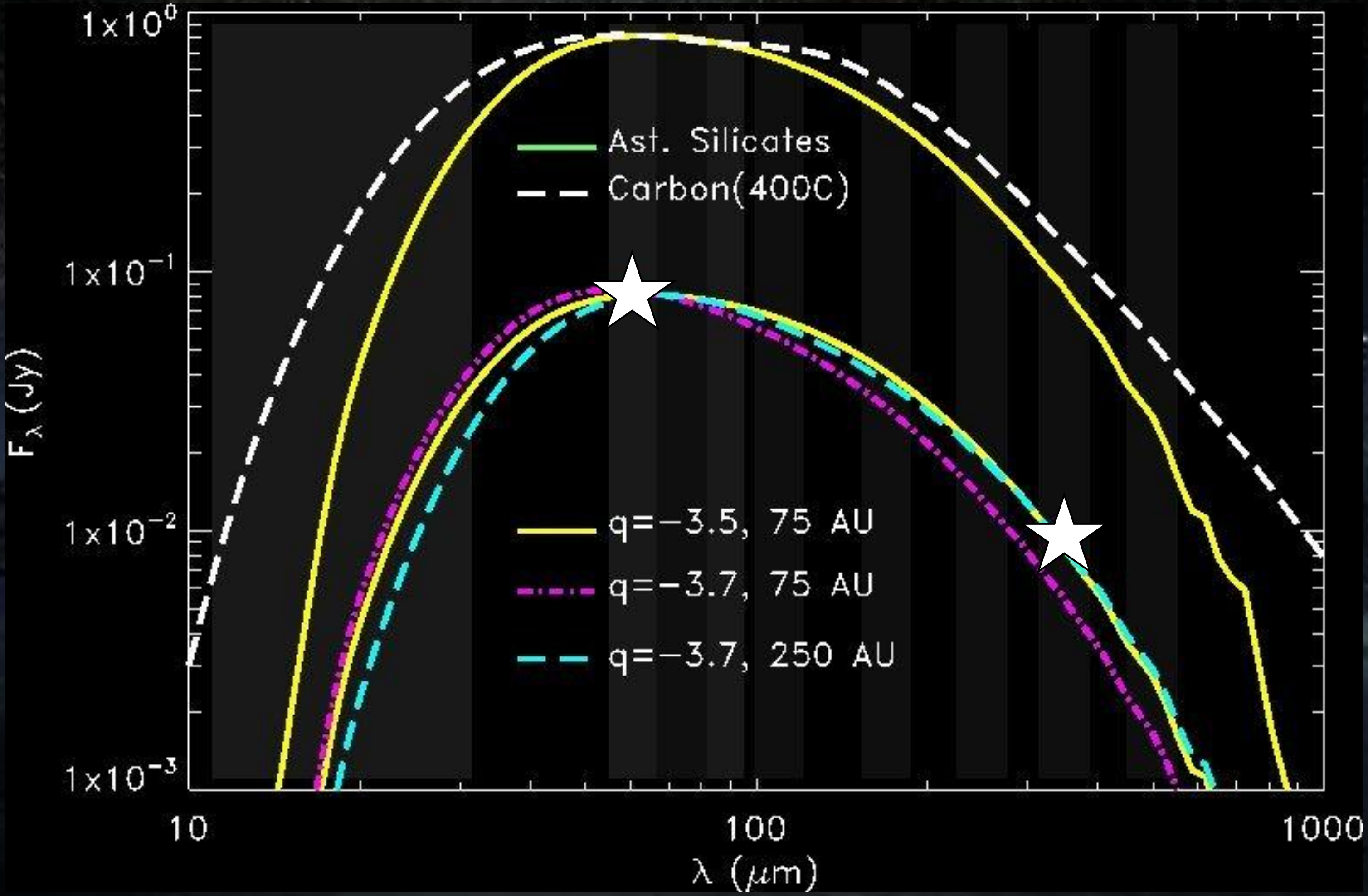
Numerical model of collision cascades by Gaspar et al. 2011



