Initial Conditions for Planet Formation: Disk Observations

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Outline for Talk

- Brief Exoplanetary System Demographics Overview
- Observational Stages of Star and Planet Formation
- Observations of Disk Frequencies and Lifetimes
- Basic Interpretation of Disk Observations
- Distribution of Disk Properties in Different Regions
- Disk Properties as a Function of Object Mass and Class
- Observations of Disks in Binary Systems

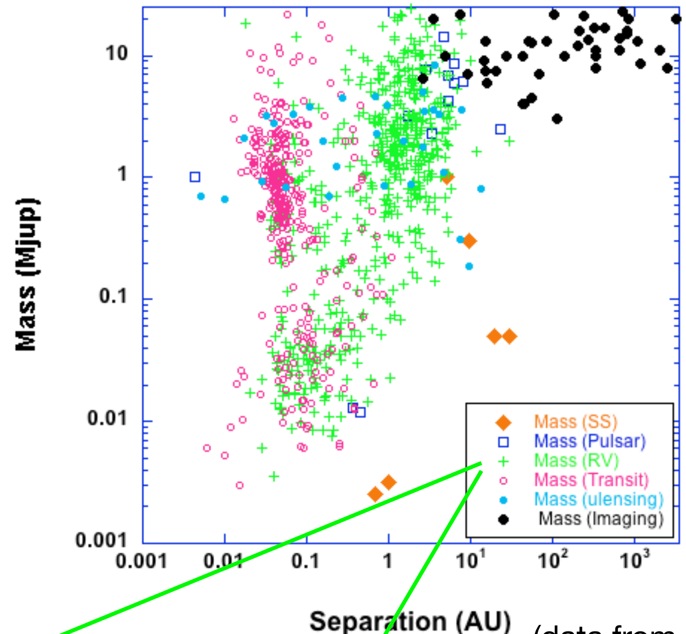
Brief Exoplanetary System Demographics Overview

Observational Demographics of Exoplanetary Systems

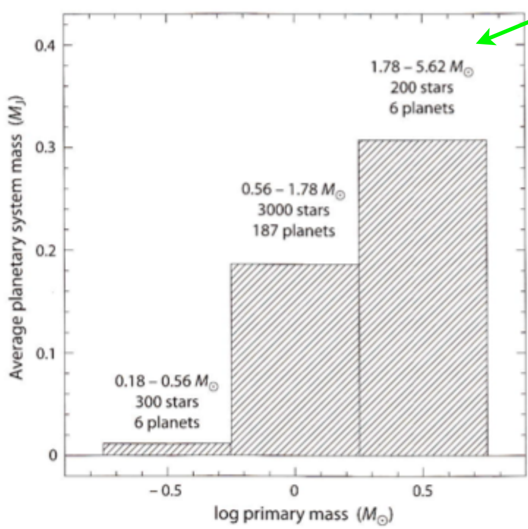
- **Exoplanets discovered with many techniques**
  - Different observational biases
  - Observational trends from single technique sample

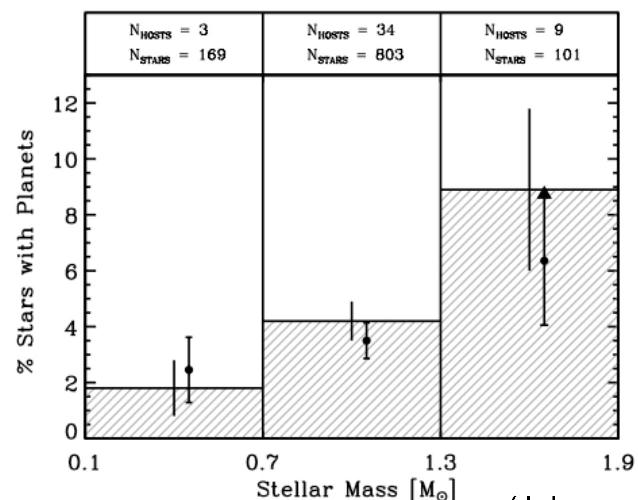
- **Exoplanets properties as a function of star mass**
  - Derived from large-scale RV programs
  - Higher planet % with host star mass
  - Higher planet mass with host star mass

- **Search for origins in disk population studies**



(data from exoplanet.eu)





(Johnson et al. 2010, 2011)

Observational Demographics of Exoplanetary Systems

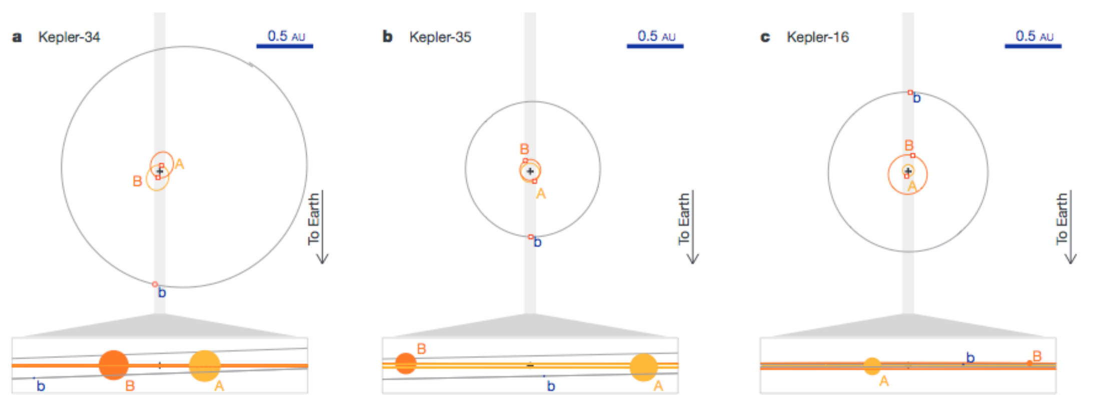
- **Exoplanets detected in binaries**
  - Exoplanets in binaries with a range of separations
  - Binary planet % similar to single star planet %
  - Circumbinary systems identified with *Kepler*
- **Important to investigate disks in binary systems**

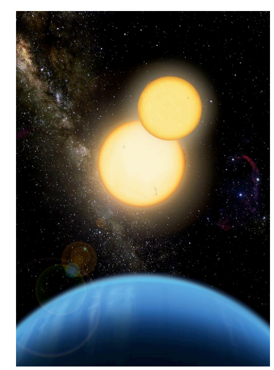
a_{crit}	N_{star}	$N_{planets}$	$\frac{N_{planets}}{N_{stars}}$
<20 AU	21	2	0.095 ± 0.088
>20 AU	23	2	0.087 ± 0.079
VLUD Singles sub-sample	85	8	0.094 ± 0.043
Entire VLUD binary sub-sample	44	4	0.091 ± 0.059

(Bonavita & Desidera 2007)

Example very wide binary planet host star

(16 Cyg A & B)

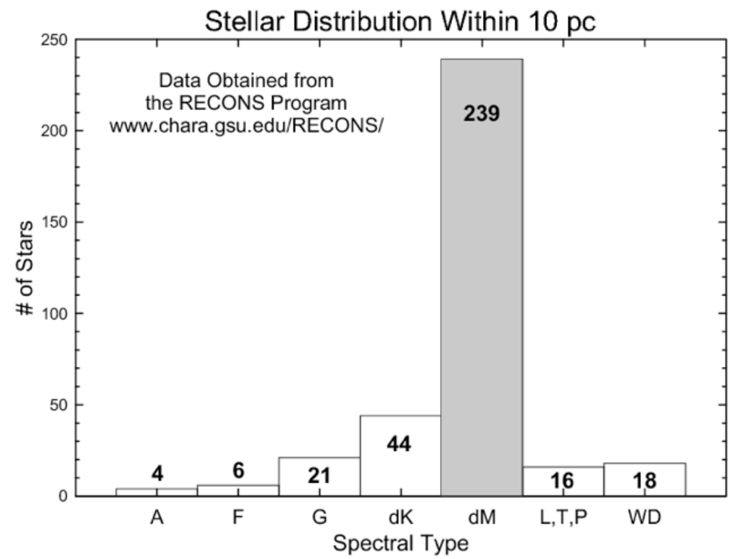


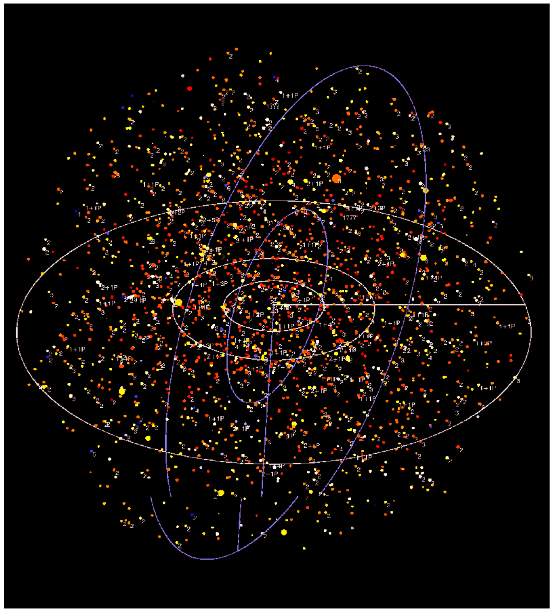


(Welsh et al. 2012)

Stellar Demographics and Upcoming Exoplanet Mission

- **Stellar mass function**
    - Majority of stars low mass stars
        - Both in nearby field and SFRs
    - TESS mission will observe large # of M-stars
        - Population survey for close-orbit planets
        - Search Habitable Zone of M-stars
- **Need to extend disk observations to low mass stars**

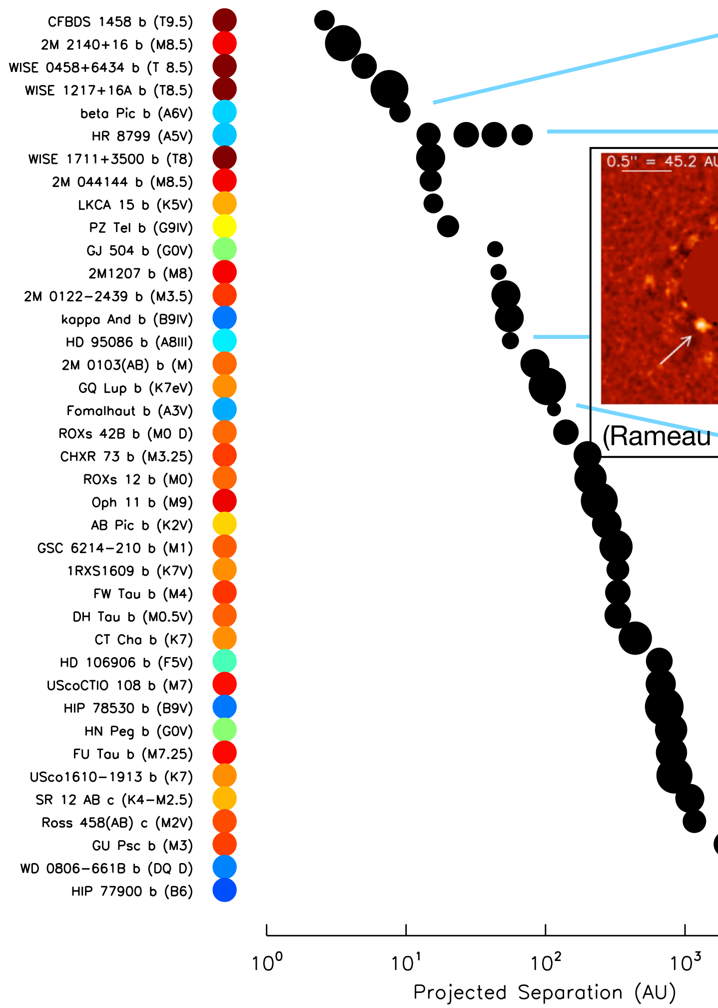


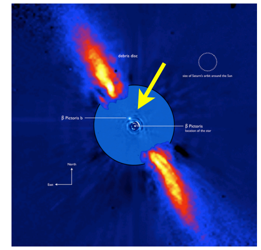


(Reidel & RECONS)

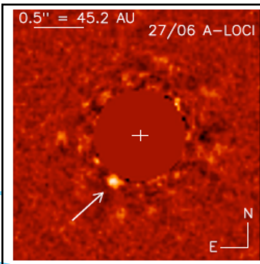
Overview of the Imaged Exoplanet Population

- **Host stars range from massive B-stars to brown dwarfs**
- **Separations range from ~3 – 3000 AU**
- **Sample biased toward younger stars – systems with disks**

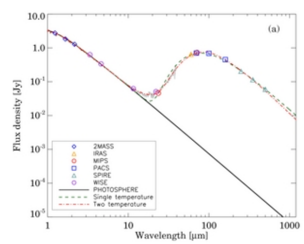




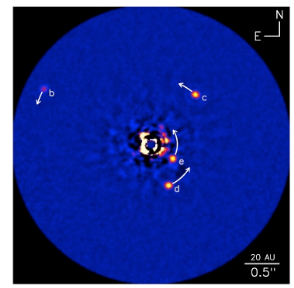
(Lagrange et al. 2009)



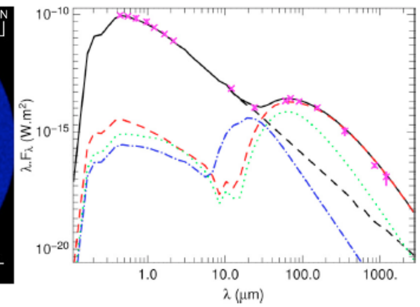
(Rameau et al. 2012)



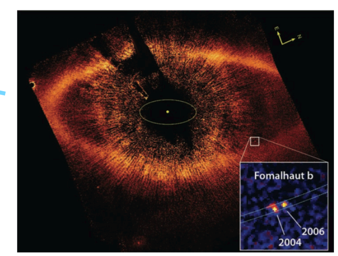
(Moor et al. 2013)



(Marois et al. 2010)



(Patience et al. 2011)



