# High Angular Resolution Studies of Circumstellar Disks

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2005 Michelson Fellows Symposium

# Talk Outline

- Motivation & Background
  - Benefits of high angular resolution
  - Disks and binaries
- Infrared Interferometry
  - Inner disk sizes
  - Comparison with disk and planet formation models

**Hot Inner Disks**

- Millimeter Interferometry
  - Ophiuchus & Taurus dust disks
  - Comparison with star and planet formation models

**Cool Outer Disks**

- Submillimeter Observations
  - Disks around low mass stars/brown dwarfs
- Summary and Conclusions

# Motivation

- Study properties of disks around young stars

- Disks very important for star and planet formation process
  - Provide raw material for planet formation
  - Influence angular momentum evolution

- These observations probe the size scales and timescales important for disks

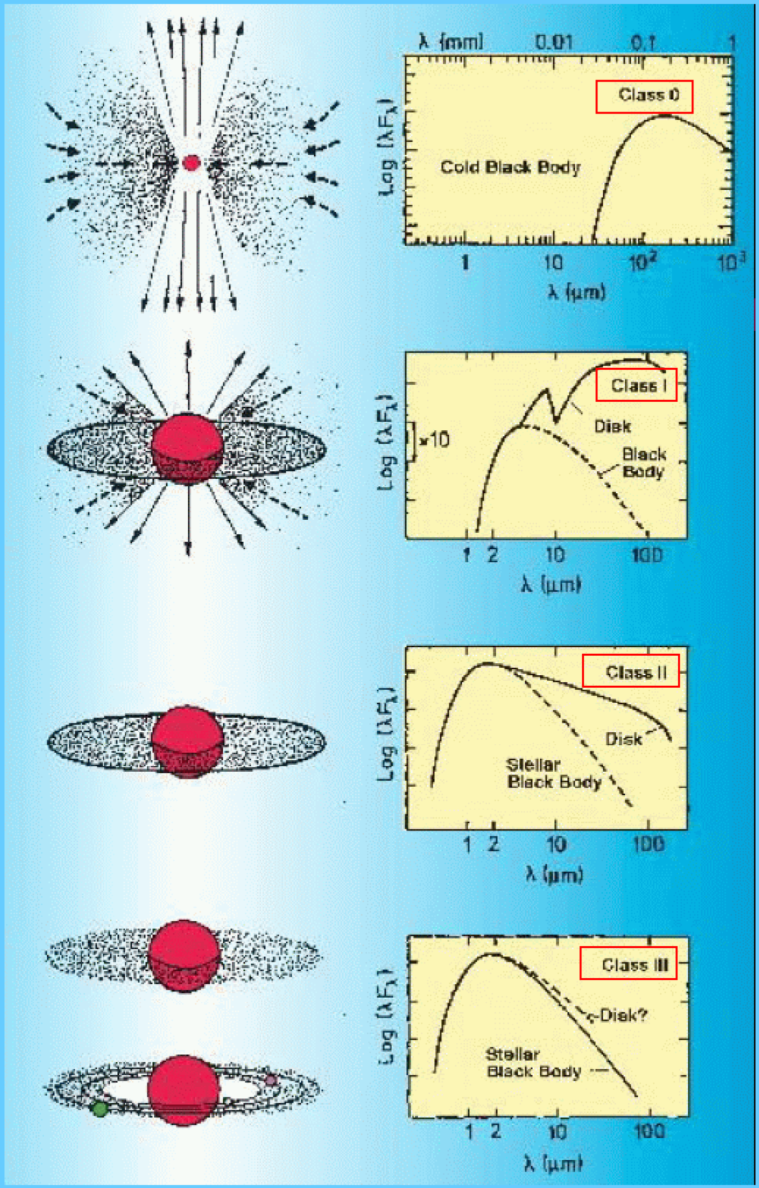
# Background - Targets

Young stars are classified by SED shape
SED - spectral energy distribution
flux as a function of wavelength

Classes correspond to evolutionary stages
decrease in amount of dust from 0 -> III
0: very embedded in envelope
I: some infalling material
II: passive disk
III: weak or no disk, possibly planets

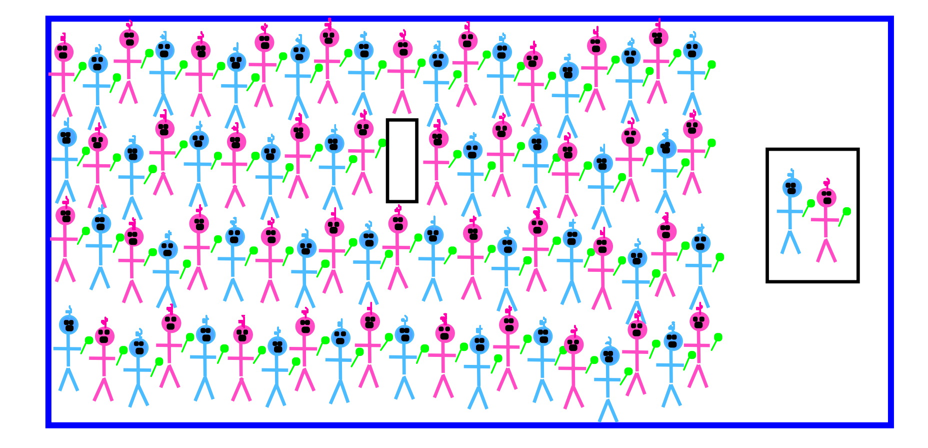
Interferometry sample
IR - Class II, III
mm - Class I, II

Imaging sample
submm - Class II



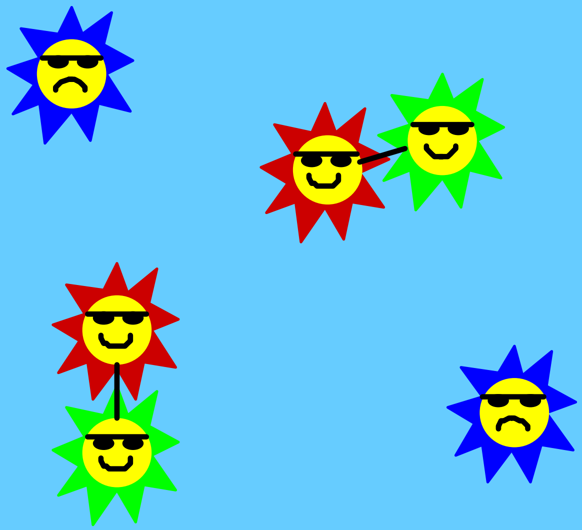
# Background - Binaries

## Binary Frequency in Different Samples



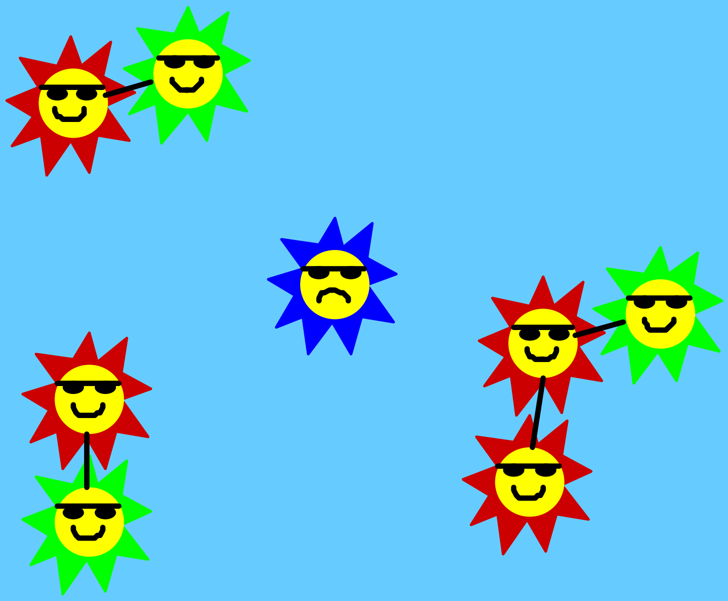
People ~1%

### Solar-type Field Stars
### ~50%-60%



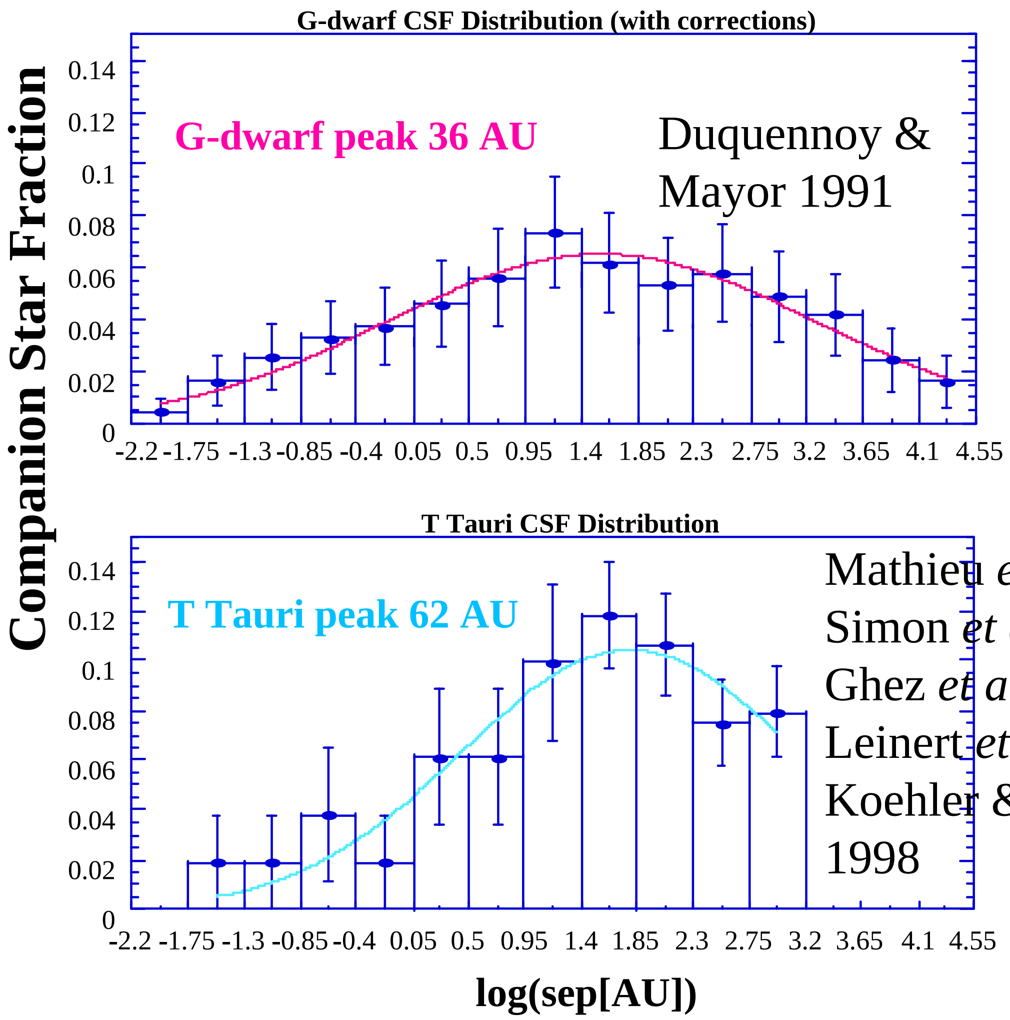
Duquennoy & Mayor 1991

### Nearby T Tauri Stars
### approaches 100%



Ghez et al. 1993, Leinert et al. 1993
Simon et al. 1995, Koehler & Brandner 1998

# Background - Binaries




T Tauri Binaries

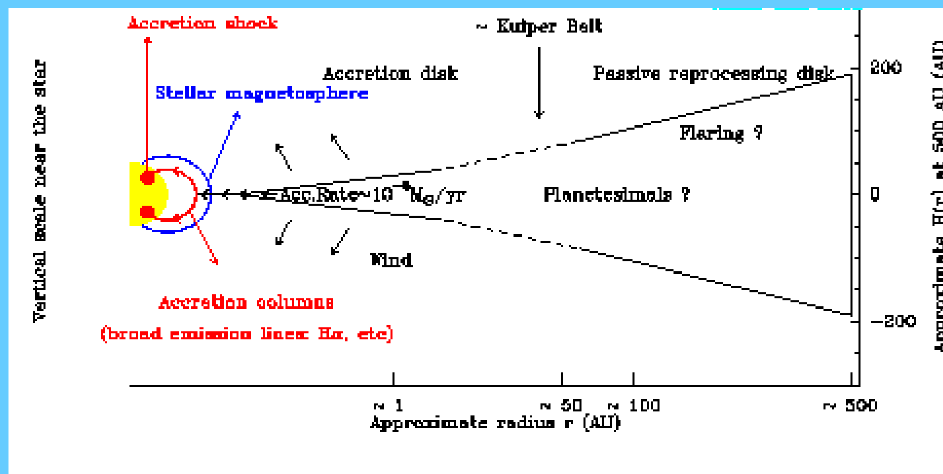
- ~2x higher than field
- Based on Class II
- Recent Class I shows similar binary excess at ~300-2000 AU (Haisch *et al.* 2004)

