New Observational Constraints on the Formation of Massive Stars from Infrared Interferometry

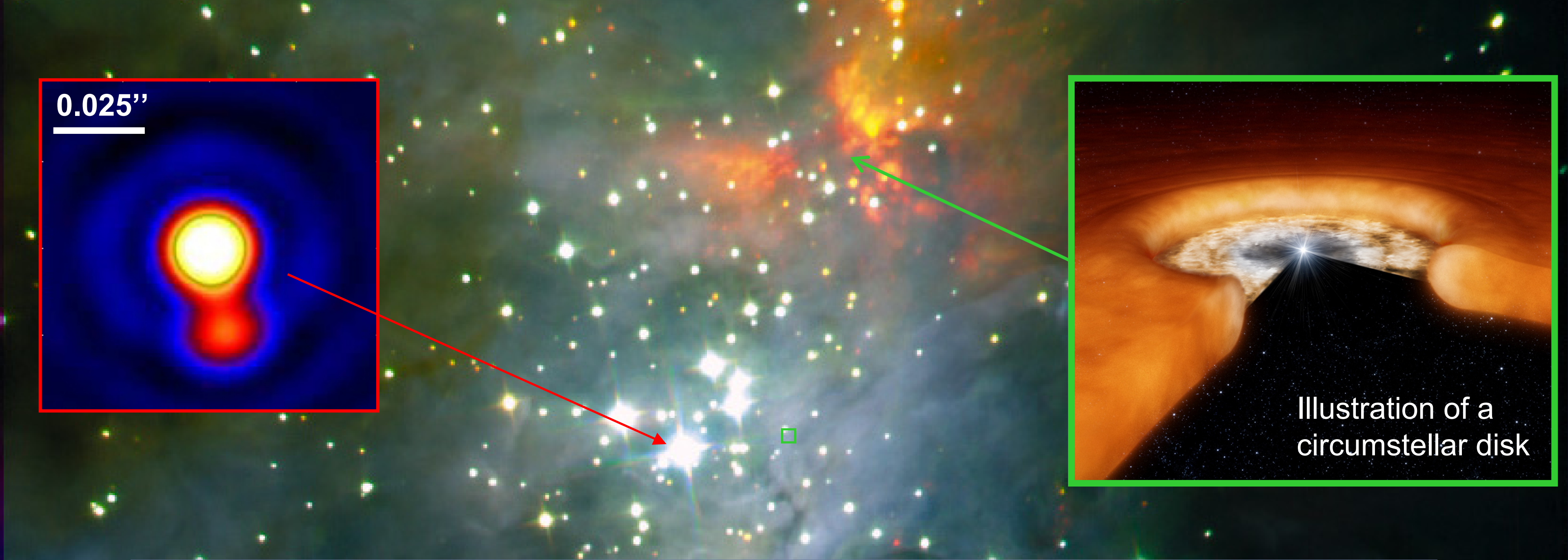
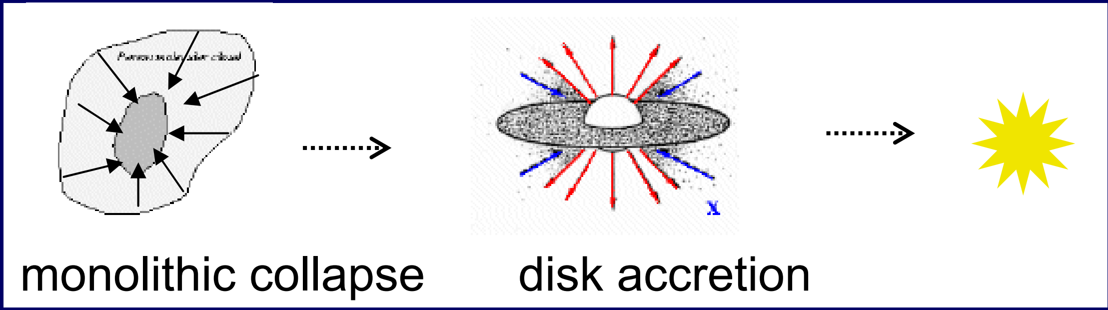


Illustration of a circumstellar disk

Thomas Preibisch
University Observatory Munich

How to form high-mass stars ?