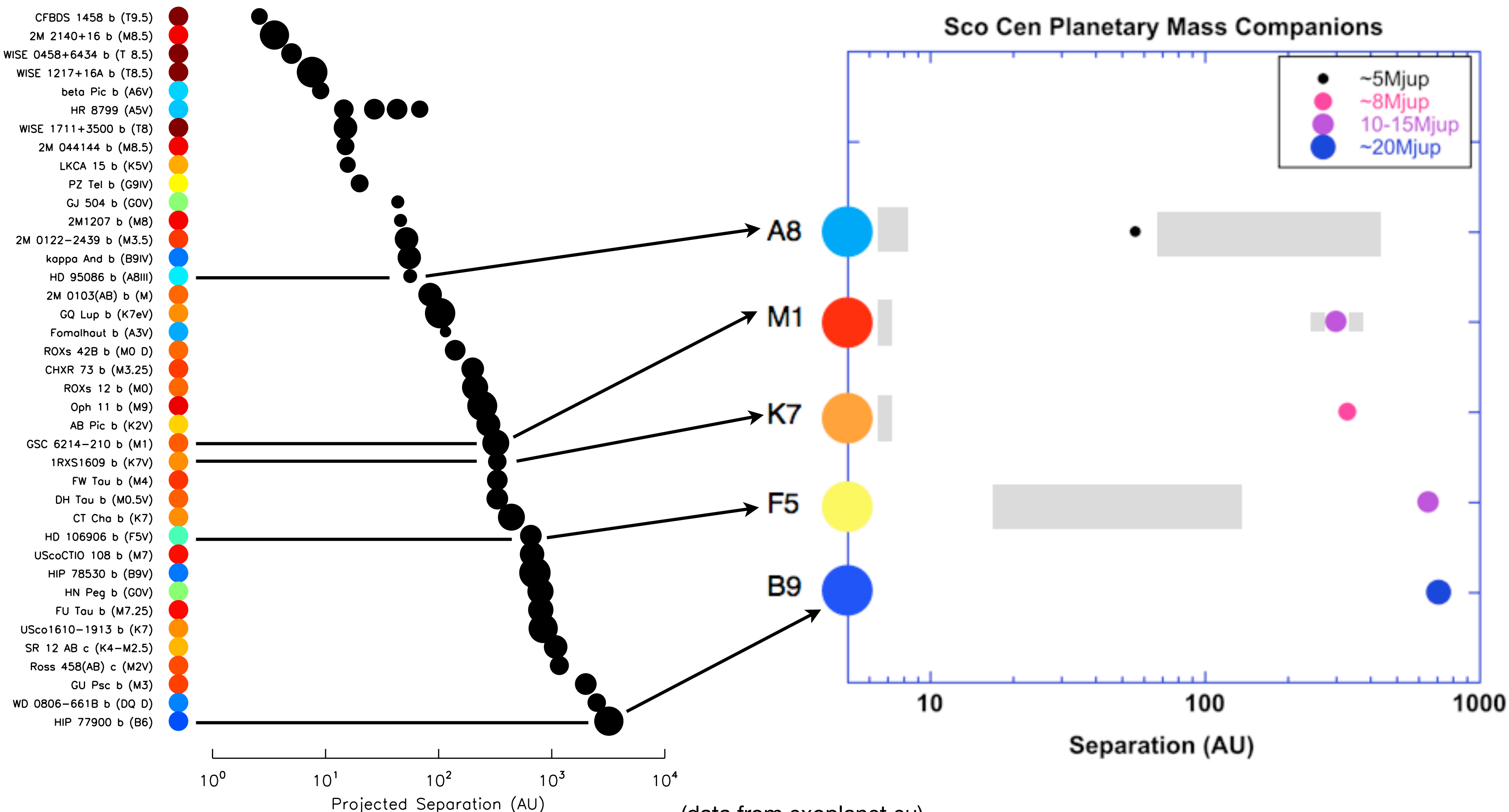
(Kalas et al. 2008)

(data from exoplanet.eu)

Exoplanet and Disk Population in a Young Association

- **Sco Cen young OB Association with 5 imaged planet mass companions**
- **Range of disk properties with planets and disks at a similar age**

Some exoplanets in disk gaps, some have circumplanetary disks

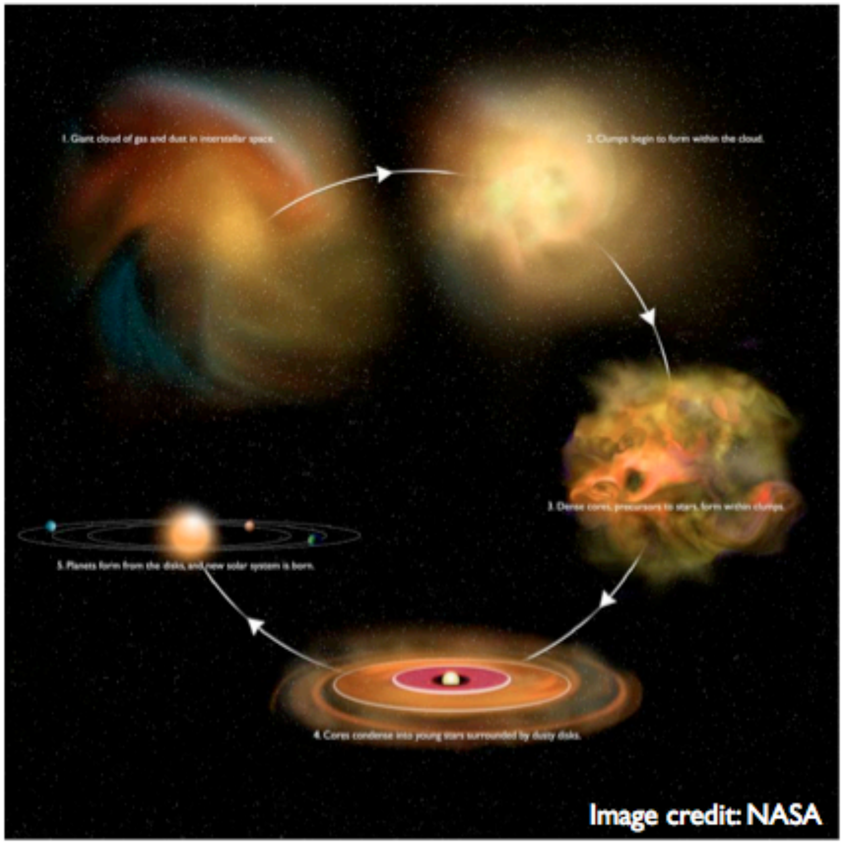


(data from exoplanet.eu)

Observational Stages of Star and Planet Formation

Star and Planet Formation Process

THEORY



1. ISM

↓

2. Molecular clouds

↓

3. Protostellar collapse

↓

4. Young star & disk formation

↓

5. Dust coagulation / planetessimals / planet formation

OBSERVATION

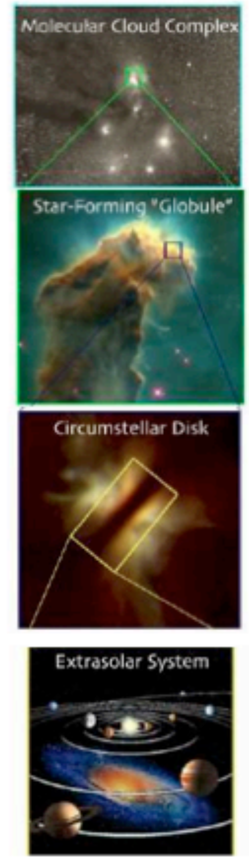
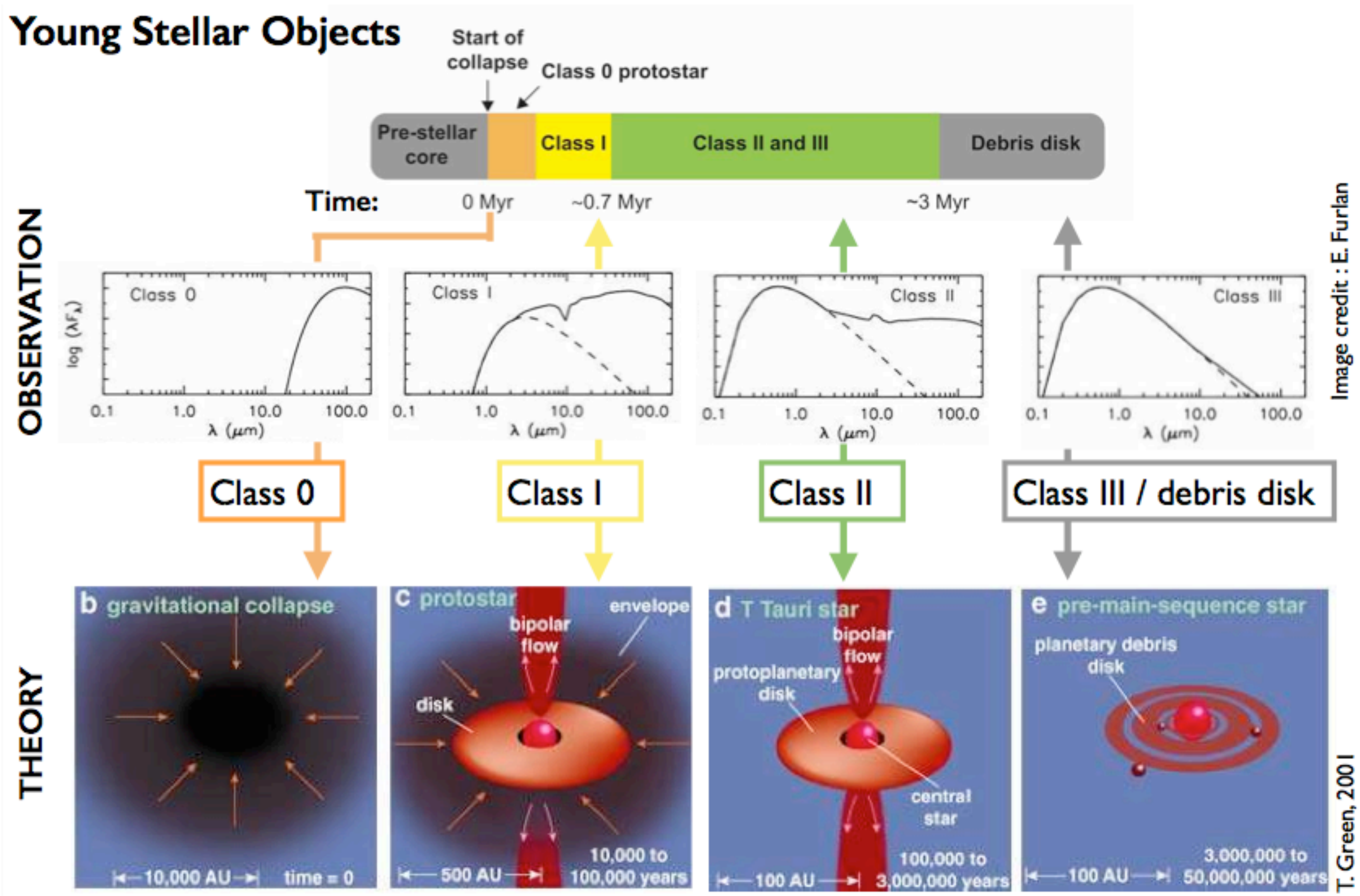


Image credit: A. Goodman

- **Example observations show optical images**

  Multi-wavelength observations probe different regions of the disk

Spectral Energy Distributions of Young Stars



- **Slope of the spectral energy distribution defines the object as Class 0, I, II, III**
- **Focus on Class II stage**

Arizona State University

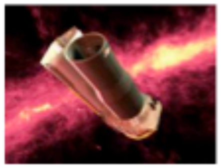
Observations of Disk Frequencies and Lifetimes

Facilities for Disk Observations

Disk emission: observations

λ

- *Spitzer* Space Satellite (2003 -)



  - Infrared Array Camera (IRAC): 4 channels [3.6], [4.5], [5.6], [8.0]
  - Infrared Spectrograph (IRS): low and high res from 5-40 μm
  - Multiband Imaging Photometer (MIPS): 3 channel [24], [70], [160]

- *Herschel* Space Observatory (2009 - 2013)

  - **Photodetector Array Camera and Spectrometer (PACS):** 2 imaging arrays Blue (70 or 100 μm) and Red (160 μm)
  - Spectral and Photometric Imaging REceiver (SPIRE): ~200 - 700 μm
  - Heterodyne Instrument for the Far Infrared (HIFI): ~200 - 600 μm

- Atacama Large Millimeter Array (ALMA)

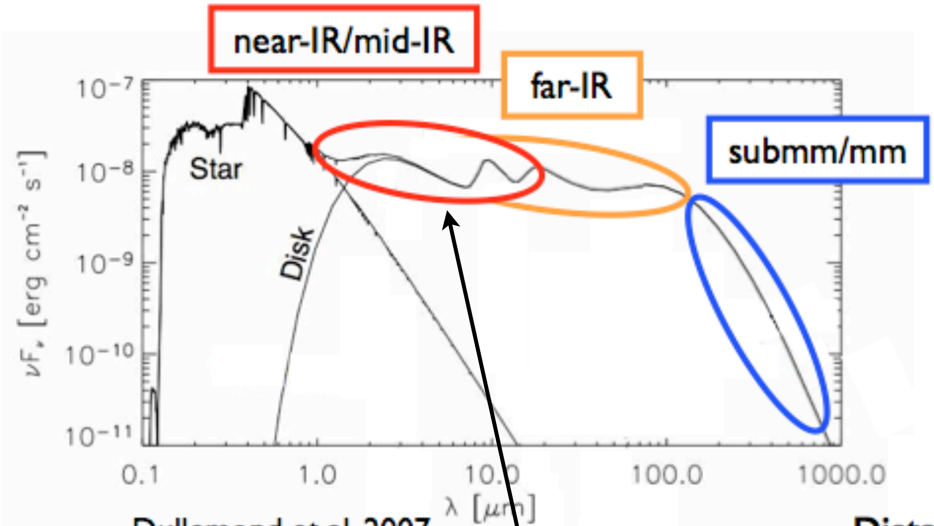
Cycle 1: - 32 antennas; baselines ~100m - 1km;
- Bands 9, 7, 6, 3 (450 μm-3mm)
- Bandwidth: 8 GHz

- **Existing or Planned Large-scale surveys of star-forming regions**

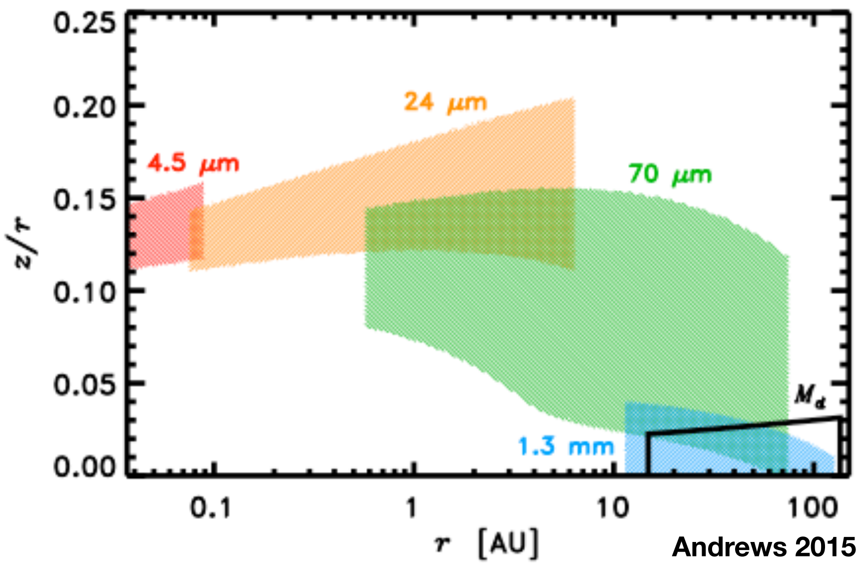
Also 2MASS, WISE, Northern submm single dish + interferometers