OVRO sample covers wide separations due to resolution limit

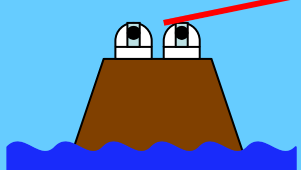
# Background - Disk Sizes

- High angular resolution essential to study disk structure

- Disk size < ~500 AU        Solar System size: Mercury 0.4AU, Kuiper belt 50AU




Ophiuchus D = 160pc



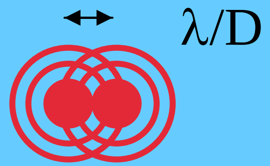
Sun-Earth 1AU = 0”.006 = 6mas

Kuiper belt 50AU = 0”.3

Disk ~500AU = 3”.0

# Angular Resolution Limits

- **Single Aperture** - Angular resolution limit set by the telescope diameter




Diffraction limit of largest single telescopes:

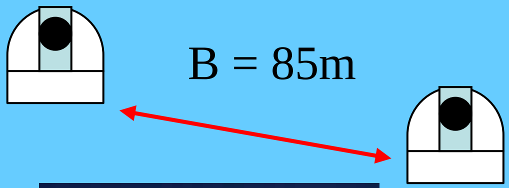
IR (2.2μm) - Keck 10m, λ/D = 0”.045 - cannot resolve inner disk

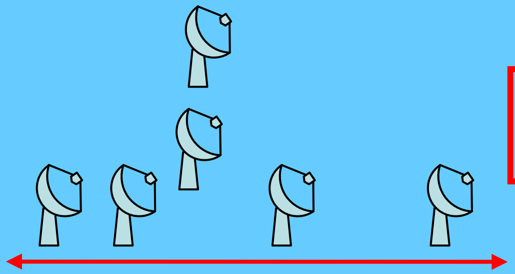
mm (3mm) - IRAM 30m, λ/D = 20” - cannot resolve multiple sources
confusion with the cloud emission

- **Interferometer** - Angular resolution limit determined by the longest baseline

**Keck Interferometer**

λ/B = 0”.005 = 5mas



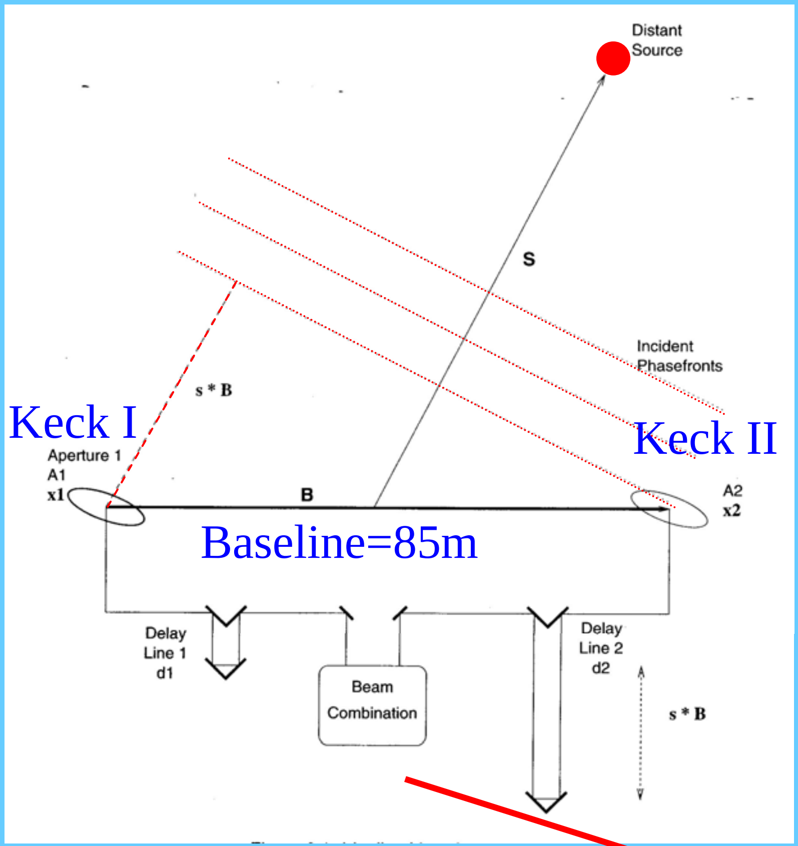



Adjustable, Bmax = 440m

**OVRO Interferometer**

λ/Bmax = 1”.3 at 3mm

# Keck Interferometer Project - Inner Disks of Young Stars

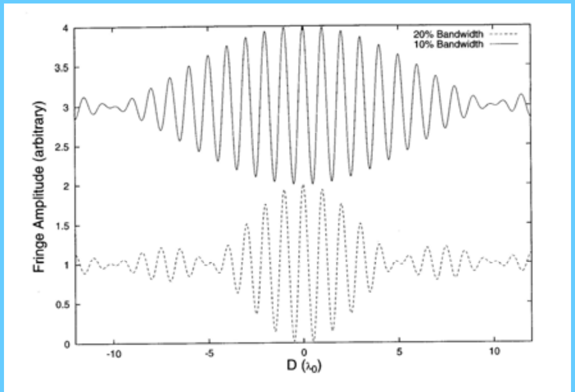



(Figure adapted from Boden 1999)

- Michelson interferometer
- Adjust delay line to match path length
- Combine signal from both telescope
- Measure amplitude of fringes

As Earth rotates, proj. baseline changes
Over time measure different baselines

Output Fringes




Visibility = fringe amplitude
$V^2$ is measured

# Keck Interferometer Observations

- Visibilities are related to source brightness distribution by Fourier transform

| **Source** | | **Visibility ($V^2$)** |
|---|---|---|
| Point Source (Unresolved) | | Uniform value = 1.0 |
| 2 Point Sources (Binary star) | Fourier Transform → | Cosine periodic funtion |
| Gaussian (Resolved) | | Gaussian |

- Measure $V^2$ and fit with model function
  estimate size of emitting region

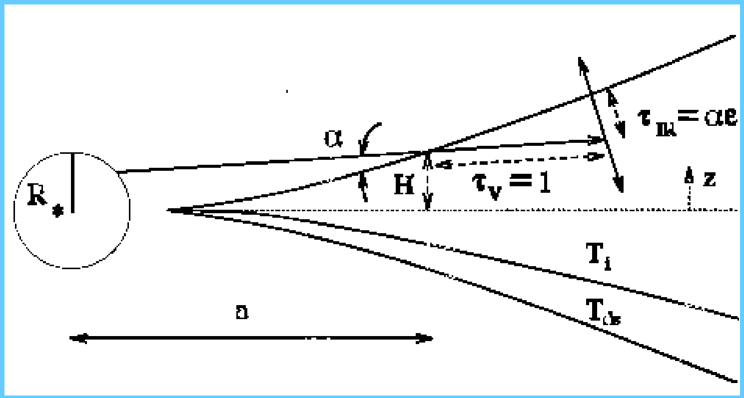
# Keck Interferometer Results

Targets with visibilities significantly less than 1.0 are **spatially resolved**

| Target | Type | $V^2$ | Result |
|---|---|---|---|
| AS 209 | CTTS | .70-.89 | Resolved |
| AS 353 | CTTS | .63 | Resolved |
| HD 163296 | Herbig Ae | .36-.40 | Resolved |
| RR Tau | Herbig Ae | .42-.52 | Resolved |
| HBC 634 | WTTS | .71-.98 | Uncertain |
| HBC 380 | WTTS | .99 | Unresolved |
| HD 107146 | submm disk | 1.0 | Unresolved |

# Models of Circumstellar Disks

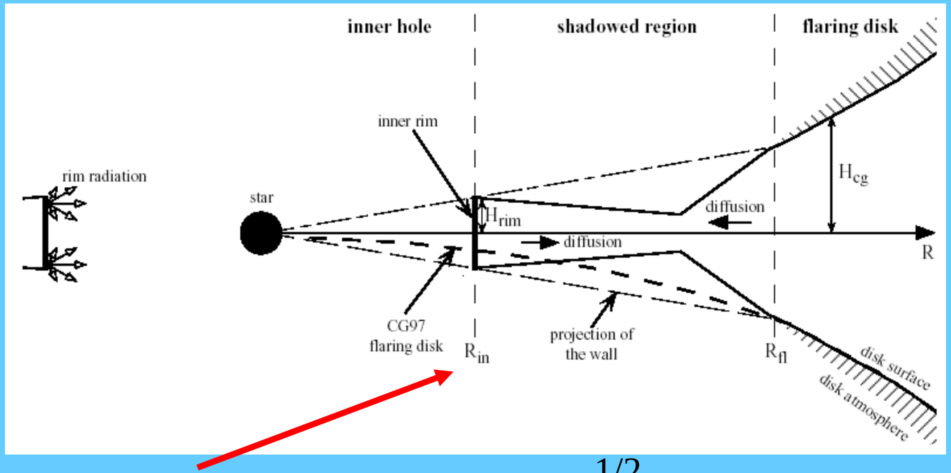
Standard flared disk model predicts that the infrared emission originates very close to the star




(Chiang & Goldreich 1997)

Revised model includes a puffed up inner edge to the disk caused by stellar radiation vaporizing dust particles close to the star - predicts larger sizes

This model fit to interferometry data

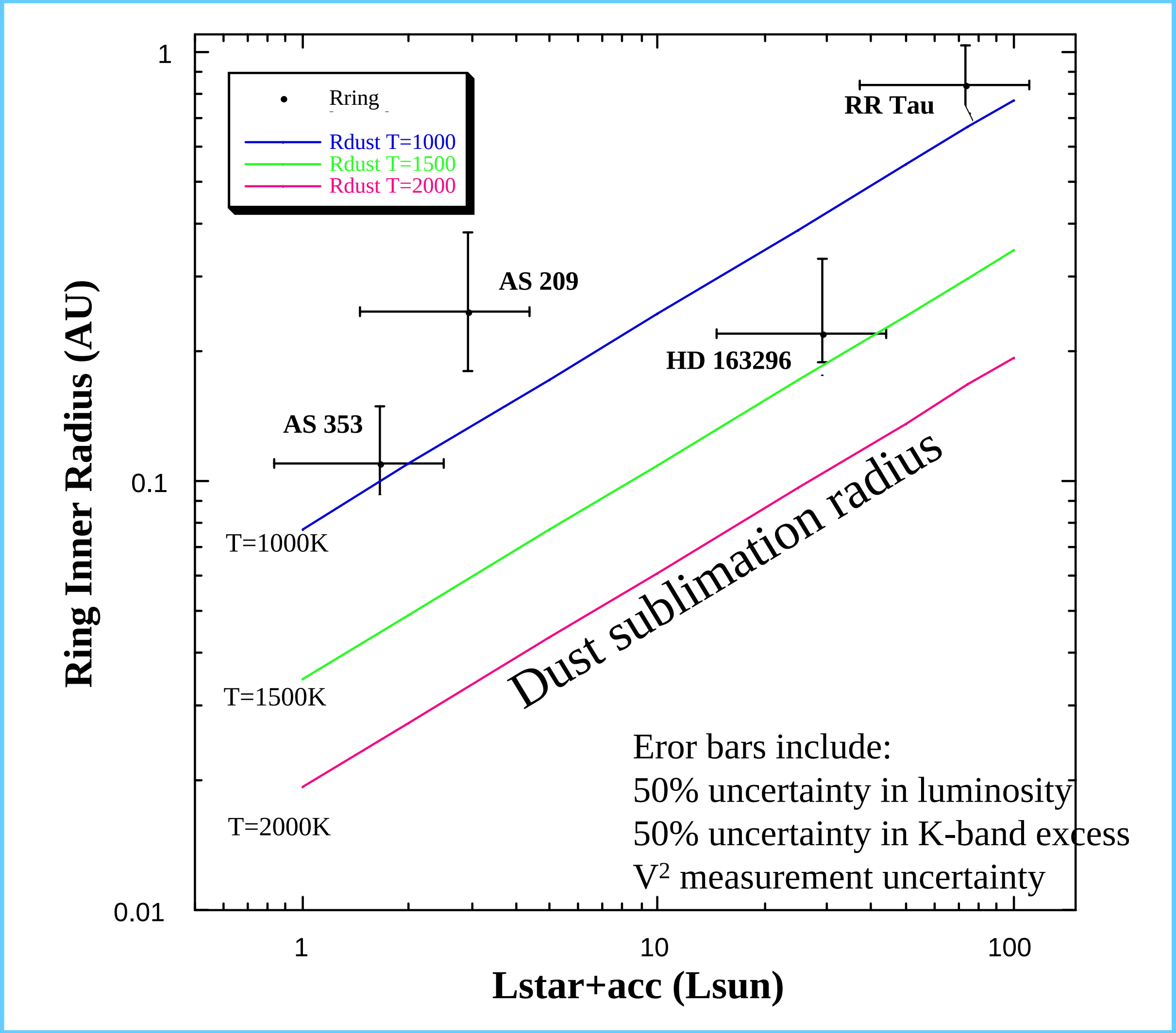



$$R_{dust} = \frac{1}{2}\left[\frac{L_*}{4\pi\sigma T^4_{dust}}\right]^{1/2}$$

(Dullemond *et al.* 2001)

