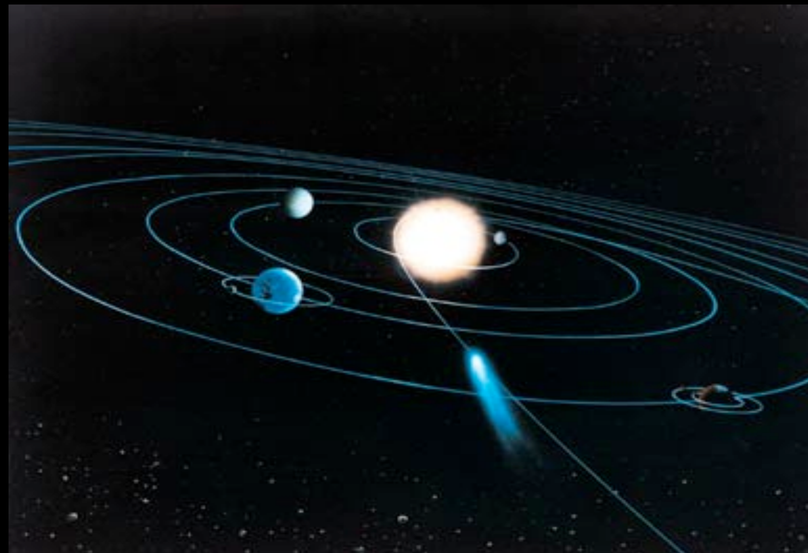
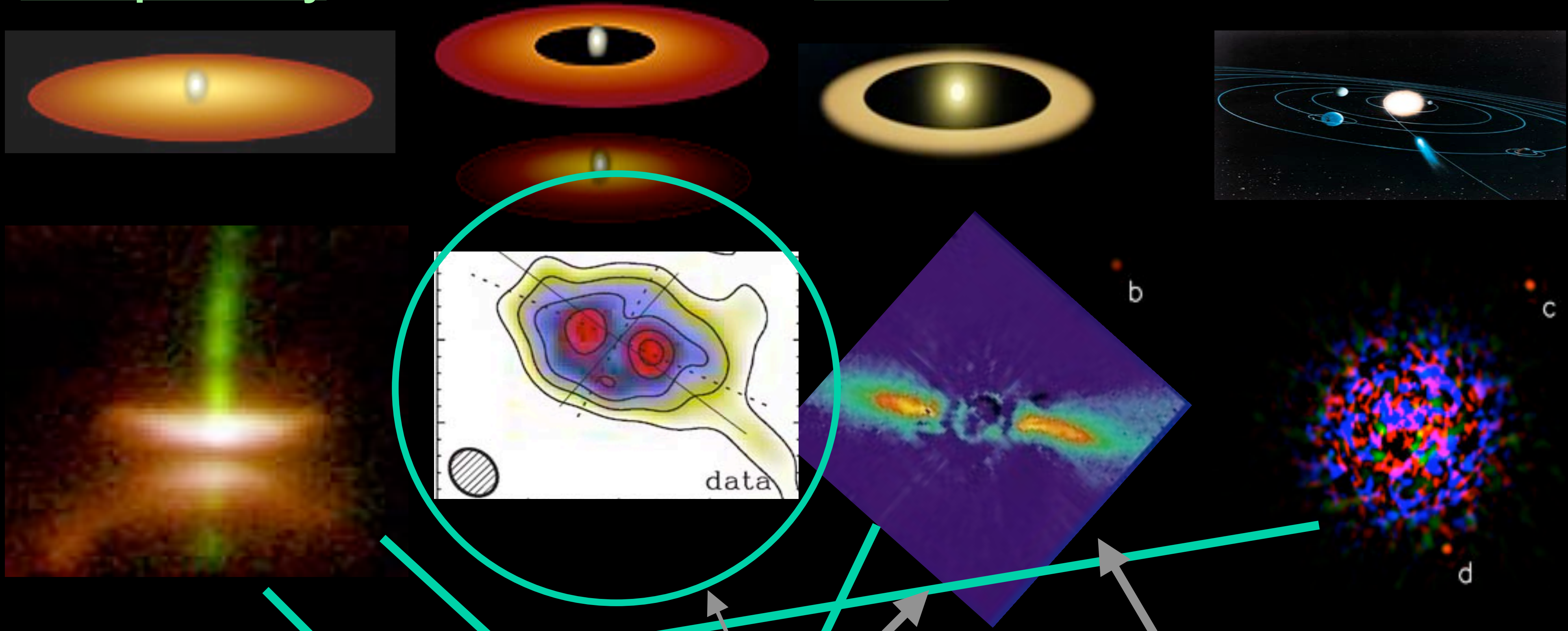
The Time History of Planet Formation: Observation Confronts Theory



Thayne Currie (CfA/NASA-Goddard)

Issues to Address in this Talk

Protoplanetary **Debris**



1. Timescales for Protoplanetary Disk Evolution/Gas Giant Planet Formation

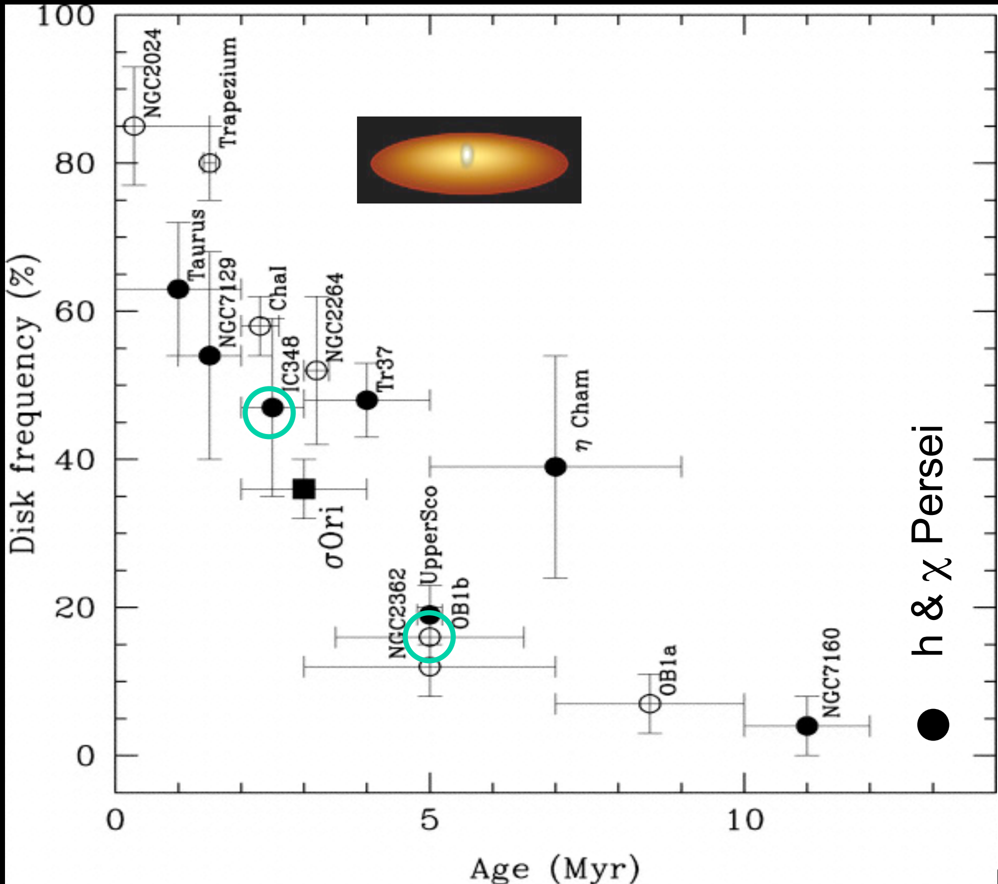
2. Nature of Transitional Disks/late-stage Protoplanetary Disk Evolution