Example Multi-wavelength Disk Observation

Disk emission: observations



Dullemond et al. 2007



Andrews 2015

Distance:	1 AU	10 AU	100 AU
Tdust:	1500 K	150 K	15 K

- **Presence of a disk can be inferred from a subset of wavelengths**

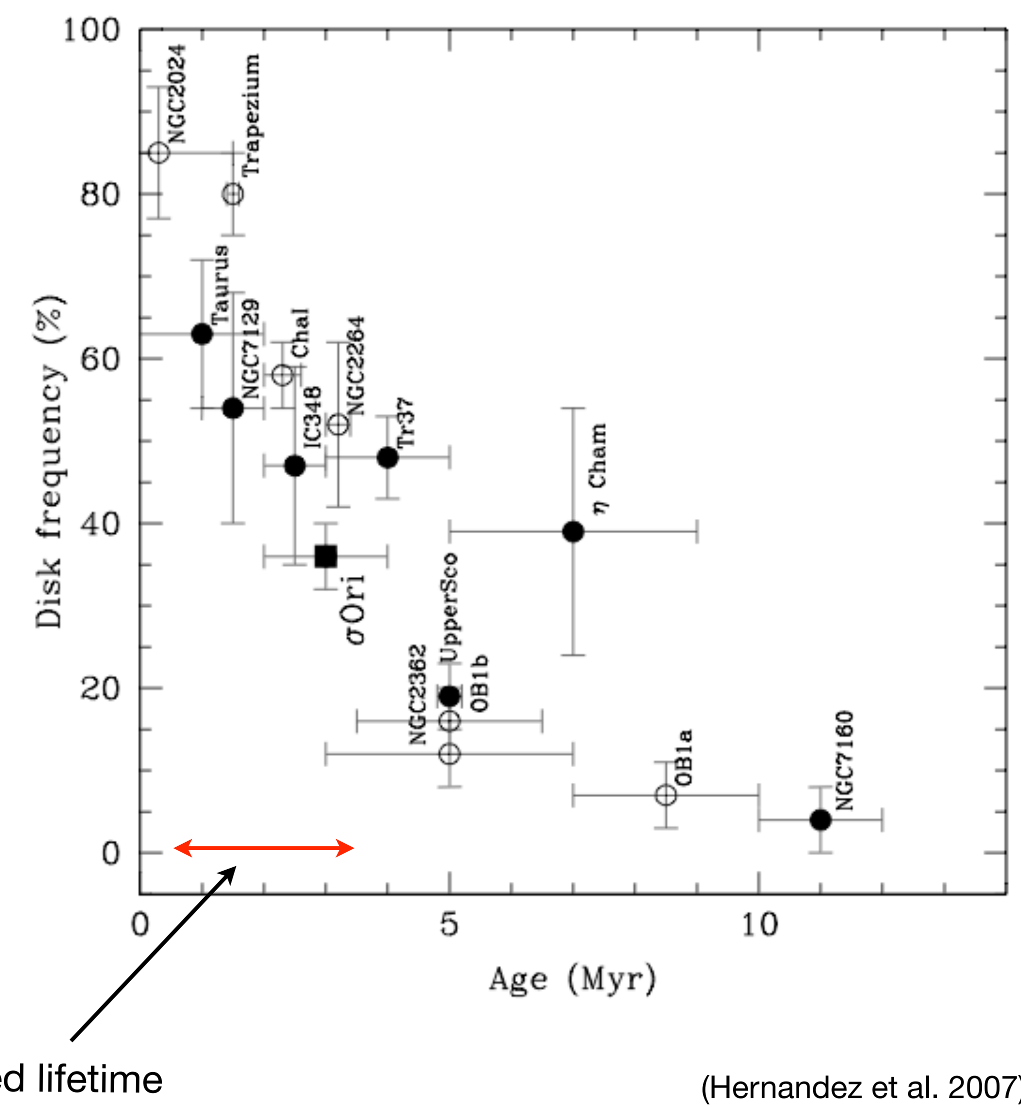
  Surveys with *Spitzer* (e.g. Cores to Disks Legacy) observed many star-forming regions

Disk Lifetimes from Star-forming Region Observations

- **Samples from <1 Myr to ~10 Myr**
  IR excess from Spitzer IRAC
  Dust excess emission

- **Measure disk % vs. time**
  Systematic decline with time
  ~80% at <1 Myr
  ~10% at 5 Myr

- **Disk lifetime only few Myr**
  Limit on planet formation



(Hernandez et al. 2007)

Disk Lifetimes Relate to Planet Formation Scenarios

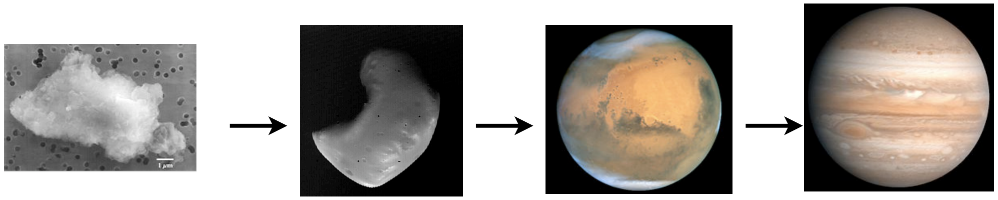
- **Two Main Formation Scenarios**

- **Core Accretion Model**

  (e.g. Bodenheimer & Pollack 1986)

  Timescale to form giant planets increases at farther orbit radius

  More difficult to form wide orbit planets

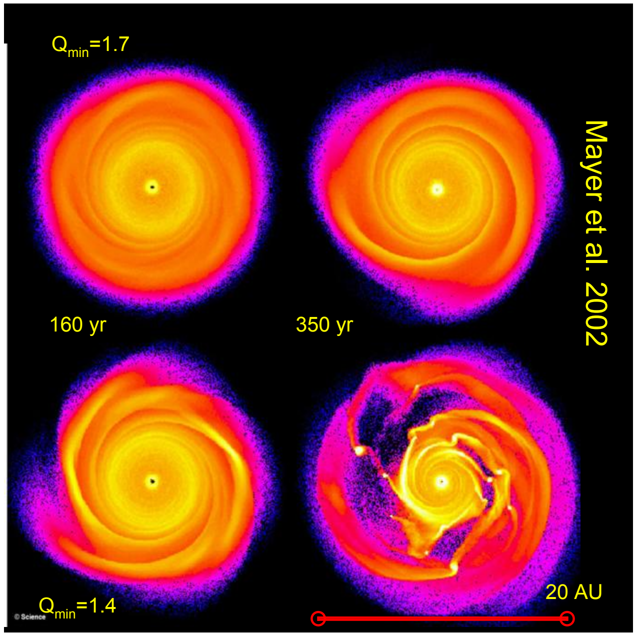


(NASA)

- **Gravitational Instability Model**

  (e.g. Boss 1997)

  Timescale to form giant planets much more rapid



- **Empirical Comparisons from Disk Observations**

  Lifetimes of disks

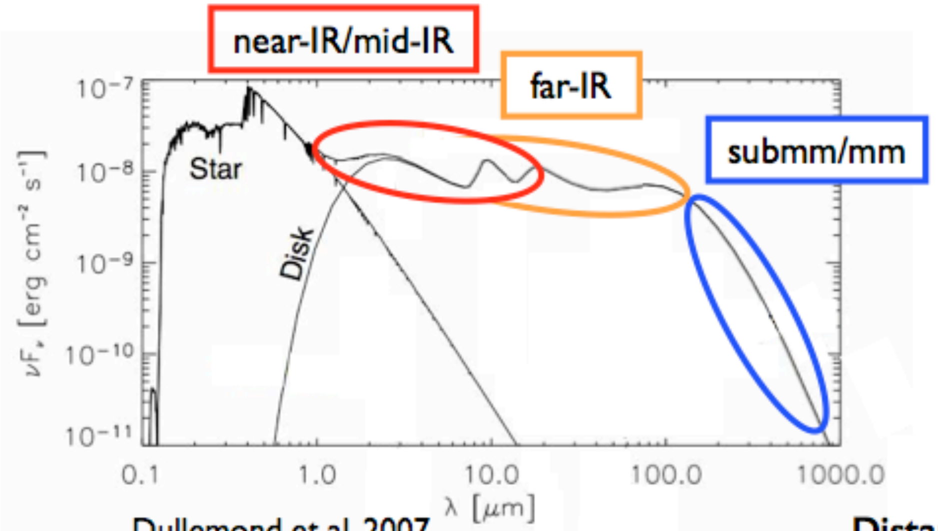
  Masses of disks

  Dependence on environment, object mass, etc

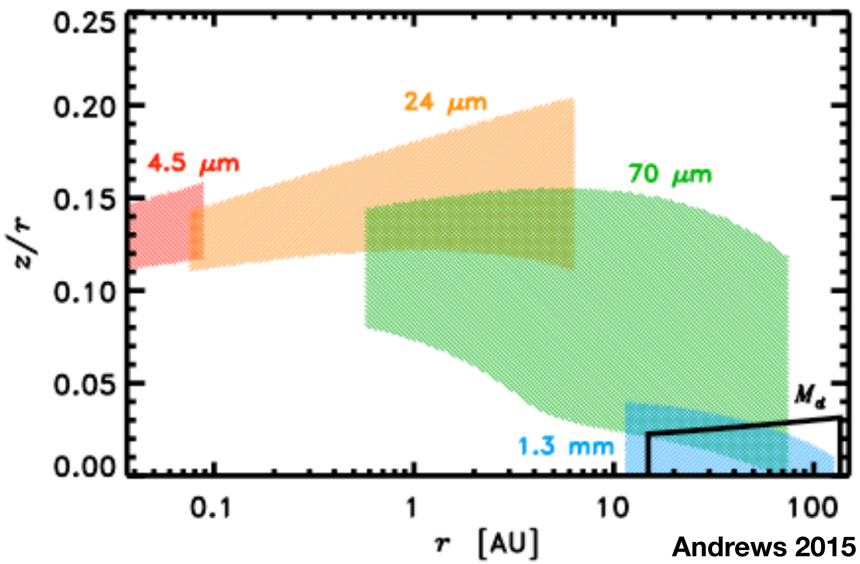
Basic Interpretation of Disk Observations

Disk Observations and Model Fits

Disk emission: observations & models



Dullemond et al. 2007



Andrews 2015

Distance: 1 AU — 10 AU — 100 AU

Tdust: 1500 K — 150 K — 15 K

Model parameters: **MCFOST** example (Pinte)

1. Central object:
   - $T_{eff}, M_\star, R_\star = SpTy$

2. Disk structure:
   - $R_{in} = R_{sub}, \; R_{out}$
   - $h(r) = h_0(\frac{r}{r_0})^\beta$
   - $\Sigma(r) = \Sigma_0(\frac{r}{r_0})^{-p}$

3. Grain properties
   - $dn(a) \propto a^{-3.5} da$
   - a_{min}
   - a_{max}

4. Disk mass
   - M_{disk}

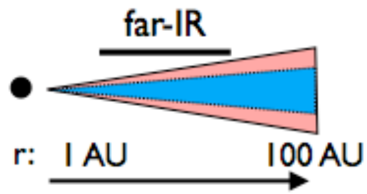
     $100:1 - \text{gas : dust}$

Disk Observations and Model Fits

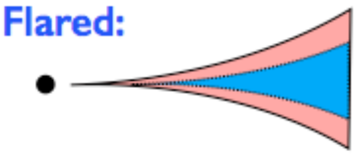
Disk emission: far-IR

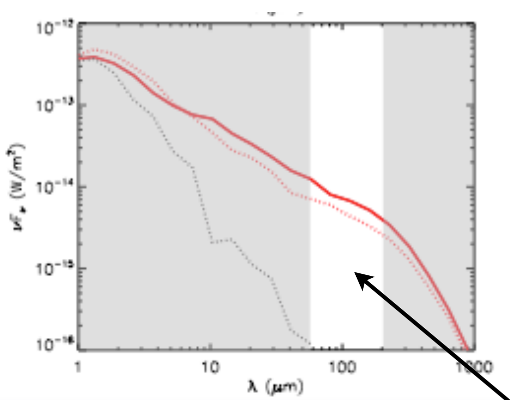
Geometrical factors: • $h(r) = h_0(\frac{r}{r_0})^{\gamma}$ • Disk inclination

Flat:



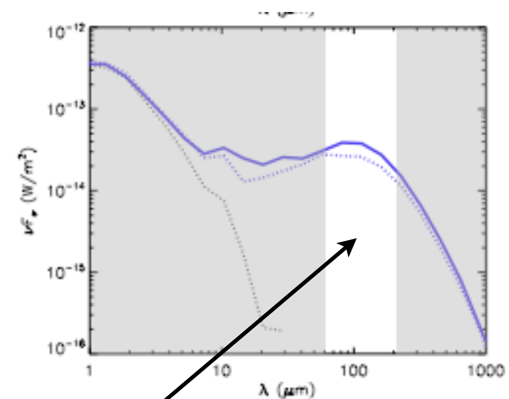
Flared:





γ

~1.0 v.s ~1.3



Far-IR SED shape different with different flaring index

Disk Observations and Model Fits

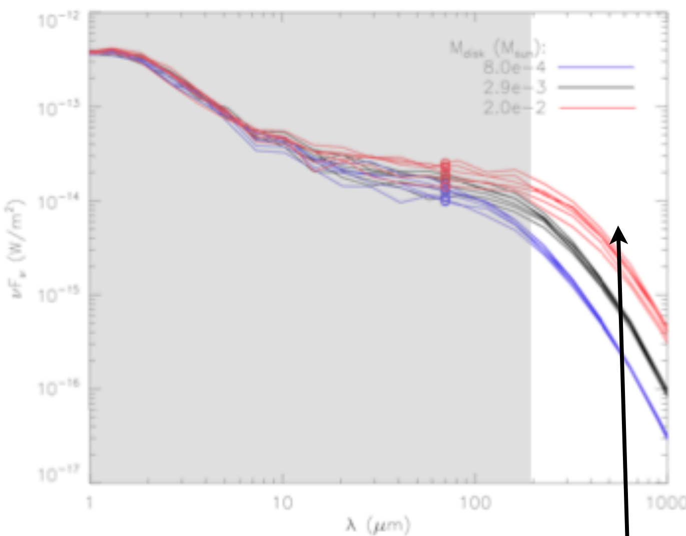
Disk emission: submm

- Rayleigh-Jeans limit ($k_BT >> h\nu$)
- Assume disk emission optically thin

Disk dust mass:

$$M_{dust} \propto \frac{F_\nu}{T_d \kappa_\nu}$$

$$T_d = 20 \text{ K}$$
$$\kappa_{230\text{GHz}} = 2.3 \text{ cm}^2 \text{ g}^{-1}$$