# Keck Interferometer Results

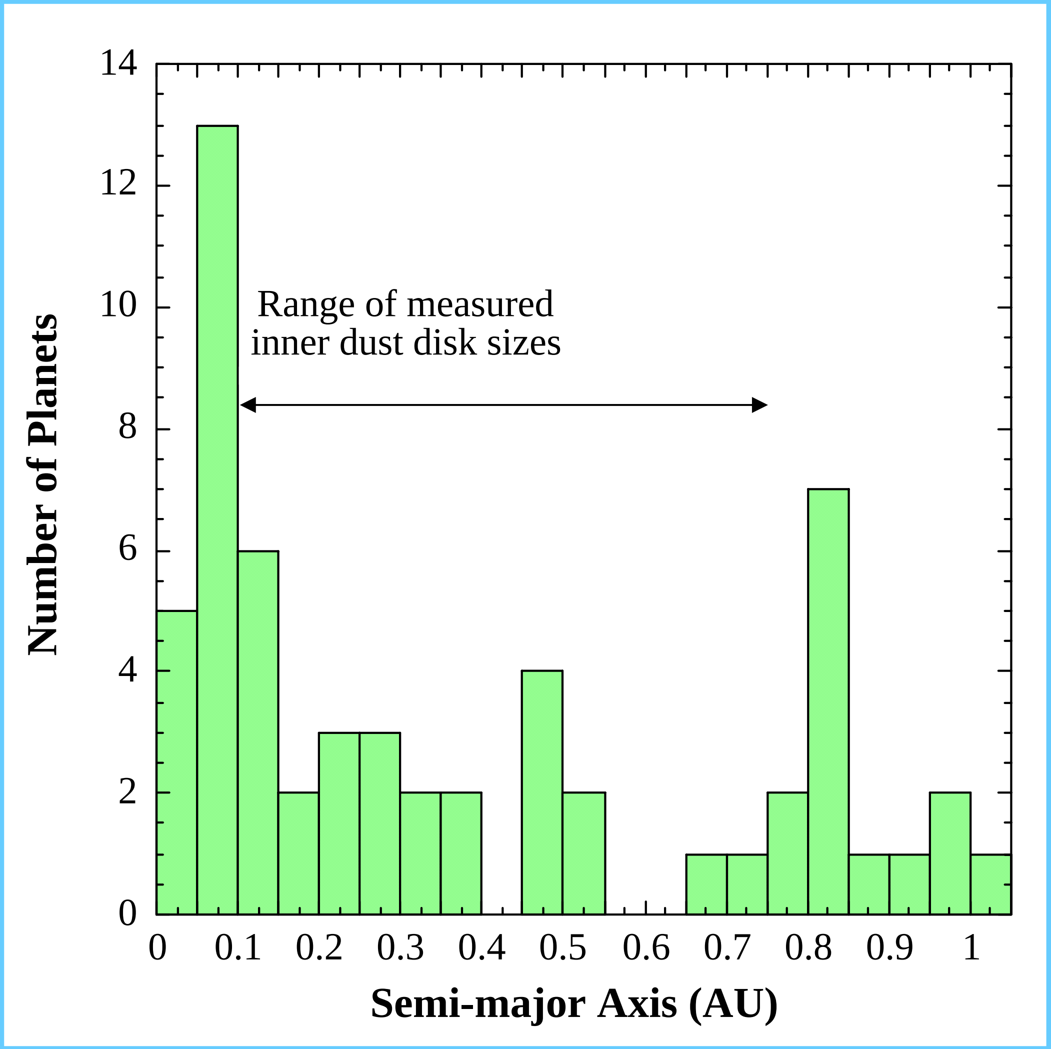
## Comparison of Observed and Predicted Sizes




- The inner disk sizes suggested by the ring model are typically larger than the dust destruction radius predicted for stars with the combined stellar and accretion luminosities of the targets

- Dust sublimation temperatures of 1500K - 2000K are expected, but 1000K is shown for comparison

# Comparison with Radial Velocity Planets




- Radial velocity searches detect planets interior to measured inner disk sizes

- Hot Jupiters are not believed to form at such close distances

(California & Carnegie planet search - www.exoplanets.org)

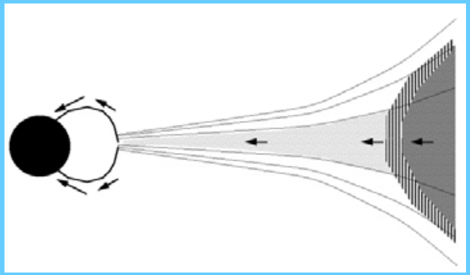
# Implications for Planet Formation

• Gas giant planets believed to form outside the ice line ~5AU

• Gap forms in the disk around the planet and the planets spirals inward

• Planet migration mechanism requires material between planet and star for angular momentum transfer to work

• A completely evacuated region interior to the interferometry measured inner edge would present a problem for this model, but there may still be gas interior to the dust destruction radius



(*e.g.* Muzerolle *et al.* 2004)

# OVRO Interferometer Project - Outer Disks in Young Binaries

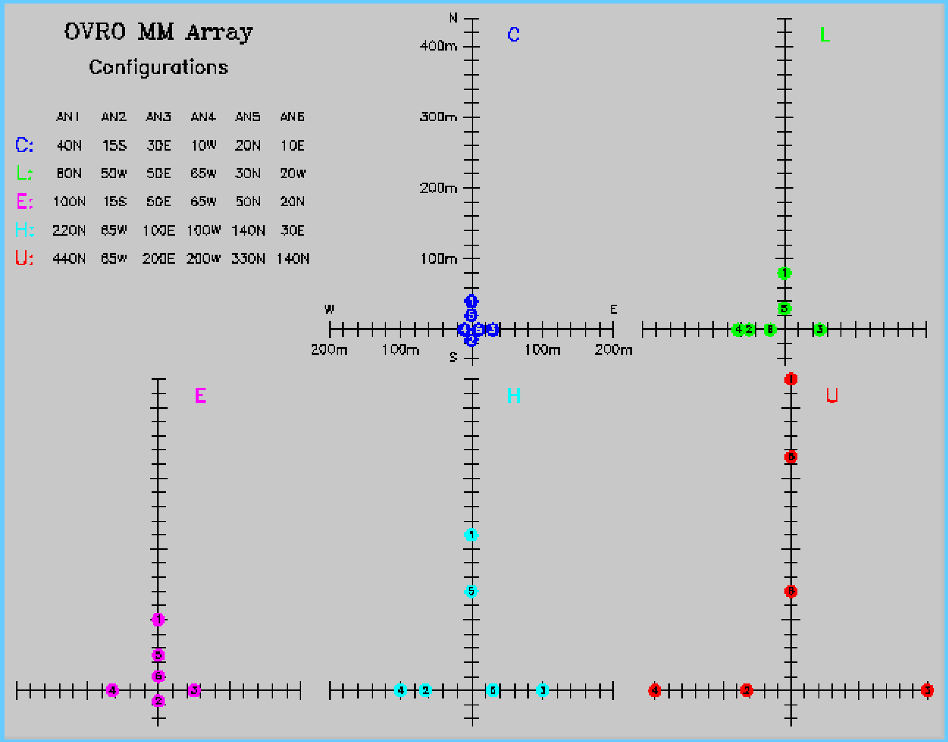
## Owens Valley Millimeter Observatory (OVRO)

6-antenna (10m each)

Central frequency 112 GHz (3mm)
Continuum bandwidth 4 GHz (Oph)
Continuum bandwidth 8 GHz (Tau)

Baselines 35-240m from
Beam size ~4” x 3”

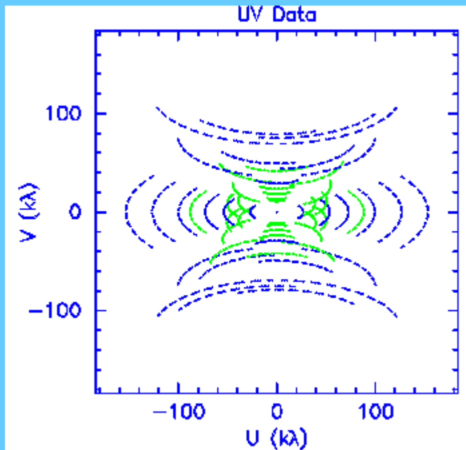
Quasars and planets used for calibration



# OVRO Interferometer

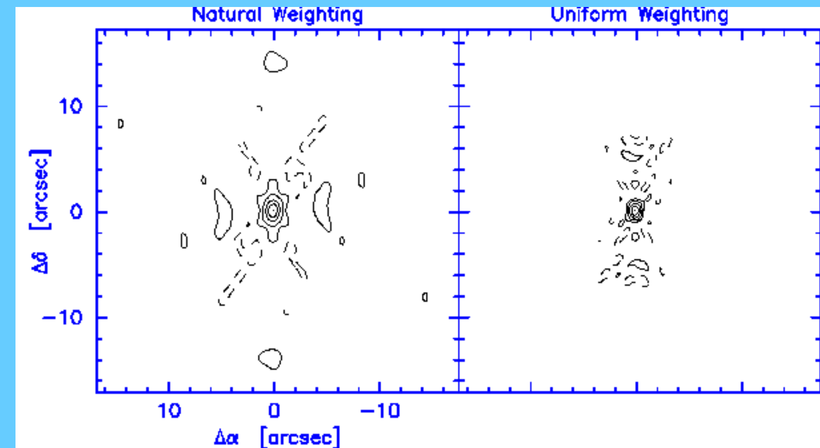
With multiple baselines at OVRO it is possible to form images

6 antennae ⟶ 15 baselines



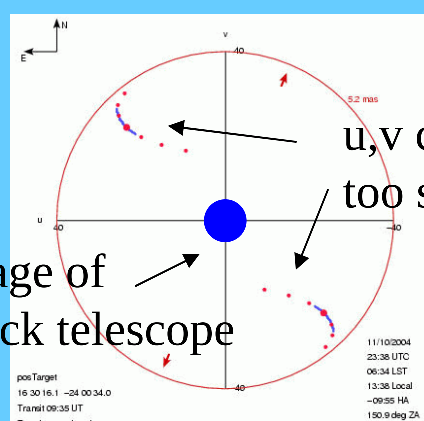

Fourier

Transform




The OVRO beam is small enough to resolve each component of binary stars

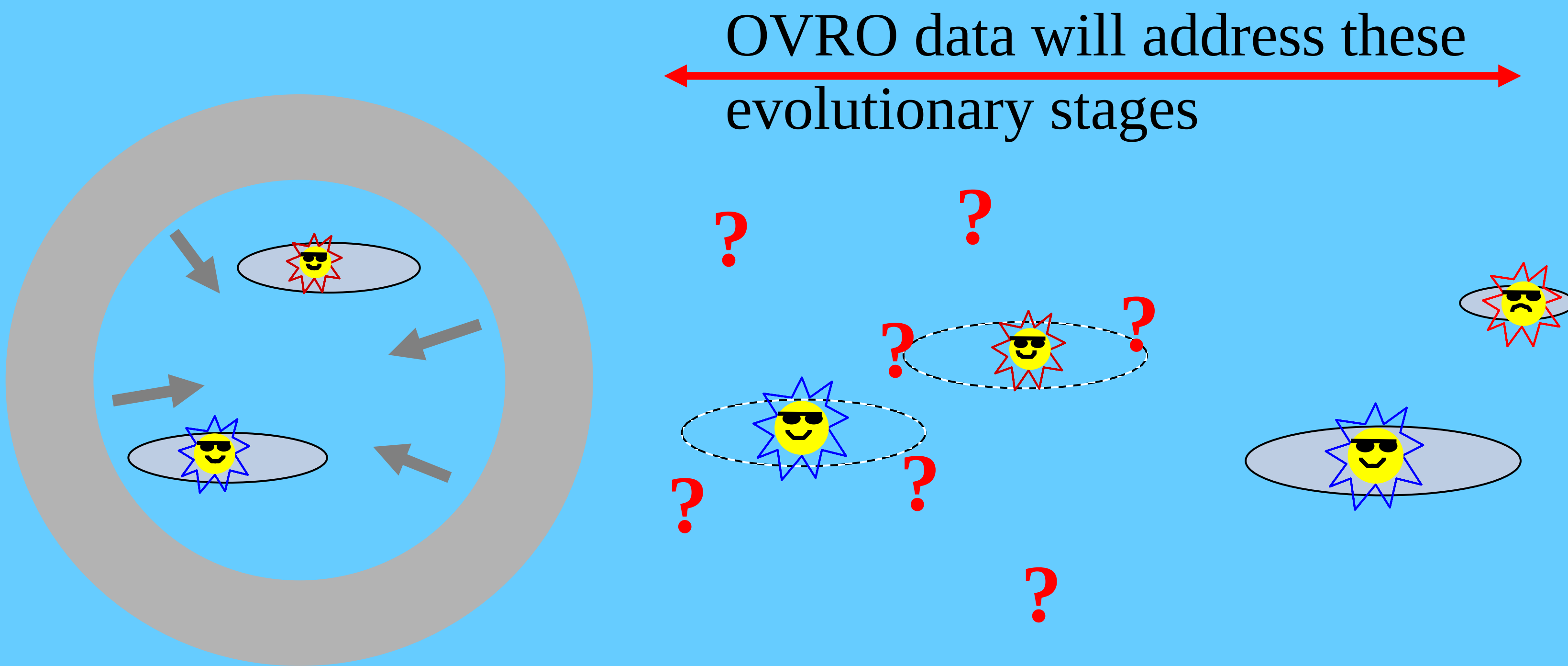
With a single baseline at Keck it is not possible to form images




u,v coverage of Keck interferometer
too sparse for images

u,v coverage of
Single Keck telescope

# Background




Class 0 | Class I | Class II

Material around each star + extended envelope

Is there disk material around each star or only one?