See poster by Gaspar and Wyatt et al. 2011

Particle Size Distribution

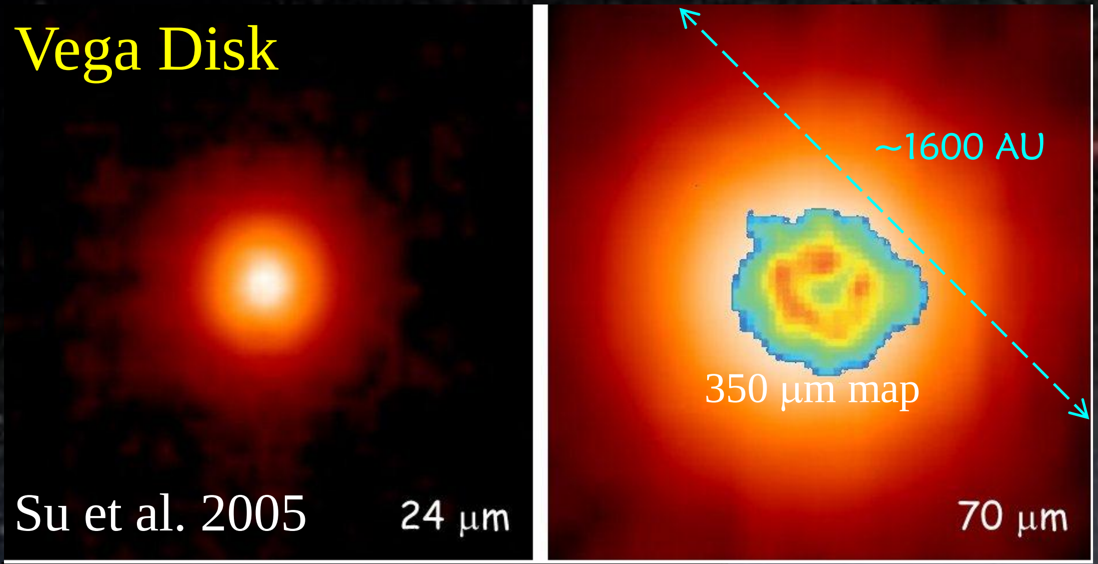
Challenges of Interpreting Observations due to unresolved sources and degeneracy of SEDs

