Spatially resolved investigations on YSO disk structure

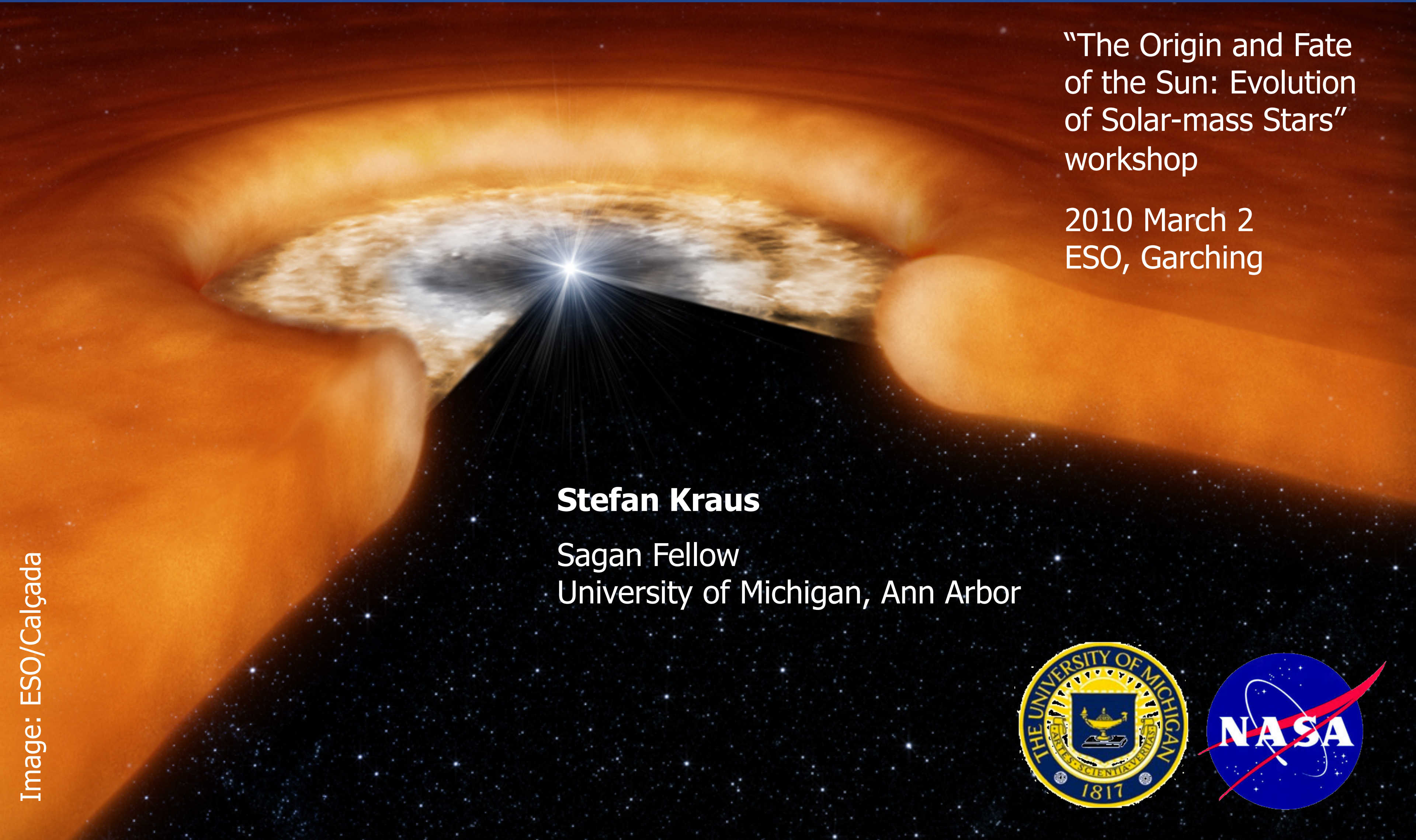


Image: ESO/Calçada

"The Origin and Fate of the Sun: Evolution of Solar-mass Stars" workshop

2010 March 2
ESO, Garching

Stefan Kraus

Sagan Fellow
University of Michigan, Ann Arbor

Outline

1. Paradigm of star formation

2. SED model fitting and the need for spatially resolved observations

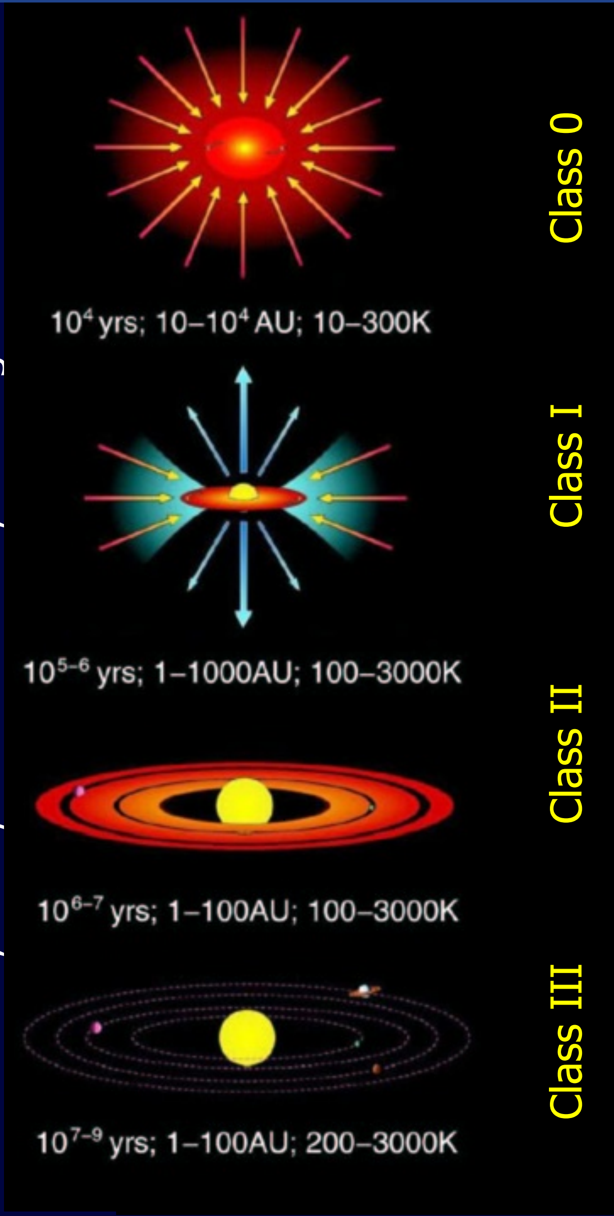
3. Spatially resolved observations in continuum emission
   3.1 …using (sub-)millimeter interferometry
   3.2 …using mid-infrared interferometry
   3.3 …using near-infrared interferometry

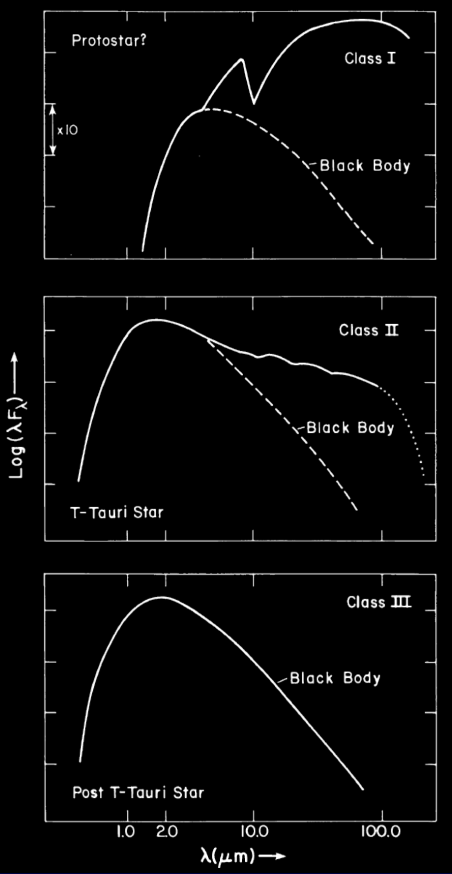
4. Spatially resolved observations in spectral lines

5. Future science prospects

Paradigm of star formation

Lada 1987, NASA/Shu et al. 1987, McCaughrean





- Gravitational collapse
- Hot Cores, Masers, Protostar (optically invisible)

- PMS with actively accreting disk
- Outflows
- System still strongly embedded

- Mainly passive disk
- Planet formation

- Main-sequence star
- Planets

Structure of YSO disks

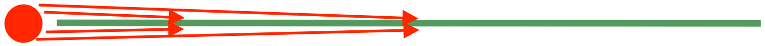
SED Modeling: Viscous disks

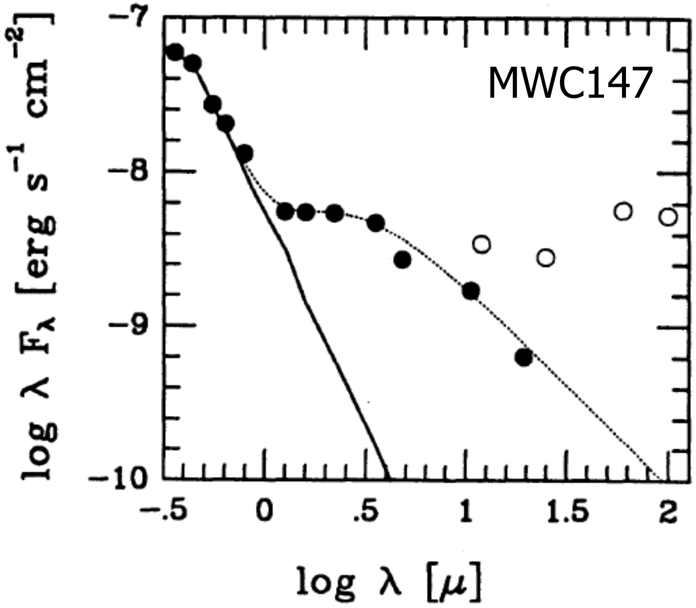
Viscous accretion disk models
(Shakura & Sunyaev 1973,
Lynden-Bell & Pringle 1974)

SED model fits of Herbig Ae/Be stars, including viscous disk and radiative heating from the central stars (e.g. Hillenbrand et al. 1992)

➜ Problem:
Derived Mass Accretion Rates are higher than estimated from UV veiling

Geometrically thin disk





Hillenbrand et al. 1992

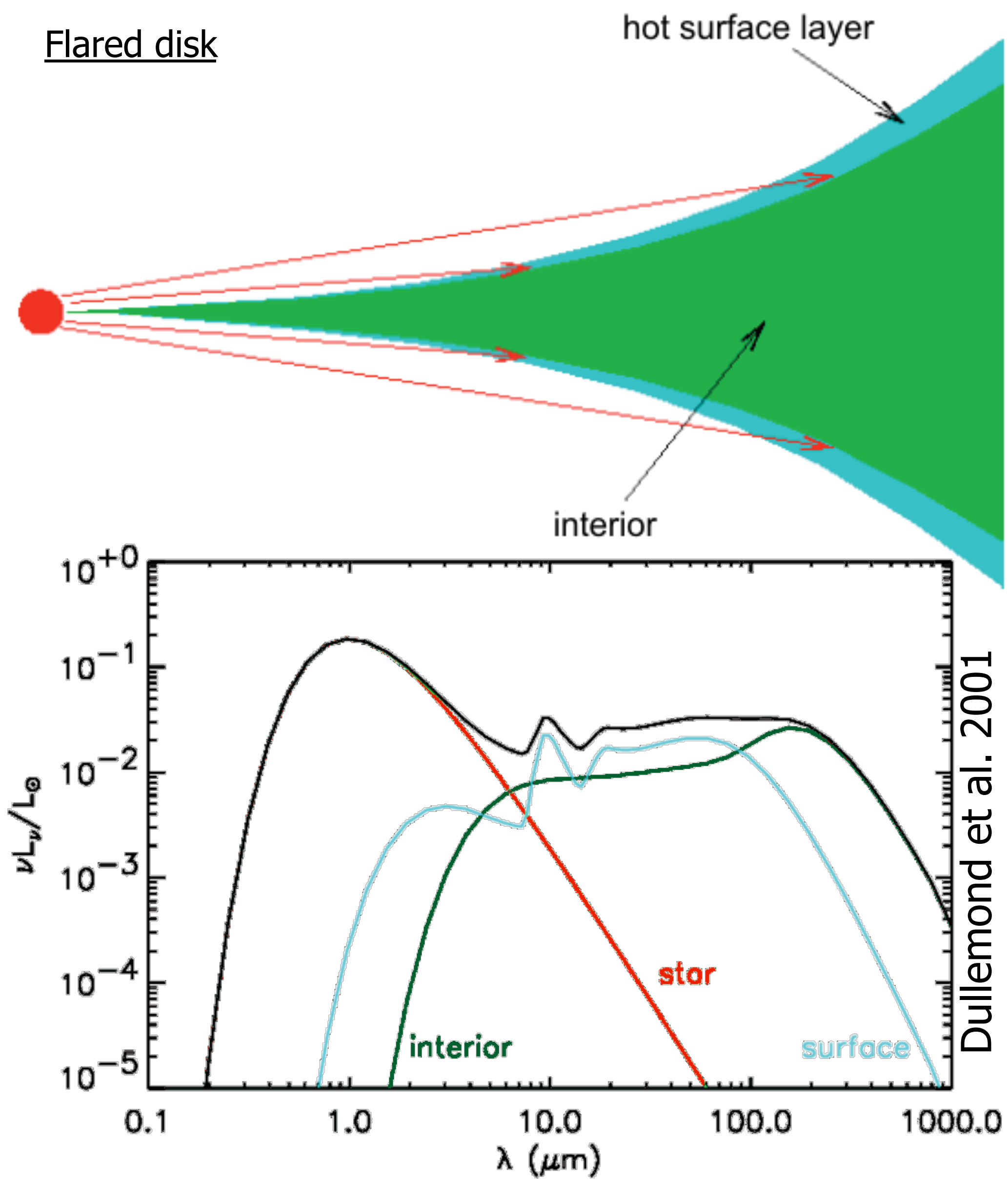
Structure of YSO disks

SED Modeling: Irradiative disks

Irradiated passive disk
(Adams, Lada & Shu 1987)

Vertical hydrostatic equilibrium
➜ Flared disk geometry
(Kenyon & Hartmann 1987)

➜ Two-Layer Approximation
(Chiang & Goldreich 1997)



Dullemond et al. 2001

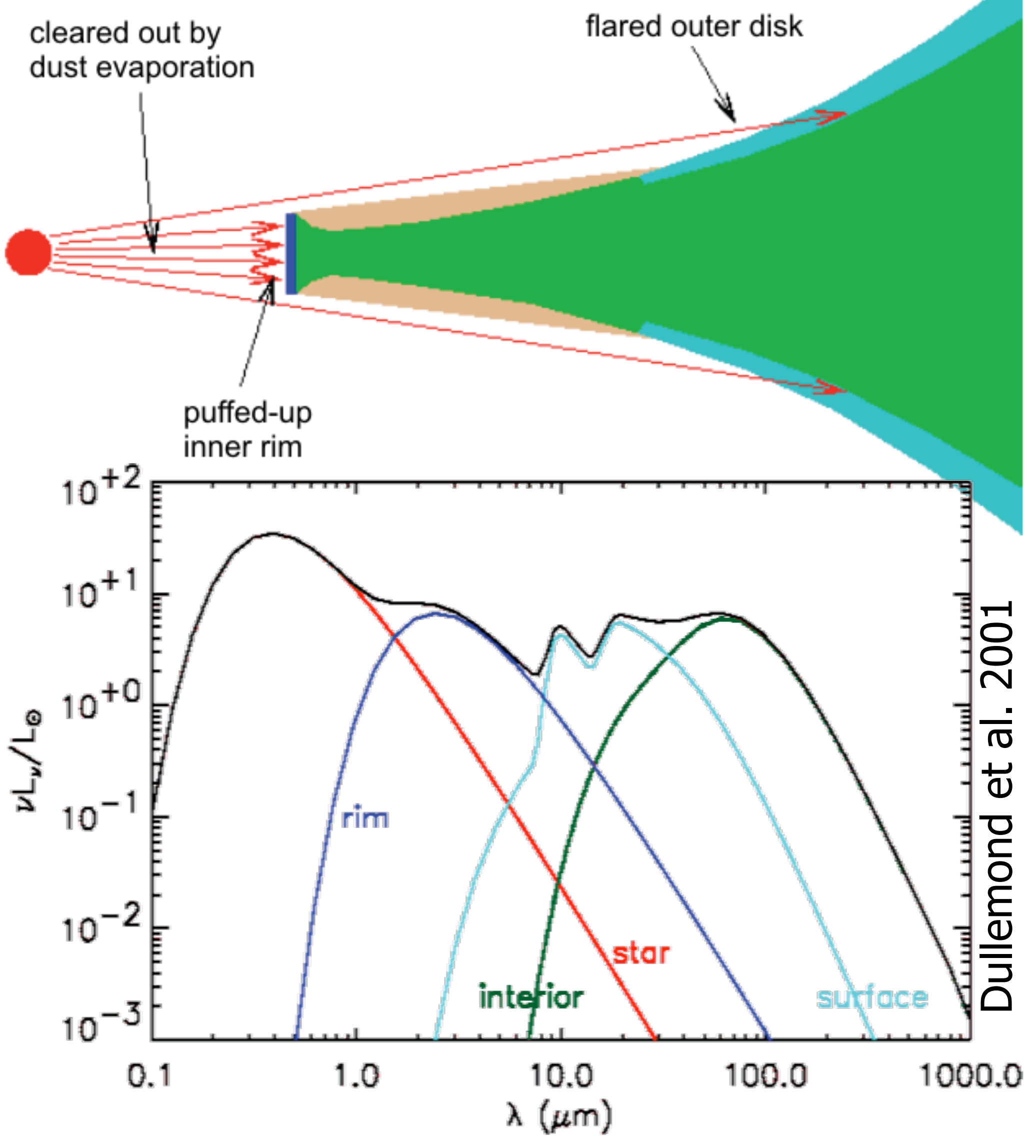
Structure of YSO disks

SED Modeling: Puffed-up Inner Rim

Both intermediate-mass & low-mass YSOs
(Herbig Ae/Be & T Tauri stars)
shows an unexpected high NIR flux
(~3 μm bump).

Dust sublimation ($T_{subl} \approx 1500K$)
➜ Puffed-up-inner rim
(Natta et al. 2001,
Dullemond et al. 2001,
Muzerolle et al. 2003)

Flared disk + Puffed-up inner rim



Dullemond et al. 2001

Structure of YSO disks

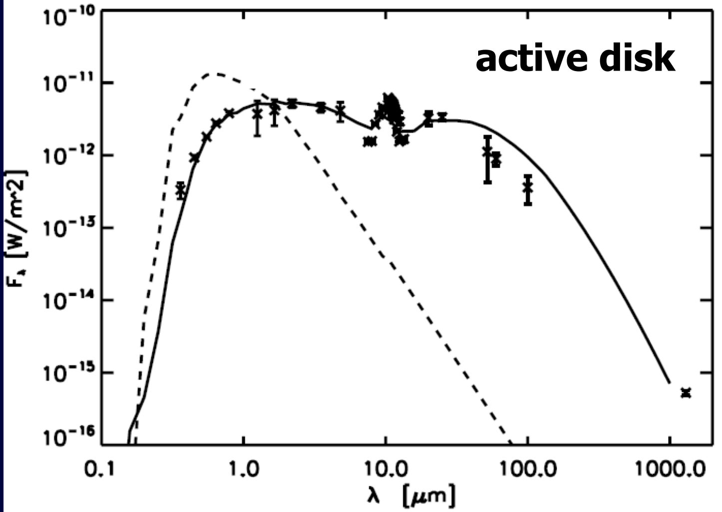
The need for high angular resolution observations

- Validate the basic model assumptions and identify the dominant physical mechanisms
- Fitting the SED can lead to highly ambiguous results:
  - degeneracies in parameter space when fitting a certain model (e.g. Thamm et al. 1994, Robitaille et al. 2007)
  - degeneracies between different model classes, e.g. active/passive disk models (e.g. Men’shchikov & Henning 1997, Kraus et al. 2008, Schegerer et al. 2008)

➜ Spatially resolved information are essential to constrain the real disk structure!

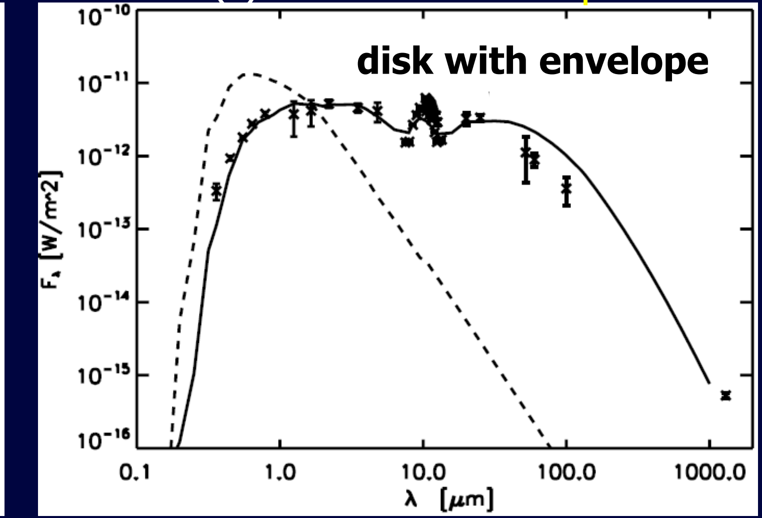
$\dot{M}_{acc} = 9\times10^{-8}\ M_\odot/yr$

$\Sigma(r) \propto r^{-1.3}$



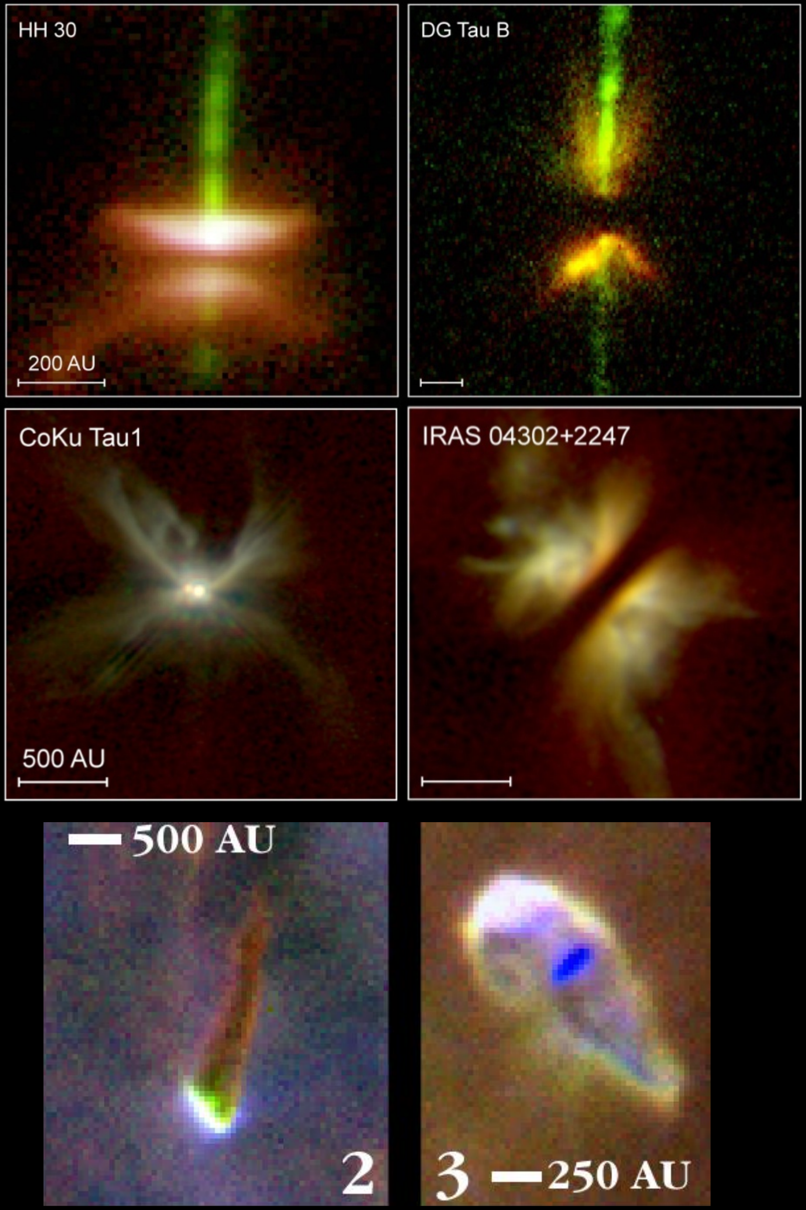
$\dot{M}_{acc} = 2\times10^{-8}\ M_\odot/yr$

