Broad-band interferometric observations of pre-main sequence stars.

EuroWinter School
Observing with the Very Large Telescope Interferometer

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Outline

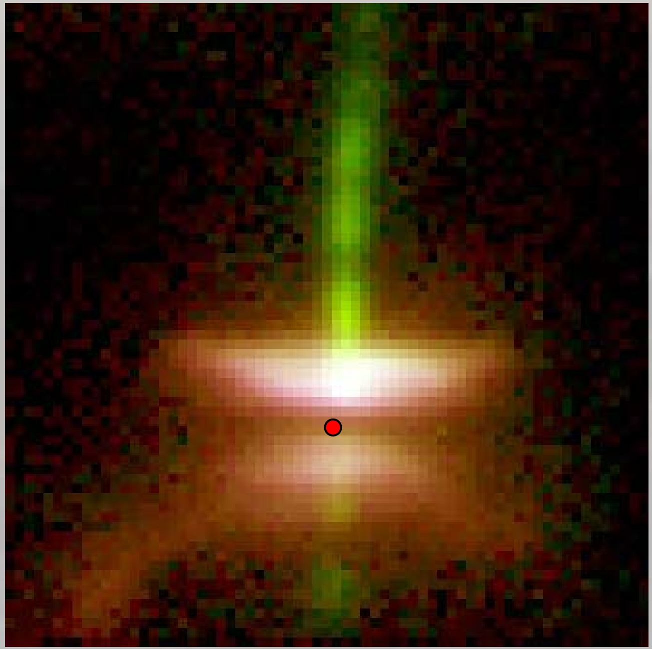
1. Young stellar objects: the astronomical unit frontier.
2. FU Ori interferometric observations.
   - *IOTA-PTI Raw data reduction.*
   - *Data calibration.*
   - *Testing standard accretion disk models.*
3. Disks and the VLTI.

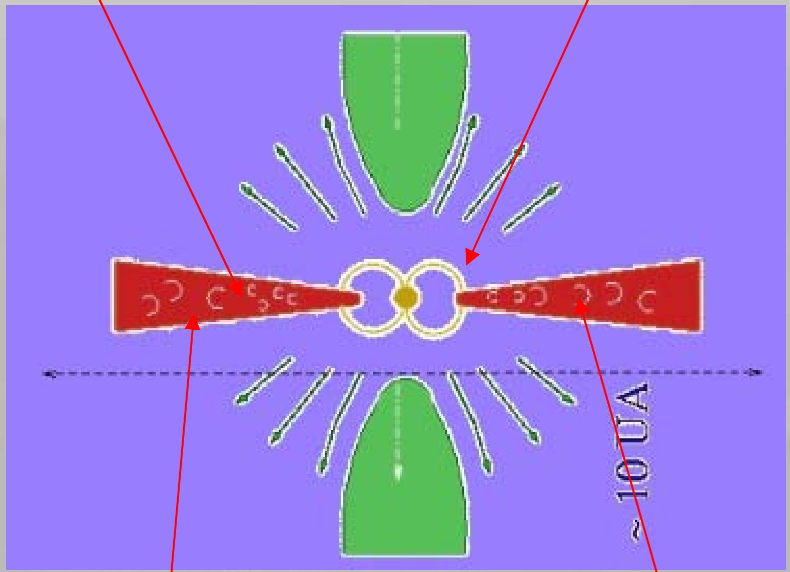
Why observing PMS stars with IR interferometers ?

