5. Protoplanetary Disks

Stellar evolution

Circumstellar disks are found:

• at all stages of stellar evolution, from proto-stars to post main sequence stars (Su et al. 2007)

• around stars of all mass, from free-floating planets of $8M_{Jupiter}$ (Luhman et al. 2005; Jayawardhana & Ivanov 2006) to OB stars of $26M_{sun}$ (Chini et al. 2006)

Dark cloud cores

1 pc

t = 0

Gravitational collapse

10,000 AU

t~10^4 – 10^5 years

Protostar, embedded in 8,000 AU envelope, disk, outflow

t~10^5 –10^6 years

T Tauri star, disk, outflow

100 AU

t~10^6 –10^7 years

Pre-main-sequence star, remnant disk

100 AU

t > 10^7 years

Main-sequence star, planetary system (?)

50 AU
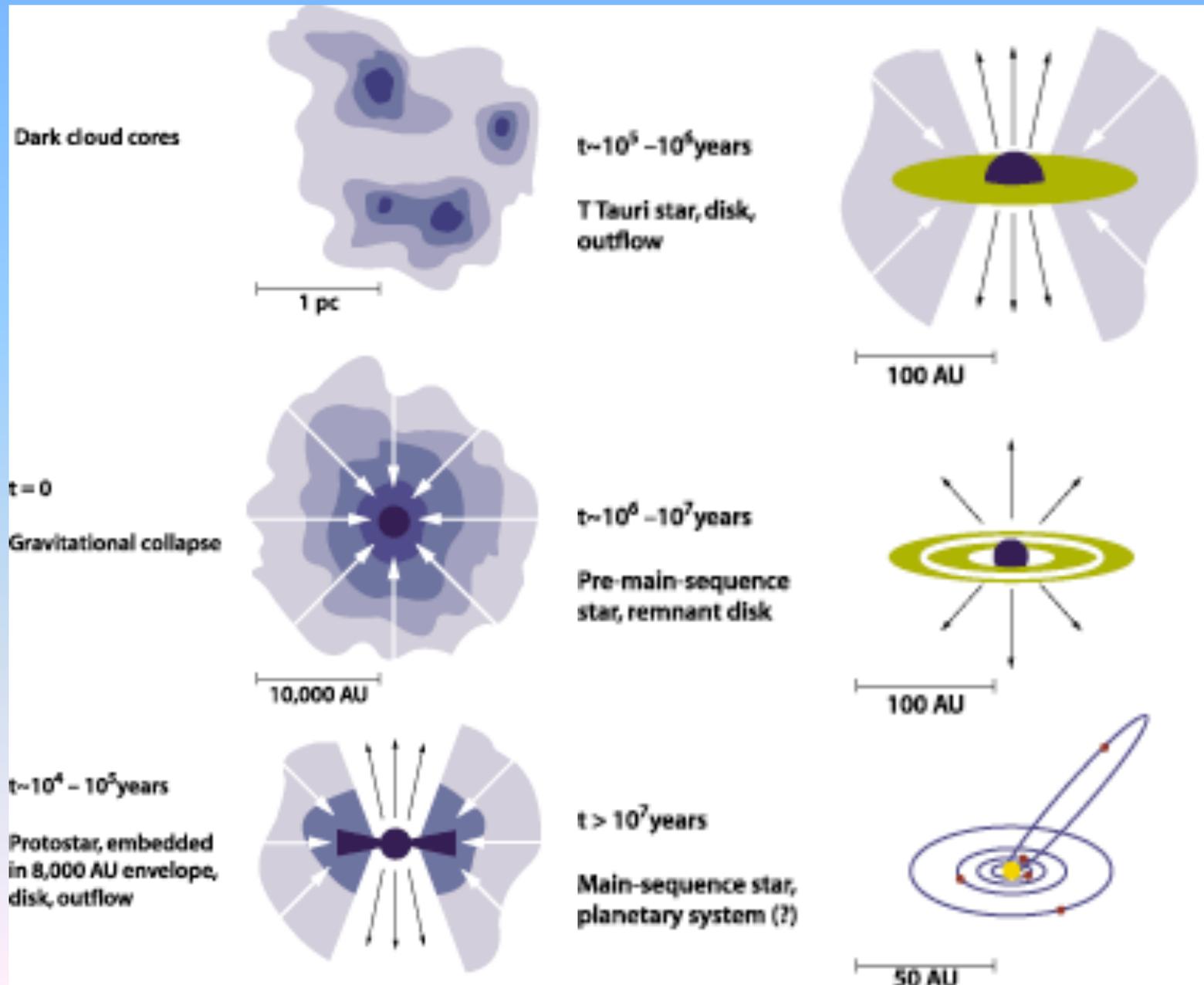
Disk composition

There are two components in a disk:

- **gas**
    - range of species (e.g., CO, H_2)
    - detected by line emission or in absorption in front of the star

- **dust**
    - range of compositions (silicate/graphite/PAHs/ices)
    - range of sizes (sub-μm to planets)
    - detected by scattered starlight, or thermal emission

Pre-main sequence protoplanetary disks: have gas and dust at 0.1-100AU, optically thick, last 10 Myr, primordial

Main sequence debris disks: have only dust at one radius (~30AU), optically thin, replenished

Wavelength vs radius probed

Circumstellar disks have been studied at all wavelengths from optical to cm
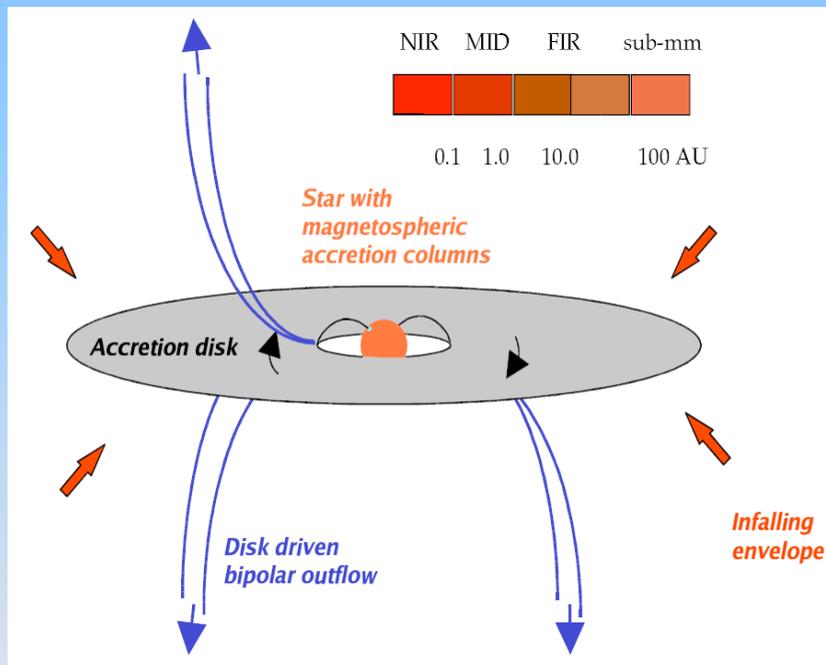
Different wavelengths probe different locations in the disk; e.g., thermal emission from an optically thin disk, assuming black body grains:

$$T_{dust} = 278.3 \, L_*^{0.25}/r^{0.5}$$

$$\lambda_{peak} = 2898\mu m/T = 10.4 r^{0.5}/L_*^{0.25}$$

$$r_{probed} = 0.01\lambda^2 L_*^{0.5} \; AU$$

NIR=0.1AU, MIR=1AU, FIR=30AU, SUB=1000AU (though smaller as not observed at peak)

Wavelength vs dust size probed

Thermal emission: $F_\nu \propto \sigma_{tot} Q_{em} B_\nu(T)$
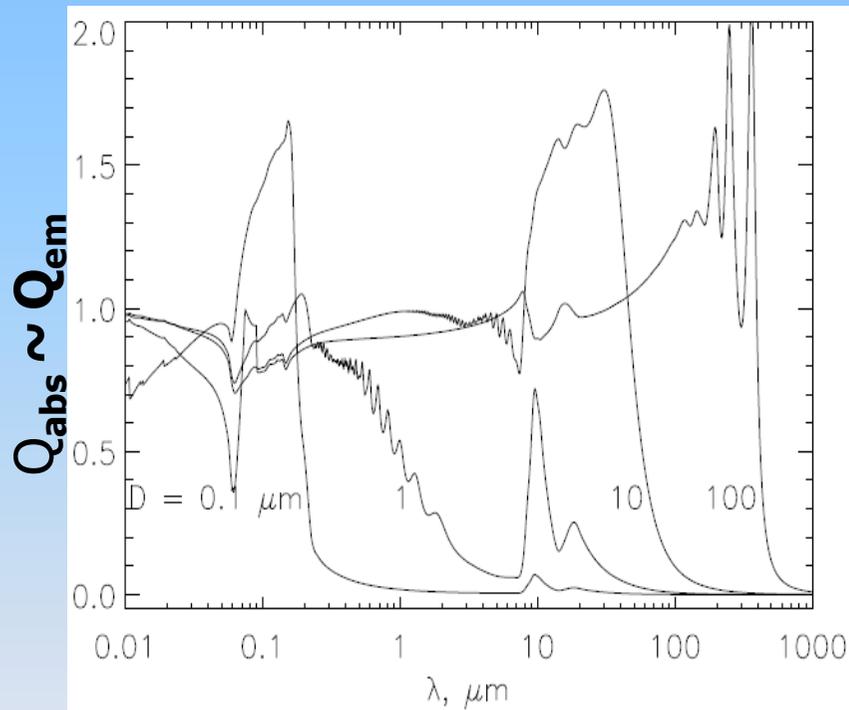
Grains emit:
- efficiently at short wavelengths
  $\lambda < D$: $Q_{em} = 1$
- inefficiently at long wavelengths
  $\lambda > D$: $Q_{em} = (D/\lambda)^n$

Observations at different wavelengths:
- probe different dust sizes
- tell us about the size distribution

Rule of thumb:
- $\lambda < 100 \mu m$ probes smallest (few μm) grains
- $\lambda > 100 \mu m$ probes grains of size $D \approx \lambda$

Problem of number of nearby stars

Local stellar density is low, ~0.27/pc^3, meaning:

(1) There are few nearby young stars

- average lifetime of 10Gyr implies nearest star <10Myr is ~16pc

- stars form in clusters of hundreds; nearest ones are at 140pc

- hard to find 10-100Myr as no youth indicators (molecular cloud)

- young star streams (e.g., TWHya association, β Pic moving group)

(2) There is a finite number of stars amenable to resolved imaging with current telescopes, so advances in resolution (and/or sensitivity) are required

Accretion diagnostics: CTTS

Disks of pre-main sequence stars first inferred from strong vis/UV emission lines (Joy 1945, Herbig 1962): Hα, HeI, OI, NaD, CaII
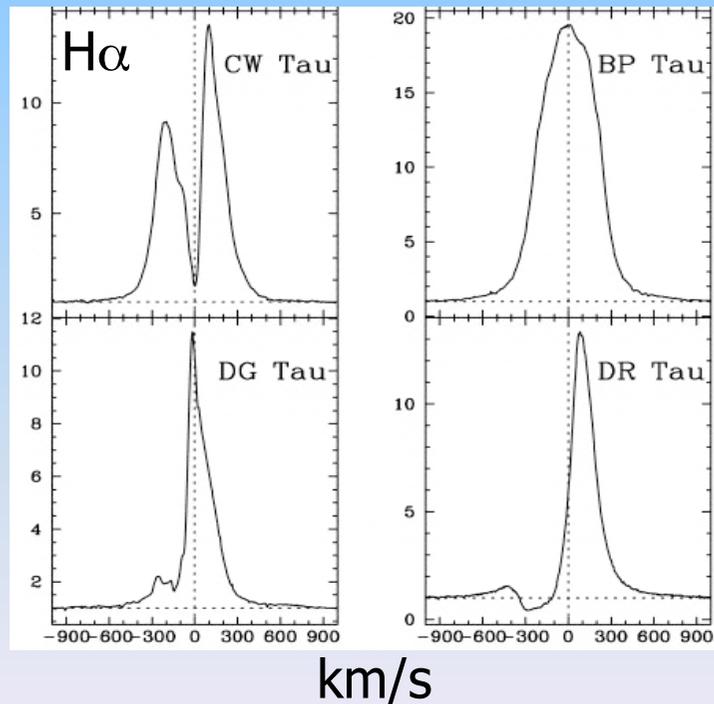
Magnetospheric accretion: accretion disk disrupted by stellar magnetic field means material falls onto star along field lines (Uchida & Shibata 1985)

km/s
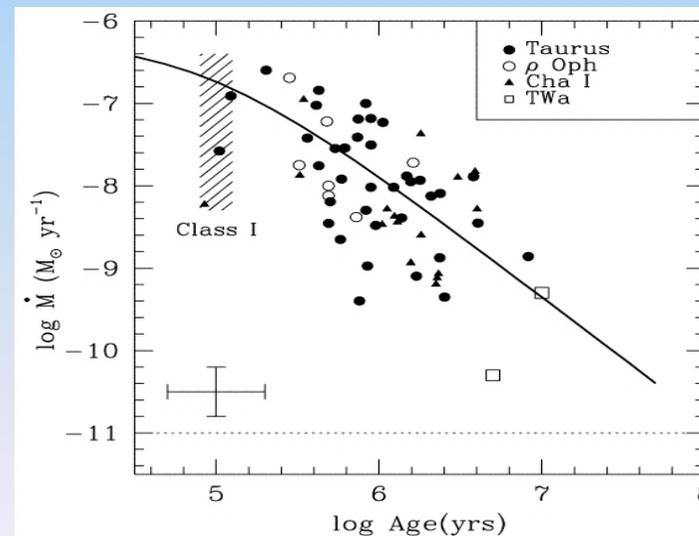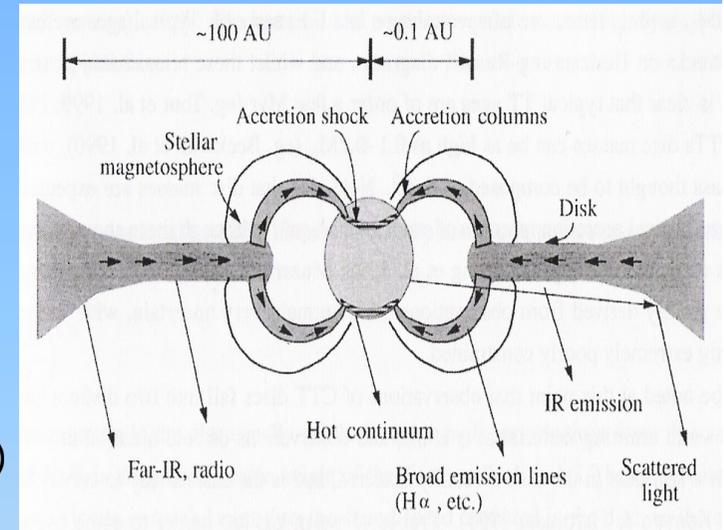
Modelling emission lines gives mass accretion rate of ~$10^{-8}M_{sun}$/yr, falling with age

Classical T Tauri stars (CTTS) (accreting stars) lie in clusters (T associations)

X-rays: WTTS

CTTS are strong X ray sources, indicative of strong magnetic activity (Ku & Chanan 1979), but X-rays do not correlate with the presence of a disk (Rebull et al. 2006)

Weak-line T Tauri stars (WTTS):
Several stars without accretion, but strong X rays spatially coincident with CTTS (Walter et al. 1998)

Naked T Tauri stars (NTTS): another name for WTTS (i.e., young stars with no disk). Generally assumed CTTS evolve into WTTS

Many WTTS discovered recently by ROSAT/Chandra surveys (e.g., Huelamo et al.; Fiegelson et al.)
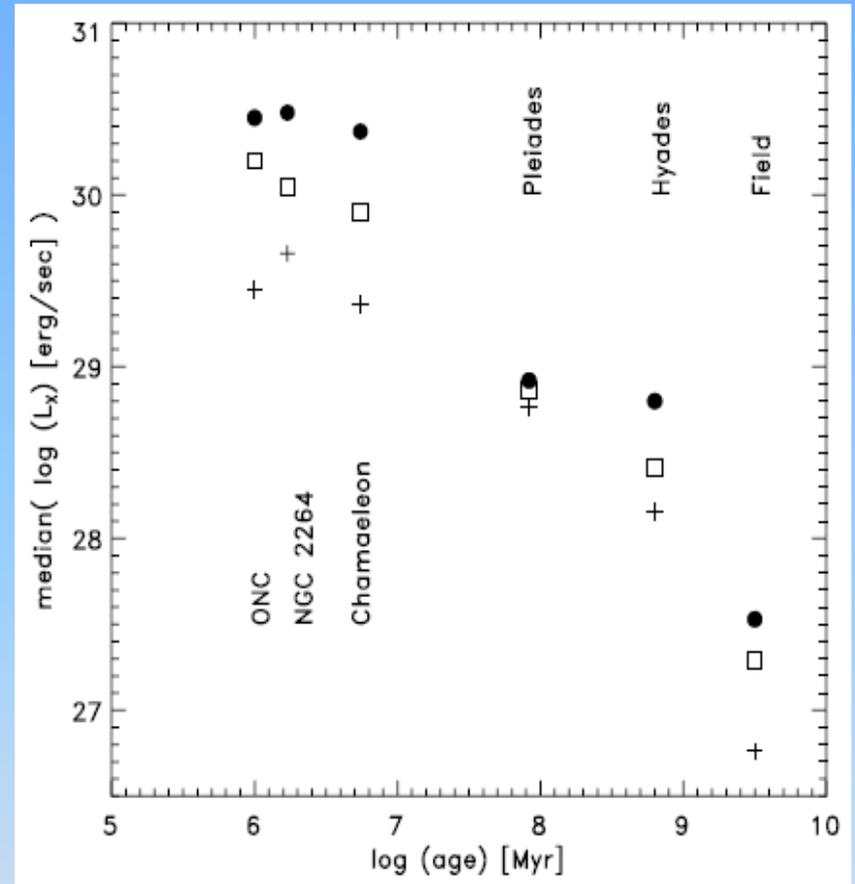
Accretion vs stellar mass: HAeBes

Herbig AeBe stars (HAeBes):
high mass (1.5-10M$_{sun}$) counterparts to CTTS, A/B stars with emission lines and nearby nebulosity

Evidence for accretion from analysis of emission spectrum $10^{-5 \text{ to } -6}$M$_{sun}$/yr (Hillenbrand et al. 1992), or line profiles 10^{-8}M$_{sun}$/yr (Muzzerole et al. 2004)

NB, any X-rays likely to come from late-type companions (Stelzer et al. 2006)
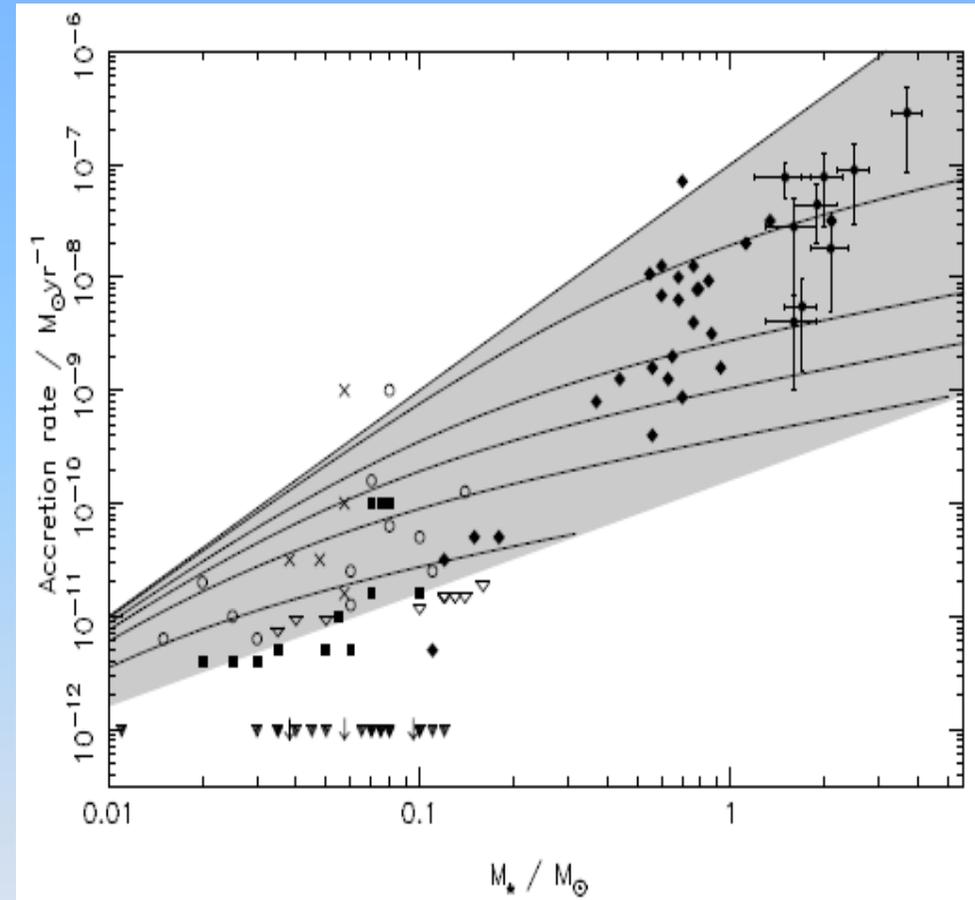
Across the mass spectrum: **dM$_{acc}$/dt ∝ M$_*$²** (Muzzerole et al. 2005; Natta et al. 2006), perhaps evidence for low mass stars having larger disks (Alexander & Armitage 2006) or just selection effect (Clarke & Pringle 2006) or magnetic activity of low mass stars (Hartmann & D'Alessio 2006) or outcome of star formation (Dullemond et al. 2006)

Indirect disk evidence: stellar rotation

Rotation periods of PMS stars are evidence for disks (Herbst & Mundt 2005):

• rotation known from starspots

• periods of stars in clusters of different ages gives evolution of specific angular momentum corrected for stellar evolution (contraction, wind losses)

