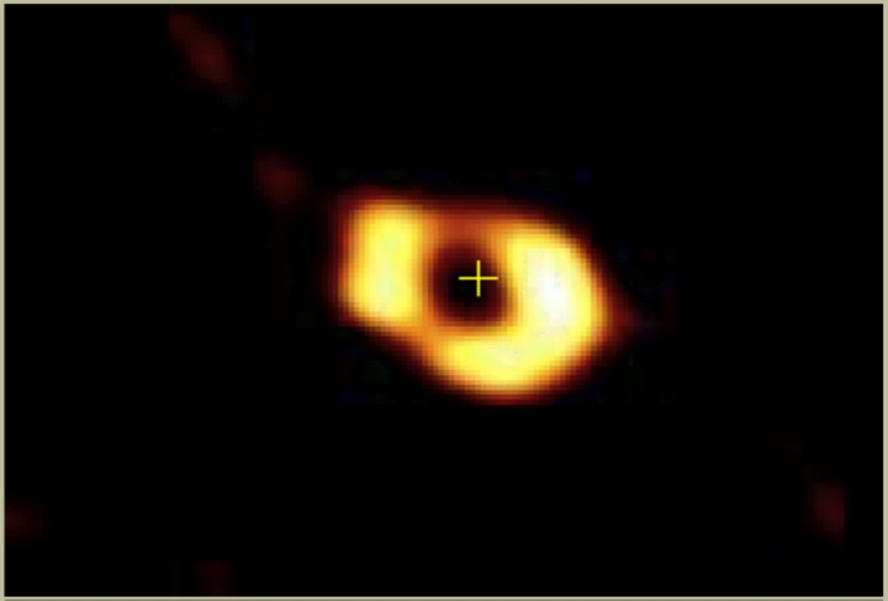
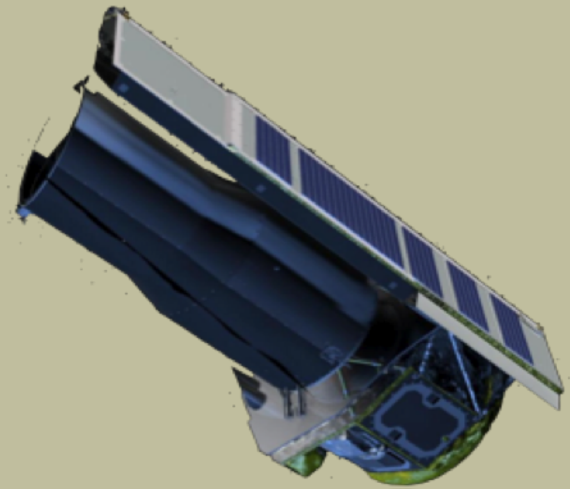
The observed diversity of YSO disk properties





Bruno Merín

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Outline

- Motivation: How do disk evolve? How do planets form?
- Pre-Spitzer SED classifications and indications
- New Spitzer classes and the need for new names
- Statistical properties of the new disk samples
- Hints on disk evolution from new data
- Evolutionary scenario and planet formation
- Discussion & Conclusions

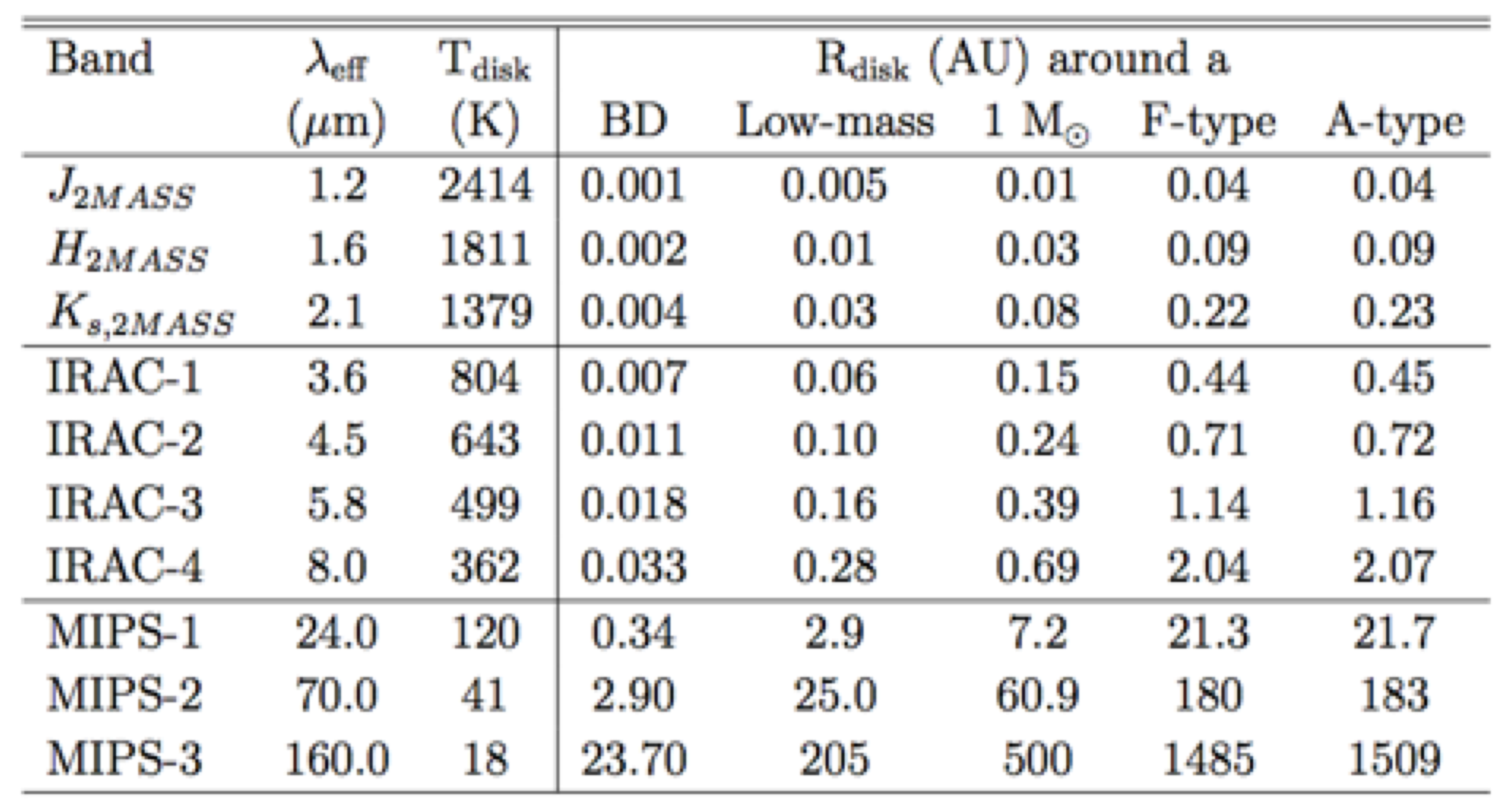
The power of Spitzer

- Statistical samples of large numbers of young objects in all evolutionary stages down to brown dwarf limit
  - Complete magnitude-limited samples (100 -> 1000 SEDs)

Evans, Robitaille et al. Talks

- Appropriate wavelength coverage to study the planet-forming regions in disks.
  - IRAC, MIPS and IRS (3.6 – 70 µm)
  - Probes temperatures from 100 to 1500 K
  - Probes the disks at 0.1 – 30 AU (size of Neptune’s orbit)

IRAC and MIPS-24 fluxes probe 0.1 to several AUs



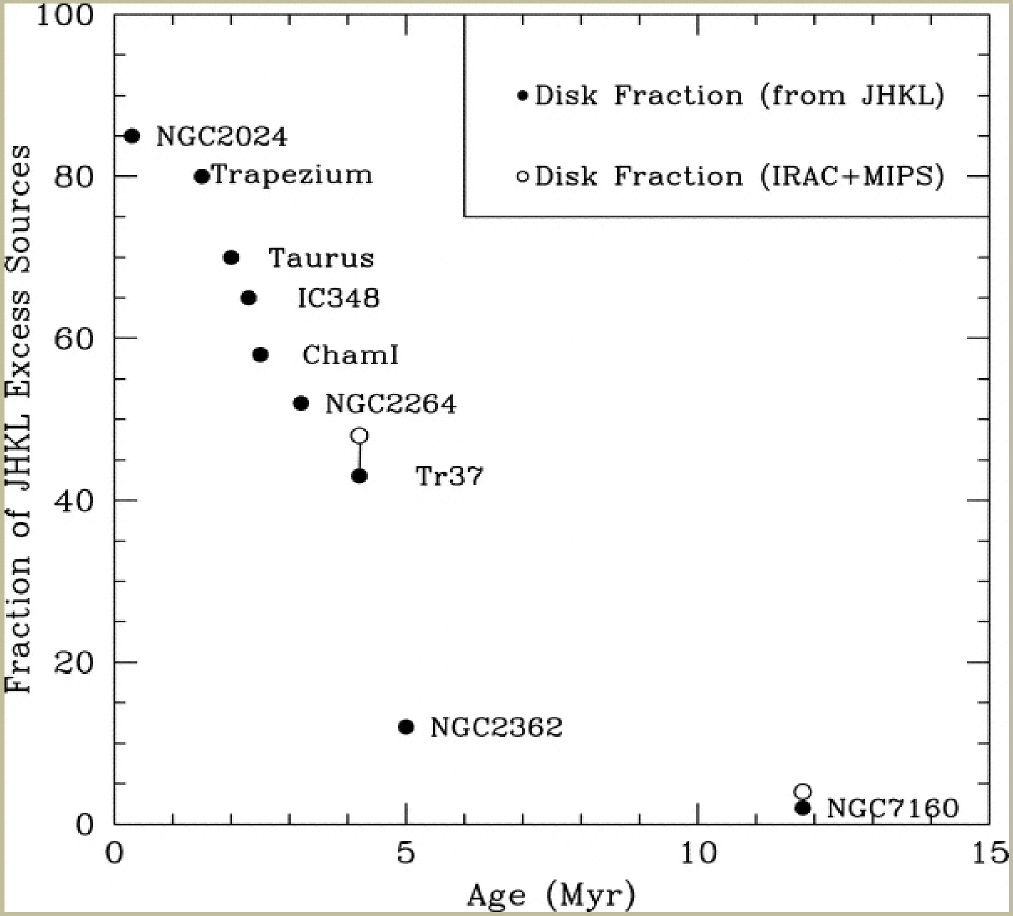
Band	$\lambda_{\rm eff}$	$T_{\rm disk}$	$R_{\rm disk}$ (AU) around a				
	(μm)	(K)	BD	Low-mass	1 $M_\odot$	F-type	A-type
J_{2MASS}	1.2	2414	0.001	0.005	0.01	0.04	0.04
H_{2MASS}	1.6	1811	0.002	0.01	0.03	0.09	0.09
$K_{s,2MASS}$	2.1	1379	0.004	0.03	0.08	0.22	0.23
IRAC-1	3.6	804	0.007	0.06	0.15	0.44	0.45
IRAC-2	4.5	643	0.011	0.10	0.24	0.71	0.72
IRAC-3	5.8	499	0.018	0.16	0.39	1.14	1.16
IRAC-4	8.0	362	0.033	0.28	0.69	2.04	2.07
MIPS-1	24.0	120	0.34	2.9	7.2	21.3	21.7
MIPS-2	70.0	41	2.90	25.0	60.9	180	183
MIPS-3	160.0	18	23.70	205	500	1485	1509

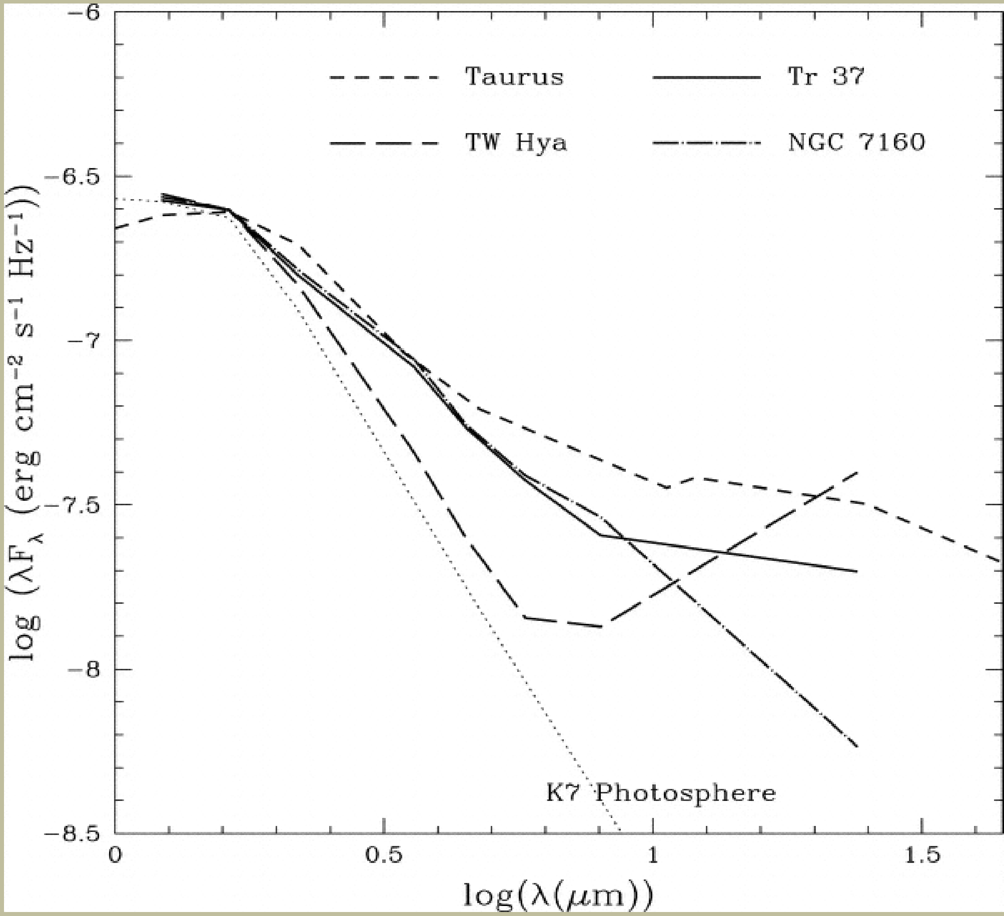
Poster #80 Puravankara

Merín et al. 2009b

Current indications

The inner disks disappear at a constant rate from 1 to 10 Myrs.