Accretion mechanisms

- magneto-hydrodynamics
- turbulence

Accretion-ejection link





Physico-chemical processes:

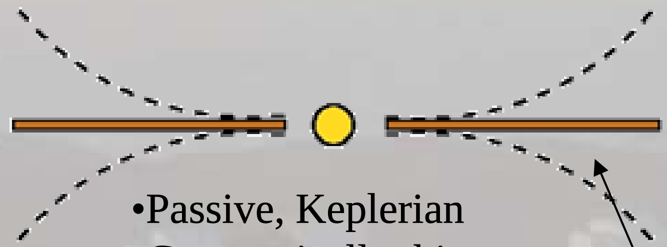
- dust aggregation
- planetesimals formation
- planet formation

Multiple systems formation

Probing the inner AU

The SED diagnostic

The standard accretion disk model and its variants:



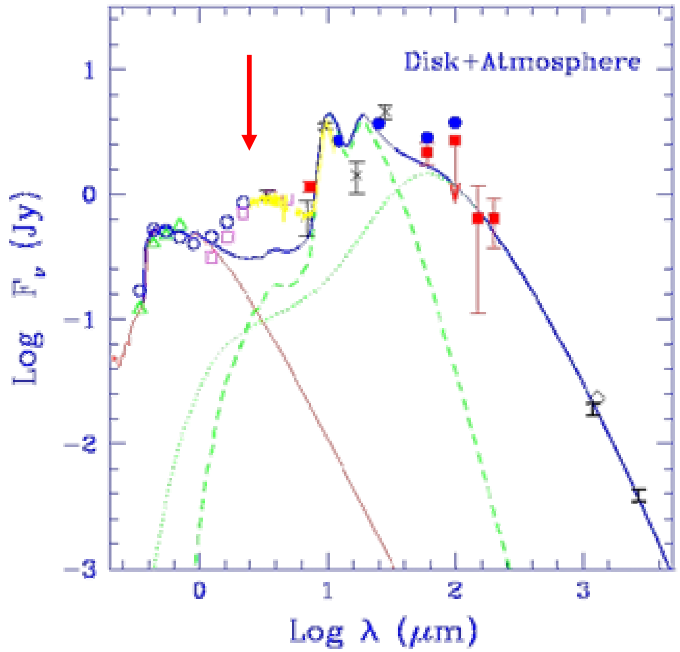
- •Passive, Keplerian
- •Geometrically thin
- •Optically thick
- •...
- •Hydrostatic equilibrium
- •Energy sources

} **Vertical structure**

Conciliating SED, veiling current models:

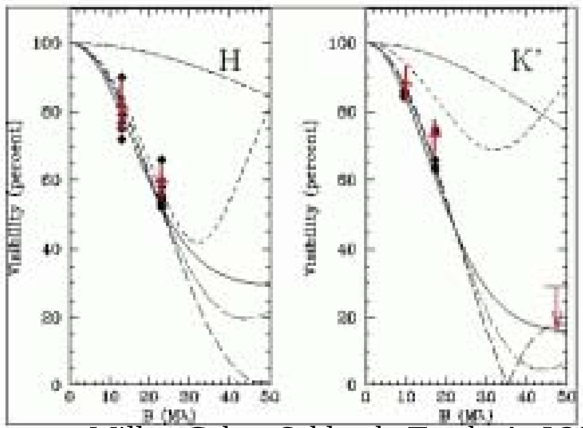
- Ok for some T Tauri but ...
- Fails for all HAeBe in the near infrared

AB Aurigae



Natta et al. A&A, 2001

Challenging theories and models



Millan-Gabet, Schloerb, Traub, ApJ,2001


Tuthill, Monnier, Danchi 2001

Near infrared interferometric measurements:

Herbig AeBe:

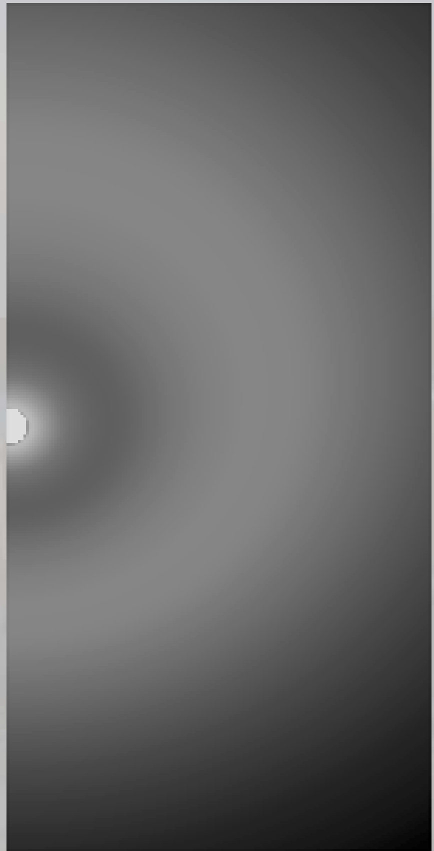
- 12/16 resolved in H or K band;
- Standard disk model fails 11/12;
- Internal cavity bigger than predicted;
- 11/12 Apparent symmetry;

