Michelson Science Center

Near-Infrared Interferometry of Young Stars: IOTA-3T & KI

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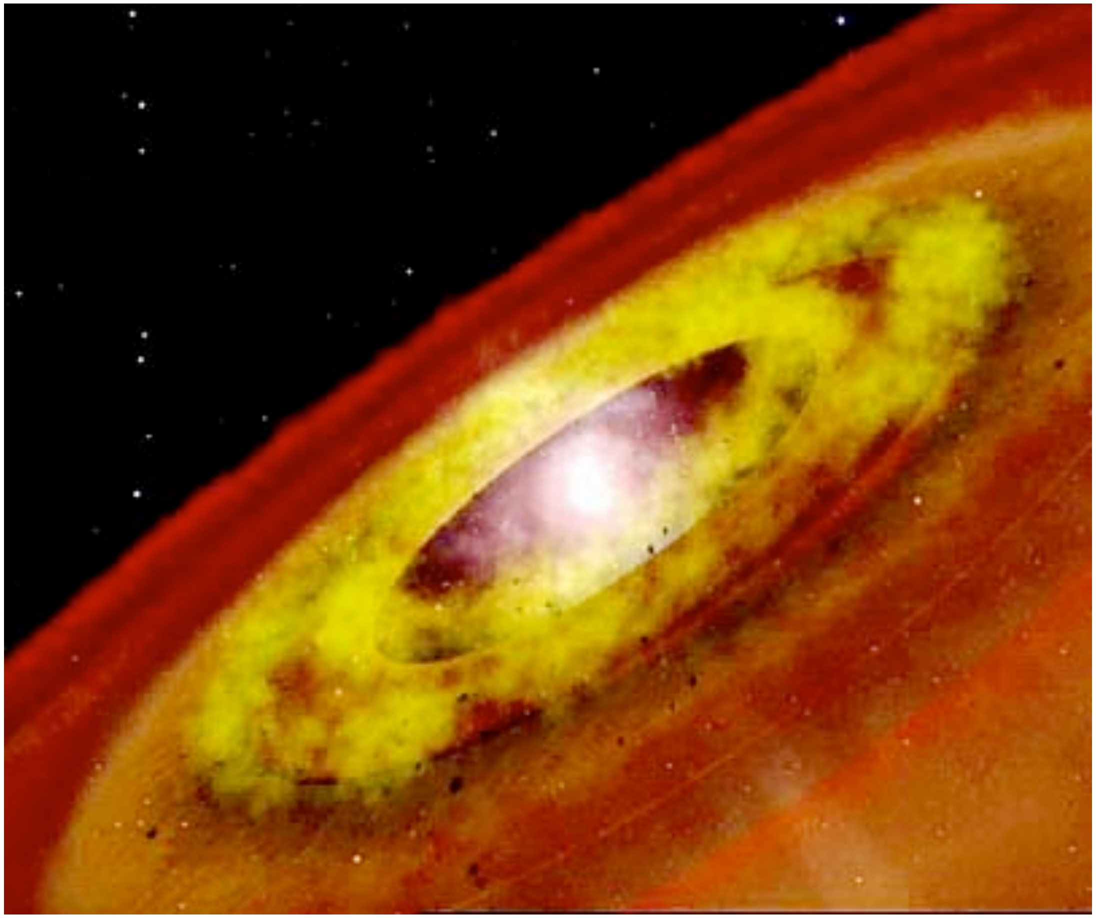
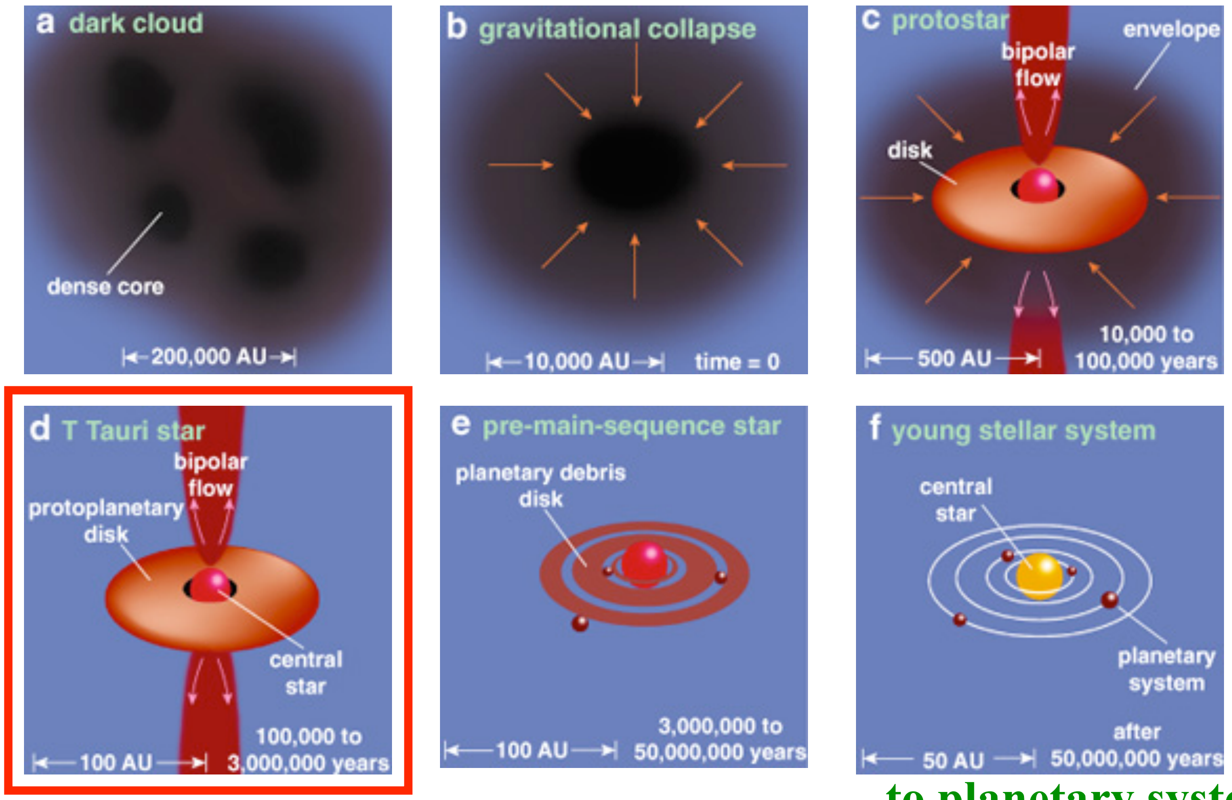