Submm/mm Flux increases with Mass

ARIZONA STATE UNIVERSITY

Disk Observations and Model Fits

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Dust opacity index:

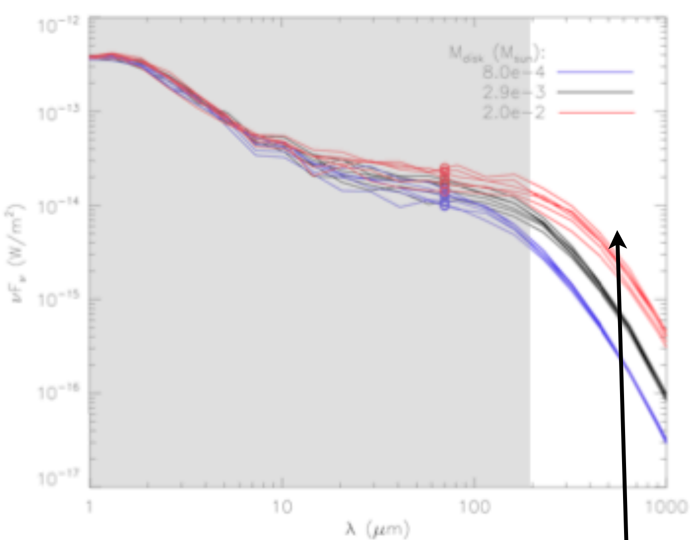
$$\kappa_\nu \propto \nu^{\beta} \longrightarrow a_{max}$$

$$F_\nu \propto \kappa_\nu \nu^2 = \nu^{\alpha_{\text{mm}}}$$

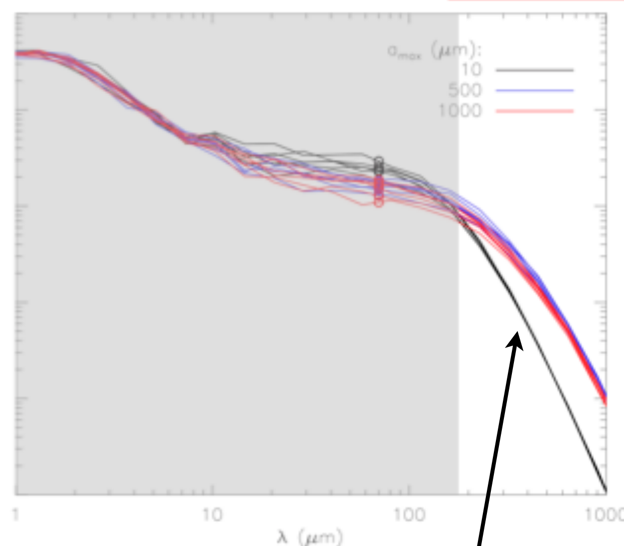
$$\alpha_{\text{mm}} = \beta + 2$$

~4 → ISM grains

~2 → mm grains



Submm/mm Flux increases with Mass

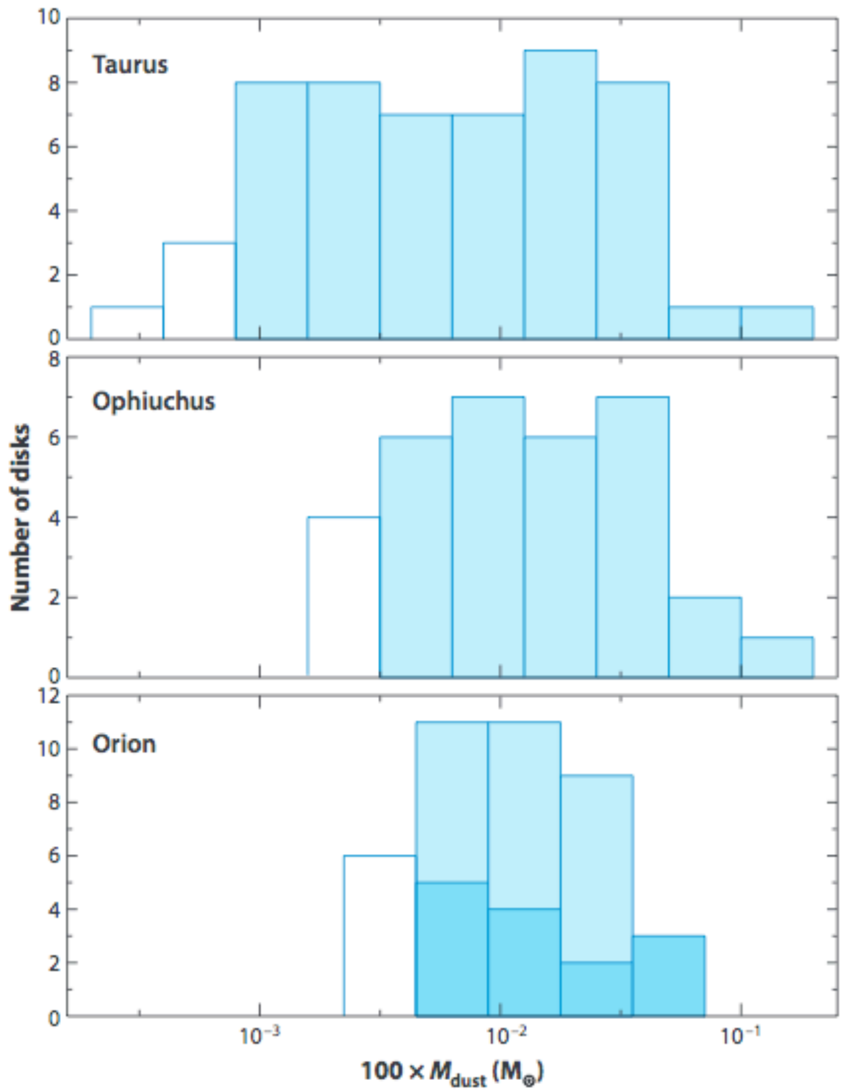


Submm/mm Slope steeper with smaller particles

Distribution of Disk Properties in Different Regions

Distribution of Disk Masses in Several Regions

- **Masses from submm surveys**
    - Sample Clas II members
    - Assume gas:dust ratio
    - Limits on material for planets
    - Spans orders of magnitudes
- **Sensitivity**
    - Varies with target and region
    - Complicates comparison



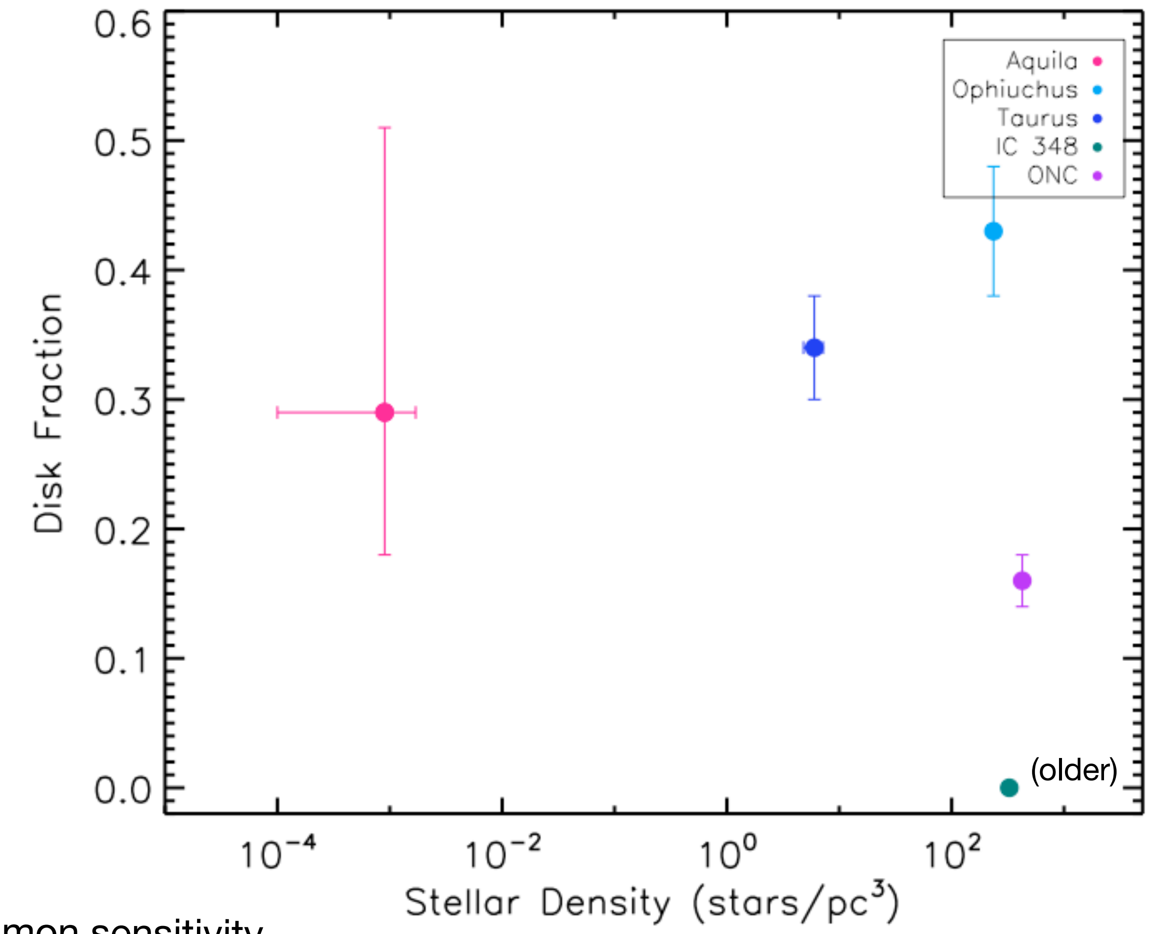
(Compiled in Williams & Cieza 2011)

Disk Fraction in Regions with Different Densities

- **Taurus**

- **Ophiuchus**

- **Orion**



- **Stellar density varies in SFRs**

  Compare disk frequency with common sensitivity

  Require larger samples with ALMA

(Andrews & WIlliams 2005+2007, Eisner & Carpenter 2006, Carpenter 2002, Bulger et al., in prep.)

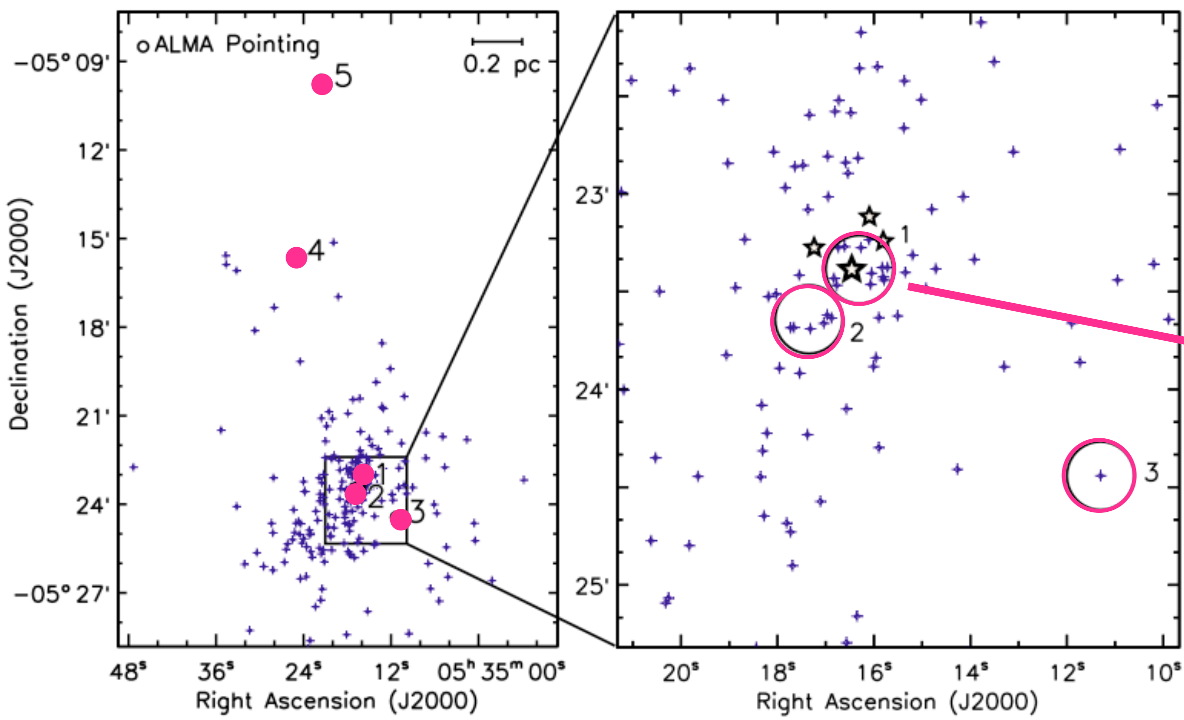
Effect of Stellar Radiation Environment on Disks

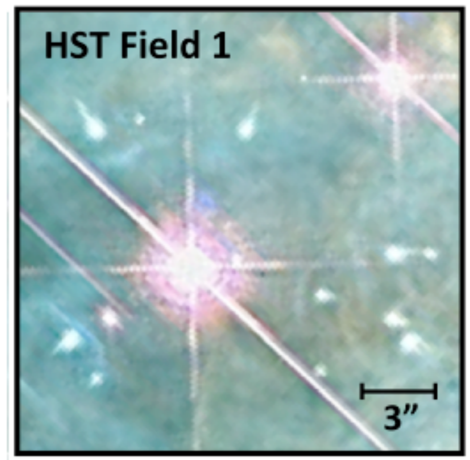
- **Orion Trapezium contains O-stars**

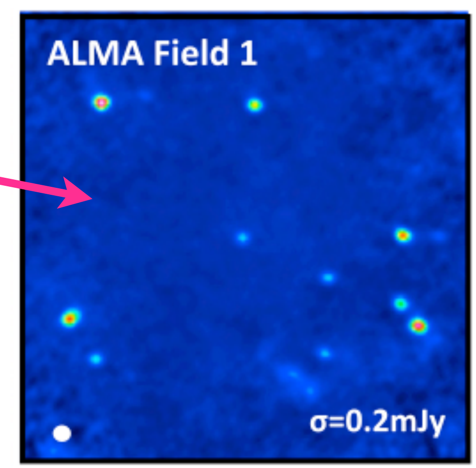
  ALMA study of regions at different distances from theta 1C

