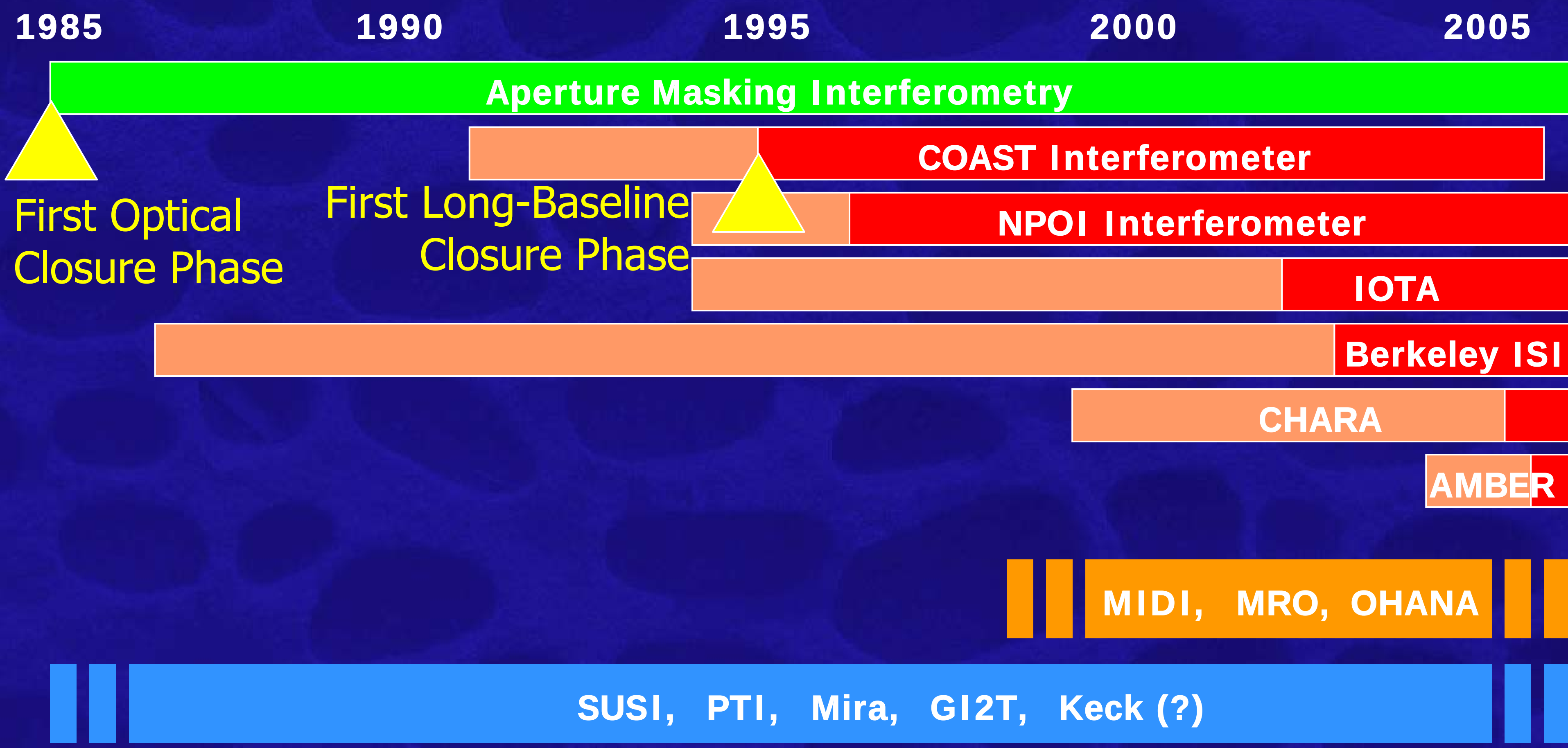
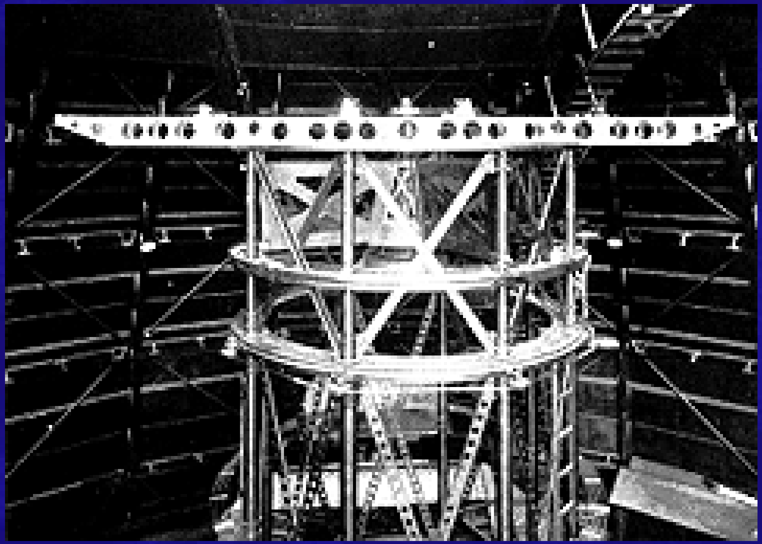
Science with Closure Phases

Peter Tuthill
Sydney University

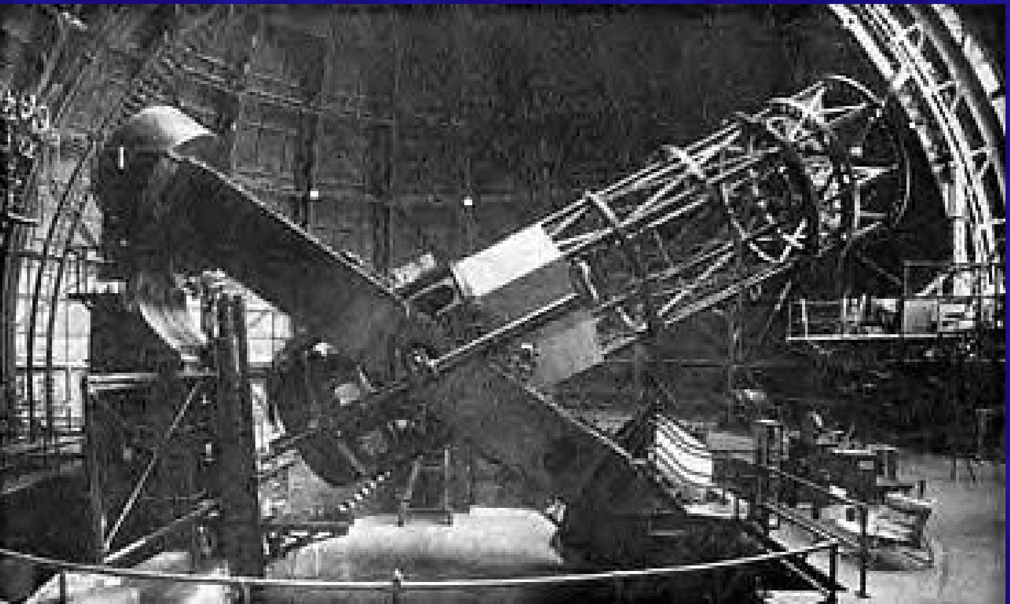
Closure Phase
The Newest Toy in the Store …



The first golden age of Interferometry:

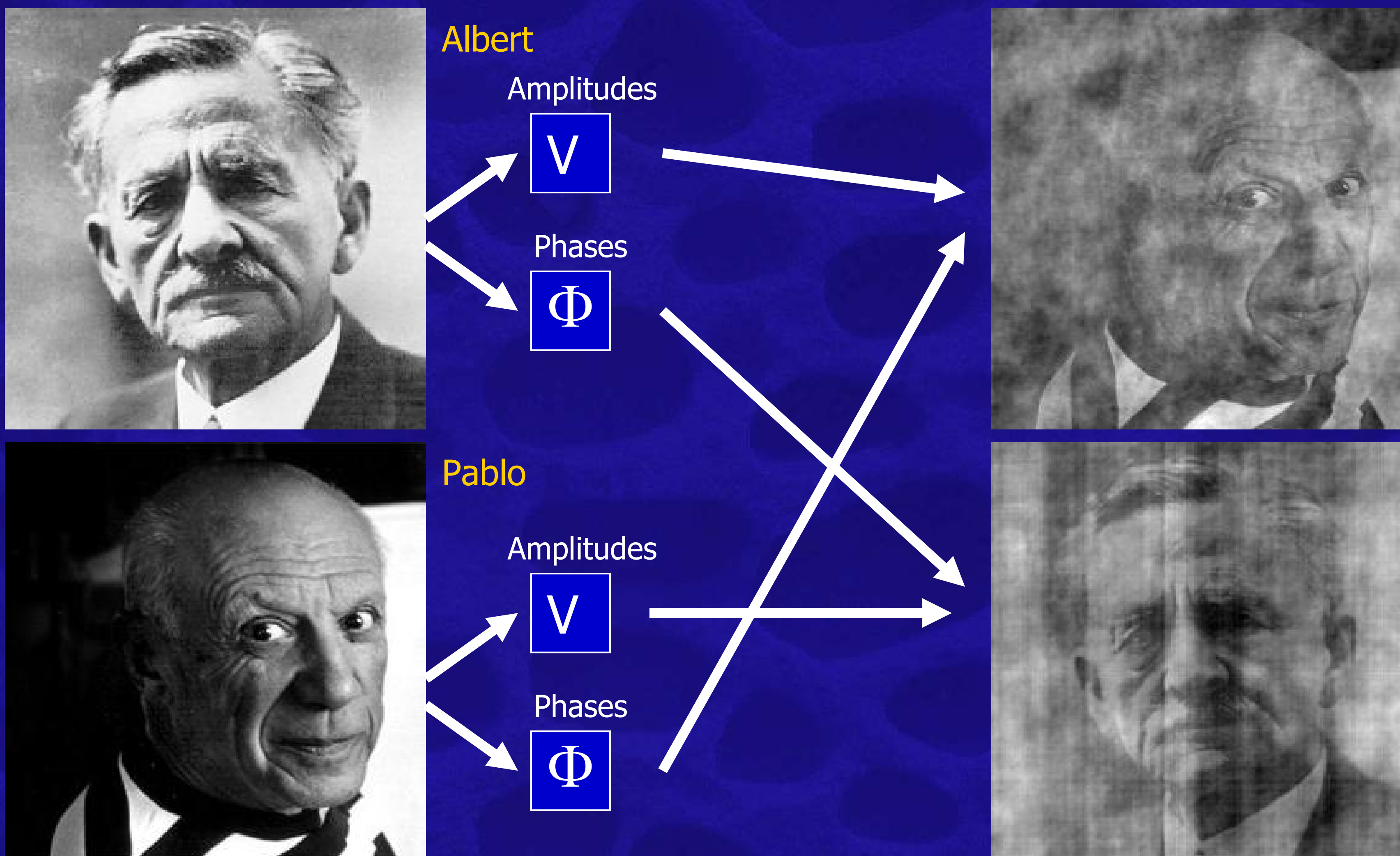


Albert Michelson



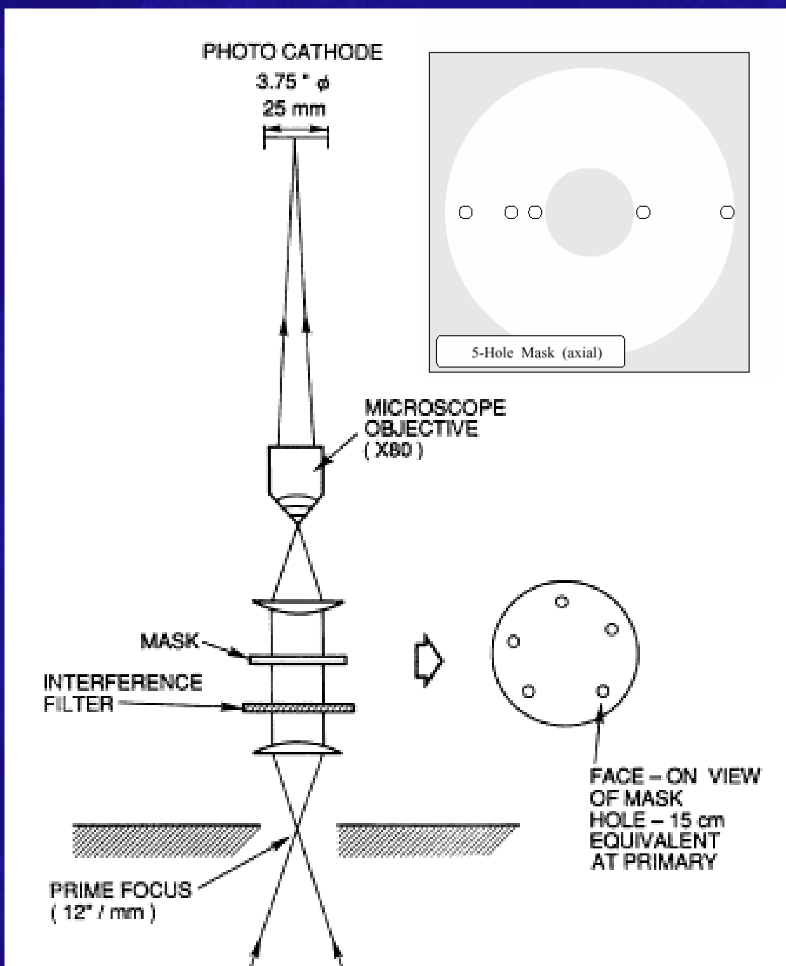
- Moons of Jupiter
- Binary Stars
- Red Giant Stars
  - **Angular Diameters**
  - **Betelgeuse + others**

Amplitudes and Phases



Baby Steps – Aperture Masking

Baldwin et al. Nature 1986, 320, 595: First Optical Closure Phase
Haniff et al Nature 1987, 328 694: First CLP Image



Nakajima et al., AJ 1989, 97, 151

α Her

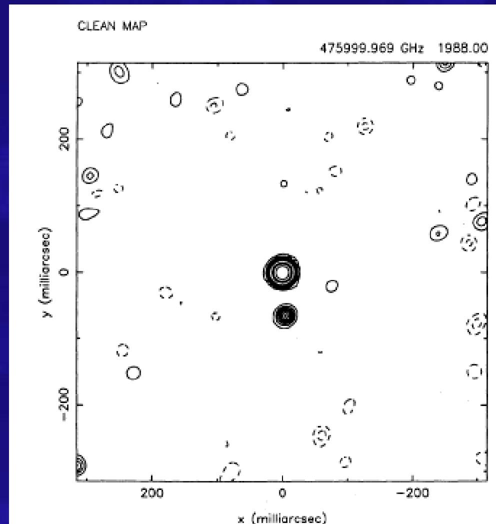


Fig. 7. Reconstructed image of σ Her. Contour levels are −2%, −1%, 1%, 2%, 3%, 5%, 10%, 20%, 30%, 40%, 50%, and 60% of the maximum. The top is to the north and to the left is the east.

β CrB

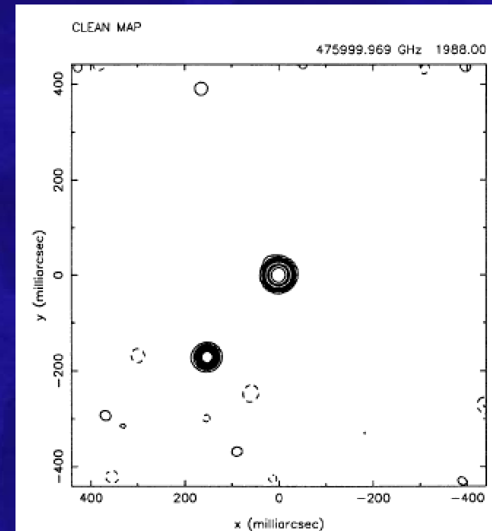
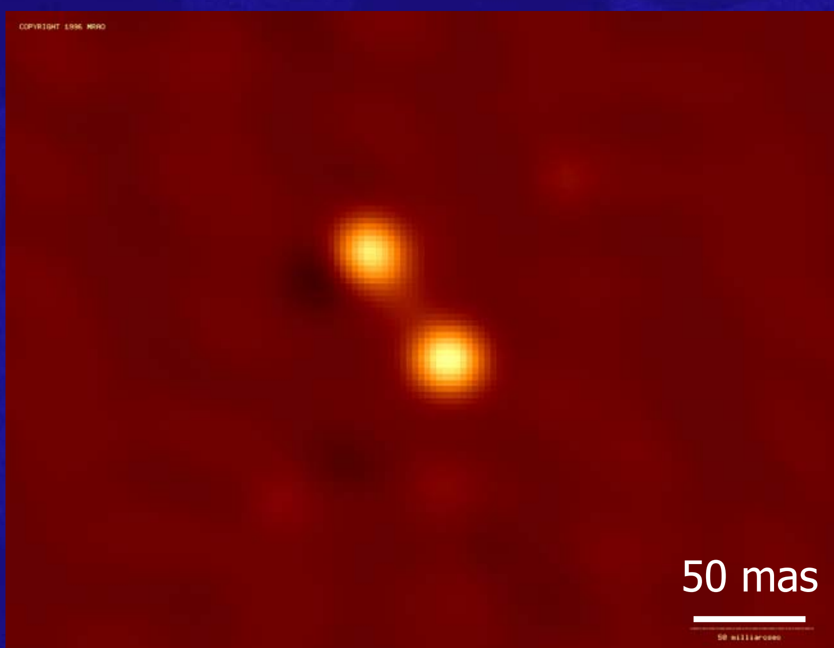


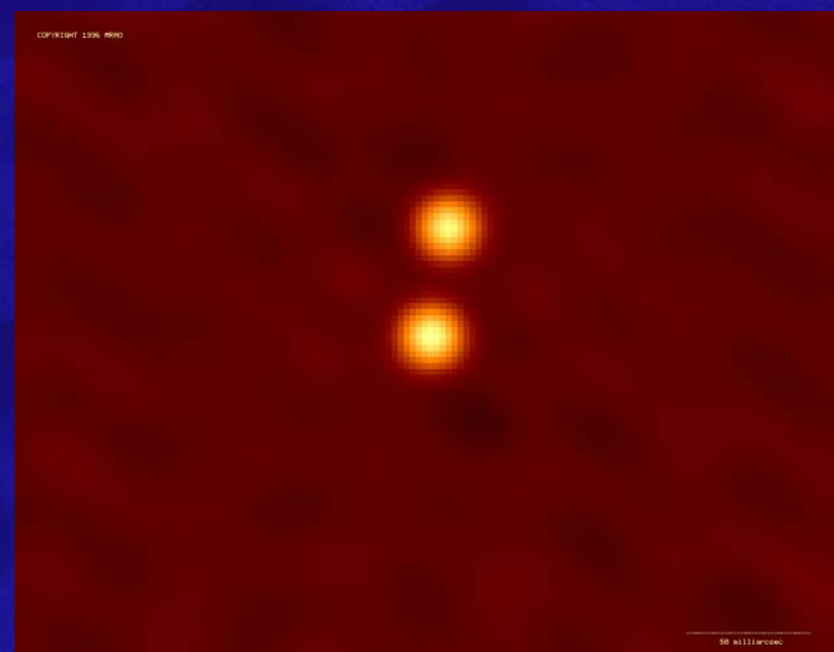
Fig. 4. Reconstructed image of β CrB. Contour levels are −2%, −1%, 1%, 2%, 3%, 5%, 10%, 20%, 30%, 40%, 50%, and 60% of the maximum. The top is to the north and the left to the east.

Capella, First long-baseline optical image (COAST/Cambridge)

