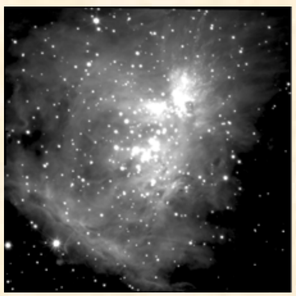
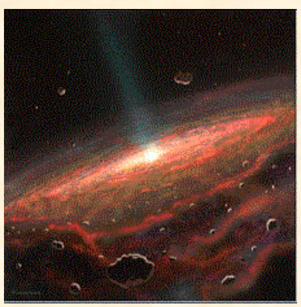
Lynne A. Hillenbrand



Hillenbrand & Carpenter

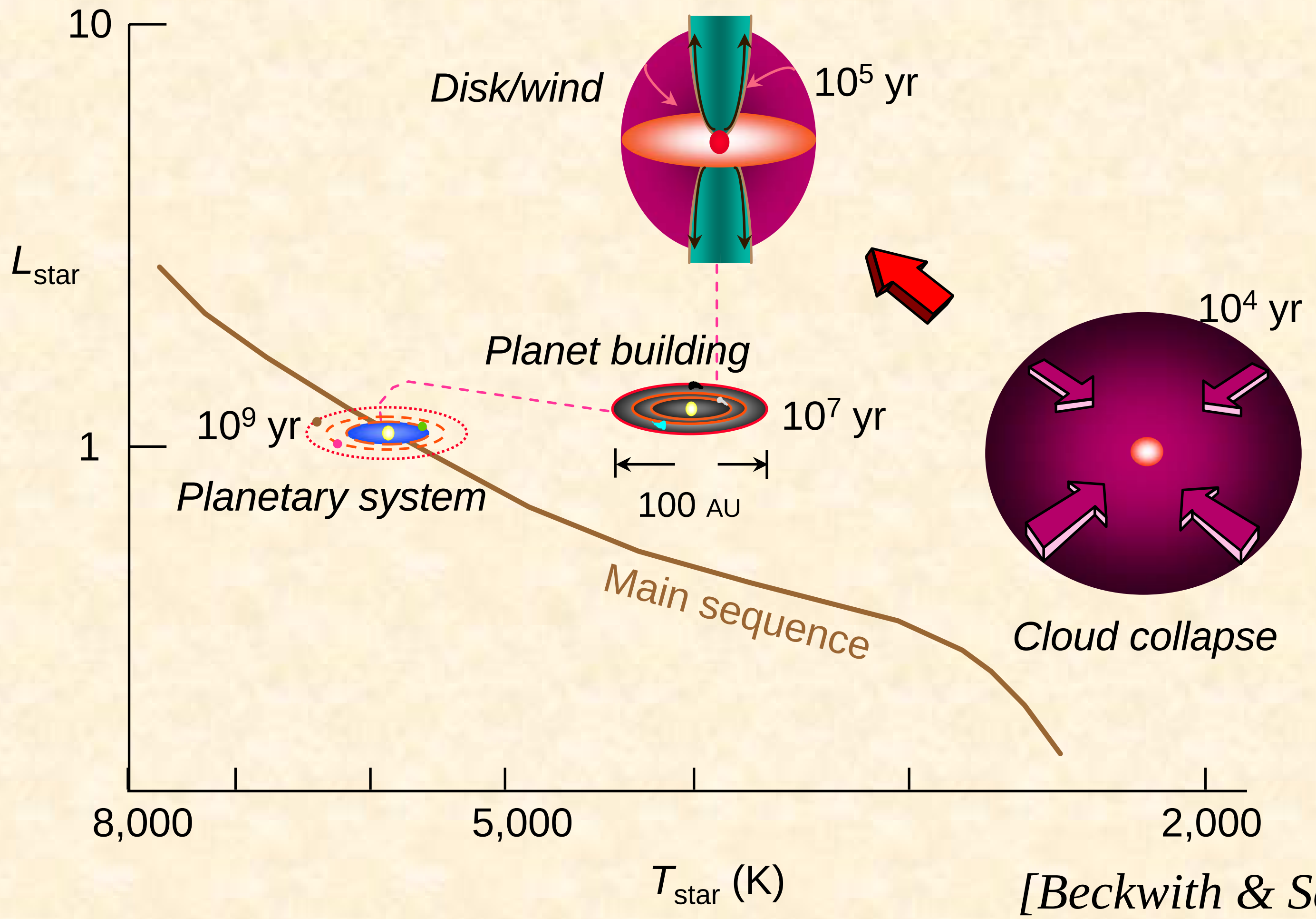


W. Hartmann

Spitzer Imaging and Spectroscopy of Disks

(Or imagine some flashier title if you must)

Pre-main Sequence Evolution



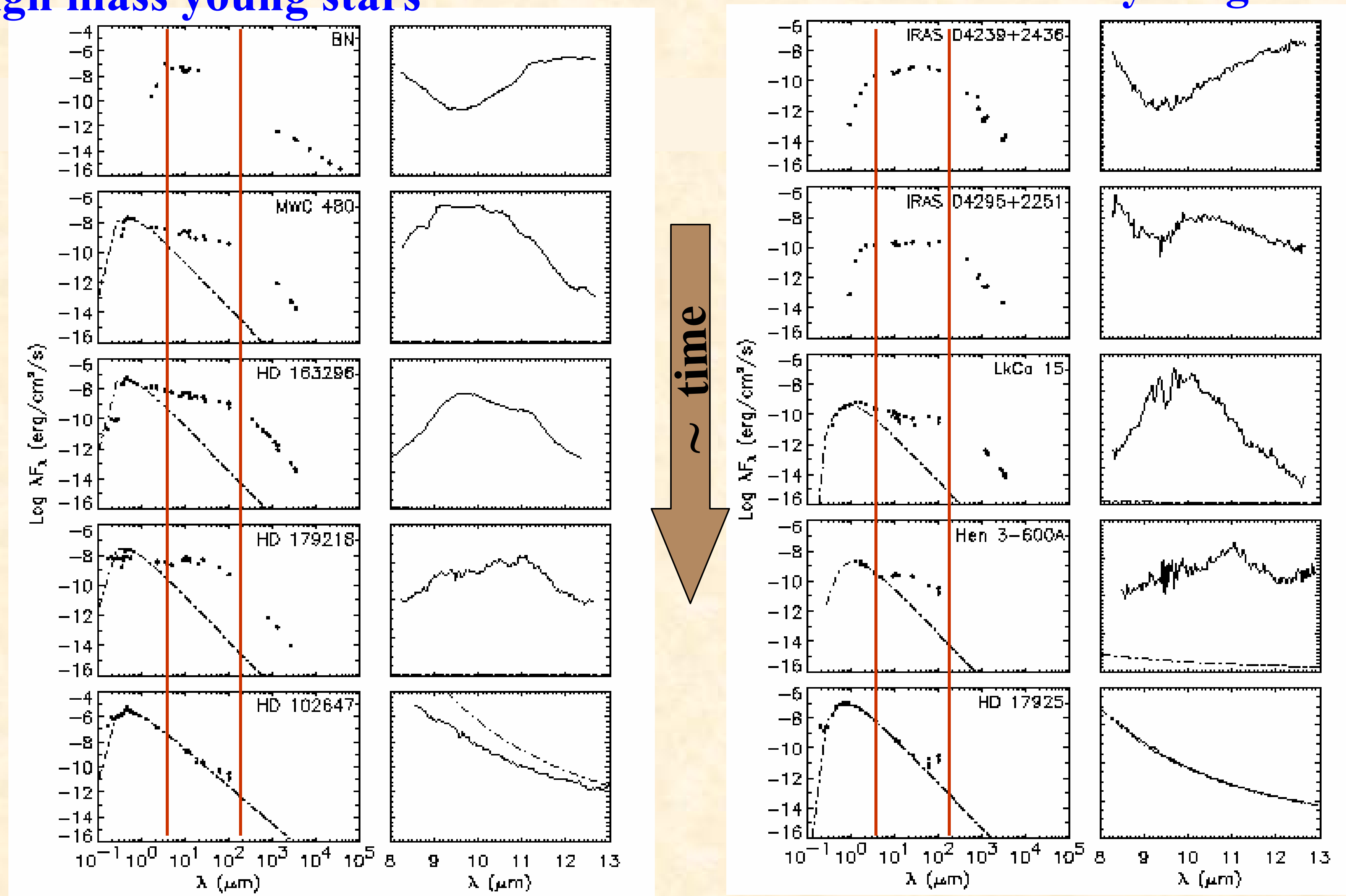
[Beckwith & Sargent 1996]

Kessler-Silacci et al. (2004)

SED & Mineralogical Evolution

High mass young stars

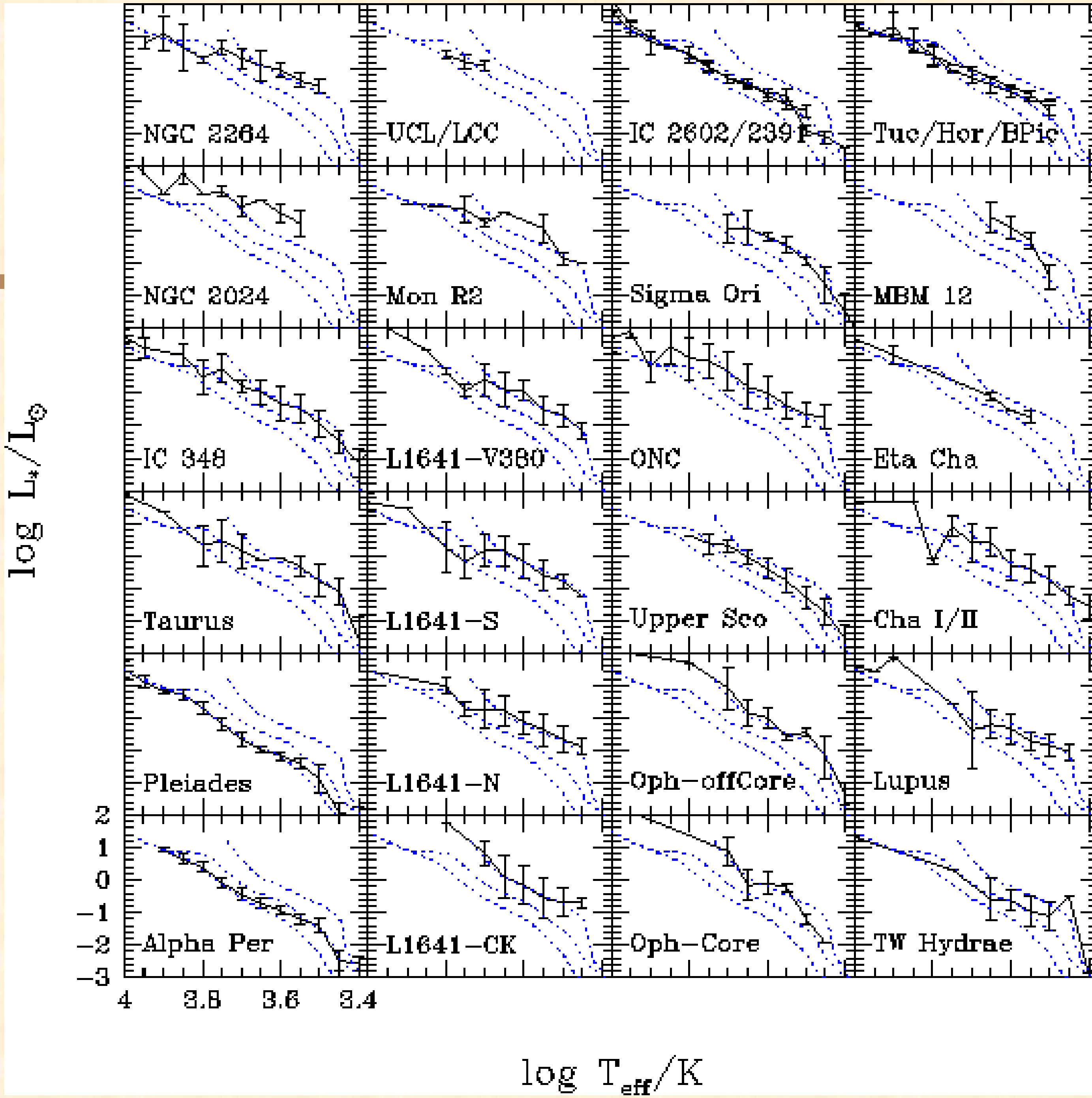
Low mass young stars



Survey of Young Star Clusters

<1 Myr old

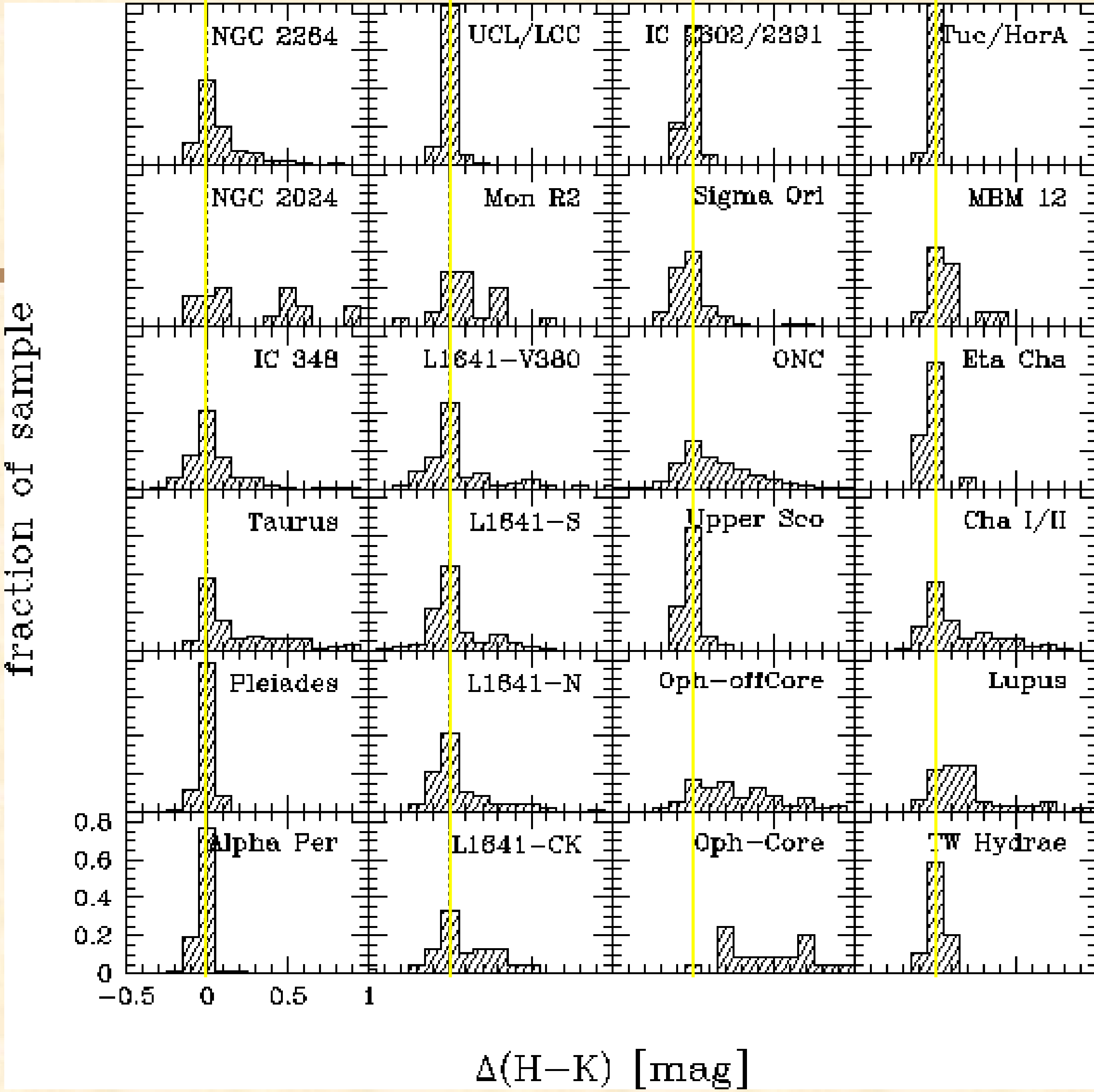
100 Myr old



Stellar evolution towards the main sequence:

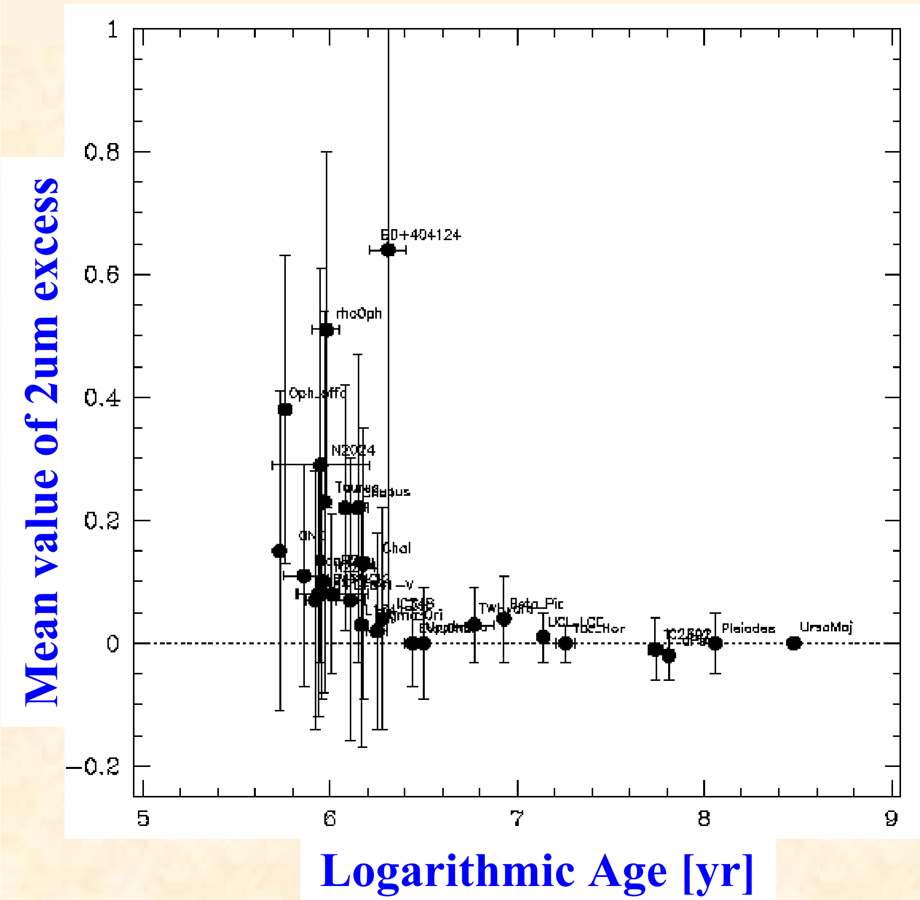
<1 - 120 Myr

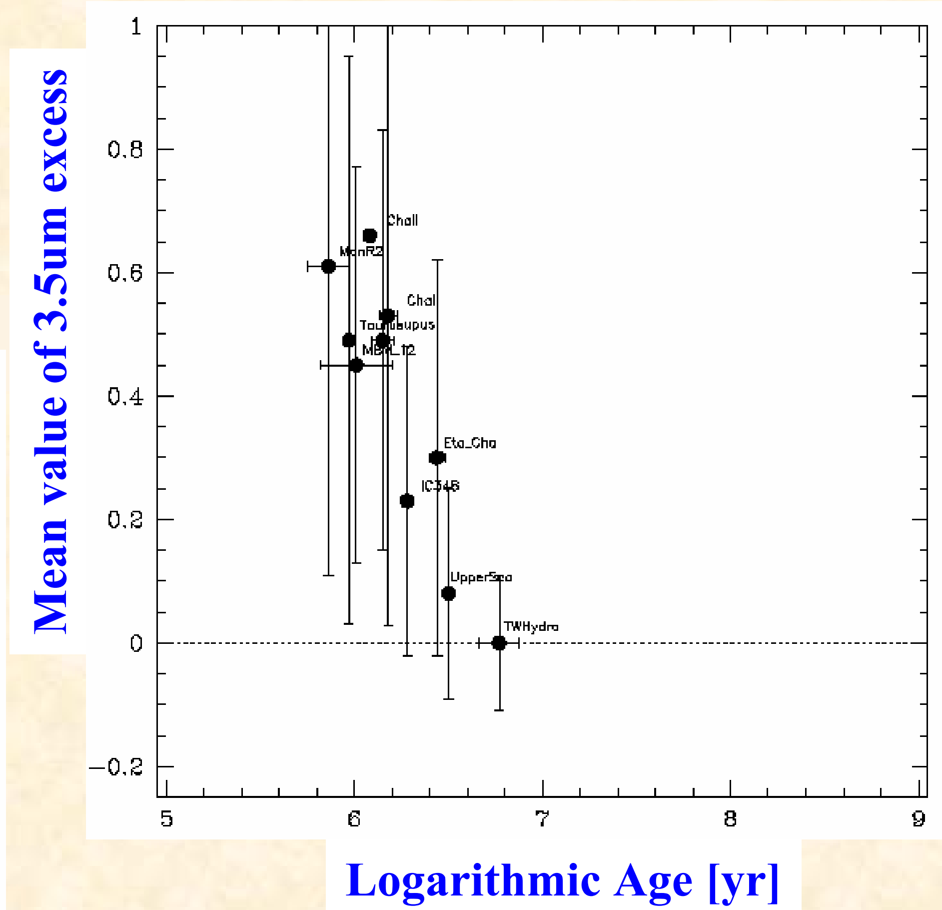
Accretion disk index



substantial range of values

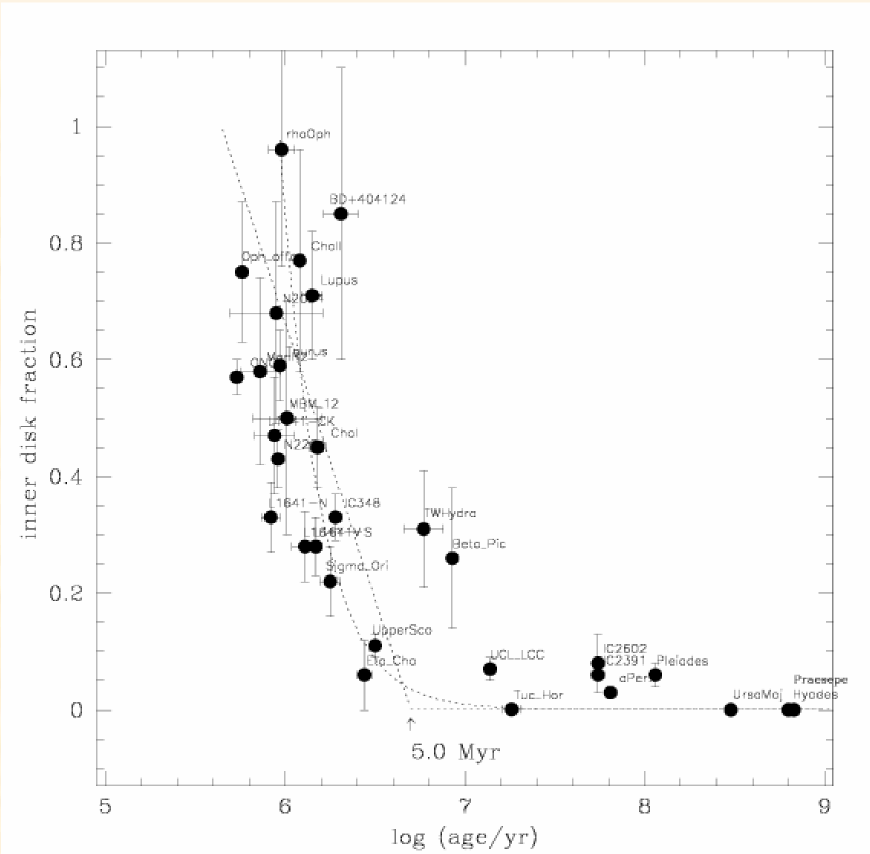
Inner Disk Dissipation: Mean Excess



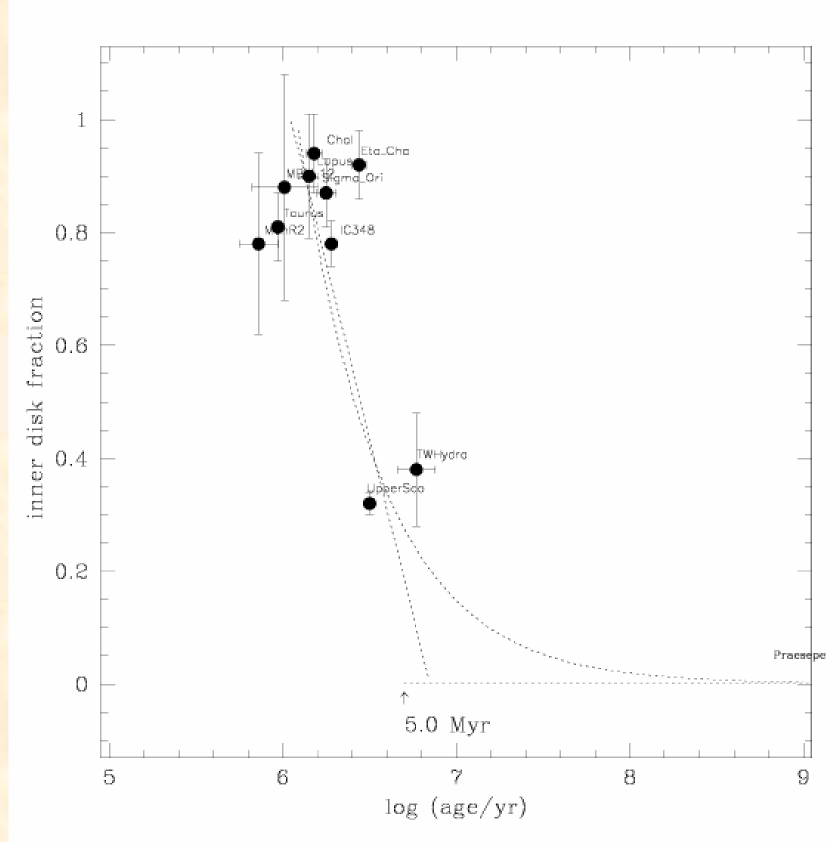


Typical *accretion* disk lifetime <3 Myr

Inner Disk Dissipation: Disk Fraction



Logarithmic Age [yr]



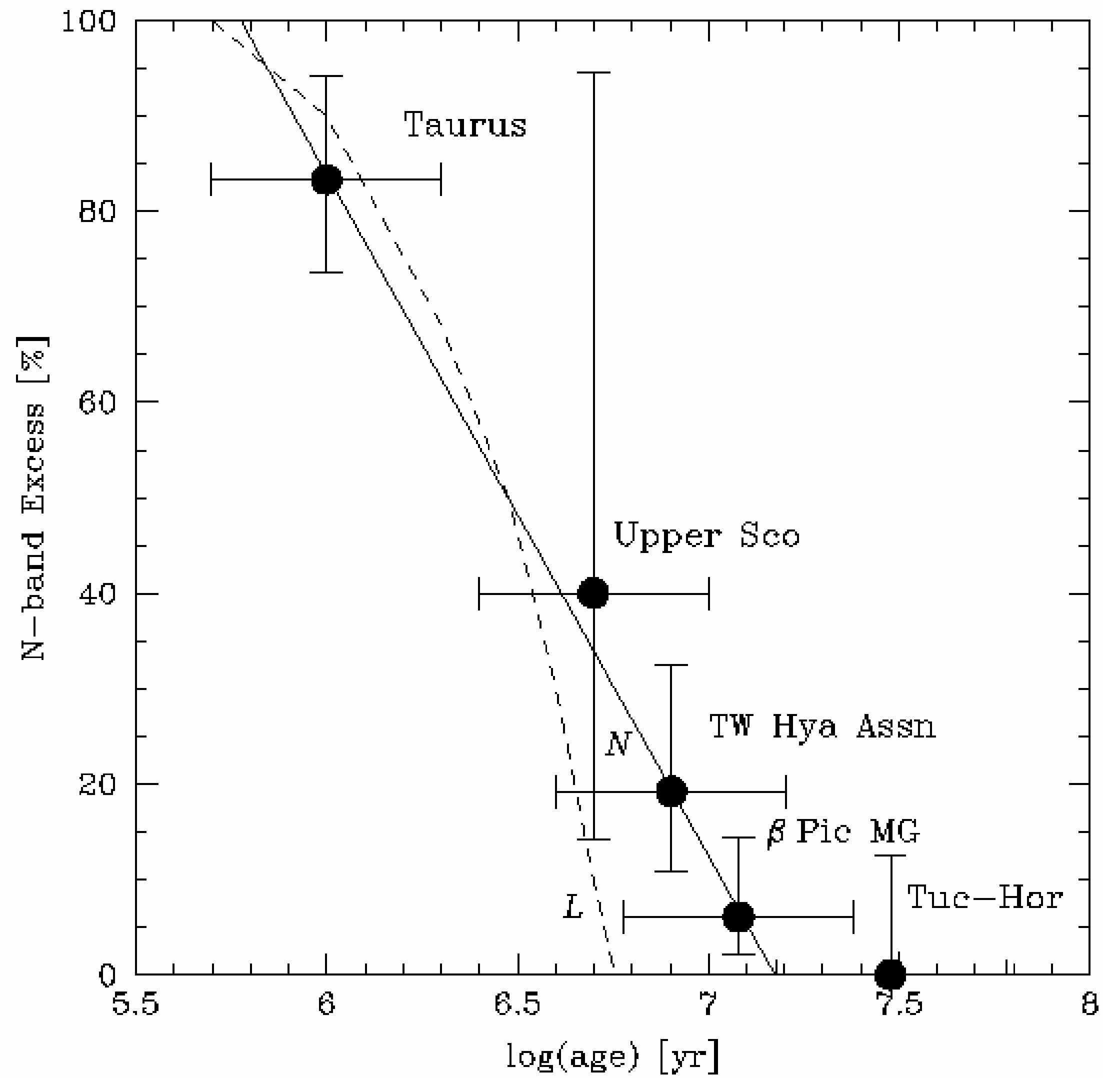
Logarithmic Age [Myr]

Near-IR: r < 0.1 AU, M~ 2-10 M_{Ceres}

Existing data suggest <3-10 Myr as maximum *accretion* disk lifetime

Mid-Disk Dissipation

Mamajek et al. (2004)



Meteoritic evidence suggests earth formed in <10 Myr with moon-forming impact occuring at ~30 Myr

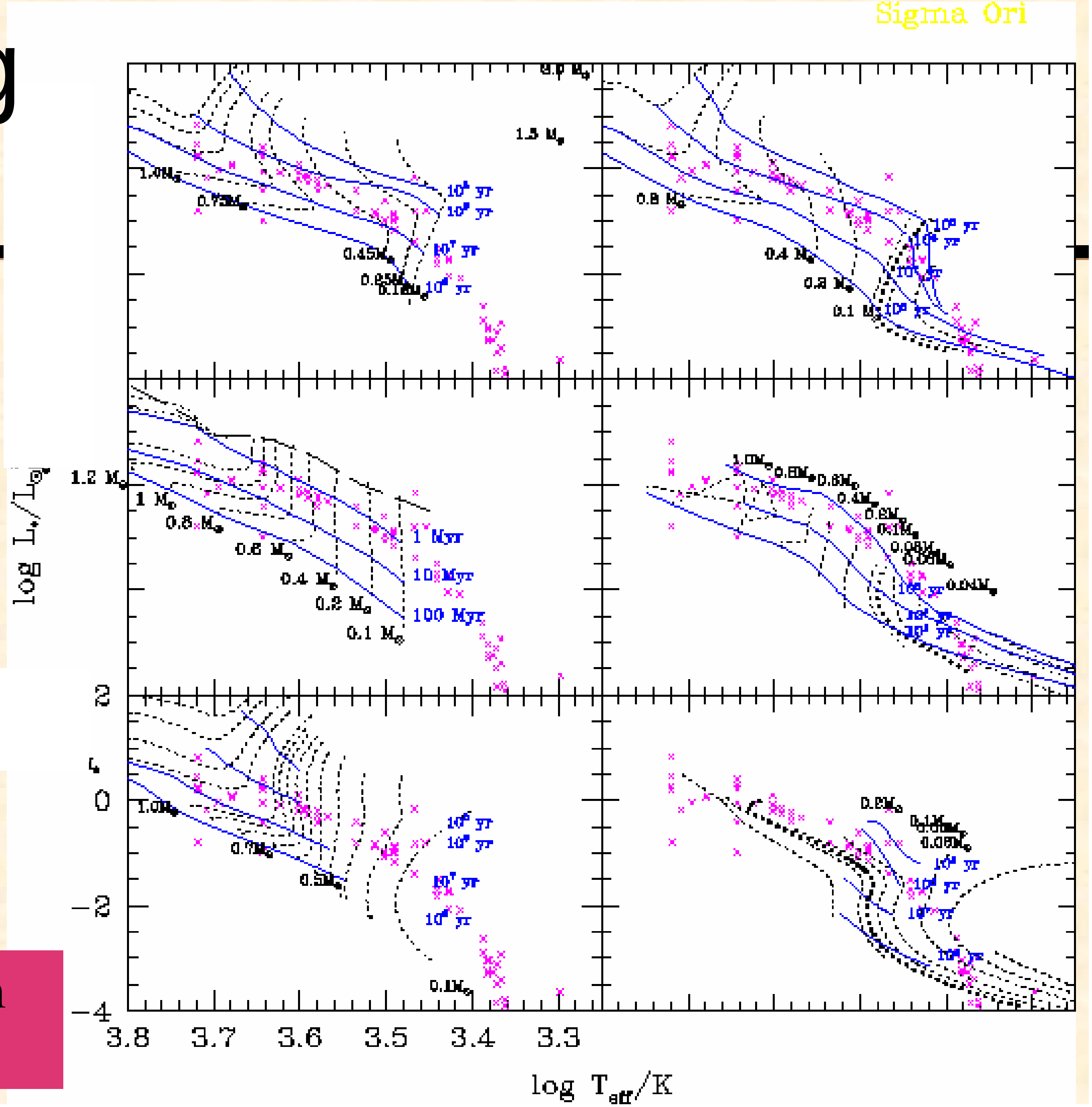
Mid-IR: 0.1-1.0 AU; M ~ 0.1-2 M_{Earth}.

Compare to terrestrial planet zone maximum disk lifetime ~10 Myr

Estimating Stellar Ages

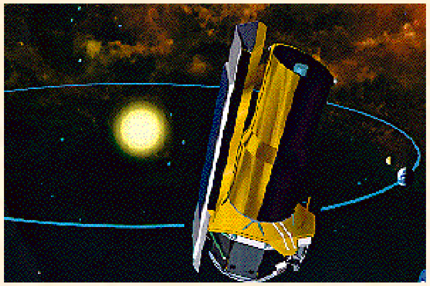
Different theory groups predict different paths through luminosity and temperature as stars contract to hydrogen burning "main sequence"

==> uncertainties in age are factors of 3



Stellar Parameters: A Caution

- Pre-main sequence evolutionary tracks:
  - under-predict stellar masses by 30-50%
    [Hillenbrand & White 2004 but c.f. Boden et al. poster]
  - under-predict low-mass stellar ages by 30-100%
  - over-predict high-mass stellar ages by 20-100%
  - disagree between calculations
- Evolutionary time scales have large systematic uncertainties



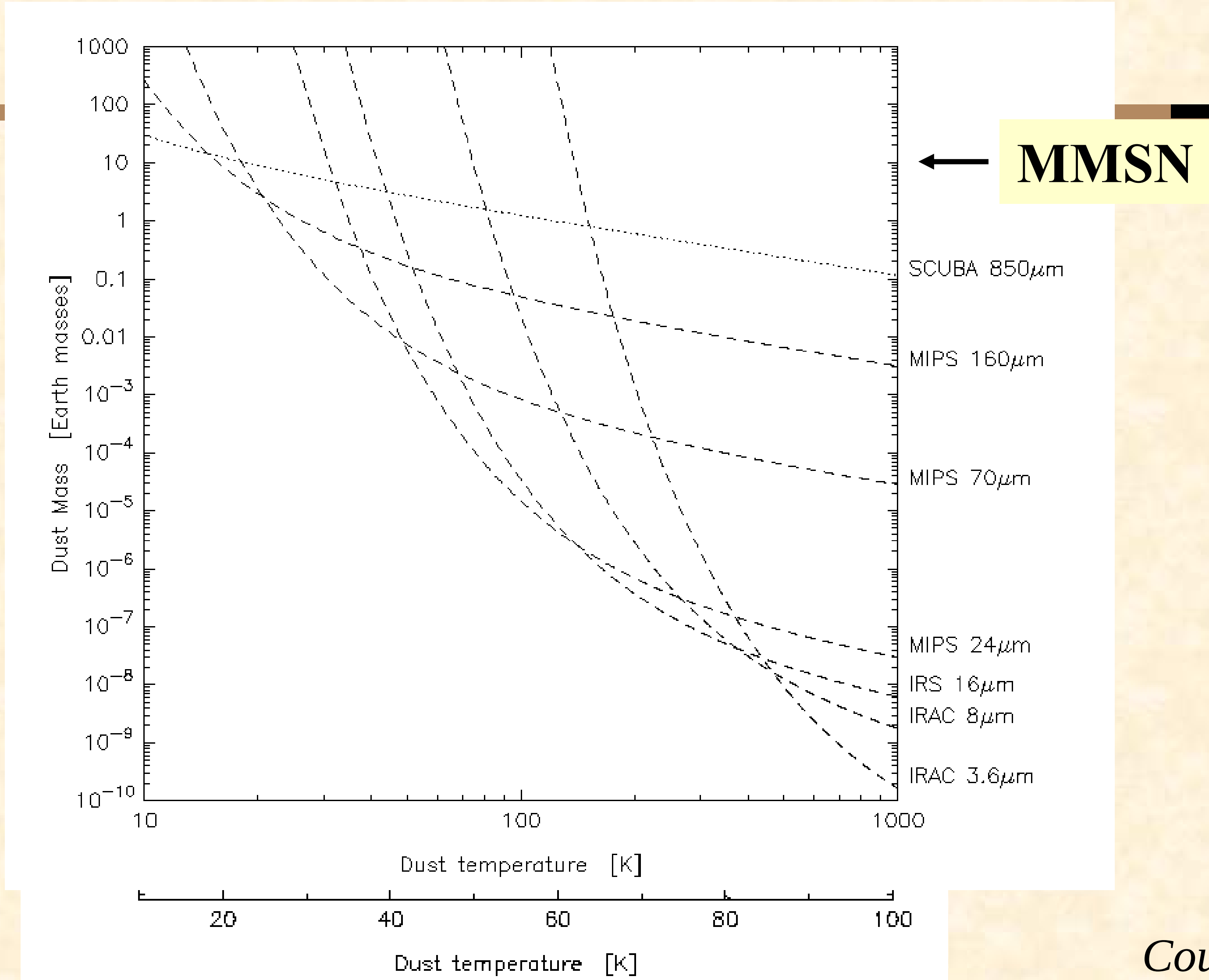
Spitzer Disk Science

- First Look Survey (Padgett et al.; Stolovy et al.)

- IRS Disks GTO Team (Watson et al.)
- IRAC and MIPS GTO Cluster Surveys (Young et al.; Rieke et al. Megeath et al.; Fazio et al.)
- Other GTO Disk Studies (Jura et al.; Werner et al.; Low et al.; Beichman et al.)

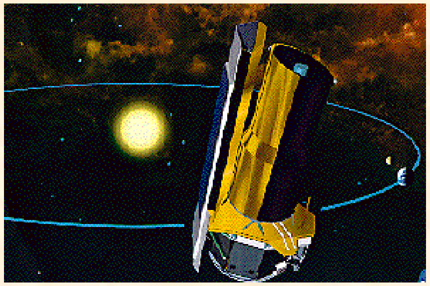
- Galactic Plane Survey Extraordinaire (Churchwell et al.)
- Cores to Disks (Evans et al.)
- Formation and Evolution of Planetary Systems (Meyer et al.)

