Observations of circumstellar disks with infrared interferometry

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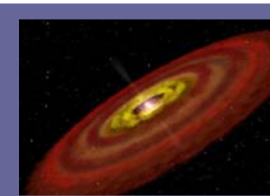
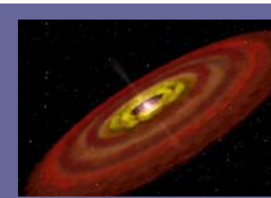


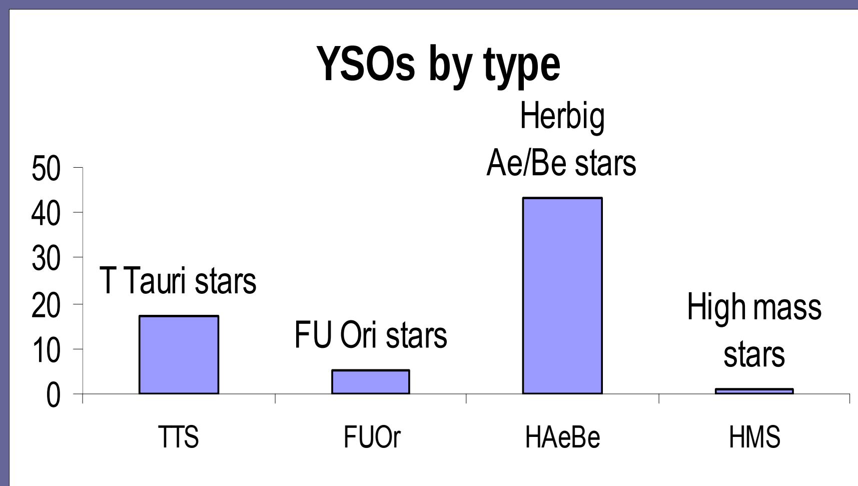
Outline

- Observations of young stellar object disks
  - Inner disk
    - Dust
    - Gas
  - Middle disk
    - Composition
    - Structure
  - Jets and winds
  - FU Ori's
- Stellar properties
- Debris disks
- Future prospects

Thanks to R. Milan-Gabet and F. Malbet for slides, also see review of field in Protostars and Planets V

Census of results

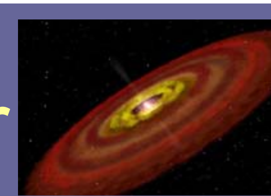




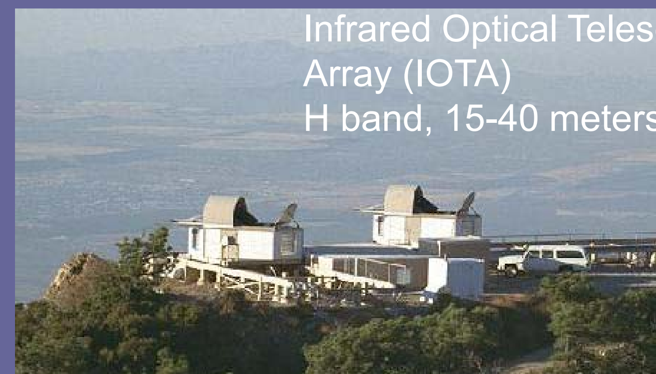
→ **66 young stellar objects** observed and published to date,

→ **30 refereed articles**

Telescope and Instruments used for YSO observations

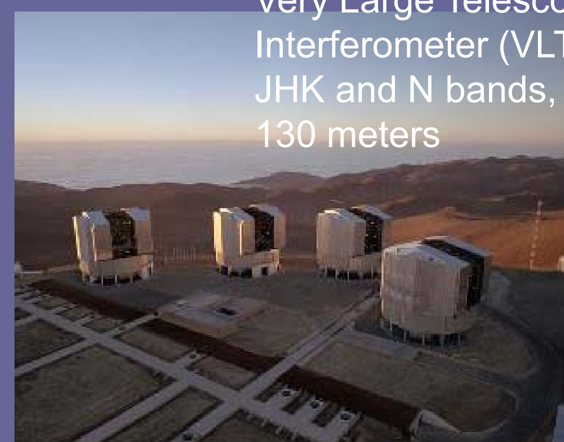


Palomar Testbed Interferometer (PTI)
H and K bands, 85-100 meters



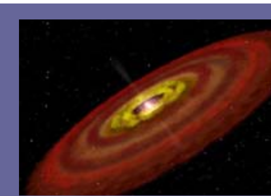
Infrared Optical Telescope Array (IOTA)
H band, 15-40 meters

Keck Interferometer (KI)
H and K bands, 85 meters

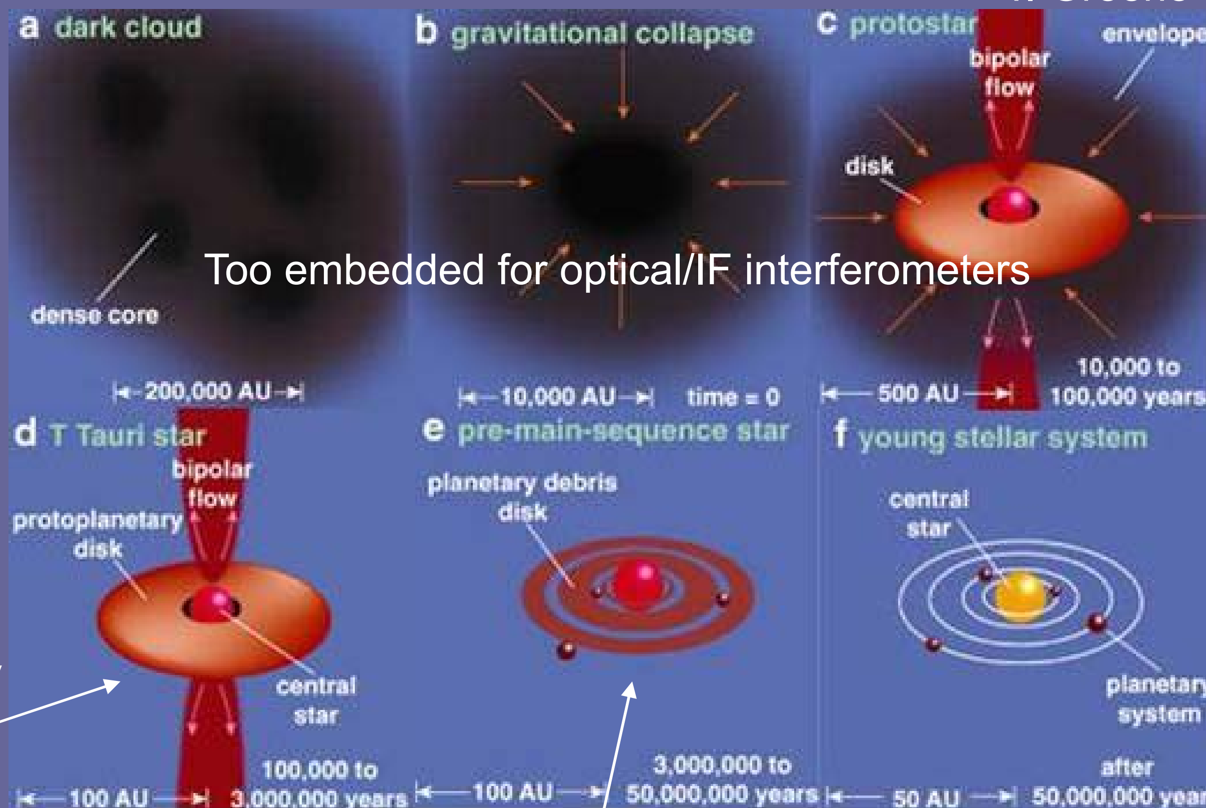


Very Large Telescope Interferometer (VLTI)
JHK and N bands, 47-130 meters

Star formation stages



T. Greene

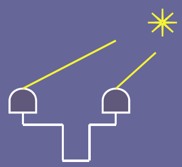


Too embedded for optical/IF interferometers

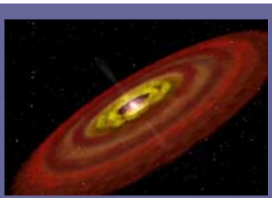
Most observations are at the disk only stage

Debris disk stage requires high dynamic range

Some instruments are targeting planets (not this talk)

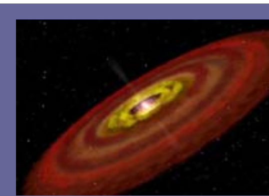


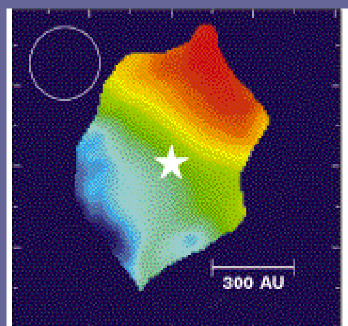
Why interferometry?



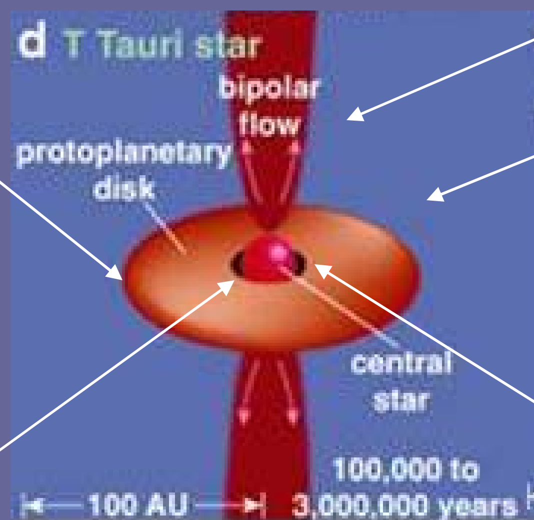
- Resolution
  - The nearest regions of star formation are ~140 parsecs away
  - At this distance 1 AU subtends an angle of 7 milliarseconds
  - The fringe spacing for a 100 meter baseline operating at 2 microns is 4 milliarcseconds and at 10 microns is 20 milliarcseconds
- Sensitivity
  - The inner disk (< few AU) has substantial near-infrared emission
    - Probes hot dust
  - The middle disk (1-10 AU) emits at mid-infrared
- Complimentary to other wavelengths
  - Millimeter (CARMA, ALMA) = 10s to 100s of AU, cool dust

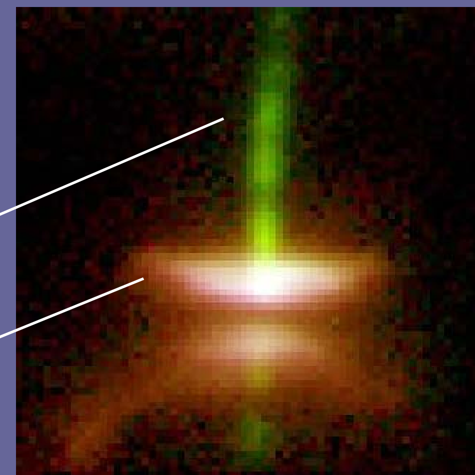
Where does interferometry fit in?



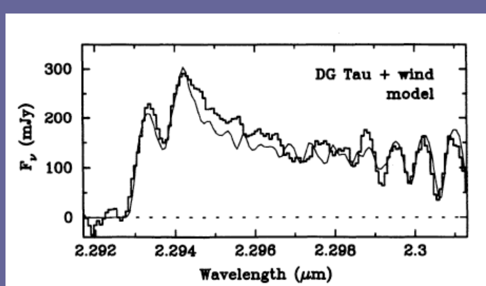


Millimeter interferometry: disk size, mass and kinematics

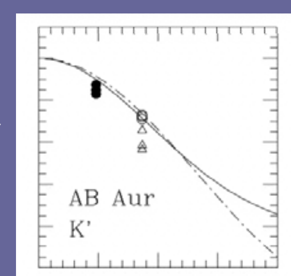




Optical and near-IR imaging: outer surface (scattering) and jets

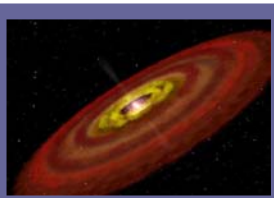


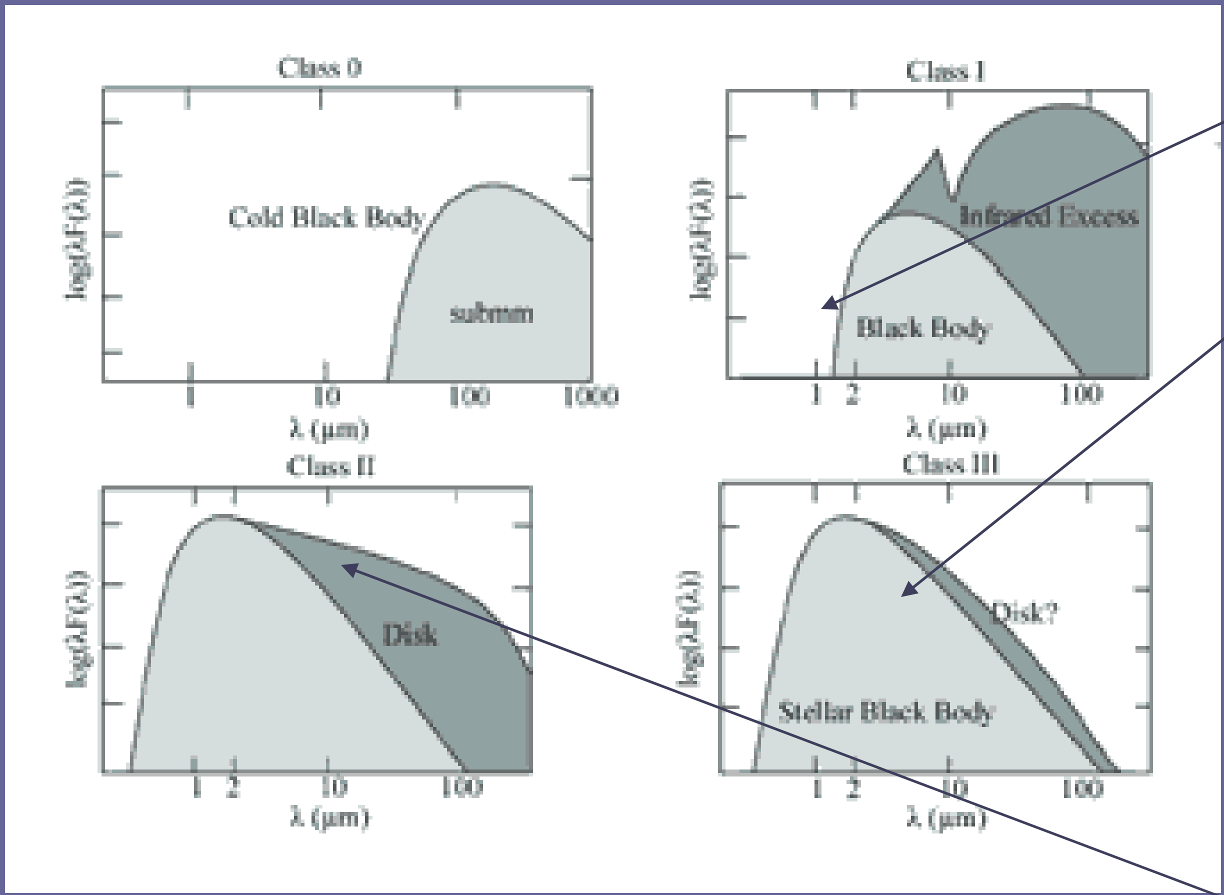
Optical and infrared spectroscopy: accretion and kinematics



Infrared interferometry: central disk size and structure

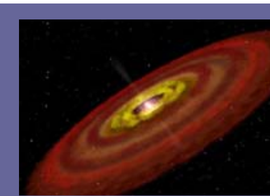
What is interferometry looking at?