Outline

- Motivation for YSO disk science
- Motivation for optical interferometry in the NIR
- Recent results from KI
- Recent results from IOTA-3T
- Future prospects

Forming stars, disks, and planets

From molecular cloud collapse …

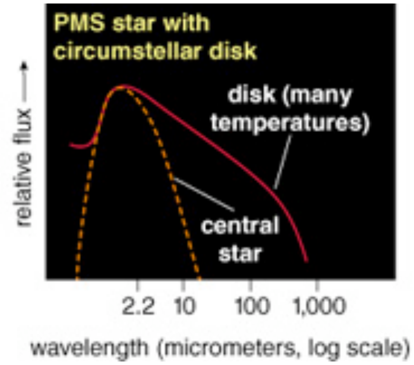


Credit: T. Greene (NASA/Ames)

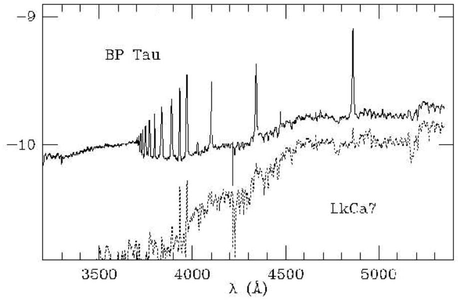
… to planetary systems

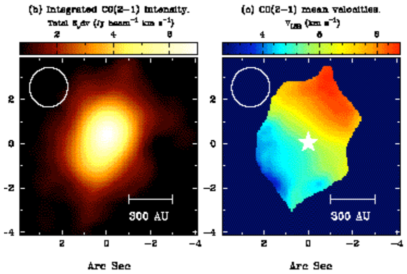
Young pre-planetary disks are important for star formation (conduits for accretion onto star) as well as planet formation (reservoirs of planetary material).

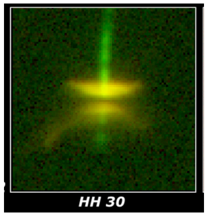
There exists strong observational support for existence of disks



- Spectroscopy and Spectro-photometry (many references …)
- mm-wave interferometry (e.g. Mannings 1997)
- Thermal images from the ground (e.g. Koerner 1998, Jayawardhana 1998)
- HST imaging (e.g. O’Dell 1993, Stapelfeldt 1999)







But …

- ❑ Unresolved spectro-photometry is degenerate w.r.t. the spatial distribution of material (e.g. many matter distributions can reproduce the same SED).
- ❑ Single telescopes or radio interferometers probe spatial scales of ~ 100s AU with resolution ~ 10s AU

Consider a NIR interferometer:

- ✓ NIR wavelengths probe the hottest inner disk material (1000-3000K)
- ✓ B ~ 100m, 2.2 μm => resolution ~ $\lambda/2B$ = 4mas or 0.7 AU at 150 pc

  (compared w. 45mas for largest telescope, and perfect AO)

NIR interferometers can resolve the inner disk at ~ 1 AU scales; and help determine the local physical conditions; which need to be understood before we can understand how terrestrial planets form and giant planets migrate there.

A Young and Active Field:

Name	Type	Instrument	Band	Reference
FU Ori	FUOr	PTI, IOTA, VLTI	H, K	[1, 12]
AB Aur	HAeBe	IOTA, PTI	H, K	[2, 4, 6, 10]
T Tau N	TTS	PTI	K	[3]
SU Aur	TTS	PTI	K	[3]
MWC 147	HAeBe	IOTA, PTI	H, K	[3, 4, 8]
V380 Ori	HAeBe	IOTA	H	[4]
MWC 166	HAeBe	IOTA	H	[4]
Omega Ori	HAeBe	IOTA	H, K	[4]
MWC 863	HAeBe	IOTA	H, K	[4]
MWC 361	HAeBe	IOTA	H, K	[4]
V1685 Cyg	HAeBe	IOTA, PTI, KI	H, K	[4, 6, 10, 15]
MWC 1080	HAeBe	IOTA, PTI	H, K	[4, 6, 10]
MWC 297	HAeBe	IOTA, PTI, VLTI/AMBER	H, K	[4, 8, 10, 18]
V1295 Aql	HAeBe	IOTA, PTI	H, K	[4, 8, 10]
MWC 614	HAeBe	IOTA, PTI, VLTI/MIDI	H, K, N	[4, 8, 9]
V594 Cas	HAeBe	IOTA, PTI	H, K	[4, 8]
MWC 275	HAeBe	IOTA, VLTI/MIDI, KI	H, K, N	[4, 9, 11, 15]
T Ori	HAeBe	IOTA	H	[4, 10]
LkHa 101	HAeBe	ISI	N	[5]
VV Ser	HAeBe	PTI	K	[6, 10]
AS 442	HAeBe	PTI, KI	K	[6, 10, 15]
DG Tau	TTS	KI	K	[7, 17]
V1057 Cyg	FUOr	PTI, KI	K	[8, 19]
HD 142527	HAeBe	VLTI/MIDI	N	[9, 11]
HD 144432	HAeBe	VLTI/MIDI, KI	N, K	[9, 11, 15]
HD 100546	HAeBe	VLTI/MIDI	N	[9]
HD 179218	HAeBe	VLTI/MIDI	N	[9]
KK OPh	HAeBe	VLTI/MIDI	N	[9]

Name	Type	Instrument	Band	Reference
CQ Tau	HAeBe	PTI	K	[10]
MWC 120	HAeBe	PTI	K	[10]
HD 158352	HAeBe	PTI	K	[10]
MWC 480	HAeBe	PTI, KI	K	[10]
MWC 758	HAeBe	PTI	K	[10, 15]
HD 141569	HAeBe	PTI	K	[10, 15]
RY Tau	TTS	PTI	K	[13]
DR Tau	TTS	PTI	K	[13]
AS 207A	TTS	KI	K	[14]
V2508 Oph	TTS	KI	K	[14]
AS 205A	TTS	KI	K	[14]
PX Vul	TTS	KI	K	[14]
UX Ori	HAeBe	KI	K	[15]
ZCMa-NW	HAeBe	KI	K	[15]
HD 58647	HAeBe	KI	K	[15]
HD 146666	HAeBe	KI	K	[15]
HD 143006	HAeBe	KI	K	[15]
HD 150193	HAeBe	KI	K	[15]
WW Vul	HAeBe	KI	K	[15]
AS 477	HAeBe	KI	K	[15]
HD 98800B	TTS	KI	K	[16]
BP Tau	TTS	KI	K	[17]
DI Tau	TTS	KI	K	[17]
GM Aur	TTS	KI	K	[17]
LkCa15	TTS	KI	K	[17]
RW Aur	TTS	KI	K	[17]
V830 Tau	TTS	KI	K	[17]
V1515 Cyg	FUOr	KI	K	[19]

