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Interferometric observations of YSOs

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Outline

- What interferometry can tell us
  - Disks
  - Multiplicity
- Summary of observations
  - T Tauris
  - Herbig AeBe's
- Future

Why infrared interferometry

- Resolution
  - At 140 pc (distance to nearest star forming regions) 1 AU subtends 7 milliarcsec
- Sensitivity
  - Material in the inner disk (~1000 K) emits in the infrared
- A 2 μm interferometer with a 100 meter baseline has a fringe spacing of 4 milliarcsec

Inner regions of circumstellar disks

- What is the structure of the inner 1 AU?
  - Jet/outflow models
    - In the X-wind model (Shu et al) launch region is at the magnetic truncation radius (few stellar radii)
    - In disk wind model (Pudritz et al) launch region is outside truncation radius
  - Planet formation and migration theories
    - Initial conditions for planet formation

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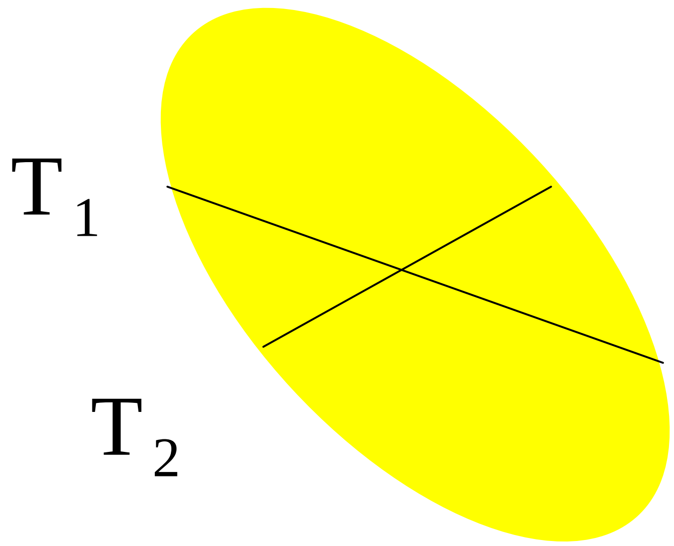
What can be done with 1 baseline?

- Is the source resolved?
- Is the source symmetric?
  - Look for change in V with baseline rotation



$T_1 > T_2$ therefore

$V_1 < V_2$

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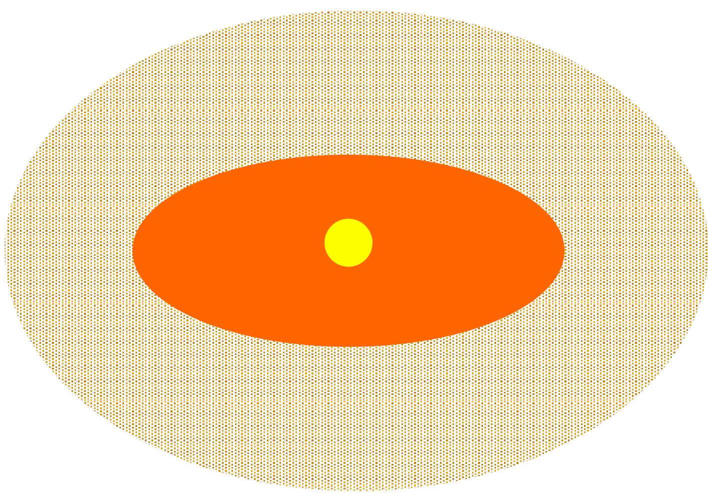
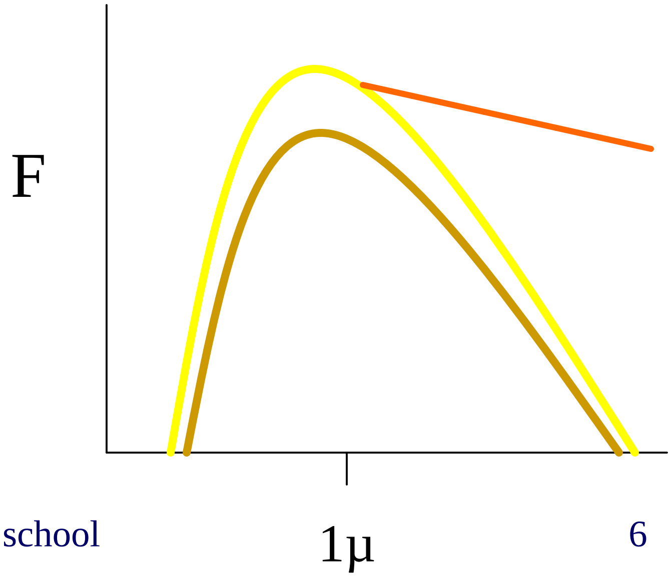
Components seen by interferometer