- Low-mass star formation:



- High-mass star formation:

1) Radiation pressure versus accretion
2) Dense packing of high-mass stars
3) No good evidence for disks

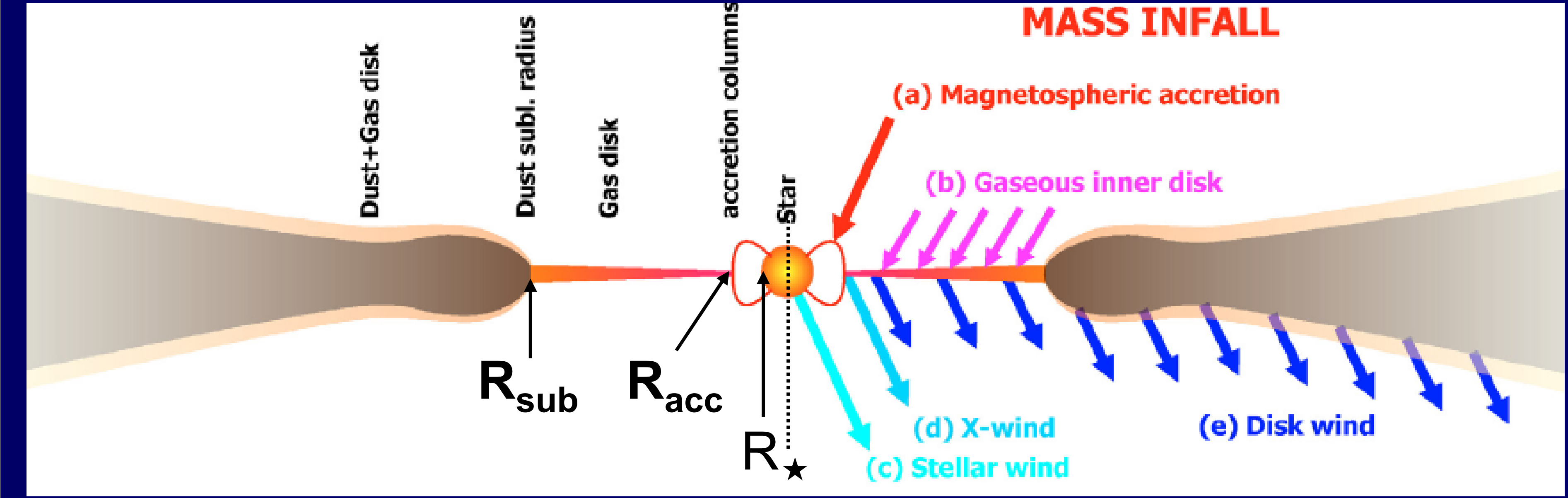
?

→ *fundamental differences to low-mass stars formation scenarios*

Look at: - **Circumstellar matter** around high-mass stars
- **Multiplicity** of high-mass stars

