Probing gas and dust in the inner-most AU of protoplanetary disks with spectro-interferometry

Sagan/Michelson
Fellows Symposium

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Image: Calçada

Exploring the inner-most AU of protoplanetary disks

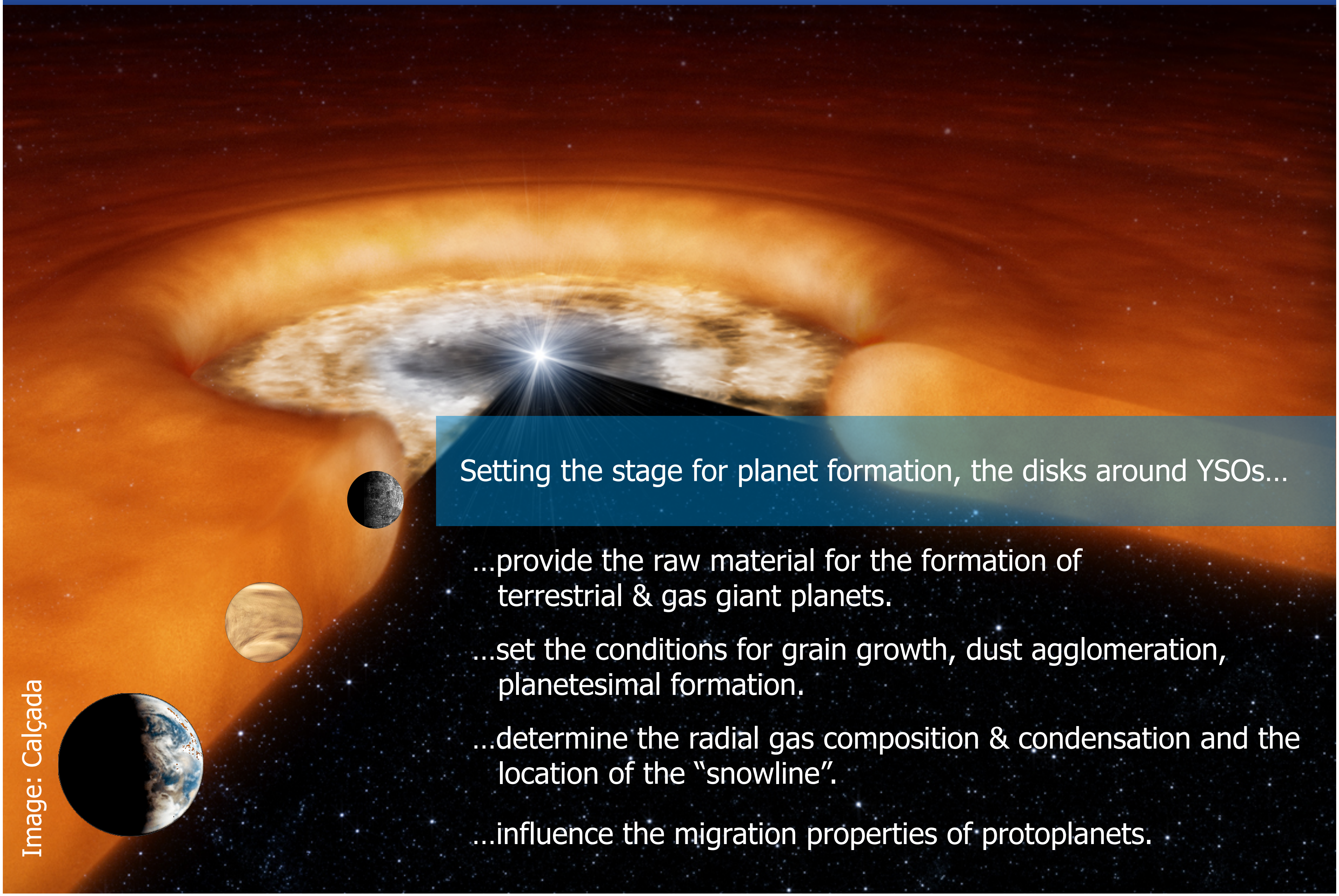


Image: Calçada

Setting the stage for planet formation, the disks around YSOs…

…provide the raw material for the formation of terrestrial & gas giant planets.

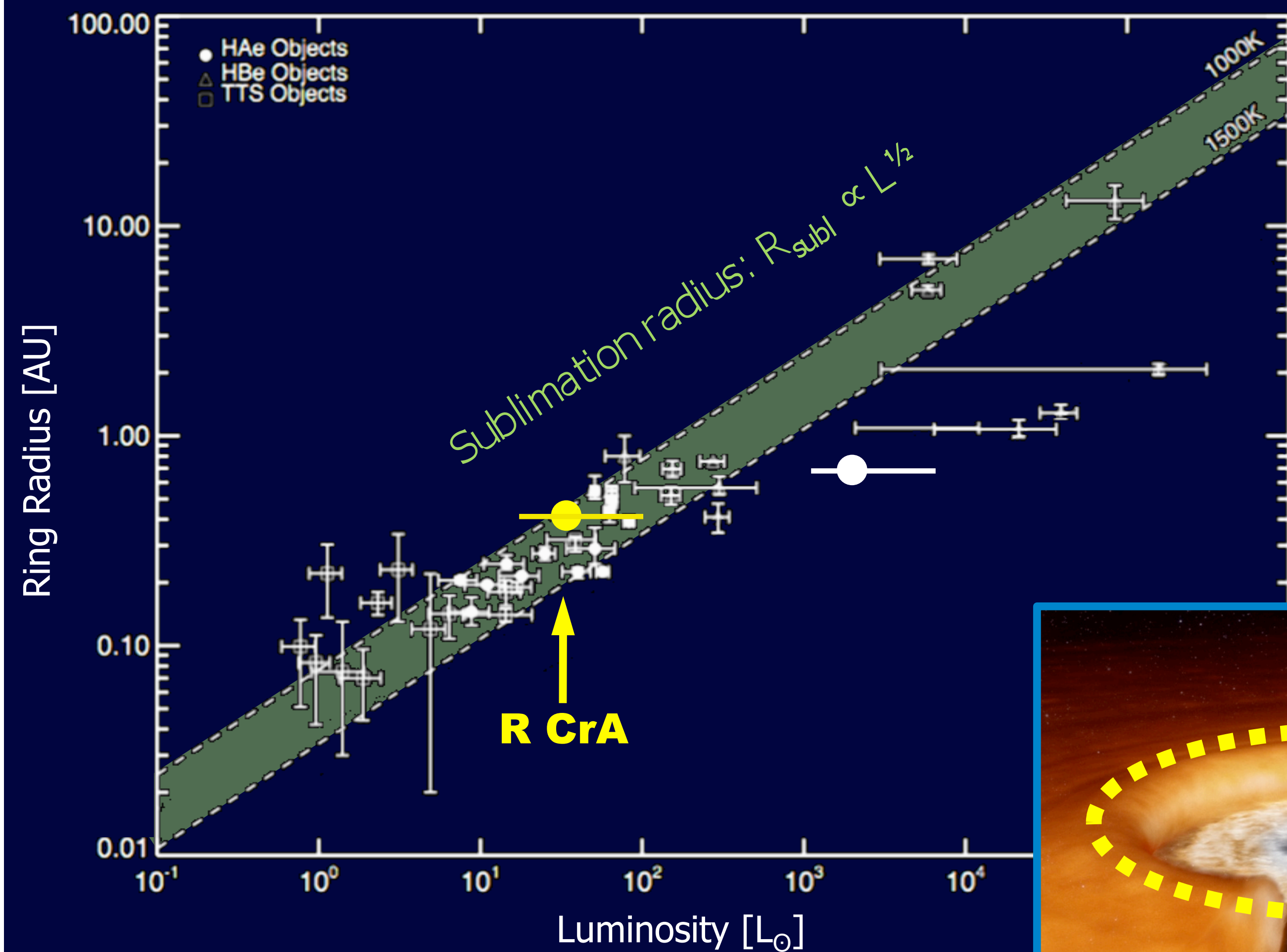
…set the conditions for grain growth, dust agglomeration, planetesimal formation.

…determine the radial gas composition & condensation and the location of the “snowline”.

…influence the migration properties of protoplanets.

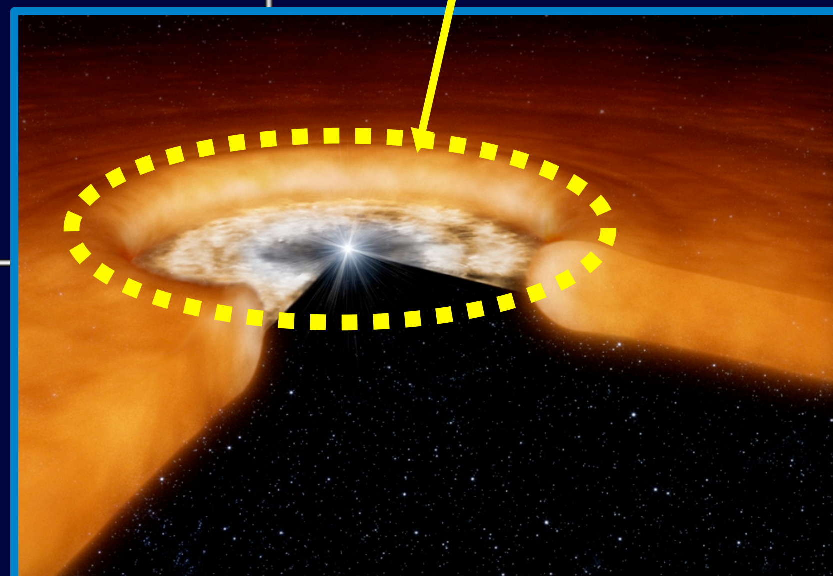
Constraints on the inner disk structure

Millan-Gabet et al., PPV



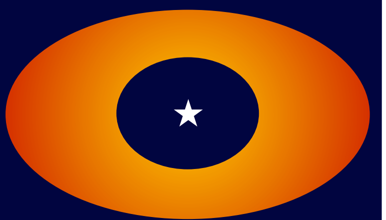
The measured NIR disk sizes scale roughly with $L_{\star}^{1/2}$ (Monnier et al. 2002/05)

➜ NIR emission is expected to trace mainly hot dust at the dust sublimation radius



Constraints on the inner disk structure

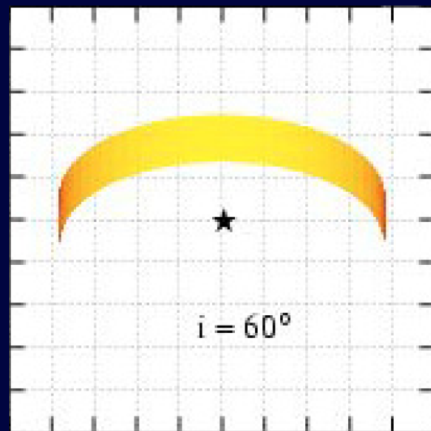
GEOM. FLAT DISK



e.g. temperature gradient models

No asymmetries (CP ≡ ZERO!)

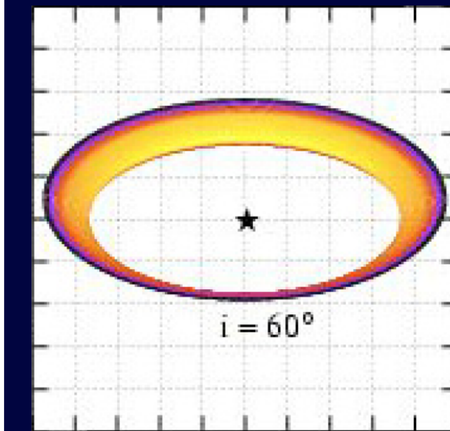
VERTICAL RIM



Natta et al. 2001
Dullemond et al. 2001

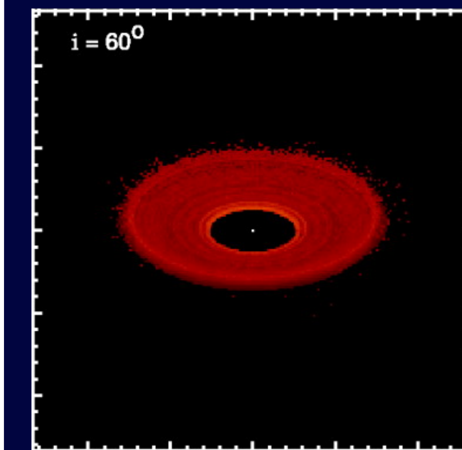
Strong asymmetries (strong CP signal)

CURVED RIM



Isella & Natta 2005

VERY CURVED RIM



Tannirkulam et al. 2007
Kama et al. 2009

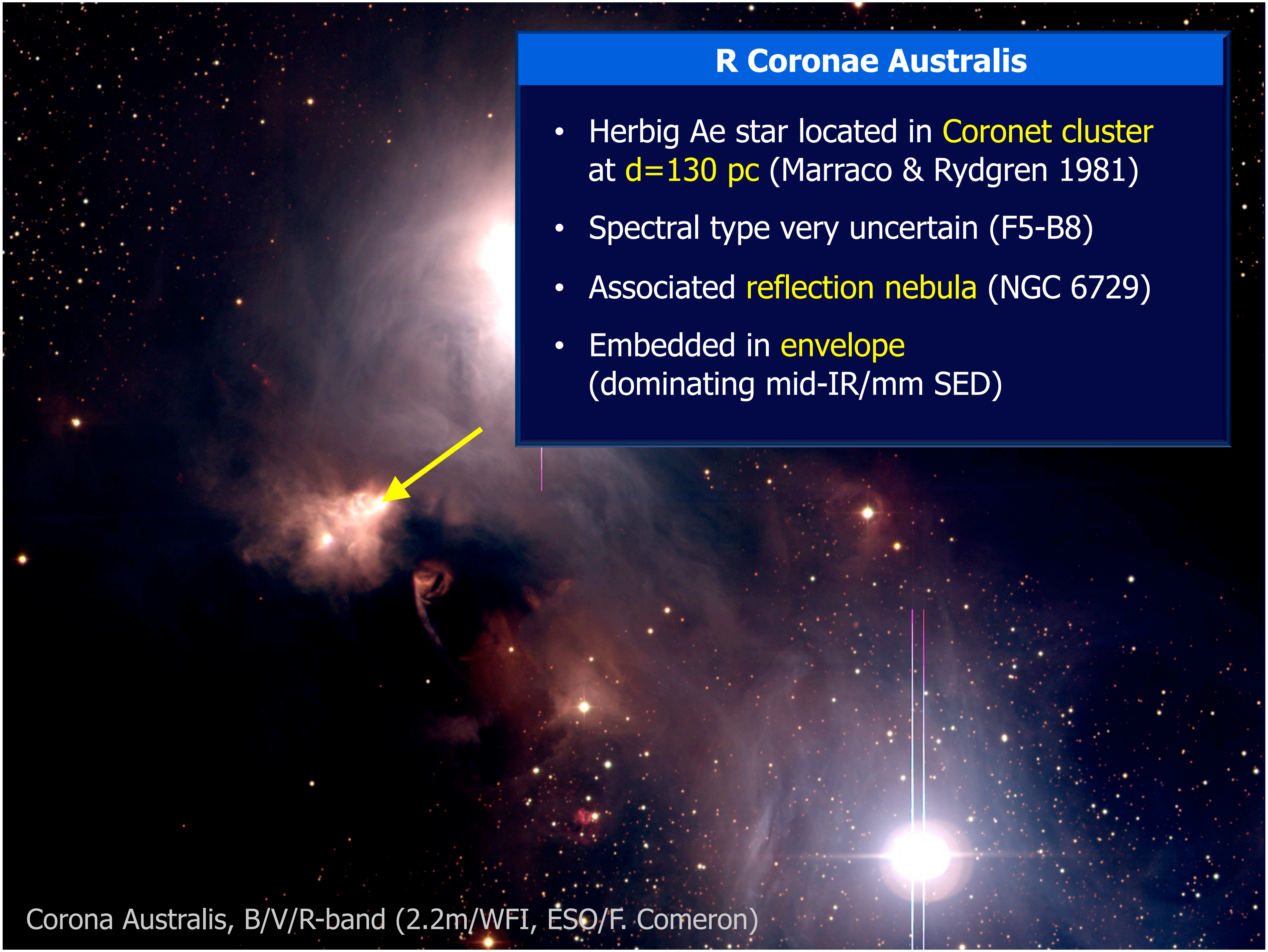
Weak asymmetries (weak CP signal)

Interferometric observables:

Visibilities ➜ measures object extension (in first order)
Closure Phases (CPs) ➜ measures deviations from point-symmetry

R Coronae Australis

- Herbig Ae star located in Coronet cluster at d=130 pc (Marraco & Rydgren 1981)
- Spectral type very uncertain (F5-B8)
- Associated reflection nebula (NGC 6729)
- Embedded in envelope (dominating mid-IR/mm SED)



Corona Australis, B/V/R-band (2.2m/WFI, ESO/F. Comeron)

VLTI Spectro-Interferometry

Long-baseline interferometry meets spectroscopy

VLTI Science Instruments:

AMBER (3T): 1-2.5 μm $\lambda/\Delta\lambda$=35,1500,12000

MIDI (2T): 8-13 μm $\lambda/\Delta\lambda$=30,230

Infrastructure:

4 × 8.2m Unit Telescopes

4 × 1.8m Auxiliary Telescopes

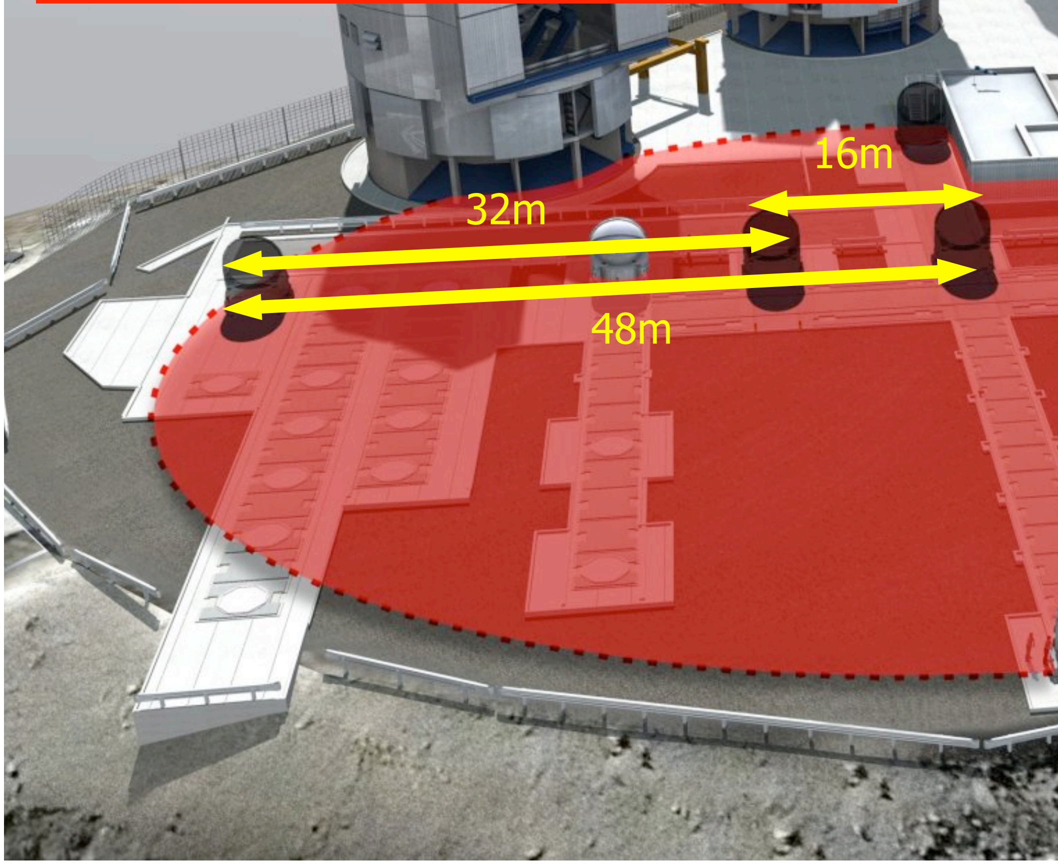
FINITO: Fringe Tracking

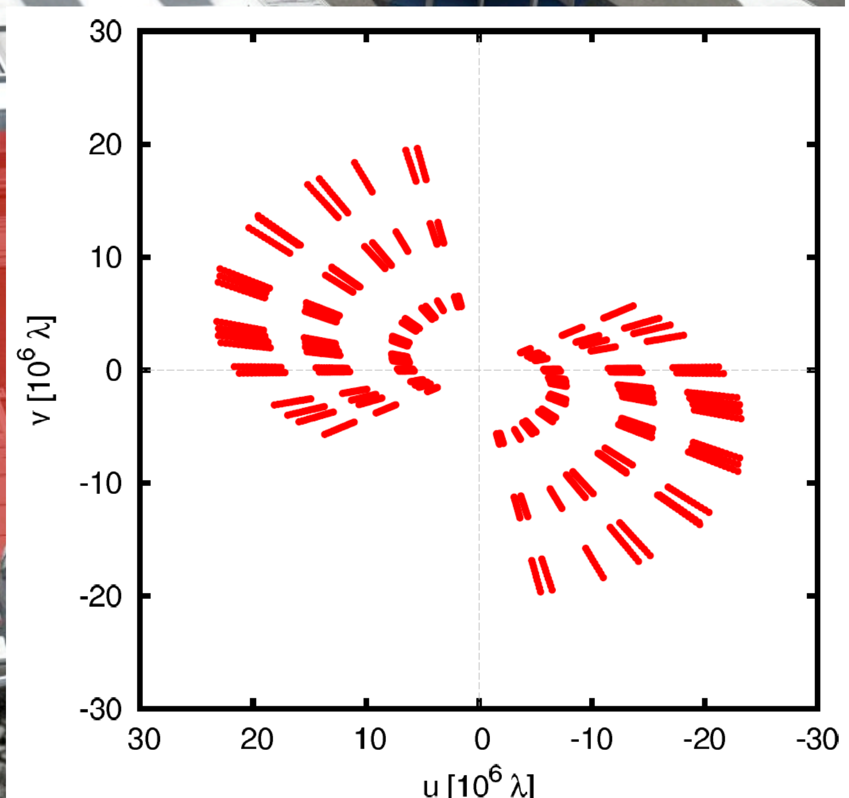
R CrA: Revealing the asymmetries of the inner dust rim

