Placing our Solar System in Context

Summary Results from the FEPS Spitzer Legacy Science Program

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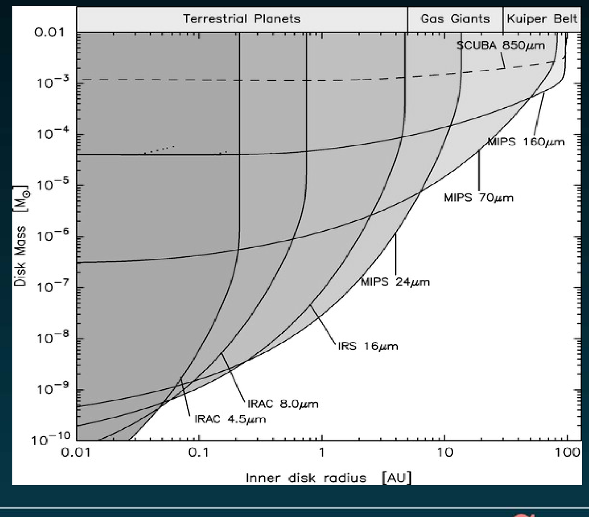

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Summary

We summarize results from the Formation and Evolution of Planetary Systems (FEPS) Spitzer Legacy Science Program (Meyer et al., 2006). FEPS obtained Spitzer observations of 336 Sun-like stars with ages from ~3 Myr to ~3 Gyr, constructing spectral energy distributions (SEDs) from 3-160 microns including 5-35 micron spectrophotometry, and obtaining for a subset of the stars higher resolution mid-infrared spectra. The SEDs yield constraints on the geometric distribution and mass of dust while the spectra enable a search for emission from gas in circumstellar disks. We investigate both gas and dust as a function of stellar age. Our main goals were to study the transition from primordial to debris disks at ages < 100 Myr, to determine the lifetime of gas-rich disks in order to constrain theories of Jupiter-mass planet formation, and to explore the diversity of planetary architectures through studies of debris disk diversity. We summarize here the results including: 1) the lifetime of inner disks emitting in the IRAC bands from 3-30 Myr (Silverstone et al. 2006); 2) dust mineralogy in primordial disks (Bouwman et al. 2008); 3) limits on the lifetime of gas-rich disks from analysis of a IRS high resolution spectral survey (Pascucci et al. 2006; Pascucci et al. 2007), 4) detection of warm debris disks using MIPS 24/IRS as well as HST follow-up (Hines et al. 2006, 2007; Meyer et al. 2008); 5) physical properties of old, cold debris disk systems detected with MIPS 70 (Kim et al. 2005, Hillenbrand et al. 2008); and 6) exploration of the connection between debris and the presence of radial velocity planets (Moro-Martin et al., 2007ab). A synthesis of final statistical results from our program can be found in Carpenter et al. (2009, in press).

Sample

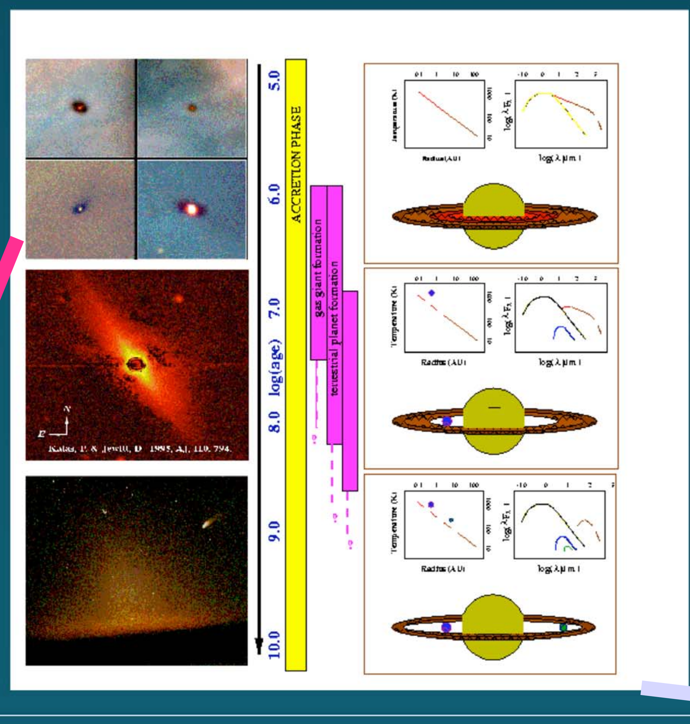
Age Bin	Nstars	Distance	Regions
3-10 Myr	50	80 - 60 pc	Tau, Oph, Cha, Lup, Upper Sco
10-30 Myr	60	60 - 160 pc	Tau, Oph, Cha, Lup, Cen Crux
30-100 Myr	65	40 - 180 pc	IC2602, α Per, Field
100-300 Myr	65	20 - 120 pc	Ursa Major, Castor, Pleiades, Field
0.3-1 Gyr	65	20 - 60 pc	Hyades, Field
1-3 Gyr	50	20 - 60 pc	Field