• see also Irwin et al. 2008

1Myr
2Myr
50Myr
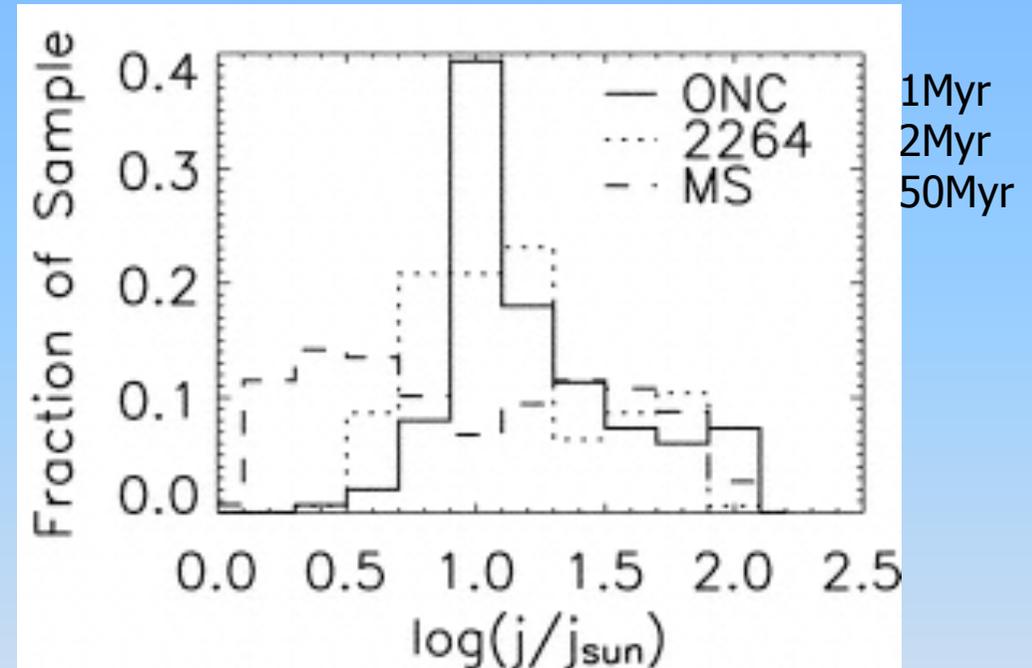
• 50-60% of stars conserve angular momentum on PMS, spinning up as they contract = rapid rotators on MS

• 40-50% of stars lose most angular momentum = slow rotators on MS

Slow rotators are those with disks which locked stellar rotation

Backed up by fewer slow rotators in high density regions (Wolff et al. 2007) and faster rotation for diskless stars (Rebull et al. 2006; Kundurthy et al. 2006)

Near-IR photometry

Near-IR excess is evidence for hot dust and is found using colour-colour plots:

$$m = -2.5\log(F/F_0)$$
$$m_a - m_b = 2.5\log[(F_a/F_b)(F_{b0}/F_{a0})]$$
$$\sim 0 \text{ for photospheric emission}$$

although spectral type dependence and reddening from intervening dust, and problems identifying remnant envelope (Hartmann et al. 2005) and unseen binary companions (Torres 2005)

In general stars classified as CTTS have near-IR excesses, while WTTS don't

Hartmann et al. (2005)

Kenyon & Hartmann (1995)
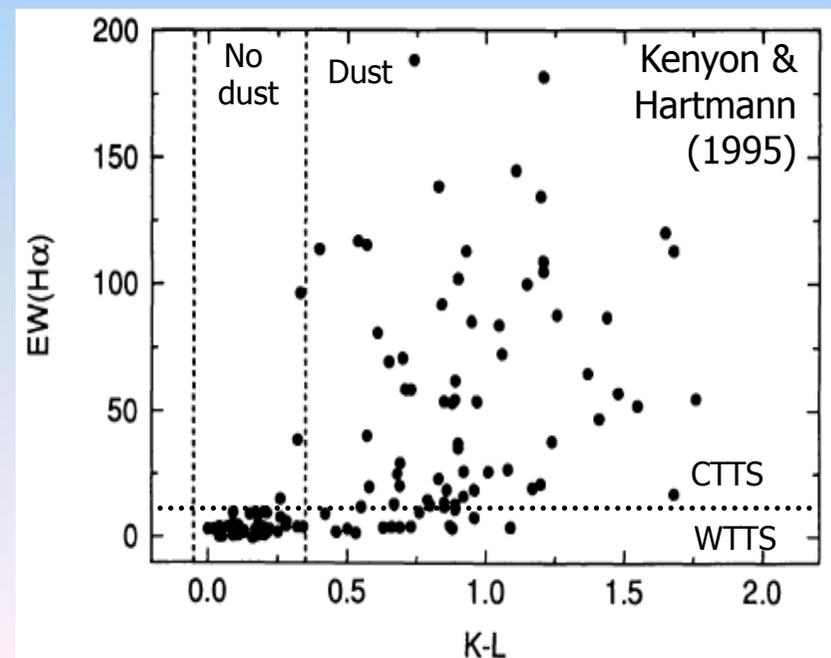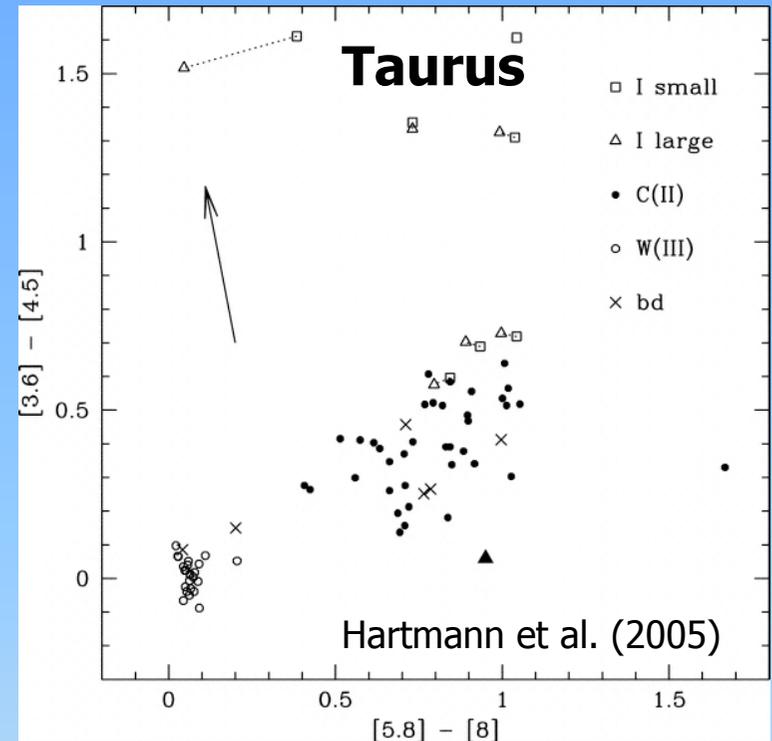
Transition

Stars either have disks, or they don't, meaning transition from disky to diskless is fast (~0.1Myr) compared with disk lifetime (~10Myr) (Hartmann et al. 2005; Silverstone et al. 2006)

• Transition objects are seen at higher rate in old clusters (Megeath et al. 2006)

• Very few CTTS are diskless, while most WTTS are diskless (Padgett et al. 2006), meaning more likely for dust to persist without gas than vice versa (Lada et al. 2006)

• Disks of low mass stars last longer than those of high mass stars (Currie et al. 2007)

ηCha 5-9Myr
Megeath et al. (2006)

h & χ Per 13Myr
Currie et al. (2007)
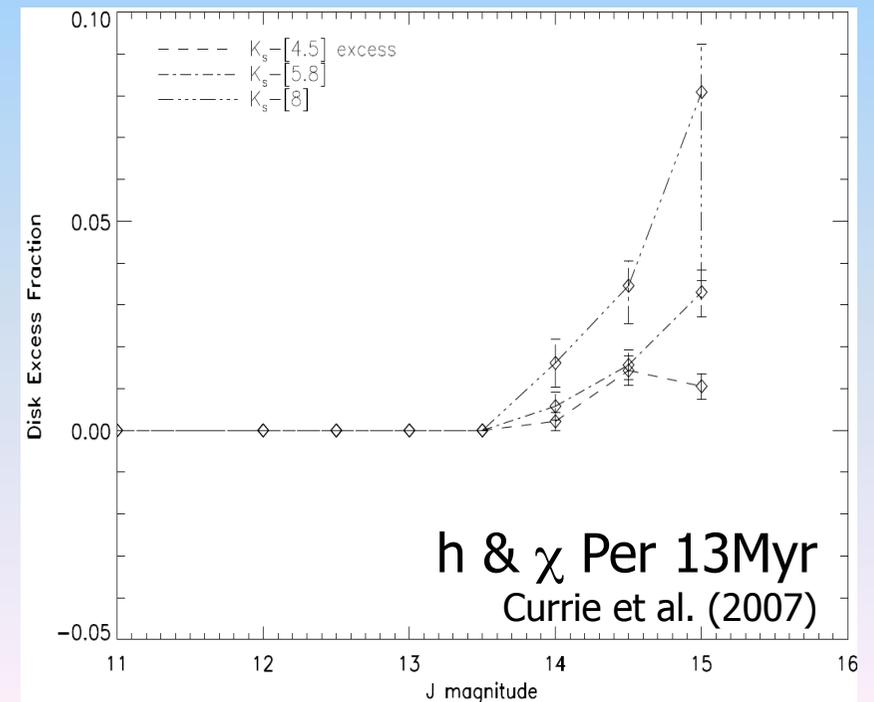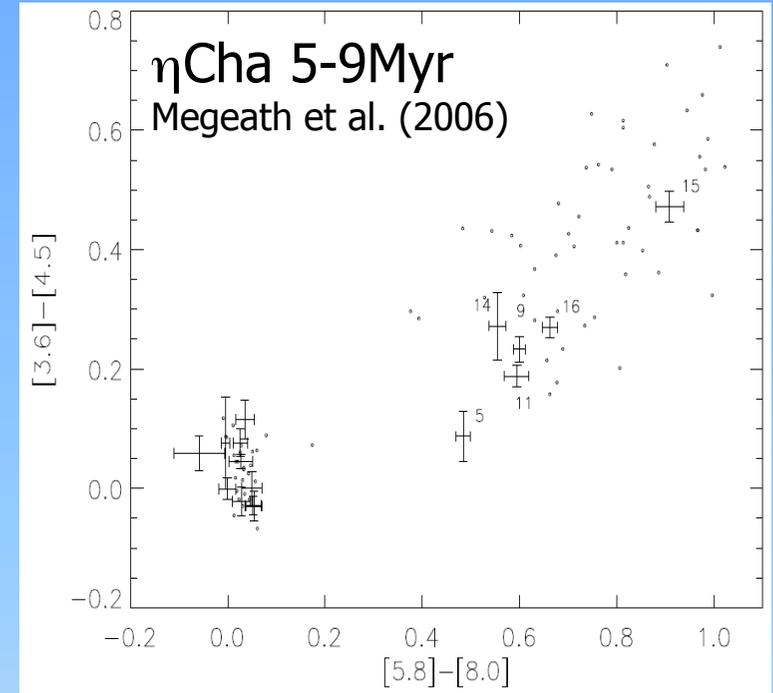
Inner disk lifetimes

Fraction of stars with JHKL excess declines from ~100% to 0% over 6Myr

(Haisch, Lada & Lada 2001)

This means hot dust at 0.1AU disappears in 6Myr which constrains the time over which planet formation must occur

NB: Doesn't imply disk luminosity decreases monotonically with time, rather disk lifetimes lie in the range 0-6Myr
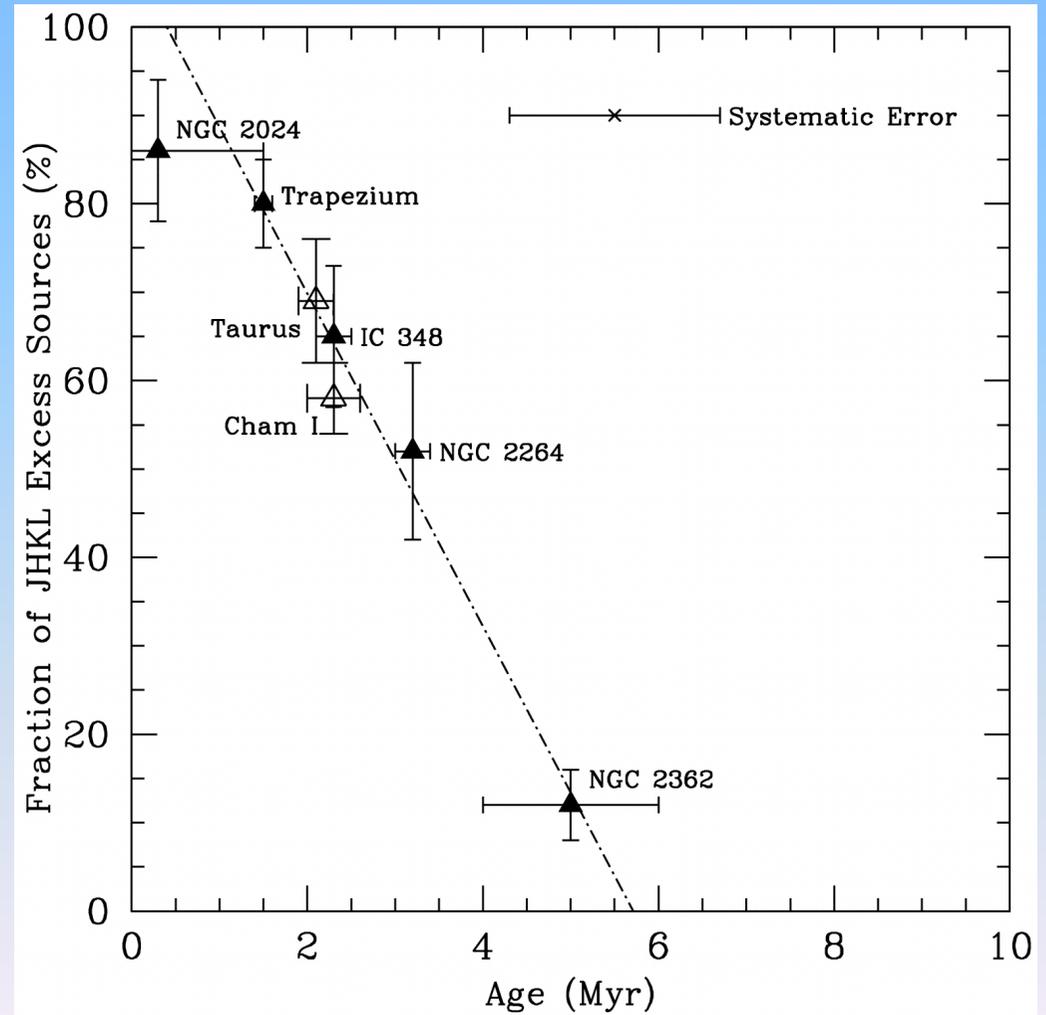
Spectral type dependence

Brown dwarfs have excess ratios like sun-like stars implying same formation mechanism (Luhman et al. 2005) , but debate whether fraction of stars with disks is function of spectral type, (Lada et al. 2006; Oliveira et al. 2006; Riaz et al. 2006; Scholz et al. 2007; Currie et al. 2007; see Kennedy & Kenyon 2009)

Natta et al. (2001)

2-3Myr Lada et al. (2006)
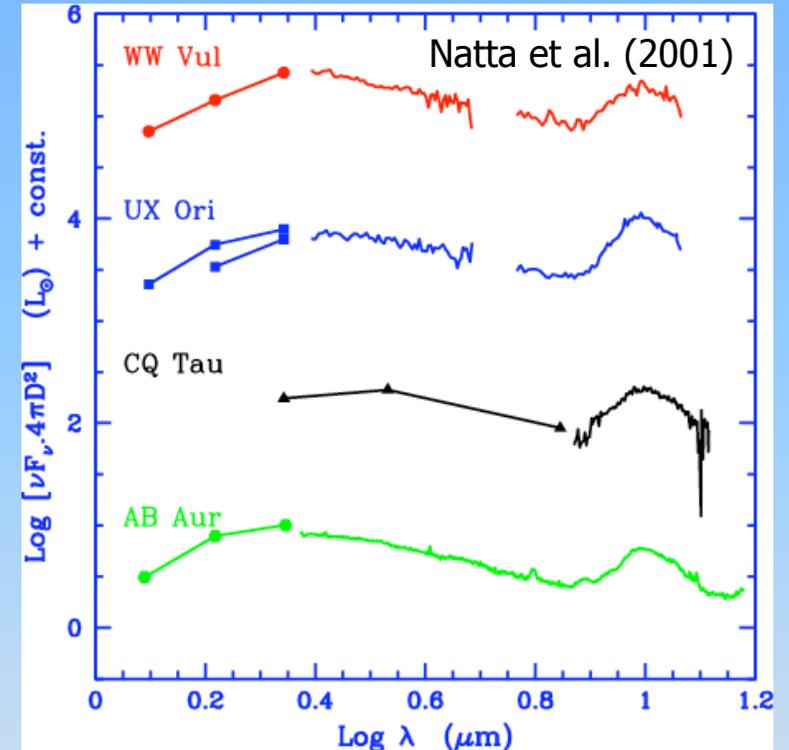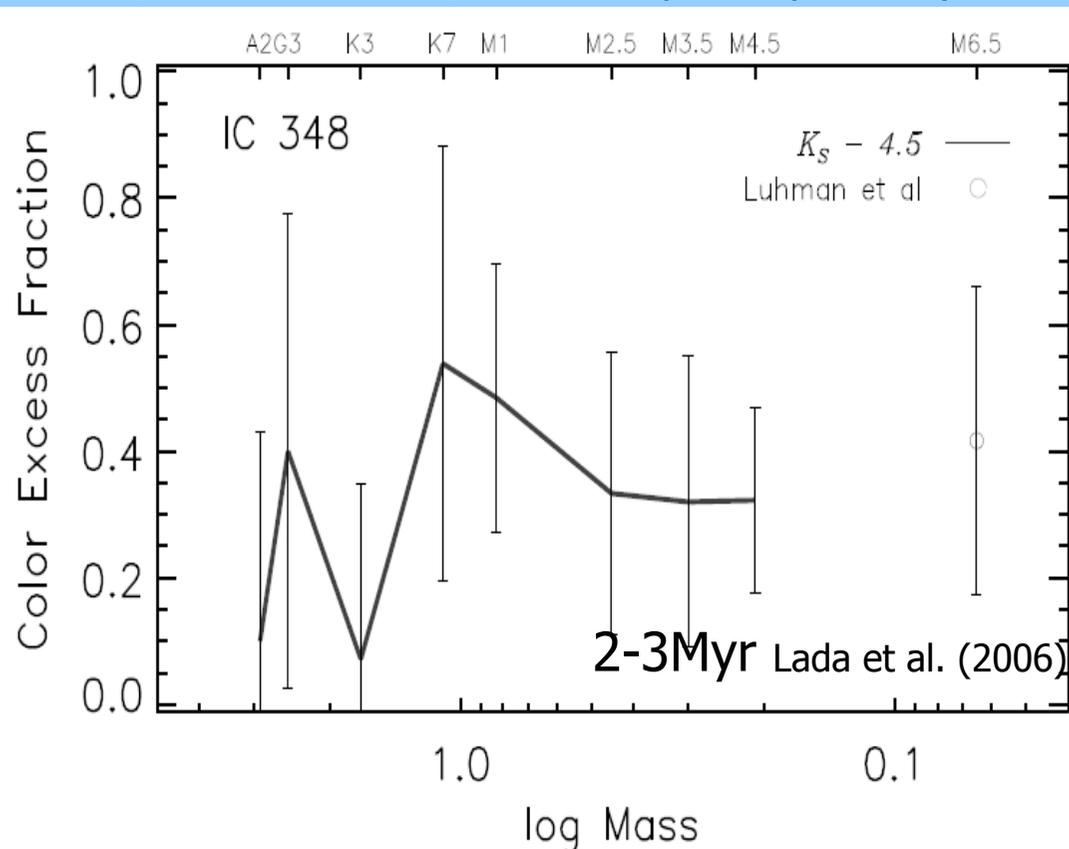
HAeBes have too little near-IR flux implying an inner hole, and emission peak ~3μm led to puffed up inner rim model (Natta et al. 2001) present also in CTTS (Cieza et al. 2005)

Near-IR interferometry

Inner hole resolved with near-IR interferometry (Milan-Gabet et al. 2005; Monnier et al. 2005; Akeson et al. 2005; Eisner et al. 2005, 2007)

Correlation of hole size with stellar luminosity caused by dust sublimation at 1500K; disk inclination (measured as elongation) explains scatter
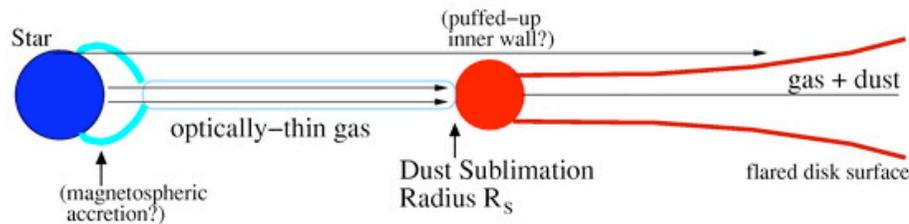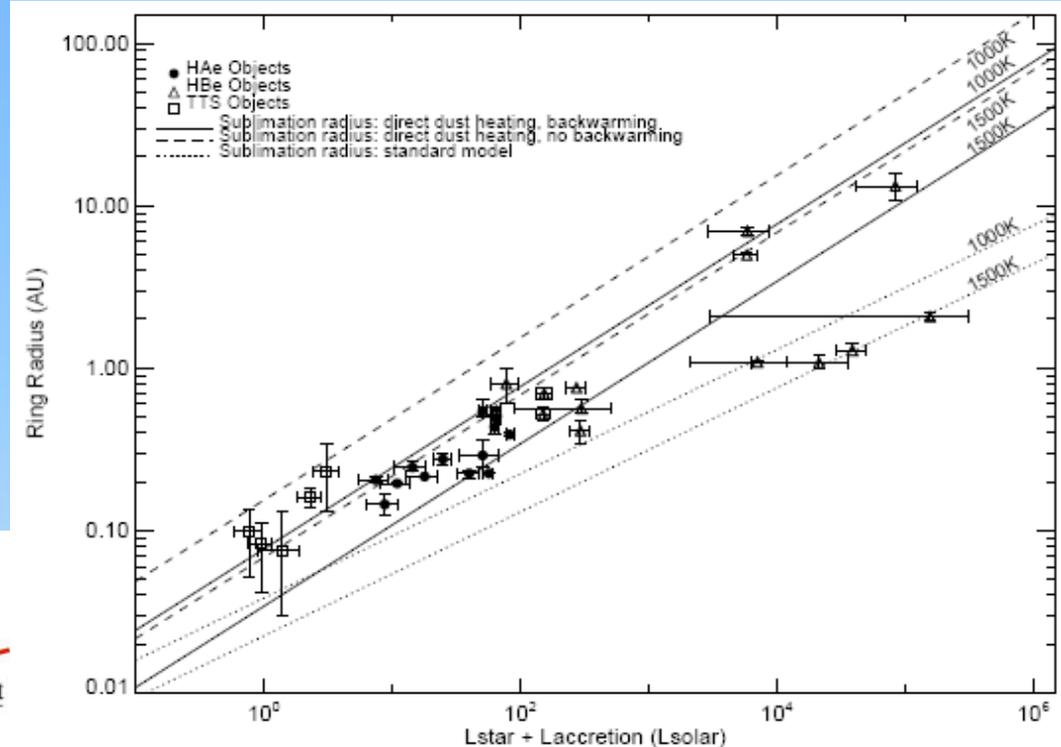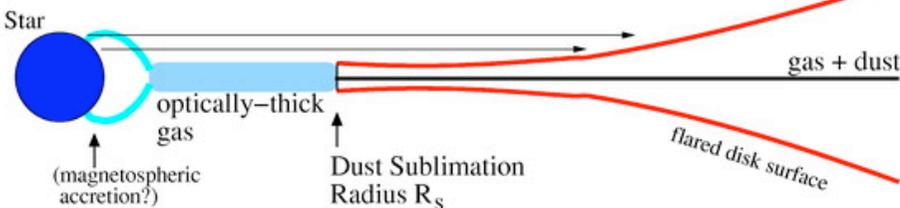
HAeBe holes too small: explained by optically thick gas in hole

CTTS holes too large: uncertain stellar flux, transition objects, or small grains

Inner gas disk

Truncation of inner gas disk measured from CO overtone/fundamental and OH rovibrational lines (e.g., Najita et al. 2003, 2006; Salyk et al. 2007)

Gas closer to star than dust (dissociation of CO at >4000K cf >1500K for dust)...