→ **58 young stellar objects** observed to date,

→ **18 refereed articles**, 1 submitted, all since 1998

[1] Malbet, F., Berger, J.-P., Colavita, M. M., et al., **1998**, ApJ, 507, L149, **FU Orionis Resolved by Infrared Long-Baseline Interferometry at a 2 AU Scale**

[2] Millan-Gabet, R., Schloerb, F. P., Traub, W. A., et al., **1999**, ApJ, 513, L131, **Sub-Astronomical Unit Structure of the Near-Infrared Emission from AB Aurigae**

[3] Akeson, R. L., Ciardi, D. R., van Belle, G. T., et al., **2000**, ApJ, 543, 313, **Infrared Interferometric Observations of Young Stellar Objects**

[4] Millan-Gabet, R., Schloerb, F. P., & Traub, W. A., **2001**, ApJ, 546, 358, **Spatially Resolved Circumstellar Structure of Herbig AE/BE Stars in the Near-Infrared**

[5] Tuthill, P. G., Monnier, J. D., Danchi, W. C., et al. ., **2002**, ApJ, 577, 826, **Imaging the Disk around the Luminous Young Star LkHa 101 with Infrared Interferometry**

[6] Eisner, J. A., Lane, B. F., Akeson, R. L., et al., **2003**, ApJ, 588, 360, **Near-Infrared Interferometric Measurements of Herbig Ae/Be Stars**

[7] Colavita, M., Akeson, R., Wizinowich, P., et al., **2003**, ApJ, 592, L83, **Observations of DG Tauri with the Keck Interferometer**

[8] Wilkin, F. P. & Akeson, R. L., **2003**, Ap&SS, 286, 145, **Palomar Testbed Interferometer Observations of Young Stellar Objects**

[9] Leinert, C., van Boekel, R., Waters, L. B. F. M., et al., **2004**, A&A, 423, 537, **Mid-infrared sizes of circumstellar disks around Herbig Ae/Be stars measured with MIDI on the VLTI**

[10] Eisner, J. A., Lane, B. F., Hillenbrand, L. A., et al., **2004**, ApJ, 613, 1049, **Resolved Inner Disks around Herbig Ae/Be Stars**

[11] van Boekel, R., Min, M., Leinert, C., et al., **2004**, Nature, 432, 479, **The building blocks of planets within the ‘terrestrial’ region of protoplanetary disks**

[12] Malbet, F., Lachaume, R., Berger, J.-P., et al., **2005**, A&A, 437, 627, **New insights on the AU-scale circumstellar structure of FU Orionis**

[13] Akeson, R. L., Walker, C. H., Wood, K., et al., **2005**, ApJ, 622, 440, **Observations and Modeling of the Inner Disk Region of T Tauri Stars**

[14] Eisner, J. A., Hillenbrand, L. A., White, R. J., et al., **2005**, ApJ, 623, 952, **Observations of T Tauri Disks at Sub-AU Radii: Implications for Magnetospheric Accretion and Planet Formation**

[15] Monnier, J. D., Millan-Gabet, R., Billmeier, R., et al., **2005**, ApJ, 624, 832, **The Near-Infrared Size-Luminosity Relations for Herbig Ae/Be Disks**

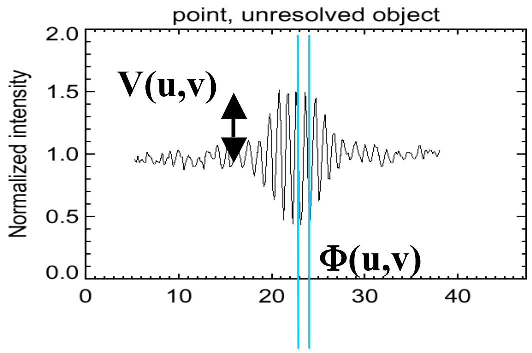
[16] Boden, A. F., Sargent, A. I., Akeson, R. L., et al., **2005**, ApJ, in press (astro-ph/0508331), **Dynamical Masses for Low-Mass Pre-Main Sequence Stars: A Preliminary Physical Orbit for HD 98800 B**

[17] Akeson, R. L., Boden, A. F., Monnier, J. D., et al., **2005**, ApJ, in press (astro-ph/0508561), **Keck Interferometer observations of classical and weak line T Tauri stars**

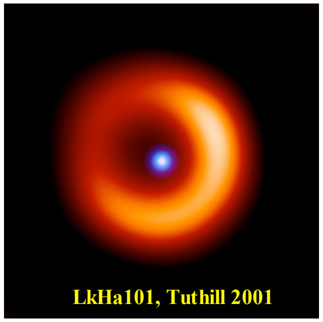
[18] Malbet, F., Benisty, M., De Wit, W. J., et al., **2005**, A&A, in press (astro-ph/0510350), **Disk and wind interaction in the young stellar object MWC 297 spatially resolved with VLTI/AMBER**

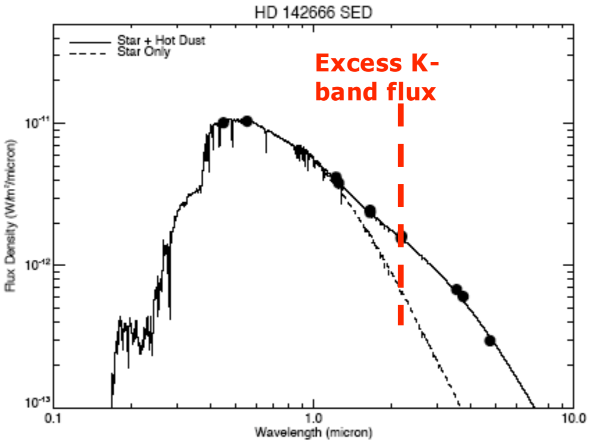
[19] Millan-Gabet, R., Monnier, J. D., Akeson, R., et al., **2005**, ApJ, submitted, **Keck Interferometer Observations of FU Orionis Objects**