Primary disk, but little/no Secondary disk material

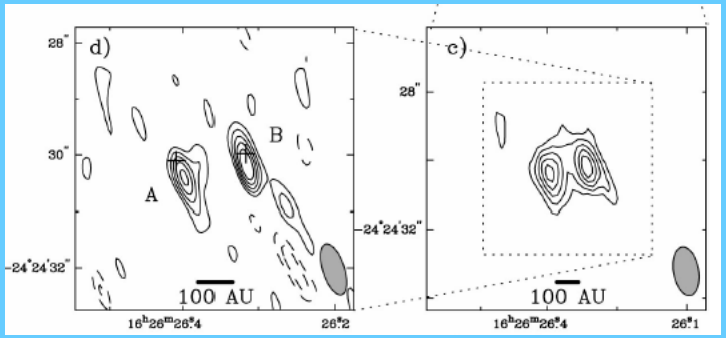
**OVRO Binary Sample**

Separation wide enough to be resolved (100's - 1000 AU)
Flux strong enough to be detected

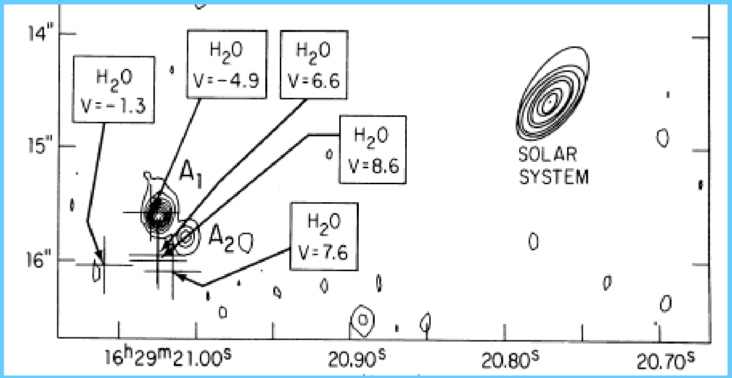
(Haisch *et al.* 2004, Duchene *et al.* 2003, Simon *et al.* 1995)

# Previous Observations

- **Ophiuchus Class 0** systems show a disk around each binary component

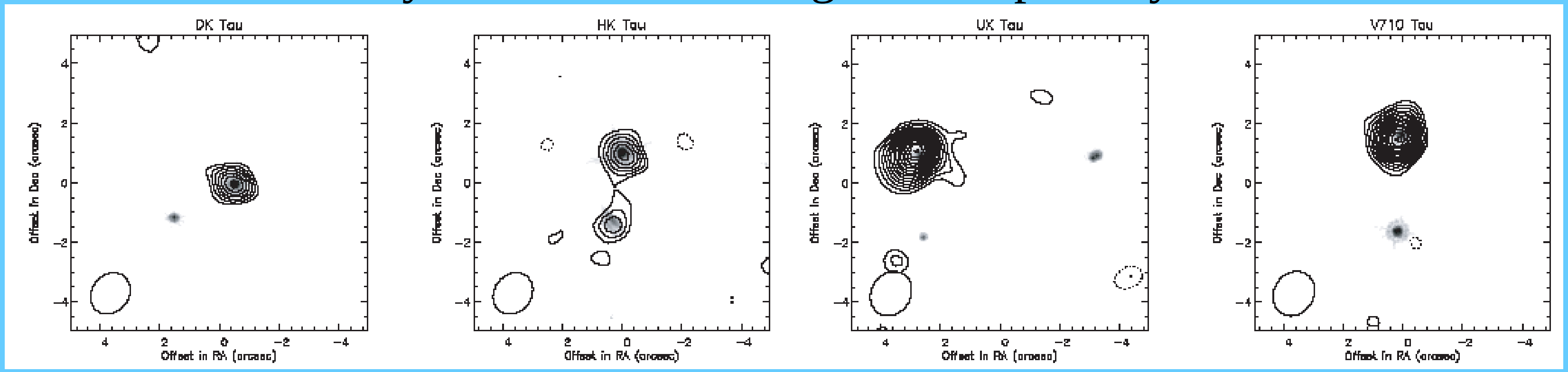



(Looney *et al.* 2000)




(Wooten 1989)

- **Taurus Class II** systems show a strong bias for primary disks

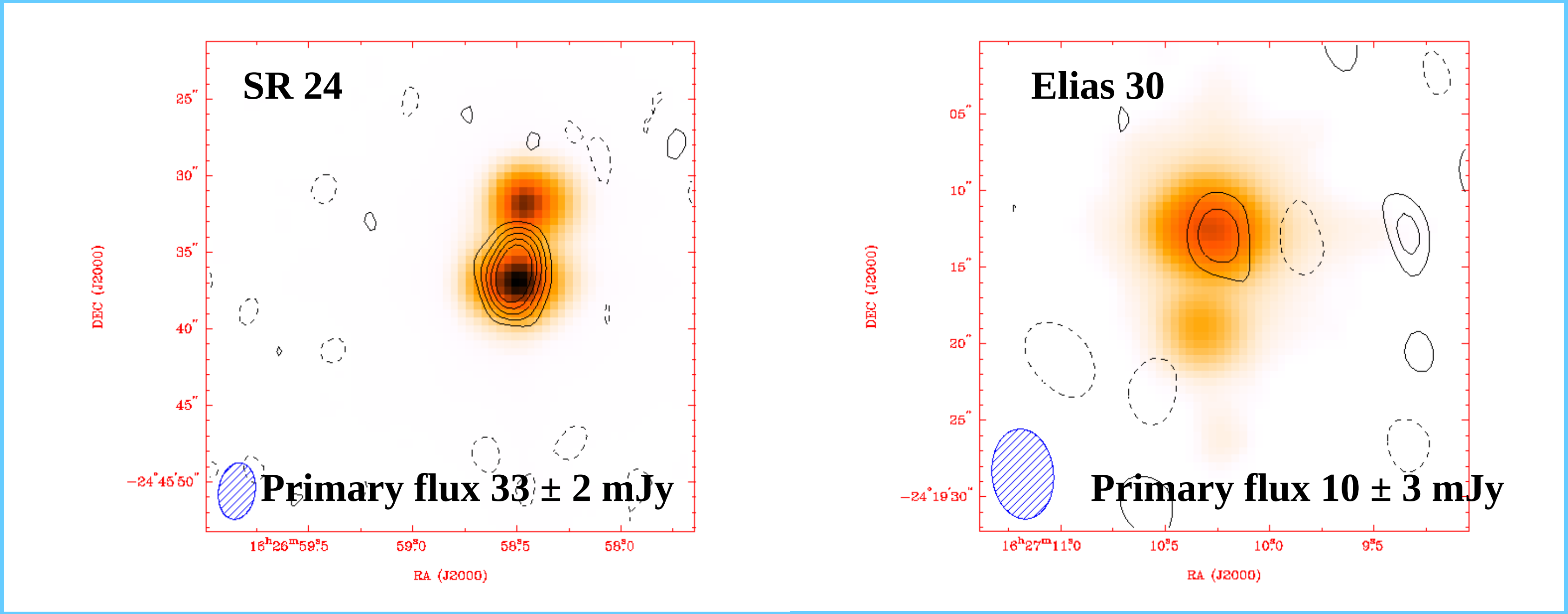



(Jensen & Akeson 2003)

What happens to disks during the **Class I/II** stage in **Ophiuchus** and **Class I** stage in **Taurus**?

# Ophiuchus Continuum Results

## Class II Targets

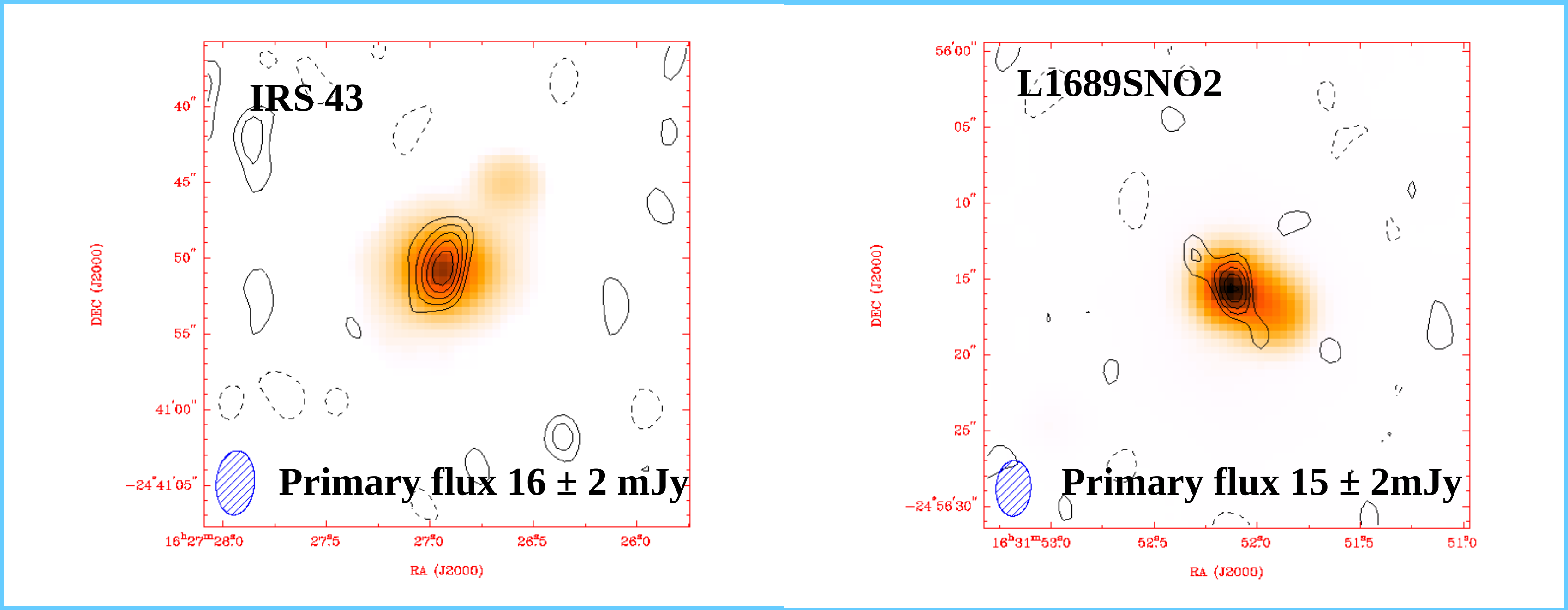



Millimeter emission dominated by primary
Similar results to Class II Taurus binaries

Contours - mm map
Image - 2MASS, alignment from absolute positions
Levels -2(dashed), 2, 3, 4, 5, 6 times RMS noise in map

# Ophiuchus Continuum Results

## Class I Targets




Millimeter emission dominated by primary even at earlier evolutionary stage

Circumsecondary disk masses very limited even at Class I stage

IR excesses, Hα indicate there is hotter, inner disk material and accretion

# Dust Opacity Scaling

Solve for power law index β $\kappa(\nu) = \kappa_o (\nu / \nu_o)^{\beta}$

Assign previously measured 1.3mm (240 GHz) flux to primary and combine with new 3mm (112 GHz) flux:

$$\beta = \frac{\log(F_{240GHz} / F_{112GHz})}{\log(240\ GHz / 112\ GHz)} - 2$$

β values range from **0.0 ± 0.2** to **1.6 ± 0.4**

within range of previous measurements of T Tauri stars

lower than ~2 expected from interstellar dust grains

Possible explanations: **grain growth**, differences in **composition/structure** of grains