→ **High spatial resolution required**

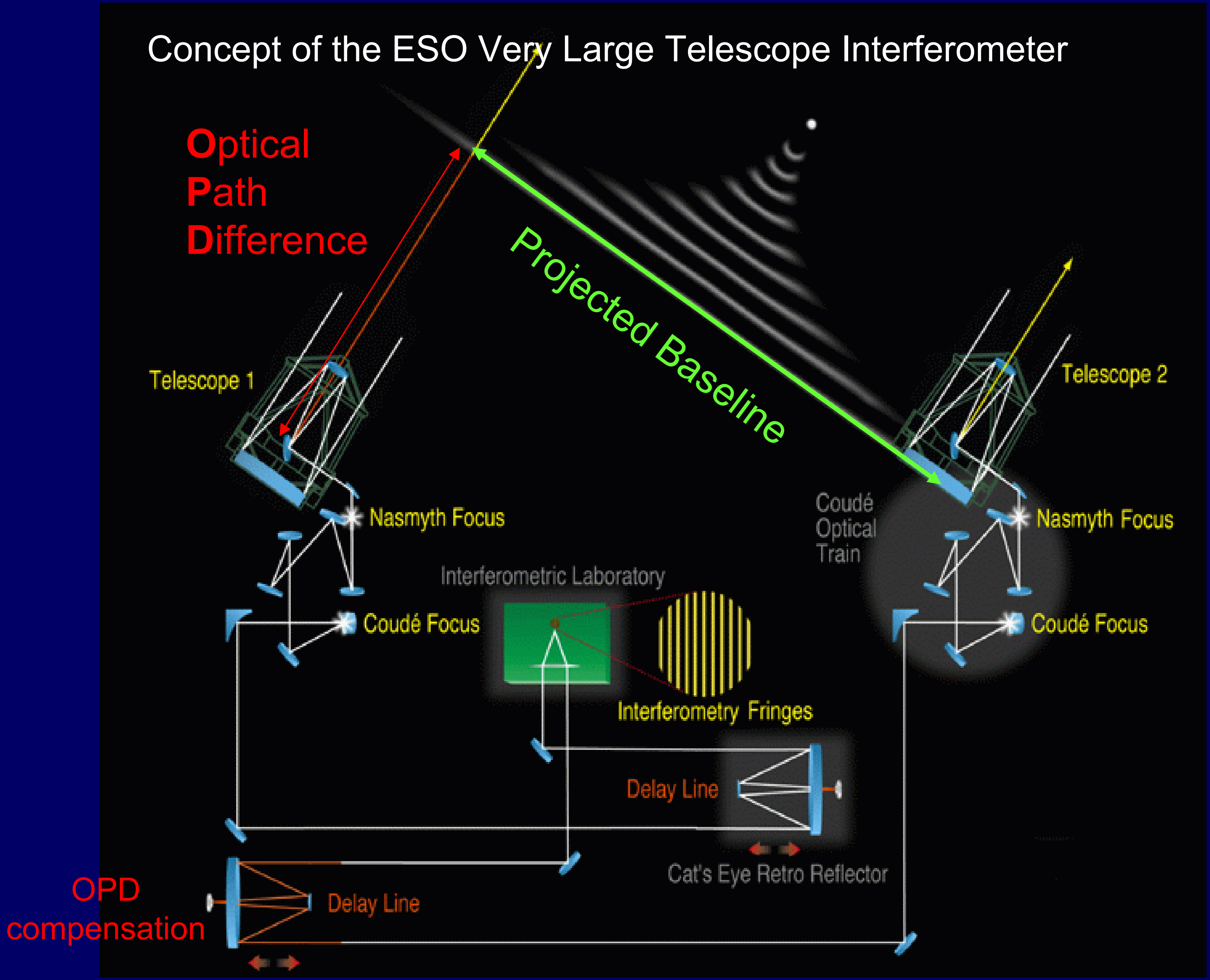
Typical size scales in milli-arcseconds (mas)