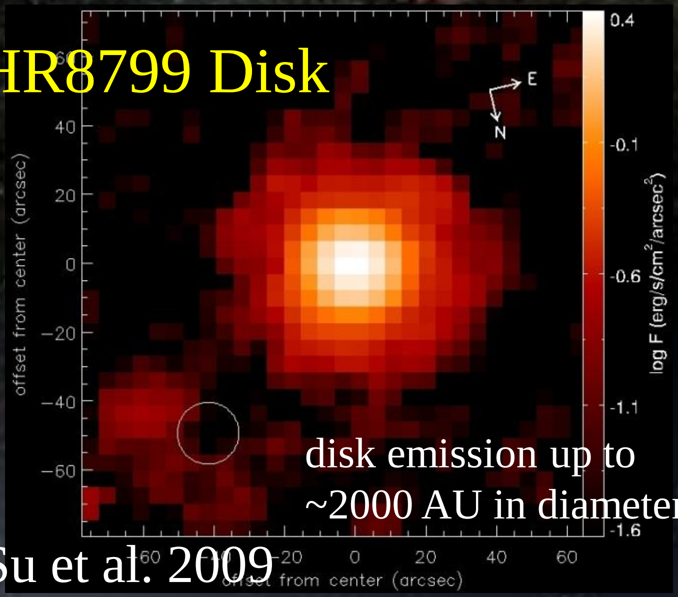


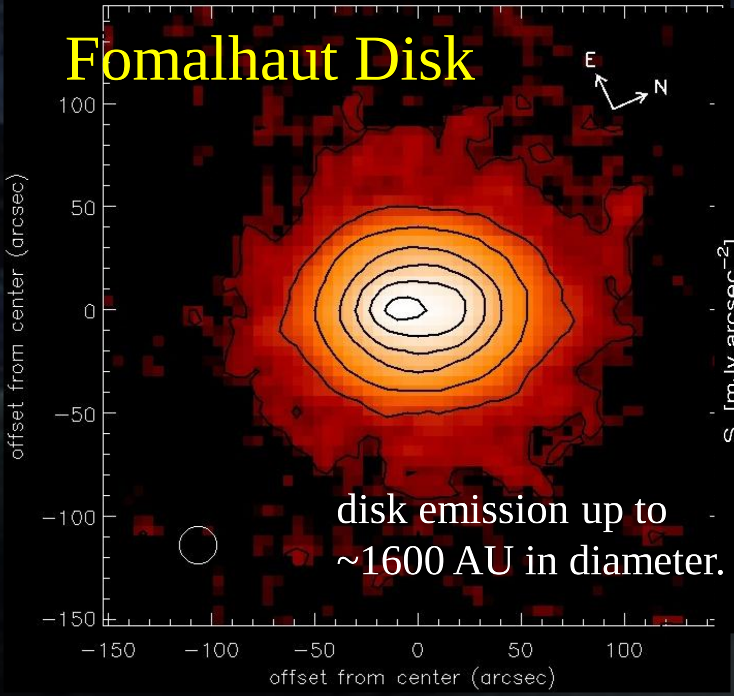
→ Need Resolved Disk Images!!

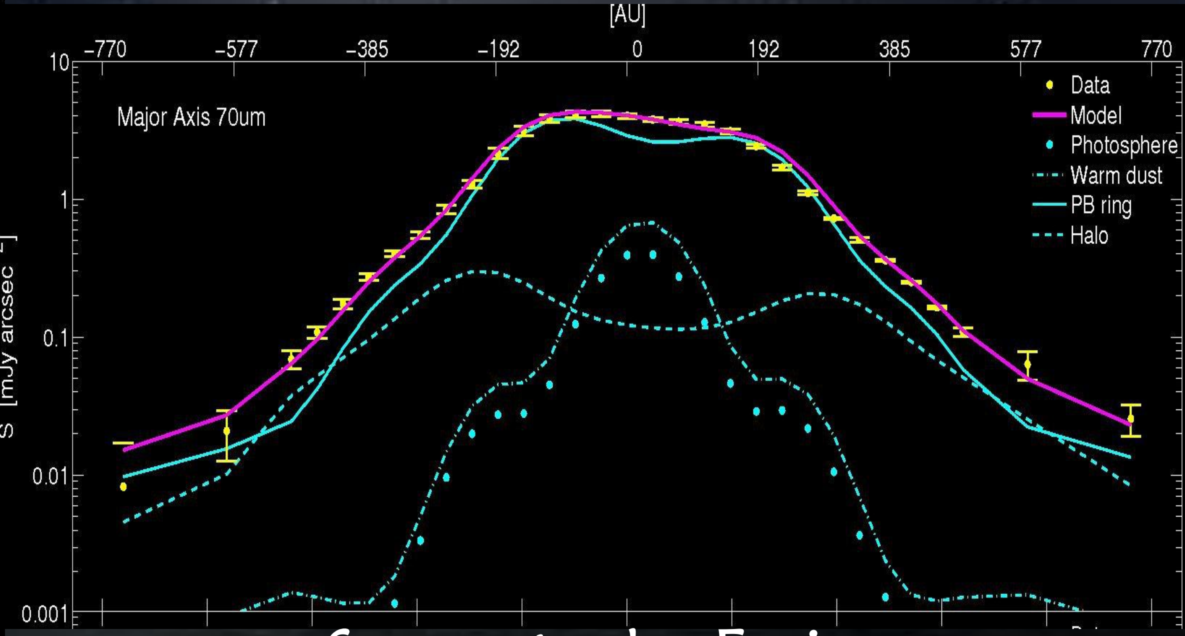
Tracing small grains: high level of dynamical activity or of large collisions among planetesimals