VLTI/AMBER observations

24 AMBER observations with 3 ATs
(during 4 nights in June 2008)

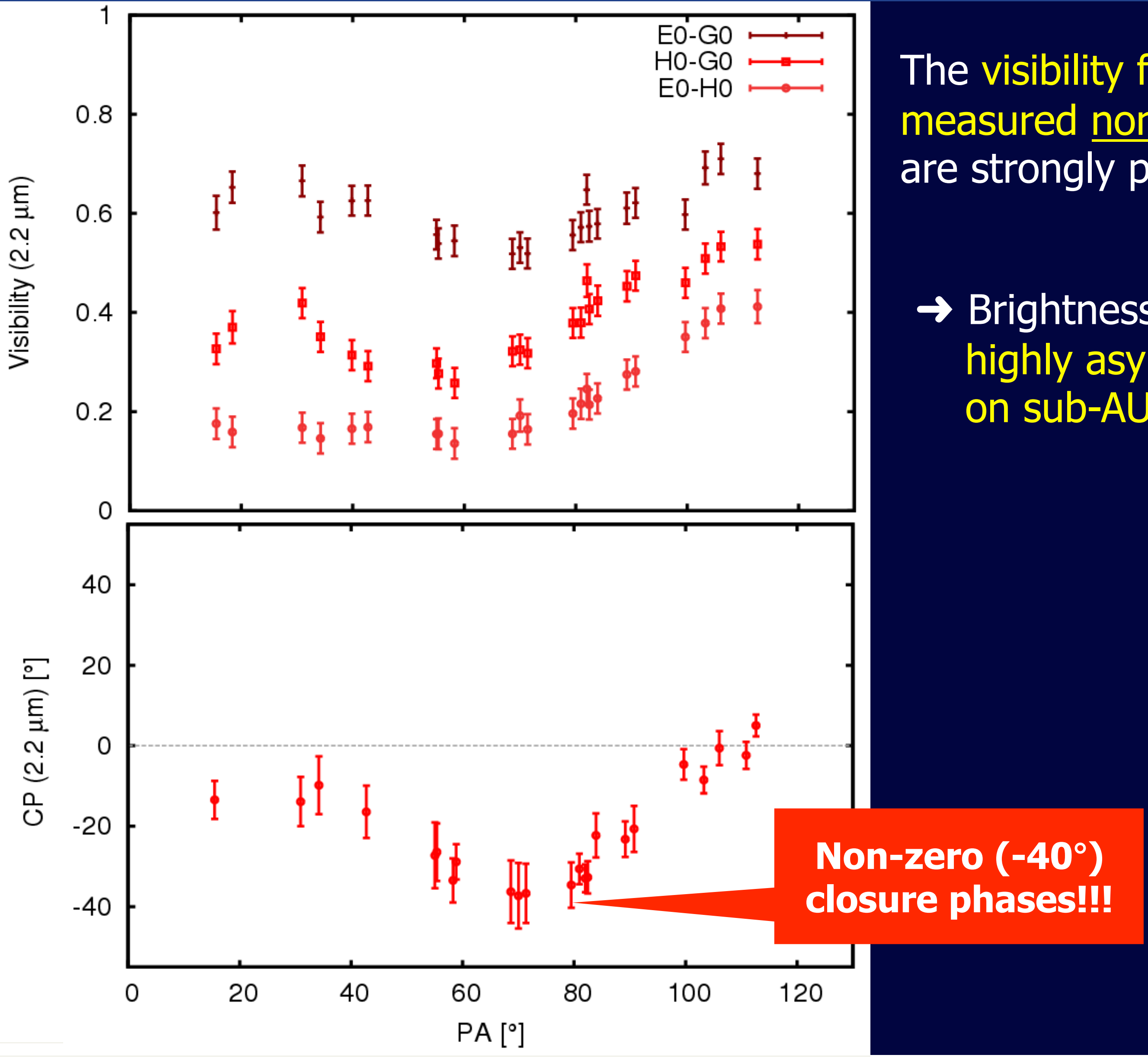
H+K band (1.6-2.5 μm), $\lambda/\Delta\lambda=35$
E0-G0-H0 telescope triplet





R CrA: Revealing the asymmetries of the inner dust rim

Position-angle dependence of visibilities & CPs

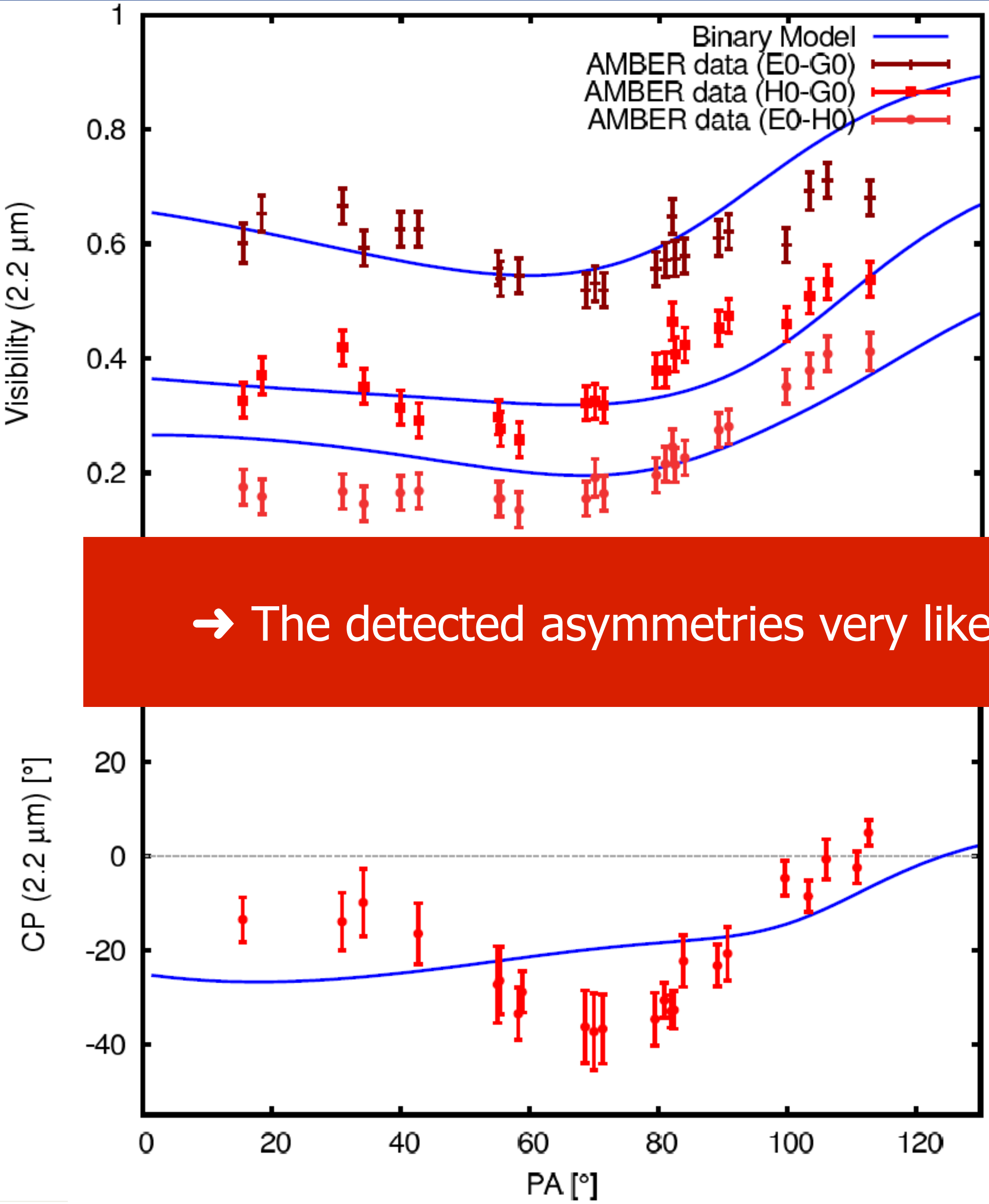


The visibility function and the measured non-zero closure phases are strongly position angle-dependent!

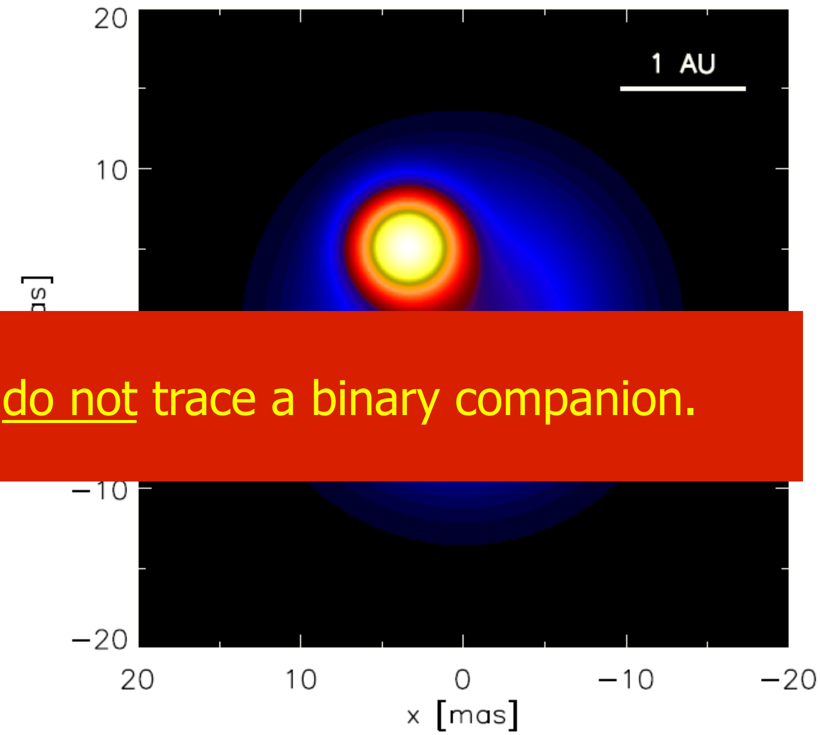
➜ Brightness distribution is highly asymmetric on sub-AU scales!

R CrA: Revealing the asymmetries of the inner dust rim

BINARY STAR model



Scenario:
Close binary system
(possibly with resolved disks)

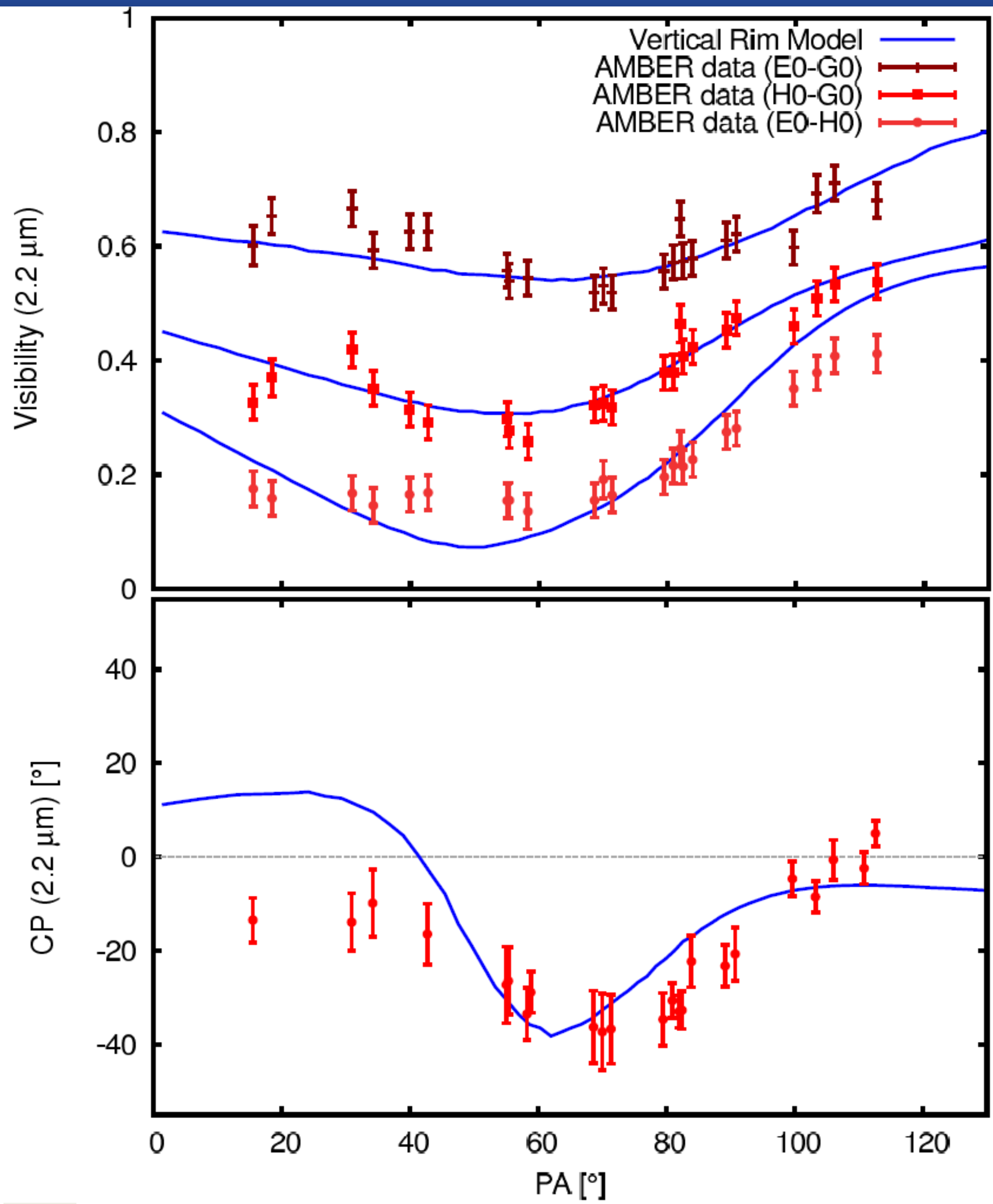


➜ The detected asymmetries very like do not trace a binary companion.

$\chi^2 = 3.9$

R CrA: Revealing the asymmetries of the inner dust rim

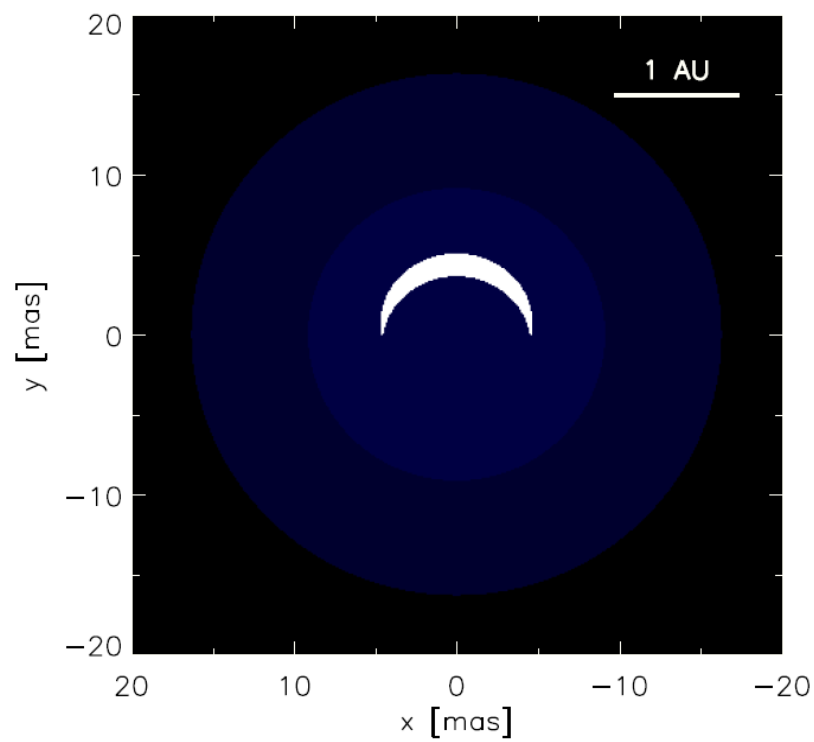
VERTICAL RIM model



Scenario:

Vertical puffed-up inner rim

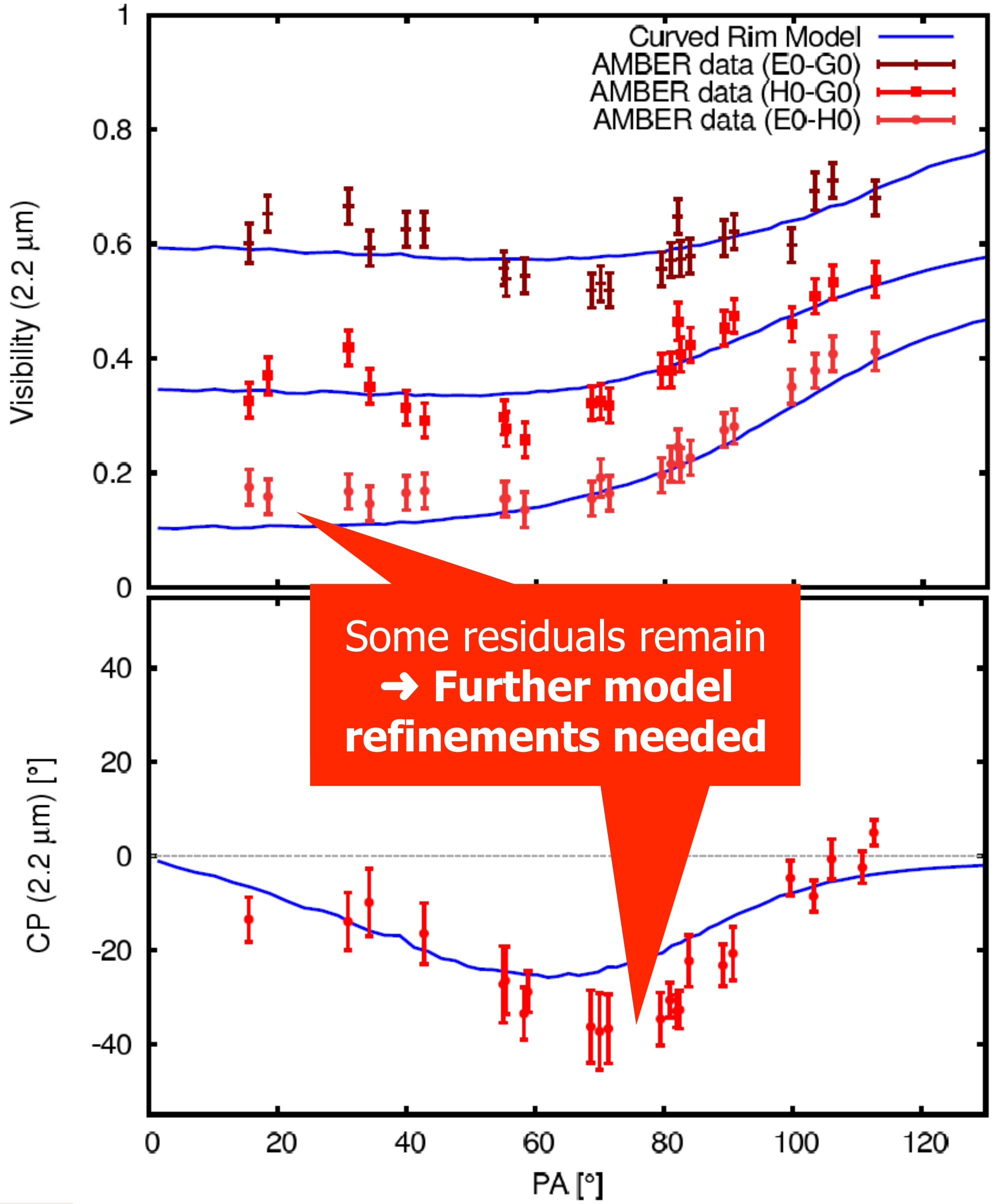
(motivated by Dullemond et al. 2001)



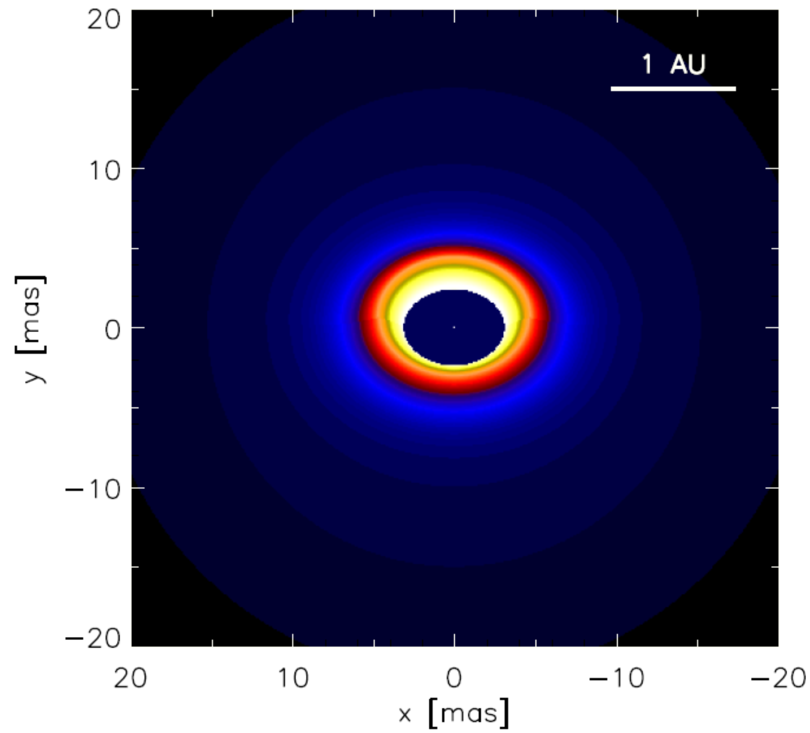
$\chi^2 = 3.3$

R CrA: Revealing the asymmetries of the inner dust rim

CURVED RIM model (1/2)



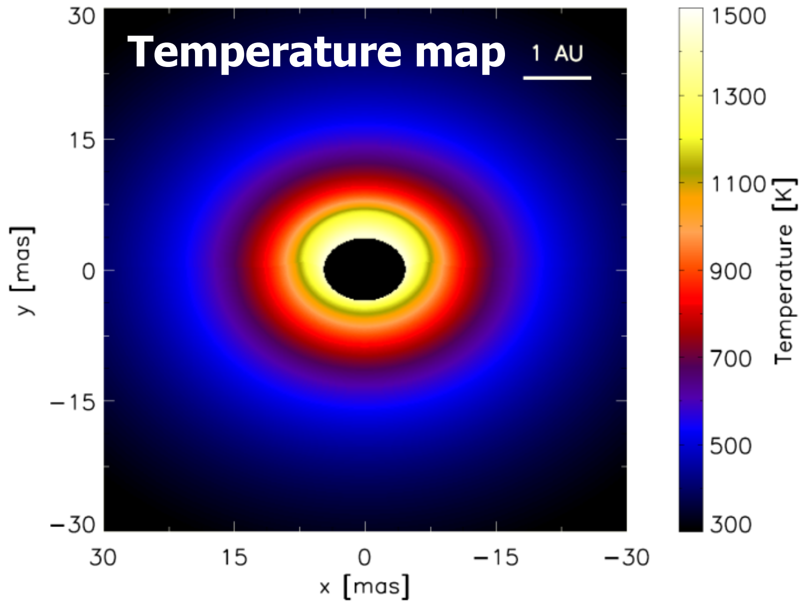
Scenario:
Curved puffed-up inner rim
(following Isella & Natta 2005)

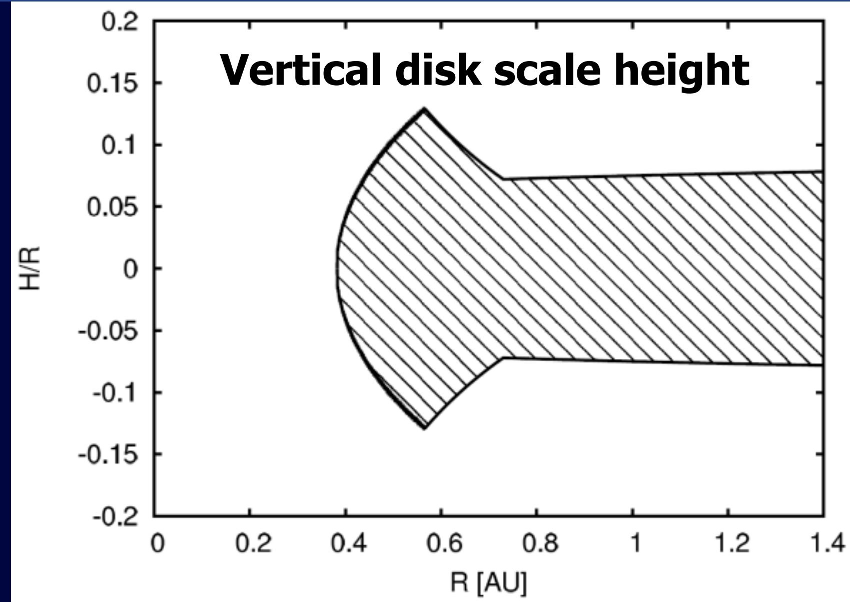


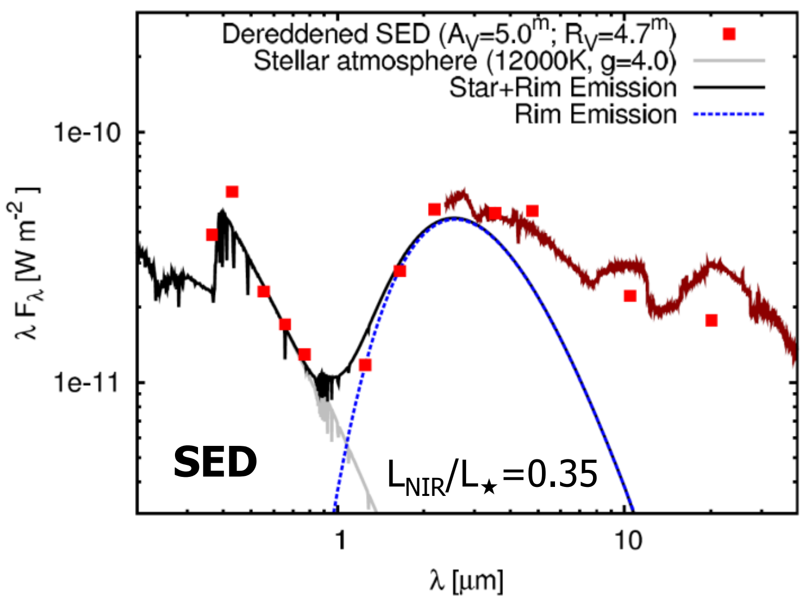
$\chi^2 = 2.1$

R CrA: Revealing the asymmetries of the inner dust rim

CURVED RIM model (2/2)