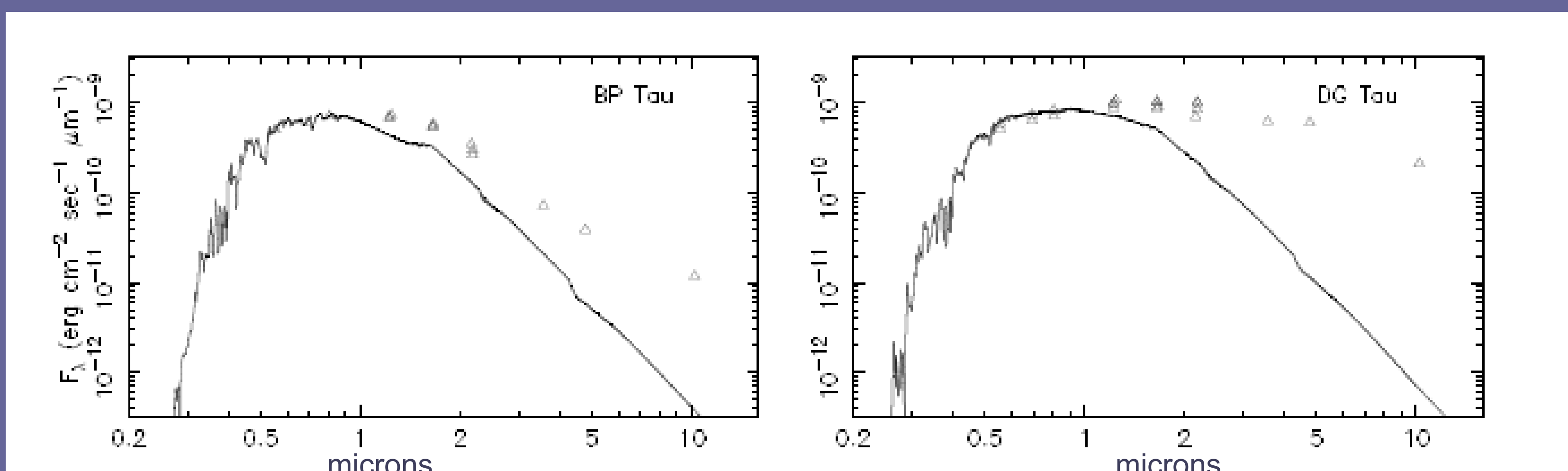
1. The central star
   - Not visible at short λ in early stages
   - Too small to resolve (for now) in later stages

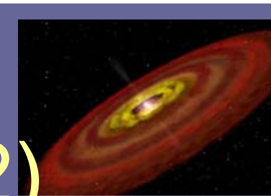
2. The excess
   - Scattered light in optical and near-IR
   - Thermal emission in near-IR to cm



General method for observing disks

1. Get visibility measurements on your favorite target
2. Determine the non-disk (stellar, scattering, envelope) contribution at the appropriate wavelength
   - SED fitting (issues with non-contemporaneous data as many of these sources are variable)
   - High resolution spectroscopy veiling measurements (better, but not much data yet)
   - Interferometer field of view helps exclude large structures





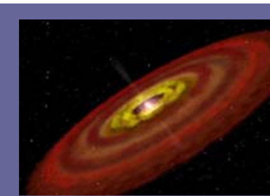
General method for observing disks (2)

3. Fit your favorite model
   - Can determine inclination if enough baseline angle coverage
   - Models range from geometric (thin ring) to full radiative transfer
     - But beware if you have only 1 baseline or little wavelength coverage: many models (gaussian, ring, point source + incoherent) will fit data

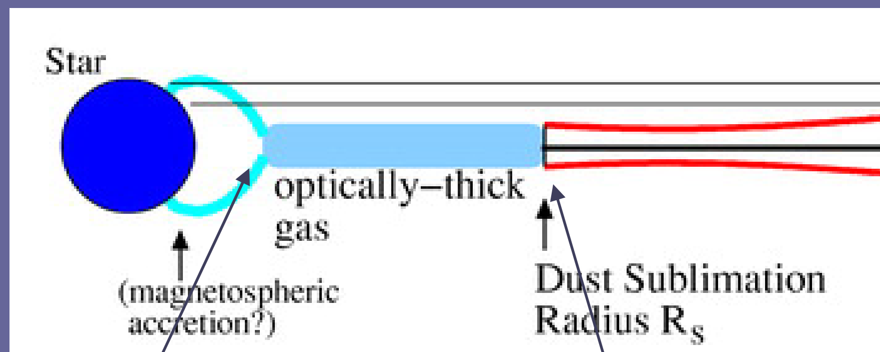
$$V_{total} = \frac{V_{star} f_{star} + V_{disk} f_{disk} + V_{extended} f_{extended}}{f_{star} + f_{disk} + f_{extended}}$$

$$\approx \frac{V_{star} f_{star} + V_{disk} f_{disk}}{f_{star} + f_{disk} + f_{extended}}$$

Warning: The errors from step 2 are often larger than the measurement errors (step 1)



The Inner Disk

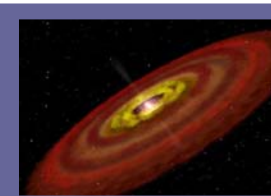


Where does the disk start?

Where does the dust start?

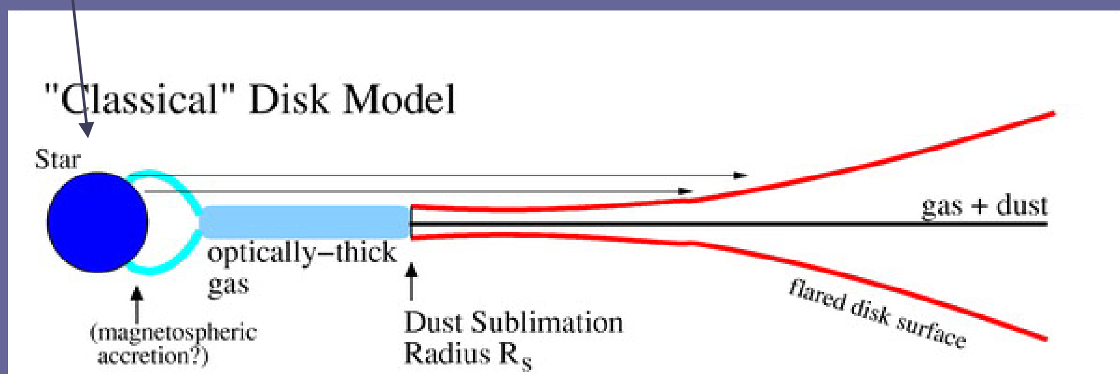
Is there emission from another component on small scales?

T Tauri/Herbig disk model



Star is unresolved (few R_{solar})

Disk visibility will depend on size and flux profile

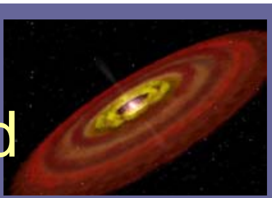


Disk extends to ~100 AU

$$T(\text{disk}) \propto \text{radius}^{-3/4}$$

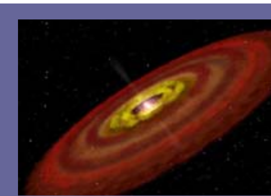
Inner radius often set by matching the excess infrared flux. Some theories predict the inner radius is a few times the stellar radius.

Initial YSO observations: Near-infrared at PTI and IOTA

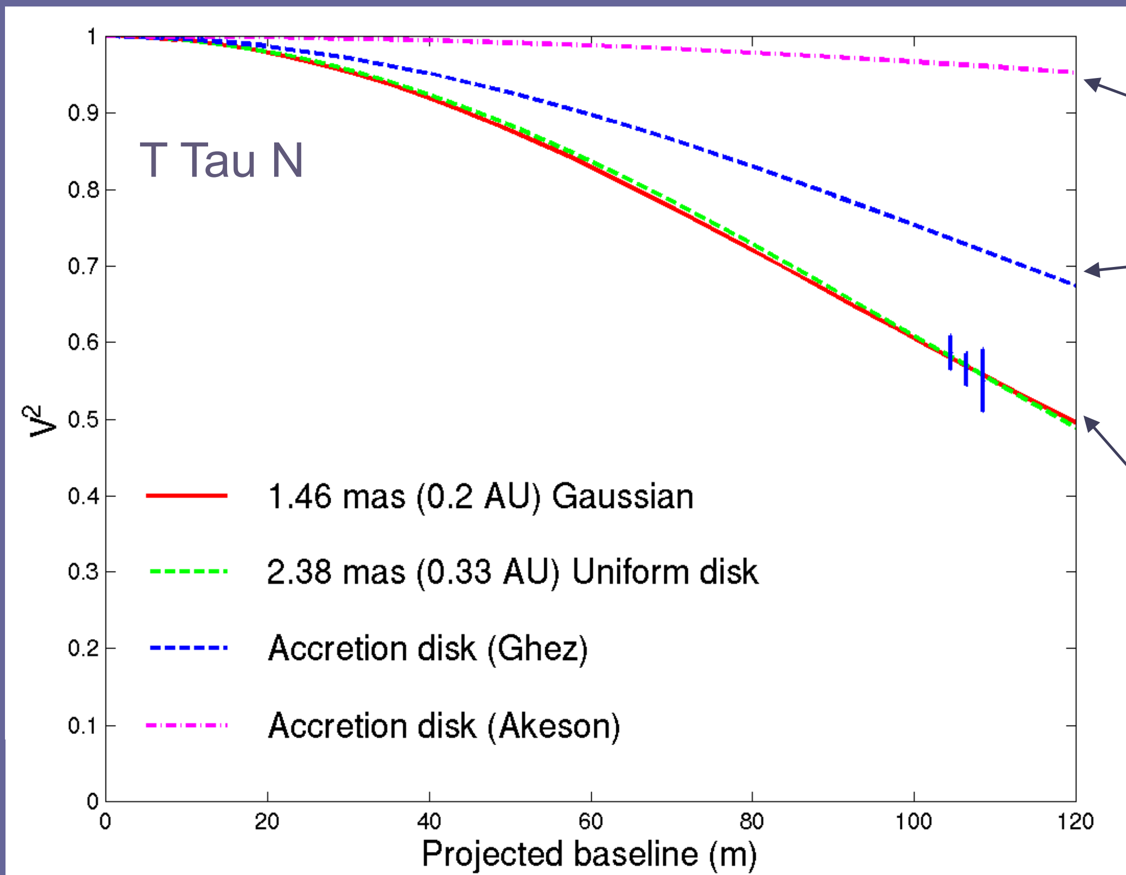


- Herbig AeBe stars
  - AB Aur (Millan-Gabet et al 1999, IOTA)
  - Survey of 15 Herbigs (Millan-Gabet et al 2001, IOTA)
  - General conclusions:
    - Late type Herbigs NOT consistent with flat accretion disks (too large, too few inclined sources)
- T Tauris
  - 2 sources observed at PTI (Akeson et al 2000)
  - Also larger than predicted, but inclined disks observed
- FU Oris
  - FU Ori (Malbet et al 1998) consistent with accretion disk model

T Tauris



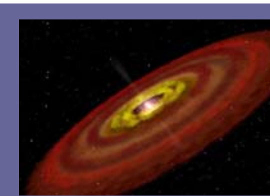
Akeson et al 2000



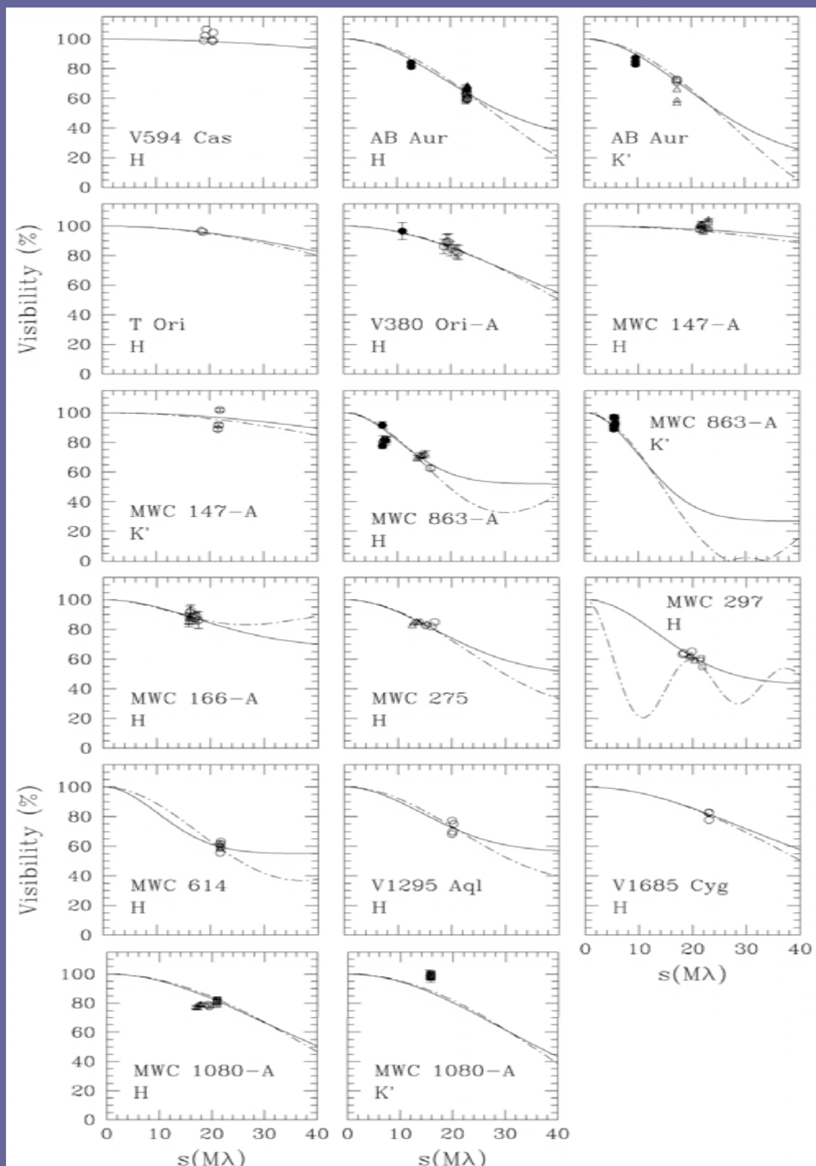
Visibilities predicted by models fit to other kinds of data

PTI data points, note some change in baseline due to earth rotation

* Both accretion disk models <u>overestimate</u> the visibility and thus <u>underestimate</u> the size of the K band emission region
* Similar result for SU Aur

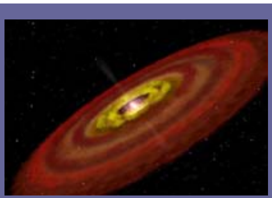


Herbig Ae/Be's



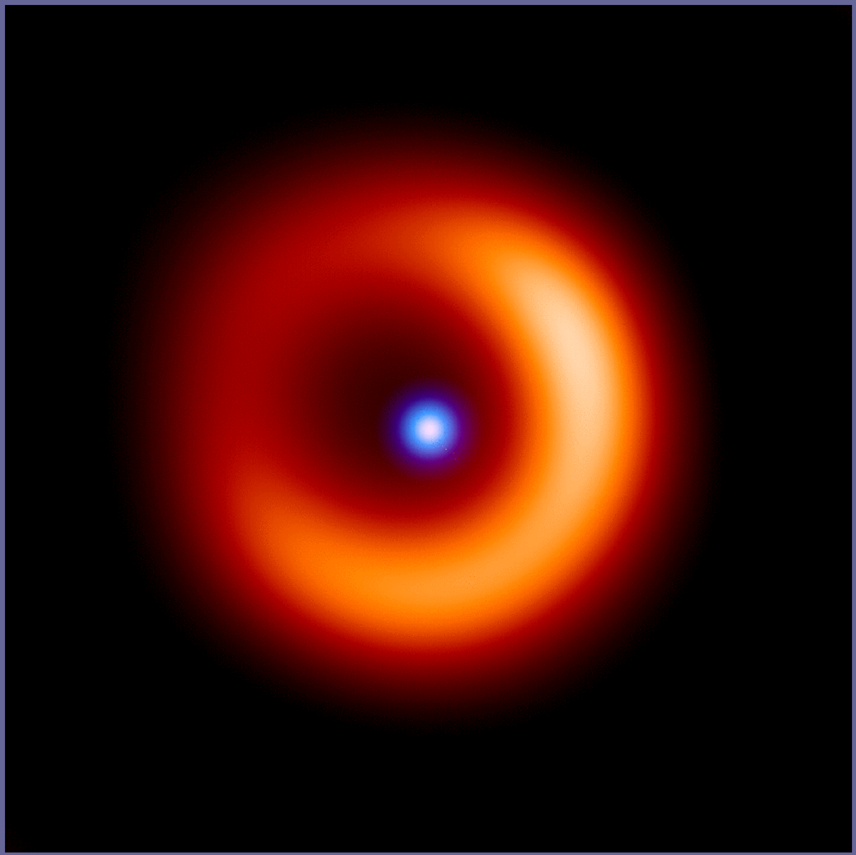
- Survey of 15 sources
  - 1 binary discovered
  - All resolved sources larger than predicted from $T \propto r^{-3/4}$
  - No asymmetries observed
    - Are there disks, halos/envelopes or both?

Millan-Gabet et al (2001)

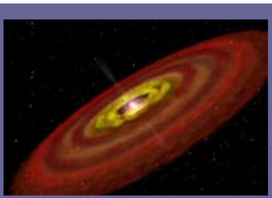


Observational evidence: Keck Aperture Masking

- Direct evidence for disk (inner cavity, elongated)
- Size consistent with heating of optically thin dust



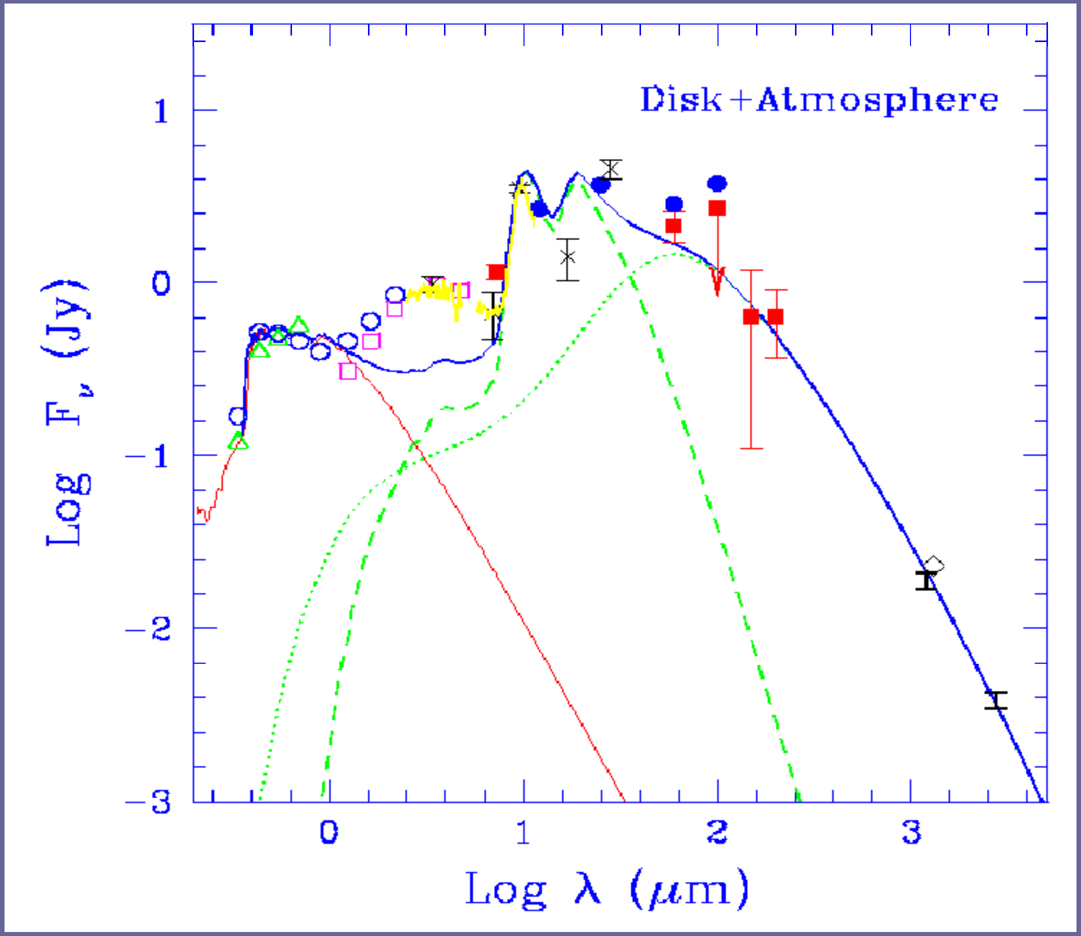
- LkHα 101
- Image formed with prior point source (maximum entropy method) and aperture masking data (Tuthill et al 2002)