Sep 13 1995



Sep 28 1995

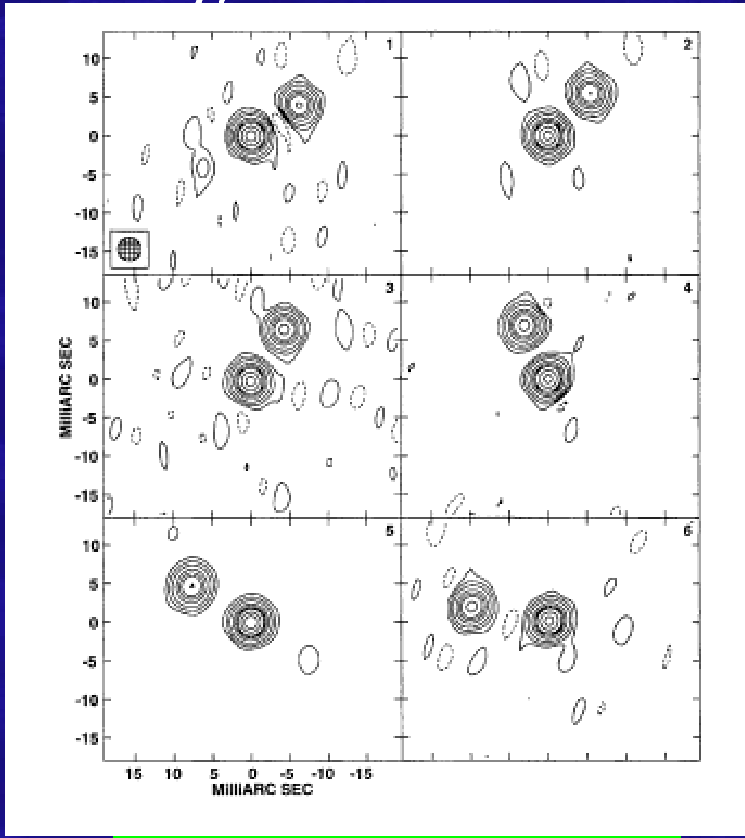


Baldwin et al
MNRAS 1996 306 L13

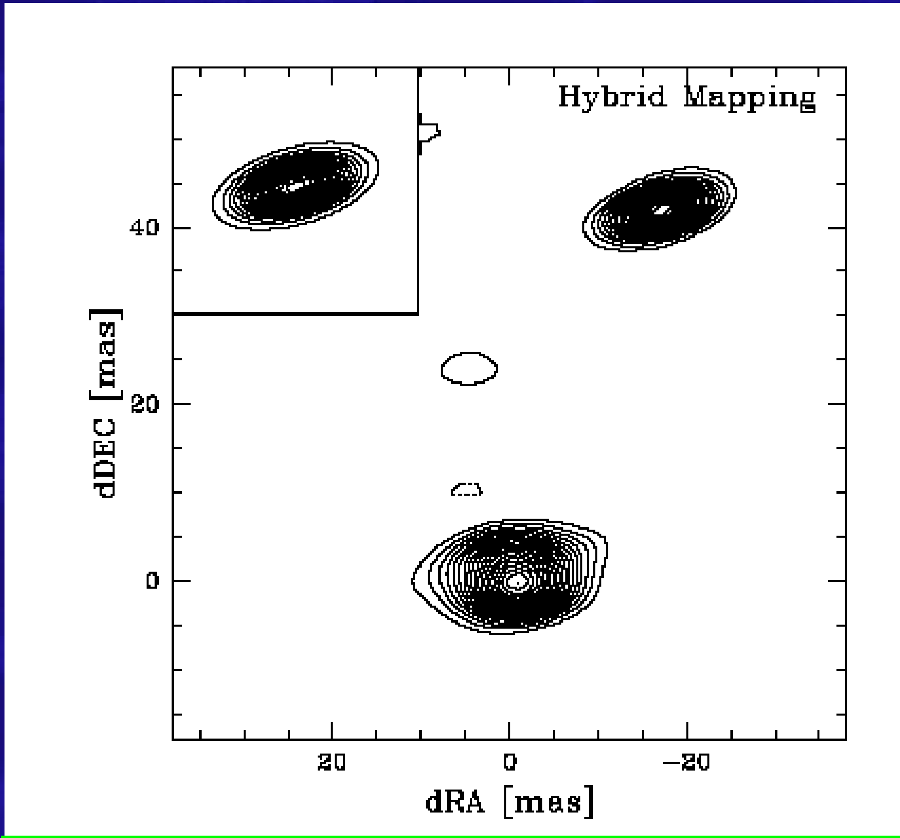
Take a bow, COAST interferometer

Bright Binaries: Interferometer Baby Food

Mizar NPOI images
May/June 1996



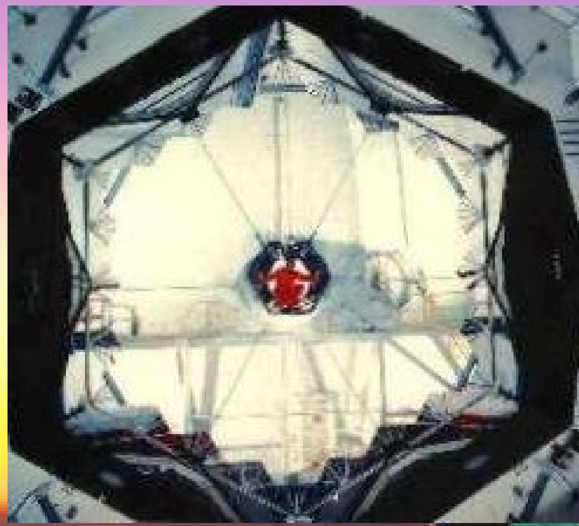
Capella IOTA images
November 2002

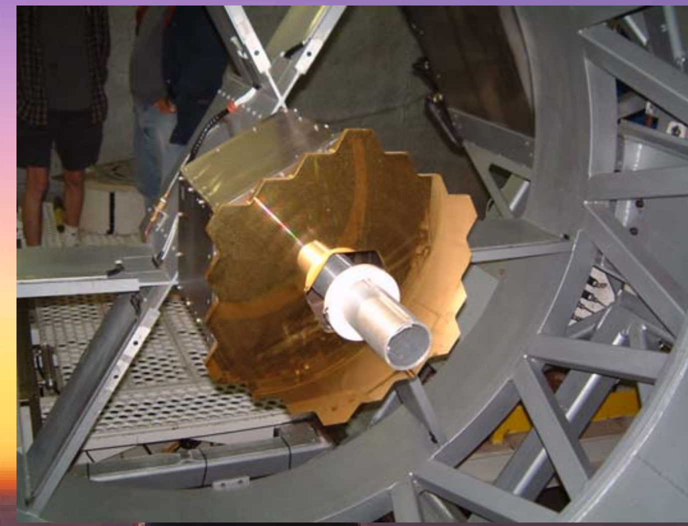


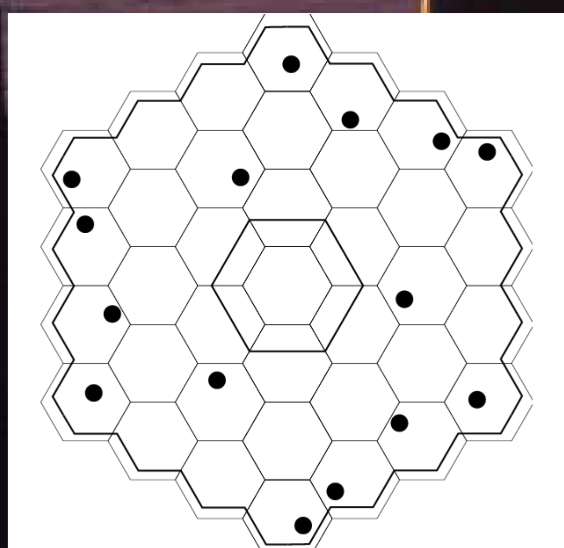
Benson et al 1997
AJ 114 122

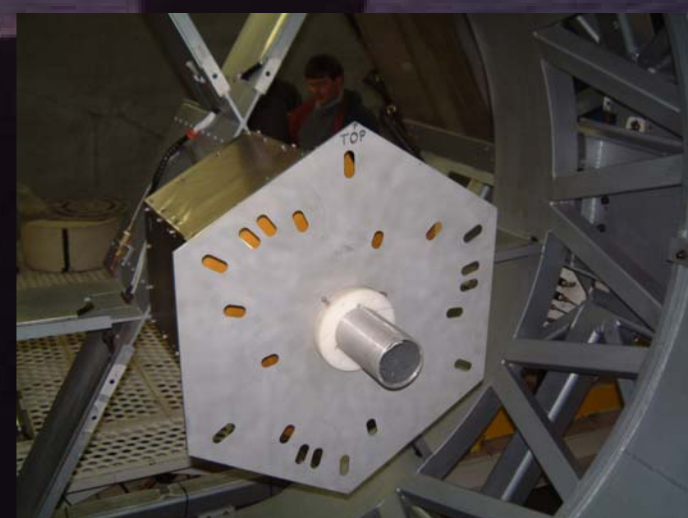
λ Vir+WR 140 - Monnier et al. 2004
Capella - Kraus et al. 2005

Masking the Keck









NPOI Flagstaff, Arizona

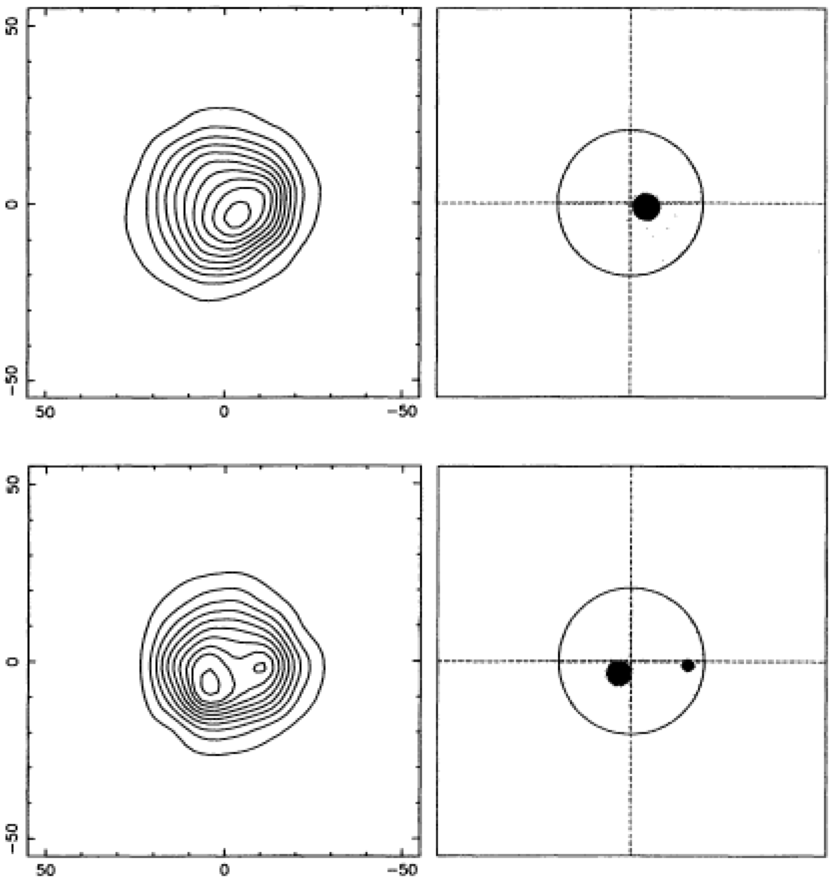
Closure Phase Science: Target Classes

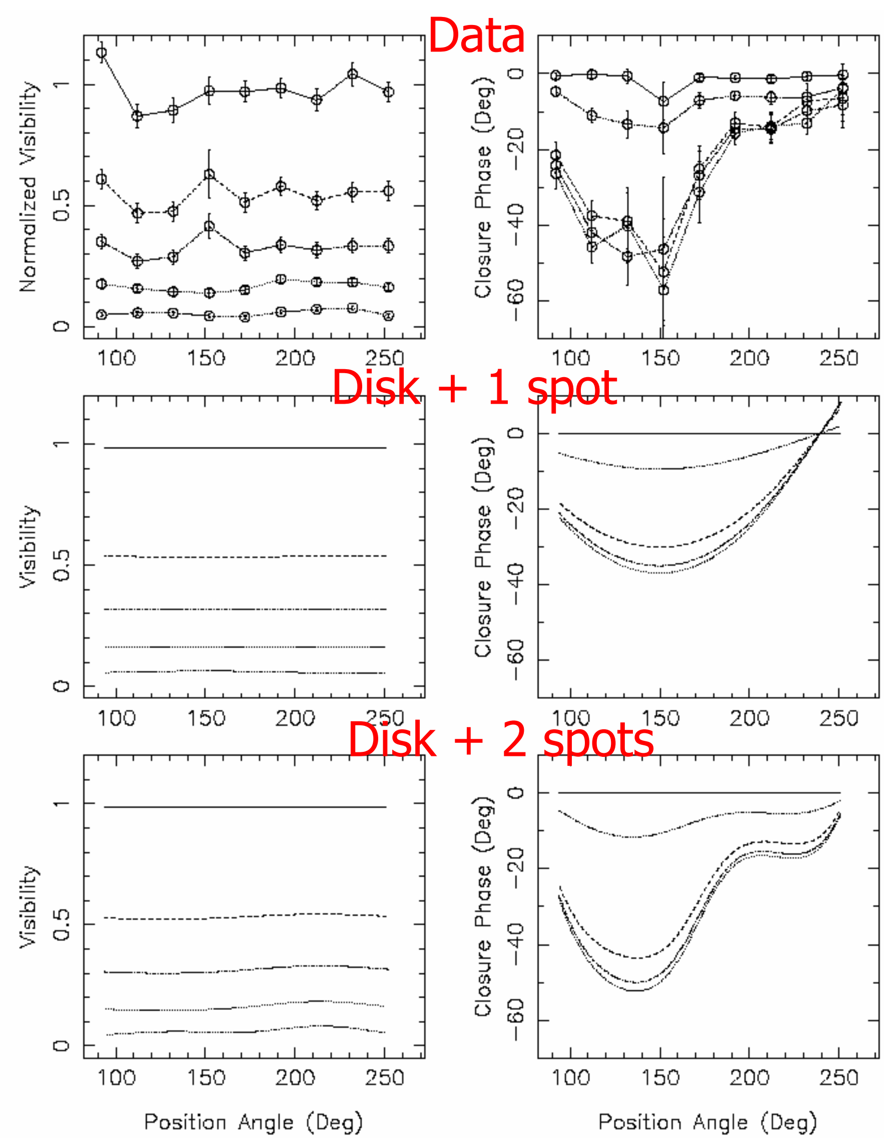
- Binaries
- Evolved Stars
  - Surfaces
  - Circumstellar Dust
- Young Stellar Objects
- Circumstellar matter in Hot Stars
- Stellar Surface Imaging
- Binaries II

Highly Evolved Stars

- Grand-cycle-of-matter
  - >50% of ISM enrichment (all dust nuclei)
  - Uniquely rich astro-chemistry
  - Implications for stellar populations (defusing SN, perturbing ISM)
- Probes of distance, structure, metallicity
  - High Luminosity, tight P-L relation
- Fascinating astrophysics lab
  - Masers, radiation-driven winds, shocks
  - Mass-Loss, PNe Formation, disks

M-Giant Photospheres



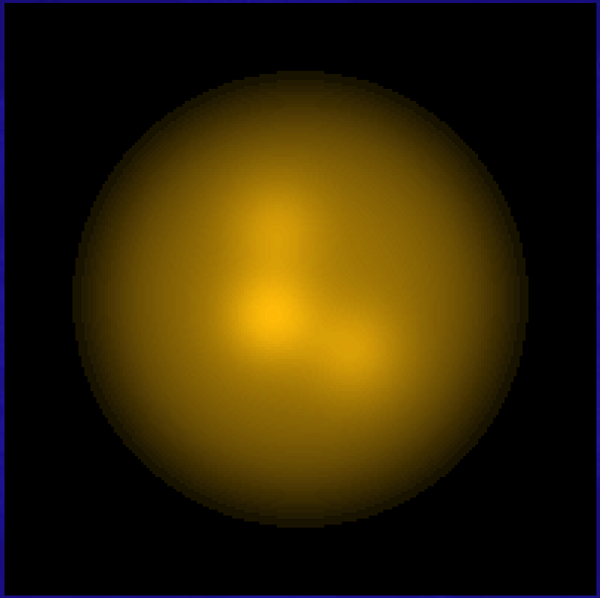


Tuthill et al., MNRAS 1997, 258 529
Tuthill et al., MNRAS 1999, 306 353

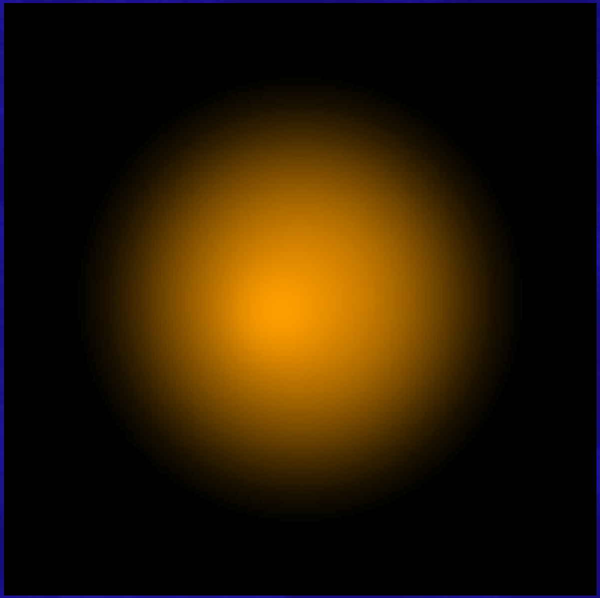
The Evolving Face of Betelgeuse

Buscher et al 1990 MNRAS 245 7
Wilson et al 1997 MNRAS 291 819
Young et al 2000 MNRAS 315 635

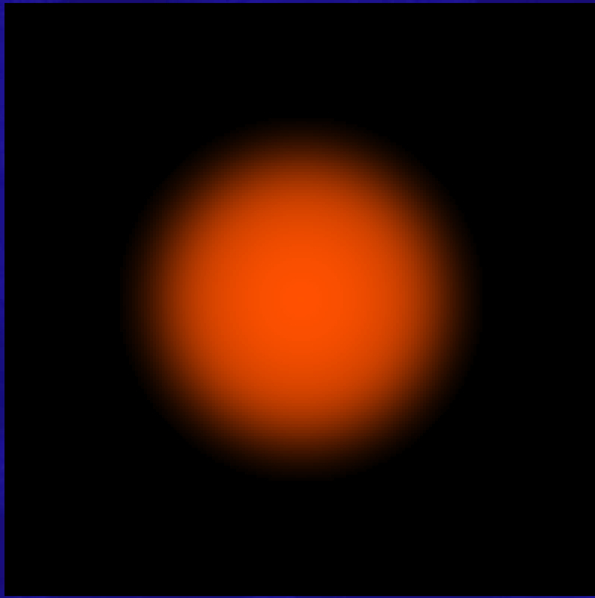
WHT 700nm



COAST 905nm



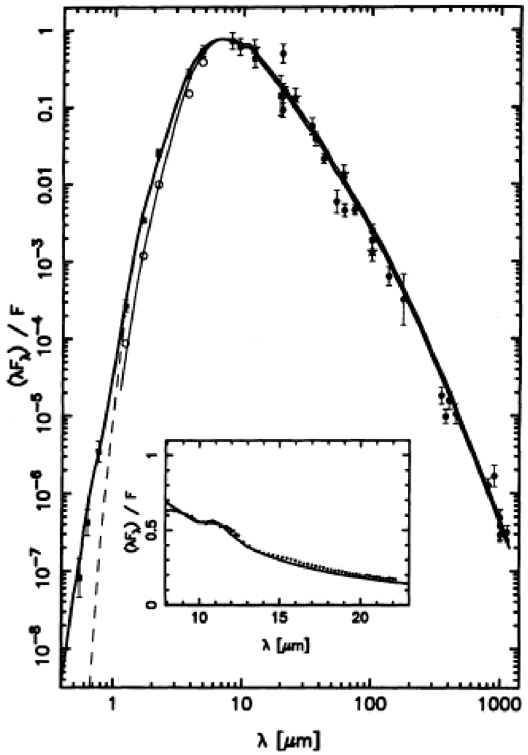
COAST 1290nm



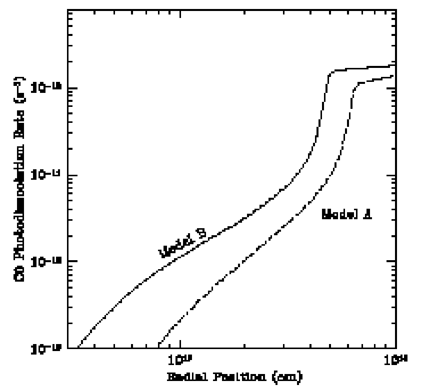
Physical models of IRC +10216

Spherical Cows

Ivezic & Elitzur 1996



Doty & Chun 1998



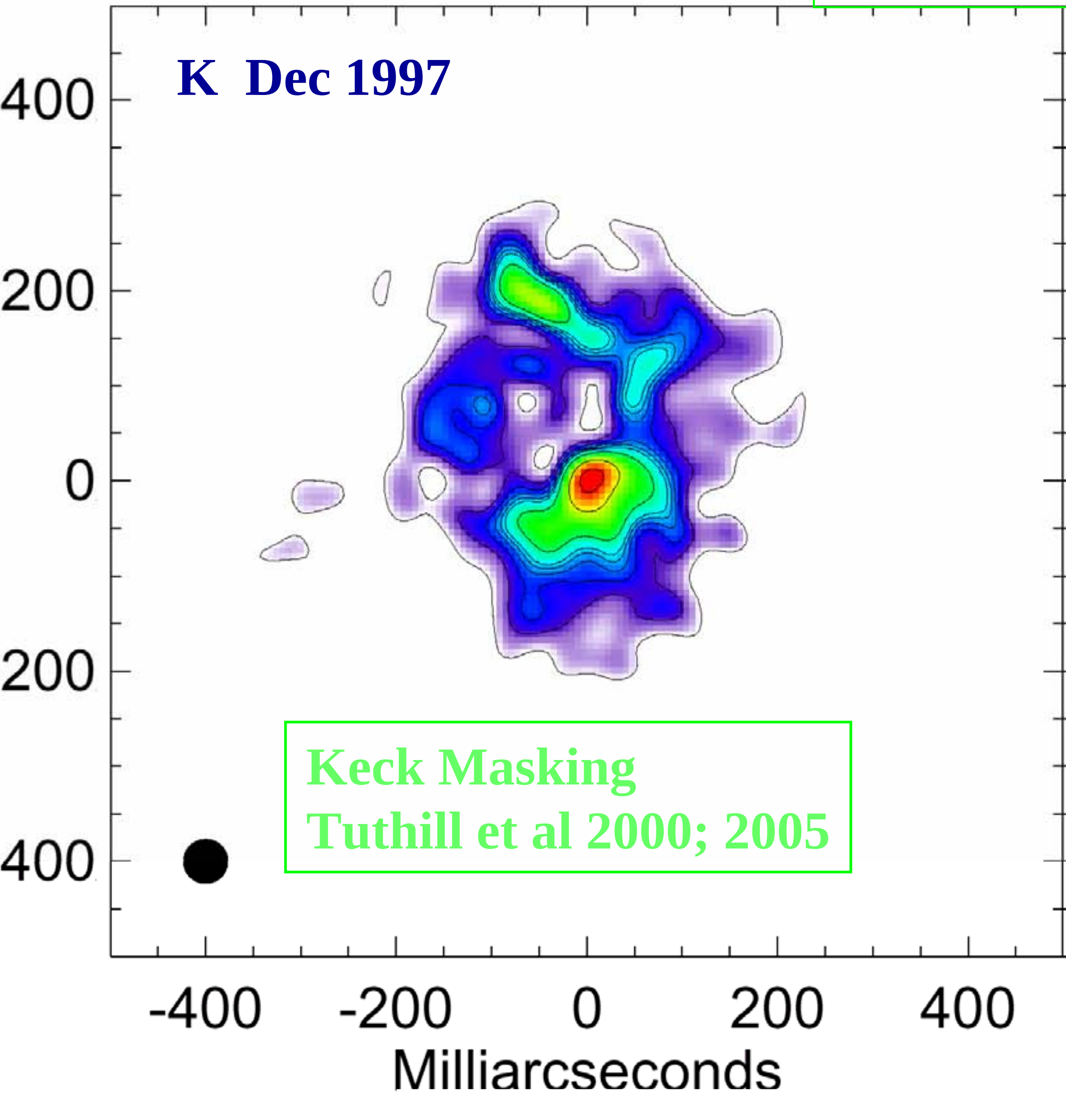
1.—Effect of different dust-shielding treatments on the CO photo-ociation rate. Note how the effect of self-consistent dust radiative trans-(model B) can change the dissociation rate by over an order of ;nitude over a model with semianalytic radiative transfer through dust del A).

2.1. *General*

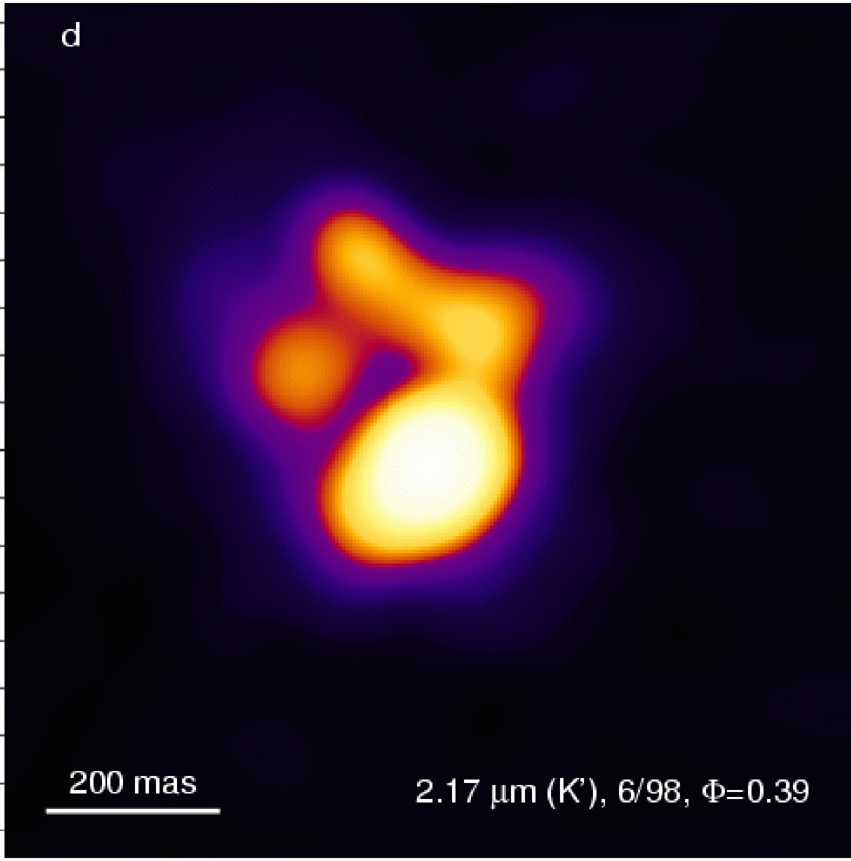
We assume that the gas in IRC +10216 expands in a spherically symmetric outflow with a speed of $v = 16$ km s^{-1} and with a mass-loss rate of $5 \times 10^{-5} M_\odot$ yr^{-1}. The UV dust opacity is taken to be $\tau_{1000} = \tau(1000 \text{ Å}) = 12.7$ from $r_{in} = 10^{16}$ cm to the outer edge (NM), and the temperature distribution is taken from the fit by MGH to the Kwan & Linke (1982) temperature profile for IRC +10216.