- Stellar photosphere (unresolved at these distances d > 140 pc)
- Hot material in circumstellar disk
- Scattered light (generally incoherent contribution)





Multiplicity

- Need well-determined YSO masses to constrain evolutionary models
  - Only a few eclipsing binary systems known
  - Other methods have error ≥ 10%
- Binary orbits (and therefore masses) can be determined using visibility measurements + radial velocity or astrometry
- No published data (observations in progress)

Observations: Herbigs

- AB Aur (Millan-Gabet et al 1999, IOTA)
- Survey of 15 Herbigs (Millan-Gabet et al 2001, IOTA)
  - Spectral types range from O9 to A2
  - H and K measurements, 21 and 38 m baselines
  - 11 systems resolved
  - 1 new binary
- 5 Herbigs (Eisner et al 2003, PTI)
  - 3 sources overlap with Millan-Gabet survey
  - Spectral types range from B0 to A0
  - All sources are resolved
- 7 Herbigs (Monnier et al, KI)

The Infrared Optical Telescope Array

Project collaborators:
HS-CfA
UMass-Amherst
Paris/Meudon
LAOG, Grenoble
NASA Ames

- D = 45 cm, Bmax = 38 m, reconfigurable
- λ/2Bmax = 4.5 mas @ H-band (1.65 μm), or about 2 AU @ d(mean) = 400 pc

IOTA Herbig survey

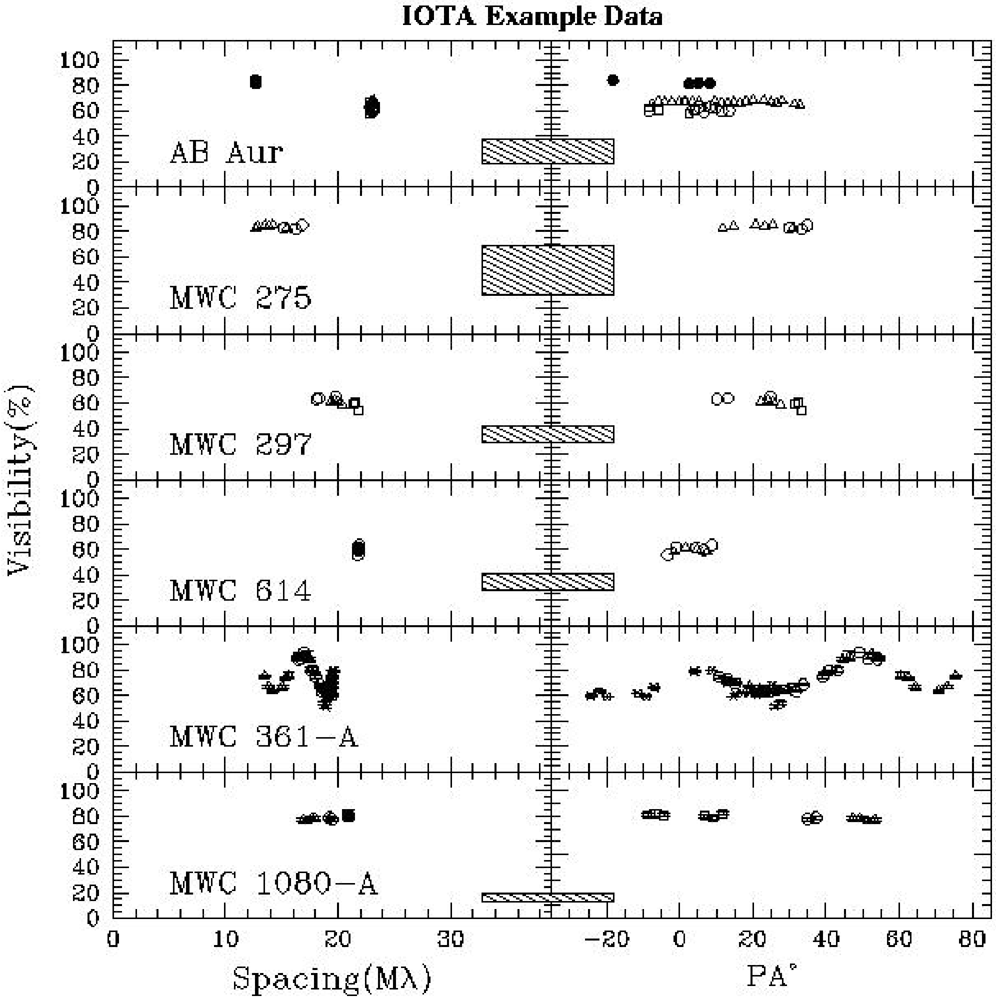
- Most sources are resolved! (11/15)