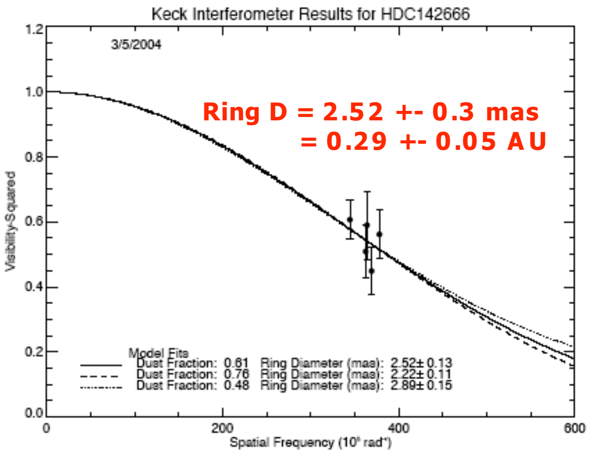
Illustrating the Technique



- Create fringes between 2 telescopes and measure their amplitude
- Related to object brightness $\hat{V}(u,v) \overset{FT}{\Leftrightarrow} I(\alpha,\beta)$
- BUT:
  - no fringe phase (w. 2 telescopes)
  - few uv points (w. few telescopes)
- Assume a reasonable & simple model (e.g. star + Gaussian or ring brightness); obtain relative fluxes from SED decomposition; fit the V2 data to extract key morphology parameters of source of NIR excess (size, shape …):