Tracing Dust Mass



Greatest mass sensitivity at shortest wavelengths

Courtesy of J. Carpenter



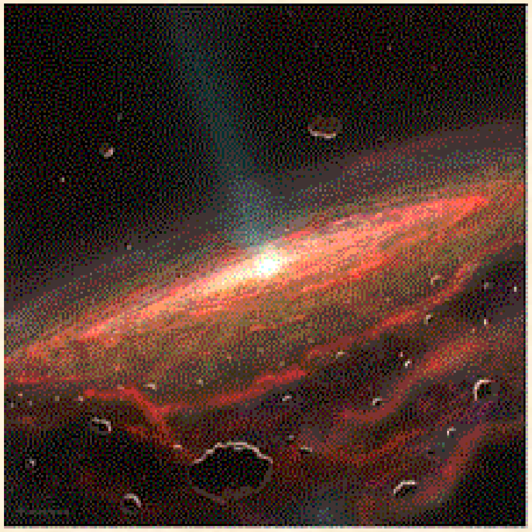
Spitzer Legacy Science: The Formation and Evolution of Planetary Systems

3 Myr - 3 Gyr

- Birth of Planetary Embryos:
  - characterize transition from primordial to debris dust disks.
- Growth of Gas Giant Planets:
  - constrain time scale for gas disk dissipation.
- Mature Solar System Evolution:
  - examine diversity of planetary systems based on debris disks.

A Spitzer/SIRTF "Legacy" Project

The Formation & Evolution of Planetary Systems: Placing Our Solar System in Context



Painting courtesy of William Hartman,

Planetary Science Institute, Tucson, AZ.

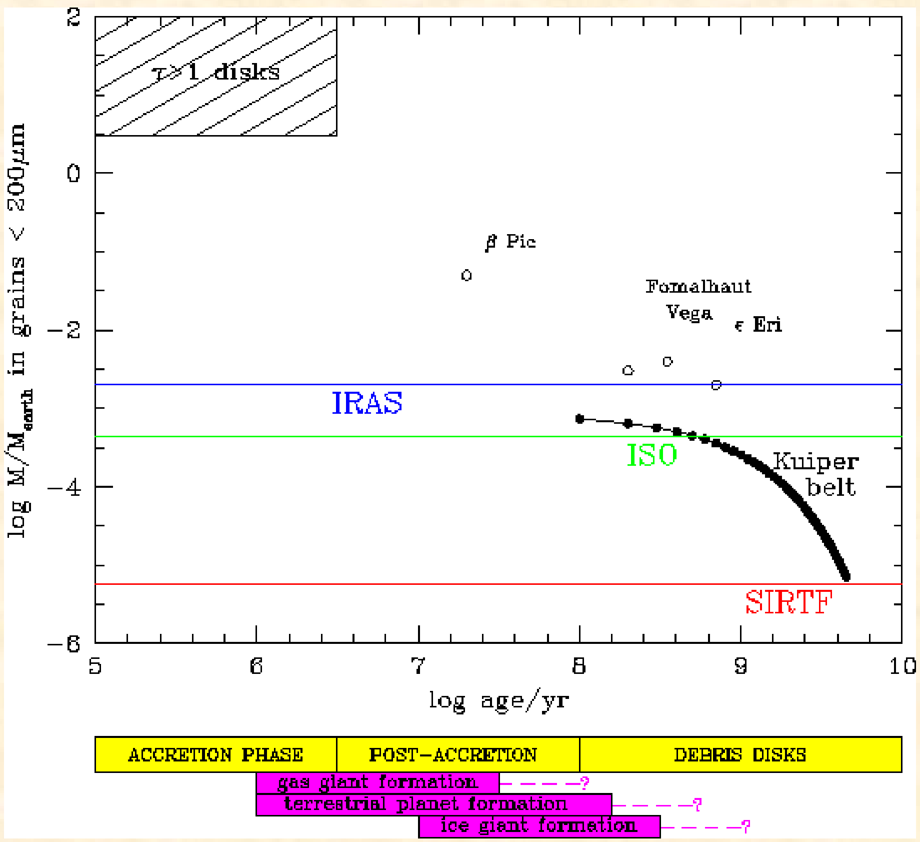
Michael R. Meyer (Steward Observatory, University of Arizona, P.I.)

L. Hillenbrand (Caltech, D.P.I.), D. Backman (NASA-Ames, D.P.I.) ,
S.V.W. Beckwith (STScI), J. Bouwman (MPIA), *T. Brooke (JPL),* J. Carpenter (Caltech),
M. Cohen (UC-Berkeley), *U. Gorti (NASA-Ames),* T. Henning (MPIA), D. Hines (SSI),
D. Hollenbach (NASA-Ames), J. Lunine (LPL), S. Kim (Steward), R. Malhotra (LPL),
E. Mamajek (CfA), A. Moro-Martin (Princeton), P. Morris (SSC), J. Najita (NOAO),
D. Padgett (SSC) I. Pascucci (Steward), J. Rodmann (MPIA), M. Silverstone (Steward),
D. Soderblom (STScI), J. Stauffer(SSC), *B. Stobie (Steward),* S. Strom (NOAO),
D. Watson (Rochester), S. Weidenschilling (PSI), *S. Wolf (MPIA),* and E. Young (Steward).

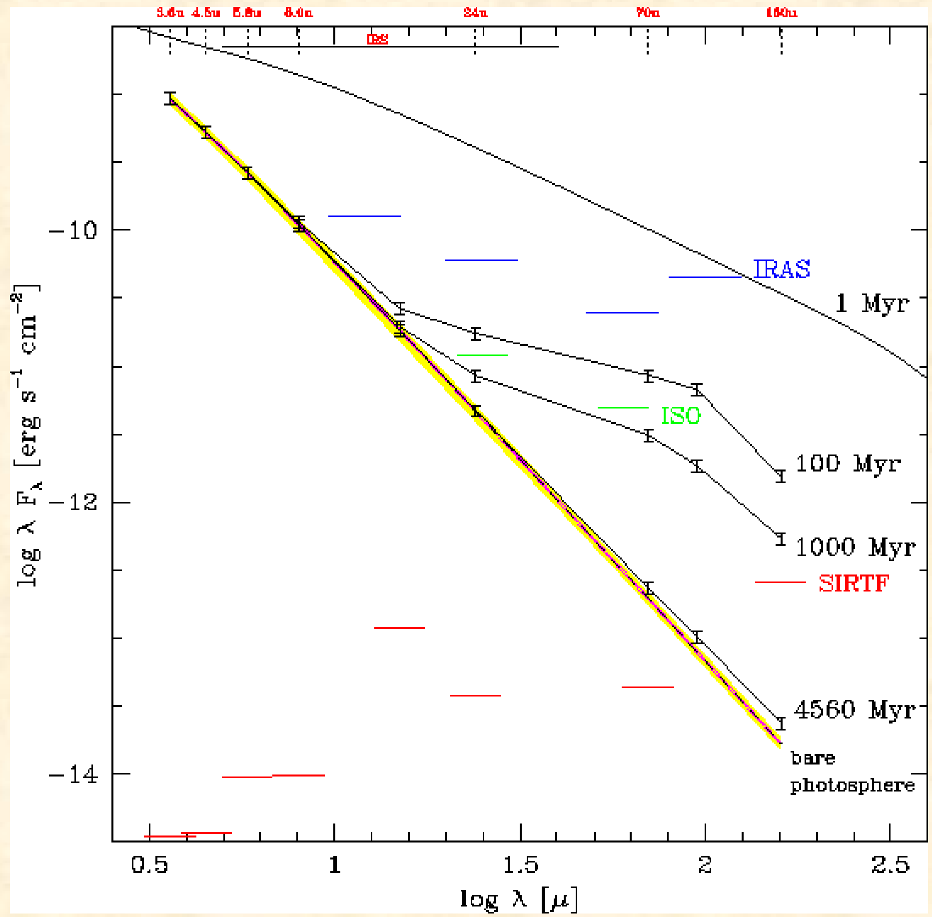
Evolution of Our Own Dust Disk in Time

D. Backman analytic model

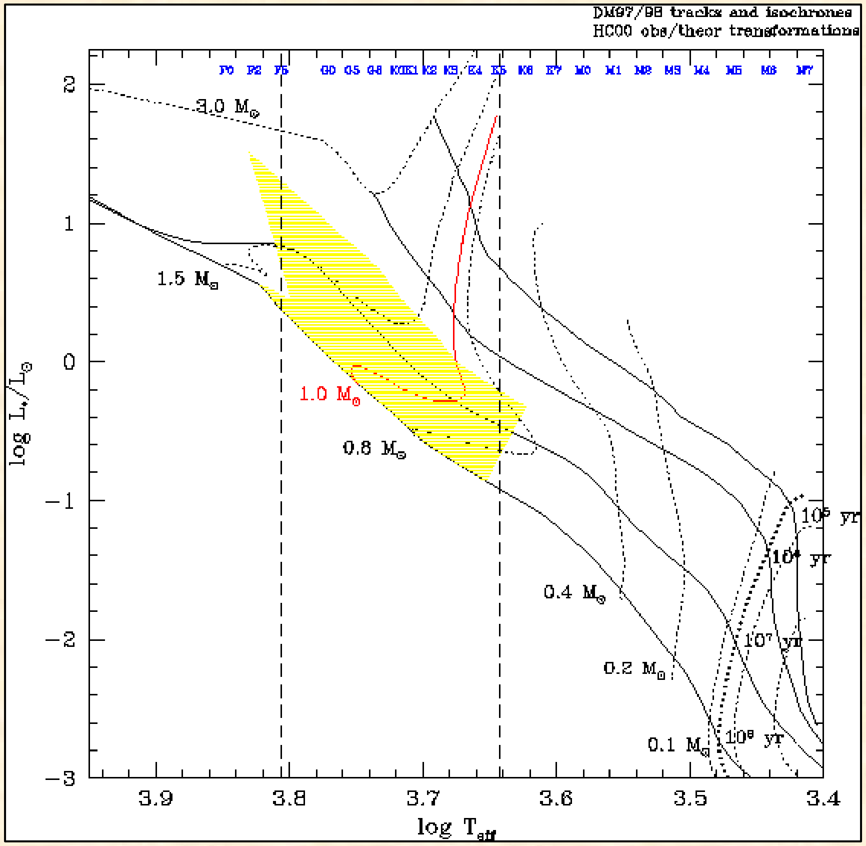
Mass in small grains



Spectral energy distribution



FEPS Source List Properties



- Mass range: 0.7 - 1.4 M_sun
- Age range: 3 Myr - 3 Gyr
- Distance: < 180 pc for pre-ms

  <50 pc for main sequence

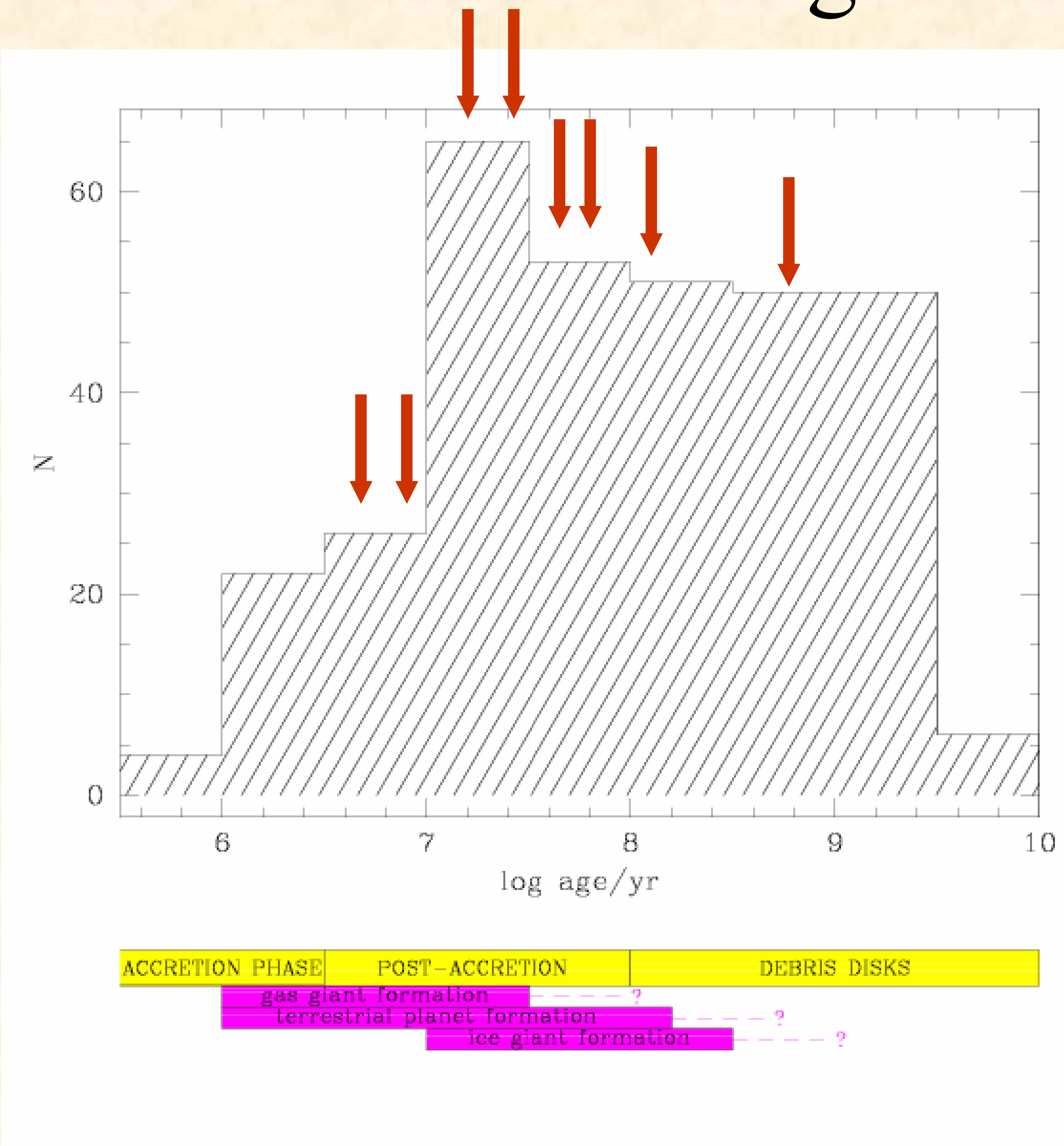
Dust disk survey: *~334 total stars*

~24 "primordial"

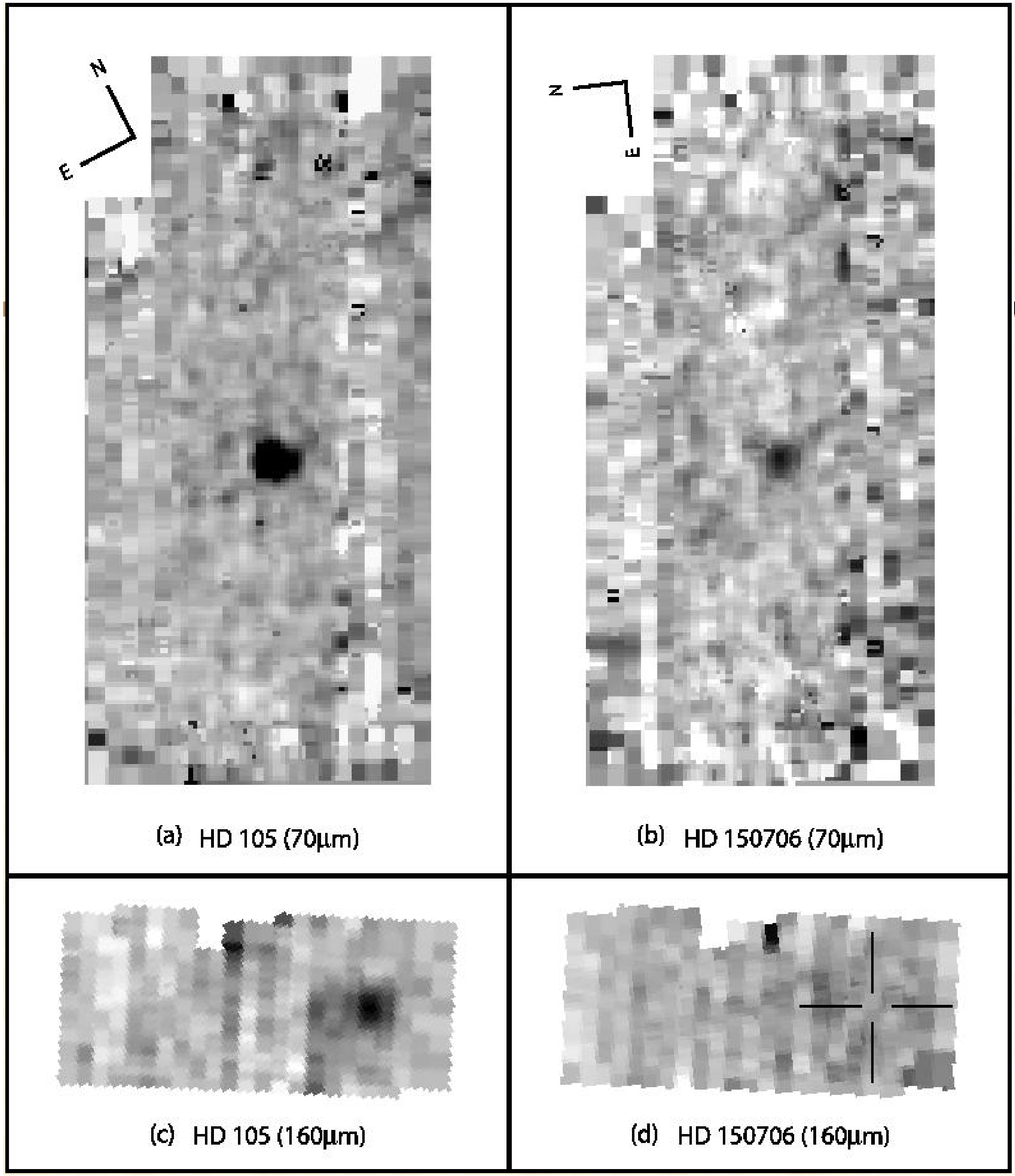
~310 "debris"

Gas disk survey: *~40 star sub-sample drawn from younger age bins*

Estimated Age Distribution



205 Field
22 Hyads (8.78)
20 Pleiads (8.08)
13 Alpha Per (7.90)
5 IC2602 (7.74)
2 Cas-Tau (7.5-8)
14 L. Cen-Cru (7.4)
23 U Cen-Lup (7.2)
17 U. Sco (6.5-7)
. 7 Cor-Aust (6.5-7)



(a) HD 105 (70µm)

(b) HD 150706 (70µm)

(c) HD 105 (160µm)

(d) HD 150706 (160µm)

First FEPS Results!

One confirmed and one new debris disk

ApJS Special Issue.