  Fields observed to measure disk flux with distance

  Dense cluster contains many sources per field







(Mann et al. 2014)

Effect of Stellar Radiation Environment on Disks

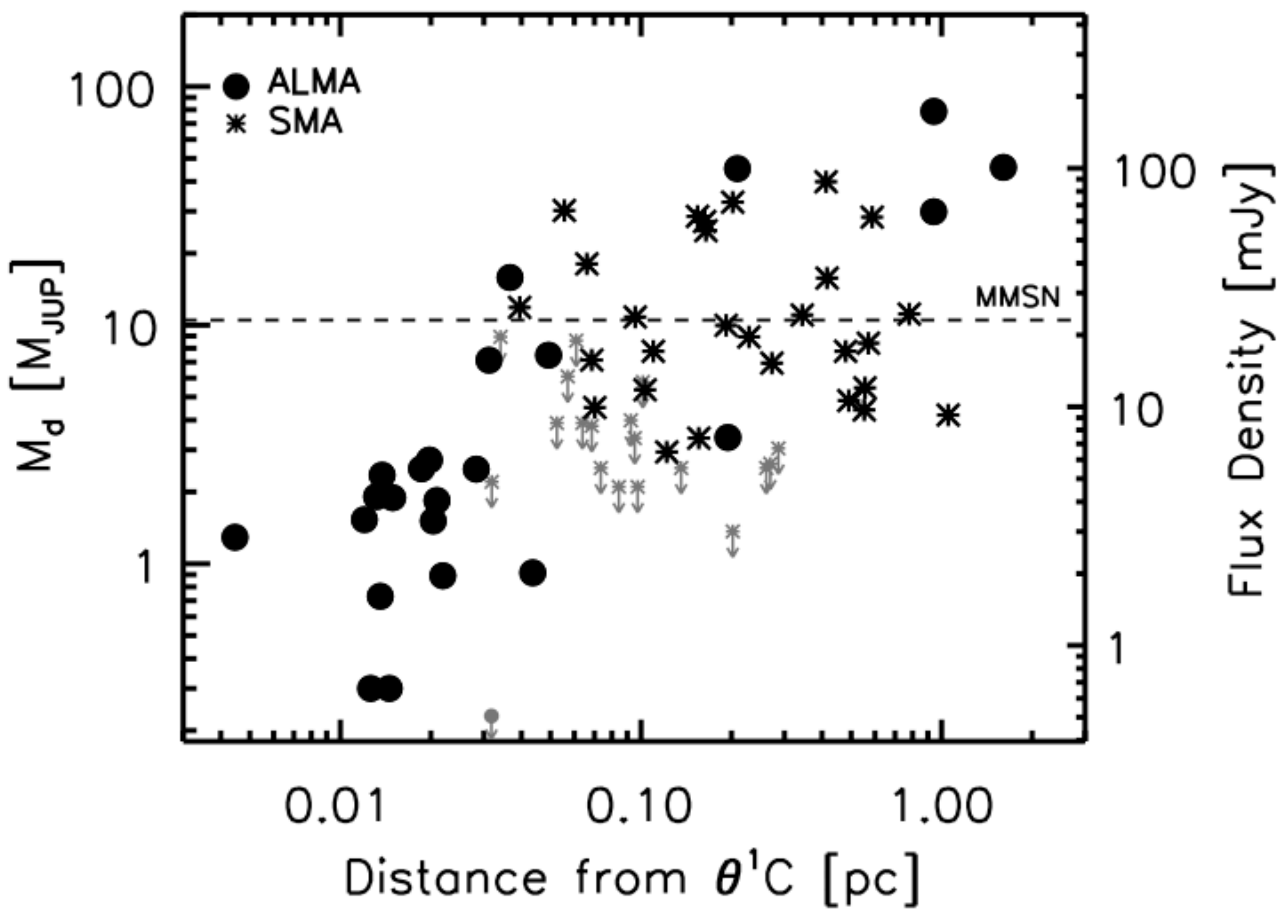
- **Combine ALMA/SMA data**

- **Systematic decline in Flux/Mass**

  Closer disks less massive

  Limited # > MMSN

  MMSN benchmark value

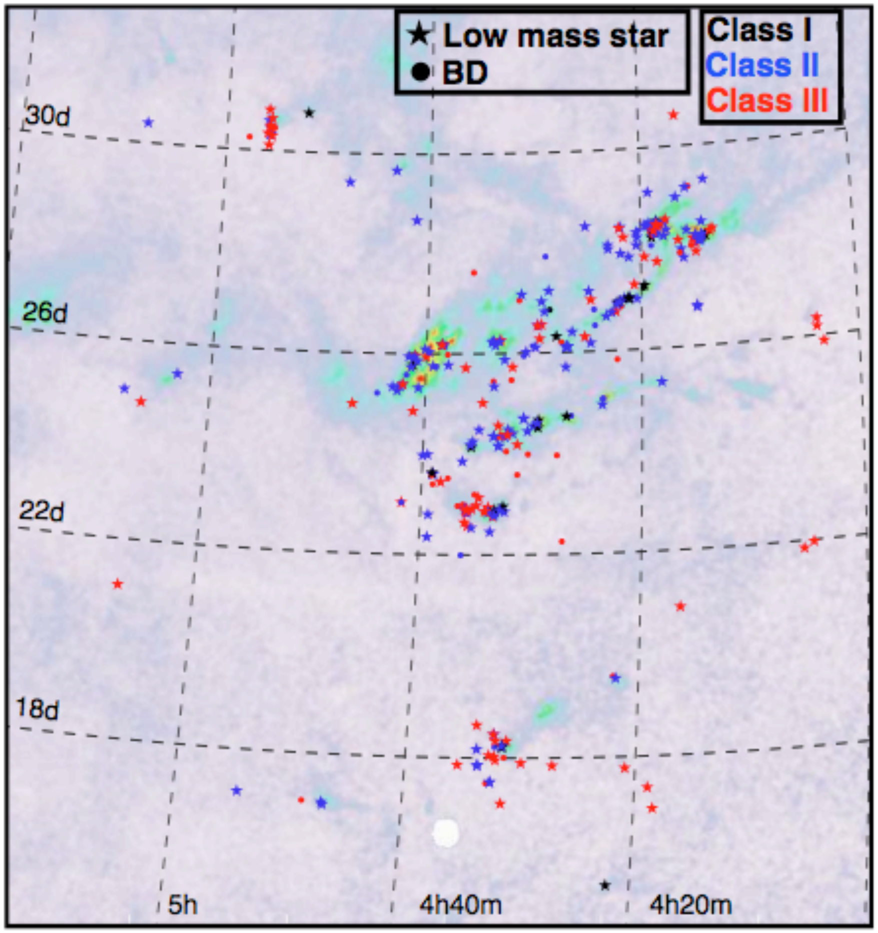


(Mann et al. 2014)

Disk Properties as a Function of Object Mass and Class

Taurus Star-forming Region Membership

The Taurus Star-Forming Region



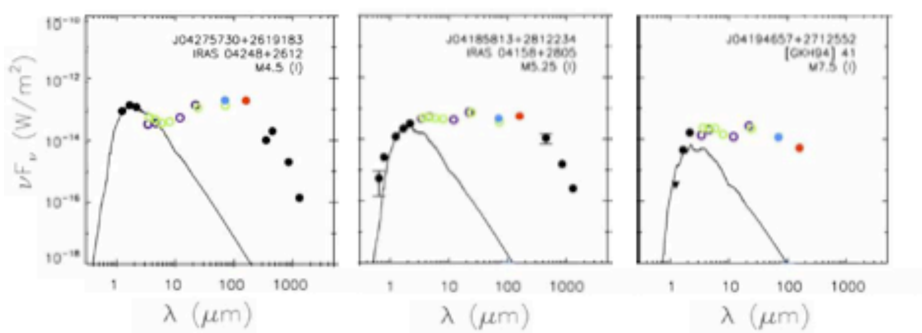
Extinction map Dobashi et al. 2005

- Population: ~350 known members
- Age: ~1 Myr
- Distance: 140 pc
- Low stellar density environment: 4-30 stars/pc^3
- **Most comprehensive coverage across full mass spectrum and Class 0,I,II,III**
- **Lacks most massive stars**

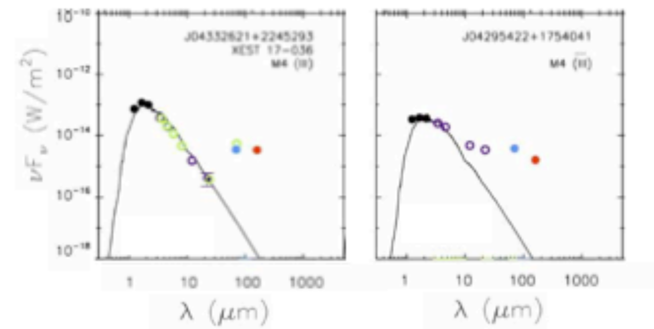
Spectral Energy Distributions for Large Sample

- **Comprehensive surveys at many wavelengths for nearest Northern SFR**
- **Examples of Class I, II, III SEDs for Taurus low mass members M4+**

Class I

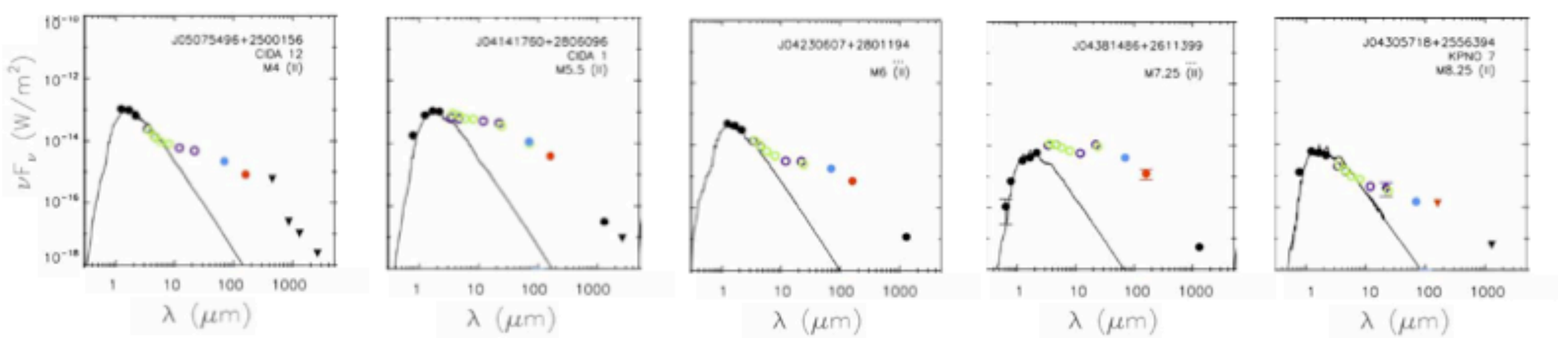


Class III



SED key:	2MASS	*WISE*	*Spitzer* IRAC, MIPS	*Herschel* PACS	*Herschel* PACS	Submm studies
λ(μm):	1-2	3-22	3-8, 24-70	70	160	450-1300

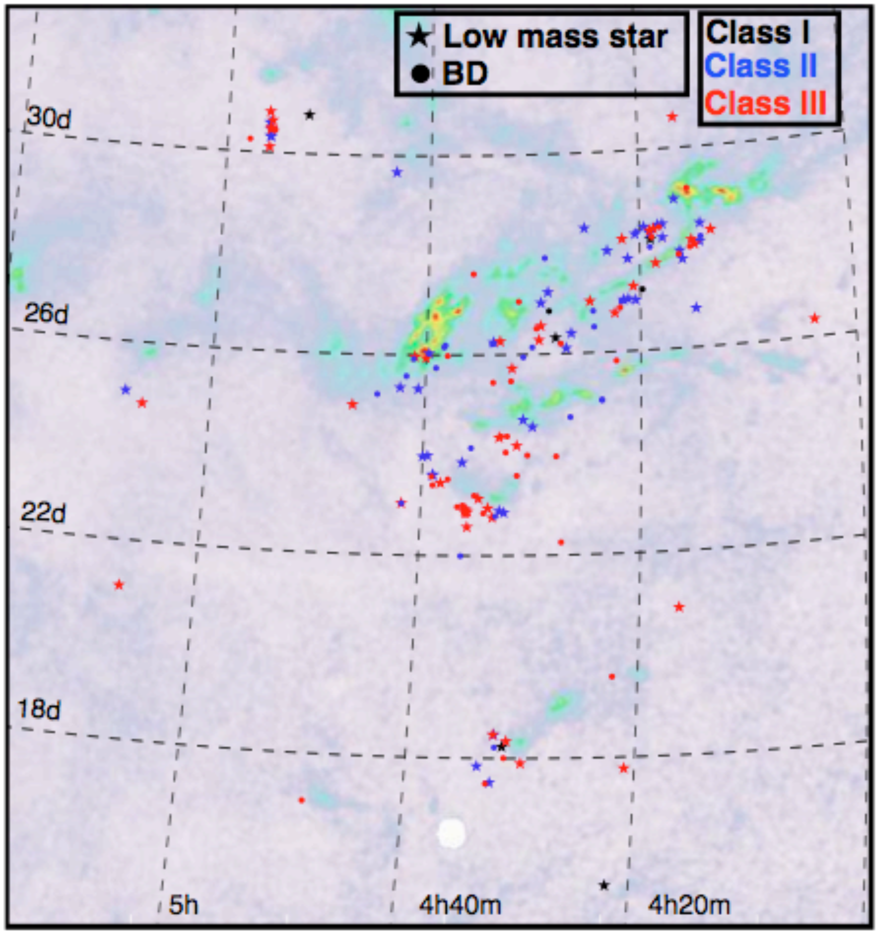
Class II



(Bulger, Patience et al. 2014)

Disk Detection as a Function of Evolutionary Class

The Taurus Boundary of Stellar/Substellar (TBOSS) Survey



Extinction map Dobashi et al. 2005

Far-IR detection rates:

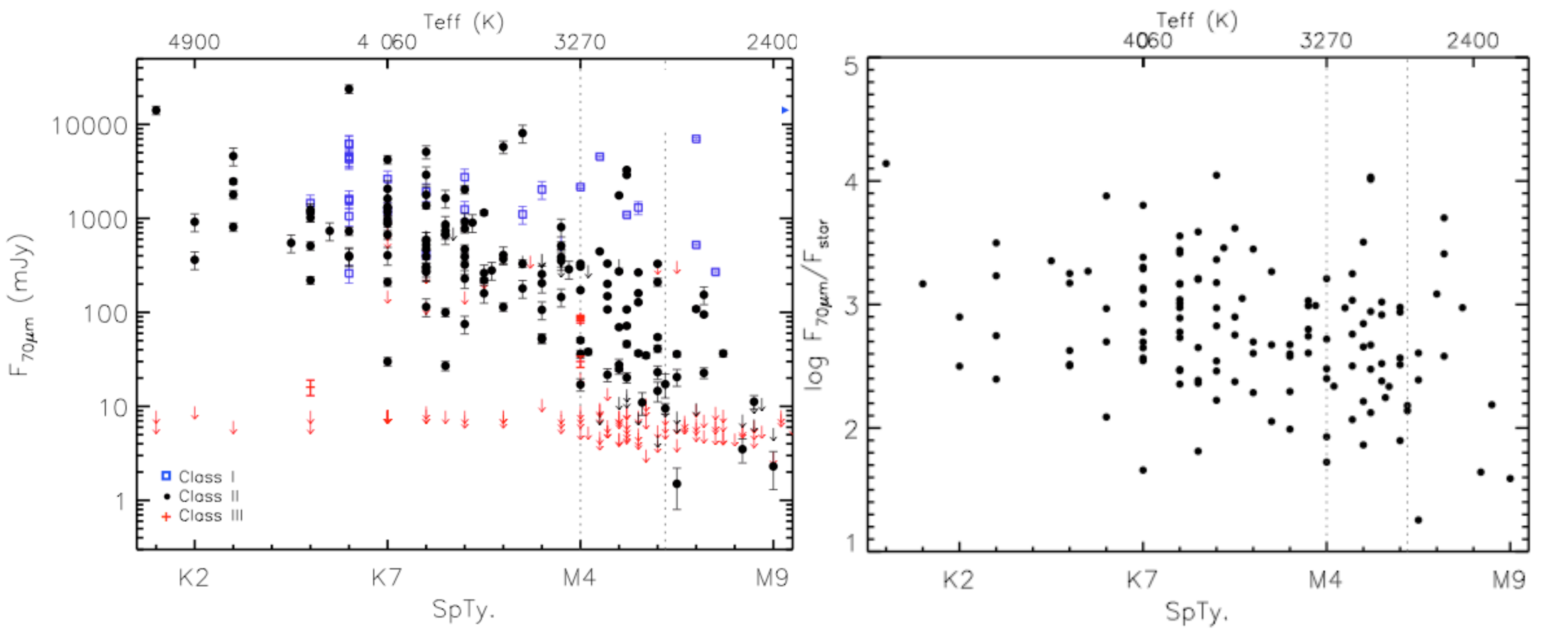
	Class I	Class II	Class III	Class I-III
M4-M6	4	44	42	90
M6.25-L0	3	25	35	63
M4-L0	7	69	77	153

70 μm detection rates: (100%) (75%) (4%)

160 μm detection rates: (100%) (42%) (4%)

Disk Detection as a Function of Spectral Type (Mass)

Far-IR Emission v.s. Spectral Type



(Rebull et al. 2010, Howard et al. 2013, Harvey et al. 2012, Bulger, Patience et al. 2014)

- **Far-IR detections across full mass spectrum**

  Flux decline with Spectral Type and large scatter at any Spectral Type

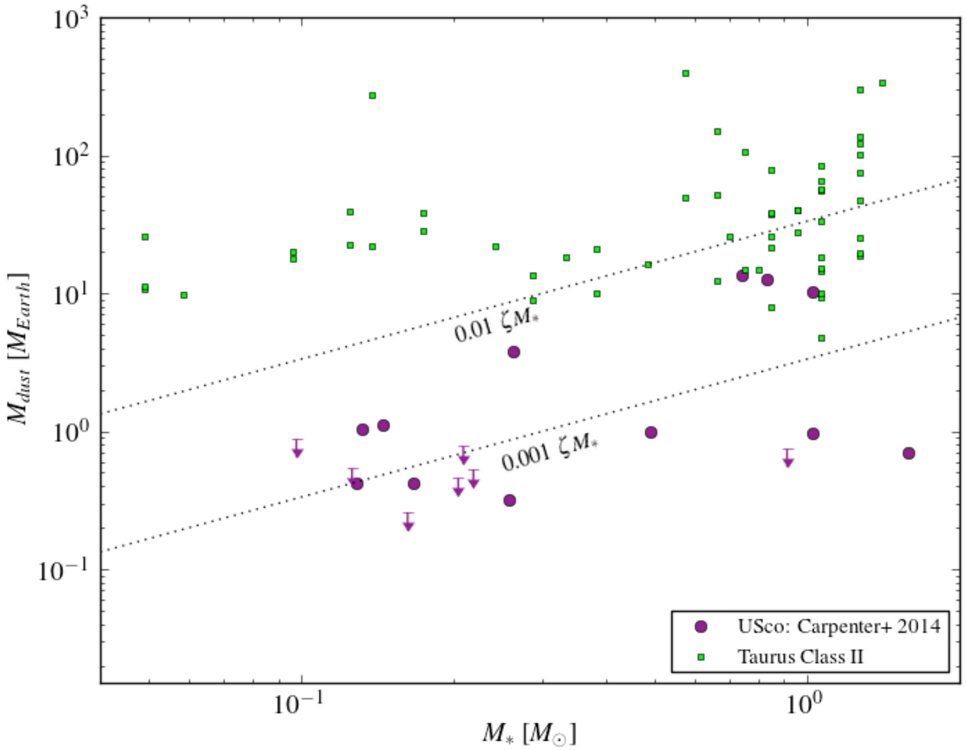
- **Far-IR excess over photosphere similar across mass spectrum**

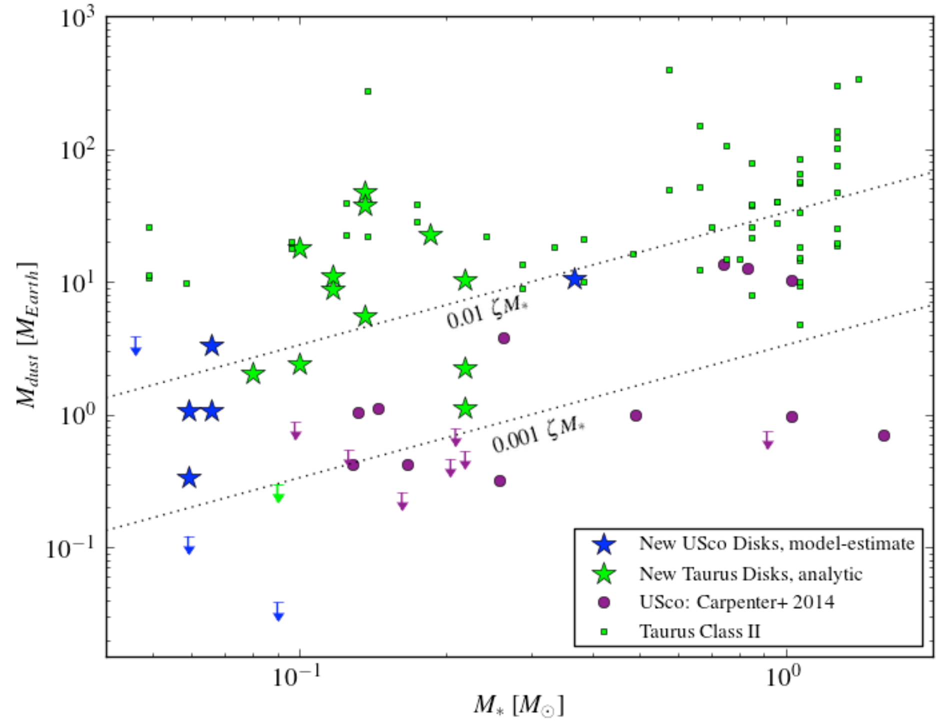
Disk Detection as a Function of Mass and Age

- **Younger Taurus and Older Upper Sco disk populations investigated as a function of mass**

  ALMA enables extension to low mass stars and brown dwarfs

  Systematic decline in disk mass with age (only detections plotted for clarity)

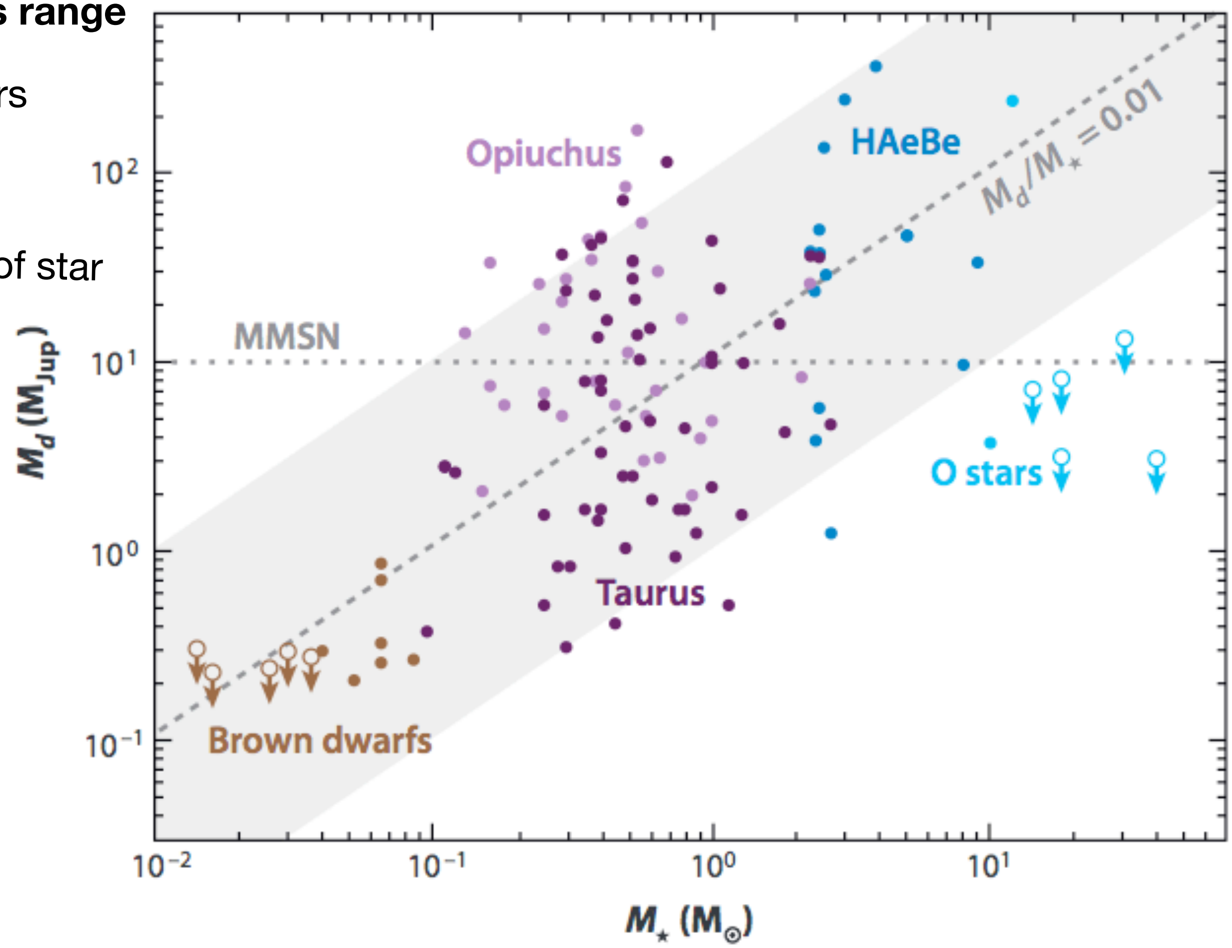




(Andrews et al. 2013, Carpenter et al. 2014, van der Plas et al., in prep., Ward-Duong et al., in prep.)

Disk Mass as a Function of Object Mass

- **Combine regions for larger mass range**
  - No disks detected around O-stars
  - B-stars -> BDs follow trend
  - Average disk masses similar % of star
- **More low mass objects in ALMA queue**



(Williams & Cieza 2011)

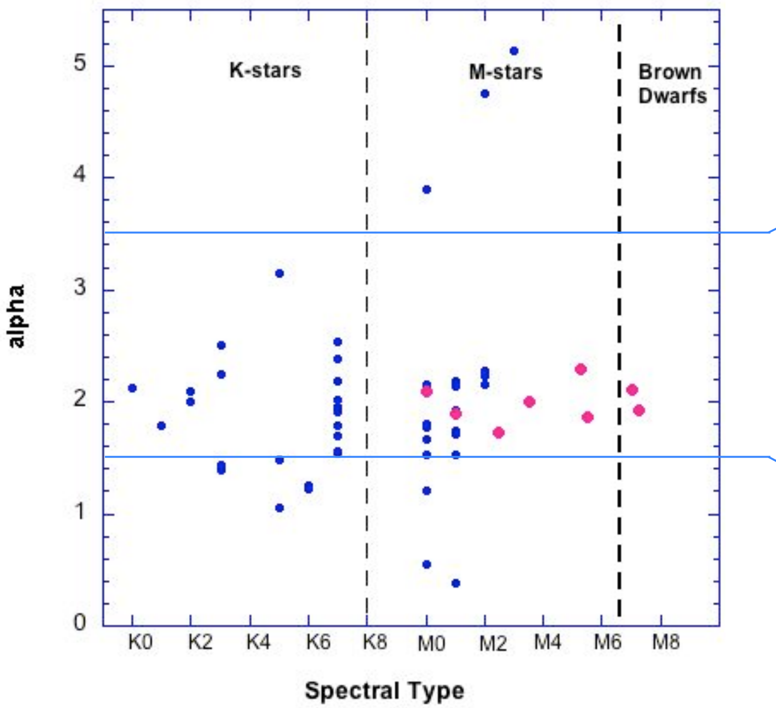
Grain Growth as a Function of Object Mass

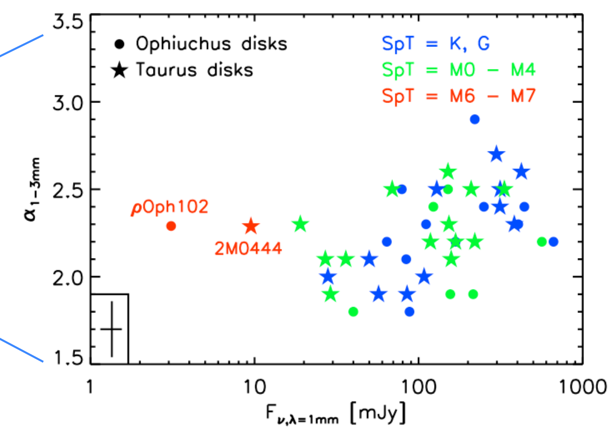
- **Slope of submm/mm fluxes indicates growth of particles**

  Power law index of submm/mm fluxes **$F \sim \nu^{alpha}$ similar for stars/brown dwarfs**

- **Models have suggested drift may present barrier to growth in disks around low mass objects**

  No evidence for distinction in initial data sets





(Ricci et al. 2012)

(Taurus data, Bulger et al., in prep.)