STAR:

Luminosity: 29 $L_\odot$

DISK:

Inclination: $i = 35°$

Disk orientation: $\phi = 90°$ (N-S)

Dust cooling efficiency: $\varepsilon \geq \varepsilon_{cr}$ (large grains)

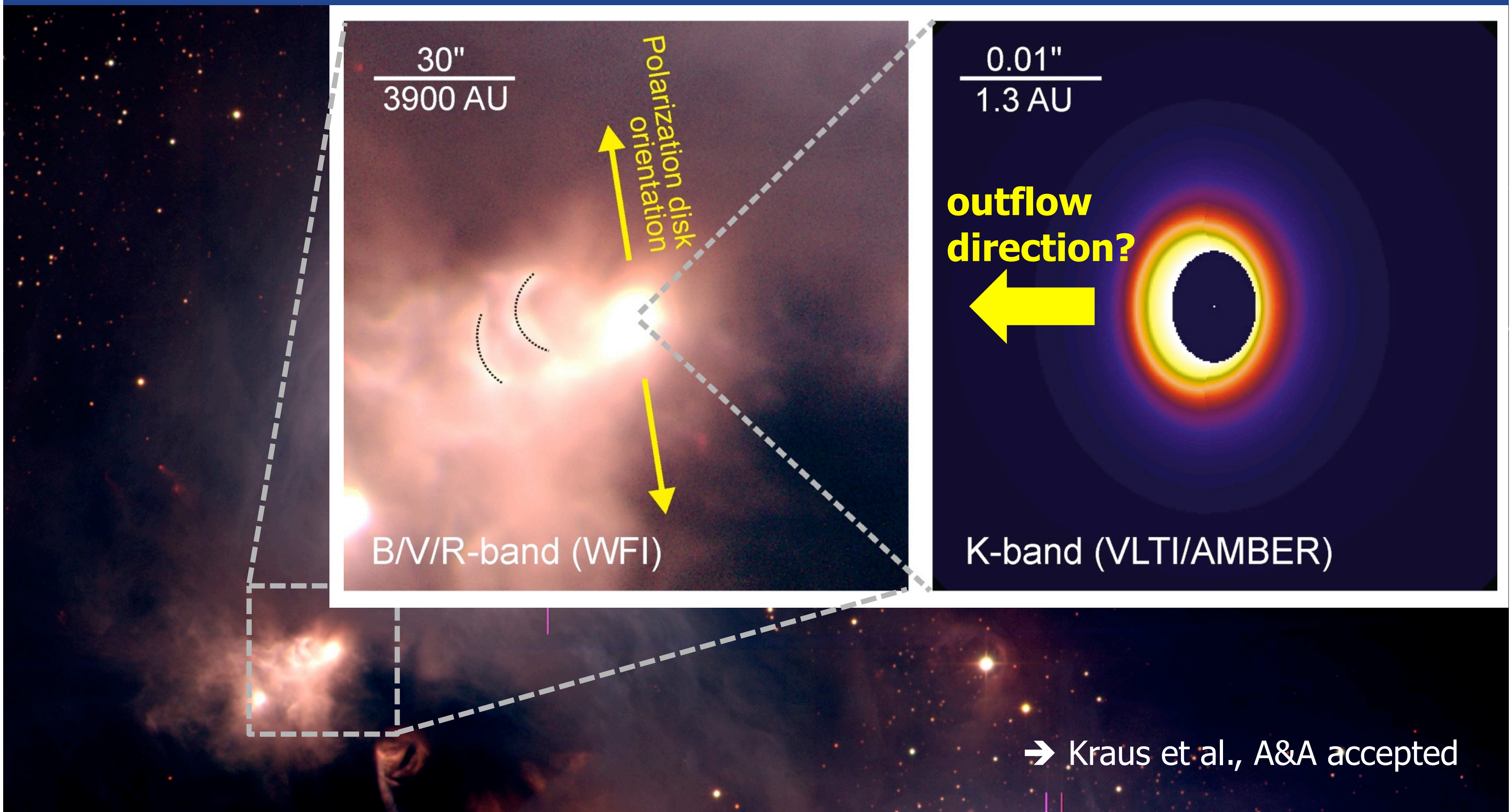
ENVELOPE:

Gauss FWHM: 32 mas

I_{env}/I_{total} 1/3

R CrA: Revealing the asymmetries of the inner dust rim

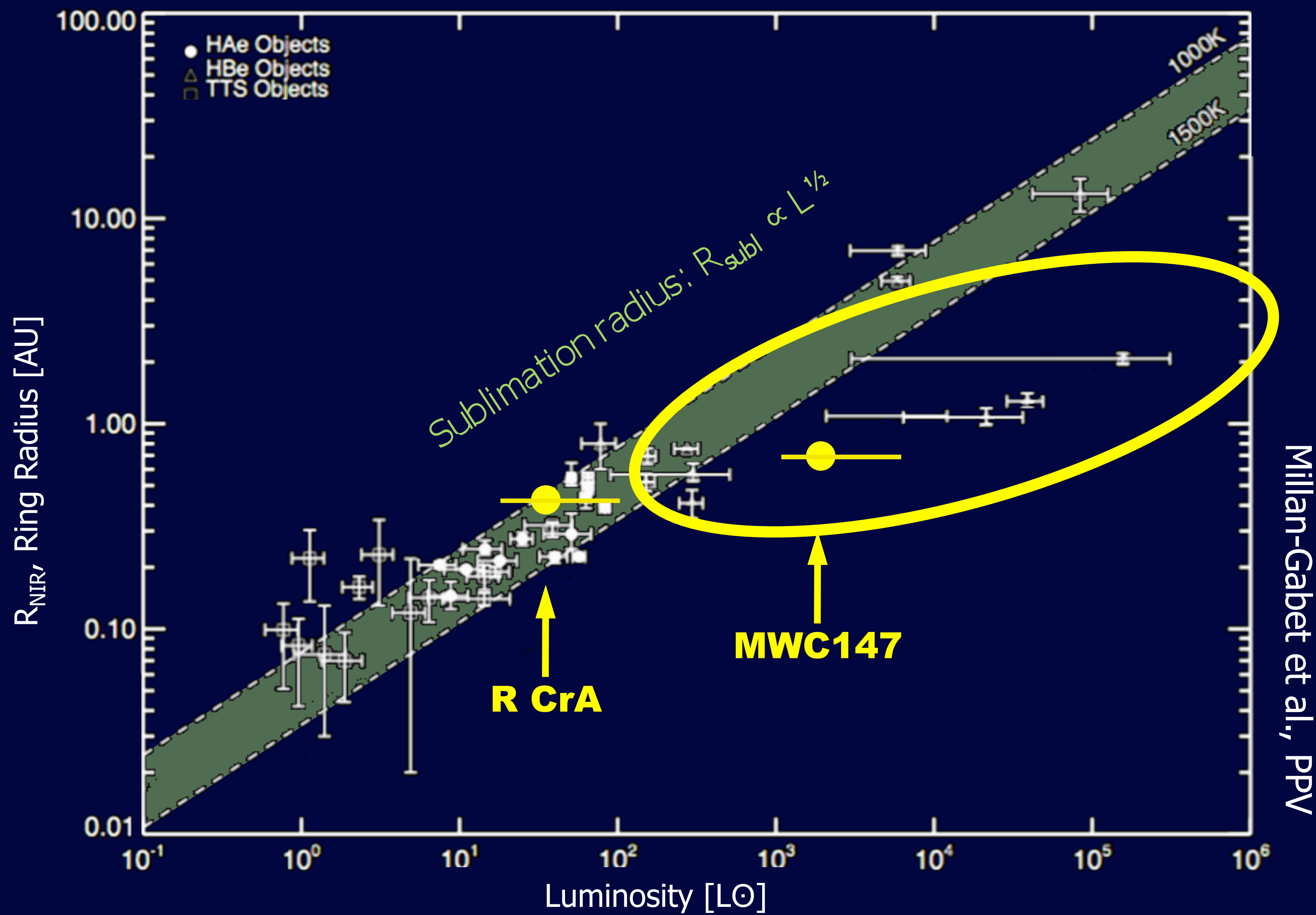
Comparison with large-scale structure



➔ Kraus et.al., A&A accepted

- Derived disk orientation is consistent with polarization disk (Ward-Thompson et al. 1985)
- Bow shock-like features appear roughly perpendicular to disk plane

Constraints on the inner disk structure

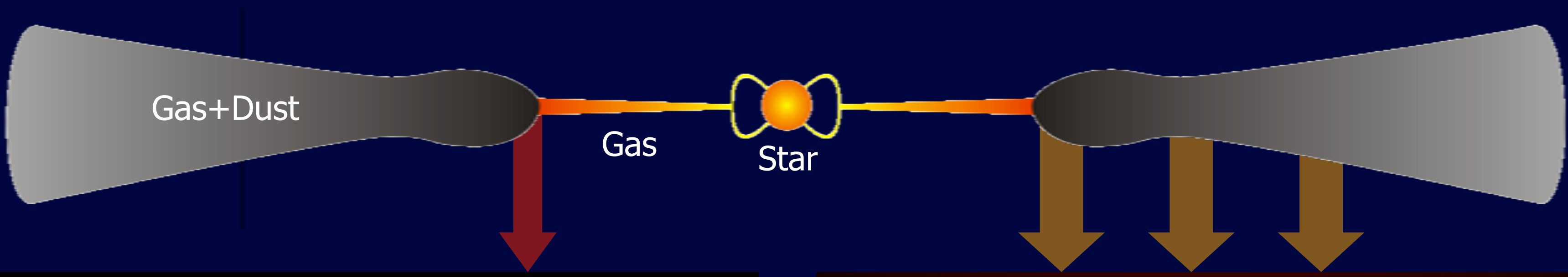


NIR broadband interferometric studies found a population of "undersized" Herbig Be disks (e.g. Monnier et al. 2005, Eisner et al. 2005, Vinković & Jurkić 2007, Tannirkulam et al. 2008)

Constraining the disk temperature distribution

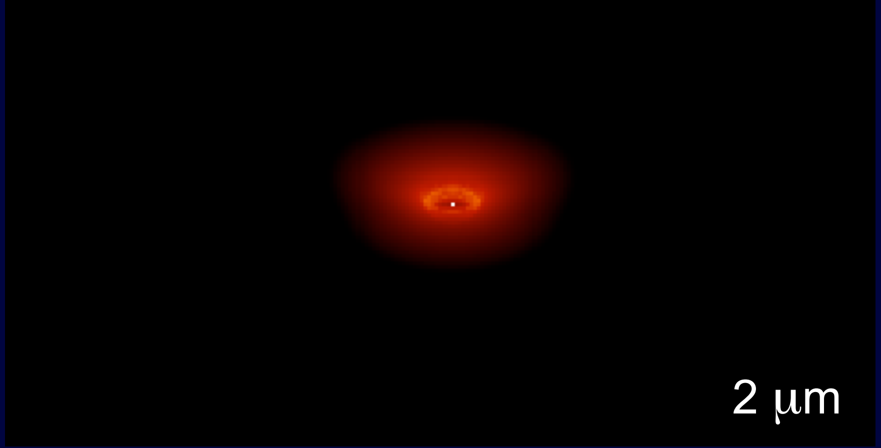
using combined NIR/MIR spectro-interferometry

The near- and mid-infrared emission probe different regions:



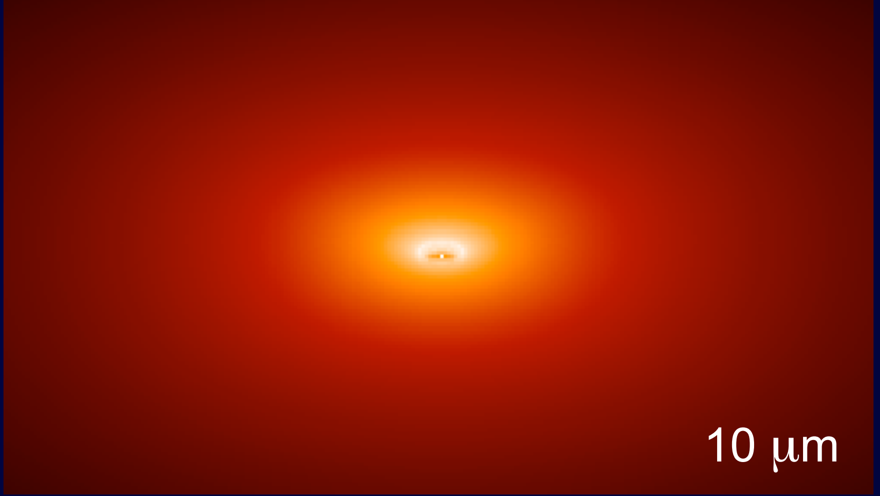
NIR:

usually dominated by hot dust **(~1500 K)** at the inner dust rim + scattered light



MIR:

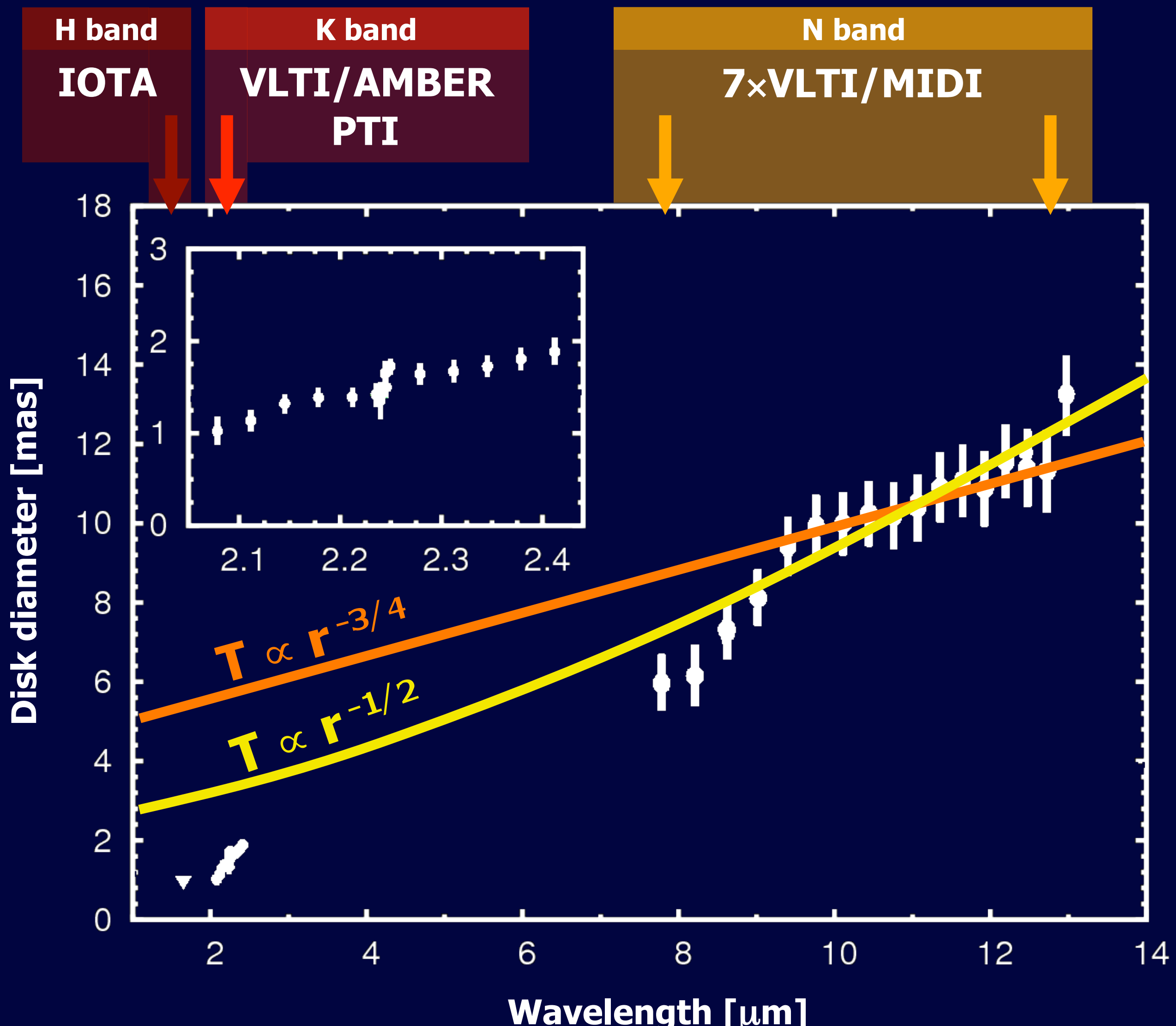
hot & warm dust **(1500-300 K)**

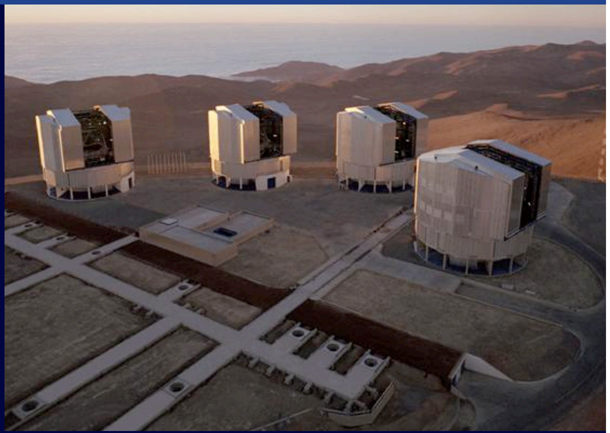


Joint NIR/MIR spectro-interferometry probes simultaneously the geometry of the disk and the physical conditions, e.g. radial temperature profile, dust mineralogy, …

MWC 147: Detection of an hot inner disk component

NIR/MIR spectro-interferometry on MWC 147





MWC 147: Herbig Be star (B6, M≈7 $M_\odot$, d=800 pc)

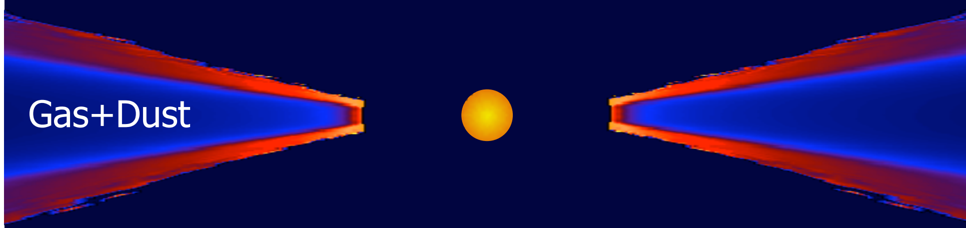
Analytic temperature-power-law models for irradiated or viscous disks ($T \propto r^{-1/2}$ or $T \propto r^{-3/4}$) cannot reproduce the measured wavelength-dependent apparent disk size

