ExoZodical Emission and Challenge and Opportunity for The Detection of ExoPlanets

C. Beichman

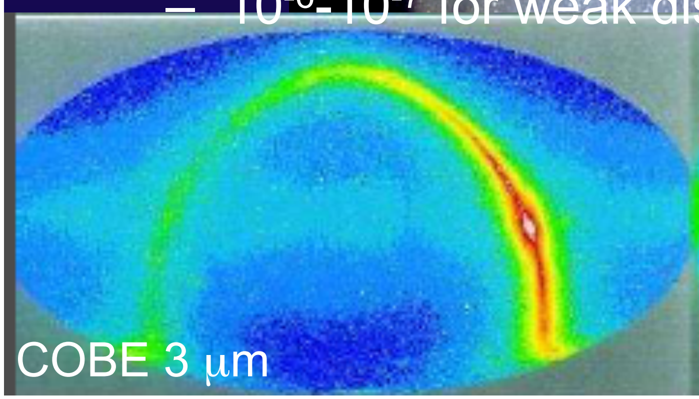
13 November 2009

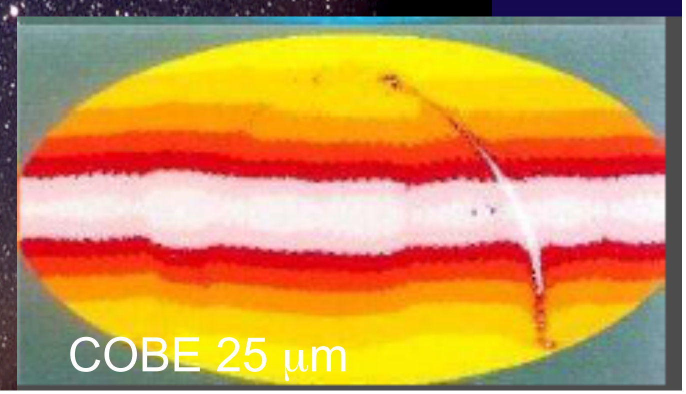
Sagan Program Workshop

With lots of help from A. Tanner (Georgia State), G. Bryden (JPL), S. Lawler (Wesleyan/UBC), R. Akeson (NExScI), D. Ciardi (NExScI), C. Lisse (JHU), Mark Wyatt (Cambridge)

Debris Disks and Formation of Planets

- Prediction of debris disks by Witteborn et al (Icarus 1982)
  - "Accretion models of planet formation and the early cratering history of the solar system suggest that planet formation is accompanied by a cloud of debris resulting from accumulation and fragmentation. A rough estimate of the infrared luminosities of debris clouds is presented for comparison with measured 10-micron luminosities of young stars. New measurements of 13 F, G, and K main-sequence stars of the Ursa Major Stream, which is thought to be about 270-million years old, place constraints on the amount of debris which could be present near these stars."
- IRAS discoveries followed in 1984 (Aumann, Gillett et al)
- Fractional luminosity, Ld/L*, a convenient metric
  - $1\text{-}10^{-2}$ for protostars & classical T Tauri stars
  - 10^{-3} to 10^{-4} for brightest, youngest (?) disks --- accessible to non-IR
  - $10^{-4}\text{-}10^{-5}$ for typical disks --- IRAS& ISO for early Sp Type→Spitzer
  - $10^{-6}\text{-}10^{-7}$ for weak disks like solar system