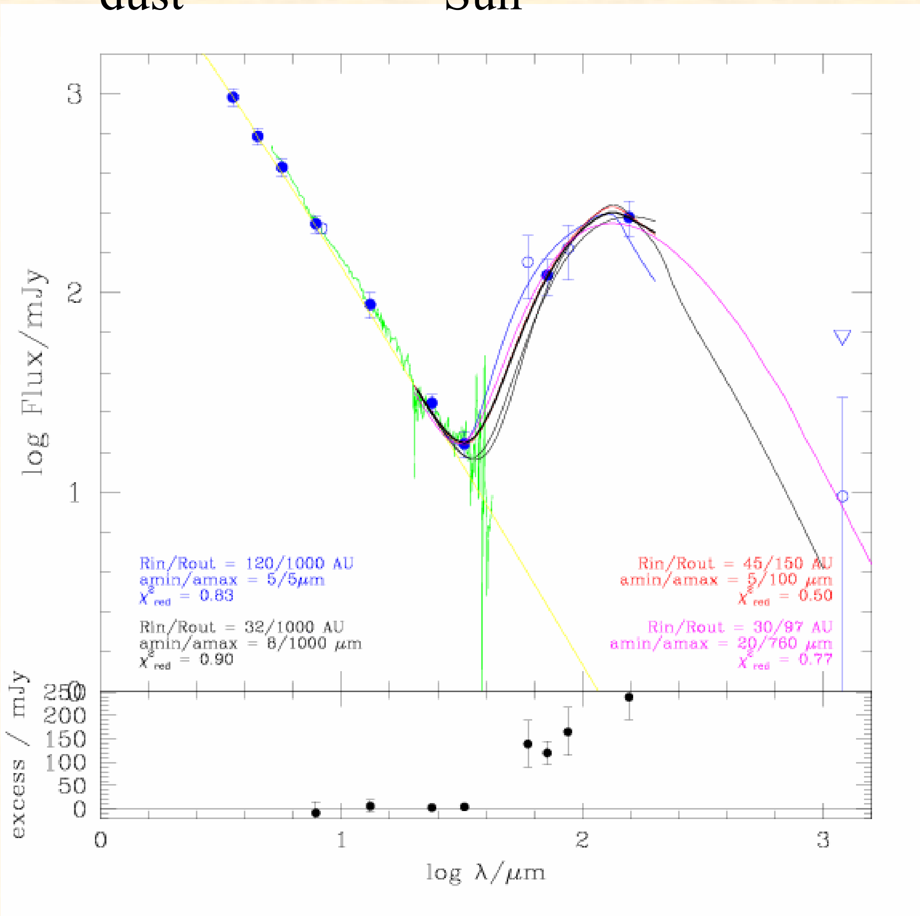
Meyer et al. (2004)

Young Debris Disks

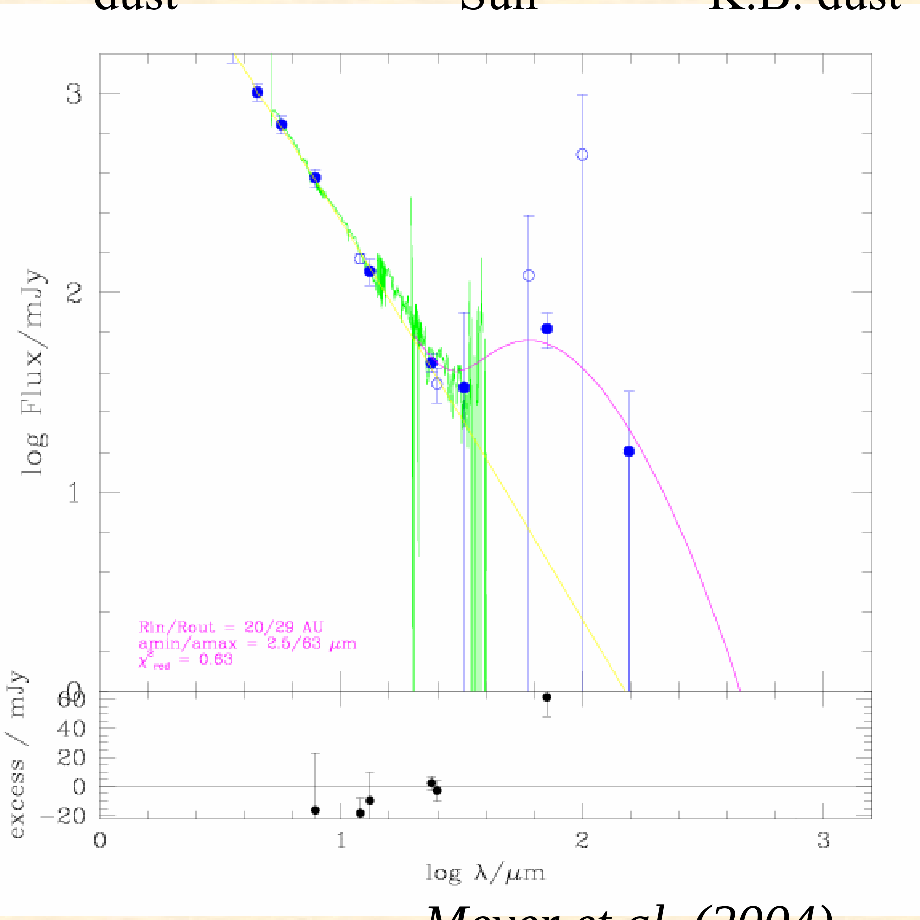
Spitzer/FEPS results!

[HD 105 at 30+/- 10 Myr] **[HD 150706 at 700+/- 300 Myr]**

$M_{dust} = 2x10^{-7}\ M_{Sun}$

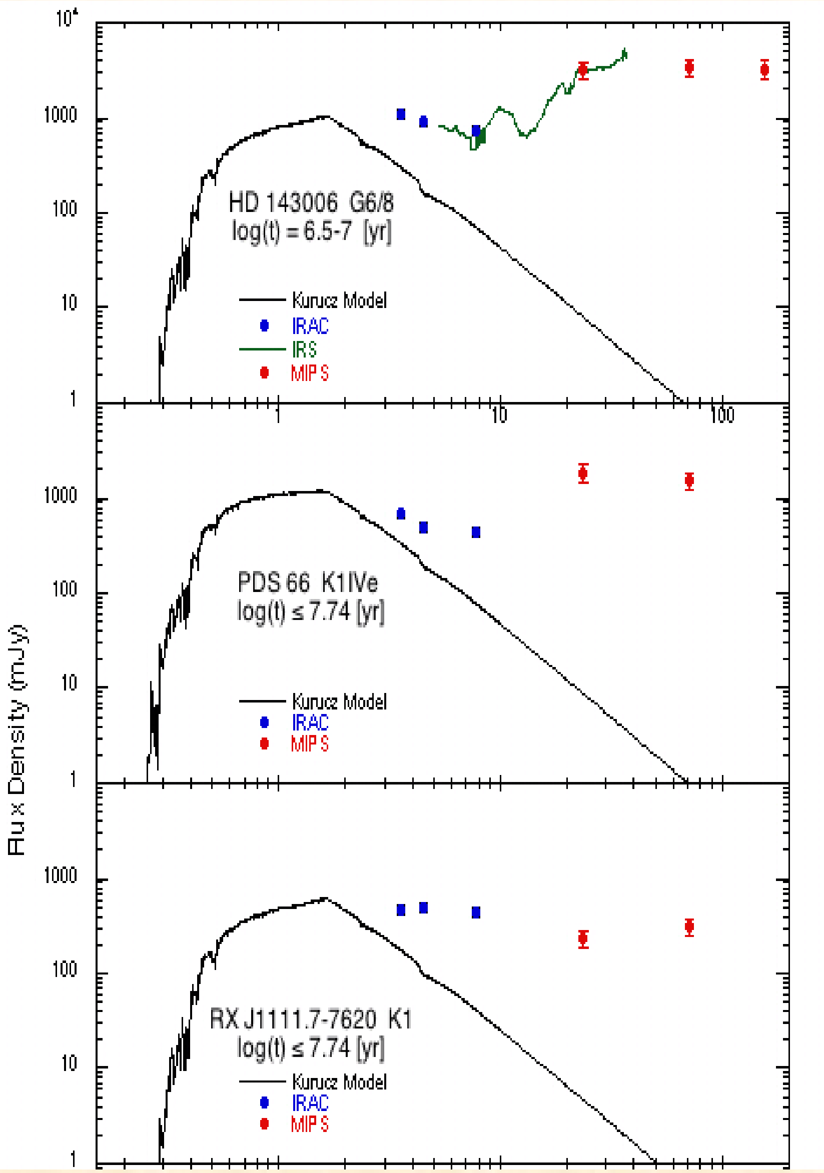


$M_{dust} = 4x10^{-10}\ M_{Sun} = 13\ M_{K.B.\ dust}$



Meyer et al. (2004)

New primordial disks from Spitzer



Spitzer/FEPS results!

HD 143006
[3-10 Myr CTTS in Upper Sco]

"Young, hot debris" (?)

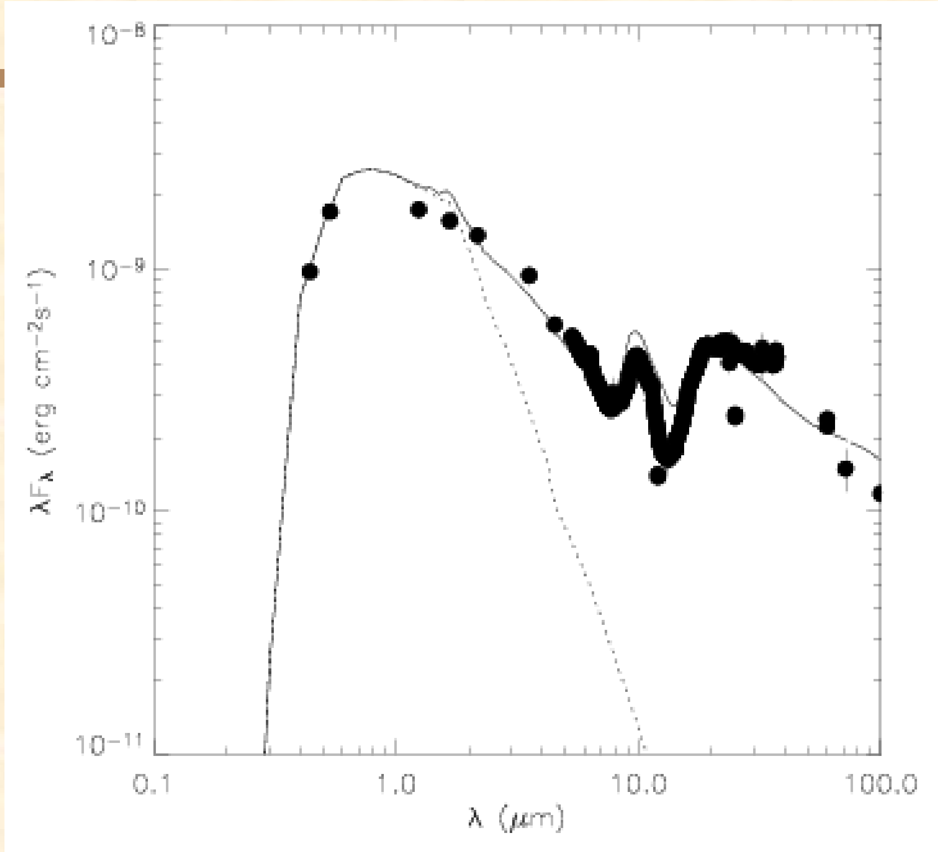
PDS 66
[15 Myr CTTS in UCL/LCC]

RXJ1111.7-7620
[3-10 Myr PTTS in Cham I]

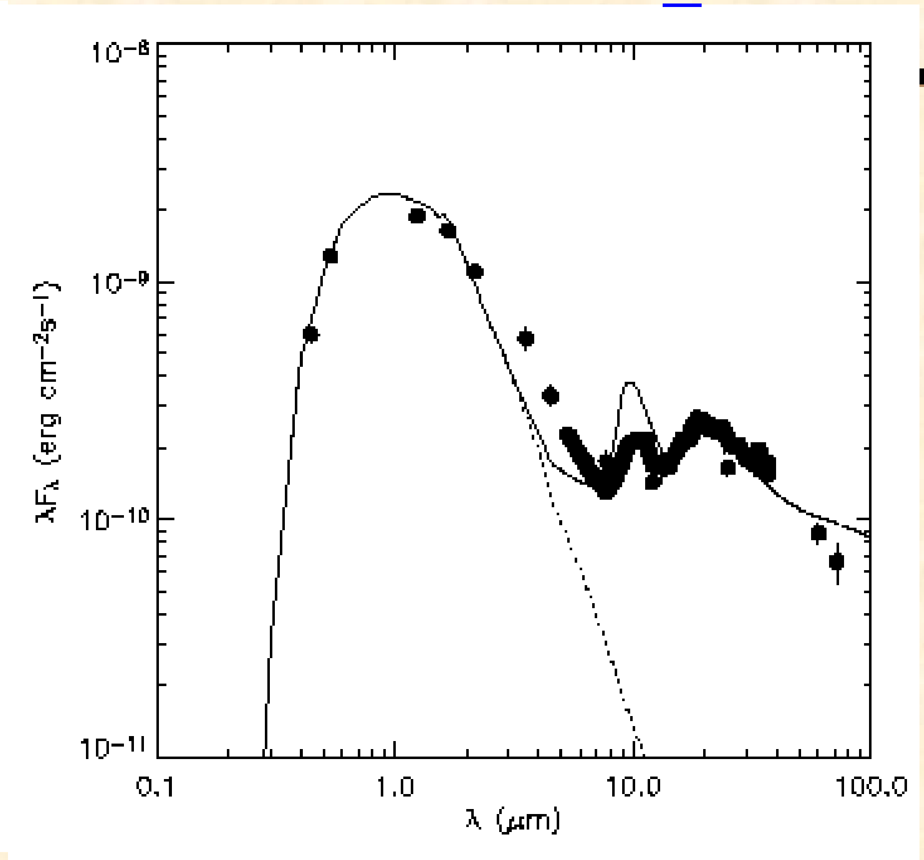
Silverstone et al. (2005)

Crude Modelling Results

HD 143006



PDS 66 = 1RXS_J1322



Standard flared disk ($\zeta = 2/7$)

Rin = 0.4 AU   Rout = 50 AU

Crystalline silicate spectrum!