→ Detailed physical modeling required

MWC 147: Detection of an hot inner disk component

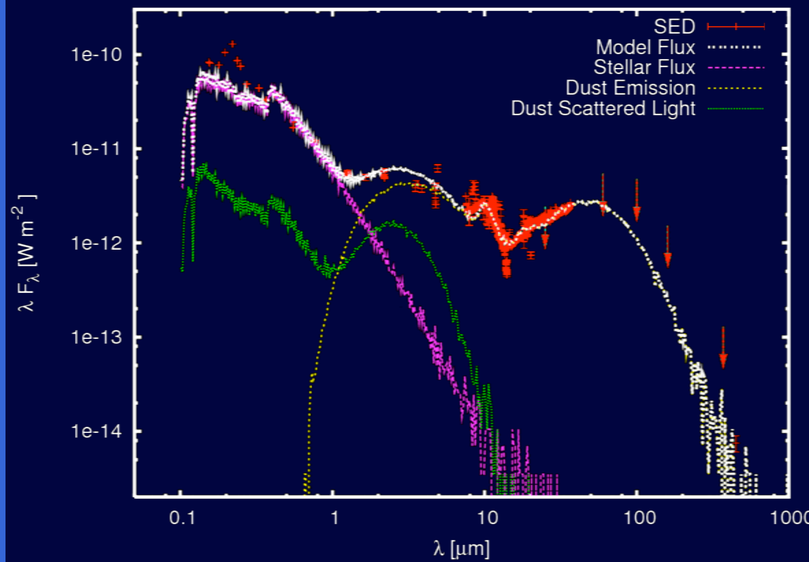
Passive disk model

Circumstellar dust disk
+ Envelope

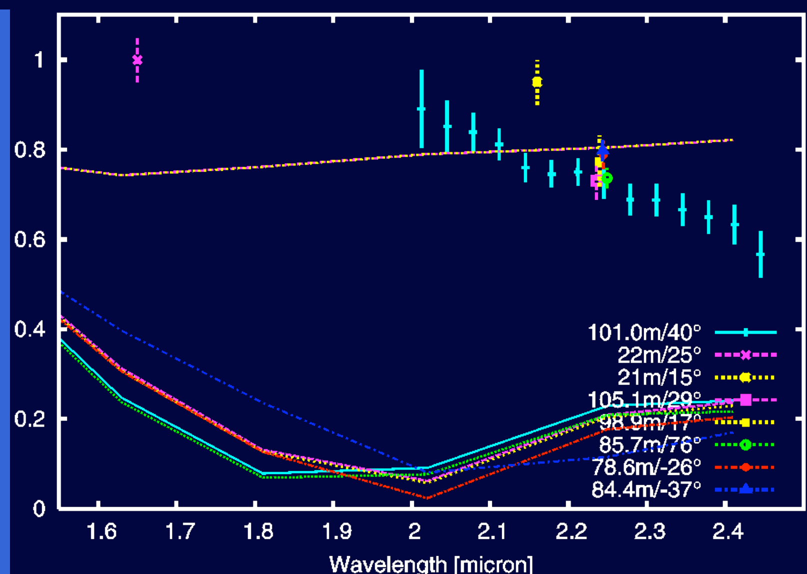


$\chi^2 = 42$

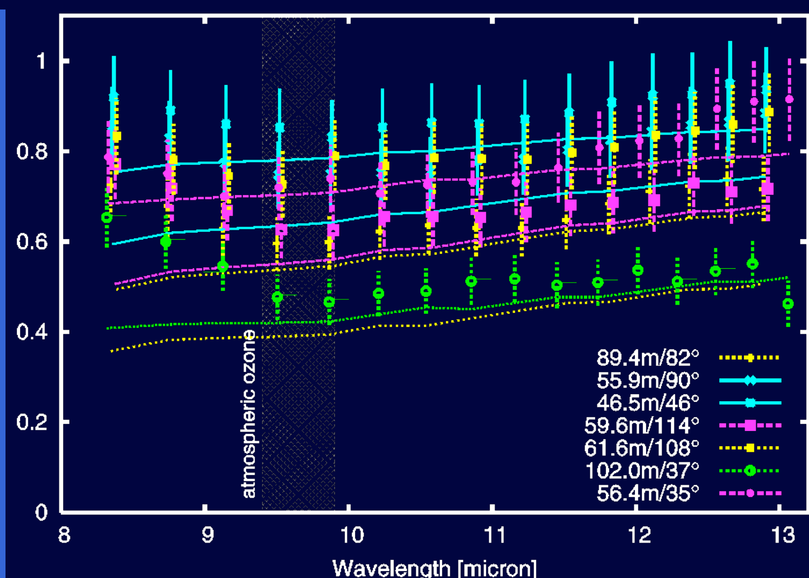
SED



NIR visibilities



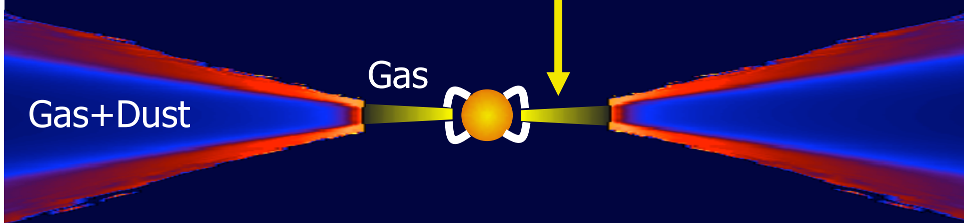
MIR visibilities



MWC 147: Detection of an hot inner disk component

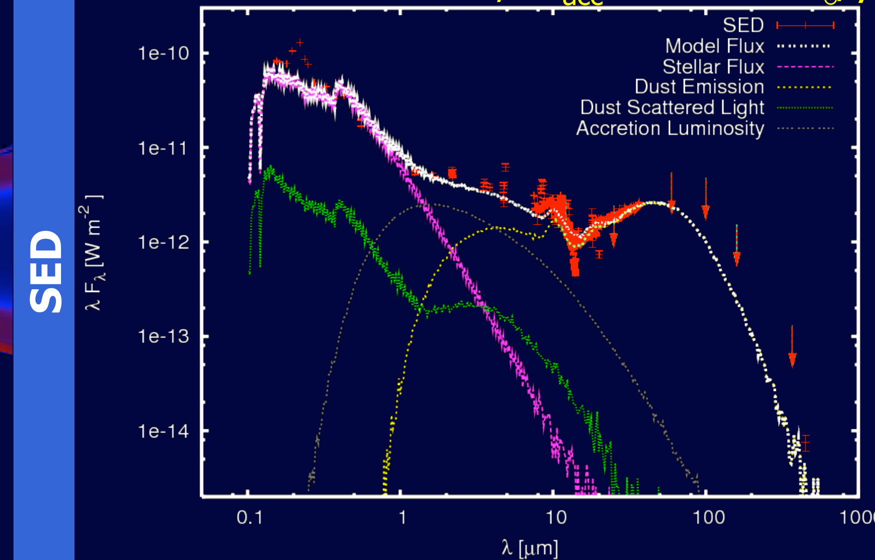
Disk with hot inner emission component

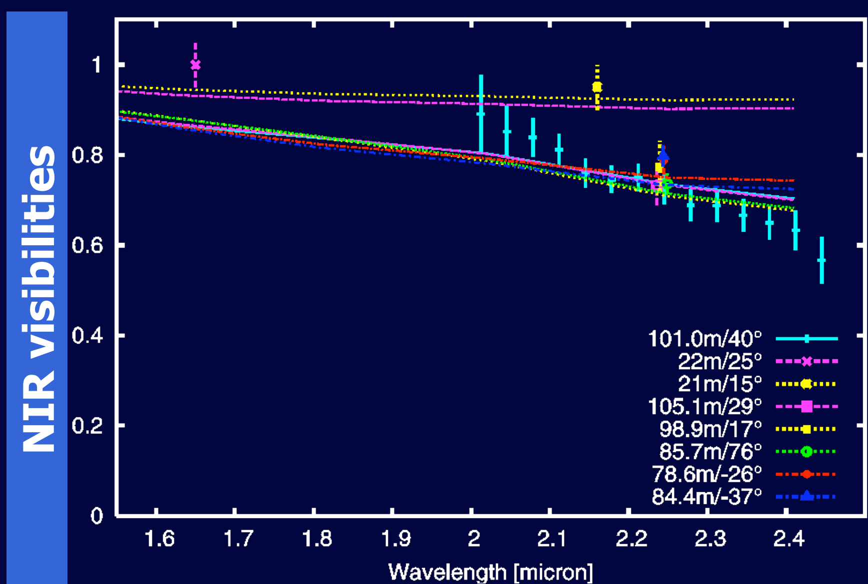
Circumstellar disk with optical thick gas located inside of the dust sublimation radius + Envelope

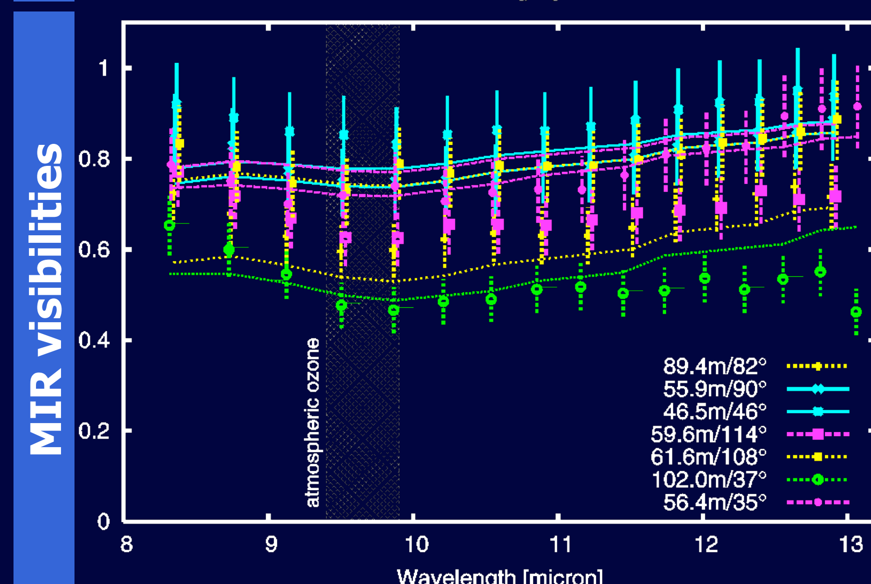


$\chi^2 = 1.3$

Inclination: 60°, $\dot{M}_{acc} = 9 \times 10^{-6}\ M_{\odot}/yr$

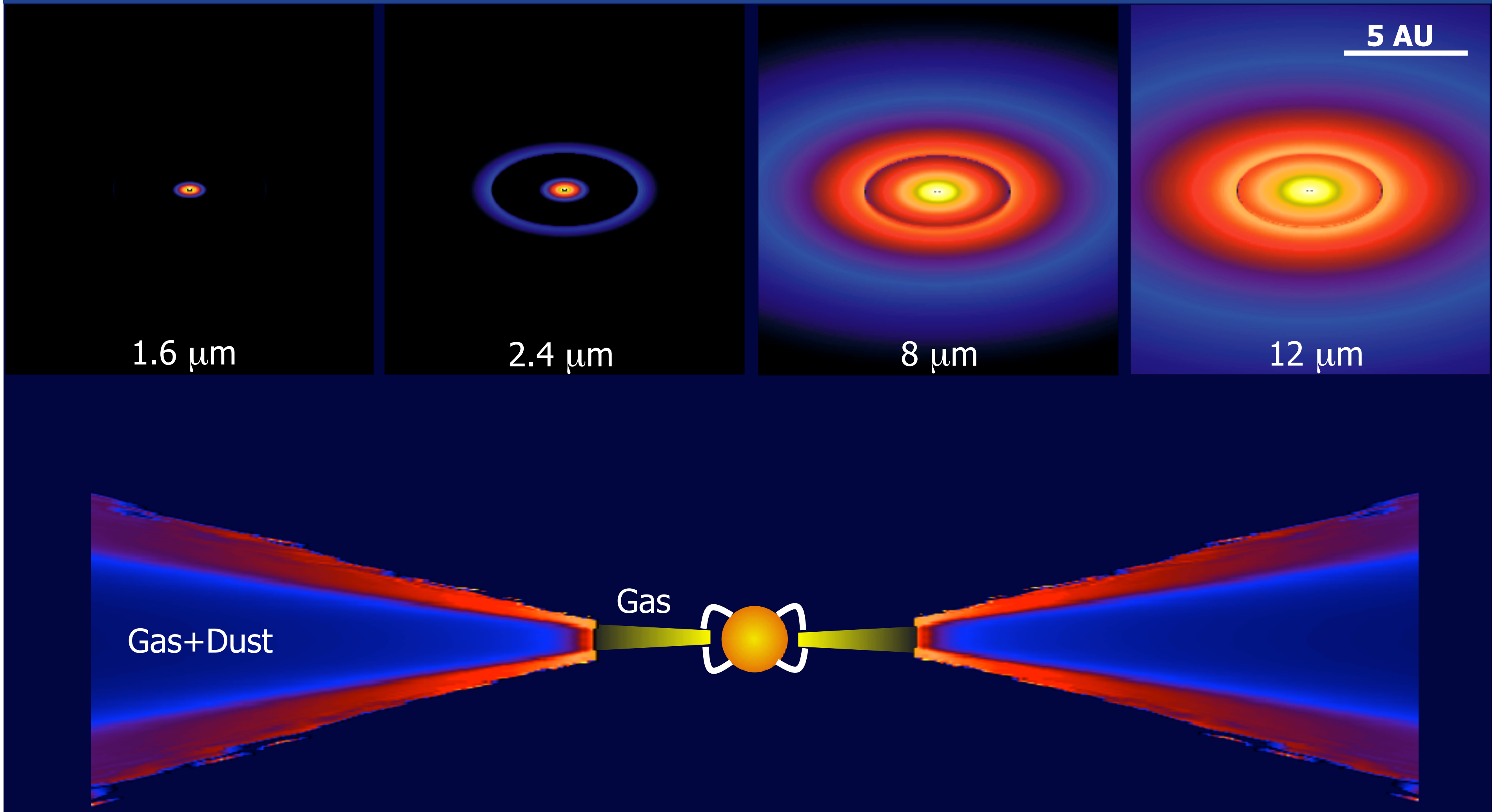






MWC 147: Detection of an hot inner disk component

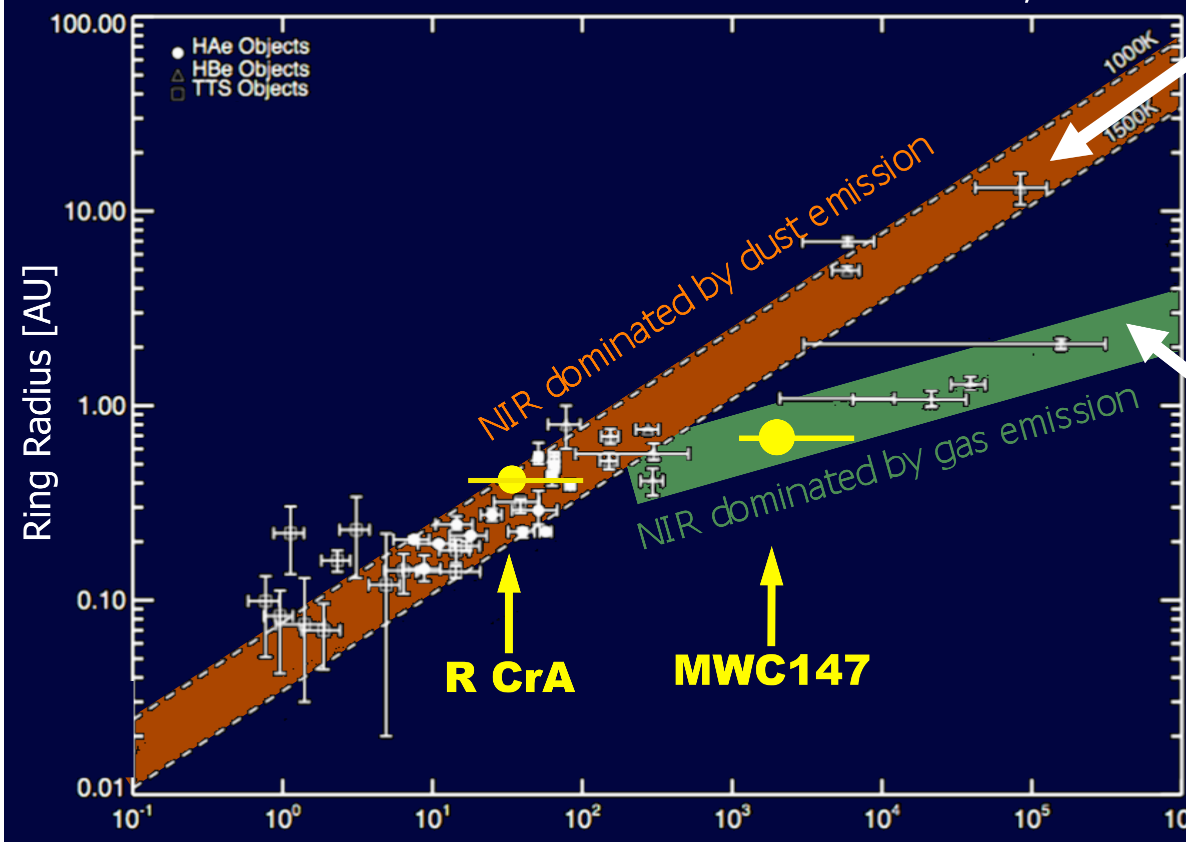
Best-fit radiative transfer model

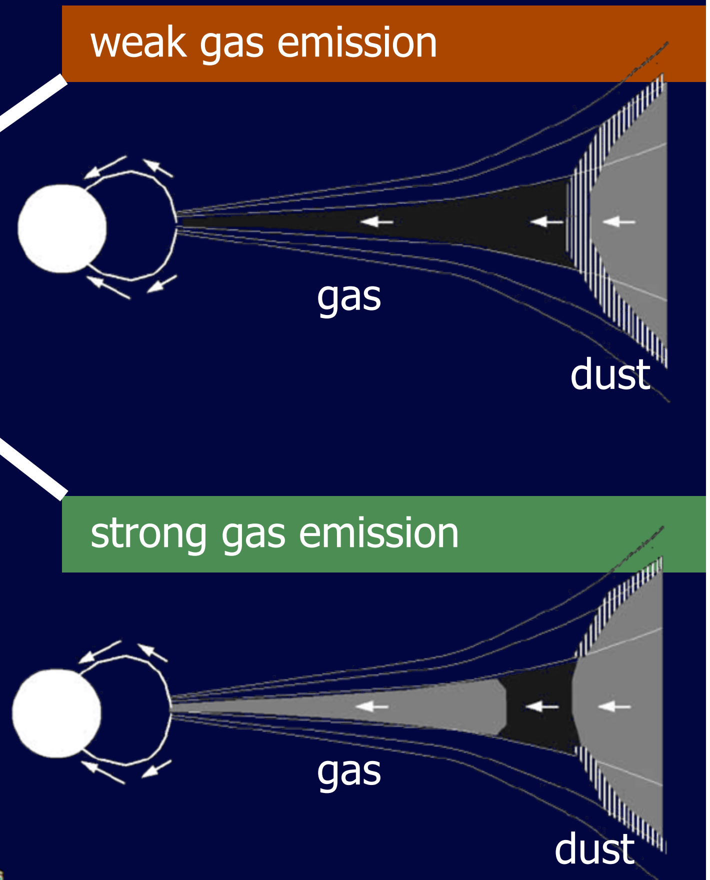


➔ Kraus et al. 2008, ApJ 676, 490

Dust & gas in the inner-most AU

Millan-Gabet et al., PPV

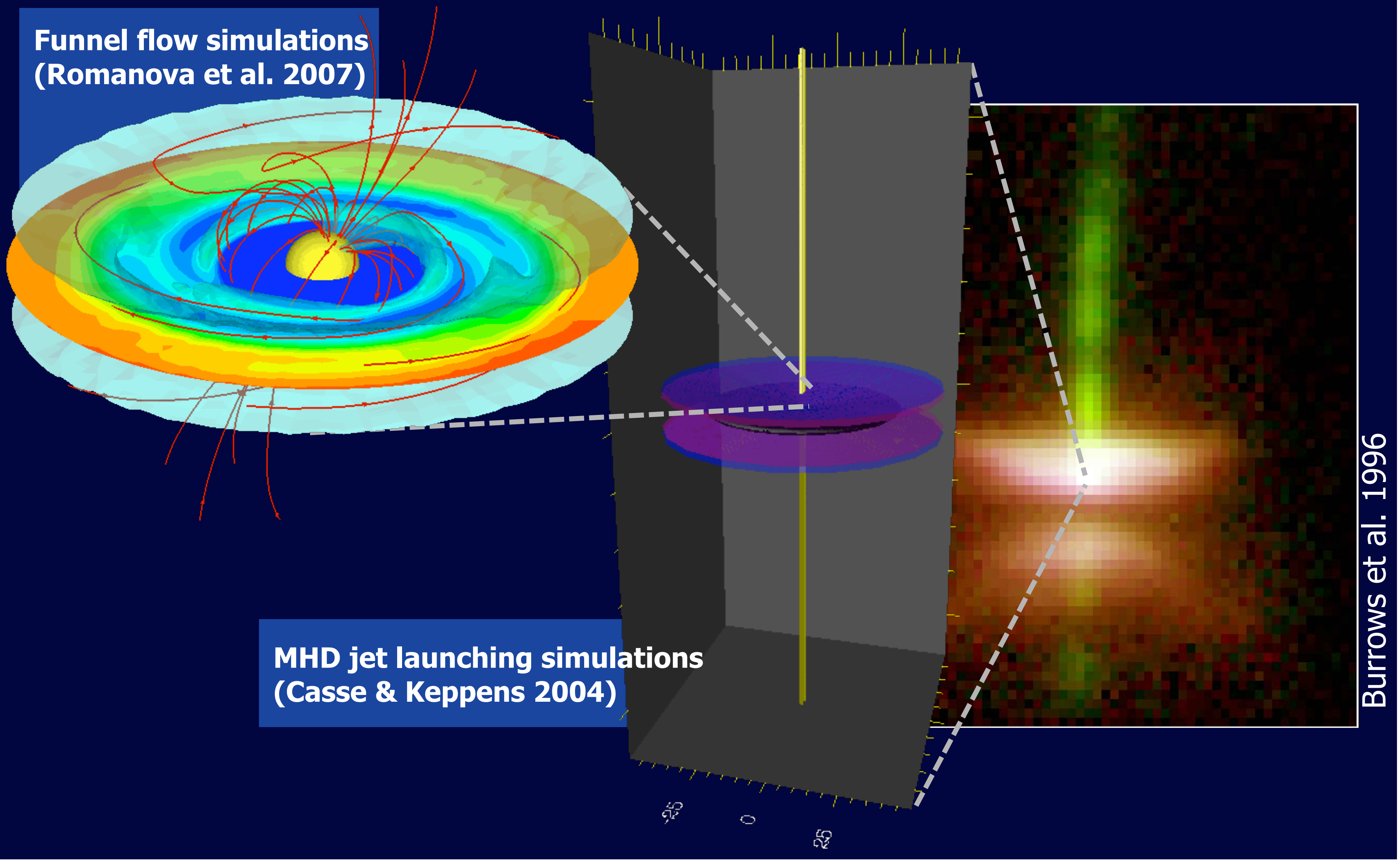




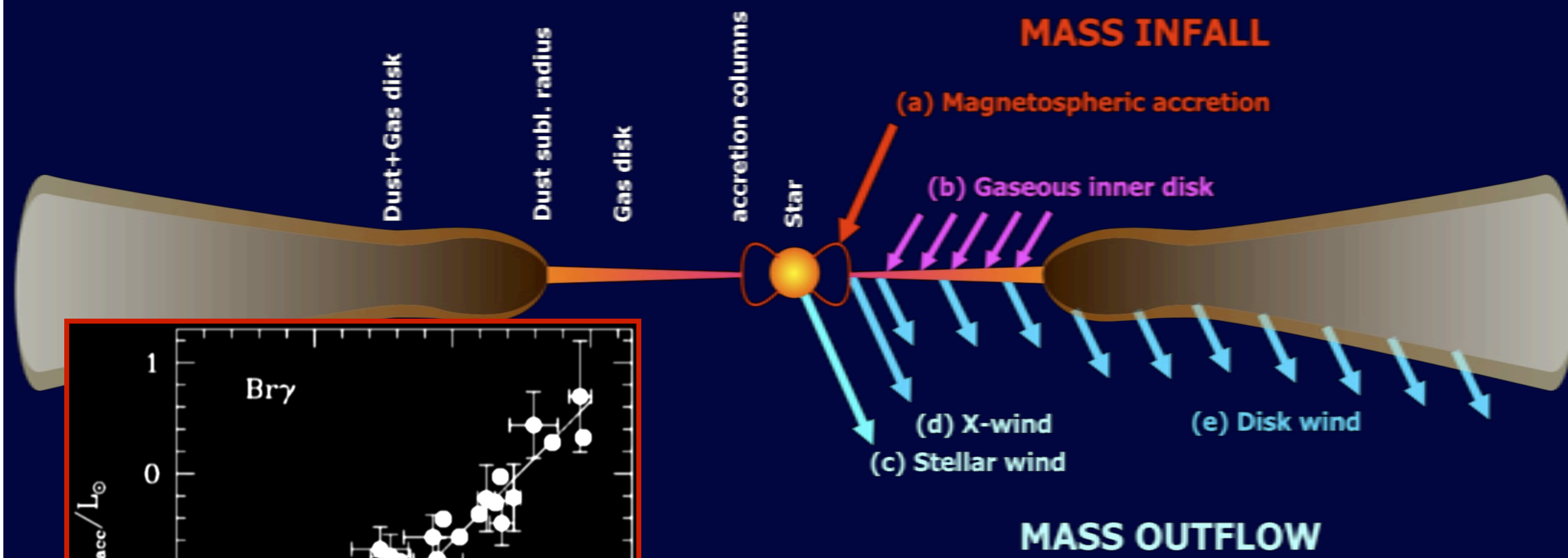
Muzerolle et al. 2004

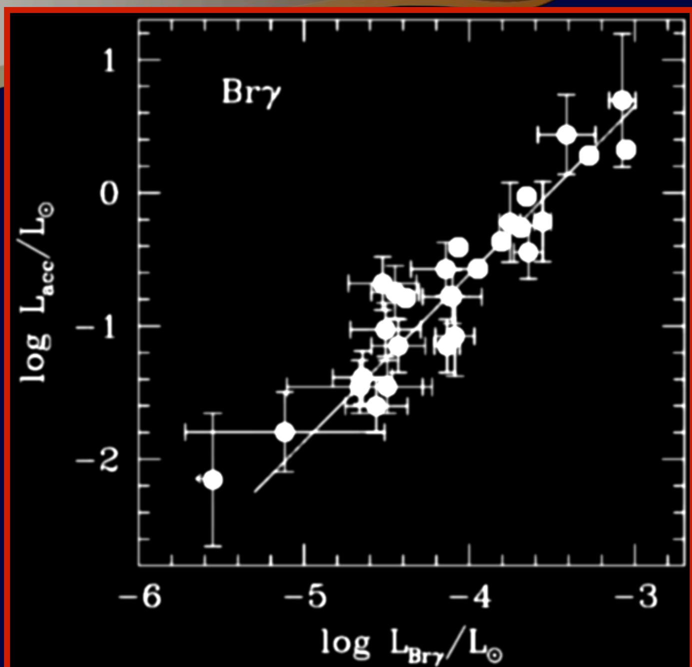
Origin of hydrogen line emission in YSOs

Besides the dust continuum emission, YSOs exhibit also gas-tracing emission lines, allowing one to trace the accretion & outflow processes in YSOs.