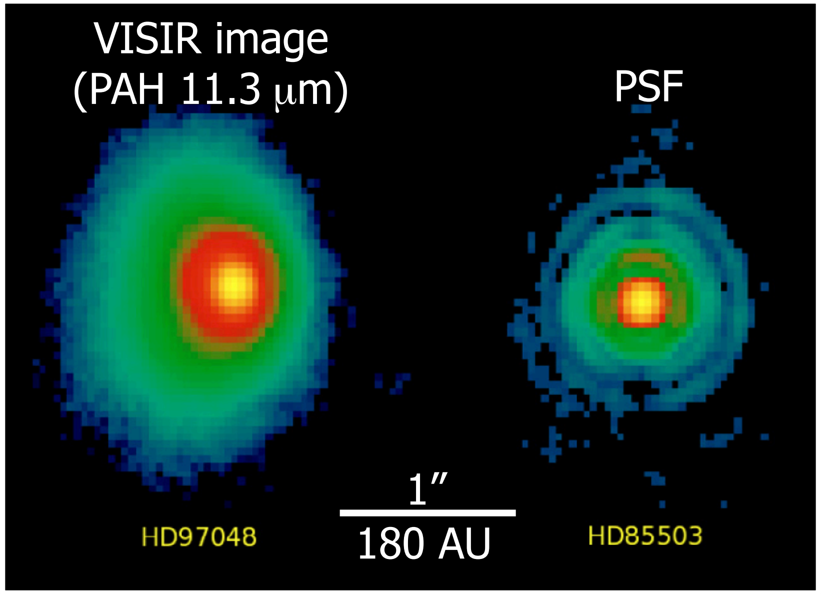
$\Sigma(r) \propto r^{-1.4}$ + envelope



RY Tau,
Schegerer et al. 2008

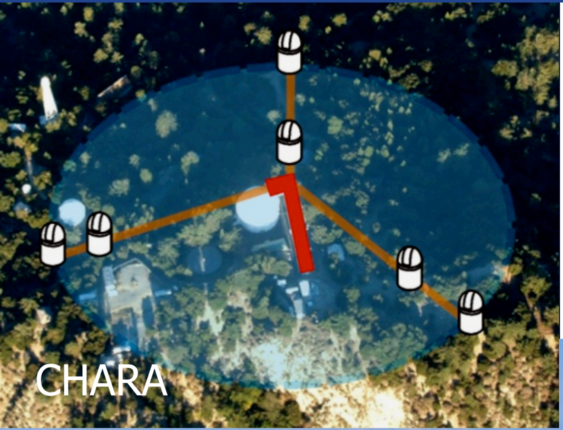
Conventional imaging of YSO disks

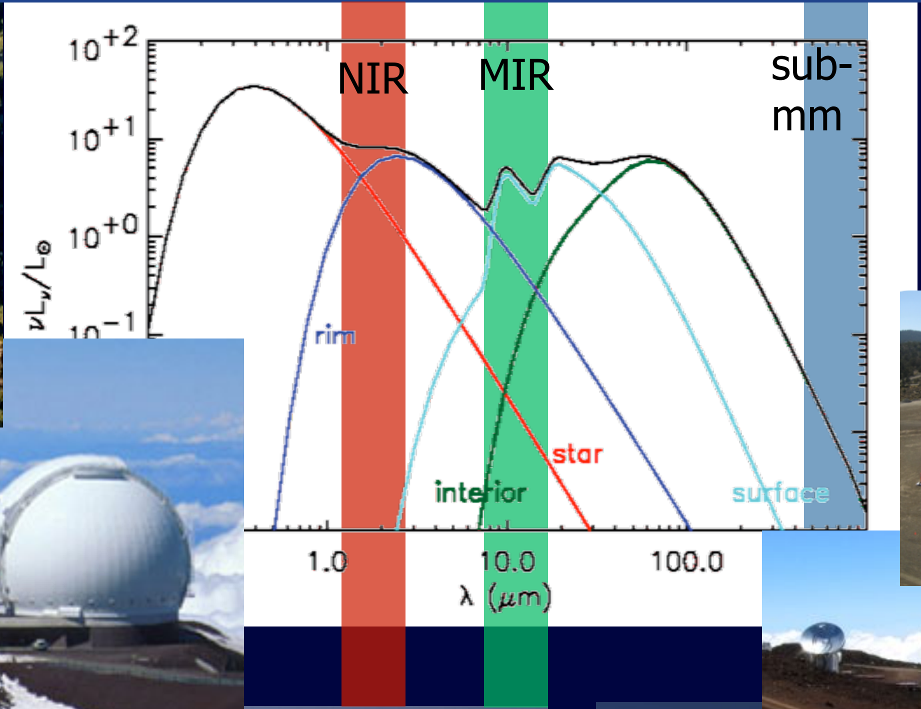


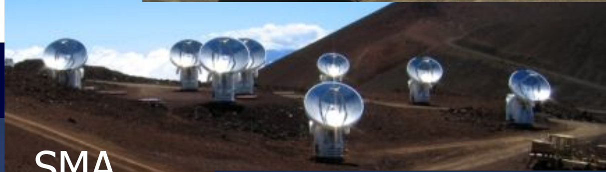


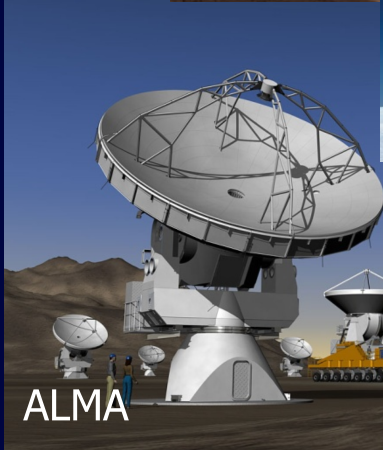
Burrows et al., Padgett et al., Doucet et al. 2007

Interferometry of YSO disks



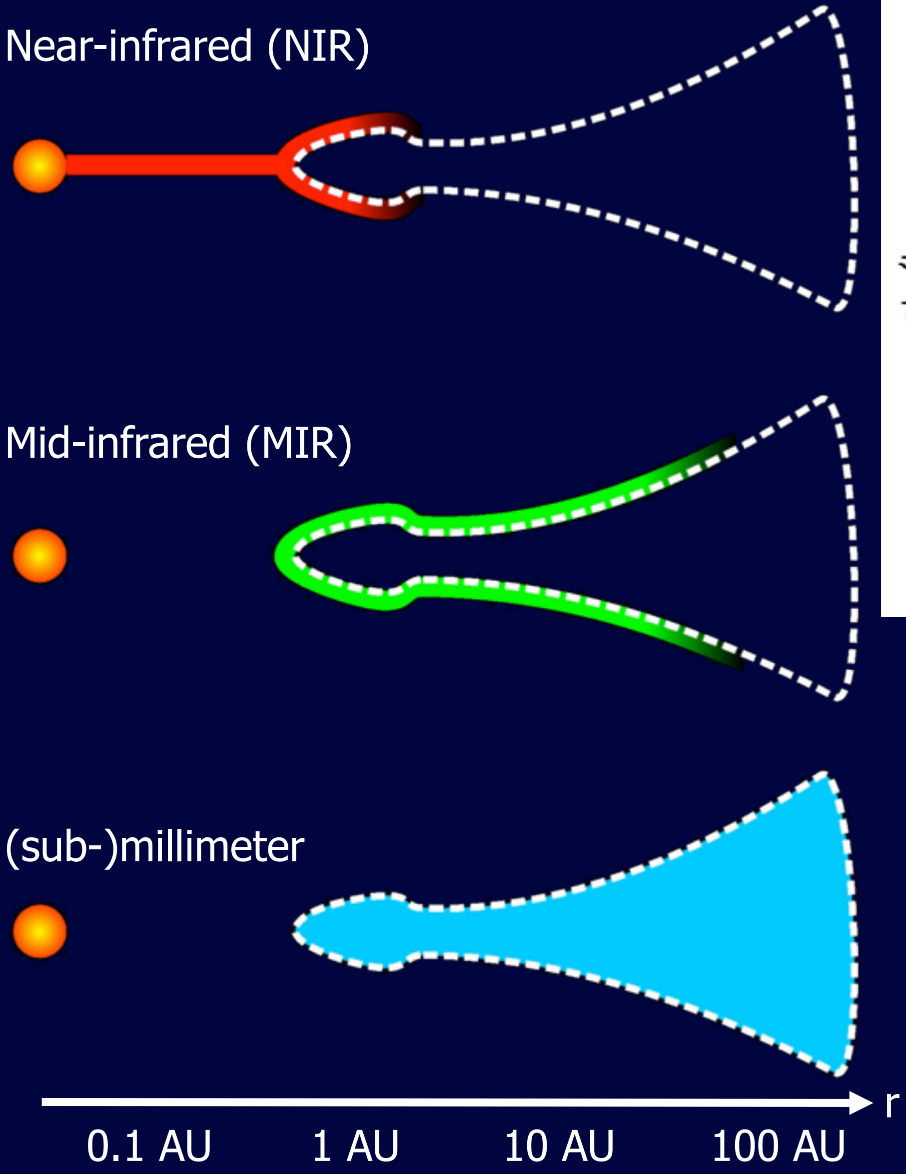


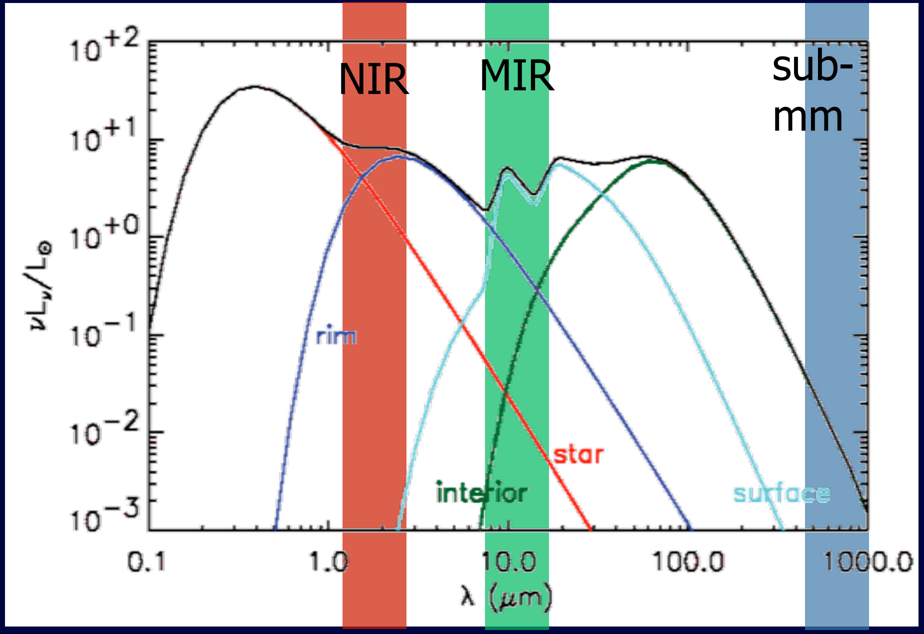




Interferometry of YSO disks

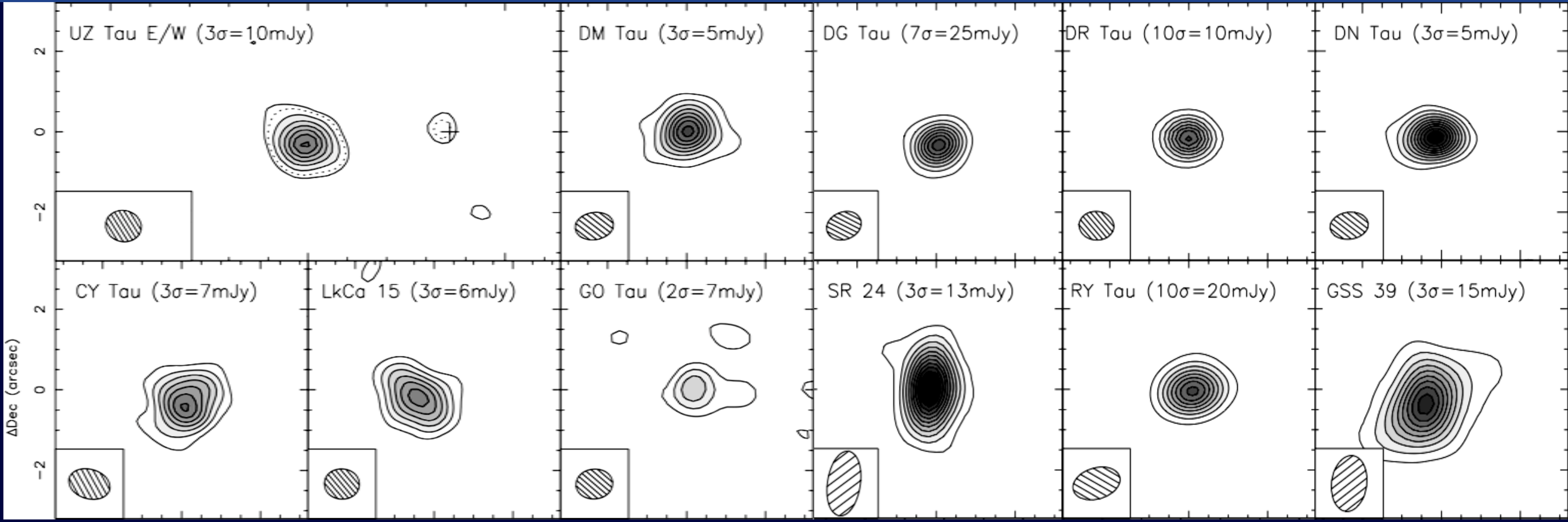
Resolving the circumstellar environment on various spatial scales



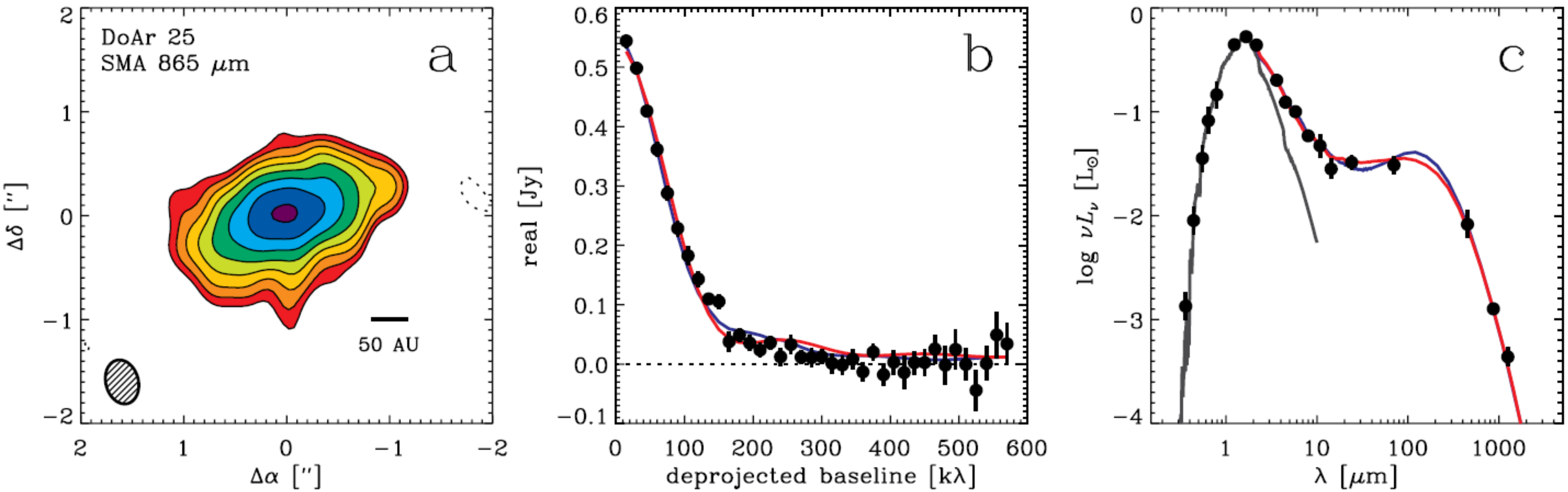


(sub-)mm interferometry

Resolving the disk structure



Isella et al. 2009



Andrews et al. 2008

(sub-)mm interferometry

Resolving the disk structure

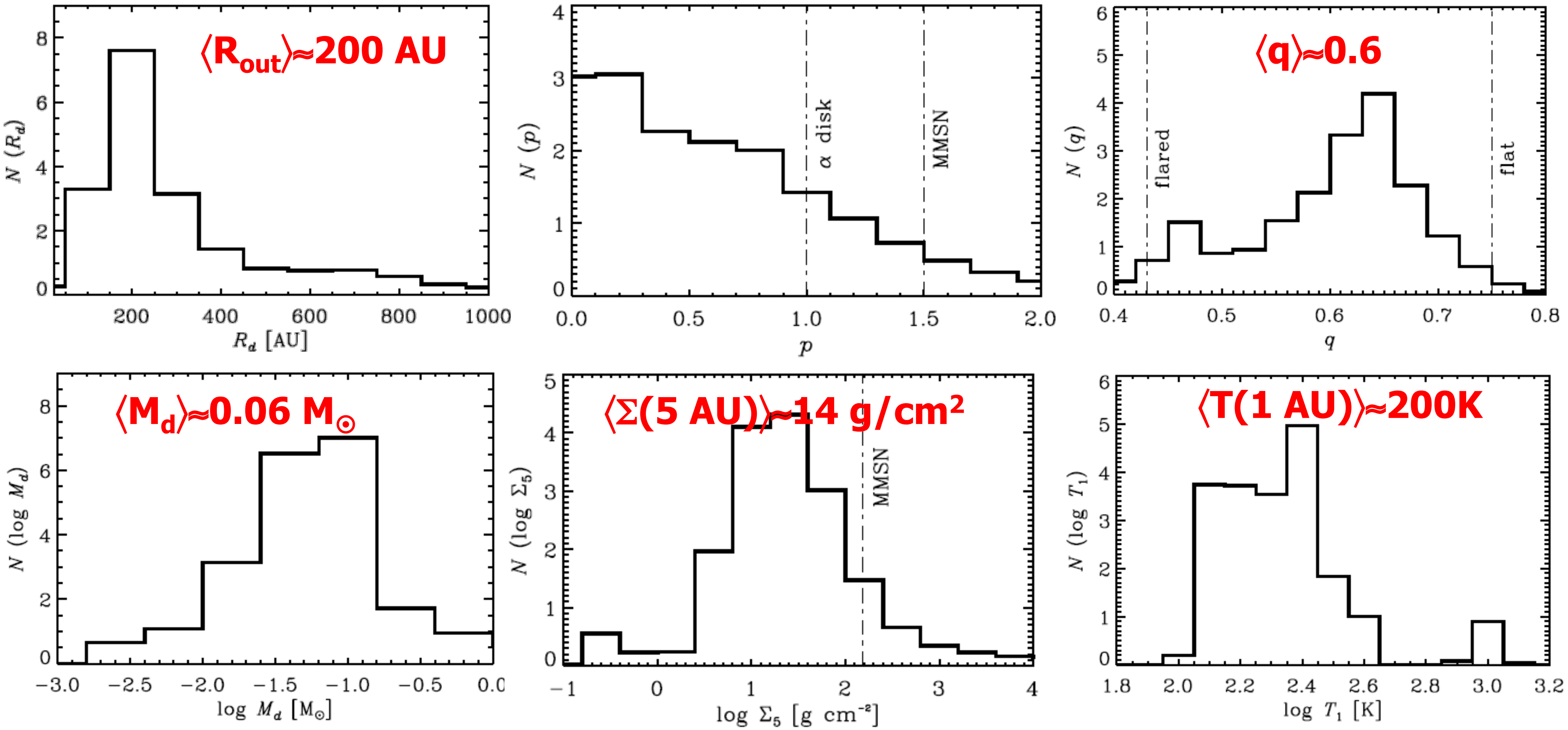
Using a disk parameterization ($T(r) \propto r^{-q}$, $\Sigma(r) \propto r^{-p}$, $\kappa_\lambda \propto \lambda^{-\beta}$) allows to derive the temperature and density profile.

24 T Tauri stars in Tau-Aur/Oph-Sco yield the following parameter distribution.

Geometry

Density

Temperature



$\langle R_{out} \rangle \approx 200$ AU

$\langle q \rangle \approx 0.6$

$\langle M_d \rangle \approx 0.06\ M_\odot$

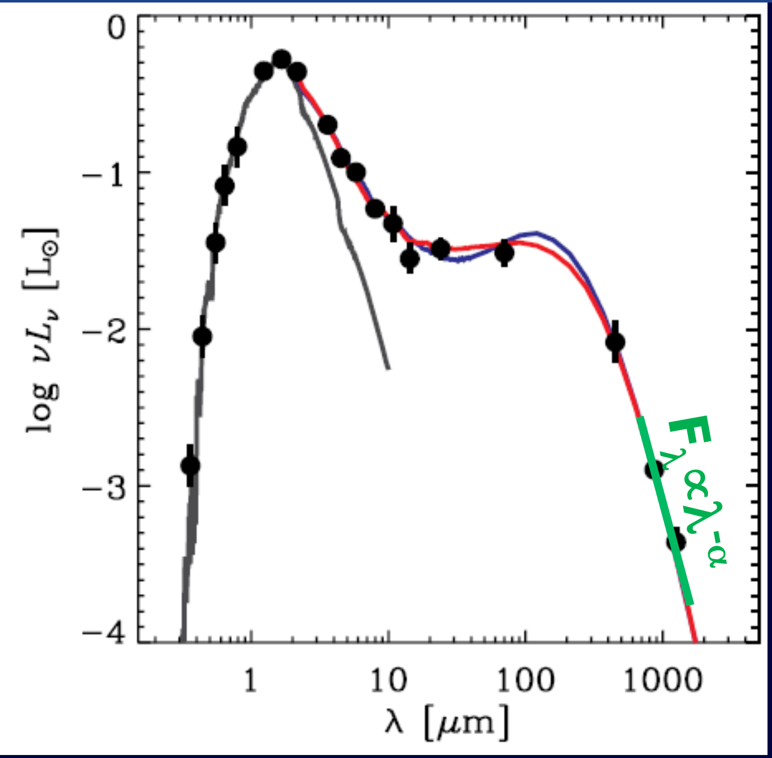
$\langle \Sigma(5\ \mathrm{AU}) \rangle \approx 14\ \mathrm{g/cm^2}$

$\langle T(1\ \mathrm{AU}) \rangle \approx 200$K

Andrews & Williams 2007

(sub-)mm interferometry

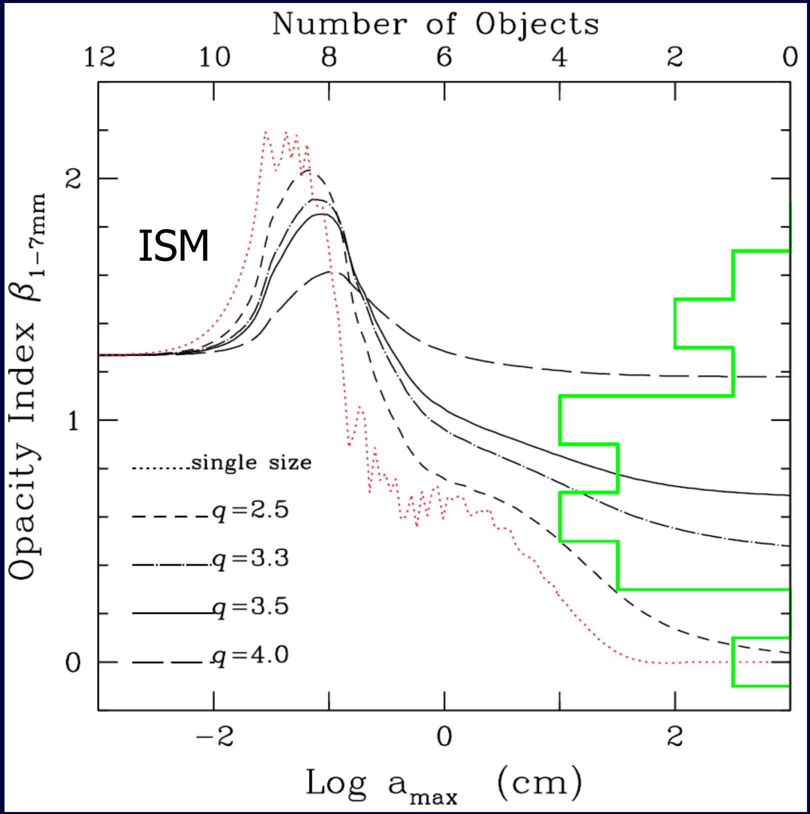
Constraints on grain growth



Rayleigh-Jeans limit → $F_\lambda \propto \kappa_\lambda \lambda^{-2}$

$\kappa_\lambda \propto \lambda^{-\beta}$ → $F_\lambda \propto \lambda^{-(\beta+2)}$

Measure spectral index → $F_\lambda \propto \lambda^{-\alpha}$ → $\beta=\alpha-2$



Natta et al. 2007, PPV; also data from Rodmann et al.