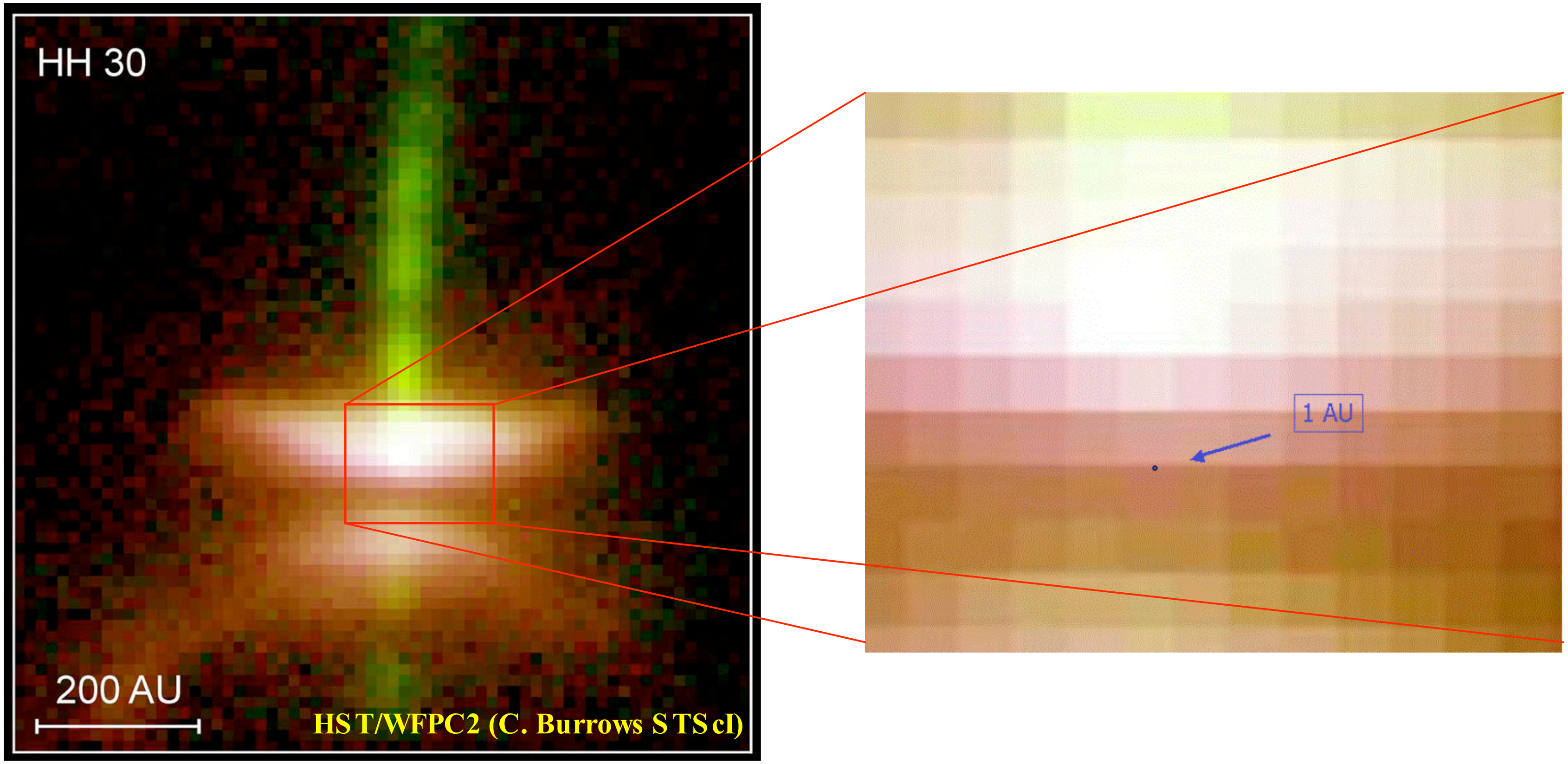




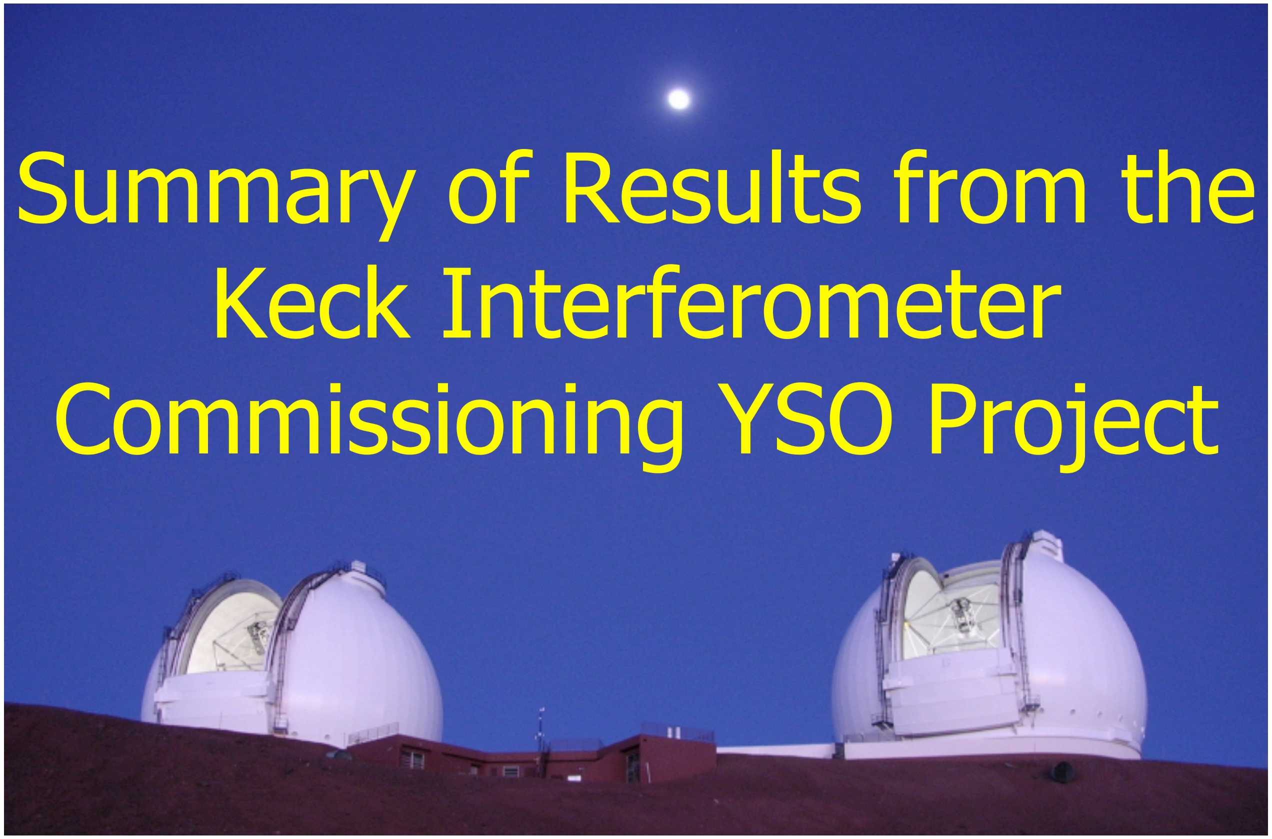


- also, do hypothesis testing of realistic disk models.

Why bother?
again, resolution in context:



HST/WFPC2 (C. Burrows STScl)



Summary of Results from the Keck Interferometer Commissioning YSO Project

Goal: Use the KI in V2 mode, to spatially resolve in the NIR the disks around a sample of well known young stars of various types (HAeBe, T Taus, FU Oris).

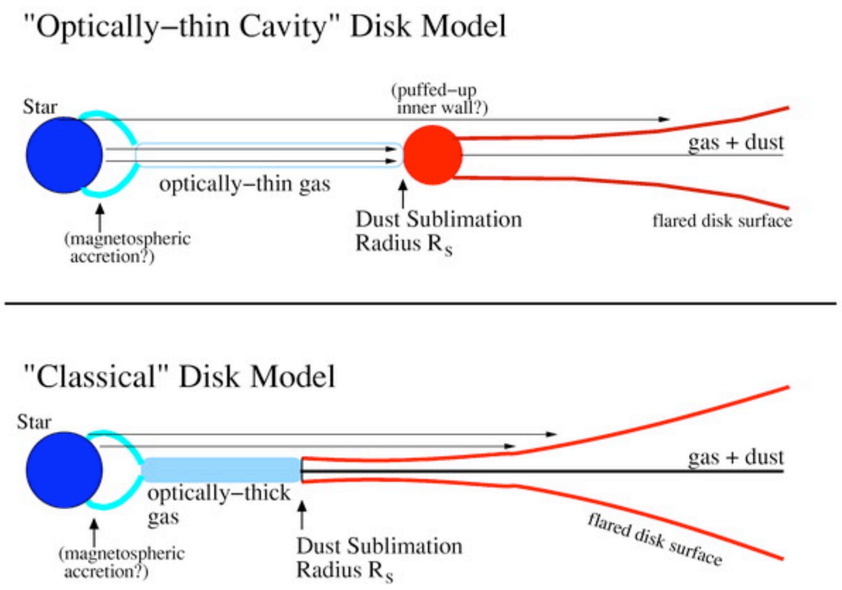
Observations: 2001-2004, papers coming out now

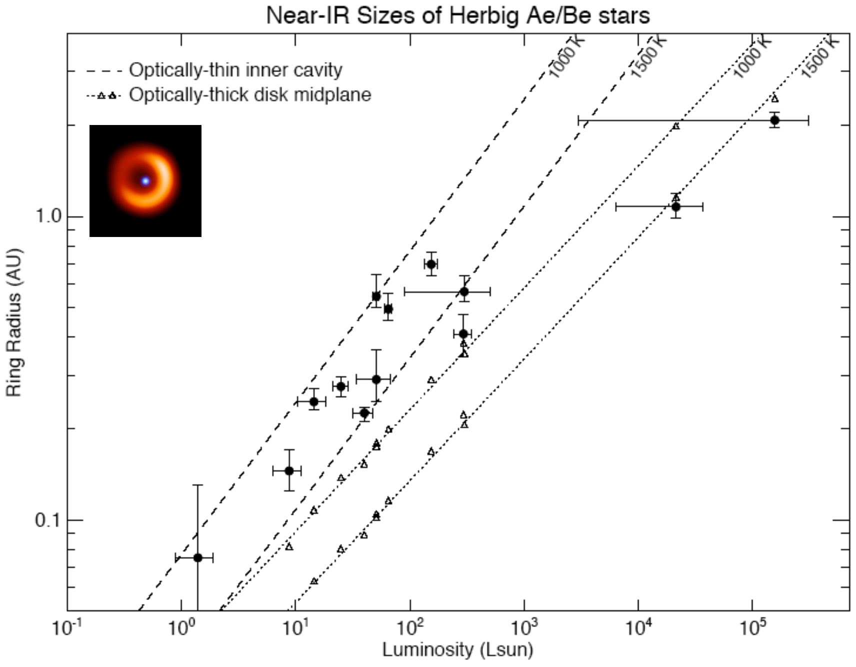
Collaborators:
J. Monnier (U. Michigan)
R. Akeson (Caltech, MSC)
J-P. Berger (LAOG, France)
KI JPL Team
KI WMKO Team

KI Results on Herbig Ae/Be Objects

Monnier et al. 2005, ApJ, 624, 832

- Young stars of intermediate mass (1-5 Msun).
- 14 well selected objects spanning B0 - A9.
- Established a tight size-L relation for HAe and late HBe, confirming earlier interferometer results (IOTA,PTI), and consistent with recently proposed "puffed-up" inner wall disk models (Natta 2001, Dullemond 2001).
- As previously pointed out (Monnier 2002, Eisner 2003,04), (most) earlier types are undersized w.r.t. these models, indicating *some* gas optical depth inside inner dust cavity, and perhaps different accretion mechanism.