  Fstar/Ftotal < V < 100%
- Constant V, within PA range explored

  [0-70 deg], 30 deg typical

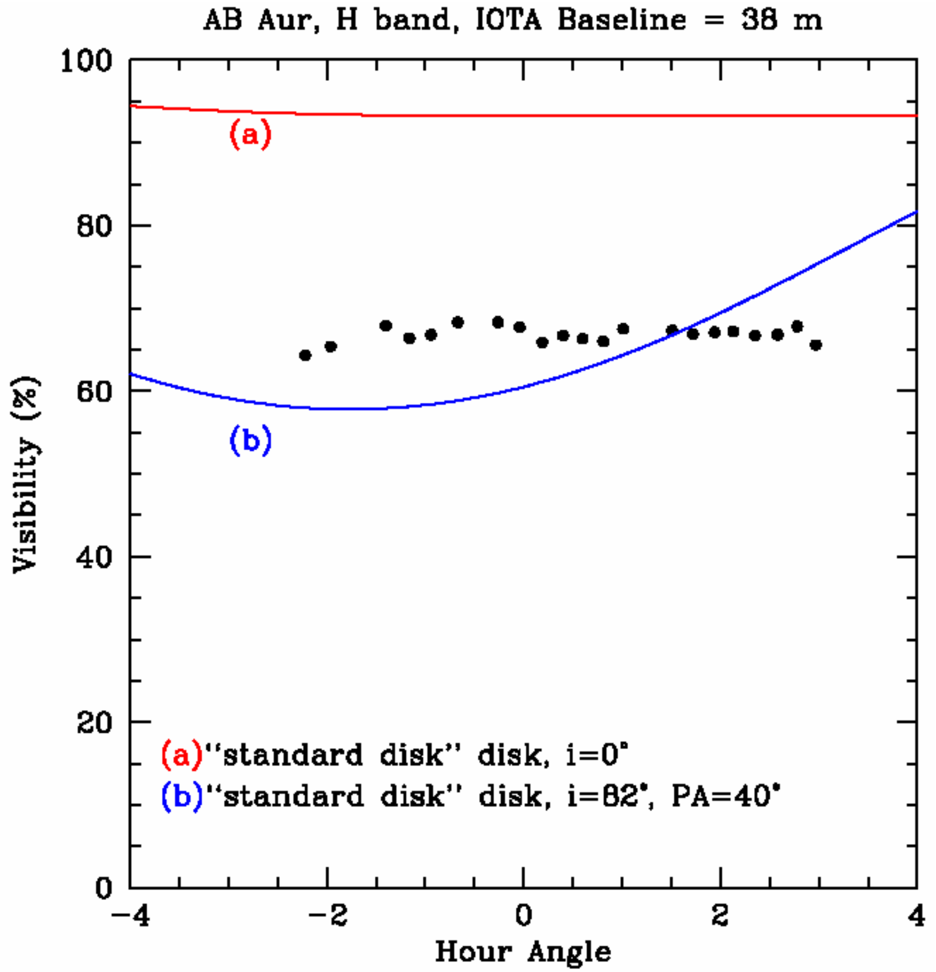
  Indicative of symmetric brightness
- Control experiments:

  ω Ori, MWC166, MWC361



Herbig example: AB Aur

- Disk model derived from SEI (red line, Hillenbrand et al) does not match visibilities
- Inclining that model for best match predicts visibility evolution with hour angle which is not seen
- Large scale (~100 AU) mater is resolved in molecular line emission (Mannings and Sargent, 1997) with inclinatic angle of 76 degrees
- Need new disk model



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Herbig results

- IOTA survey
  - No visibility evolution with baseline projection
    - Symmetric brightness distributions
  - Sizes inconsistent with standard accretion disk models
- PTI sources
  - 3 sources significantly inclined
  - B stars consistent with accretion disks
  - A stars inconsistent

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Observations: T Tauris

- Only brightest objects available to interferometers with apertures < 1 meter
- Four objects observed at PTI (Akeson et al 2000, 2002)
  - T Tau N, SU Aur, RY Tau, DR Tau
  - Stellar and scattering components important
    - Lack of contemporaneous photometry can be a problem
  - Fit sizes are larger than predicted by SED models
- First observations from Keck Interferometer (Colavita et al, 2003)
  - DG Tau (K=7)
  - K band emission even larger than PTI sources