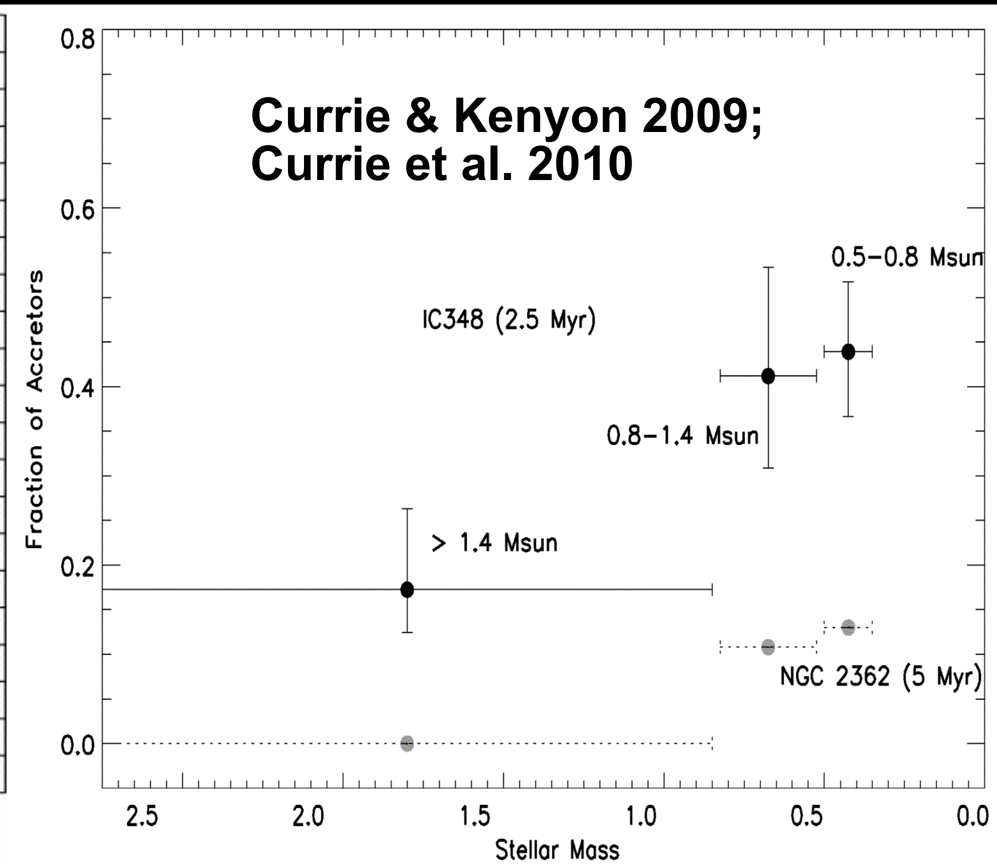
3a. Debris Disk Evolution and initial planetesimal sizes

3b. Debris Disk Evolution → stages in planet formation

(Burrows et al. 1996; Hughes et al. 2009; Mouillet et al. 1997; Marois et al.

1a. Protoplanetary Disk Evolution



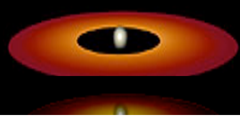


Warm primordial (protoplanetary) disk material gone by ~5 Myr for most stars (Hernandez et al. 2007; Currie et al. 2010)

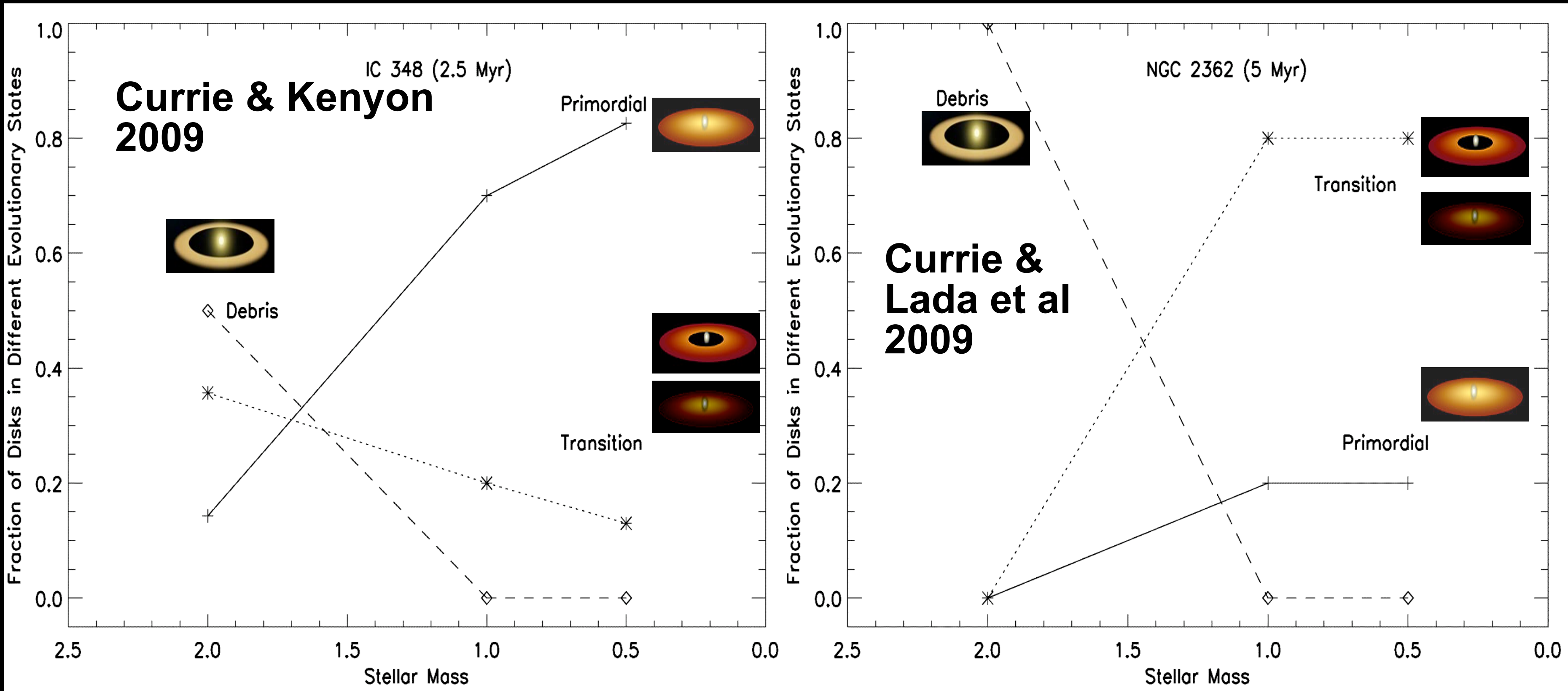
Signatures of warm gas gone by 2.5 Myr for A stars; 5 Myr for solar/subsolar mass stars