Extended Disk Halo Around Early-type Stars





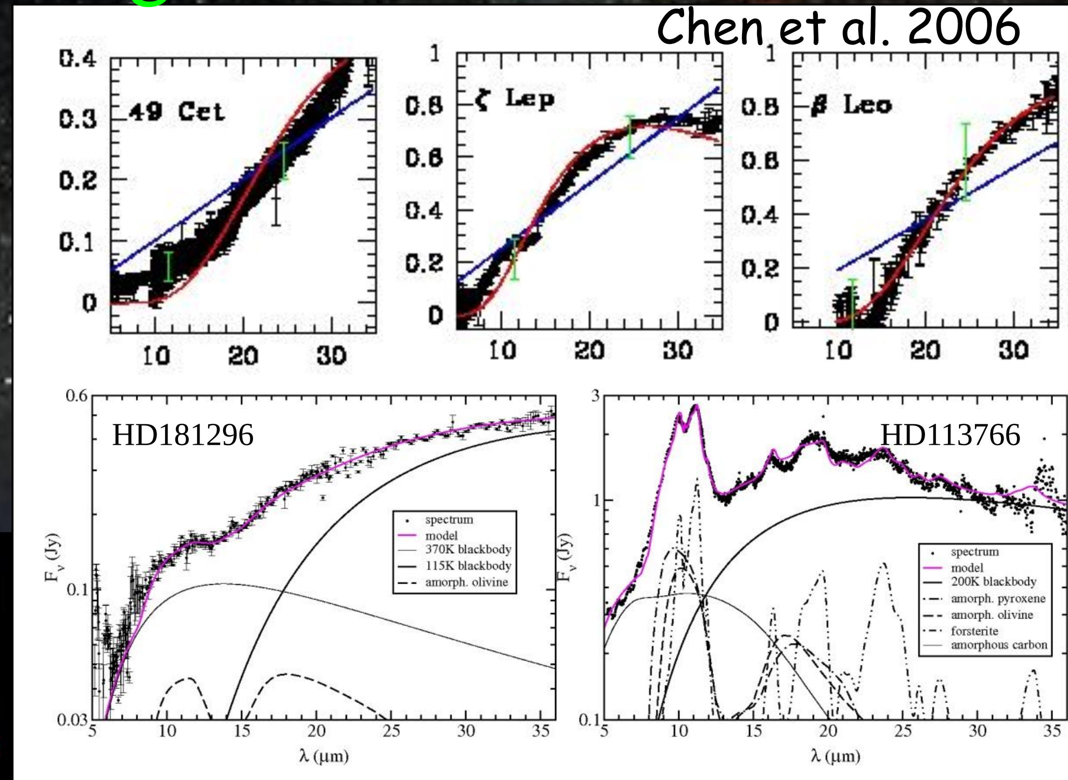




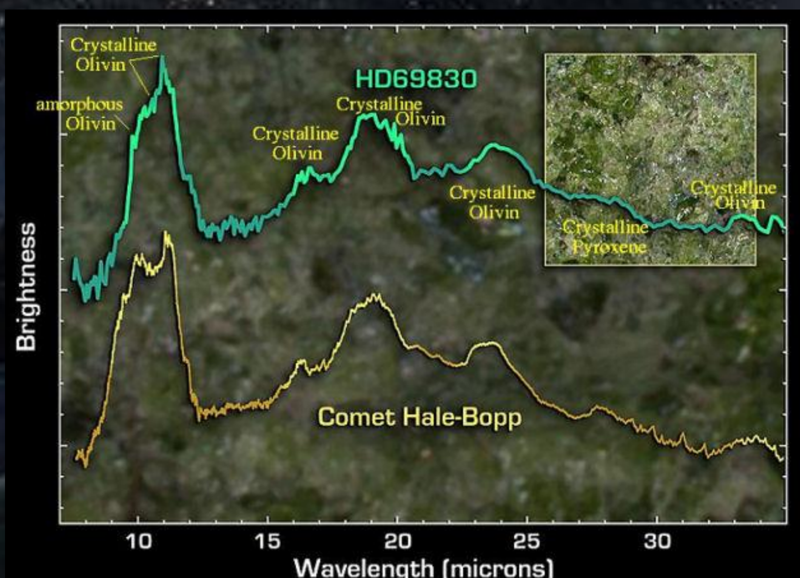
See poster by Espinoza

Signs of High Level Stirring

- most disks show featureless dust continuum, only a few% MIR spectra show solid-state features indicating the presence of small grains.