Origin of hydrogen line emission in YSOs





van den Ancker 2005

Br γ 2.16 μm hydrogen line:

- Often found in emission
- Line luminosity correlates with accretion luminosity

(empirical correlation, established for pre-main-seq. stars 0.01 … 4 $M_{\odot}$)

➜ important diagnostic line for mass accretion rate

- Involved physical mechanism not yet identified

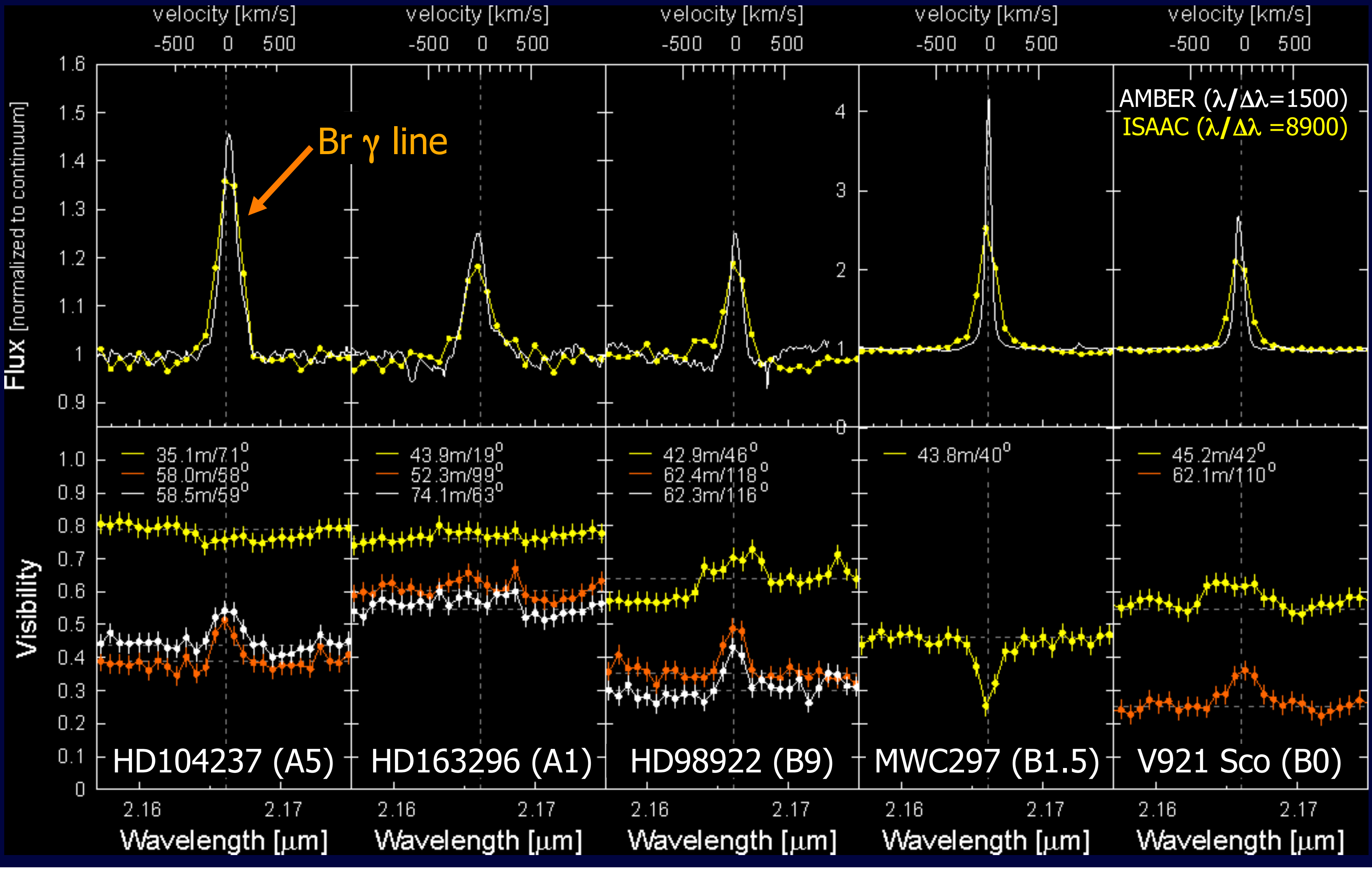
Spectro-interferometric investigations on Br γ:

Malbet et al. 2007, Tatulli et al. 2007, Eisner et al. 2007, Kraus et al. 2008, Eisner et al. 2009

Origin of hydrogen line emission in YSOs

VLTI/AMBER observations on 5 Herbig Ae/Be stars ($\lambda/\Delta\lambda$=1500)

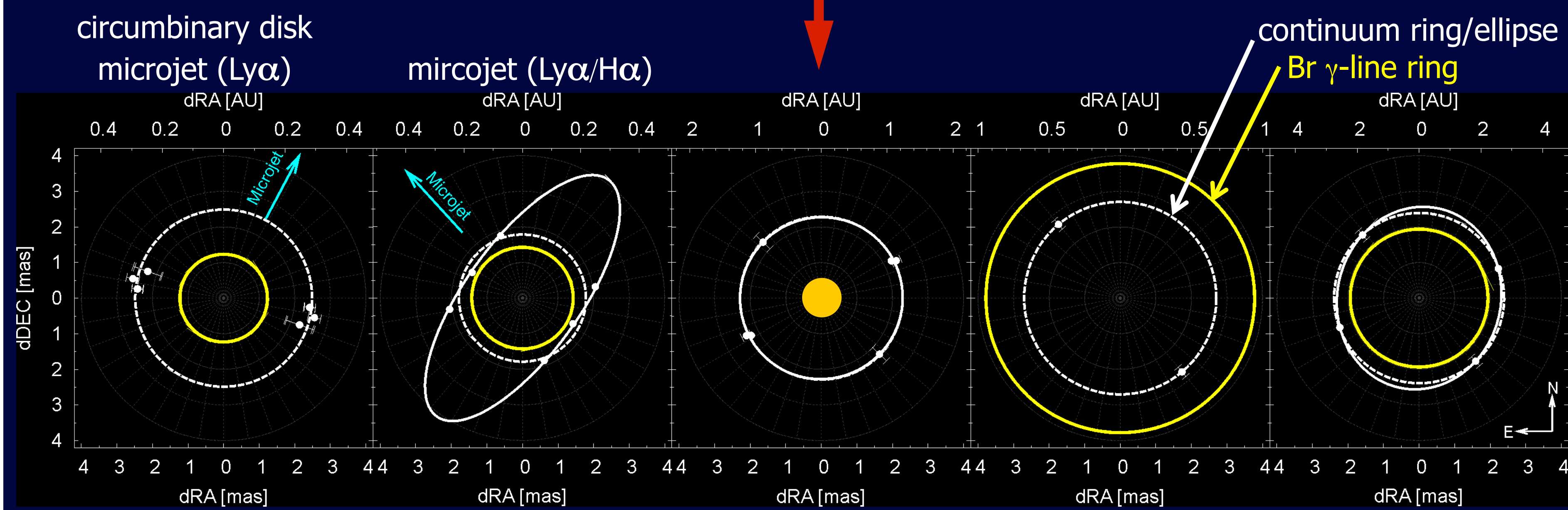
Our sample includes 5 YSOs, including archival data from Malbet et al. 2007 & Tatulli et al. 2007



Origin of hydrogen line emission in YSOs

Evidence for magnetospheric accretion & mass outflow

very compact Br γ-region (unresolved, $R_{Br\,\gamma} < 0.2\ R_{cont}$)
➜ consistent with magnetospheric accretion



HD 104237 (A5) HD 163296 (A1) HD 98922 (B9) MWC 297 (B1.5) V921 Sco (B0)

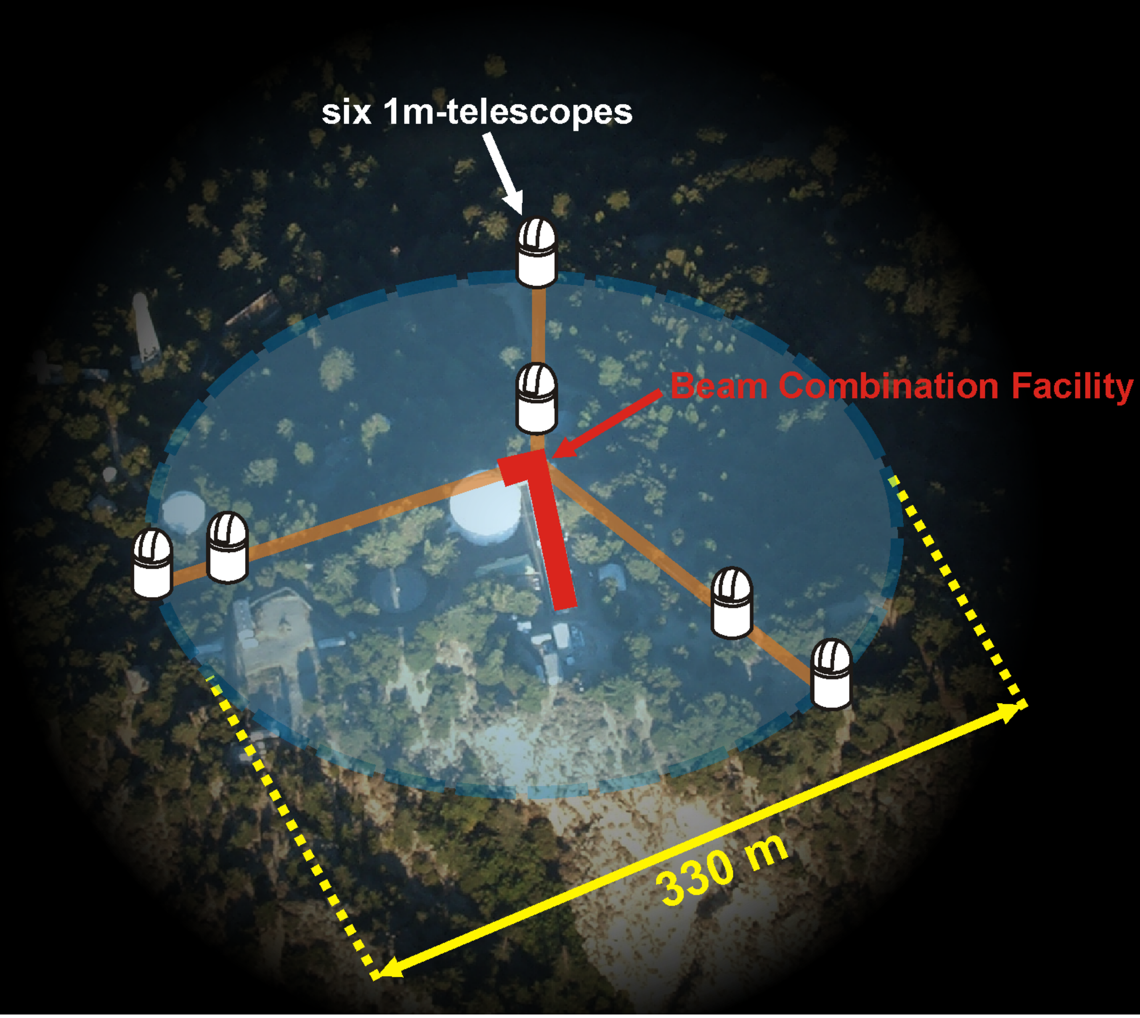
extended Br γ-region ($0.6 < R_{Br\,\gamma}/R_{cont} < 1.4$)
➜ consistent with disk wind or stellar wind

➔ Kraus et al. 2008, A&A 489, 1157

Future Science Prospects

Aperture Synthesis Imaging with CHARA

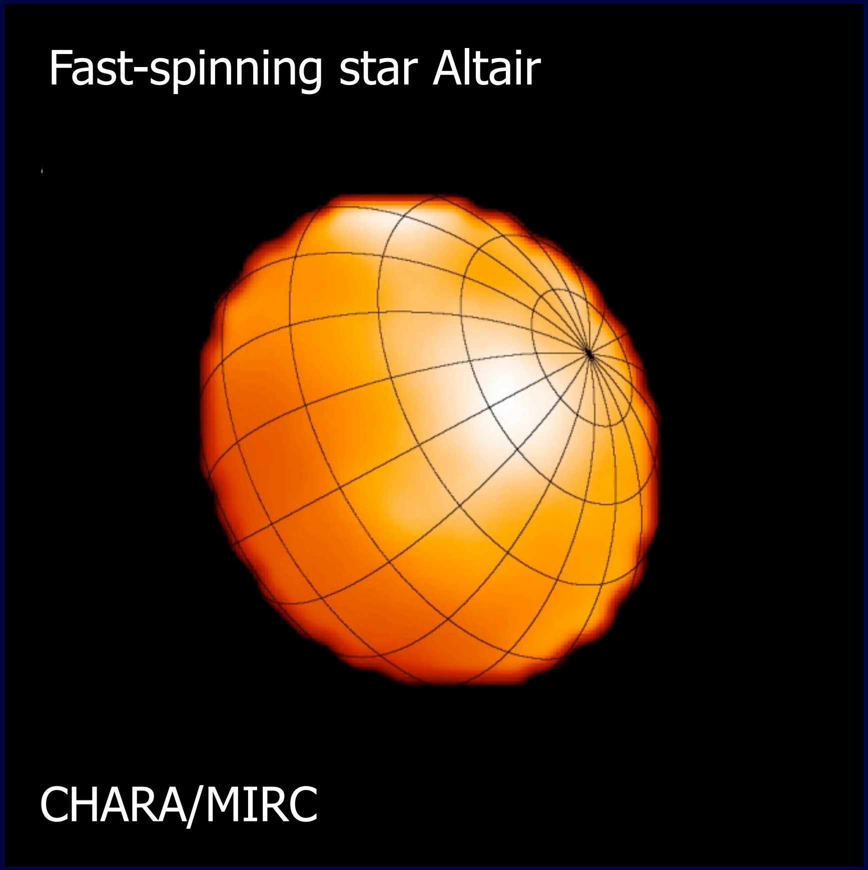
The CHARA array offers six 1m-telescopes in a Y-configuration with baseline lengths up to 330m



Together with the MIRC beam combiner and the CHAMP fringe tracker (built at Univ. of Michigan), CHARA is a particularly powerful facility for interferometric imaging.

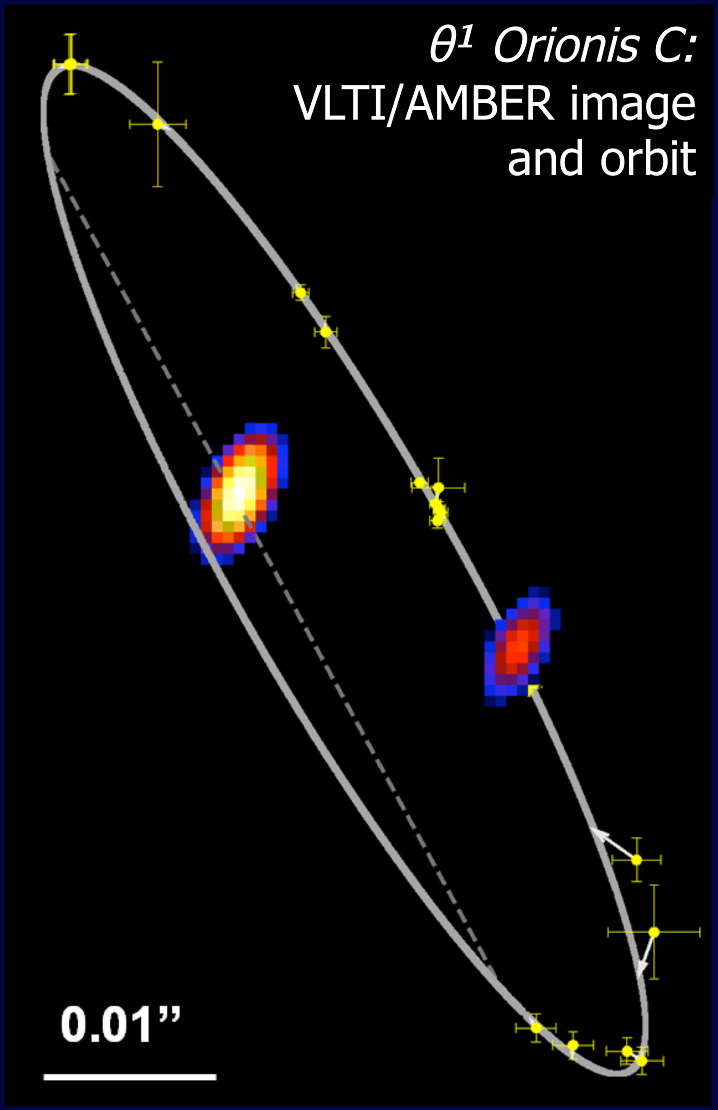
Future Science Prospects

First results from Aperture Synthesis Imaging with CHARA and VLTI



Monnier et al. 2007

(see also talk by Ming Zhao)



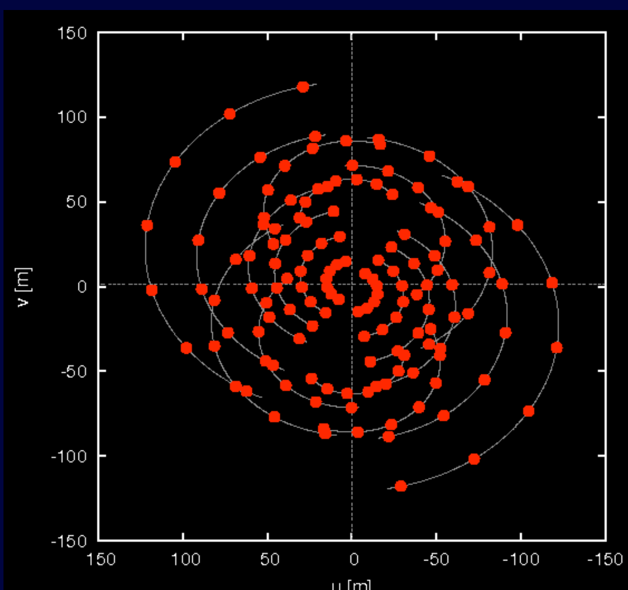
Kraus et al. 2009

Future Science Prospects

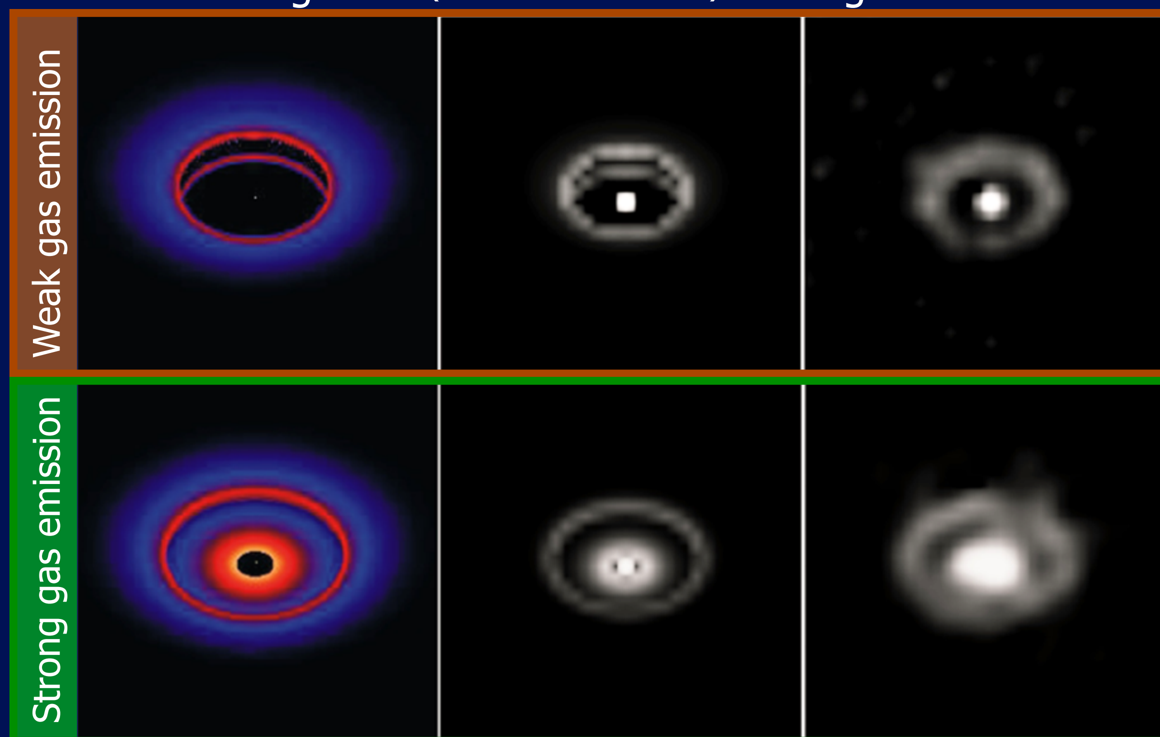
Direct imaging of the inner disk structure

Given the expected complexity in the inner-most regions of YSO disks,
it is crucial to obtain also model-independent imaging of the inner disk structure.

Simulation assuming
4 nights with 3 telescopes



Input model image | Model image (convolved with PSF) | Reconstructed image

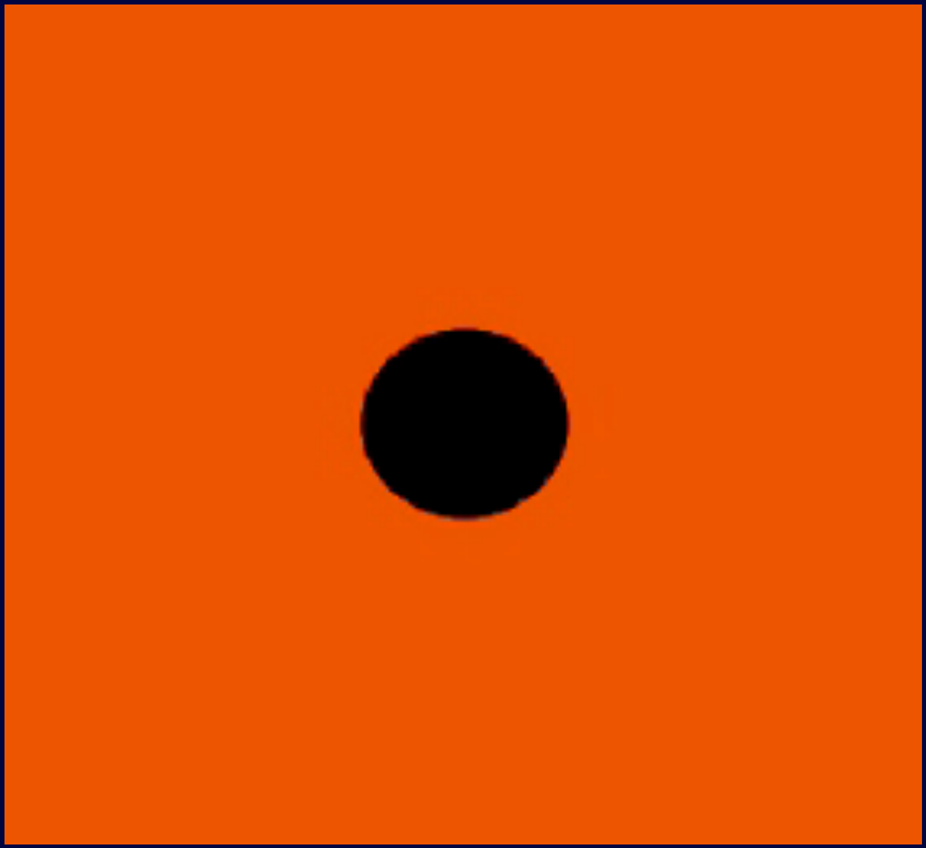


Future Science Prospects

Searching for planet-induced perturbations within the disk

Once the structure of protoplanetary disks is better understood,
we might also start searching for deviations, e.g.