...and closer than extrasolar planets
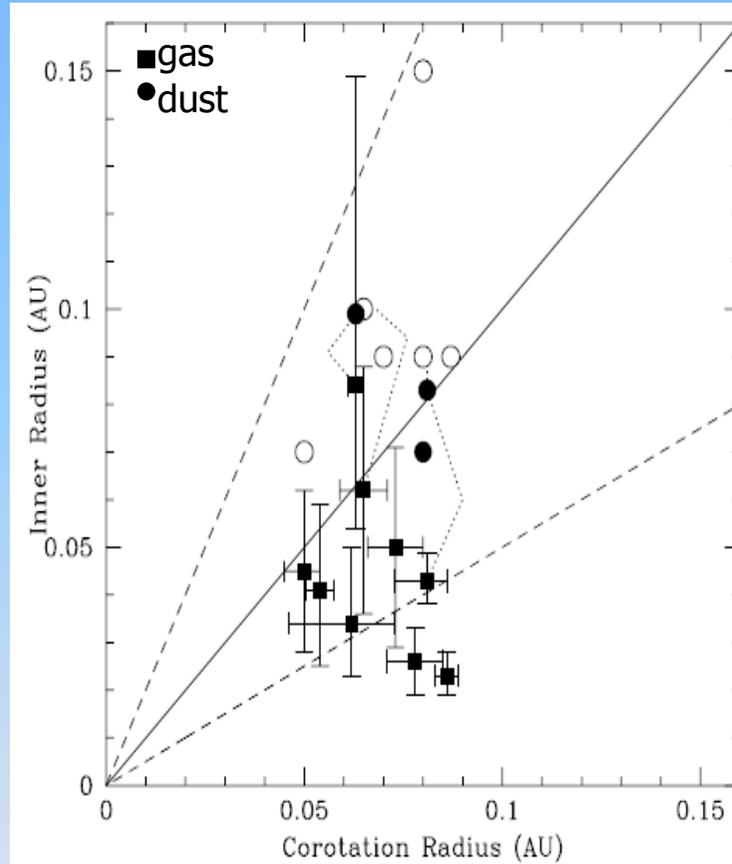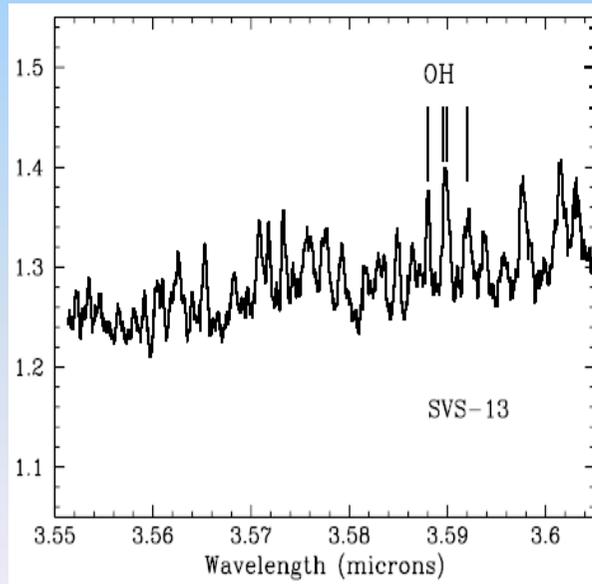
CO gas extends within co-rotation radius implying small coupling radii for magnetospheric accretion
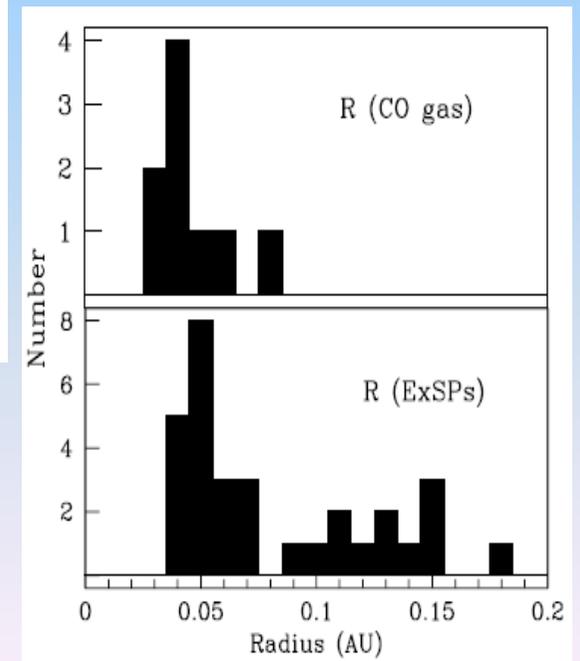
Eclipses – KH15D

KH15D is K6-K7 PMS star in NGC2264 (760pc, 2-3Myr) with a deep (4 mag) long (24day with 48.4day period) eclipse in optical and near-IR:

• Bump at zero phase

• Eclipses used to be shallower and shorter (~1 day/yr), system brighter

• Optical polarization high in eclipse, NIR colours bluer -> dust scattering

• evidence for H_2 emission

• star is spectroscopic binary with high eccentricity, same period as eclipse

Kusakabe et al. (2005)
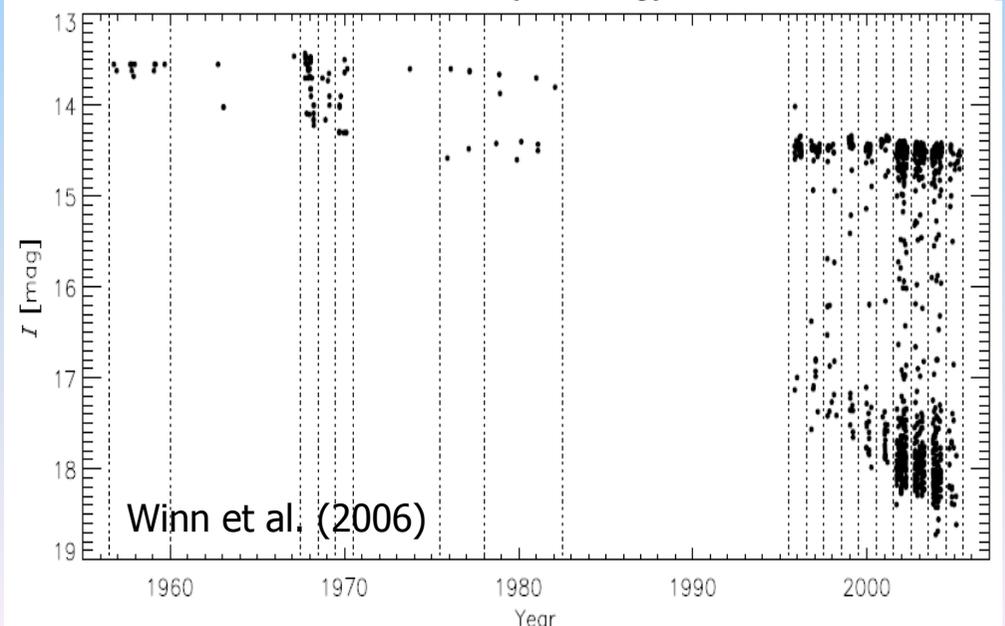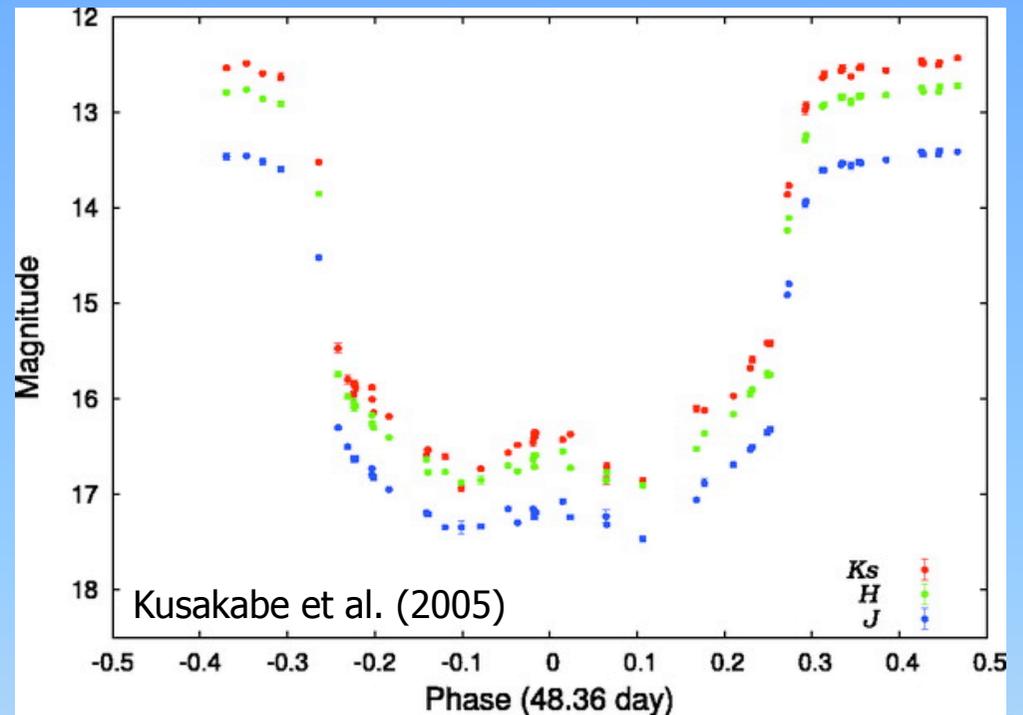
Winn et al. (2006)

See also AA Tau (Bouvier et al. 2007), ε Aur (Lissauer et al. 1996), HMW15 (Nordhagen et al. 2006)

KH15D – precessing circumbinary disk

All data fitted with model of occultation of stars and halos of scattered light (from circumstellar dust) (Winn et al. 2006)

Binary orbit and an inclined, warped, eccentric, precessing, circumbinary disk

Occulting edge = outer edge of disk

Occulting edge = inner edge of disk

Occulting edge = projection of warp
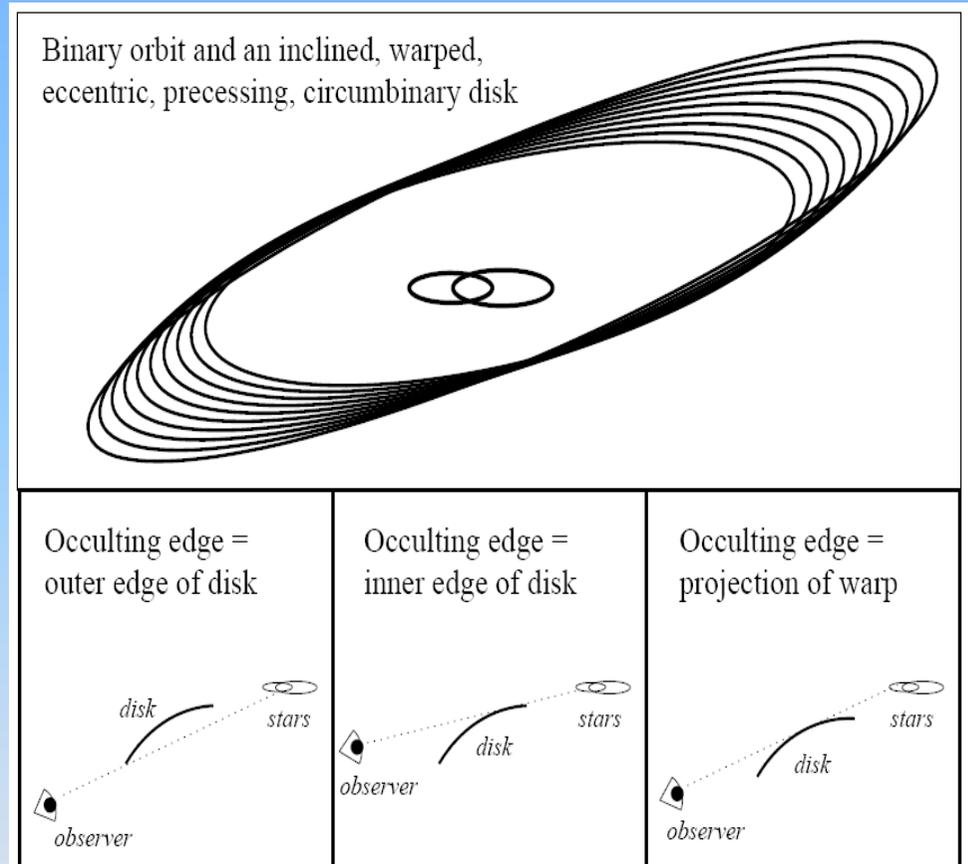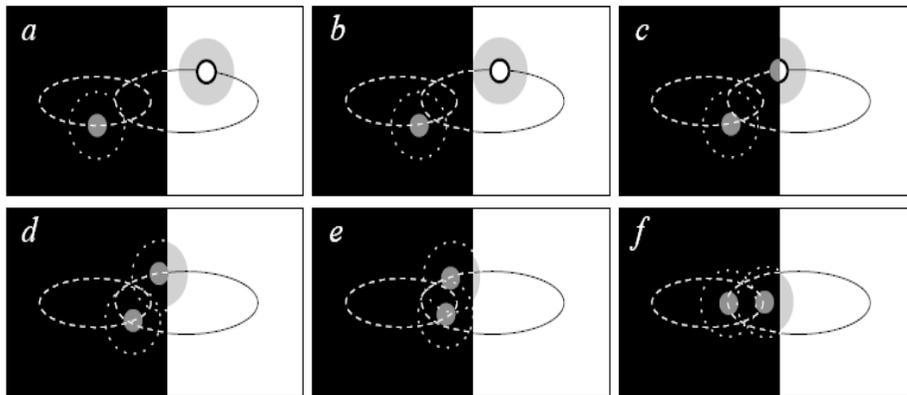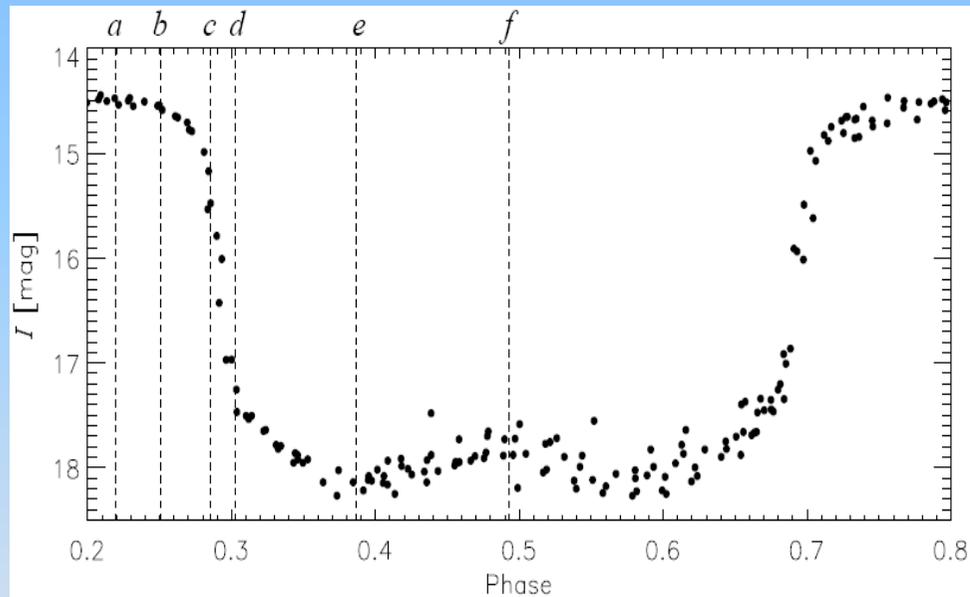
Occultation screen is circumbinary ring which is sharp edged (less than stellar radius) and precessing due to secular perturbations (disk not in same plane as binary)

Spectral energy distribution

Understanding disk structure
requires interpretation of the
spectral energy distribution
(SED): flux (F_ν) vs wavelength (λ)
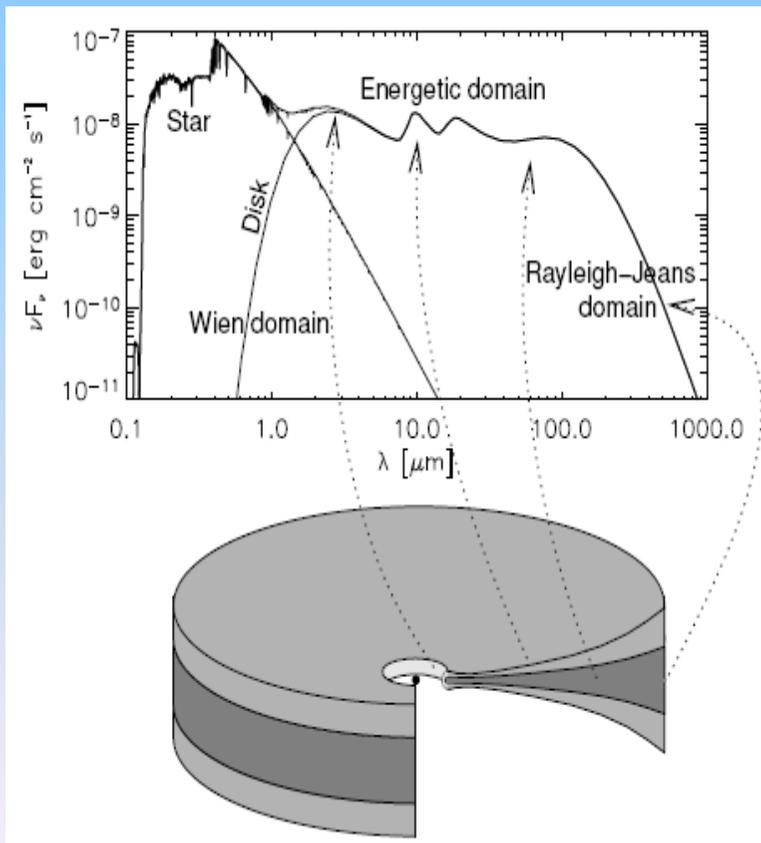
SEDs of HAeBes (Meuss et al. 2001)
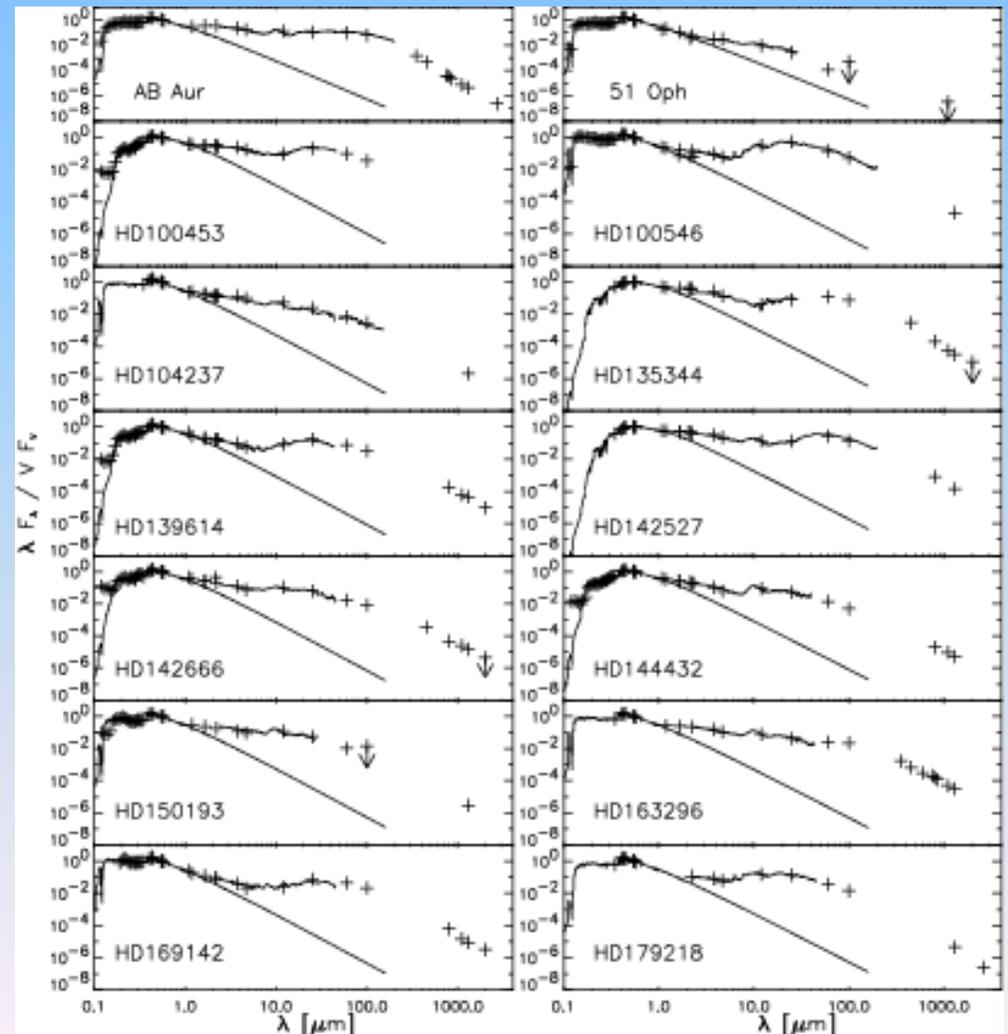
Different wavelengths trace different radii