IRC+10216 – Case Study

(Also UKIRT Masking
Haniff and Buscher 1998)



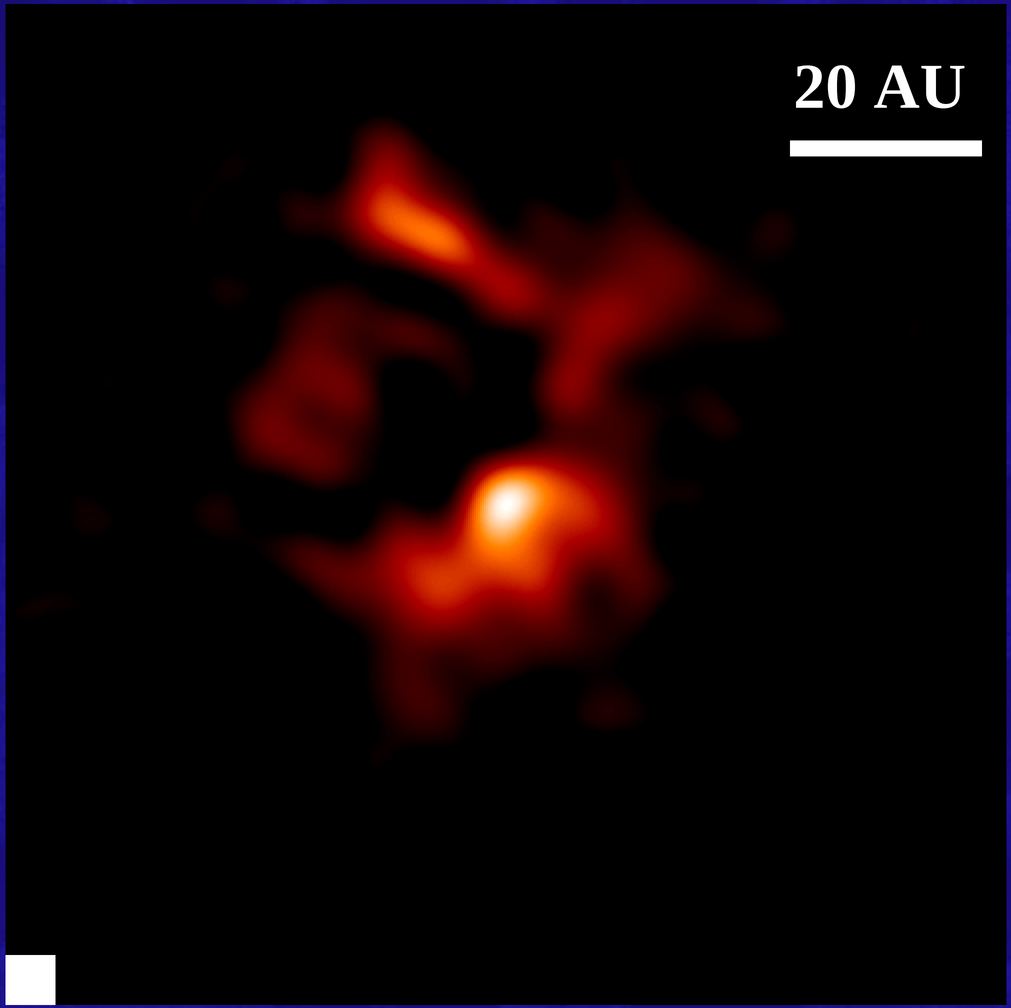
Keck Masking
Tuthill et al 2000; 2005



Russian SAO Speckle
Weigelt et al 1998+

IRC+10216: Carbon star/PPNE

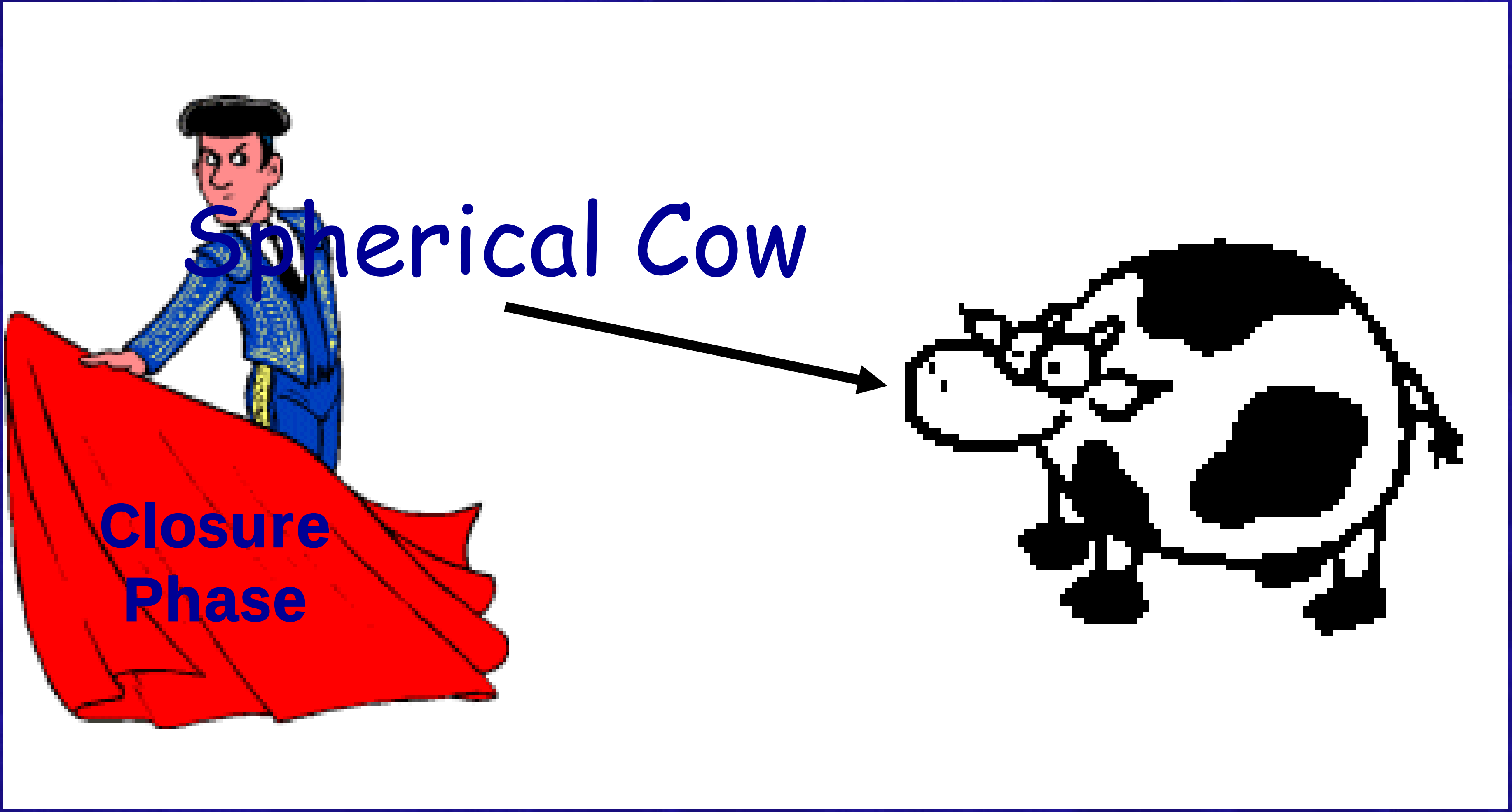
3.5 years motion



- Mass-loss in inner regions asymmetric and clumpy, outer regions spherical.
- Onset of Bipolarity ?
- Time-lapse studies with a tagged flow – directions and accelerations!
- New Dust Nucleation?

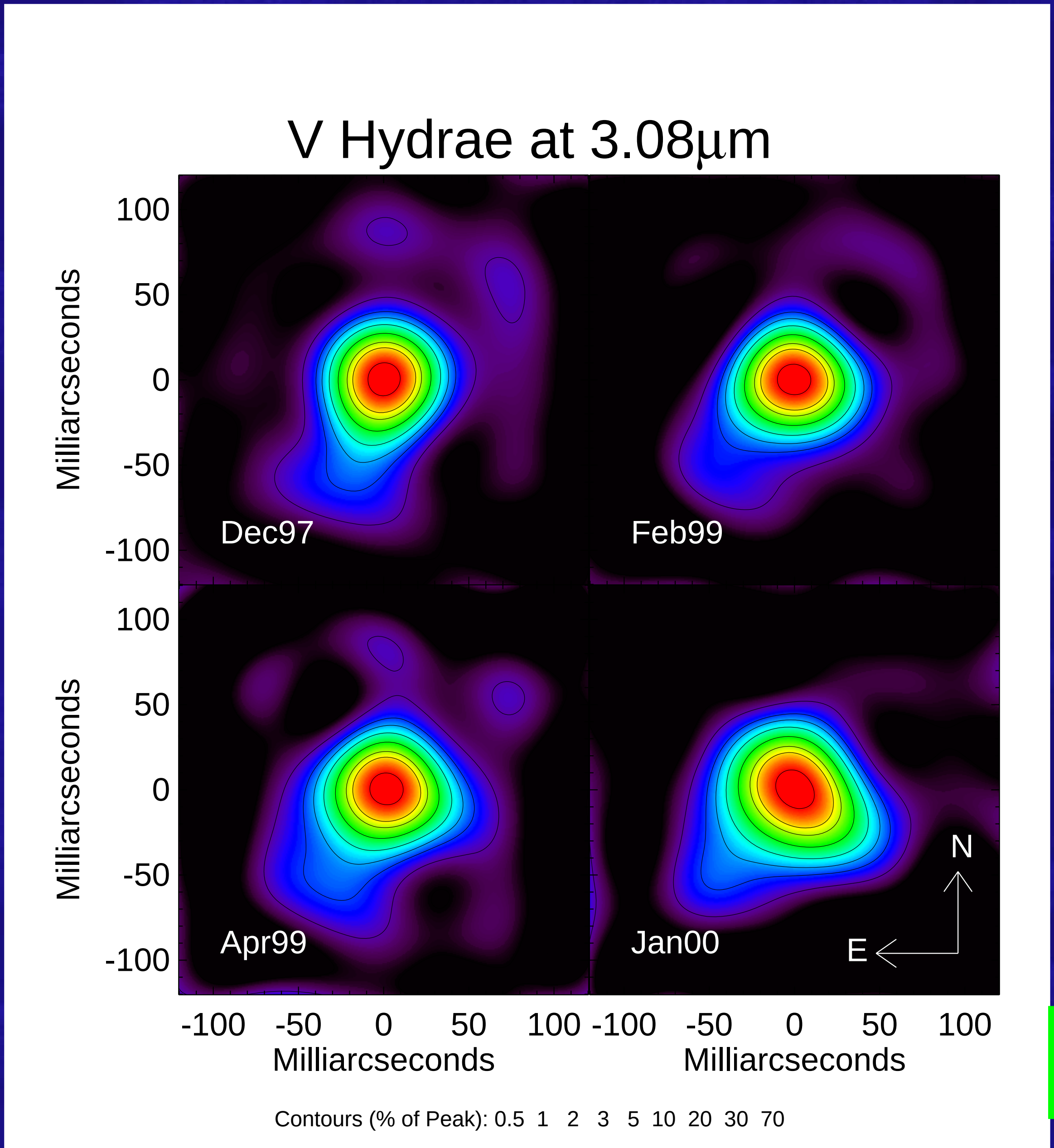
Tuthill et al. ApJ 2000
Tuthill et al. ApJ 2005

Key Idea: What are closure phases good for?



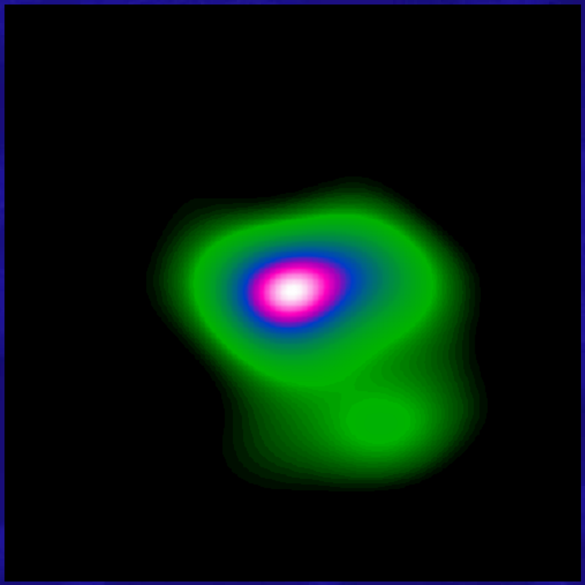
Closure Phases lift degeneracy

CLP Imaging Evolved Stars



Teaser Images from Aperture Masking

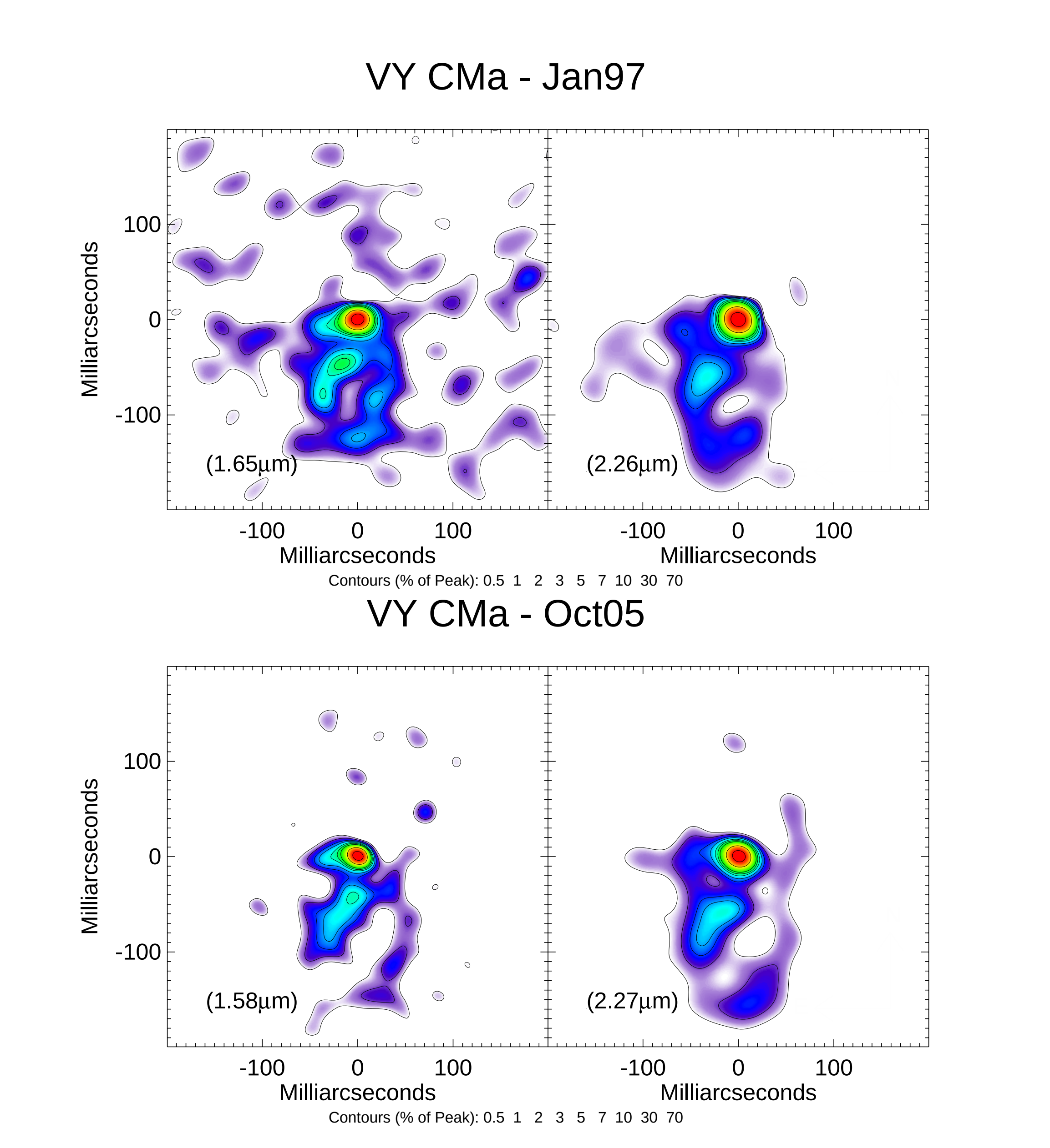
CIT 6



Monnier et al. ApJ 2000

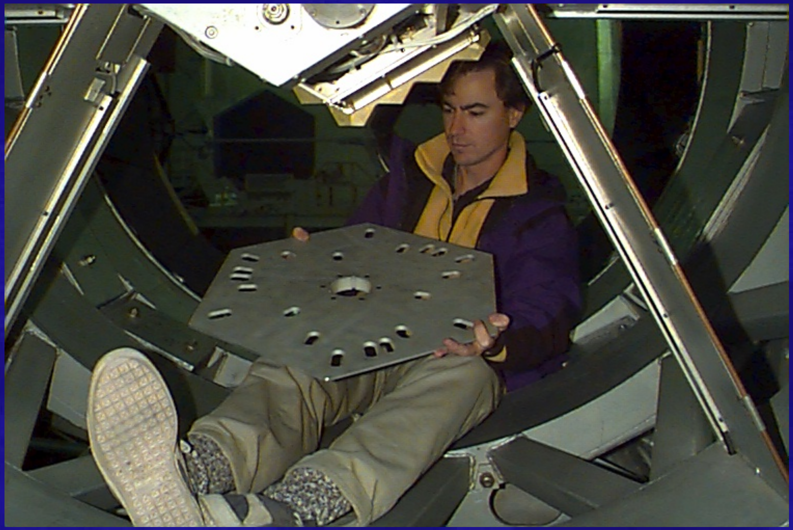
Tuthill et al. 2006 in prep.