Overall FEPS Goals

- Characterize transition from primordial to debris disks
- Constrain timescale of gas disk dissipation
- Examine the diversity of planetary systems
- Address *Is our Solar System common or rare?*

[See FEPS program plan by Meyer et al. (2006)]

From Protoplanetary Disks to Mature Planetary Systems



Primordial Disks:
- gas rich; dust dynamics dominated by gas
- opacity dominated by primordial grains
- grains grow

Transition Disks:
- gas/dust clearing
- opacity drops as planetesimals grow

Debris disks:
- gas poor; dynamics dominated by planets
- opacity dominated by 2nd generation grains produced via collisions of planetesimals.
- stellar radiation and stellar winds remove small grains on time scales shorter than stellar age.

[See review by Meyer et al. (2007)]

Spitzer Observations

IRAC imaging photometry at 3.6 µm, 4.8 µm, 8.0 µm
IRS spectrophotometry from 5 - 35 µm plus limited higher resolution spectra
MIPS imaging photometry at 24 µm, 70 µm, 160 µm

Debris Disk Models

Dust models are based on color temperatures of excess flux measured in IRS and MIPS bands. Relations between grain temperature, orbital radius, and stellar luminosity (Backman & Paresce 1993) are adopted for modified blackbody grains between the blow-out size (~0.3 um) up to large bodies (bigger than the wavelengths of observation). Lack of data beyond the peak of emission prevents characterization of outer boundary (R_{OUT}). Information from mineralogical features can help characterize grain properties (Bouwman et al. 2008), which then allows use of more sophisticated dust models (Wolf & Hillenbrand, 2003). Total disk masses are uncertain depending on grain properties such as radius and density (and lower limits going as the square-root of the maximum particle size). For all debris disks detected here the dynamics of dust are dominated by mutual collisions and grain lifetimes are much shorter than the ages of the stars.

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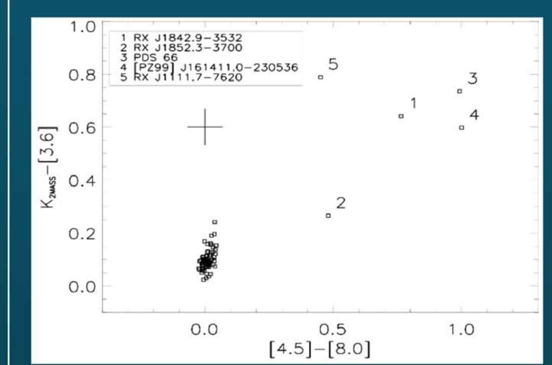
Dissipation of Primordial Dust and Gas-Rich Disks

(Bouwman et al. 2008; Silverstone et al. 2006; Pascucci et al. 2006, 2007; Hollenbach et al. 2005)

- Age range: 3 - 15 Myr
- Among the 74 sources 3-30 Myr analyzed for continuum excess emission, only 5 gas-rich primordial disks are detected in the IRAC bands,with 4/5 aged <10 Myr.
- With only 12% of 3-10 Myr sources in our sample having IRAC excesses, we conclude that optically-thick disks at 0.3-3 AU typically dissipate in < 3 Myr.
- Lack of gas emission-line detections in 15 stars 3-300 Myr old limit the timescale for gas giant and ice giant planet formation as well migration scenarios for the evolution of protoplanetary orbits.
- [Ne II] emission detected around a handful of young primordial disks may trace photo-evaporation mechanisms of disk dissipation.
- IRS spectra indicate correlation between disk geometry (flaring) and grain growth, as well as compositional gradients in primordial disks.