# Disk Masses

Disk masses are calculated from the 3mm flux and the value of β

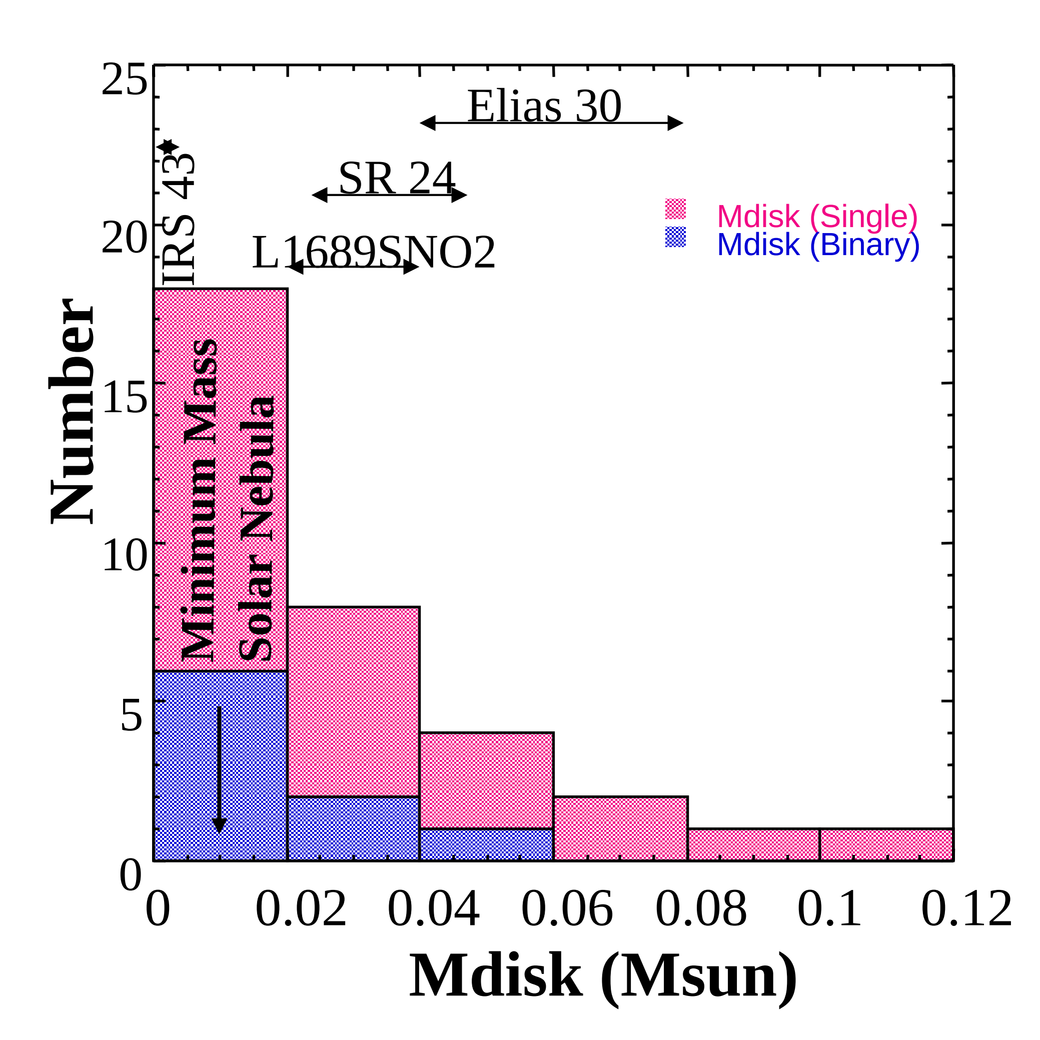
$$M_D\,(M_{sun}) = \frac{F_{3mm}\,(mJy)\,D^2\,(pc)}{6.4x10^7\,T\,(K)\,\kappa} \qquad \kappa(112GHz) = 0.01\,(112\ GHz\,/\,1000\ GHz)^{\beta}$$

This assumes that the material is optically thin

Optically thin


Optically thick

# Ophiuchus Disk Masses



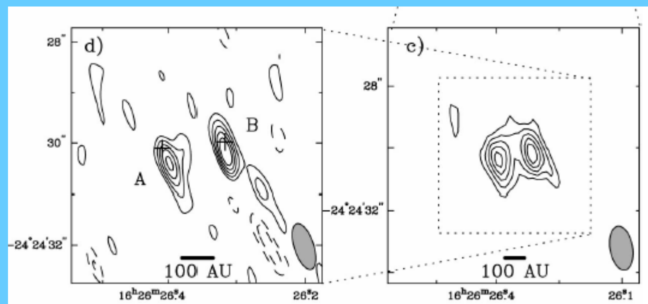

Disk masses shown with T=15-30K

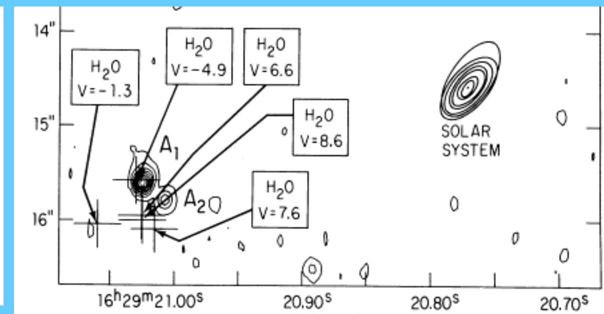
Comparable to disk masses measured for Taurus members based on single dish data

Comparable to Minimum Mass Solar Nebula

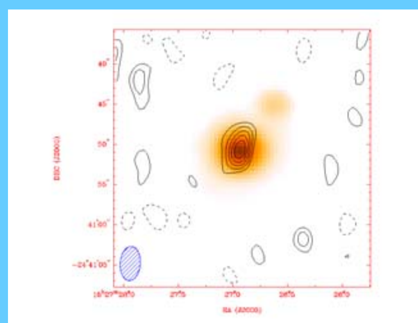
# Evolution of Dust Disks in Ophiuchus Binaries

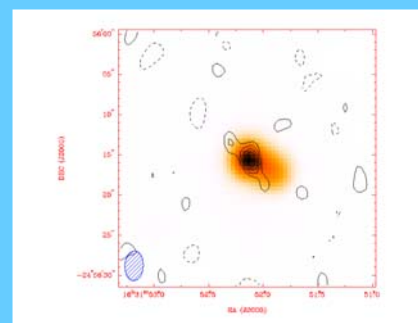
Class 0
(2 disks)



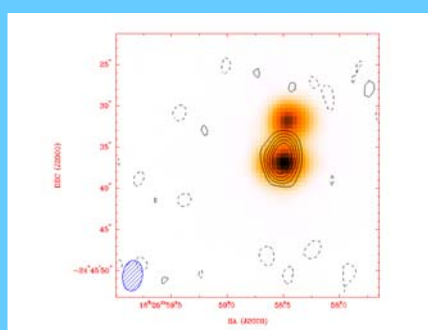



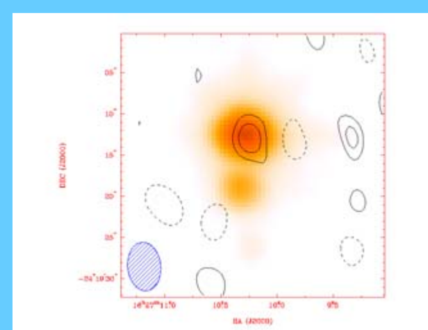

Class I
(1 disk)



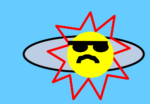


Class II
(1 disk)





What is the dissipation timescale for the secondary disk ?



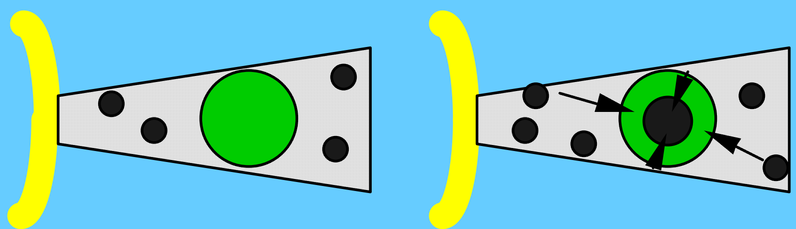
# Theoretical Disk Dissipation Timescales

Majority of secondary disk mass dissipated by Class I stage

How does this compare to planet formation timescales?

2 categories of giant planet formation models:

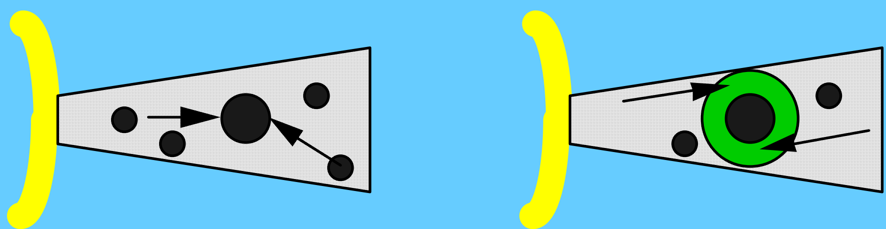
**Gravitational Instability**



Faster

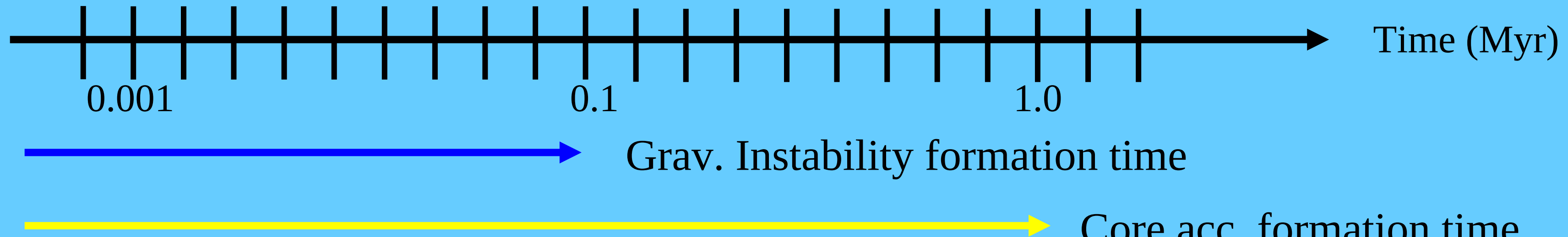
Boss 1997

**Core formation by accumulation**



Favored

Bodenheimer & Pollack 1986



# Ages of Class I/II Stars

Stellar Ages difficult to determine

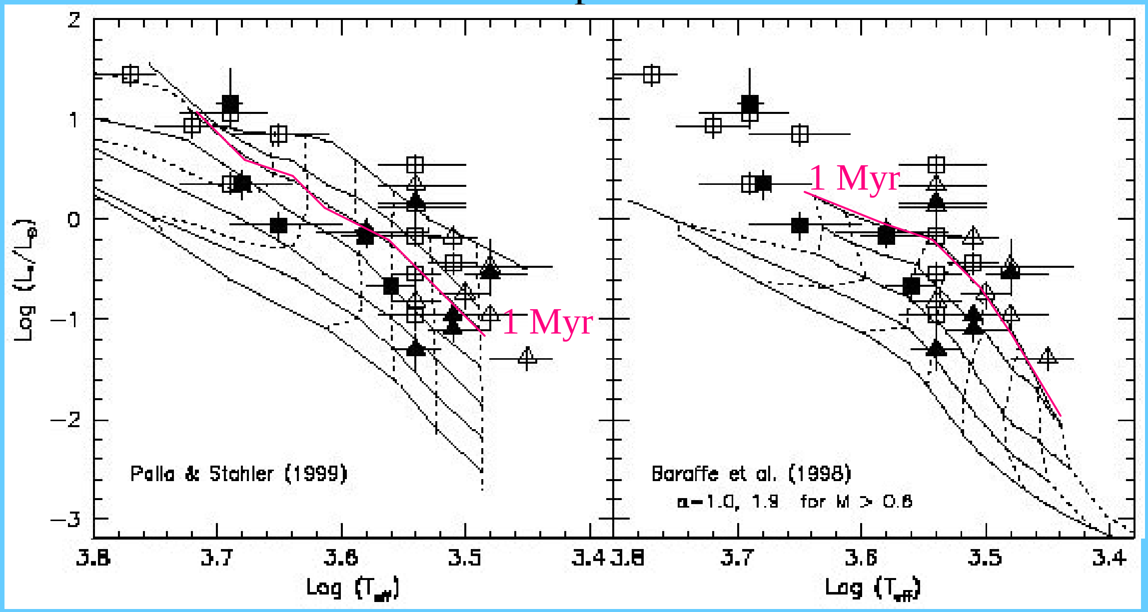
Class II ages from comparison with theoretical evolutionary tracks

- Stellar spectra determine temperature and luminosity
- Typical ages ~1-few Myr

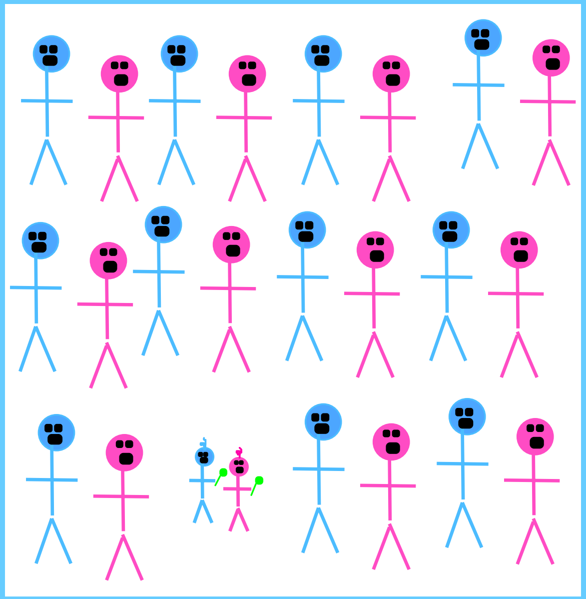
Class I ages often estimated statistically