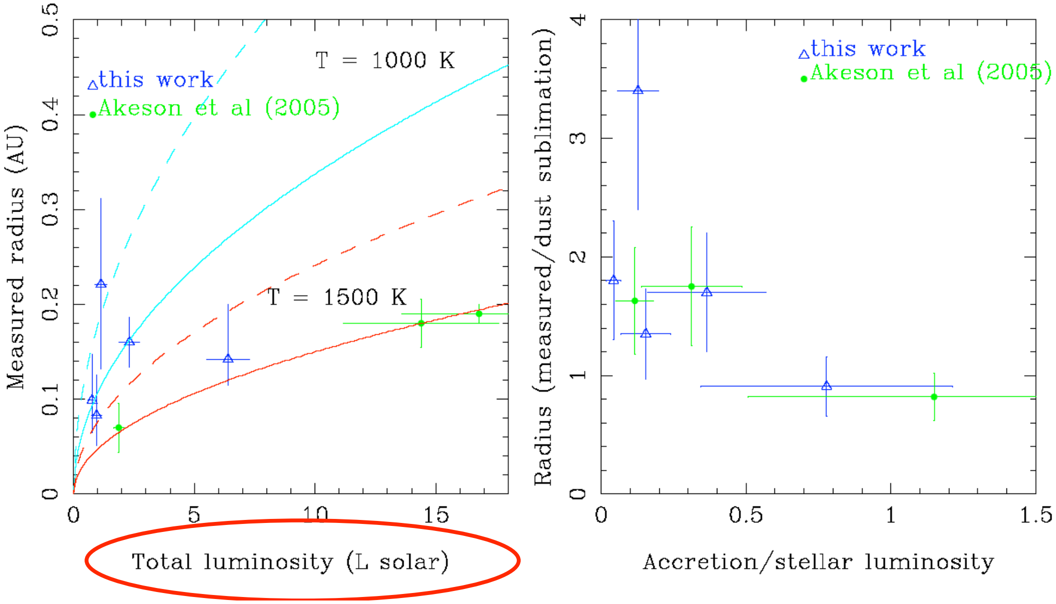




KI Results on T Tauri Objects

Akeson et al. 2005, accepted by ApJ

- Solar type young stars.
- 7 objects w. a range of disk properties (IR excess, Ha width).
- Inner wall models have been extended to T Tauri objects (to explain NIR excesses & 1st KI result - DG Tau, Colavita 2003) BUT adding accretion shock luminosity as central heating source (Muzerolle 2003, D'Alessio 2004).
- KI NIR sizes are consistent w. this picture, though may require a range of inner wall conditions (opt. thin vs. thick dust; sublimation T).
- Perhaps lower accretion rate objects are more evolved, and their larger NIR sizes indicate inner disk dissipation by e.g. photoevaporation.

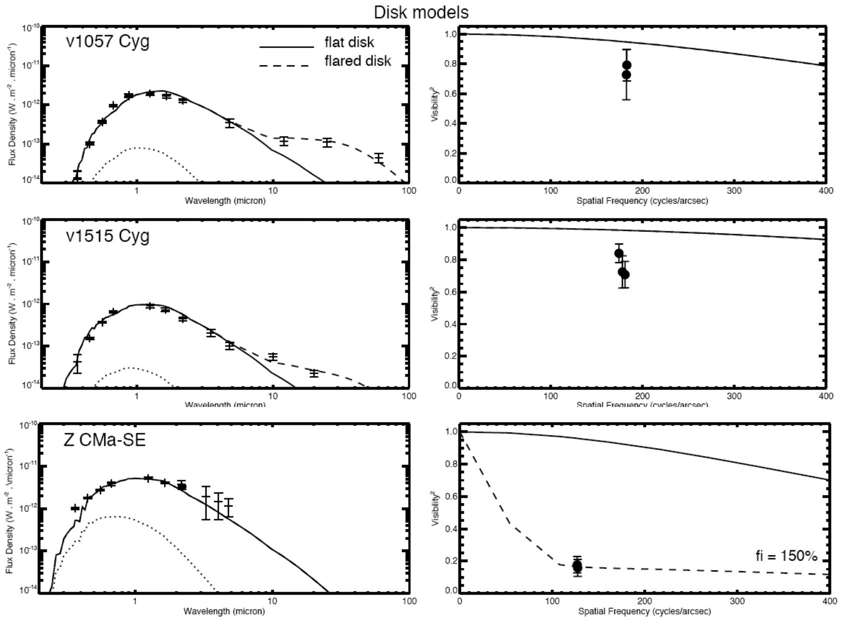


See also J. Eisner talk on KI results for Ophiucus sample

KI Results on FU Ori Objects

Millan-Gabet et al. 2005, submitted to ApJ

- T Tauri objects surrounded by disks that have recently undergone episode of accretion outburst.
- Interesting test case for models of accretion disks, since post-outburst emission is dominated by the disk. PTI, IOTA, VLTI observations of FU Ori itself confirmed expectations from standard single power law disk models (Malbet 1998, 2005).
- 3 KI objects VERY resolved. NOT consistent w. isolated standard disks.
- Proposed interpretation: "contamination" by flux coming from large scales (e.g. scattering by several AU structure, outer disk or, more likely, envelope).
- If confirmed, compromises the notion to use some of the best known FU Oris for ***clean*** tests of disk theories …
- Could they *all* be binaries, as proposed by some theories of the FU Orionis phenomenon …? (Bonnell 1992)



Preliminary Results from IOTA-3T YSO Closure Phases

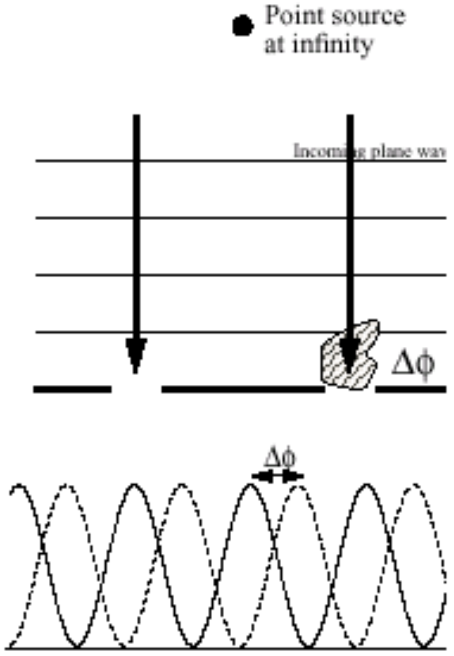
<u>Goals</u>: Use the new IOTA-3T capabilities to perform the first CP measurements of YSOs, constrain higher order disk morphology, make crude images?