Now compare frequency of disks that are

1) [illegible]ial, 2 [illegible]nal, [illegible]s



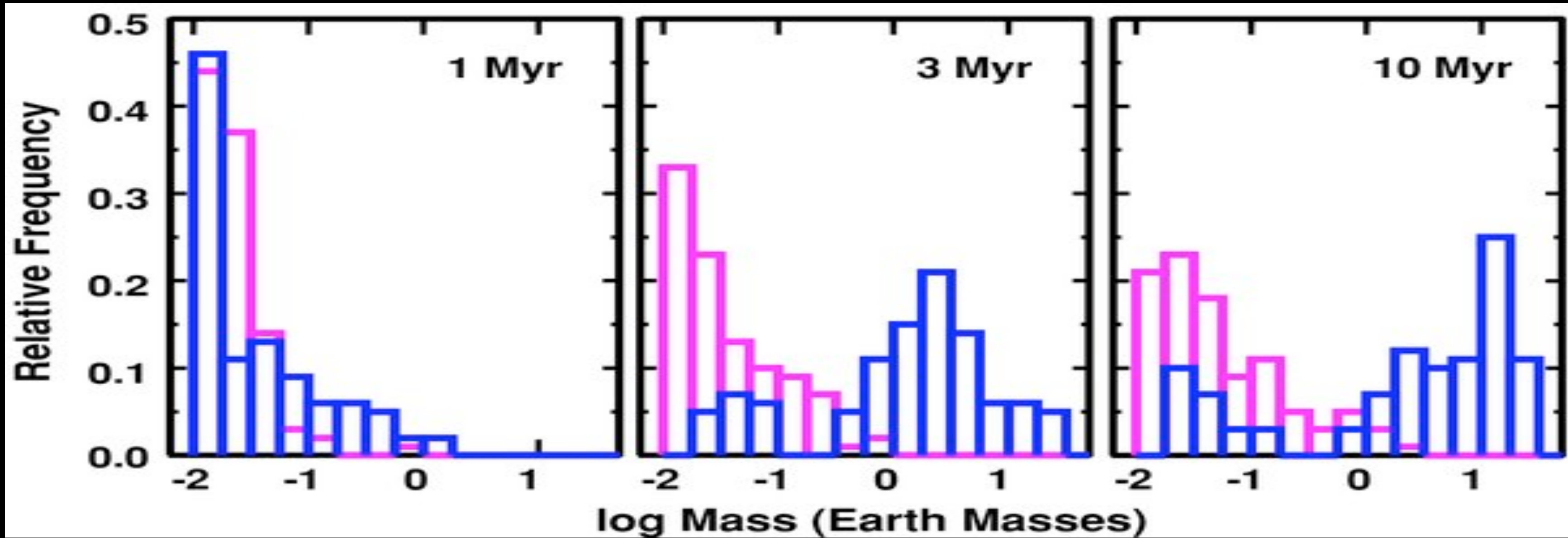
1b. Protoplanetary Disk Evolution



Timescale for gas giant planet formation:
MS A stars: 2.5 Myr or less; Solar/subsolar-mass stars: 5 Myr or less

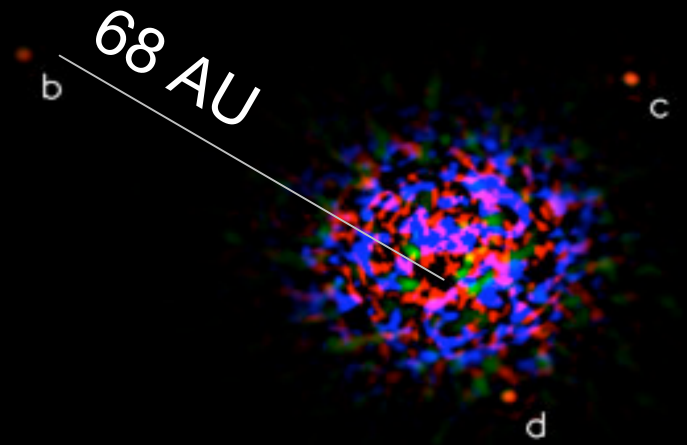
Less time for A stars, yet planets around A stars are frequent (e.g. Johnson et al. 2007) → formation must be very efficient

1c. Gas Giant Planet Formation



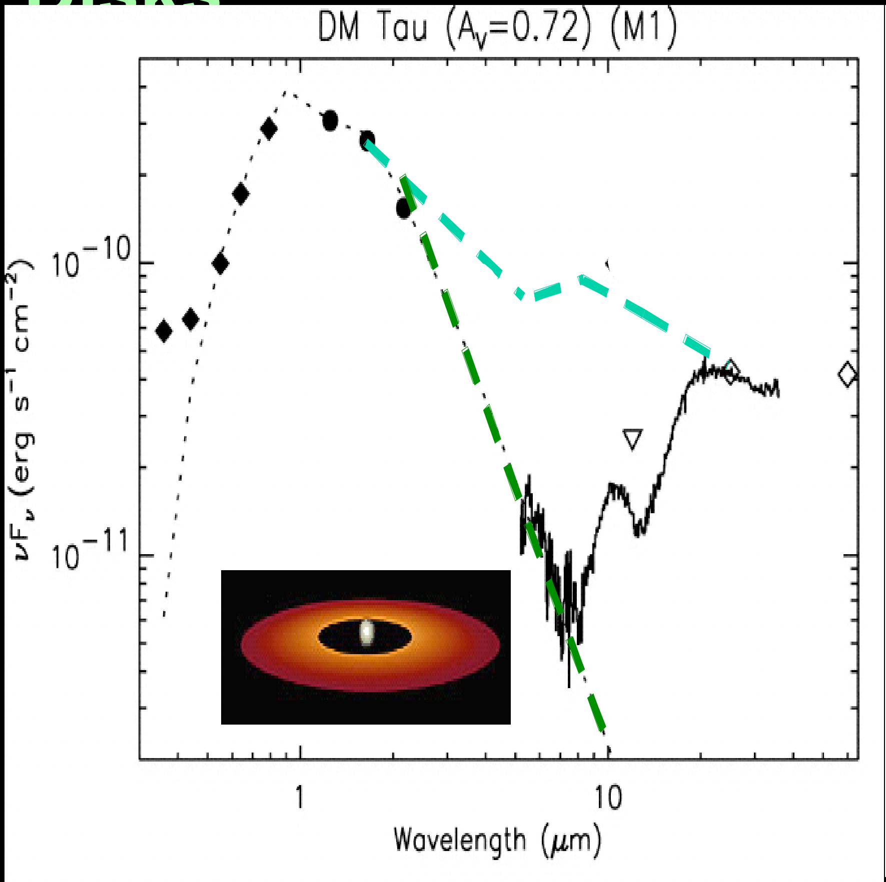
Rapid, successful core accretion: Jovian planets forming at ~5 AU by ~3 Myr (Kenyon and Bromley 2009). Need tiny (< 10--100 m) planetesimals and gas→ lots of slow-moving fragments