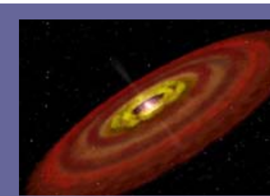
Another Herbig mystery

Dullemond et al

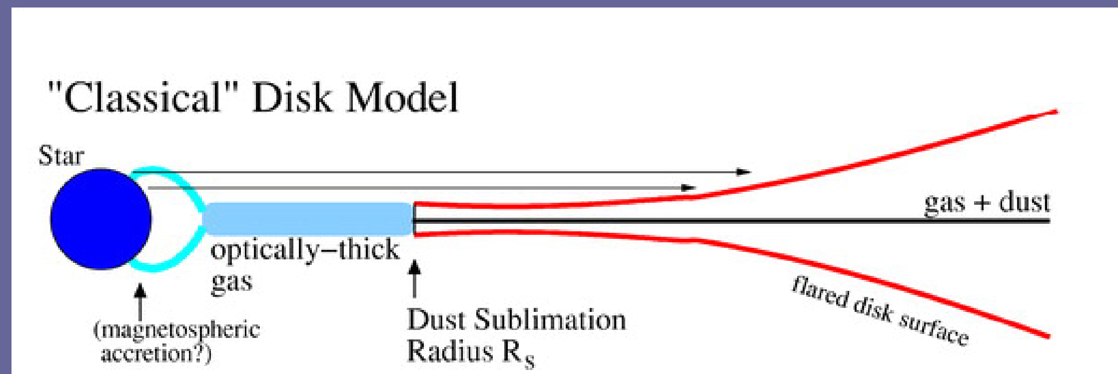
- Near-infrared bump seen in the SEDs of some Herbig sources is inconsistent with smooth temperature profile



Observations driving theory

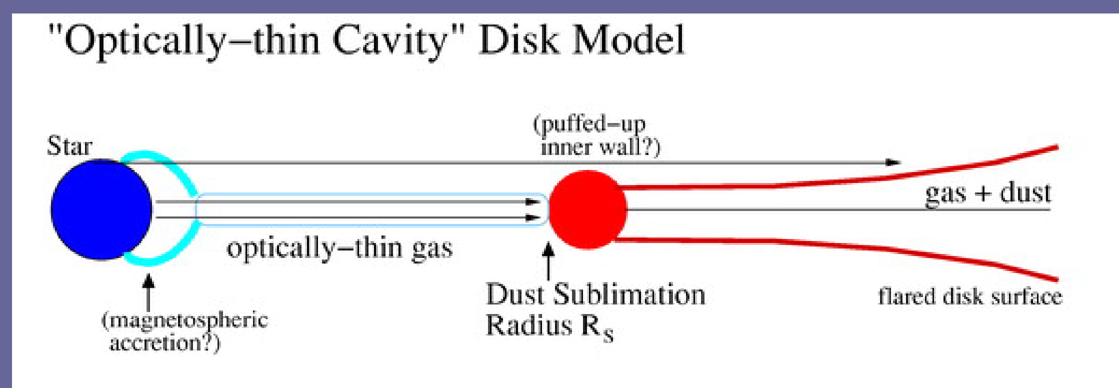


- In classical model, the disk should extend to a few stellar radii and there is no flux discontinuity at the sublimation radius (dust:gas = 1:100)

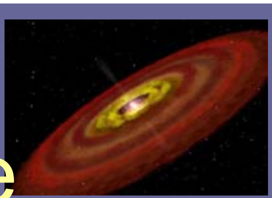


High visibility (mostly/entirely unresolved)

- Physical models developed by several groups (Natta, Dullemond, Muzerolle) in which the dust sees the stellar flux directly and is vertically extended

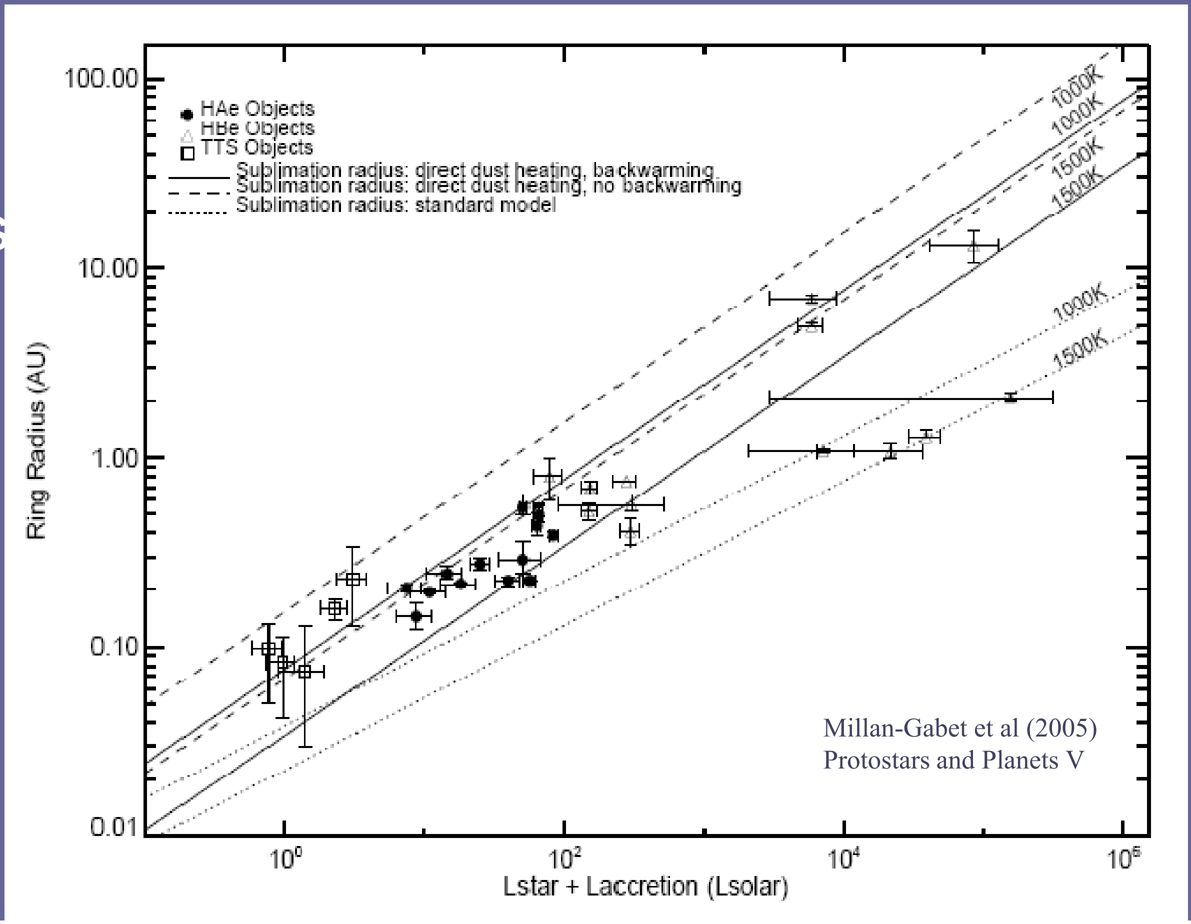


Low visibility (resolved)



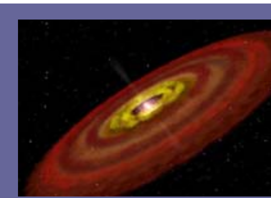
Disk size across the luminosity range

- Inner dust disk size related to luminosity (stellar and accretion) over several orders of magnitude in luminosity
- Evidence for Herbig disks seen on longer baselines (inclined sources)
- Some of the more massive Herbigs (Be) are consistent with optically thick inner cavity



Near-infrared data from IOTA, PTI, KI

Compare near-IR size to other disk scales

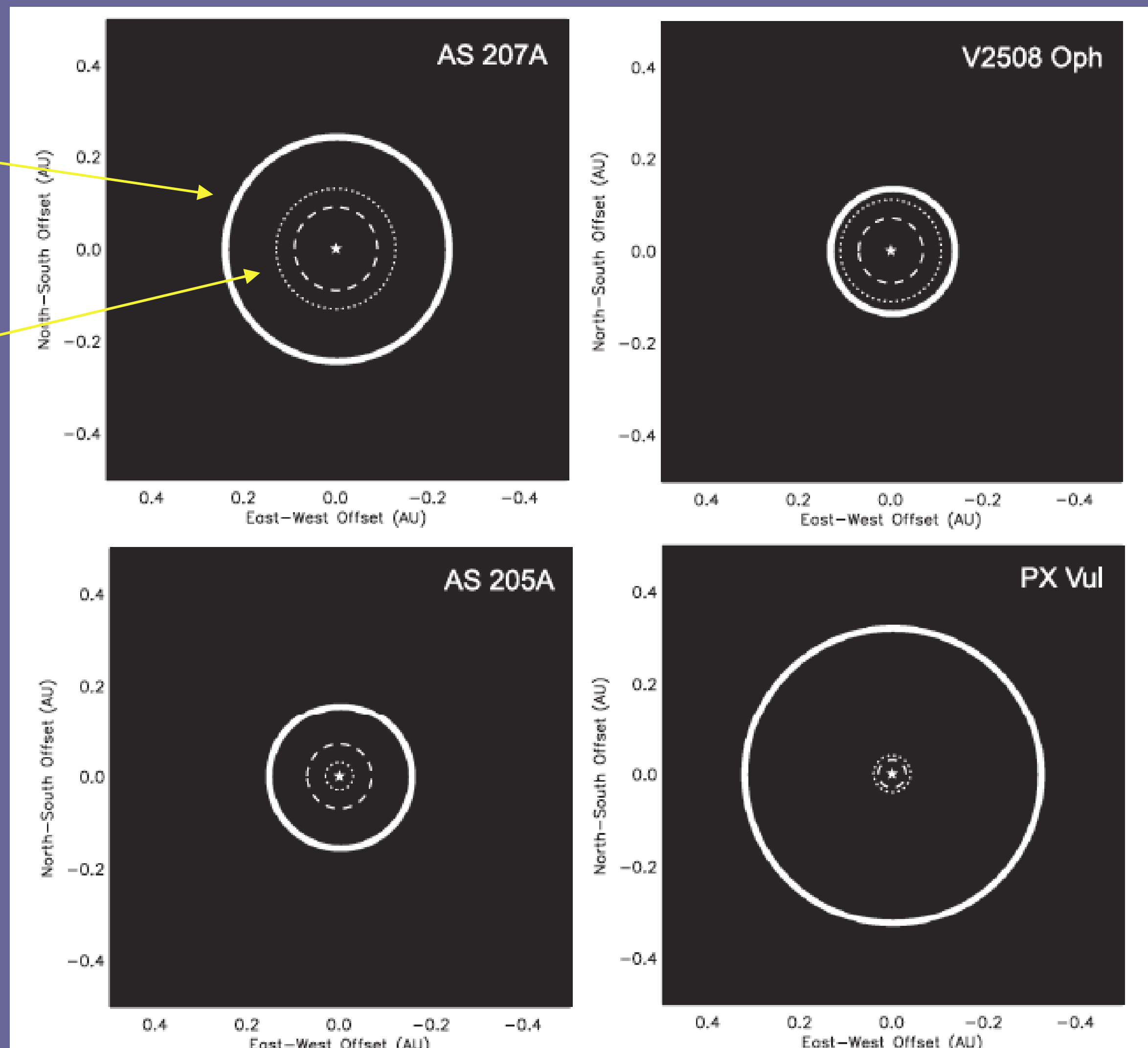


Eisner et al (2005)

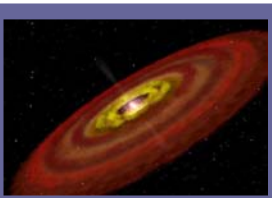
Near-IR size

Magnetospheric truncation radius

Disk emission is always further from the star than expected from truncation, but consistent with dust sublimation

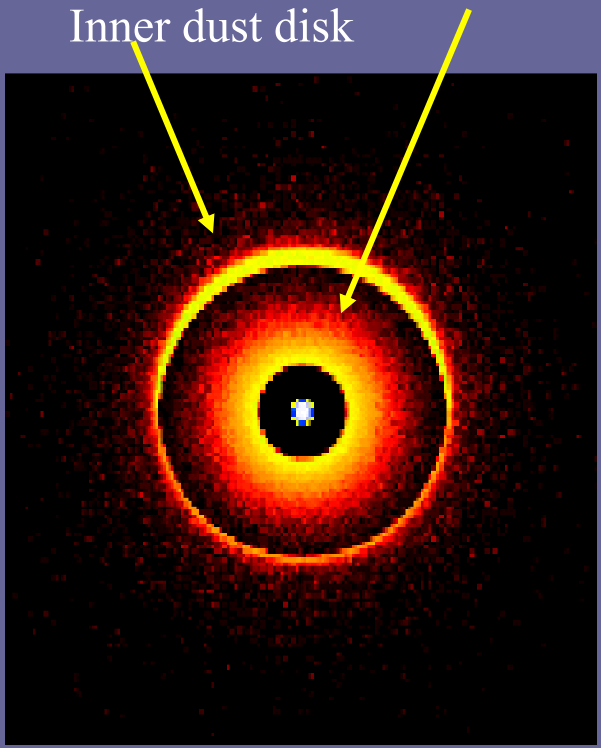


Example detailed disk models

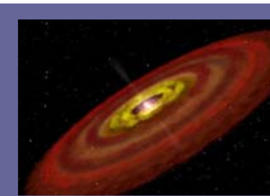


Akeson et al 2005

- Use well studied T Tauri sources with visibilities on 3 baselines (have inclination)
- Monte Carlo models: include disk accretion, accretion onto the star and scattering
  - Components: central star, gas and dust disk: dust dissipated at 1600 K, smooth density profile, standard gas to dust ratio
  - Gas inner radius set at corotation radius
    - Warm CO inner radii observed by Najita et al, Carr et al
  - Fit visibilities and SED
- For sources with large dust radii (RY Tau and SU Aur), the gas emission is significant at 2 μm
- For these sources, the contribution from emission extended to the interferometer (larger than 10 mas) is less than 10% at K

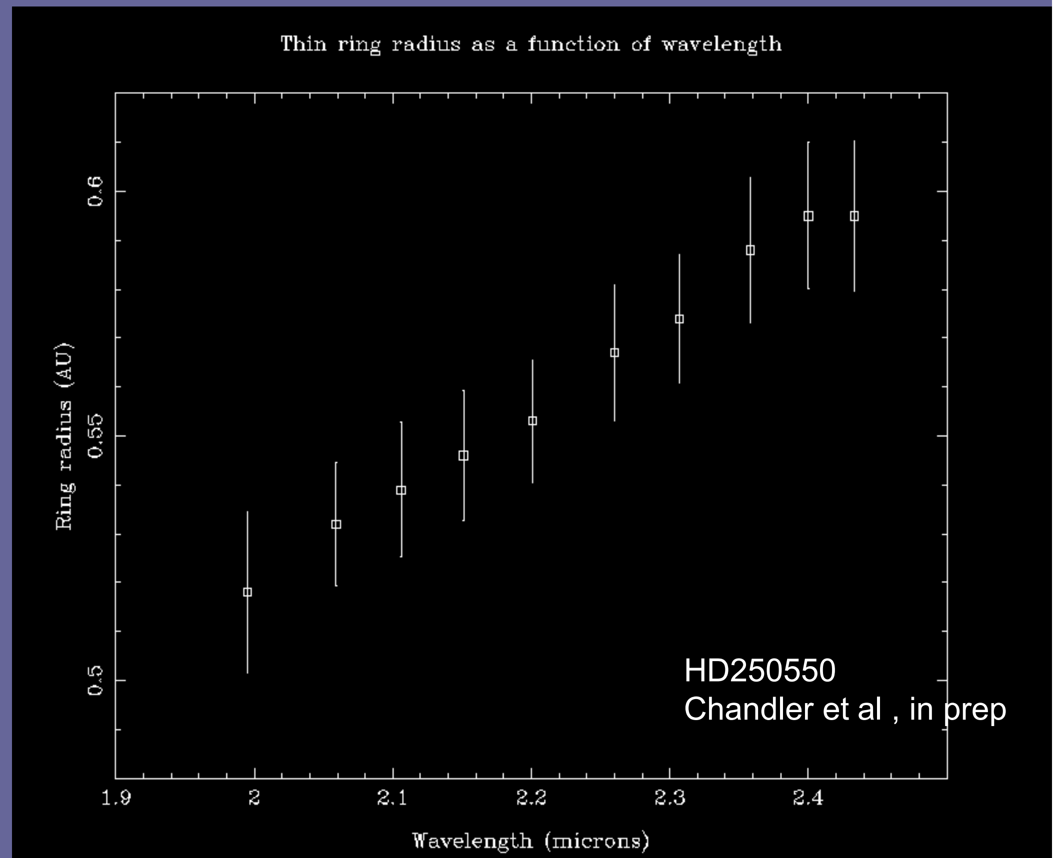


K band model image, 1 AU across



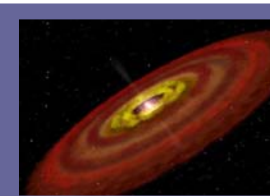
Further constraints on inner rim

- Even moderate spectral resolution across the band can further constrain the structure
  - If the emission is dominated by the inner rim, the size should be the same at all wavelengths
  - If not, a temperature profile can be fit



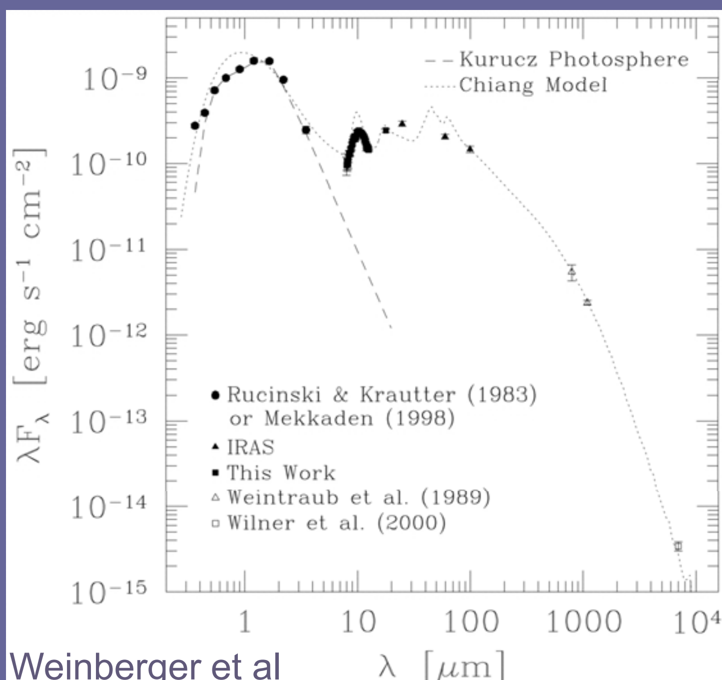
$$T(\text{disk}) \propto r^{-0.5 \pm 0.1}$$