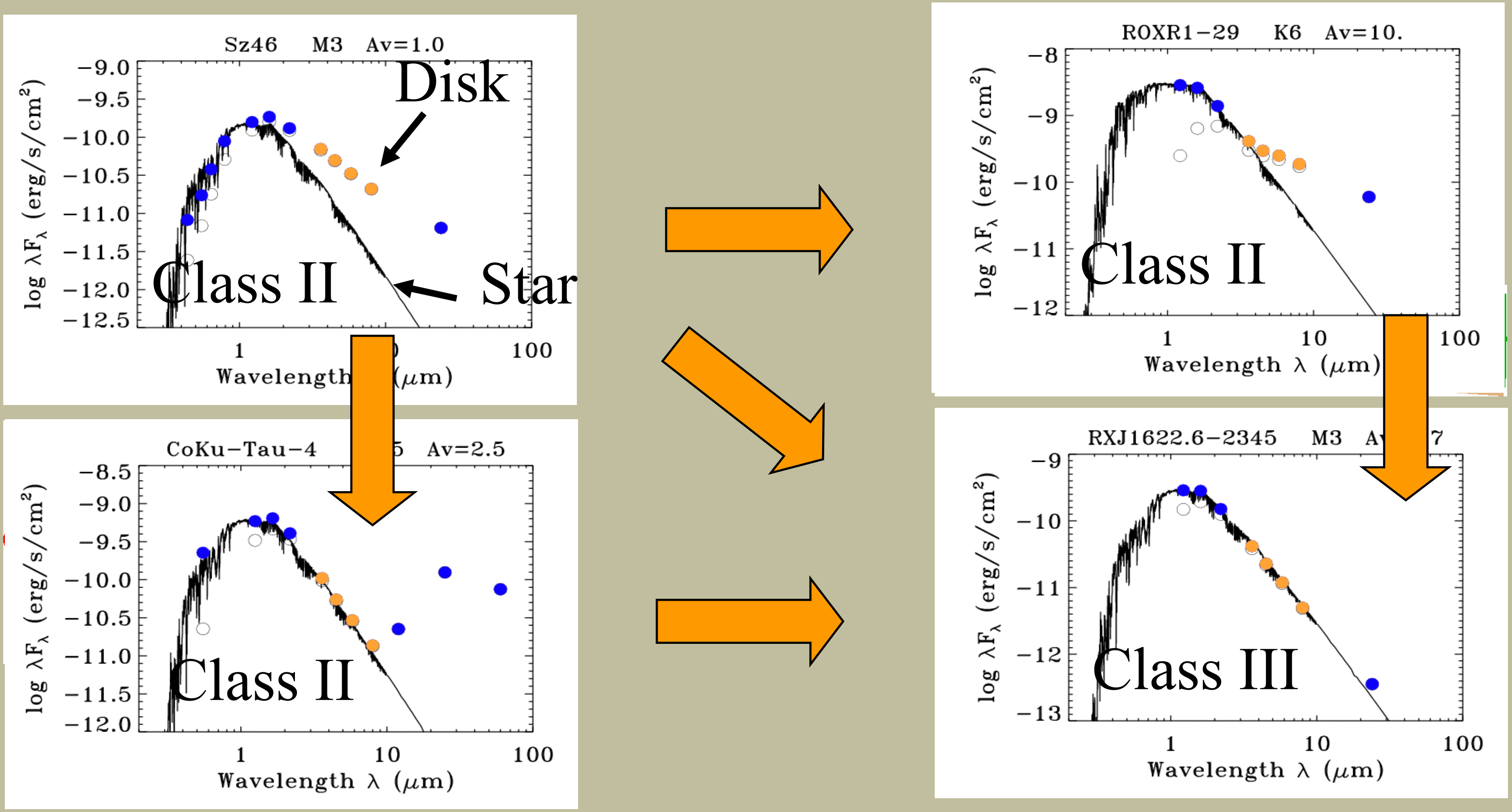


Calvet, Hernandez & MuzerolleTalks

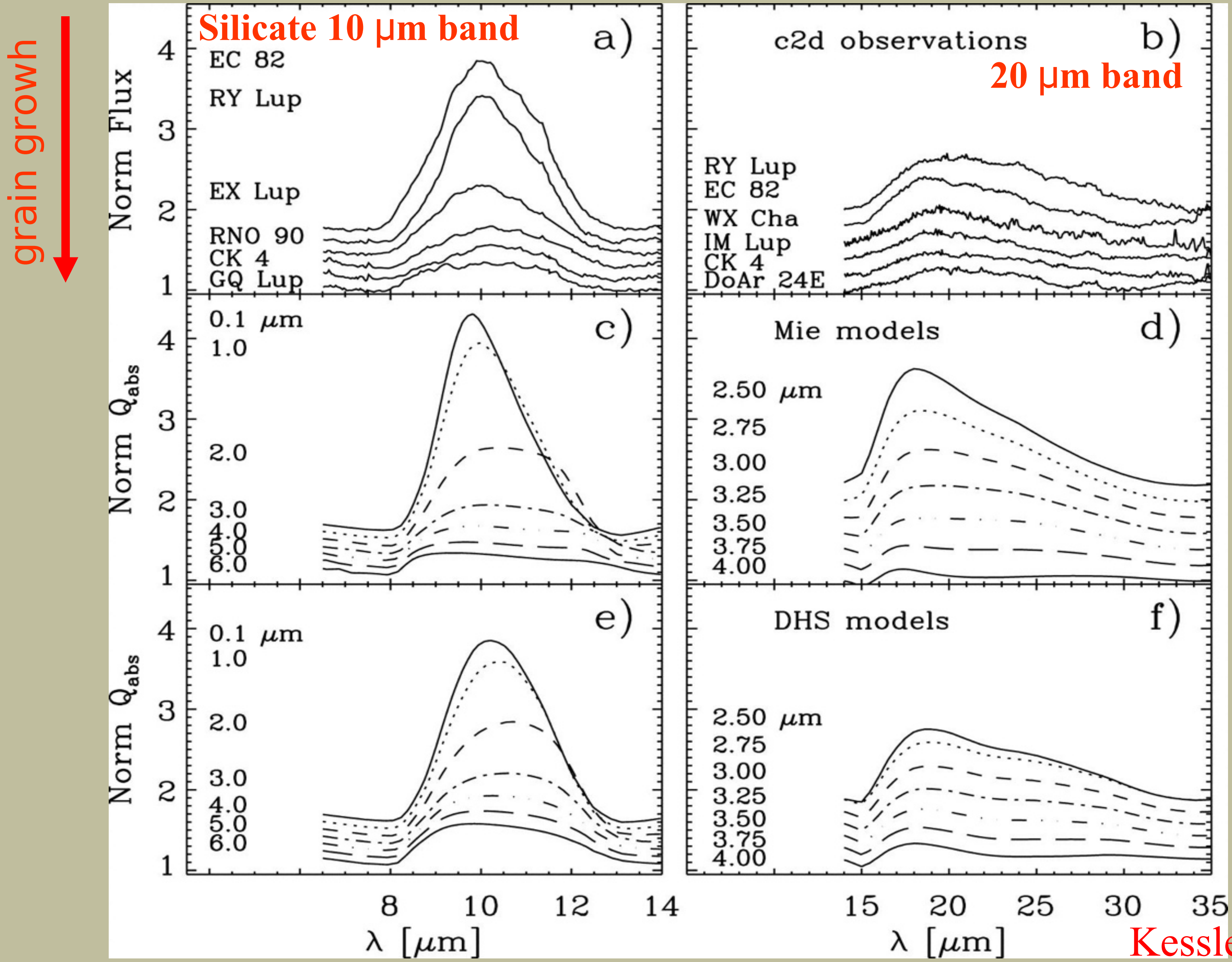
Haisch et al. (2001)
Sicilia-Aguilar et al. (2006)

Disk evolution

Spitzer data shows that there are multiple ways to disperse a circumstellar disk and suggests multiple evolutionary paths



There is clear evidence for grain growth in a large fraction of T Tauri disks



Data

Models

Kessler-Silacci et al. 2006

Disk evolution

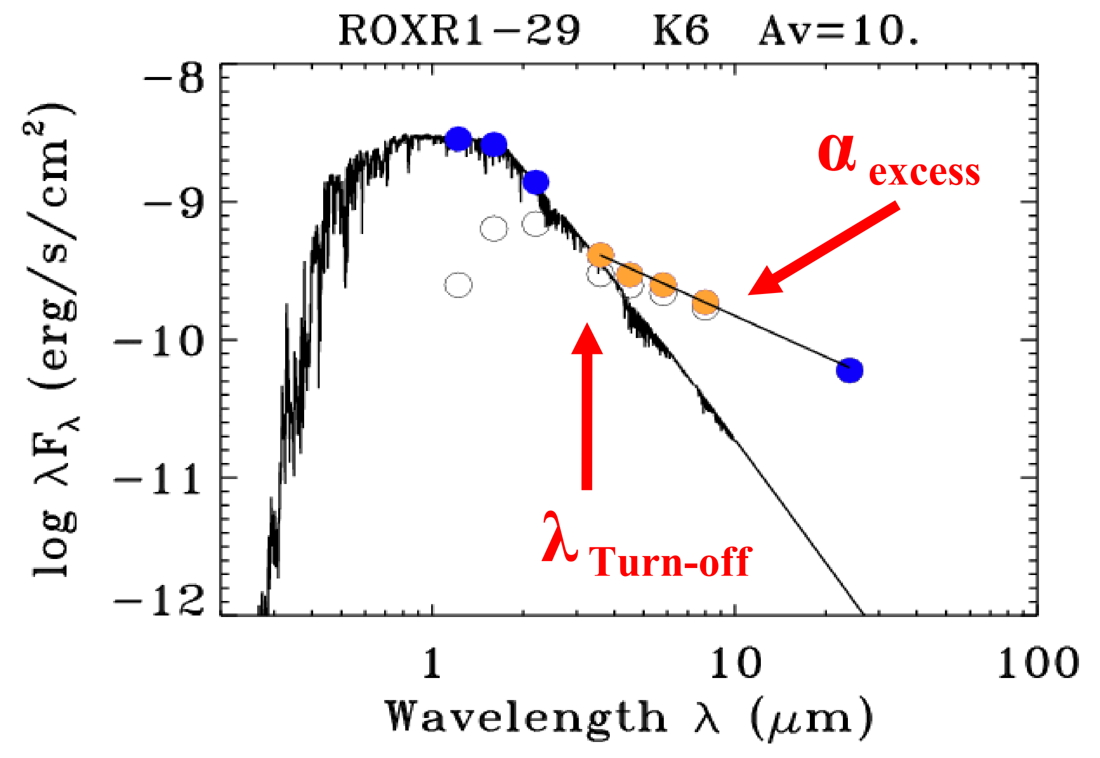
Processes that disperse the disks:

- Grain growth and settling in protoplanetary disks
- Photoevaporation of disks by UV stellar flux
- Disruption of disks by stellar companions/flybys
- Planet formation?

We need to observe stars actively forming planets

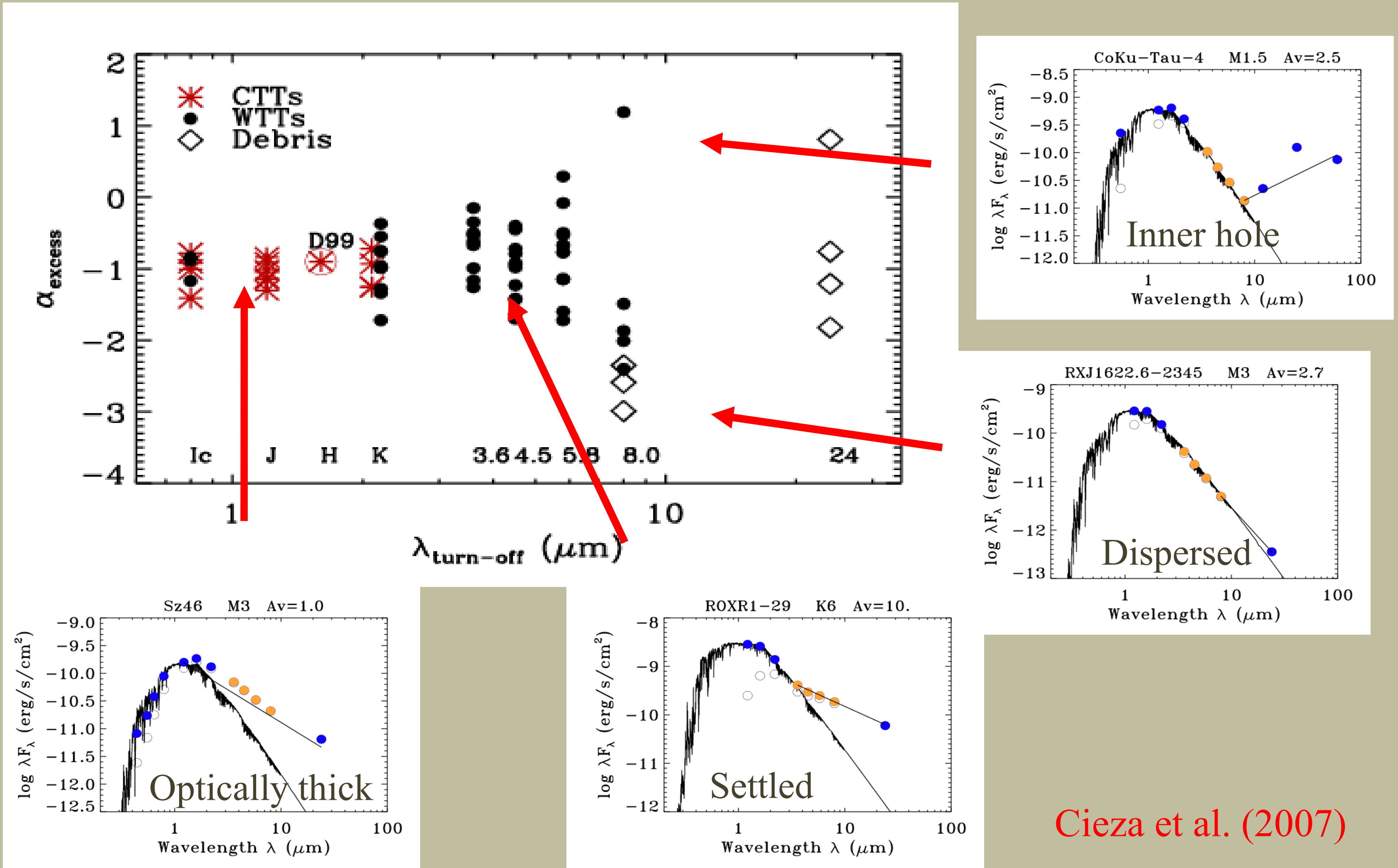
New 2D SED classification schema

Provides a more detailed description of the inner disks.