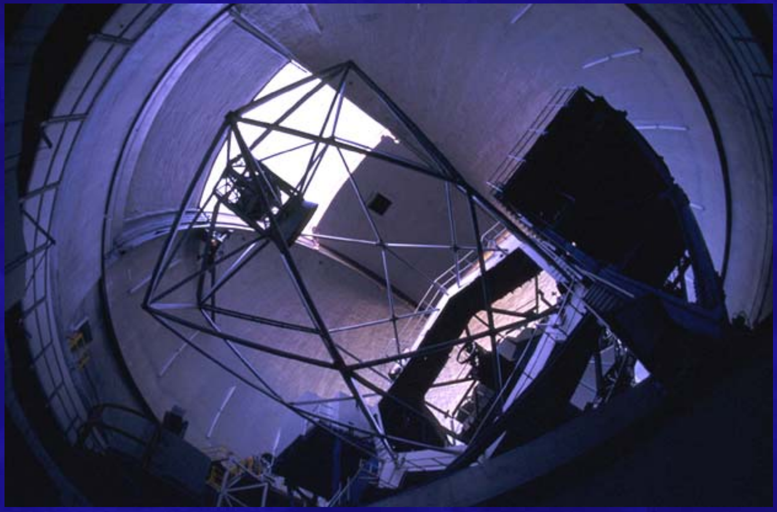
Extreme mass-losing sgiant VY CMa



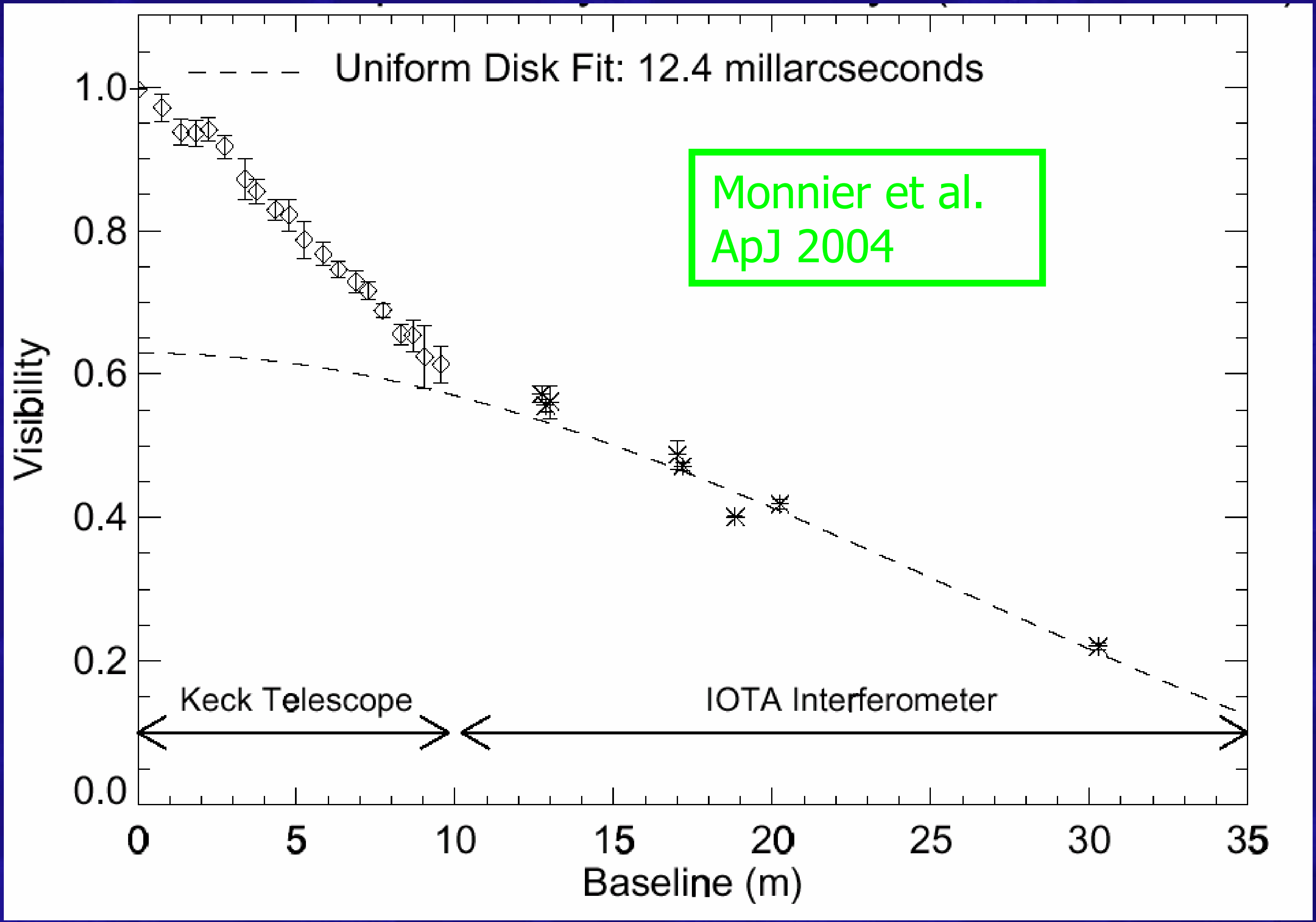
Monnier et al.
ApJ 1999

Multi-Facility Synthesis

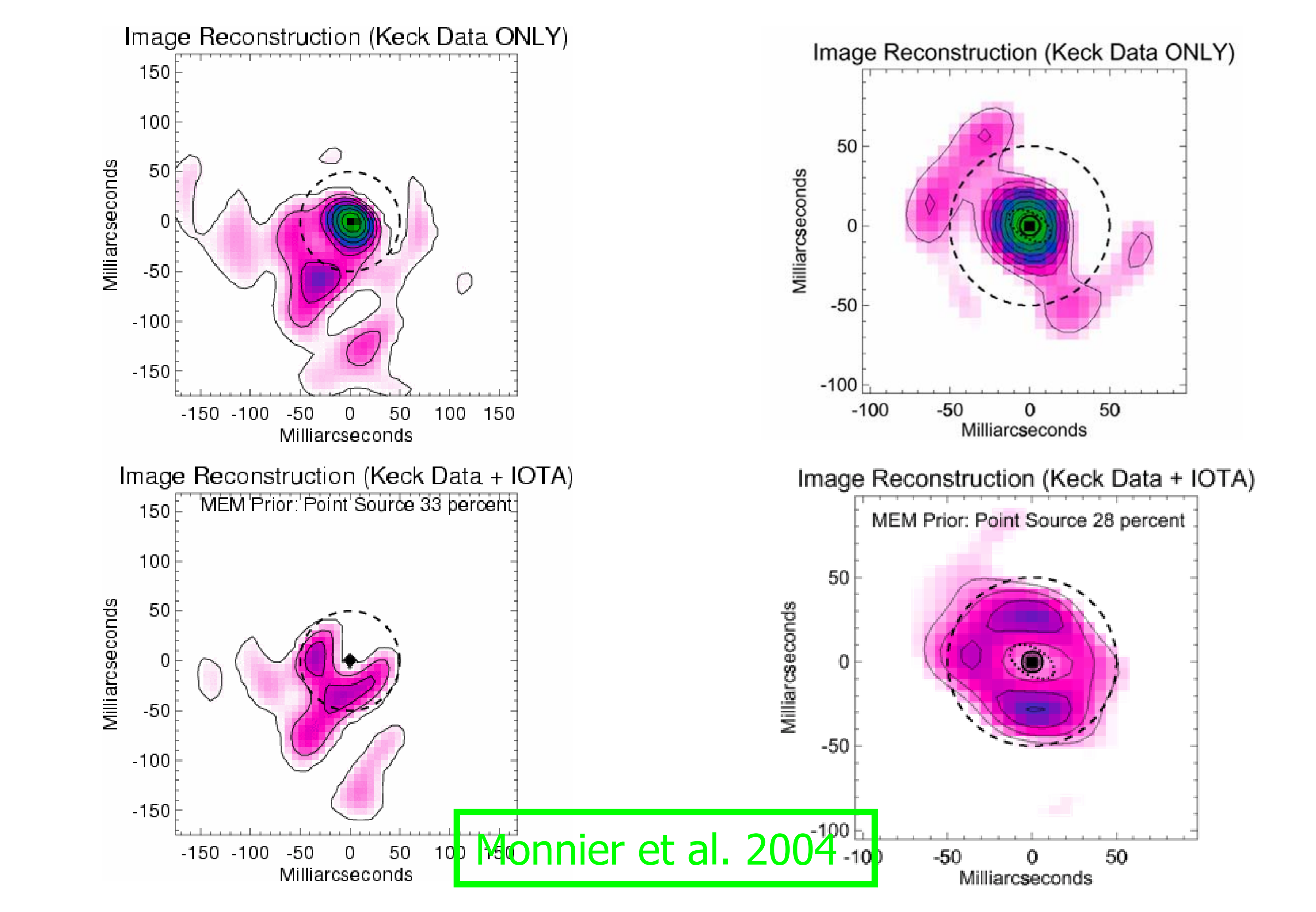




Carbon Star V Hya



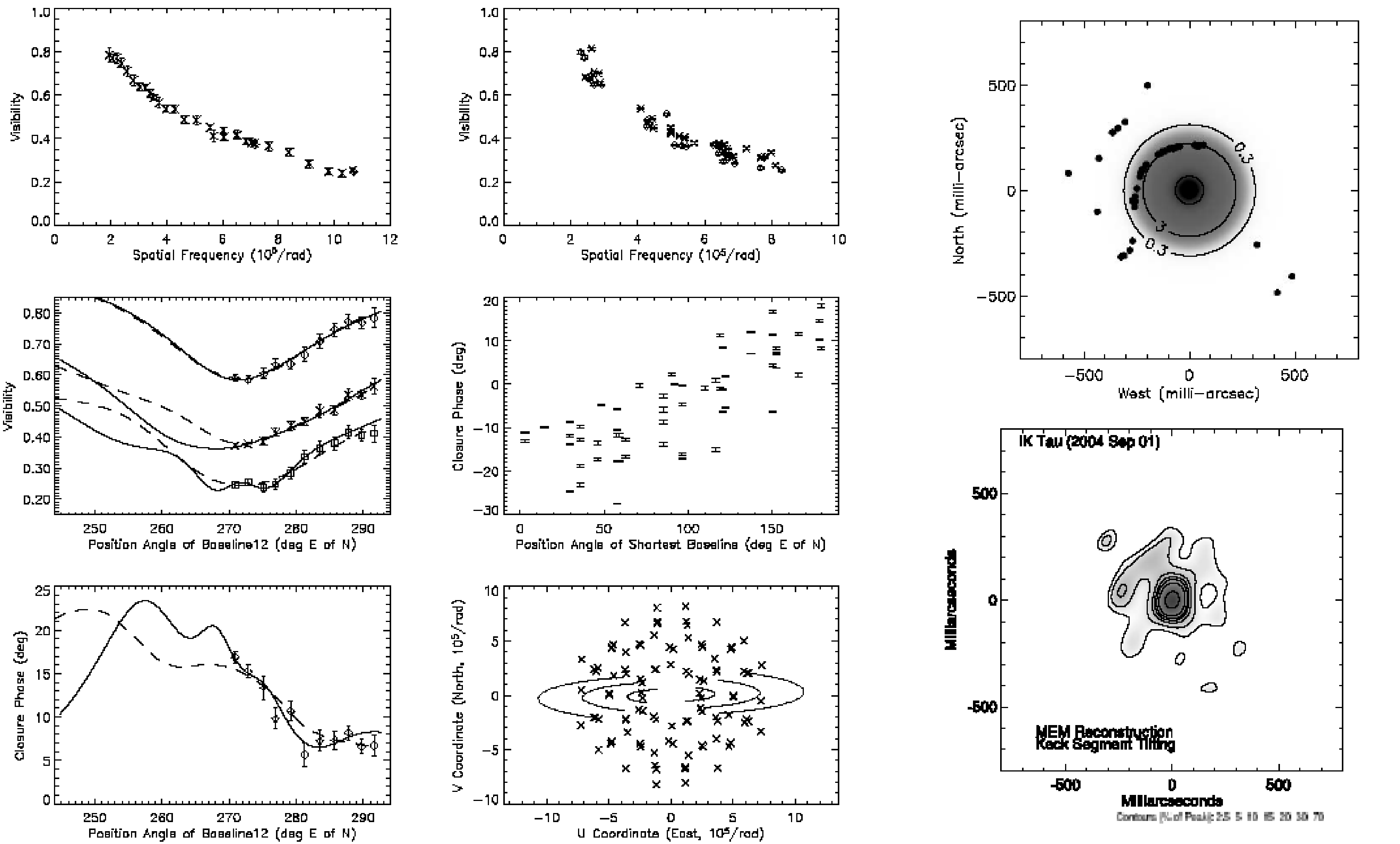
Multi-Instrument Synthesis



Monnier et al. 2004

Weiner et al
2006 ApJ
636 1067

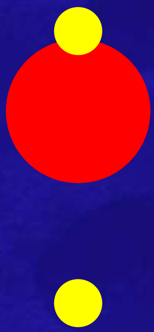
Berkeley ISI + Keck Mask: Mid-IR closure phase imaging



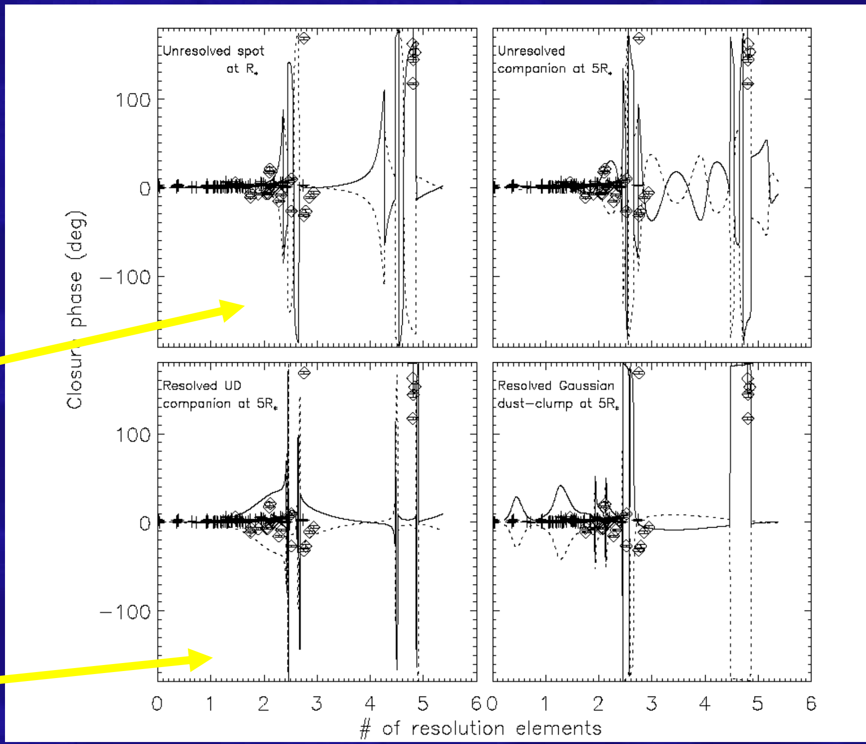
`The Mira Imaging Project' (IOTA, ISI, VLBA)

Ragland et al. 2006

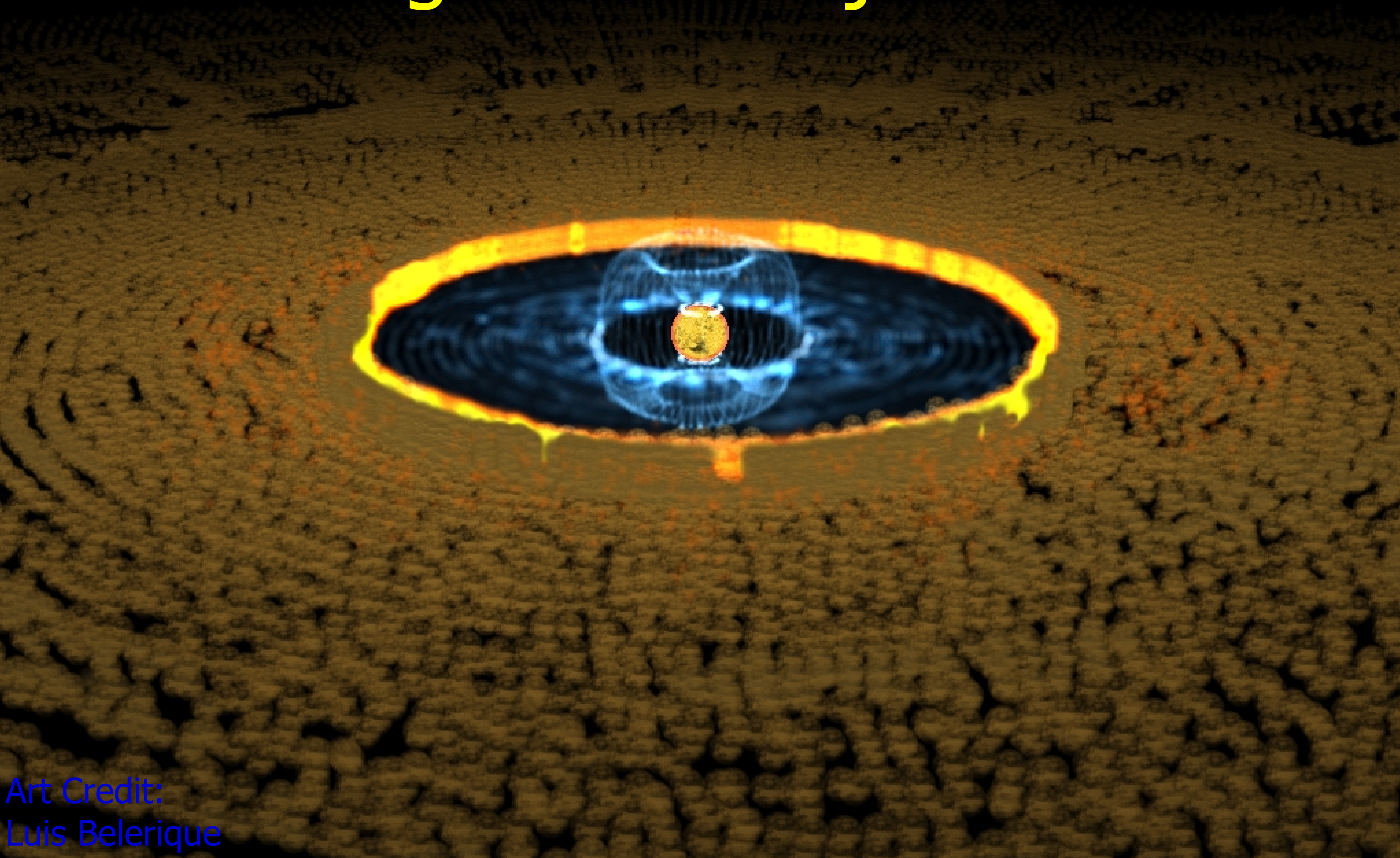
- First Results: 56 AGB stars
  - 29% of sample AGB stars show asymmetry
  - 75% of well-resolved stars show asymmetry
  - 100% of well-resolved O-rich Miras asymmetric
- All Miras probably asymmetric
- More Fourier Coverage needed for incisive astrophysics



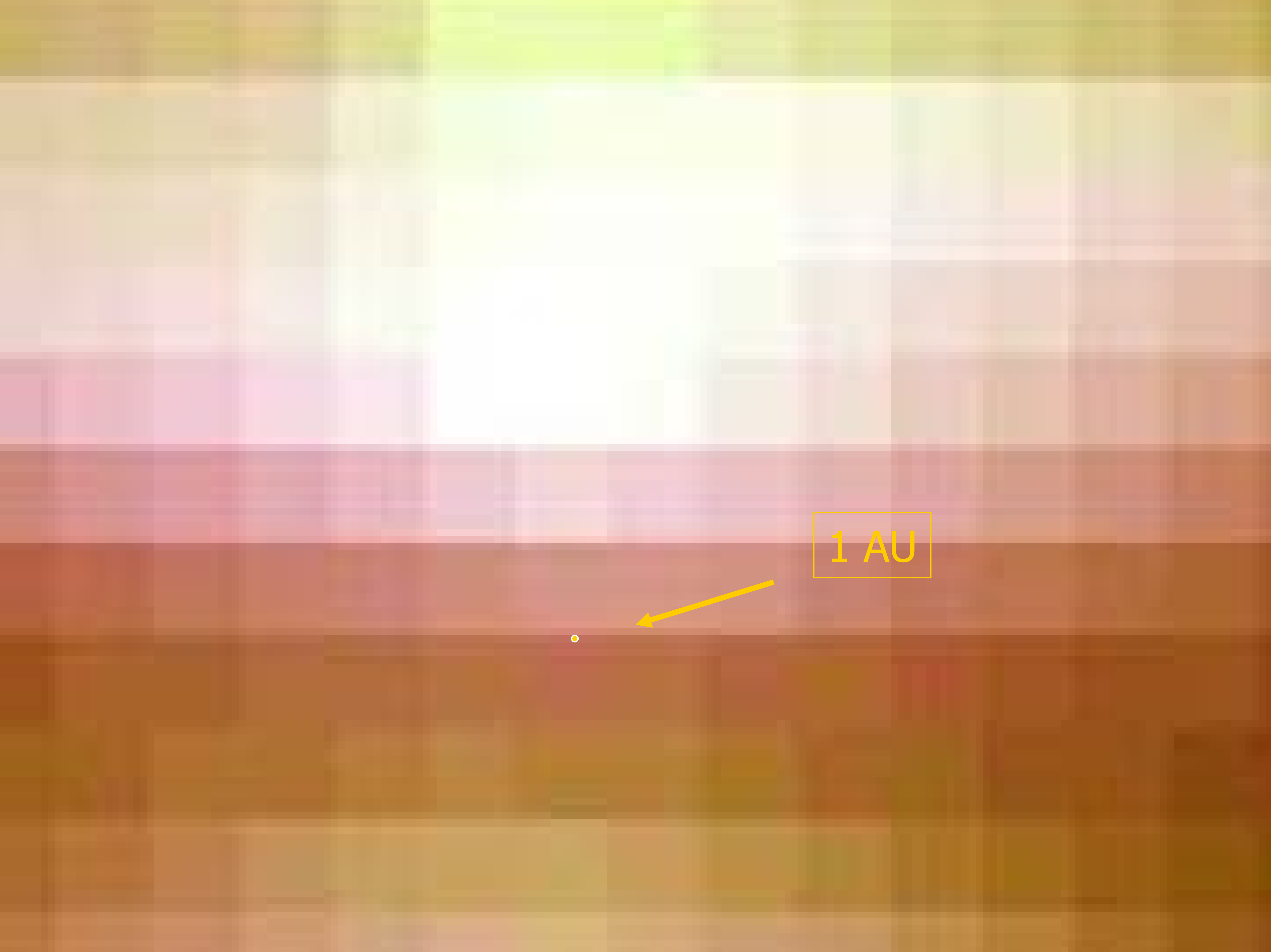
4 models; disk + various spots/circumstellar features



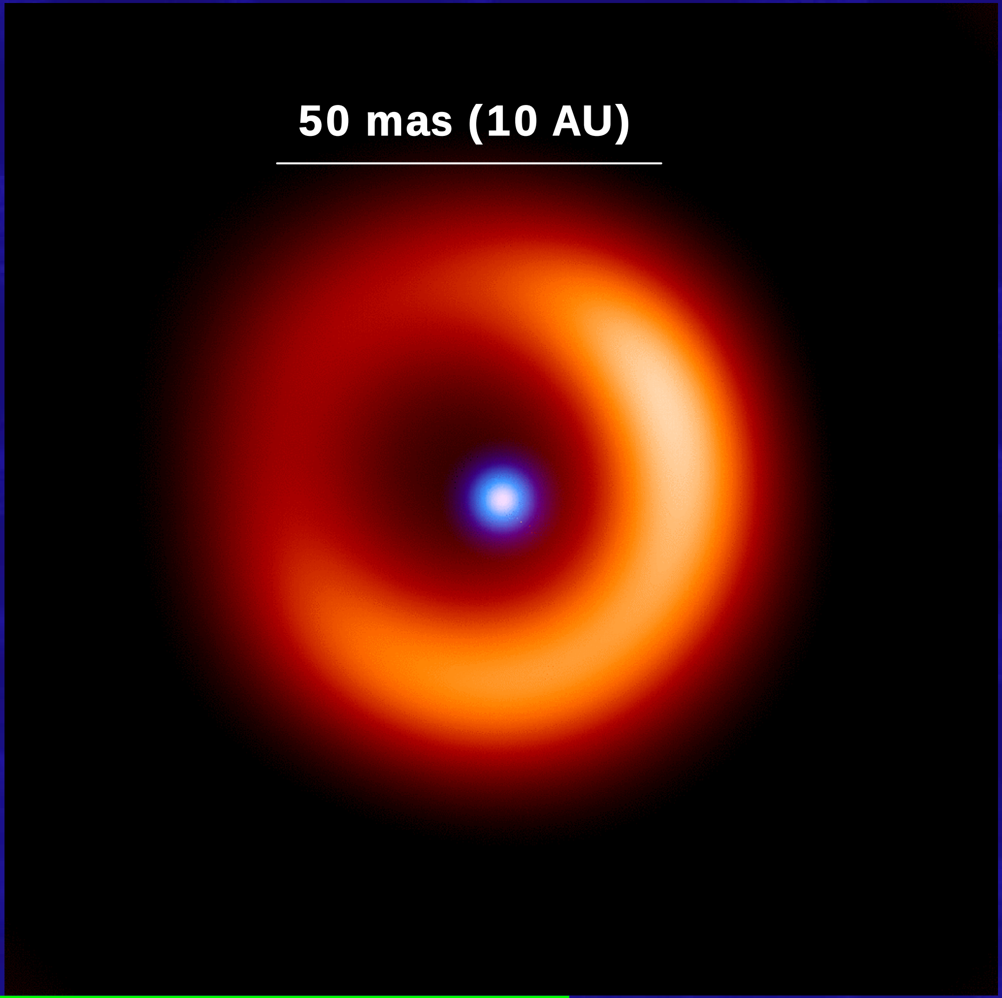
Young Stellar Objects



Art Credit:
Luis Belerique


1 AU

LkHα 101: Our closest image of a starbirth

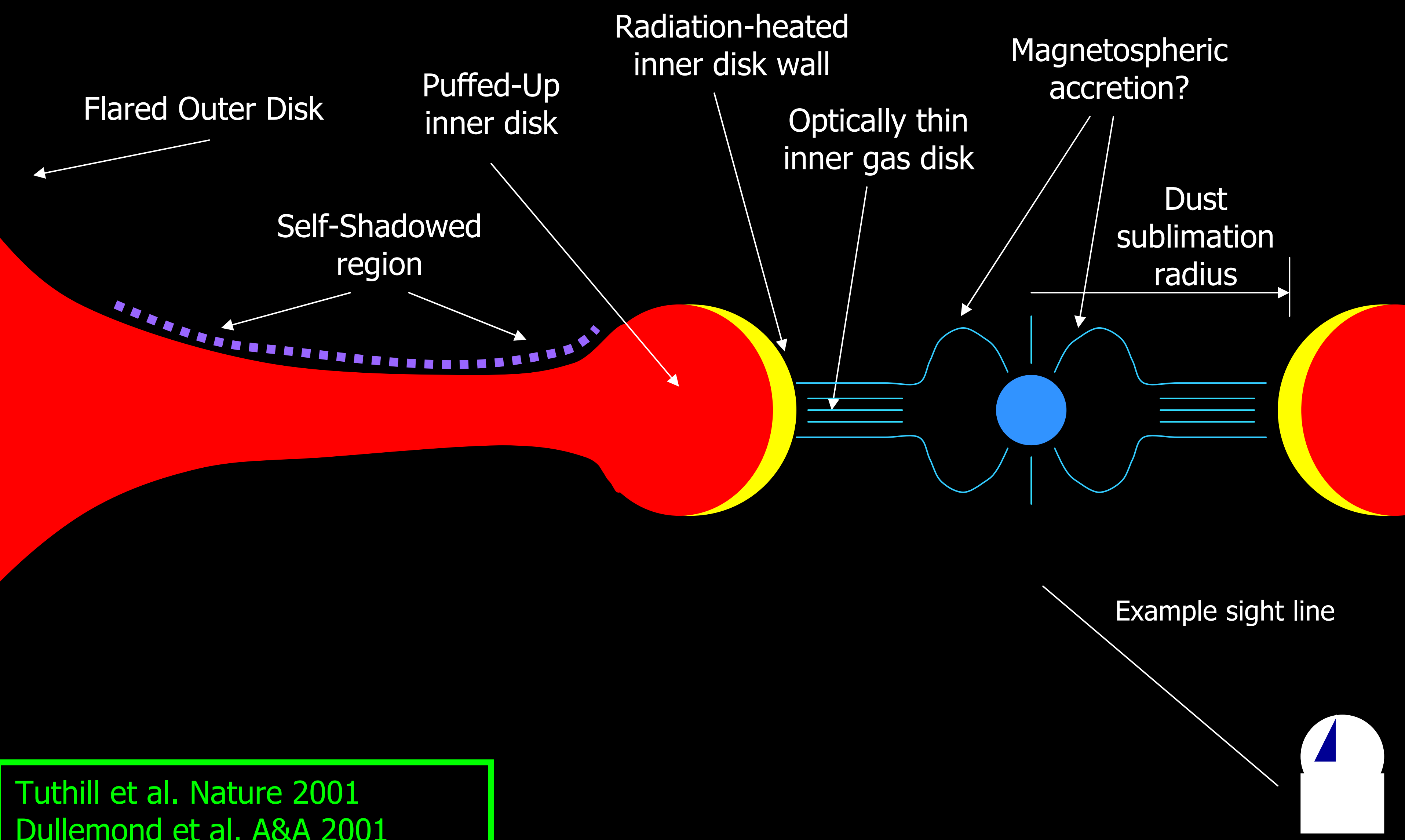


- Face-on view of Herbig Ae/Be star
- Settle debate:
  Disk vs Envelope
- SED fitting ambiguous: central cavities now proven
- Too Large (order of mag) Overturns power-law thermal profiles
- Disk cavity physics governed by dust sublimation radius
- Asymmetric Brightening –

  inclined line of sight.