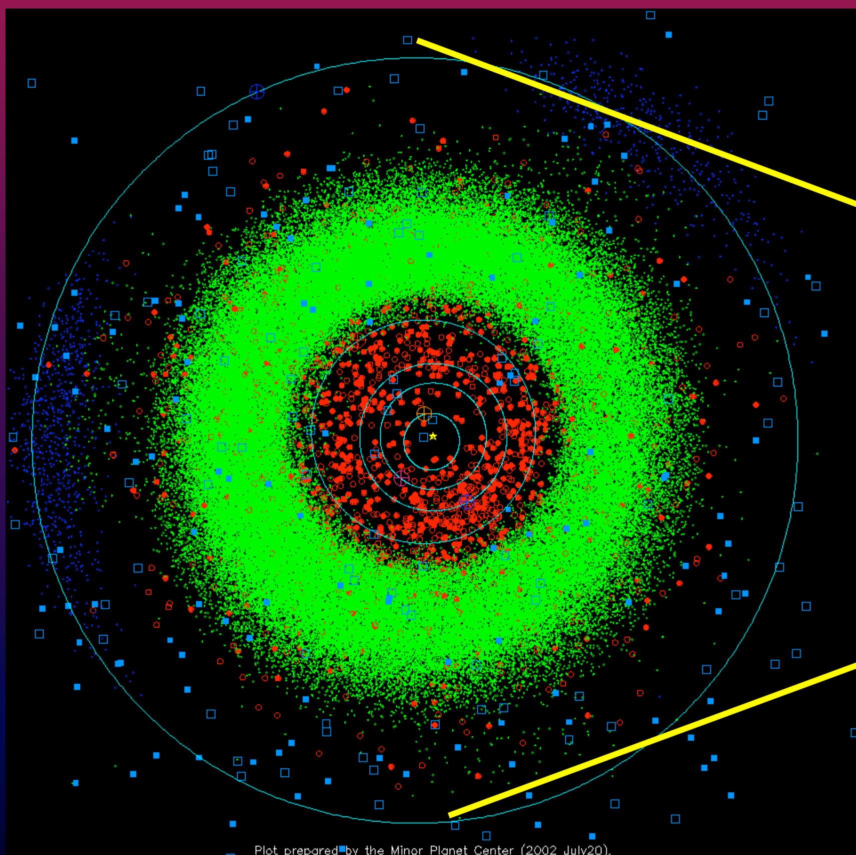


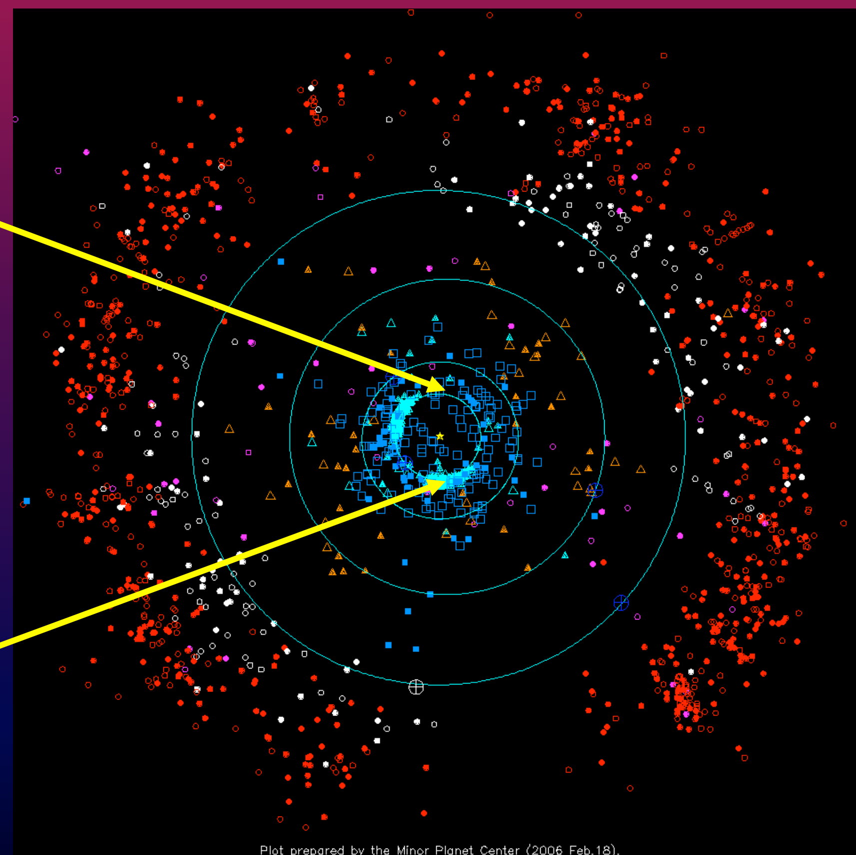


Solar System's Debris Disk

Inner System: Asteroid Belt
T>150K, refractory

Outer System: Kuiper Belt
T<150 K, volatile

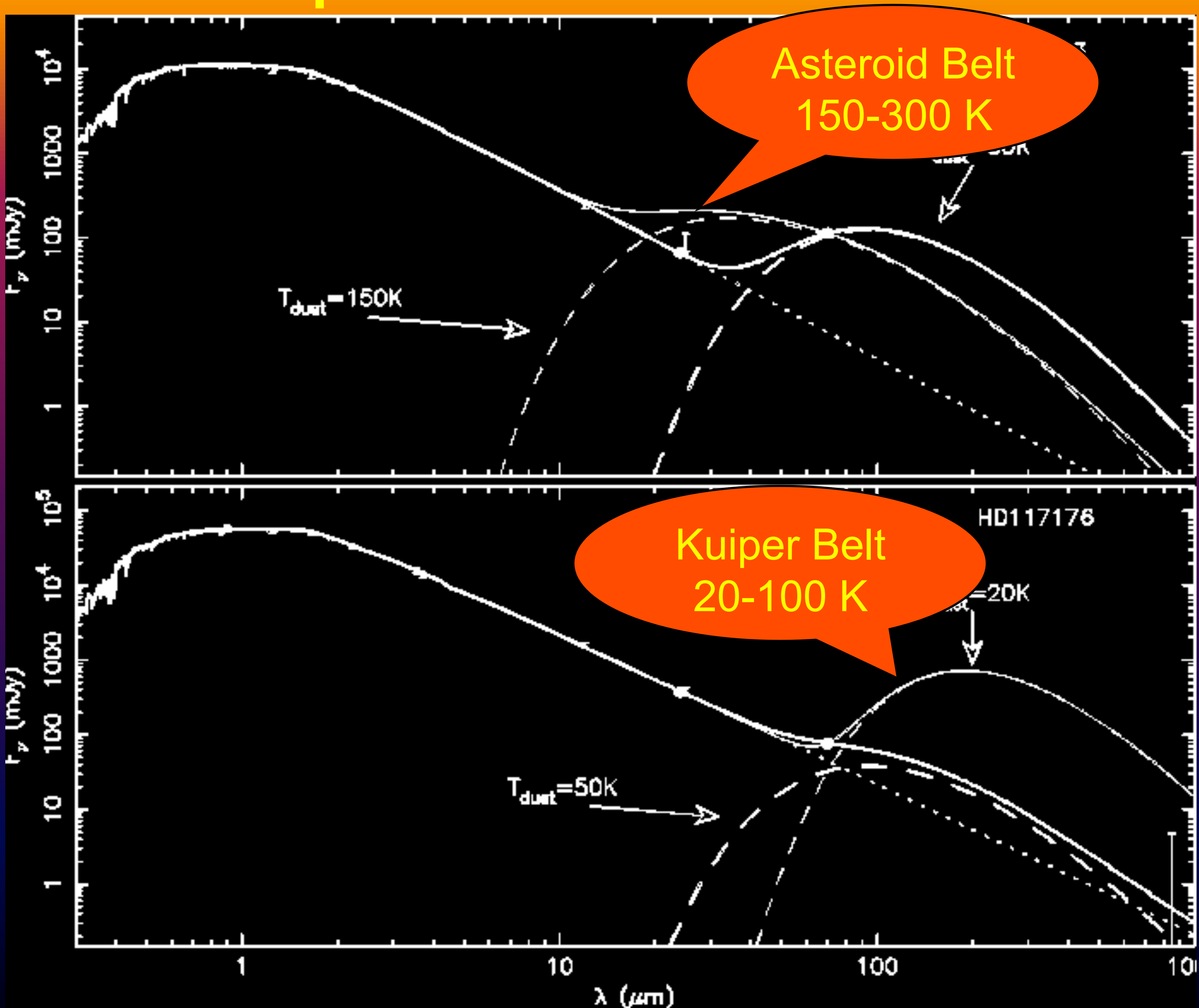




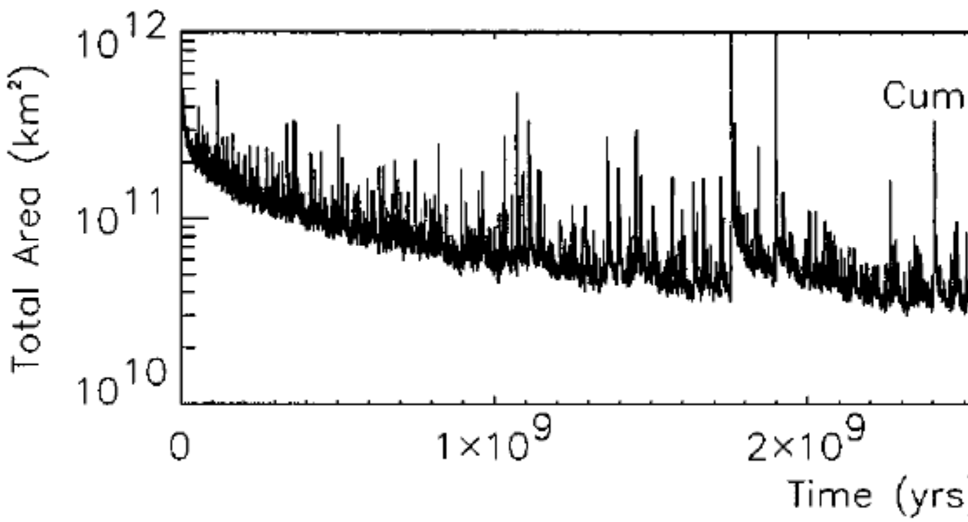
|----------- 10 AU -----------|

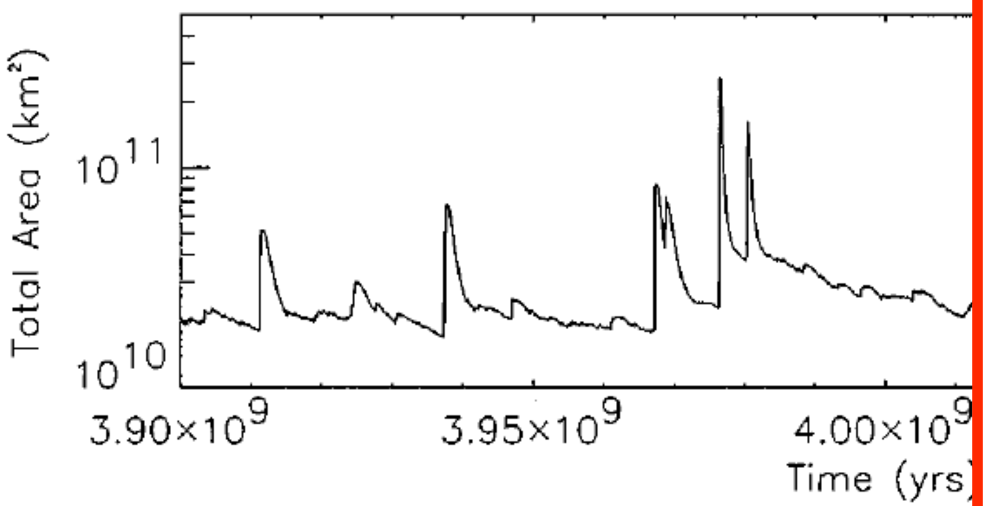
|------------100 AU ------------|

Properties of Disks

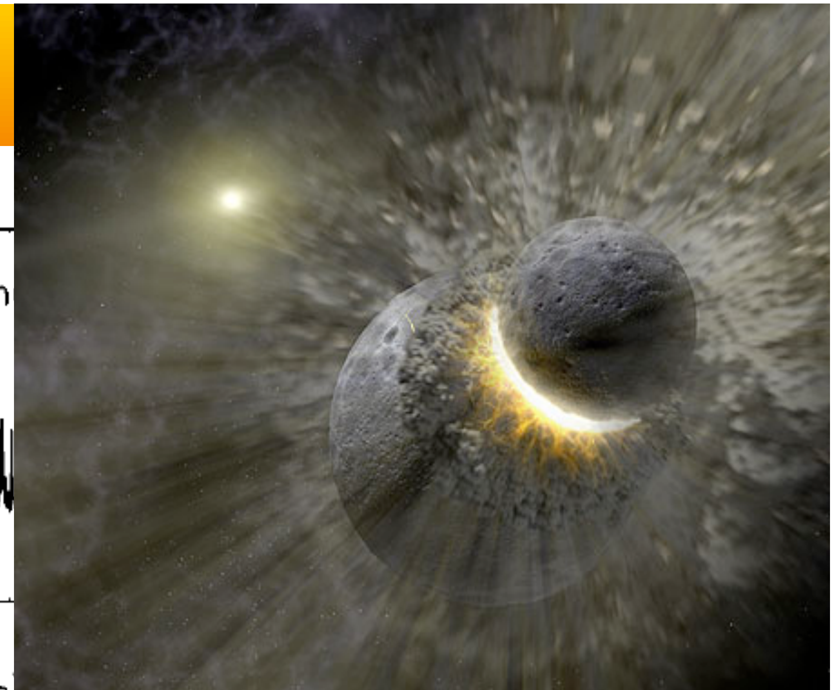


Collisions as Dust Source

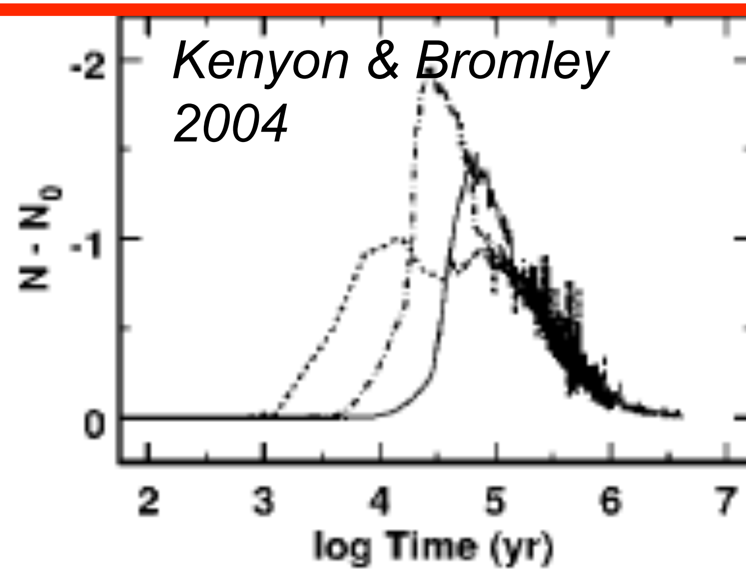




Grogan, Dermott and Durda 2001. Icarus. 152.



Collision of planetesimals



Spitzer Limits to Kuiper Belts

- $L_d/L_* \sim 10^{-5} \sim 10^{-6}$ for cold Kuiper Belt dust (30-60 K, >10 AU; 70 μm) for roughly 14% of stars.
- No statistical difference between debris disk incidence for stars with or w/o planets
- Stars with planets may have brighter disks
- Planets sculpt disks (rings)

Bryden et al 2009

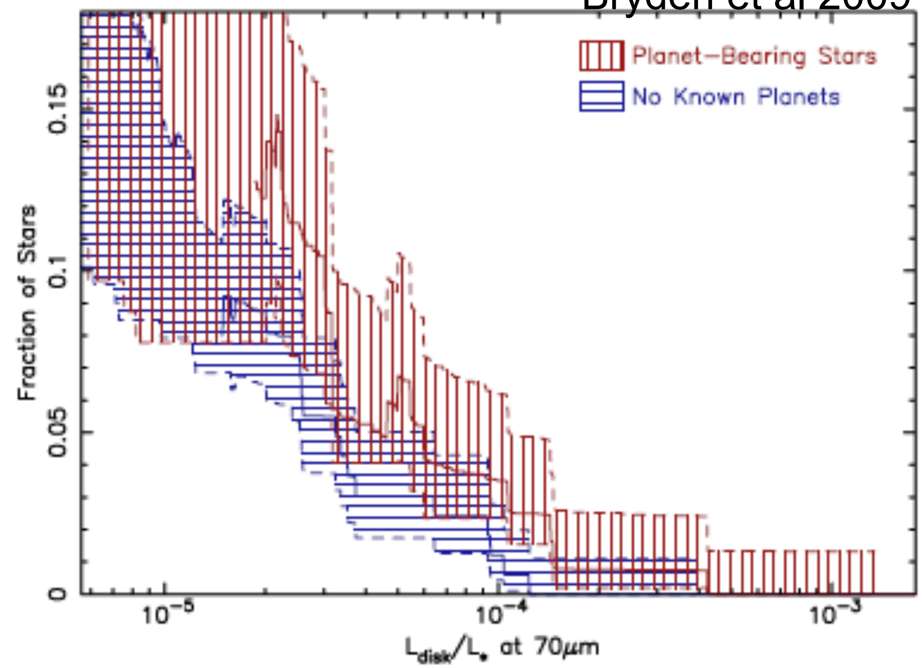
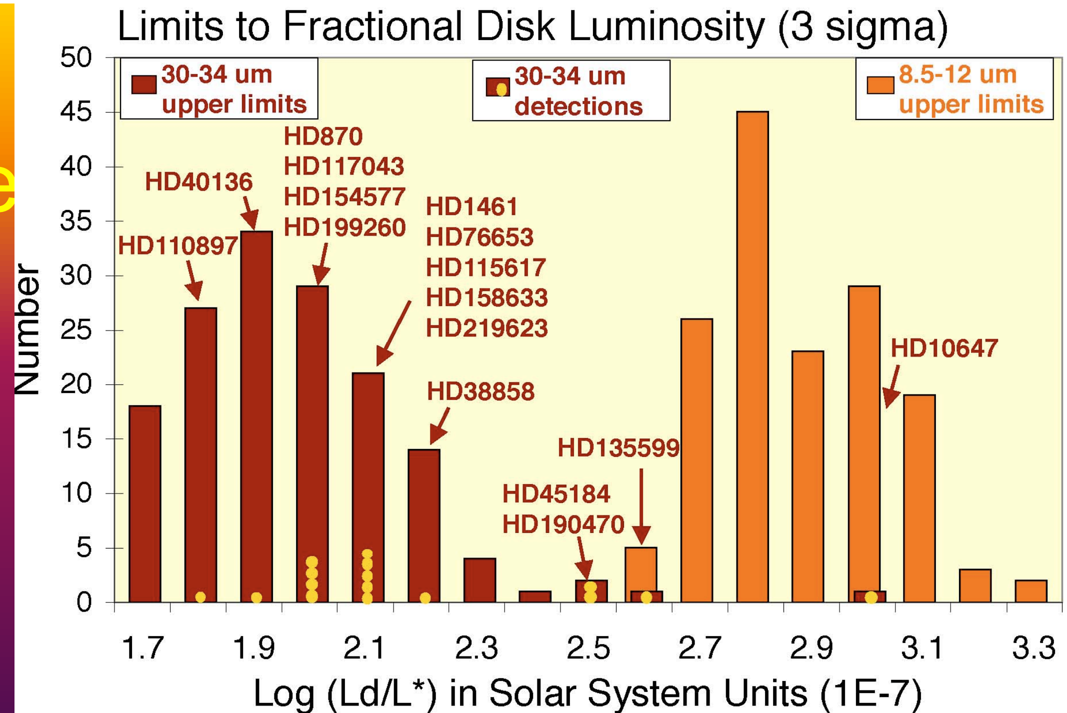


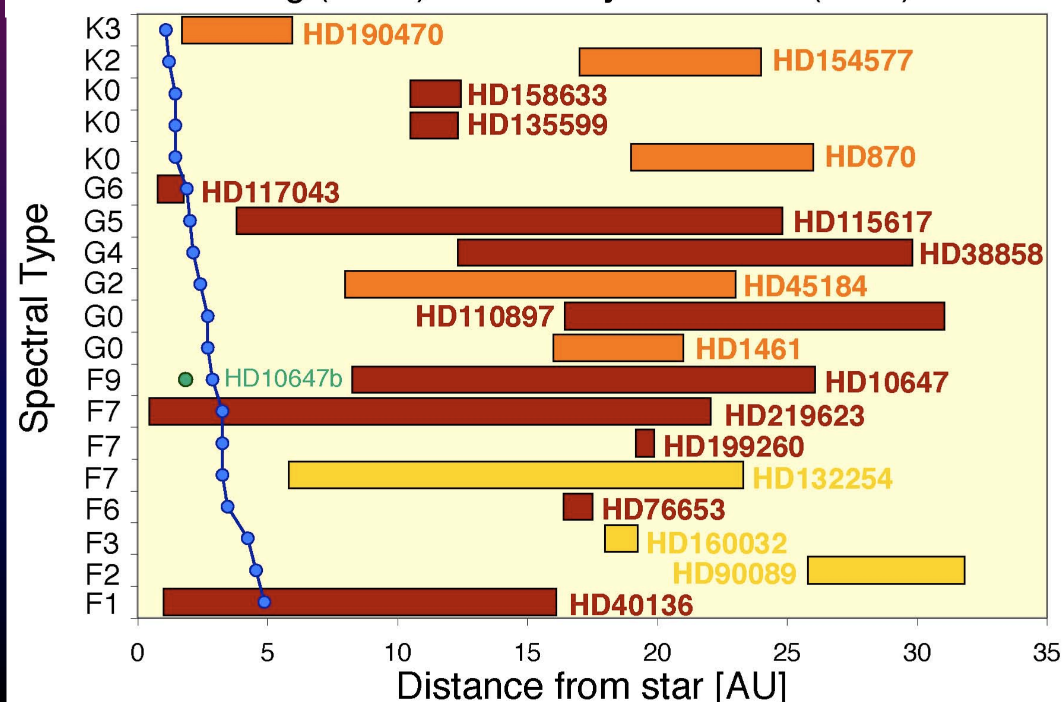
Table 2
Summary of Detection Statistics at 70 μm

Metric	Stars Without Known Planets	Stars With Known Planets[a]
Detection of significant IR excess	23/165 (14% ± 3%)	13/139 (9% ± 3%)
Detection of strong excess ($L_{dust}/L_* > 10^{-4}$)	2/165 (1.2% ± 0.9%)	4/113[b] (3.5% ± 1.7%

Spitzer Limits In the Habitable Zone

- Warm dust (70-150 K) located outside iceline ~100 Zodi
- Hot dust in Habitable Zone (10 μm) @ 1,000 zodi (3 σ) for 1-2% of mature stars
- Only 1-2 systems with strong HZ disk at Spitzer photometric levels

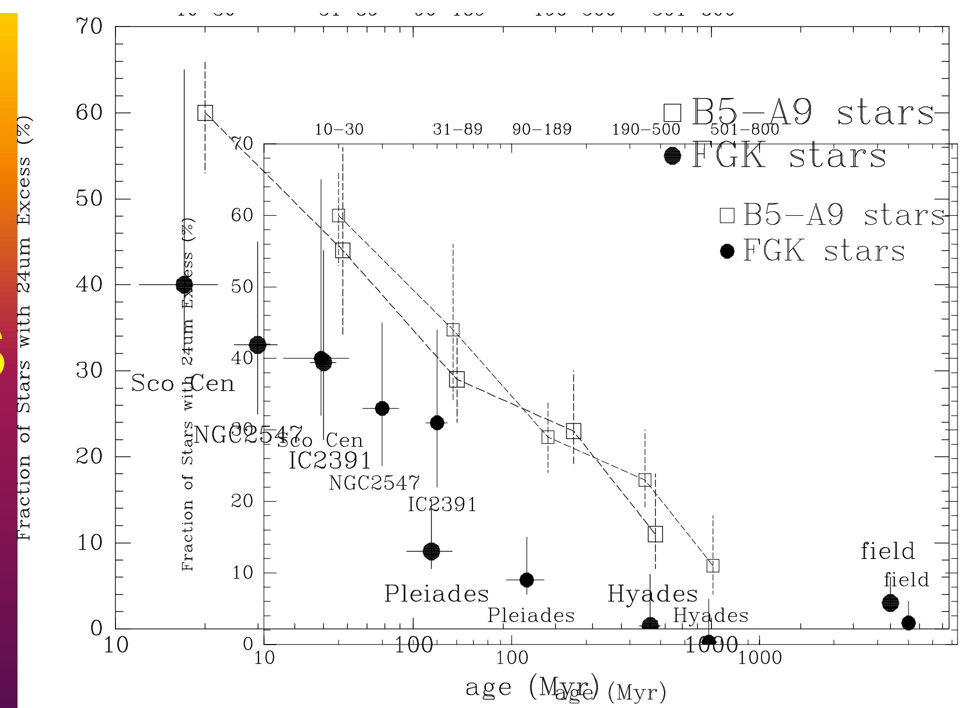


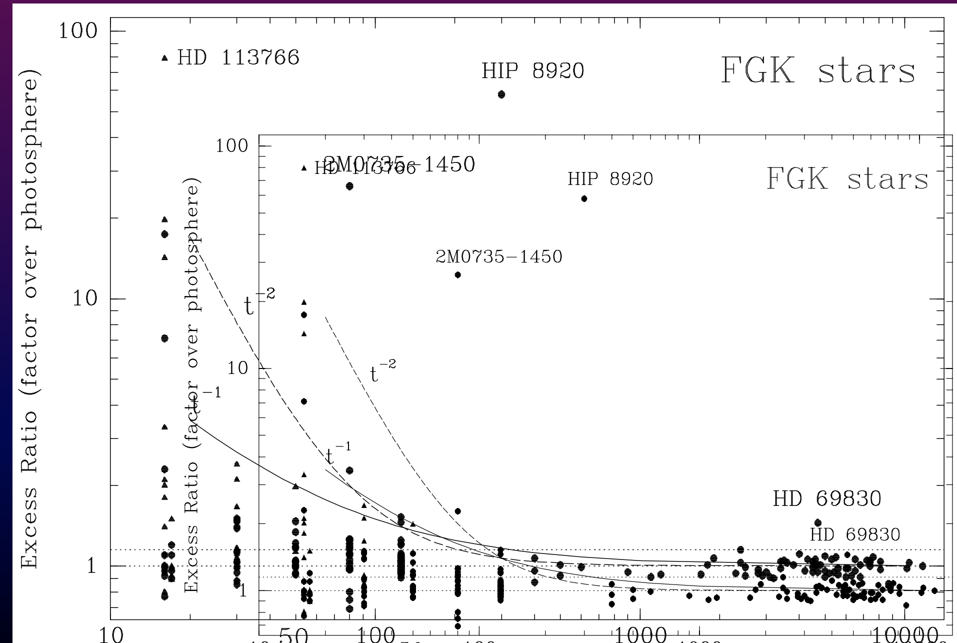


9

Disk Fraction Declines with Age: Primordial→Debris

- Spitzer surveys of AFGK stars (Rieke 2004; Siegler 2007) confirm and extend ISO results (Habing; Sylvester; Weinberger; Dominik and Decin)
- Young, hot disks common, but rare beyond 100 Myr (MIPS/FEPS) → formation of planetesimals and planets common evolutionary feature <100Myr
- Sporadic later outbursts due to collisions (Vega; Su 2004)