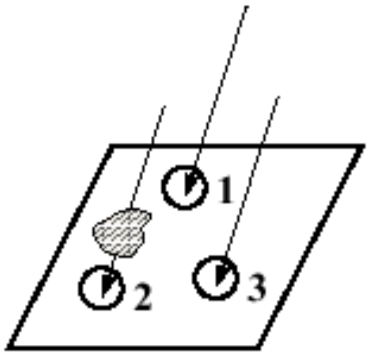
<u>Observations</u>: 2002-2004, writing papers now …

<u>Collaborators</u>: J. Monnier (U. Michigan)
J-P. Berger (LAOG, France)
E. Pedretti (U. Michigan)
W. Traub (JPL, SAO)
P. Schloerb (U. Massachusetts)

The “Closure Phase” is Not Corrupted by the Atmosphere

From Monnier 2003
“Observing with the VLTI”





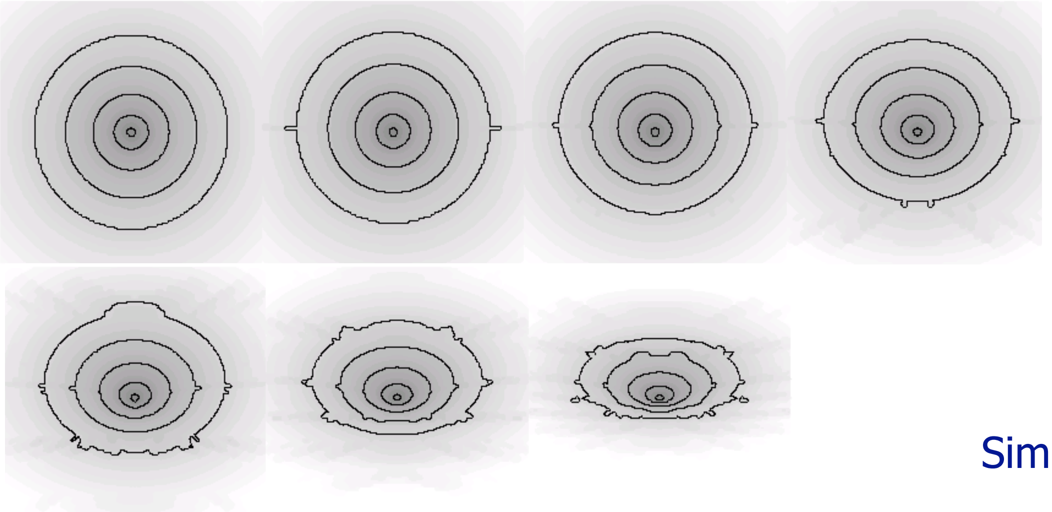
Observed Intrinsic Atmosphere

$$\Phi(1\text{-}2) = \Phi_o(1\text{-}2) + [\phi(2)-\phi(1)]$$
$$\Phi(2\text{-}3) = \Phi_o(2\text{-}3) + [\phi(3)-\phi(2)]$$
$$\Phi(3\text{-}1) = \Phi_o(3\text{-}1) + [\phi(1)-\phi(3)]$$

Closure Phase (1-2-3) $= \Phi_o(1\text{-}2)+\Phi_o(2\text{-}3)+\Phi_o(3\text{-}1)$

- CP = 0 for centro-symmetric sources
- CP measures degree of asymmetry => easy check!
- CP strongly constrains models
- CP enables imaging

Expected Closure Phases from (Flared) Inclined Disks

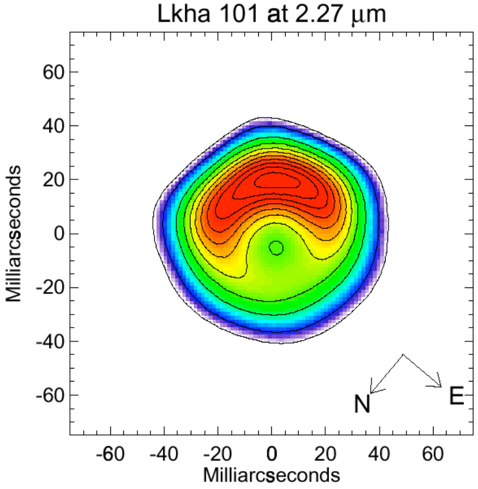


Simulations:

CP can reach 50 deg (VLTI)

Malbet et al. 2001

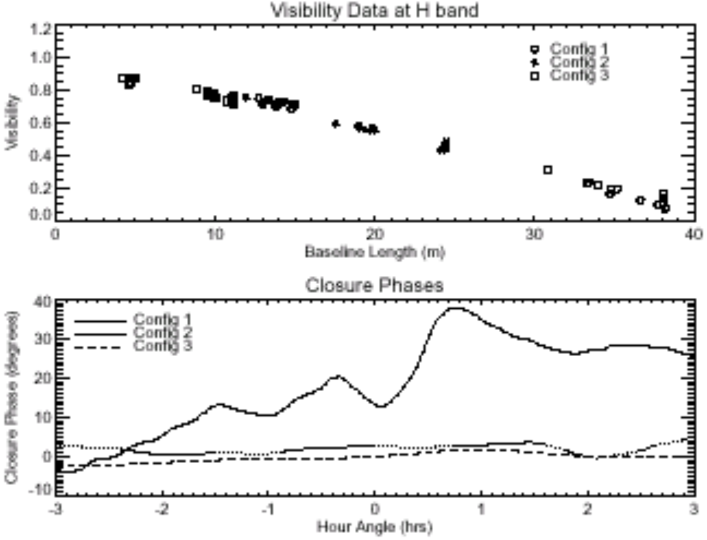
Real data: LkHa 101 image:



Tuthill, Monnier & Danchi 2001

Simulated IOTA response:

(LkHa 101 made x7 smaller)



Credit: J. Monnier (U. Michigan)

The IOTA-3T YSO Survey

- 13 HAeBe, 2 T Tauri Objects
- 10 have CP consistent with zero ☹
- aside from binaries (2) most detections have weak (few degree) CP signal.