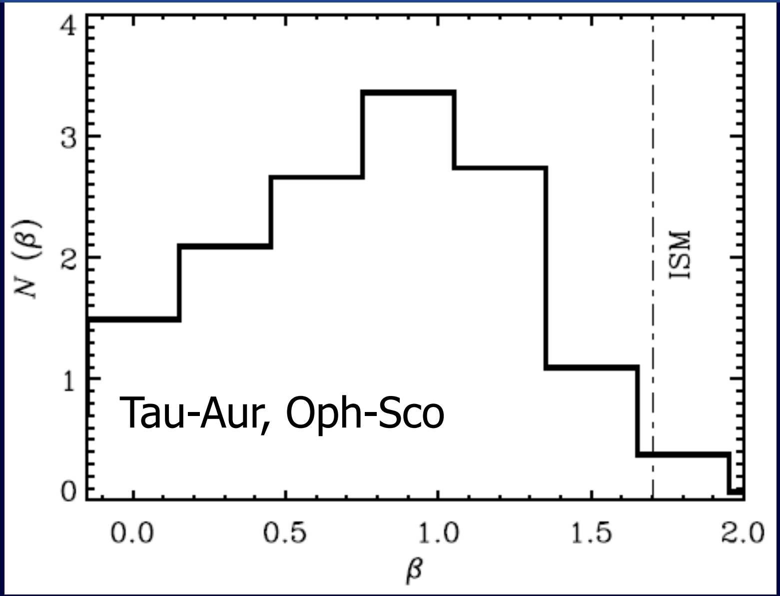
Opacity index for grain distribution $n(a) \propto a^{-q}$ from Pollack et al. 1994

Opacity index β indices best tracer for dust properties in midplane/outer disk, but high spatial resolution required to determine optically thick emission contributions ($F_\lambda \propto \lambda^{-2}$).

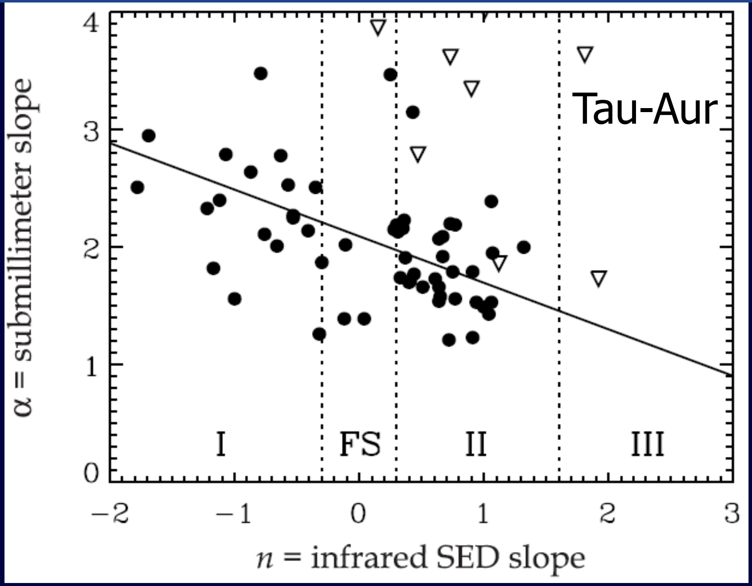
(sub-)mm interferometry

Constraints on grain growth

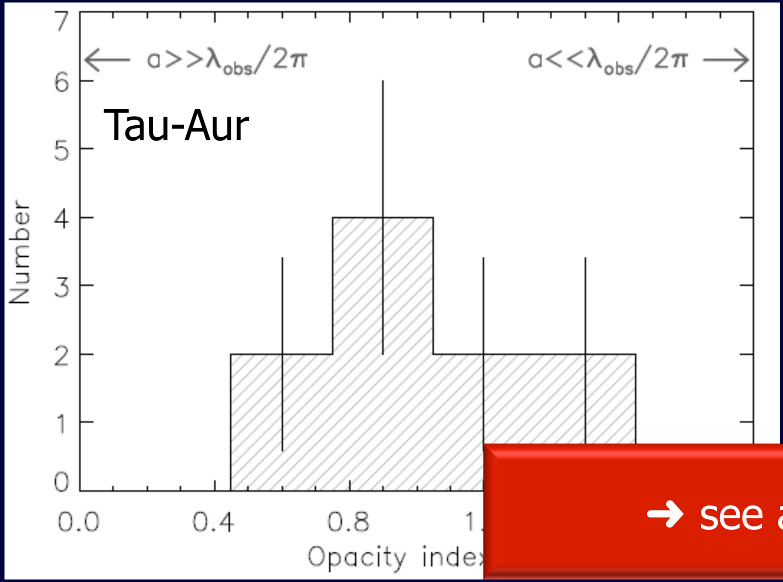
Andrews & Williams 2007



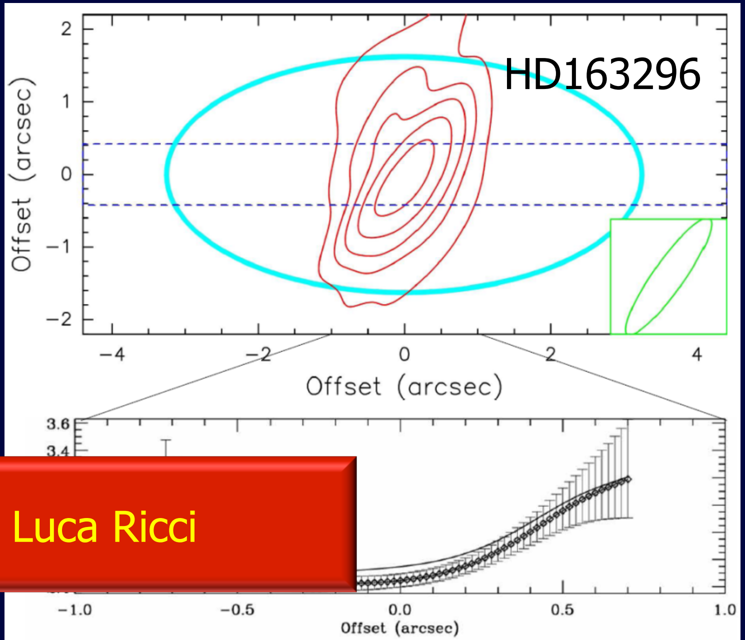
Andrews & Williams 2005



Rodmann et al. 2006



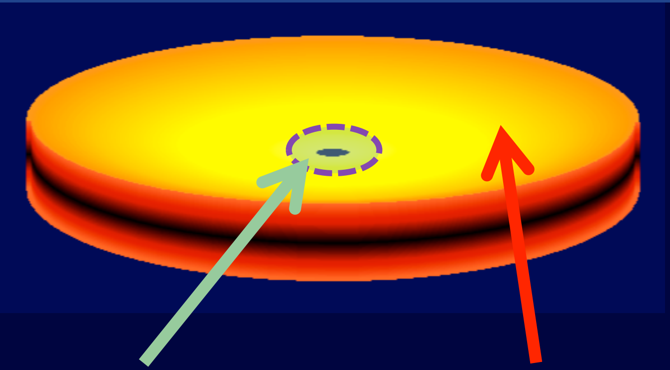
Natta et al. 2007, PPV



➜ see also talk by **Luca Ricci**

MIR interferometry

Probing radial gradients of grain growth

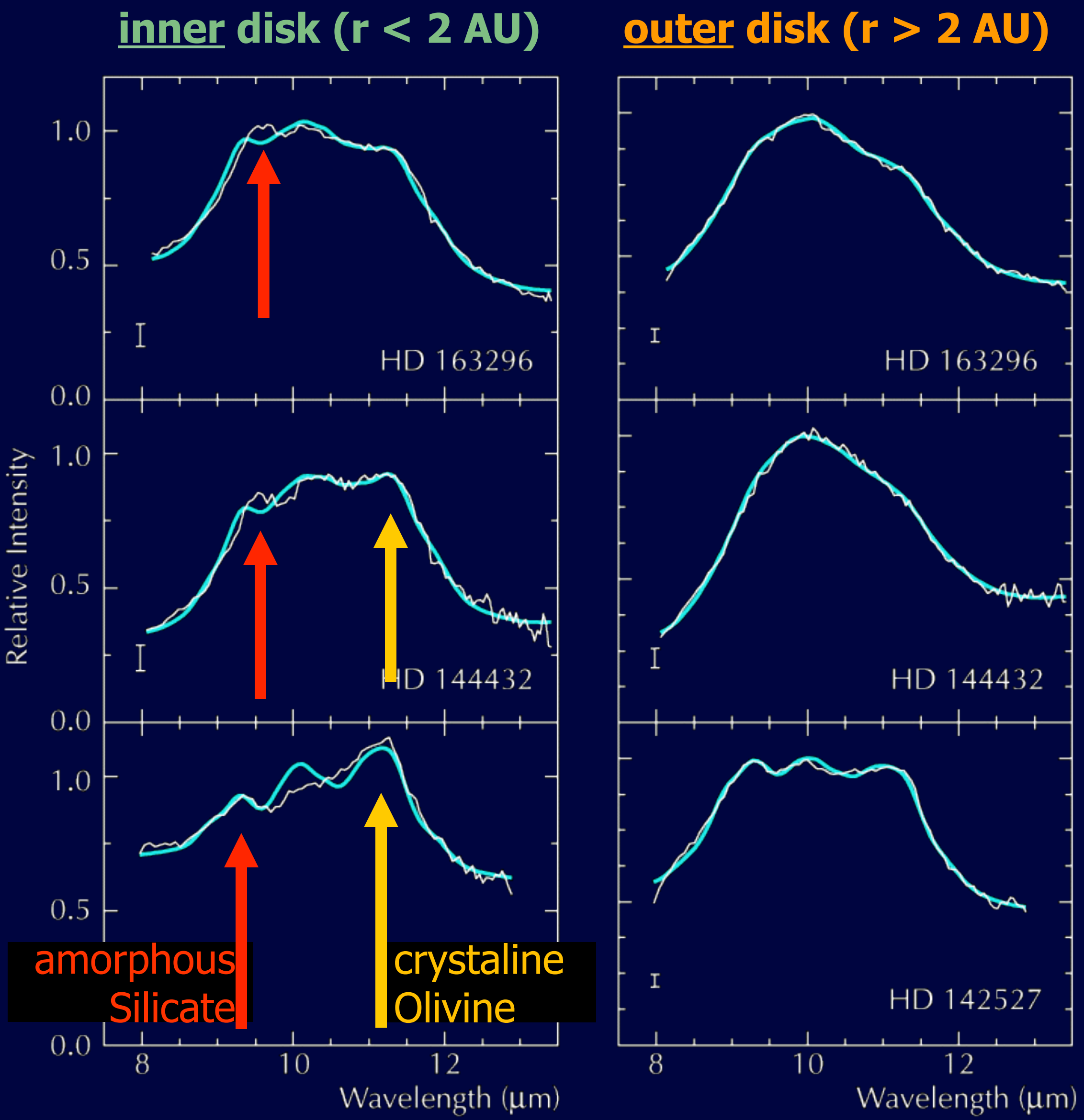


inner disk
(r < 2 AU)
unresolved

outer disk
(r > 2 AU)
resolved

Mid-Infrared interferometry allows to separate the flux contributions from different spatial scales.

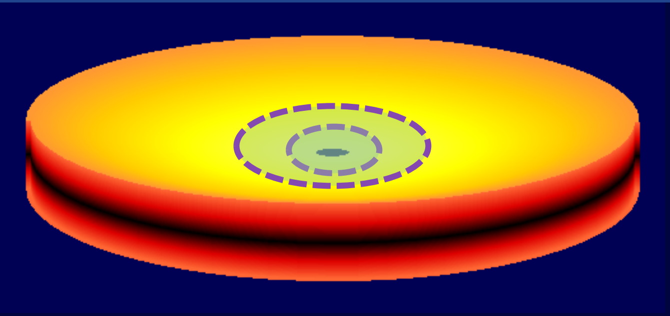
➜ Spectra from inner and outer disk regions differ significantly!



van Boekel et al. 2004

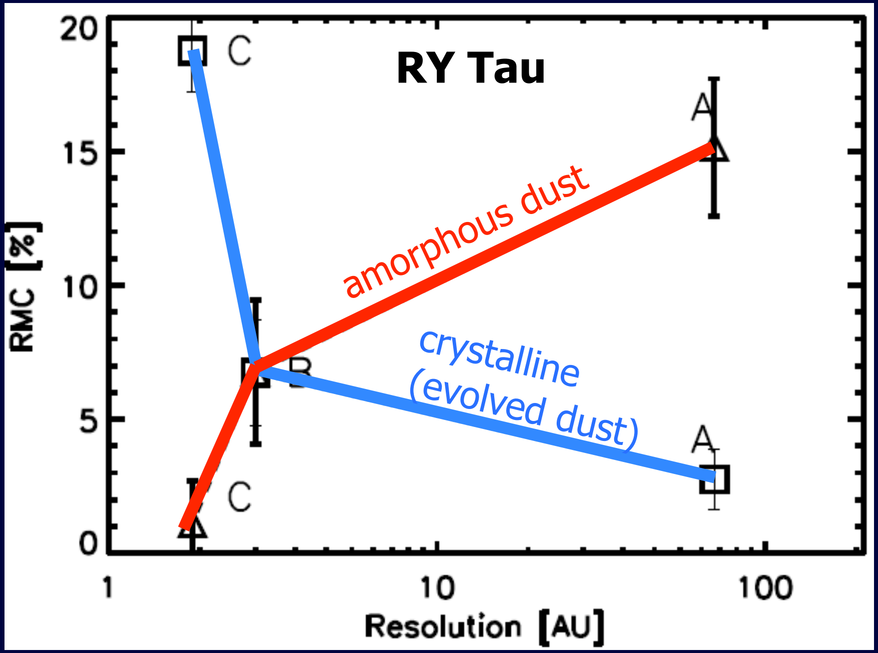
MIR interferometry

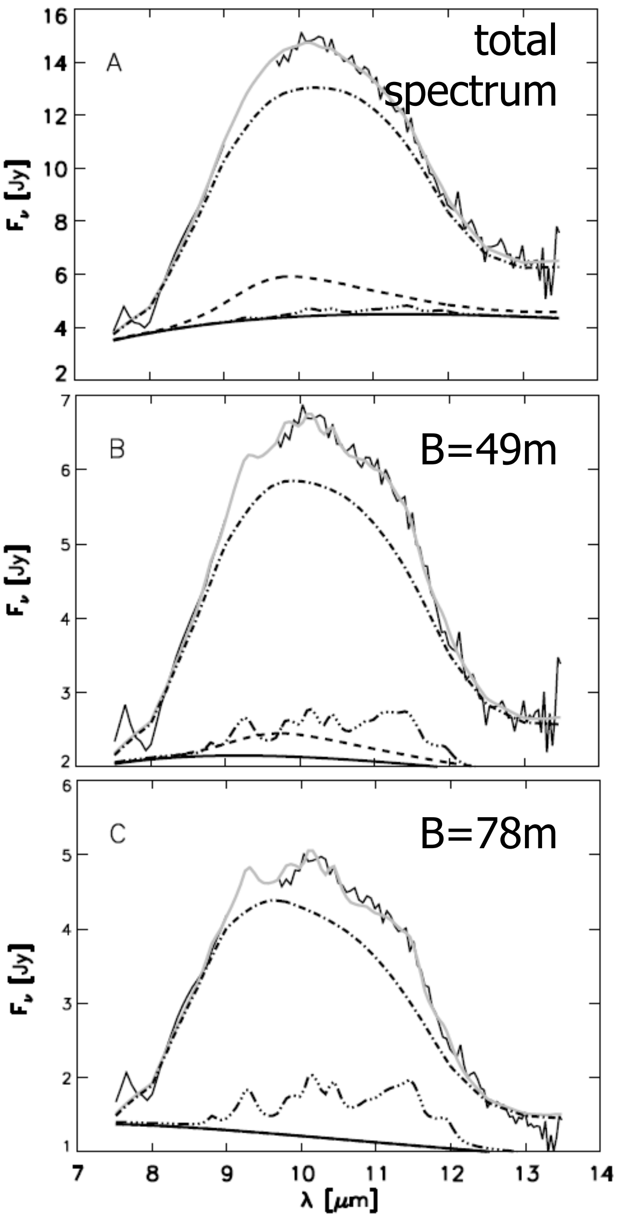
Probing radial gradients of grain growth



Using different baseline lengths allows one to probe dust mineralogy as function of radius

➜ Dust in the inner disks is highly crystallized and consists of larger grains than dust in outer disk.



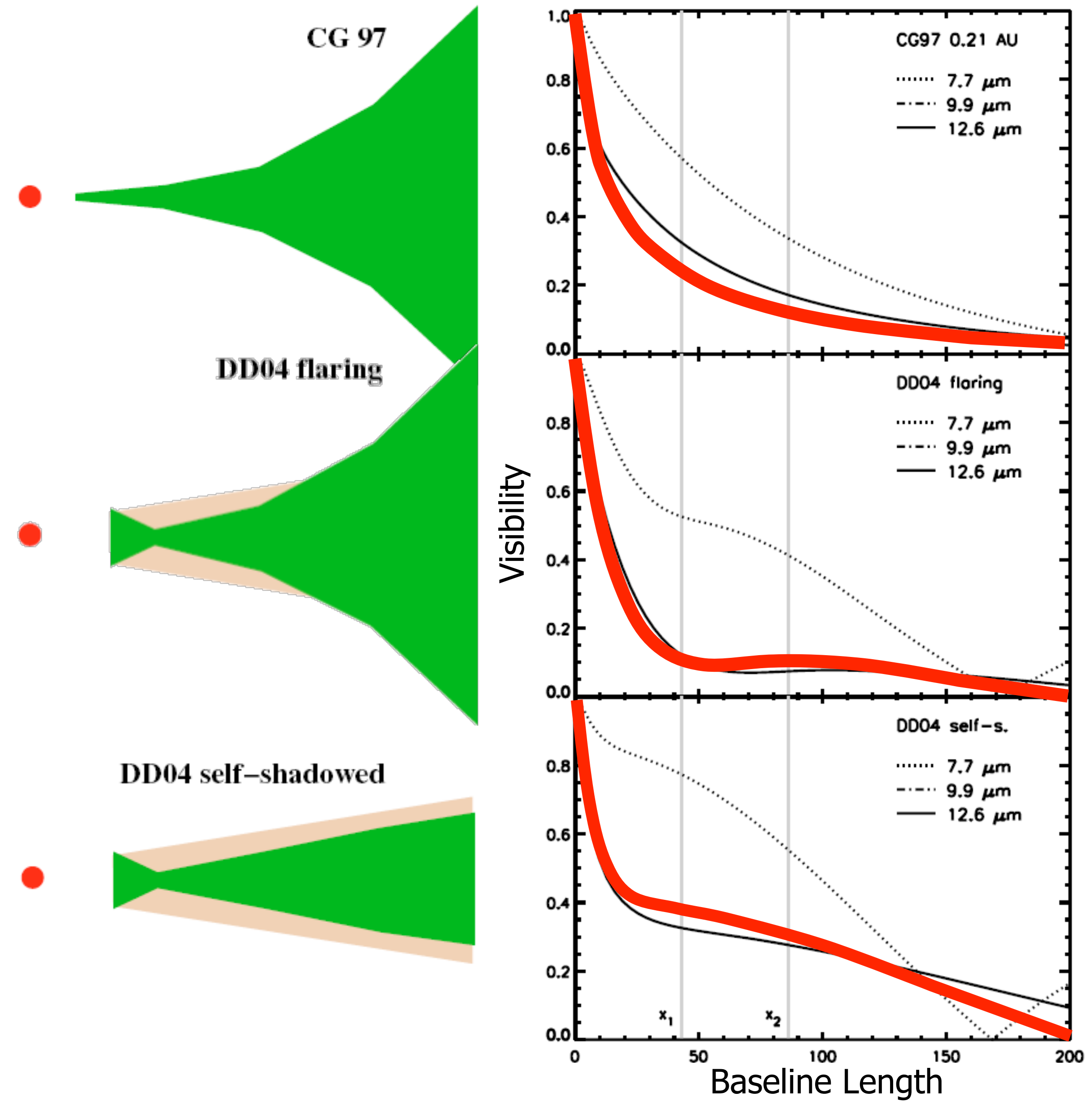


Schegerer et al. 2008

MIR interferometry

Constraints on disk flaring

Mid-infrared interferometry provides an excellent measure for the disk flaring properties

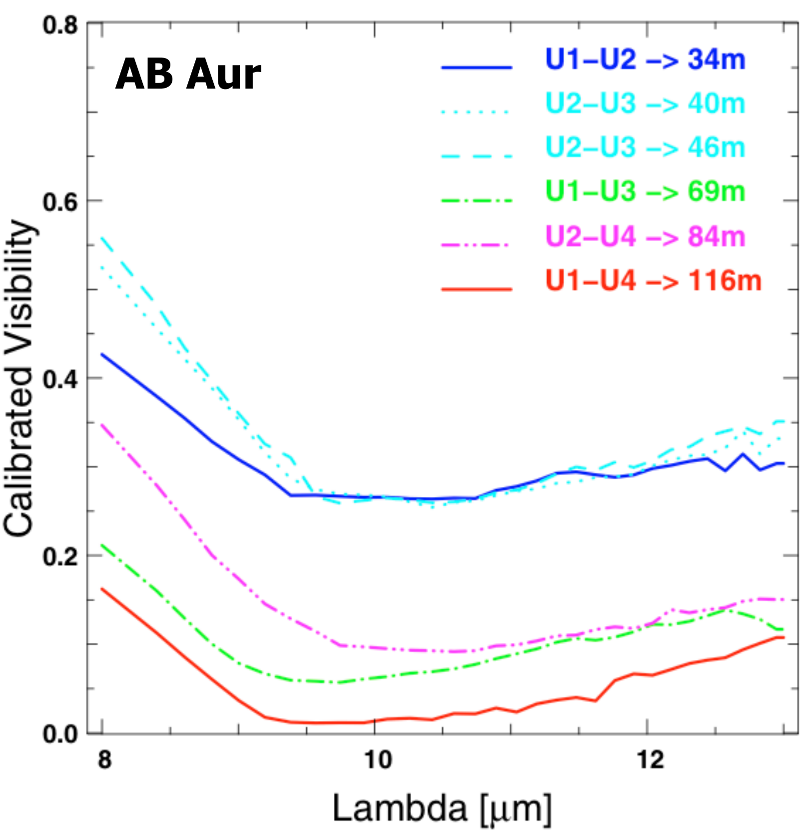


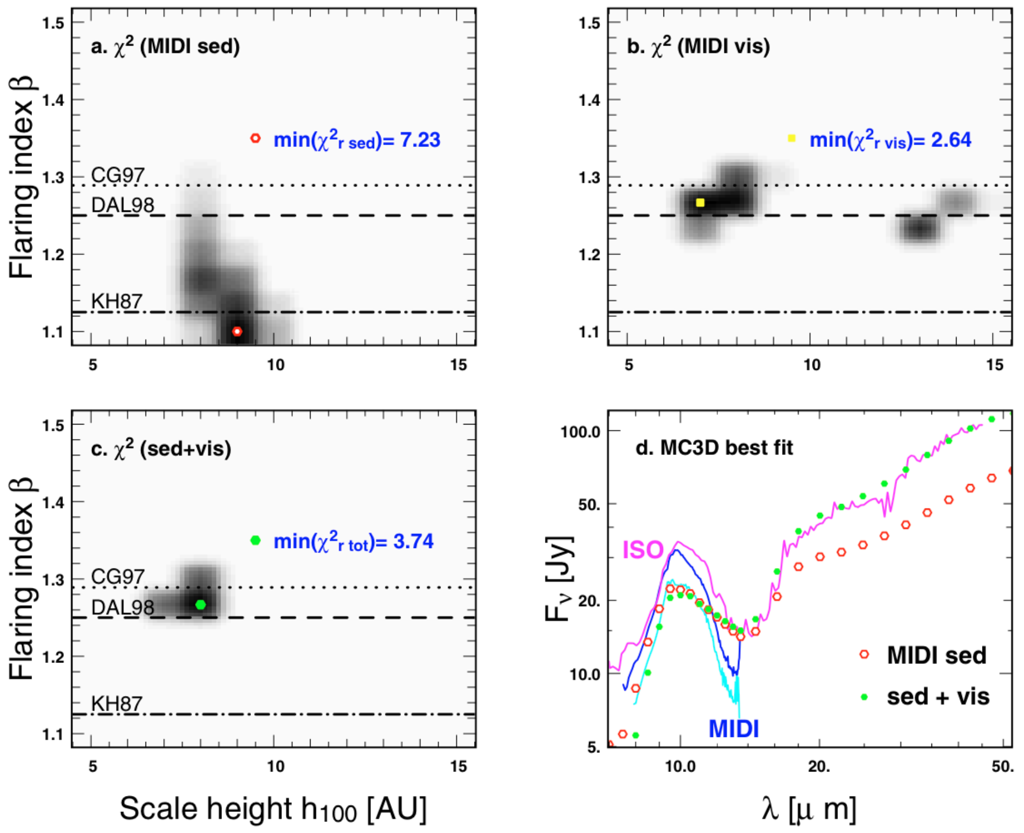
van Boekel et al. 2005

MIR interferometry

Constraints on disk flaring

Di Folco et al. 2009





Radiative transfer modeling constrains the disk flaring index β to 1.25-1.30, consistent with prediction of multi-layer flared disk models (β=1.25, D'Alessio et al. 1998; β=1.29, Chiang & Goldreich 1997)