T Tauris:

- 3/3 resolved
- 2/3 uncompatible with std disk model
- Internal cavity bigger than predicted

Akeson et al. 2001,Tuthill, Monnier, Danchi 2001, Millan-Gabet et al. 2001,Akeson et al. 2000,Malbet,1998.

The Fu Orionis case



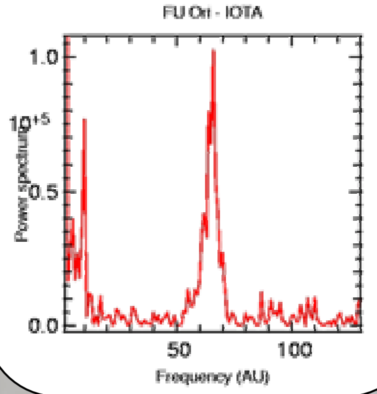
Turner,Bodenheimer,Bell, ApJ, 1997

FU Orionis stars:

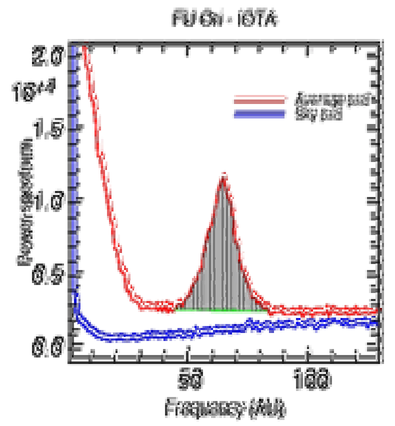
- T Tauri stars;
- Have undergone photometric outbursts attributed to accretion disk instability;
- Disk luminosity ovewhelms star luminosity;
- Ideal LB interferometry target to test accretion disk models

FU Ori raw data reduction (1)

IOTA



Square visibility estimated from fringe energy



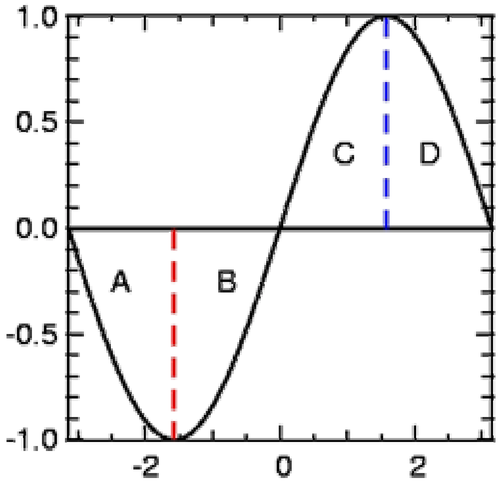
Retrieving visibilities requires hunting for

Biases and noises:

- •Photometric fluctuations
- •Readout noise
- •Photon noise
- •1/f noise
- •Piston noise
- •Interferogram selection

FU Ori raw data reduction (2)

PTI



Bias estimation-subtraction

$$V^2 = \frac{\pi^2}{2} \frac{(A-C)^2 + (B-D)^2}{(A+B+C+D)^2}$$

Error estimation:

Iota

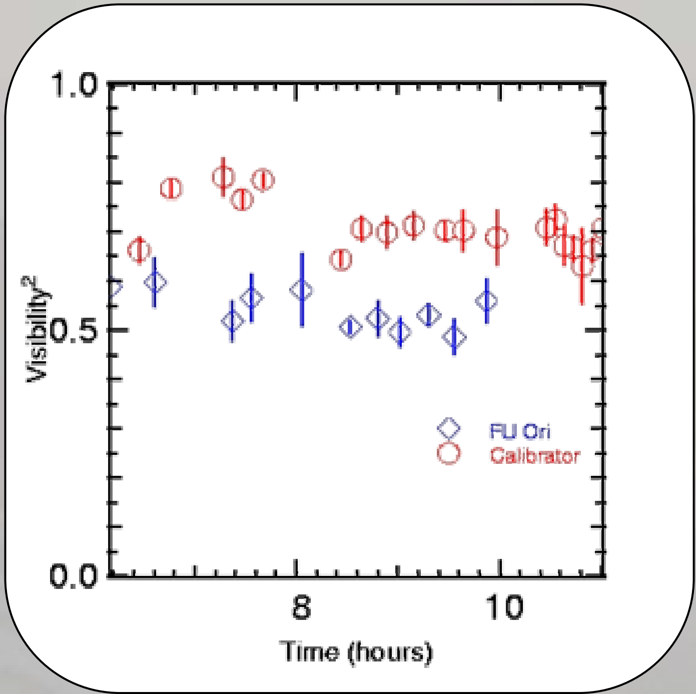
Estimating an error is non trivial.

$$\sigma^2 \qquad \frac{\sigma^2}{N} \qquad \textbf{?}$$

Evaluating biases is non trivial:
- knowledge of underlying physics
- numerical methods (bootstrap)

Efron - Tibshirani 1998(Chapman&Hall/CRC)

Fu Ori: data calibration



Instrumental visibility

- Polarization
- Dispersion
- Atmosphere...

All phenomenon have different timescales.

Data calibration:

- Asserting transfer function stability
- Interpolation at the measurement point
- The accuracy goals leads to certain constraints
  - -calibrators diameters
  - -number of calibrators
  - -spectral type
  - -angular distance on the sky

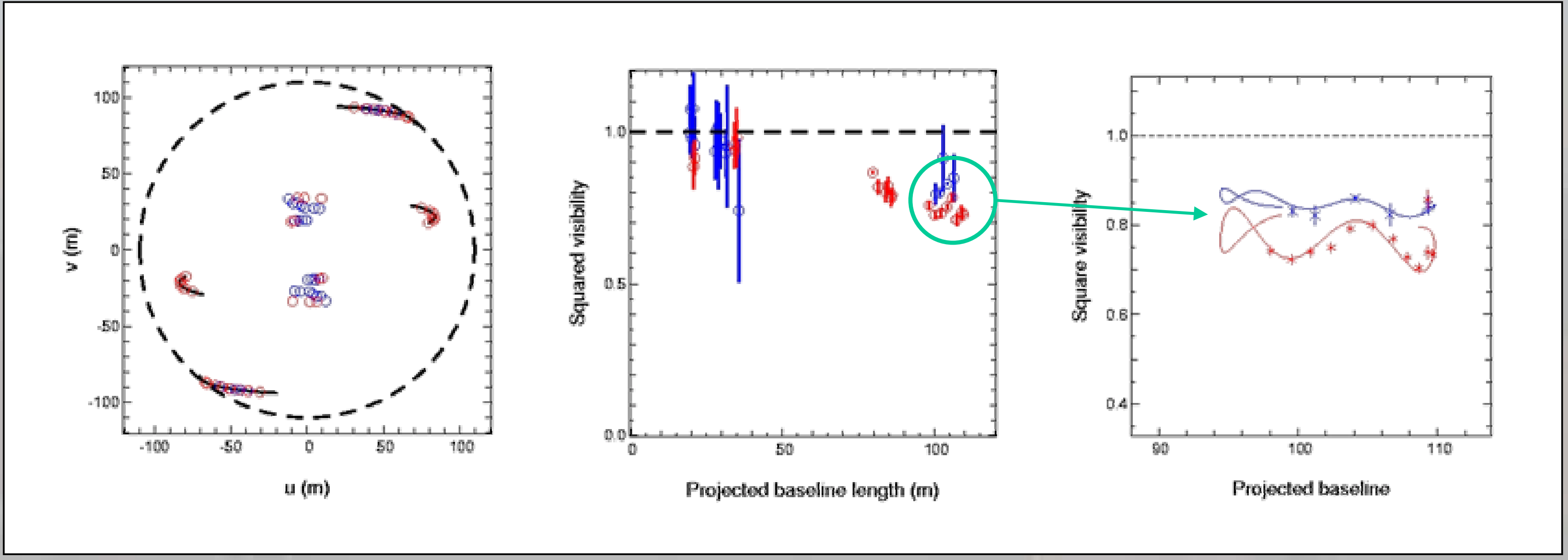
Error estimation:

$$V^2_{finalfuori}(u,v) = f(V^2_{obsfuori}, V^2_{ical}(\phi_i), w_i, \frac{1}{\sigma^2_{cal}})$$

$$\varepsilon_{final-fuori} = g(\varepsilon_{meas-fuori}, \varepsilon_{meas-cal}(i), \varepsilon_{diam})$$

Fu Ori calibrated data:

and (u,v) coverage



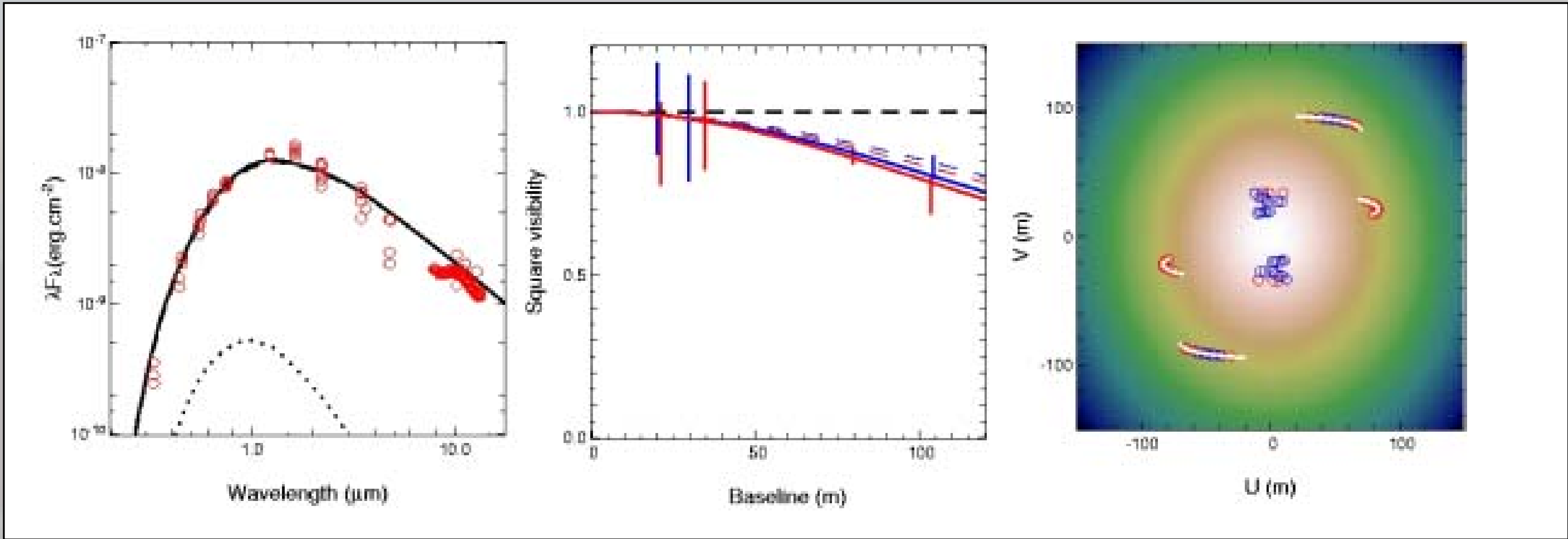
Two remarks:

•FU Ori is resolved at long baselines;

•There is evidence for small oscillations in the visibility curves.