Gap opening due to Jupiter-mass planet



Simulation by Frederic Masset

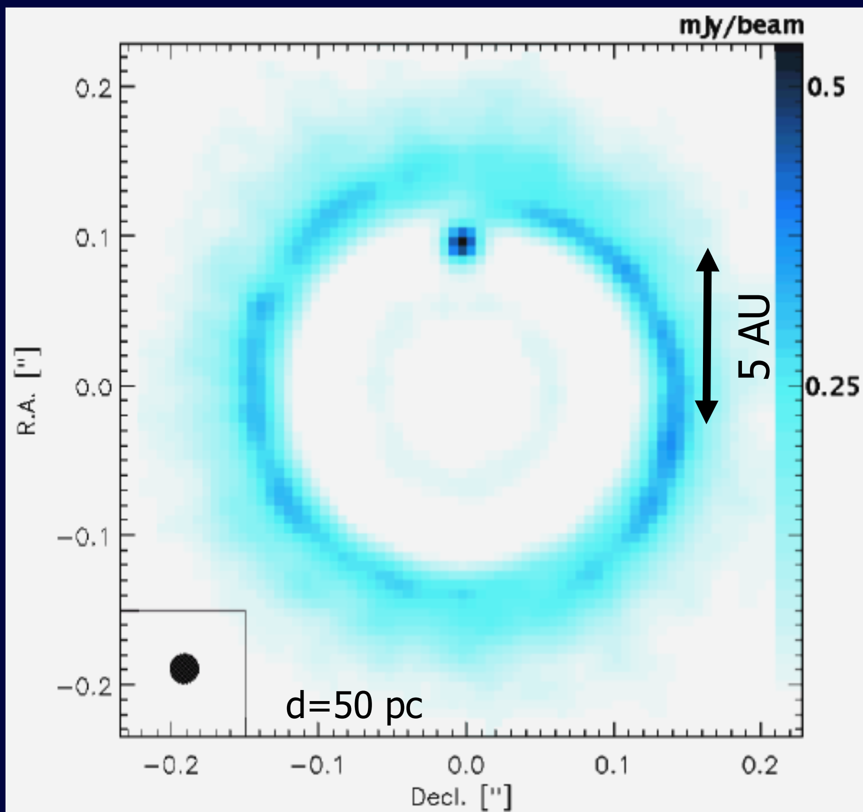
(see also talk by
Hannah Jang-Condell)

Future Science Prospects

Searching for planet-induced perturbations within the disk

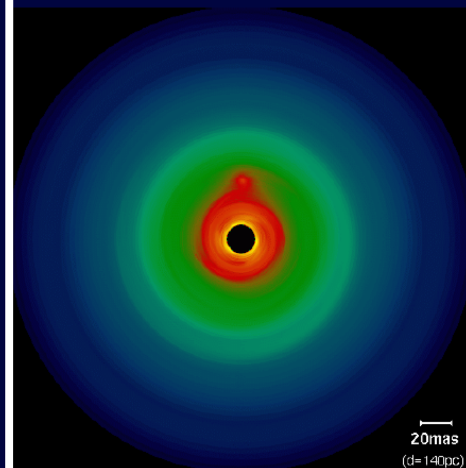
Detect the forming planet…

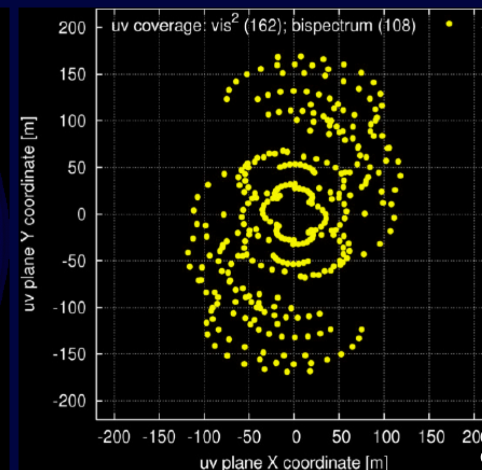
…either through the cleared gap region
(ALMA, 900 GHz),



Wolf & D'Angelo 2005

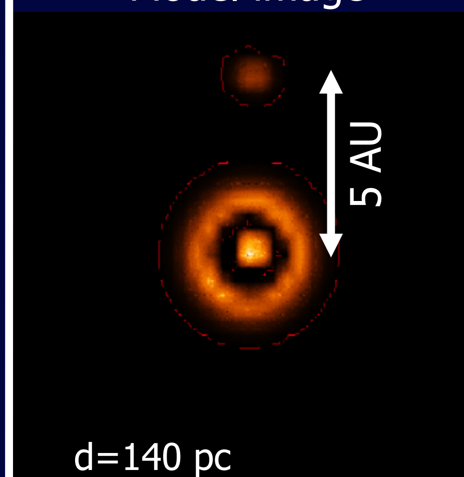
…or through the hot accretion around the planet
(10 μm, 3 nights with 4 tel.)

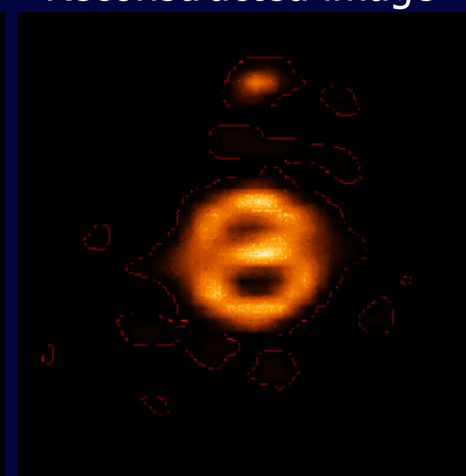




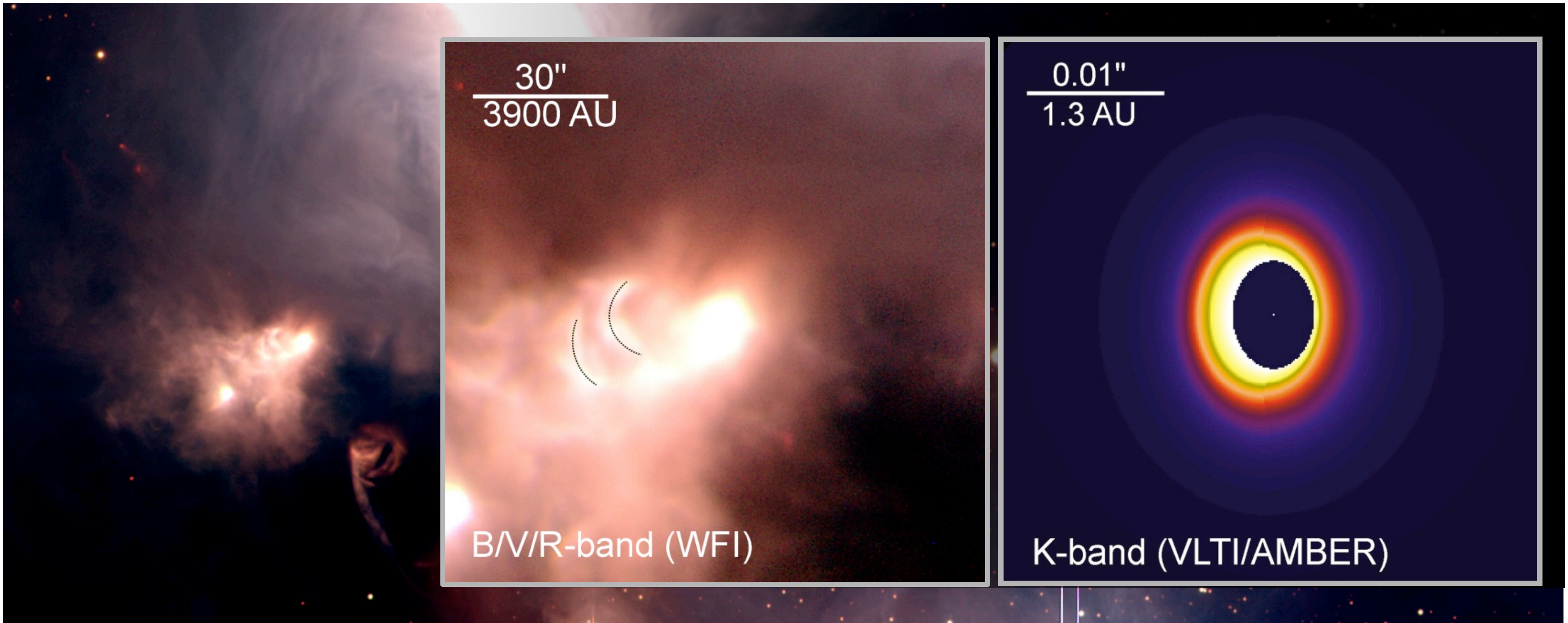
Model image

Reconstructed image





Wolf & MATISSE consortium 2008

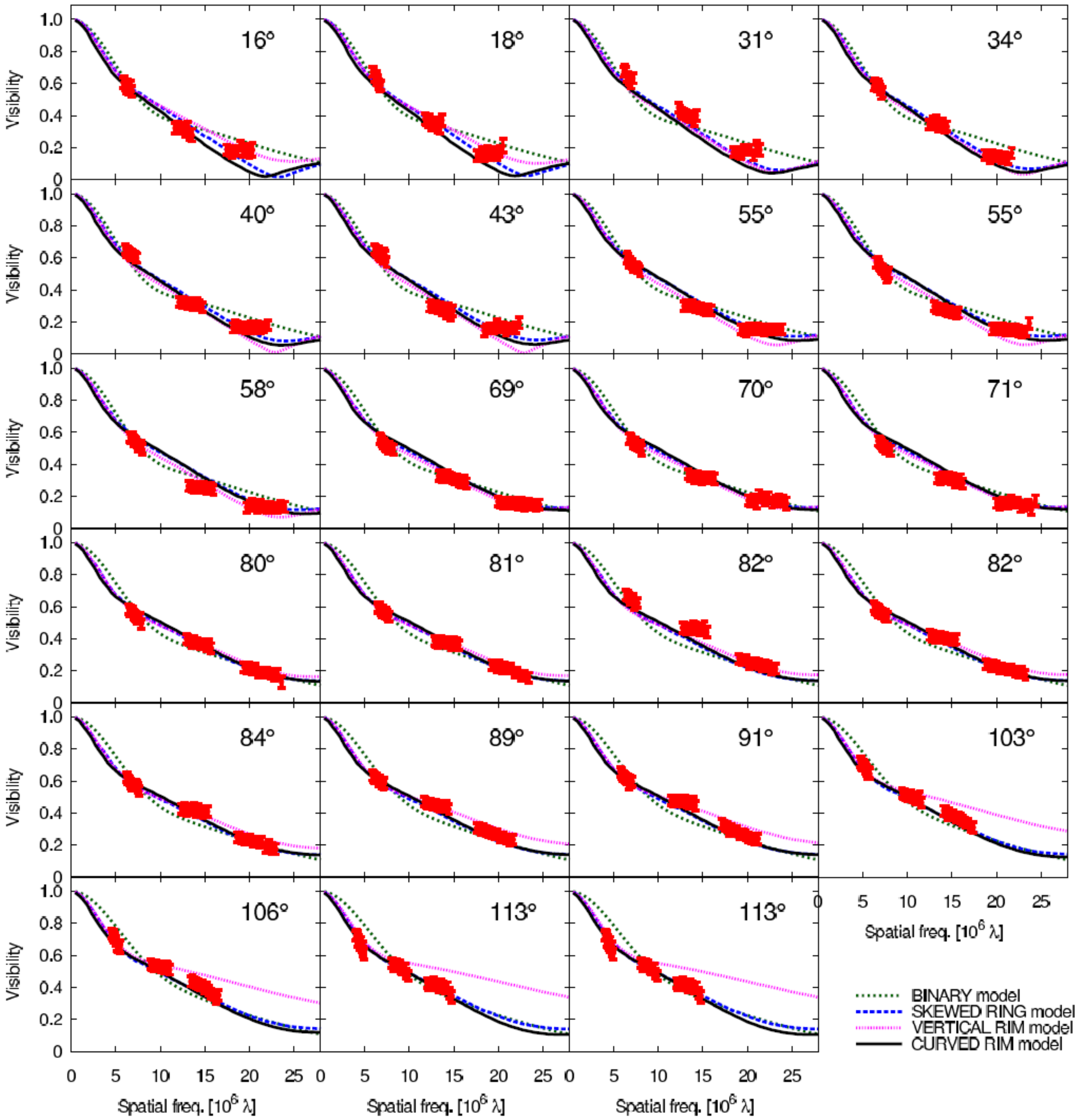


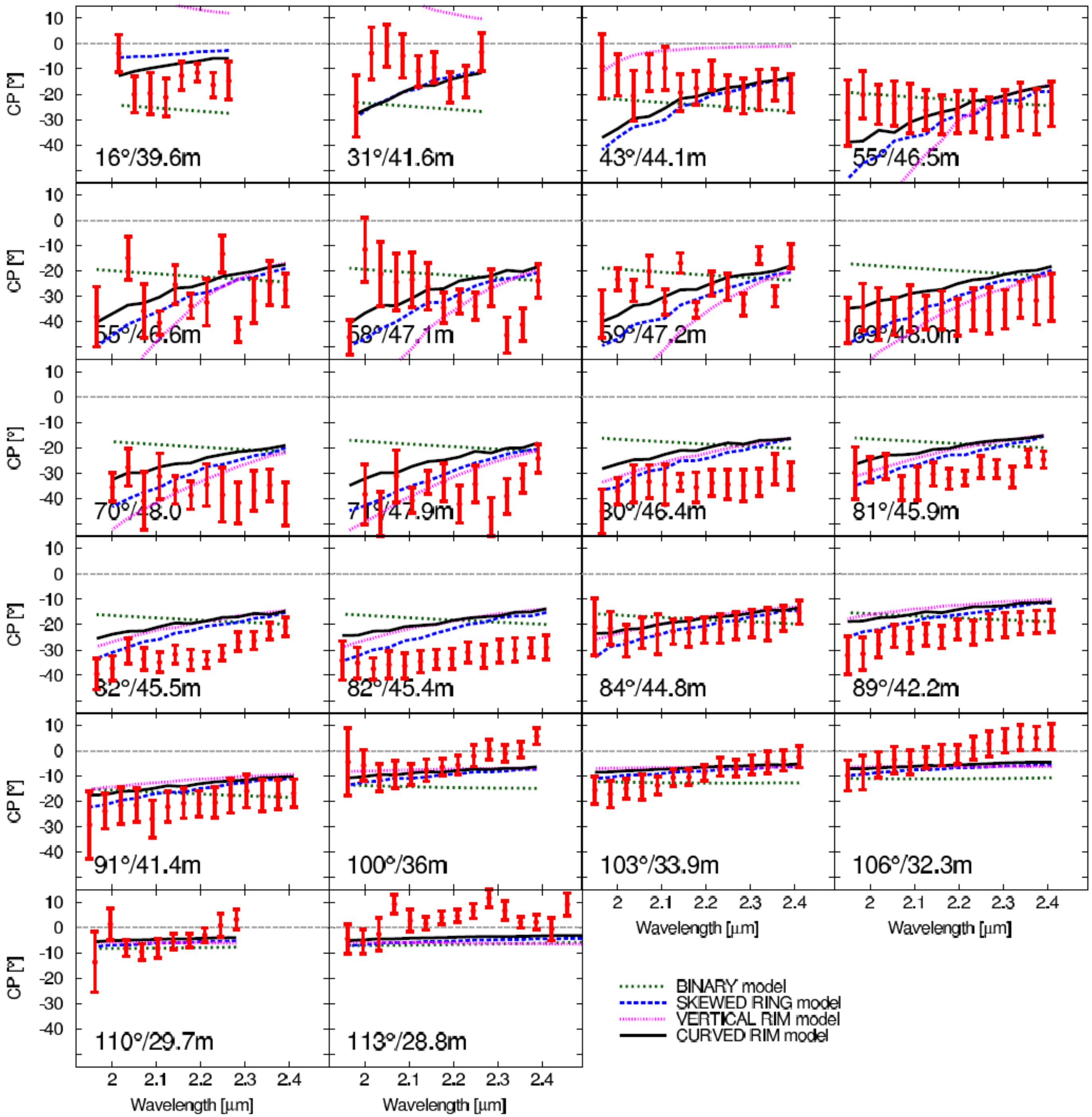
Spectro-interferometry allows one to probe the initial conditions of planet formation, e.g. by

…constraining the detailed vertical disk structure at the dust sublimation radius
(R CrA, using closure phases, Kraus et al., A&A accepted)

…measuring the radial disk temperature distribution
(MWC 147, using NIR+MIR interferometry, Kraus et al., 2008a)

…tracing line emission and the associated mass infall/outflow processes
(Br γ survey, using high spectral dispersion, Kraus et al., 2008b)

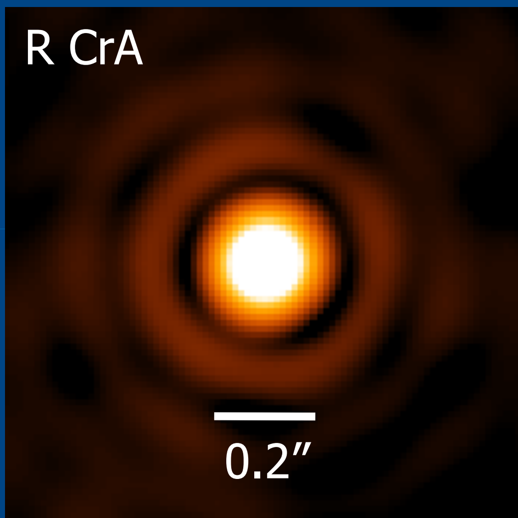

16°
18°
31°
34°
40°
43°
55°
55°
58°
69°
70°
71°
80°
81°
82°
82°
84°
89°
91°
103°
106°
113°
113°
Visibility
Spatial freq. [10^6 λ]
BINARY model
SKEWED RING model
VERTICAL RIM model
CURVED RIM model


16°/39.6m
31°/41.6m
43°/44.1m
55°/46.5m
55°/46.6m
58°/47.1m
59°/47.2m
69°/48.0m
70°/48.0
71°/47.9m
80°/46.4m
81°/45.9m
82°/45.5m
82°/45.4m
84°/44.8m
89°/42.2m
91°/41.4m
100°/36m
103°/33.9m
106°/32.3m
110°/29.7m
113°/28.8m
CP [°]
Wavelength [μm]
BINARY model
SKEWED RING model
VERTICAL RIM model
CURVED RIM model

Revealing the asymmetries of the inner dust rim

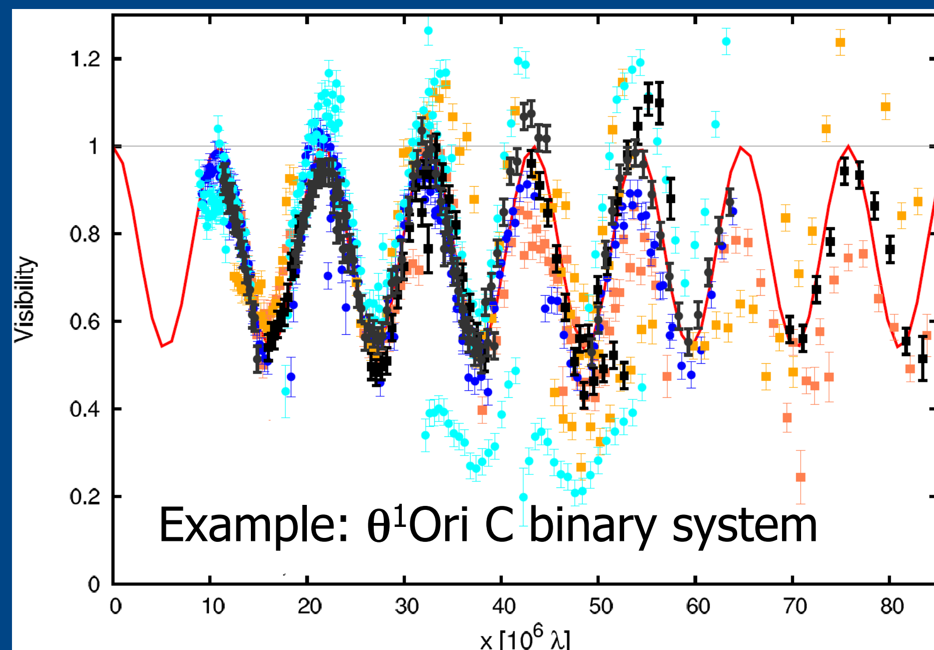
BINARY STAR model (1/2)

Takami et al. (2003) proposed presence of a companion star with ρ > 60 mas (8 AU)
Can the detected asymmetries be explained with a binary star scenario?



1.) No companion at ρ>95 mas (flux ratio 1:100)
(from diffraction-limited bispectrum speckle imaging with the ESO 3.6m, H-band)

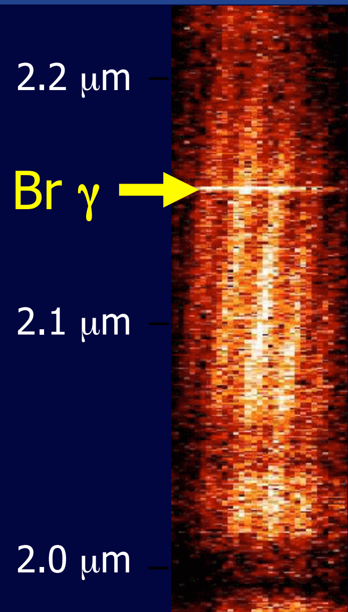
2.) No companion at ρ>20 mas
(flux ratio 1:40)
(our AMBER H/K-band observations **do <u>not</u> show** the characteristic wavelength-differential binary visibility/phase modulations)