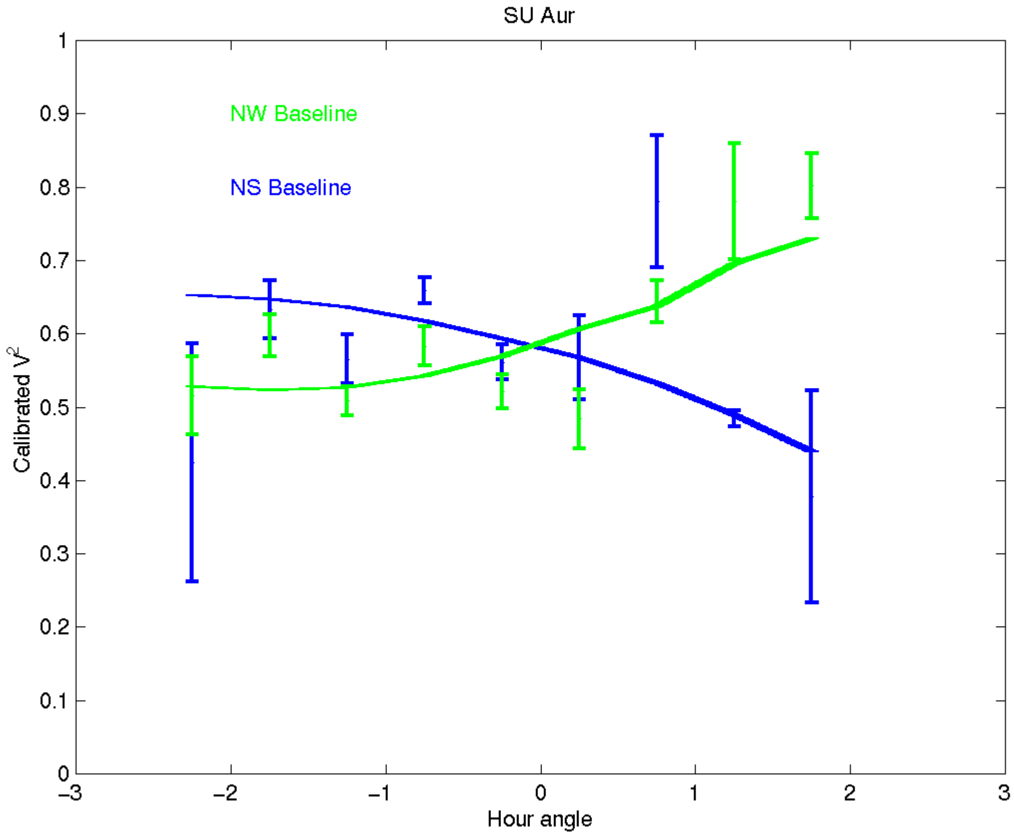
Palomar Testbed Interferometer

- T Tauri observations use:
  - K band
  - 2 baselines: 110 and 85 meters

Example T Tauri: SU Aur

- High luminosity (13 L_{solar}) source with broad absorption lines
- PTI K band observations on NS (110 m) and NW (85 m) baselines

- V^2 evolution with hour angle
- Model
  - PA = 127 ± 10
  - inclination = 62 ± 8