Tuthill et al. Nature 2001,
Tuthill et al. ApJ 2002

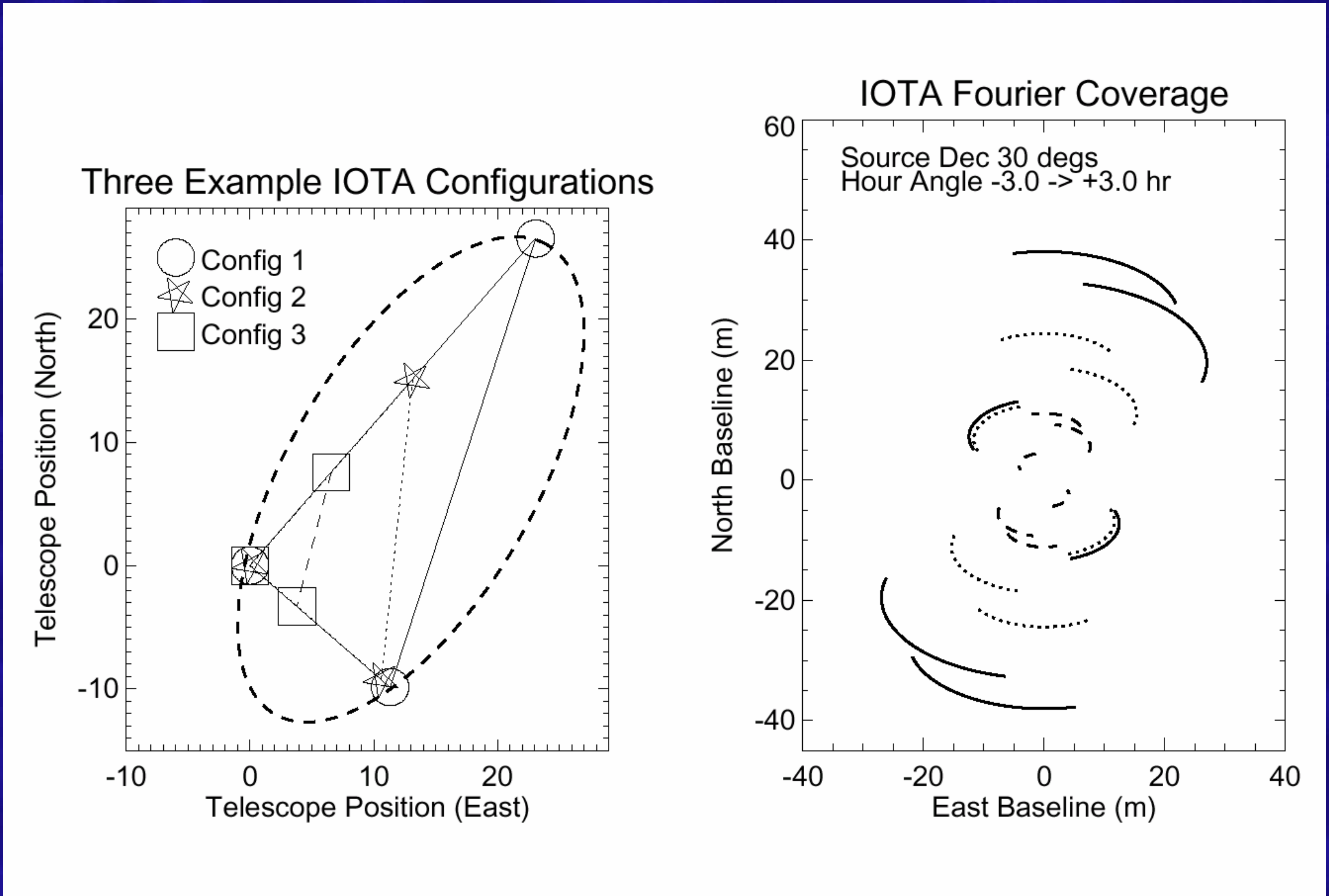
Accretion Disk Geometry



Tuthill et al. Nature 2001
Dullemond et al. A&A 2001

Towards an Imaging Array: Closure Phases with IOTA3

IOTA Fourier Coverage



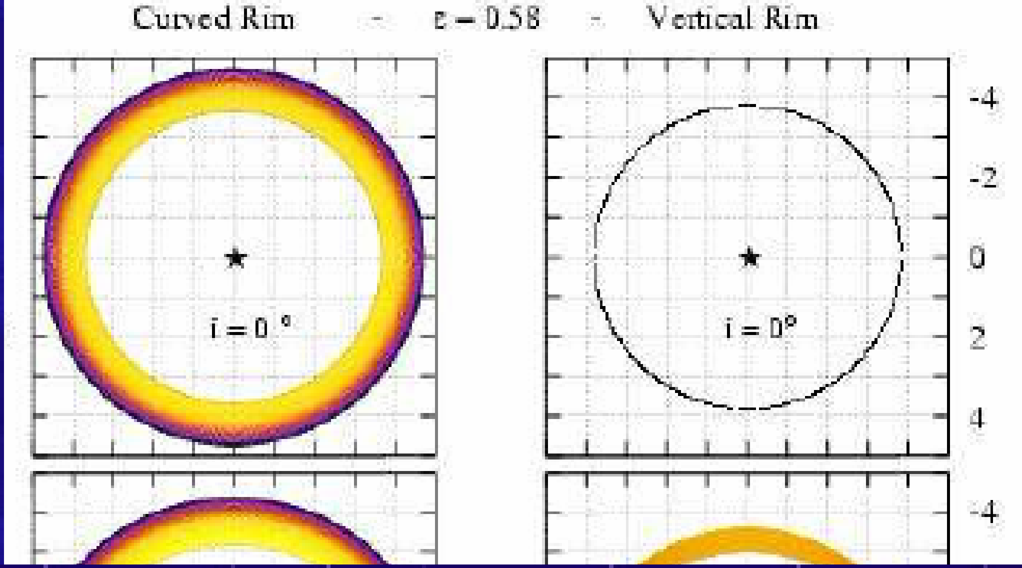
Expected YSO Closure Phases

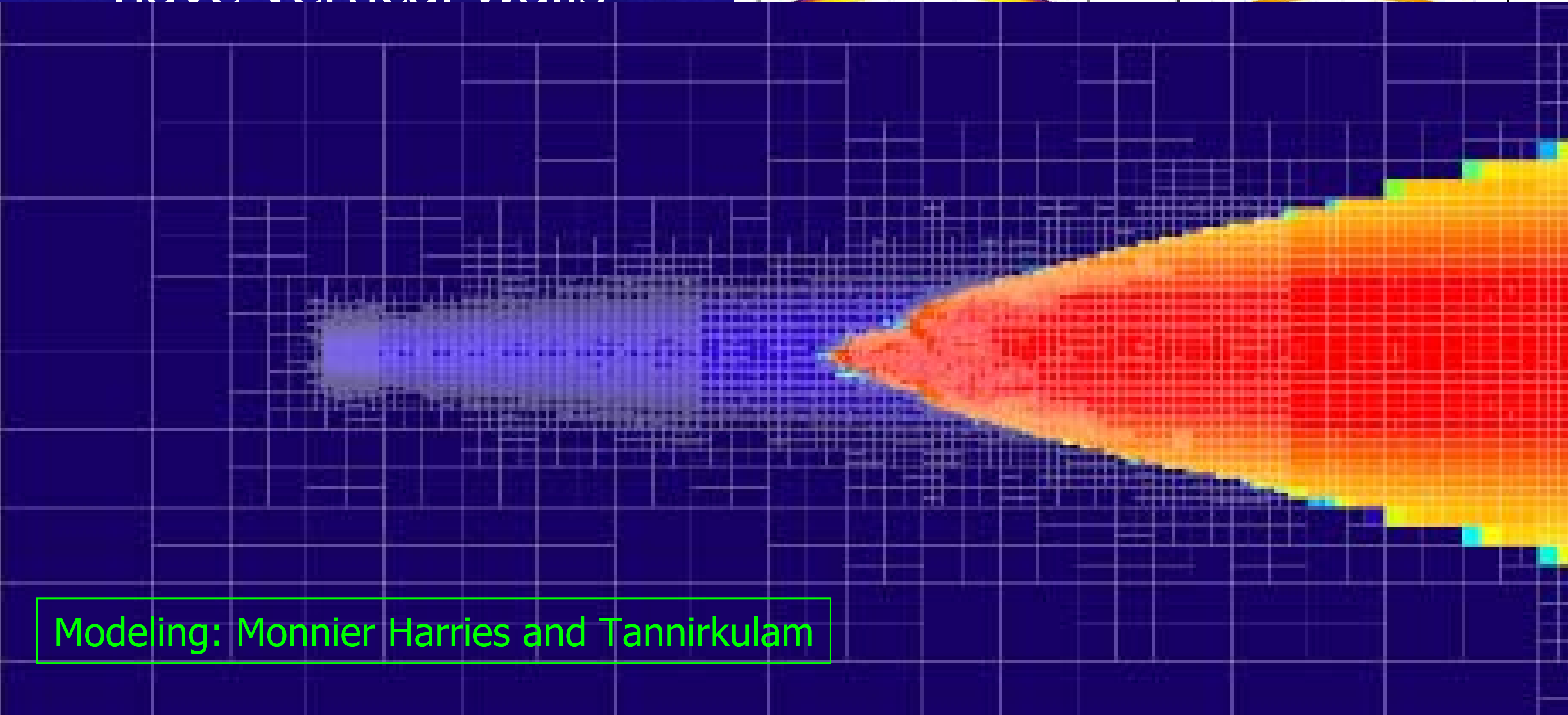
Closure Phase is function of

- Amount of **skewness** (deviation from centro-symmetry)
- Resolution of Interferometer (point sources all look symmetrical..)
- Brightness distribution (model-dependent = good)

Why should we expect skew?