See also Eisner et al (2006), Kraus et al submitted

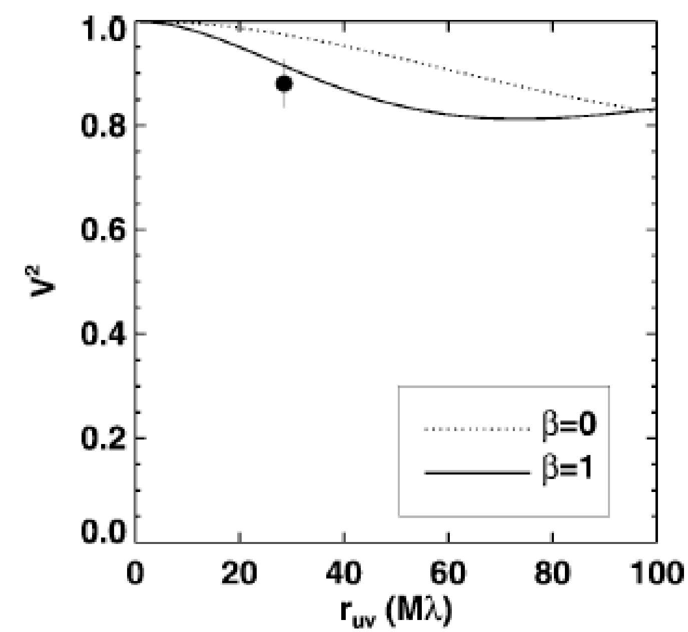


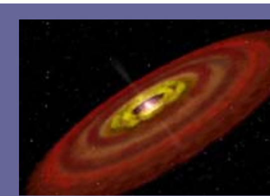
Older T Tauri stars: TW Hya

- 10 Myr old star, 55 pc
- Excess starts in near-infrared
- K band observations of Eisner et al (2006)
  - Large grains (β=0) can not fit visibility data, but smaller grains (β=1) can; Both can fit SED
  - But small grain lifetime is << 10 Myr, must be replenished
  - Grains extend to within 0.06 AU of central star



Weinberger et al

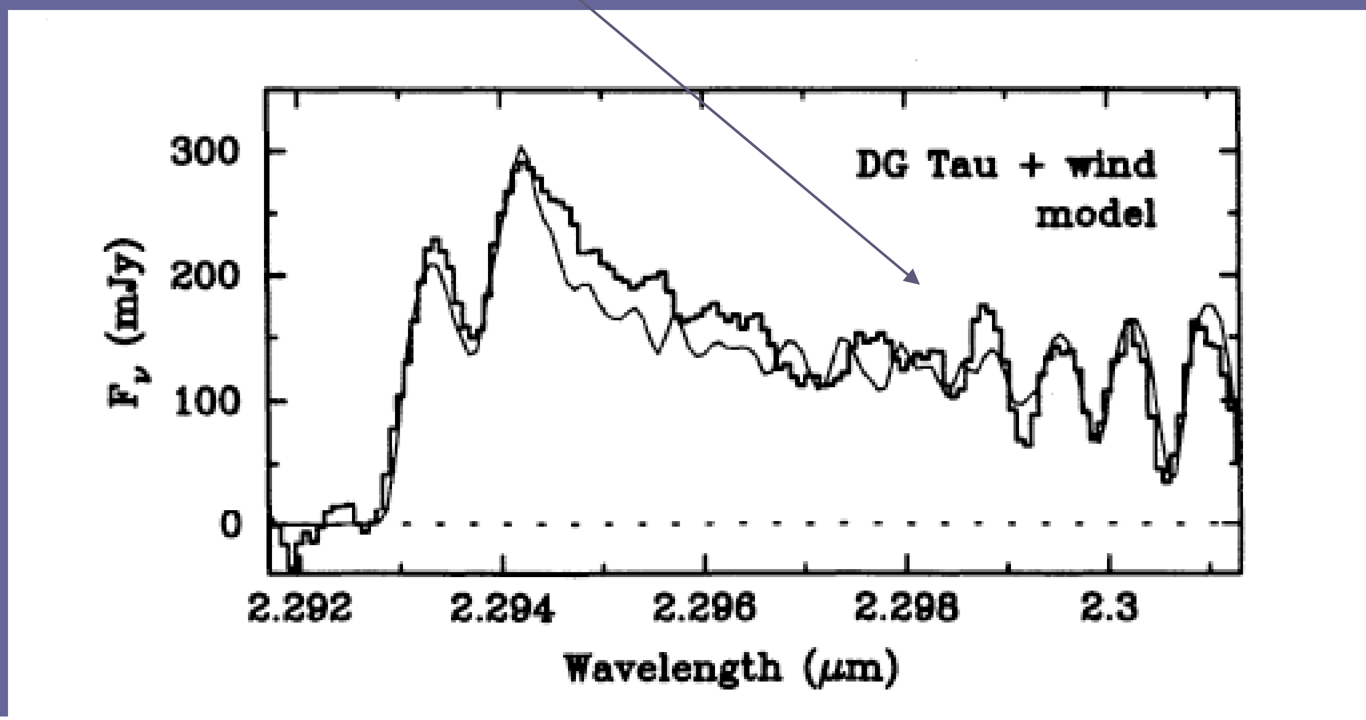


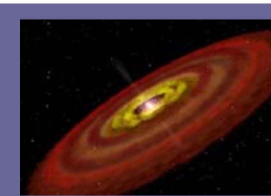


Gas tracers in the near-infrared

- HI (Br γ)
    - Traces accretion
- CO overtone bandheads
    - Kinematics
- H_2O

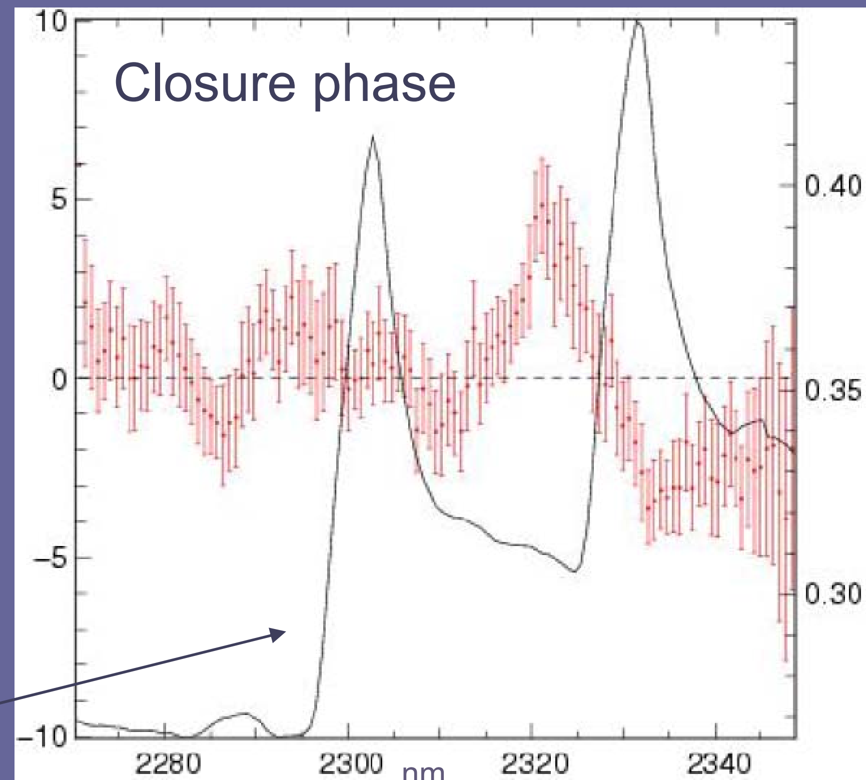
Chandler et al (1995)





CO emission in 51 Oph

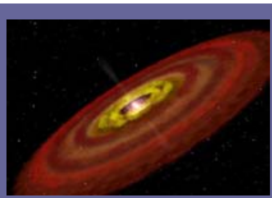
Closure phase deviations from 0 detected
- Consistent with Keplerian rotation in central disk

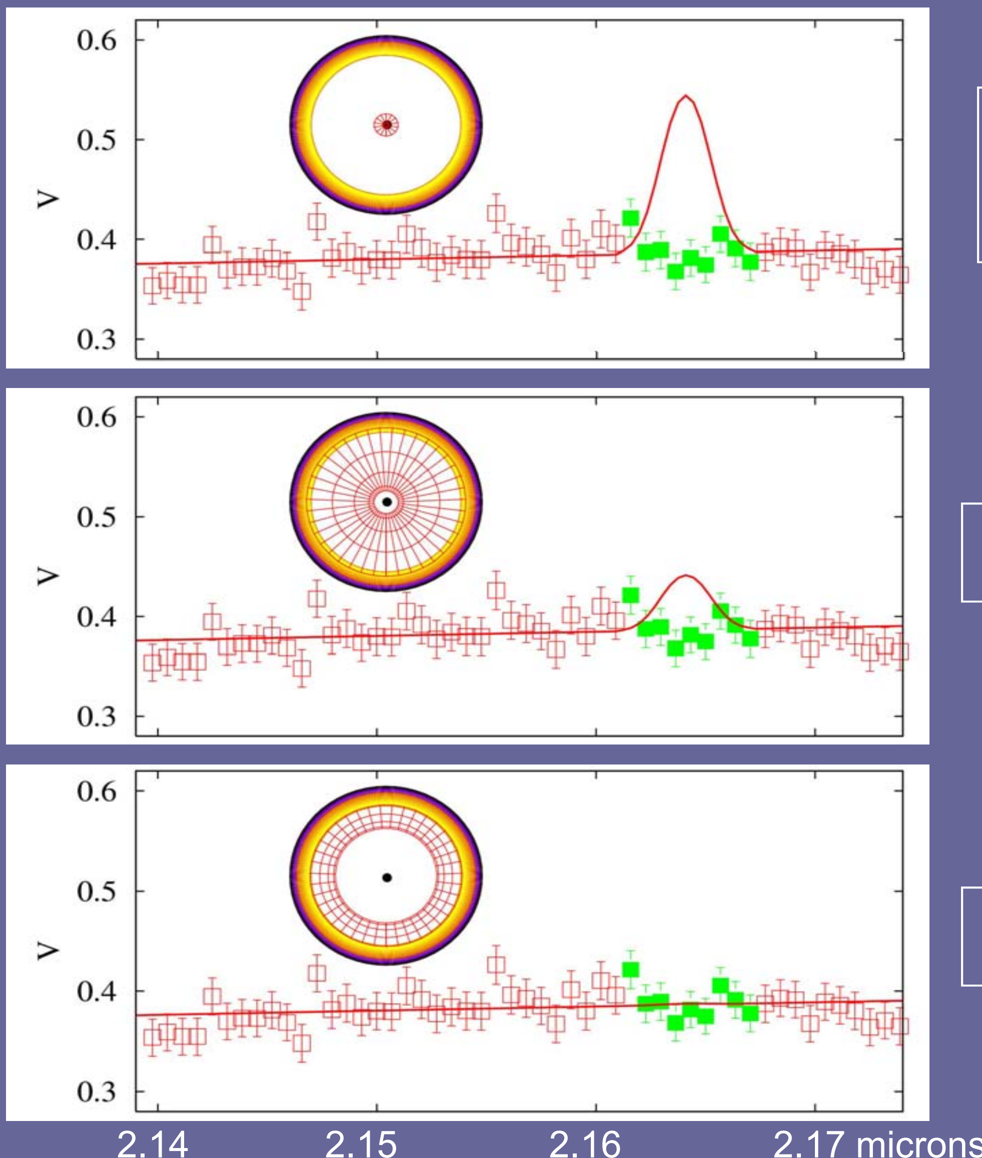


AMBER flux

Tatulli, Gil et al. (2007, in prep.)

Nature of Brγ in the Herbig Ae star HD104237



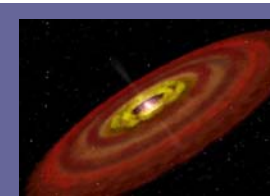


Disk truncated by magnetosphere

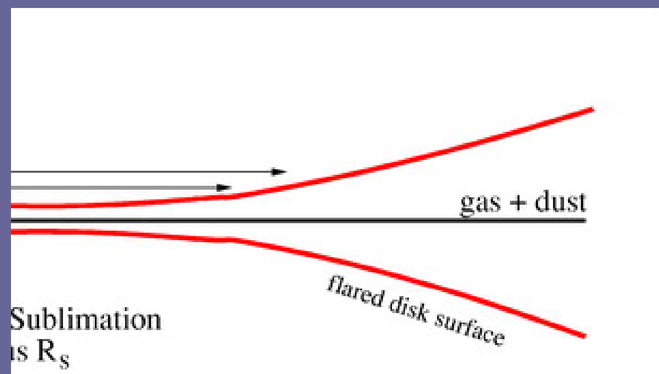
Gas within the disk

Outflowing wind

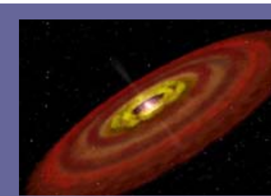
Tatulli et al. (2007, A&A 464, 55)



Middle disk

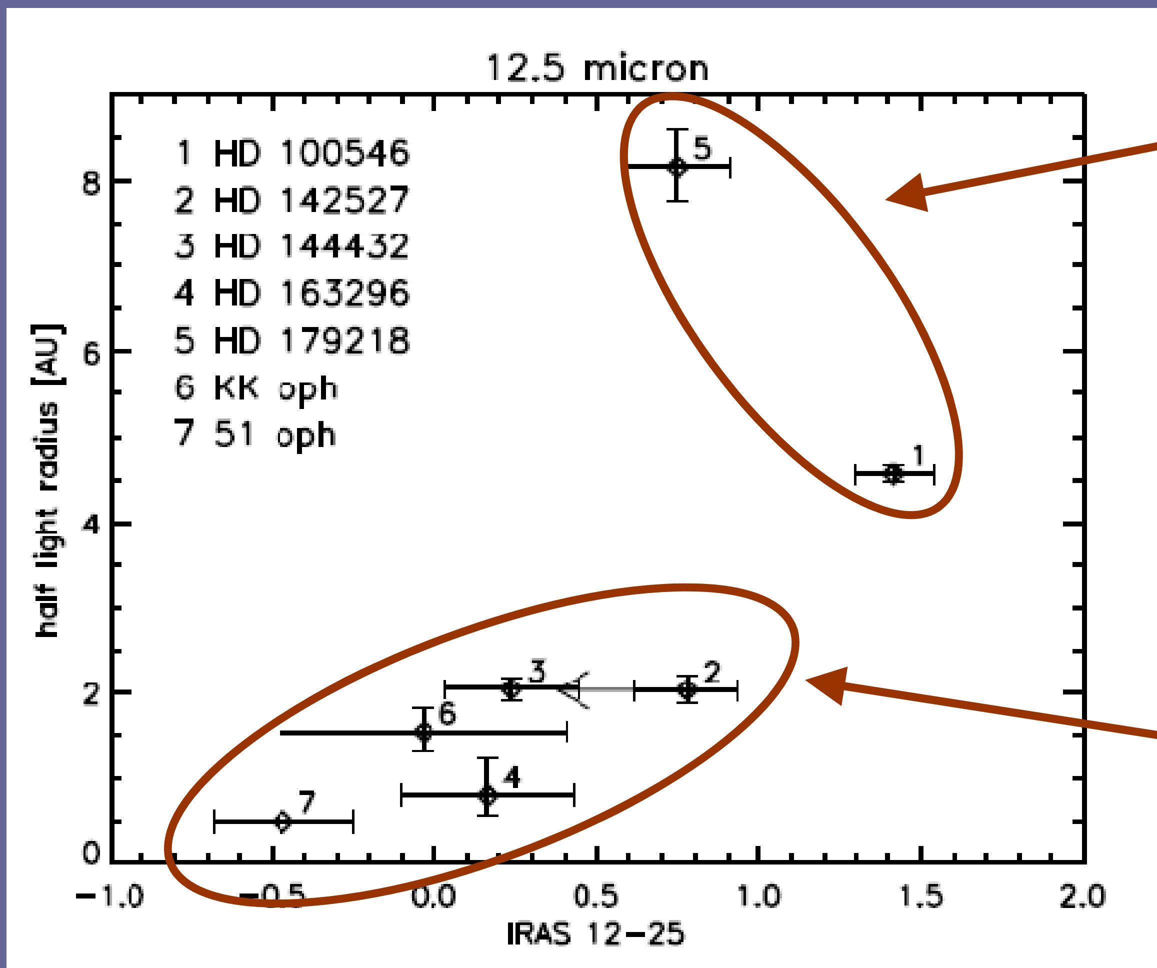


- Issues
  - What is the disk structure (flared, flat, envelope?)
  - What is dust composition as a function of stellar mass, age and disk radius

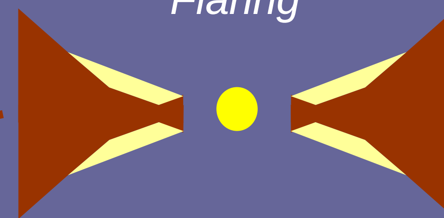


Vertical structure at 10 microns

Survey of several Herbig stars with MIDI

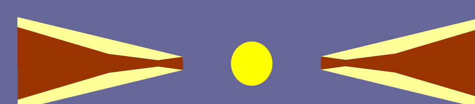


Flaring



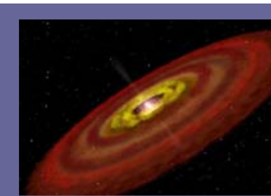
Sizes consistent with flat self-shadowed / flaring disk model SED classification