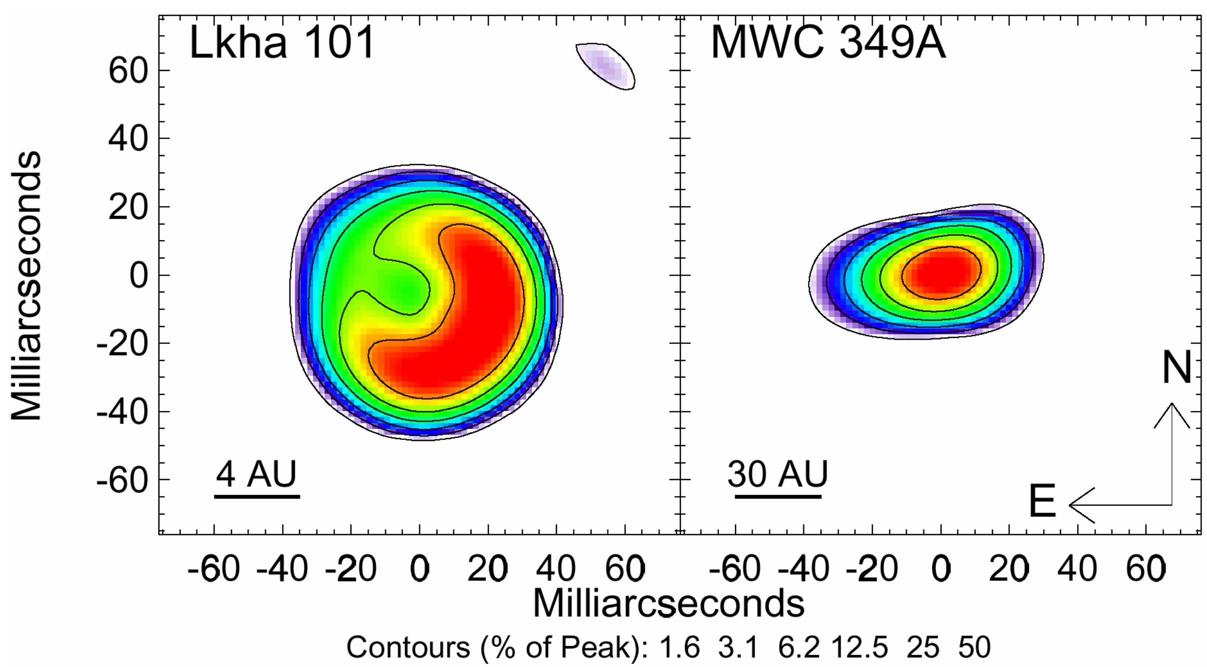


Observations: FU Ori's

- Disk emission dominates at K band
  - Easier to model visibilities
- FU Ori (Malbet et al 1998)
  - Resolved
  - Consistent with accretion disk model with accretion rate ~ 5 * 10^{-5} solar mass/yr
- V1057 Cyg (Wilkin and Akeson, 2003)
  - Resolved
  - Circularly symmetric (consistent with other data)

Complimentary observations: Keck Aperture Masking

- Two extreme YSOs clearly resolved
- Direct disk evidence (inner cavity, elongated)
- Inner cavity size also “too large”
- Size consistent w. heating of opt thin dust …



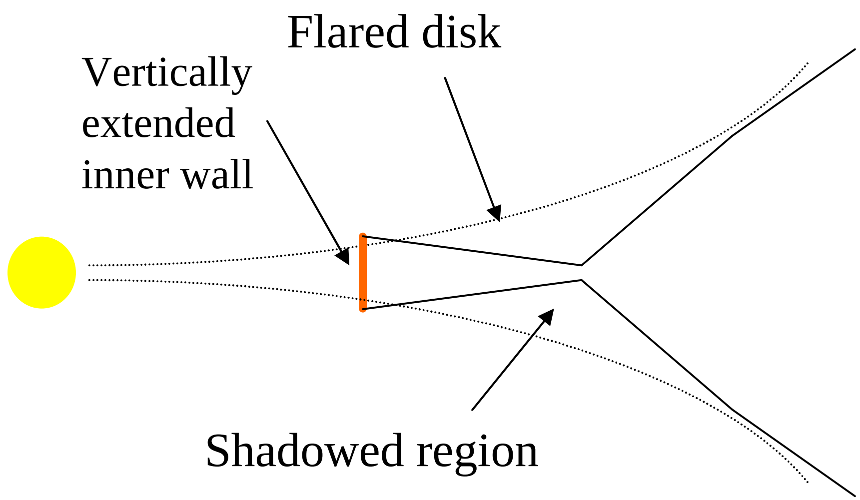
Tuthill, Monnier & Danchi 2001 Danchi, Tuthill & Monnier 2001