IR classification

Classification scheme based on mid-IR colours (Lada & Wilking 1984; White et al. 2007):

- class **I** = embedded star with envelope
- class **II** = star with disk emission (CTTS)
- class **III** = star without disk (WTTS)

Probably evolutionary sequence (Adams, Lada & Shu 1987) with class **0** (protostar) added recently
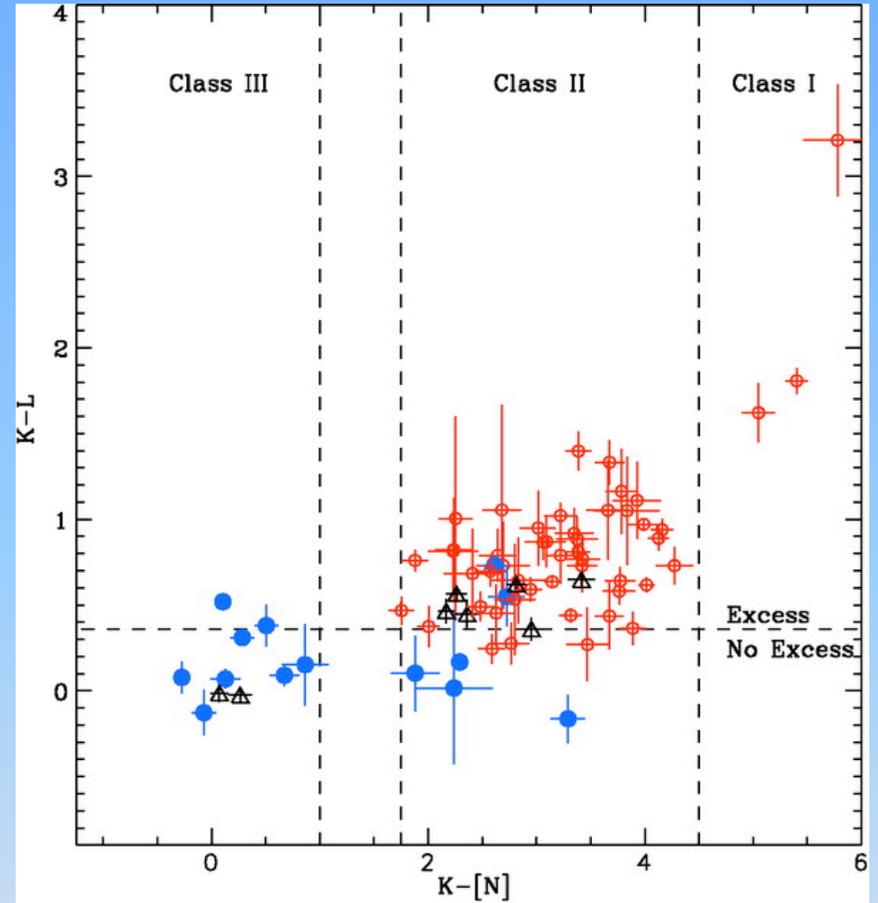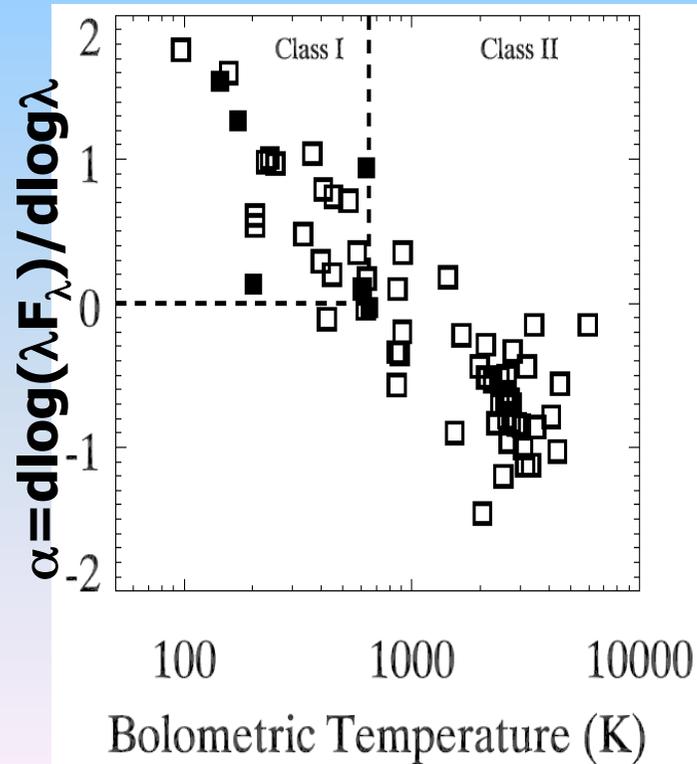
Passive disks: mid-IR without near-IR excess (McCabe et al. 2006):

- 10% of class IIs not accreting
- not just variable accretion
- mostly around secondaries and late-type stars

Classification of HAeBes

HAeBes classified into 2 groups (Meuss et al. 2001):

- **Group I** = SED fit with black body + power law
  - **Ia**=with solid state features, **Ib**=without

- **Group II** = SED fit with just power law
  - **IIa**=with features, **IIb**=without

Difference is geometry: outer disk of group II sources shielded from stellar radiation by puffed up inner rim
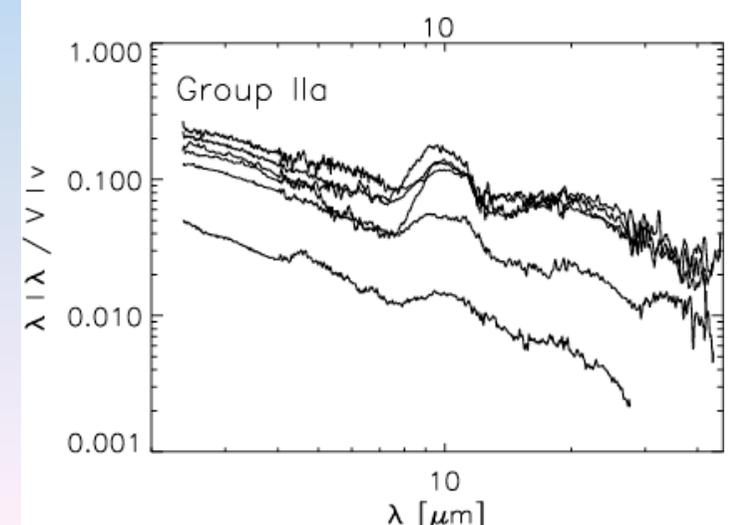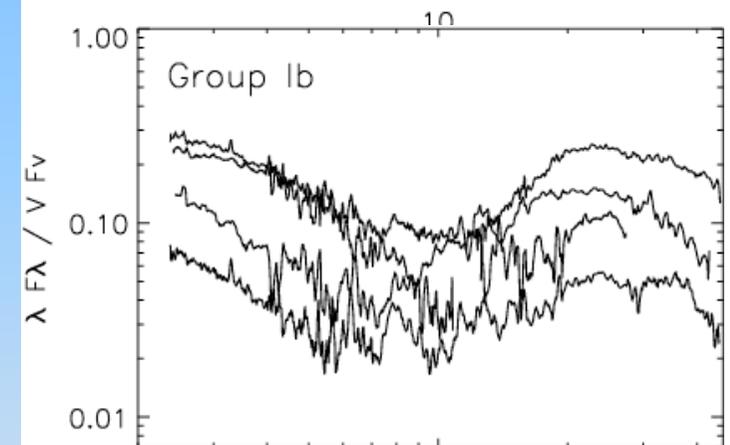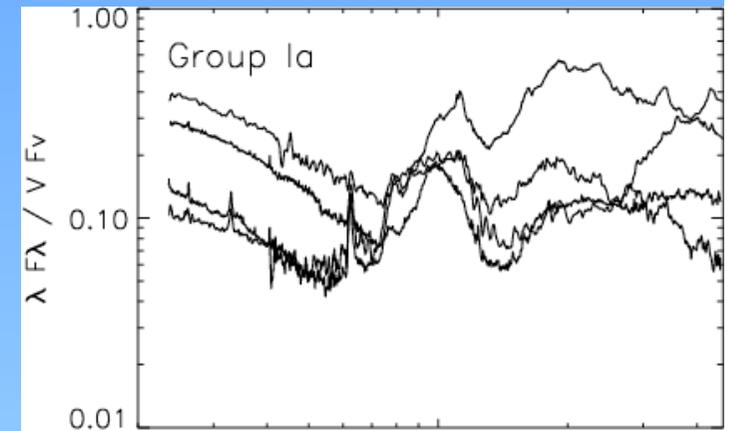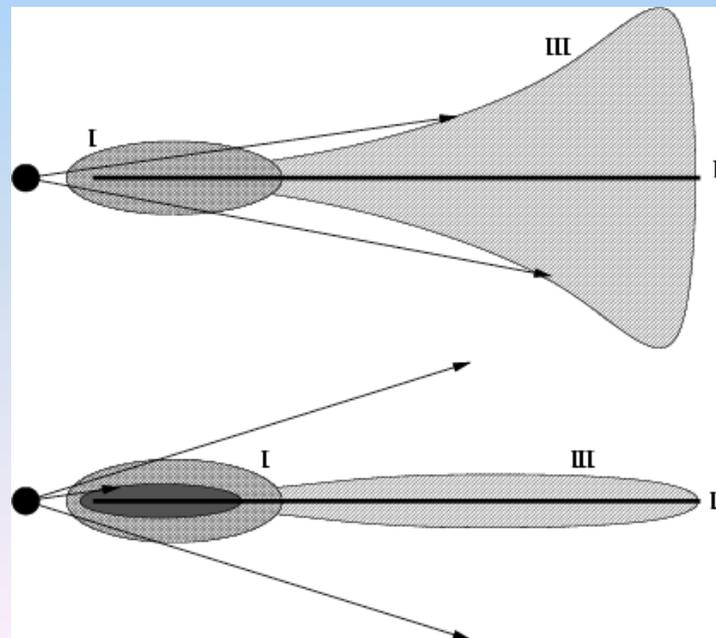
Mid-IR Spectroscopy

Mid-IR features indicate grain composition
(Meuss et al. 2001; Kessler-Silacci et al. 2006; Acke & van den Ancker 2006; Geers etal. 2007; Siciliar-Aguilar et al. 2007):

- Silicates at 10 and 18μm

  crystalline at 11.3, 27.5, 33.5, 35.8, 70μm

  amorphous at 9.8μm

- PAHs at 6.2, 7.7, 8.5, 11.2μm (more common in HAeBes, Geers et al. 2007)

- Nanodiamonds at 3.5μm

Siciliar-Aguilar et al. (2007)
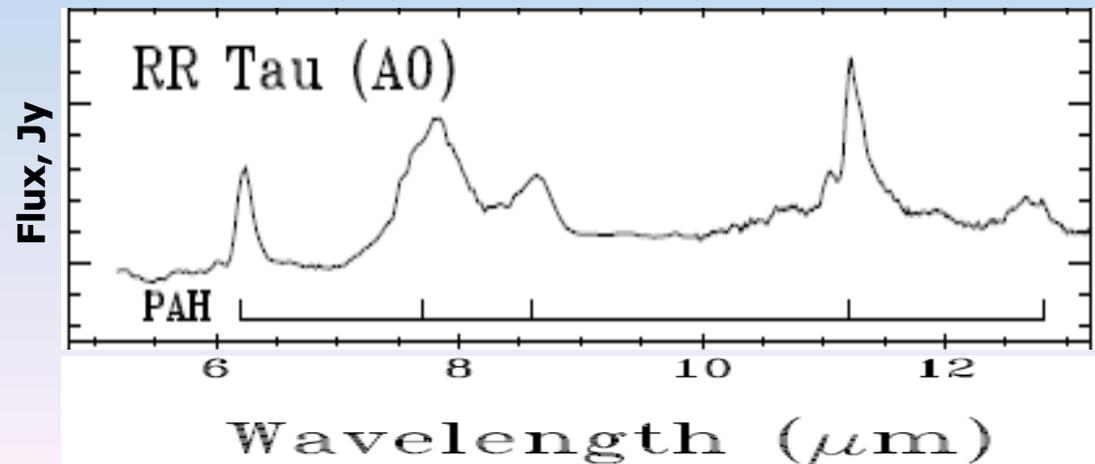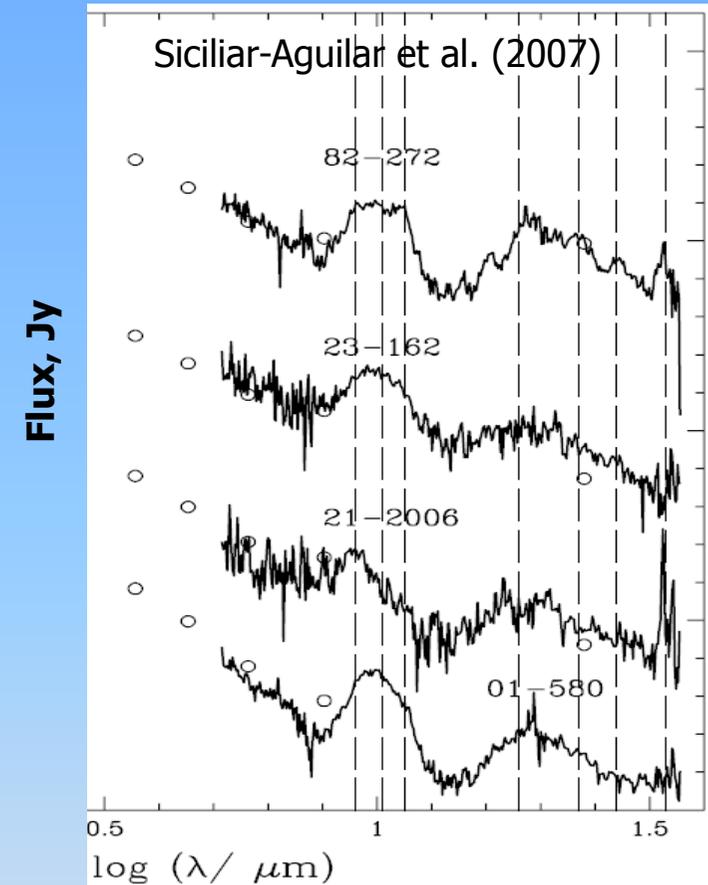
Crystallinity of silicates

T Tauri and HAeBe spectra show:

(a)

Trend in crystalline/ amorphous with strength of silicate feature indicates grain growth to $2\mu m$ (Bouwman et al. 2001; van Boekel 2003)
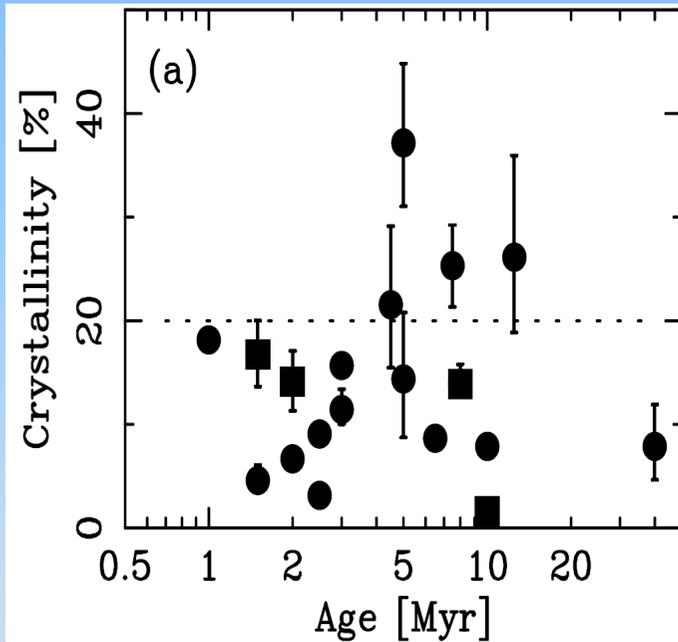
Most mass is in amorphous silicates, no trend with age (Honda et al. 2006; Kessler-Sillacci et al. 2006)
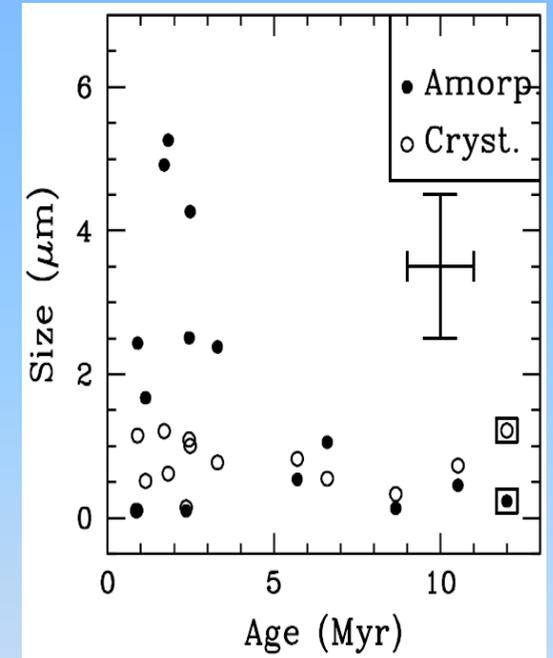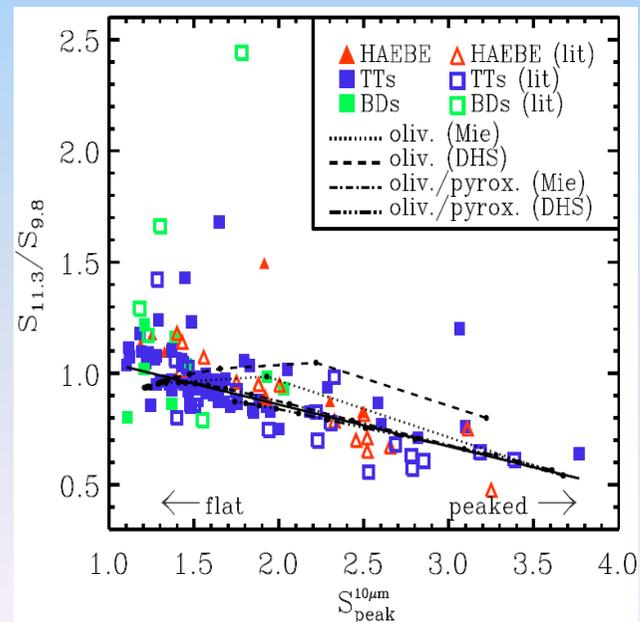
Modelling silicate features suggest larger amorphous grains at young age indicative of settling (Siciliar-Aguilar et al. (2007)

Mid-IR interferometry

Mid-IR interferometry has resolved HAeBes
(Leinert et al. 2004; Preibisch et al. 2006; Liu et al. 2007),
implying 1-10AU with size colour relation
consistent with the classification scheme
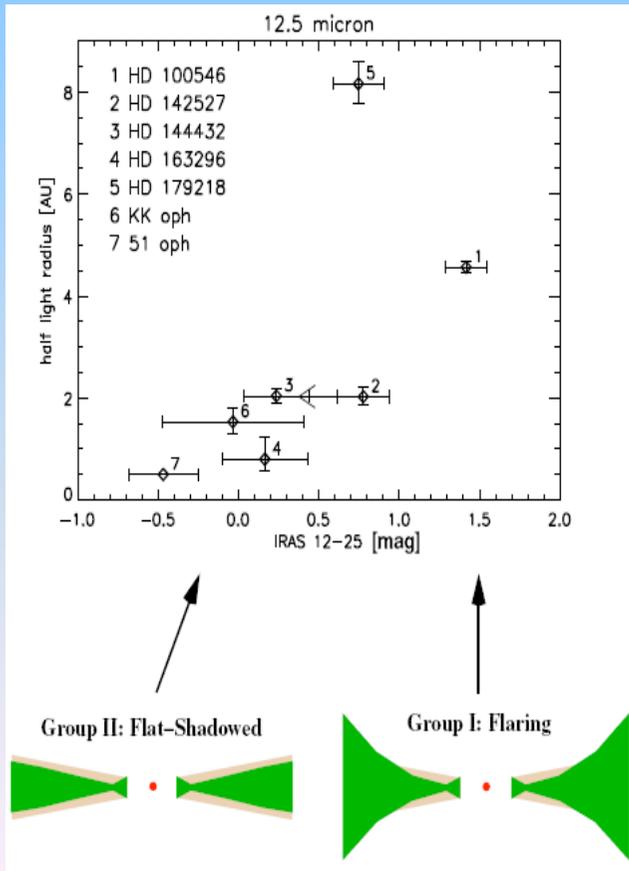
Also shows spectrum
changes with radius:
inner dust has high
fraction of crystalline
silicates, whereas
total disk has more
amorphous silicates
(van Boekel et al. 2004; Leinert
& Schegerer 2006)
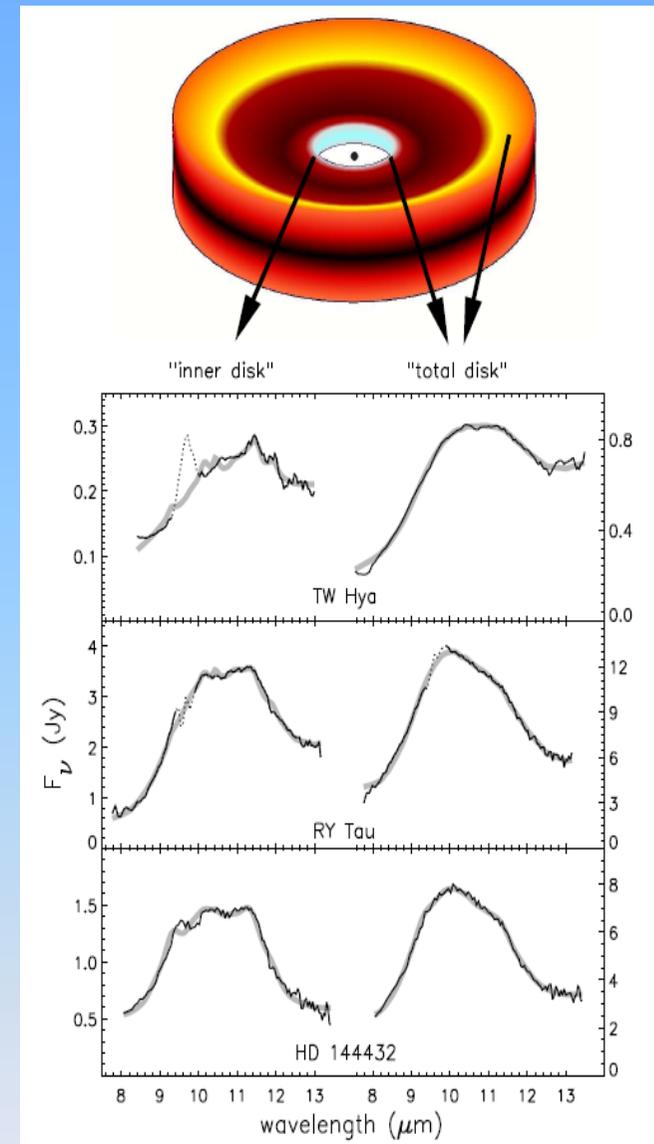
Radial mixing or local heating means solar
system has crystalline silicates at range of
distances (Crovisier et al. 1997; Gail 2004)