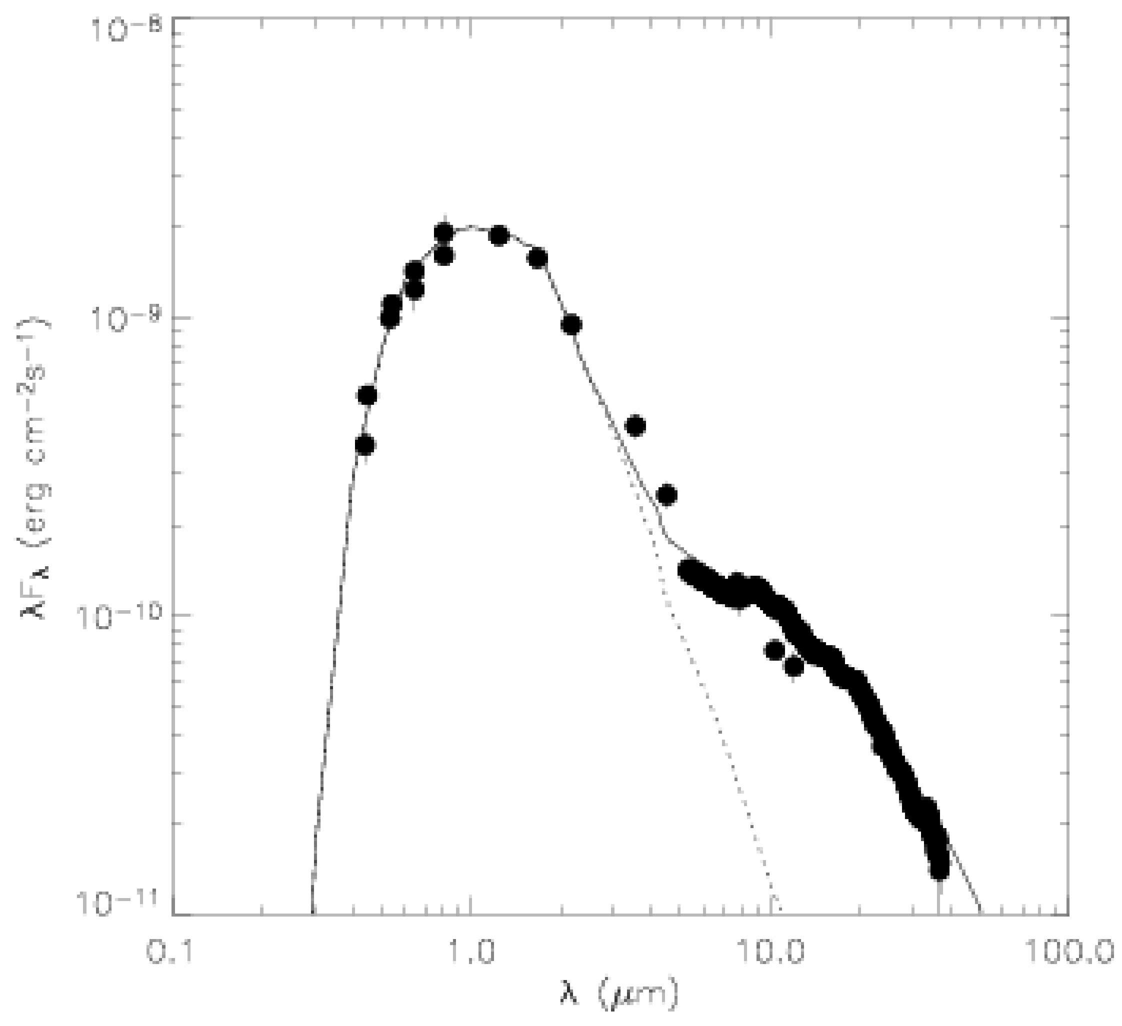
Crude Modelling Results

1RXS_J1614

FLAT disk

Rin = 0.12 AU

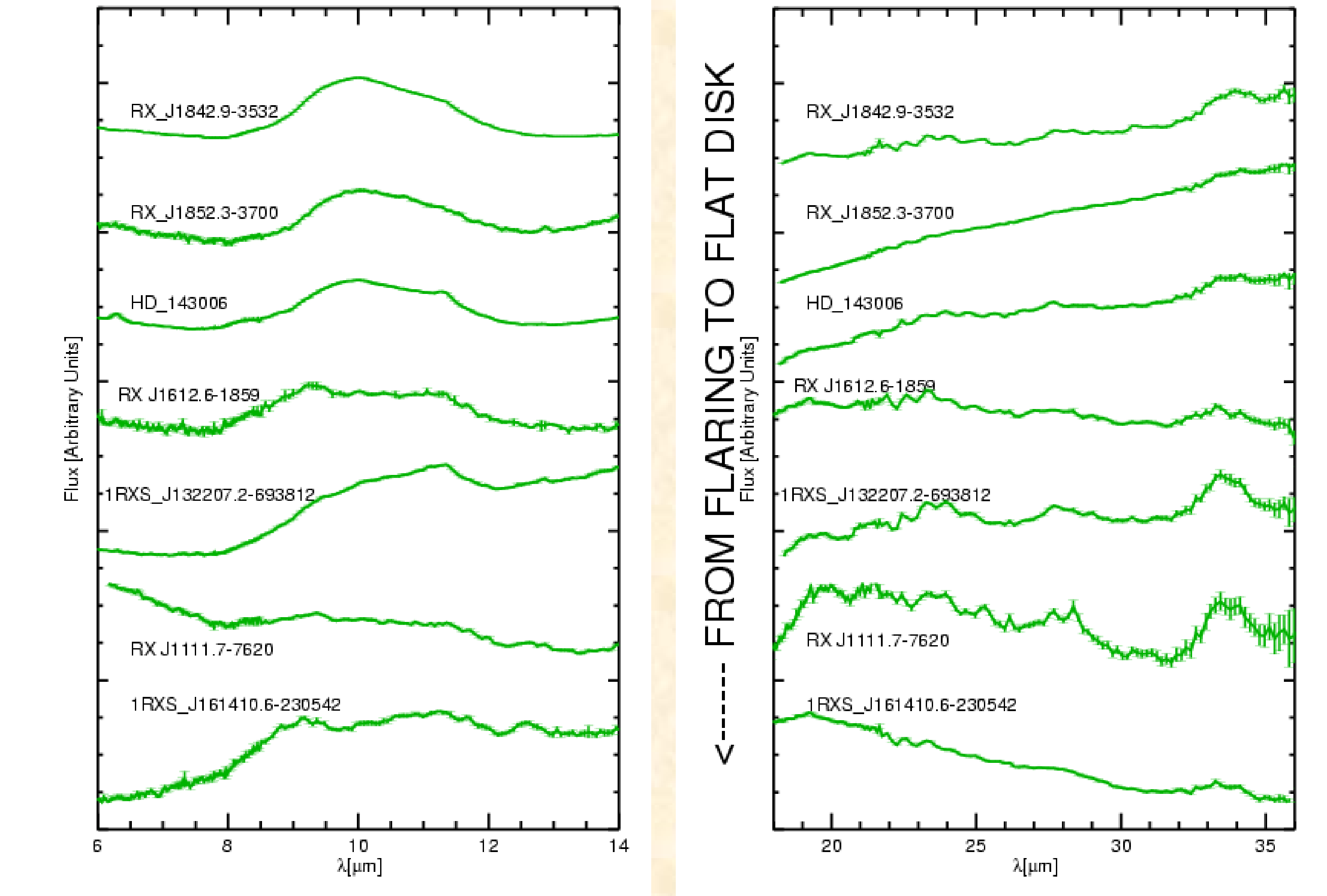
Rout = 1 AU



Mineralogical Evolution

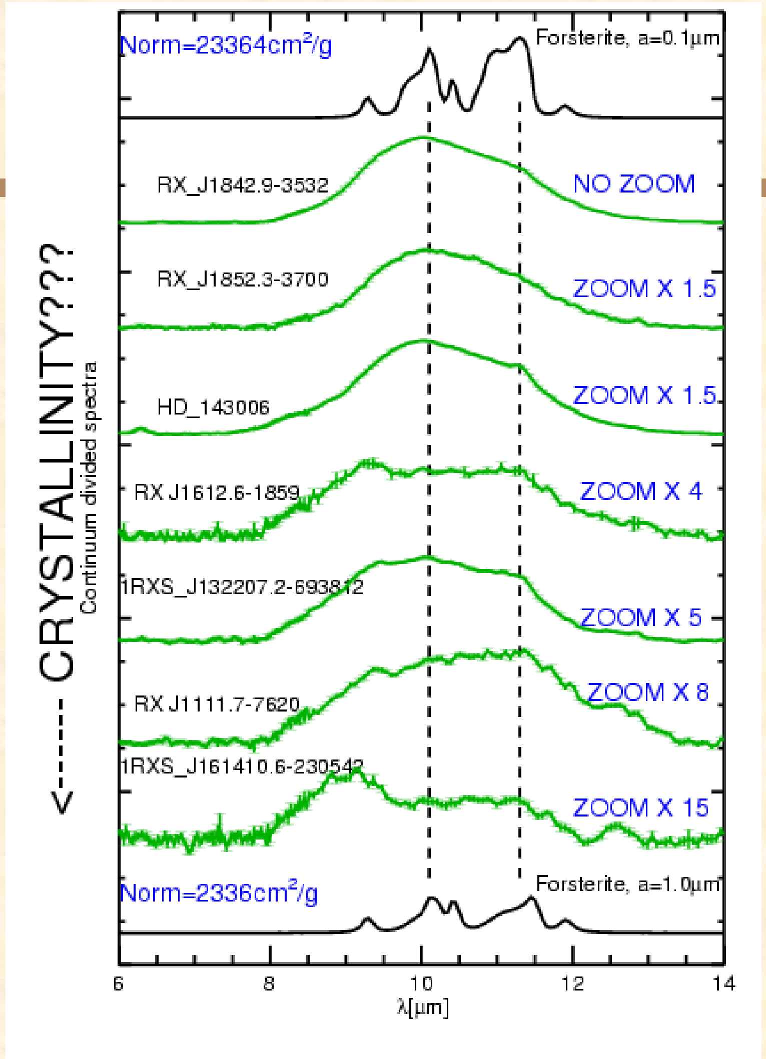
Solar-type young stars

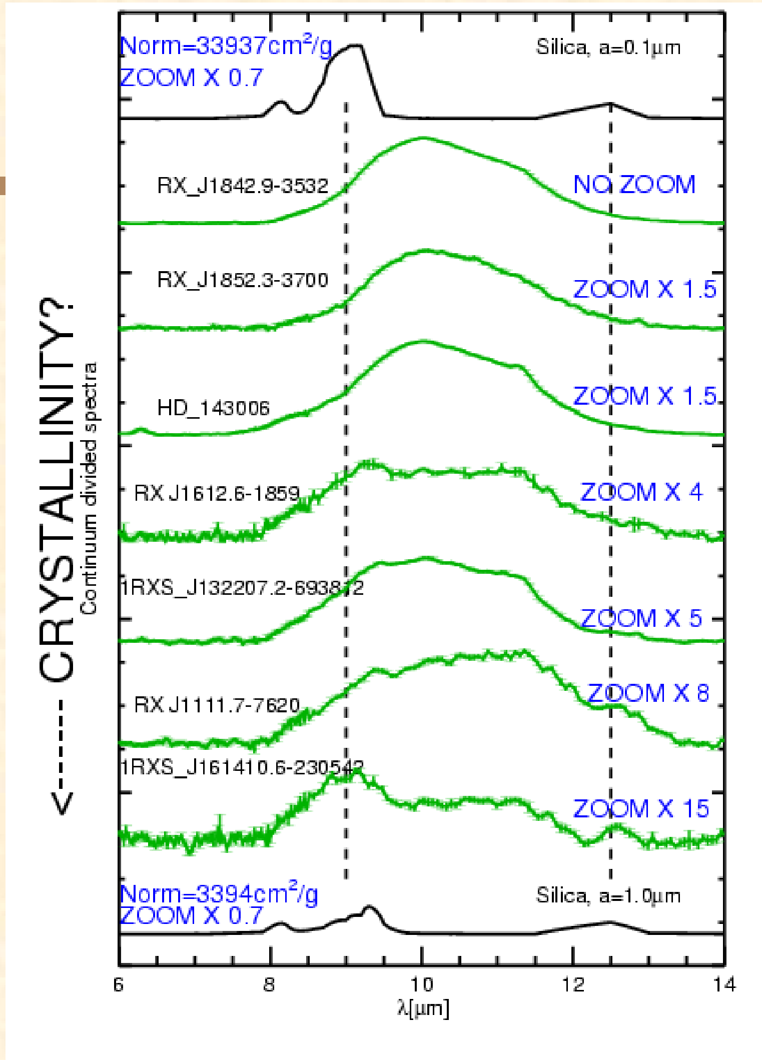
Spitzer/FEPS results!



Bouwman et al. (2005)

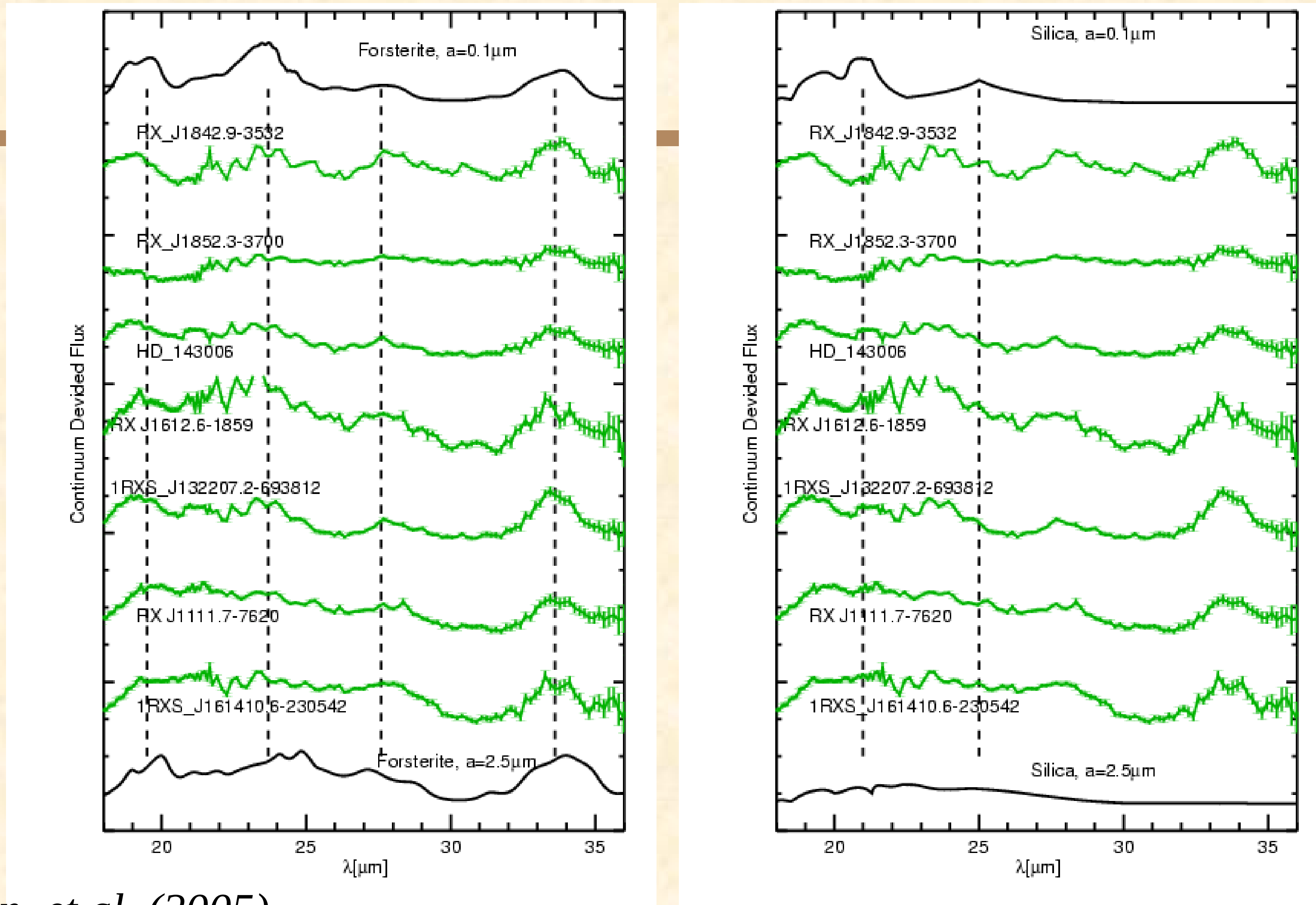
Spitzer/FEPS results!





Bouwman et al. (2005)

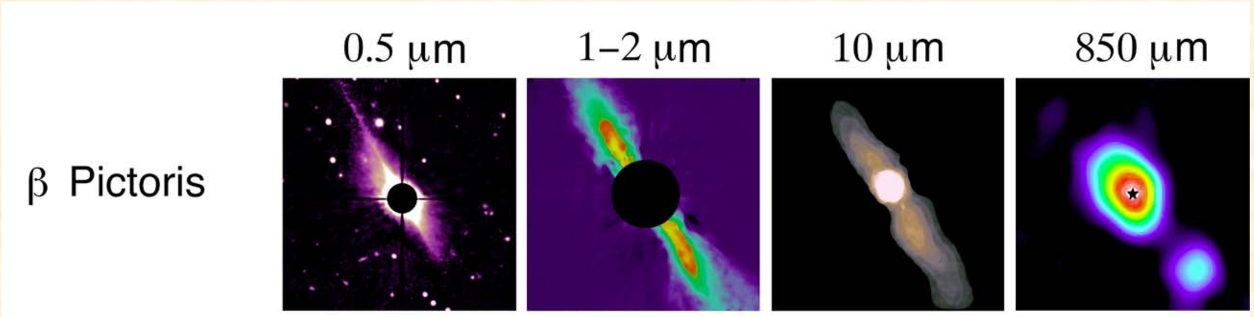
Spitzer/FEPS results!



Bouwman et al. (2005)

Transition from Primordial to Debris

- Transition time from optically thick to optically thin disks is short (e.g. Skrutskie et al. 1990; Wolk & Walter 1996).
- Soon after dusty disk material begins agglomerating to form planetesimals they likely collide and re-form dust.

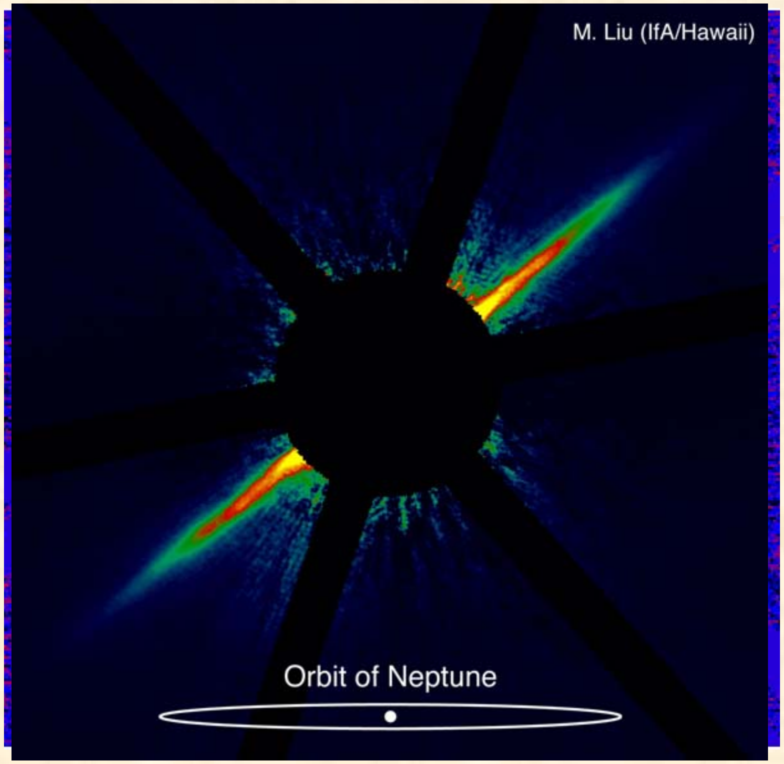


12-20 Myr

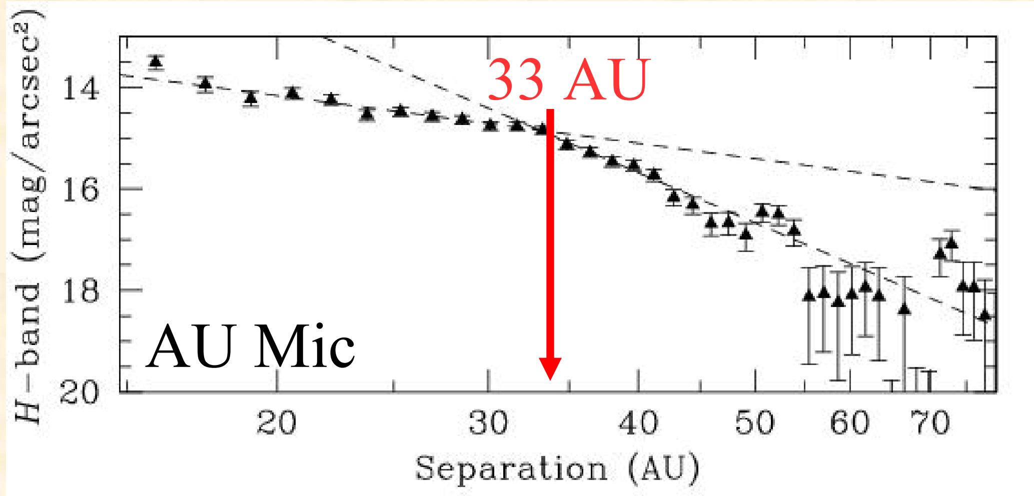
2-3 M_{Sun}

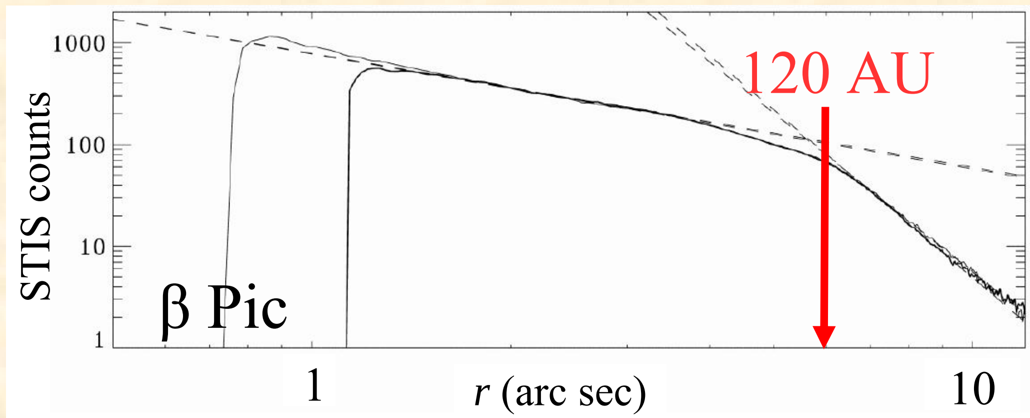
Kalas

AU Mic: Transitional Disk?



[Liu 2004]





AU Mic:

- SED suggests inner disk clearing
- AO and HST imaging resolves structure
- no planets >1M_{Jup} at >20 AU

AU Mic vs. β Pic:

- similar radial profiles
- similar process: grain growth vs. collisions+PR

[Metchev et al. 2005; astro-ph/0412143]

What is the Difference Between "Primordial" and "Debris" Disks?

Primordial

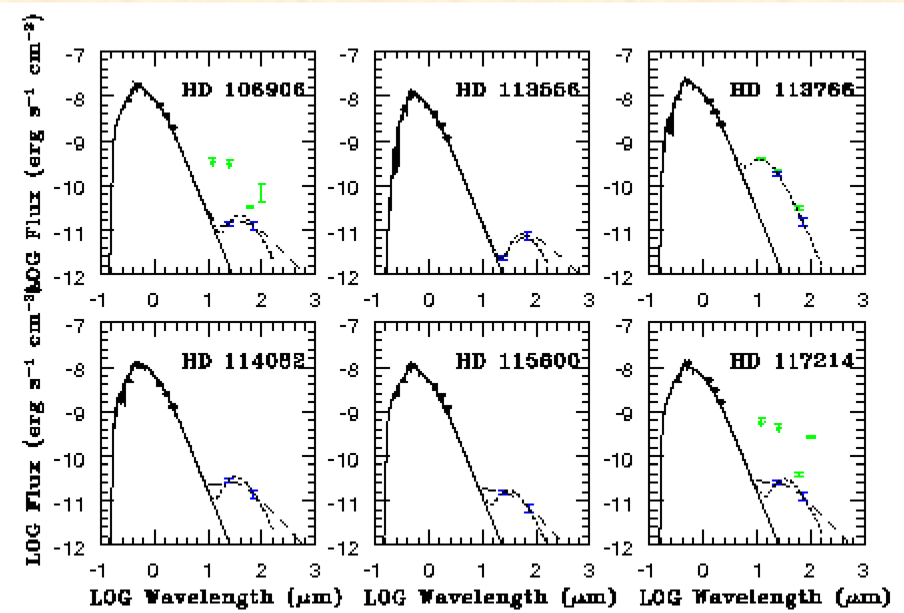
- Dust and gas
- 0.01 - 0.1 M_{sun}
- Initially optically thick
- Material distributed over large radial range (hot ==> cold)
- Dynamics dominated by gas
- Grains are sticking/growing

Debris

- Dust only (gas poor)
- <1 M_{moon}
- Optically thin
- Dust generally at large radii only (cold K.B. analogs) with warm A.B. analogs rare.
- Dynamics dominated by radiation pressure /collisions
- Grains are being destroyed

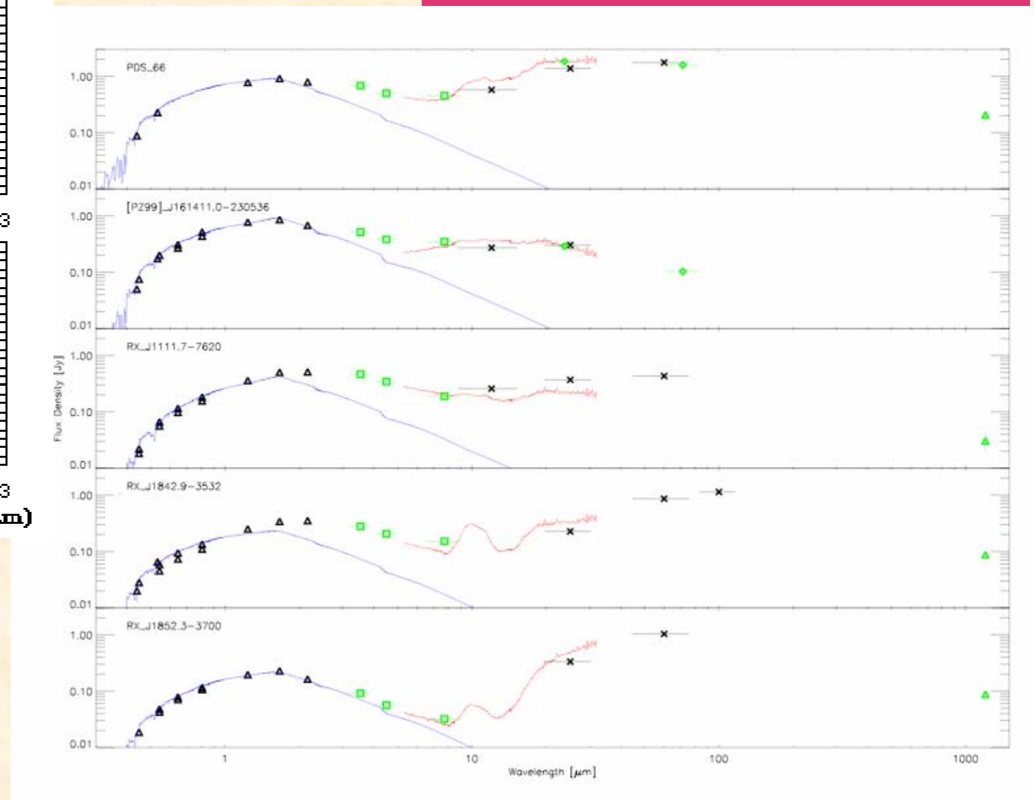
How do we distinguish, observationally, between "primordial" and "debris" ?