➜ see also talk by Thorsten Ratzka (T Tau, TW Hya)

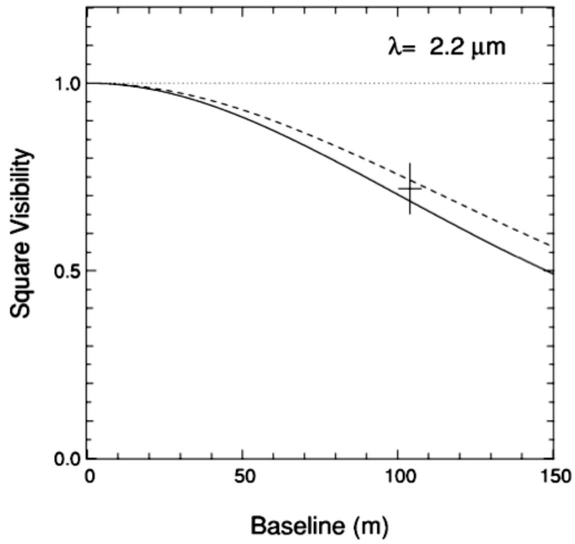
Near-infrared interferometry: FU Orionis stars

Outbursting low-mass stars, undergoing most active phase of mass accretion

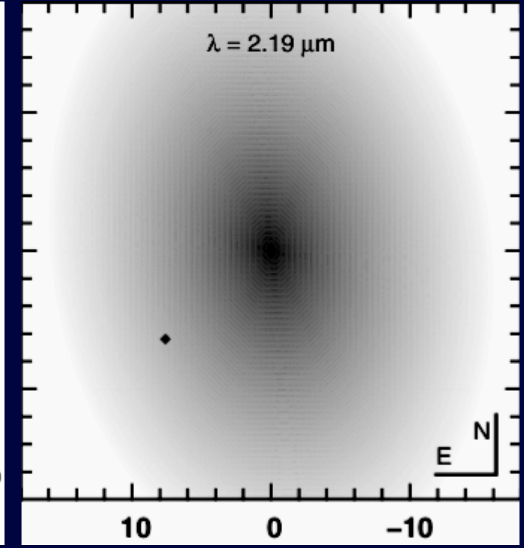
FU Ori: Disk structure in NIR (Malbet et al. 1998) and MIR (Quanz et al. 2006) consistent with standard viscous accretion disk model (q=0.75):

$$T(r) \propto \left(\frac{r}{r_{in}}\right)^{-q} \qquad q = 0.71^{+0.05}_{-0.04} \qquad r_{in} = 5.5^{+2.9}_{-1.8}\, R_{\odot}$$

Indications for a hot spot or close companion? (Malbet et al. 2005)

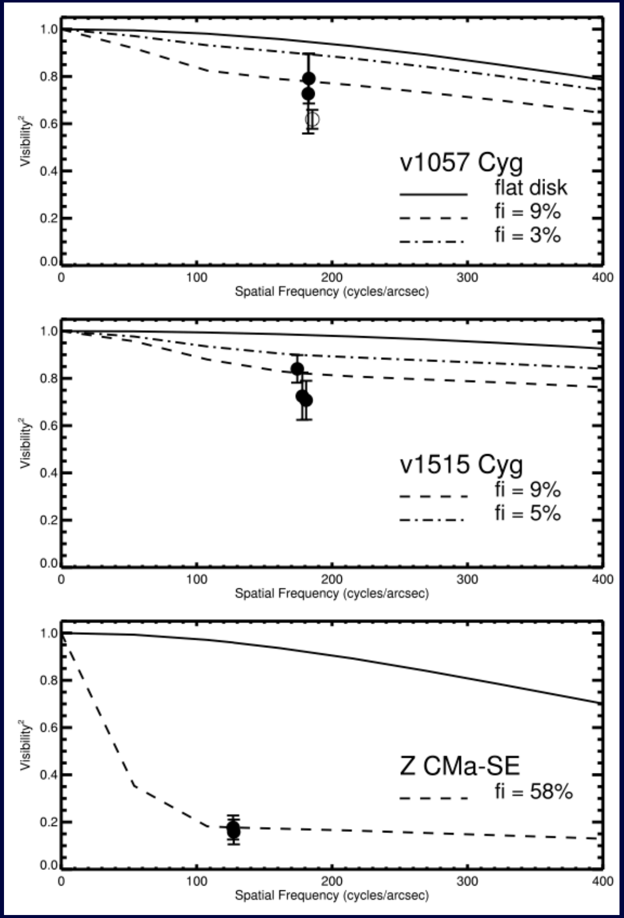


Malbet et al. 1998



Malbet et al. 2005

V1057 Cyg, V1515 Cyg, Z CMa: Consistent w/viscous disk model, but requires strong envelope contributions

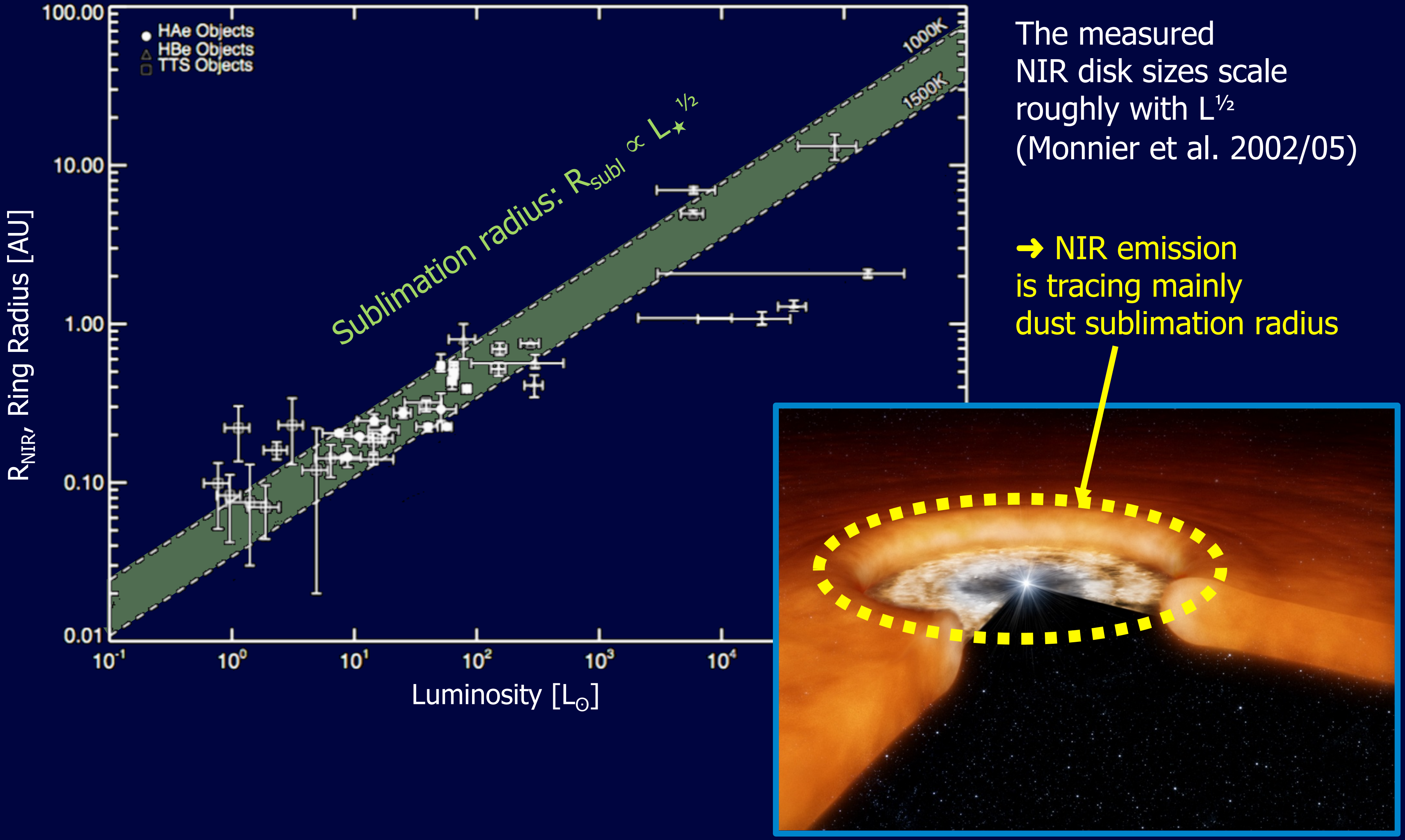


Millan-Gabet et al. 2006

Near-infrared interferometry

The Size Luminosity Relation

Millan-Gabet et al., PPV



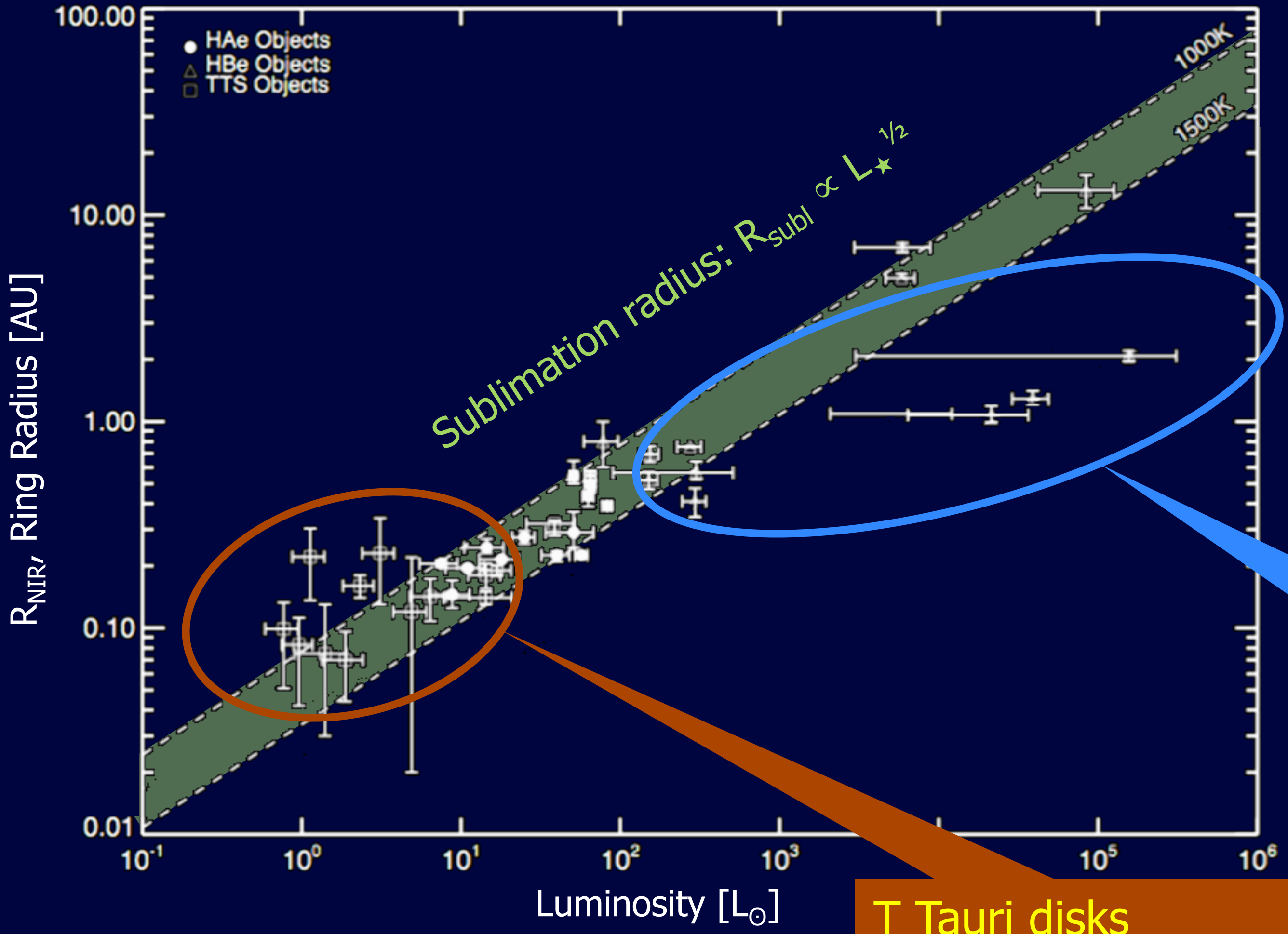
The measured
NIR disk sizes scale
roughly with $L^{1/2}$
(Monnier et al. 2002/05)

➜ NIR emission
is tracing mainly
dust sublimation radius

Near-infrared interferometry

The Size Luminosity Relation

Millan-Gabet et al., PPV



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

➜ NIR emission
is tracing mainly
dust sublimation radius

…however:

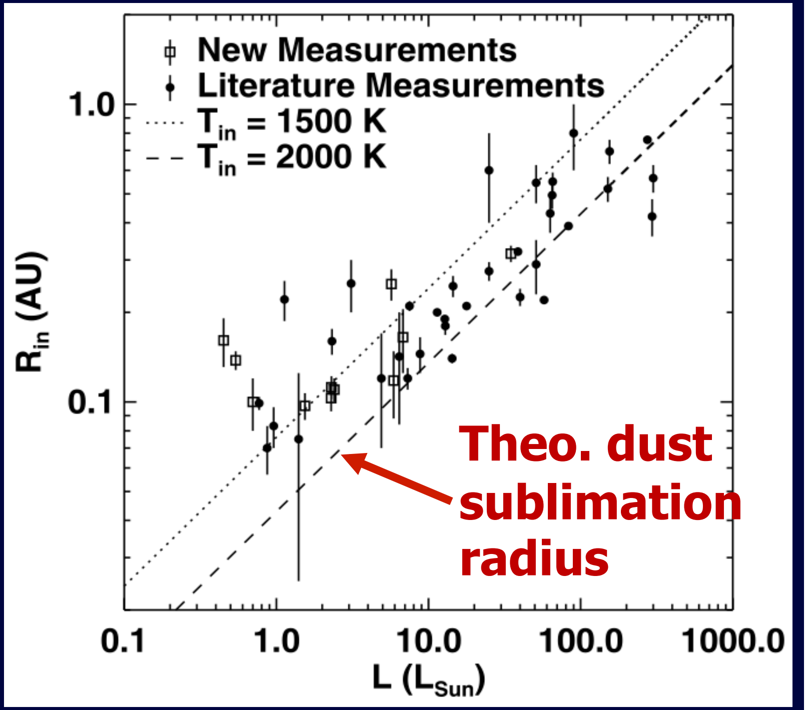
Herbig Be disks
appear often
systematically **smaller**

T Tauri disks
appear often
systematically **larger**

Near-infrared interferometry

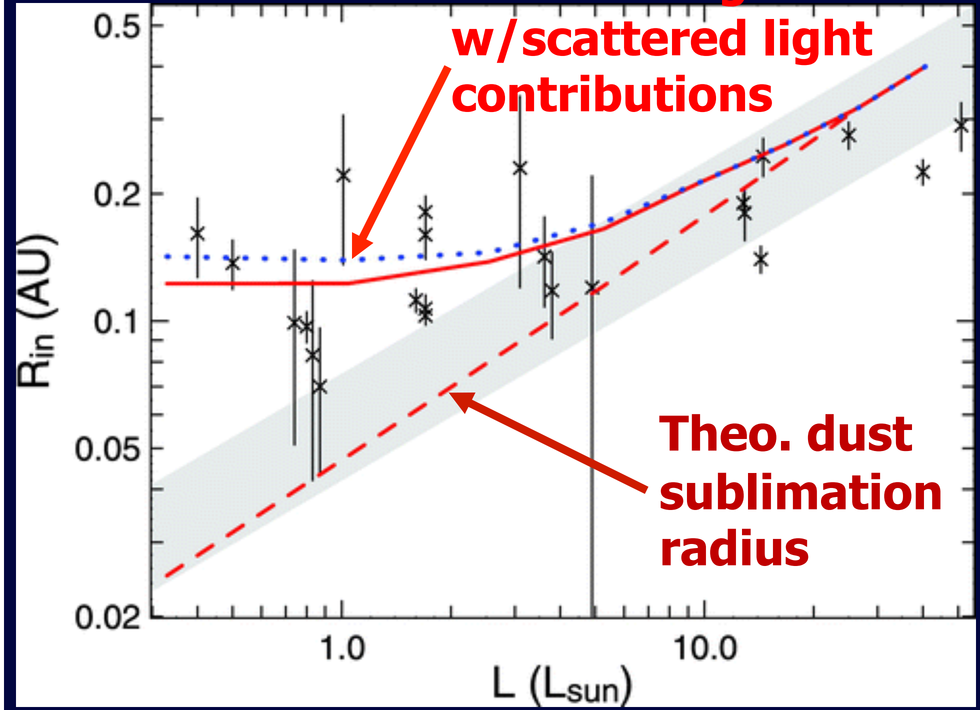
Importance of scattered light for low-mass YSOs

Eisner et al. 2007



Theo. dust sublimation radius

Derived ring radius w/scattered light contributions



Theo. dust sublimation radius

Pinte et al. 2008

Potential solutions:

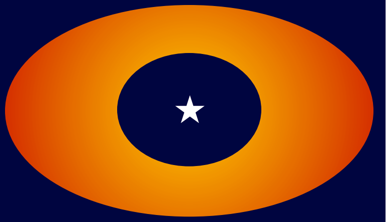
- Lower dust sublimation temperature due to lower gas pressure?
- Smaller dust grains?
- Photoevaporation?
- Magnetospheric truncation?

Radiative transfer simulations suggest:

- Deviations from $R_{subl} \propto L_\star^{1/2}$ law can be explained with scattered light contributions from flaring dust disk
- Bias increases towards lower luminosities since cooler objects radiate larger fraction of L_{bol} at NIR wavelengths

Near-infrared: Constraints on the dust rim geometry

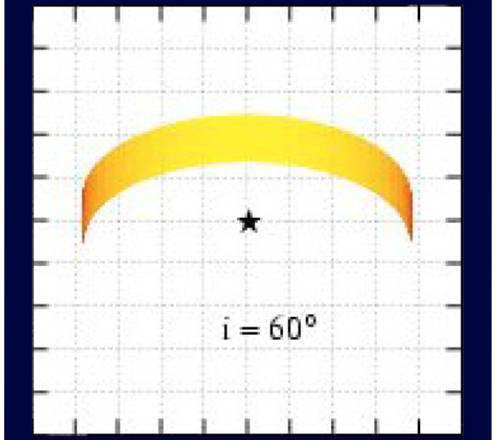
GEOM. FLAT DISK



e.g. temperature gradient models

No asymmetries
(CP ≡ ZERO!)