Optical/near-IR coronagraphy

The best way of resolving small disks is at shortest wavelengths with a coronagraph

Non-axisymmetric features detected, although asymmetry from scattering (back- is stronger than forward-scattering) and effect of disk warping/shadowing mean interpretation is degenerate

Scattering is generally by small (sub-μm sized grains) evidenced by disk colours

Krist et al. (2005): ACS images show empty <150AU, ring is 37deg from face-on; variability on 5yr timescale

GG Tau

depression

spur

secondary nebula

gaplets

"gap"

filaments

HD142527

1"=140 AU
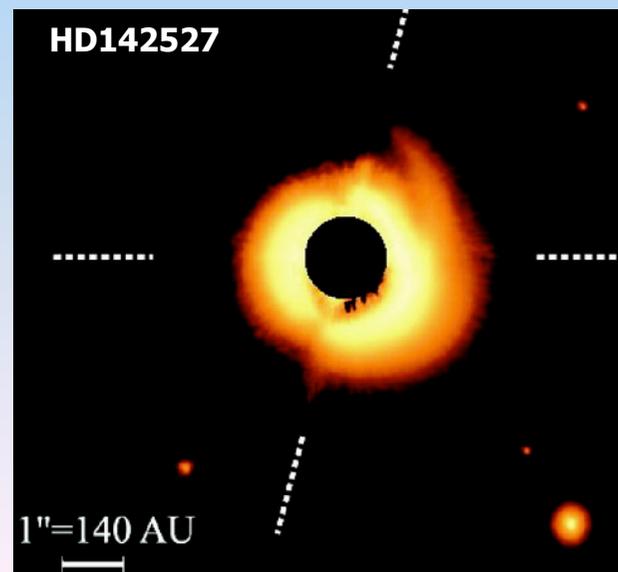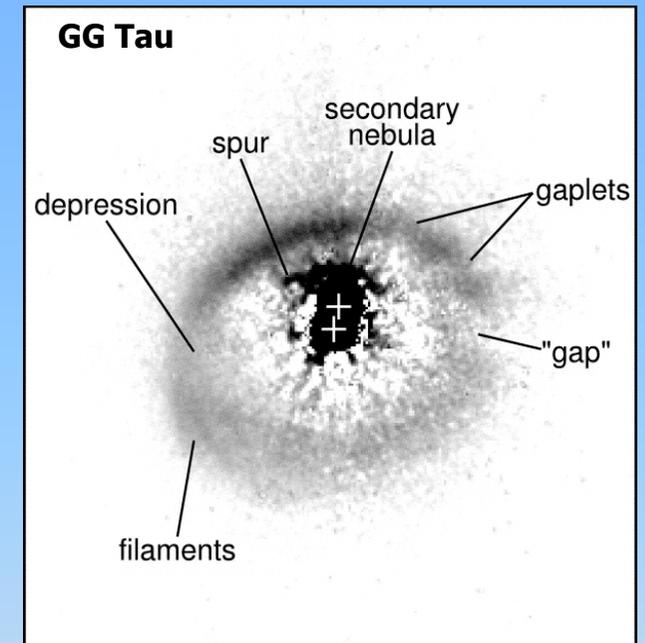
Fukagawa et al. (2006): H and K images show two bright arcs opposite each other, spiral arm

Detectability of HAeBes
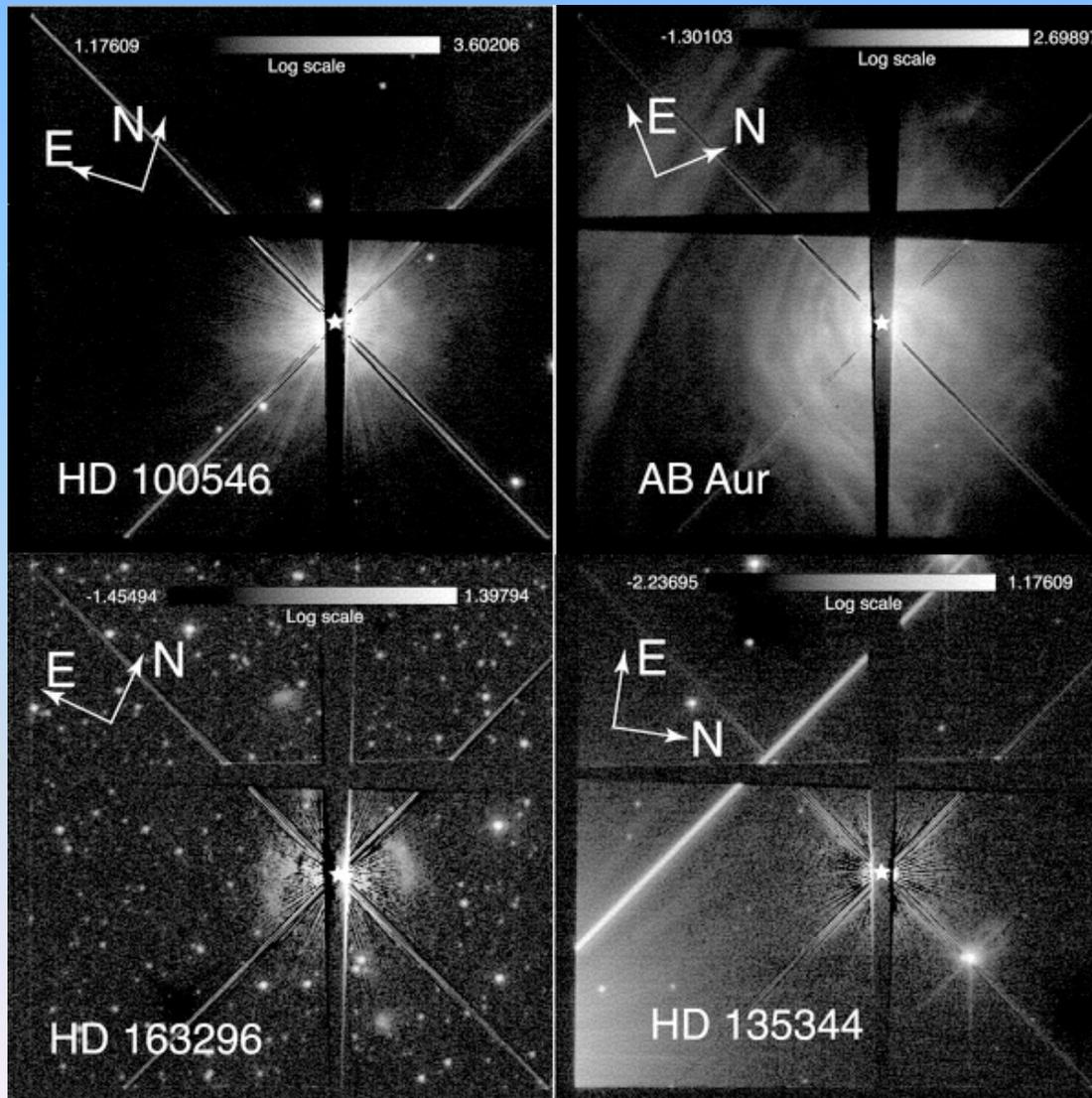
Detectability of HAeBes not correlated with mid-IR to sub-mm characteristics, only with PAH emission from dust high above mid-plane -> optical images don't sample whole disk (Grady et al. 2005)
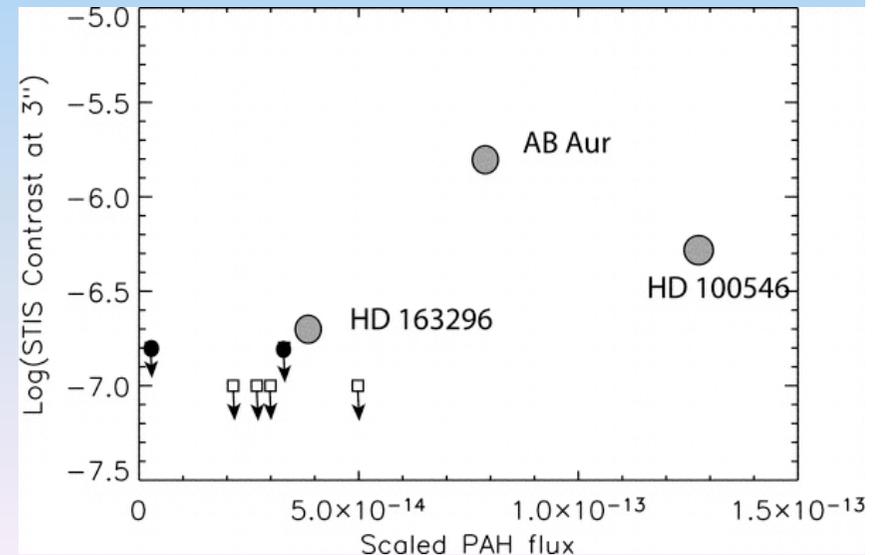
Near-IR polarimetry

Near-IR polarimetry acts as a natural coronagraph because stellar emission is not polarised whereas disk scattered light is (Kuhn, Potter & Parise 2001; Apai et al. 2004)

TW Hya (Hales et al. 2005)

HD169142 (Kuhn et al. 2001)
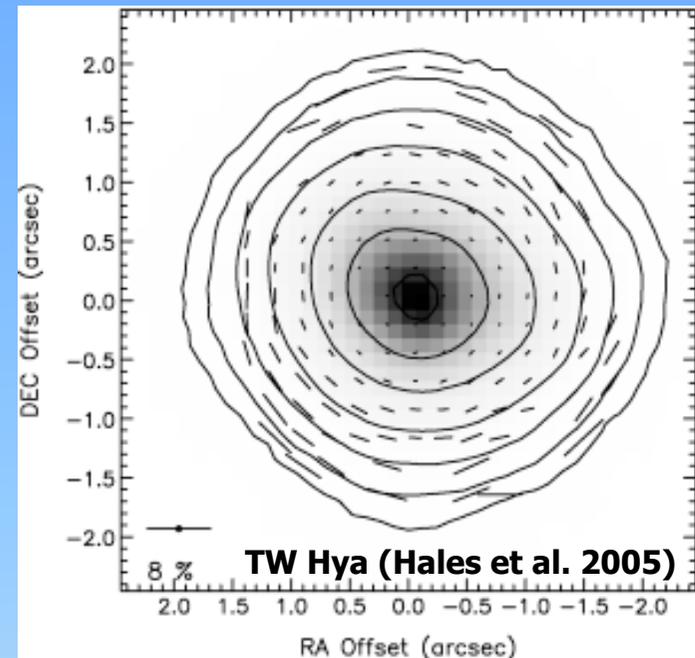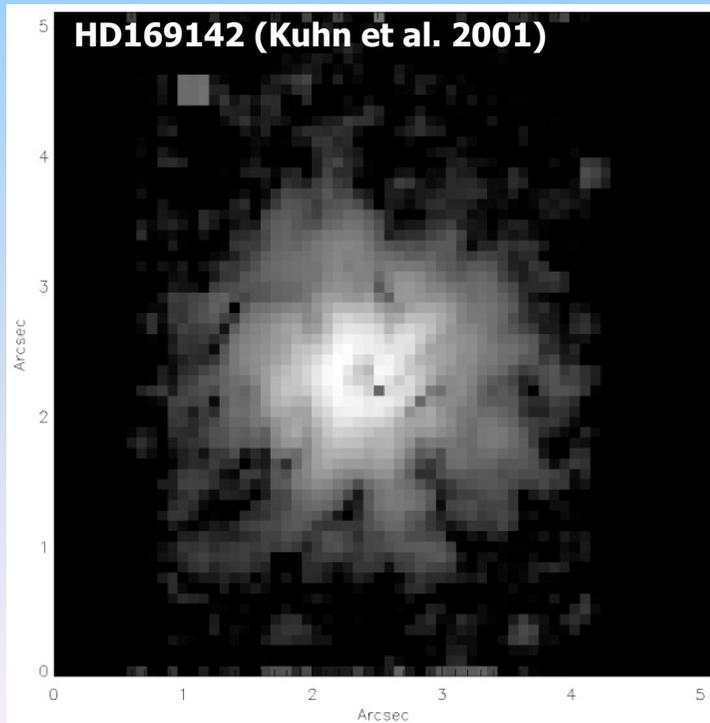
JHK polarisation maps (Hales et al. 2005):
- flared disks easier to detect
- constant polarisation with radius
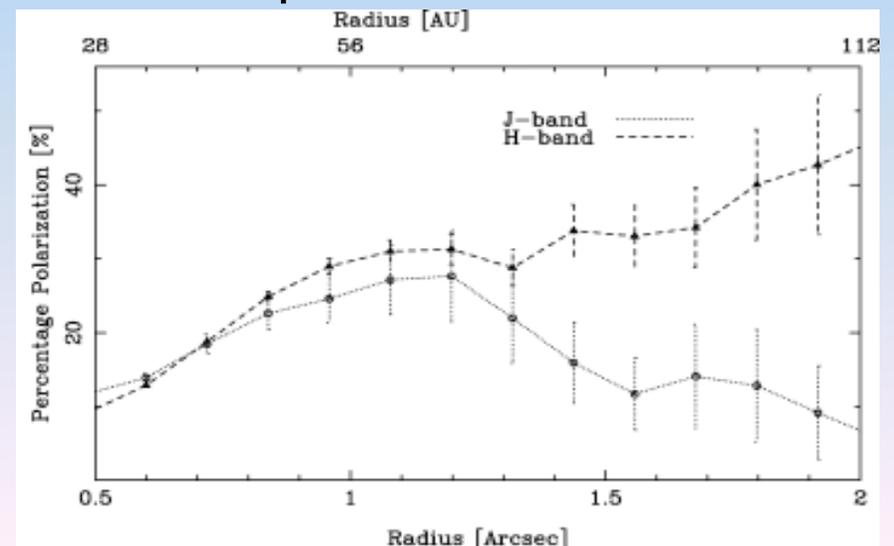
Sub-mm/mm photometry

Dust mass: $\quad\quad\quad$ $\mathbf{M_{dust} = F_\nu d^2/[B_\nu(T)\,\kappa_\nu]}$

$\quad$ where d is distance, $\kappa_\nu = 1.5Q_\nu/(D\rho) \approx \kappa_0(\lambda_0/\lambda)^\beta$ is mass opacity
$\quad$ [κ_0=0.17m^2/kg, λ_0=850μm, β=1]

NOTE disk mass often quoted with x100 gas/dust factor [factor constant within a region (Vuong et al. 2003; James et al. 2006; Santos et al. 2008; although see Padoan et al. 2006)]

Best measured in sub-mm:
- unaffected by uncertainties in T_{dust}
- disks are optically thin
- larger grains contain most mass
- little contribution from stellar photosphere

Sub-mm observations also
- measure β from spectral slope ($F_\nu \propto \lambda^{-\alpha}$) since $F_\nu \propto \lambda^{-2-\beta}$
- help pin down dust temperature
- resolves disk emission (interferometry)

Disk properties: mass, spectral slope

Surveys of star forming regions with single dish (JCMT, CSO, IRAM) and interferometers (OVRO, PdB, SMA)

153 PMS in Taurus-Auriga (Andrews & Williams 2005):

• WTTS and CTTS have different mass and spectral slope distributions

• $<M_{disk}>$ ~0.005M_{sun} (±0.71dex), α=2.01±0.57

• 61% detected is same as NIR implying outer disk goes with inner disk

Comparable results for rho Oph (Andre and Montmerle 1994; Andrews & Williams 2007), and Herbig Ae stars (Mannings & Sargent 1997)
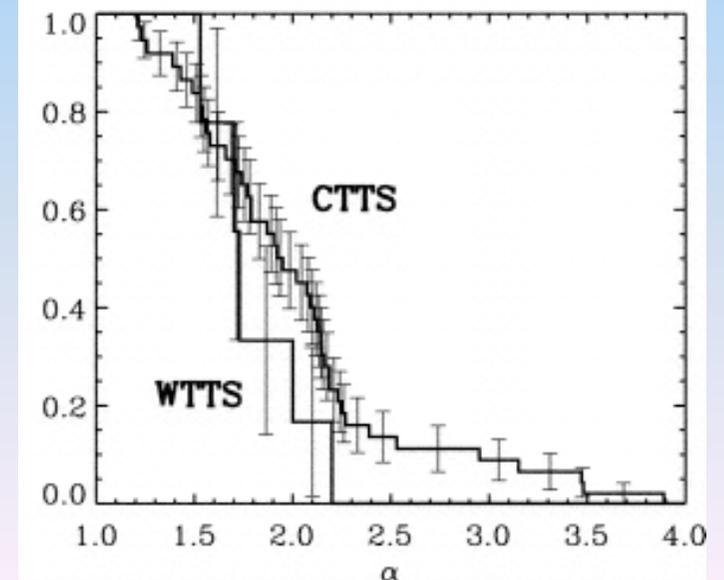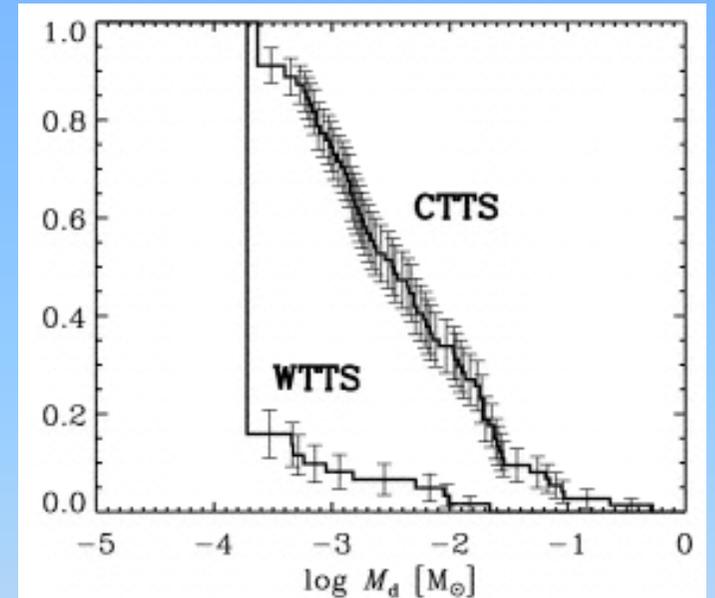
Disk properties vs age

No evidence for disk evolution on pre-main sequence
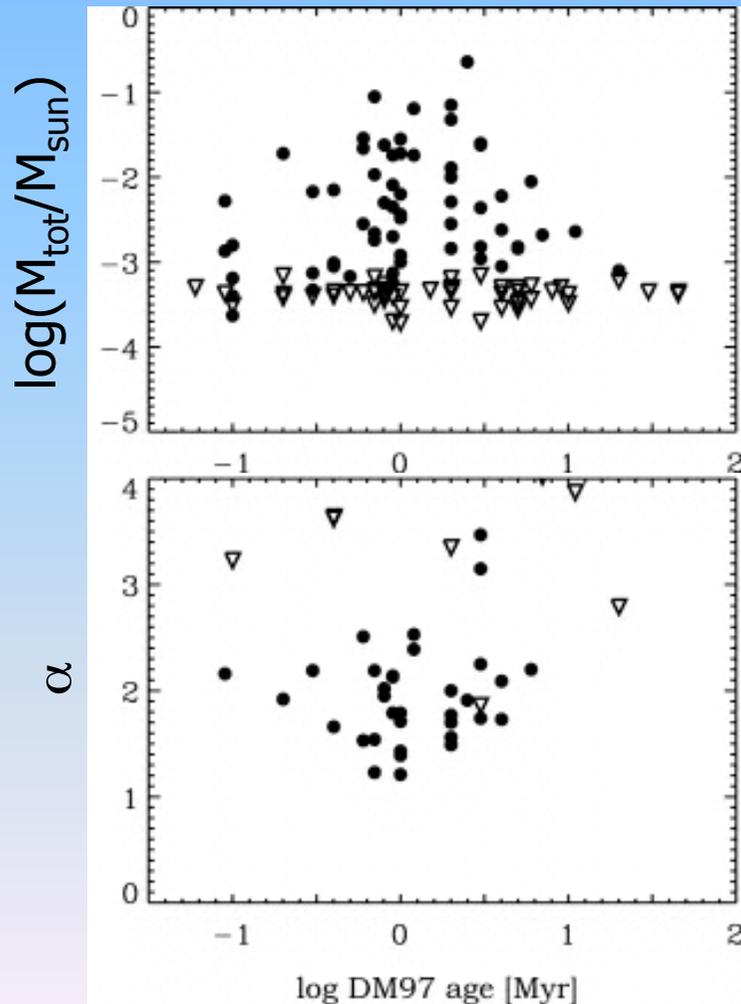
Mass is roughly constant (Mannings & Sargent 2000; Wyatt, Dent & Greaves 2003; Andrews & Williams 2005)

Spectral slope also unchanged (Andrews & Williams 2005)
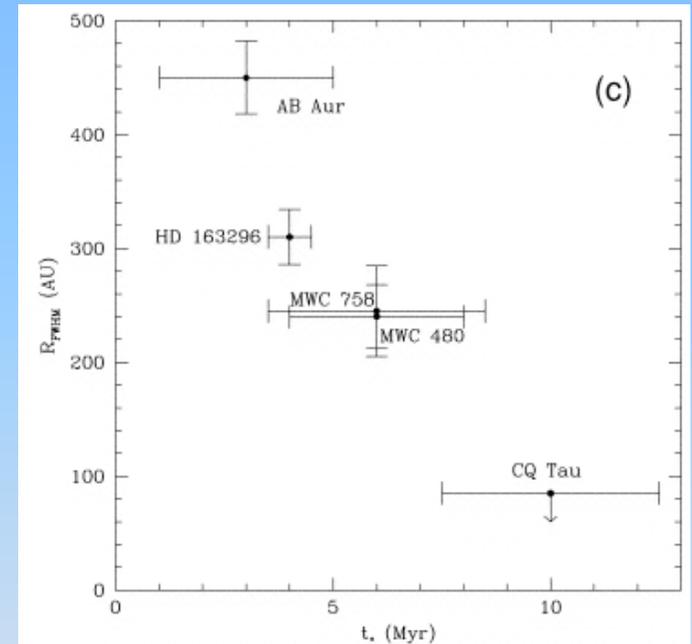
Possible decrease in gas radius with age (Mannings & Sargent 2000), but spectral type dependence? (AB Aur/CQ Tau are most/least massive of sample)

Disk properties vs stellar mass

Controversial whether disk mass is a function of stellar mass
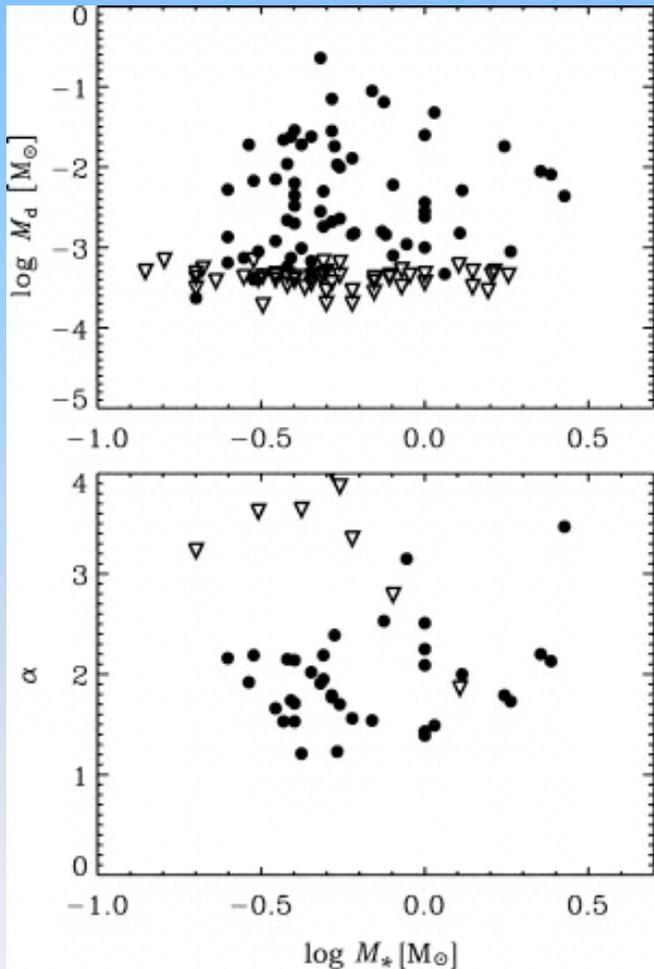
No correlation of disk mass or spectral slope with mass or age for TTS (Andrews & Williams 2005) and HAeBes (Mannings & Sargent 2000).