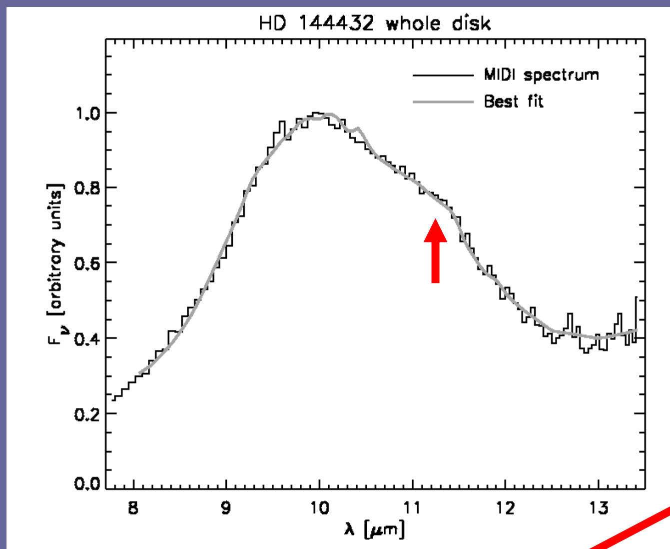
Self-shadowed

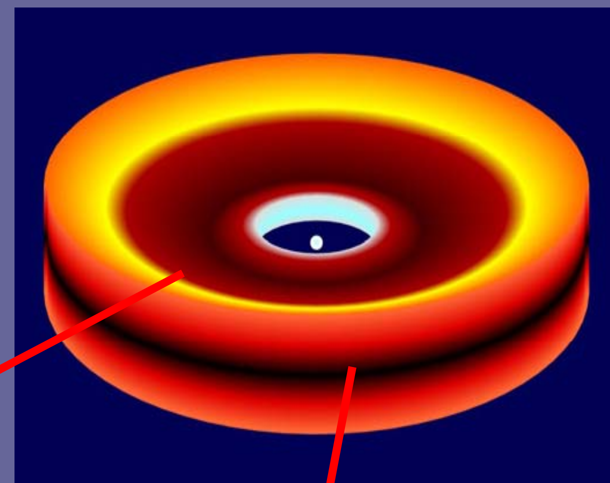


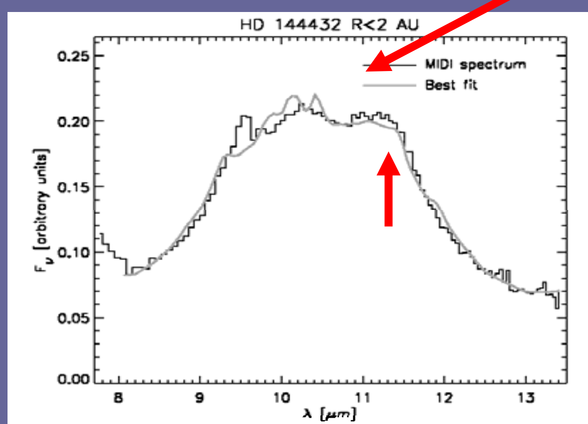
Leinert et al. (2004)

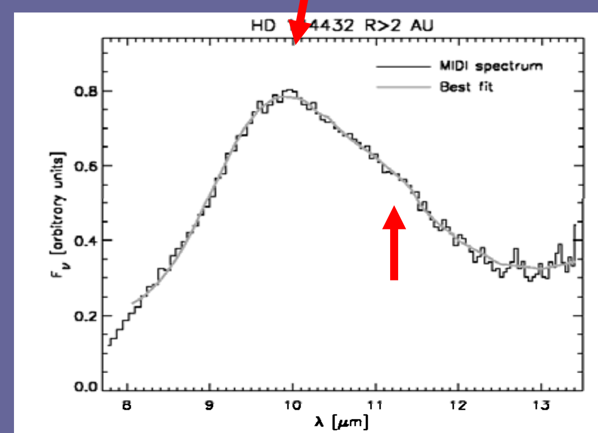
Disk mineralogy



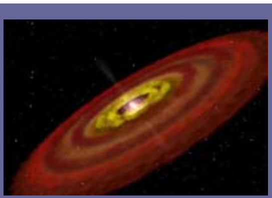








Van Boekel et al. (2004)

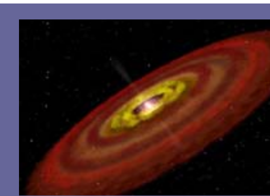


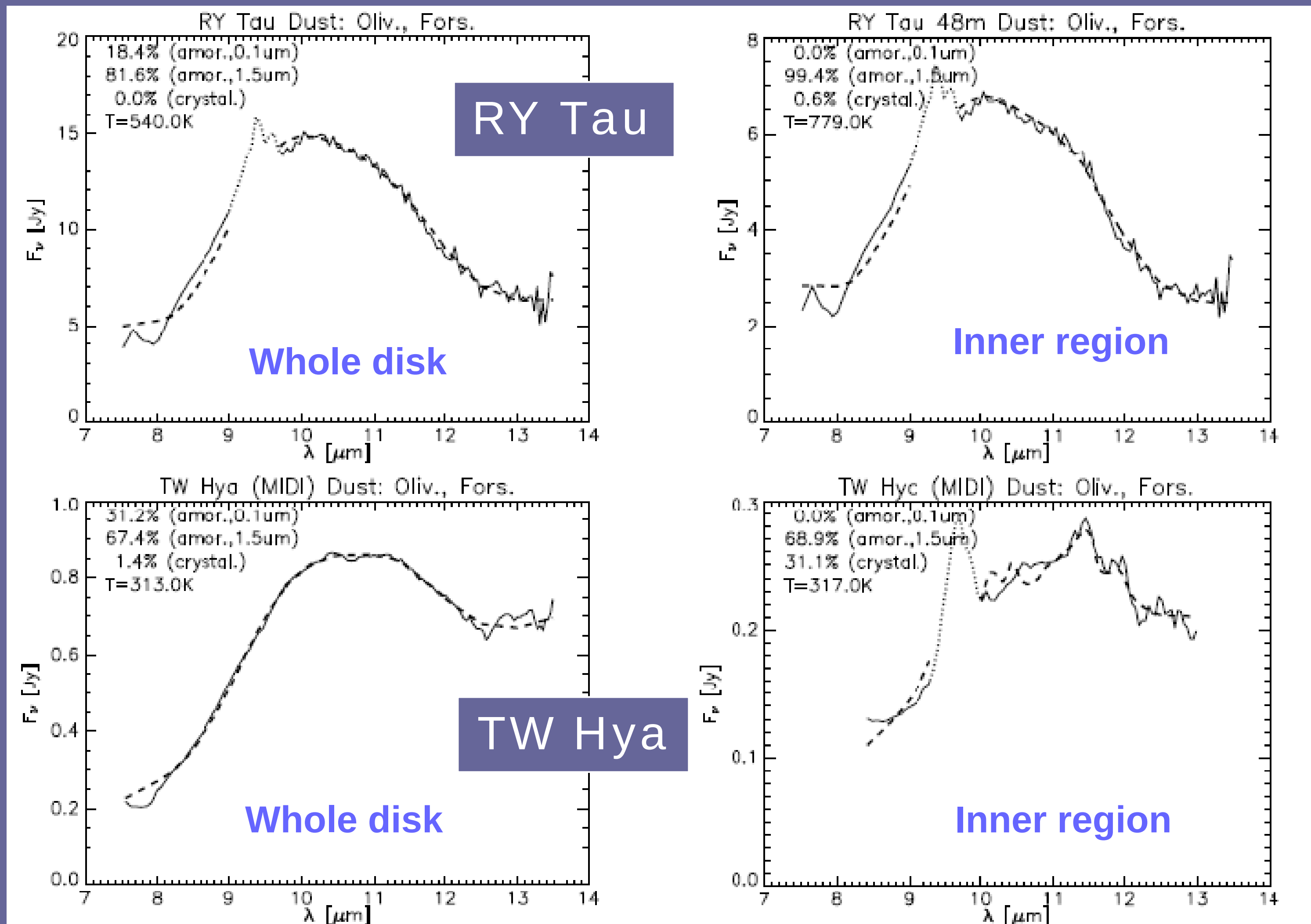
Dust mineralogy in disks

- Inner disks (< 2 AU) have:
  - larger silicate grains
  - higher fraction of silicates is crystalline (40-100%)

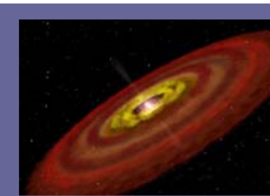
- Consistent with:
  - Chemical equilibrium processing and thermal annealing in inner disk
  - Radial mixing models

… also in T Tauri disks

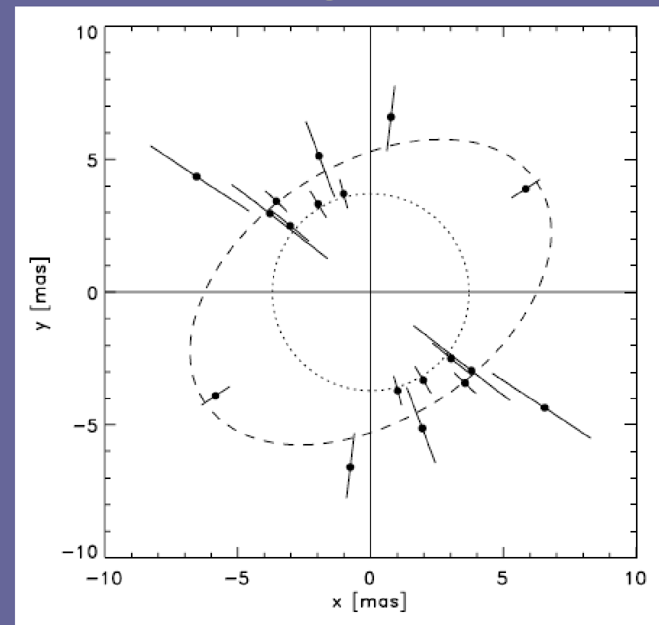




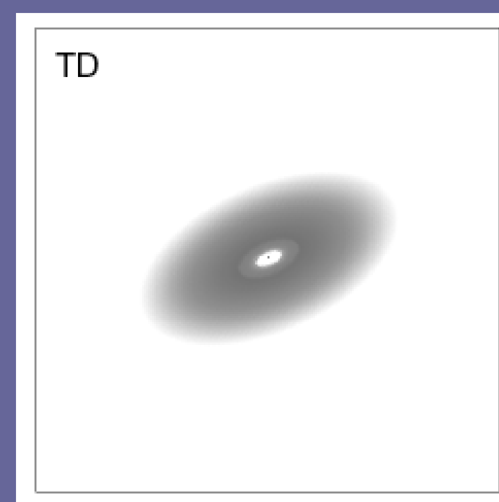
Leinert et al. in prep.



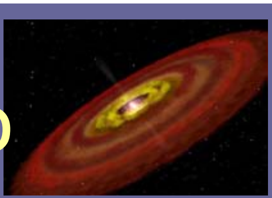
Not all sources fit the paradigm



- Preibisch et al (2005) observed the Herbig star A star HD 5999 with MIDI
  - Visibilities much higher than sources in Leinert et al Herbig sample
  - Correspond to a physical size of 1-3 AU
  - If the disk has a power-law density distribution, it must be truncated at ~2-3 AU

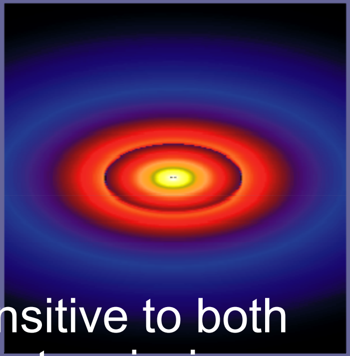


Combining observations from near to mid-IR

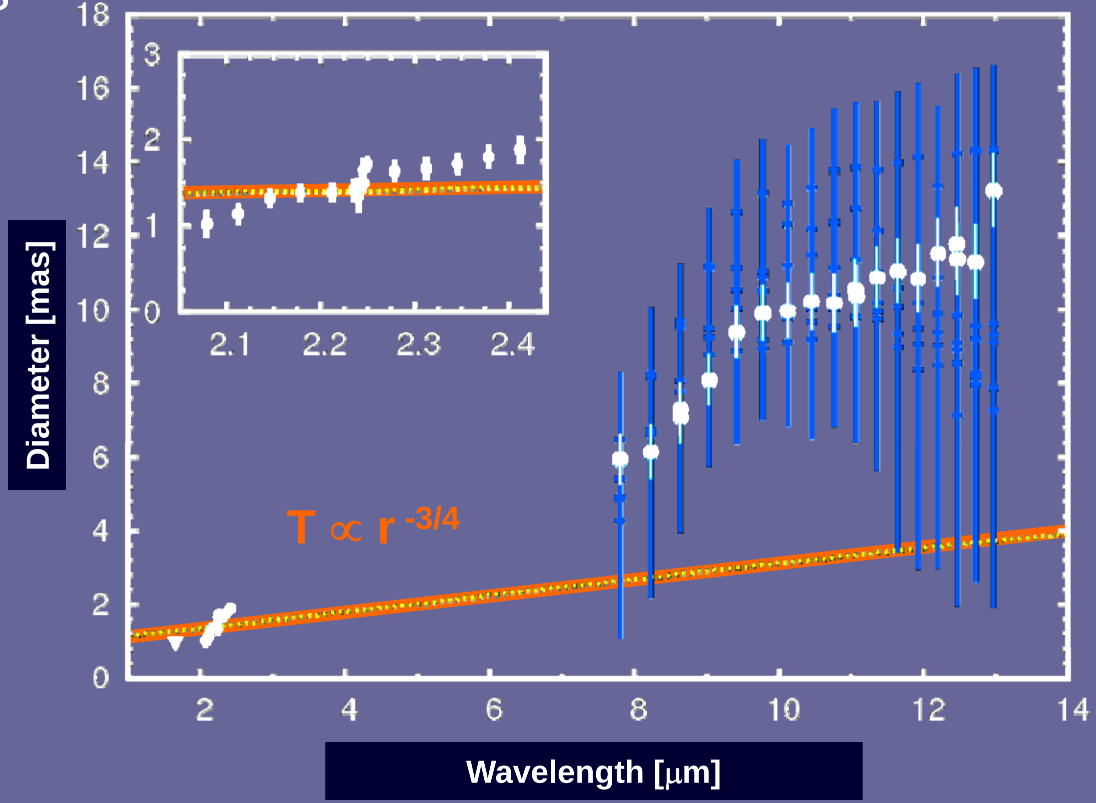


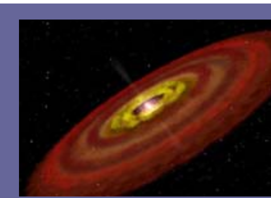
- MWC 147, Herbig Be
- Kraus et al (submitted) combine H (IOTA), K (AMBER) and N (MIDI)
- Measured size not consistent with $T \propto r^{-3/4}$
- 2-D radiative transfer modeling -> optically thick gaseous disk inside of the dust sublimation radius

- H and K band sensitive to inner gas emission

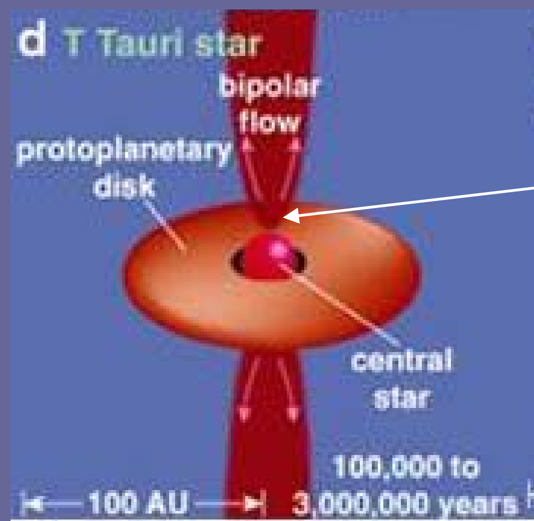


- N band sensitive to both gas and dust emission





Winds and jets

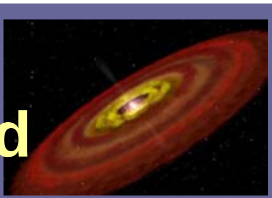


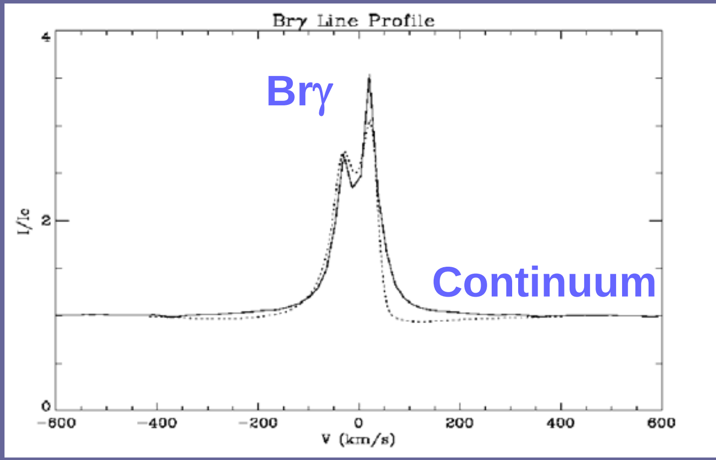
Where is the jet launched?

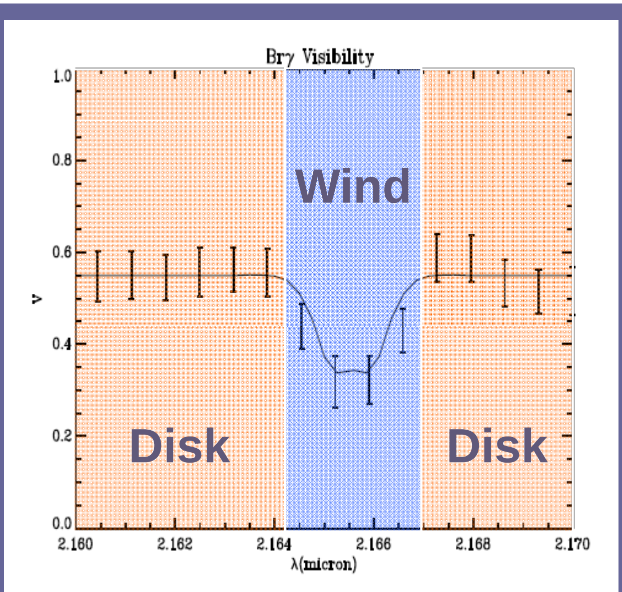
What is the structure at the base?