- $\lambda_{\text{turn-off}}$ is the last photospheric wavelength in microns
- α_{excess} is the SED slope in λF_λ long-ward than $\lambda_{\text{turn-off}}$

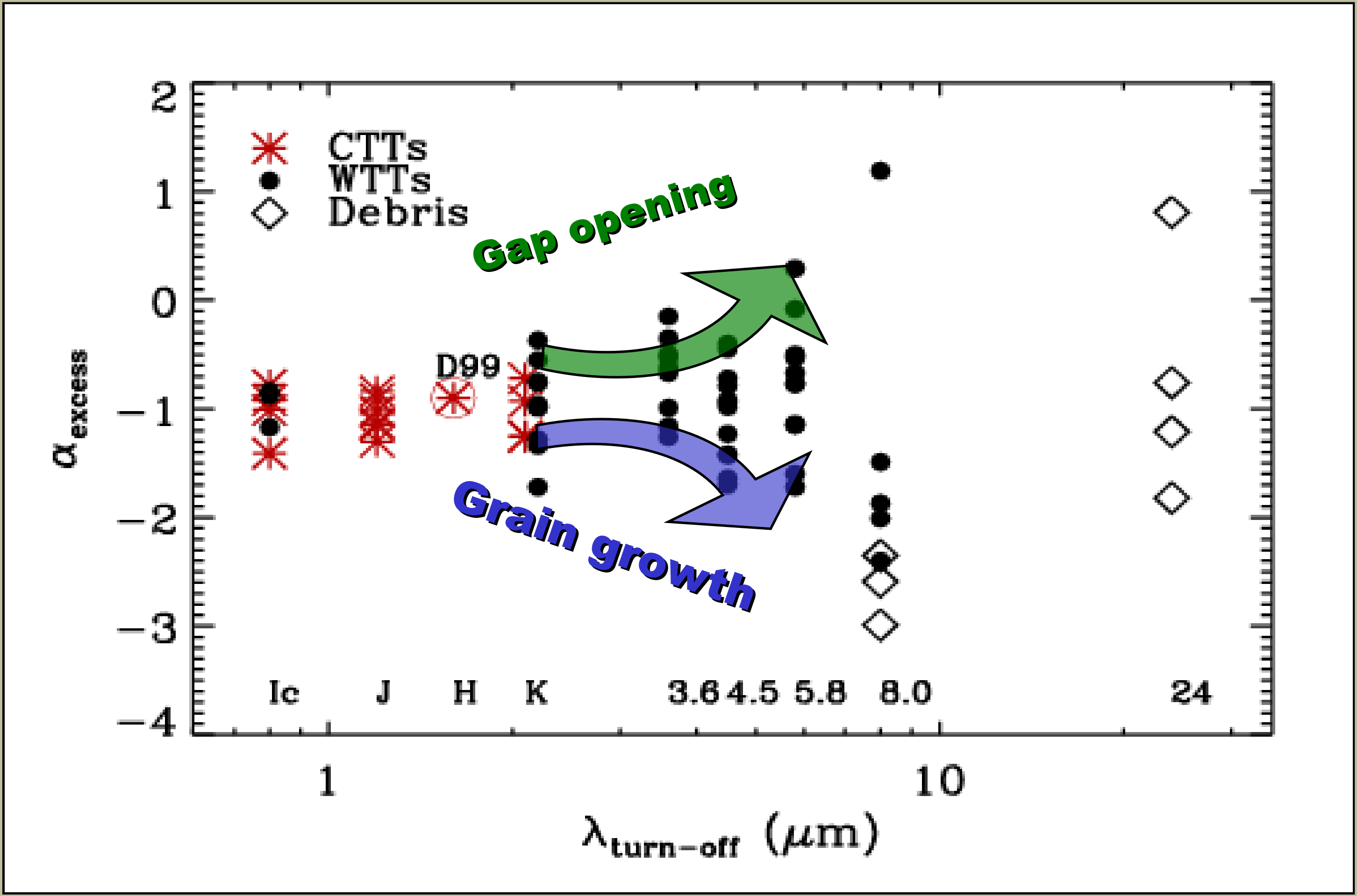
These parameters allow the identification of different states of the inner disks in different diagram locations



Cieza et al. (2007)

Mapping evolutionary paths

The distribution of different evolutionary stages in the diagram suggests different possible evolutionary paths from CTTs to WTTs and to Debris disks

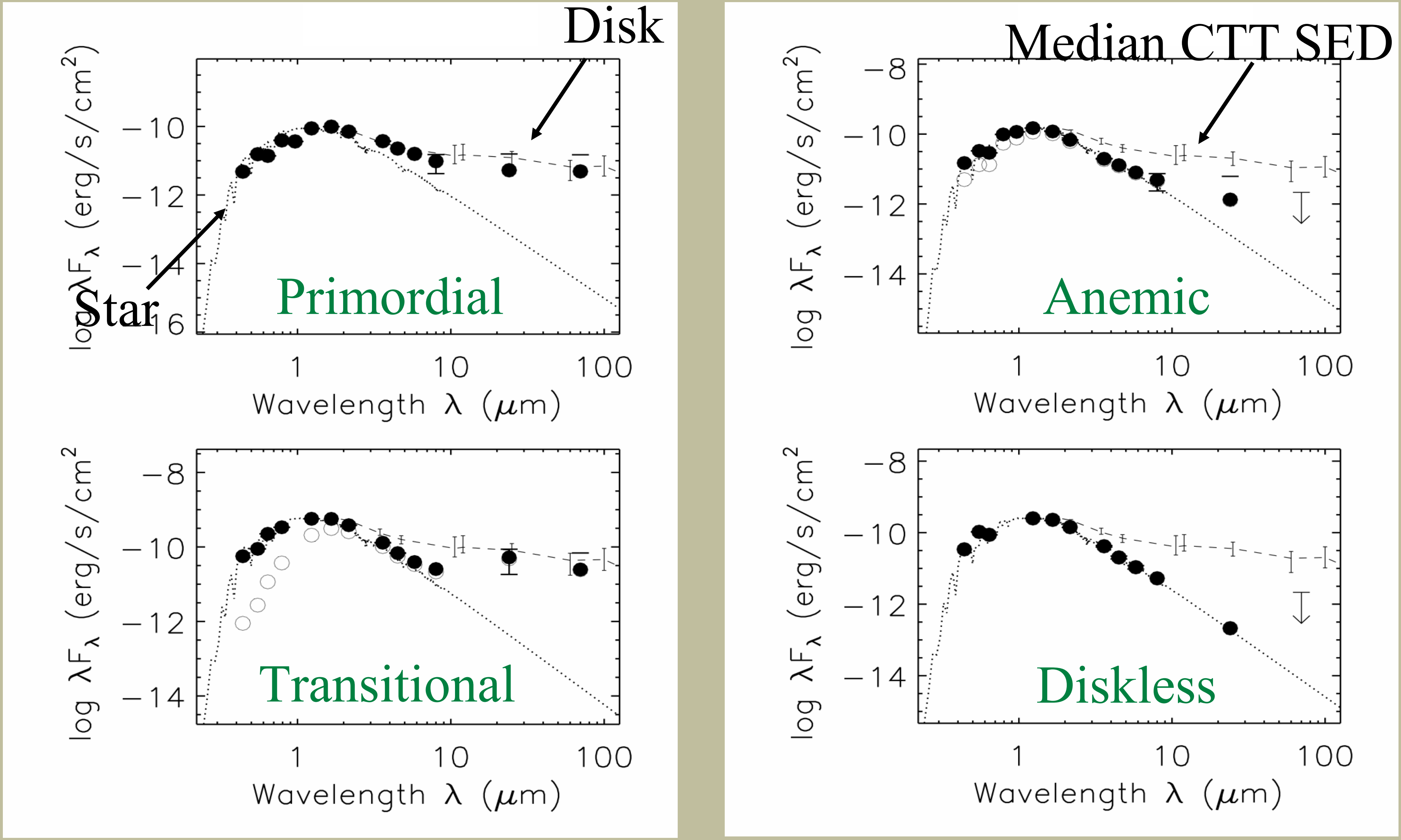


Cieza et al. (2007)

We also must review our naming conventions

Neal Evans’ discussion panel on Thursday

Let’s define four main types of Spitzer SEDs by comparison with the median SED of the T Tauri stars in Taurus and a photosphere



There are many new disk samples

- Taurus (Hartmann et al. 2005, Najita et al. 2008, Taurus Legacy Project)
  - ~100 stars, ~ 1 Myr, 1 M_{sun}
  - Transitional+anemic disks are more massive and have smaller accretion
- IC 348 (Lada et al. 2006, Currie 2008)
  - ~ 300 stars, ~2-3 Myr, 0.3 M_{sun}
  - Largest mass fraction for solar-mass stars
  - Disk fractions are a strong function of the stellar mass
- IC 5146 (Harvey et al. 2008)
  - ~ 200 stars, 1 Myr, 0.3 - 2 M_{sun}

Talks: Evans, Allen, Robitaille, Hora, Megeath, Muzerolle, Carpenter
Posters: # 2 Rebull, #10 Guieu, #12 Wolff, #20 Matthews, #42 Peterson

There are many new disk samples

- FEPS (Silverstone et al. 2006, Carpenter et al. 2008)
  - ~ 74 stars, ages < 30 Myr, masses $0.7 < M_{star} < 1.5\ M_{sun}$
  - ~314 stars between 3 Myr and 3 Gyr, ~ 1 M_{sun}
- c2d (Evans et al. 2008)
  - IRS sample: 50 CTTS + 4 HAeBes (Kessler-Silacci et al. 2006)
  - WTTS sample: 160 stars (Cieza et al. 2006, 2008b, Wahhah et al. 2008)
  - Cloud sample: 800 stars in 5 clouds (Evans et al. 2008)
  - Cold disk sample: 34 stars in 5 clouds (Merín et al. 2009)