However increase in disk mass with stellar mass reported (Natta et al. 2001)
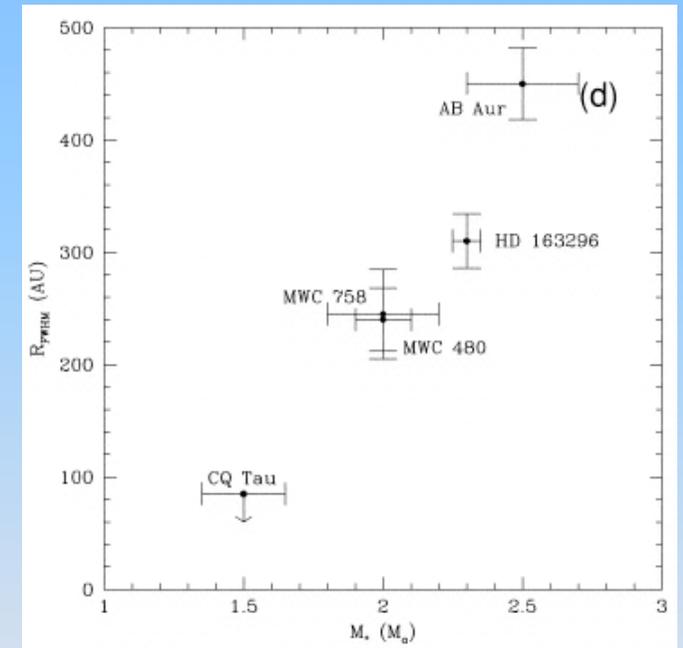
Gas disk radius may increase with stellar mass (Mannings & Sargent 2000)

Binary disks

Binarity does affect the presence of a disk (Jensen et al. 1994; Andrews & Williams 2005):
• companion **>50-100AU**: same M_{disk} distribution as single stars
• companion **<50-100AU**: lower M_{disk}
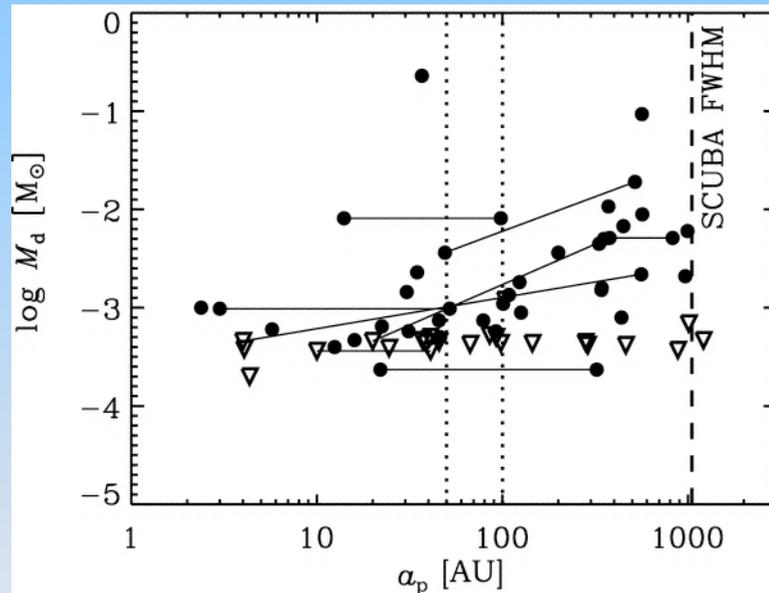
Understandable from radius range disrupted by binary (Papaloizou & Pringle 1977; Artymowicz & Lubow 1994) and origin of sub-mm emission

In 8Myr η Cha, inner disks around 80% single stars, 17% binary stars, no circumbinary disks -> binary disk lifetimes shorter (~5Myr) (Bouwman et al. 2006)
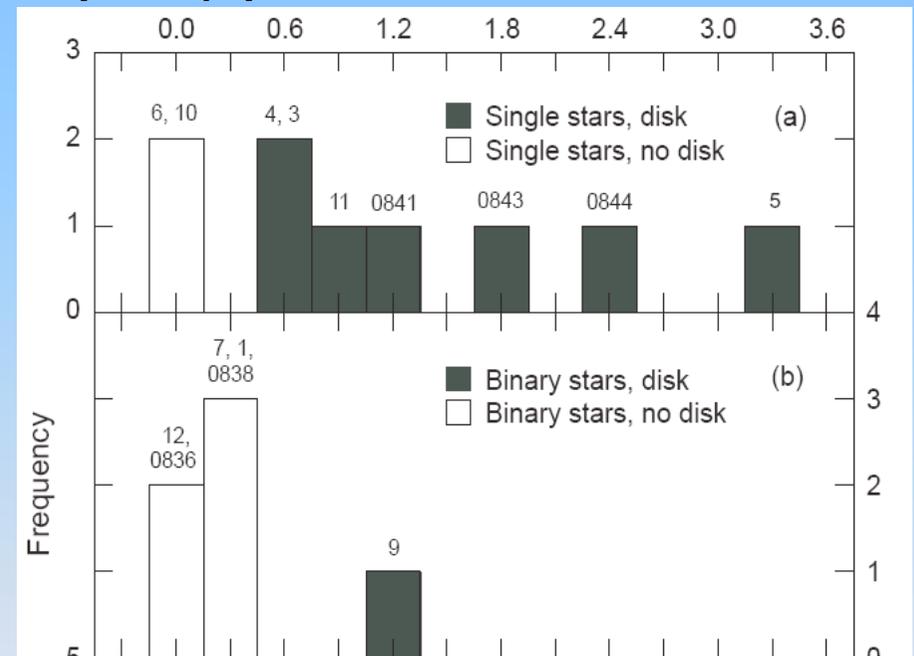
Circumprimary disks more massive than circumsecondary disks (Jensen & Akeson 2003; Monin et al. 2007)

Sub-mm interferometry

Single dish sub-mm can't resolve PMS disks (JCMT 7-14"), but mm interferometry can for brightest (OVRO/PdB/SMA) (e.g., also Peitu et al. 2007; Hamidouche et al. 2007)
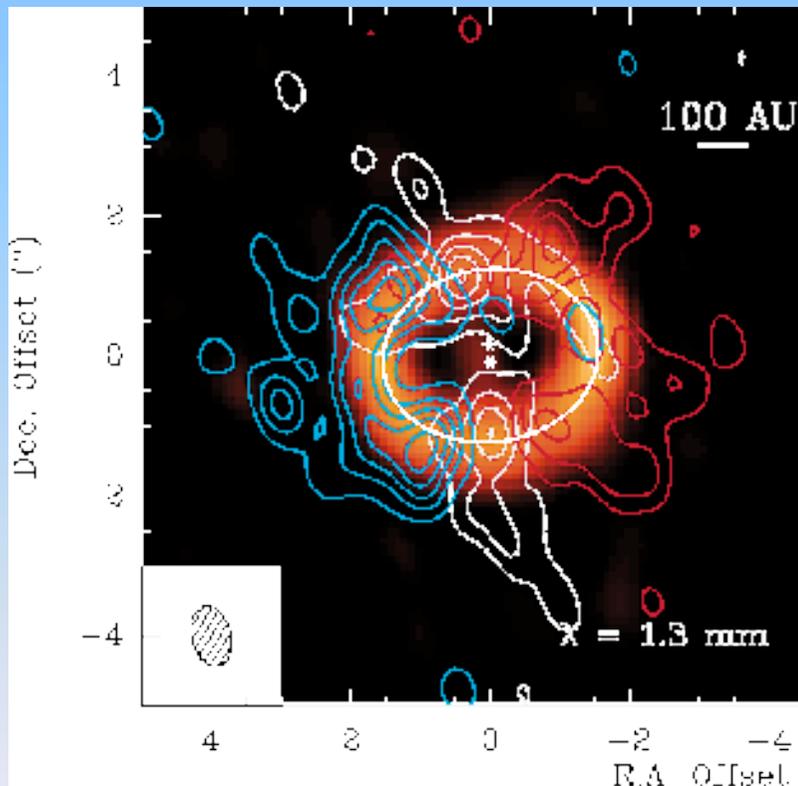
1.4mm image of GG Tau shows structure of "Ring World" (Guillotteau et al. 1999)
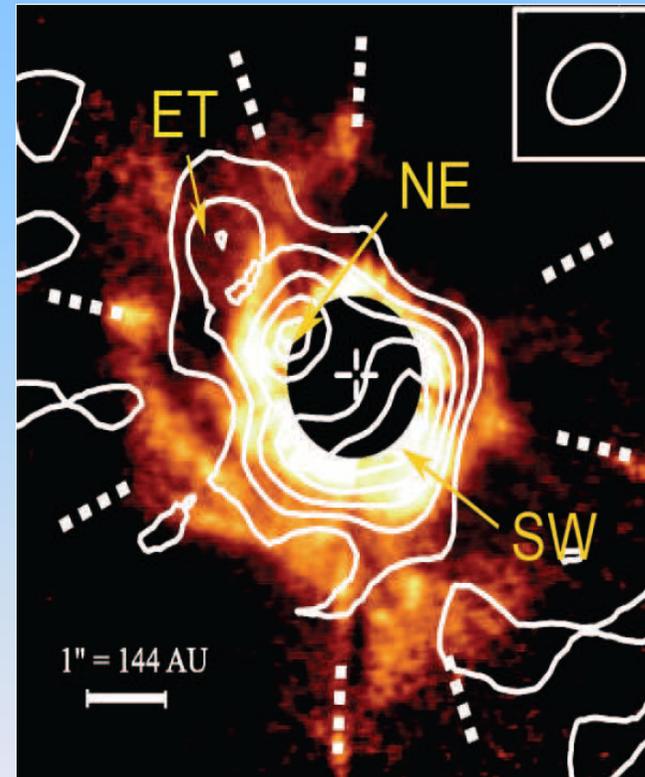
AB Aur is 110-350 AU with arc, inner hole; structure same as optical/NIR so large/small grains same distribution (Pietu et al. 2005; Corder et al. 2005; Lin et al. 2006)

Disk properties: density distribution

SMA of brightest disks
in Taurus-Auriga

(Andrews & Williams 2007):

- $R_d = 200AU$
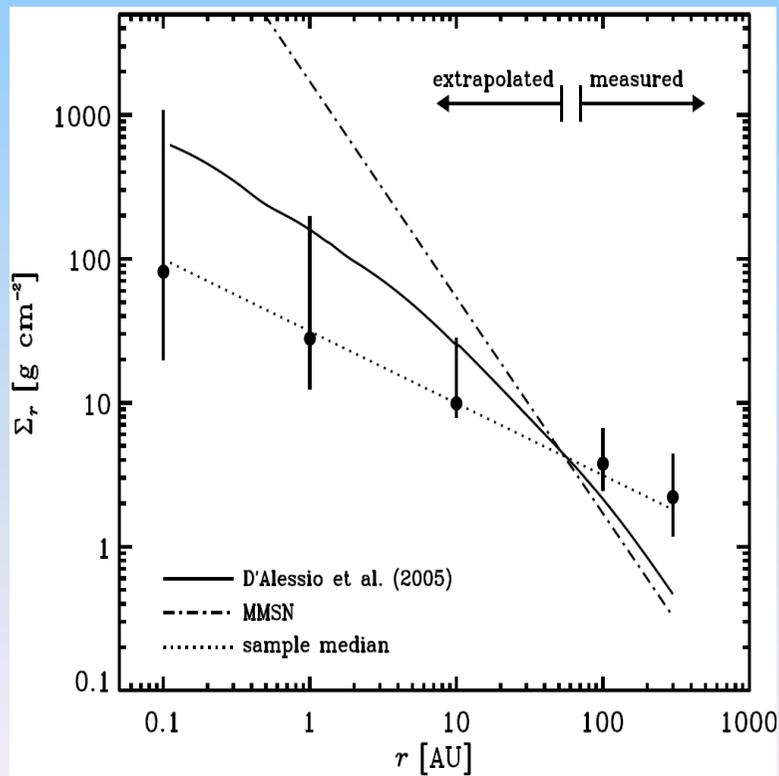
- $p = 0.7\text{-}1.0$
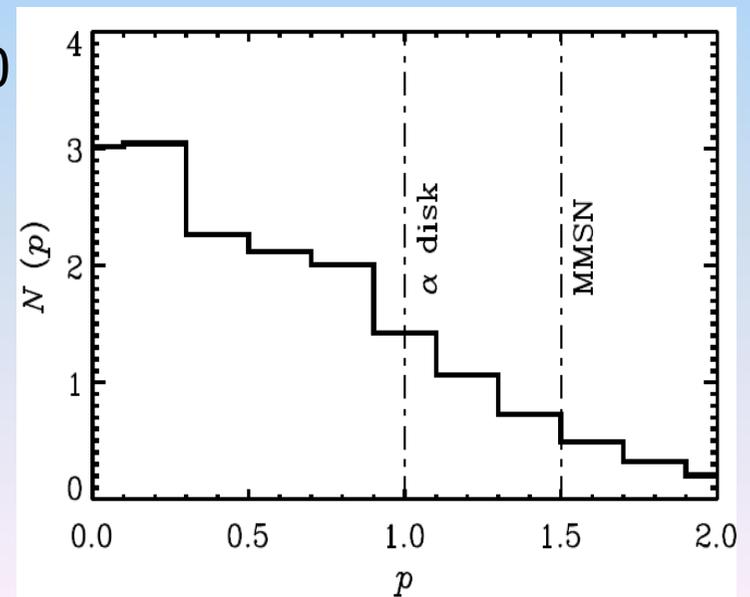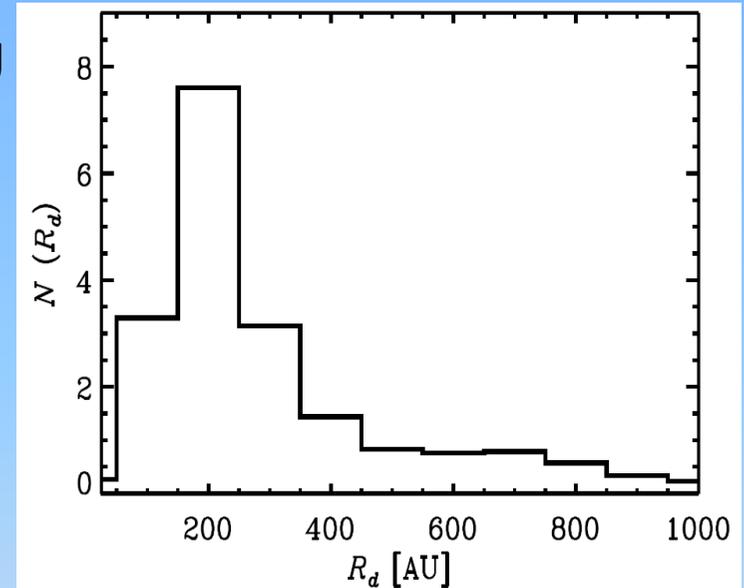
Sub-mm lines: cold gas

The sub-mm also has lines of gas emission (e.g., CO J=2-1, 3-2, 6-5; also HCN, CN, HCO+, DCO+)

Single-dish observations of lines show gas is present, and shape usually single or double peaked

Line broadened by range of gas velocities in disk and affected by optically thickness (e.g., which can fill in the central peak)

Modelling used to derive the disk outer radius, inclination and mass
(Dent et al. 2005)
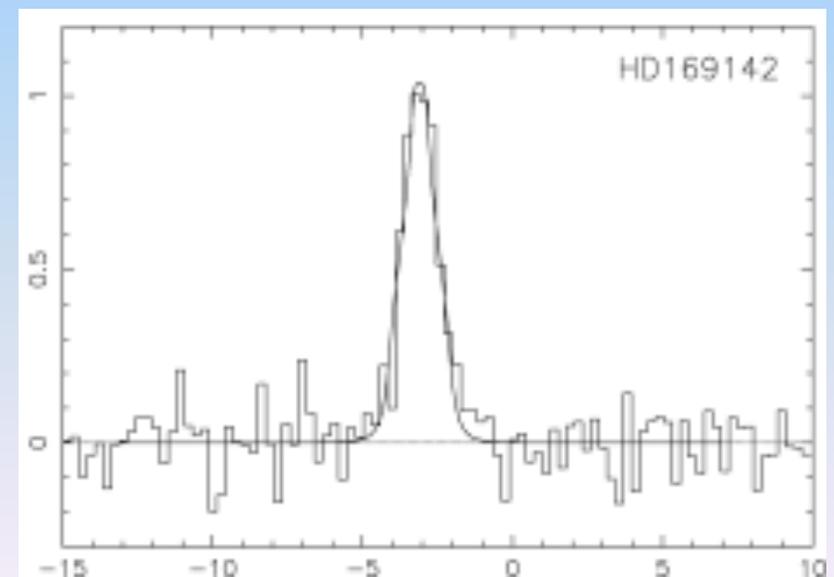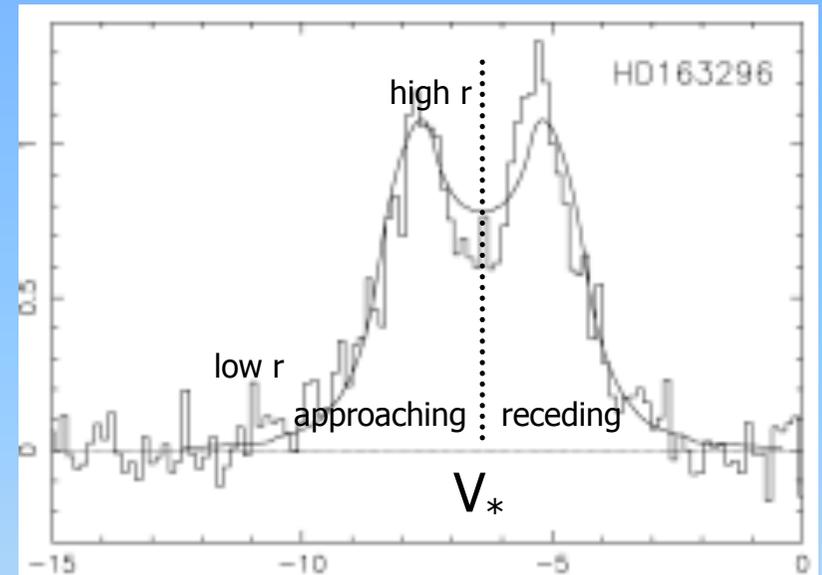
Sub-mm interferometry of gas

Sub-mm interferometry used to resolve gas emission (e.g., Koerner, Sargent & Beckwith 1993; Mannings & Sargent 1997; Simon et al. 2000):
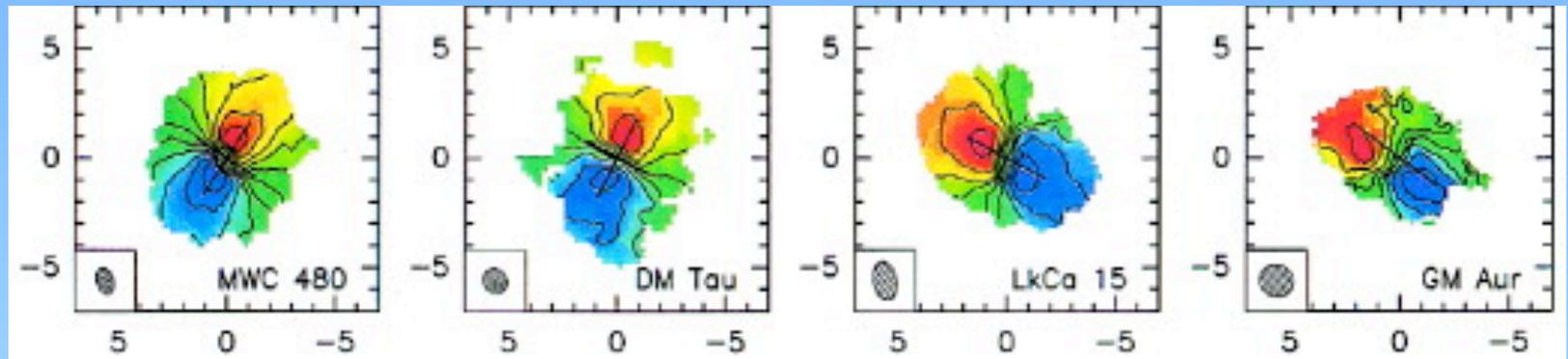
Channel maps = structure at different velocities
• direct measure of disk size (100-800 AU, bigger than dust) and inclination
• demonstrates keplerian disk rotation (dynamical masses for stars) and direction of motion
• AB Aur non-keplerian so not in equilibrium? (Pietu et al. 2005)
• RW Aur has 48AU disk around A, asymmetric disk B, as well as 600AU arm, likely stripped in recent fly-by
(Cabrit et al. 2006)