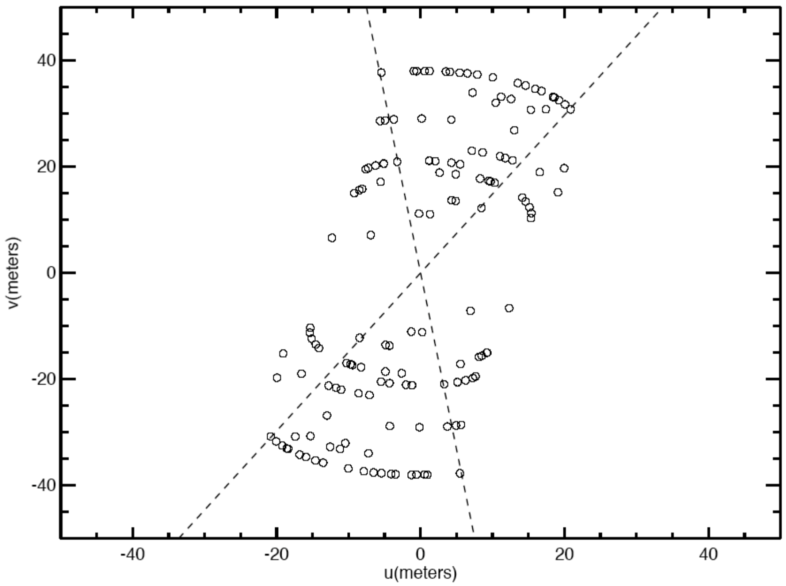
What does this mean?

Lack of disk asymmetries?

Insufficient resolution?

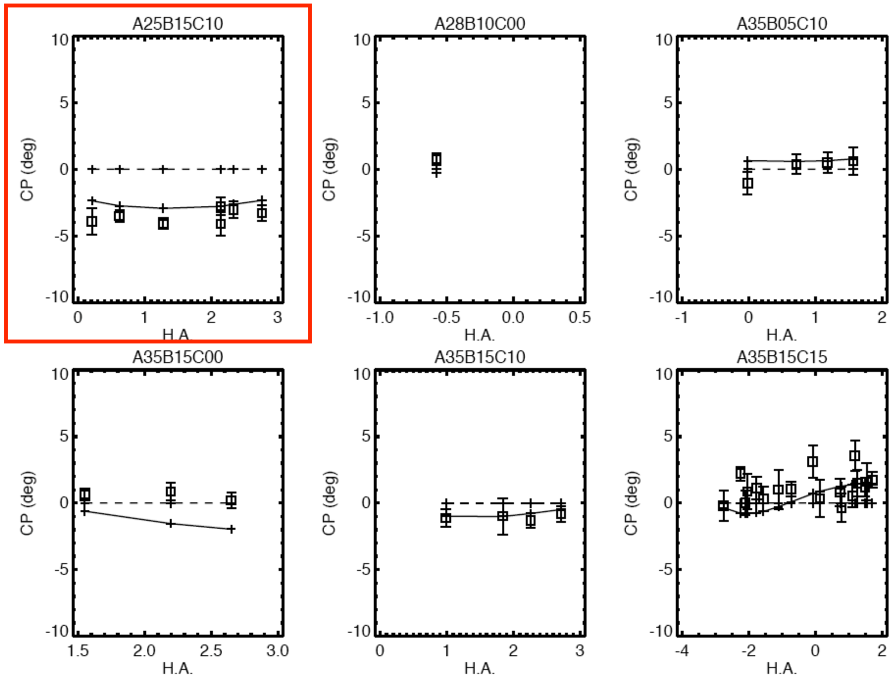
Example: AB Aur

UV coverage from 6 different 3-telescope configurations (respectable …):



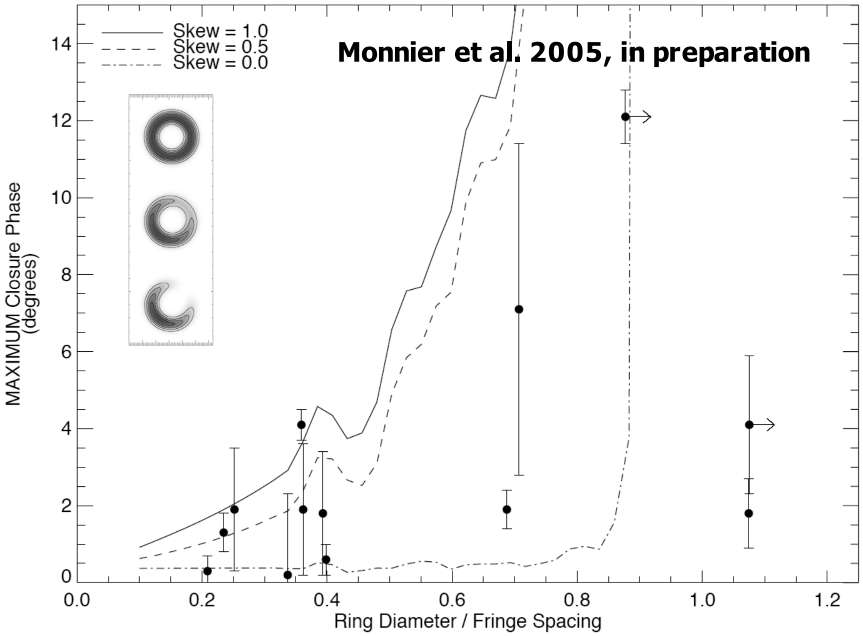
Millan-Gabet et al. 2005, in preparation

~ -4 deg CP detected in one (*small*) triangle:

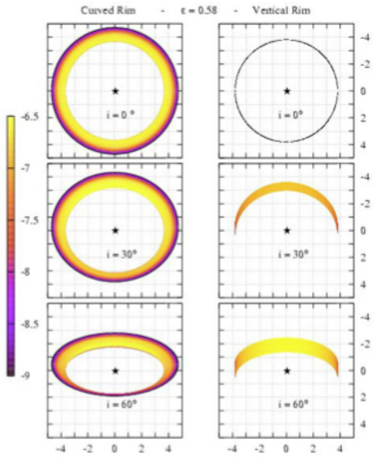


Exploring Parameter Space

- Construct a “skewed” ring model, resembling expected emission. Explore CP signal for various degrees of ring skewness and size (sample random orientations).



Monnier et al. 2005, in preparation



Conclusions:

1. CP is strongly suppressed when ring diameter < fringe spacing.
2. More resolution is required to characterize most sources.
3. Based on a few of the most resolved objects, we find no evidence for skewness greater than ~ 0.5.
4. Favors inner dust rims which are smoothly curved (Isella 2005) rather than vertical walls (Dullemond 2001).

Exciting Prospects for YSO Interferometry

- multi-band JHK (thermal or scattering?) **(KI, VLTI/AMBER, CHARA/MIRC)**
- spectral resolution (gas dynamics, jets) **(VLTI/AMBER, CHARA/MIRC)**
- explore thermal IR **(VLTI/MIDI, KI/Nulling)**
- sub-% V accuracy? (planet signatures -- gaps)
- true imaging (validate new complex models) **(VLTI/AMBER, CHARA/MIRC)**
- disk dynamics