Now we will review the statistical properties from the different samples

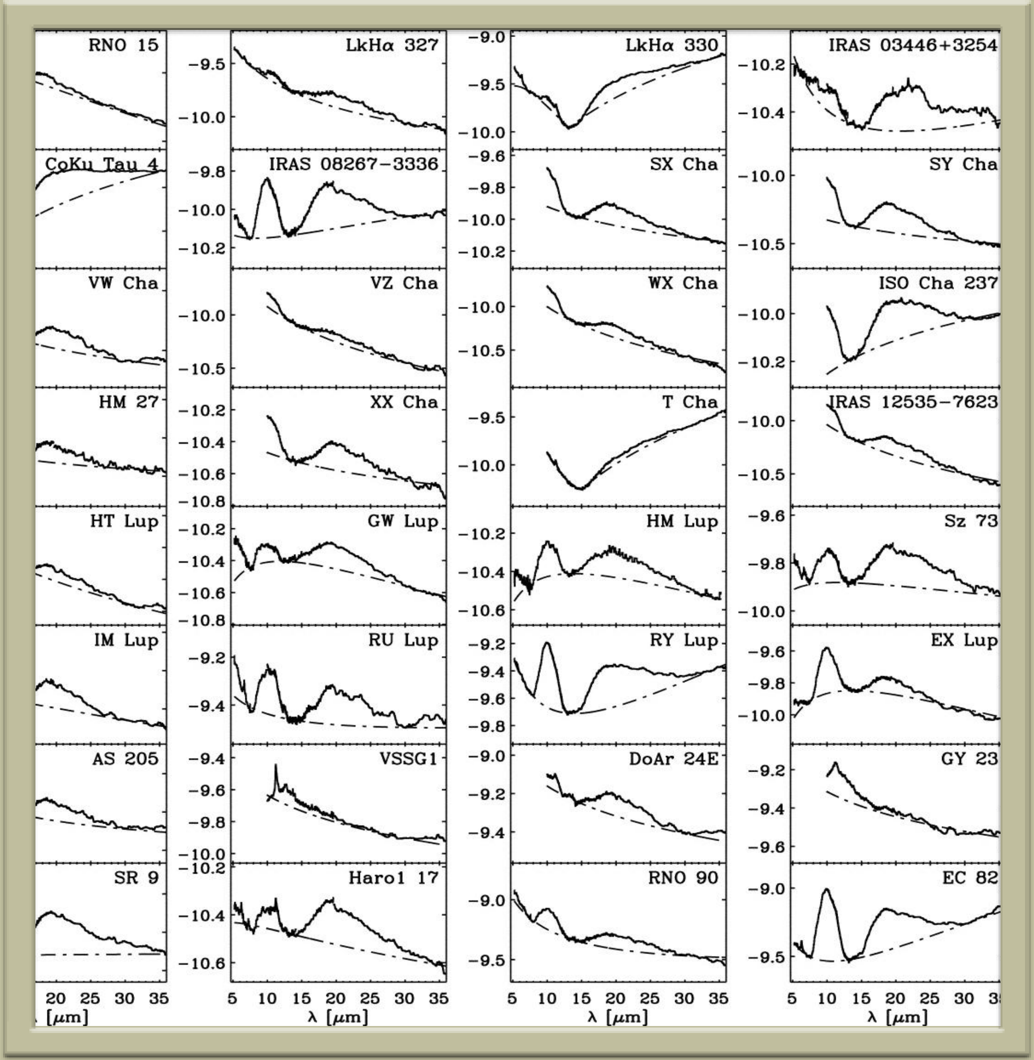
Posters: #93 McCabe

Talks: Olofsson, Bouwmans, Forrest
Posters:
#51 Glauser, #57 Carey #70 Geers

c2d IRS Sample

Kessler-Silacci et al. 2006
Brown et al. 2007

50 CTTS and HAeBe disks
4 Transitional disks



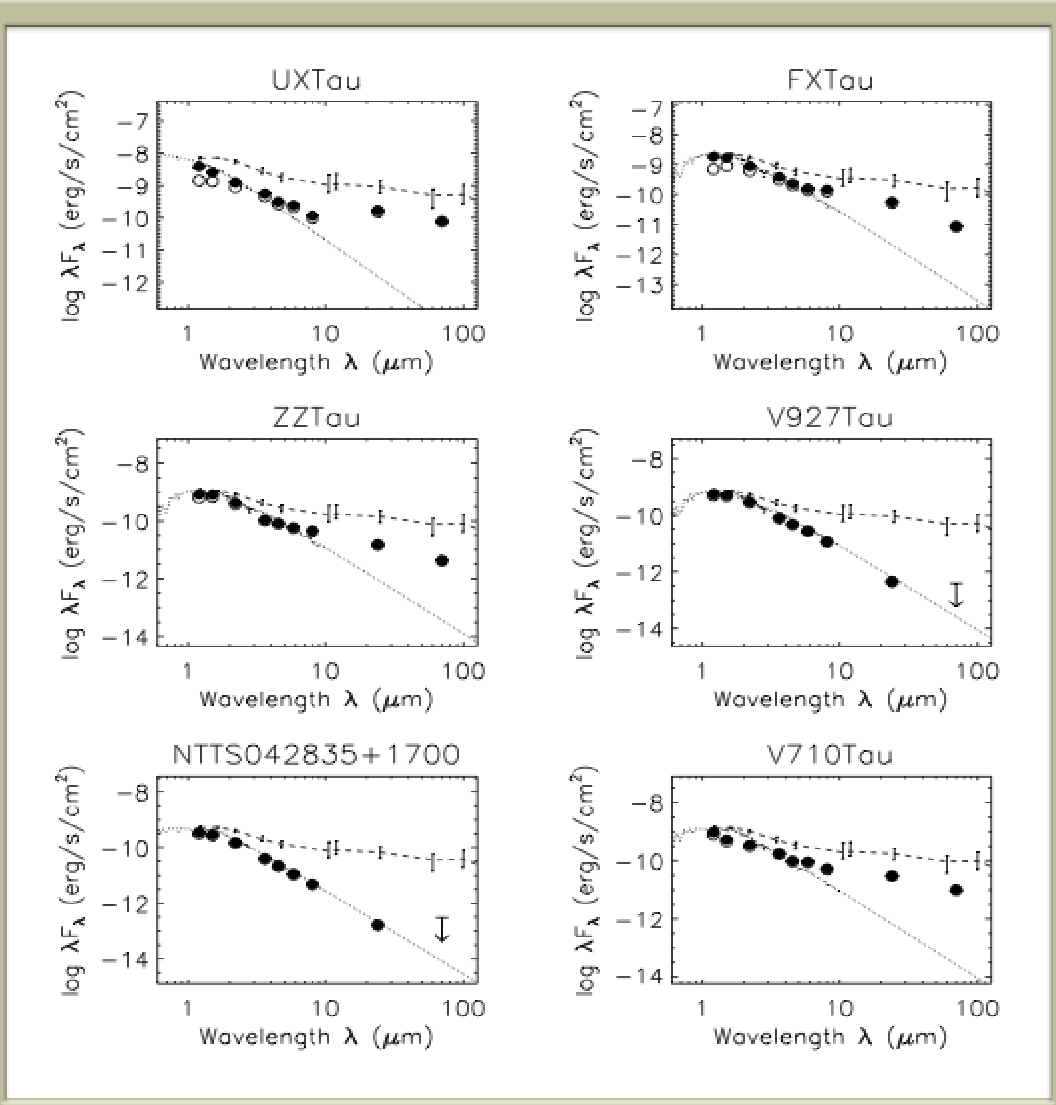
Most CTTs are primordial disks

Posters #86 Cieza
#78 Wahhaj

c2d WTTS sample

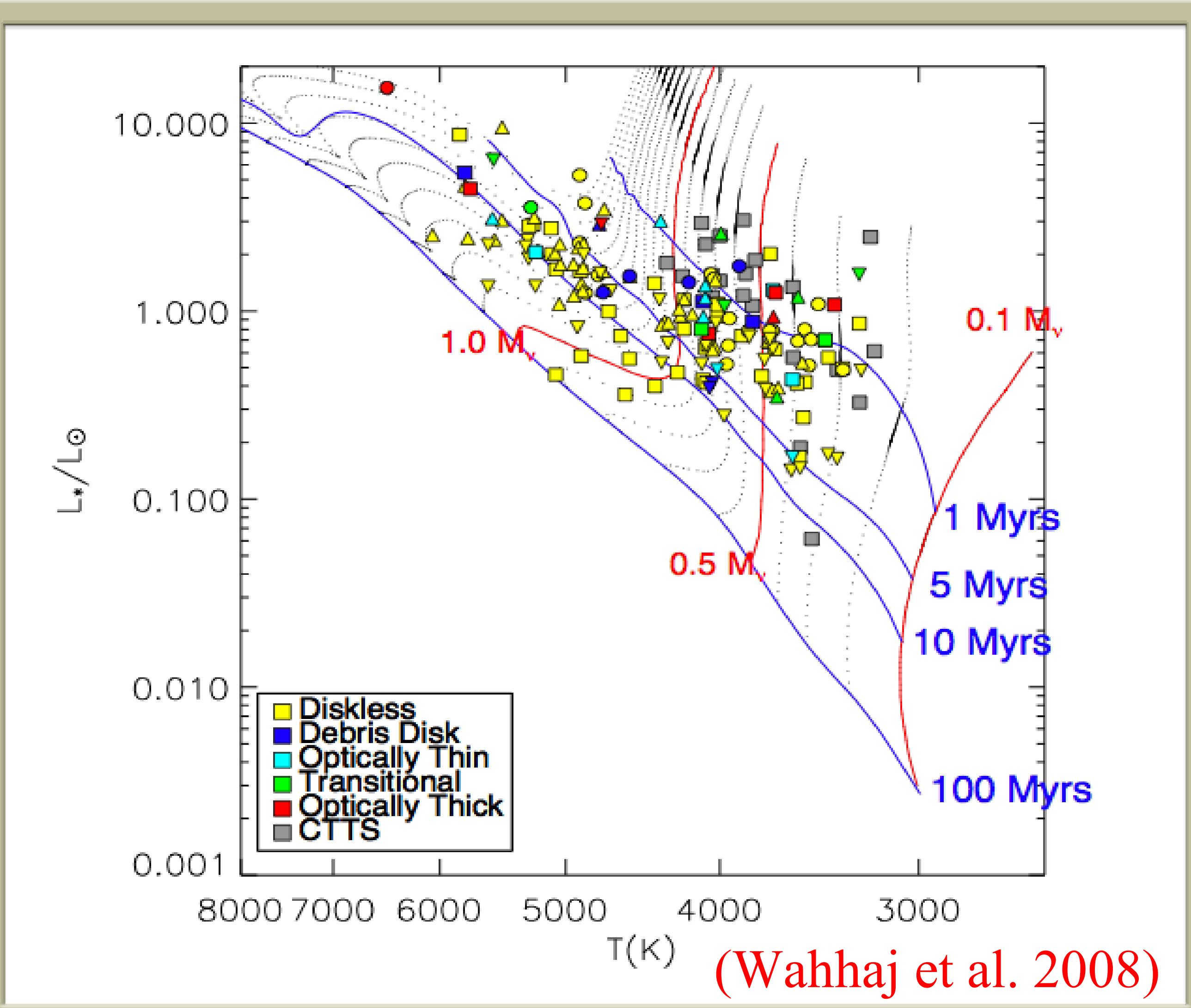
Wahhaj et al. 2008
Cieza et al. 2008b

165 WTTS stars



Most disked WTTS are anemic or debris disks

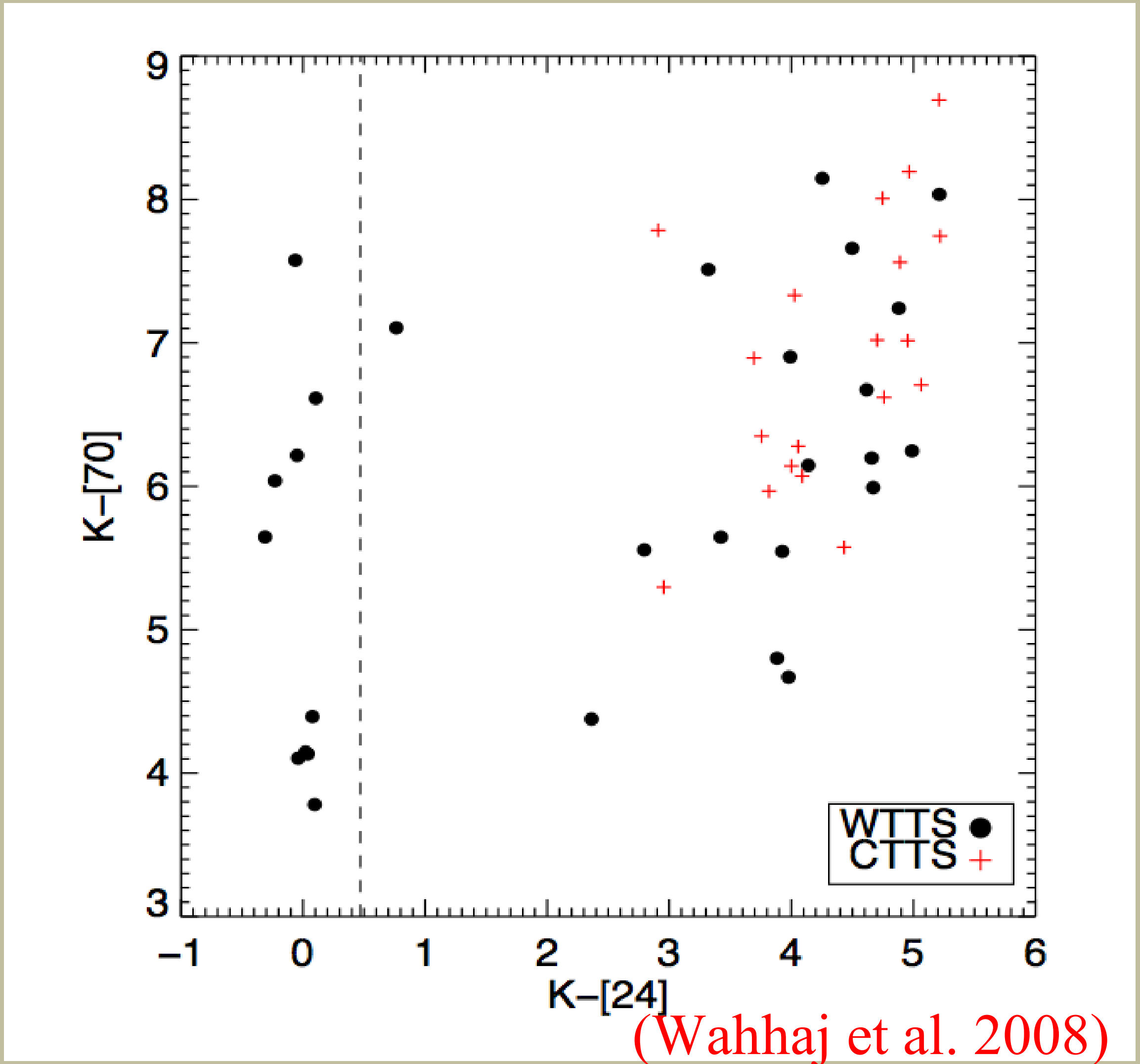
Poster
#78 Wahhaj



(Wahhaj et al. 2008)

CTTS, disked and diskless WTTS follow in time
(although with a great overlap)

Posters
#78 Wahhaj
#109 Abraham
#112 Chavero
#117 Shannon
#120 Roberge

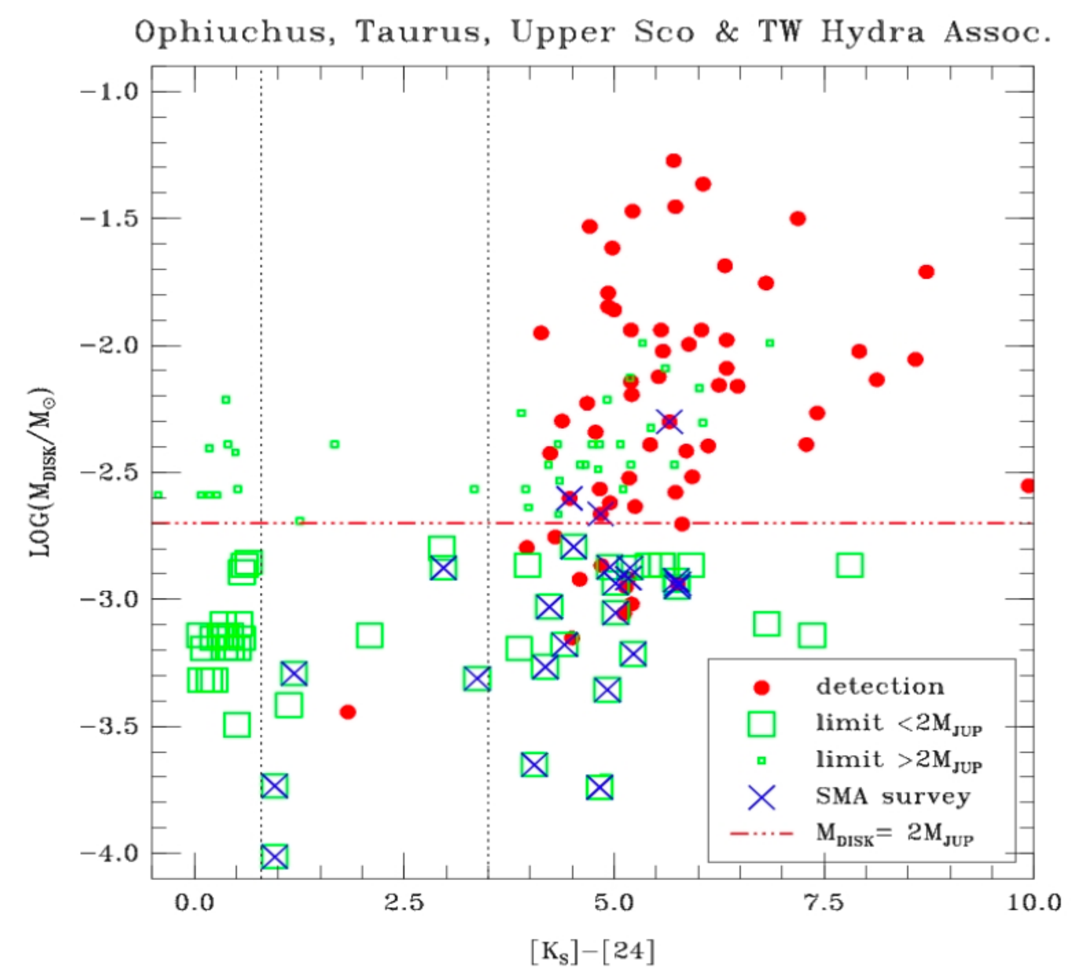


(Wahhaj et al. 2008)