- Difficult to detect photospheric features, but some detected
- 10-15% as many Class I objects as Class II objects

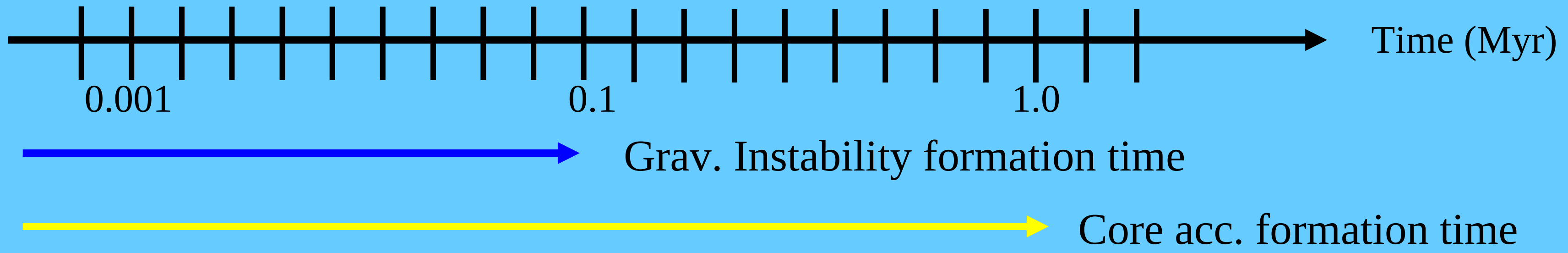
Lifetime based on comparison with models




Lifetime based on statistics



# Implications for Planet Formation



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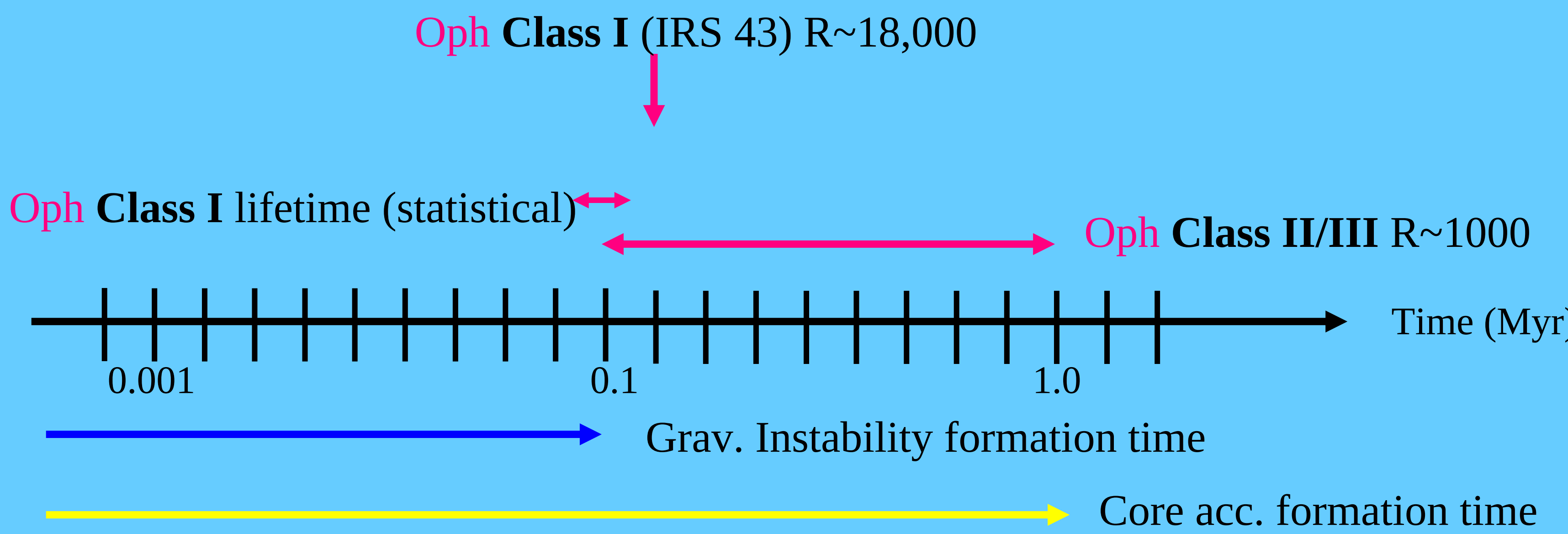
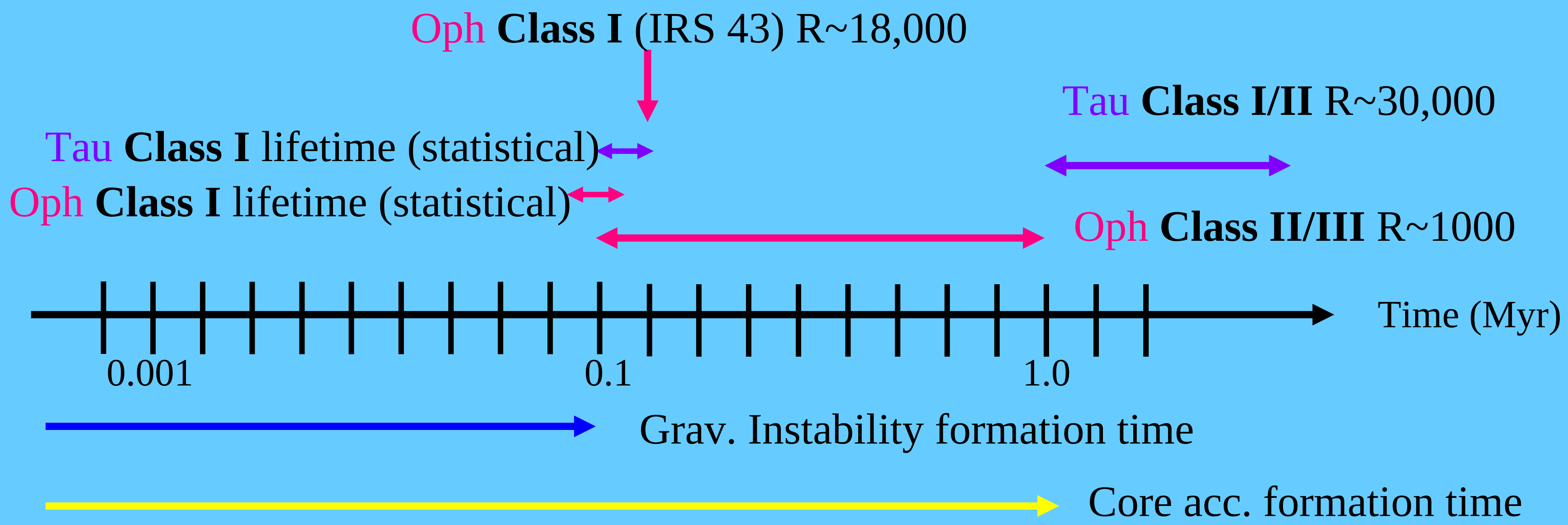



Oph: Luhman & Reike 1999, Greene & Lada 2002

# Implications for Planet Formation

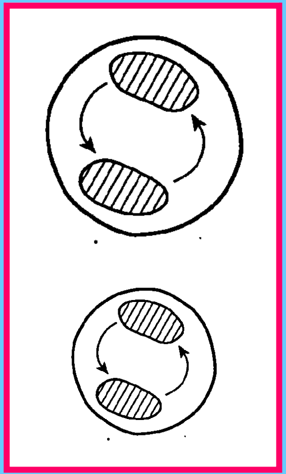



Oph: Luhman & Reike 1999, Greene & Lada 2002, Tau: White & Hillenbrand 2004

• If Class I systems are younger, then there may not have been sufficient time to form giant planets through the gradual accumulation of planetesimals

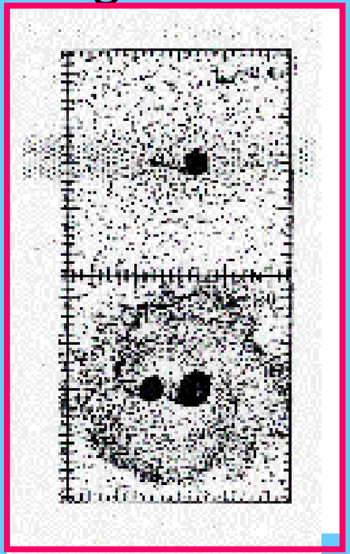
# Binary Formation Models

**Scale-free Fragmentation**



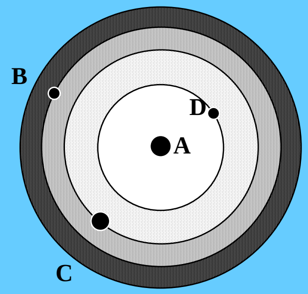
(Clarke 2000)

**Accretion after Fragmentation**



(Bate & Bonnell 1997, Bate 2000)

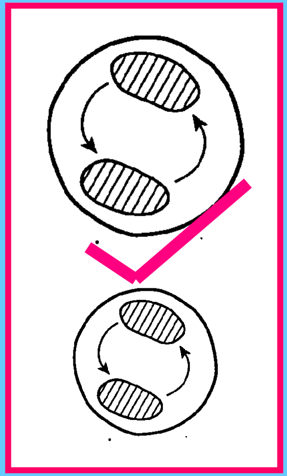
**Disk-assisted Small-N Capture**




(McDonald & Clarke 1995)

# Binary Formation Models

## Scale-free Fragmentation

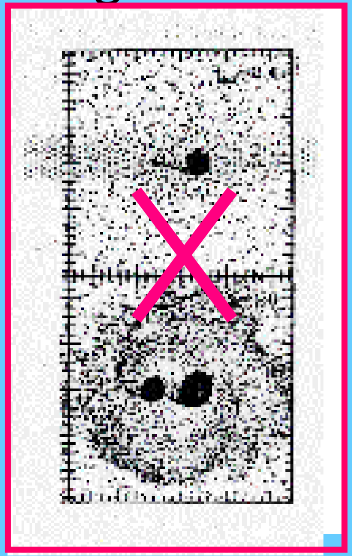


(Clarke 2000)

More massive star has more massive disk

**Consistent**

## Accretion after Fragmentation

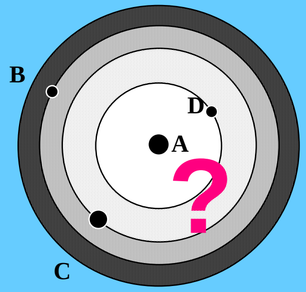


(Bate & Bonnell 1997, Bate 2000)

Disk mass ratio is a function of stellar mass ratio

**Inconsistent**

## Disk-assisted Small-N Capture




(McDonald & Clarke 1995)

Disruptive to disks, stronger effect for smaller separations

**Need larger separation range to test**

# Comparison with Radial Velocity Planets

Ophiuchus OVRO results show little disk material around secondaries relative to primaries -- how does this compare to the frequency of planets around secondaries relative to primaries?