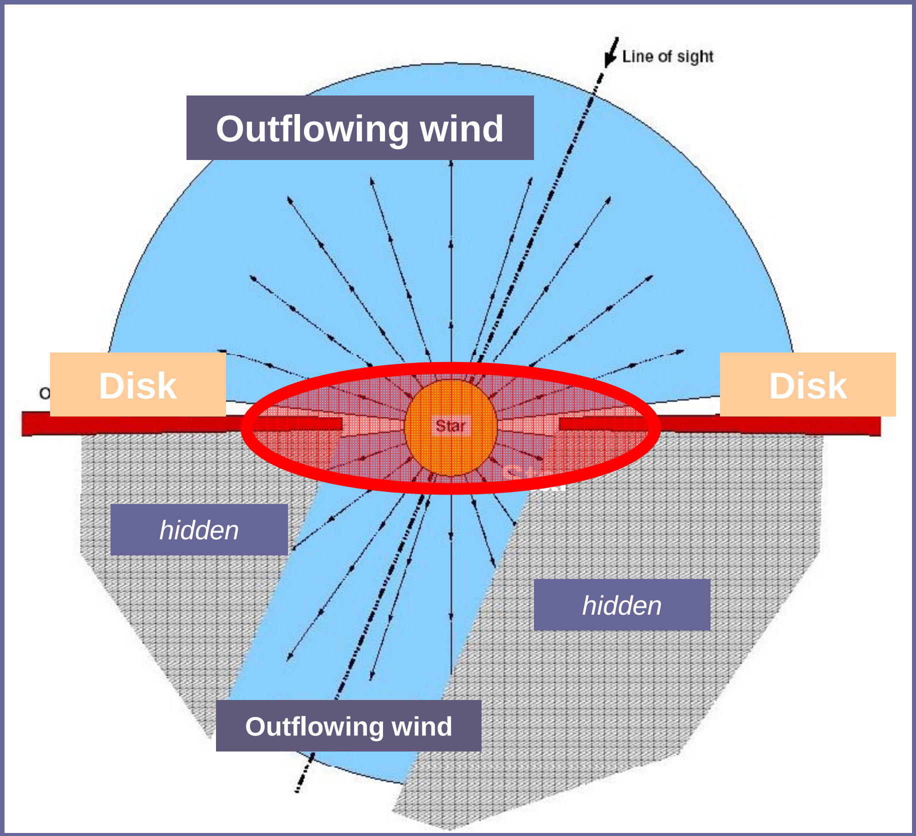
What is the relationship between the wind and the jet?

Disk and wind spatially and spectrally resolved in MWC 297





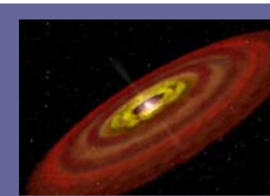




Malbet et al. (2007)

Line emission is 40% larger than continuum

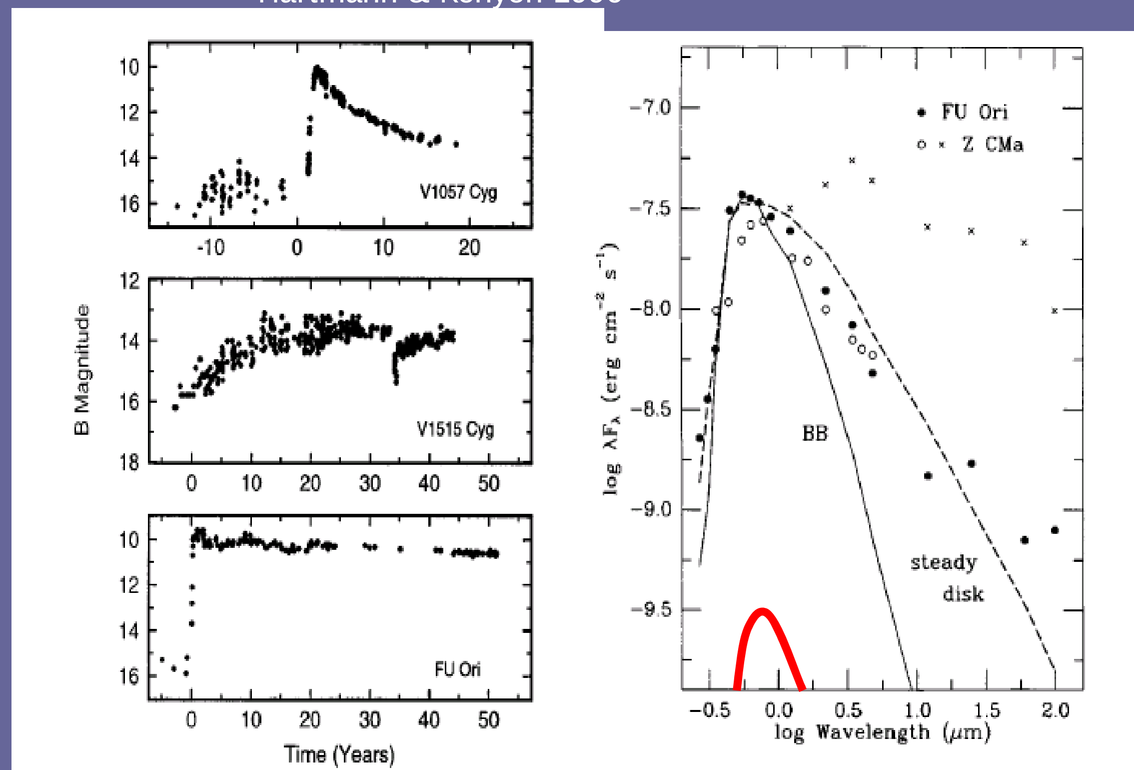
Model with an optically thick disk and a stellar wind with latitude dependant velocity



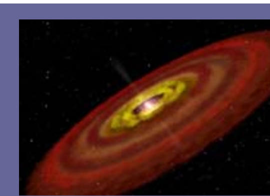
FU Ori stage

- Sub-class of YSOs with major brightening events
- Disk accretion driven
- Accretion rates up to 10^{-4} M_{solar}/yr
- SED is accretion dominated so expect $T \propto r^{-3/4}$
- Disk goes all the way to stellar surface
- Model has only 1 parameter, the temperature scaling

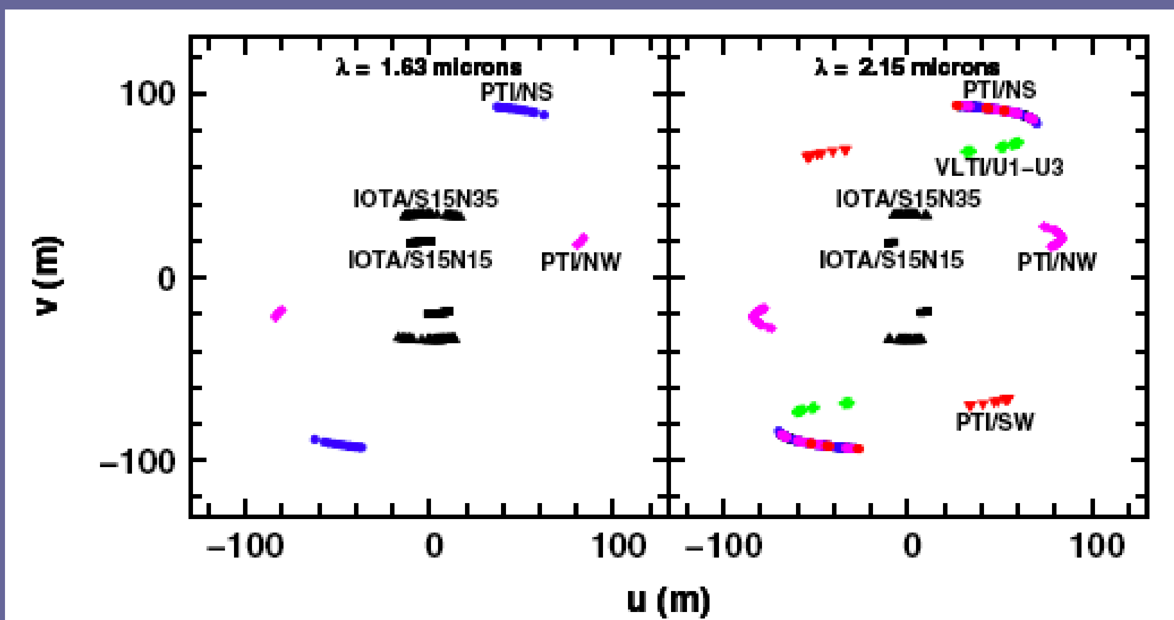
Hartmann & Kenyon 1996



FU Ori: The most observed YSO

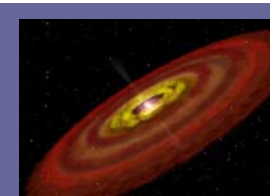


- First ever YSO observed (Malbet et al 1998)
- Malbet et al (2005) combined PTI, IOTA and VLTI data



- Data consistent with standard ($T \propto r^{-3/4}$) accretion disk
- Accretion rate and inclination constrained

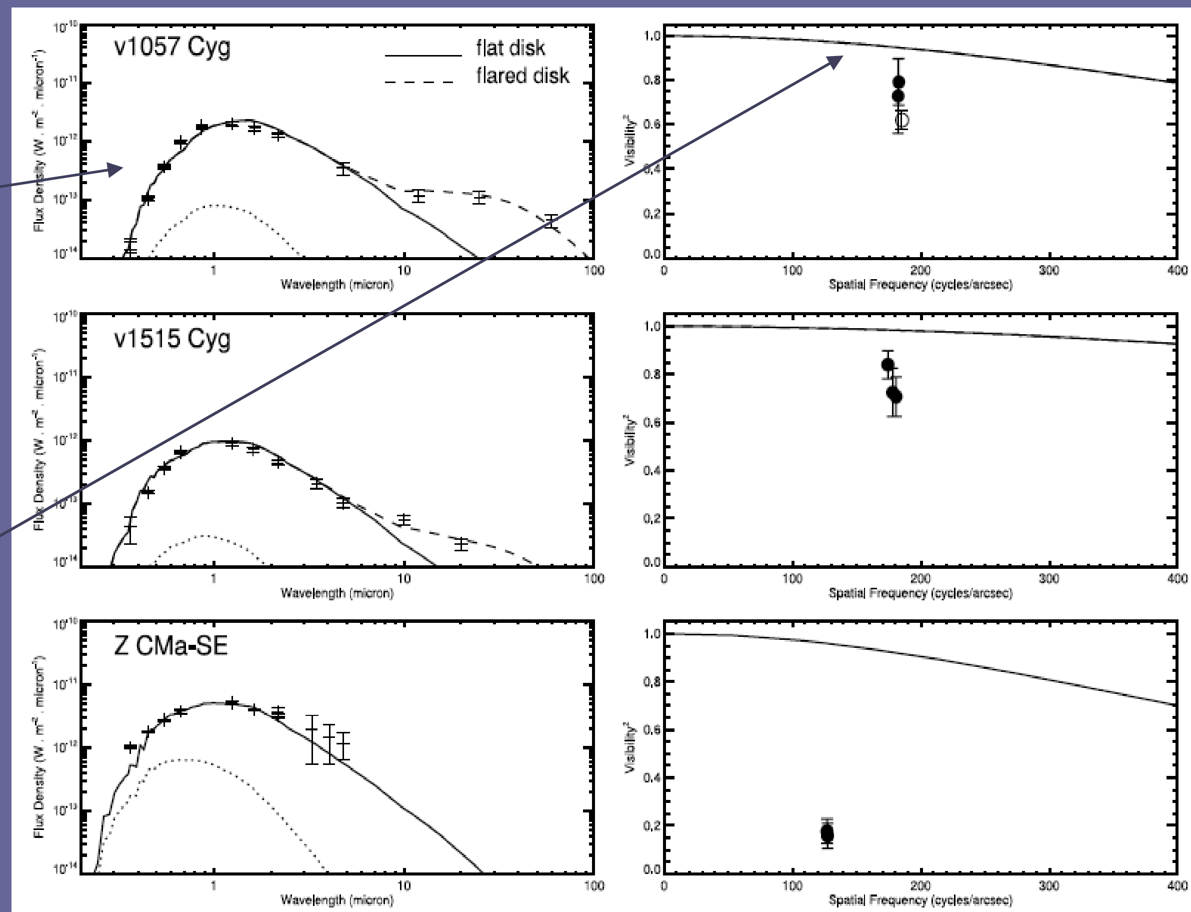
Additional FU Ori stars



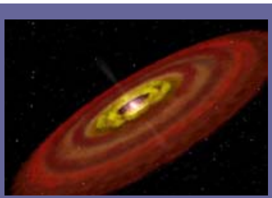
Millan-Gabet et al (2005)

Use SED to fit temperature coefficient for standard accretion disk

Predict K band visibility

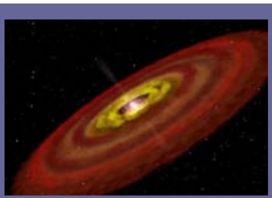


All measured visibilities are LOWER than predicted: need an additional flux component within the 50 mas field of view (envelope?)



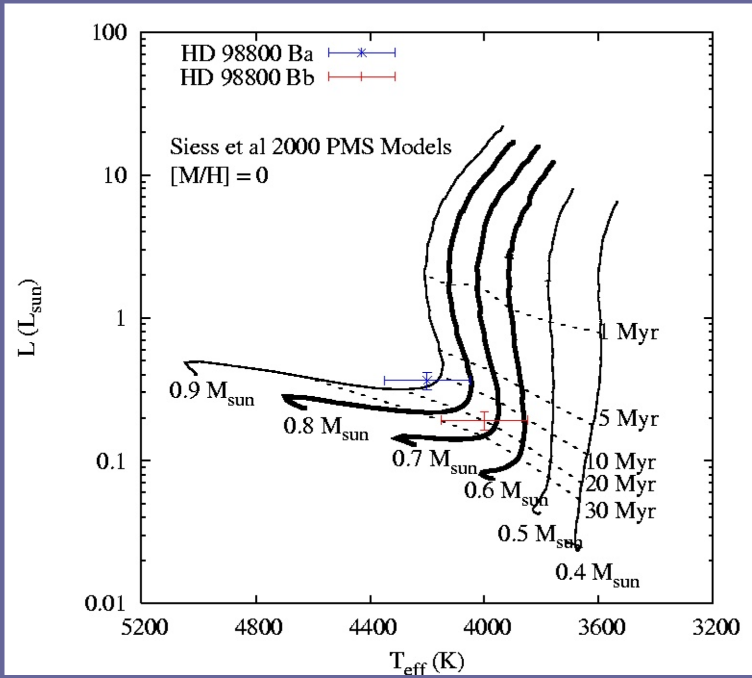
FU Oris in the mid-infrared

- V1647 Ori
  - Recent outburst (2004), could be FU Ori or UX Or
  - Abraham et al (2006) observed with MIDI
    - No spectral features => large dust grains
    - $T \propto r^{-0.53}$
- FU Ori
  - Quanz et al (2006)
    - Weak, broad silicate features
      - Large grains in disk, constrains dust evolution models if FU Oris are indeed very young
    - Two temperature profiles
      - $T \propto r^{-0.75}$ for radius < 3 AU
      - $T \propto r^{-0.52}$ for radius > 3 AU

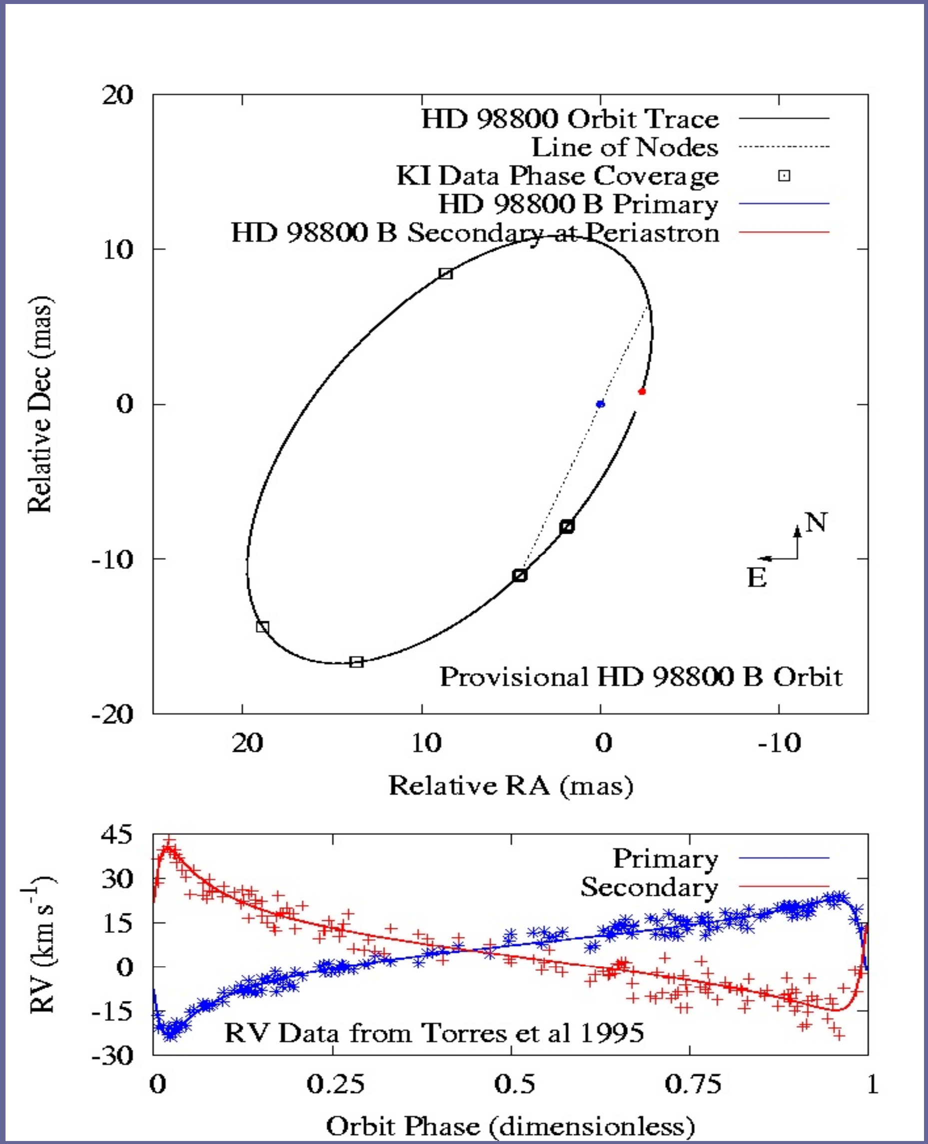


Accurate stellar masses

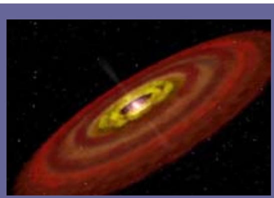
- HD 98800 is a pre-main sequence quadruple system with two spectroscopic binaries
- Estimated age of 10±5 Myr
- Physical orbit estimated with Keck Interferometer and radial velocity data
  - Distance = 42 +/- 5 pc
  - Masses = 0.69 +/- 0.07 and 0.58 +/- 0.06 M_{solar}
  - Orbit a=0.97 AU; e=0.78