There is a bimodal distribution of 70 µm sources with the 70-only excess being likely the first young debris disks

Low disk masses of WTTs

- Cieza et al. 2008b:
  - SMA/mm data for 130 WTTS and CTTS disks
  - Low disk masses for most WTTS disks
  - This together with the evolved inner disks suggests that WTTs disks are currently being photo-evaporated

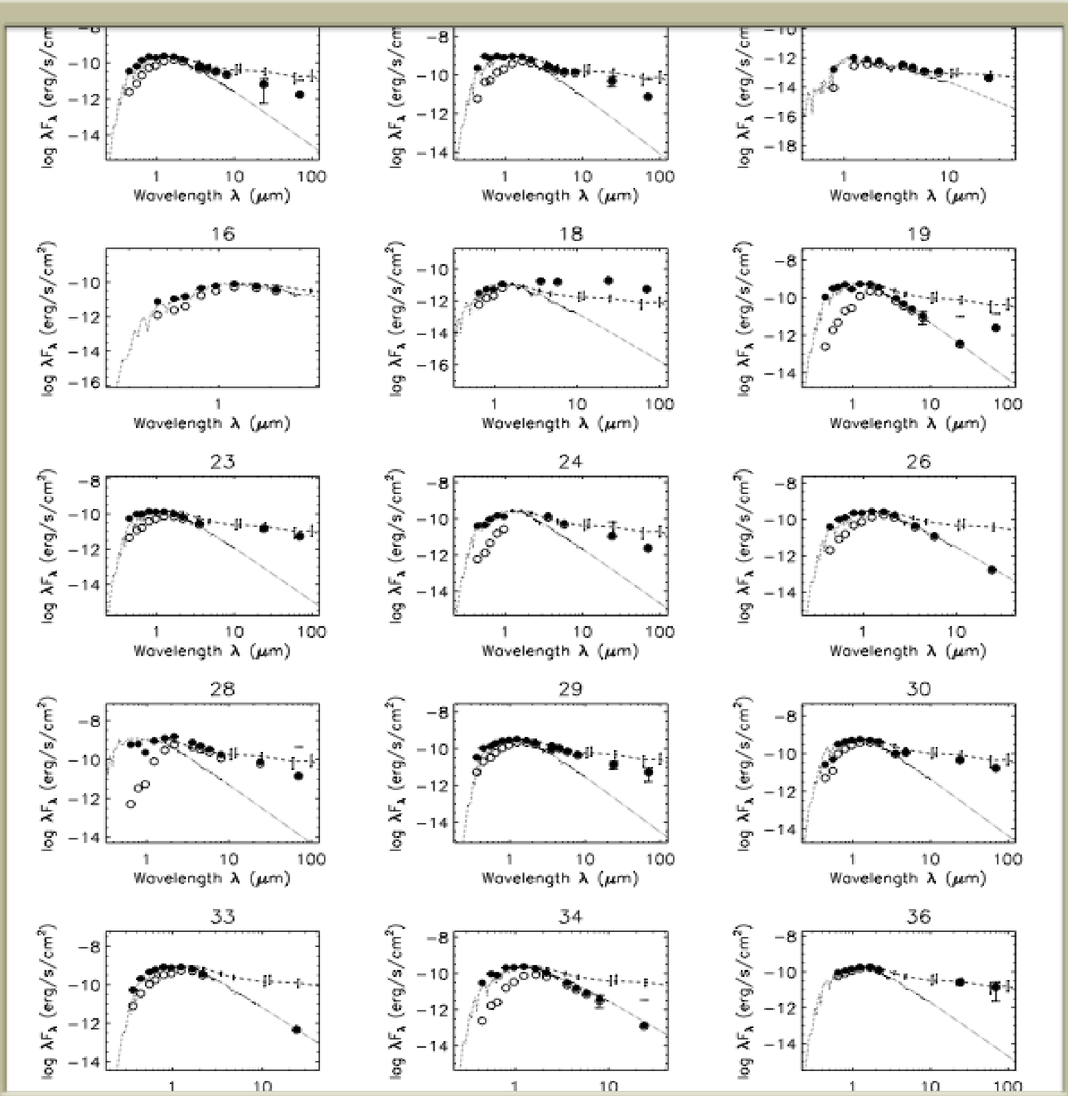


Poster #86 Cieza

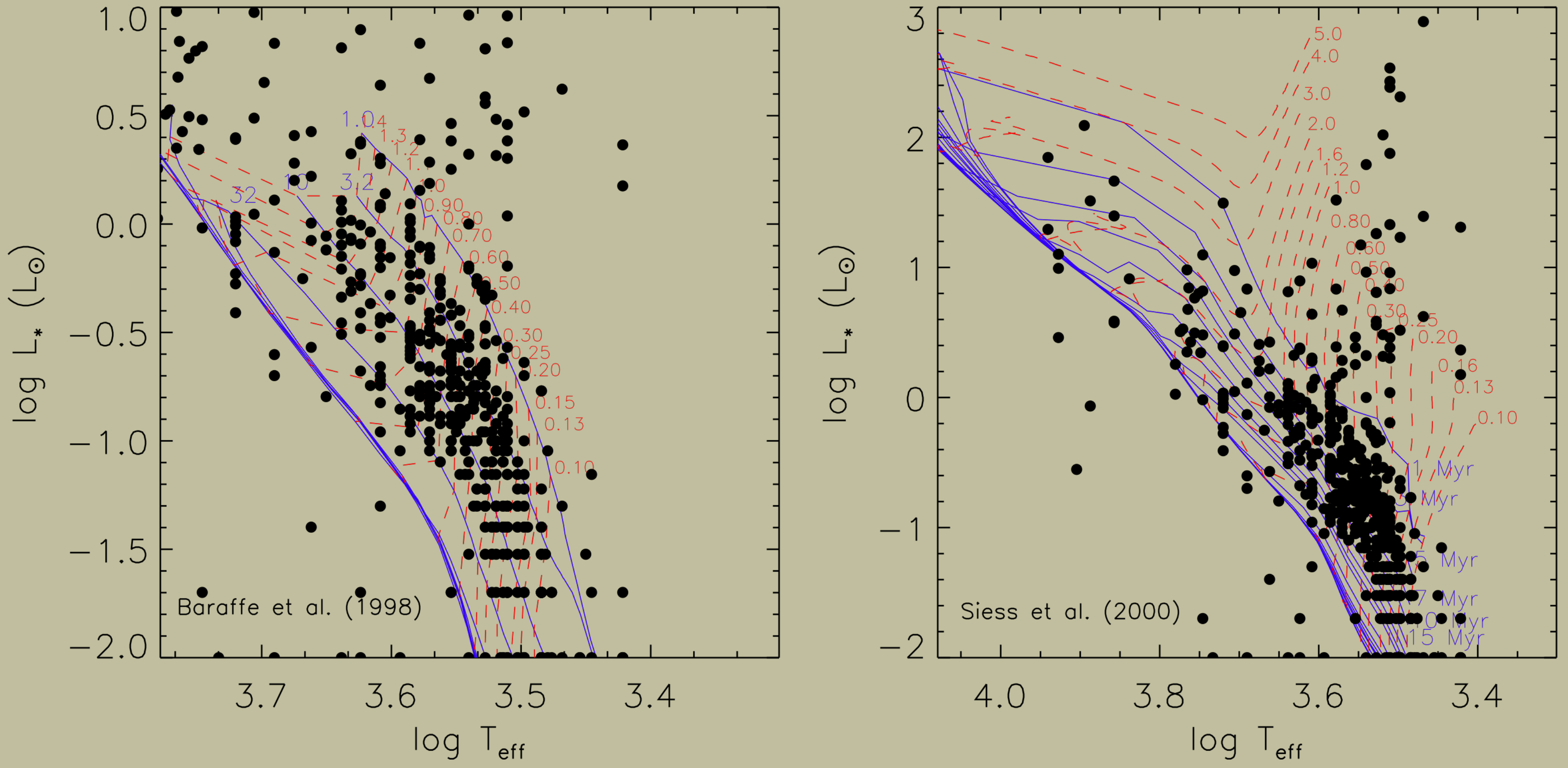
c2d cloud Sample

Merín et al. 2009b

800 stars
490 with optical data



Talks: Evans & Allen
Posters: #17 Brown & #30 Oliveira



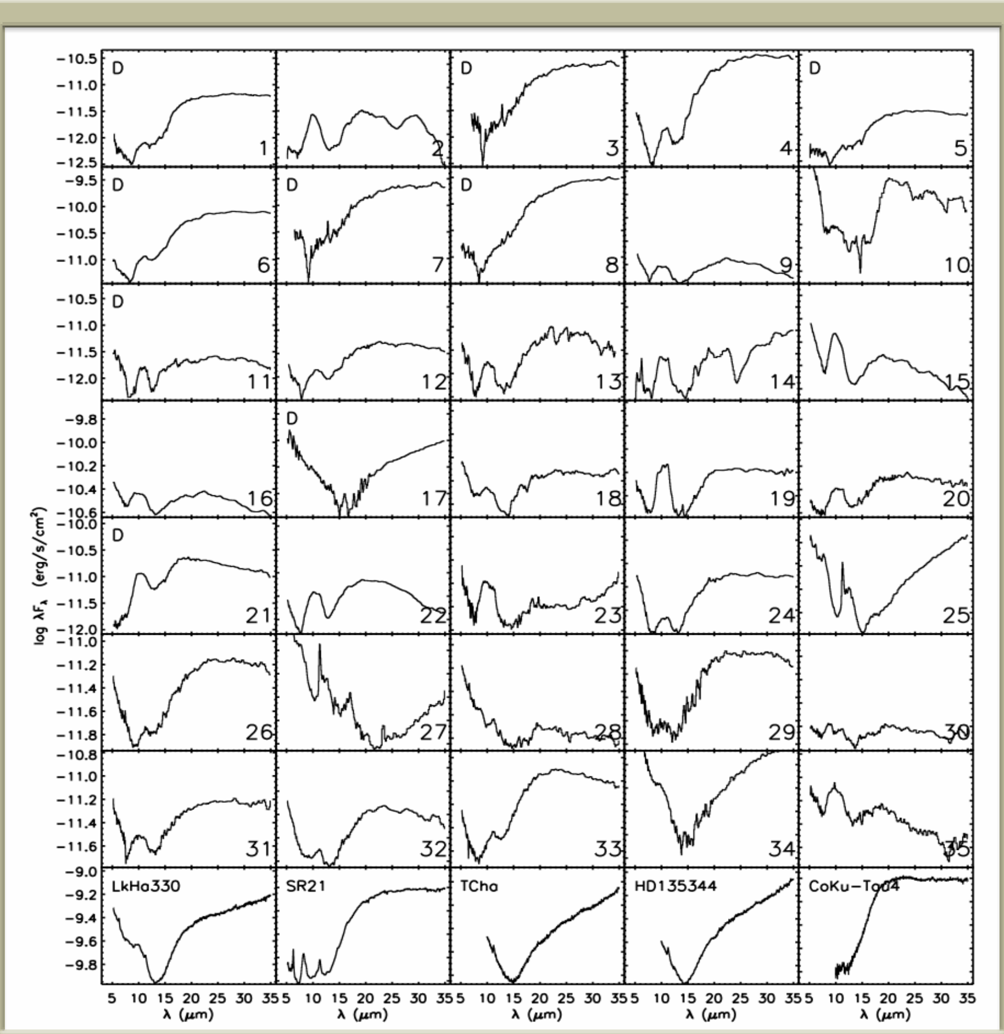
(Merín et al. 2009b)

All 493 SEDs with optical data classified and ages and masses determined from the HR diagram