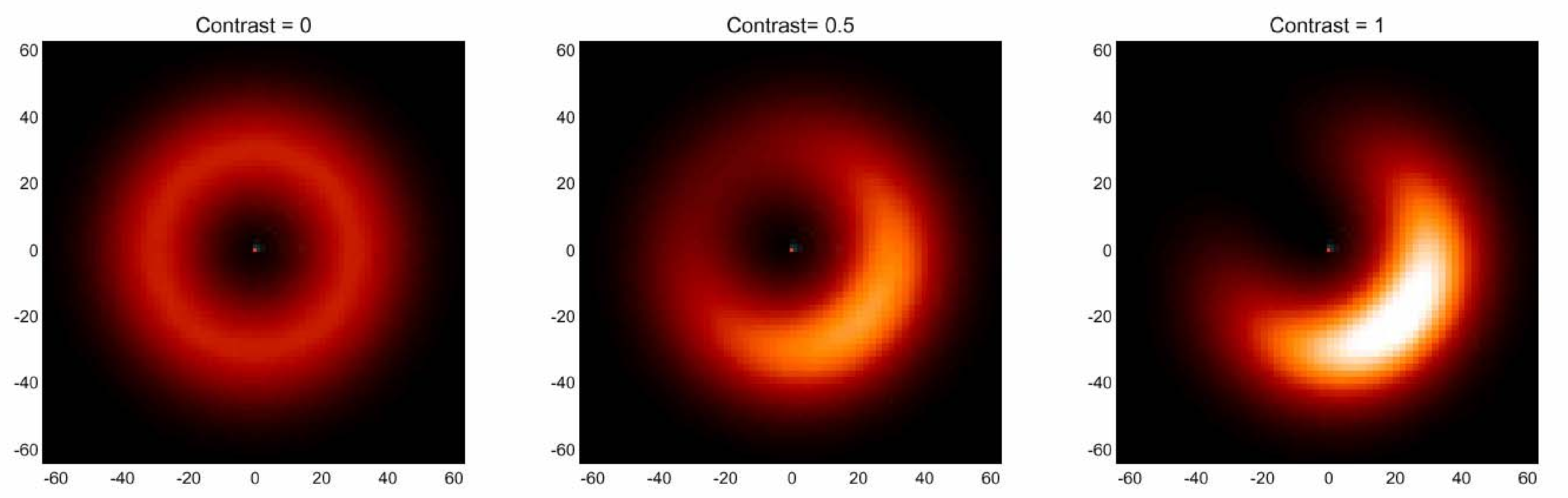
- 1st Gen models have vertical walls



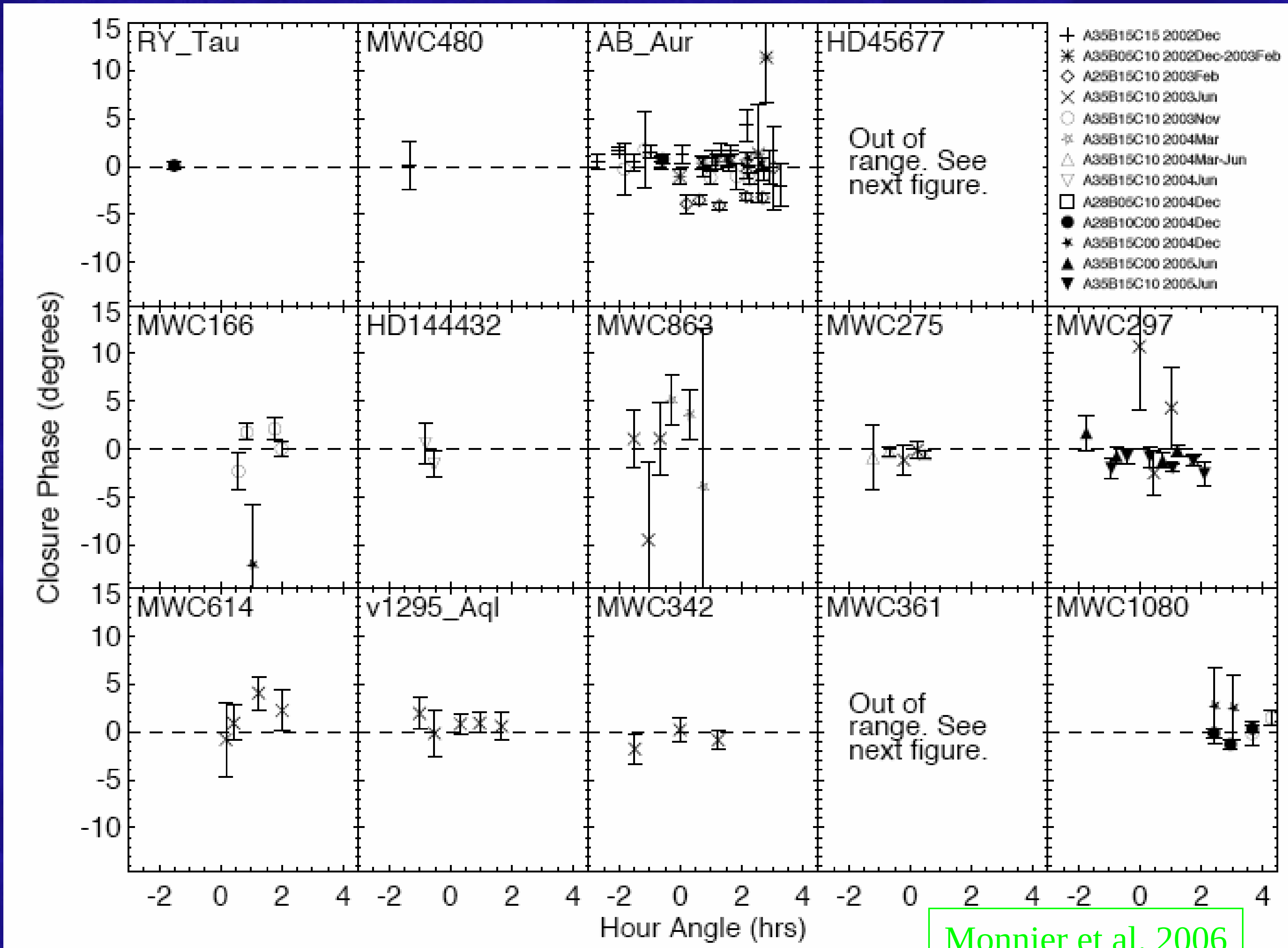


Empirical Models of Skew Disks

Simple Empirical Models of Asymmetric Disk Emission

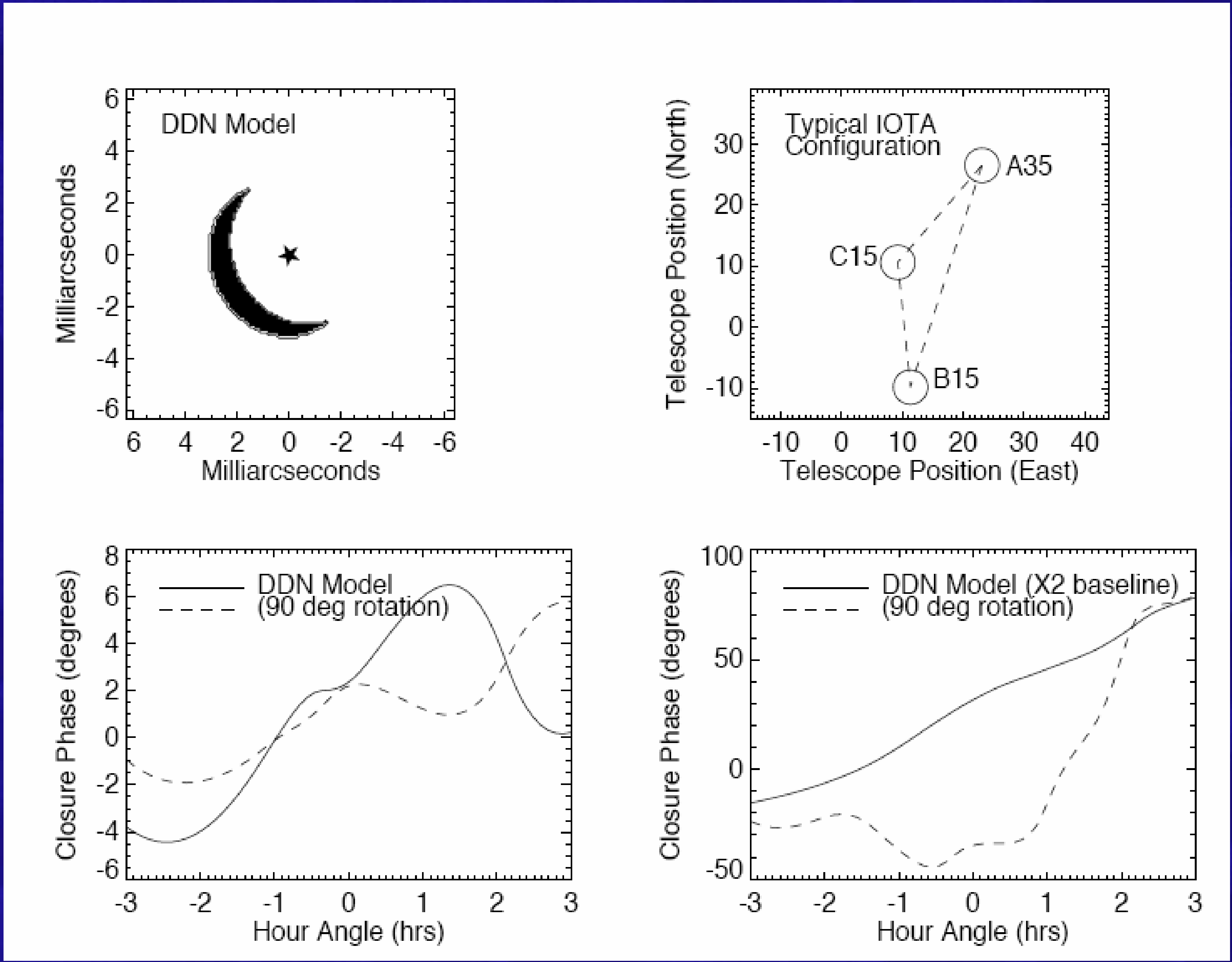


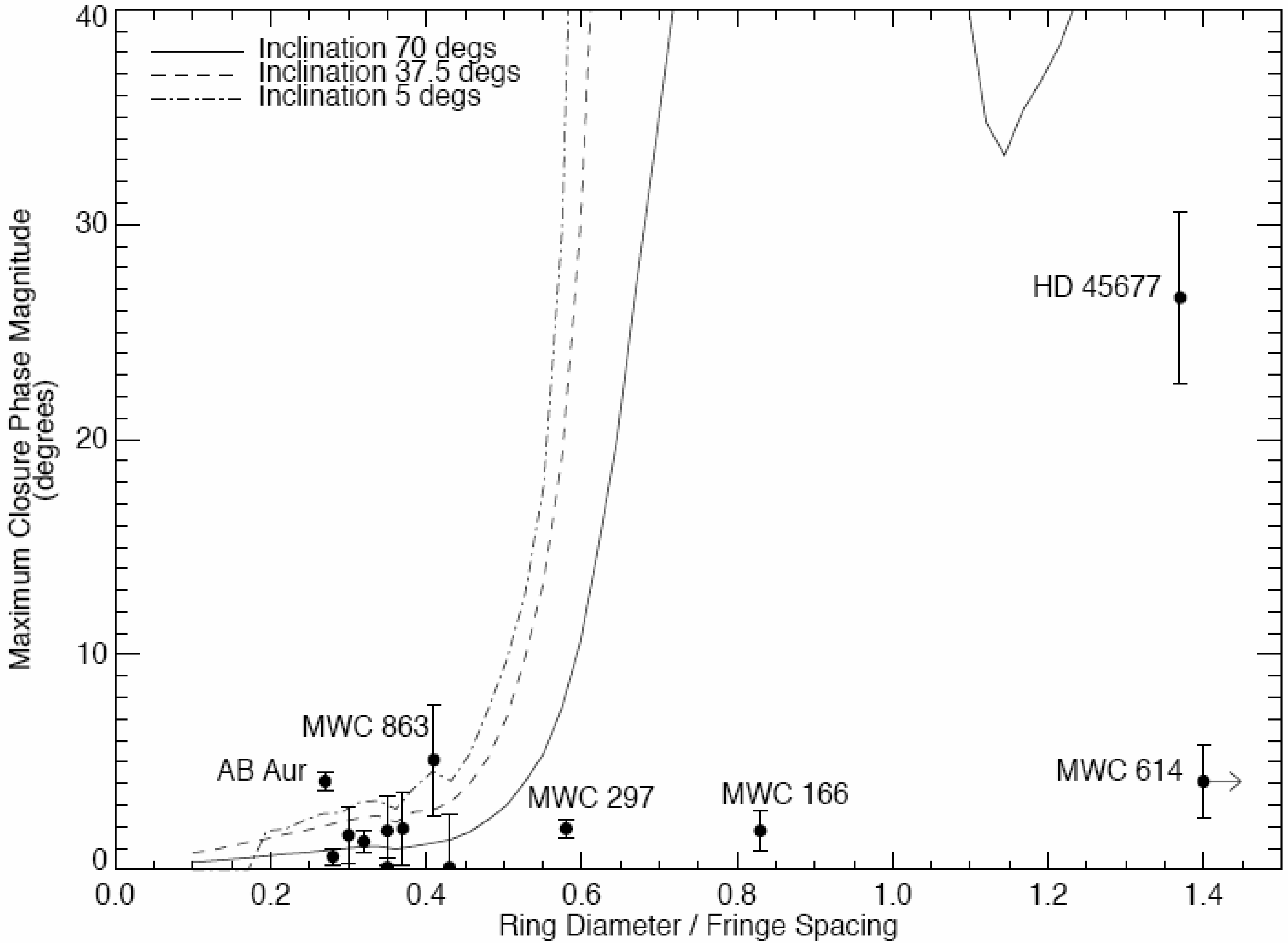
IOTA/IONIC3 YSO Closure Phases



Monnier et al. 2006

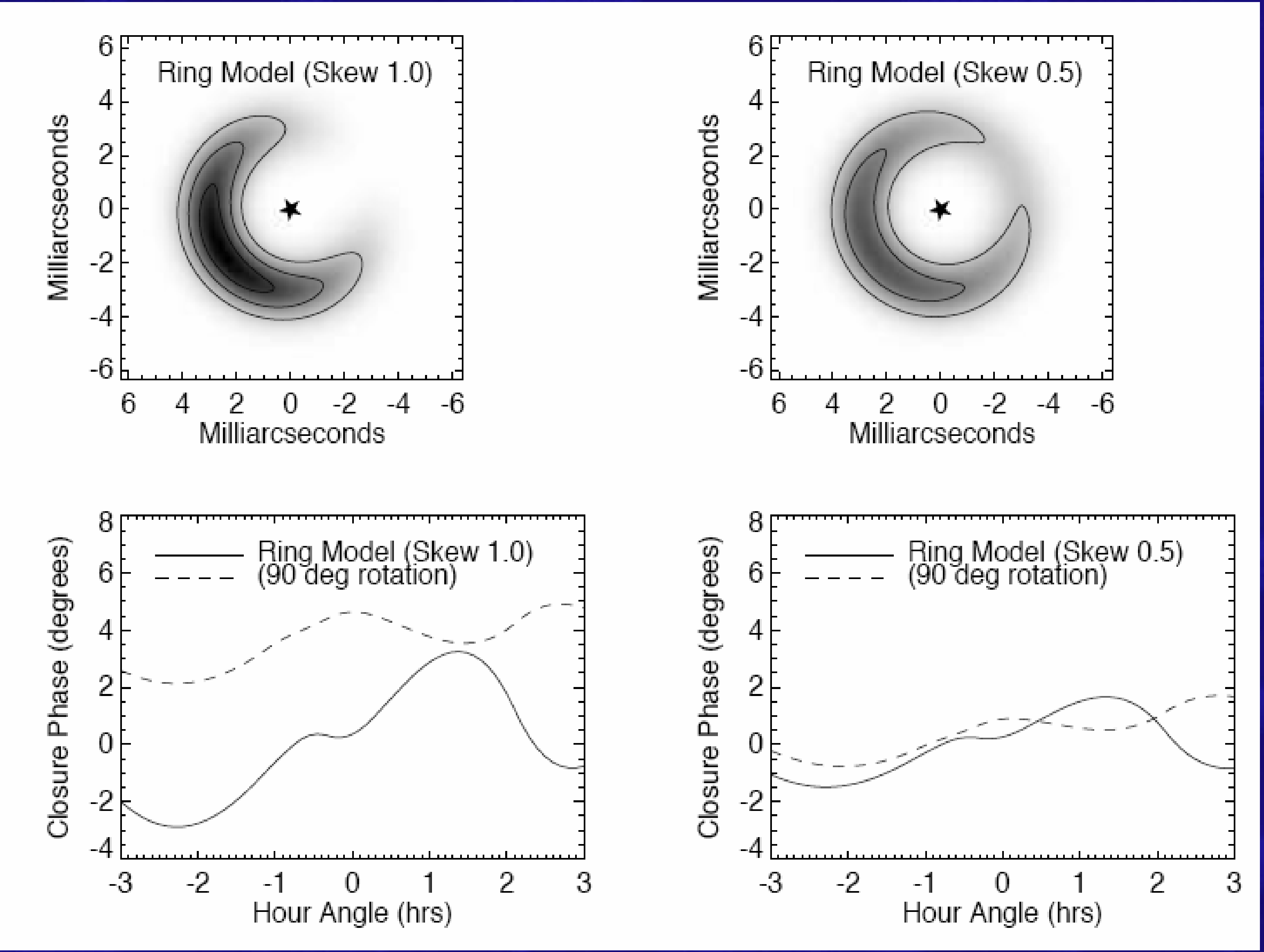
DDN Model – predicted closure phase

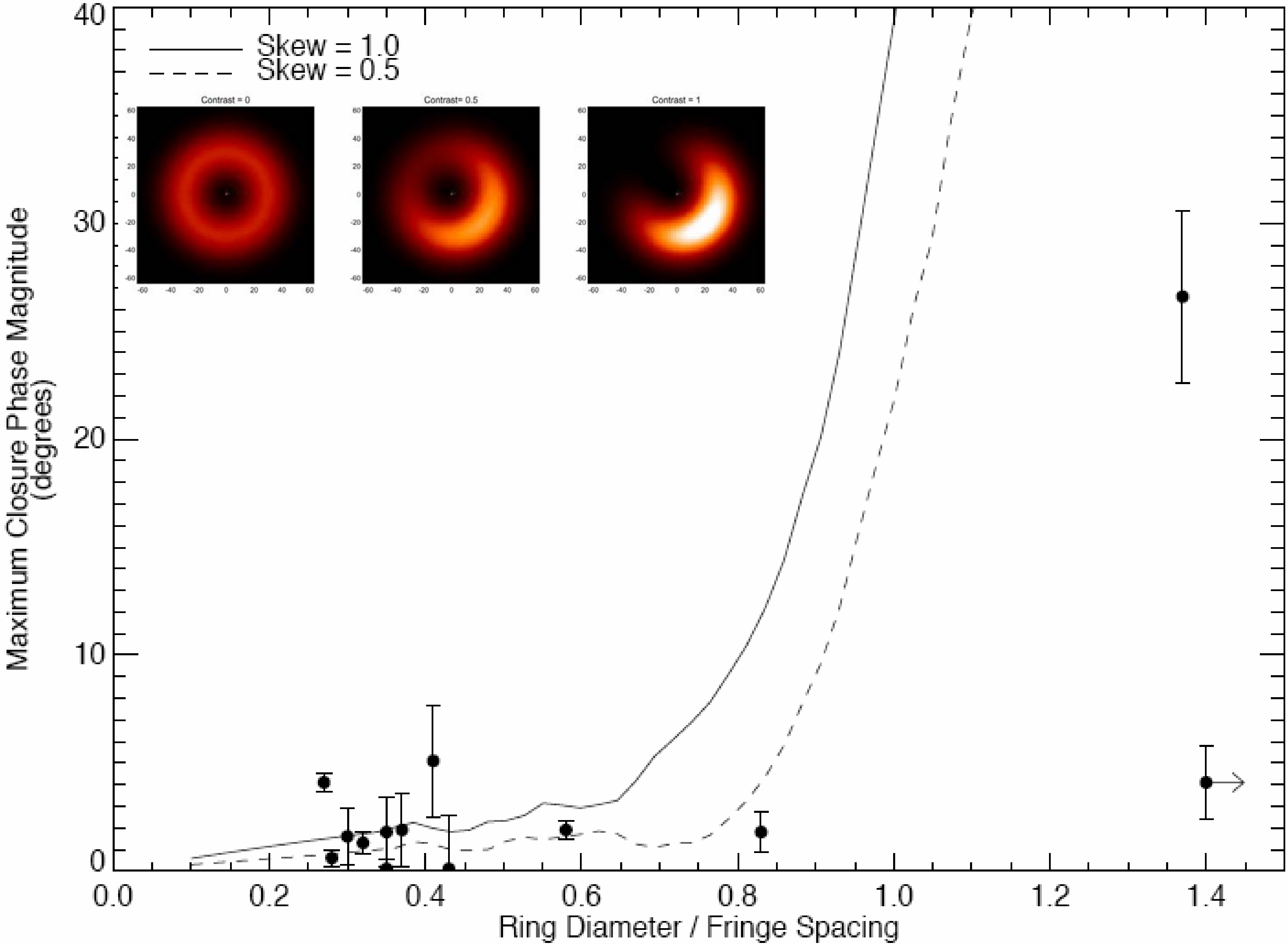




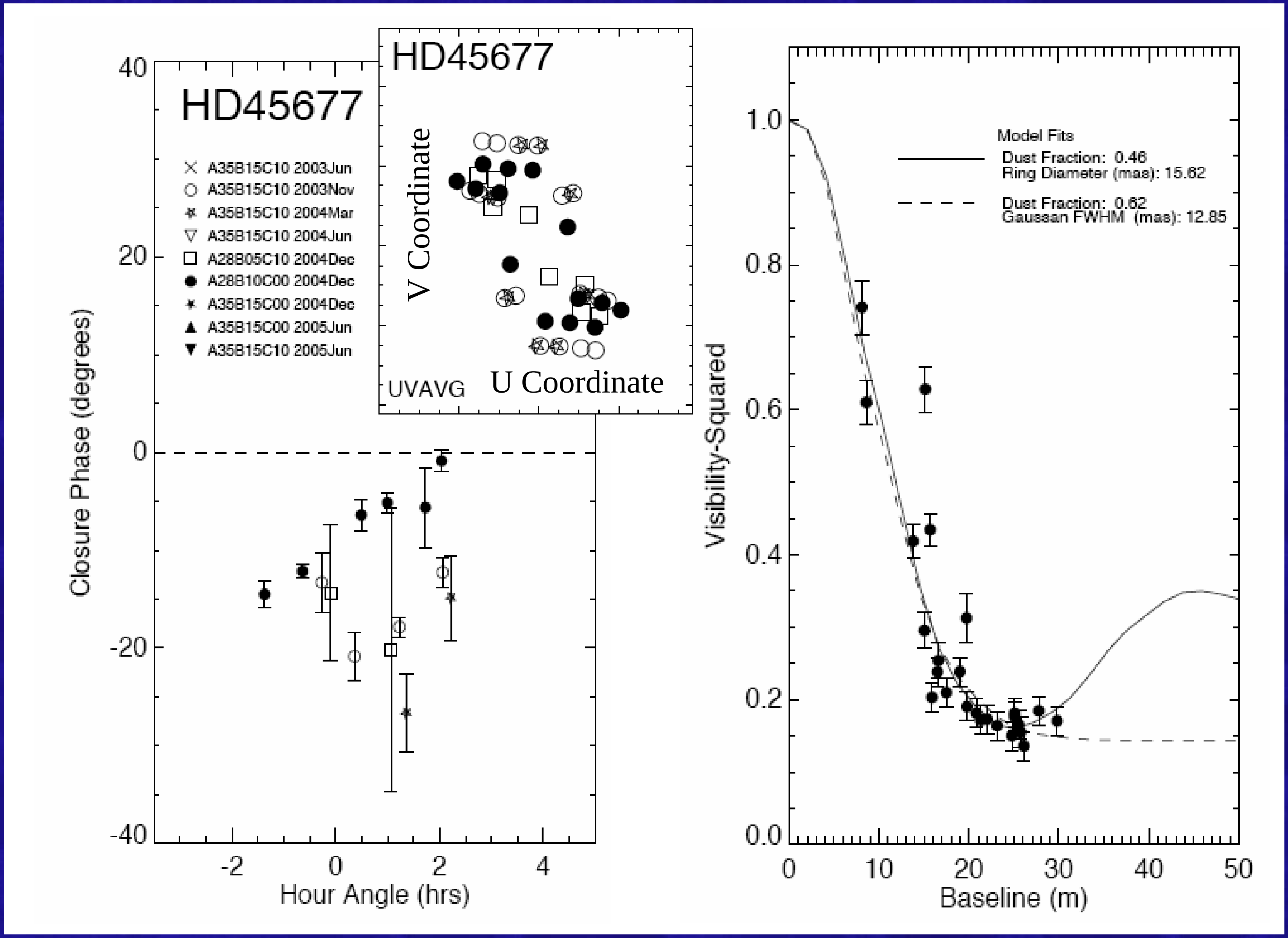
Inclination 70 degs
Inclination 37.5 degs
Inclination 5 degs
HD 45677
MWC 863
AB Aur
MWC 297
MWC 166
MWC 614
Maximum Closure Phase Magnitude
(degrees)
Ring Diameter / Fringe Spacing
0
10
20
30
40
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4

Skew Disk – predicted closure phase

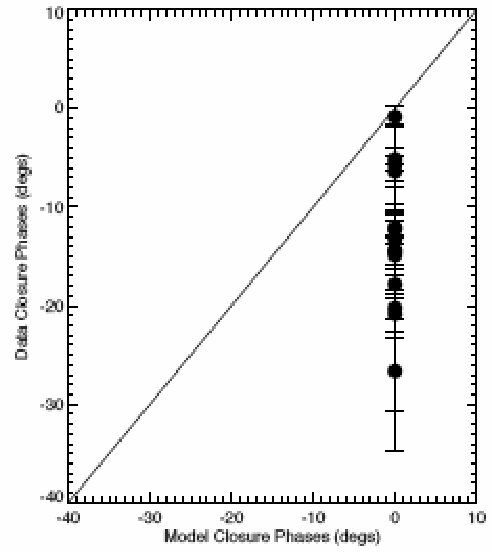


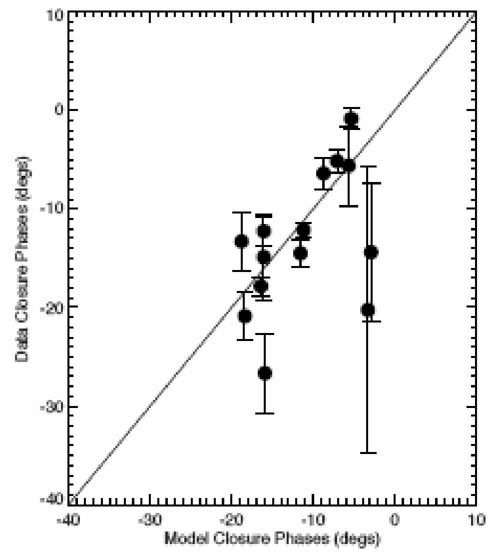

Skew = 1.0
Skew = 0.5
Contrast = 0
Contrast= 0.5
Contrast = 1
Maximum Closure Phase Magnitude (degrees)
Ring Diameter / Fringe Spacing
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
0
10
20
30
40

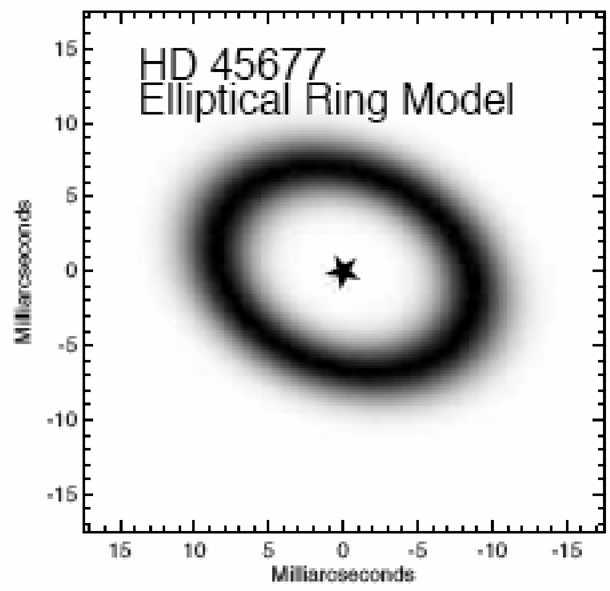
HD 45677 – a case study in parametric imaging

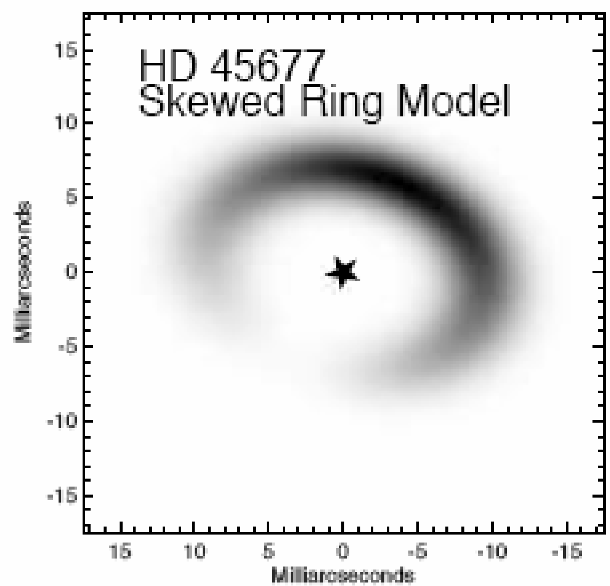


HD 45677 – Parametric Imaging Results





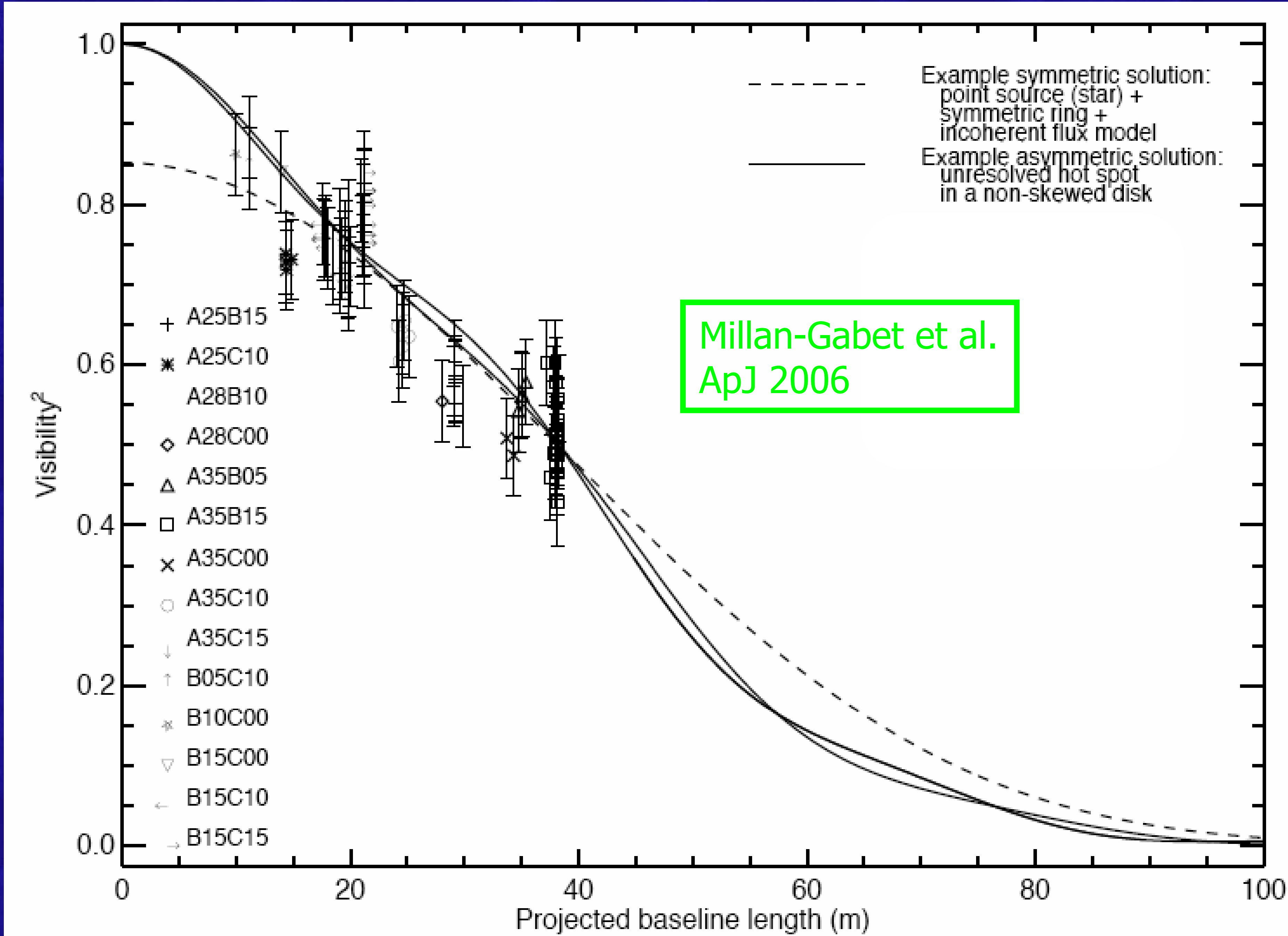




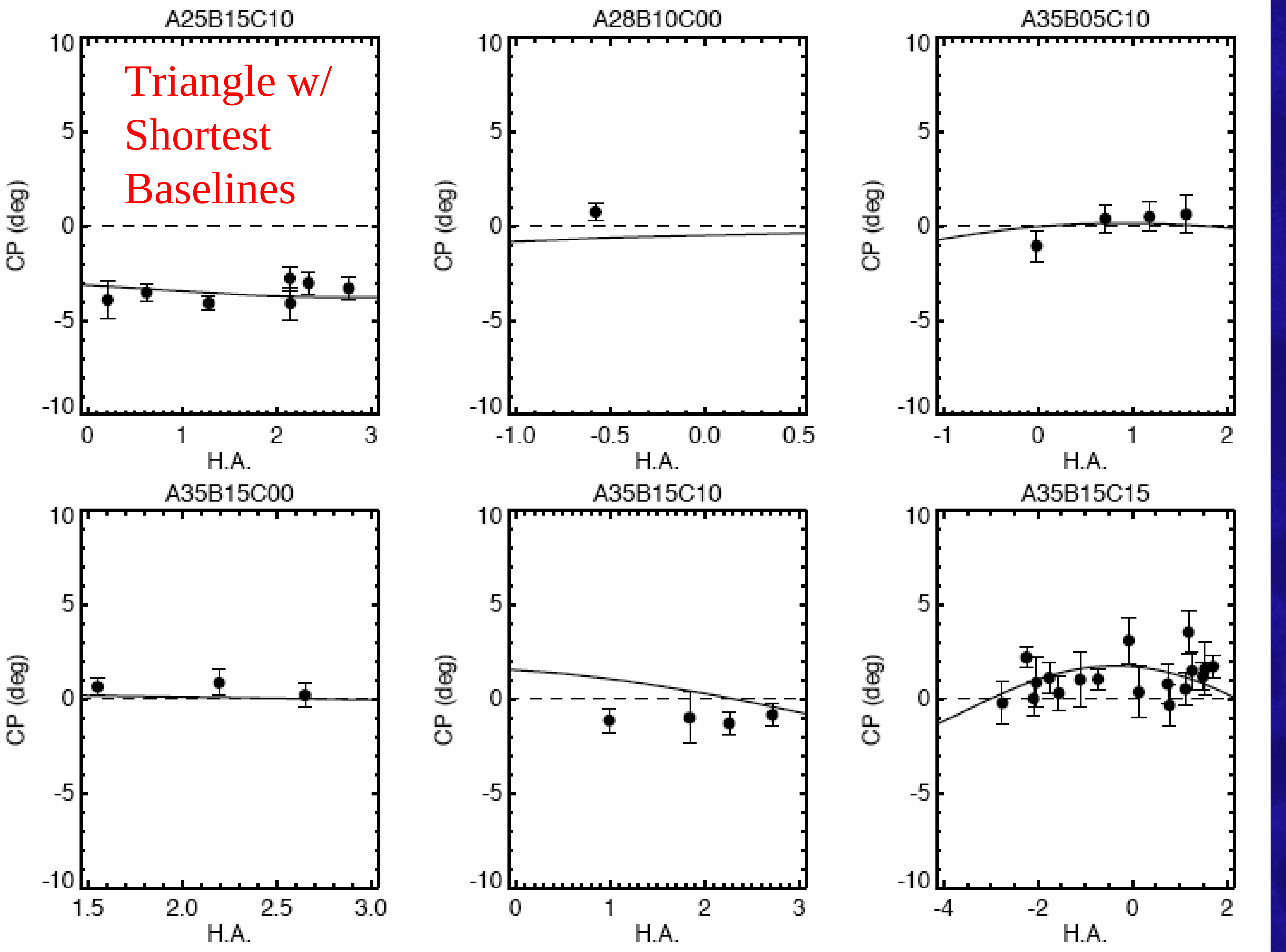
Special Case: AB Aur Disk

A Closure Phase Myste

Grady et al. 1999



Example symmetric solution:
point source (star) +
symmetric ring +
incoherent flux model
Example asymmetric solution:
unresolved hot spot
in a non-skewed disk
A25B15
A25C10
A28B10
A28C00
A35B05
A35B15
A35C00
A35C10
A35C15
B05C10
B10C00
B15C00
B15C10
B15C15
Visibility^2
Projected baseline length (m)
0
20
40
60
80
100
0.0
0.2
0.4
0.6
0.8
1.0
Millan-Gabet et al.
ApJ 2006



A25B15C10
Triangle w/
Shortest
Baselines
A28B10C00
A35B05C10
A35B15C00
A35B15C10
A35B15C15
CP (deg)
H.A.

AB Aur Results

- Long Baselines -> zero closure phase
  - Point-Symmetric on scales of 4-10 milliarcseconds
- Short Baselines -> non-zero closure phase
  - Asymmetric on scales of 10-50 milliarcseconds
  - 4 degrees CP corresonds to ~7% asymmetry
- What could this be?

Candidate Models

What interferometry won't tell us:

What is the physical cause of this localized, bright emission?