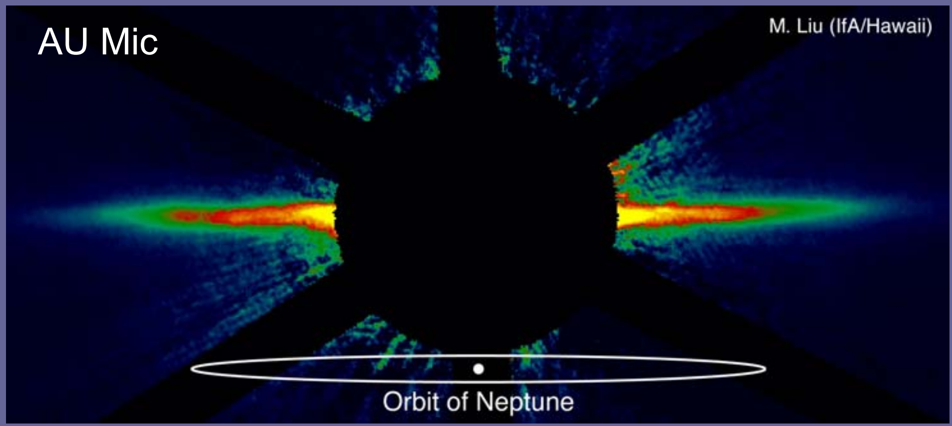
Boden et al 2005



Planetary debris disks

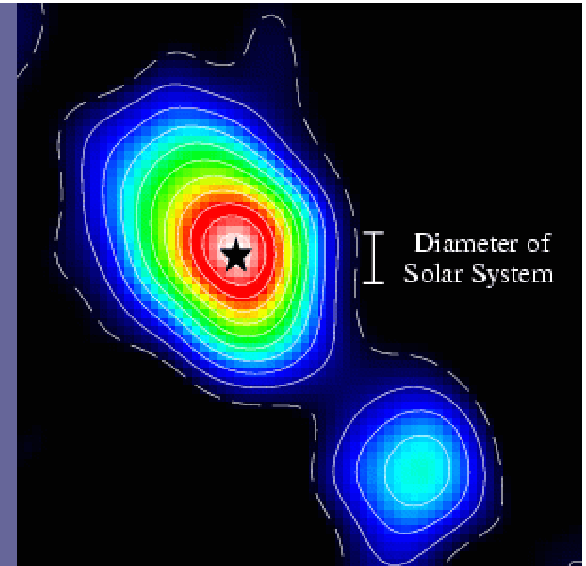


- Dust around main sequence stars first discovered by IRAS
- Spitzer observations have expanded sample to 10s of objects
- Grain lifetimes less than the stellar age indicates generation from larger bodies and structure suggest plane-sized in some cases



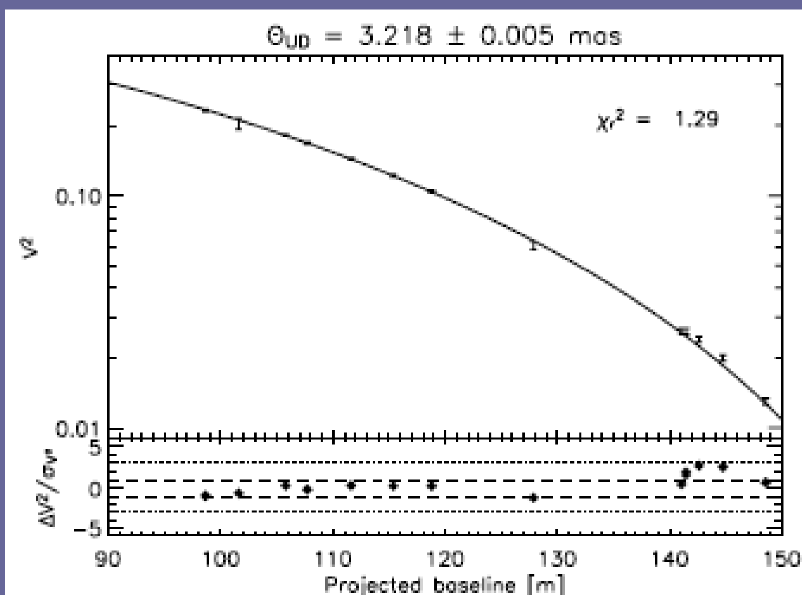
Vega

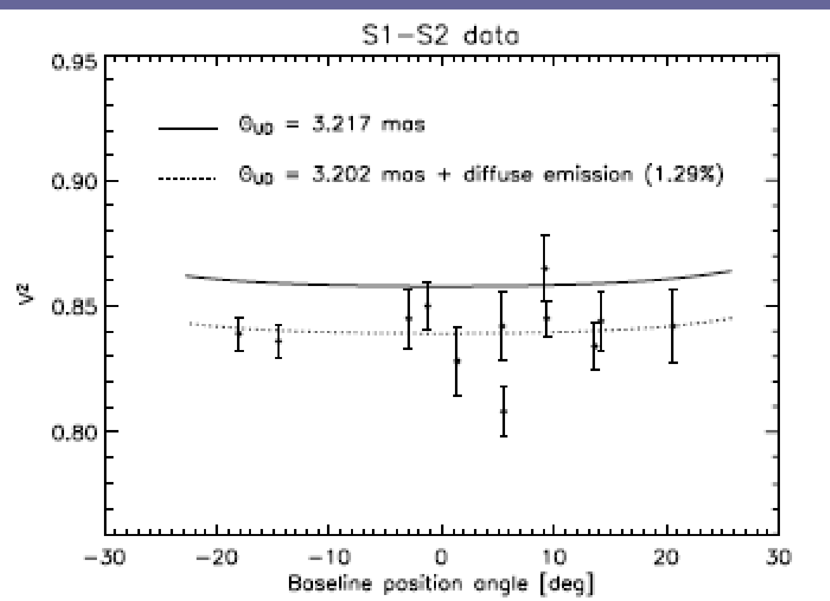
- Known debris disk at 80-100 AU
- Near-infrared excess of 1.3% detected with interferometry (high accuracy photometry difficult on very bright sources)



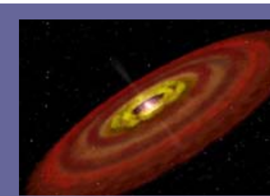
Long baselines resolve the stellar photosphere

Stellar photosphere (mostly) unresolved on short baselines, lower than expected visibilities indicate excess emission





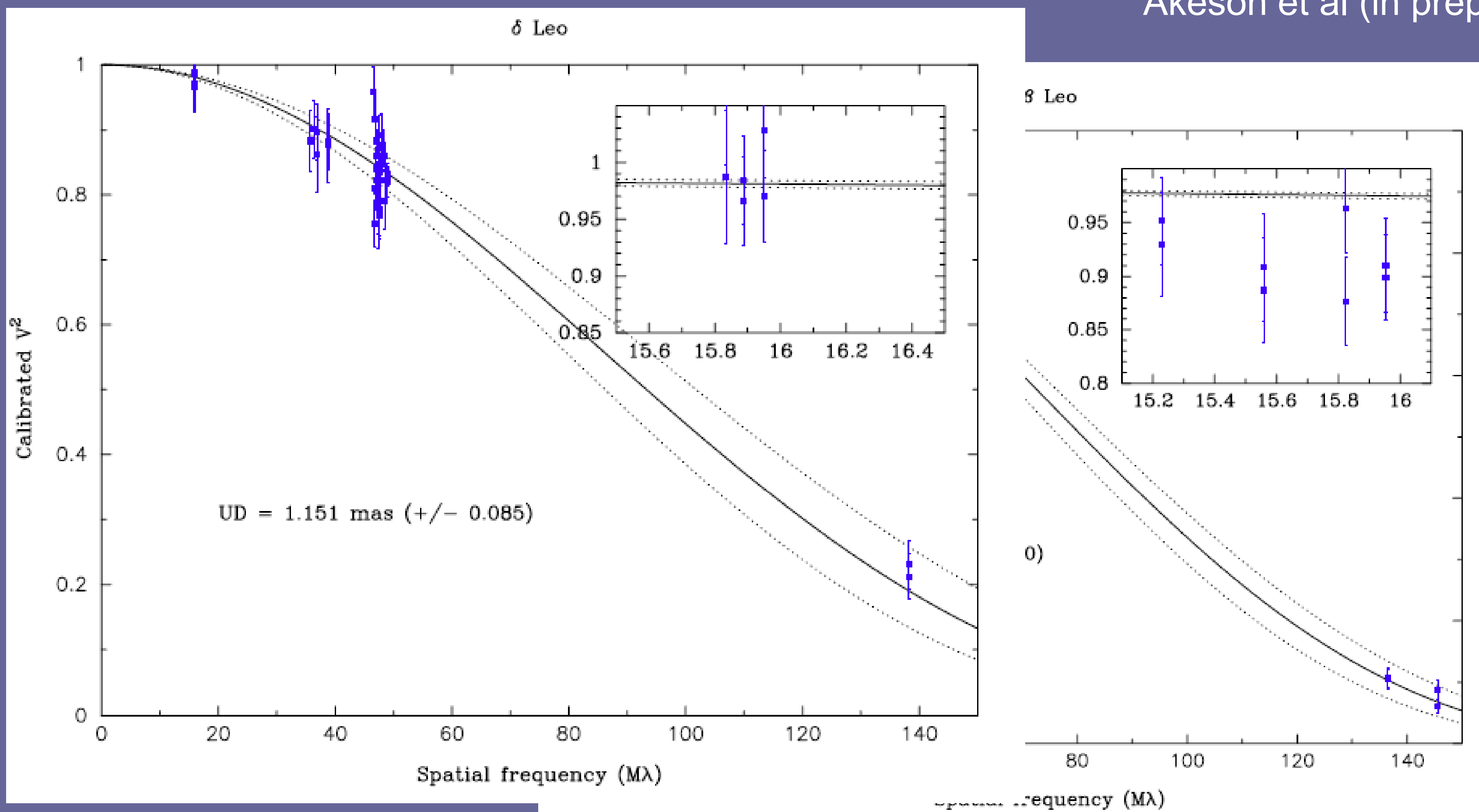
Absil et al (2006), see also Ciardi et al (2001)

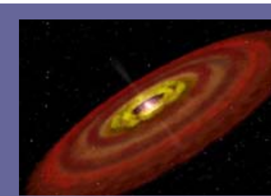


A 50 Myr-old star

- The visibility from beta Leo on short baselines is clearly lower than expected from the star → additional material
  - Lower visibility NOT seen on check star delta Leo

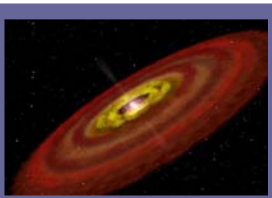
Akeson et al (in prep)





Current and near-future developments

- Better sensitivity
- Closure phase / imaging
- More observations (bigger samples)

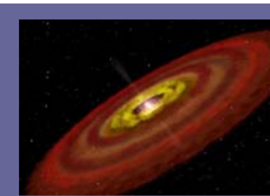


Better sensitivity

- Deal with realities of interferometry
  - Atmosphere and vibrations are major issues
    - Need to balance faster sampling with sensitivity
- Dual star and phase referencing
  - Use nearby bright target (or same target at a different wavelength) for tip-tilt/adaptive optics or angle or fringe tracking

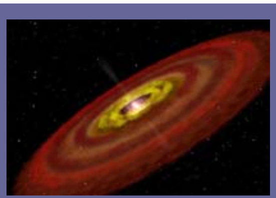
- Improved sensitivity will allow study of larger range of YSOs
  - Embedded (Class 1) T Tauris
  - Transition disks (strong excess starts in mid-infrared, ex. TW Hya)
    - Photoevaporation or planet formation?

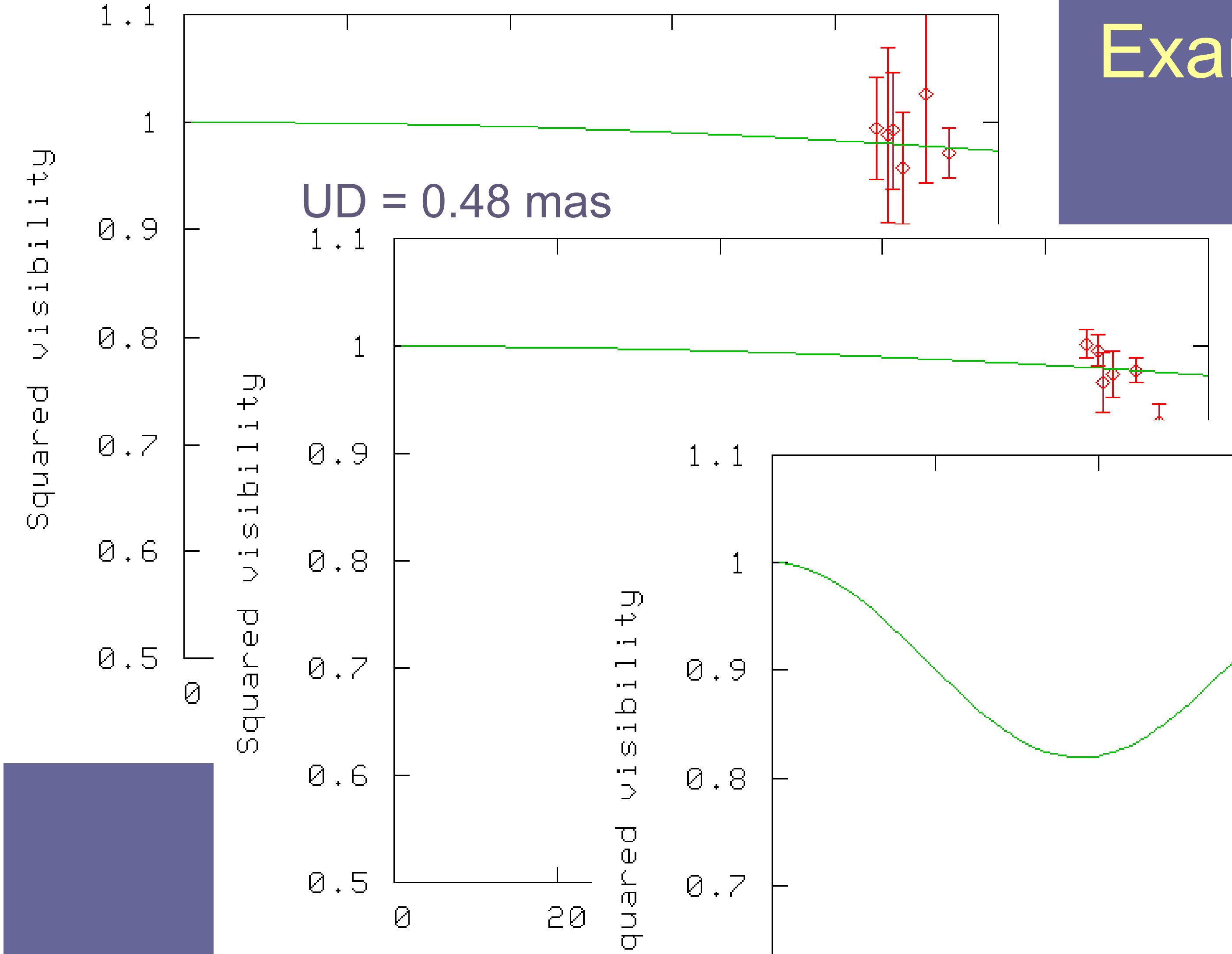
High dynamic range: precision visibilities