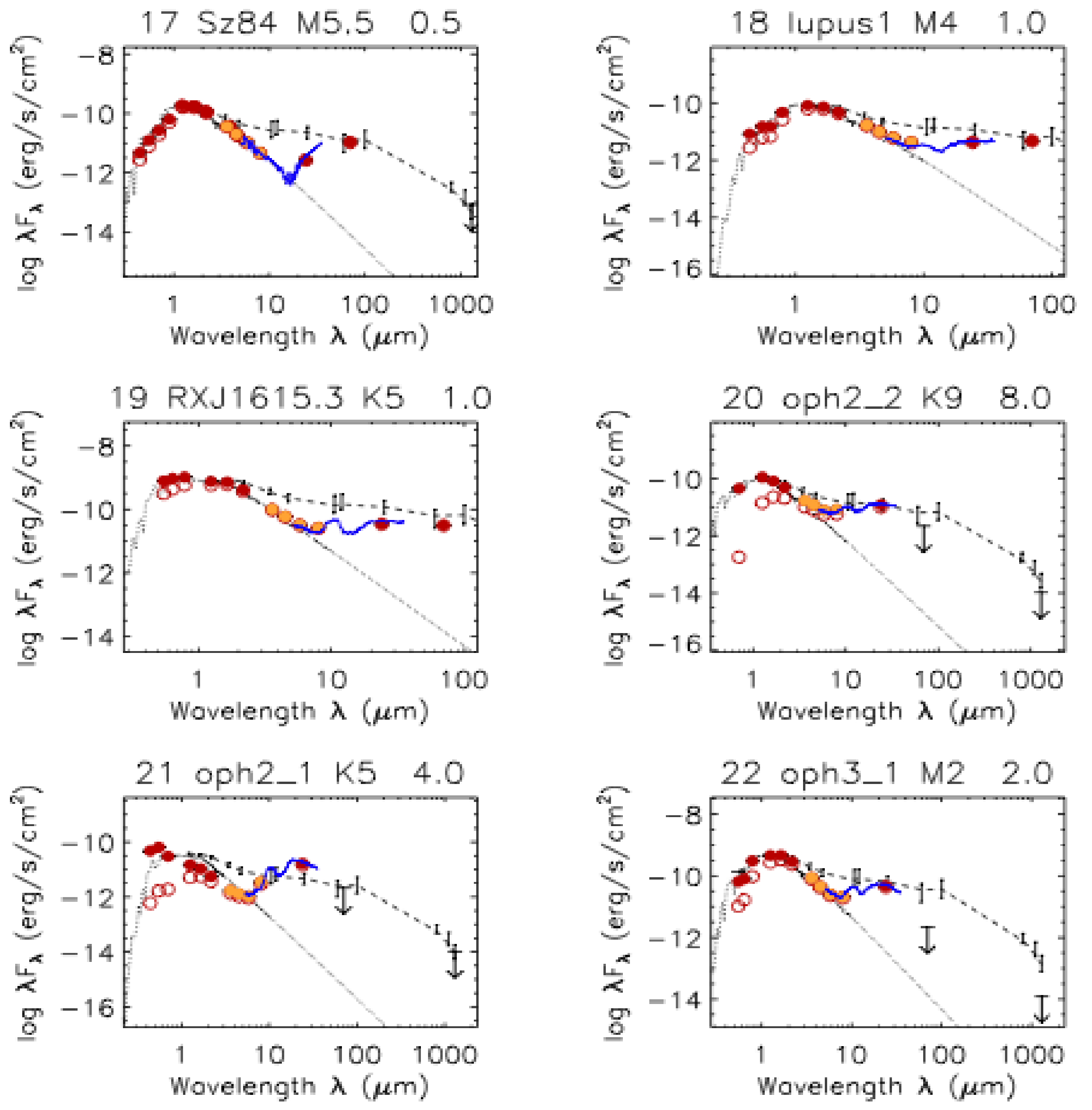
c2d cold disk Sample

Merín et al. 2009

34 transitional disks



Great variety in dust composition in transitional disks



(Merín et al. 2009)

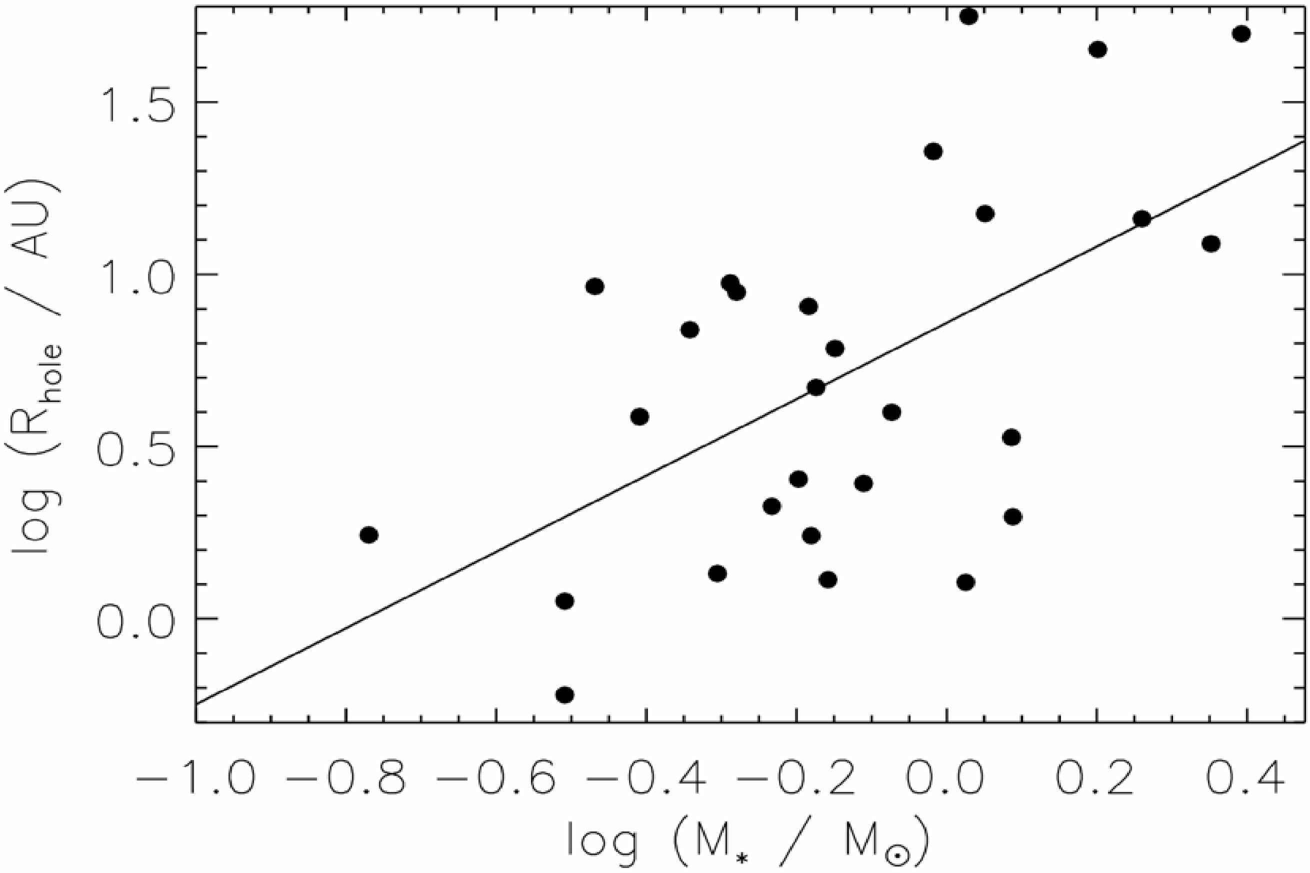
SED modeling reveals the presence of large inner holes

Possible hole scenarios

- Grain growth to particles > 100 µm
  - Soft inner disk edge
  - Long time-scales -> not observed
- EUV photo-evaporation
  - $R_{grav} \sim G M_{star} \mu p / KT \sim 10 \times (M_{star}/M_{sun})$
  - Fast time-scales
  - Mass accretion rate to central star < Photo-evaporation rate
- Close (< 30 AU) binaries
- Planet gap formation

Talks Alexander, Currie, Kraus
Posters: #91 Espaillat, #92 Kim

R_{hole} (AU) ~ $(M_{star}/M_{sun})^{1.1}$

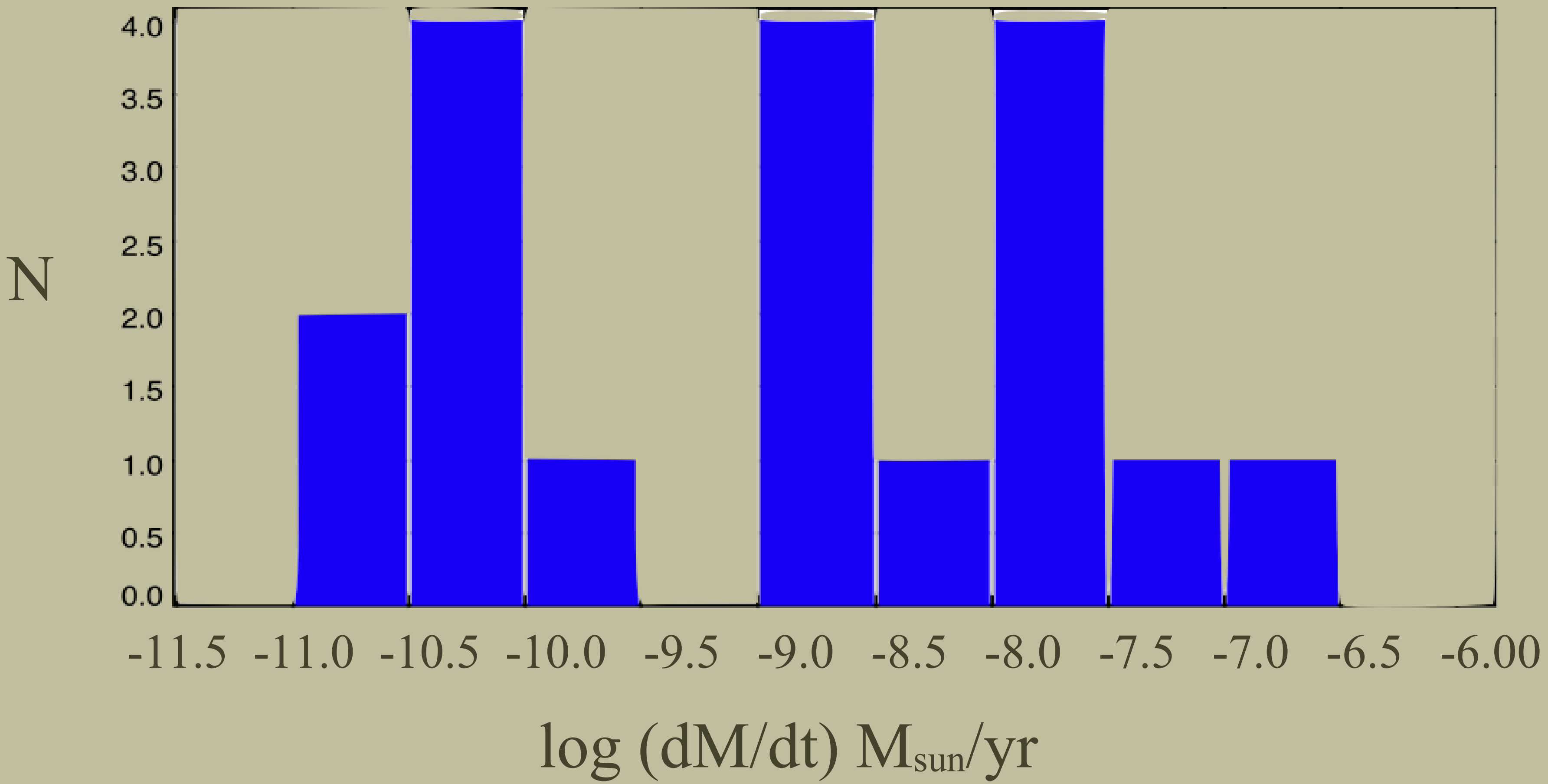


Also found in Poster #92 Kim

(Merín et al. 2009)

The sizes of the inner holes are proportional to M_{star}

.. and some stars still accrete



(Merín et al. 2009)

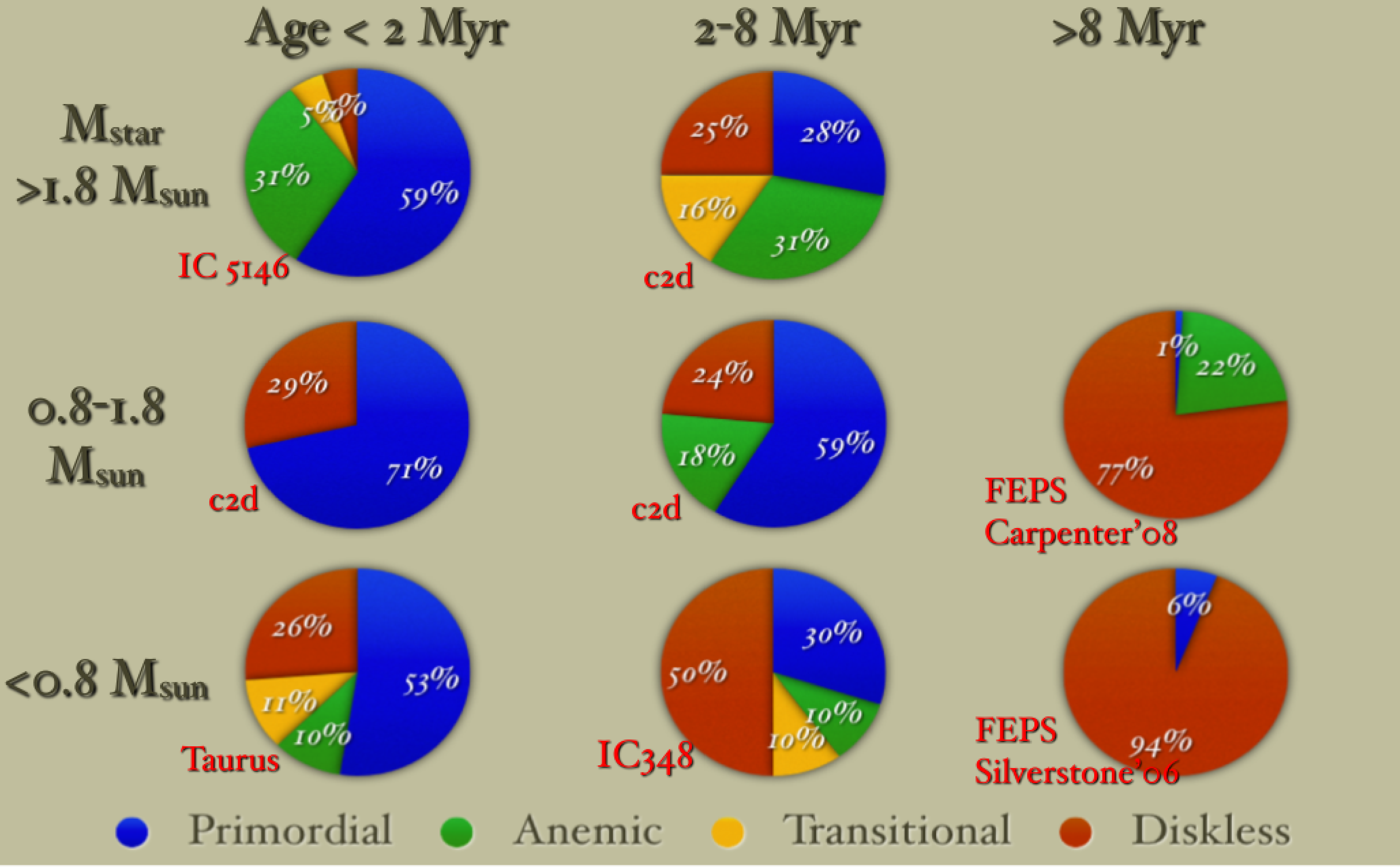
Following a demographic approach

- Following Najita et al. (2007), we now summarize the frequencies and properties of different types of disks in the different samples overcoming individual cases