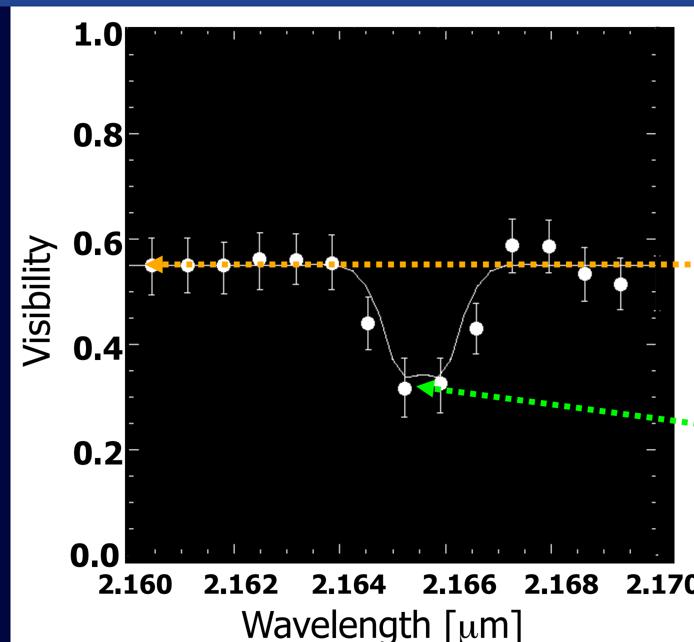


Kraus et al. 2009

Origin of line emission in YSOs

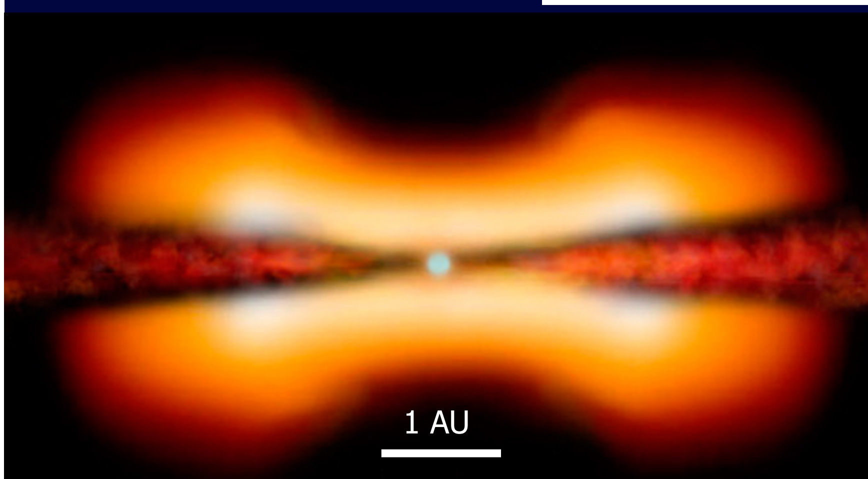
Infrared Interferometry in the Br γ hydrogen line





continuum:
V = 0.55±0.10 **Ø = 1.0 AU**

Br γ:
V = 0.33±0.06 **Ø = 1.4 AU**



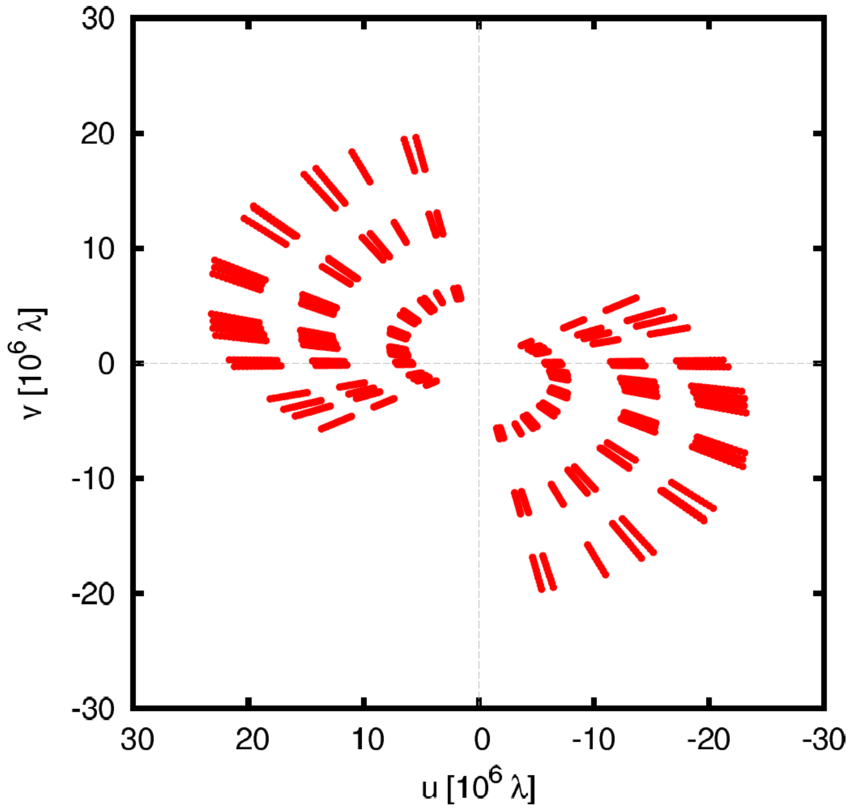
MWC297 wind model, Malbet et al. 2007

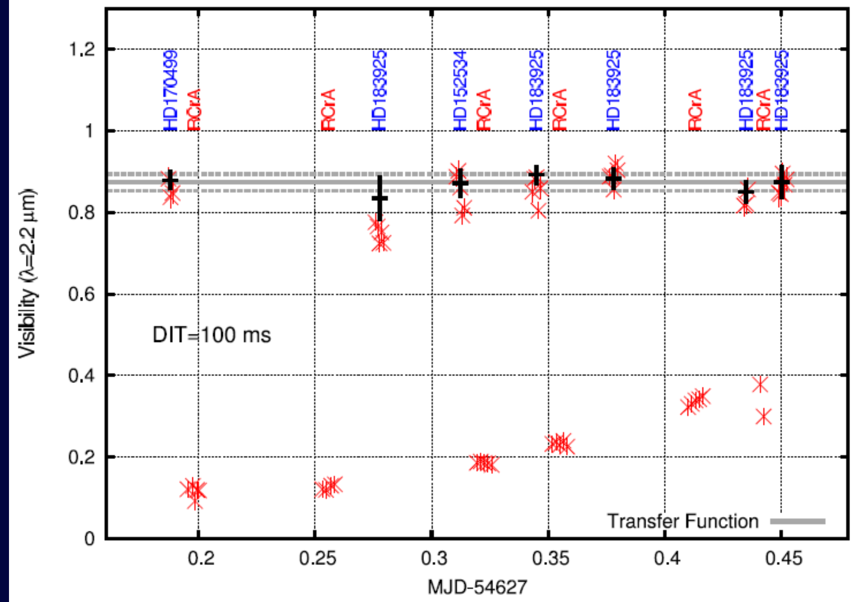
Interferometric studies investigating the origin of Br γ 2.16 μm line emission:

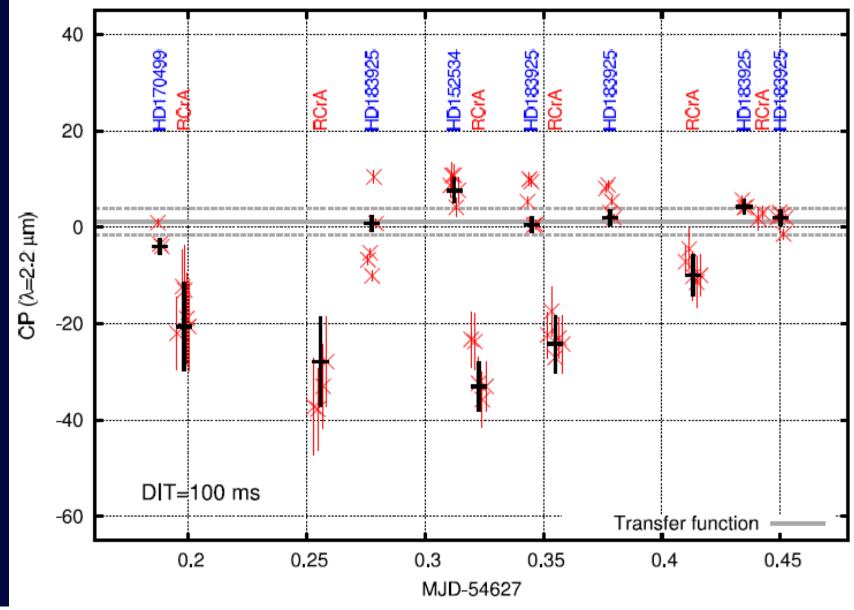
- Malbet et al. 2007
- Tatulli et al. 2007
- Eisner 2007
- Kraus et al. 2008
- Eisner et al. 2009

Revealing the asymmetries of the inner disk rim

VLTI/AMBER spectro-interferometry of R CrA







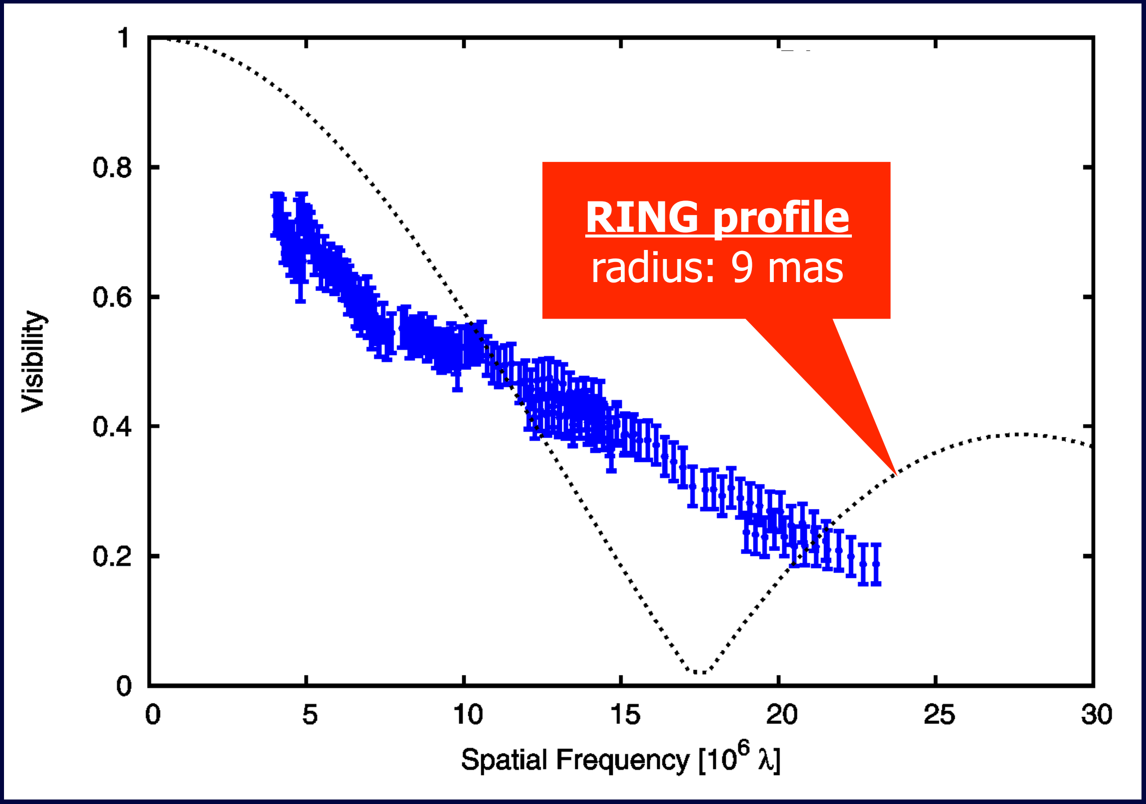
24 AMBER observations
(during 4 nights in June 2008)

Telescope triplet E0-G0-H0
LR-mode (H+K band, λ/Δλ=35)

Revealing the asymmetries of the inner dust rim

Indications for a disk + envelope geometry

Data subset:
PA=100±17°

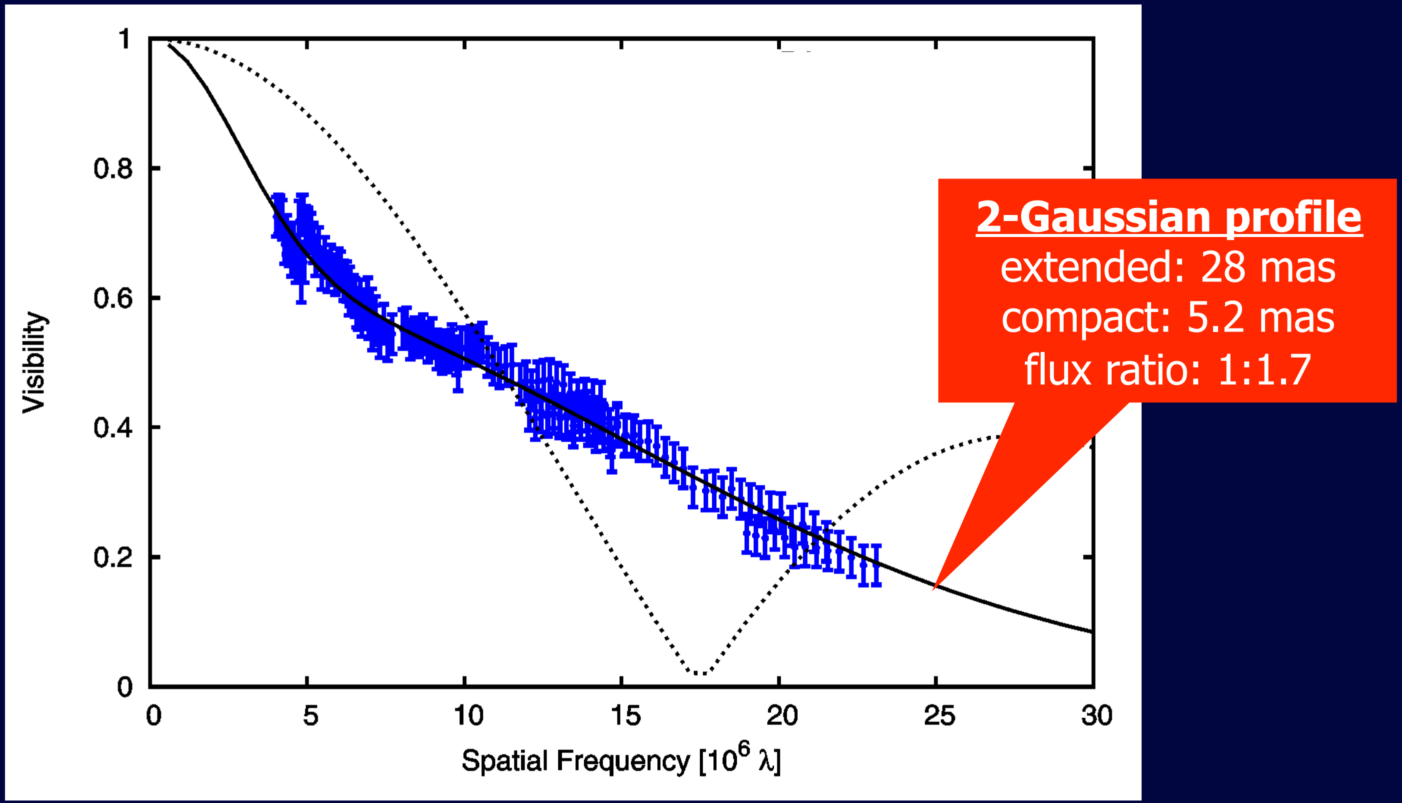


(1) Measured visibility function differs strongly from commonly assumed RING profile

Revealing the asymmetries of the inner dust rim

Indications for a disk + envelope geometry

Data subset:
PA=100±17°



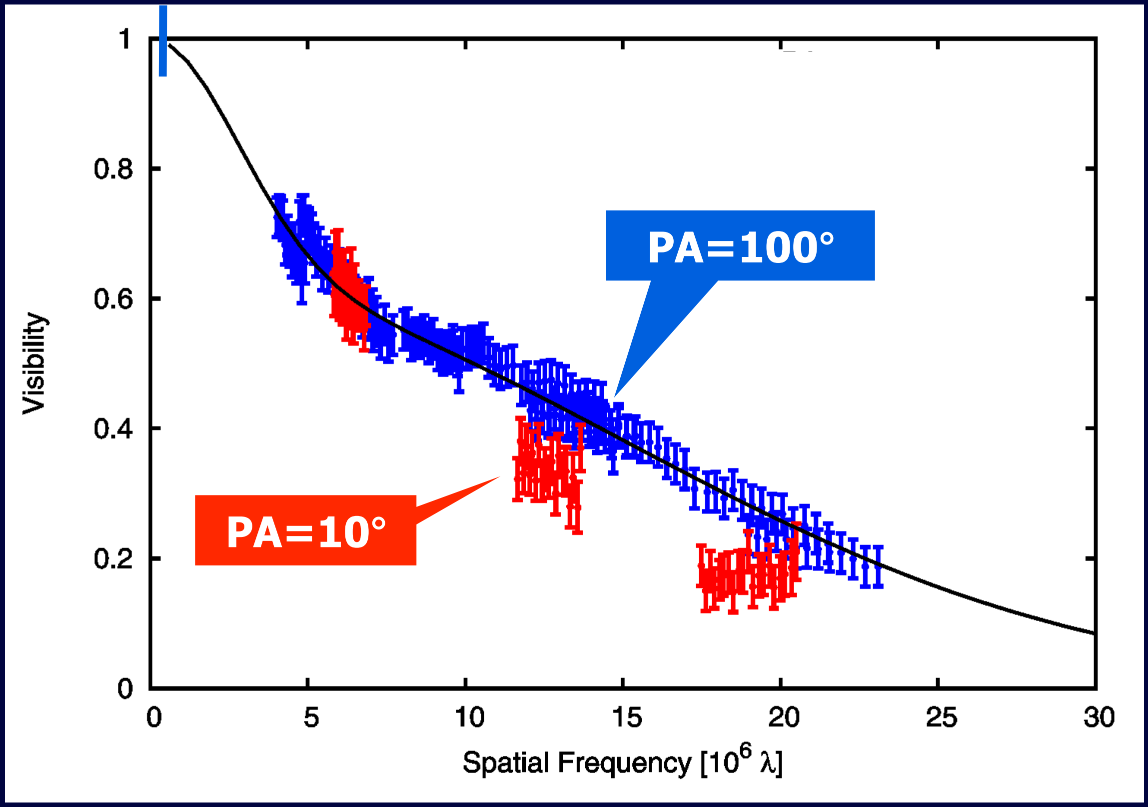
(1) Measured visibility function differs strongly from commonly assumed RING profile

(2) Pronounced change in slope in visibility function indicates 2 spatial components:

Extended component (~30 mas) & Compact component (~5 mas)

Revealing the asymmetries of the inner dust rim

Indications for a disk + envelope geometry



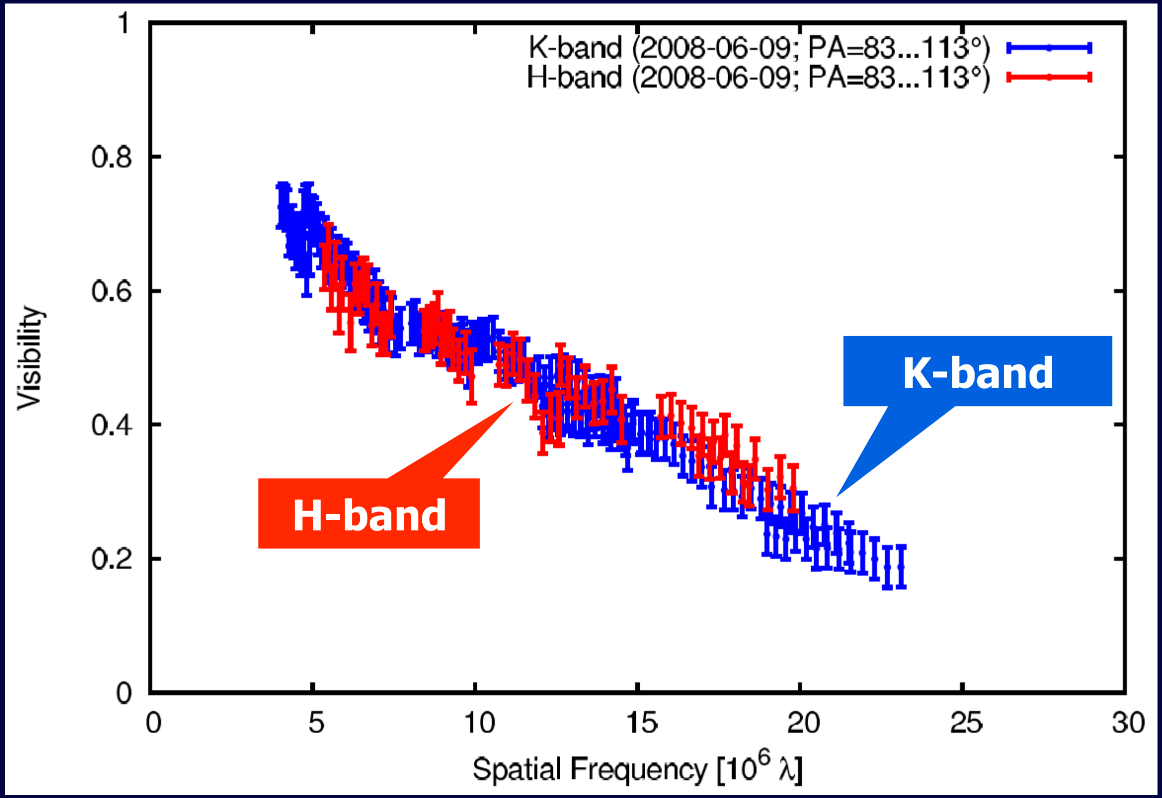
(1) Pronounced change in slope in visibility function indicates 2 spatial components:

Extended component (~30 mas) & Compact component (~5 mas)
"Envelope" "Disk"

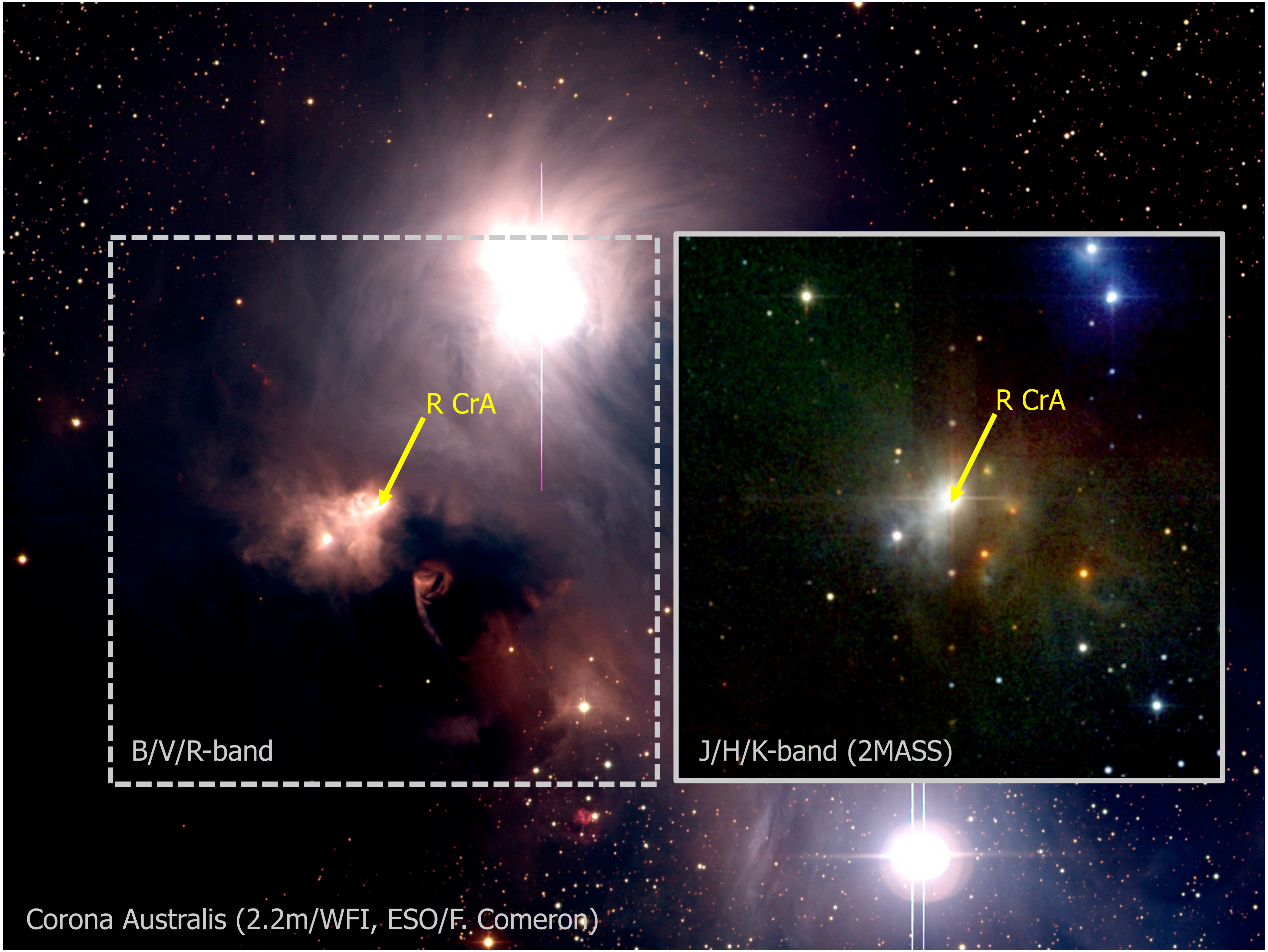
(2) Visibility profile changes with position angle

Revealing the asymmetries of the inner dust rim

H- and K-band object morphology



Comparing the H- and K-band visibilities, we do not detect significant differences in the object morphology.