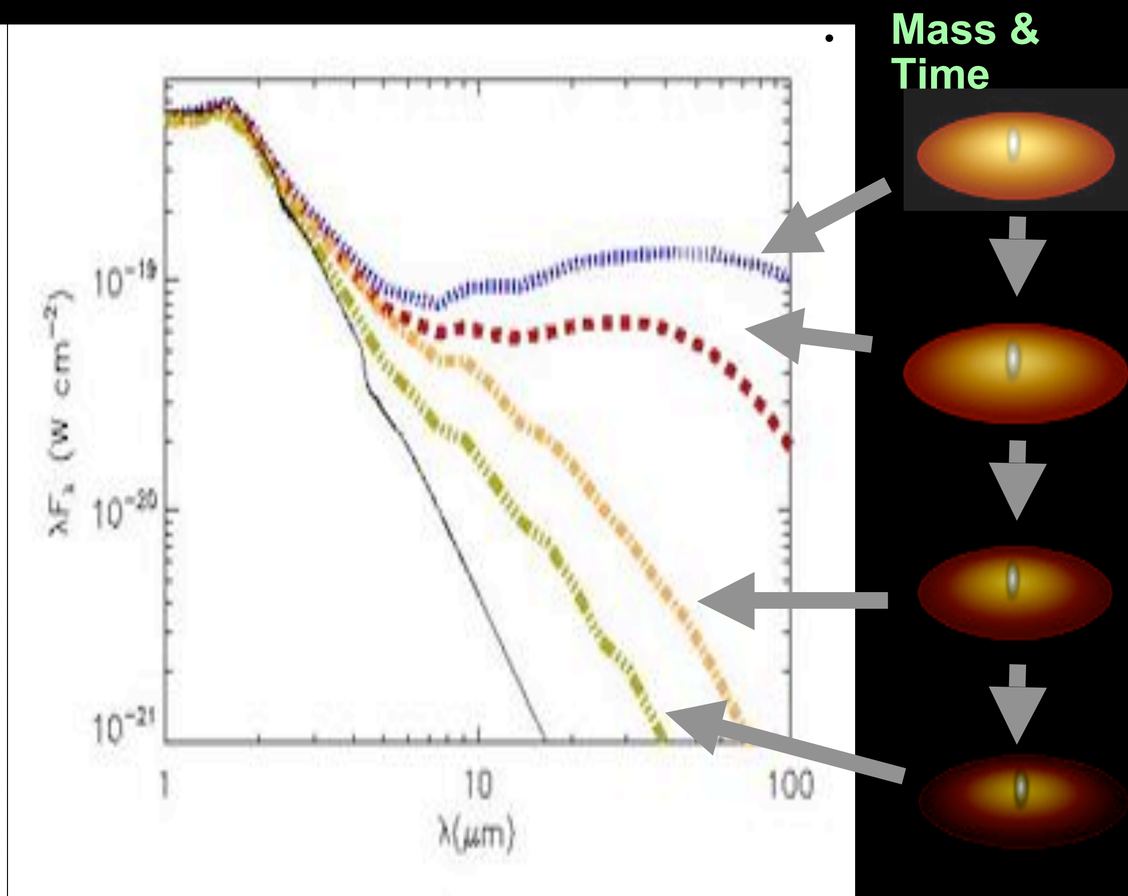
2.5 Myr ?



Can HR 8799 bcd and Fomalhaut b form by core accretion? Very difficult!