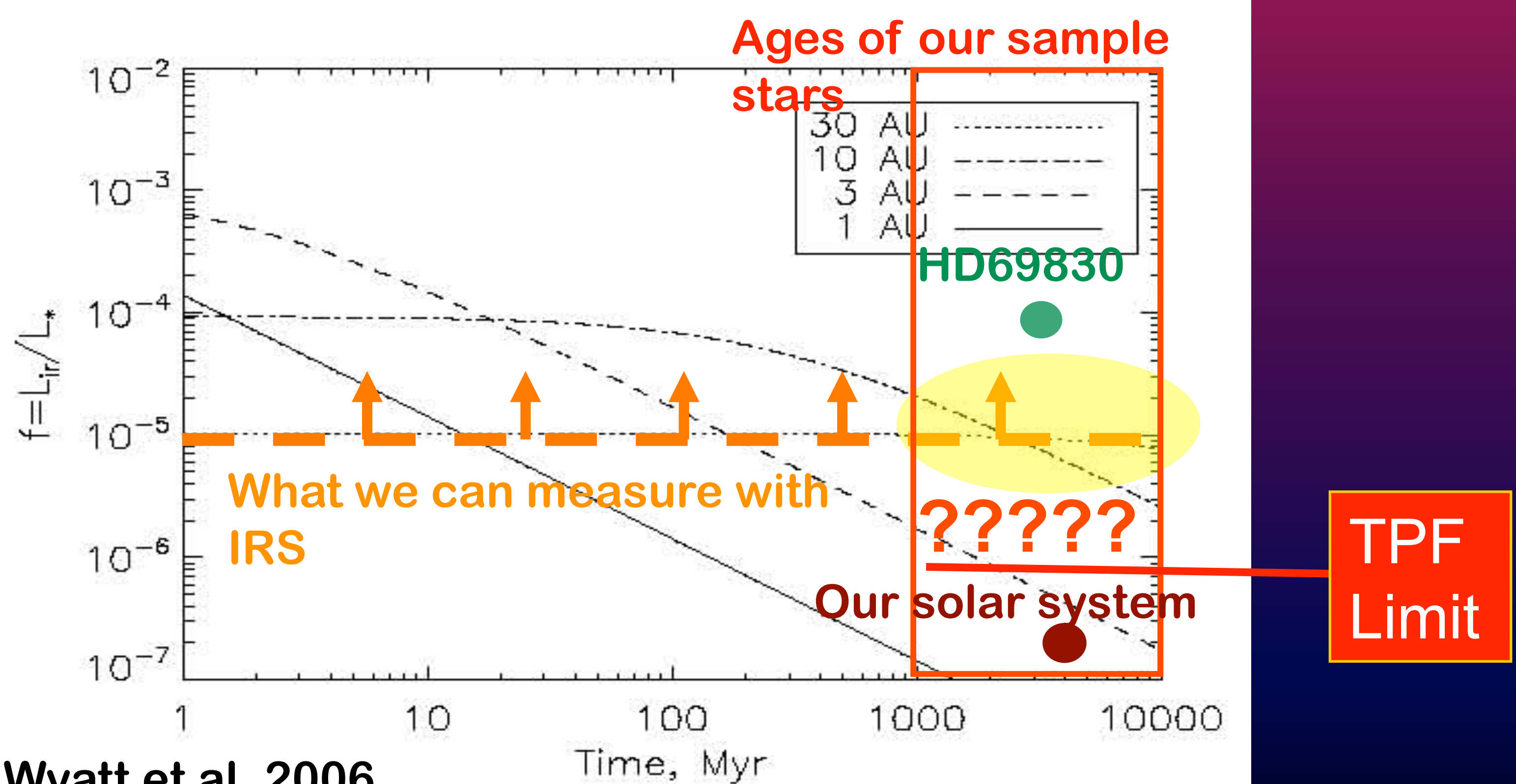




Siegler et al. 2007

Evolution of Hot Dust Disks

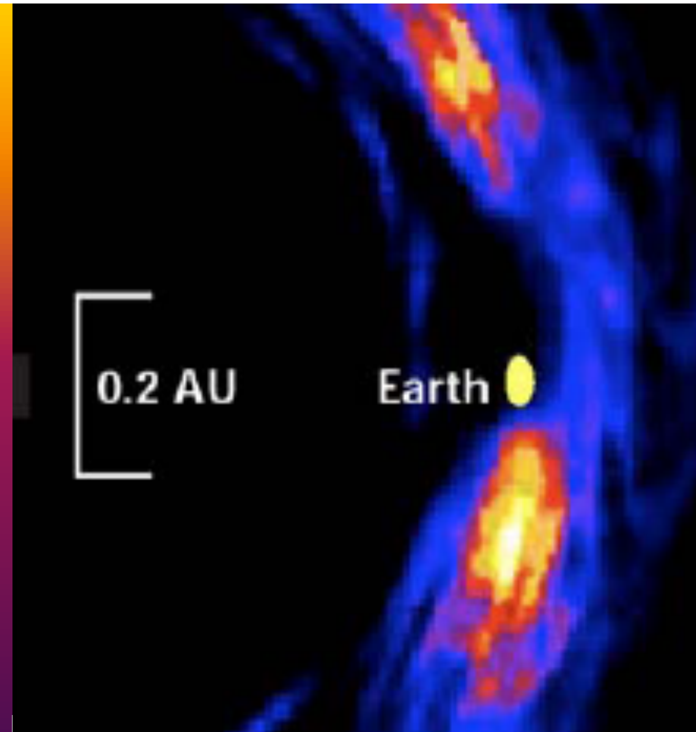
- Long term decline due to dissipation at few AU implies mature systems may be clean (few Zodi)
- Hot dust disk in mature stars may be LHB analogs

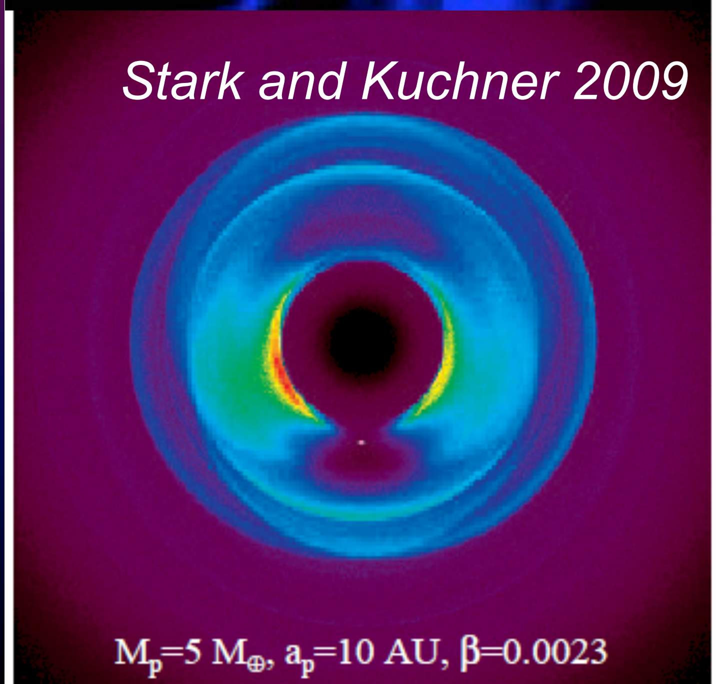


Wyatt et al. 2006

Planets Affect Their Disks

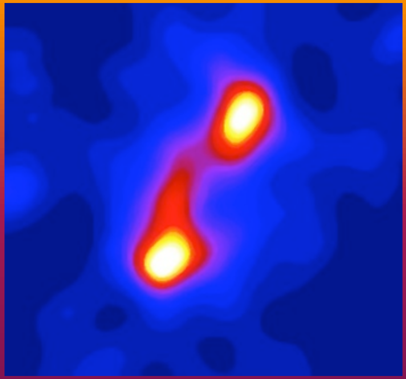
- Planets as small as Earth create resonant structures in EZ clouds (wakes and rings)
- Structures can masquerade as planets for imaging systems with low resolution (coronagraphs) or low information density (interferometers)
- Structures on eccentric orbit would produce variable emission



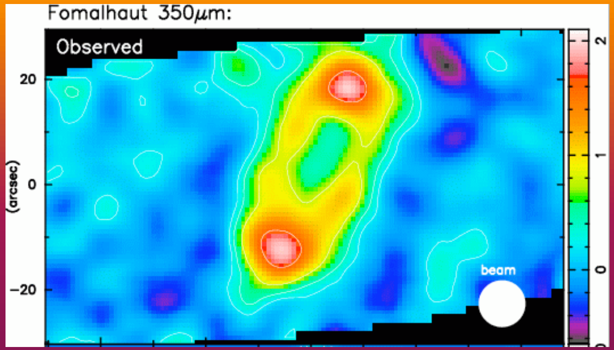


Stark and Kuchner 2009

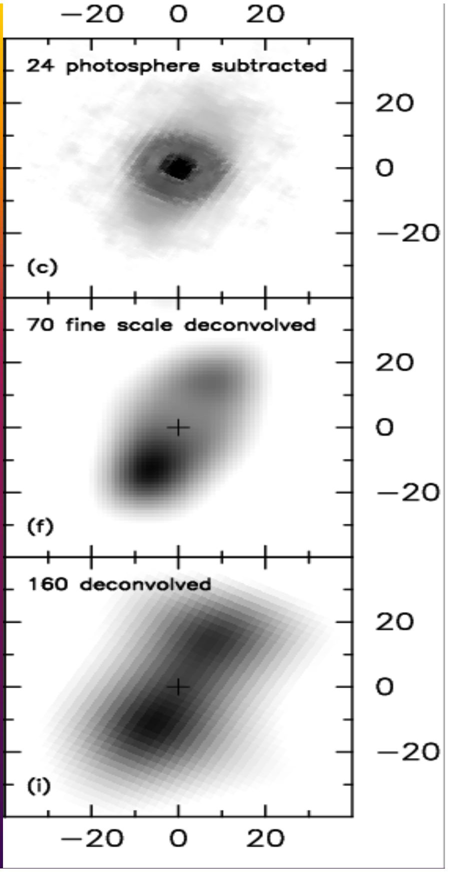
Fomalhaut's Disk Hints at Planets



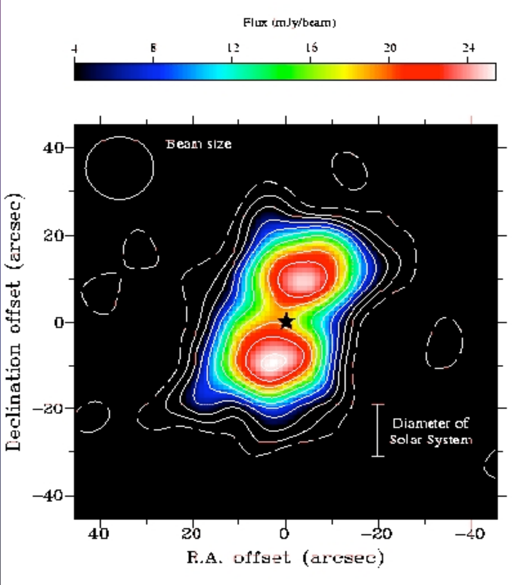
JCMT 450 µm
(Holland 1998, 2003
Wyatt 1999)
JCMT 850 µm



CSO 350 µm
(Marsh 2005)