R CrA
B/V/R-band
R CrA
J/H/K-band (2MASS)
Corona Australis (2.2m/WFI, ESO/F. Comeron)

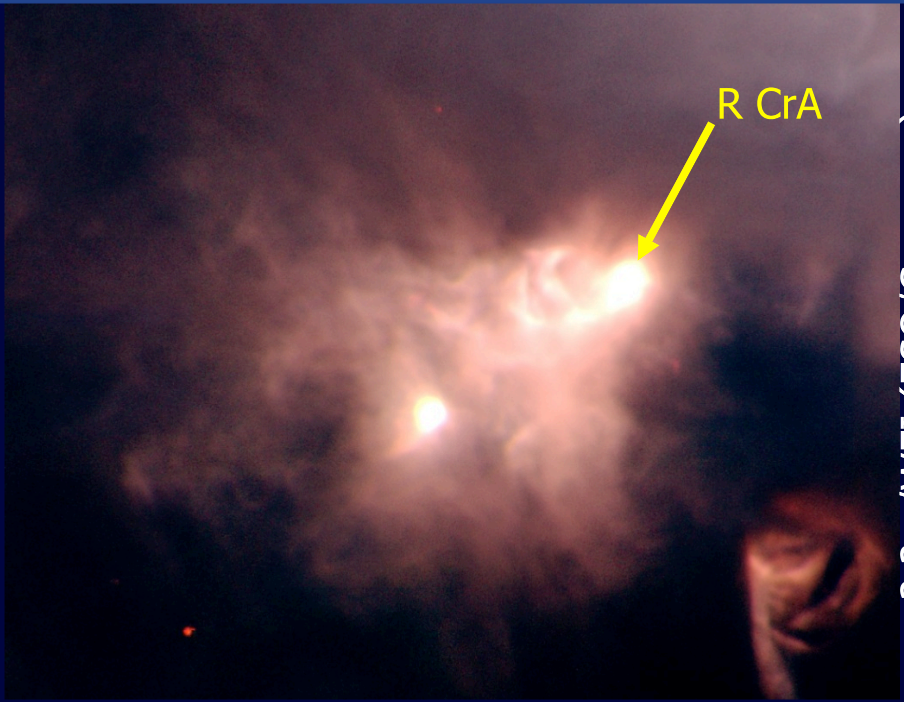
Revealing the asymmetries of the inner dust rim

R Coronae Australis

Herbig Ae star located in Coronet cluster
d=130 pc (Marraco & Rydgren 1981)

Spectral type estimates:
F5 (e.g. Hillenbrand 1992)
A5 (e.g. Herbig & Bell 1988)
B8 (e.g. Bibo et al. 1992)

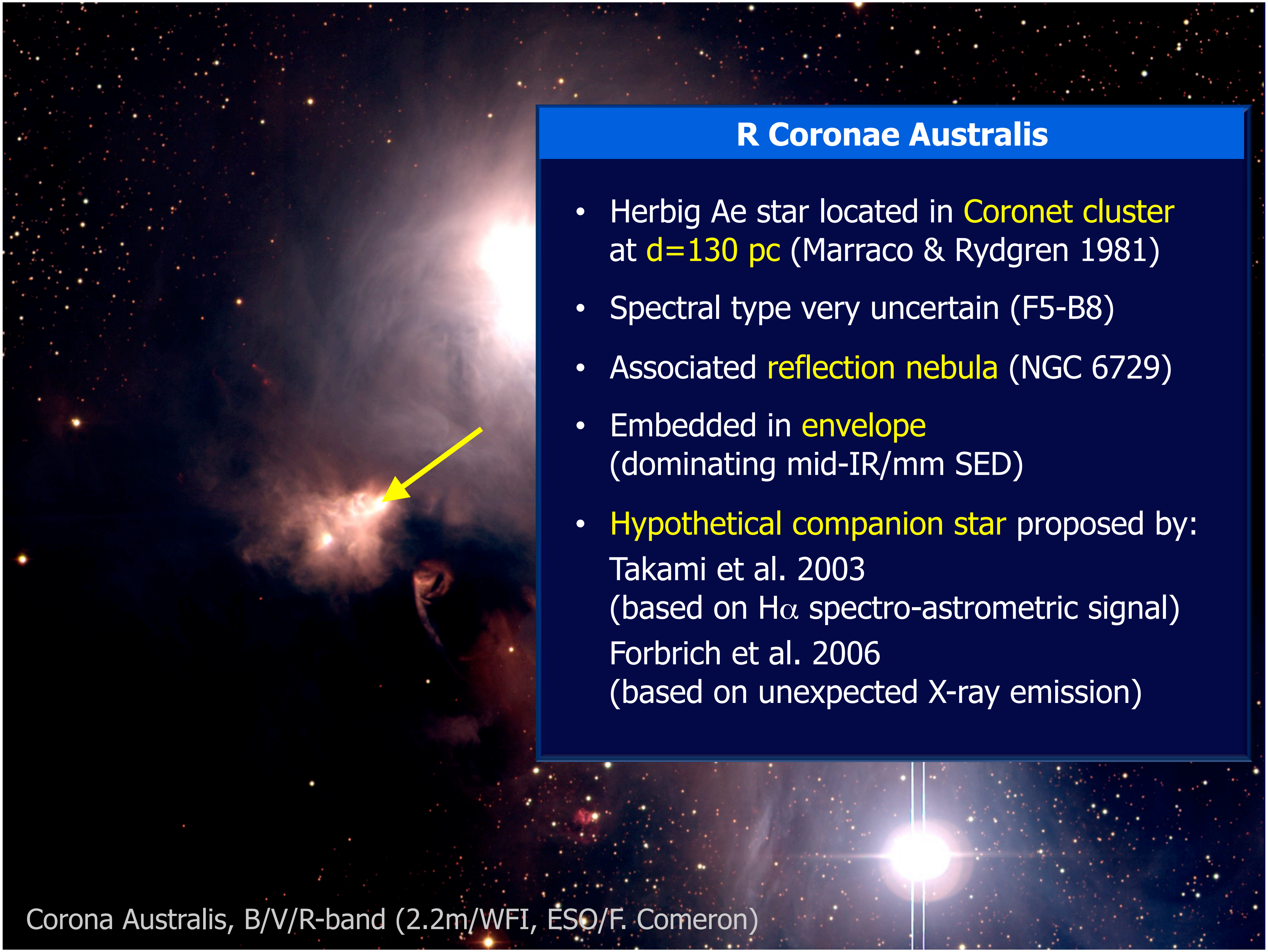
Associated reflection nebula (NGC 6729)



2.2m/WFI (ESO/Comeron)

Embedded in envelope, which dominates mid-infrared/mm SED (e.g. Natta et al. 1993)

Earlier studies proposed a companion star
…based on $H\alpha$ spectro-astrometric signal (Takami et al. 2003)
…based on unexpected X-ray emission (Forbrich et al. 2006)

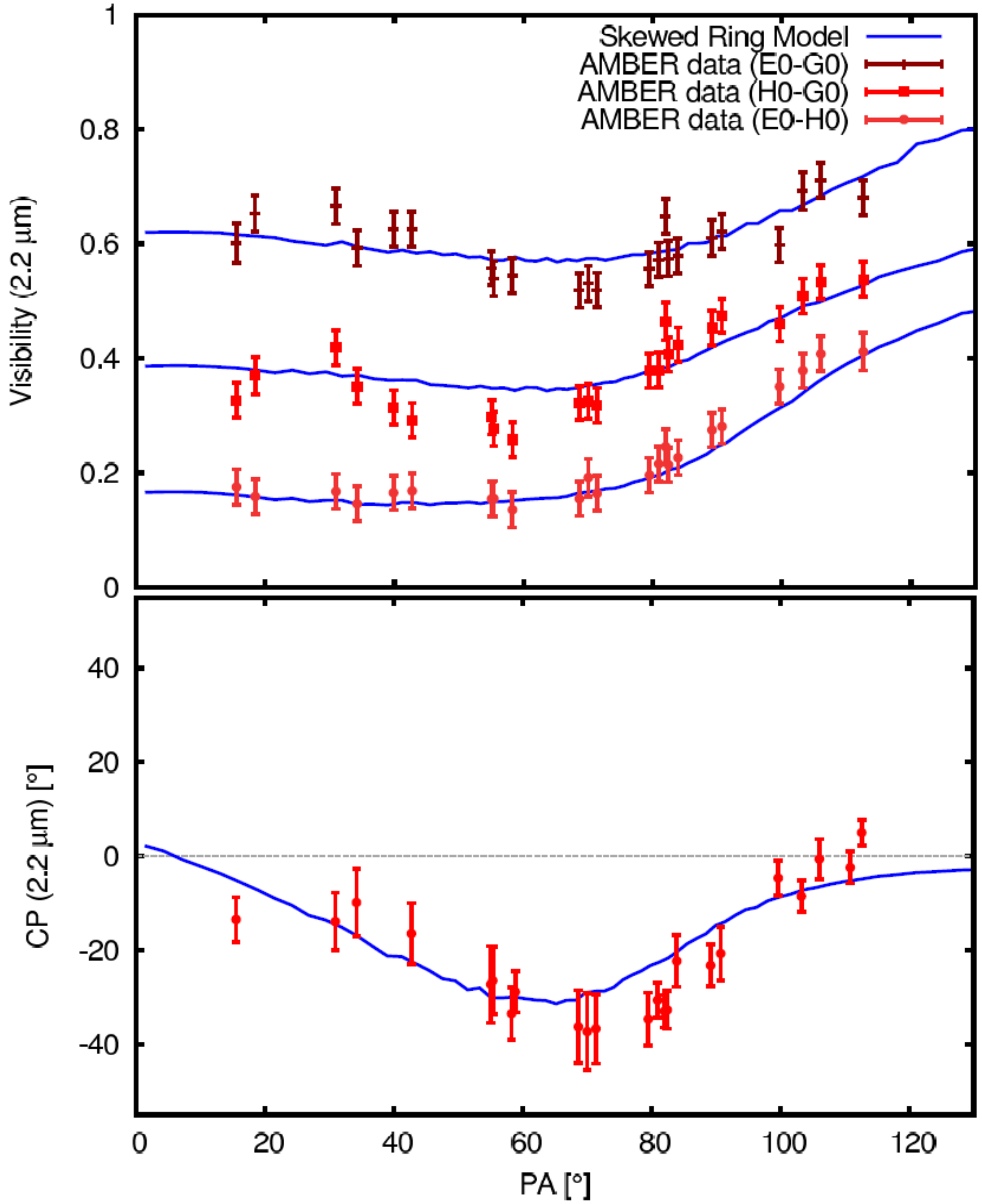


R Coronae Australis

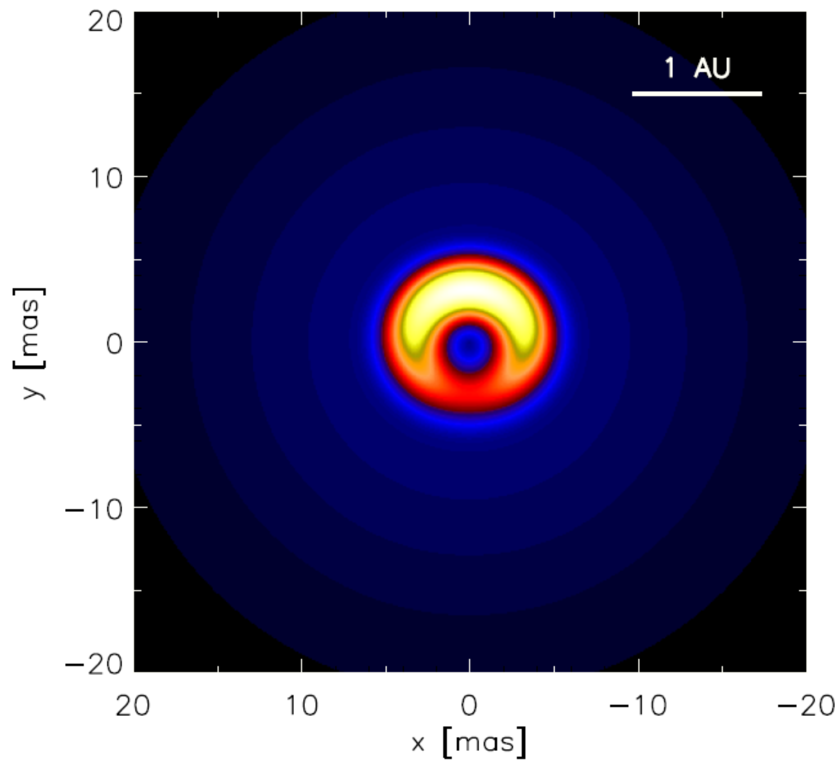
- Herbig Ae star located in Coronet cluster at d=130 pc (Marraco & Rydgren 1981)
- Spectral type very uncertain (F5-B8)
- Associated reflection nebula (NGC 6729)
- Embedded in envelope (dominating mid-IR/mm SED)
- Hypothetical companion star proposed by:
  Takami et al. 2003
  (based on Hα spectro-astrometric signal)
  Forbrich et al. 2006
  (based on unexpected X-ray emission)

Corona Australis, B/V/R-band (2.2m/WFI, ESO/F. Comeron)

SKEWED RING model



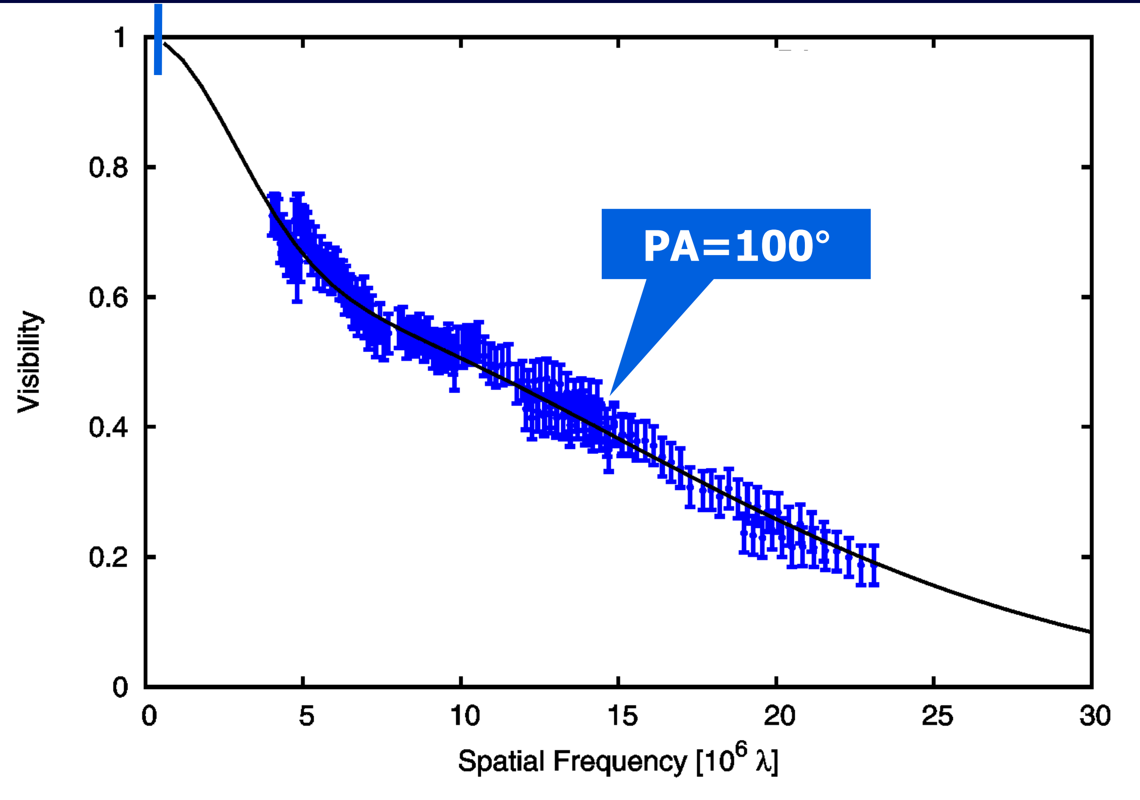
Geometric model
(motivated by Monnier et al. 2005)



$\chi^2 = 2.0$

Revealing the asymmetries of the inner dust rim

Indications for a disk + envelope geometry

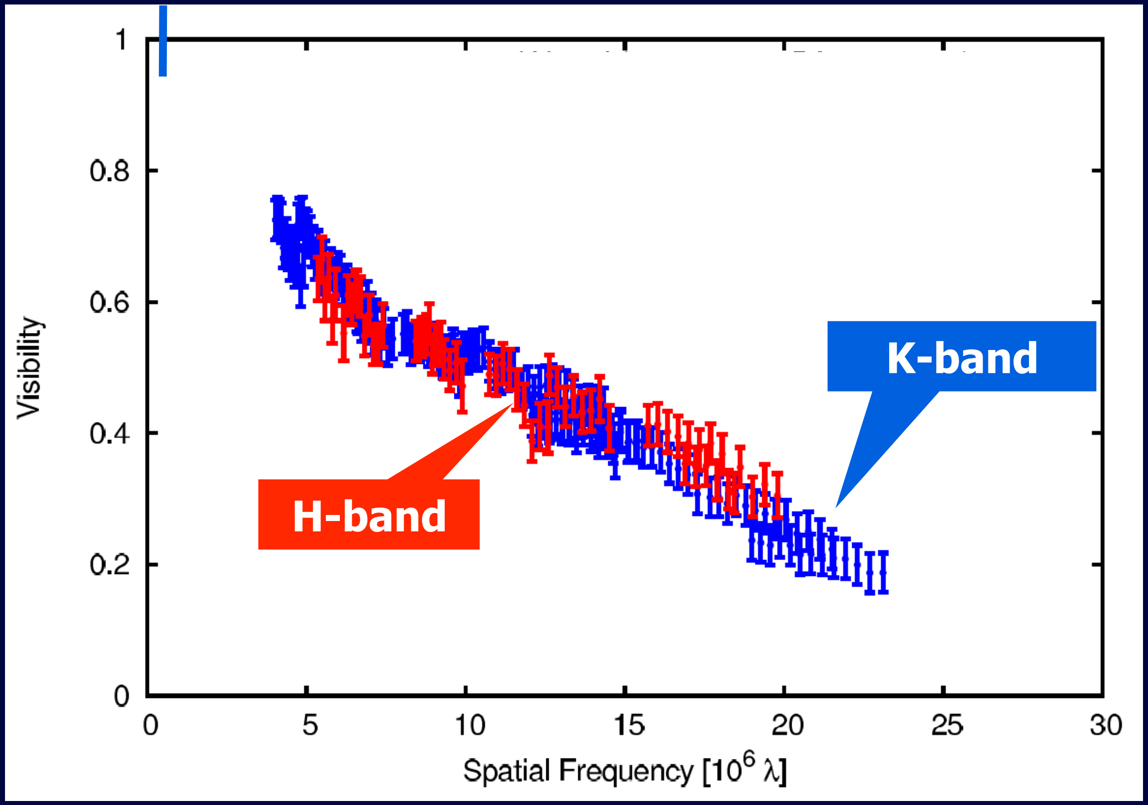


(1) Pronounced change in slope in visibility function indicates 2 spatial components:

Extended component (~30 mas) "Envelope" & Compact component (~5 mas) "Disk"

Revealing the asymmetries of the inner dust rim

H- and K-band object morphology

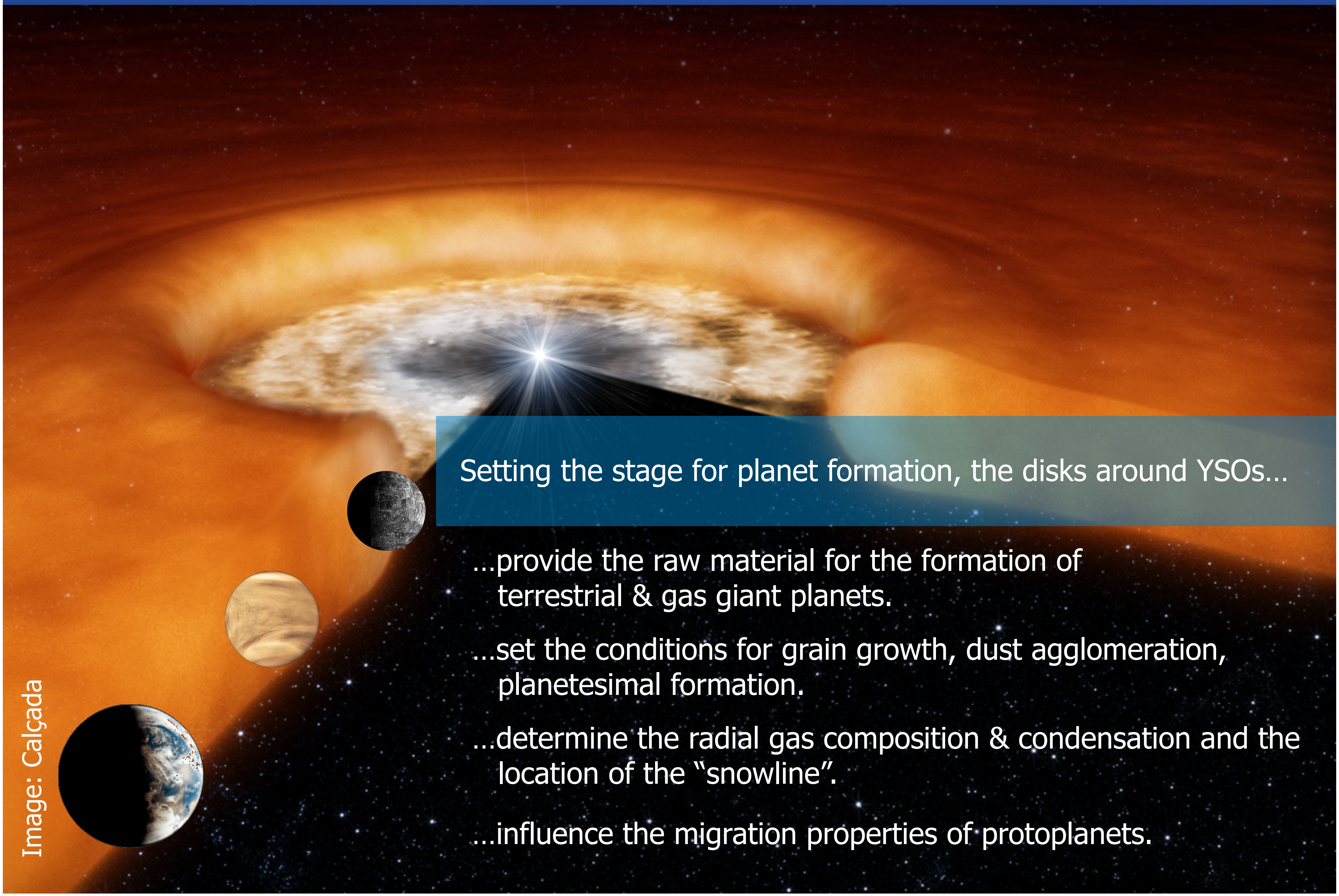


(1) Pronounced change in slope in visibility function indicates 2 spatial components:

Extended component (~30 mas) "Envelope" & Compact component (~5 mas) "Disk"

(2) Comparing H-/K-band, we do not detect the signatures of an inner hot component.

Exploring the inner-most AU of protoplanetary disks



Setting the stage for planet formation, the disks around YSOs…

…provide the raw material for the formation of terrestrial & gas giant planets.

…set the conditions for grain growth, dust agglomeration, planetesimal formation.

…determine the radial gas composition & condensation and the location of the "snowline".

…influence the migration properties of protoplanets.

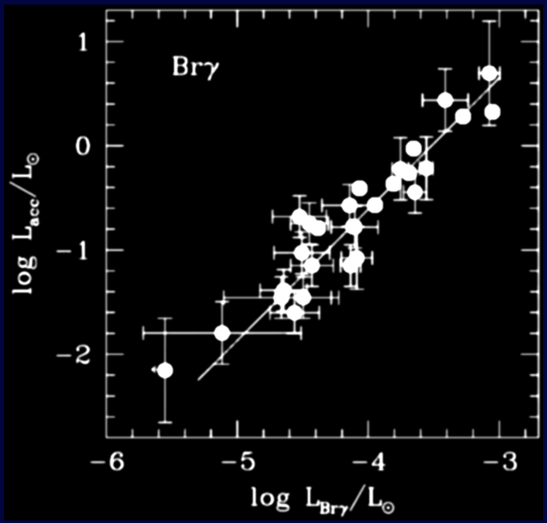
Origin of hydrogen line emission in YSOs

Evidence for magnetospheric accretion & mass outflow

What do we know about the Br γ-emitting mechanism?

(1) spectro-interferometry:
Br γ can trace both mass infall and mass outflow

(2) empirical relation:
Br γ luminosity correlates with mass accretion rate
(as determined from UV veiling, e.g. Muzerolle et al. 1998)



van den Ancker 2005

➜ Br γ *indirect tracer* of mass accretion rate

➔ Kraus et al. 2008, A&A 489, 1157