2a. The Lifetimes and Morphologies of Transition Disks



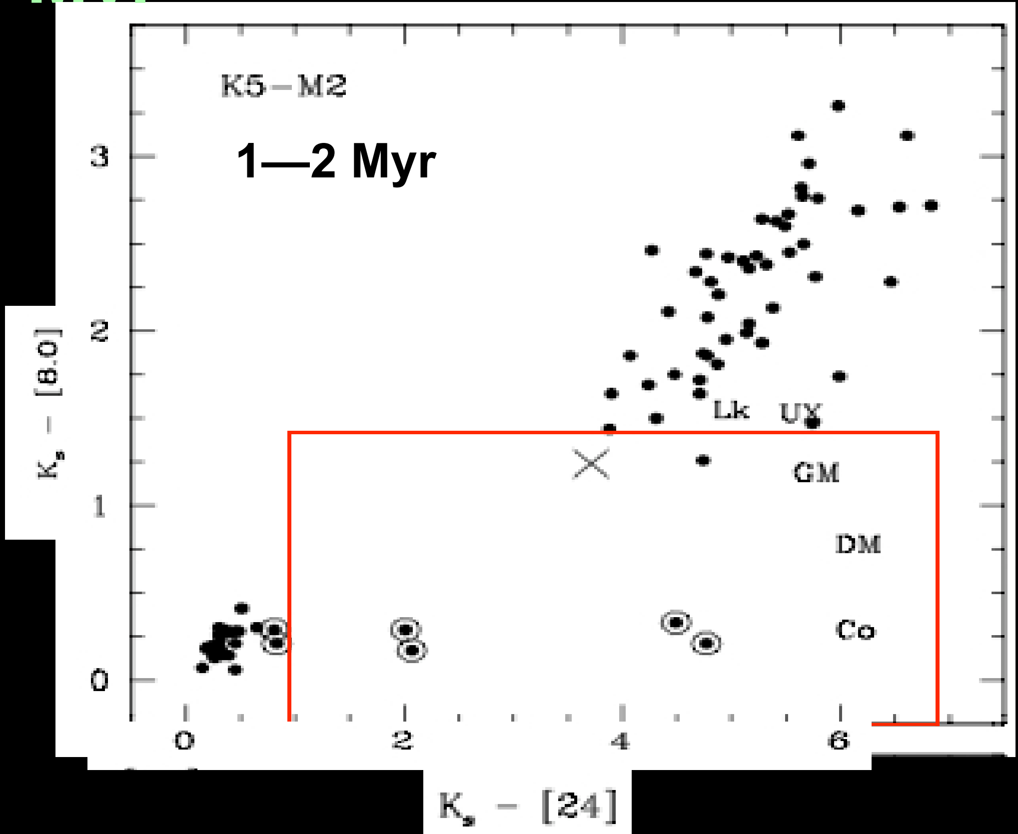


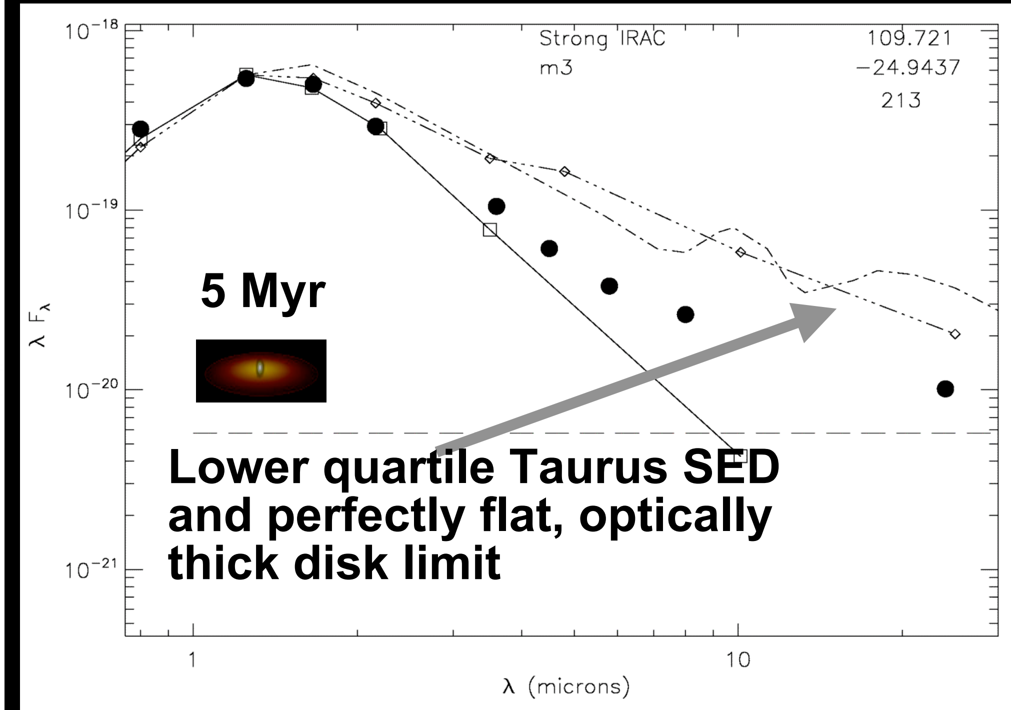
Transition disks = disk with inner regions depleted of dust (and gas?)

Based on Taurus data, transition timescale is ~

Another path: disks that are depleted more "homologously"

2b. Relative Fraction of Transitional Disks at 1 and 5 Myr



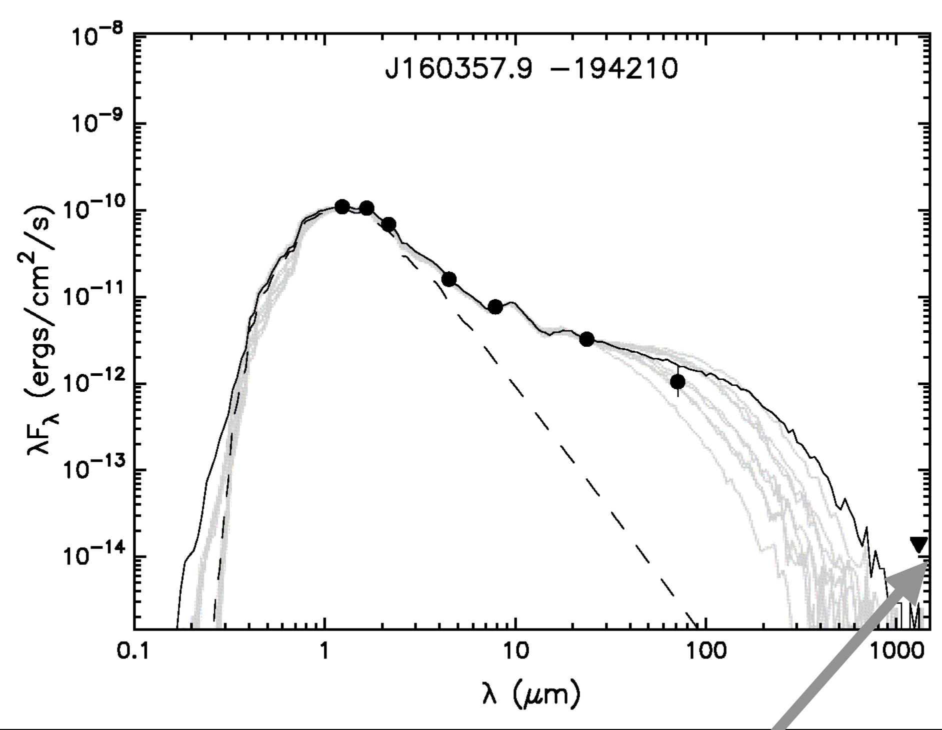


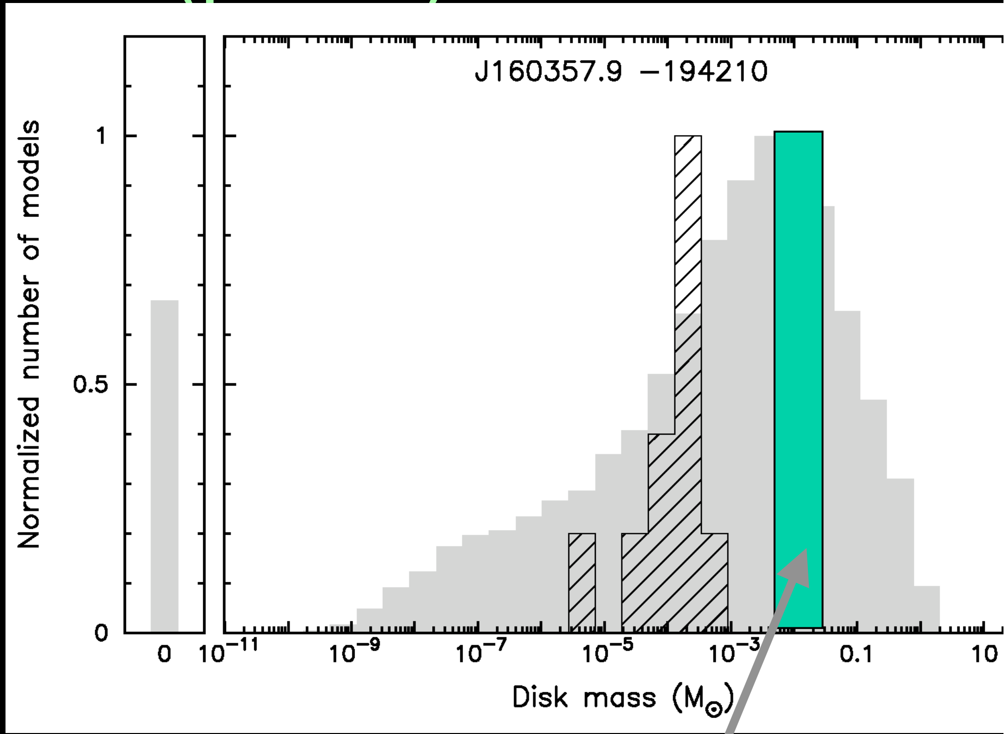
For Taurus, about 5—15% of disks are transitional
→ very short transition timescale (0.1 Myr)?