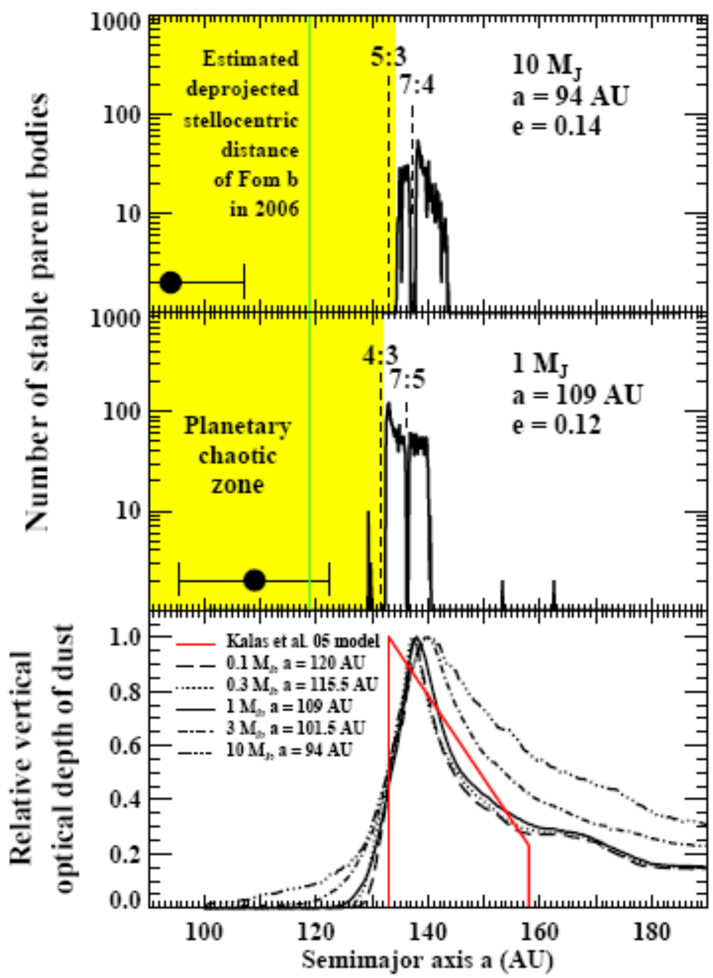


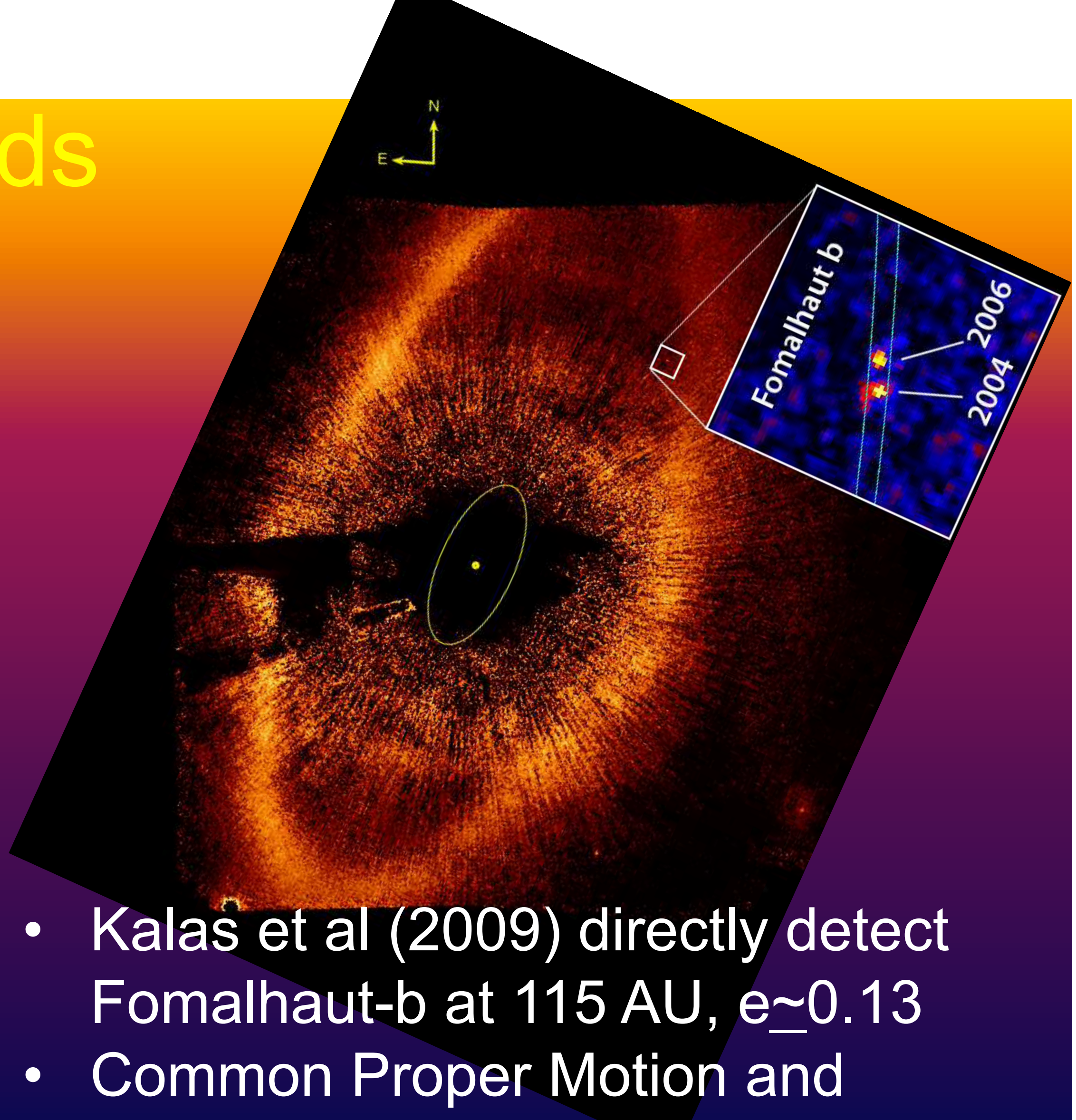
(Stapelfeldt 2004)



- A3V star: 7.7 pc, 200 Myr
- Submm suggests disk perturbed by planet, ε=0.07
- MIPS resolves SE ansa into ring with azimuthal variations from warmer dust at periastron
- 350 µm ring displaced 8 AU
  - Excess material at apocenter due to slow orbital motion
  - Perturber: 86 AU orbit and e=0.07, M>> MEarth

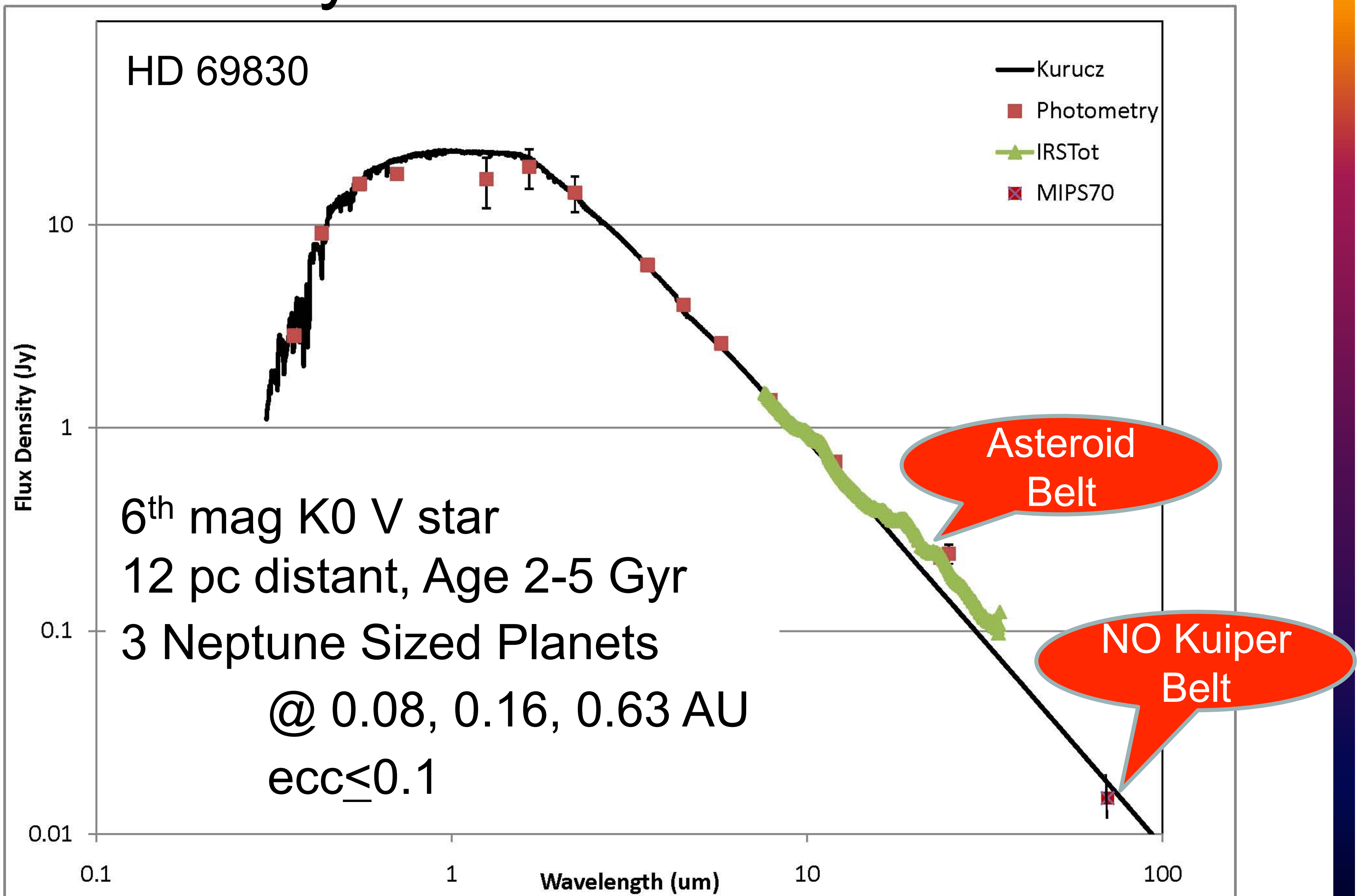
HST/Keck Finds Cause of Disk Offset





- Kalas et al (2009) directly detect Fomalhaut-b at 115 AU, e~0.13
- Common Proper Motion and evidence of orbital motion (1.4 AU in 1.7 yr)➔P=872 yr
- Quasi-dynamical mass: M< 3 MJup to avoid disrupting/spreading disk

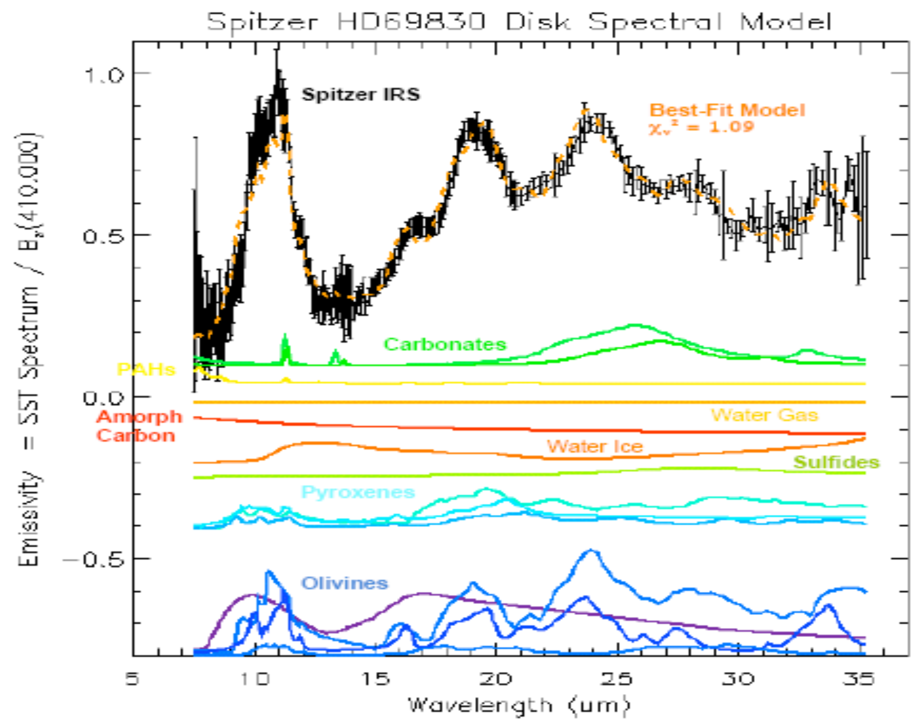
Laboratory For Planet Disk Interactions

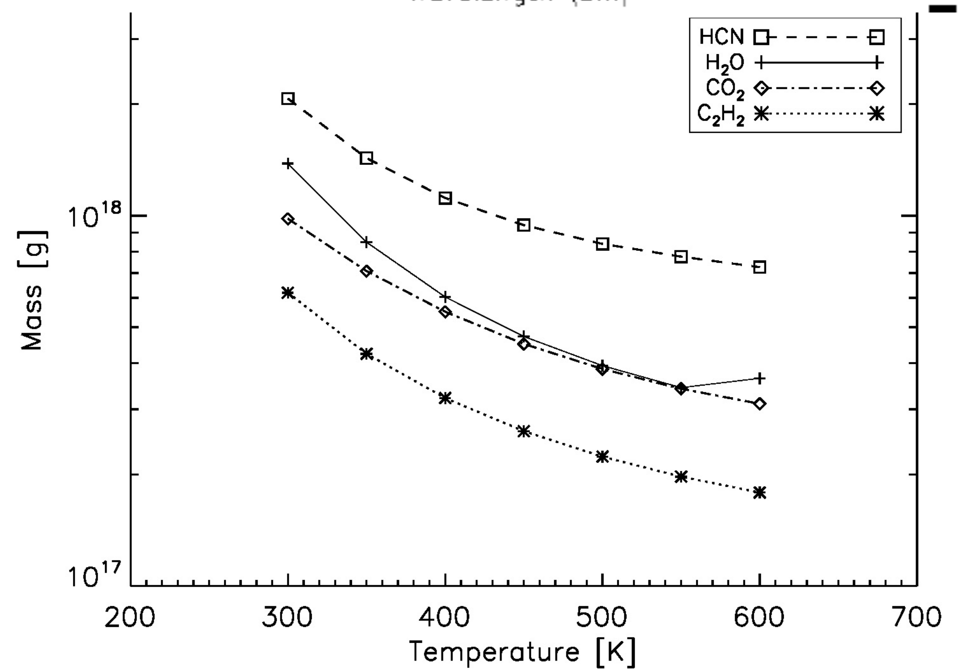


Asteroidal Composition

- Small (<1 μm) grains in 1 AU ring (350 K >>T_{BB})
- Asteroid debris different from comets 9P/Tempel 1 and C/Hale-Bopp, or comet-dominated YSO HD 100546 (Lisse et al 2007)
  - Crystalline pyroxenes & olivines, forsterite
  - Water ice (?)
  - Carbonates: siderite and magnesite
  - No Amorphous
  - No water gas, PAHs, phyllosilcates, or sulfides
- Spitzer HiRes shows no evidence for gas emission