**889** r.v. targets ⊗ CCDM catalogue

contains 65 planet stars (Nidever *et al.* 2002)

60” cutoff

→ **111** primaries → **4** planets = **4%**

→ **25** secondaries → **1** planet = **4%**

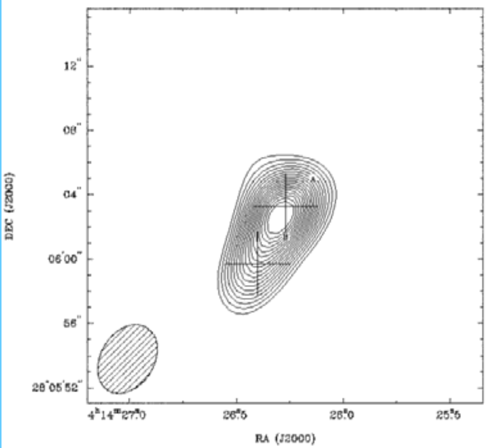
• Frequency of planets around secondaries appears similar to primaries despite differences in disk masses at earlier stages

Small number statistics for secondaries

# Taurus Continuum Results

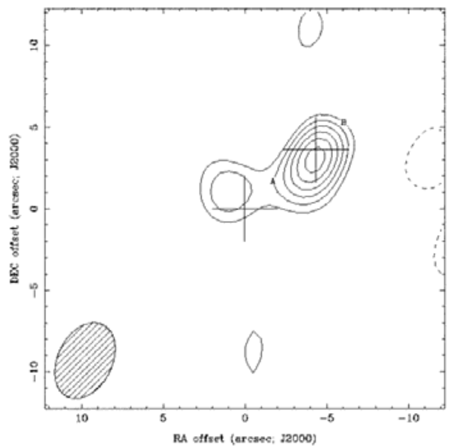
- Four Taurus Class I binaries observed
- Results different from Ophiuchus Class I/II and Taurus Class II

IRAS04113



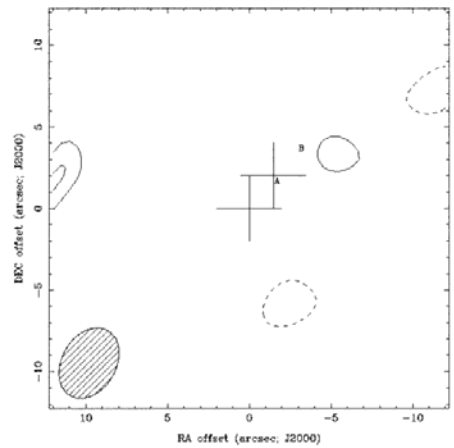

Primary and Secondary disks detected

IRAS04191



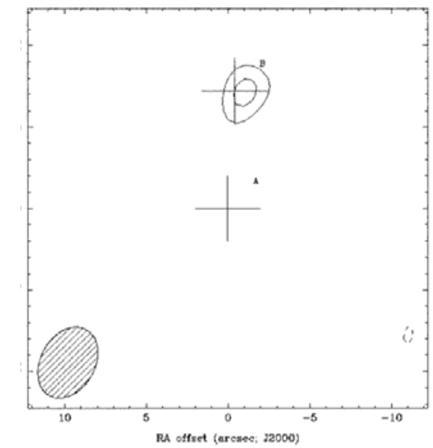

Strong secondary, Weaker primary

IRAS04248




Neither component detected

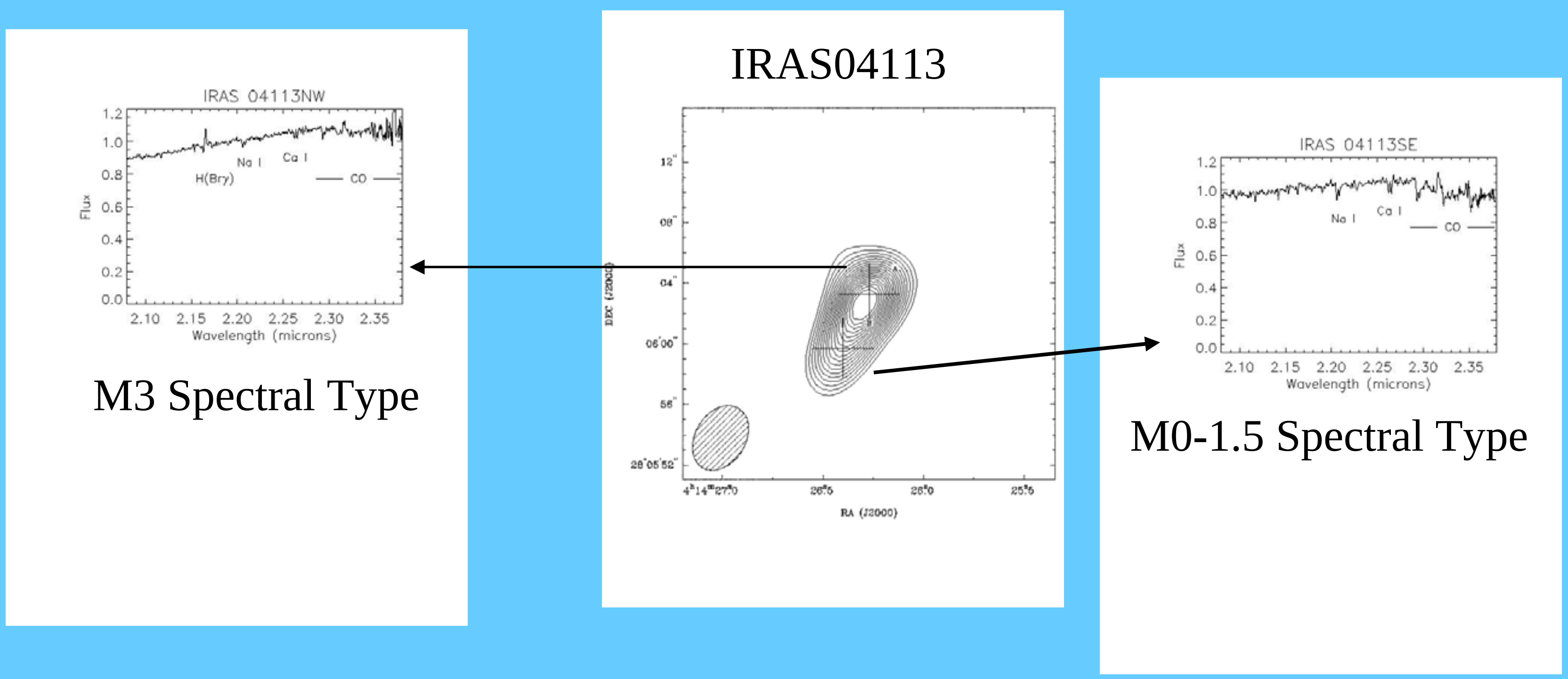
IRAS04325




Only secondary disk detected

# Taurus Continuum Results

- Possible explanations
  - Secondary star actually more massive
  - Small statistics skewed initial results
- Follow-up program to obtain spectra of each component

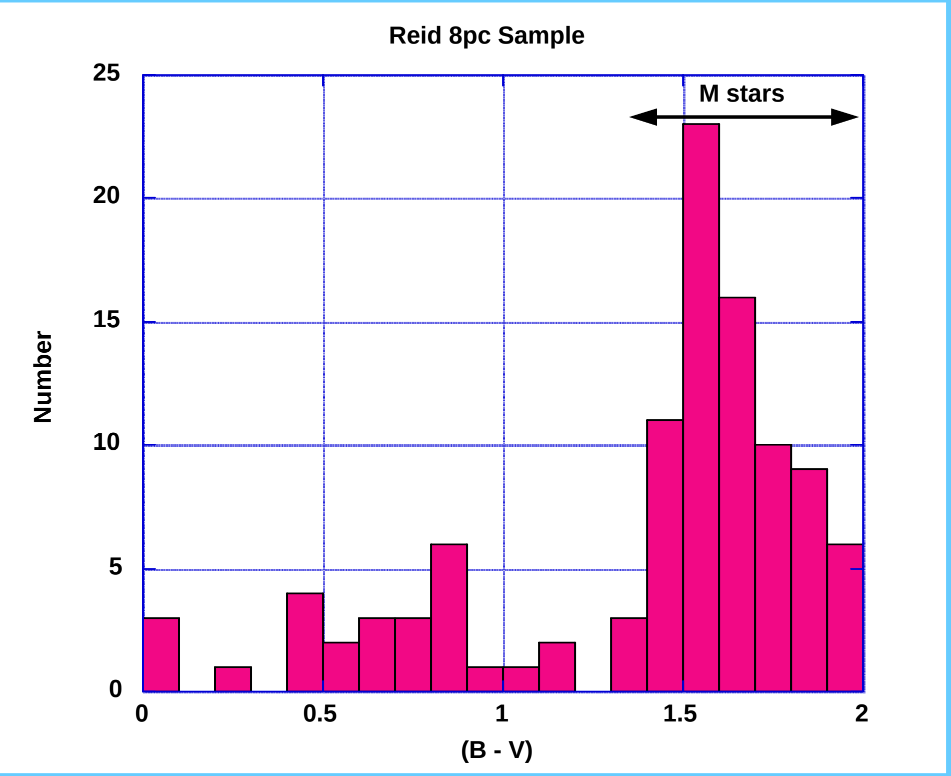


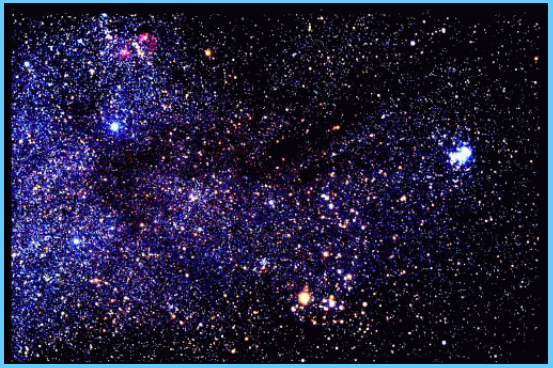
# Disks around Low-Mass Stars/Brown Dwarfs

## Motivation

M stars comprise the majority of stars
Nearest stars are predominantly M stars
May be good candidates for SIM/TPF targets

Submillimeter data detects disks around pre-Main Sequence Taurus M stars
Determine if initial conditions conducive to planet formation



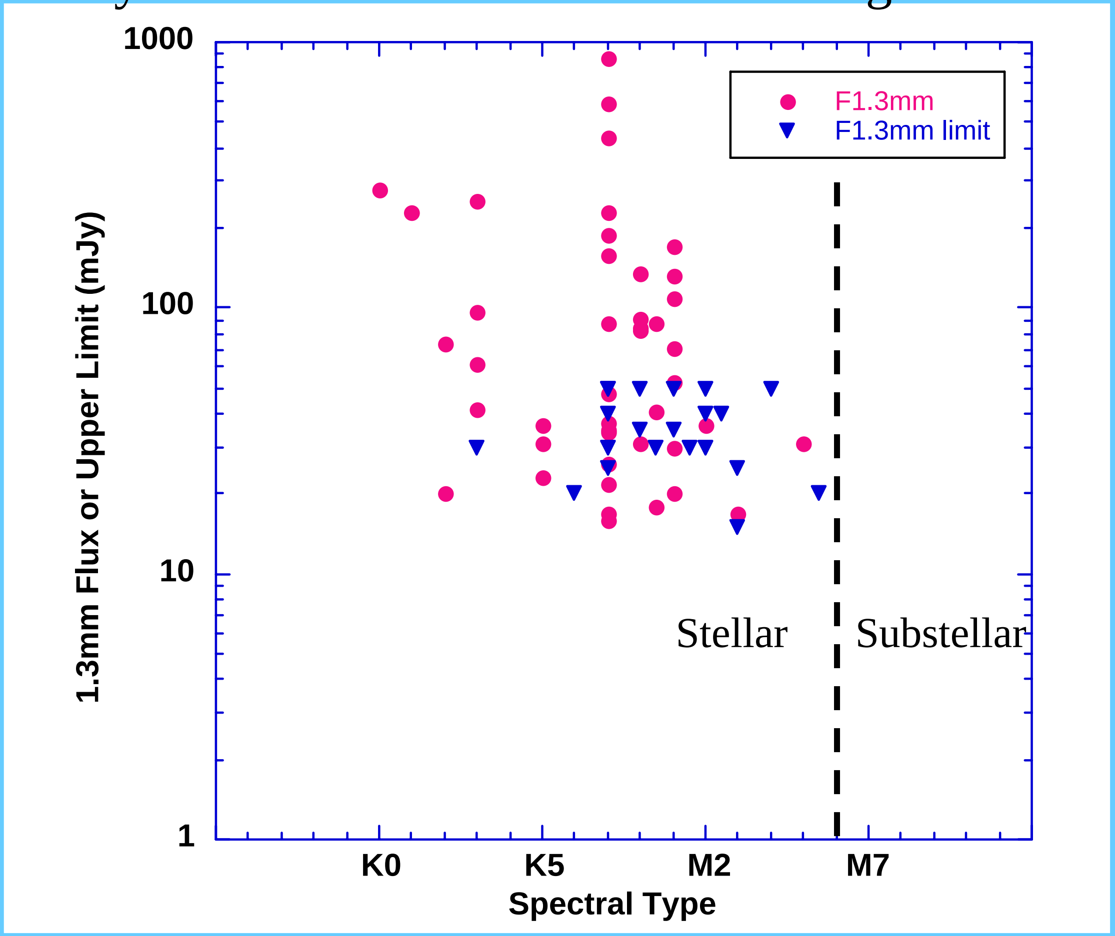



Taurus

# Background - Previous Measurements

Large surveys of Taurus concentrated on the higher mass members

(Beckwith et al. 1990)