Disks at 5-15 Myr: Primordial or Debris?



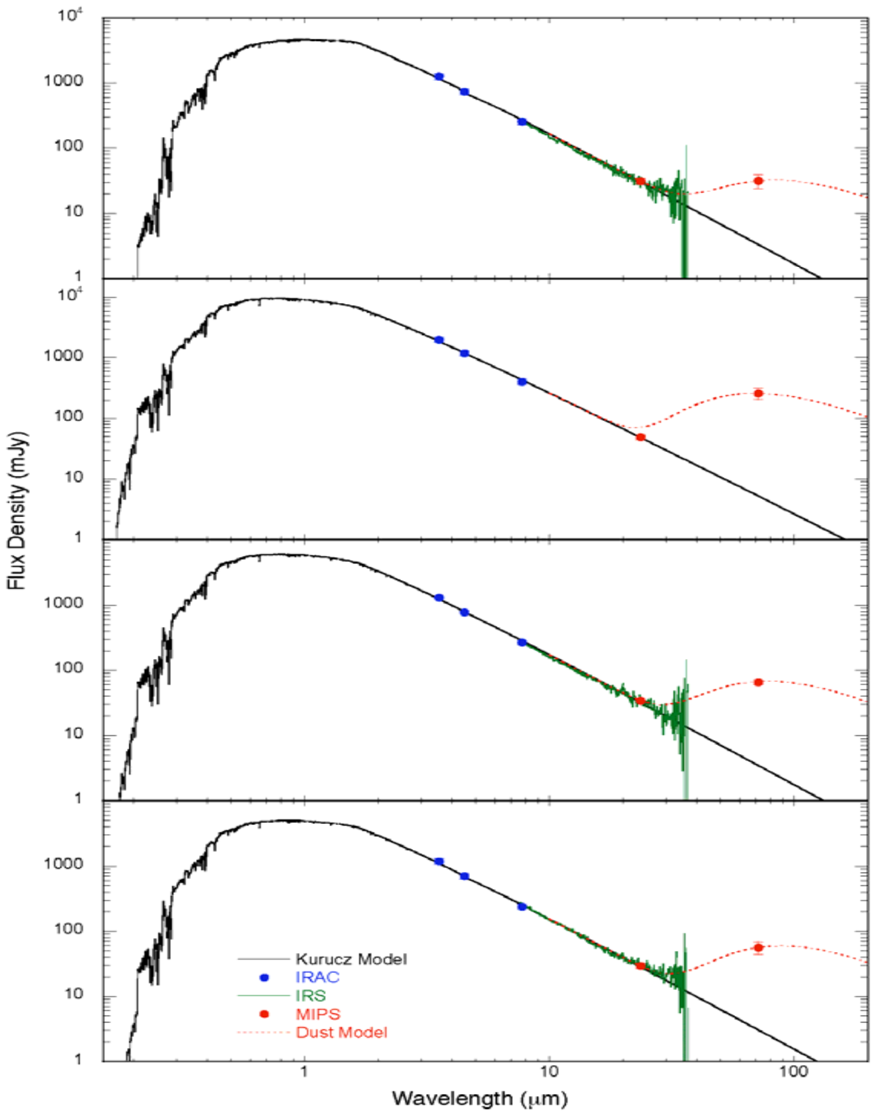
Chen et al. (2005)

Spitzer/FEPS results!



Silverstone et al. (2005)

New Debris Disks from Spitzer



HD 6963

HD 8907

HD 122652

HD 145229

Spitzer/FEPS results!

"Old, cold debris"

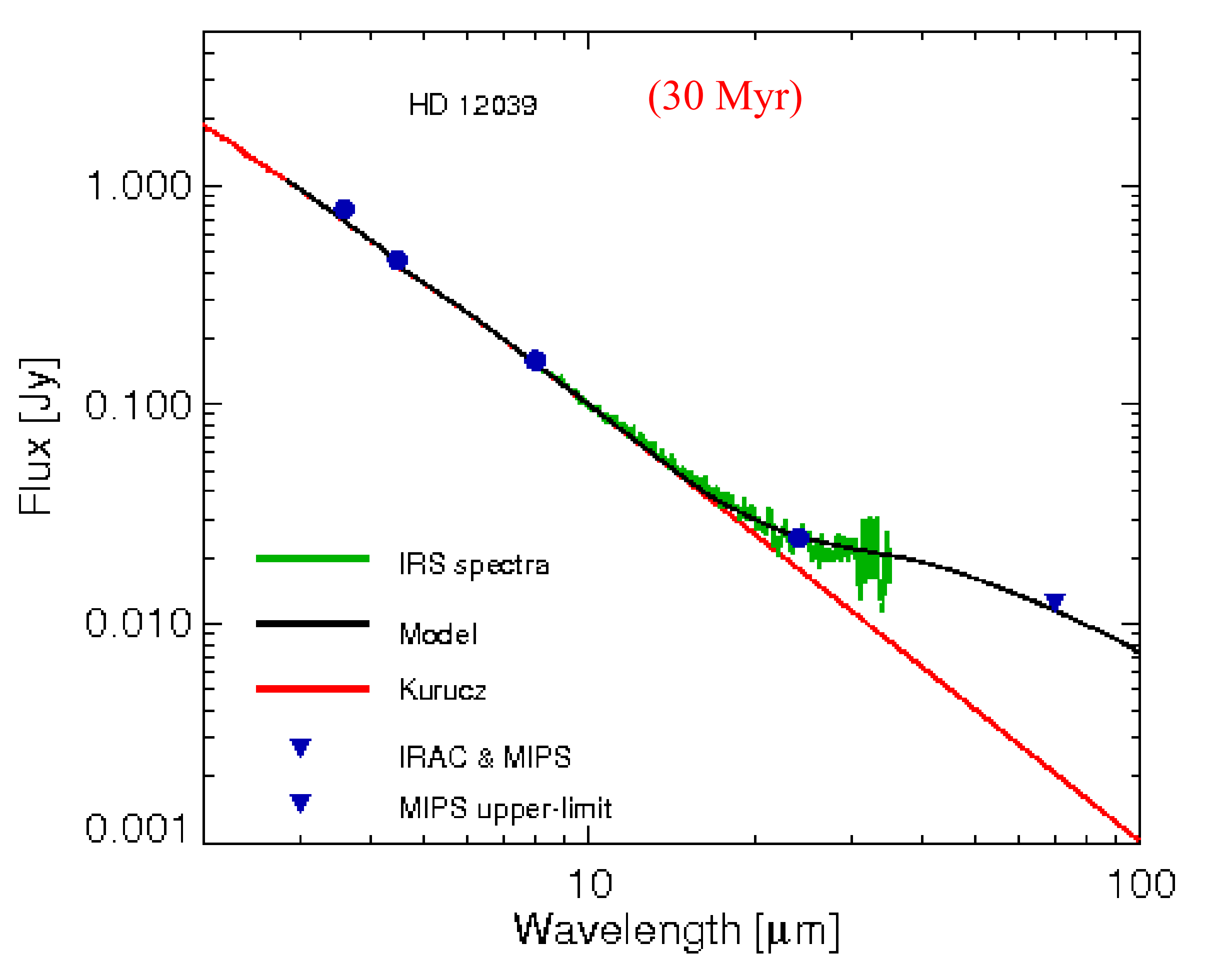
Stars: solar-mass
0.5 - 3 Gyr

Dust: 50-100 K
few x 10^{-9} M_{sun}

Kim et al. (2005)

New Debris Disks from Spitzer

Spitzer/FEPS results!



"Warm debris"

70 um upper limit
==> small disk

R_{min} = 4 AU

R_{max} < 11 AU

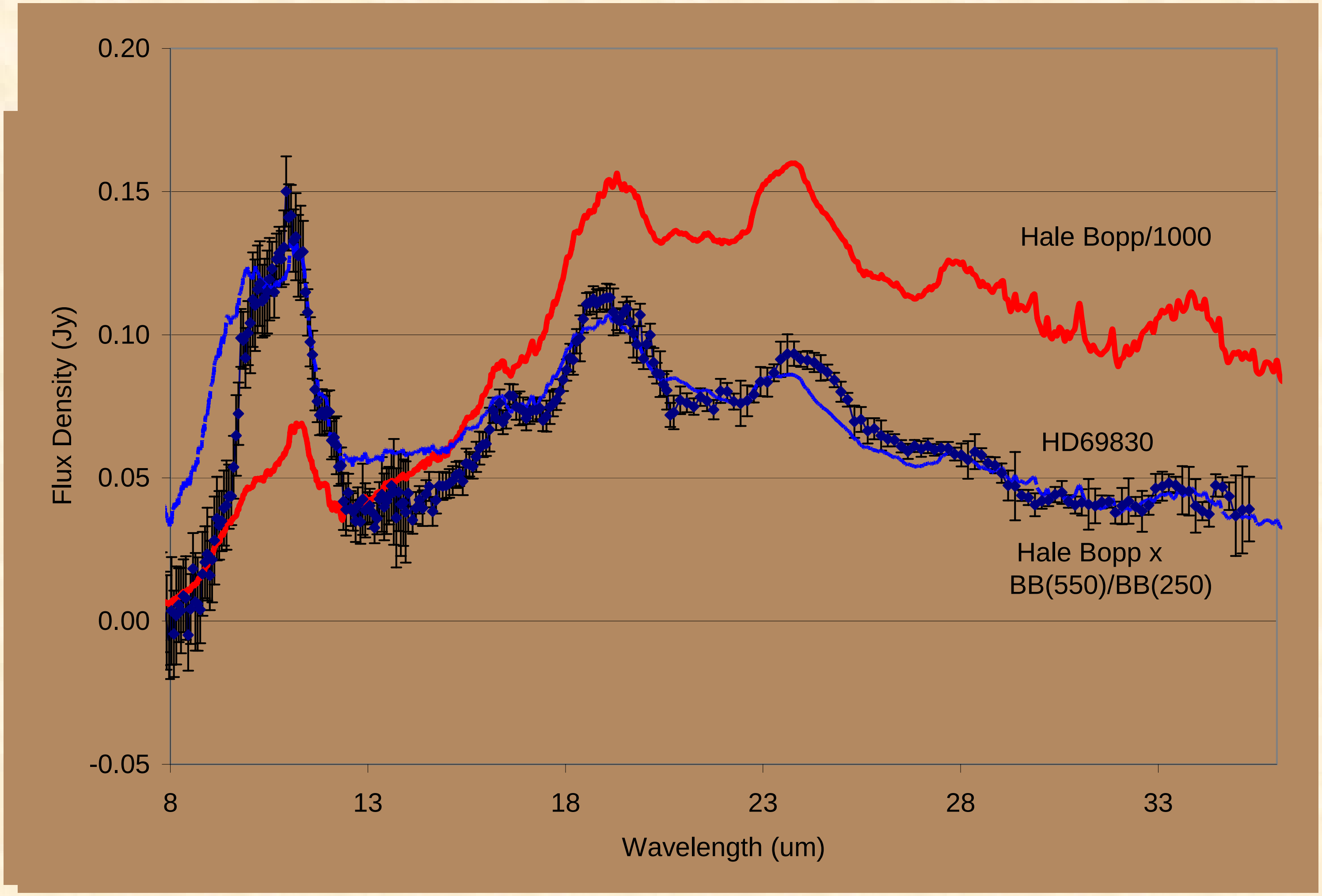
Lack of spectral features
==> large grains

a_{min} > 3-10 µm

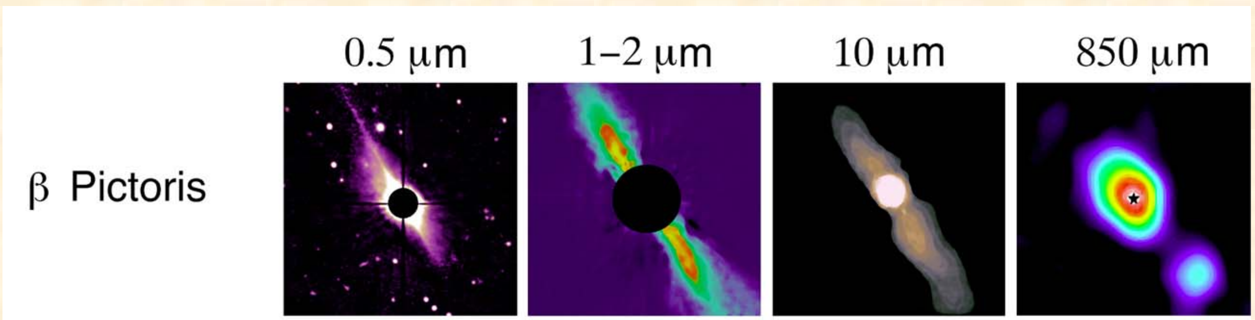
Hines et al. (2005)

“The Hale Bopp Star”

[*Beichman et al. 2005*]



Transition from Primordial to Debris



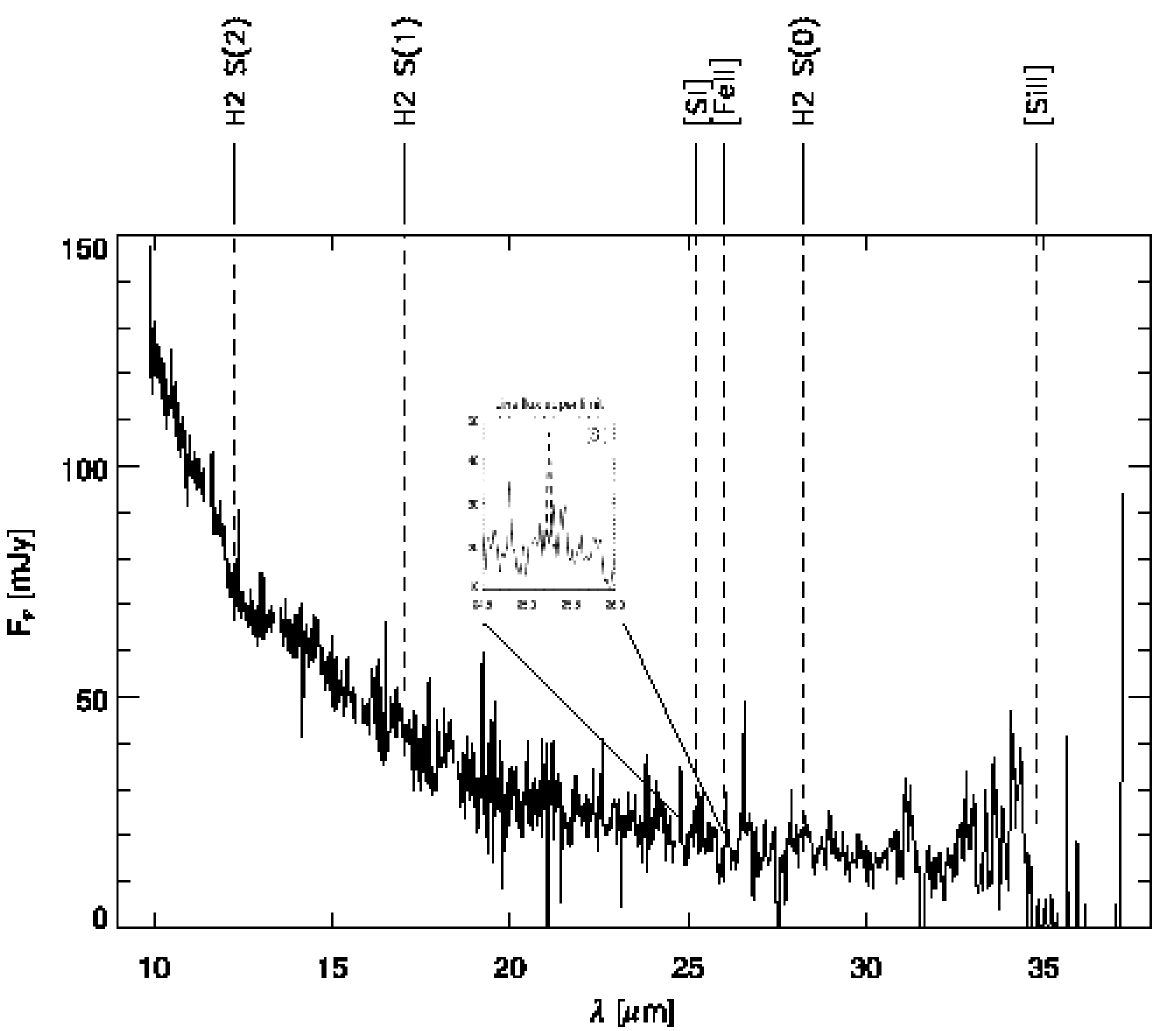
12-20 Myr

2-3 M_{Sun}

Kalas

- Mineralogy studies hold clues to dust processing.
- Gas is distinguishing feature between primordial and debris disks.

Depletion of Gas Mass



[HD 105 at 30+/- 10 Myr]

$M_{dust} = 2\times10^{-7}\ M_{Sun}$

$M_{H2} < 0.05\ M_{jup}$ (T=50 K)

$< 0.04\ M_{jup}$ (T=100 K)

$< 0.003\ M_{Jup}$ (T=200K)

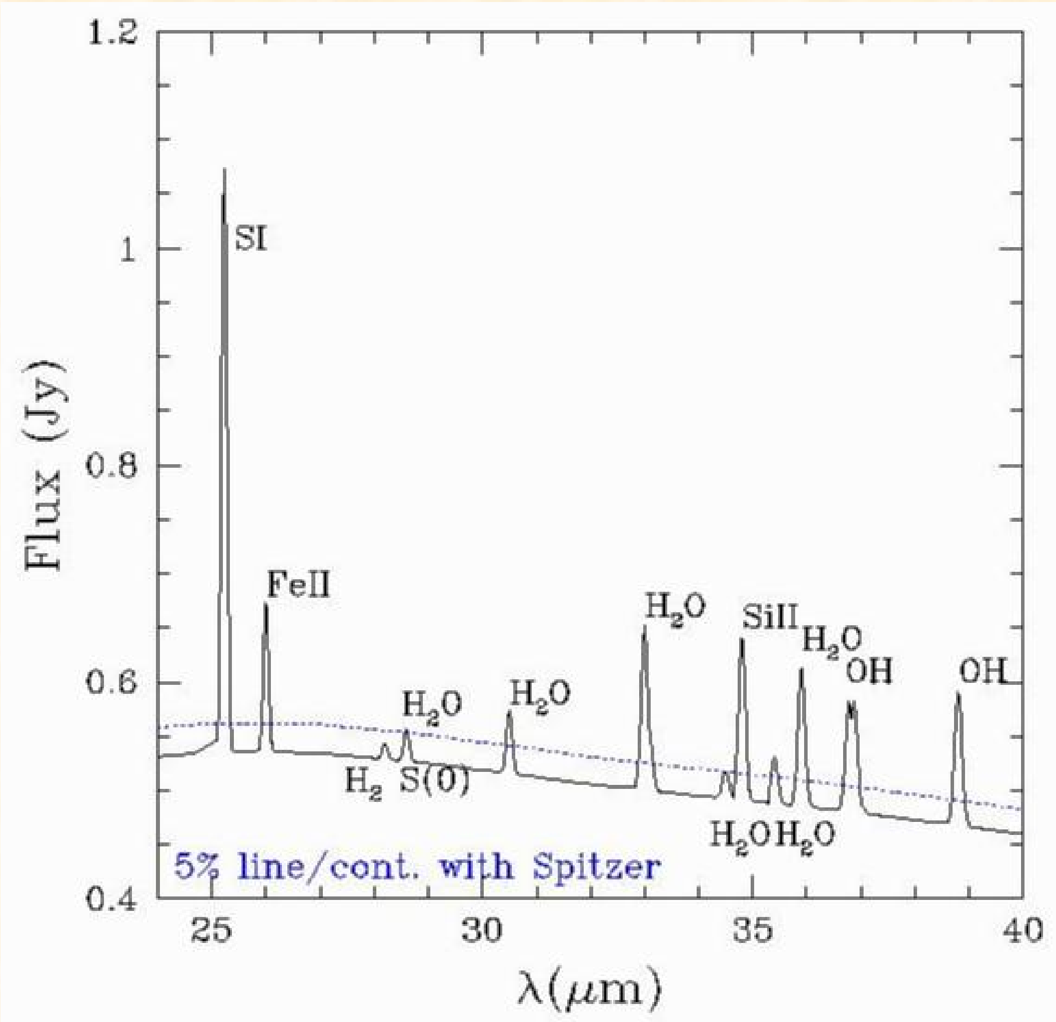
Spitzer/FEPS results!