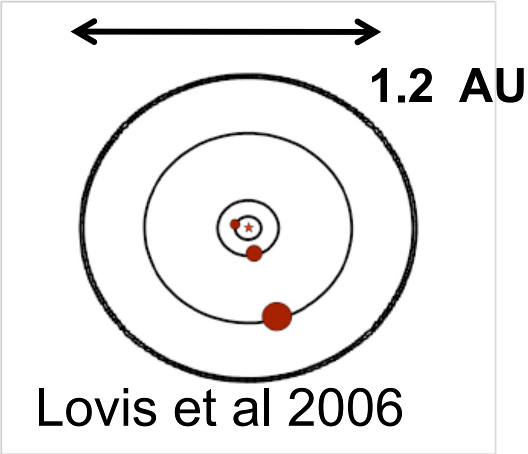
Lisse et al 2007

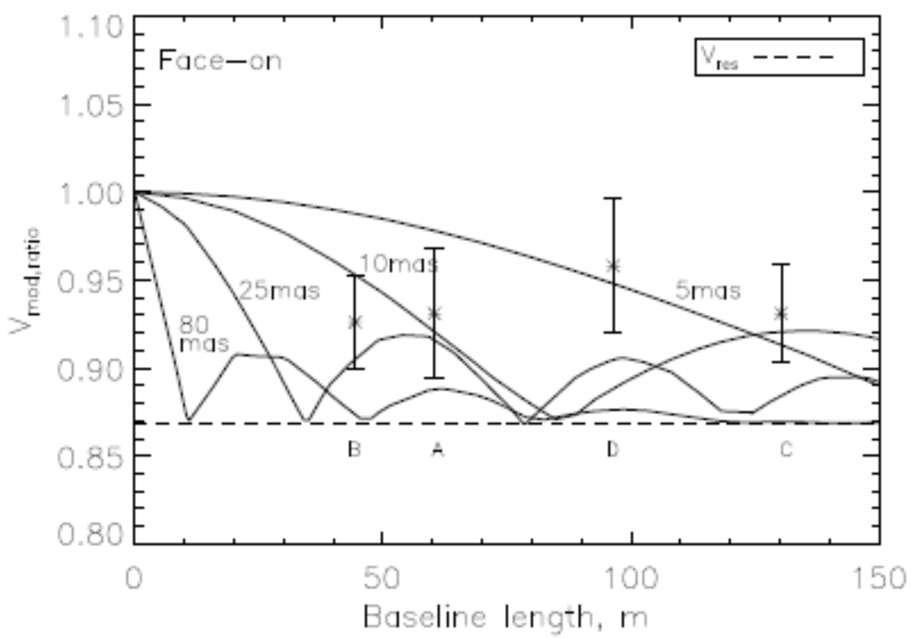


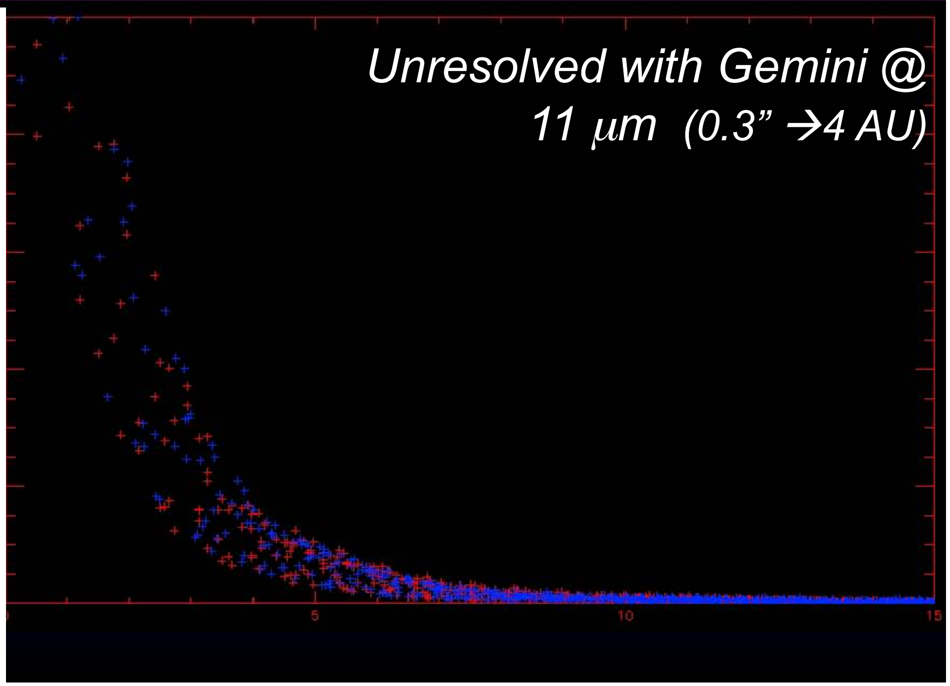


Disk Location and Extent

- SED→ material at 1 AU, 2:1 or 5:2 resonance outside the most distant planet
- VLTI/MIDI resolves emission, 0.25 -1 AU (Smith, Wyatt and Haniff 2009)
- Perhaps 30 km radius P/D asteroid disrupted @ 1 AU after perturbation by planet, trapped in 2:1 resonance with HD69830d.
- Orbital time scale → possibility of variability on < 1yr

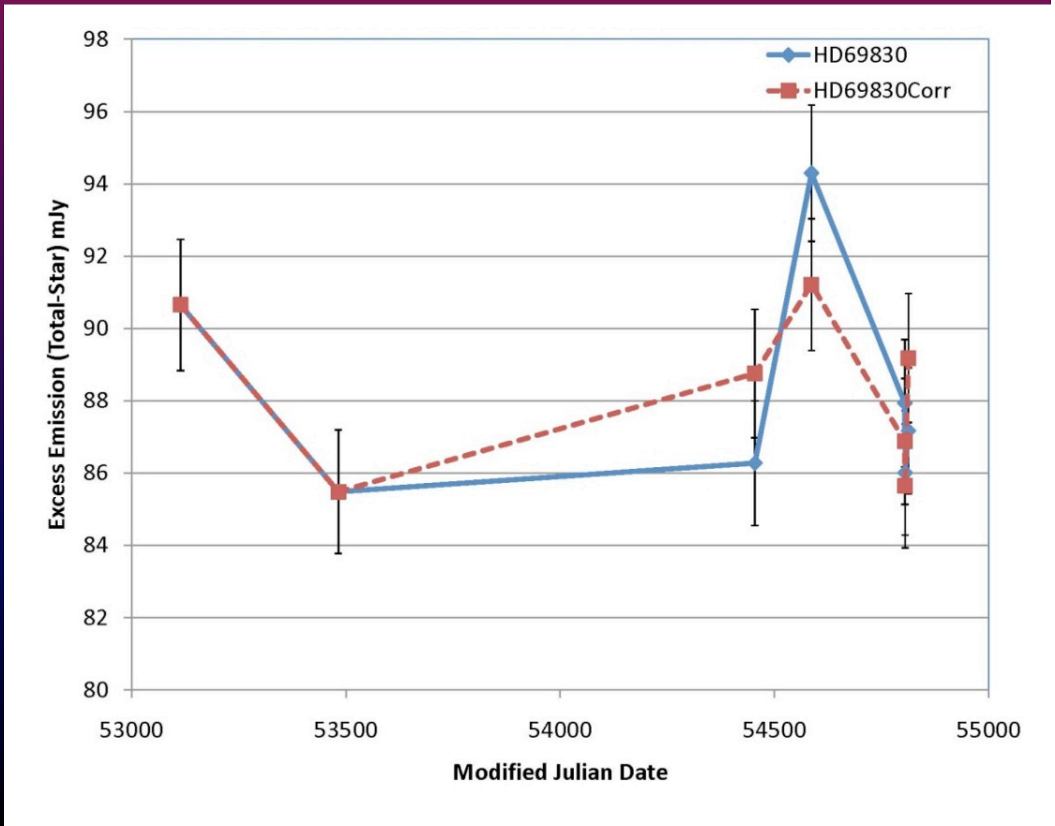




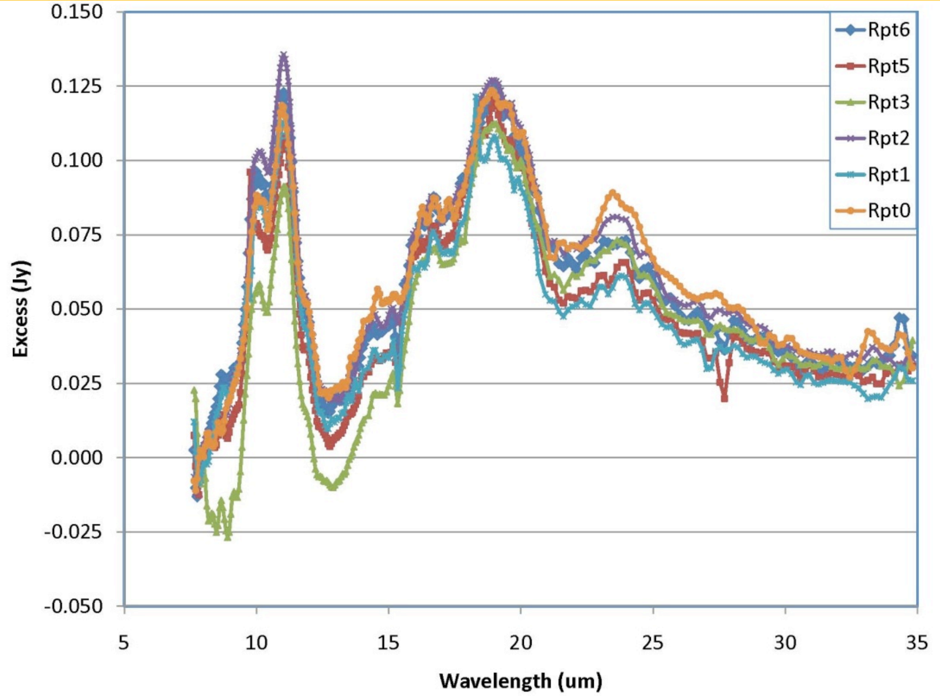


HD69830: No Photometric Variability

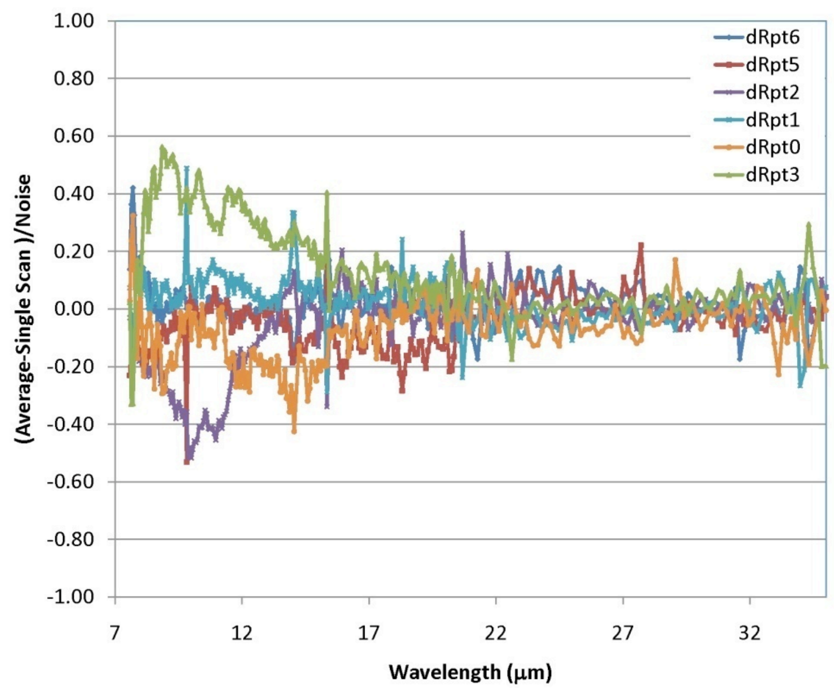
- Constant over 24 years (IRAS→Spitzer)
  - IRAS 25 μm (1983.5): 100 ± 26 mJy
  - MIPS 24 μm (2007): 70 ± 12 mJy
  - **Δ=30 ±28 mJy or <40%**
- Constant over 4 years
  - 60 images w. IRS Peakup Array at 22 μm
  - Some referenced to nearby star HD68146
  - Star+disk constant to ~1%, excess<3%



No Spectral Variability

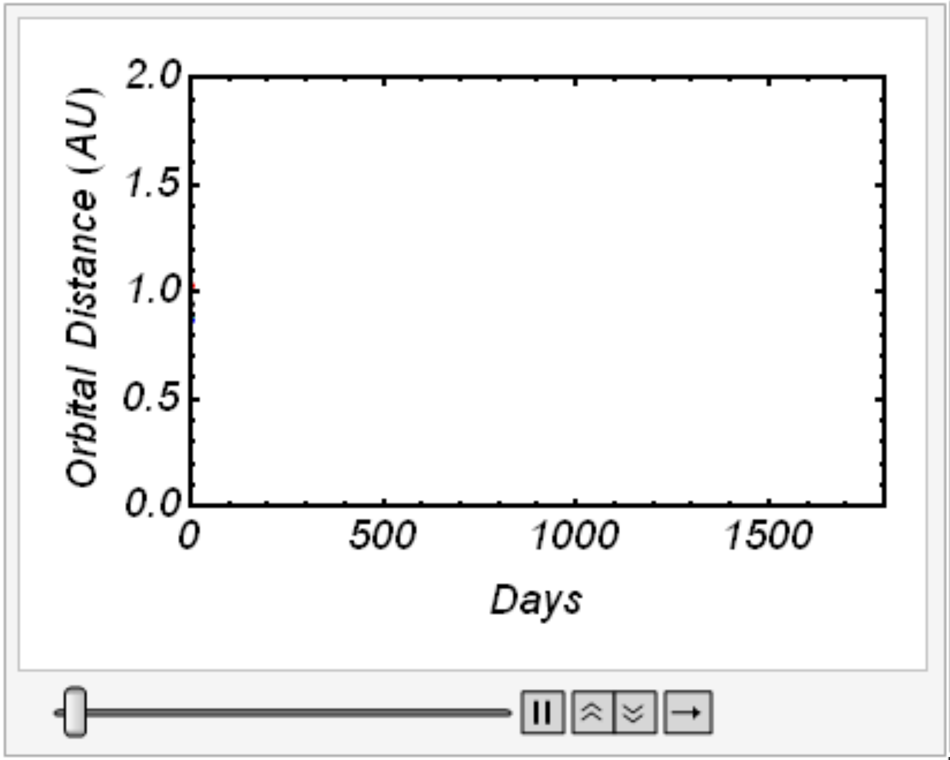


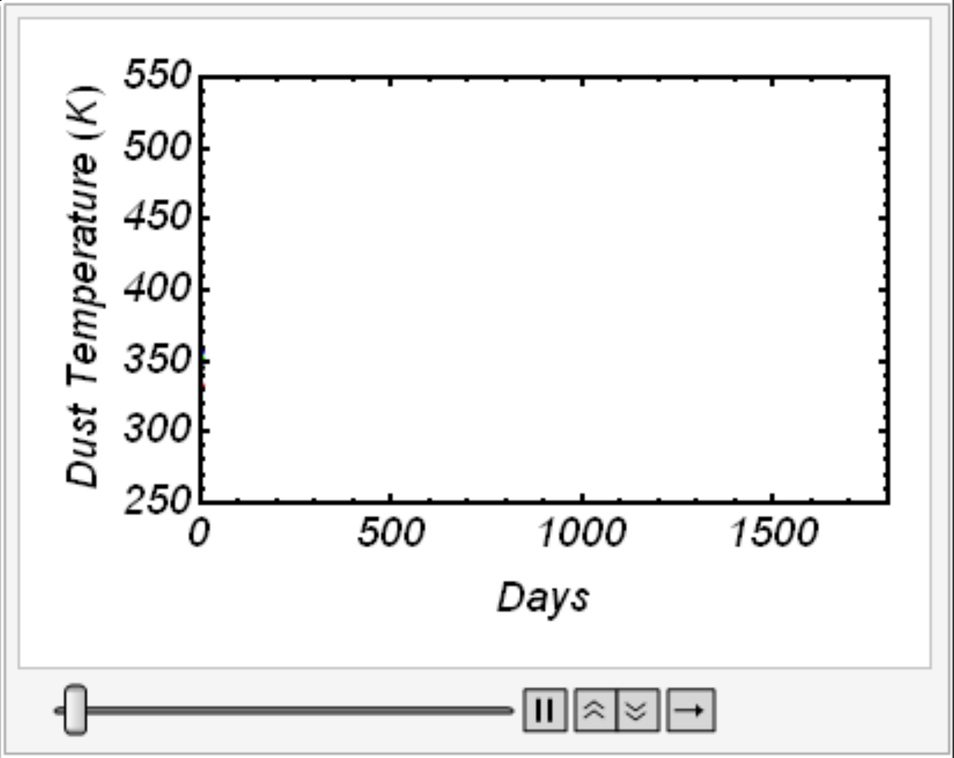
- 6 independent spectra over 4 year baseline
- χ^2 consistent with no significant variations over 4 years at few % level