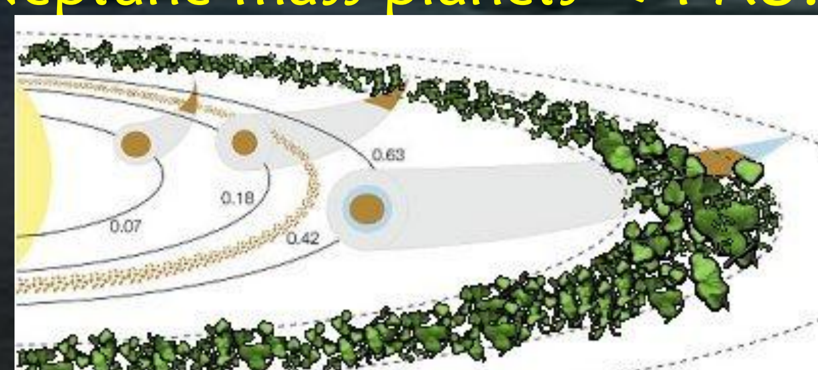


transient events in 2 Gyr old K0V HD69830?

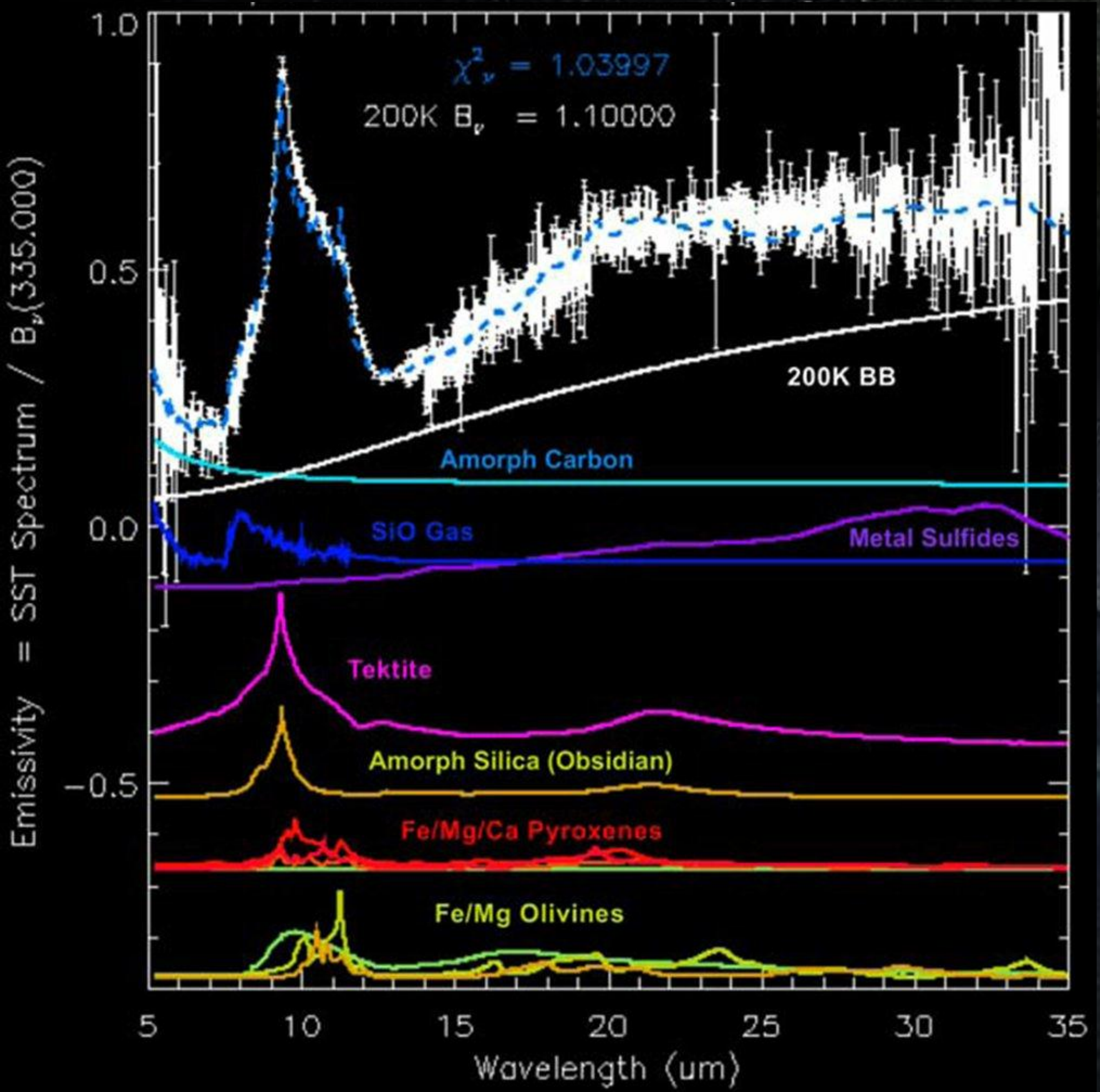


Sub-μm amorphous and crystalline silicate grains at ~ 1 AU (Beichman et al. 2005, Lisse et al. 2007)

Lovis et al. (2006) later report 3 Neptune-mass planets < 1 AU.