NO : In NGC 2362, 1) two types of transitional disks (many are 'homologously depleted': have lost substantial dust mass), 2) > 50% of disks are transitional

Currie & Lada et al. 2009

Why 'Homologously Depleted' Disks are bona fide transitional disks, not just flat Taurus-like (primordial) disks (part 2)



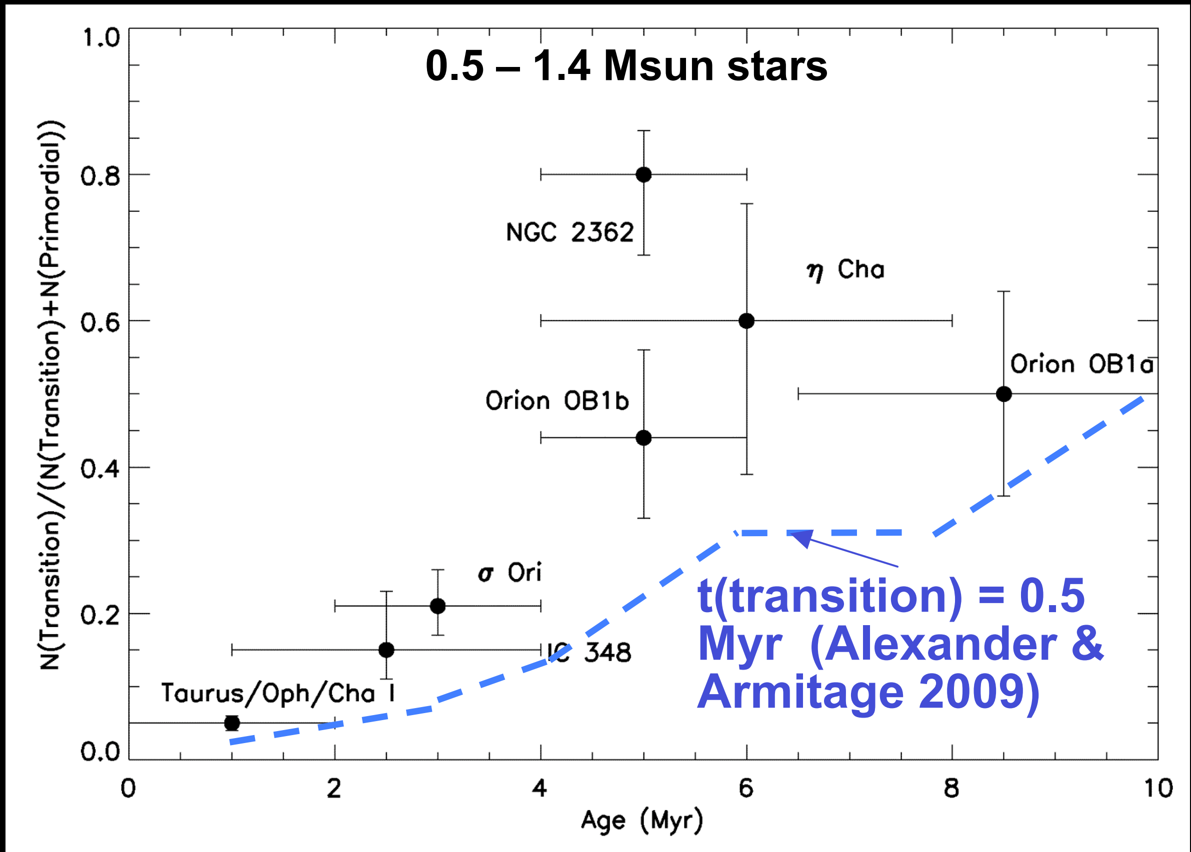


Mdisk (submm) < 1 M_jupiter:

<10x less massive than some transition disks in Taurus (e.g. Najita et al. 2007)

Best-fit Mdisk from Robitaille models ~ 0.1 M_jupiter (Currie et al. 2010b)

2c. Relative Fraction of Transition Disks Increases with Age



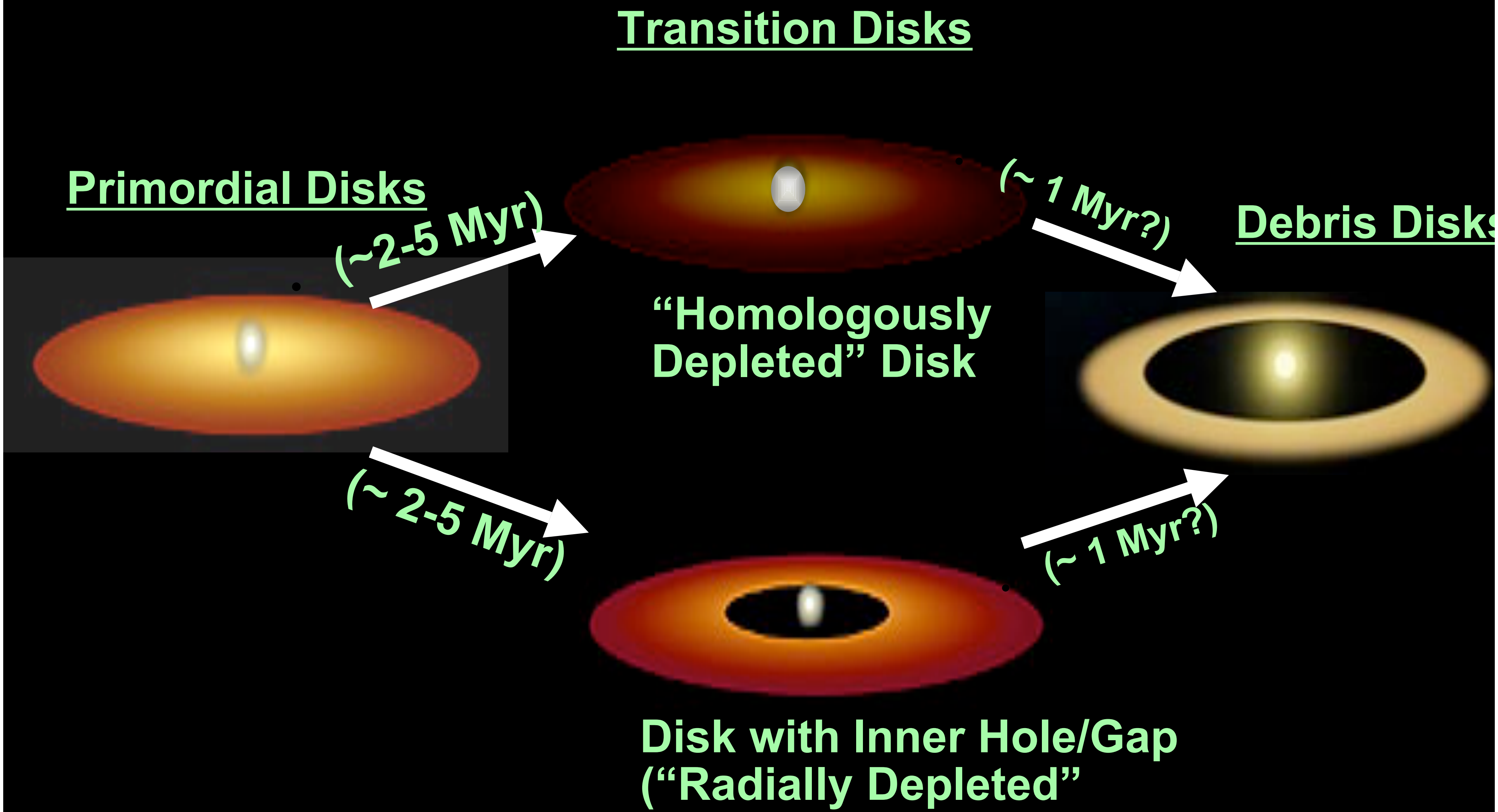
Frequency vs. time not consistent with rapid (0.01—0.1 Myr) dispersal timescale: ~1 Myr more plausible