Lack of Variability Limits Clumpiness & Eccentricity

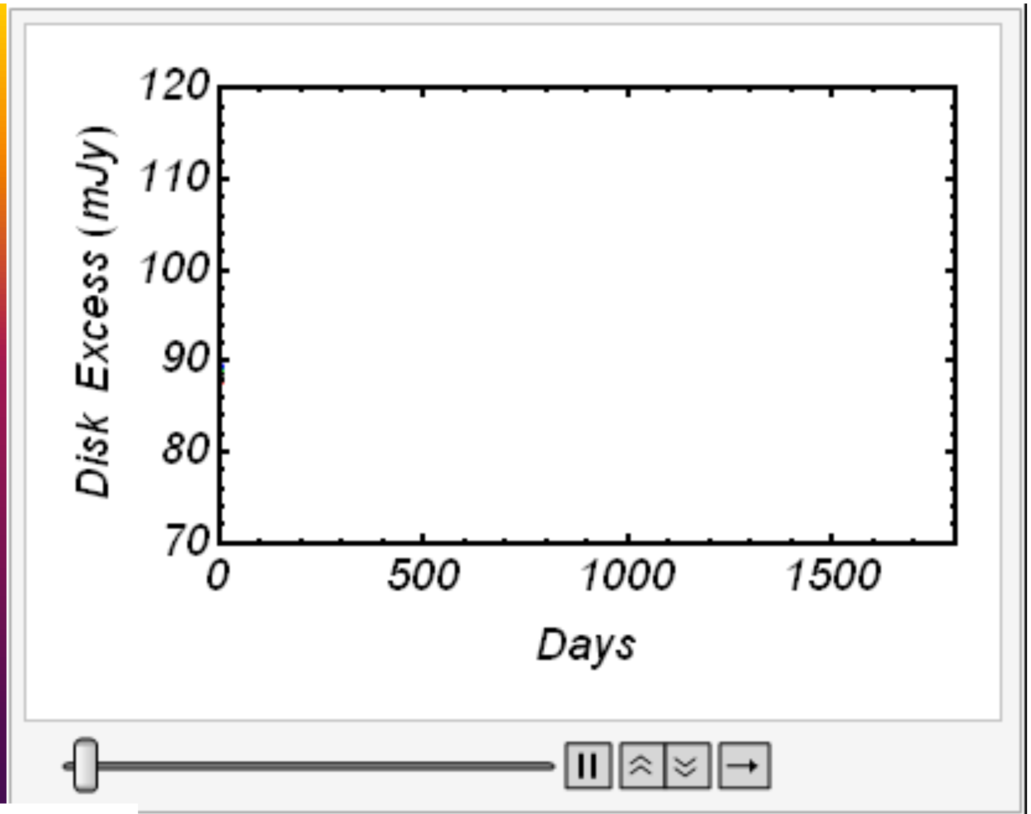
- Put resonant clump containing 10% of total excess at 1 AU with ε= (0.1, 0.2, 0.5 and 0.8)
- Planet eccentricity =0.03,0.1,0.07 (?)

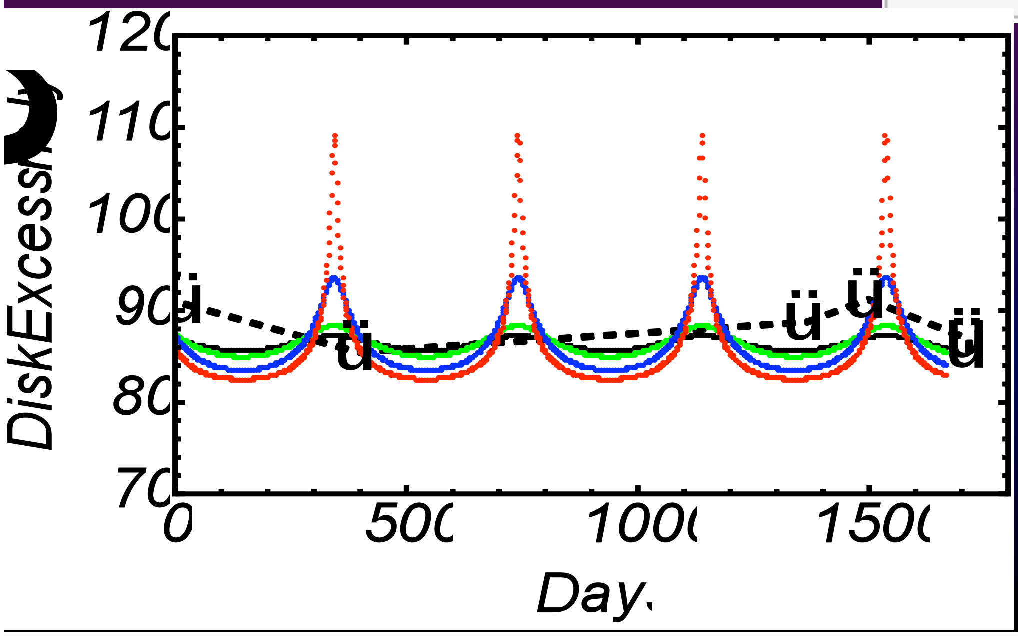




Variability Limits

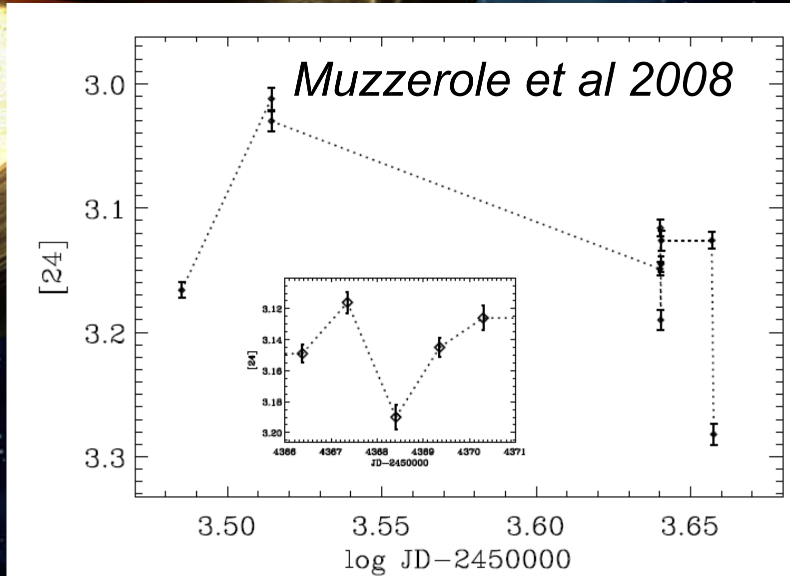
- With material on orbit with ε=0.1, 4 years of Spitzer data set limits <10% F_{total} of clumpiness

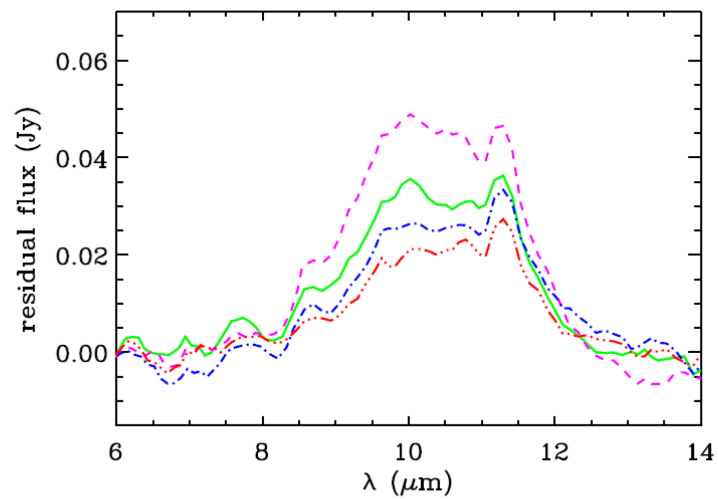




Variable Emission From Transitional Disk

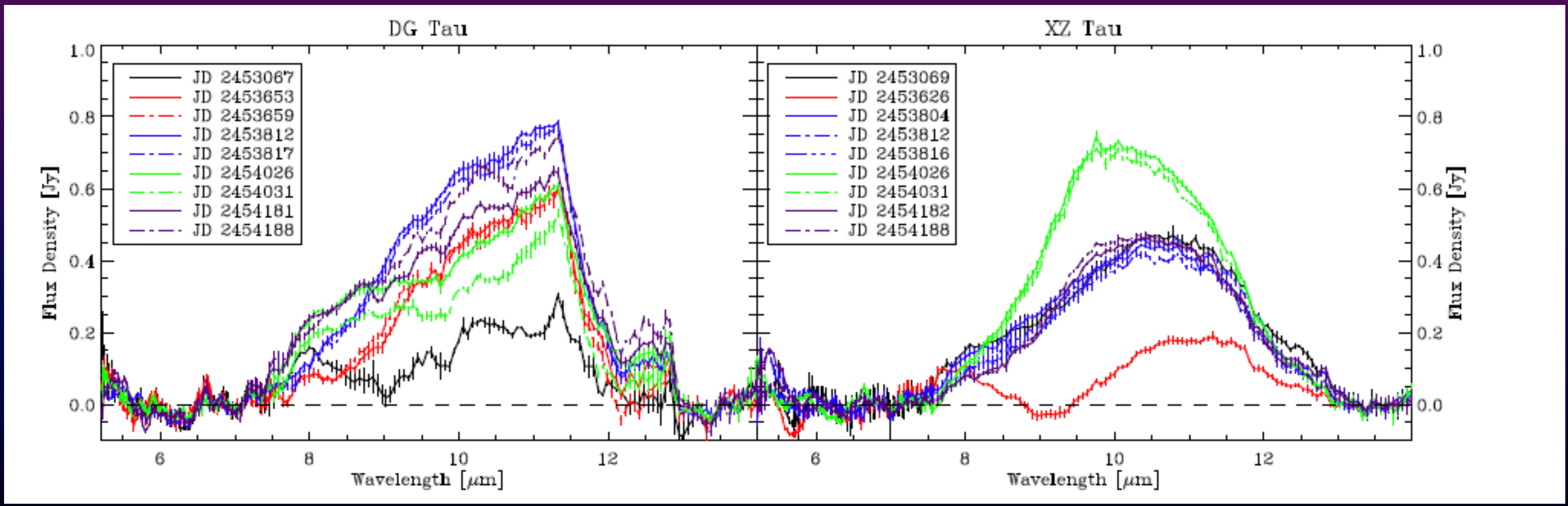
- Monthly variations in photometry & silicate feature at 20-60% level
- Variable heating of inner disk due to variable accretion rate?
- Perturbations of disk by planet at inner edge of disk (0.2 AU sublimation radius, P=3-4 weeks)?



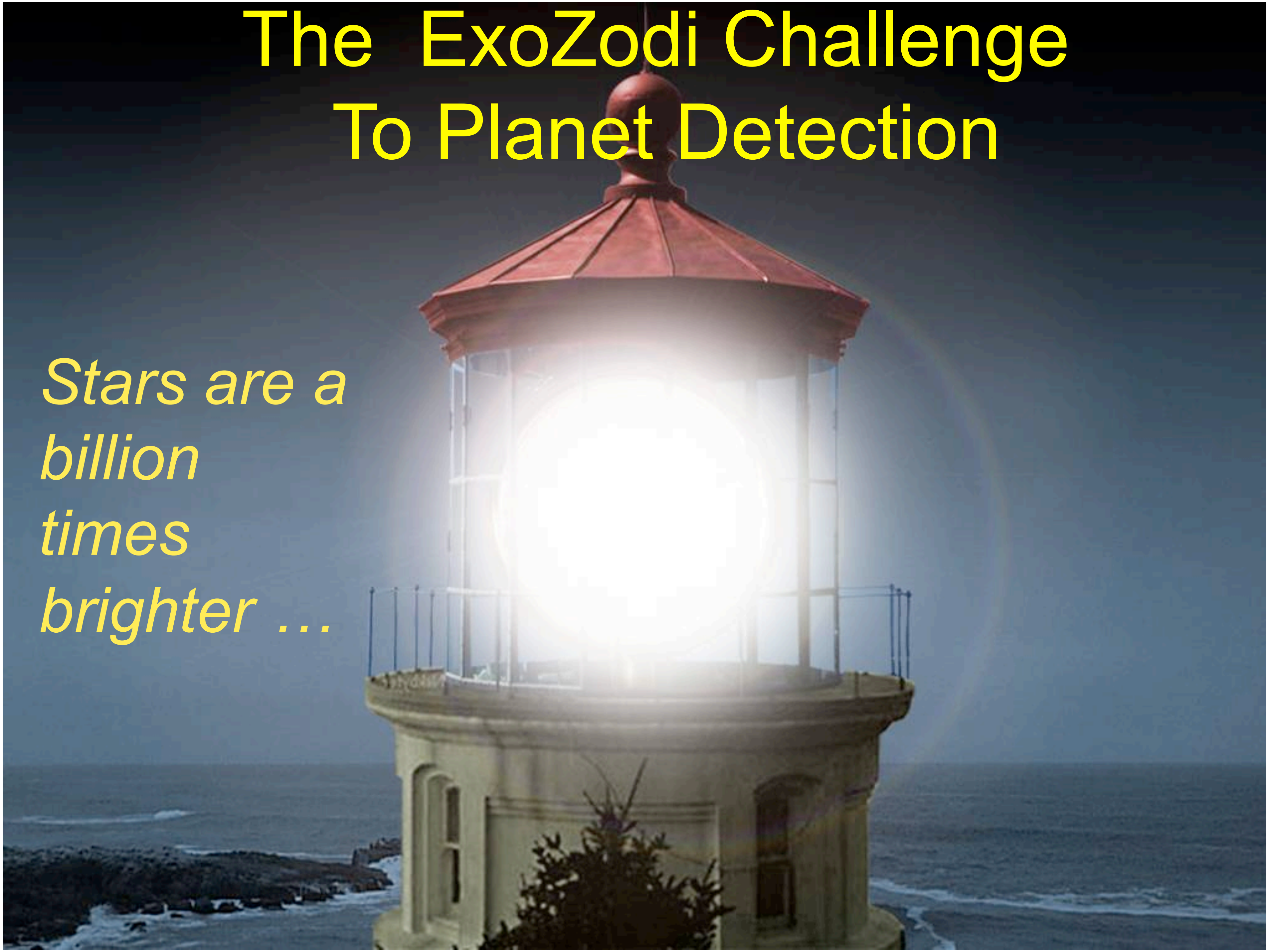


Variable Disk Emission

- Accreting T Tauri stars show variable silicate emission on monthly time scale --- possible due to shadowing in disk (Bary et al 2009)