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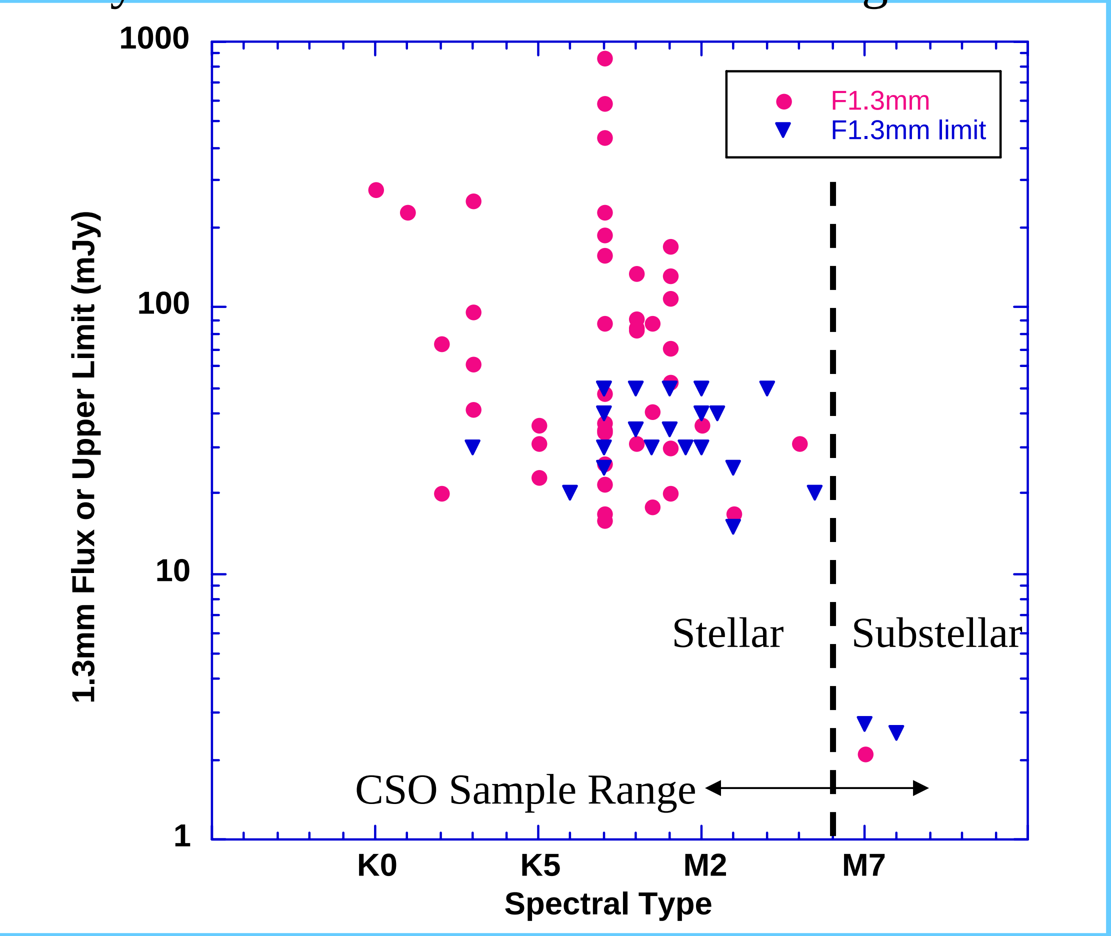



Recent detection of the first brown dwarf disk and upper limits (Klein et al. 2004)

**Project goals** - measure frequency/masses of disks around low mass stars

# Submillimeter Observations

Sample - Taurus members with spectral types M2 and later

Instrument - 10.4m Caltech Submillimeter Observatory (CSO)
SHARCII Camera (bolometer array) operating at 350μm
Beam size ~8”-9”

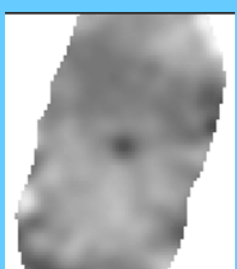
Submillimeter advantages: Higher flux relative to millimeter $F \sim \nu^2$
No contrast problem with stellar photosphere

# Submillimeter Observations - Initial Results

Initial Sample - known single star (no speckle/HST companion)
highest Hα equivalent width (accretion) for its Spectral Type

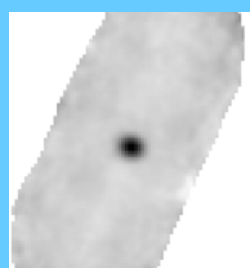
All stars detected, upper limit for brown dwarf

DE Tau
**M2**



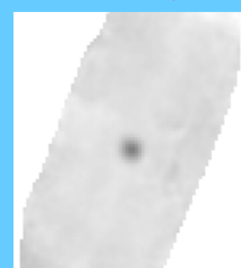
202 mJy

PSC04158
**M3**



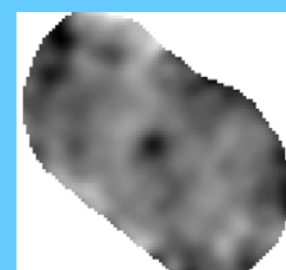
2 Jy

ZZ Tau IRS
**M4.5**



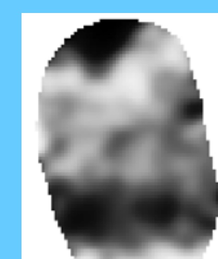
1 Jy

CIDA 1
**M5.5**



70 mJy

CFHT BD4
**M7**

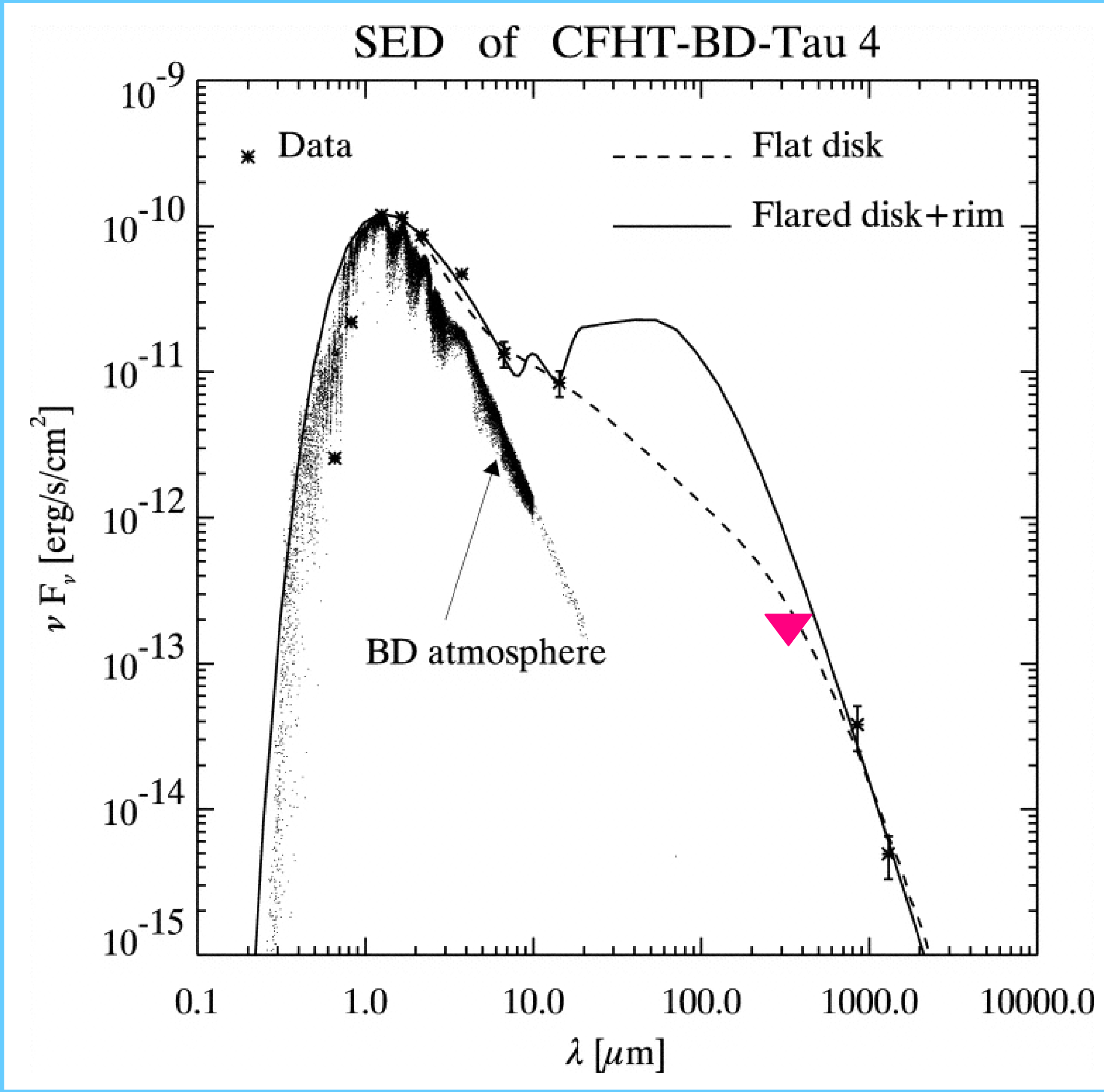


<20 mJy

← Stars | Brown dwarf

Images on inverted scale

# Submillimeter Observations - Initial Results



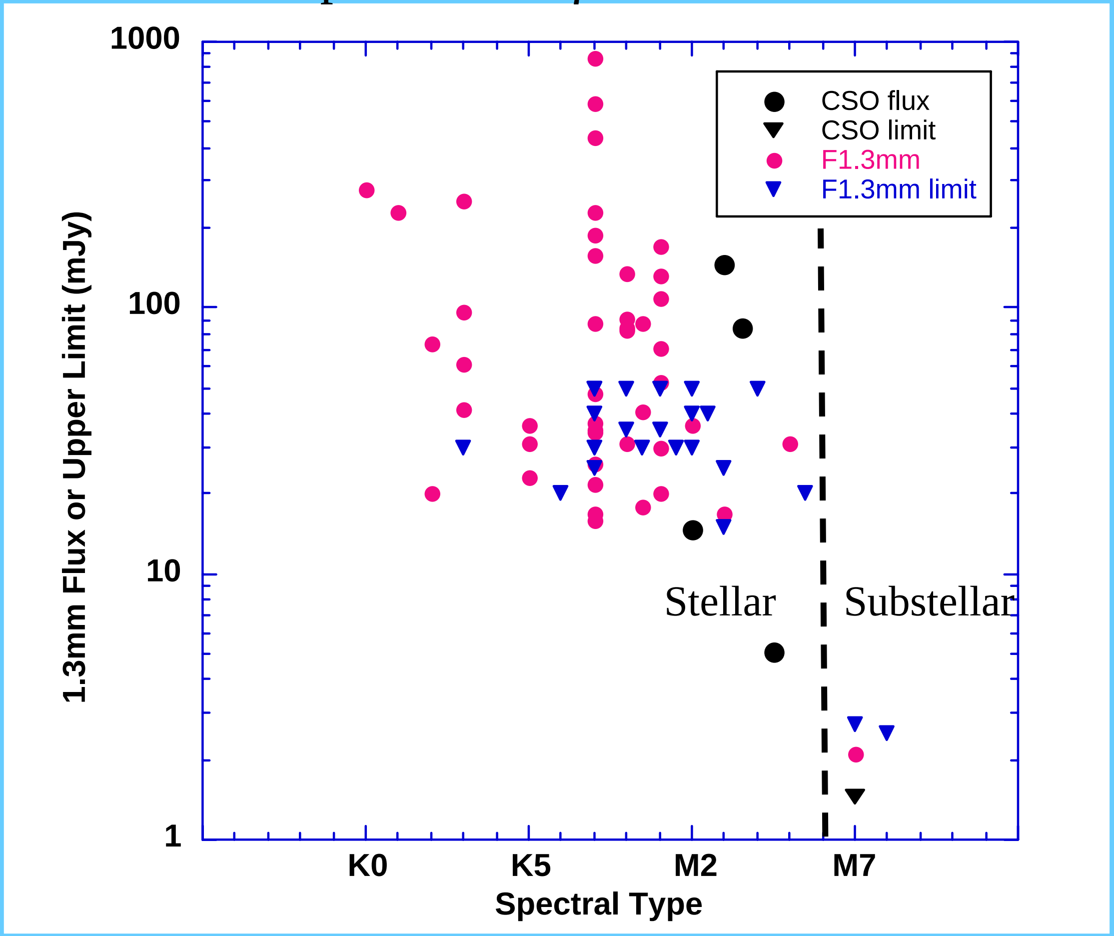

350μm data more consistent with flat disk model

Figure adapted from from Pascucci et al. 2003

# Submillimeter Observations - Initial Results

Revised plot including CSO data

(for ease of comparison 350μm fluxes scaled to 1.3mm assuming $F \sim \nu^2$)




More time scheduled this semester to increase sample

# Summary and Conclusions

## Infrared Interferometry

• T Tauri targets resolved with the Keck interferometer

Inner disk sizes larger than or similar to dust destruction radius

Planets with smaller semimajor axes implies gas remains at smaller radii

## Millimeter Interferometry

**Ophiuchus:**

• Primary dominates mm emission for both Class I and Class II sources

• Circumprimary disk masses comparable to other single/binary T Tauri stars and the Minimum Mass Solar Nebula

• Circumsecondary disk masses very limited even at early evolutionary stage

may be difficult to form planets around these stars

• Dust opacity index for primary disks is within the range of previous estimates and smaller than expected for interstellar dust grains

**Taurus:**

• Secondary disks often detected in Class I binaries, unlike Ophiuchus results

## Submillimeter Imaging

• Taurus M stars detected, brown dwarf upper limit only

• Brown dwarf upper limit more consistent with a flat disk model