- Following that, we highlight key results or hints about disk evolution from some detailed studies of small samples

- We then finish proposing a scenario which tries to explain the properties of the new Spitzer disk samples, the hints from detailed studies and some features of the Solar System formation altogether

The facts

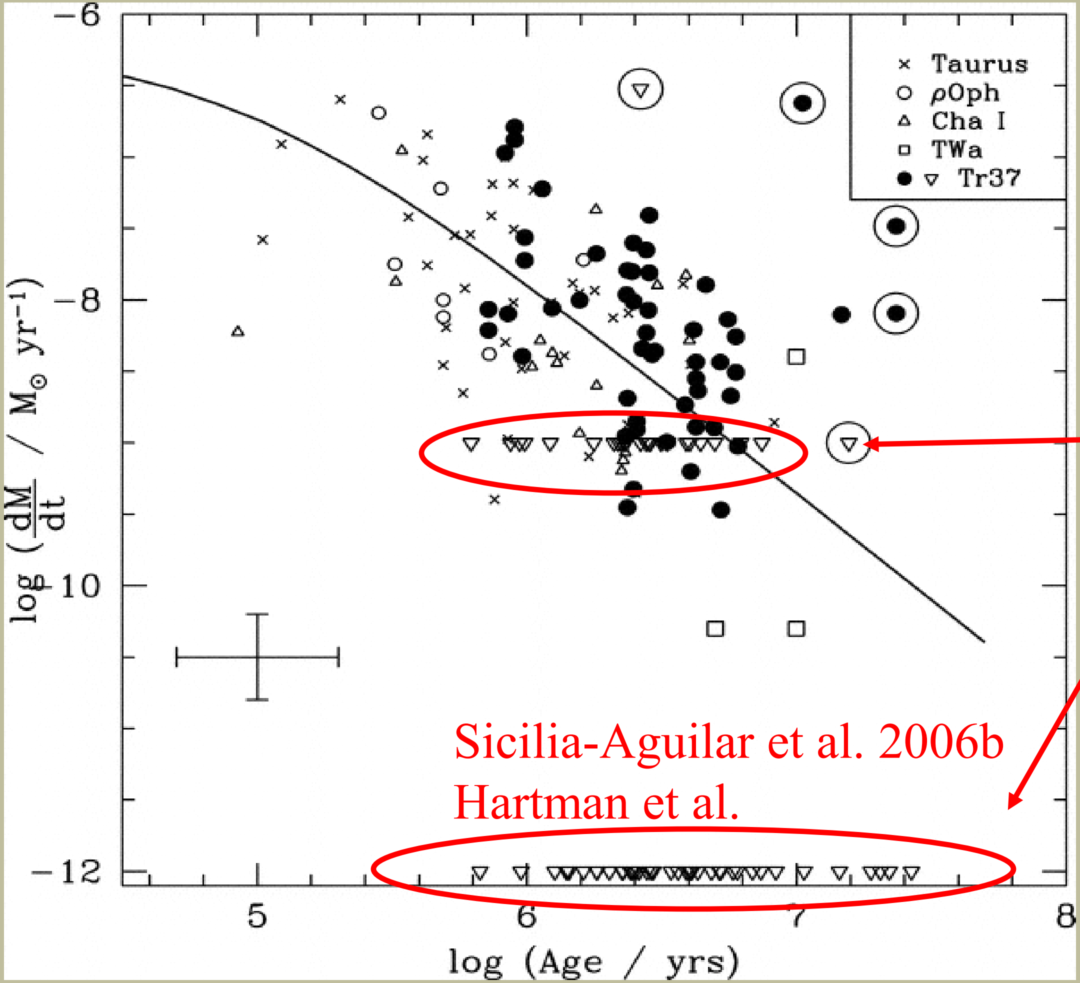

Age < 2 Myr
2-8 Myr
>8 Myr
Mstar >1.8 Msun
5%
5%
31%
59%
IC 5146
25%
28%
16%
31%
c2d
0.8-1.8 Msun
29%
71%
c2d
24%
18%
59%
c2d
1%
22%
77%
FEPS Carpenter'08
<0.8 Msun
26%
11%
10%
53%
Taurus
50%
30%
10%
10%
IC348
6%
94%
FEPS Silverstone'06
Primordial
Anemic
Transitional
Diskless

The facts

- There is a small abundance of transitional disks
- There is large variety of inner disk architectures at any given age -> multiple evolutionary paths
- There seems to be a dependency on the disk types with stellar mass
- Anemic disks have in average more massive disks and much smaller mass accretion rates
- Large ranges of mass accretion rates are found in a large sample of transitional disks

The hints I

Viscous evolution time-scales are longer than actual disk disappearance time-scales (many disk disappear faster)



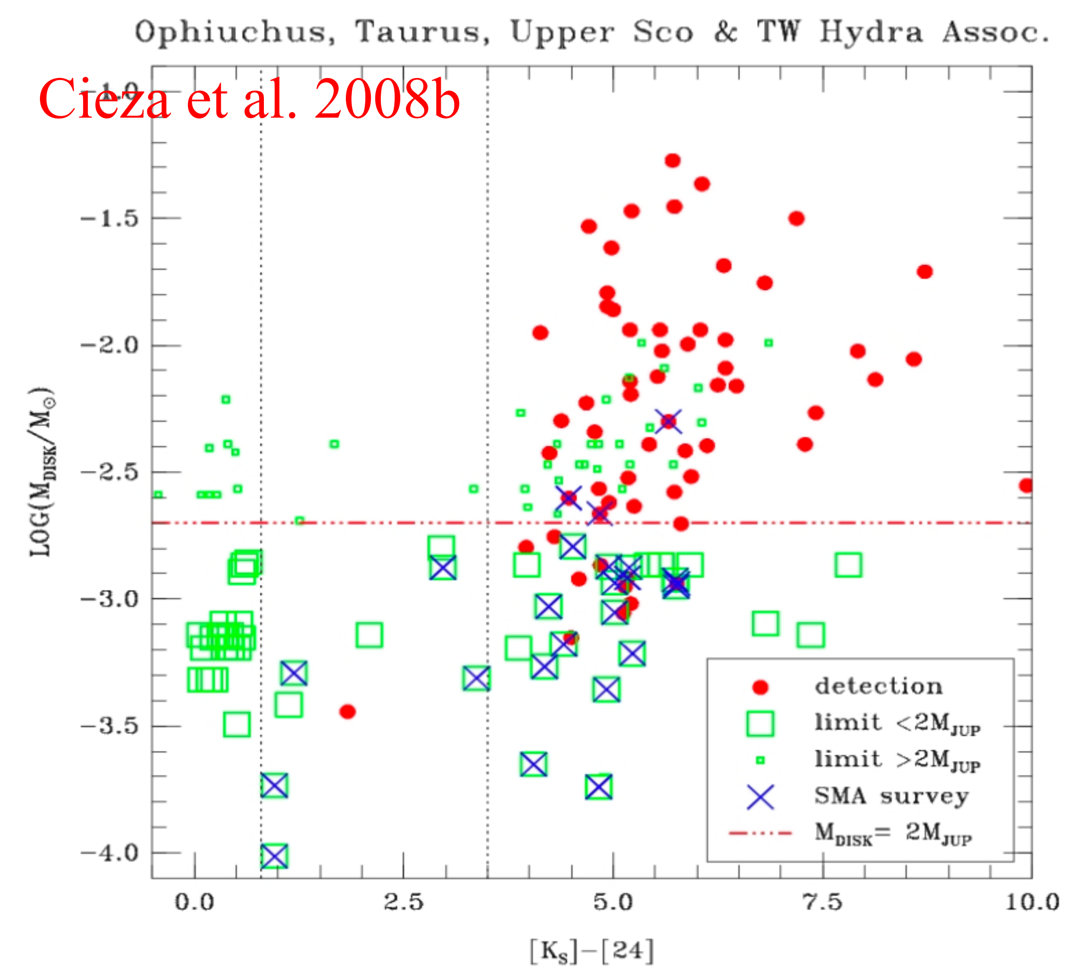
Young objects with very little accretion

Sicilia-Aguilar et al. 2006b
Hartman et al.

Talks:
Calvet, Alexander

The hints II

SEDs and disk masses of (non-accretting) WTTs are roughly compatible with photo-evaporating disks

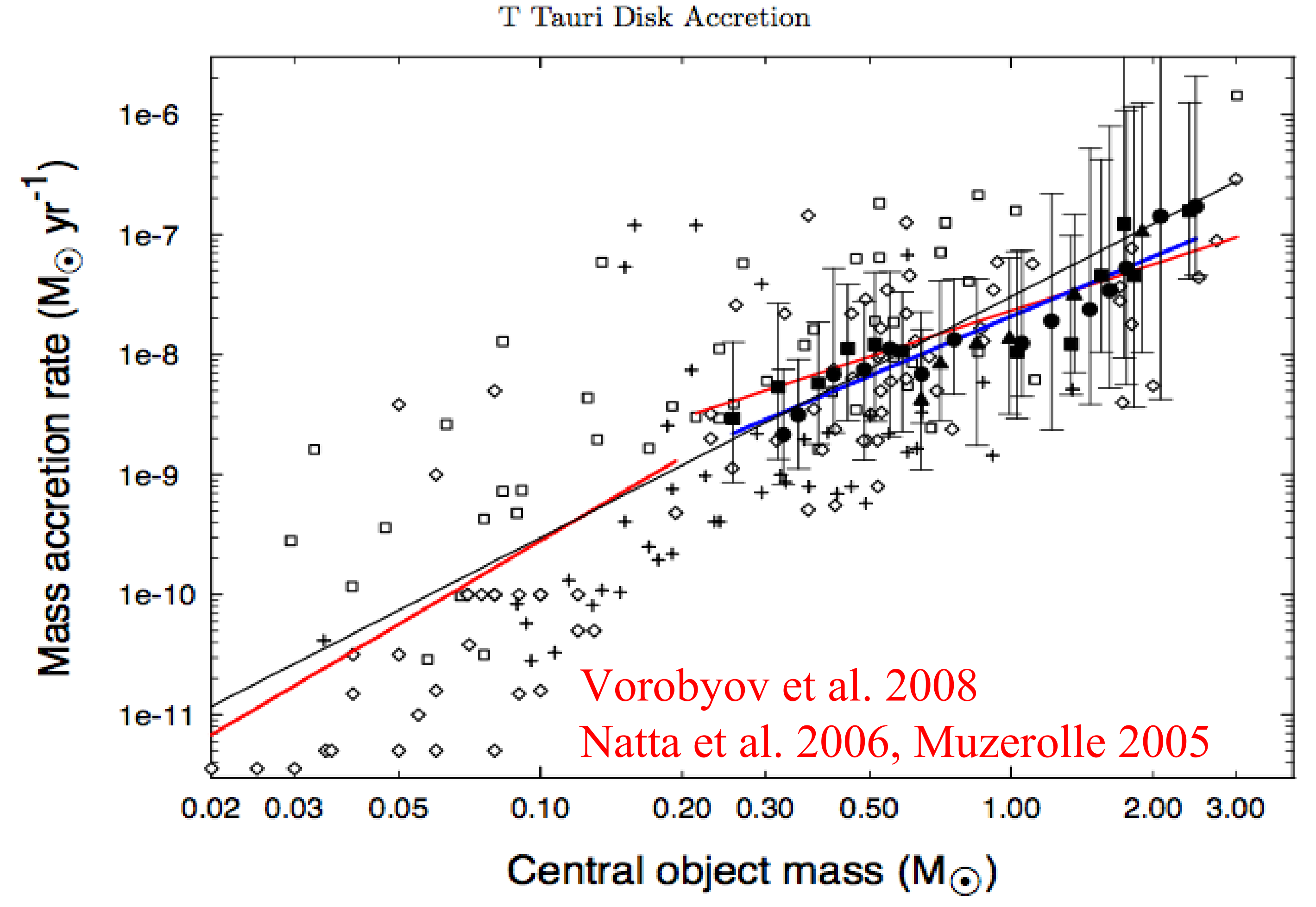

Ophiuchus, Taurus, Upper Sco & TW Hydra Assoc.