(b) $^{12}CO(2-1)$ Emission

A

B

Blue Jet
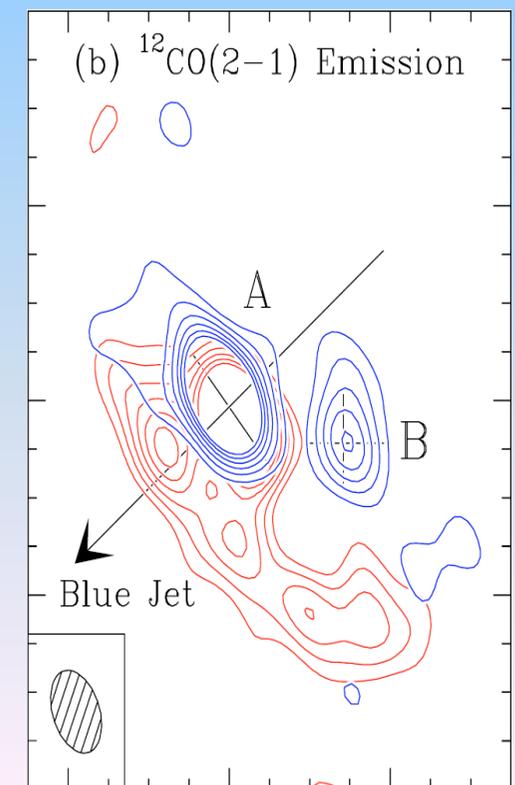
Example of TW Hya

TWHya is closest CTTS, imaged in CO J=2-1,
3-2 and 6-5 with SMA (Qi et al. 2004; 2006):

- gas in keplerian rotation extends to 200AU
- same as optical disk and dust (image)
- 7 deg from face-on
- CO depleted relative to ISM values
- exponential outer edge (Hughes et al. 2008)
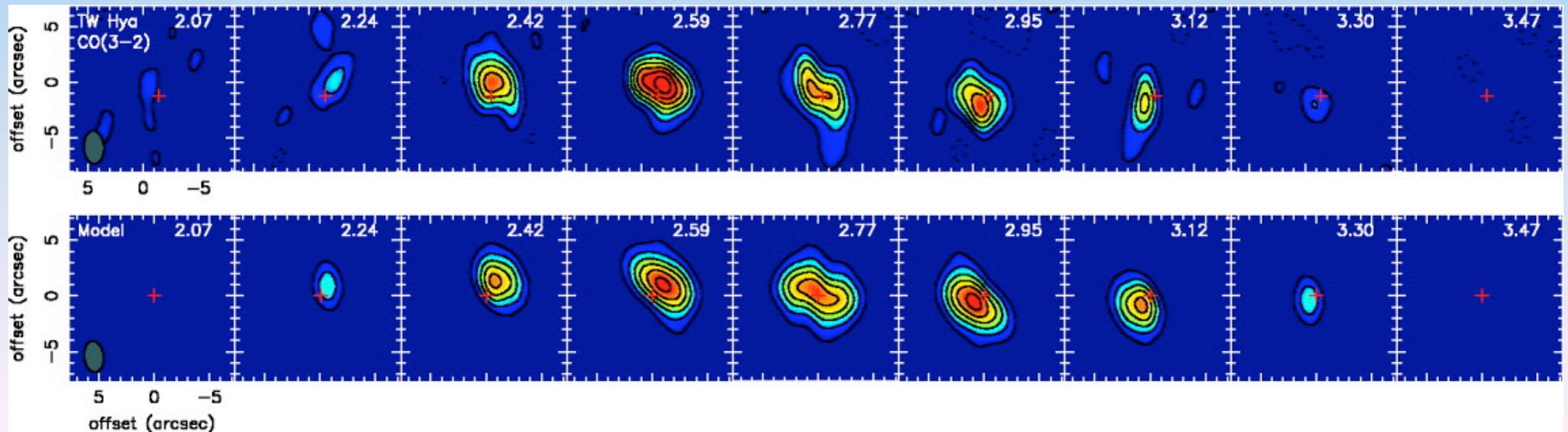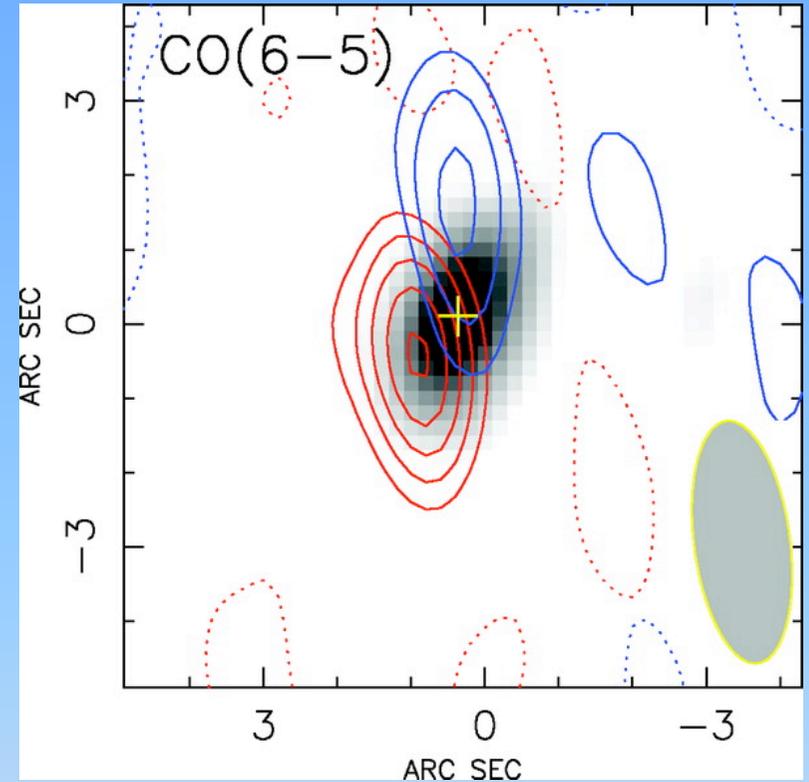
Other gas disk measurements

Gas disks also detected at other wavelengths:

H$_2$

- Most abundant gas in disks, but hard to detect because electronic transitions are in FUV (optical and rho-vibrational are weak)
- Fluorescent H$_2$ emission: detected for all but 2 CTTS STIS/GHRS/FUSE, but not WTTS (Herczeg et al. 2002, 2006)
- Mid-IR H$_2$ emission: detected for AB Aur (Richter et al. 2002; Sheret et al. 2003)

OI

- UVES of HD100546 and 97048 shows OI coincident with dust disk and clumpy, from surface layer of disk (Acke & van den Ancker 2006)

Radio interferometry

Brightest protostellar disks detected with VLA at 7mm - 3.6cm and resolved if >1"; e.g., TW Hya imaged at 7mm (0.1"=5AU resolution)
(Wilner et al. 2000)
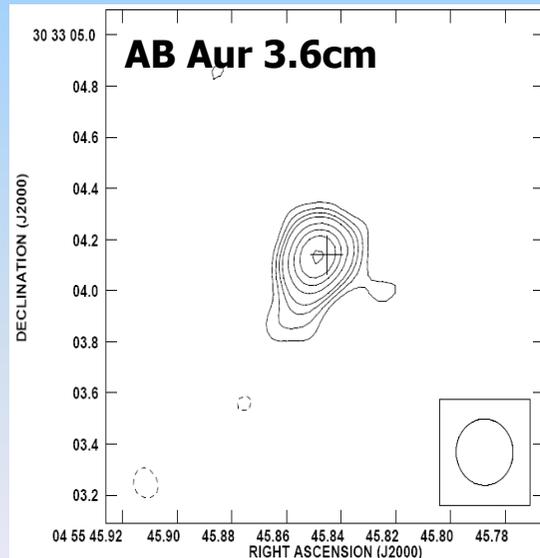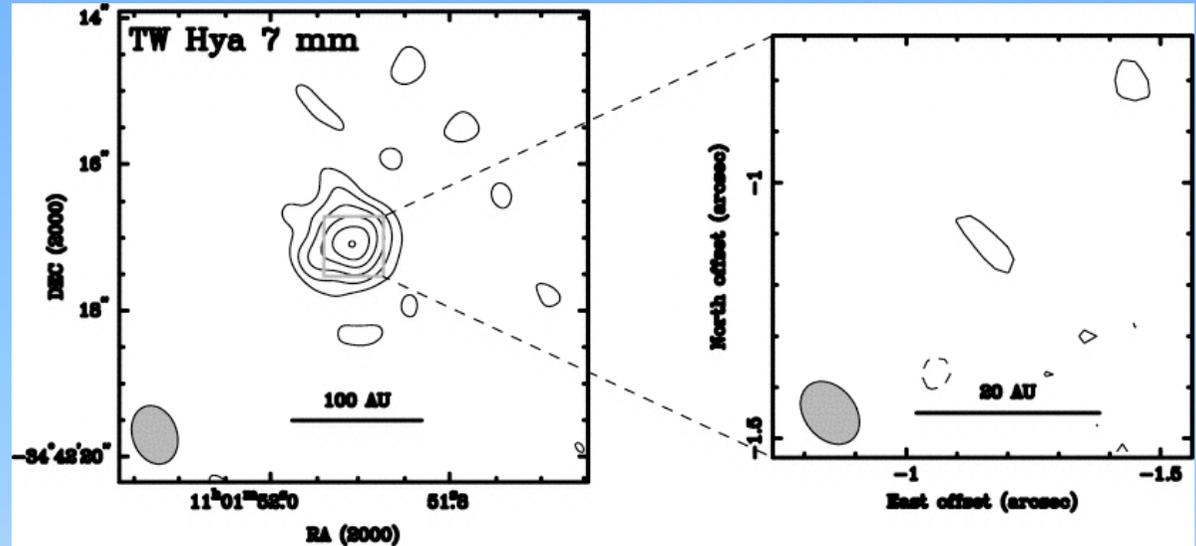
Also detects companions
(Rodriguez et al. 2007; see also Millan-Gabet et al. 2006)

Long wavelength fluxes determine spectral slope and so grain size, but must account for gas free-free emission
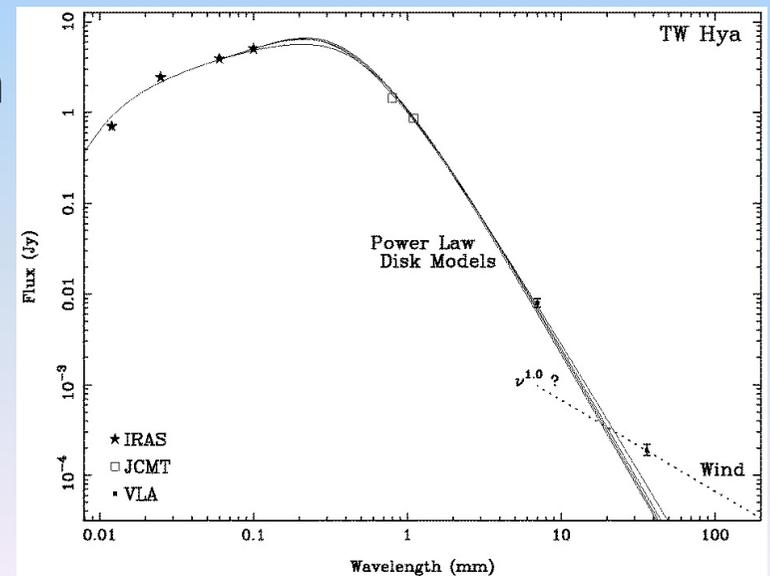
Spectral slopes in mm

Survey for radio emission (7mm) toward
14 PMS in Taurus-Auriga (Rodmann et al. 2006):
- 10 resolved at ~1.5"
- after subtracting free-free emission
α=2.3-3.2
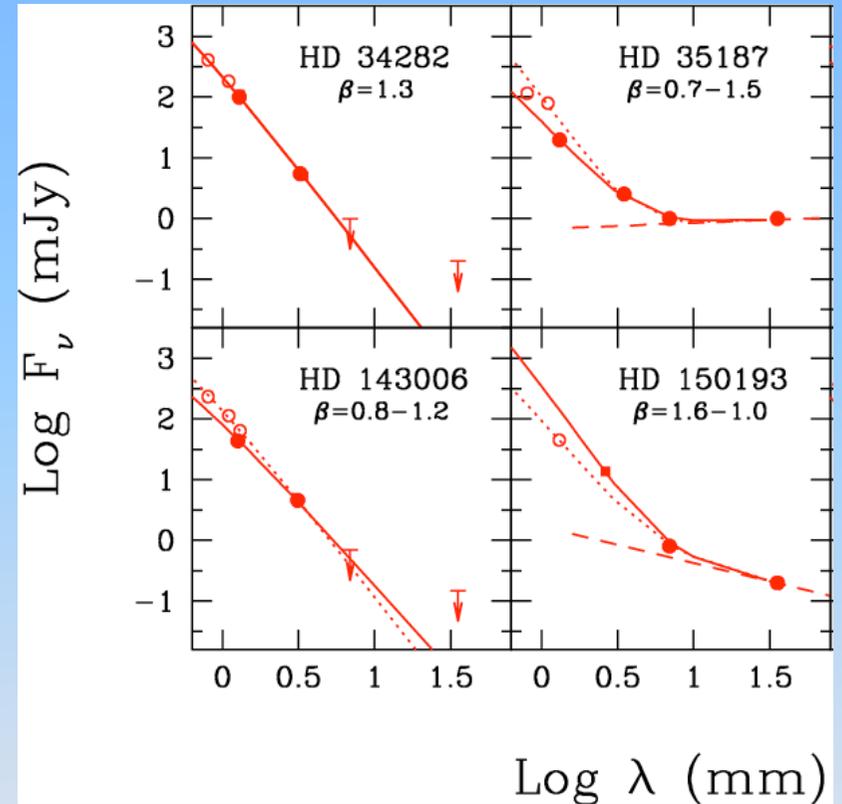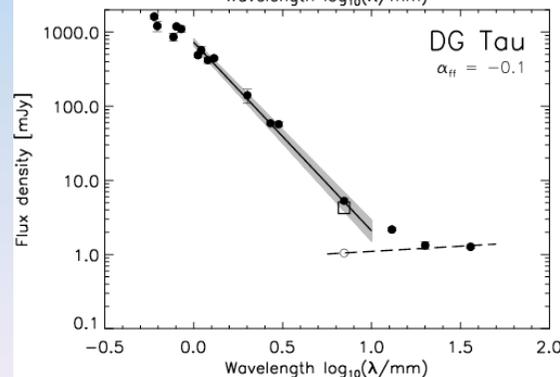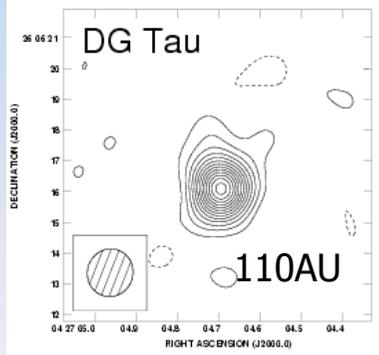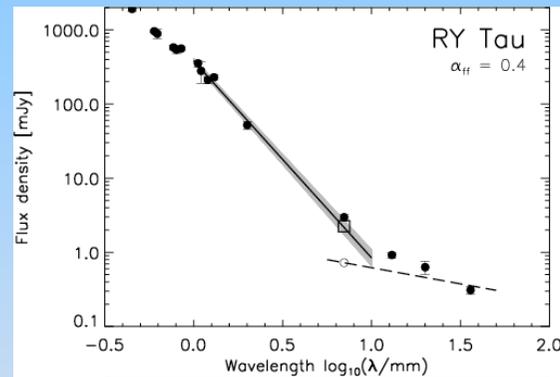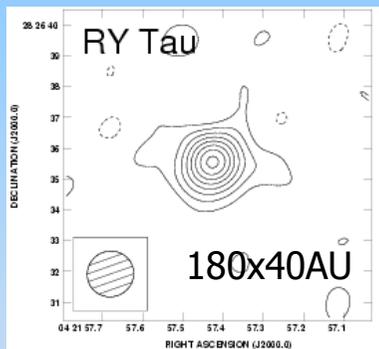
Similar surveys performed
for HAeBes (Natta et al. 2004)

Implies β=0.5 to 1.6 and so mm-sized grains

Growth to mm

Spectral slope (α) must be modelled to get opacity slope (β), because of optical depth degeneracy ($\beta=\alpha-2$ only valid for optically thin emission)
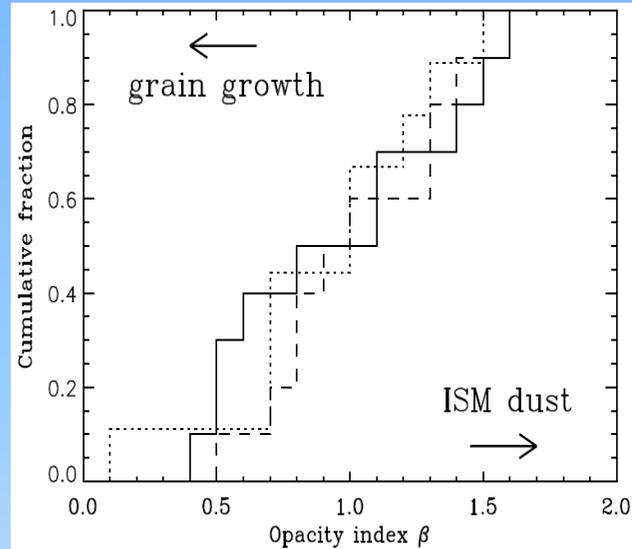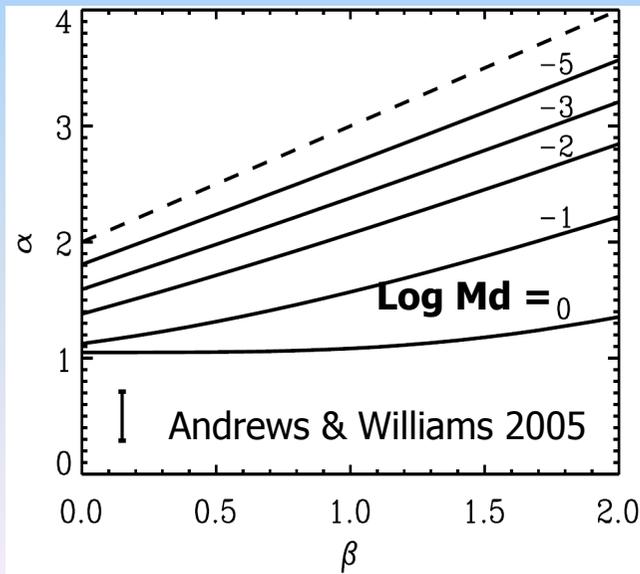
Survey compilation (Lommen et al. 2007; Andrews & Williams 2007)
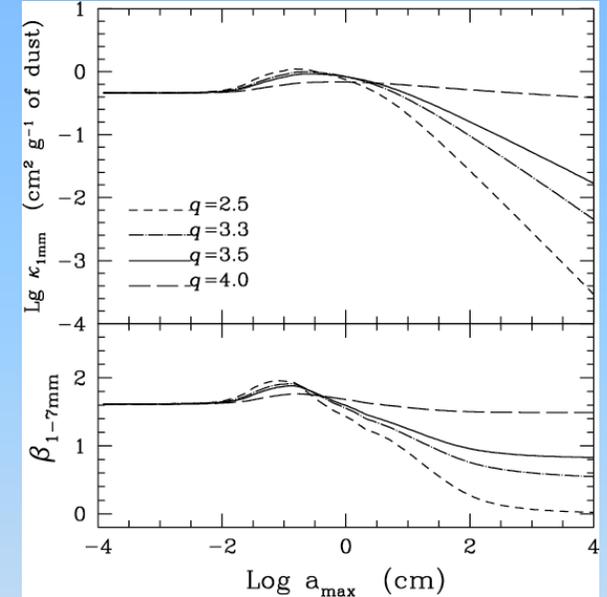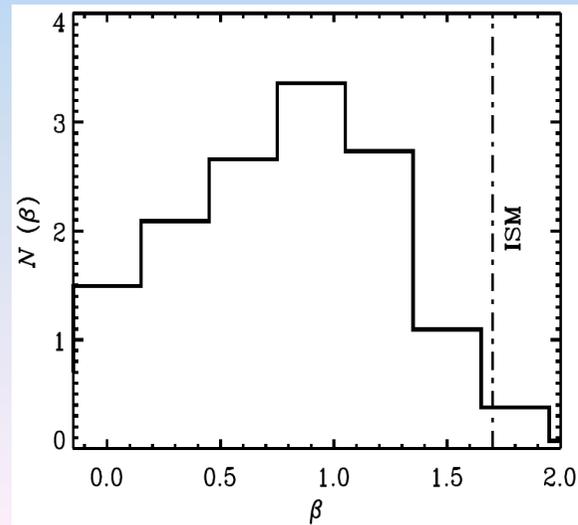
β must be modelled to get grain size, but is ~2 for sub-micron grains in ISM, ~0 for large black body grains

Proplyds

PROto-**PL**anetar**Y** **D**isk**S** detectable because in/near HII region

First proplyds found in Trapezium (Orion, 450pc, 1Myr, 1000 stars in a few pc)

Ionised gas/dust <500AU diameter with ionisation and shock fronts pointing toward, tails pointing away from nearby OB stars (θ^1 Ori C and θ^2 Ori A, O6 and O9.5, $45M_{sun}$ and $25M_{sun}$)