Protoplanetary disks "die a slow death"

Not consistent with "UV Switch" Model (rapid photoevaporation; Clarke et al. 2001)

Not consistent with gap-opening planets with high disk viscosity?
But photoevaporation in general not "ruled out": (e.g. Gorti et al. 2009; Alexander & Armitage 2009, etc.) and *does* occur (e.g. Pascucci and Sterzik 2009)

2d. Disk Evolution (New)

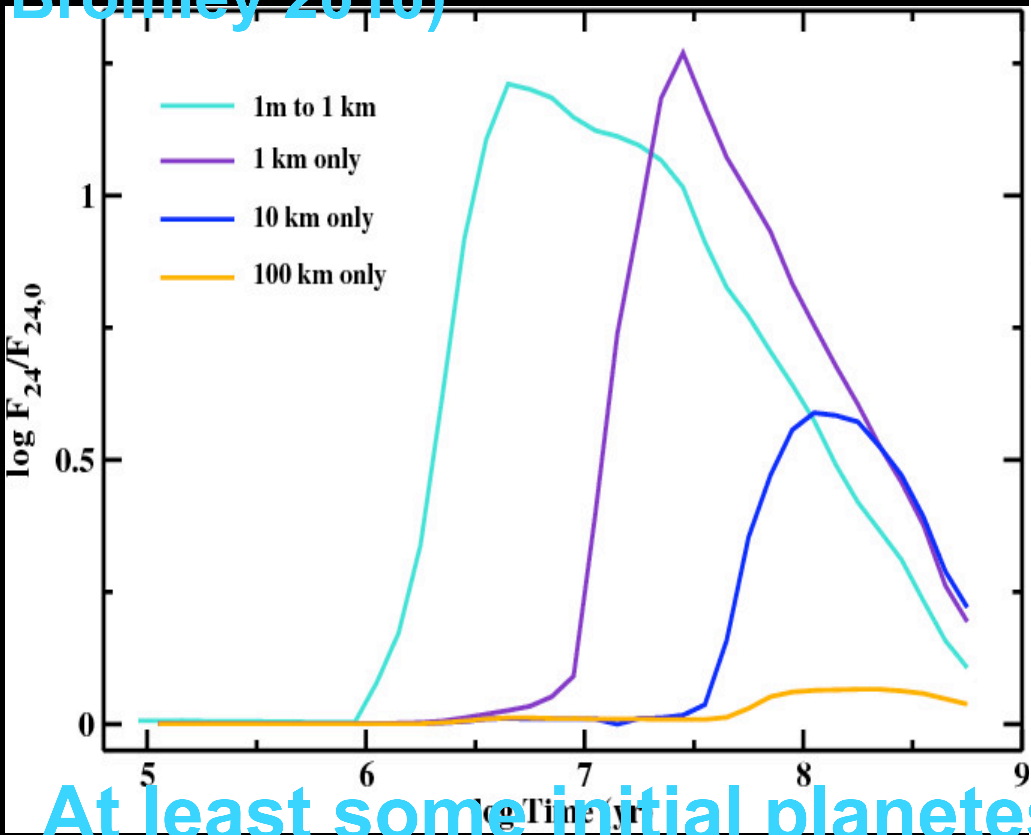


Currie & Lada et al. 2009, ApJ, 698, 1 (see

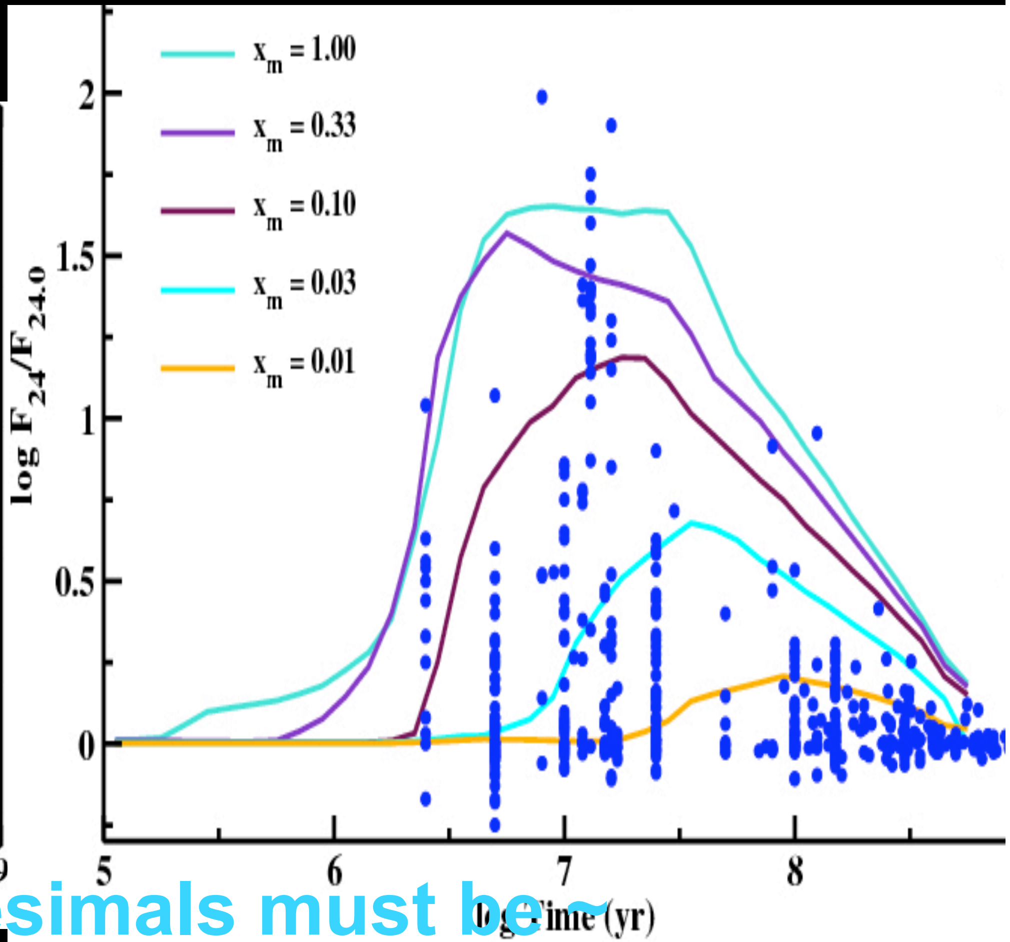
Debris Disk Evolution: Debris Luminosity vs. Planetesimal Size