Figure 1:
2MASS-IRAC Color-Color Diagram

- 74 young FEPS targets from (Silverstone et al. 2006).
- Five apparent excess objects are optically-thick disks.
- The lack of sources with optically-thin excess places constraints on the during of the transition time between thick and thin between 0.3 and 3 AU.



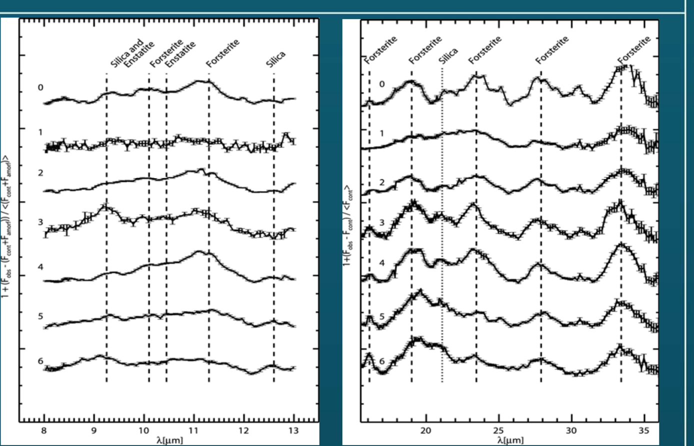


Figure 2:
IRS Low Resolution Spectra

- Mineralogical features are seen in 6 FEPS targets plus 1 extra.
- The silicate dust grains have grown to sizes at least 10 times larger than observed in the interstellar medium and show evidence for a non-negligible (5% mass fraction) contribution from crystalline species (Bouwman et al. 2008).

Figure 3:
IRS High Resolution Spectra

- Six young optically thick disks including all 5 highlighted in Figure 1.
- Four of six show [Ne II] emission with detections favored towards sources with low levels of continuum excess Pascucci et al. 2007).
- 3-sigma upper limits are shown in blue.
- Origin of line excitation is by x-ray and EUV photons. (

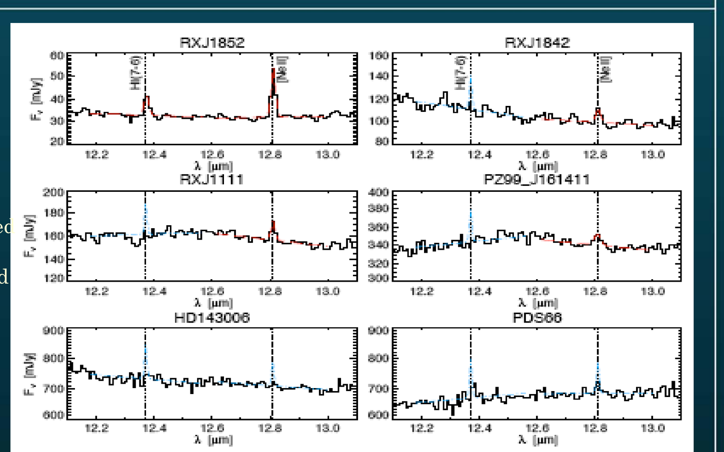
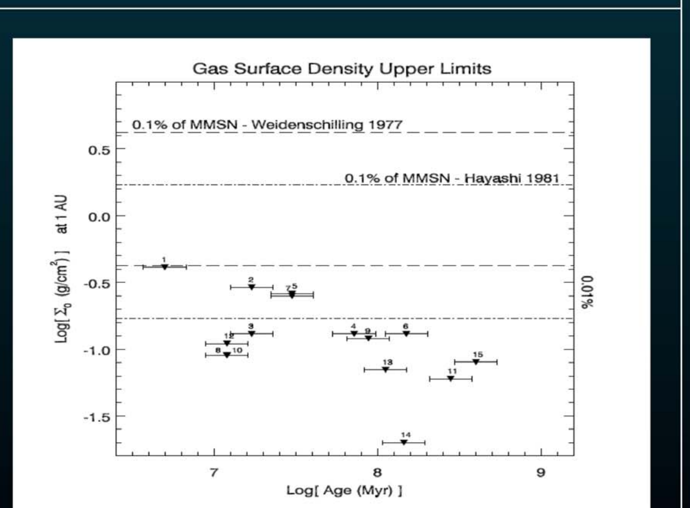