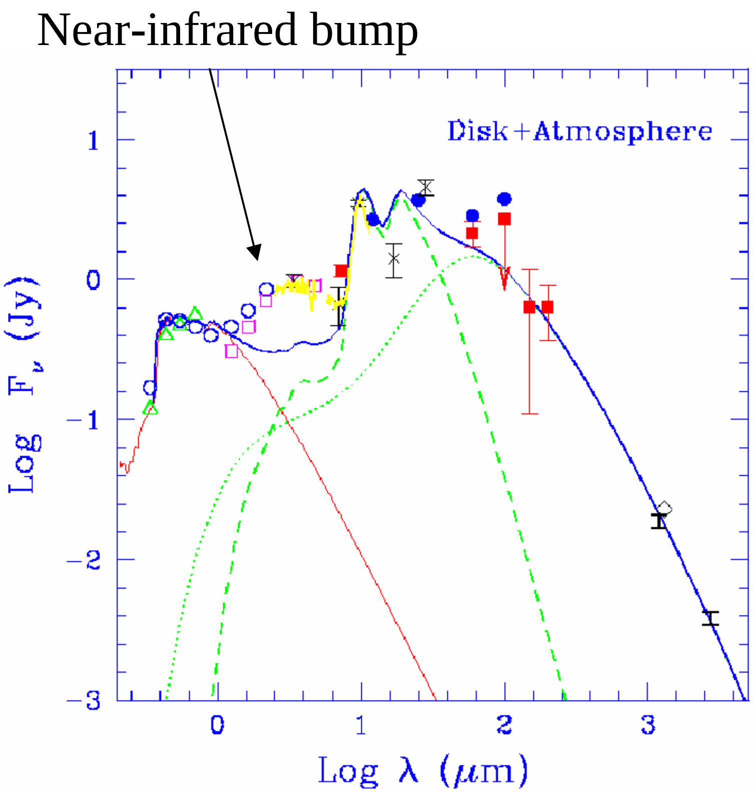
Implications for disk structure

- Observations do not agree with disk parameters determined using fits to spectral energy distributions
  - Measured inner disk radii *larger* than predictions
- Proposed model with inner disk radius set by dust sublimation temperature (Tuthill et al 2001, Natta et al 2001)
- Dullemond et al (2001) model based on Chiang and Goldreich (1997) flared disk with central hole
  - Inner rim of disk becomes vertically extended

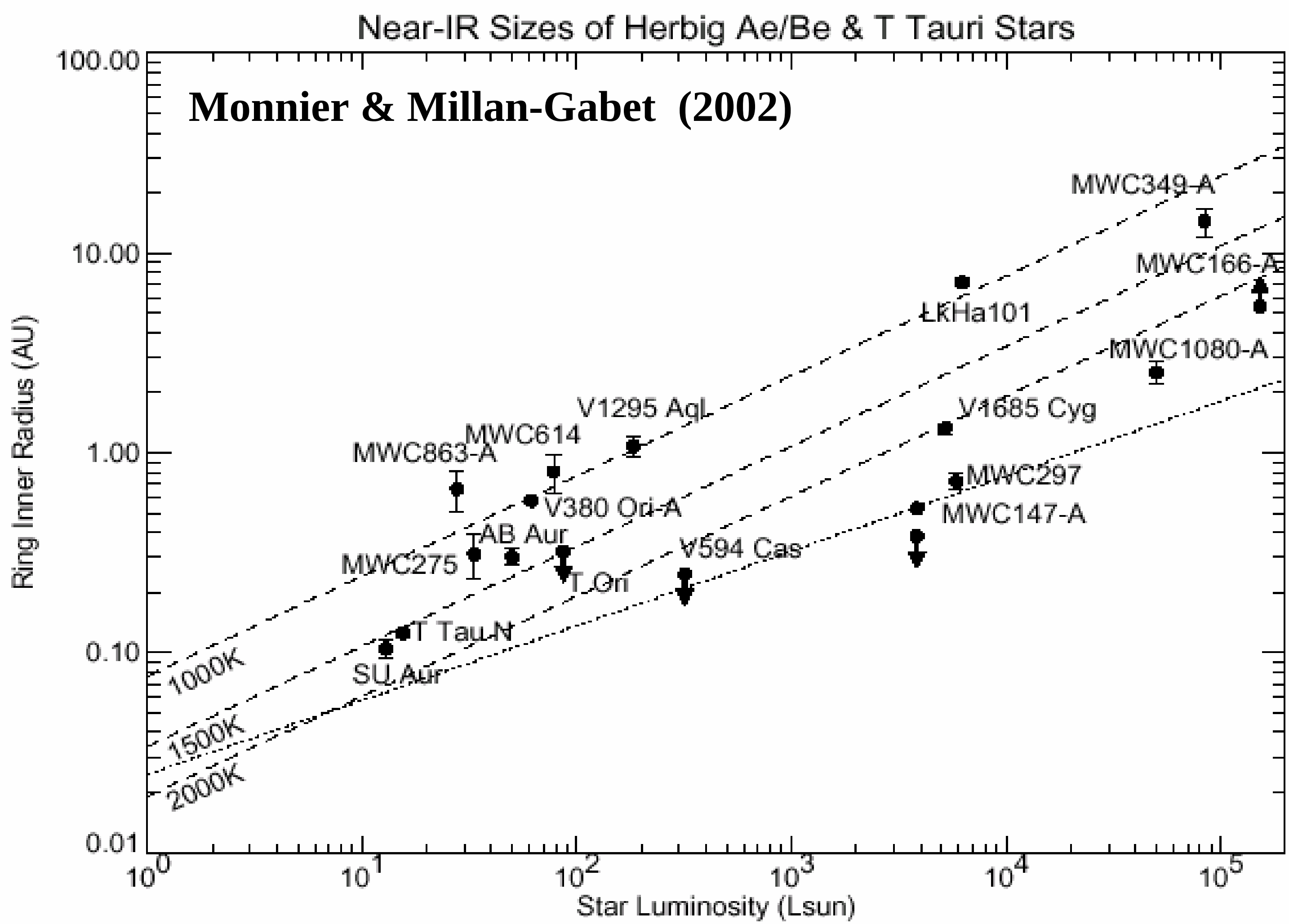
Disk model (Dullemond et al)