170-337
167-317
163-317
Theta 1 C Ori
161-324
158-323
157-323
168-326
176-325
158-326
180-331
158-327
161-328
177-341
160-353
155-338
159-338
174-414
182-413
171-340
159-350
O'Dell et al. (1998)
183-419
184-427
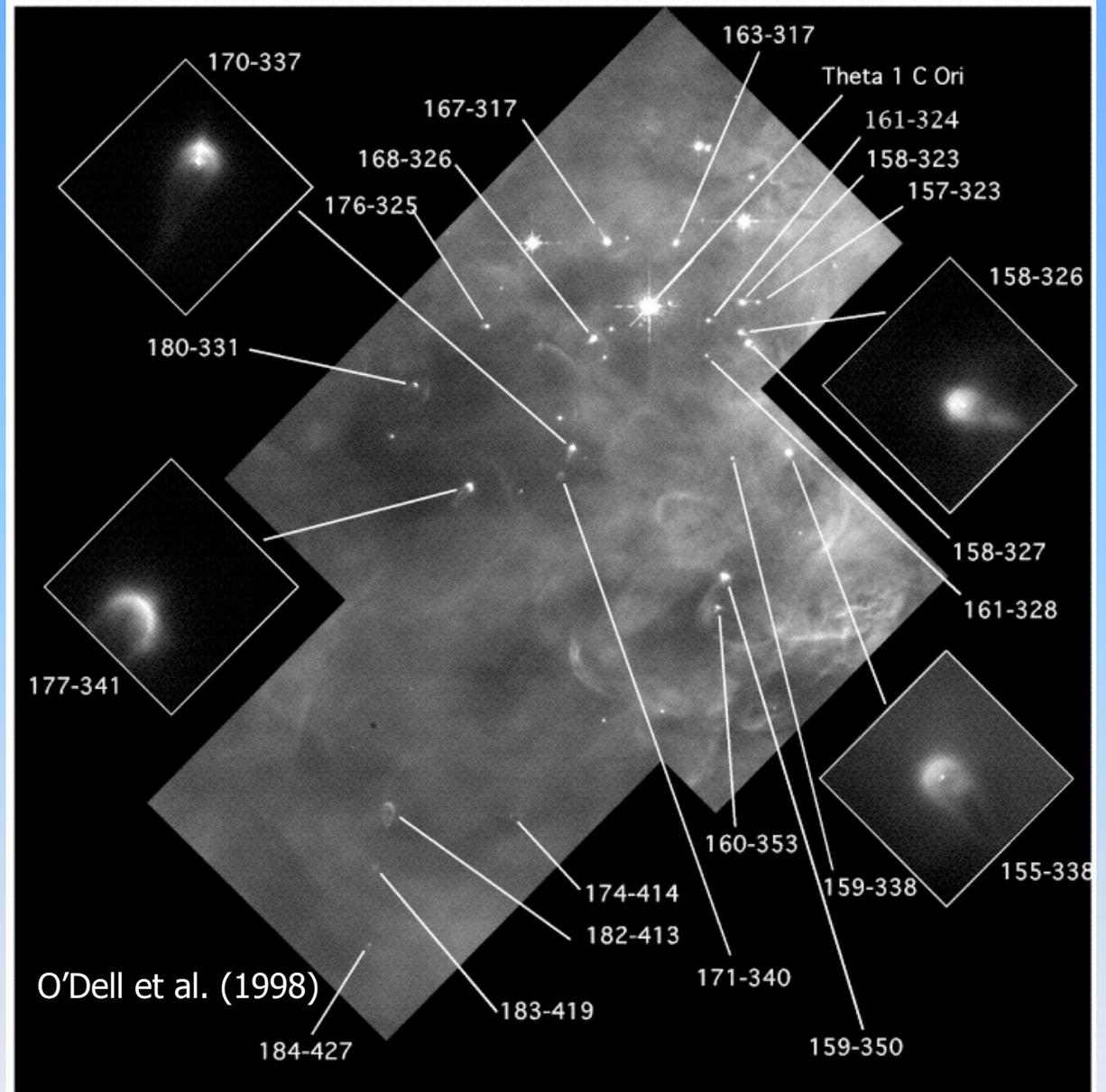
Neutral material eroded by UV of OBs; ionized gas streams off and blown into tear-drop; disk shape origin as opaque if isotropic whereas star seen

Optical silhouette

Disks detected for some proplyds either:

• in silhouette against background nebula (McCaughrean & O'Dell 1996; Bally et al. 2000)
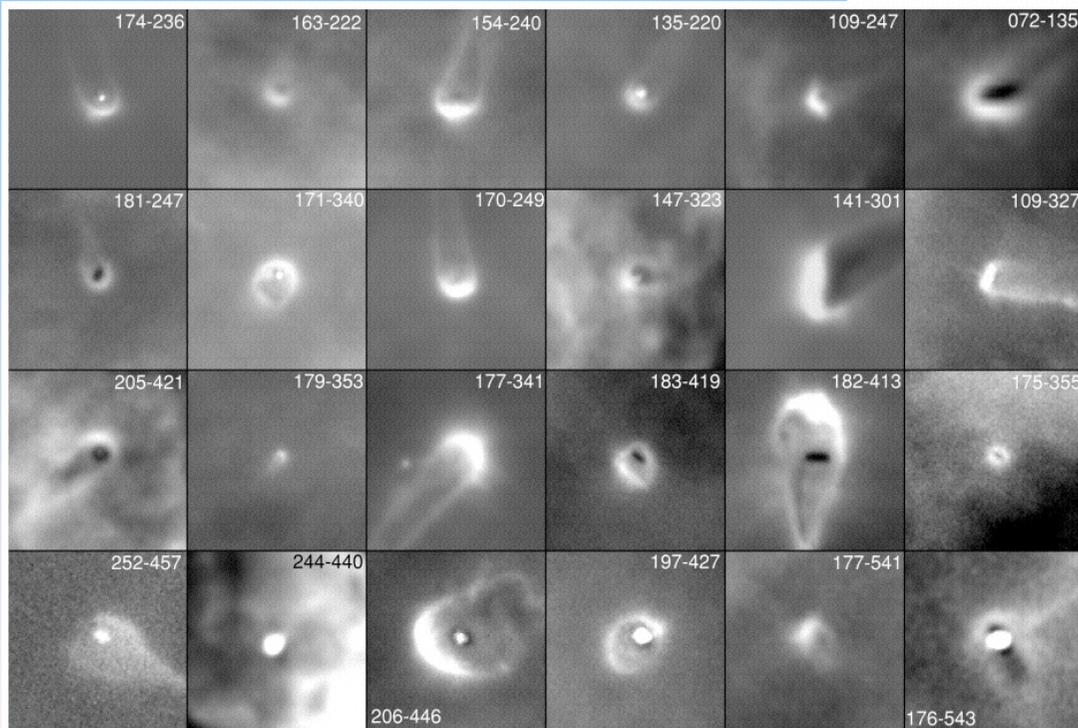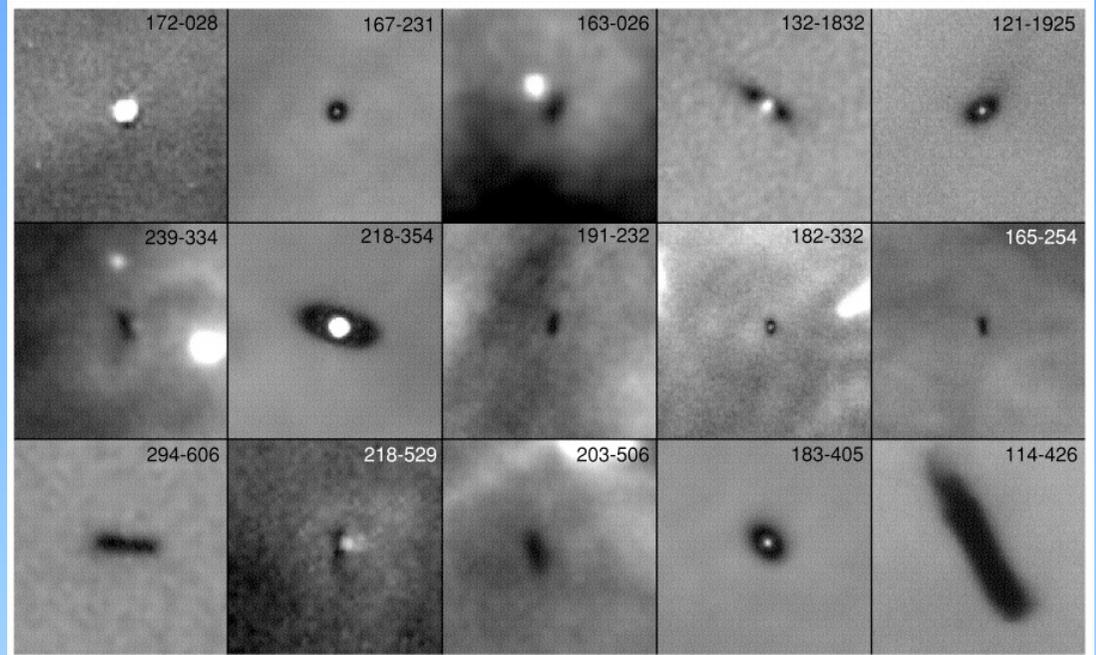
• in silhouette against own ionisation front (Bally et al. 2000)

This latter population used to get ratio of disk diameter to ionisation front diameter (49±16%) and so infer disk sizes

Disk sizes

Size distribution: $N \propto r^{-1.9}$ from a single population, possibly primordial (Vicente & Alves 2005), silhouette disks largest
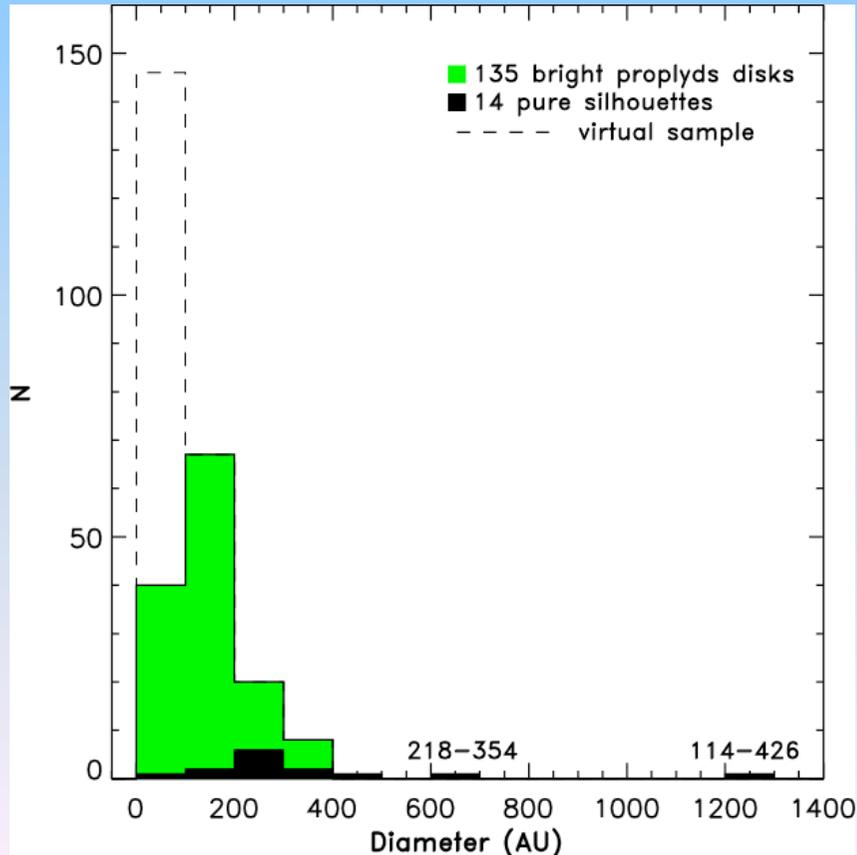
No dependence on spectral type of central star (from optical/ NIR spec), $0.3-1.5M_{sun}$
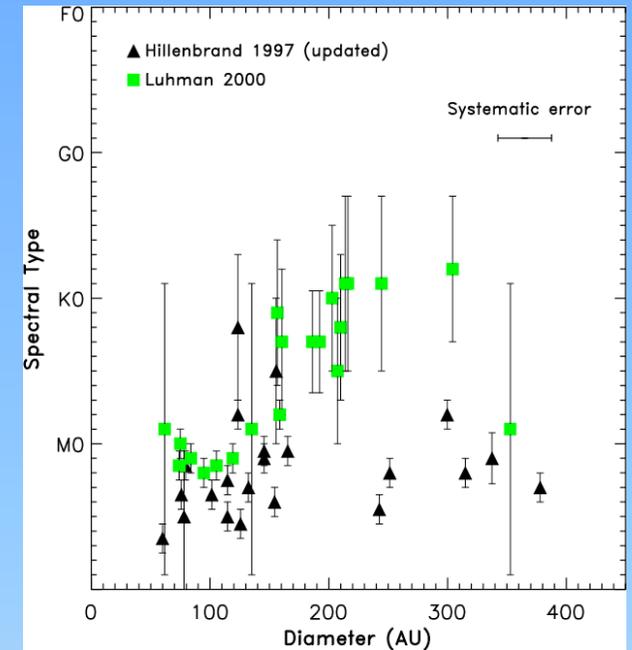
Or with distance from ionising star (Balog et al. 2007)
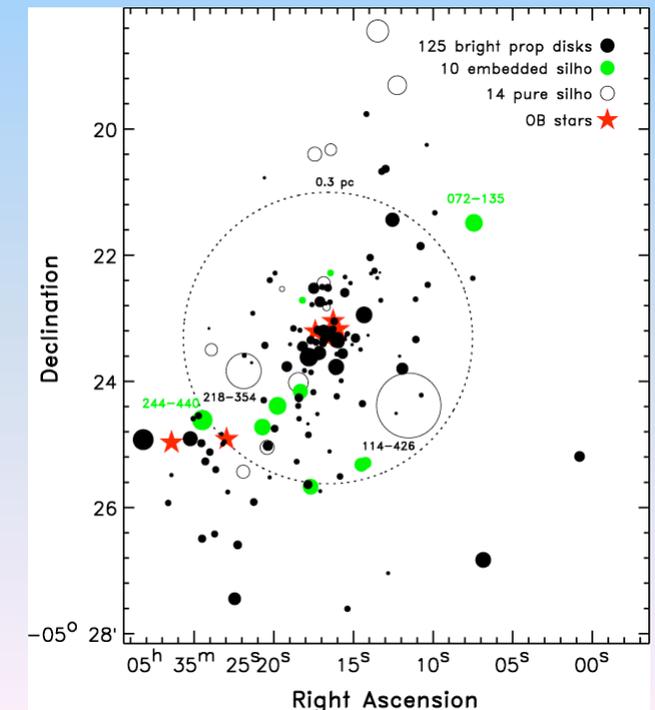
Mid-IR from proplyds

Mid-IR imaging of ONC (Smith et al. 2005):
• 80% of known proplyds detected
• 40% of naked stars have mid-IR

Disks of naked stars <0.1" (<50AU, as not resolved with HST), evenly distributed whereas proplyds closer to ionising star

ONC stars 0.5-2Myr, youngest 0.5Myr <0.3pc from θ^1 Ori C (Hillenbrand 1997), suggesting naked star disks smaller because older

Also, Shuping et al. (2006), Huff & Stahler (2006)
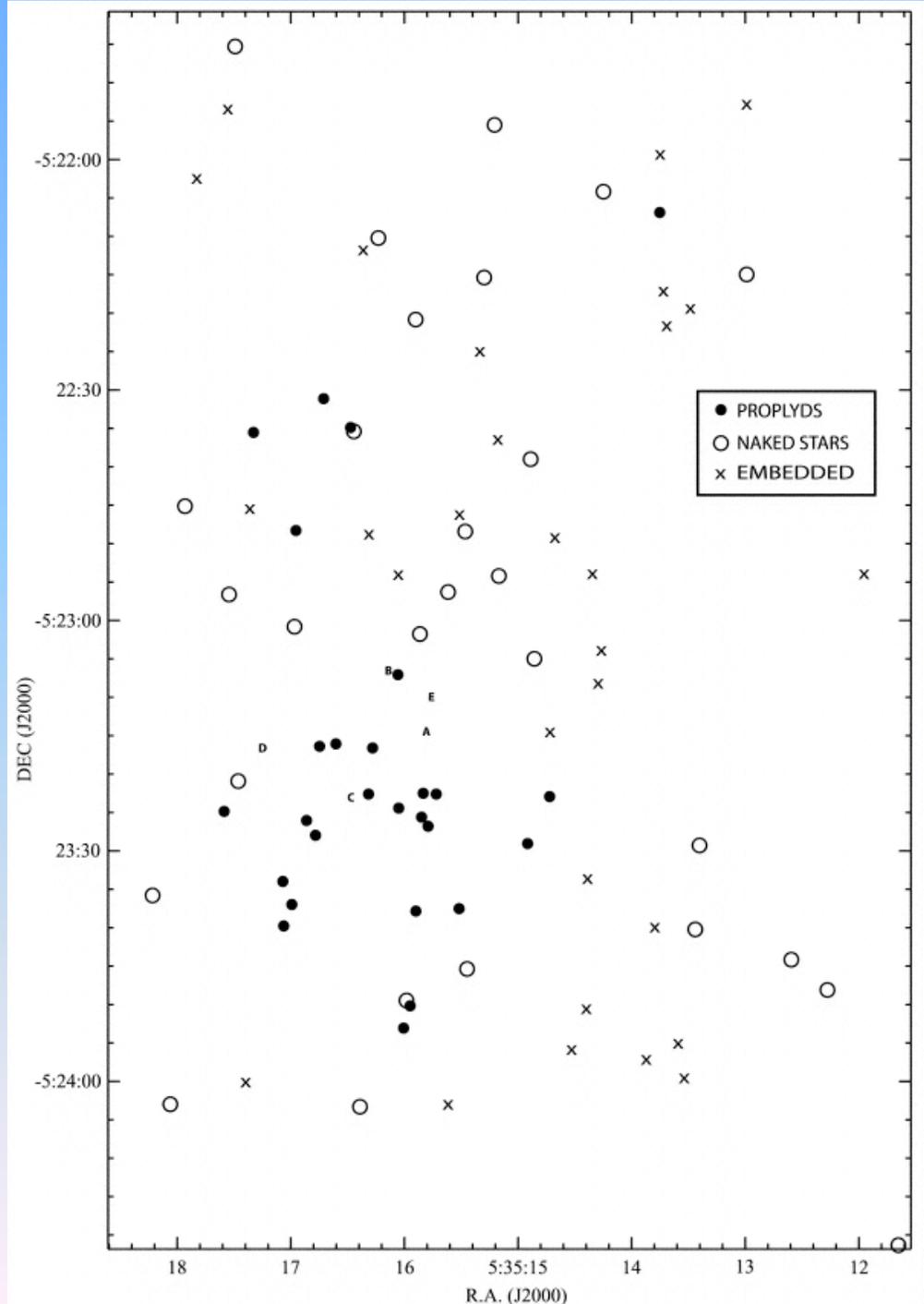
Masses

SMA (880μm) give proplyd mass after subtracting estimated free-free emission (Williams, Andrews & Wilner 2005):

- 5 are 12-24M_{Jup}
- 18 non-detected at average 0.0008M_{sun}
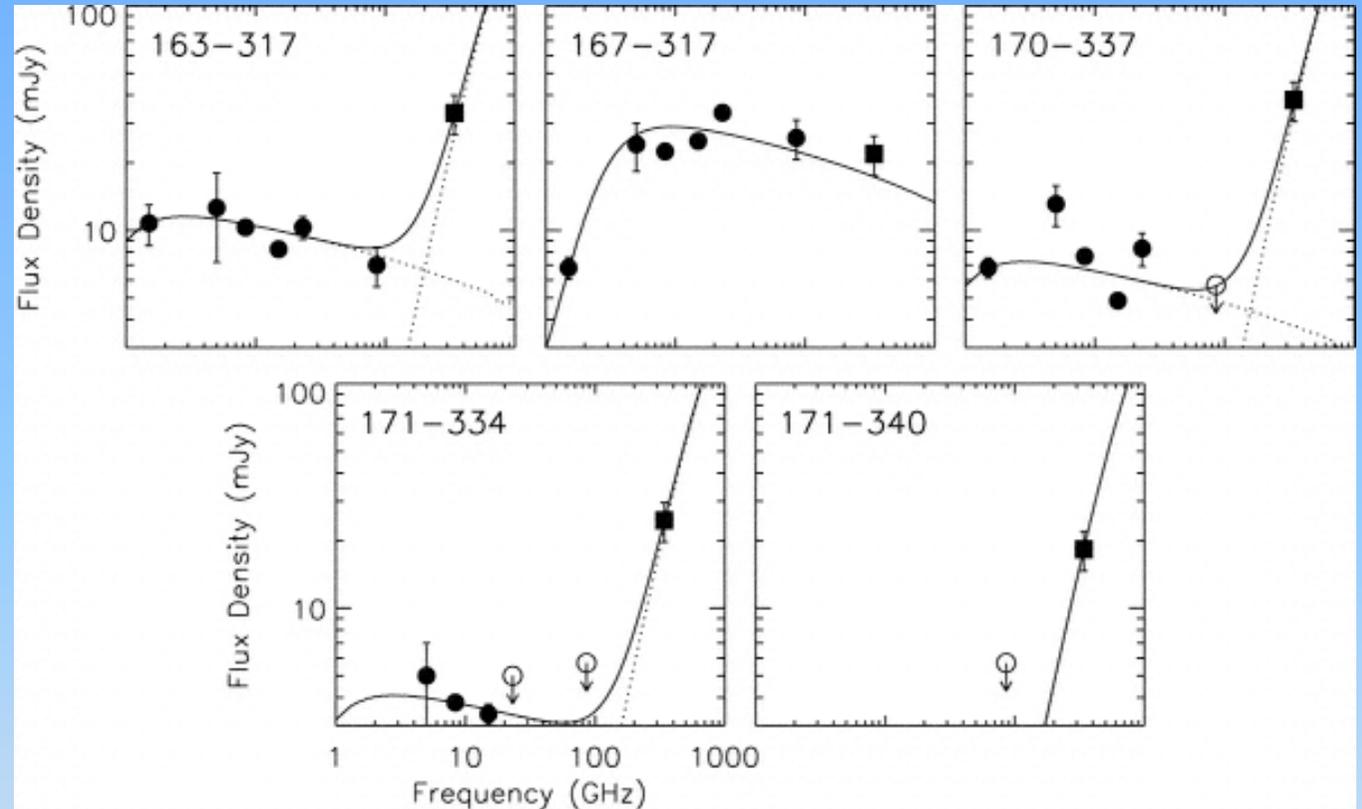
OVRO (3mm) (Eisner & Carpenter 2006) detected 6/336 at lower sensitivity (0.13-0.39M_{sun}) comparable to Taurus (~1.2%) implying mass not affected by interaction with star (but caveats about mass derivation)

VLA shows mass loss rate of ionised gas of $10^{-7}M_{sun}$/yr meaning either:
- θ^1 Ori C is 0.1Myr
- Ionised gas recombines before leaving system
- Proplyds on radial orbits (Storzer & Hollenbach 1999, but see Scally & Clarke 2001)

Disk structure from observations

Dust-structure of disk

layer of larger dust grains

hot dust surface layer

colder midplane

hot dust surface layer

dust condensation radius r_{cr} r_g

Gas structure of disk

HII

atomic layer
hot layer
H2 layer, no CO yet

CO layer, no H2 yet

intermediate warm layer: rich molecular chemistry

freeze−out of molecules

dust condensation radius r_{cr} r_g

Dullemond et al. (2007)