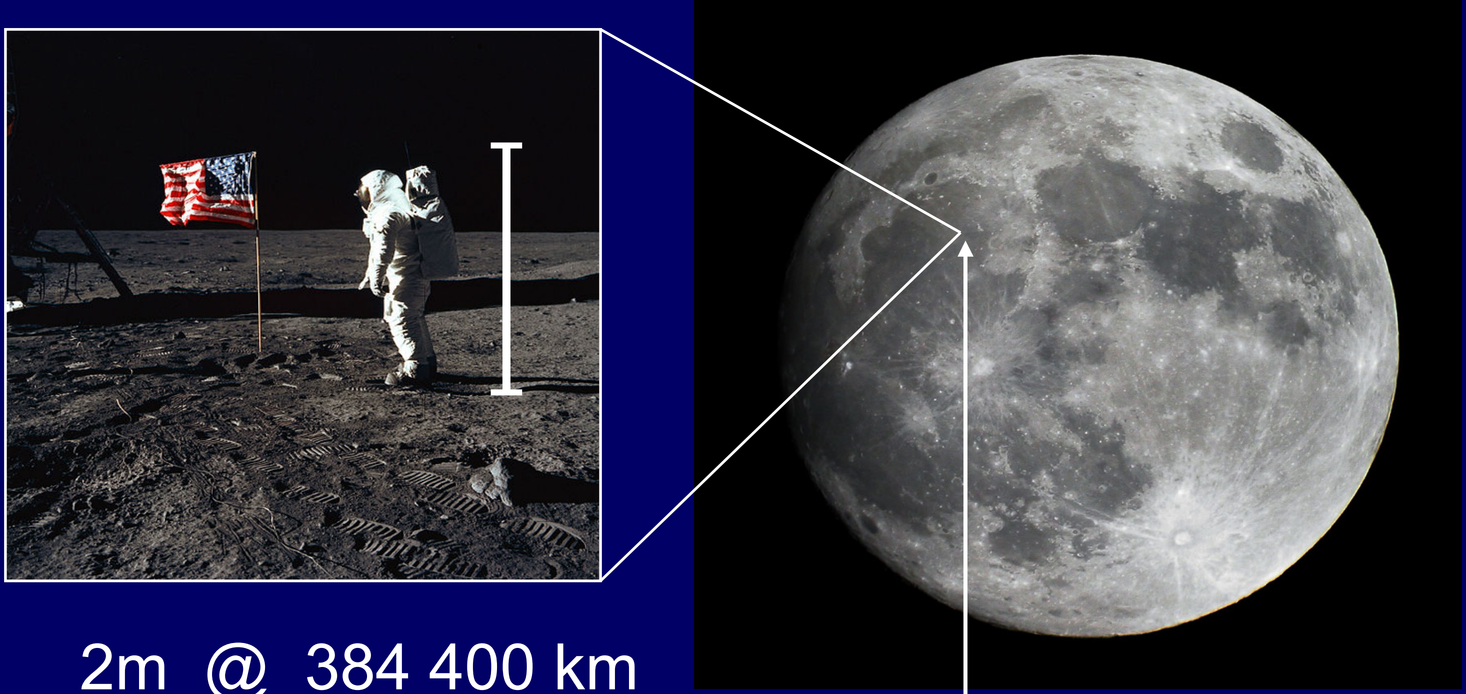


$1\ M_\odot$, D = 100 pc	$20\ M_\odot$, D = 500 pc
$R_\star \sim 0.01$ AU ~ 0.1 mas	$R_\star \sim 0.05$ AU ~ 0.1 mas
$R_{acc} \sim 0.05$ AU ~ 0.5 mas	$R_{acc} \sim 0.25$ AU ~ 0.5 mas
$R_{sub} \sim 0.1$ AU ~ 1 mas	$R_{sub} \sim 10$ AU ~ 20 mas