- Explains near-infrared feature in Herbig SEDs
- Consistent with measured sizes from interferometers



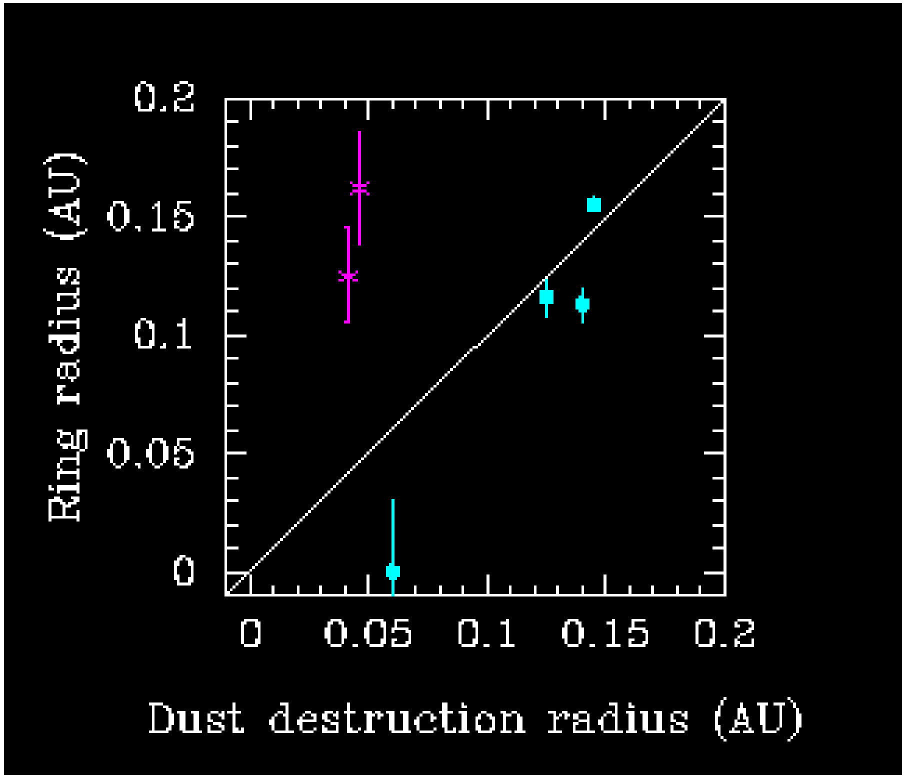


Herbig sizes and ring model



T Tauri sizes

- Use ring geometry to test disk models with inner radius set by dust sublimation temperature



Summary of observations

- Herbig Ae/Be
  - Relatively large (>20) sample observed spanning a range of spectral types
  - Most sources do not show evidence of asymmetry (e.g. inclined disk)
  - Sizes are consistent with arising from material at the dust destruction radius
- T Tauri
  - 6 objects observed to date, most very luminous
  - Visibilities *not* consistent with flat disk models, are consistent with material at dust destruction radius
- FU Ori
  - Only 2 objects observed to date, but general agreement with accretion disk models