Planetesimals large → explains asteroid belt? (Morbidelli et al. 2009)

Different Planetesimal Sizes vs. debris emission (Kenyon & Bromley 2010)



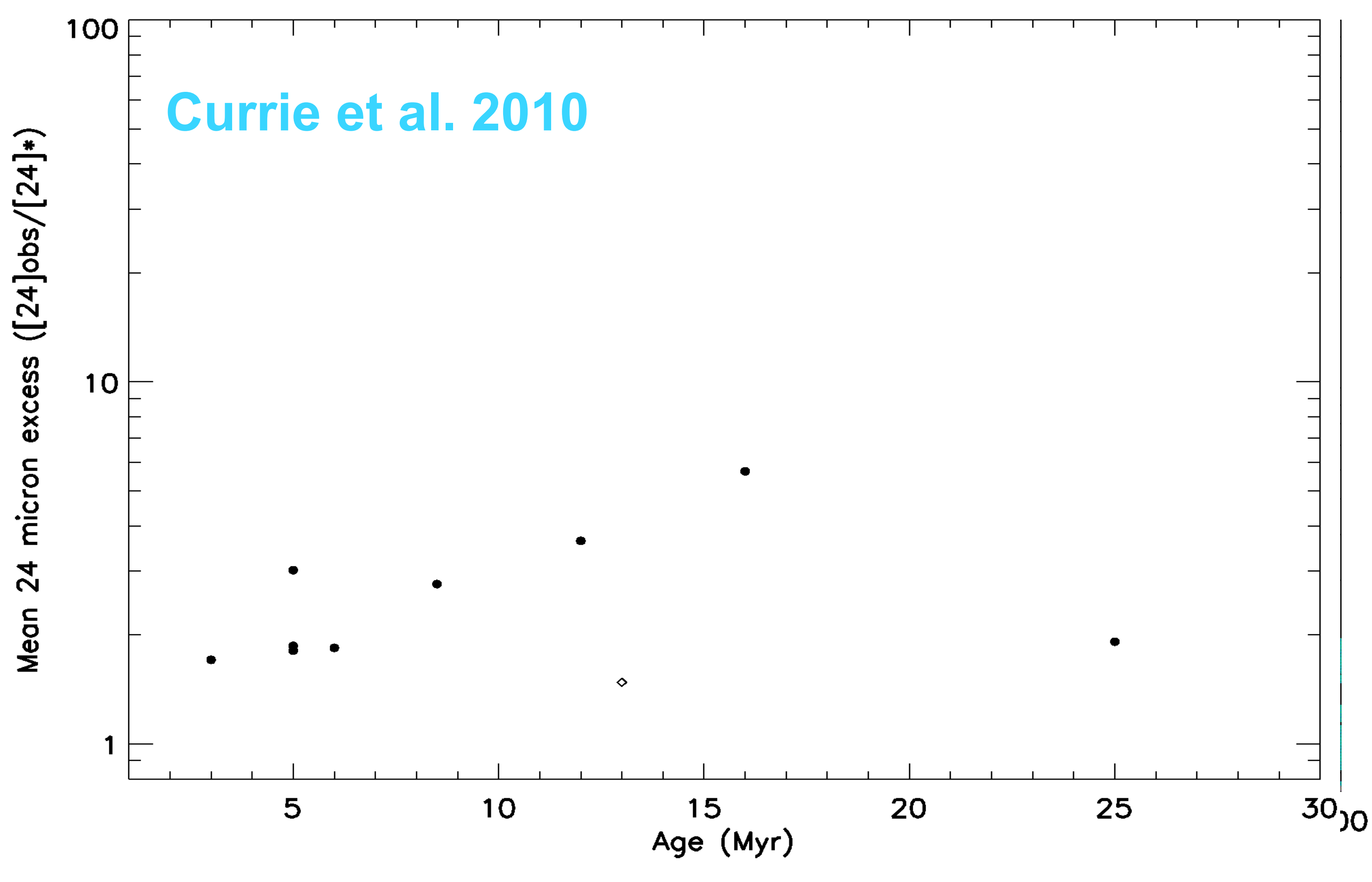
Observations of MS A stars (Currie et al. 2008)



At least some initial planetesimals must be ~ 1m—1km

Peak emission at 10—15 Myr? New data suggests

Evolution of 24 micron debris emission (Main Sequence A Stars)



Peak in debris emission at ~10-15 Myr

Due to growth of ~1000 km objects & viscous stirring?
(Kenyon and Bromley 2008; 2010)

Summary

Gas giant planet formation: < 2.5 Myr for A stars; < 5 Myr for solar-type stars. Possible if accreted planetesimals are small

Transition Disks: two morphologies, t(transition) ~ 1 Myr: requires slow-acting mechanism

Debris disk studies → At least many planetesimals must be small (1m – 1km)

Evolution of debris emission may trace stages in planet formation

Data

Cluster	***Age (Myr)***	***# of Stars***	***Work***
NGC 1333	1	137	Gutermuth et al. 2008
Taurus	~1--2	100-300	Luhman et al. 2009, Furlan et al. 2009
IC 348	2.5	307	Currie & Kenyon 2009; Lada et al. 2006
NGC 2264	3	471	Teixeira et al. 2010
Sigma Ori	3	336	Hernandez et al. 2007
Upper Scorpius	5	220	Carpenter et al. 2006, 2009
NGC 2362	5	337--1,500	Currie & Lada et al. 2009
η Cha	6—8	14	Sicilia-Aguilar et al. 2009
25 Ori	8.5	~225	Hernandez et al. 2006, 2007
h & χ Persei	14	**14,160**	Currie et al. 2010
Global Analysis	1-50	**20,000**	Currie et al. 2010