The accretion disk model:

Fitting SED and visibility curves:



Constraints on the accretion disk:

- Exploring all the disk parameter space is impossible - one has to put some thought in the fitting step (slightly resolved object)
- External constraints are crucial :SED, veiling etc...
- two color constraints: the standard accretion disk model still holds.

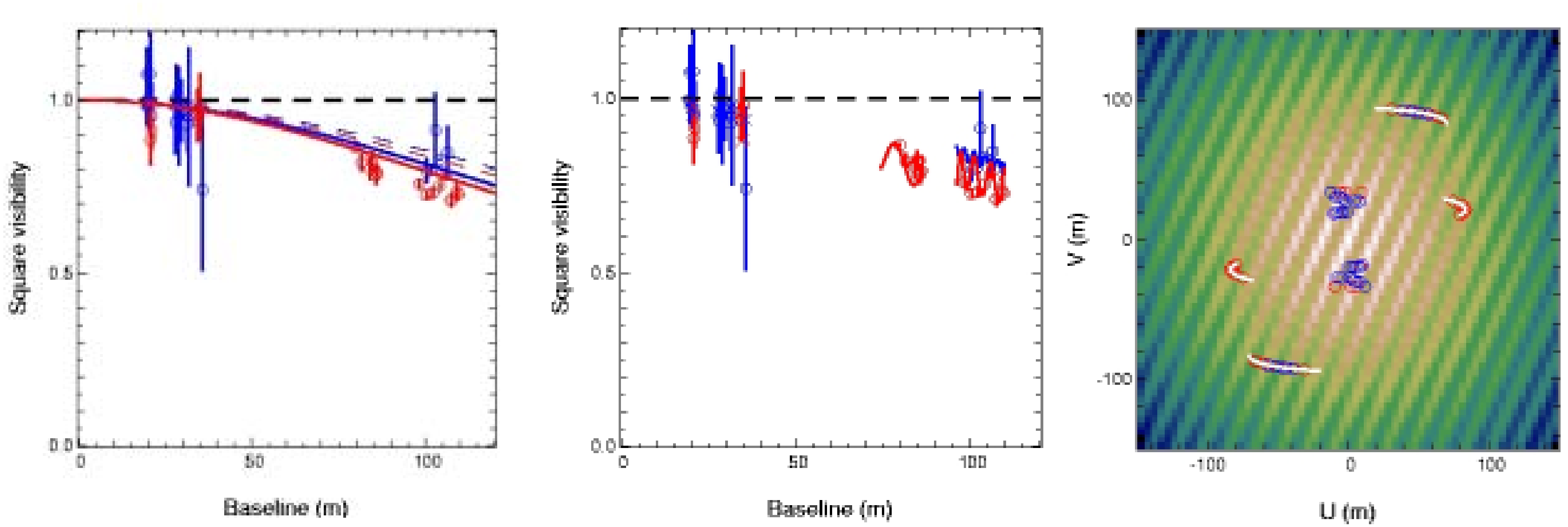
$$T \approx r^{-3/4} \quad \dot{M} = 4.10^{-5} M_{\Theta} / yr \quad A_V \approx 1.2$$

Compatible with current Fu Ori picture

Unexpected features:

The visibility model:

$$V(u,v) = \frac{1}{(1+r_{12})^2}[r_{12}^2 + V_2^2(u,v) + 2r_{12}V_2(u,v)\cos(\phi_2 - \phi_1 + 2\pi\vec{B}\vec{s})]$$



Companion ?
Other alternatives (hot spot) ?

→ $\Delta H \approx 3.8$, $\Delta K \approx 5.2$, $\rho \approx 36.5 mas$ → **Information on outburst source**

Conclusion

- Interferometric observations challenge standard models.
- Fu Ori: a unique lab to study accretion disk theory.
- Rely first on simple models.
- Disk study (tre law, disk evolution ...) needs visibility accuracy (dynamic range) for which data calibration is crucial.
- 2 range of projected baselines minimum
- SED complementary information important but ...
- Expect to be surprised even if your model fits the SED.