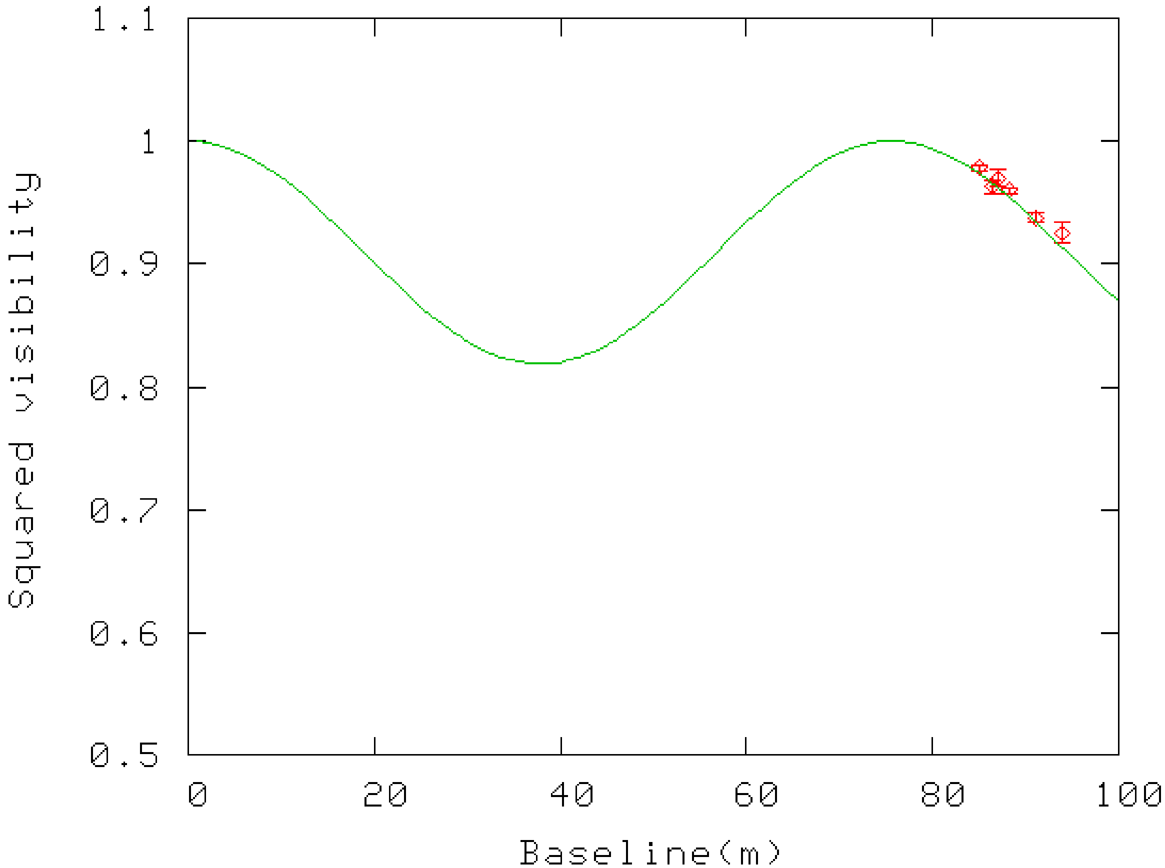


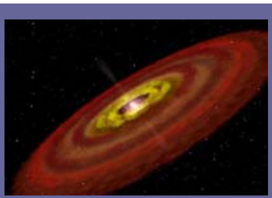
- Several instruments exist which emphasize precision (IONIC, FLUOR, VINCI, AMBER, etc)
- Many effects need to be controlled or compensated for (see Perrin & Ridgway 2005 for details)
  - Finite spectral bandwidth
  - Group delay dispersion
  - Finite scan length
  - Differential piston

Example



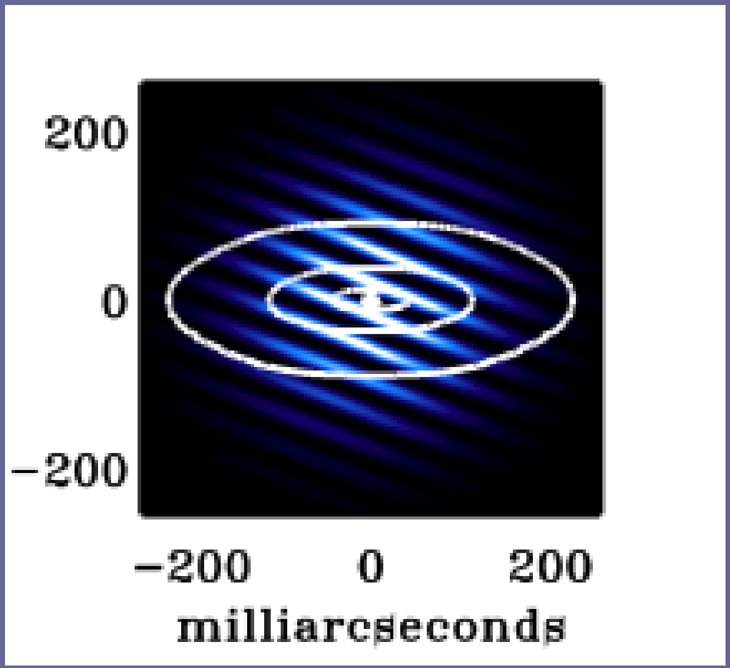

UD = 0.48 mas
Squared visibility
1.1
1
0.9
0.8
0.7
0.6
0.5
0
20
40
60
80
100
Baseline(m)

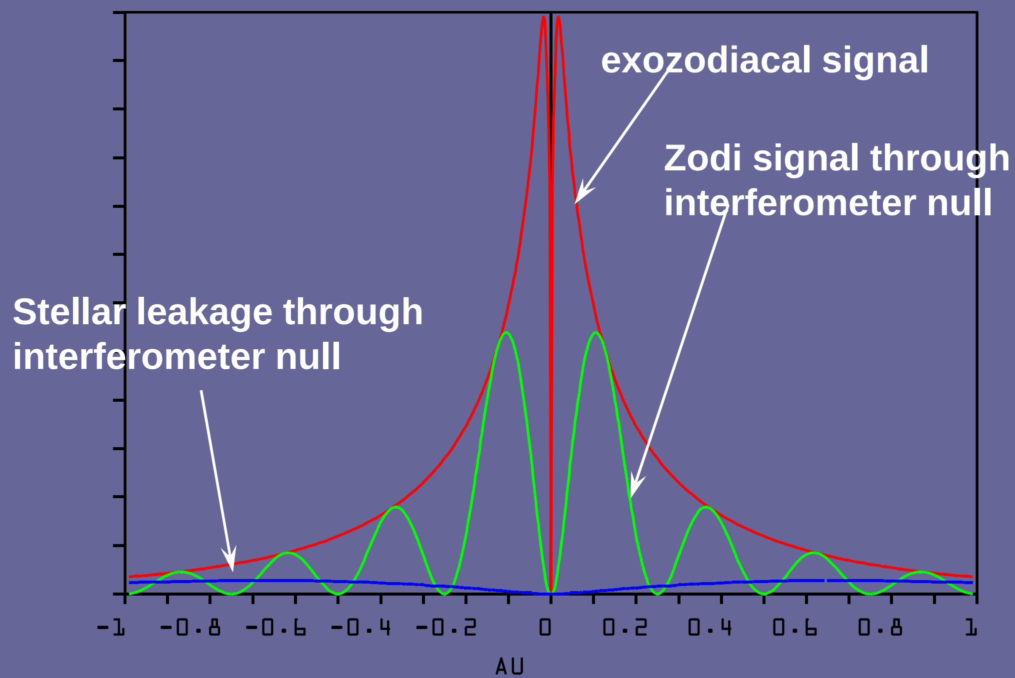




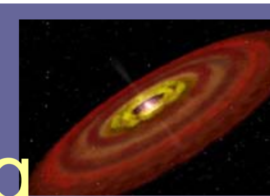
High dynamic range: Nulling

- Interferometer nuller attenuates star by centering the deconstructive fringe on the tracking center



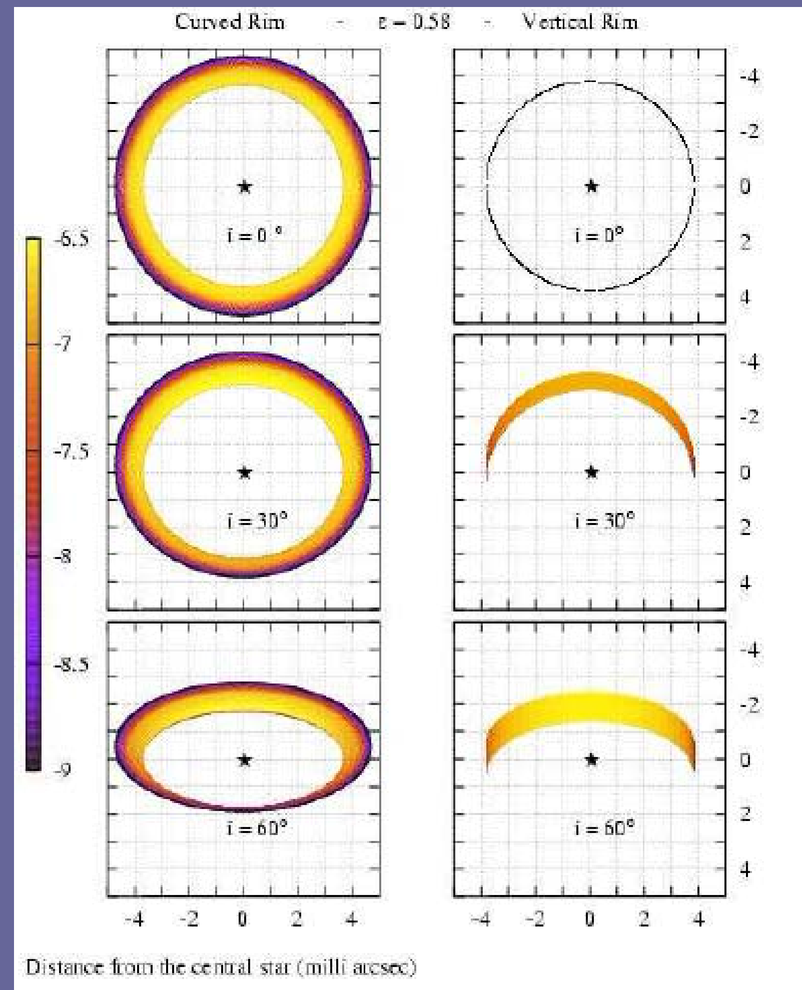


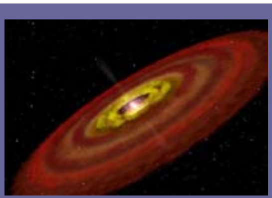
Closure phase: First steps to imaging



Isella & Natta (2005)

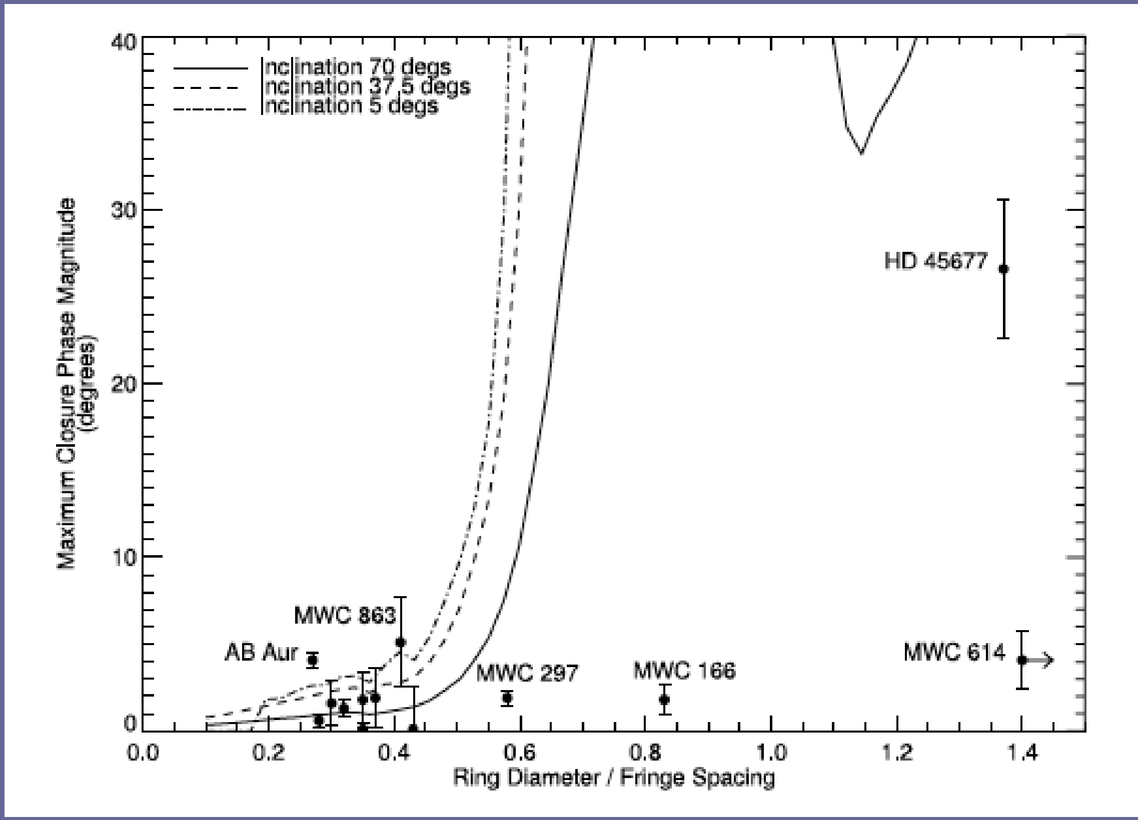
- Closure phase measures skewness
- Example: inner rim geometry
  - Vertical rim is more asymmetric and will produce higher closure phases
  - Settling of large dust grains toward midplane will produce curved rim (Tannirkulum et al)





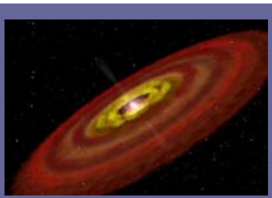
Measured closure phases

- On short (<40 meter) baselines, small closure phases are measured
- Models are degenerate at these fringe spacings, need longer baseline

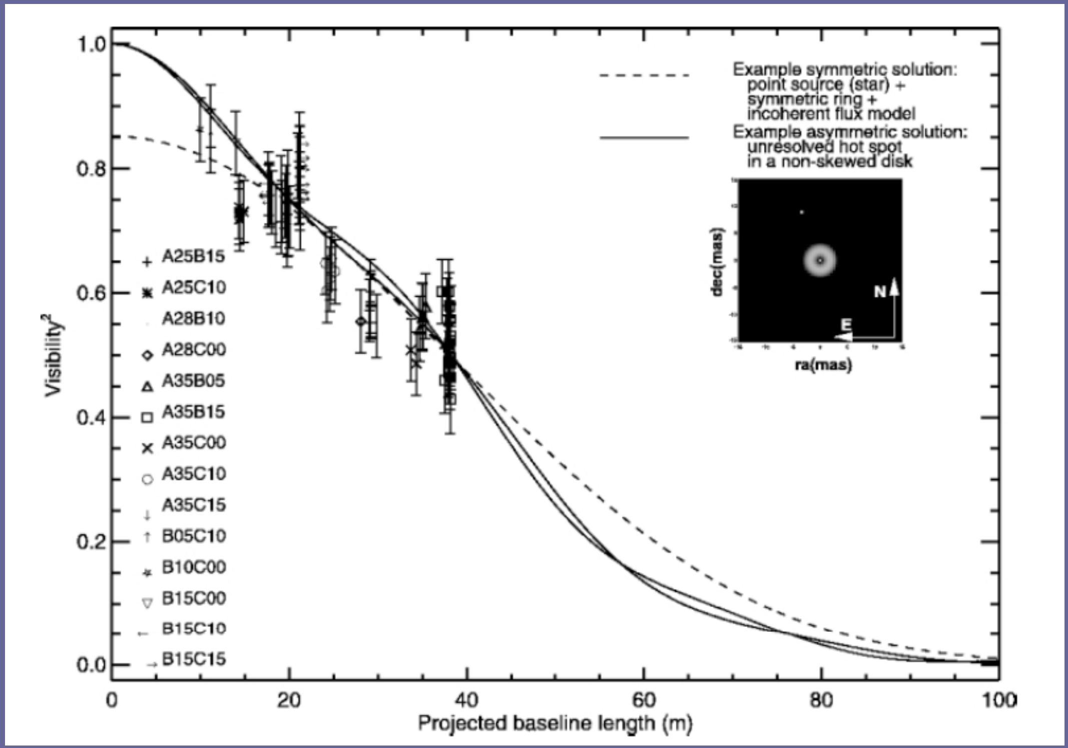


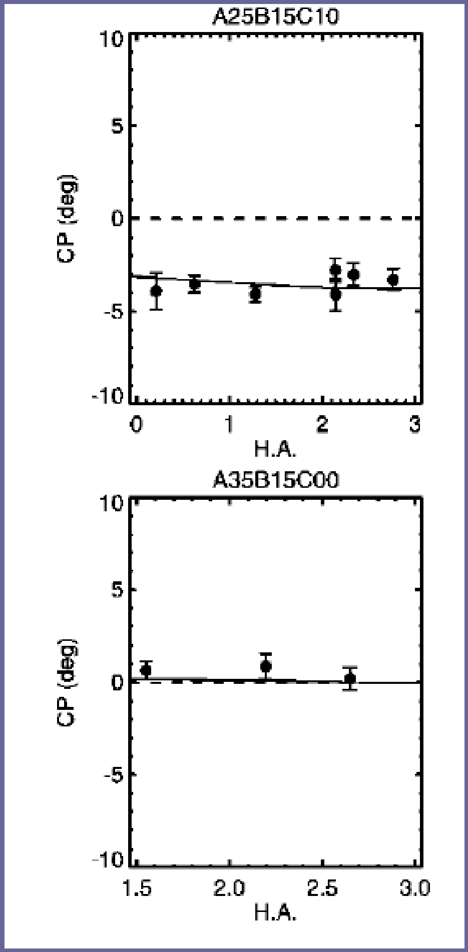
Monnier et al (2006)

Closure phase can also reveal other structures



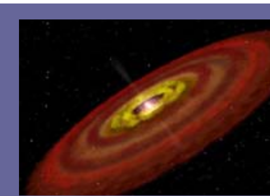
AB Aur





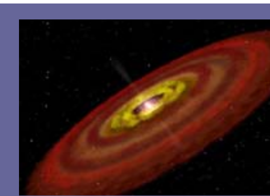
Visibilities can be fit with a symmetric model (dashed) but closure phase requires emission peak in disk (solid)

Millan-Gabet et al. (2006)



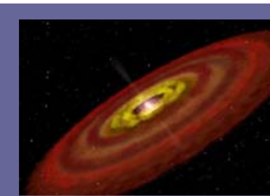
Bigger samples

- Need more time to observe samples of targets (not just the brightest ones that were up that night…)
- All of Taurus contains 220 sources with Kmag < 10, but visible magnitude is also important
- Need dedicated interferometry facilities (VLTI/AT's, CHARA, MROI)



Conclusions (and new questions)

- Star formation is arguably the area of astrophysics in which infrared interferometry has had the biggest impact
- The optically thick portion of T Tauri and Herbig Ae/Be disks DO NOT extend to a few stellar radii of the stellar surface
  - Emission is coming from near the dust sublimation radius, but not all from a single radius
  - What is the exact structure of the dust sublimation boundary?
  - How does the inner disk evolve with time?
  - How does this effect planet formation and migration?



Conclusions (2)

- The Herbig Ae stars can be either flared or self-shadowed but very massive (early Be) stars are geometrically thin
  - Is there an envelope component?
- The disk mineralogy is a function of radius
  - When does the chemical evolution start?
- Observational prospects are rapidly improving
  - Higher spectral resolution will allow observations of the gas: jets, winds, accretion
  - Closure phase and imaging will help eliminate model uncertainties/dependencies