Disk Mass as a Function of Evolutionary Class

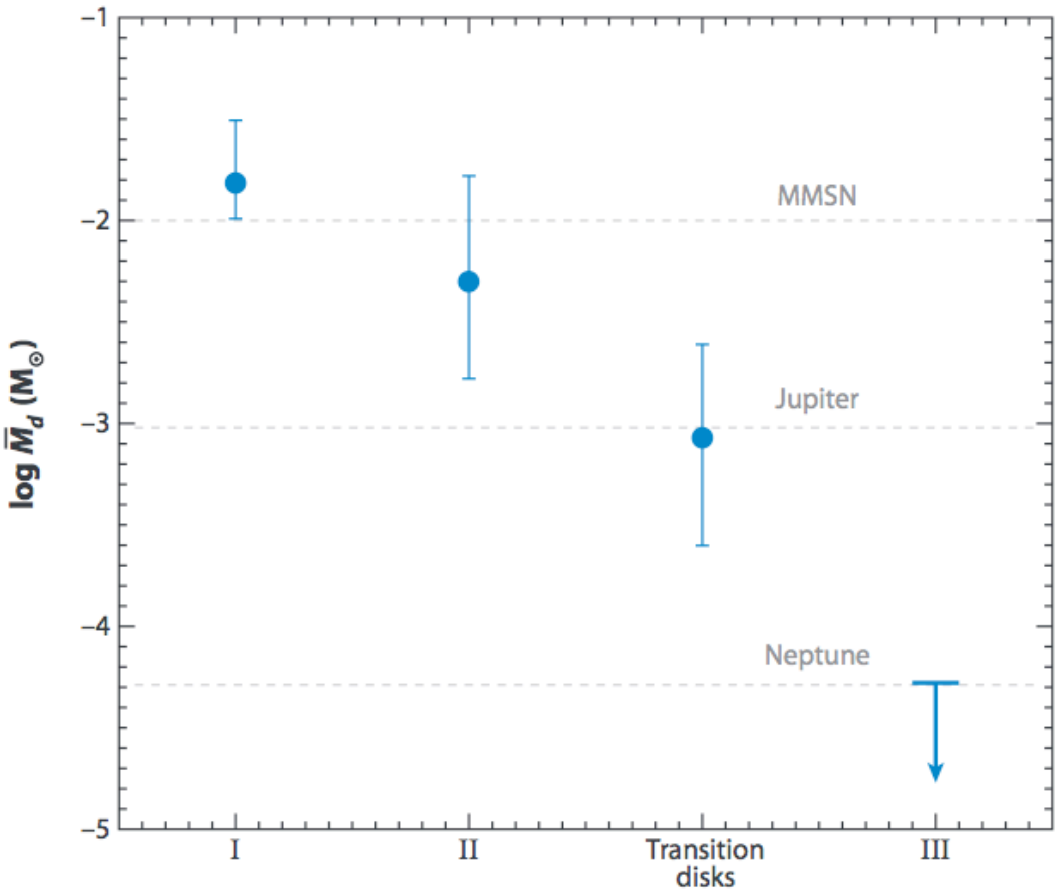
- **Previous results on Class II objects**

- **Combine Tau/Oph Class I,II,III**

  Systematic decline with class

  Most Class I >MMSN

  Transition disks lower mass



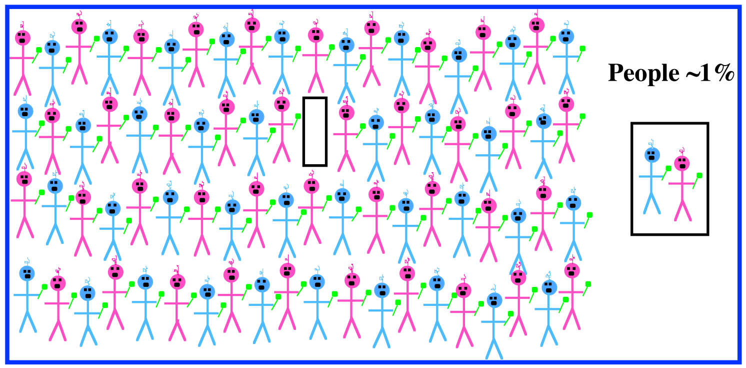
(Williams & Cieza 2011)

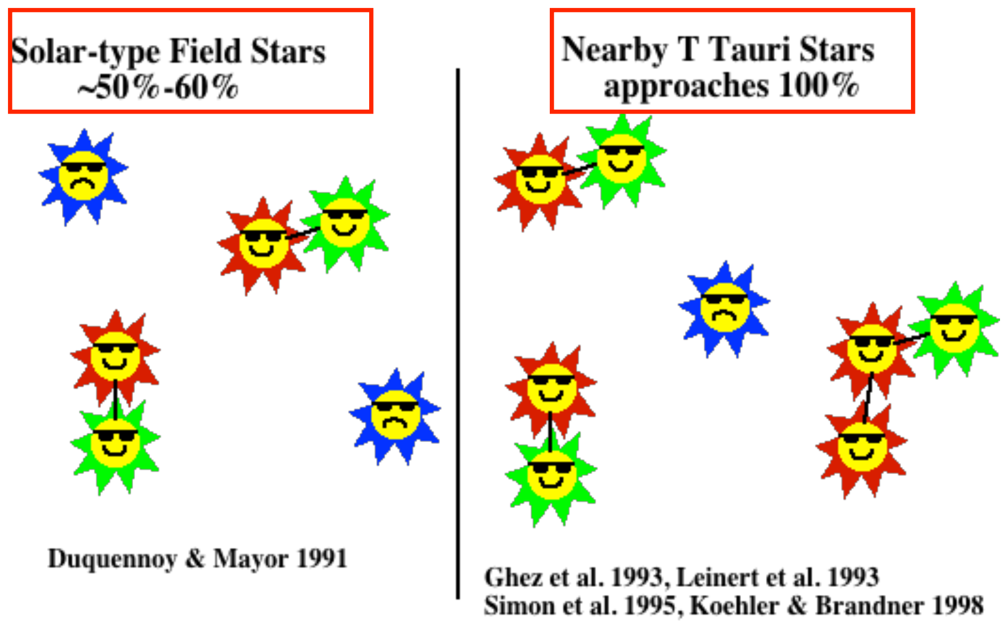
Disks in Binary Systems

Background on Binary Stars

- **Majority of stars are in stellar systems**

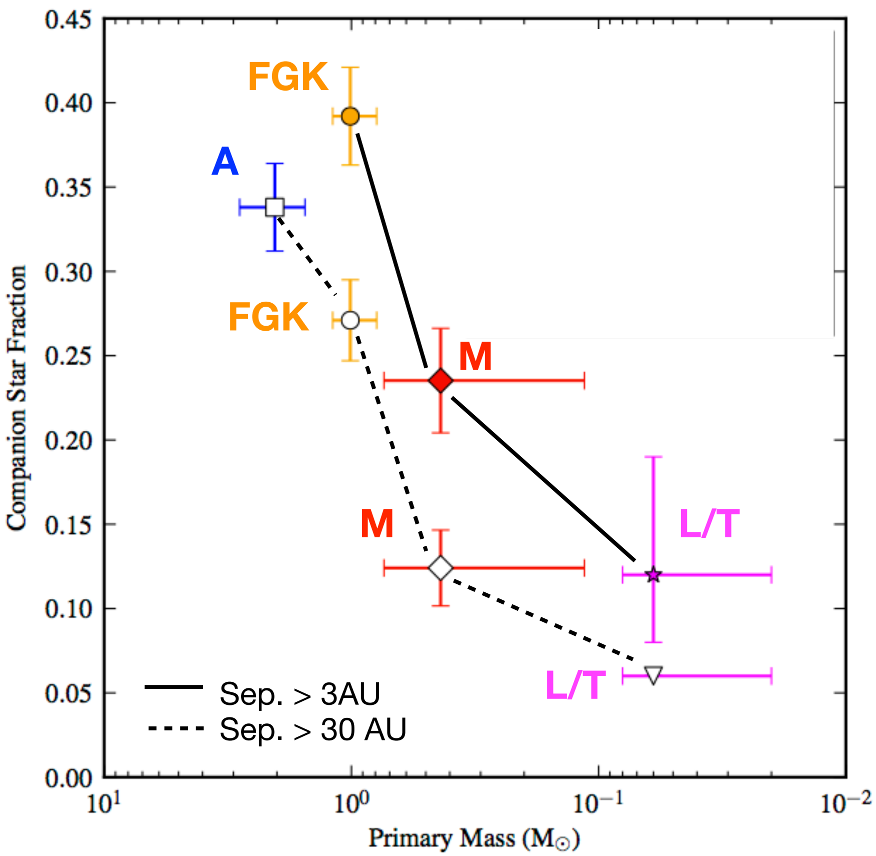
  Exoplanets known in binary systems

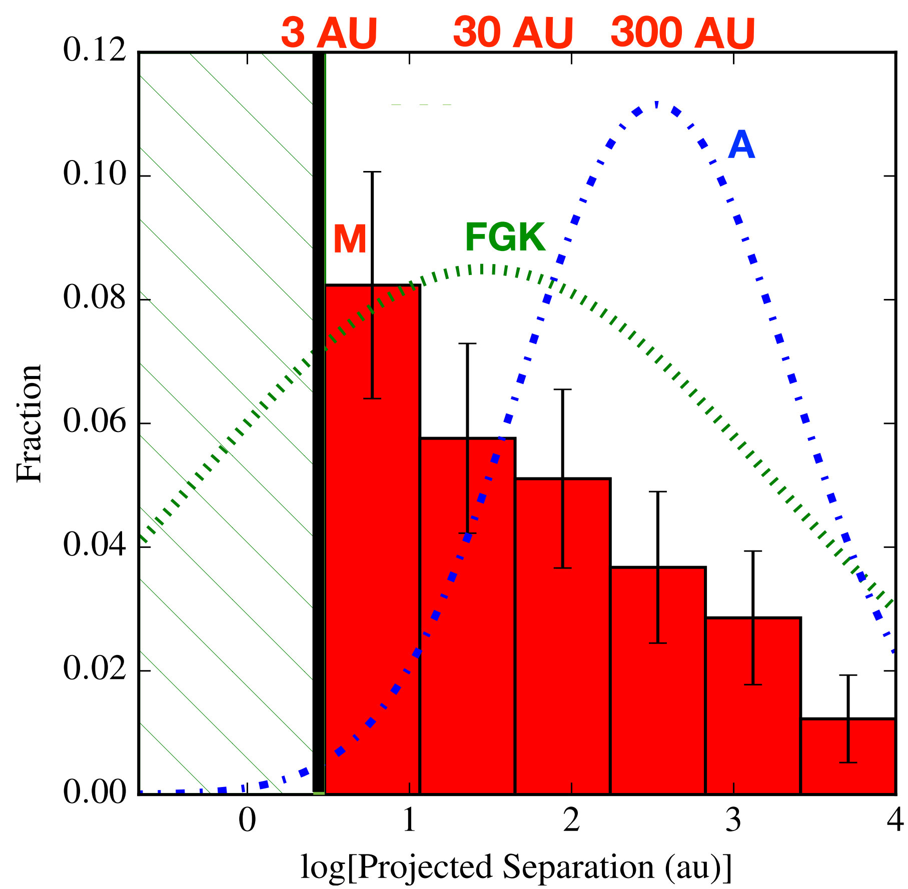




Binary Star Properties

- **Binary Fraction declines with stellar mass**
- **Typical Binary Separation declines with stellar mass**





(De Rosa et al. 2013, Raghavan et al. 2010, Ward-Duong et al. 2015, Burgasser et al. 2006, Allen et al. 2007)

Disks around Binary Stars

- **Spatially resolved study of components**

  Compare with singles + separation

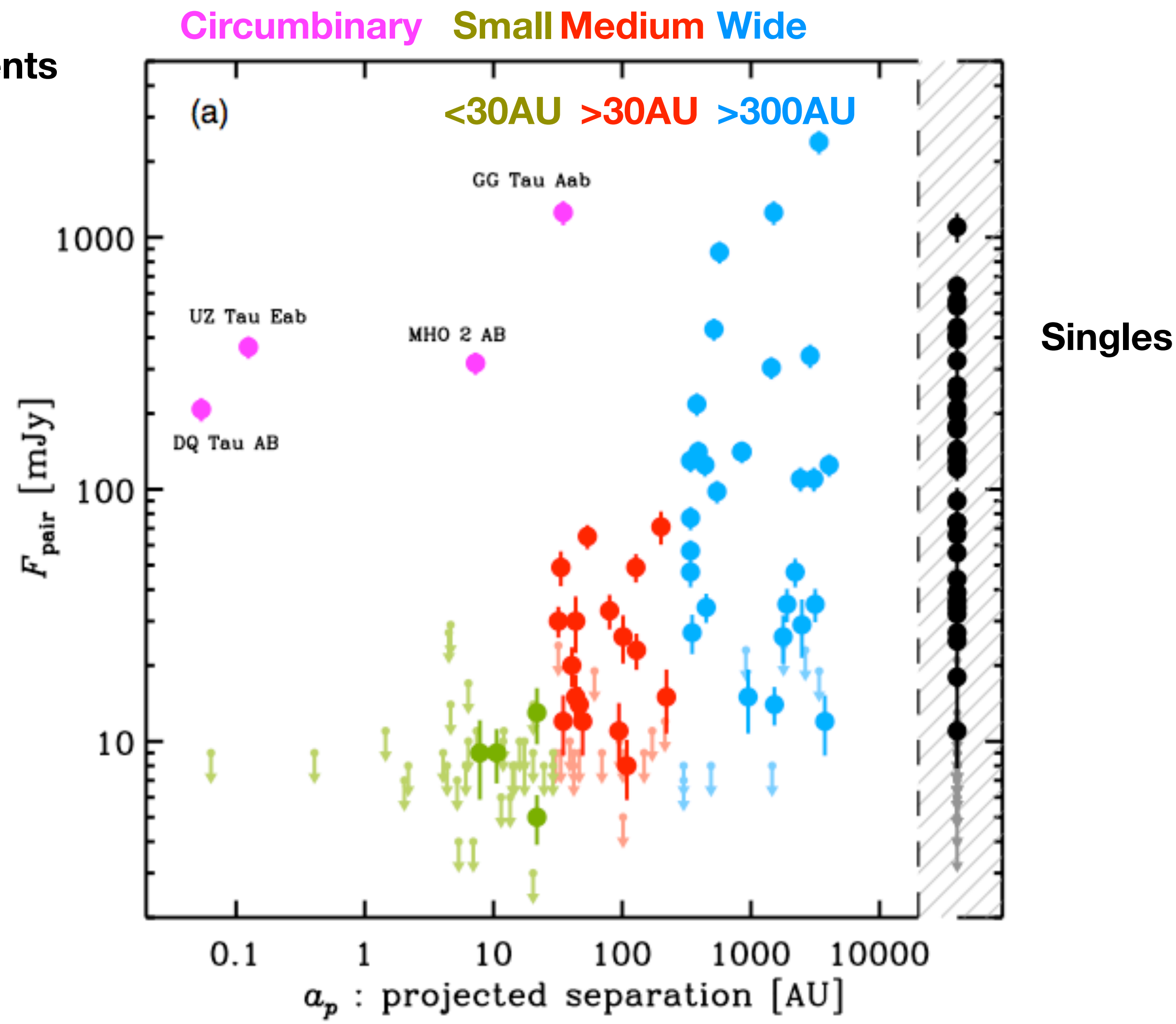
- **Disk properties vary with separation**