Millan-Gabet et al. ApJ 2006

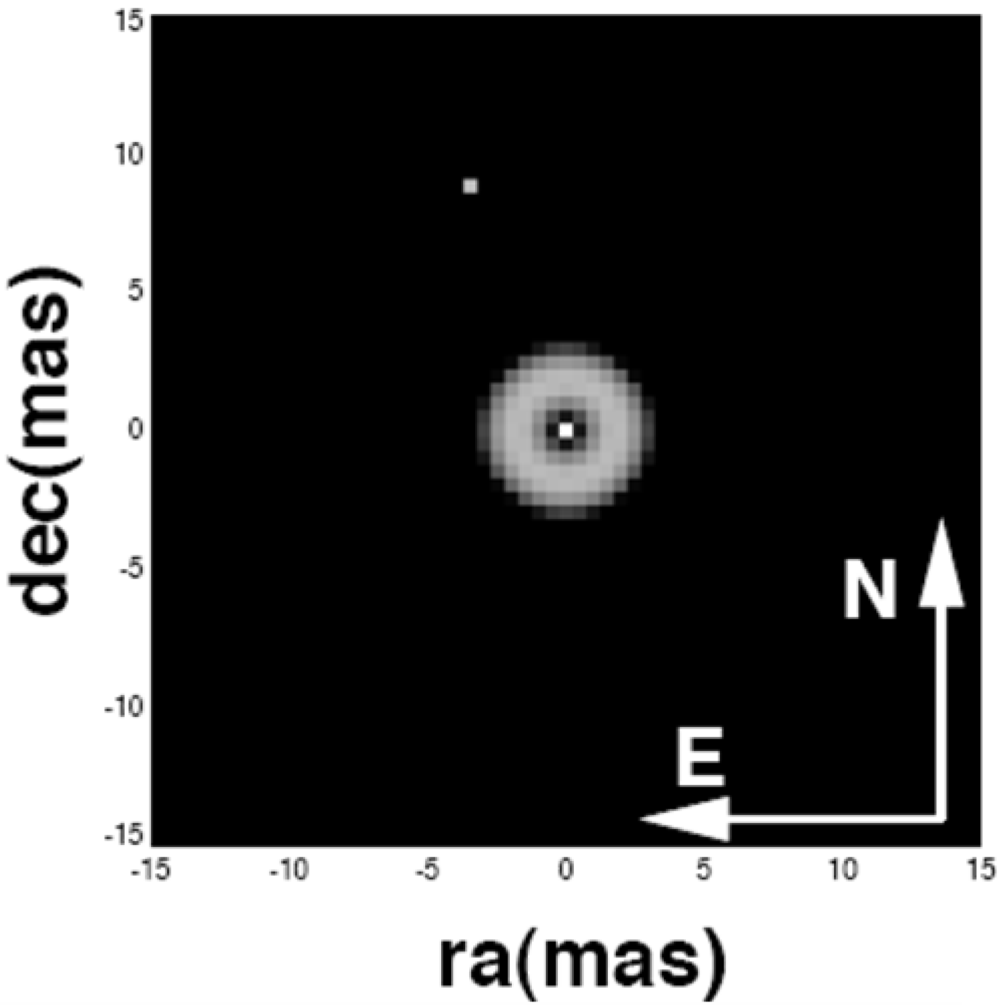
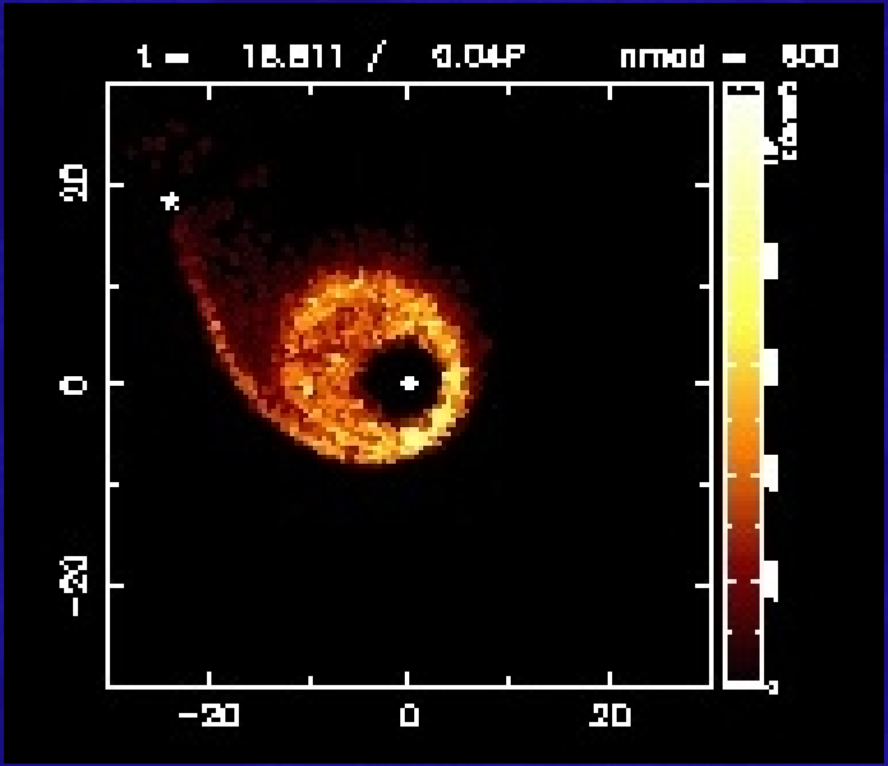


Table 1. Results from Fitting to "Disk Hot Spot" Model[a]

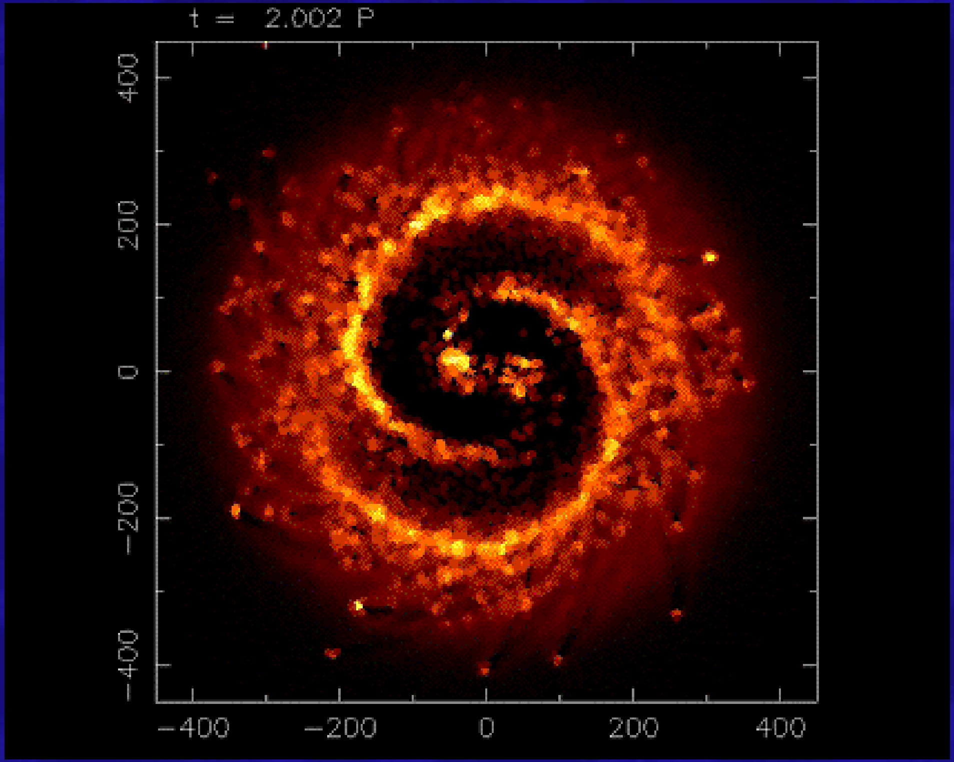
Model Description	Fraction of Light: Star	Disk	Spot	Disk Properties	Spot Properties	Reduced χ^2 (V^2,CP)
Unresolved hot spot with non-skewed disk[b]	0.3	0.68	0.02	Ring Diameter 3.6 mas Ring Width/Diameter 0.25	Unresolved Spot r_G =9 mas at PA 22°	1.5
Gaussian hot spot with skewed disk	0.3	0.62	0.08	Ring Diameter 3.1 mas Ring Width/Diameter 0.5 Max Skew=1.0 at PA 172°	Gaussian FWHM 12 mas r_G =29 mas at PA 12°	1.8

YSO imaging – plenty still to do…

Tidal Tails



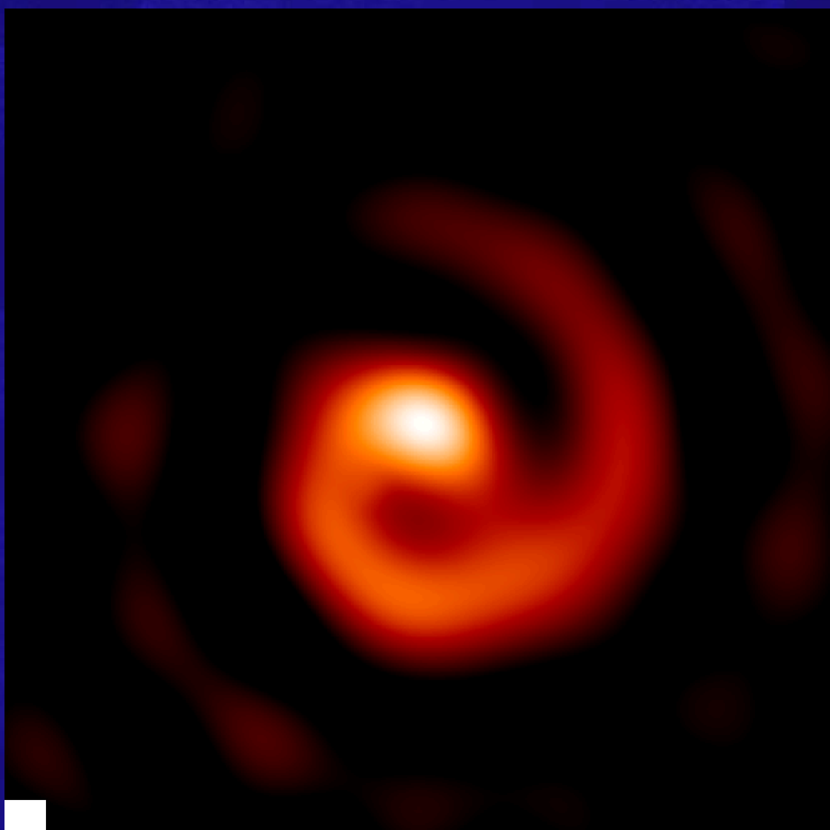
Spiral Density Waves



Simulations Courtesy Sarah Maddison

WR 104: The prototype Pinwheel Nebula

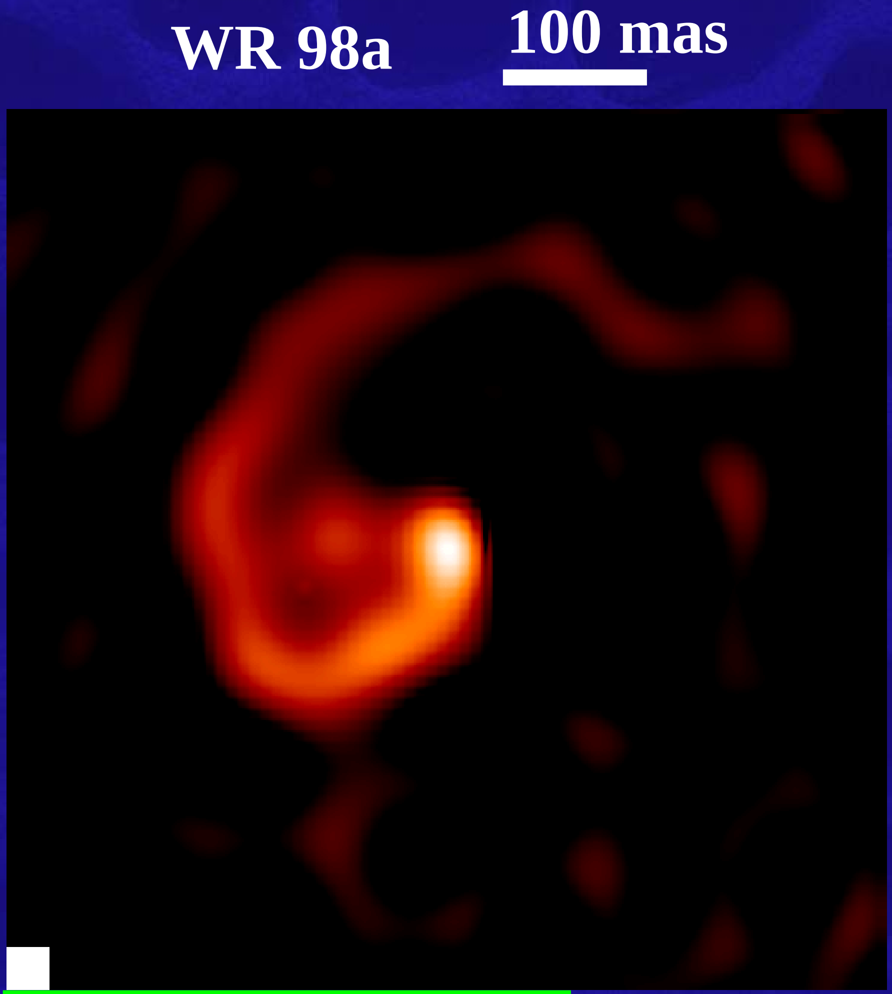
WR 104 50 mas (75 AU)

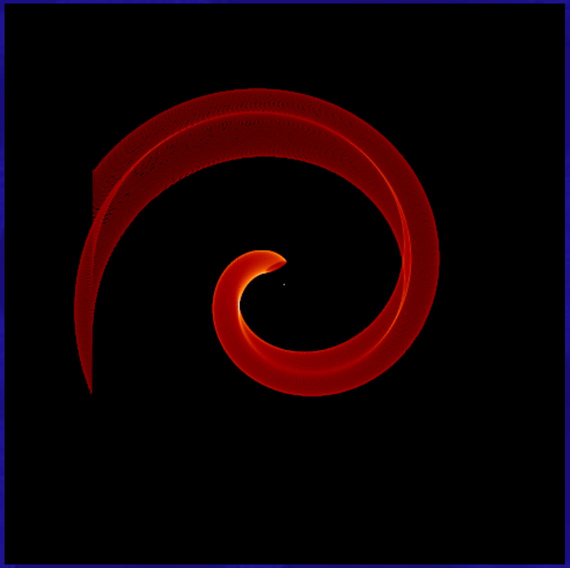


- Orbital Period 243.5 +/- 3 days
- Inclination 11 +/- 7 deg
- Motion 111 +/- 9 milliarcsec/yr
- Assuming wind 1220km/sec then dist=2.3+/-.7 kpc
- Central binary only 1-2 milliarcseconds separation, but geometric orbit inflated by the dust plume
- Highly circular orbit implies likely tidal circularization episode in the history of this binary.
- Current separation of components approximately equal to the radius of a red supergiant.
- These in turn point to Roche Lobe overflow to precipitate the WR stage in this star.
- Rotating `Eclipse' at 1 turn (optically thick dust)

Tuthill et al, Nature 1999

WR 98: A second Wolf-Rayet Colliding Wind Binary



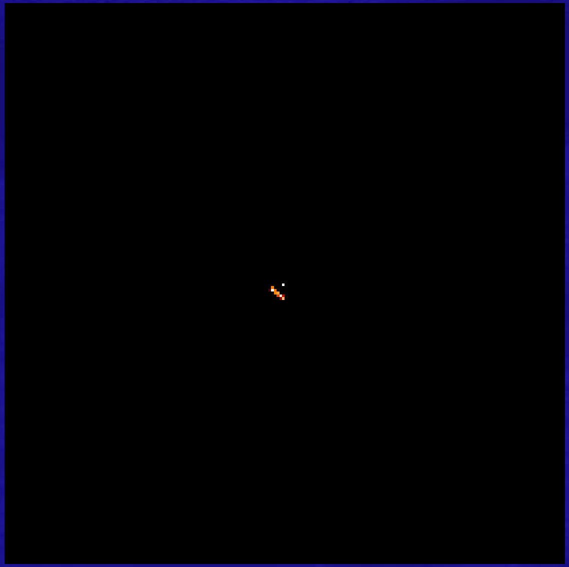


- Orbital Period 565 +/- 50 days
- Inclination 35 +/- 6 deg
- Motion 99 +/- 23 milliarcsec/yr
- Assuming wind 900km/sec then dist=1.9 kpc
- Error in Distance is limited by wind speed (spectroscopy)
- Clear regular photometric variations associated with orbital period
- If lightcurve *is* linked to Variable dust production then the eccentric orbit does not favor tidal circularization. Are Roche Lobe overflow models OK with this?

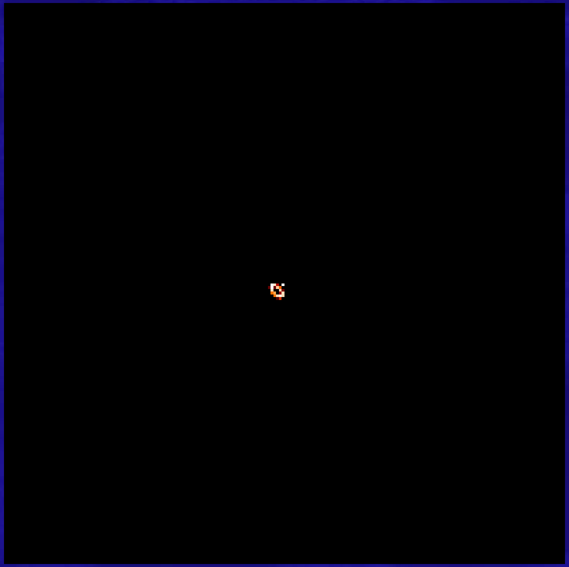
Monnier, Tuthill & Danchi ApJ 2000

Optically thin: orientation effects

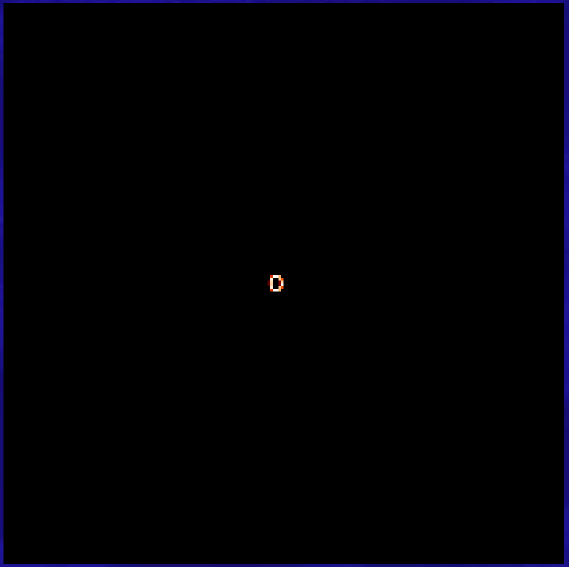
Θ=0 deg



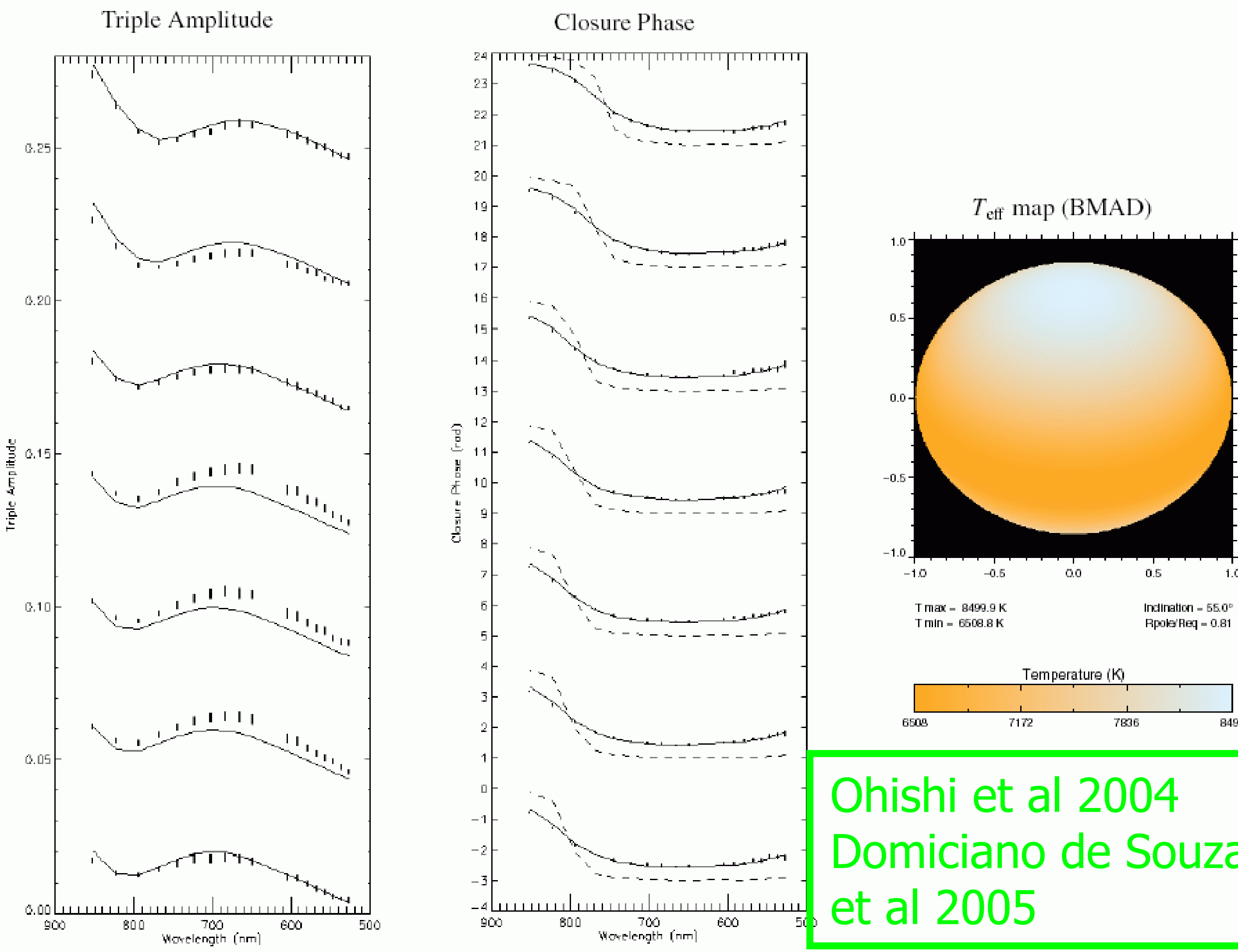
Θ=40 deg



Θ=90 deg



Surface Asymmetry on Rapid Rotators



Ohishi et al 2004
Domiciano de Souza et al 2005

Isophotoal Contours of a close eclipsing binary

MODEL ECLIPSING BINARY

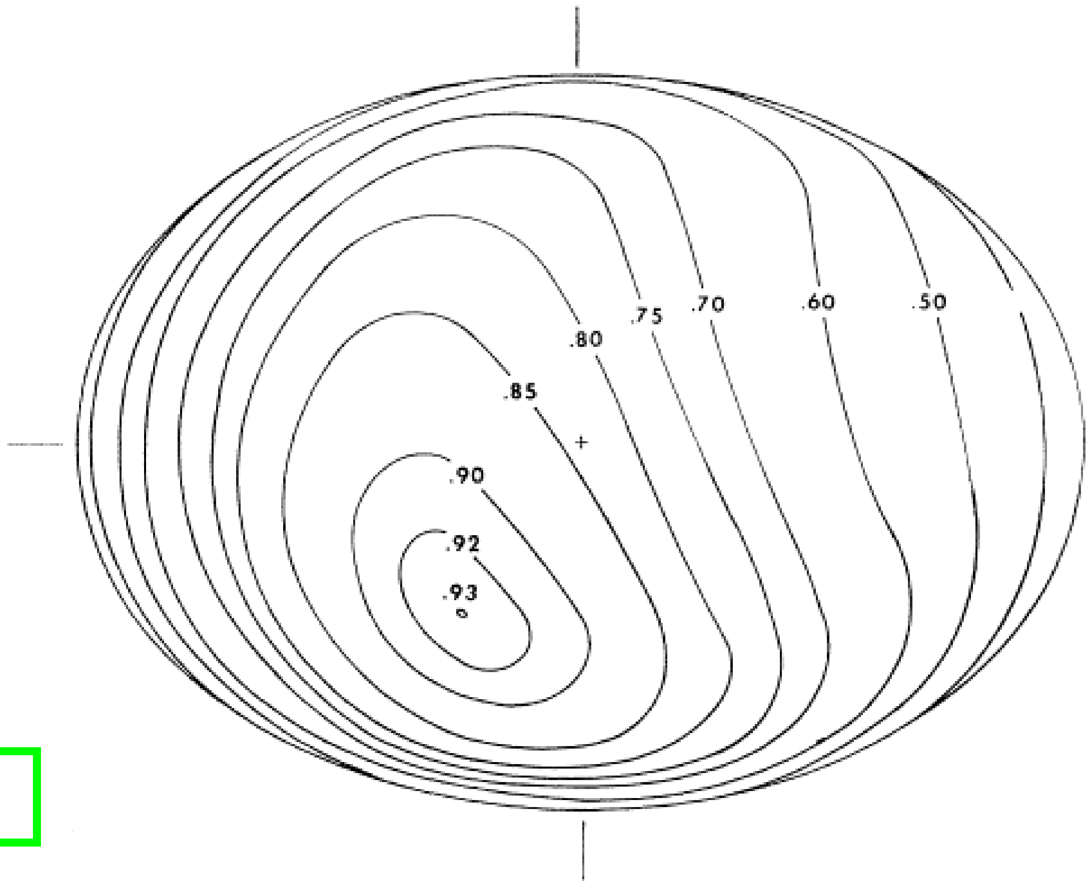
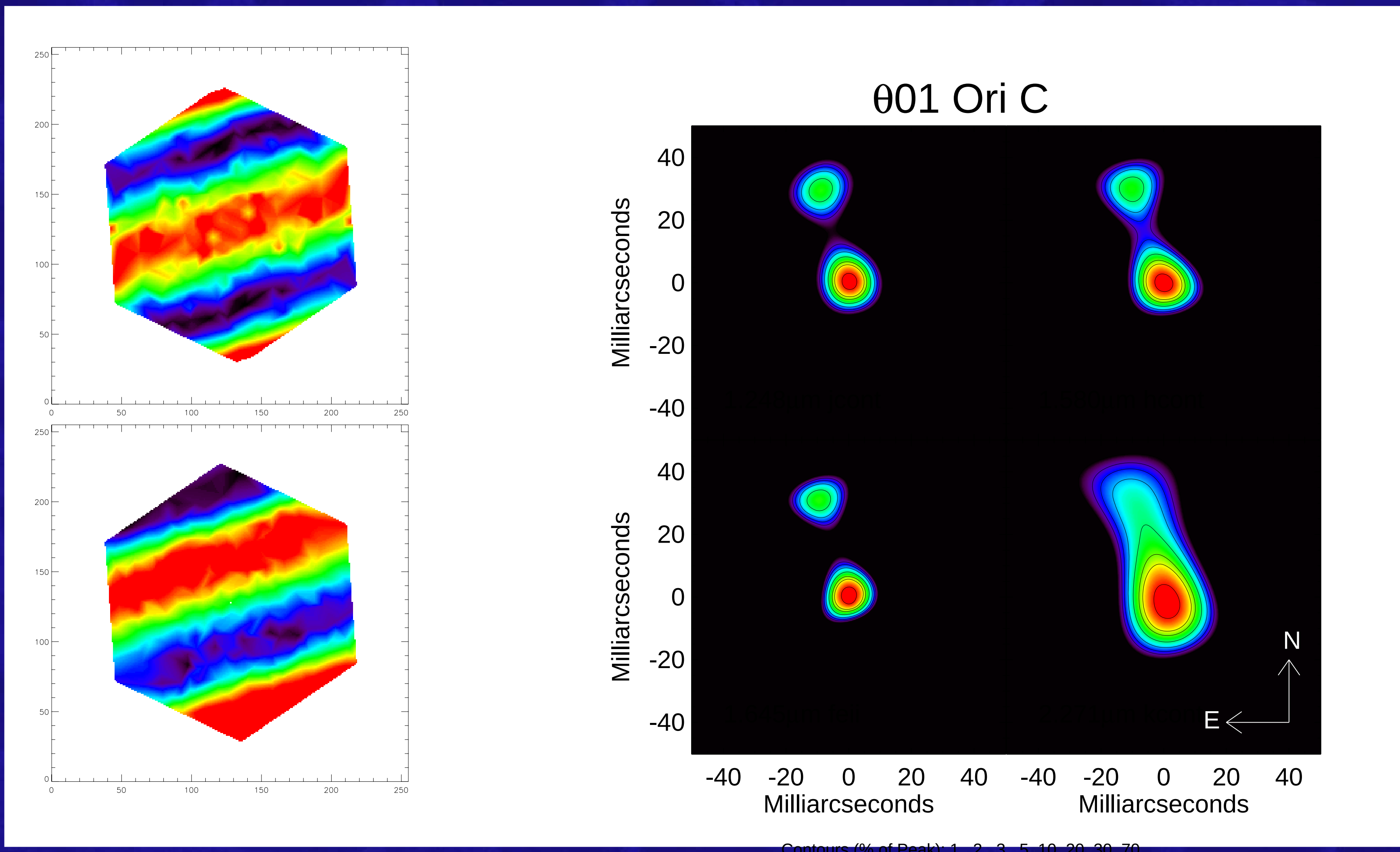


FIG. 2. Typical isophotal contours on a distorted star: *Contours* are labeled with respect to unit brightness of the sub-earth point at quadrature. These isophotes exhibit the combined effects of limb darkening, gravity brightening, and reflection. The star has an inclination of 80° and a phase angle of 30°.