Figure 4:
Gas Surface Density Upper Limits From Gas Line Non-detections

We searched for emission lines of H2, [FeII], [SI], and [SiII] using the high resolution mode of the Spitzer IRS, as well as sub-mm lines of CO with the SMT in Arizona. No emission lines were detected. Applying the models of Gorti and Hollenbach (2004) and following Hollenbach et al. (2005) we placed upper limits to the gas surface density for 15 FEPS targets with optically-thin (or lacking) dust disk signatures. The ages of the targets ranged from 3-300 Myr. Our results suggest that there is not enough gas in these systems to form gas giants (Jupiter mass), nor ice giants (Neptune mass). Furthermore, it is unlikely there is enough gas left in the terrestrial planet zone (0.3-3 AU) to damp eccemtricities of forming proto-planets as requred in some models (Pascucci et al. 2006).



Warm Disks

(Carepenter e al. 2009; Meyer et al. 2008; Hines et al. 2006, 2007)

- Age range: <10 Myr – 3 Gyr
- 24 µm excess detections identified through [8] – [24] µm colors.
- Dispersion in locus of colors for non-disked sources sets 3-sigma limits at $\sim10^{-4} - 10^{-6}$ M_{Earth}.
- ~15% of solar type stars < 300 Myr have warm debris disks while only 3% of older stars do.
- Dust temperatures T~50-200K are typical with evidence for both cool and warm components in those sources detected at 70 µm. Corresponding R_{INNNER} > 5 - 50 AU.
- Several unusual objects having very warm or outwardly truncated debris are identified.
- HD 61005: is the brightest mid-IR excess within the FEPS sample. It was later resolved using HST high contrast imaging and has morphology suggesting interaction with the ISM.

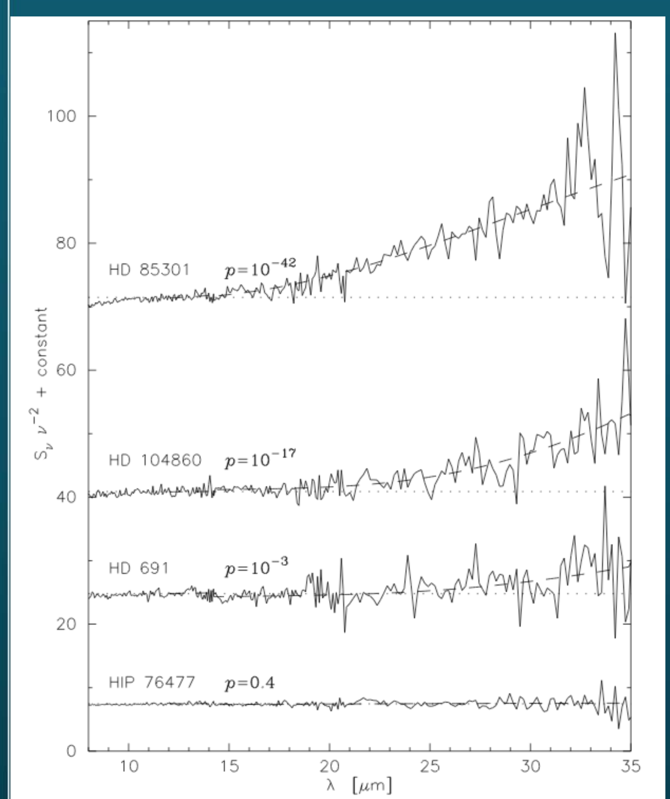


Figure 5: IRS Spectrophotometry
The F-test is used to distinguish excess sources from those consistent with Kurucz photosheres (Carpenter et al. 2009).