Signs of High Velocity Collisions

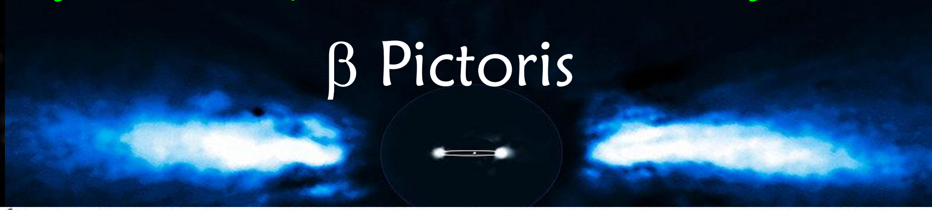


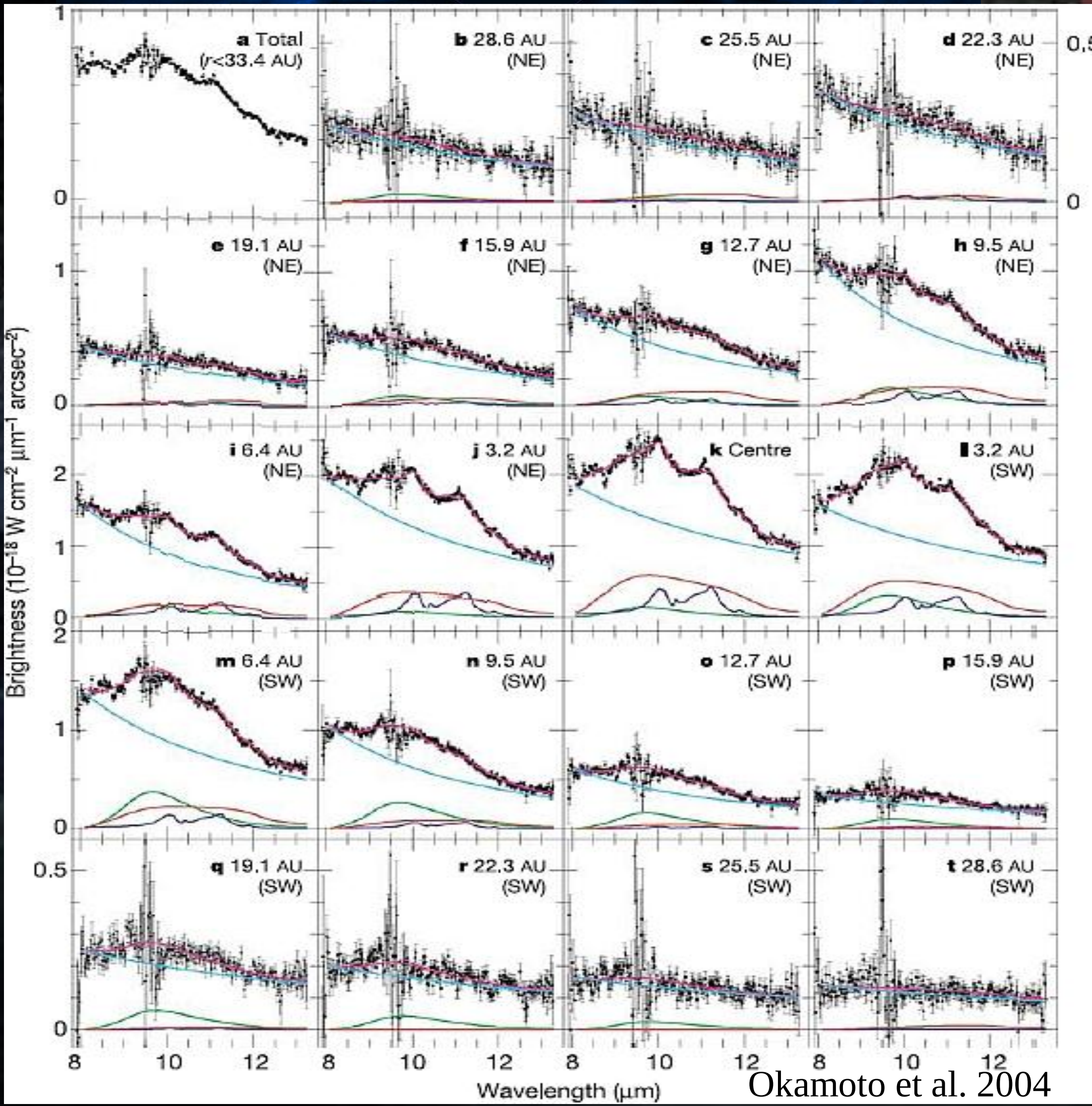
Detailed mineralogical study can constrain the nature of the collisions.