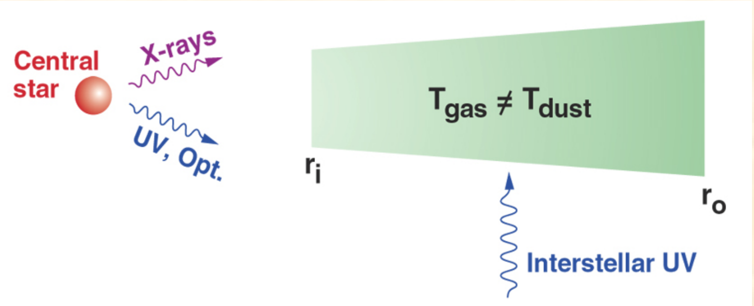
Hollenbach et al. (2005)

Meyer et al. (2004)

Predicted spectrum for source at 30 pc

Gorti & Hollenbach (2004)





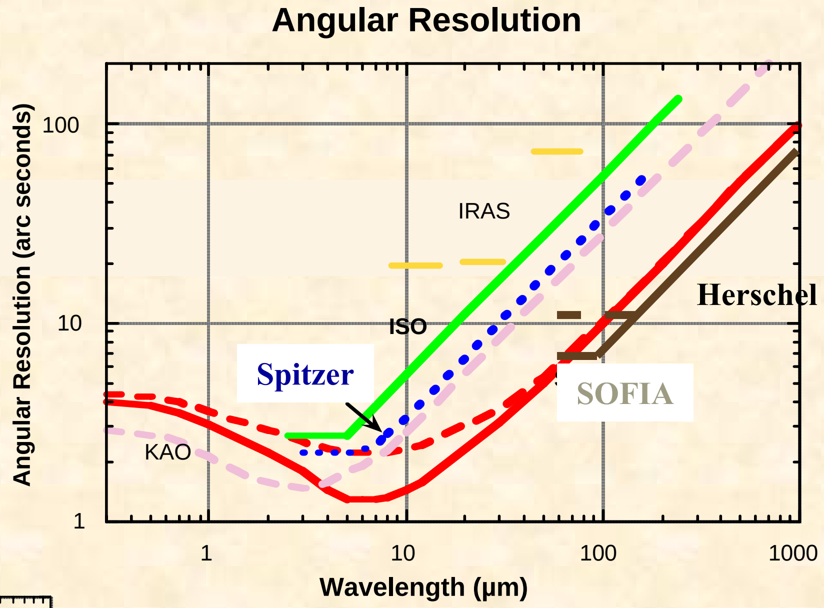
Chemistry, thermal balance, and vertical structure calculated self-consistently.

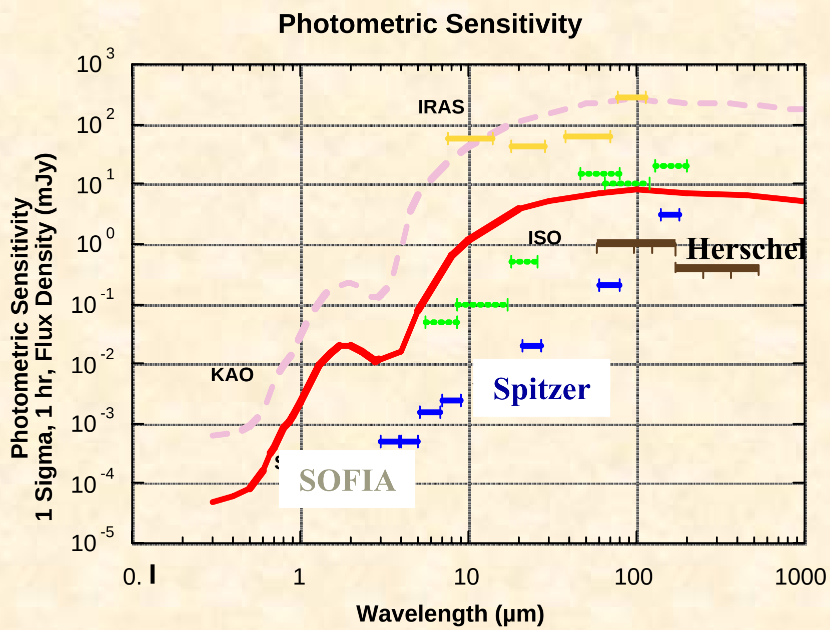
Inputs:

- Grain size distribution, composition, dust/gas ratio
- Gas mass, surface density distribution, r_i and r_o
- Stellar properties (L_{UV}, L_{Xray}, M_*)

Future Far-Infrared Missions

SOFIA and Herschel will provide images with at least three times the angular resolution previously achieved in the Far-IR.



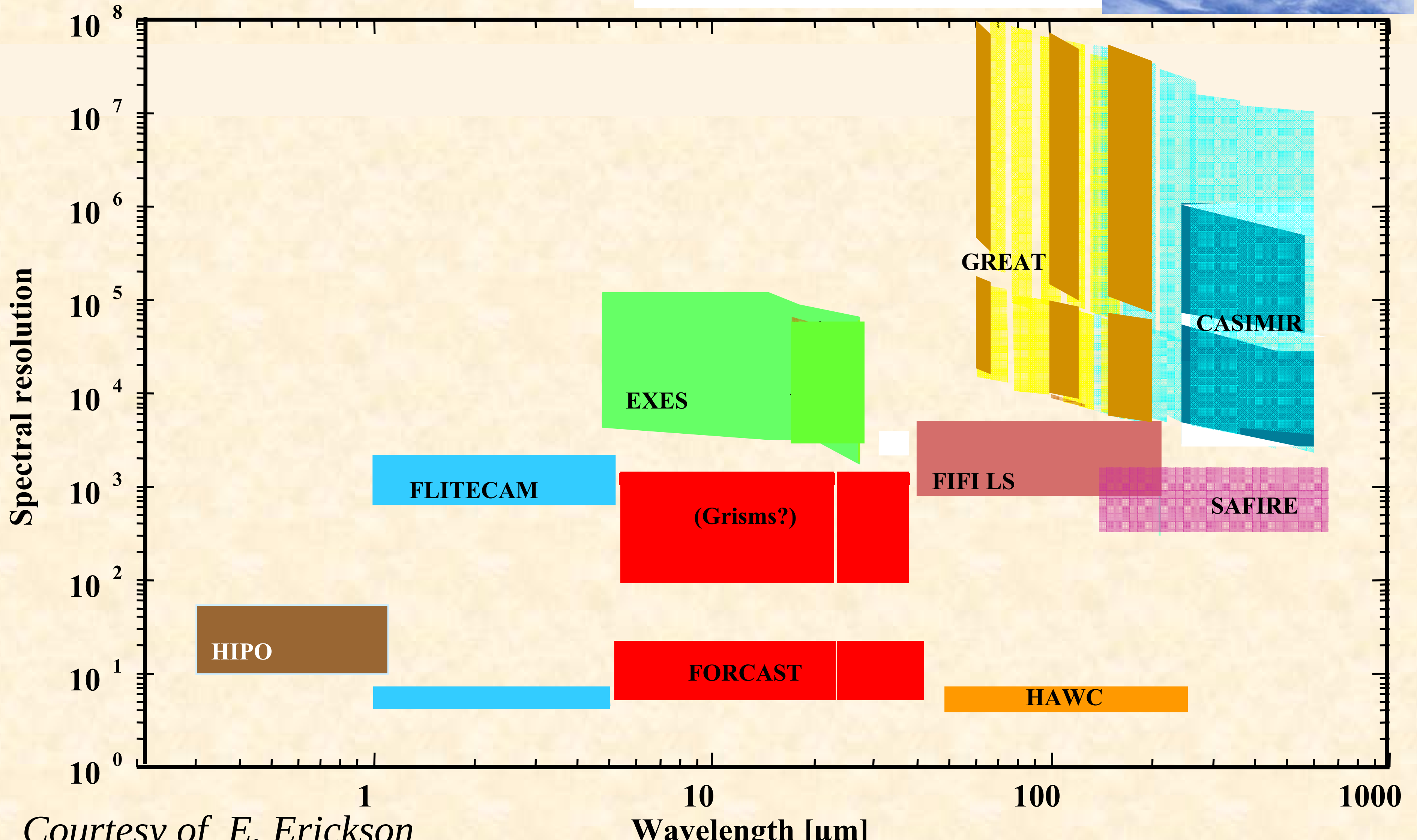


Spitzer and Herschel will provide best Far-IR sensitivity.

SOFIA will provide the widest spectral coverage over the longest lifetime.

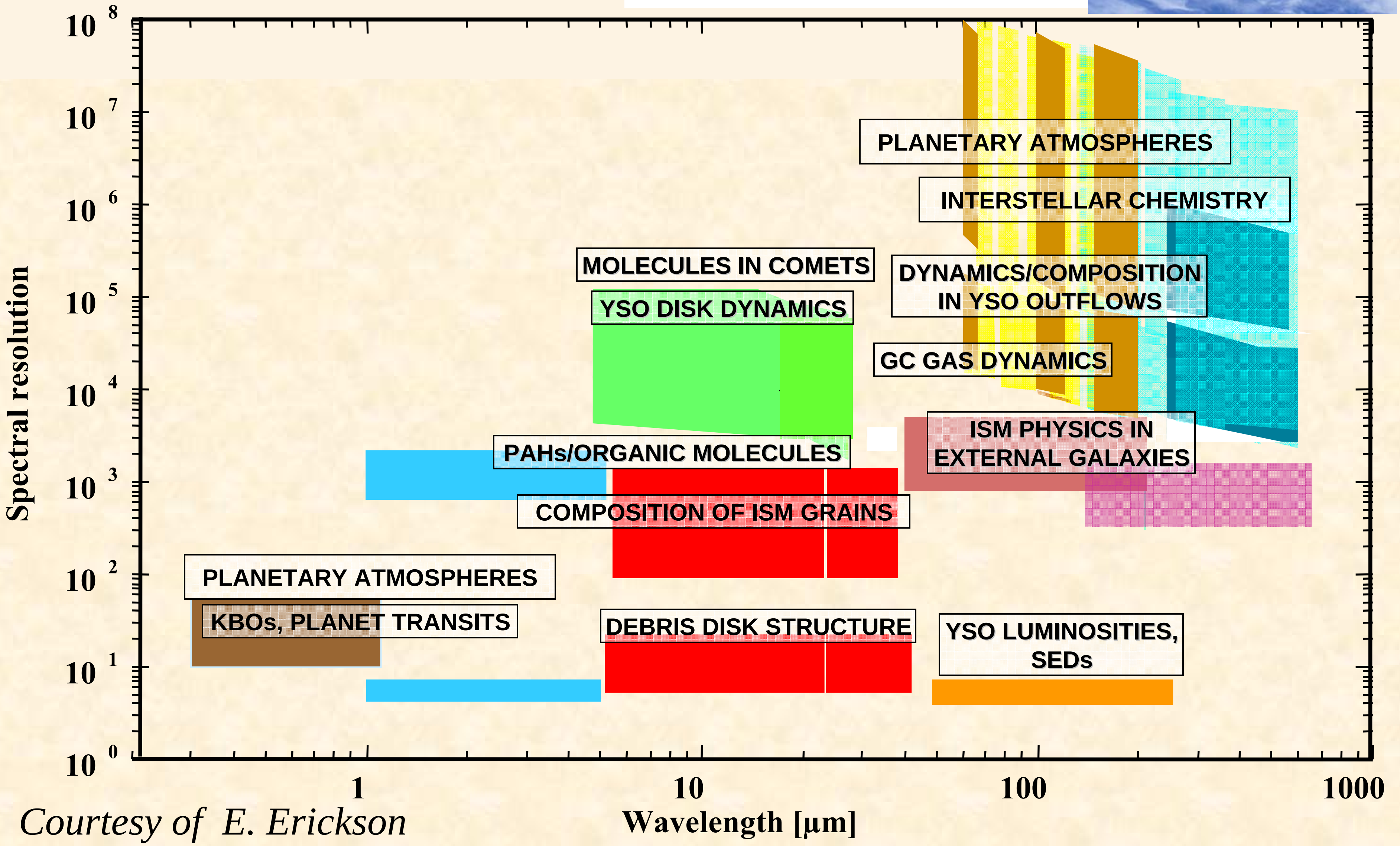
Courtesy of E. Erickson

First Generation SOFIA Instruments



Courtesy of E. Erickson

Some SOFIA science topics



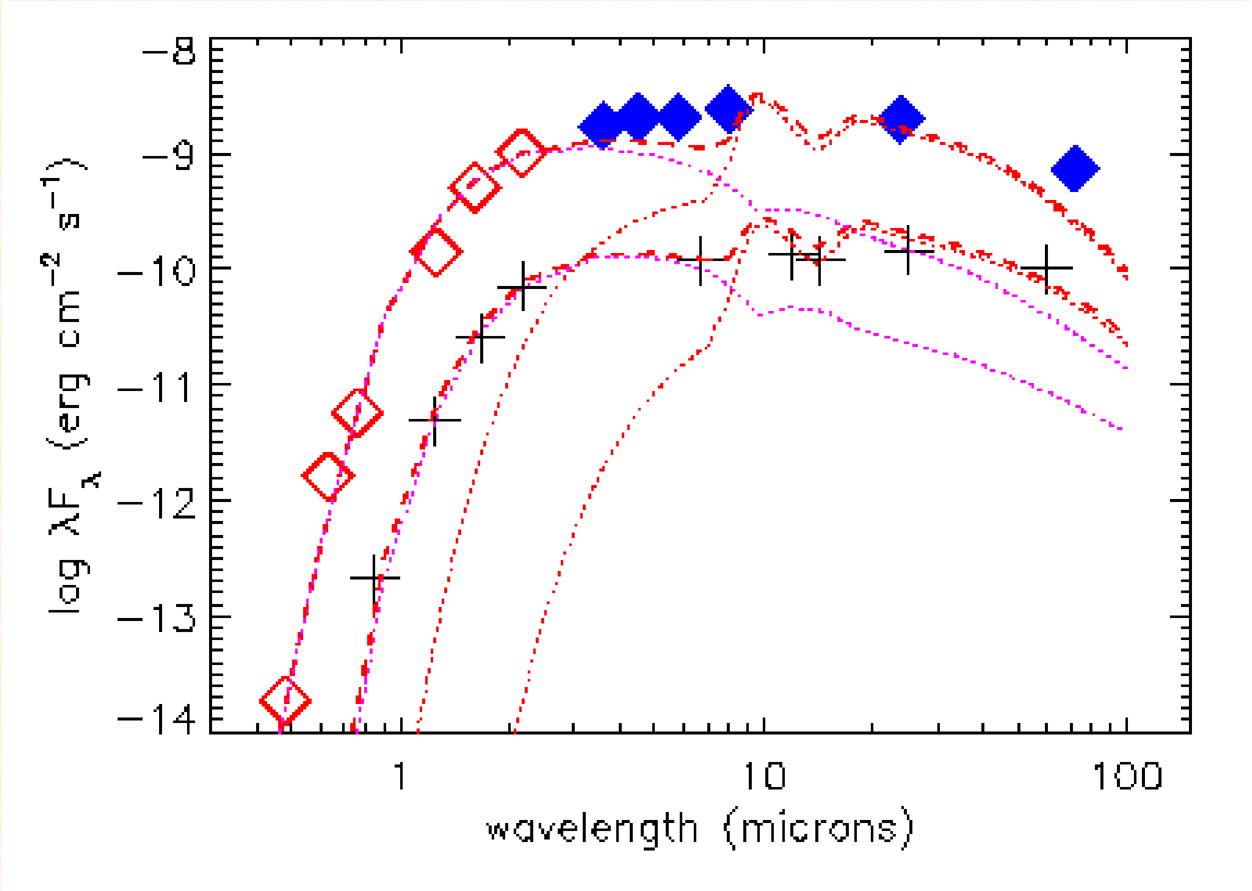
Courtesy of E. Erickson

Summary

- Spitzer is providing unprecedentedly detailed disk SEDs.
- A few pleasant surprises:
  - stunning dust spectroscopy
  - more transitional disks than previously known
  - kuiper-belt-like debris disks are common!
- A few unpleasant surprises:
  - most of the action in primordial disk evolution is <3-5 Myr
  - lack of prominent gas lines in primordial disks ==> line-to-continuum problems??
  - lack of dust spectral features in debris disks ==> large grains or large radii
  - asteroid-belt like debris disks are rare…..
- Future:
  - higher angular resolution in the far-infrared
  - sensitive gas observations to help distinguish between primordial and debris disks.