Resolution of a large telescope with adaptive optics: ≥ 50 mas

Long Baseline Interferometry





2m @ 384 400 km

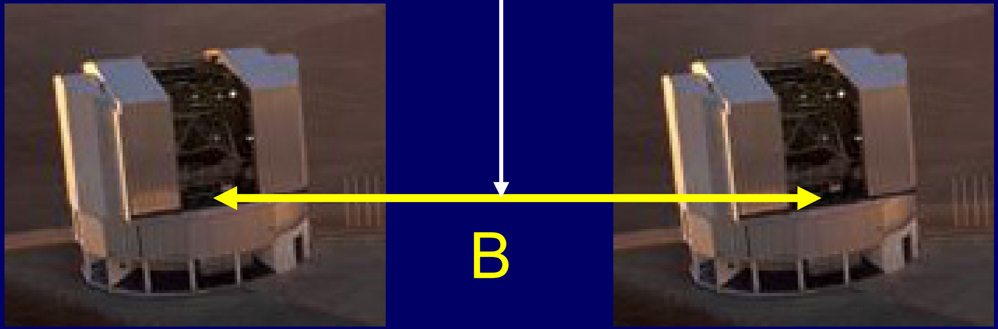
= 1 milli-arcsecond

D = 384 400 km

Near-infrared Interferometry

λ= 1 μm, B = 200 m,

→ $\phi = \lambda/B \sim$ 1 mas

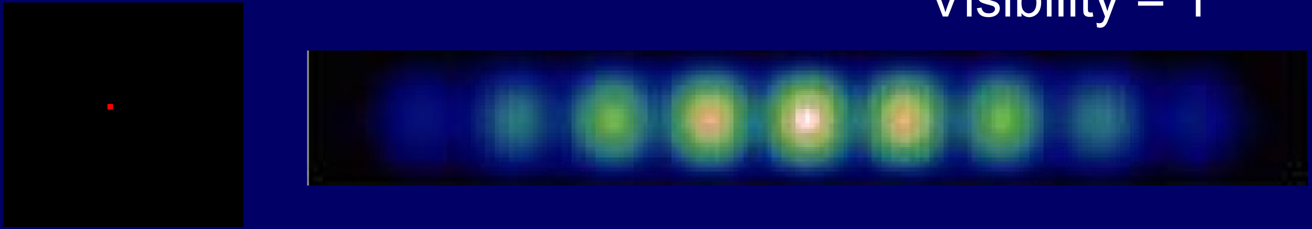


Visibility := contrast of the fringe system

- point source: $\varnothing \ll \lambda/B$

Visibility = 1

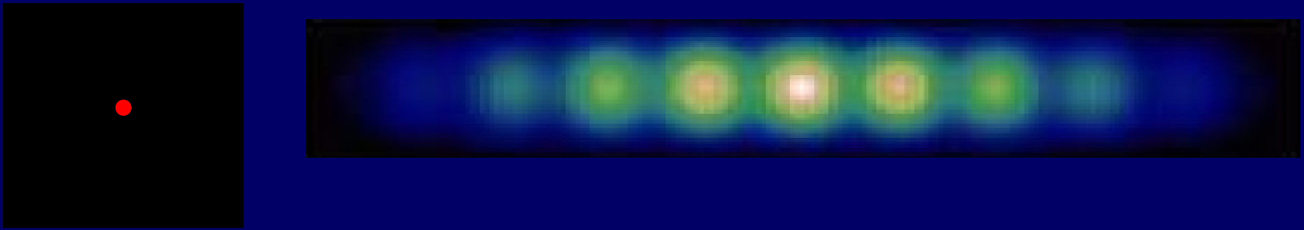
unresolved



- "small" source $\varnothing < \lambda/B$

Visibility ~ 0.8

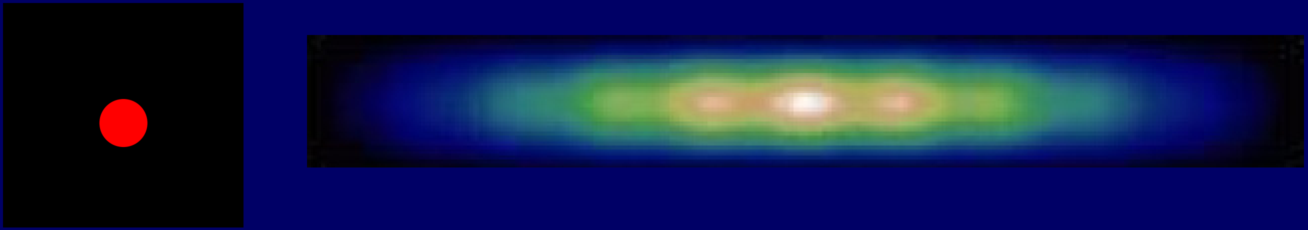
marg. resolved



- "large" source $\varnothing \sim \lambda/B$

Visibility ~ 0.2

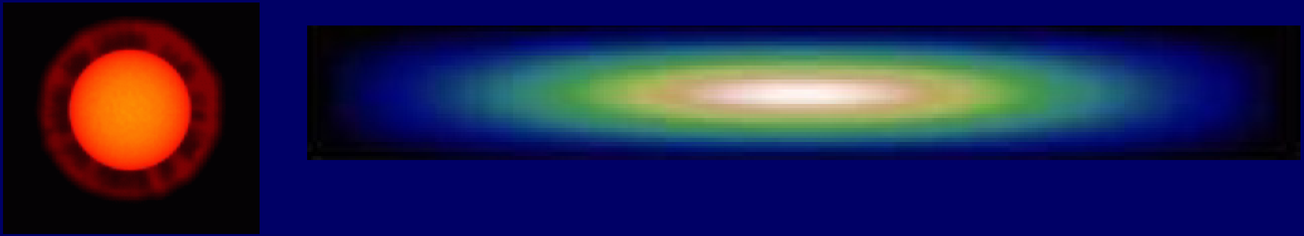
resolved



- extended source: $\varnothing \gg \lambda/B$

Visibility = 0

over-resolved



Van Cittert – Zernike theorem

$$\gamma(\vec{B}) = \int\int I(\vec{\vartheta}) \exp\left[-2\pi i \, \vec{\vartheta} \cdot \vec{B} \, / \lambda\right] \, d\vec{\vartheta}$$