  Circumbinary disks brightest

  Wide systems similar to singles

  Small/Med. considerably fainter

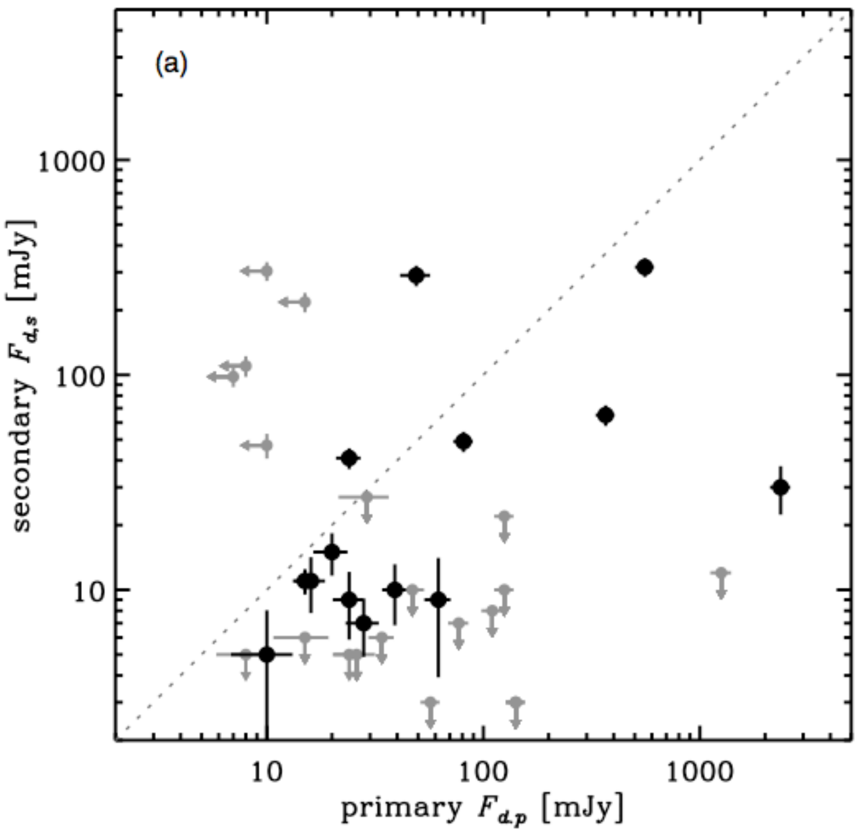
- **Disks larger than predicted from truncation models**



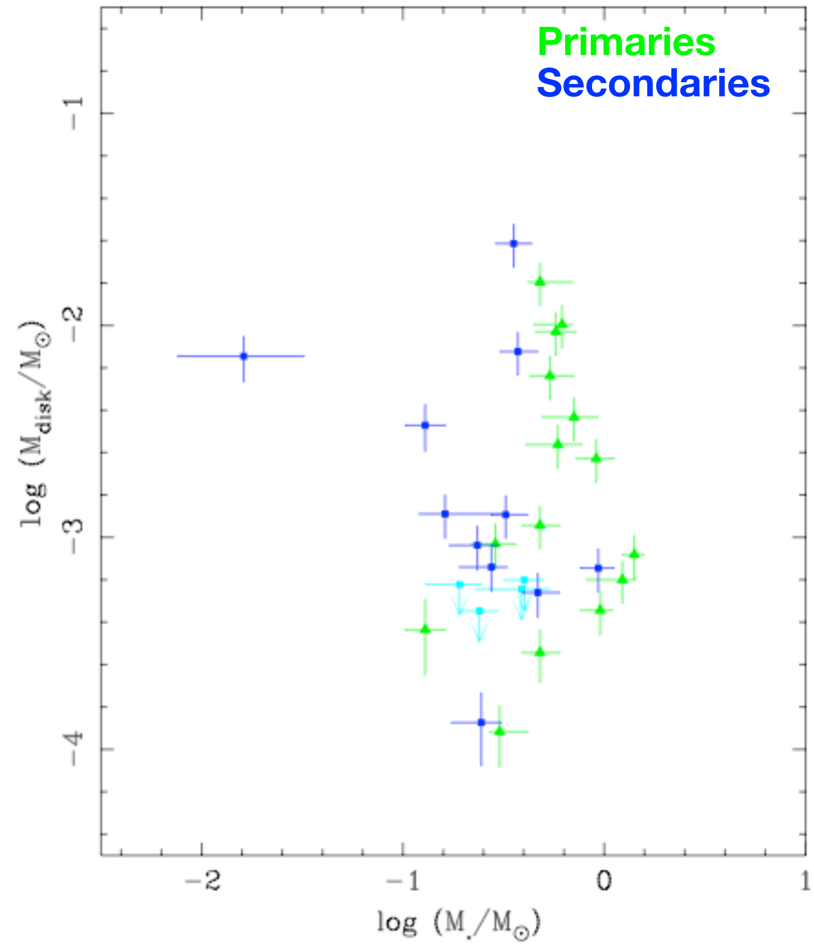
(Harris et al. 2012)

Comparison of Component Disks

- **Primary disk brighter in initial survey**
- **Similar distribution in disk mass with object mass**
  Most secondaries detected with ALMA sensitivity



(Harris et al. 2012)



(Akeson & Jensen 2014)

Comparison of Component Disks

- **Compare disk alignment w/resolved data**

    Examples of misaligned disks

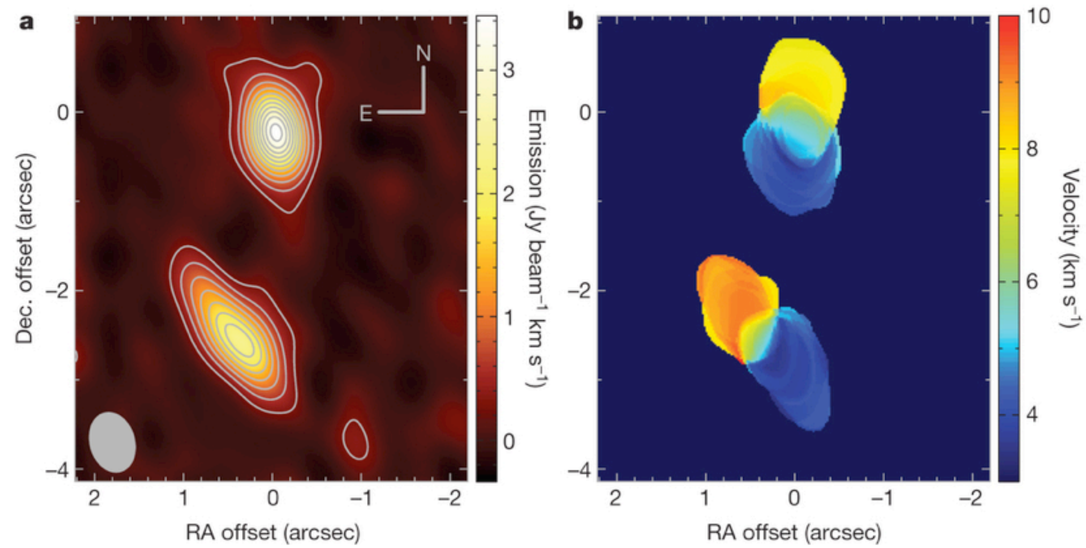
- **Disks detected with low mass secondaries**

    FW Tau ~planet mass

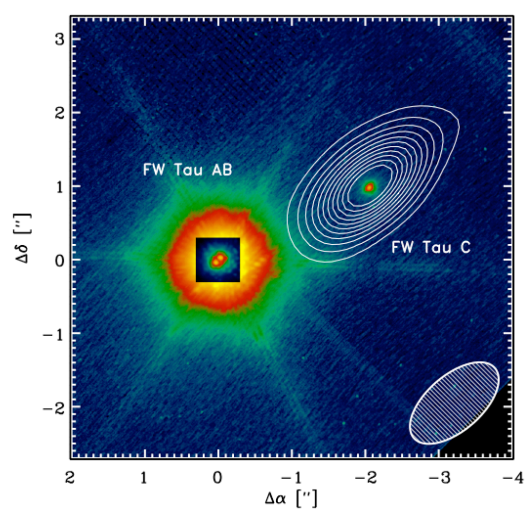
        No primary disk detection

    Taurus substellar disk misaligned

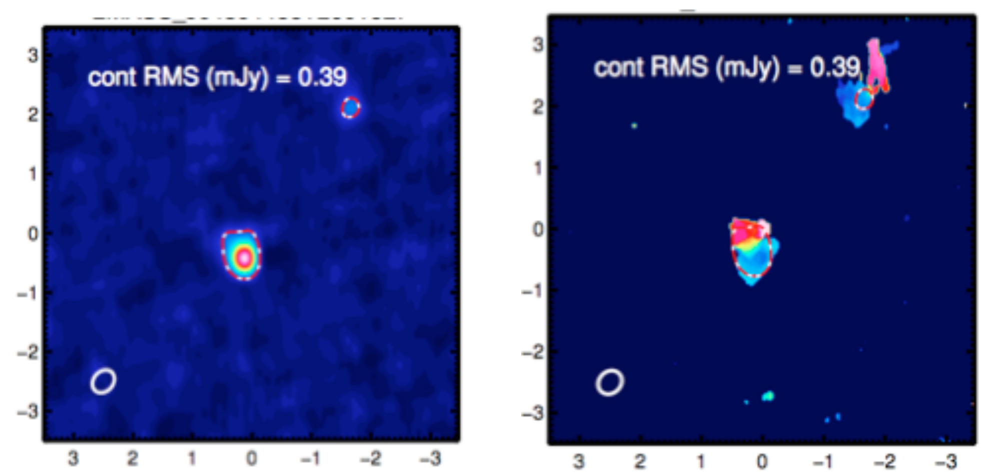
        May relate to formation mechanism



(Jensen & Akeson 2014)



(Kraus et al. 2015)

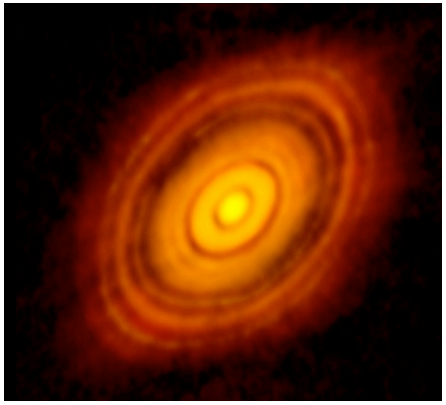


(Ward-Duong, Patience, van der Plas et al. 2015)

Spatially Resolved Disk Structures

- **Class I disk around HL Tau**

  Series of gaps throughout disk



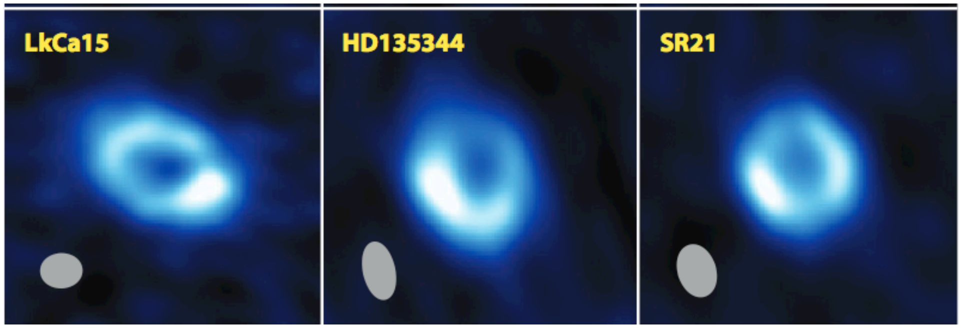
(ALMA partnership)

- **Transition disks with central clearings**

  Holes ~few AU - 50 AU

  Consistent with SED interpretation

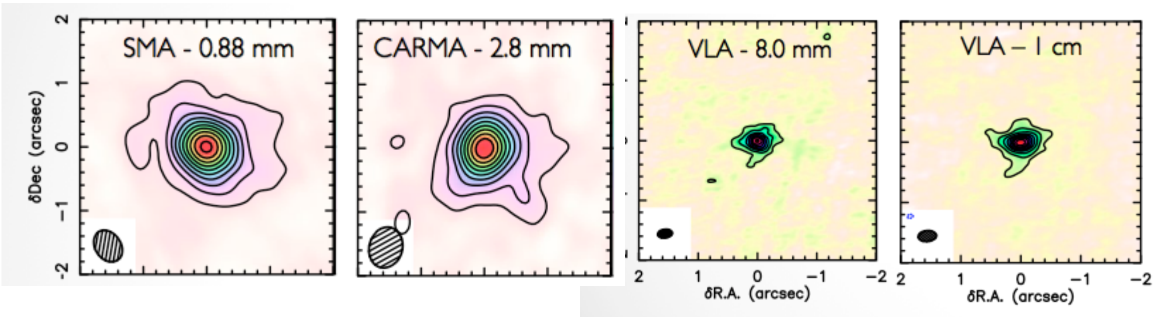
  Some show asymmetries, possible dust trap



(Compiled in Williams & Cieza 2011)

- **Gradients in grain growth in disk**

  Different disk sizes at different wavelengths



(Perez et al. 2012)

Summary

- **Exoplanetary System Demographics**

  Trends with host star mass, systems in binaries

- **Observations of Disk Frequencies and Lifetimes**

  Disk lifetimes measured from excesses only few Myr

- **Basic Interpretation of Disk Observations**

  Possible to infer properties such as disk mass, gaps, grain growth

- **Distribution of Disk Properties in Different Regions**

  Possible to infer properties such as disk mass, gaps, grain growth

- **Disk Properties as a Function of Object Mass and Class**

  Decline in Disk mass with lower host star mass and later evolutionary class

- **Observations of Disks in Binary Systems**

  Fluxes lower for closer systems, examples of misaligned disks, circumplanetary disks

- **Spatially resolved structures detected, more to come with ALMA, VLA, etc...**