Wood 1971

Binaries and faint companions



Sparse-Aperture AO results: Closure-Phase Binary Fingerprints

STEPS binaries (Pravdo & Shaklan)

M-Dwarfs with Astrometric Companions

High dynamic range, high angular resolution.

M-Dwarf G78-28

Low-mass binary

Closure Phase

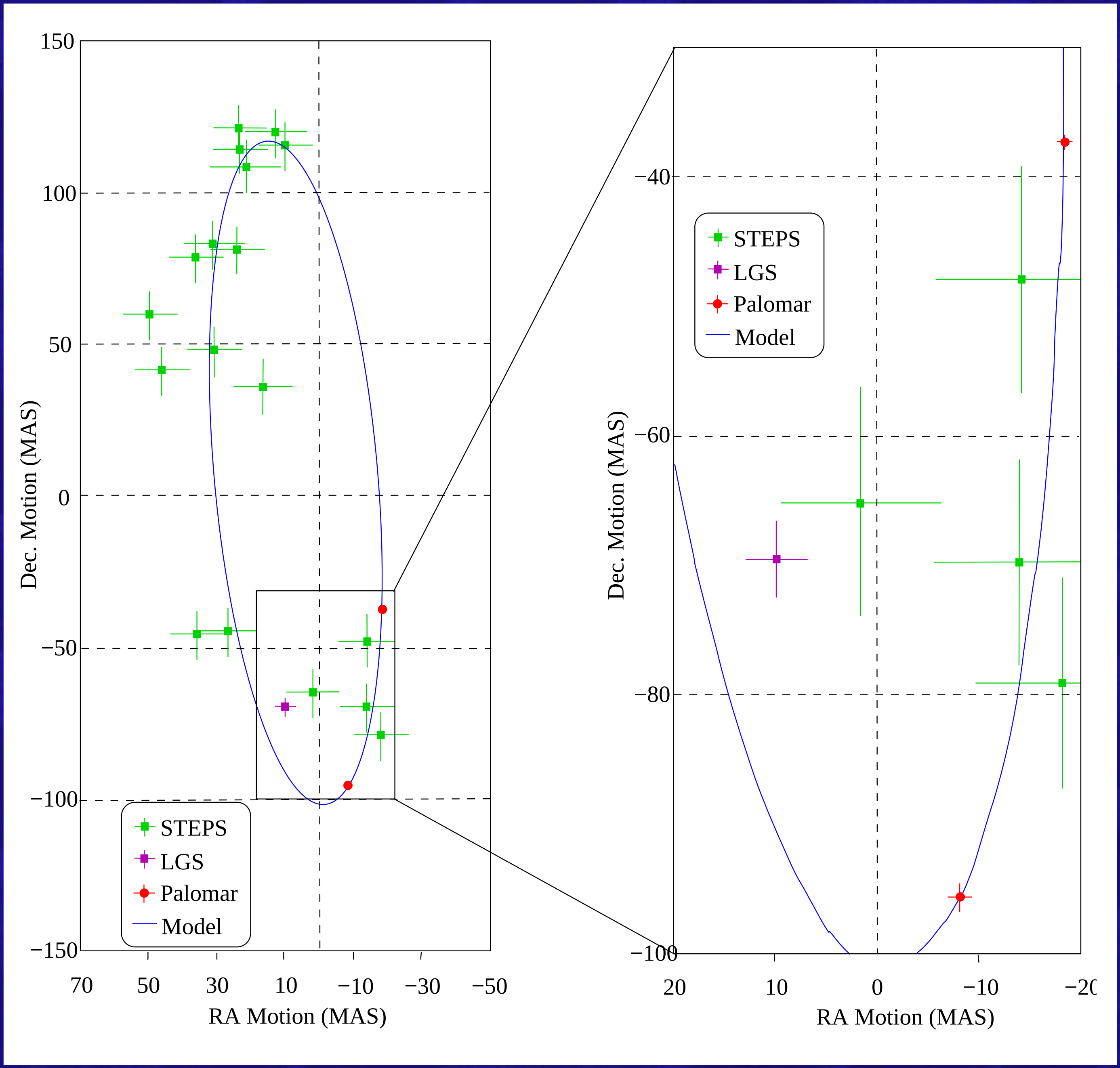
Triangle (index)

Brightness Ratio

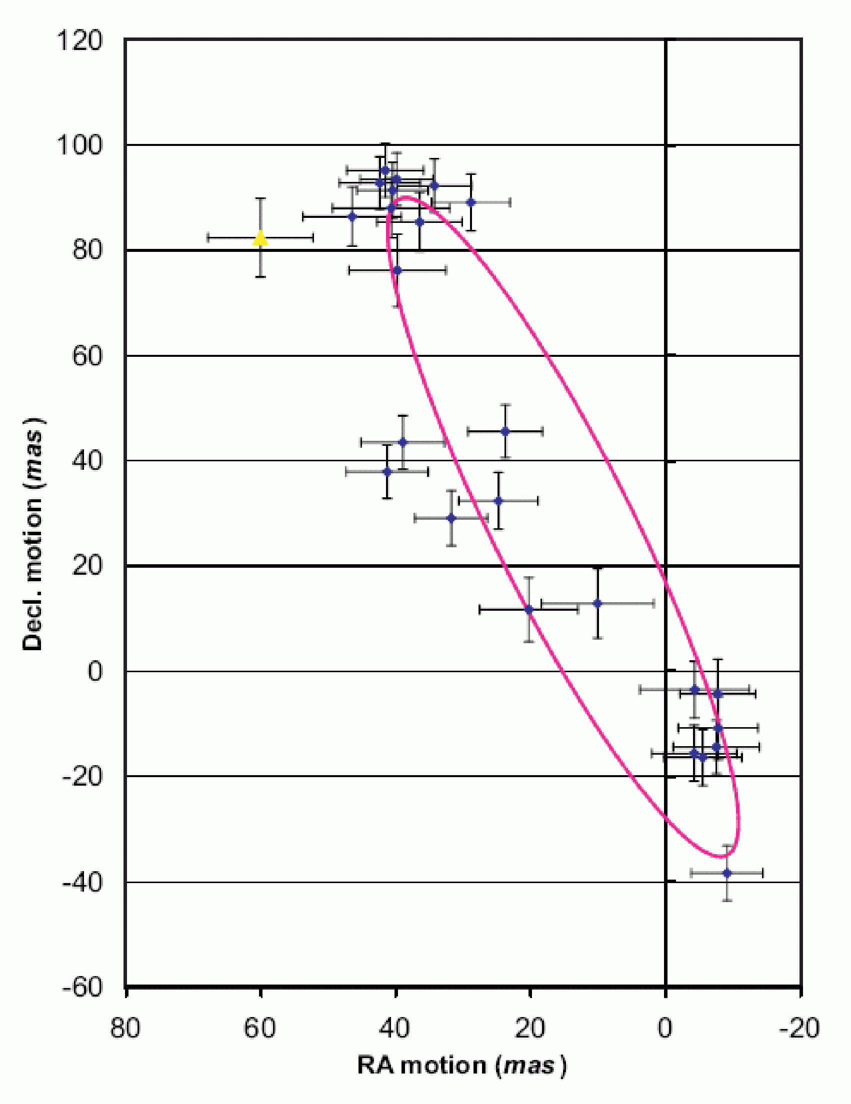
Separation (mas)

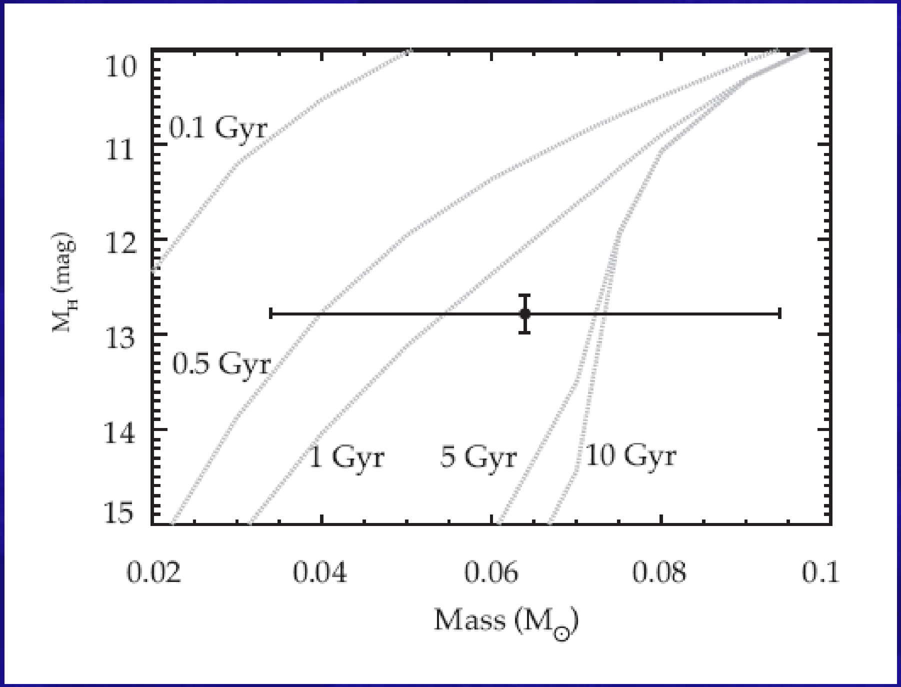
G78-28 orbital data summary

Pravdo et al. ApJ 2006



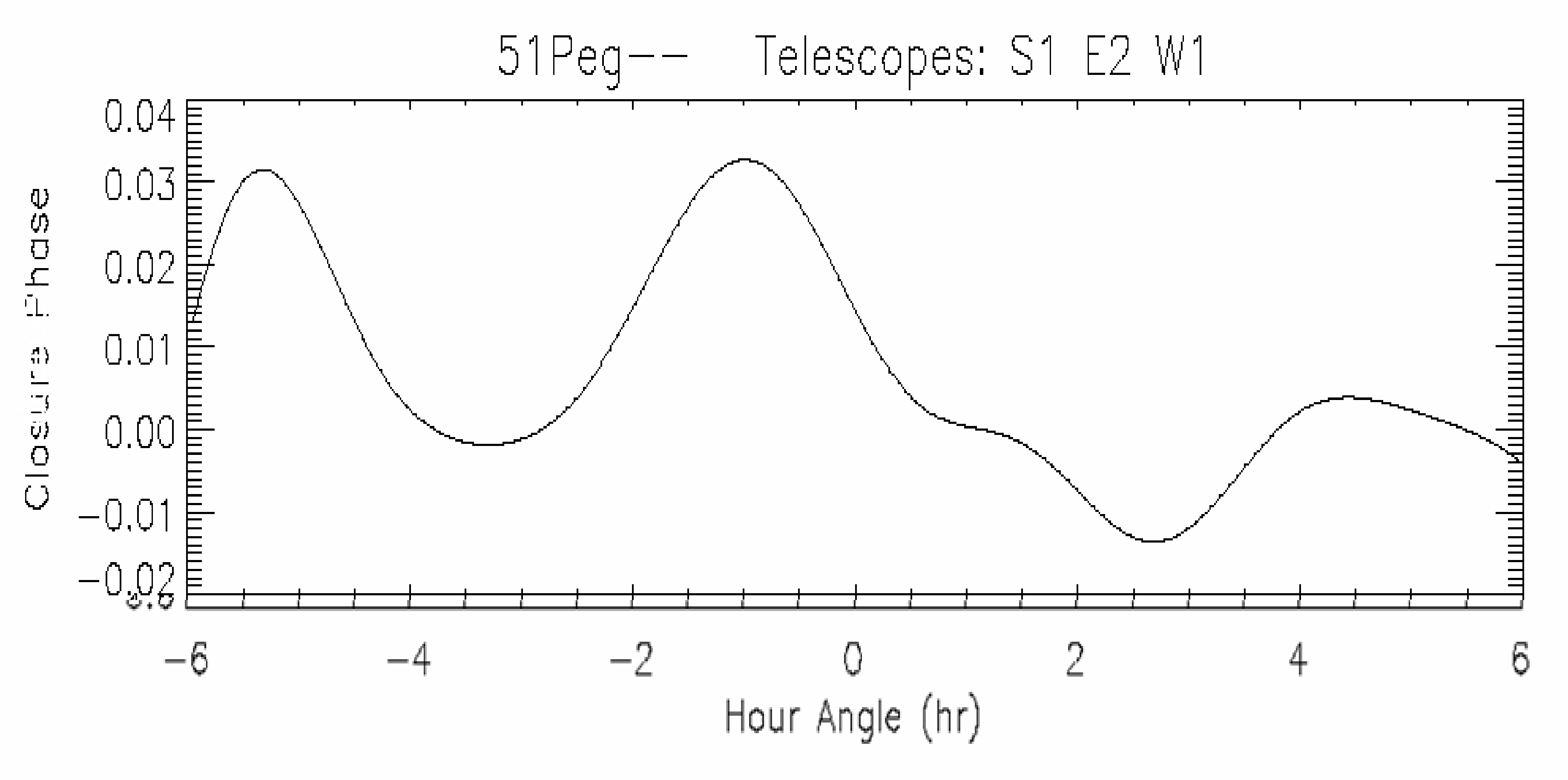
Direct Detection Brown Dwarf GJ 802B (AO masking interferometry)



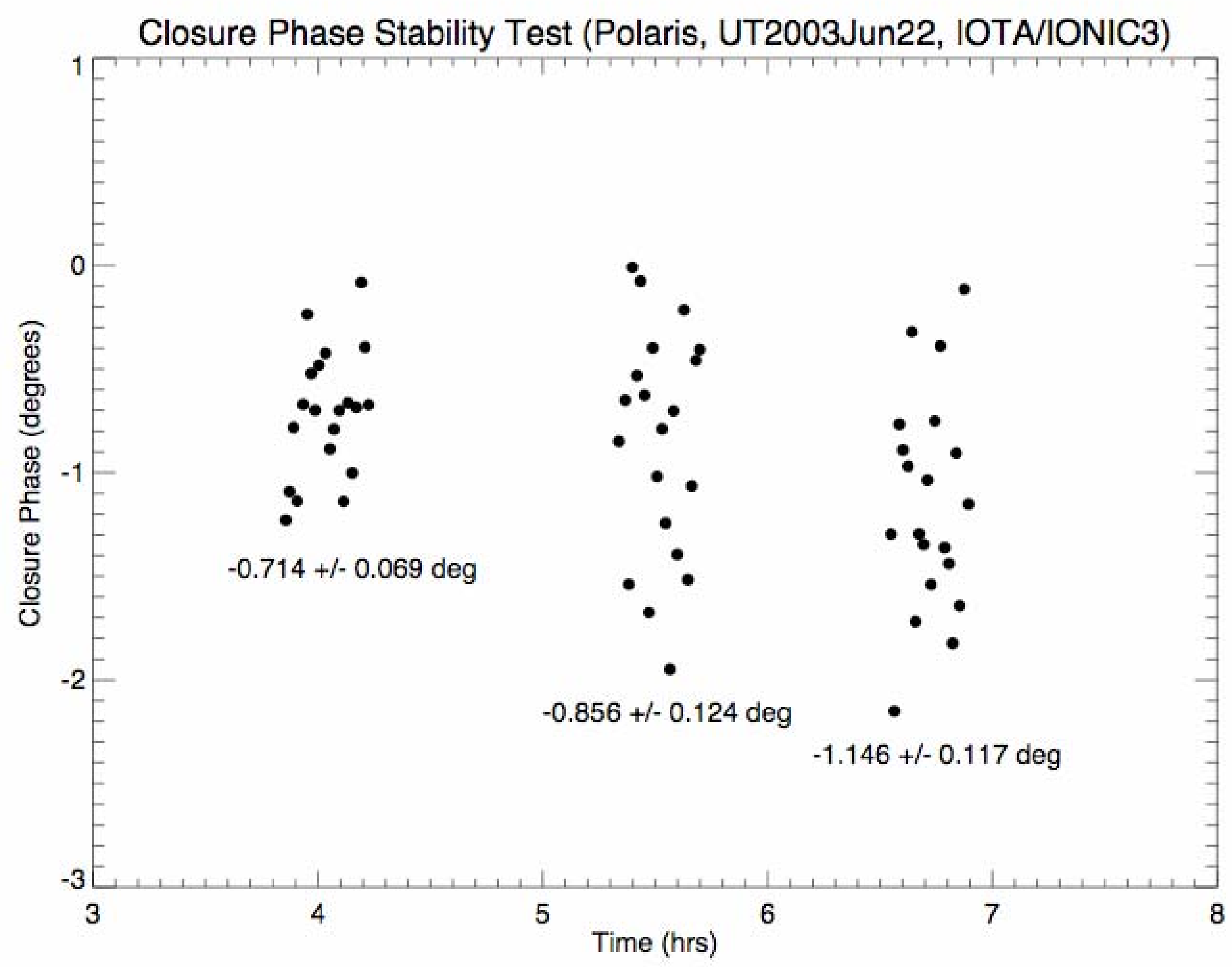


Lloyd et al. ApJ 2006 (submitted)

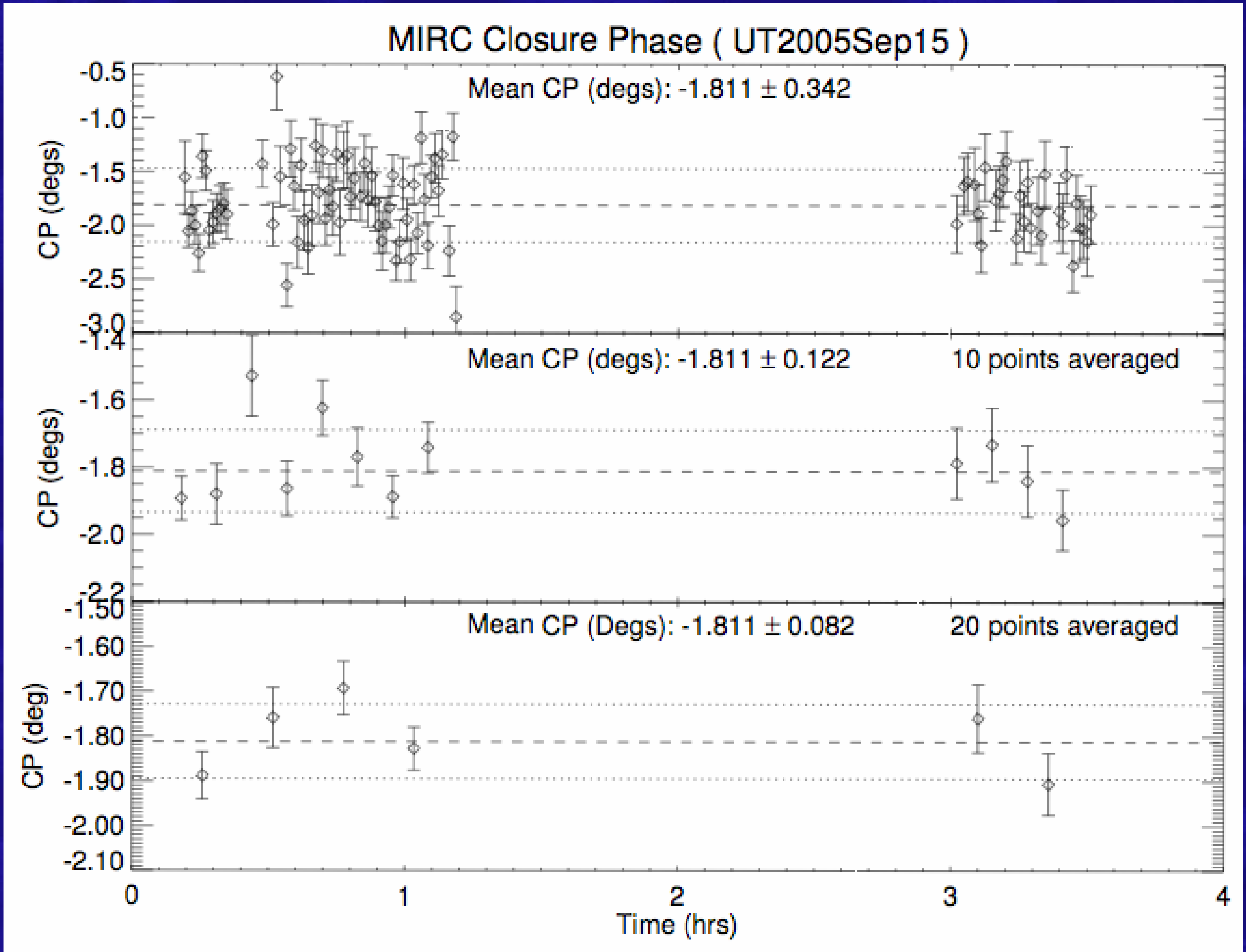
Science Case: Measuring Spectra of Hot Jupiters



Precision Closure Phase -- State of the Art



CHARA Closure Phase Stability



Zhao et al

Conclusions

- Historically, masking interferometry has delivered interesting precursor science to long baseline interferometric imaging.
- Imaging with long baseline interferometers is almost there, but we still lack an efficient imaging machine.
- Brown dwarfs are now possible with masking – next step planets.
- Long baselines interferometers advancing rapidly.

Lenticular (wave) cloud
Mauna Kea, 95mph winds

Thank You!