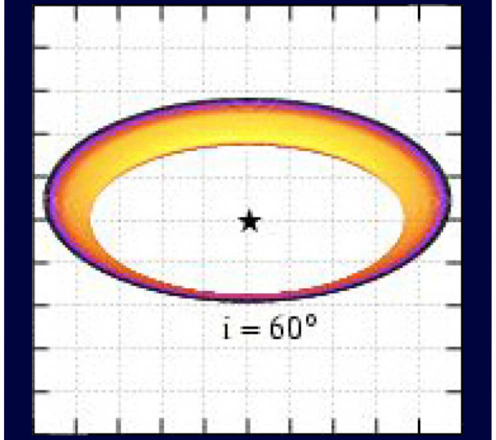
VERTICAL RIM



Natta et al. 2001
Dullemond et al. 2001

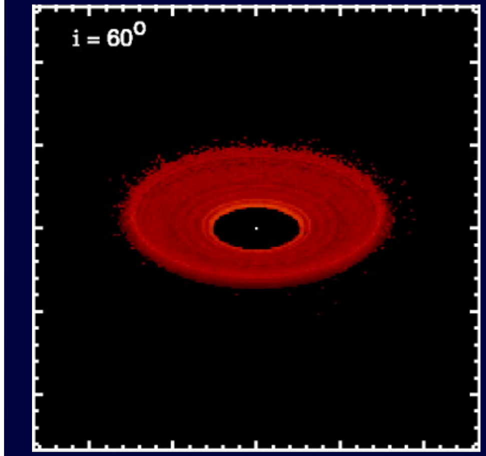
Strong asymmetries
(strong CP signal)

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

Near-infrared: Constraints on the dust rim geometry

R Coronae Austrinae:
  Herbig Ae star, d=130 pc

24 VLTI/AMBER observations
H+K band (1.6-2.5 μm), $\lambda/\Delta\lambda$=35

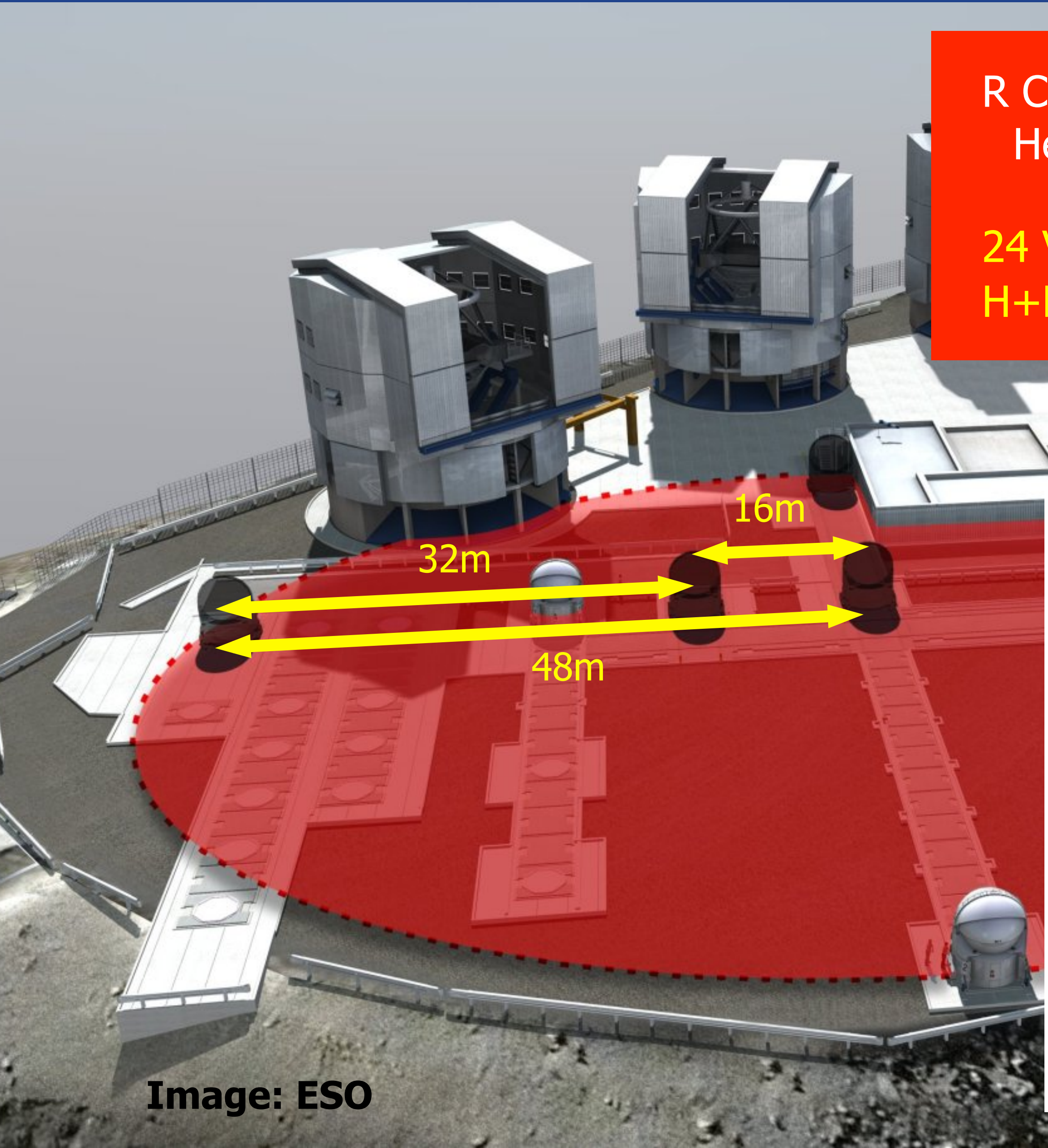
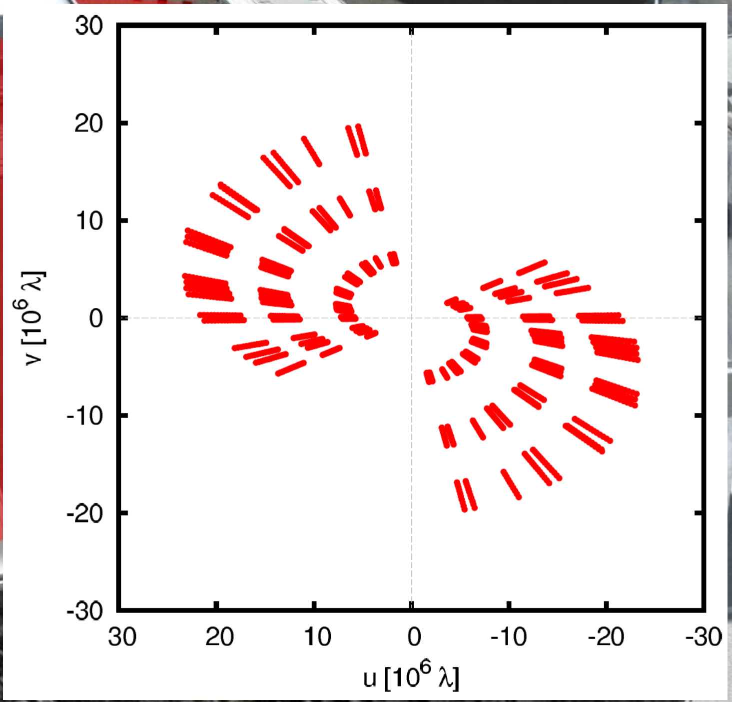
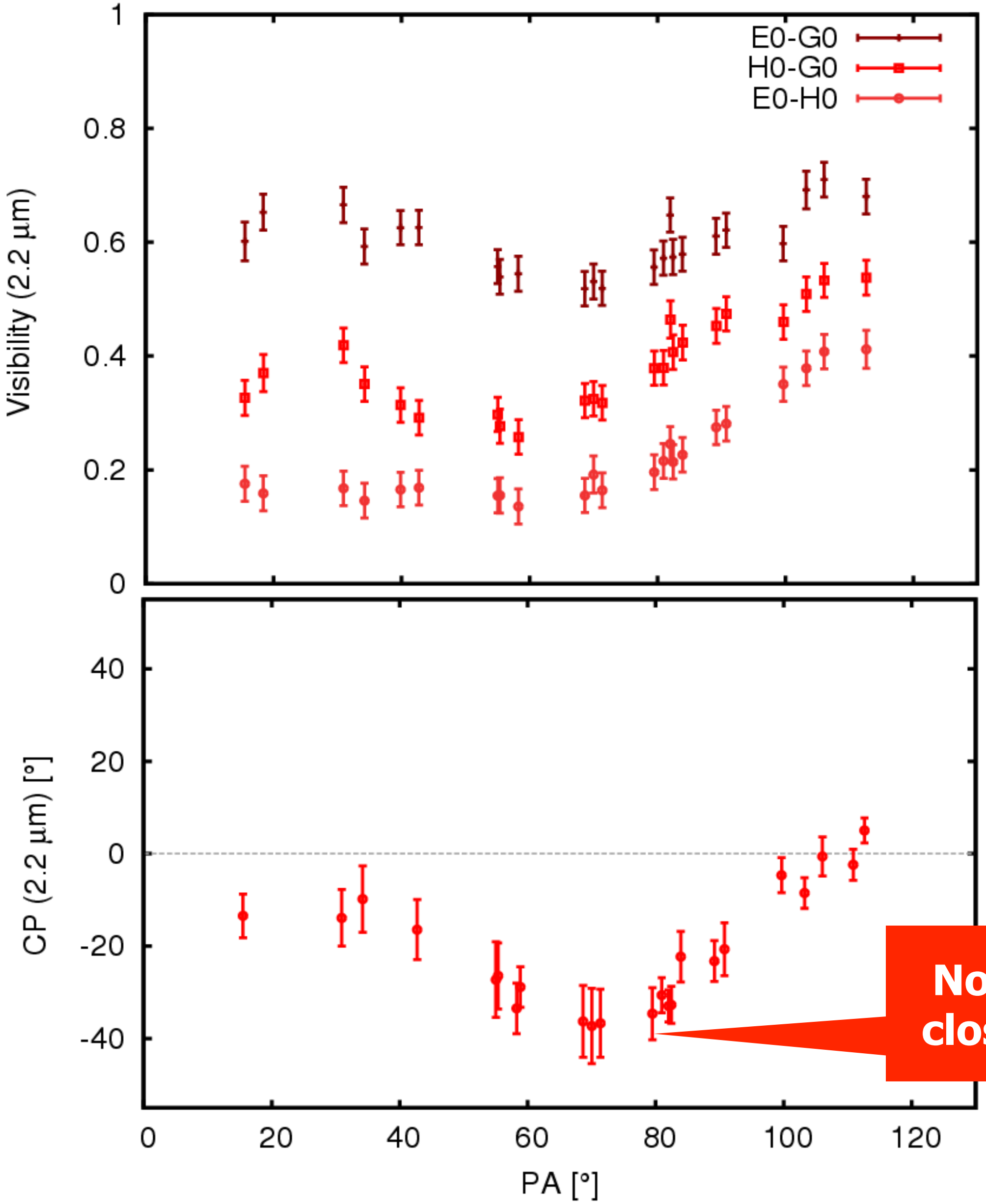


Image: ESO



Near-infrared: Constraints on the dust rim geometry

Position-angle dependence of visibilities & CPs



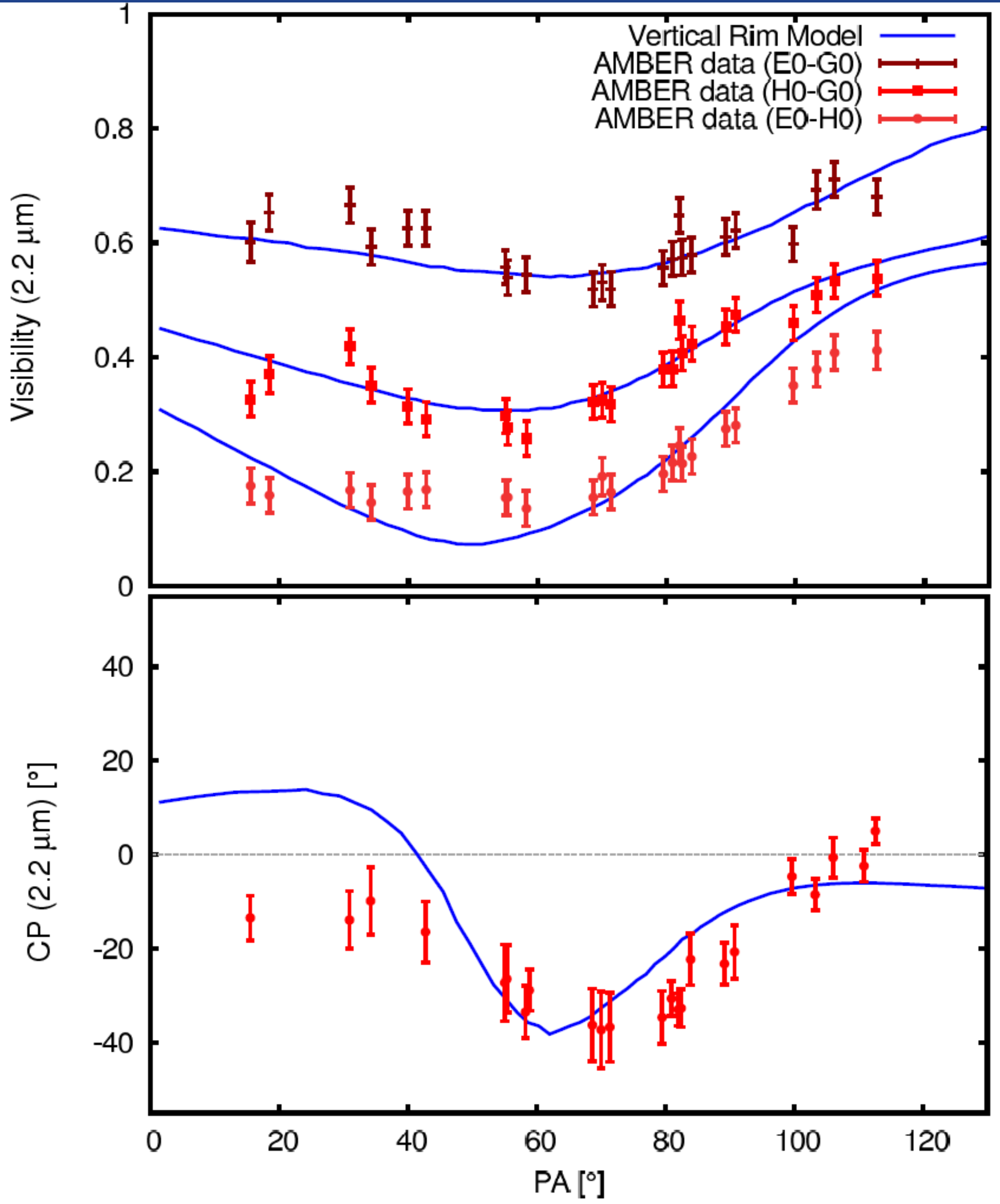
Non-zero (-40°) closure phases!!!

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

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

Near-infrared: Constraints on the dust rim geometry

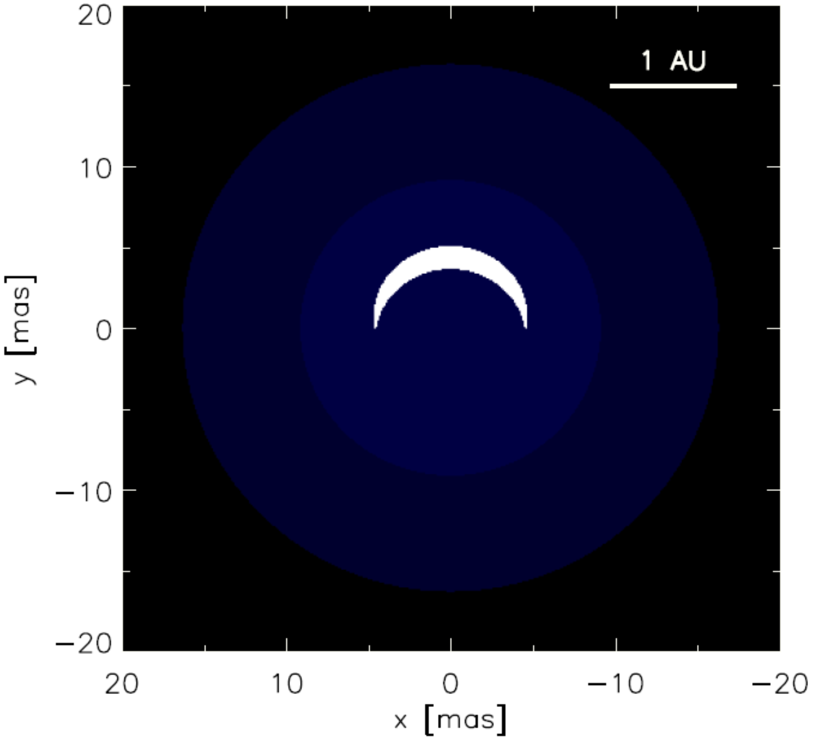
VERTICAL RIM model



Scenario:

Vertical puffed-up inner rim

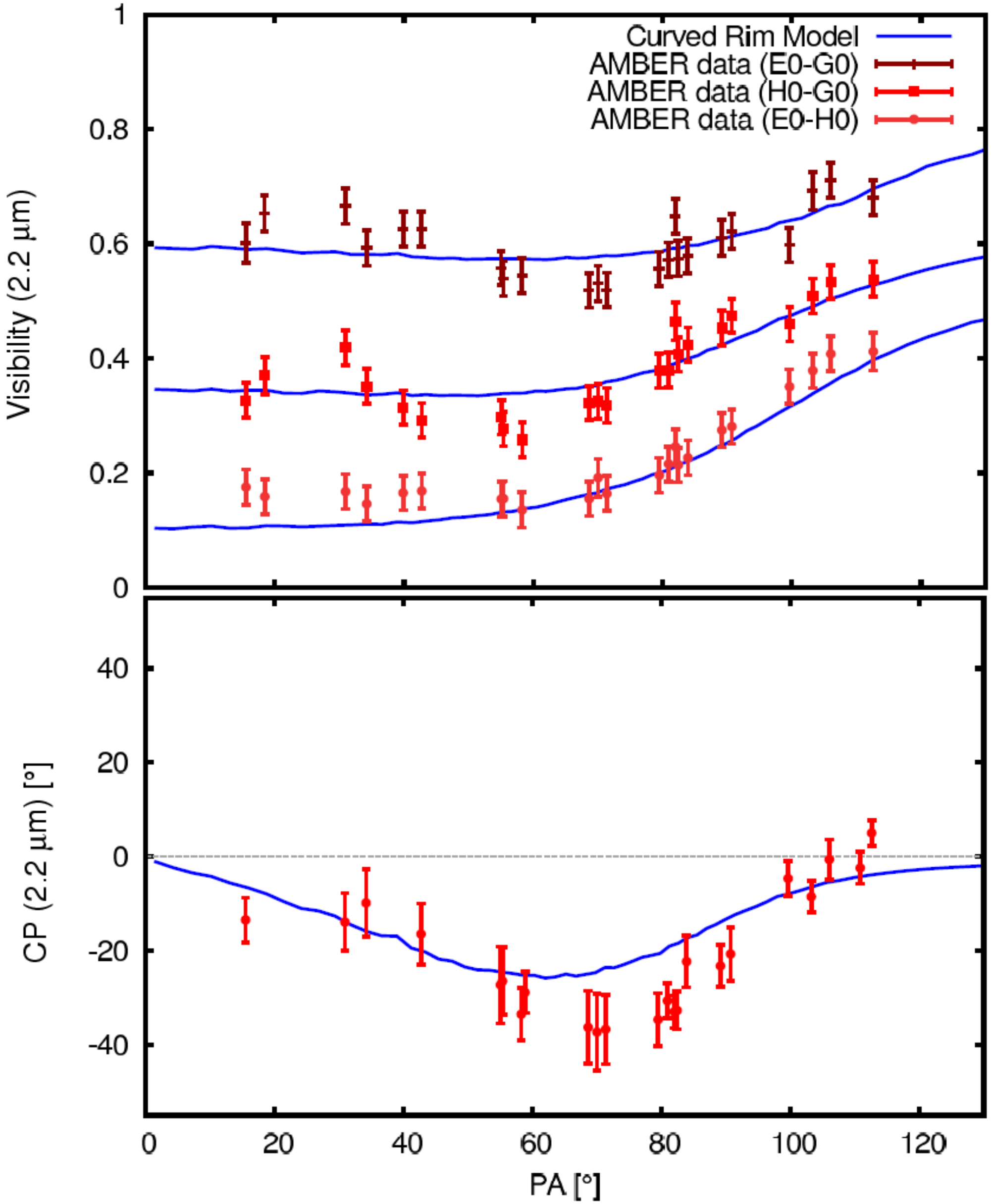
(motivated by Dullemond et al. 2001)



$$\chi^2 = 3.3$$

Near-infrared: Constraints on the dust rim geometry

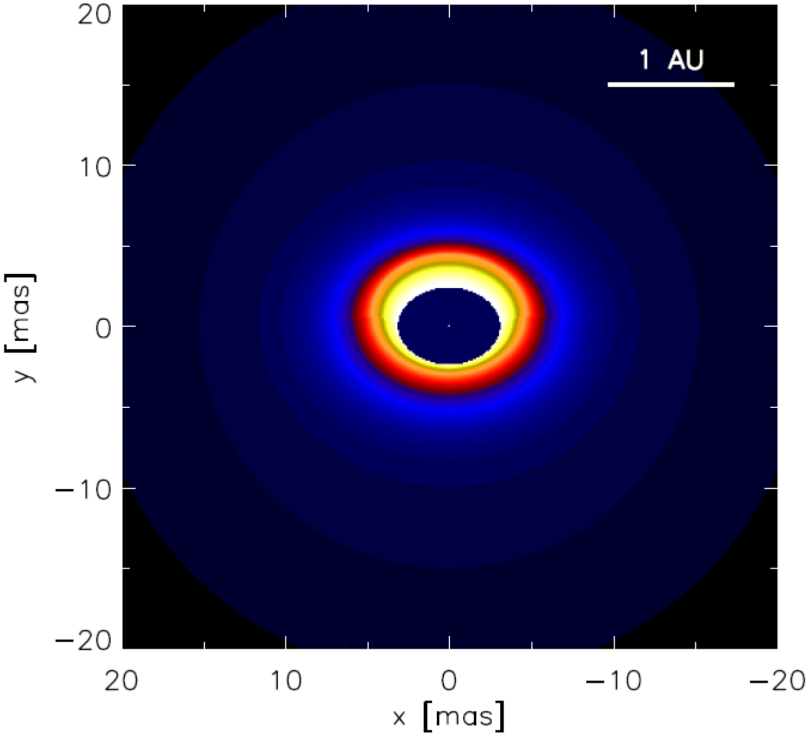
CURVED RIM model (1/2)



Scenario:

Curved puffed-up inner rim

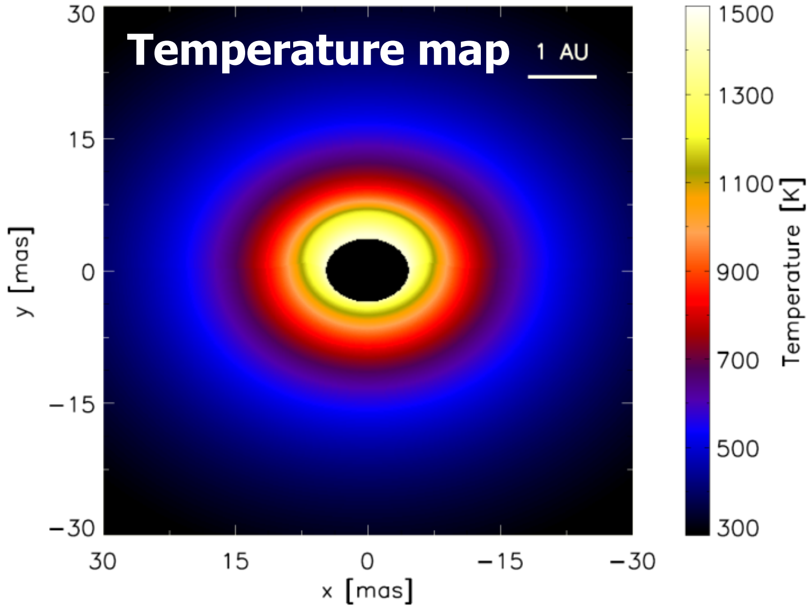
(following Isella & Natta 2005)

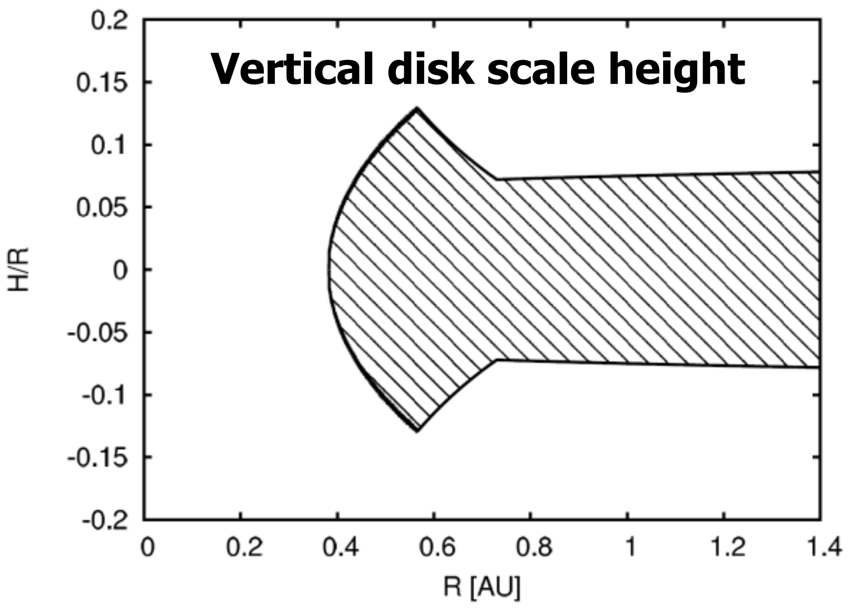


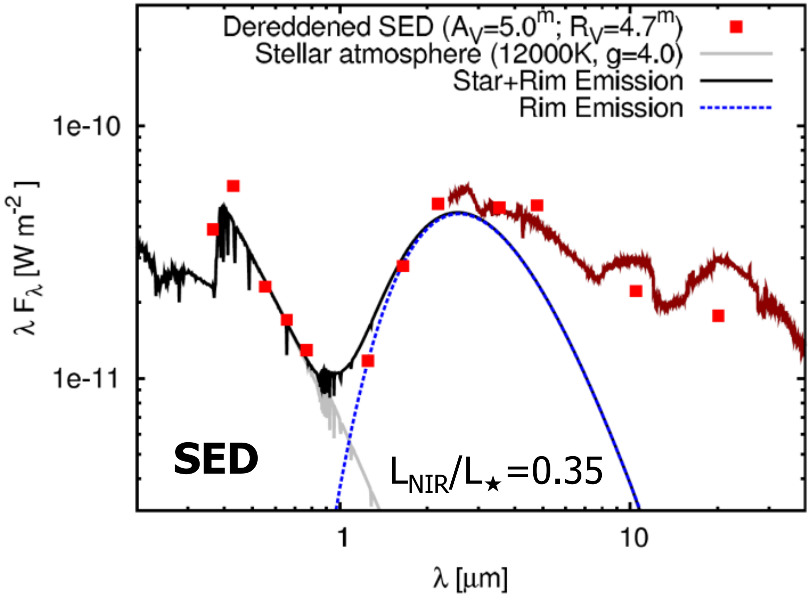
$\chi^2 = 2.1$

Near-infrared: Constraints on the dust rim geometry

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)