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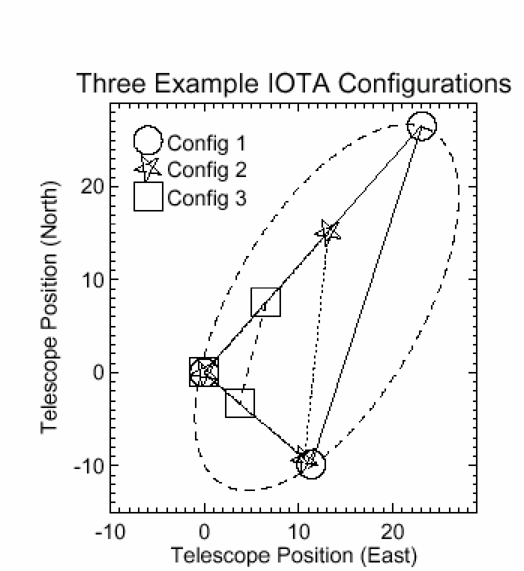
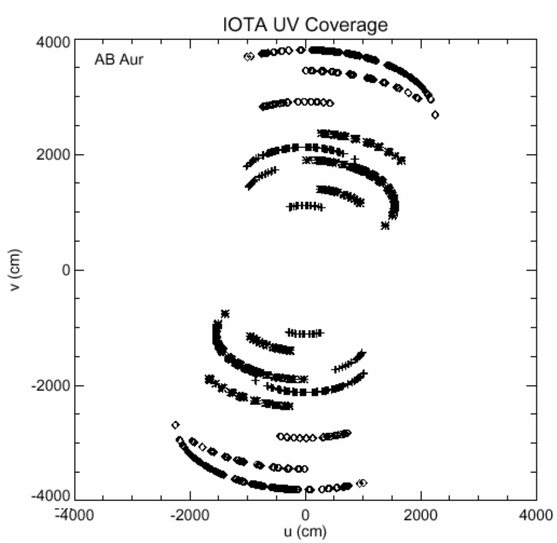
Open issues

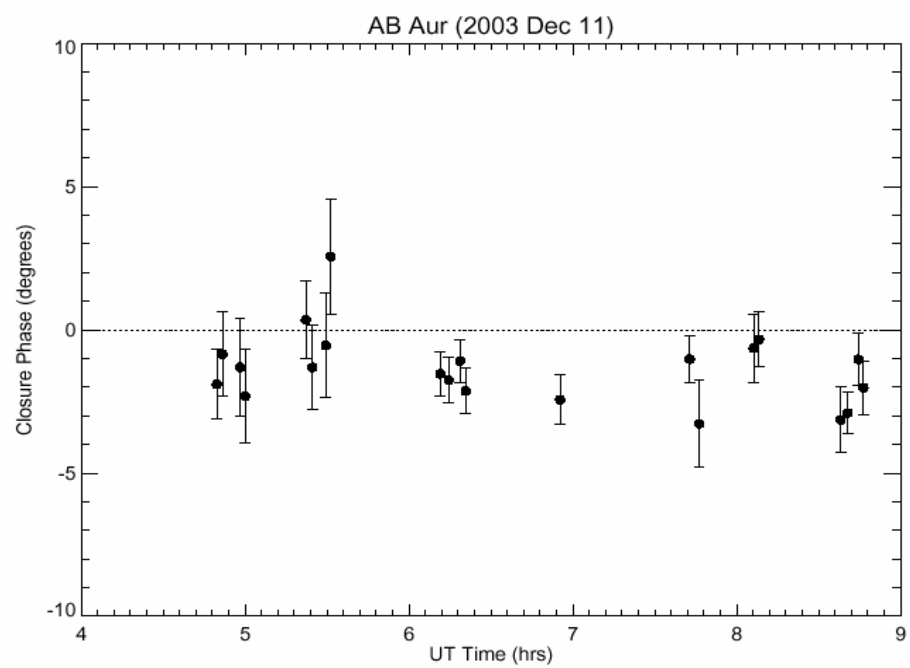
- Herbigs
  - Majority of sources observed have symmetric visibilities
    - Not consistent with sample of disks with randomly distributed inclination angles
    - Observations with mm interferometry suggests material at ~100 AU is in a disk
- T Tauri
  - Contributions of stellar and scattered light components
    - Many T Tauris are significantly variable (tenths of magnitudes) in the near-infrared
  - Are the bright sources observed so far unusually large?
- Disk models
  - Vertically-extended inner wall for T Tauri systems
  - Implication of large inner disk radius for disk winds and planet formation

Future: Multiple baselines





- IOTA 3 way combination
- Nice uv coverage
- No non-zero closure phase yet detected



Future: Large aperture interferometers

Keck Interferometer

CHARA

VLTI

Future: Observations

- Herbigs
  - Complete range of spectral types
  - Many baselines to resolve symmetry issue
- T Tauri
  - Survey of sources with a variety of stellar properties (spectral type, age, infrared excess etc.)
  - Youngest sources will be difficult as tracking is generally done at optical wavelengths
- Mulitiplicity
  - Need observations over a long time span (e.g. a 5 mas binary is Taurus has a ~200 day period)
  - Surveys for multiplicity require lots of observing time
- Beyond
  - Debris disks

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Future: Methods

- Visibility
  - 10 meter class telescopes very sensitive
    - Sufficient sensitivity at K to detect almost all Class I and II sources in Taurus
- Imaging
  - 3 or more telescopes with closure phase
- Astrometry
  - Multiplicity
- Nulling
  - For high dynamic range