YSO science with the VLTI

imaging not standard by-product but ...

A lot of exciting science

- **resolving multicolor structures TTS, HAeBe**

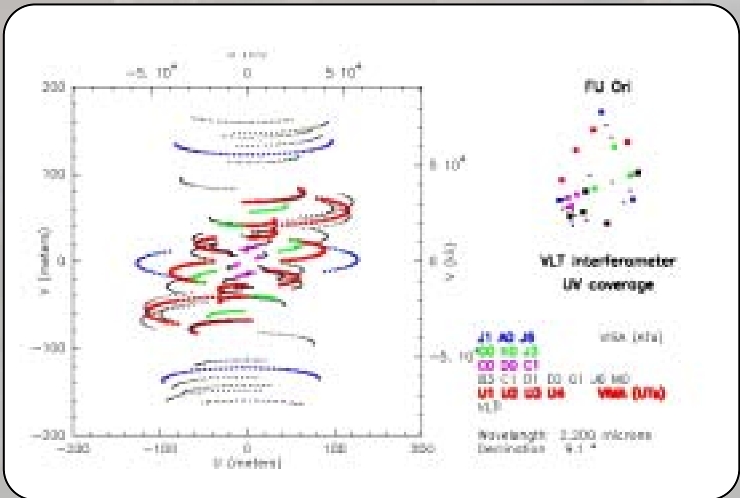
AMBER -MIDI will not probe the same part of the disk (thermal emission, scattering ...)

- **circumbinary disk-star interaction**

- **using spectral resolution:**

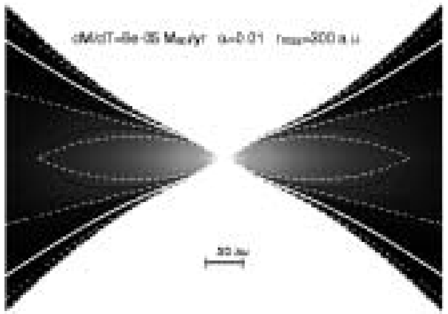
constraining wind physical properties, interaction with disk,
probing circumstellar dynamics (under certain conditions)

- **using closure phase closure information**



En attendant l'image Fu Ori

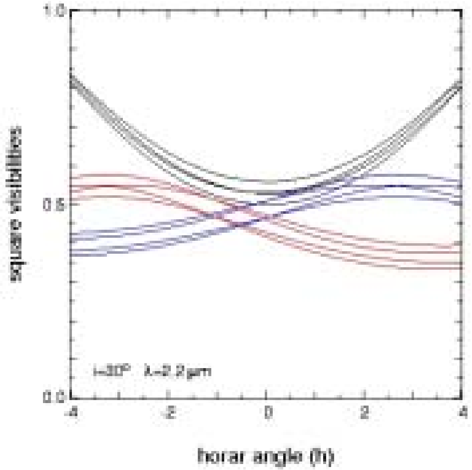
Collab: F. Malbet, R. Lachaume, J.L. Monin

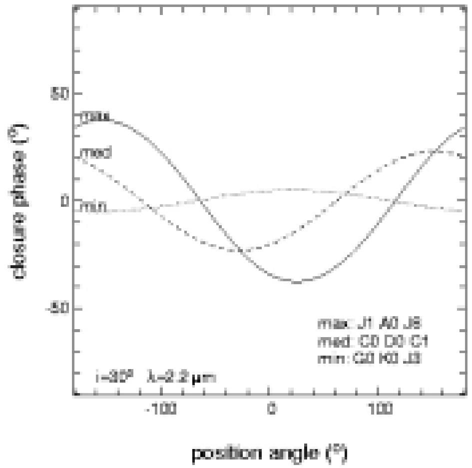


VLTI configurations :

- **J1 A0 J6 (max)**
- **C0 D0 C1 (med)**
- **G0 K0 J3 (min)**

Required accuracy: 1%





From Malbet et al, Spie, 2000