The signatures of dust condensation from silicon oxide vapor (silica) and SiO gas (products of collisons with v_{vel} >10 km/s, a lunar formation impact) are found in HD 172555 (Lisse et al. 2009).

Future Prospect in Debris Disk Studies using MIRI/JWST

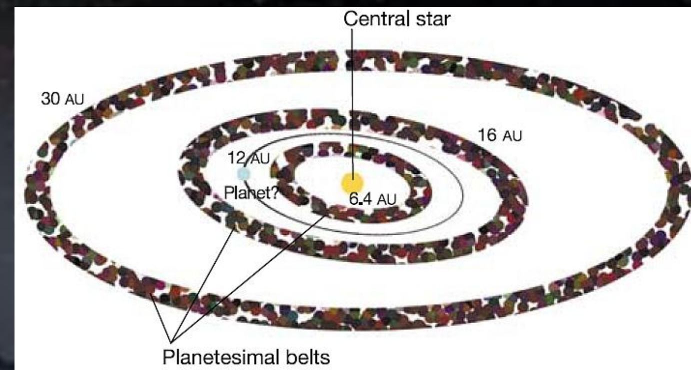
Spatially Resolved Spectroscopy





Okamoto et al. 2004

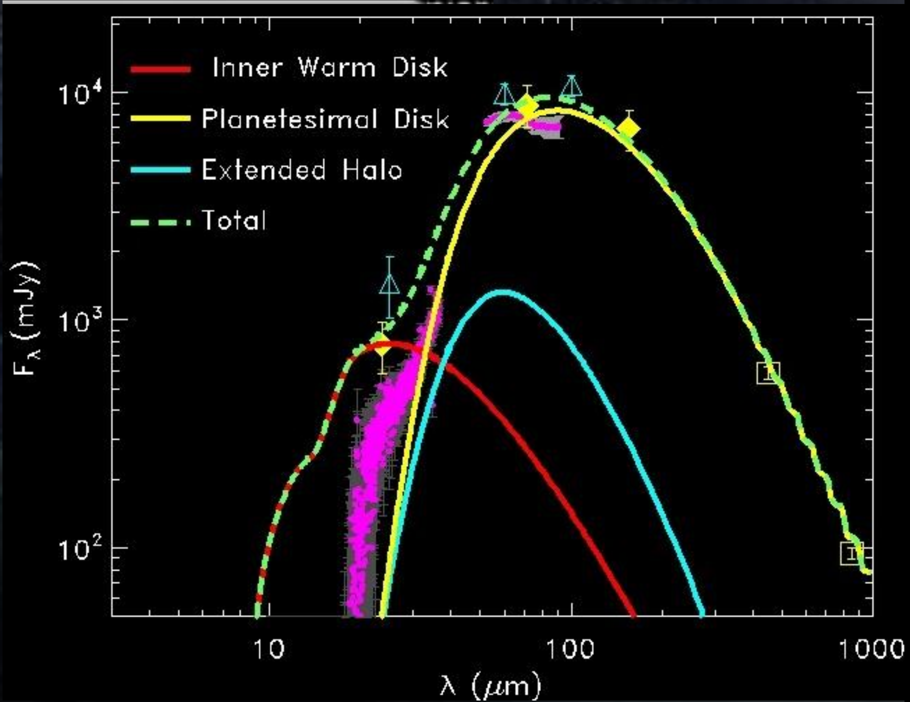
MIRI Spectrometer (MRS): high spatial (0.23") and spectral (R=2200~3500) resolution.