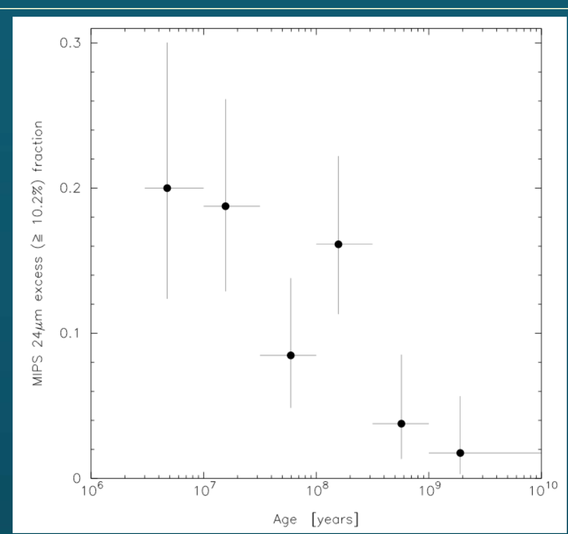


Figure 7:
Evolution of Terrestrial Temperature Debris Around Sun-like Stars

The fraction of objects in the unbiased FEPS sample of 314 stars with detected 24 micron excess emission, plotted as a function of stellar age. The mid-infrared excess is thought to arise from collisional processes similar to those that gave rise to the terrestrial planets in our Solar System (e.g. Kenyon & Bromley, 2006; Currie et al. 2008). As we observe only the product of the excess frequency and its duration, the data can be interpreted in two ways: either the phenomenon of excess emission is long-lived (30-300 Myr) and uncommon (10-20 %) or the phenomenon is short-lived (3-30 Myr) and the fraction passing through the excess phase is high (> 60 %). If the latter is correct, these data suggest that many, if not most sun-like stars could harbor terrestrial planets (Meyer et al. 2008).

A fully integrated analysis of the distribution of dust around solar type stars as a function of dust temperature and stellar age appears in Carpenter et al. (2009).

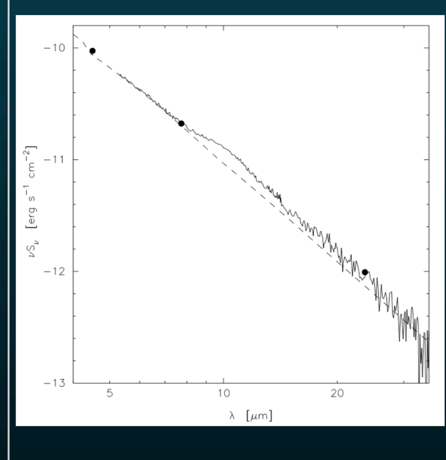


Figure 6: Peculiar warm SED of 1RXS J051111.1+281353
The Spitzer IRS spectrum and IRAC/MIPS photometry are compared to a Kurucz photosphere. (Carpenter et al. 2009).

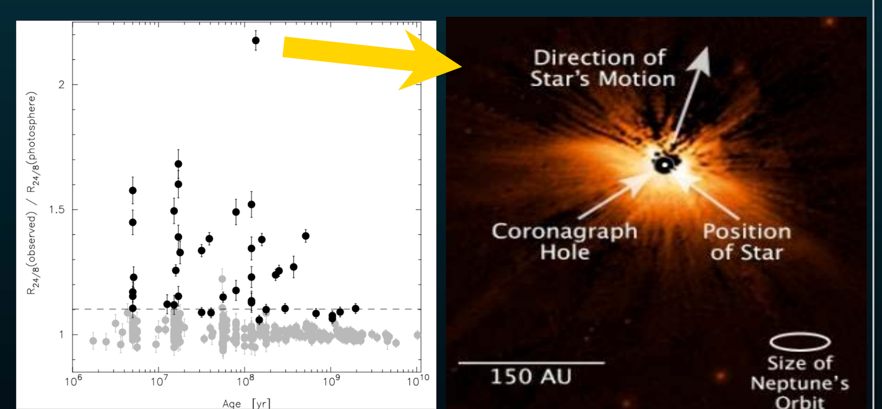


Figure 8: HST/NICMOS image of HD 61005
The disk is seen in scattered light using the coronagraph. The morphology suggests interaction with the ISM (Hines et al. 2007). It is the brightest 24 µm excess in FEPS.