Complex Visibility Function

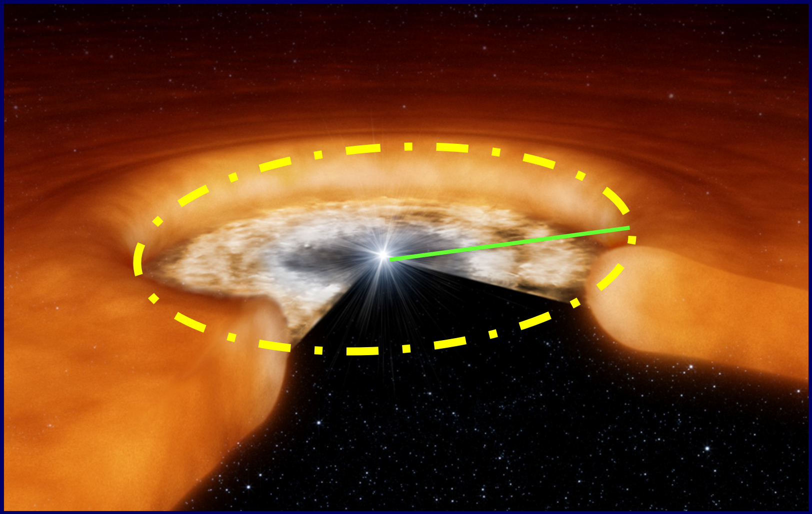
Projected Baseline

Object intensity distribution

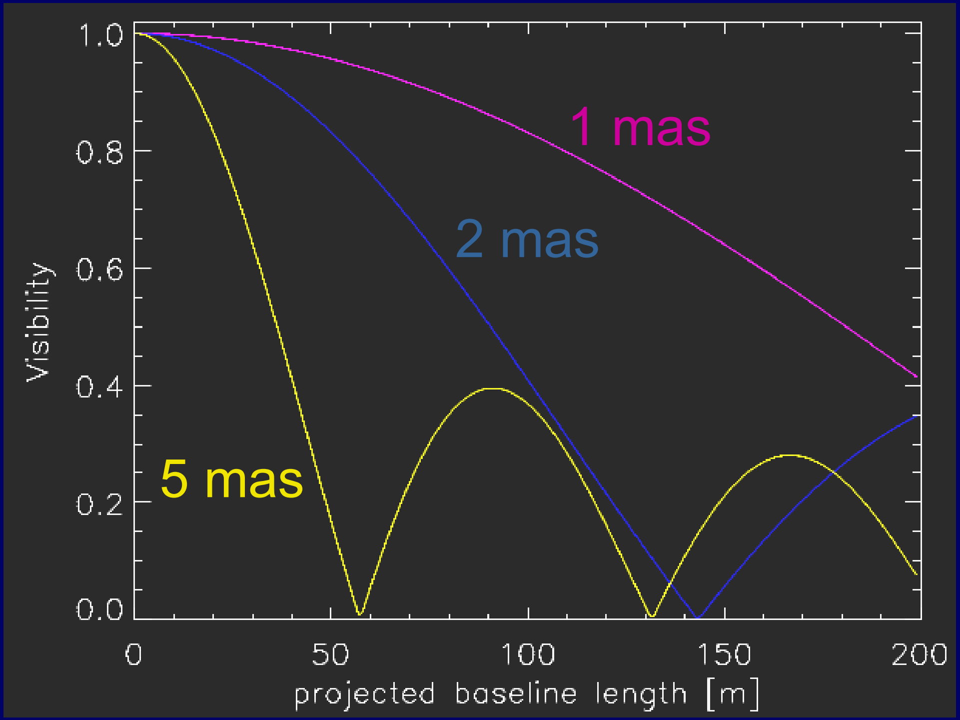
Spatial frequency:
$\boldsymbol{B} / \lambda = (u,v)$

The observed visibility $V \propto |\gamma|$ is the *Fourier Transformation* of the object intensity distribution.