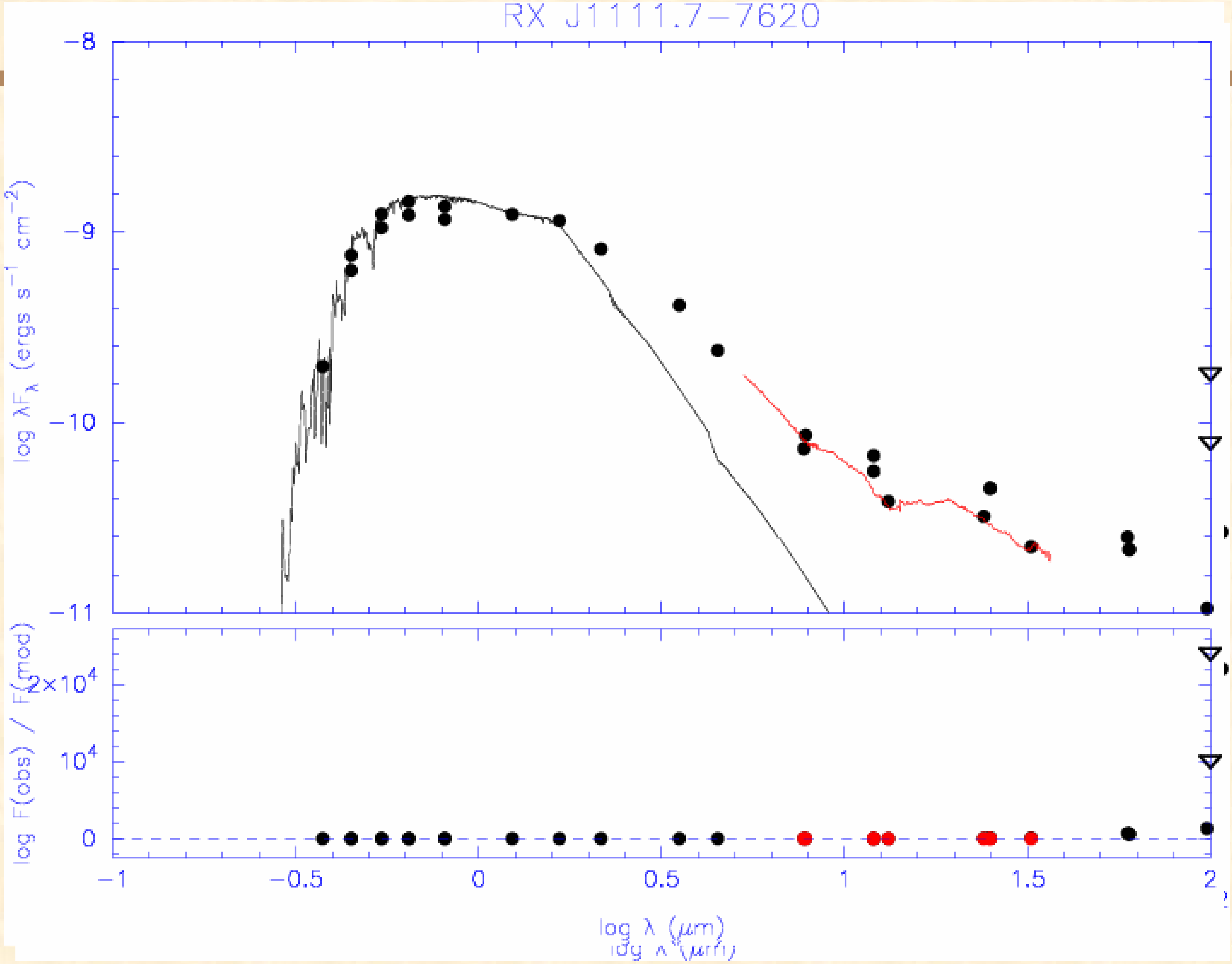
The Time Domain

- Accretion history
  - – steady state
  - – outburst



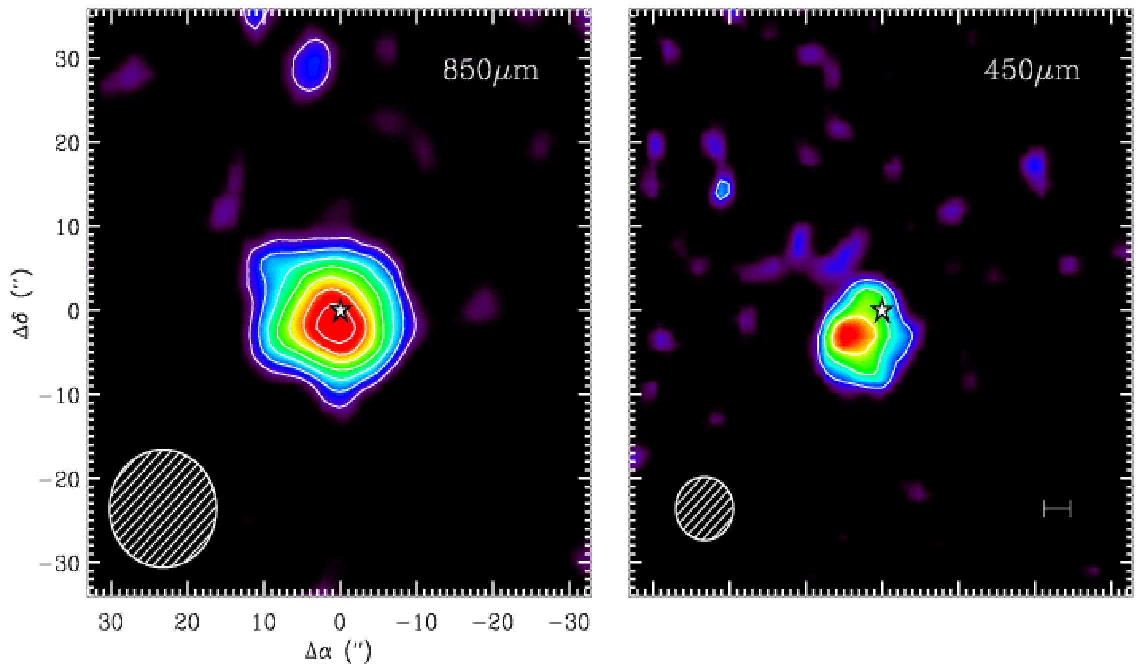
Muzerolle et al. 2004

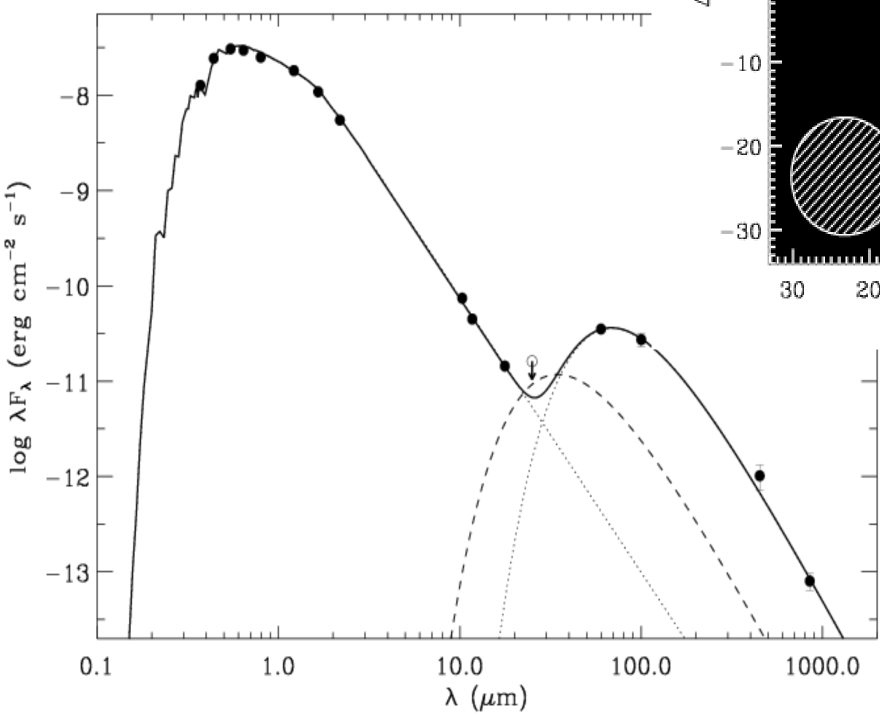
Spitzer/FEPS results!



Also, First Spatially Resolved Debris Disk Surrounding Young Solar Analog

HD 107146 at 200 +/- 100 Myr

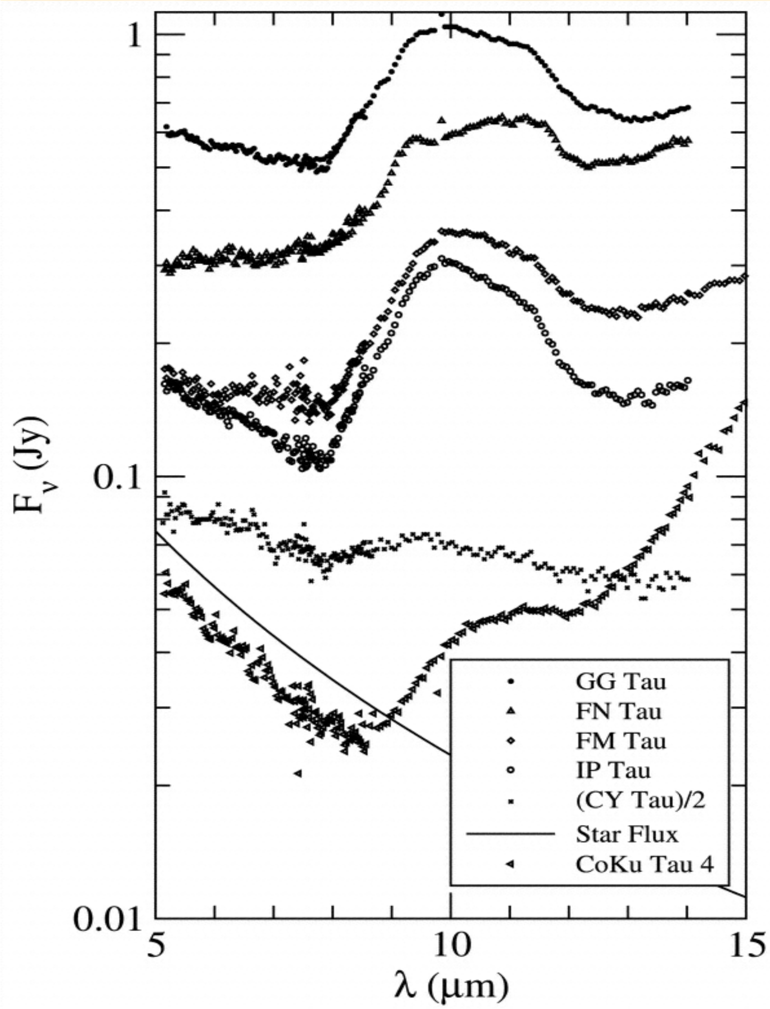




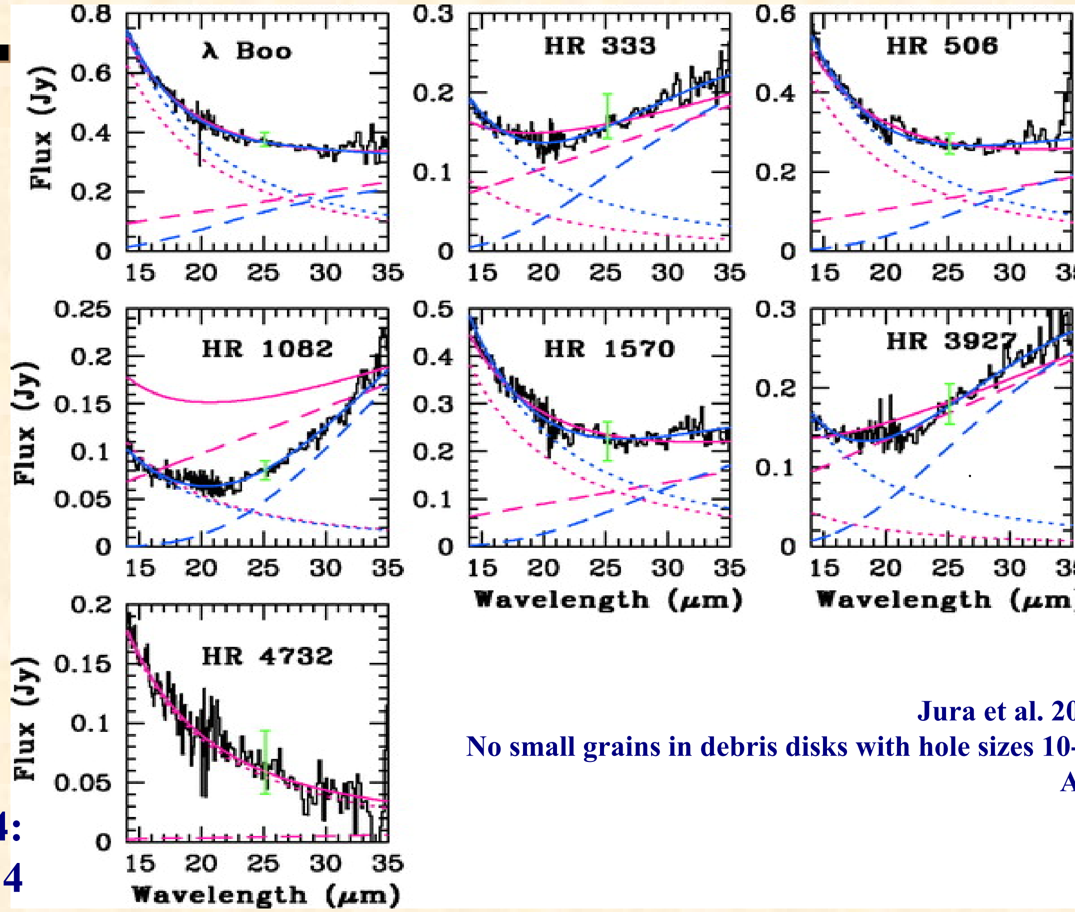
[*Williams et al. 2004*]

$\mathbf{T_{dust} = 60\ K ==> R_{in} = 30\ AU}$

Do holes in disks indicate planets?



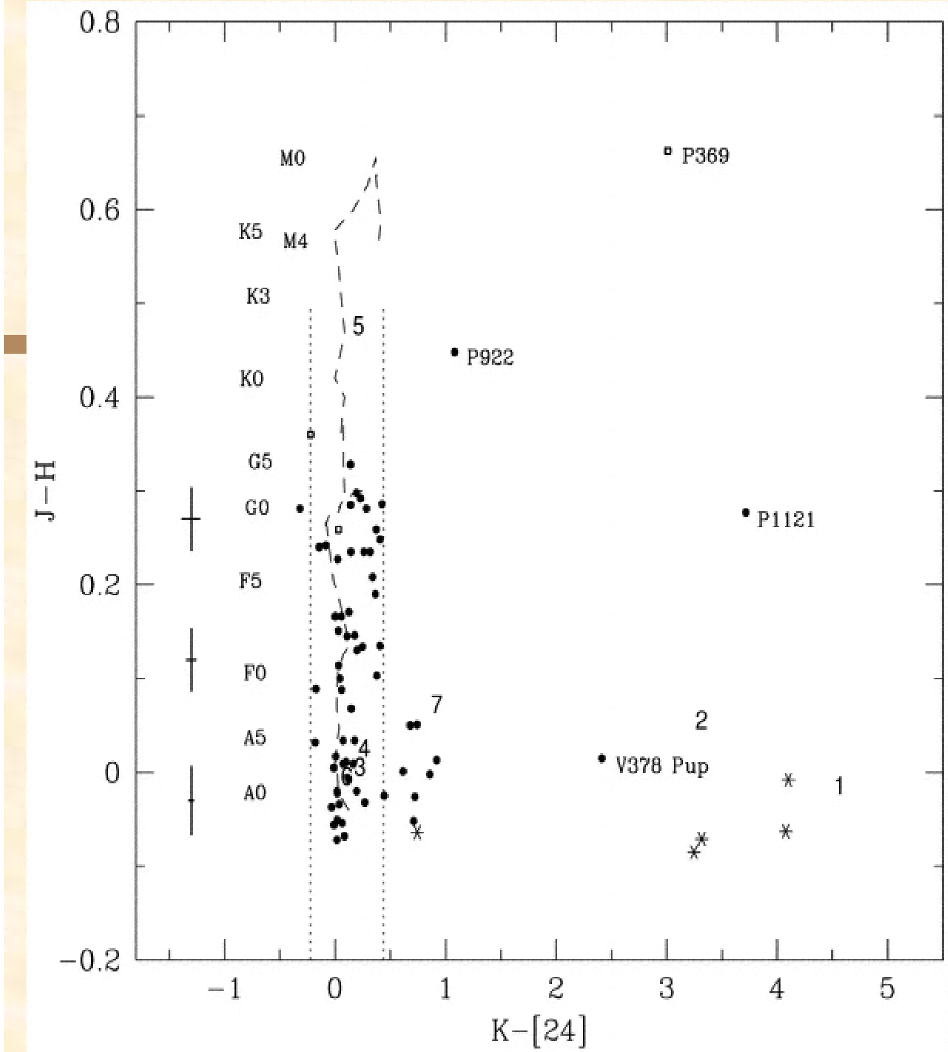
Forrest et al. 2004:
Inner hole in disk of CoKu Tau 4



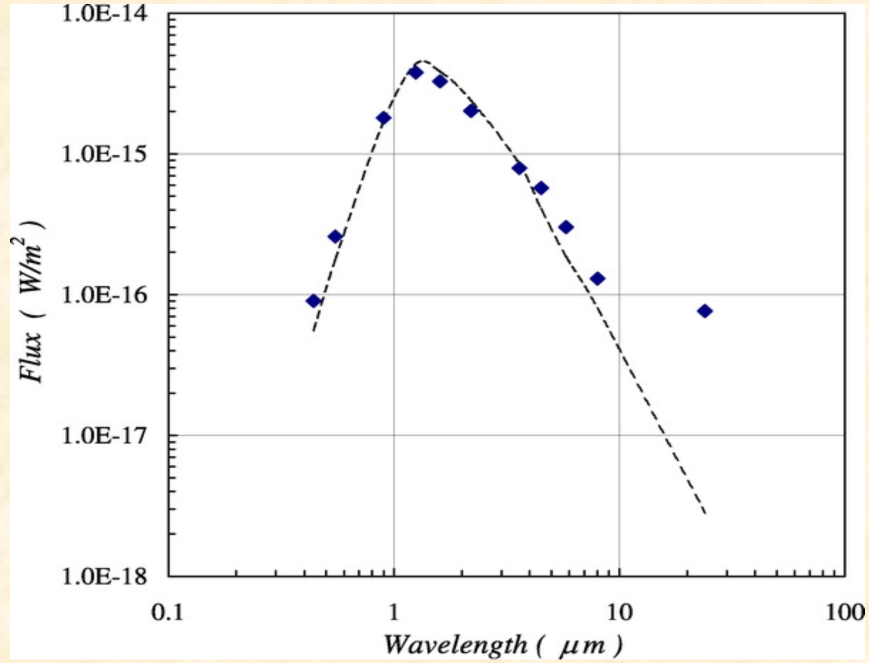
Jura et al. 2004
No small grains in debris disks with hole sizes 10-50 AU.

Stapelfeldt et al. 2004 An inner debris belt in Fomalhaut's disk?

low stochastic is outer disk volution from 10-100 Myr?



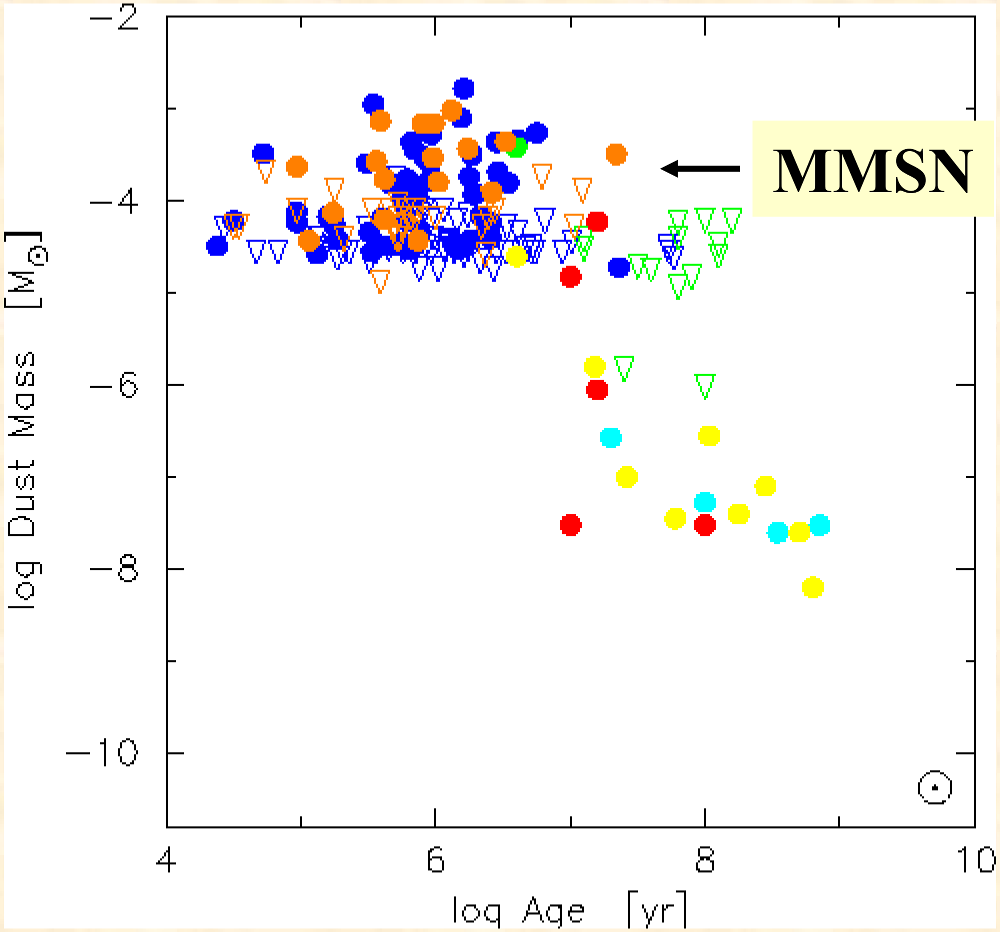
Gorlova et al. 2004 Transient, massive disks around 100 Myr old sun-like stars?



Young et al. 2004 Outer disks around late-type stars 25 Myr old

Rieke et al. 2004 Consistent results from A star survey.

Outer Disks Dissipation: Depletion of Dust Mass



Courtesy of J. Carpenter and M. Meyer

- Mass derived from millimeter flux (yellow = mid-infrared)

$M_{tot} = M_{dust} + M_{gas} = 100 \times M_{dust}$

M_{tot} (MMSN) = $0.02\ M_{sun}$

- Age derived from HR diagram

Steady evolution?

Ledge?