The ExoZodi Challenge To Planet Detection

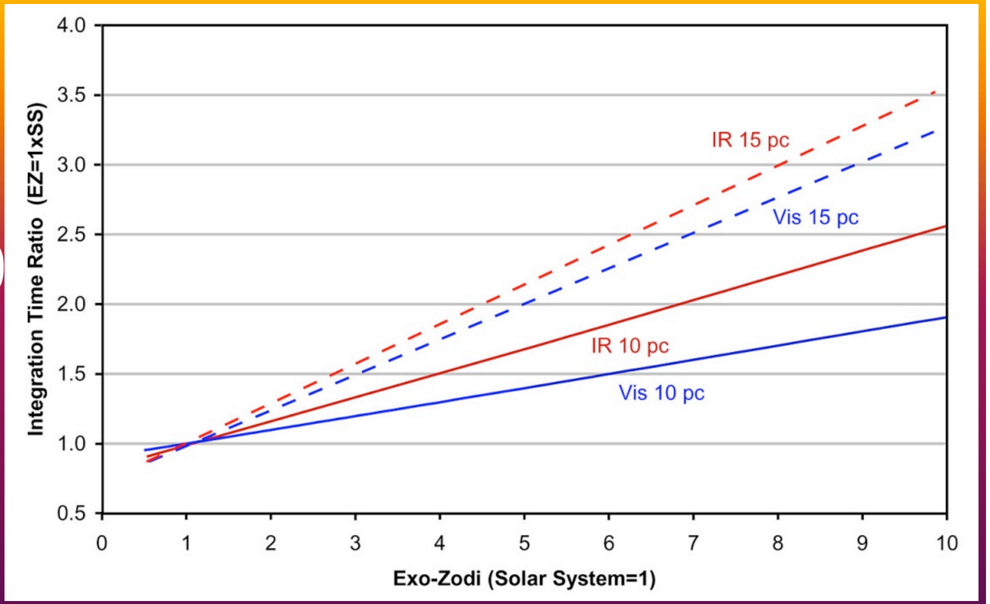


Stars are a billion times brighter …

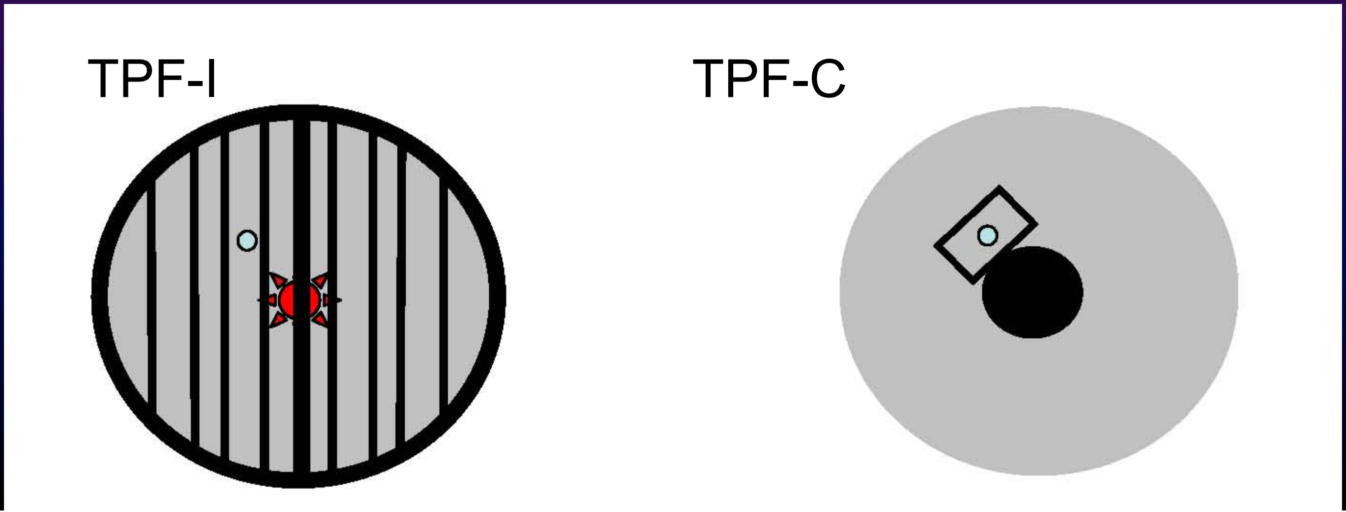

…than the planet
…hidden
in the glare.


Like this firefly.
Hidden in the
Exo Zodi Fog

The Problem for Earth-Detection



- Total ExoZodi (EZ) ~300 x planet signal for Solar System Zodiacal cloud
- Photon noise from (EZ) can overwhelm planet
- Signal within single pixel (~λ/D) significant for >10 zodi for either visible or IR

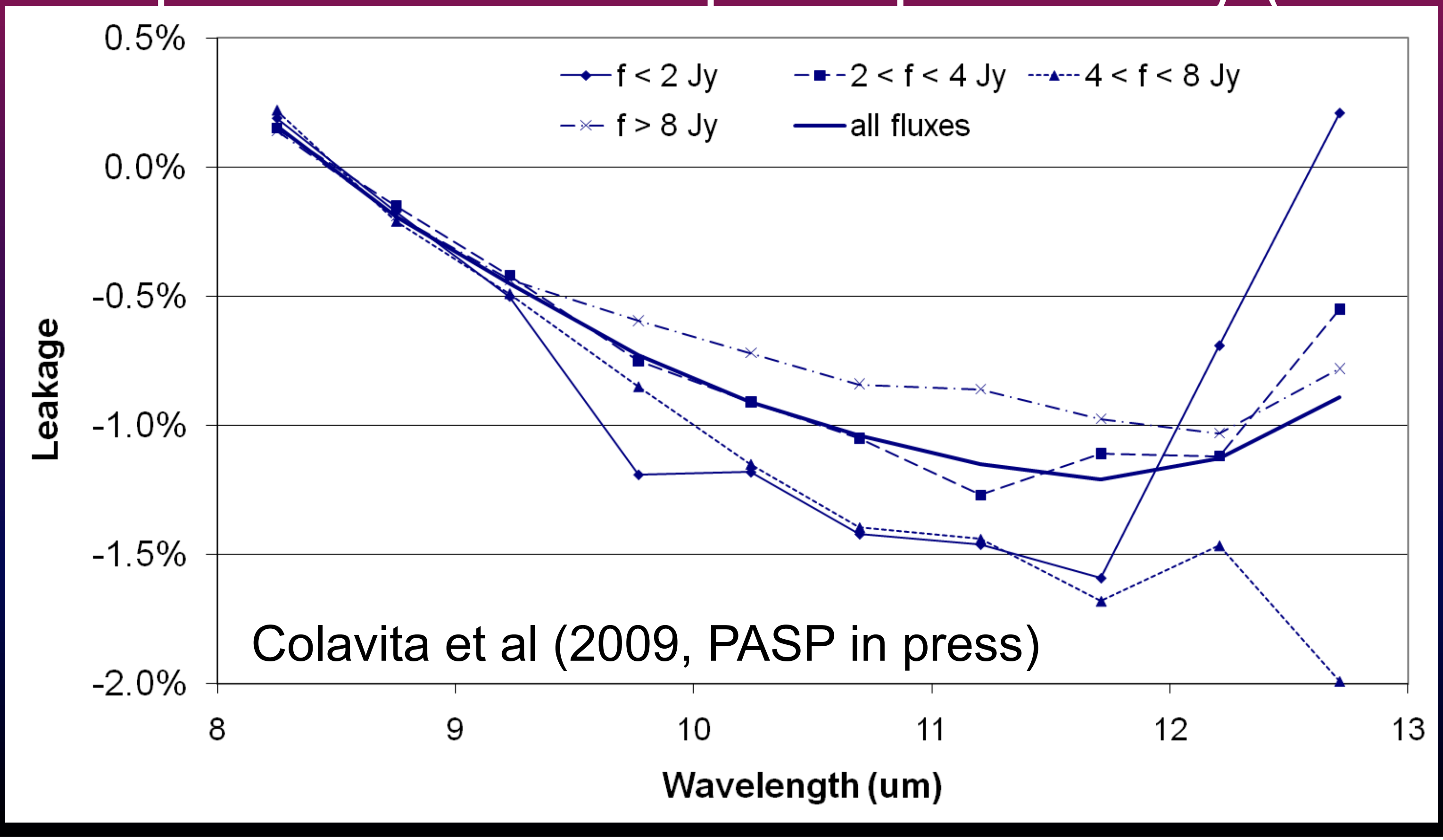


Keck Interferometer: The Next Step

- Spitzer (even JWST) limited by photometric accuracy
- Interferometers null star signal to reveal disk: 10 mas resolution with Keck → 0.1-1 AU
- Keck survey of nearby stars for ExoZodi
  - –Hinz (UofA), Kuchner (GSFC), Serabyn (JPL)
- Known disks & nearby main sequence stars

Observing Summary

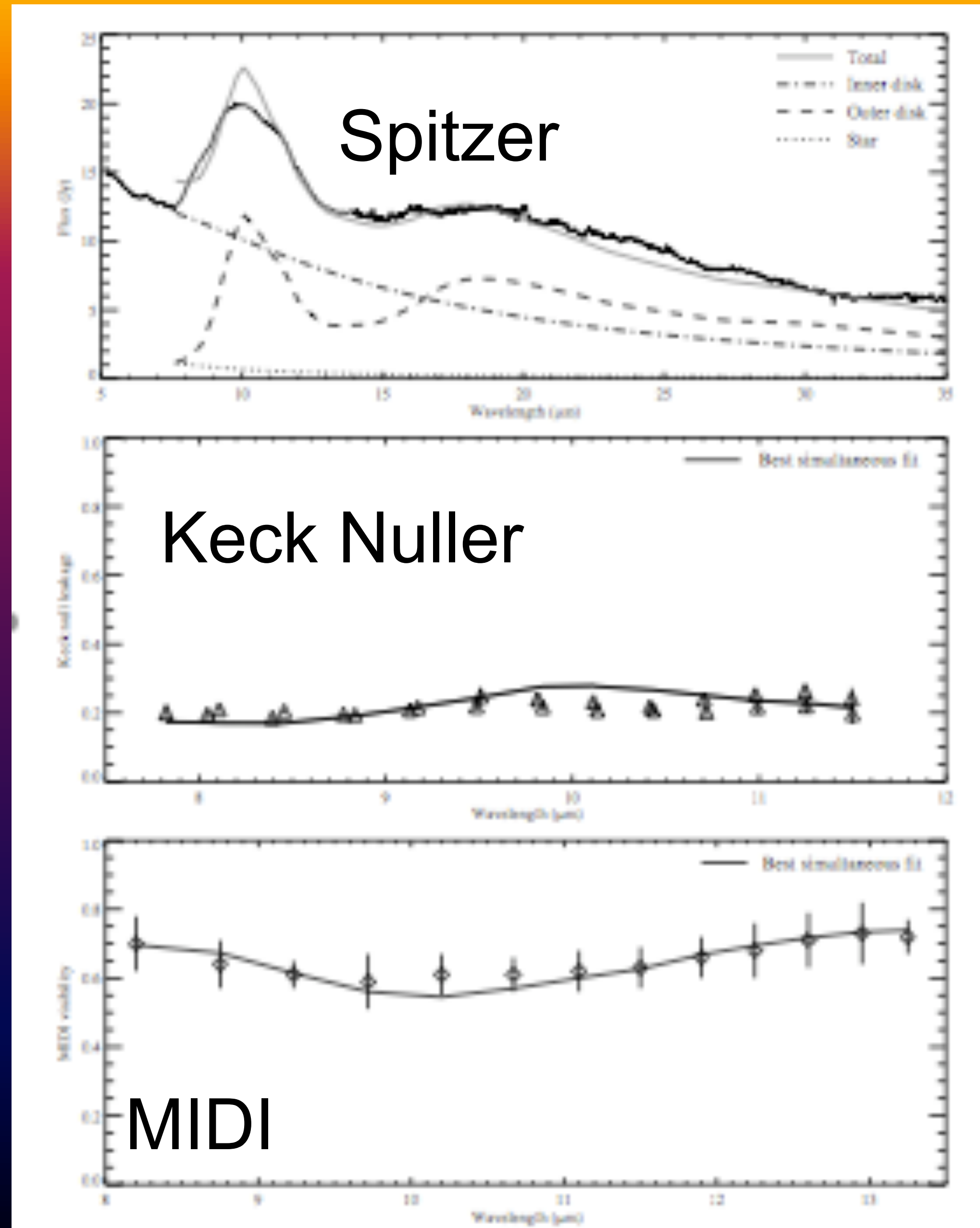
- 8 runs Feb. '08 – Jan. '09: 32 interferometer nights
- 44/46 targets observed
- No excess for 40 targets (ΔF/F<0.1-1%)
- 3-5× improvement over Spitzer photometry (0.5-2%)