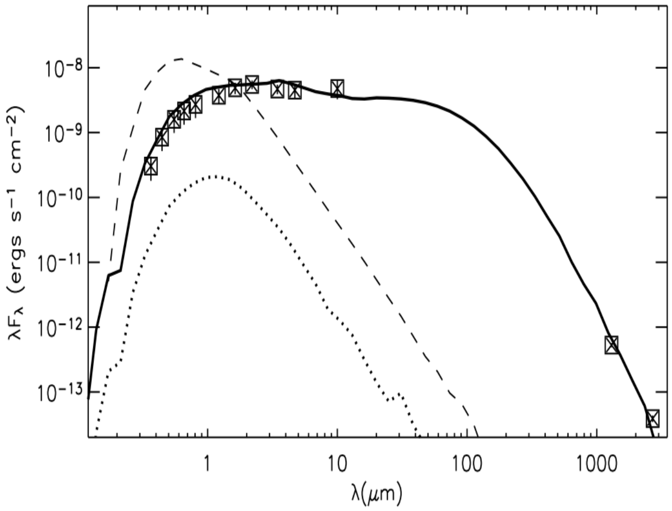
ENVELOPE:

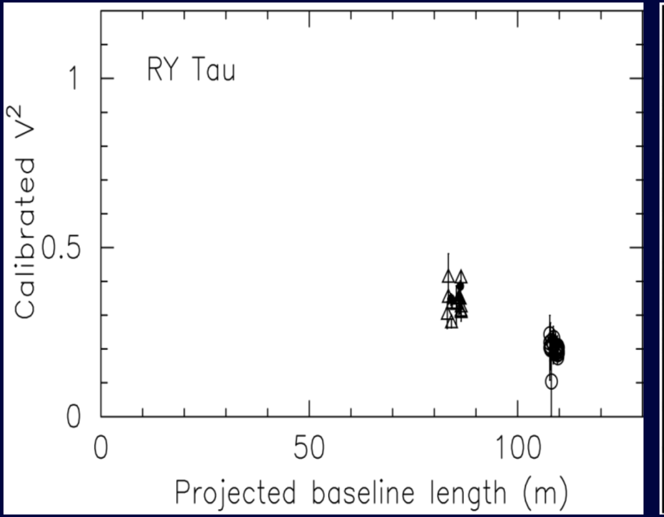
Gauss FWHM: 32 mas

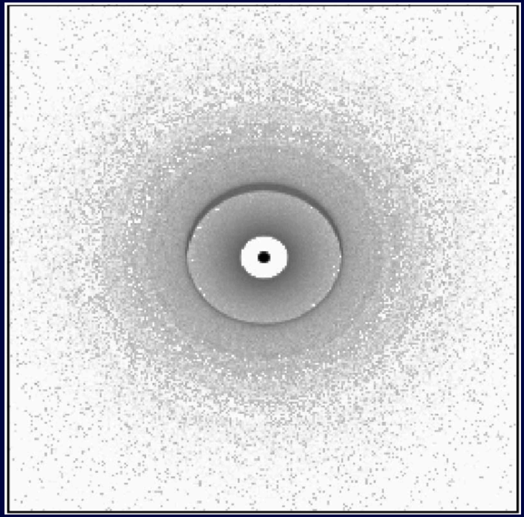
I_{env}/I_{disk} 0.5

Near-infrared: Hot inner emission component

RY Tau: PTI K-band interferometry:





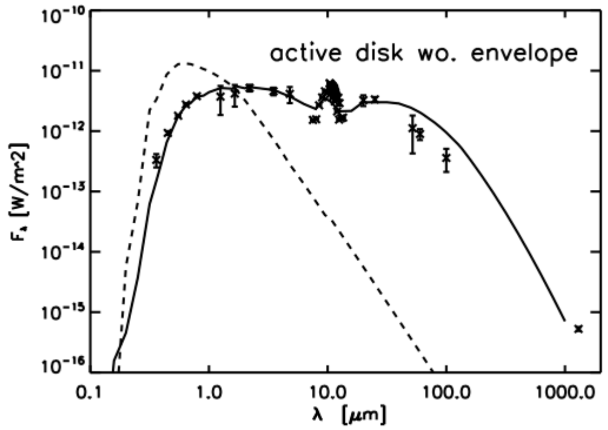


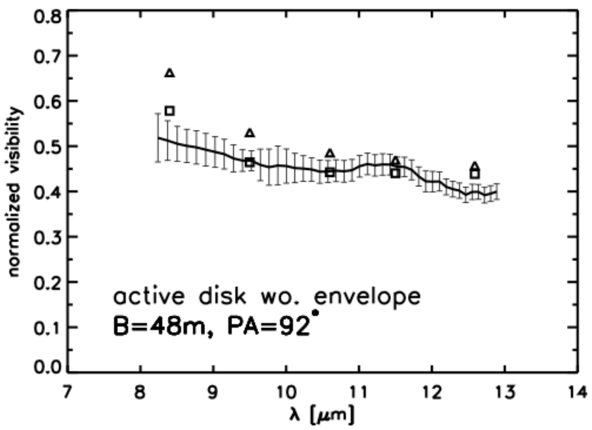
Akeson et al. 2005

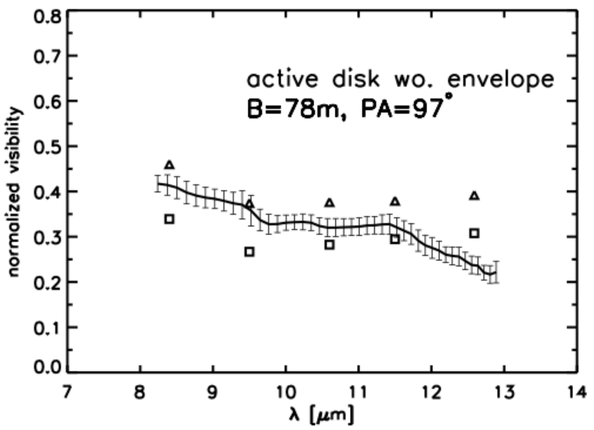
Fitted ring radii about a factor of ~2 smaller than the expected dust subl. radius

➜ Discrepancy can be solved by including gas emission

RY Tau: VLTI/MIDI N-band interferometry:

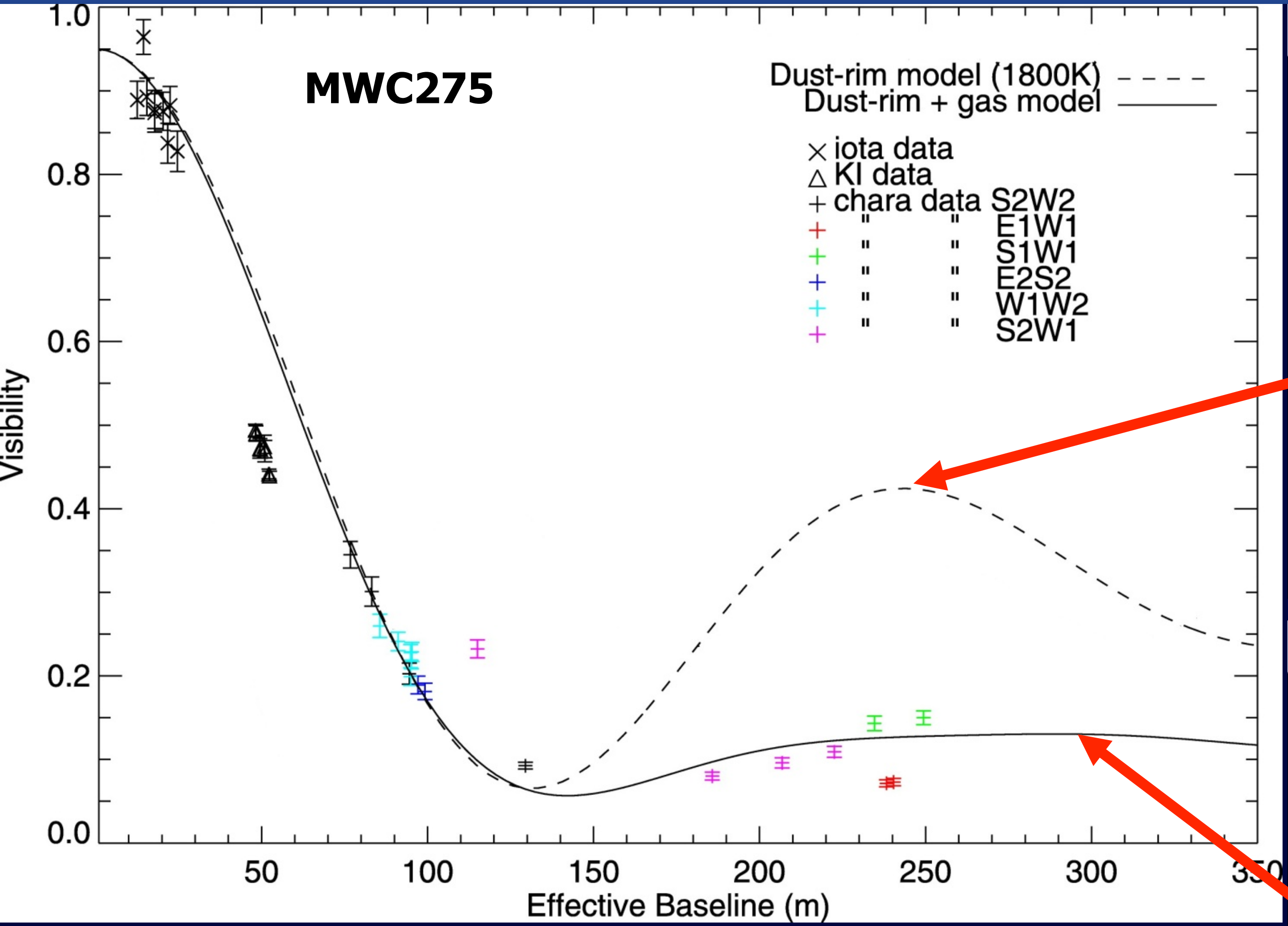




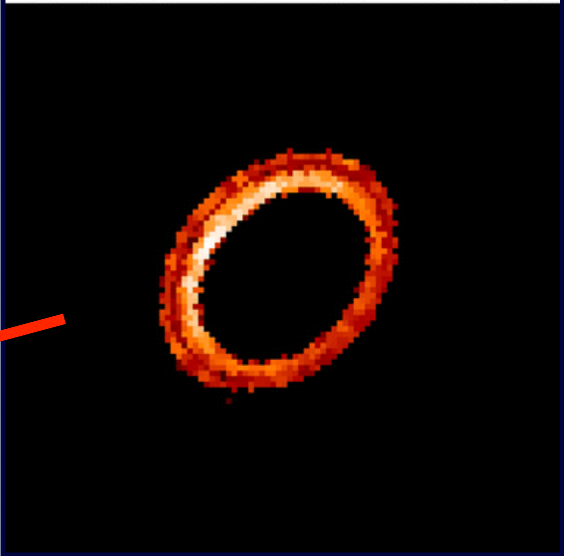


Schegerer et al. 2008

Near-infrared: Hot inner emission component



Standard (1800K) inner rim (K-band image)



Standard inner rim + gas (K-band image)

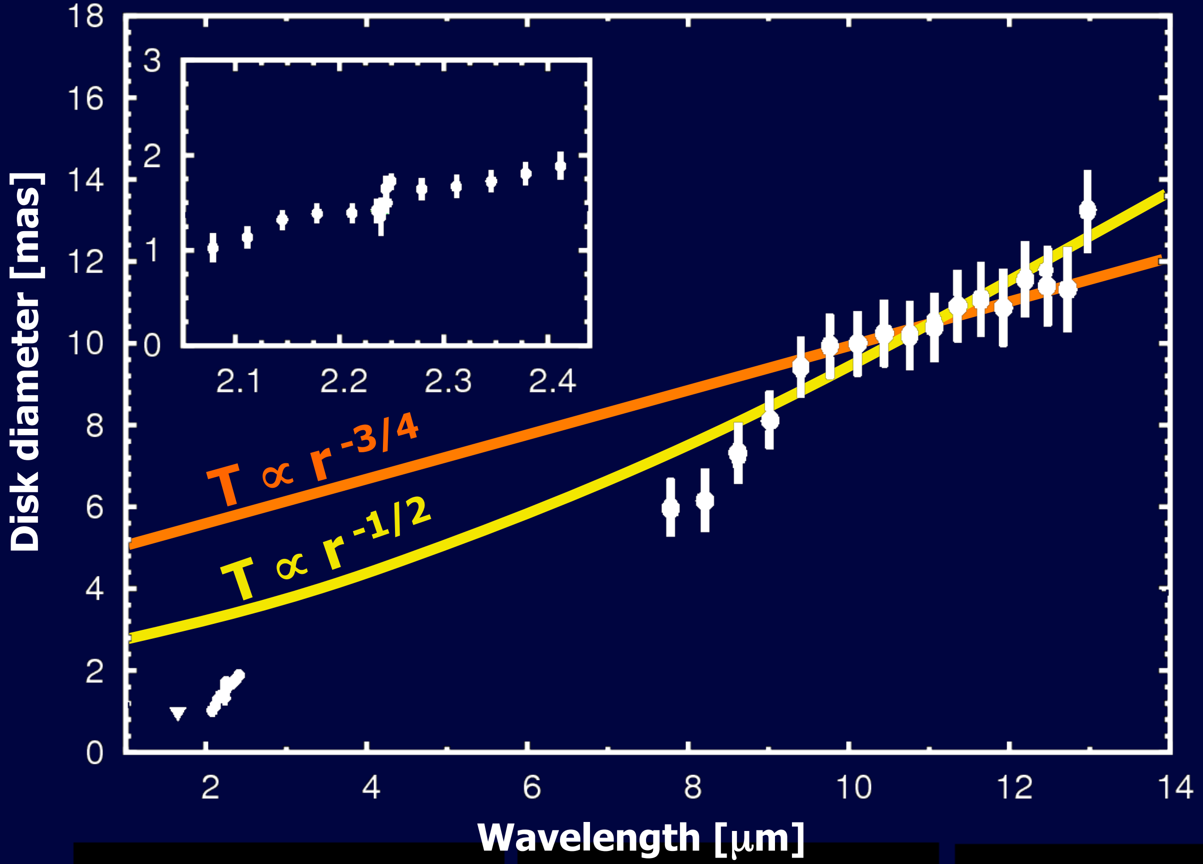
Tannirkulam et al. 2008

Very long baselines are essential to measure the geometry of the inner emission component.

➜ see also talk by Fabrizio Massi

Physical origin of emission still strongly debated:
Gas emission vs. Refractory grains
(Monnier et al. 2005, Kama et al. 2009, Benisty et al. 2010)

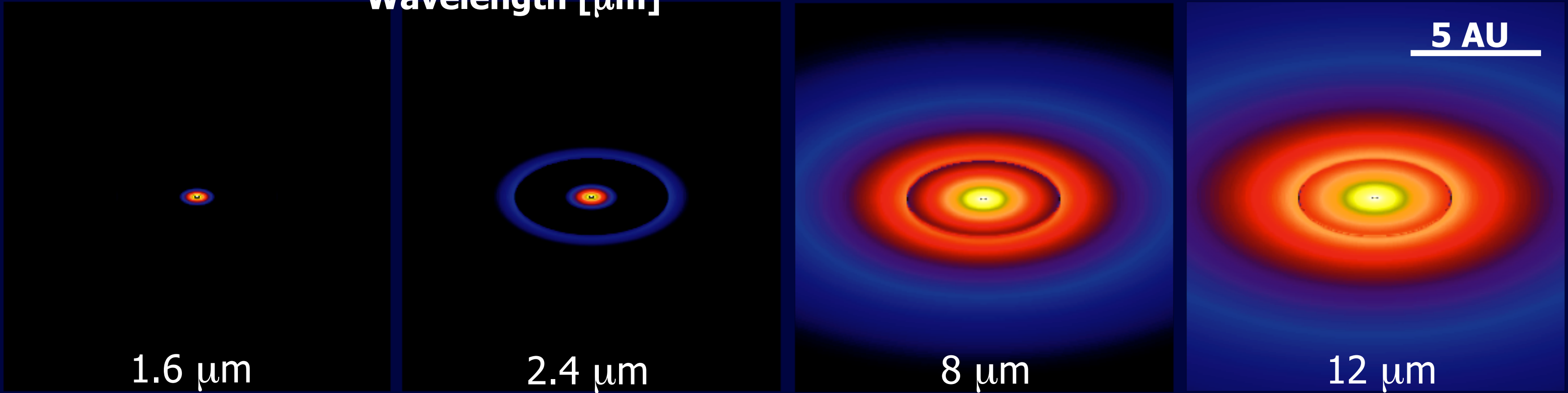
Near-/Mid-infrared: Hot inner emission component



Spectrally dispersed interferometry (e.g. K-band: Eisner et al. 2007; H-/K-/N- band: Kraus et al. 2008) constrains disk temperature profile

Analytic temperature power laws 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

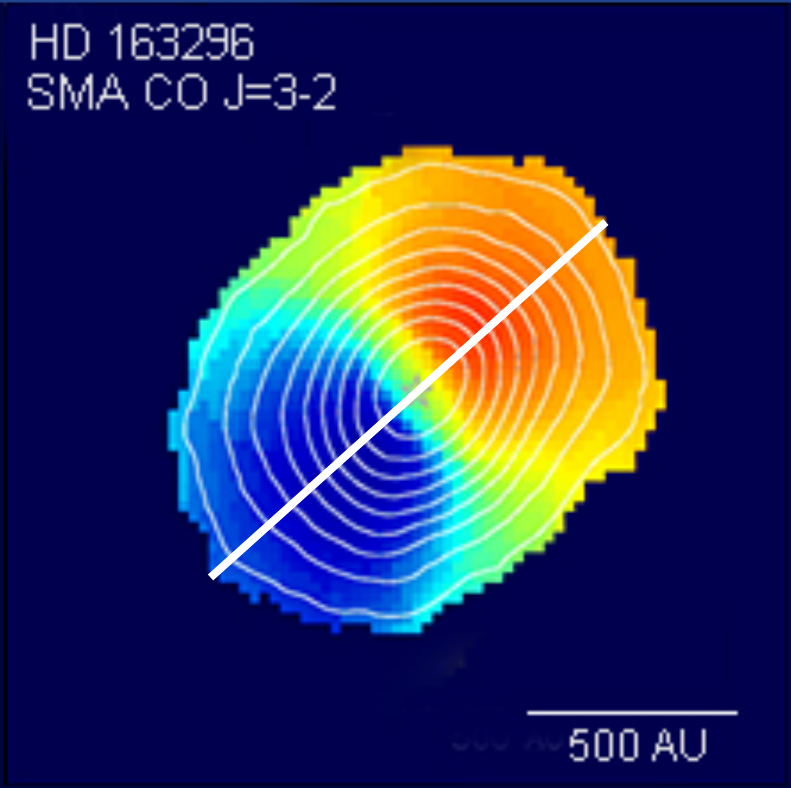
→ Consistent with hot inner component according to RT modeling