Cold Kuiper Belt-like disks

(Carpenter et al. 2009; Hillenbrand et al. 2008; Moro-Martin et al. 2007a,b Kim et al. 2005)

- Age range: 300 Myr – 3 Gyr
- 70 µm excesses identified through [24] – [70] µm colors and Kurucz model comparison.
- Kuiper-Belt like debris in 31 sources based on 70 µm excess, confirming 10 from IRAS / ISO.
- ~10% of solar type stars have cold debris disks.
- Typical grains with a_{dust} ~10 µm imply P-R drag time scales ~2 – 30 Myr.
- Radiation blowout sizes $a_{MIN,\ silicate}$ ~0.3 – 0.7 µm imply few small grains.
- Dust optical depth ~ L_{dust}/L_* ~10^{-4}-10^{-5} and M_{dust} ~10^{-10}–10^{-11} M_{Sun} from blackbody models.
- R_{INNNER} > 20 - 30 AU based on photometry only.
- Evidence for *extended* debris disks based on multiple temperature components in excesses.

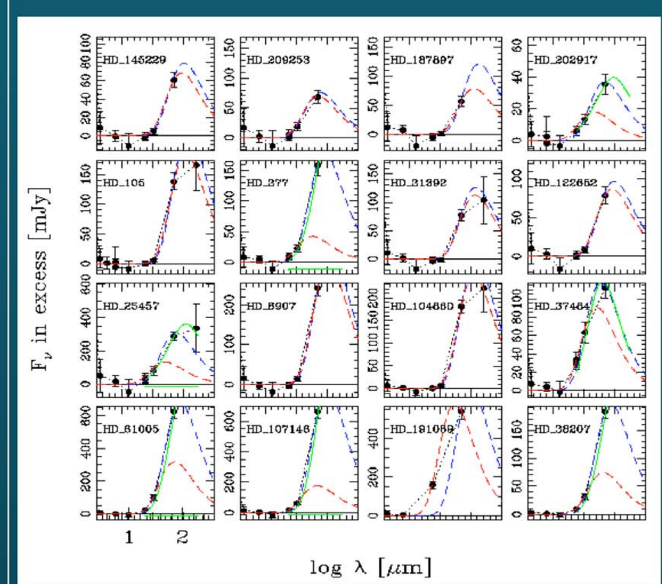


Figure 9:
Excess emission distributions for several of the cold debris disk sources.
Residual Spitzer emission after removal of stellar contribution. The blue lines are fits to the 33-70 µm excess while the red lines are fits to the 24-33 µm emission; differences indicate multi-temperature dust (except for HD 191089 for which there is missing data). The green lines are composite disk fits when excess emission is detected at three or more wavelengths.