51 Ophiuchus: A β Pictoris Analog Measured with the Keck Interferometer Nuller

Stark et al. 2009, ApJ

Simultaneous fit to Spitzer, MIDI, and Keck Nuller data



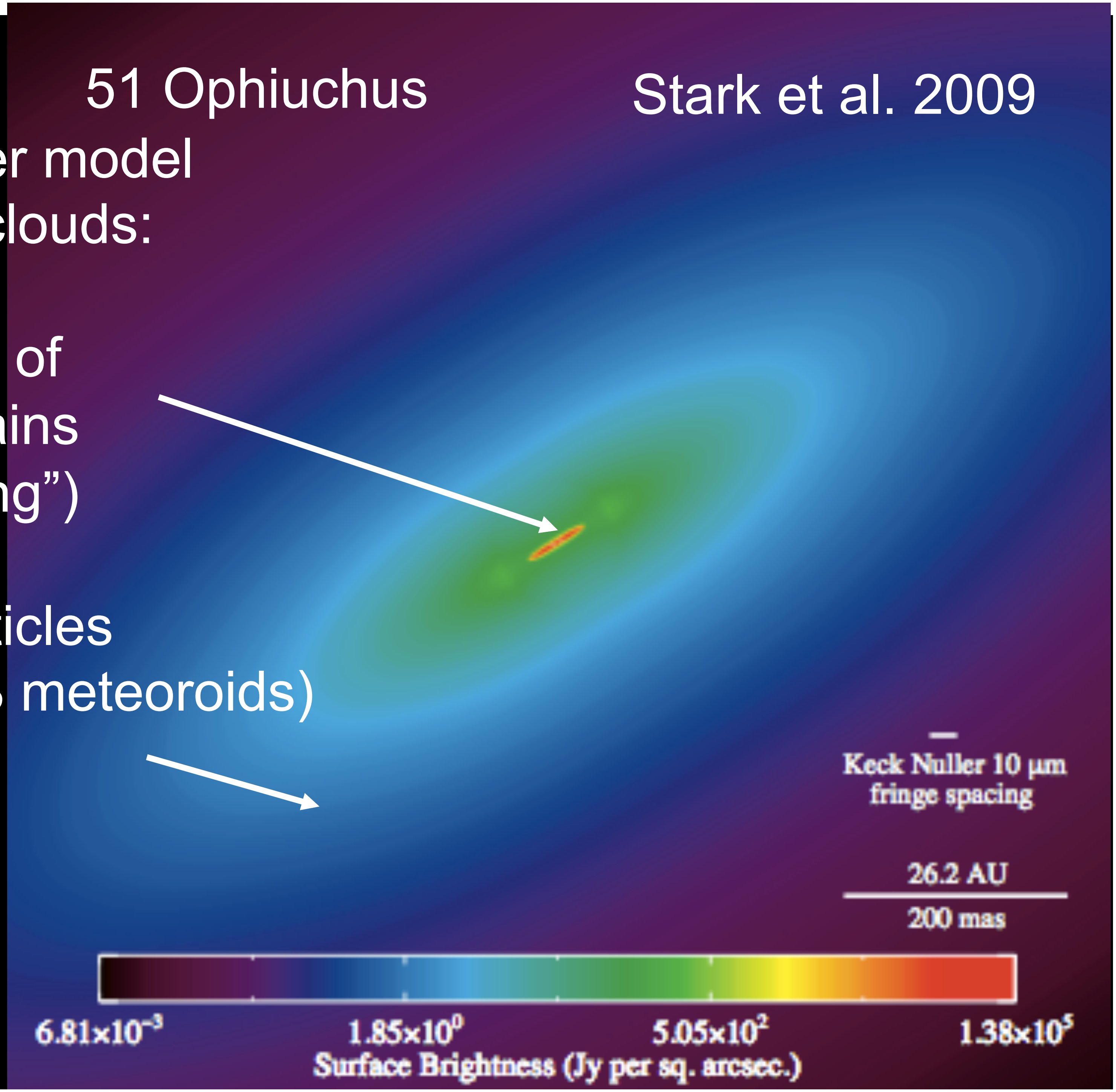
51 Ophiuchus

Stark et al. 2009

10 parameter model with 2 dust clouds:

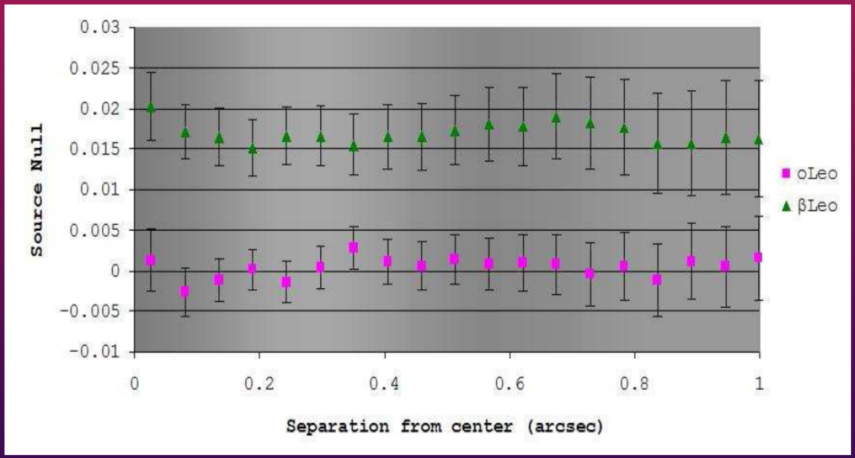
1) inner ring of large grains ("birth ring")

2) small particles (maybe β meteoroids)



LBTI ExoZodi Science

Nulling observations with the MMT (Phil Hinz)

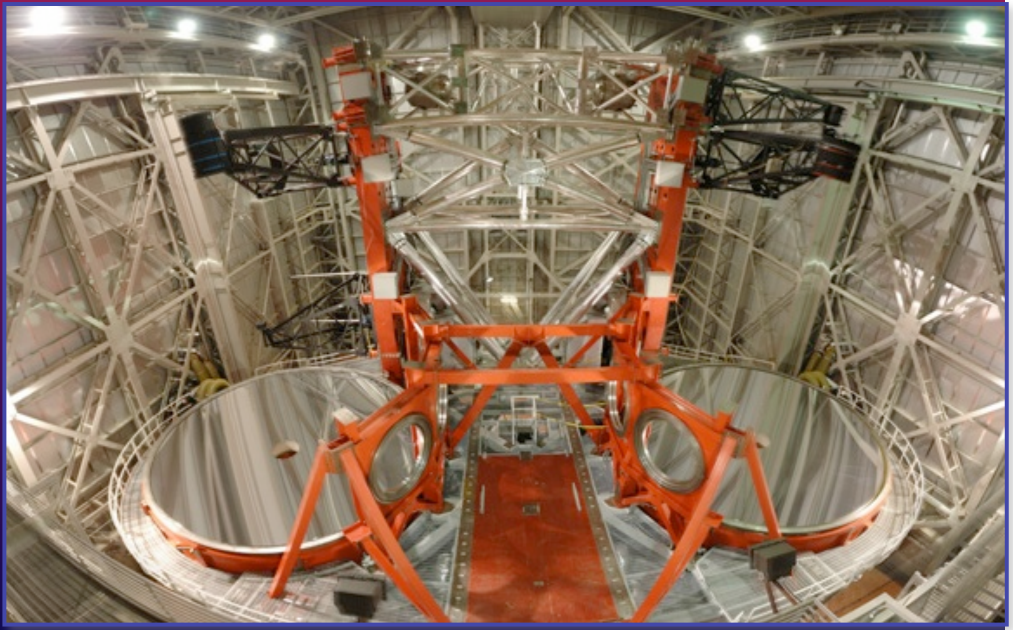


Detection of a 390±70 zody dust disk around β Leo and a non-detection around o Leo with an uncertainty of 50 zodi.

- MMT nulling experiments indicate detection of disks with an uncertainty of 25-75 zodi
- The larger apertures and faster correction of the LBT will improve this limit by a factor of 6
- LBTI could characterize debris disks with an uncertainty of ~3-10 zodi around nearby stars.
- Planned survey of 60 stars once LBTI becomes operational

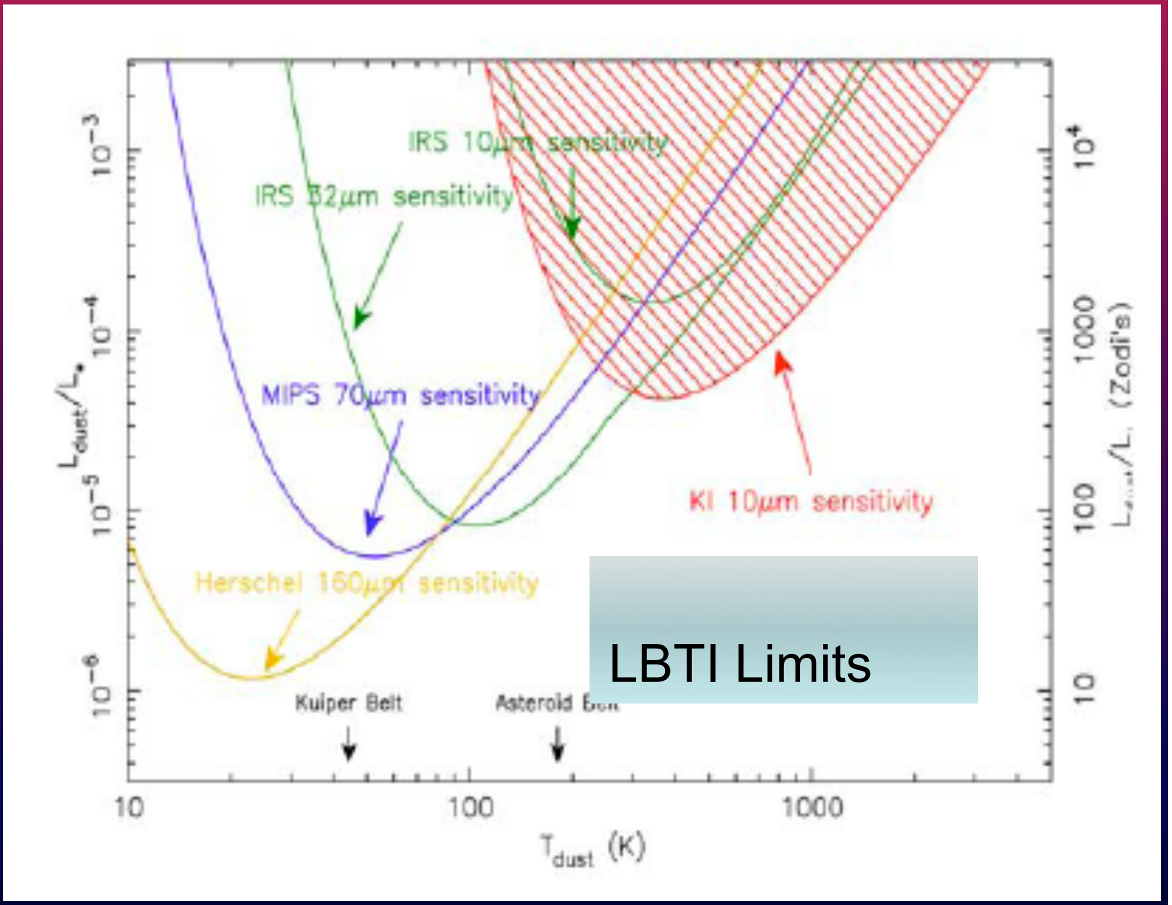
LBTI: Next^2 Step

- Lower background of LBTI (wrt KI) should enable LBTI to push down to 10 zodi (5-10x better than KI)
- Starting in 2012, LBTI will undertake a survey of 60 nearby stars for zodiacal dust to 3-10 times our own planetary system

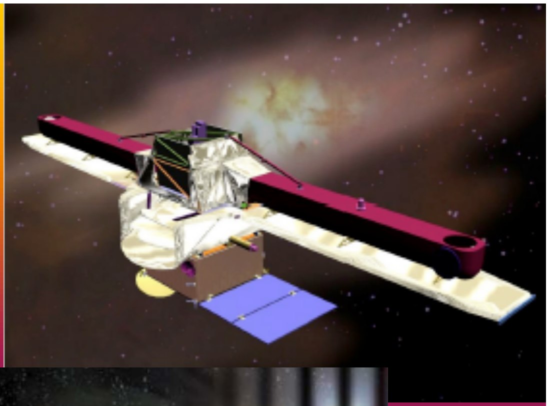


Ground-based Zodi Survey Prospects

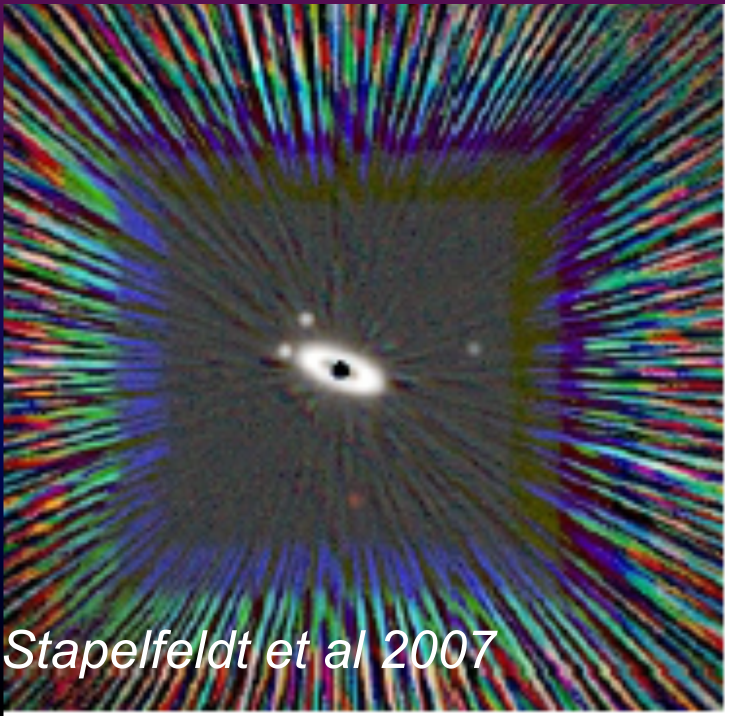
- Space-based (Spitzer, JWST) cannot get below 1000 Zodi at 10 μm
- Ground based observations at few hundred Zodi, 3-4x Spitzer
- LBTI will go below 100 SS, perhaps as low as 10 SS, approaching TPF limit
- Modest extrapolation with theory may satisfy concerns



The Next[3] Step: A Dedicated Space Mission



- 5-10 μm interferometry from space can reach 1 zodi
  - Pegase separated s/c interferometer
  - FKSI interferometer on a stick being (Danchi et al)
- Visible coronagraphy (Trauger, Stapelfeldt)
  - High contrast imaging with ~2 m telescope at 1-5 zodi as well as imaging nearby Jupiters



Stapelfeldt et al 2007

The Next$^{\infty}$ Step: Imaging And Characterizing Earths