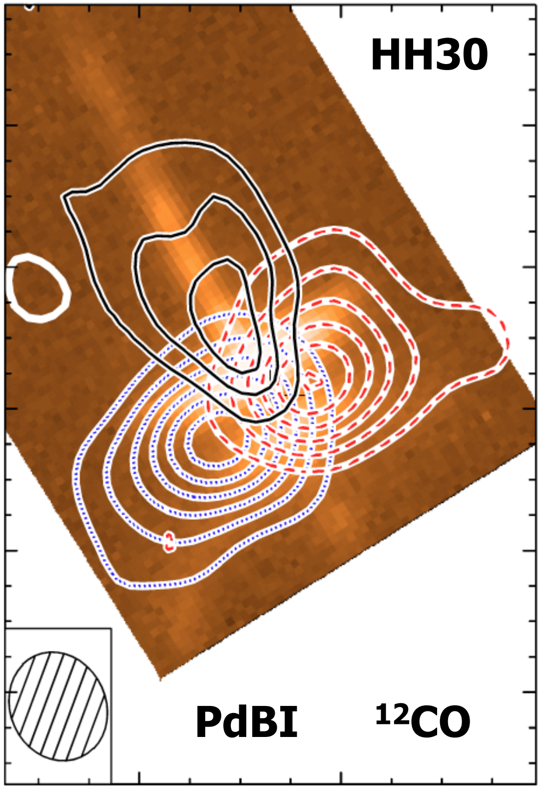


Kraus, Preibisch & Ohnaka 2008

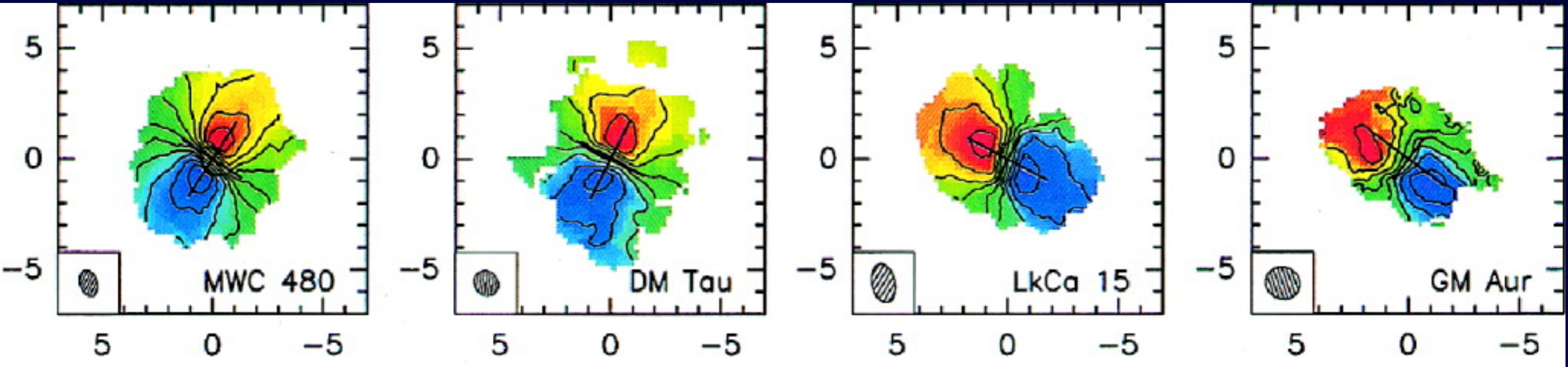
Interferometry in spectral lines

Isella et al. 2006





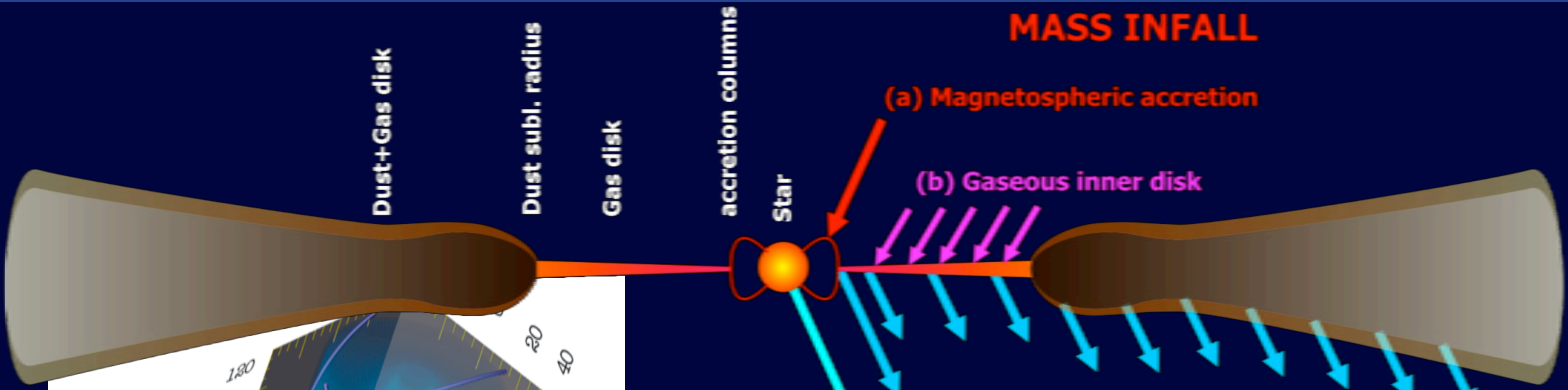
Pety et al. 2006

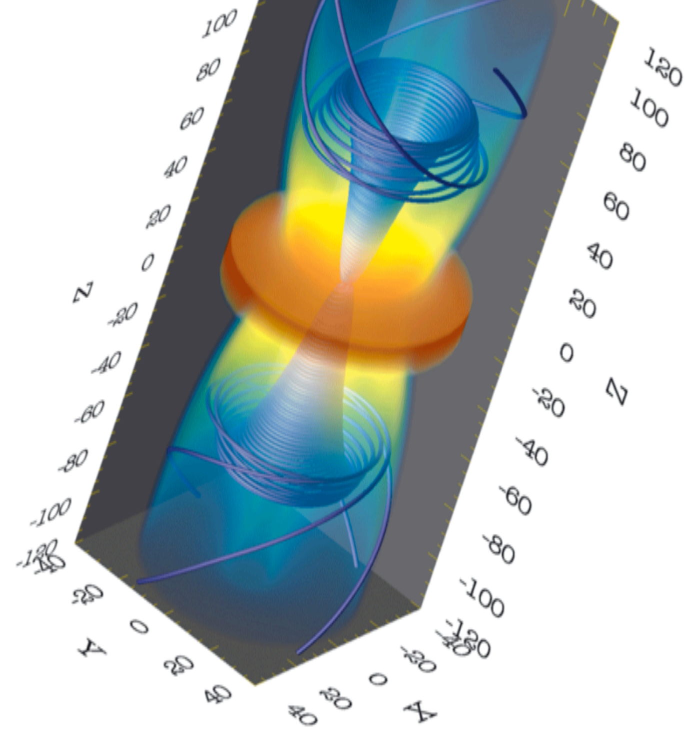


Simon et al. 2000

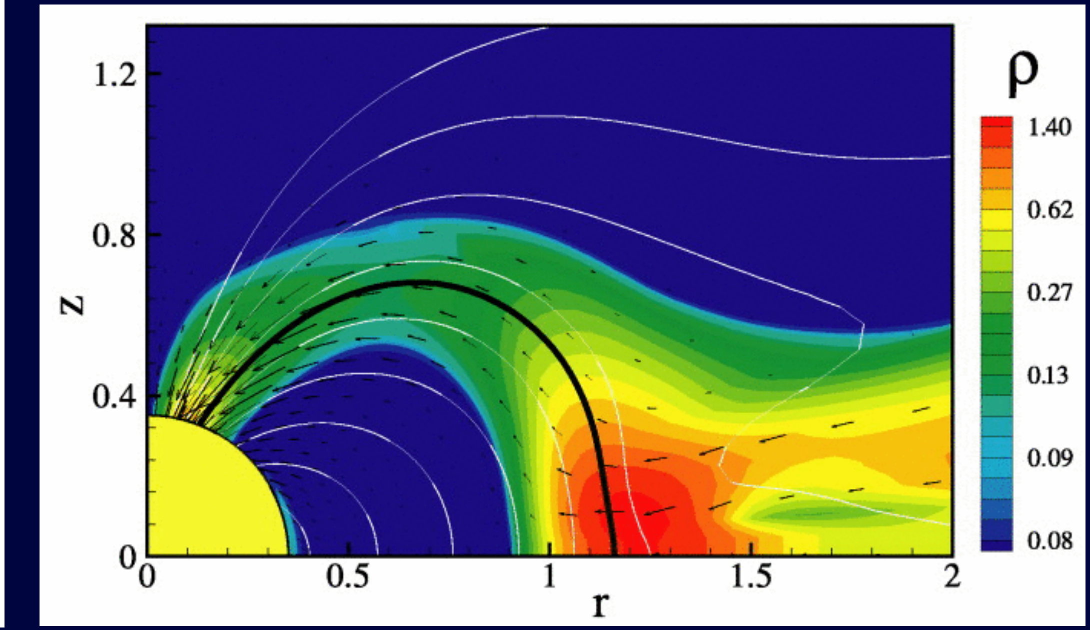
Resolving the Br γ-emitting region in YSOs

Which physical mechanism is traced by the hydrogen line emission?



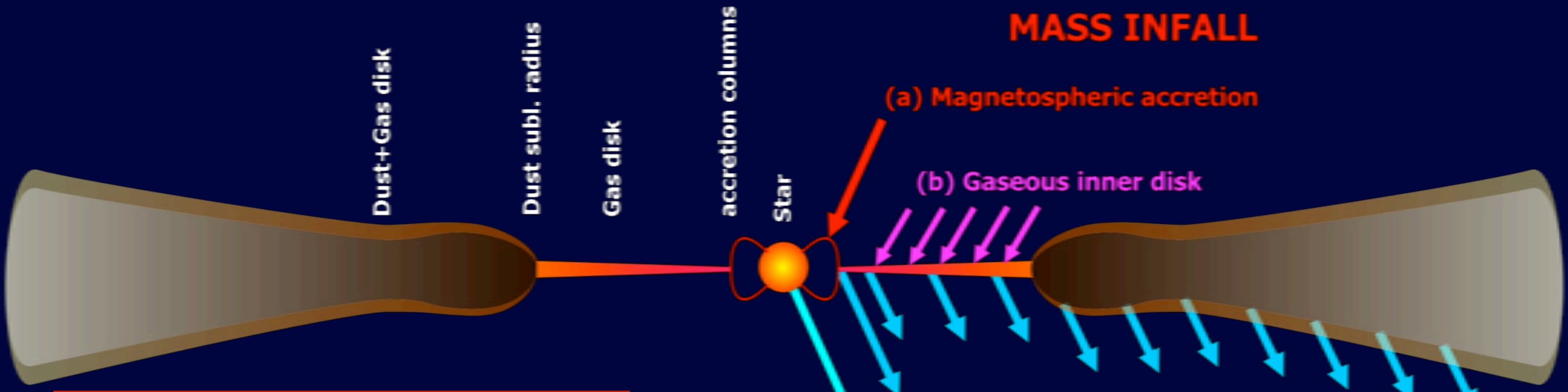


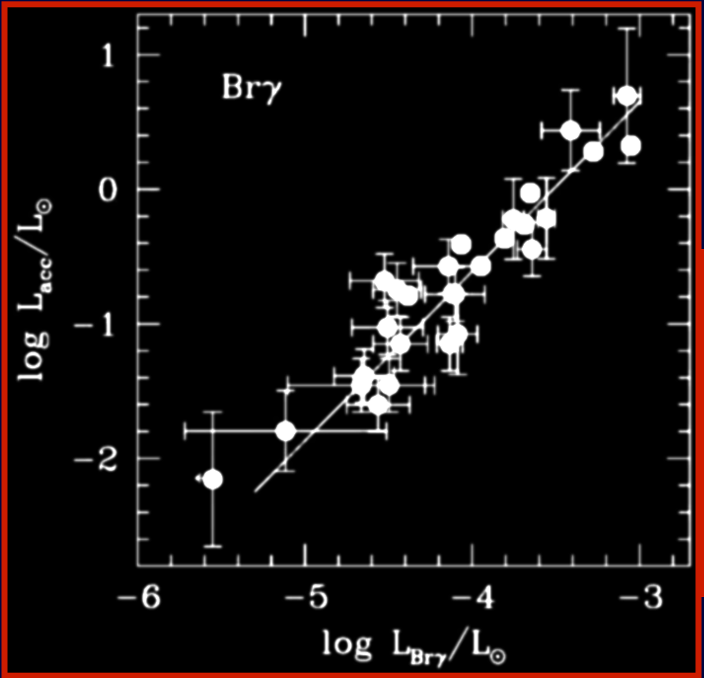
MHD disk wind (Zanni et al. 2007)



Funnel flow (Romanova et al. 2002)

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 $M_\odot$)

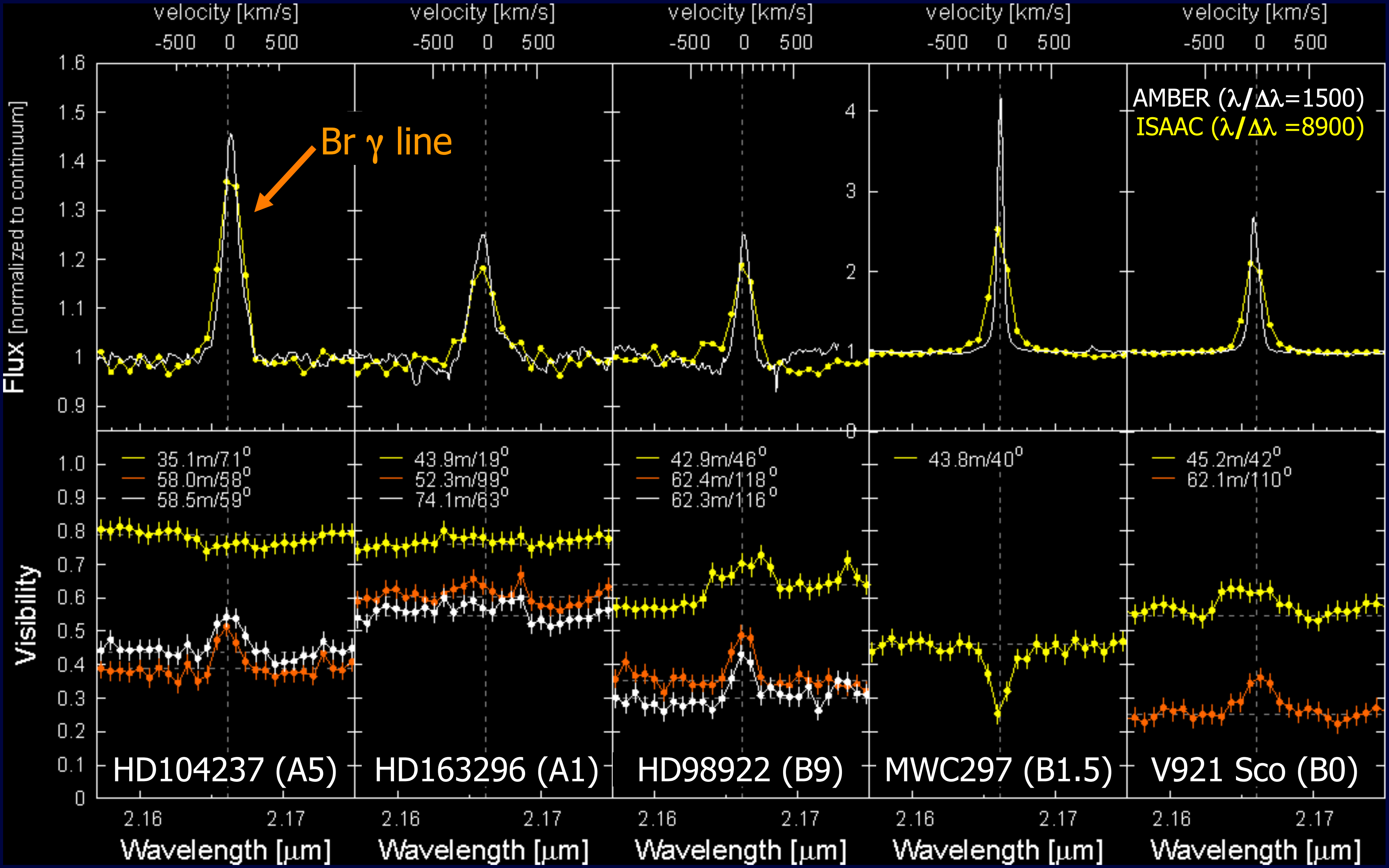
➜ important diagnostic line for mass accretion rate

- Involved physical mechanism not yet identified

Origin of hydrogen line emission in YSOs

VLTI/AMBER observations

AMBER R=1500 observations on 5 YSOs (Malbet et al. 2007, Tatulli et al. 2007 & Kraus et al. 2008)



Kraus et al. 2008

Origin of hydrogen line emission in YSOs

VLTI/AMBER observations

very compact Br γ-region (unresolved, $R_{Br\,\gamma} < 0.2\,R_{cont}$)

➜ consistent with magnetospheric accretion

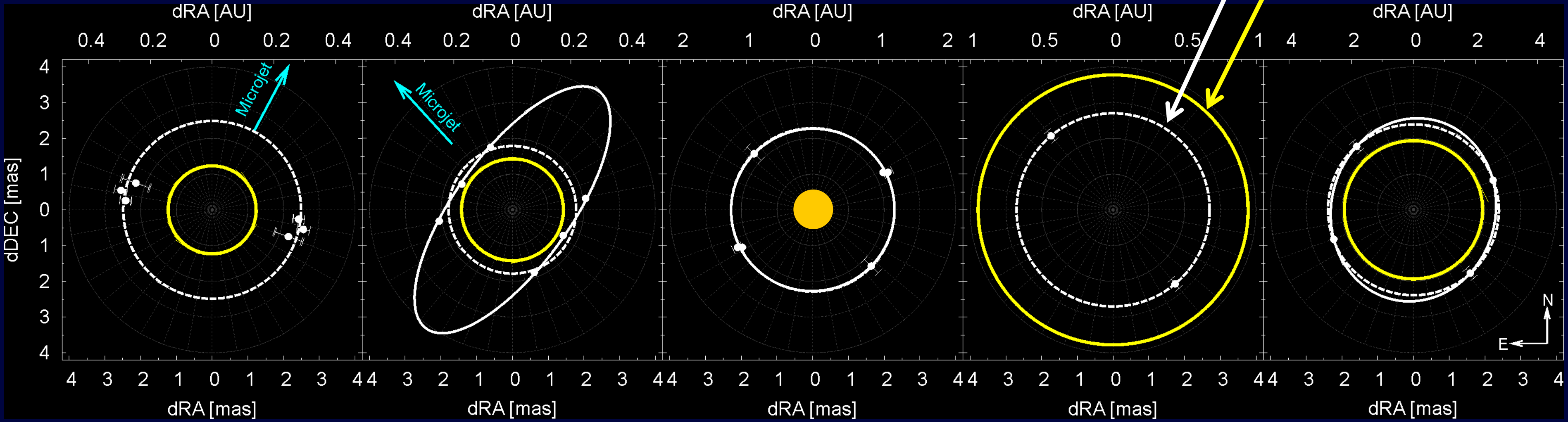
circumbinary disk

microjet (Lyα)

microjet (Lyα/Hα)

continuum ring/ellipse

Br γ-line ring



HD104237 (A5)

HD163296 (A1)

HD98922 (B9)

MWC 297 (B1.5)

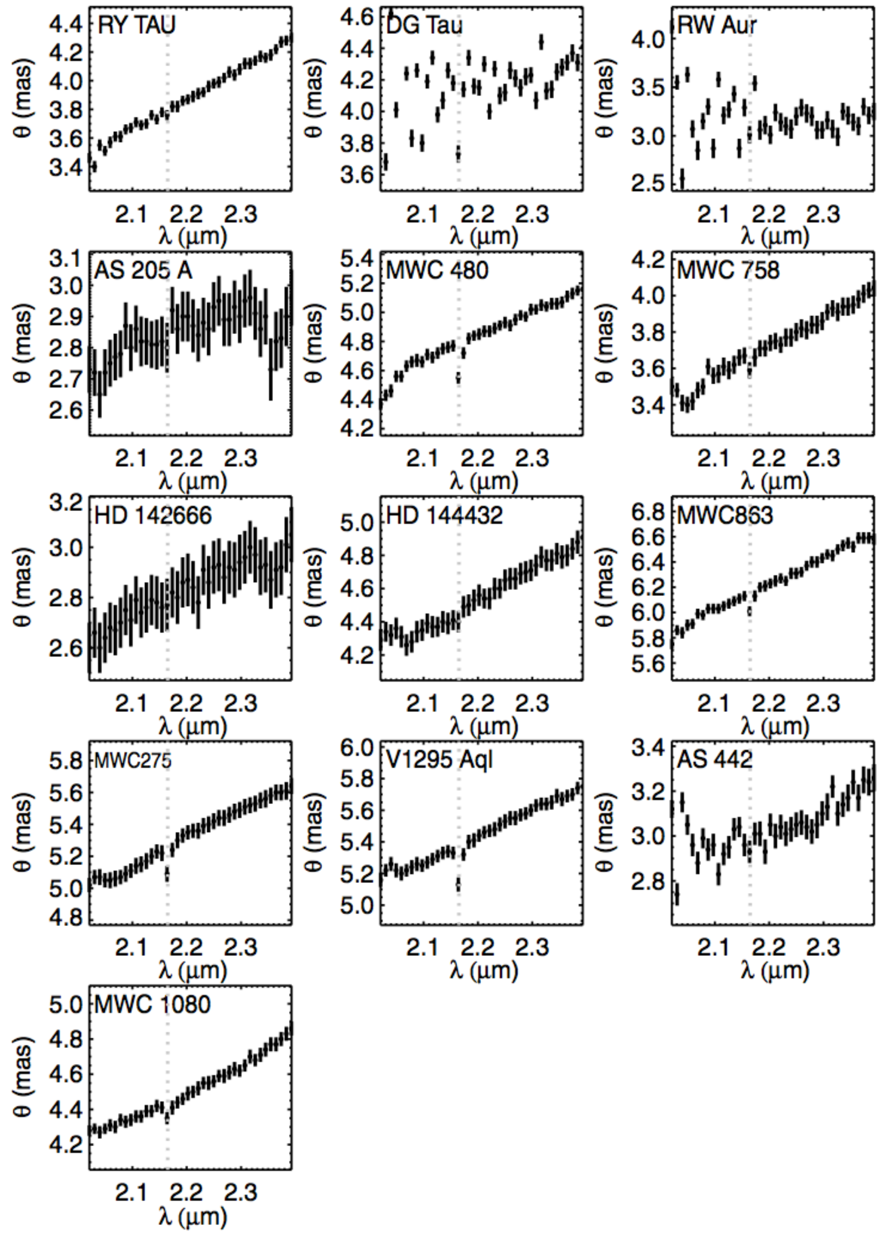
V921 Sco (B0)

extended Br γ-region ($0.6 < R_{Br\,\gamma}/R_{cont} < 1.4$)

➜ consistent with disk wind or stellar wind

Origin of hydrogen line emission in YSOs

Keck Interferometer observations



Eisner et al. 2009

Keck Interferometer prism (R=230) observations on 13 YSOs (+2 overresolved/unresolved), including also T Tauri stars (Eisner et al. 2007, 2009).

$R_{Br\gamma} \leq R_{cont}$ for all sources,
➜ consistent with magnetospheric accretion

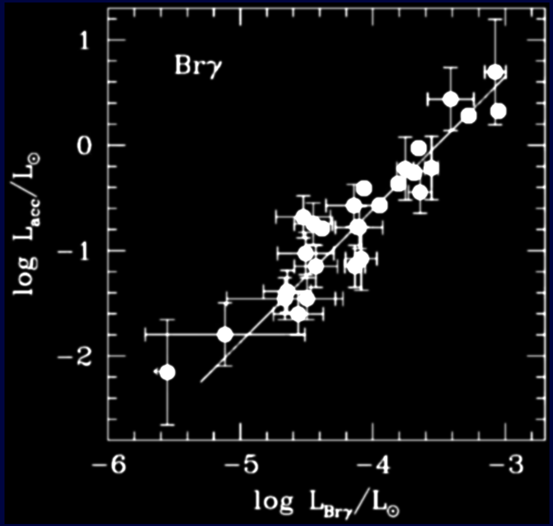
Origin of hydrogen line emission in YSOs

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)



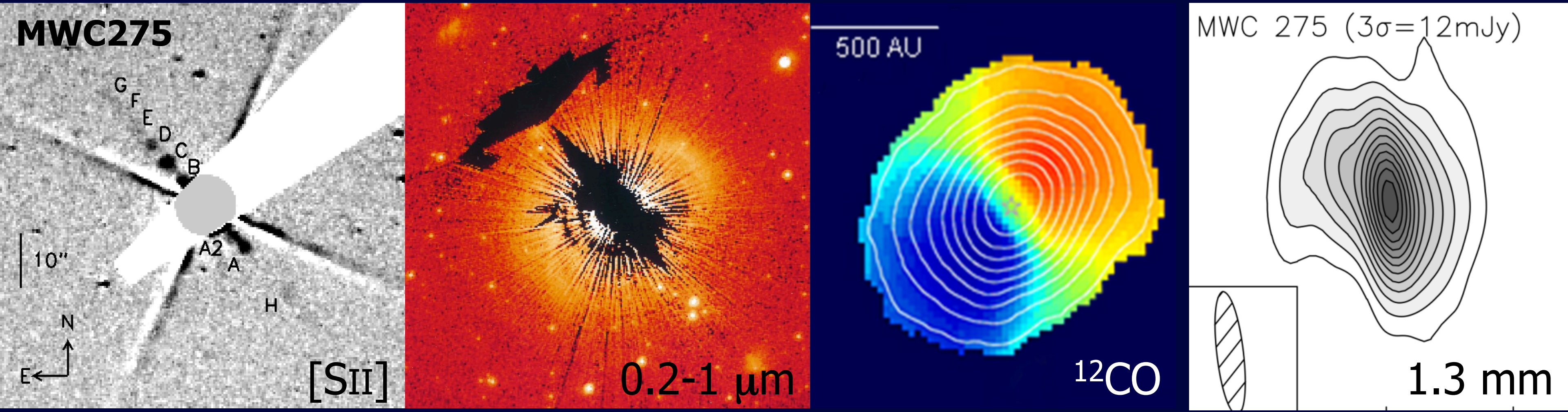
van den Ancker 2005

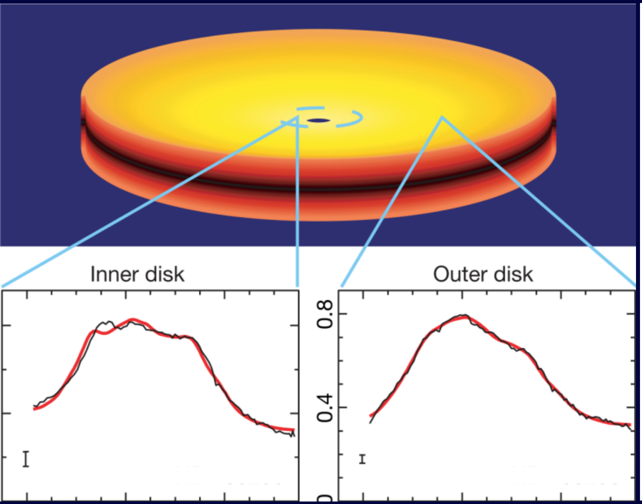
➜ Br γ *indirect tracer* of mass accretion rate

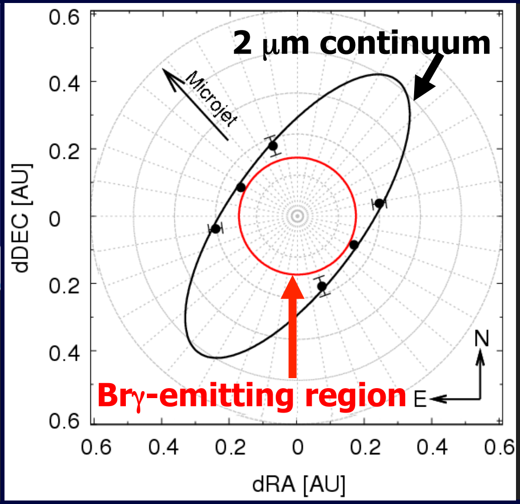
(suggests tight quantitative connection between accretion- & outflow processes)
(cf. spectroscopic studies, e.g. Cabrit et al. 1990: $\dot{M}_{eject}/\dot{M}_{acc} \approx 0.1$)

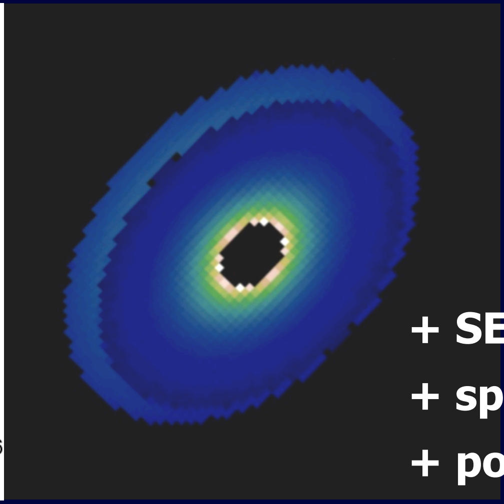
Future Science Prospects (1/2)

1. Solve model ambiguities inherent to SED model fitting and single-wavelength observations
   ➡ Use multi-wavelength approach and combine complimentary techniques









+ SED
+ spectroscopy
+ polarimetry
+ ...