Cieza et al. 2008b

Poster
#86 Cieza

The hints III

The mass accretion rate is known to be proportional to the stellar mass squared over a wide range in stellar mass



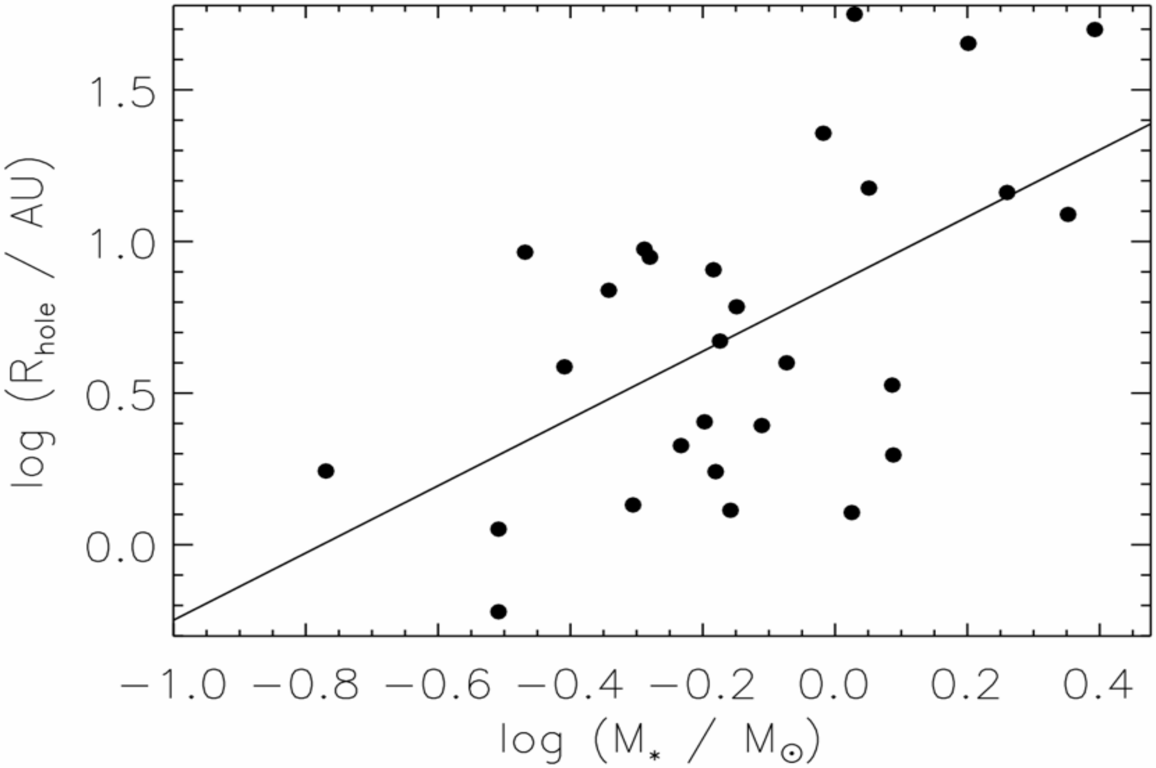
Vorobyov et al. 2008

Natta et al. 2006, Muzerolle 2005

The hints IV

The inner hole sizes in transitional disks are also consistent with being photo-evaporated and there is range of mass accretion rates

R_{hole} (AU) ~ $(M_{star}/M_{sun})^{1.1}$

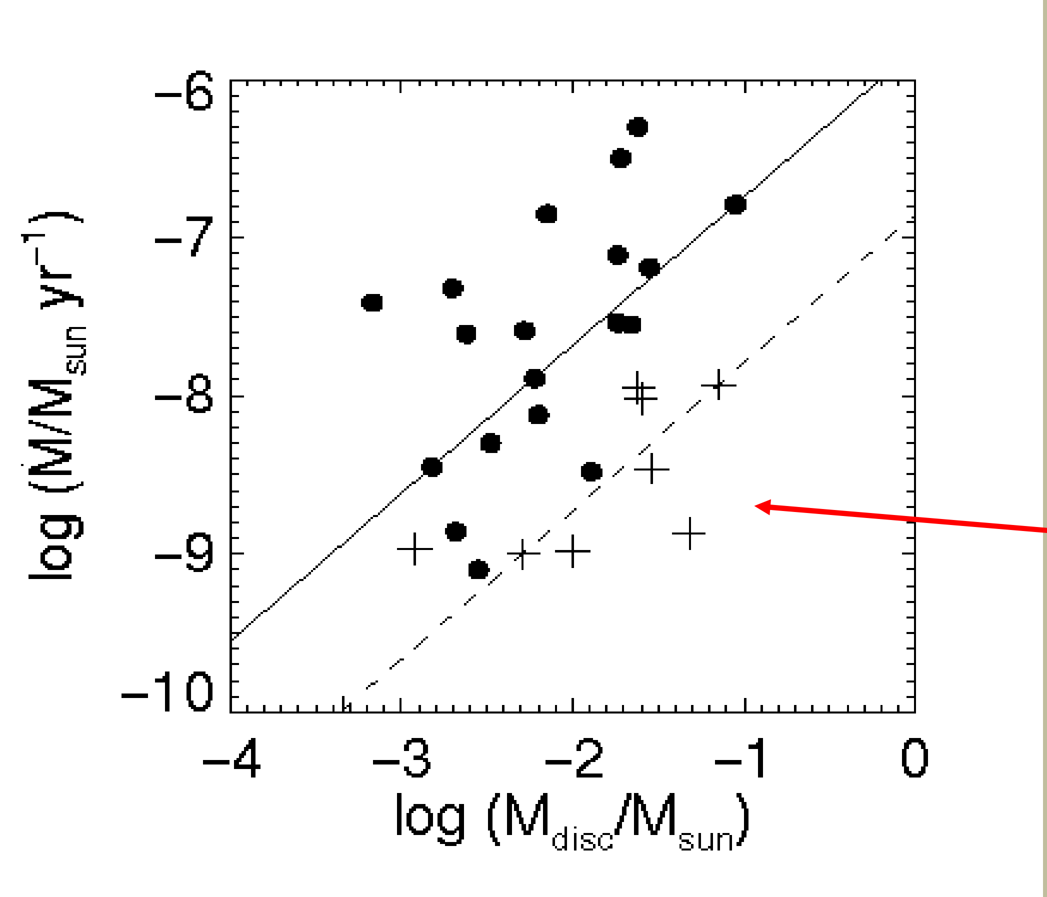


Poster #92 Kim

(Merín et al. 2009)

The hints V

Anemic and Transitional disks are in general 4 times more massive and have an order of magnitude smaller mass accretion rates than primordial disks



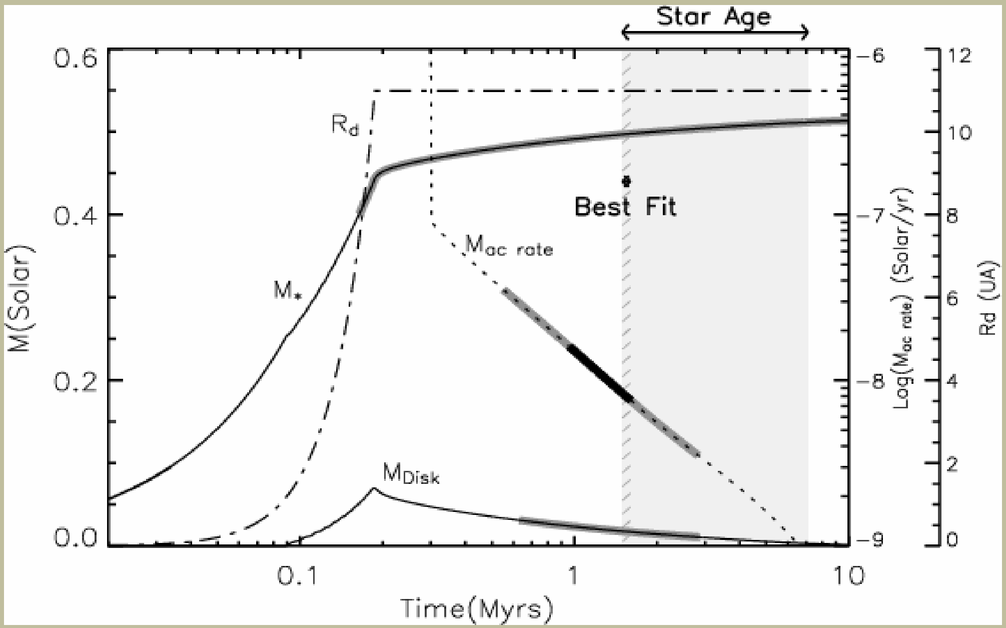
Anemic and Transitional disks in Taurus (plus signs)

Talk: Muzerolle, Furlan, Calvet
Poster #92 Kim

(Najita et al. 2007)

The hints VI

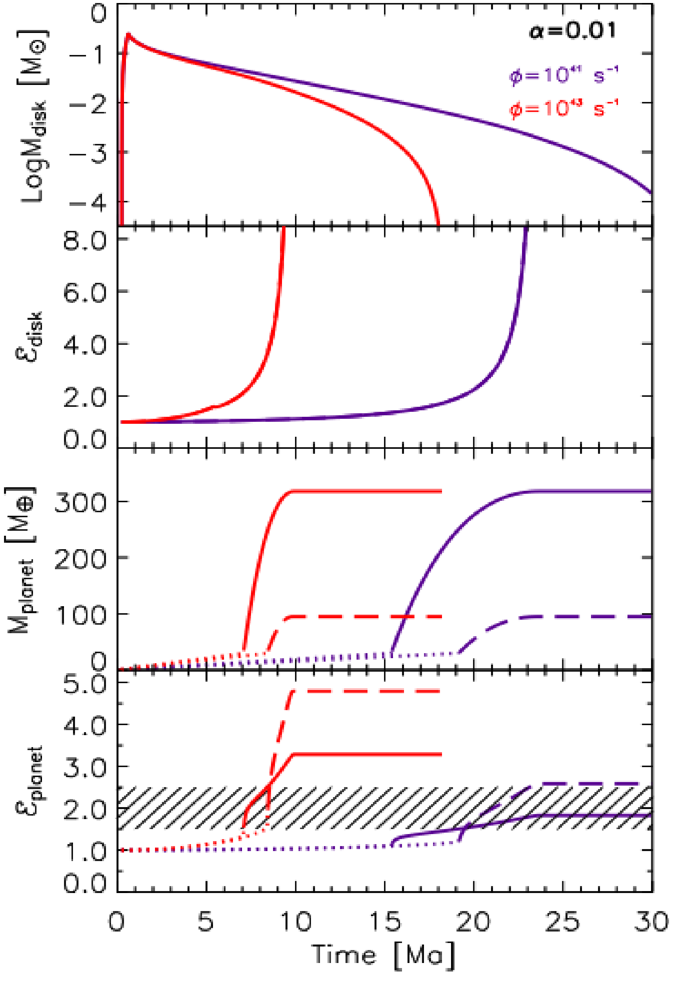
The formation of Jupiter happened late in a dispersing disk.



Hueso & Guillot 2005

Talks: Alexander, Chiang

Guillot & Hueso 2006



Matches the 2x enrichment in noble gases in Jupiter as measured by the Galileo probe

A possible simple scenario

1) Most stars start their PMS lives with disks with masses broadly proportional to the stellar mass except close binaries

2) Maybe the most massive and lightest disks are destroyed by gravitational instability and efficient photo-evaporation, respectively. The great majority of the disks undergo physical transformations and eventually get dispersed before 10 Myr

3) Dust grow in very short time-scales and proto-planets start growing very soon after 1 Myr. During this phase there is a competition between viscous evolution with accretion to the star and photo-evaporation of the disk. In this phase the disks go from primordial to anemic or transitional SED phase.

4) The viscous time-scale is inversely proportional to the mass accretion rate and therefore to the stellar mass squared. Hence, the more massive the star, the faster the accretion, the grain growth and the disk evolution.

A possible simple scenario

5) Viscous evolution time-scales are larger than observed time dispersal time scales for a subsample of the disks. The growth of proto-planets in the inner disk would decrease the accretion towards the star by acting like mass sinks in the disk. This would reduce the time dispersal time-scale for some cases.

6) In a soft transition which depends on the disk mass, the growth of planets in the inner disk reduces accretion and allows photo-evaporation to start dominating over accretion, clearing out the inner disk quickly from that moment onwards.

7) Proto-planets growing very fast in a massive disk will stop accretion and allow photo-evaporation carving large inner holes at early ages, producing transitional disk SEDs. Proto-planets growing in low-mass disks will require longer times to significantly decrease accretion and might never end up opening a gap in the disk, which is already dispersing at their formation time. These objects will go from primordial to anemic/settled and cleared stages without having a transitional phase.

A possible simple scenario

- According to this, the final fate of a proto-planetary disk would depend finally on its initial mass, which might roughly depend on the stellar mass and have a broad distribution of values depending on the star+disk formation history (mostly its initial angular momentum, multiplicity and history of encounters).

- Also accordingly, massive disks could form more massive planets in shorter time-scales. Then these proto-planets would be more likely to find themselves embedded in a still dense disk, which would force them to migrate inwards, dragging possible telluric proto-planets along. Planets in lighter disks would stay closer to where they were formed, as perhaps happened in the Solar System.

This would explain..

- Why do we find 1 Myr-old disks without any IR excess and ~ 5-Myr disks with primordial circumstellar disks in all regions?
  - Besides the formation history, different initial disk masses would impose different evolutionary velocities and paths to the objects making some disks disappear very fast while keeping others for long
- Why the disk mass fraction is greatest for the solar mass stars in IC348 (3 Myrs, Lada et al. 2006) and for the 0.8 M_{sun} stars in the 5 Myr-old Upper Sco OB association (Carpenter et al. 2008)?
  - The solar-mass disks from 3 Myrs have already evolved and disappeared at 5 Myrs, while the lower-mass disks are still viscously accreting and will disappear later.

This would explain..

- Why from the whole c2d IRS disk sample (ages ~ 1-2 Myrs) only the most massive objects have large inner holes (Brown et al. 2007)?
  - At the early ages of the sample (1-2 Myr), only the most massive stars and disks have already grown massive proto-planets, diminished accretion and photo-evaporated large inner holes in their disks while T Tauri disks are still actively accreting
- Why most 2-6 Msun stars in IC 1805 have depleted their disks by 2 Myr (Poster #12 Wolff)?
  - All massive disks have already been dispersed at that age

This would explain..

- Why with latest statistics of extrasolar planets (Udry et al. 2007) suggest that low-mass stars tend to have in average lower-mass planets and larger planet multiplicity?
  - Low-mass planets tend to form in low-mass disks typically around low-mass stars. The process is slow and by the time they are formed the disks are already dispersing, as it seems to have happened in the Solar System. More massive planets in massive disks will tend to migrate and to reduce the planetary multiplicity by pushing the smaller planets into the star.

Conclusions

- Spitzer observations of large samples of 1 to 10 Myr disks allow to constrain the planet formation models.
- Proto-planetary disks around single stars follow different evolutionary paths depending primarily on the initial disk mass, likely related to the stellar mass.
- The evolution time-scale of the disks is proportional to the stellar mass, and disks around massive stars evolve faster than disks around low-mass stars.
- Early proto-planet growth might reduce the accretion to the central star allowing photo-evaporation to dominate over accretion and to clear the disks on shorter time-scales.

Thanks you for your attention.

Gracias por su atención.

Dank u voor uw aandacht.