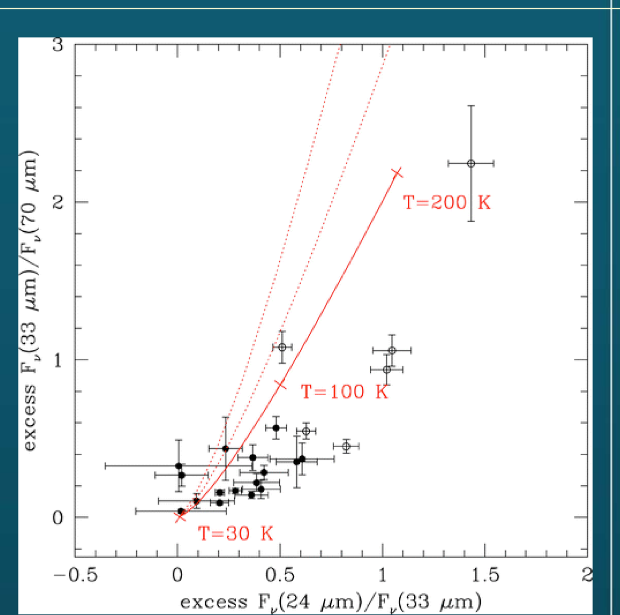


Figure 10:
Warm Dust vs. Cool Dust - Extended debris
Blackbody (red solid line) and modified blackbody (red dotted lines) temperature sequences from 30 to 200 K compared to measured flux ratios for FEPS disks. Although most objects are within 1-2 σ of the expected blackbody relationship, the systematic offset suggests that such single-temperature models may not be the most appropriate models. Rather than narrow rings, many of the FEPS disks appear extended (Hillenbrand et al. 2008).

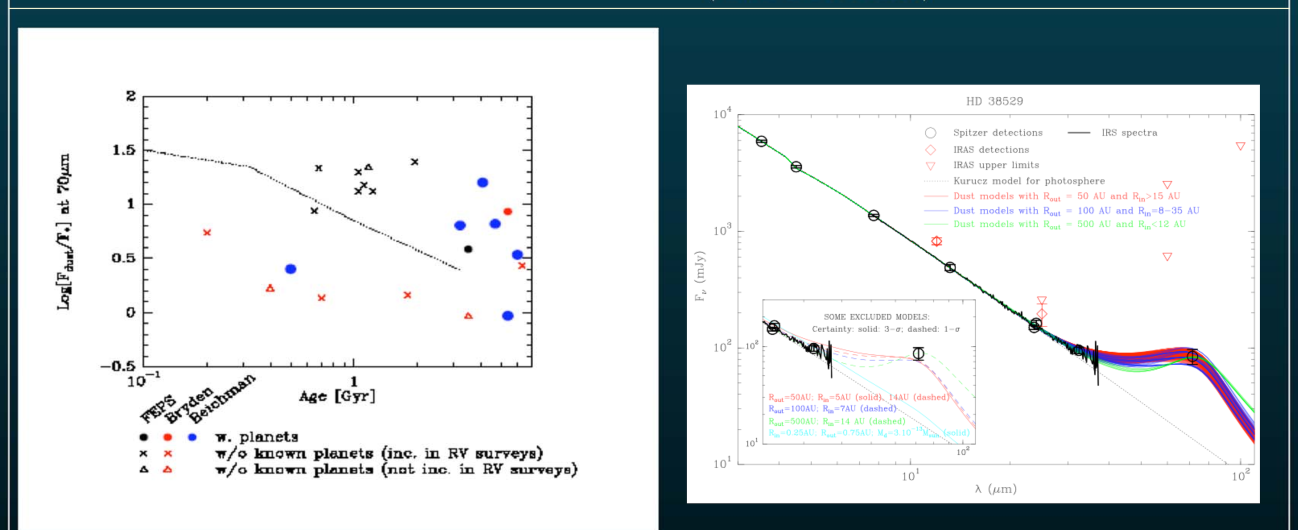


Figure 11: No correlation of dust excess for stars with and without planets:
While there was a preliminary suggestion of correlation between the presence of a planet and the frequency and magnitude of detected debris dust from Beichman et al. (2005), we are unable to confirm such based on statistical analysis of both the Bryden et al. (2006) and FEPS samples (Moro-Martin et al. 2007a). The frequency of massive debris disks (>100 times solar system levels) in both samples is 10-15 % regardless of the presence of known radial velocity planets. This is consistent with the notion that the conditions to generate debris -- presence of planetesimal belts with at least one large oligarch -- are less stringent than those required to form gas giant planets. Solid line model in left panel from Kenyon and Bromley with attached uncertainty estimated at an order of magnitude. One planet host star in the FEPS sample, HD 385289 (shown at right) has a debris disk at 70 microns with modeling of the a = 0.13 and 3.74 AU, Msin*i* = 0.8 and 12.2 $M_{Jupiter}$ planet impact on dust disk dynamics carried out by Moro-Martin et al. 2007b.