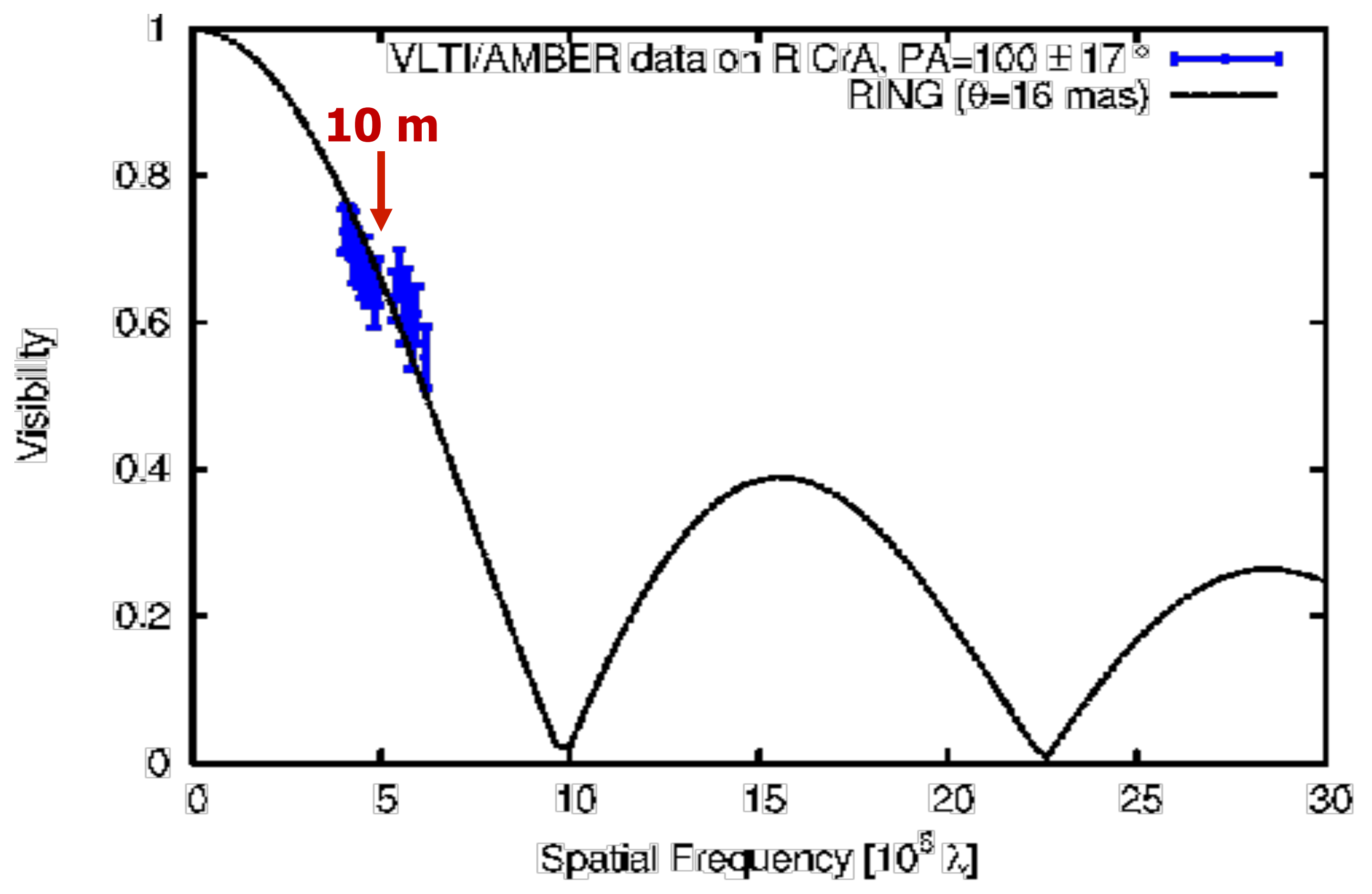
Wassell et al. 2006
van Boekel et al. 2004

Grady et al. 2000
Kraus et al. 2008

Isella et al. 2007, 2009
Benisty et al. 2010

Future Science Prospects (2/2)

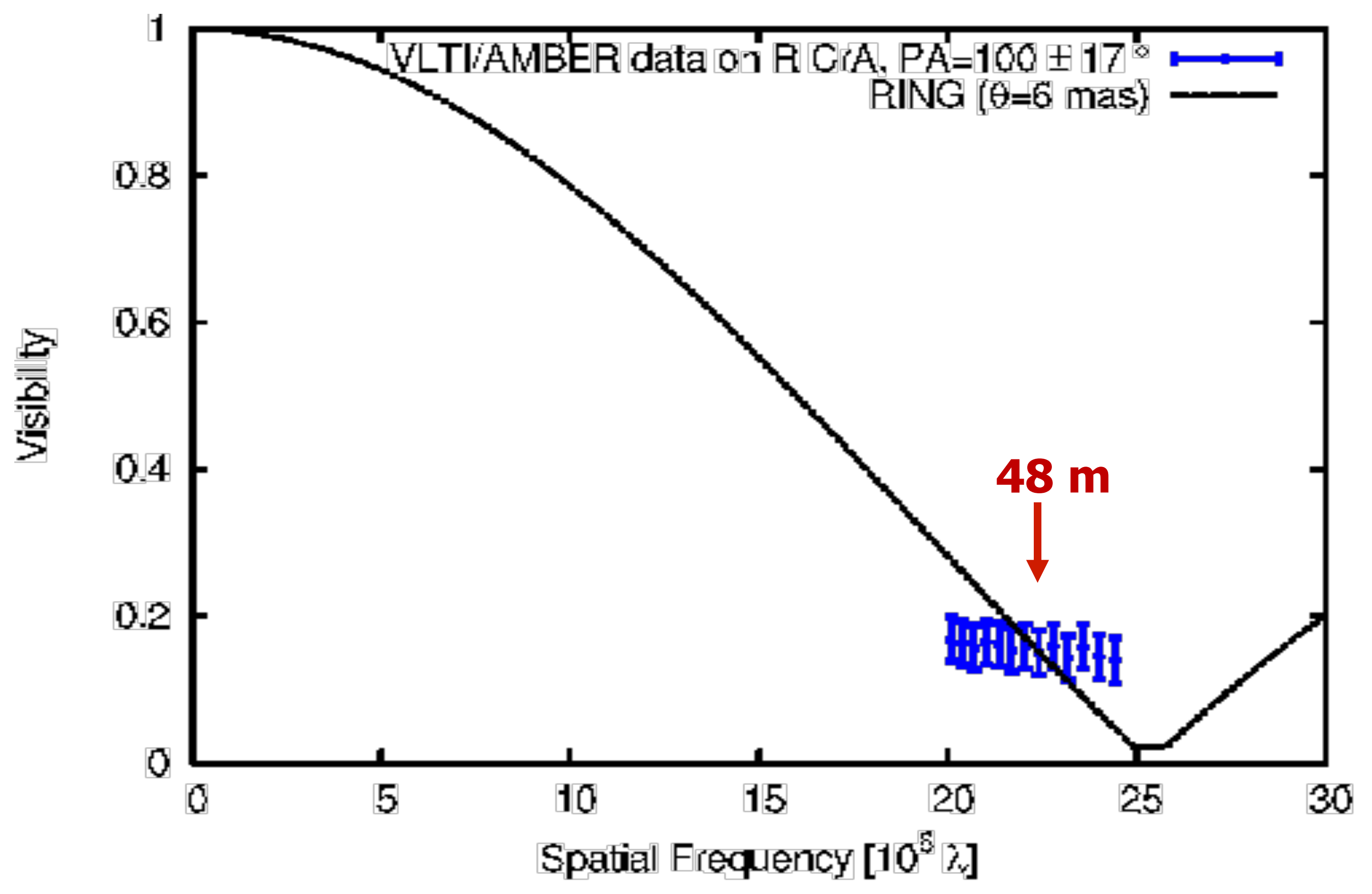
2. Facing the complexity expected for the inner disk regions



Example: R CrA (Kraus et al. 2009)

Future Science Prospects (2/2)

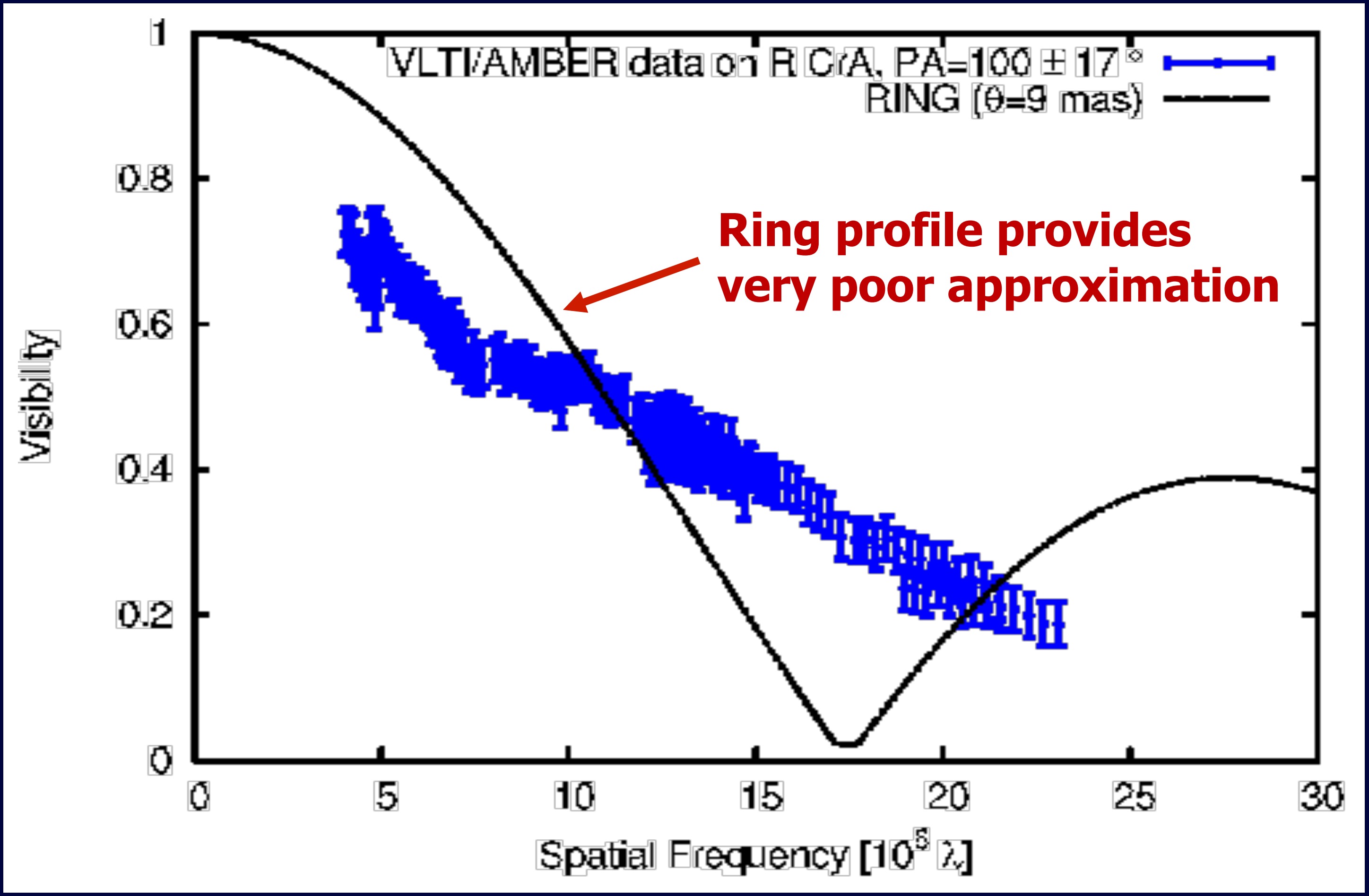
2. Facing the complexity expected for the inner disk regions



Example: R CrA (Kraus et al. 2009)

Future Science Prospects (2/2)

2. Facing the complexity expected for the inner disk regions
   ➡ Detailed studies essential to avoid systematic biases



Example: R CrA (Kraus et al. 2009)

Future Science Prospects (2/2)

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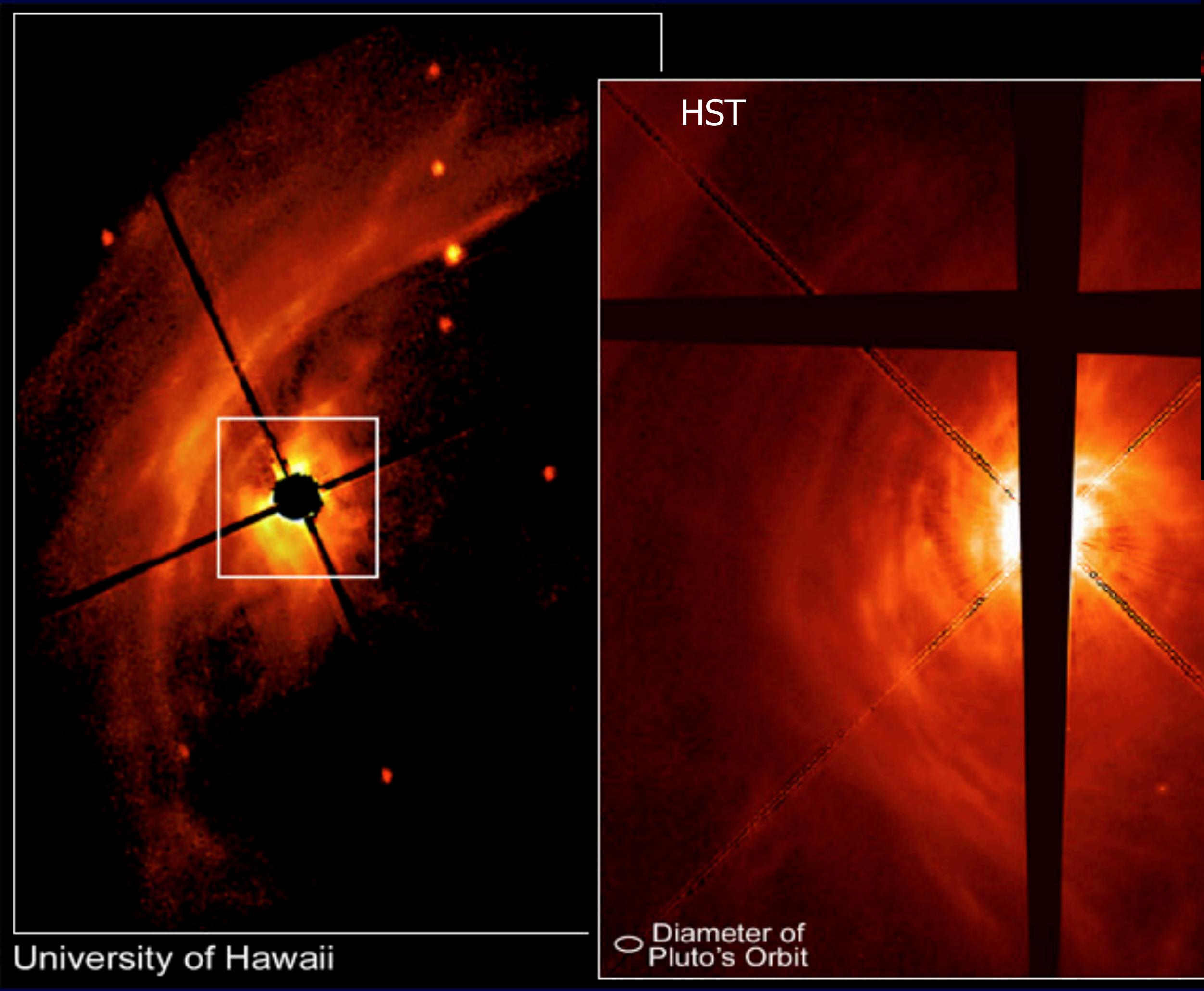
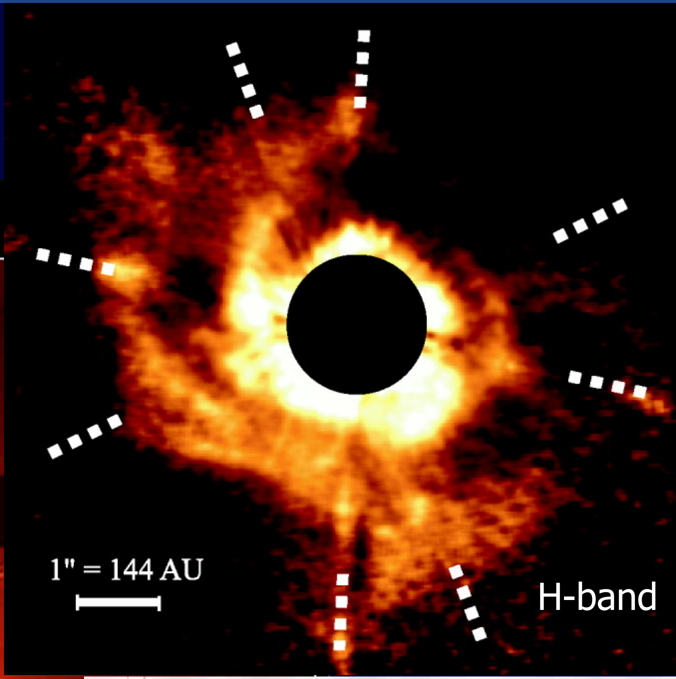
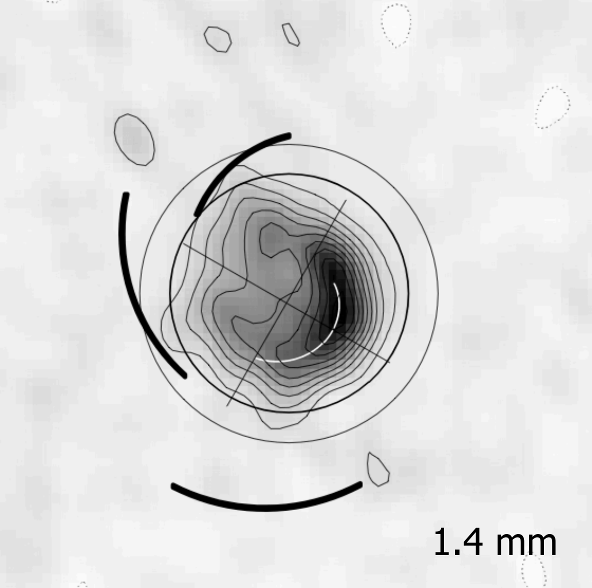


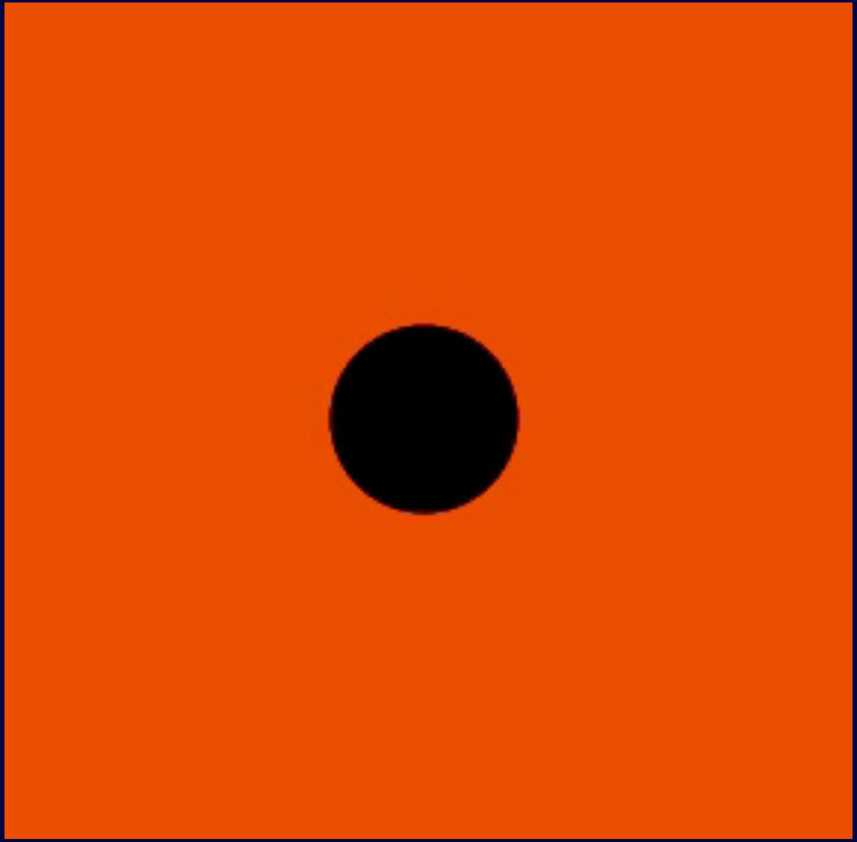




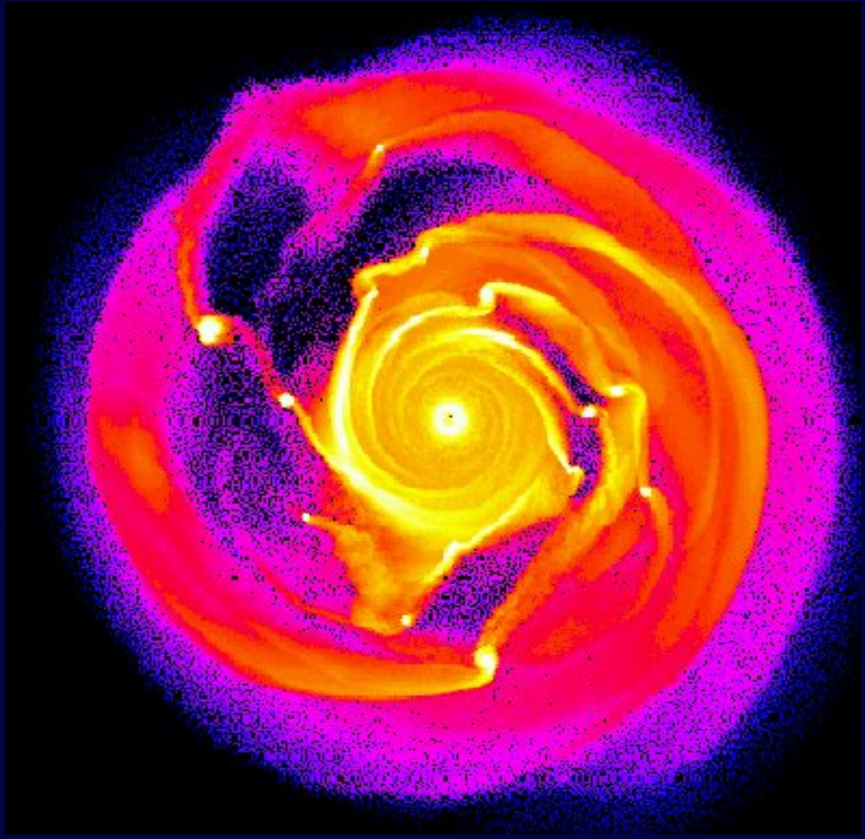
Grady et al. 1999, Fukagawa et al. 2004, Pietu et al. 2005

Future Science Prospects (2/2)

2. Facing the complexity expected for the inner disk regions
   - ➡ Detailed studies essential to avoid systematic biases
   - ➡ Aperture synthesis imaging required to move beyond axial-symmetric models



Frederic Masset



Quinn et al. 2003

Thank you
for your attention


ESO-PR 35/08

- Existing facilities allow resolving YSO disk structure at various wavelengths, including
  - near-infrared (≥ 0.1 AU, tracing dust subl. region and hot gas & dust),
  - mid-infrared (≥ 1 AU, tracing extended dust disk), and
  - (sub-)millimeter (≥ 10 AU, tracing density structure).
- Interferometric line observations trace accretion & outflow processes and constrain the gas distribution and kinematics
- Detailed multi-wavelength imaging studies will be crucial to solve model ambiguities and to reveal the signatures of planet formation