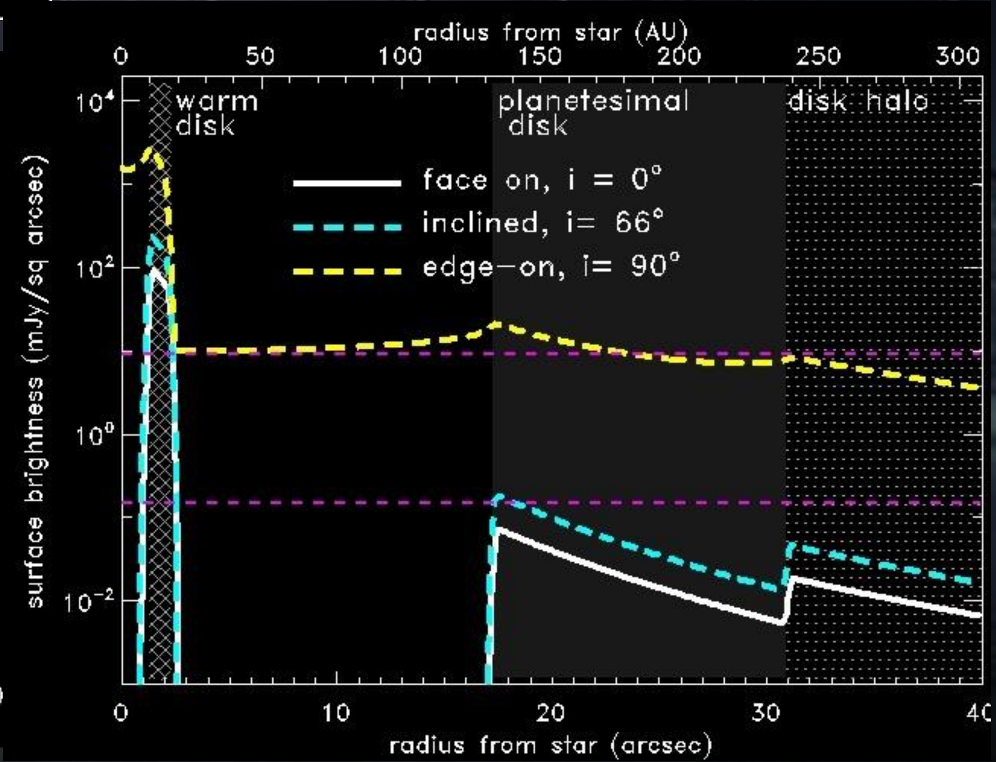


Spatially spectroscopic studies around β Pic disk: Crystalline grains are concentrated near the center where terrestrial planets are being built.

Resolving Terrestrial Planet Formation Zone

Resolving inner disk structure
Questions to answer:
- location the inner belt(s)
- asymmetry? sharpness?





Conclusions and Future Prospects

- Decay of Debris Disk Activity
  - Slow evolution of excesses at 70 μm (material beyond the snow line.
  - Rapid drop in 24 μm excess incidence (<1 Gyr) (material inside the snow line) for both A-type and solar-like stars.
- Disk Structures (Inner and Outer Zones)
  - Broad range of dust temperatures
  - Similarity of warm disk temperatures for early-type and solar-like stars suggests a role for the ice line in disk structure.
- Resolved Disks + Detailed SEDs
  - Disks and directly imaged planets
  - A general behavior pattern in disk SEDs for planets beyond the snow line?

Conclusion and Future Prospect

- High Levels of Dynamic Activity: Small Grains
  - Bright halo associated with early-type stars as indication of higher levels of dynamical stirring
  - A handful (rare) cases show presence of Crystalline silicates, suggesting lunar-like impact even is rare.
- Future Prospects
  - Herschel: PACS 70 μm observations are resolving many cold debris disks.
  - All sky infrared survey like AKARI and WISE is adding more debris disk candidates for future follow-ups.
  - MIRI/JWST will provide both high spatial and spectral resolution studies of debris disks at 5-25 μm to understand the terrestrial planet formation zone.
  - Other great opportunities: NIRCam/JWST, ALMA…