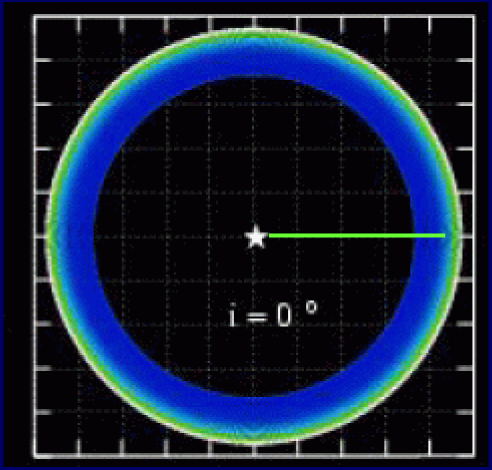
Near-infrared emission from young stellar objects is thought to be dominated by the emission from hot dust at the dust sublimation radius



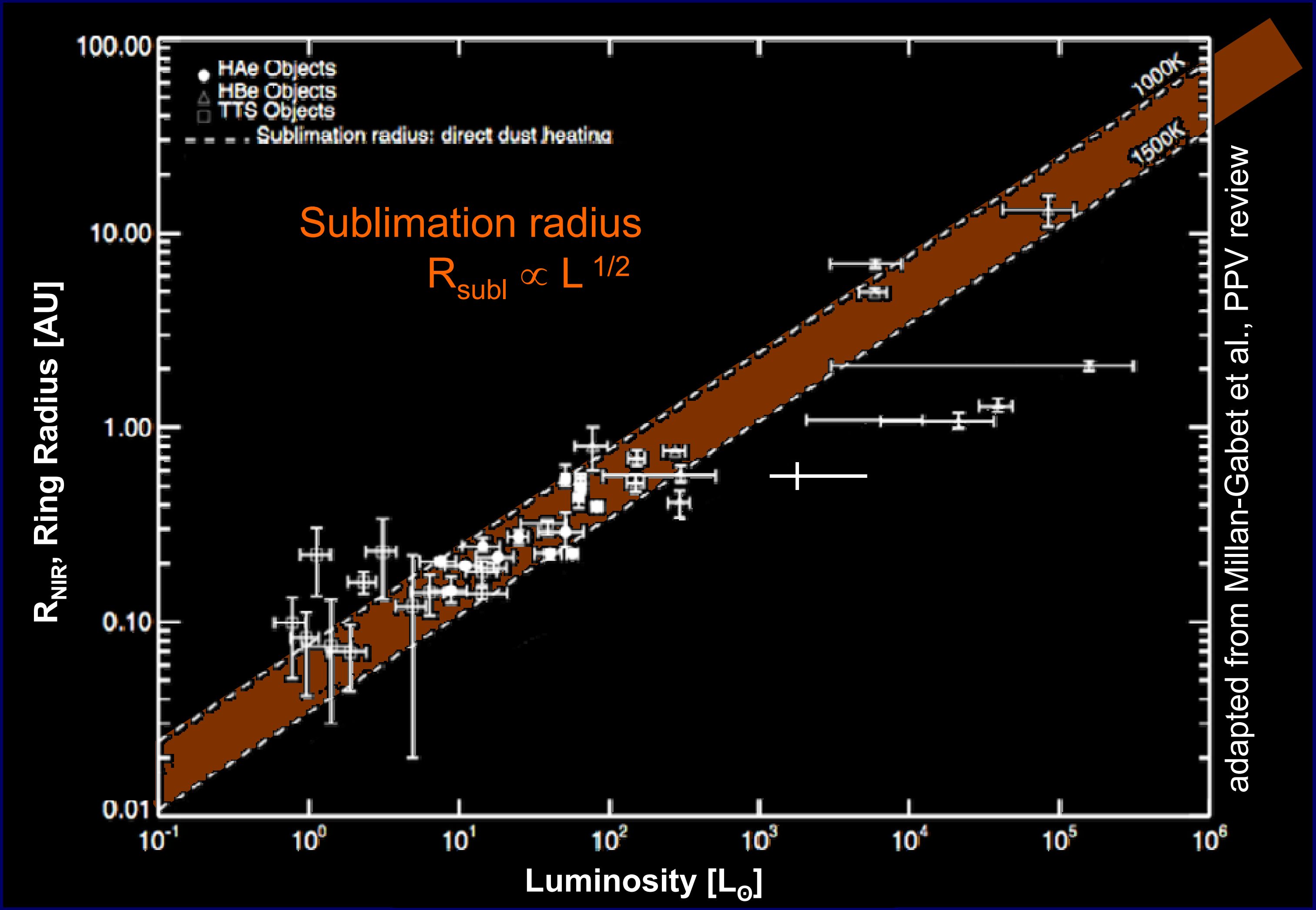
Model view from above



Visibility curves for ring models with different inner radii

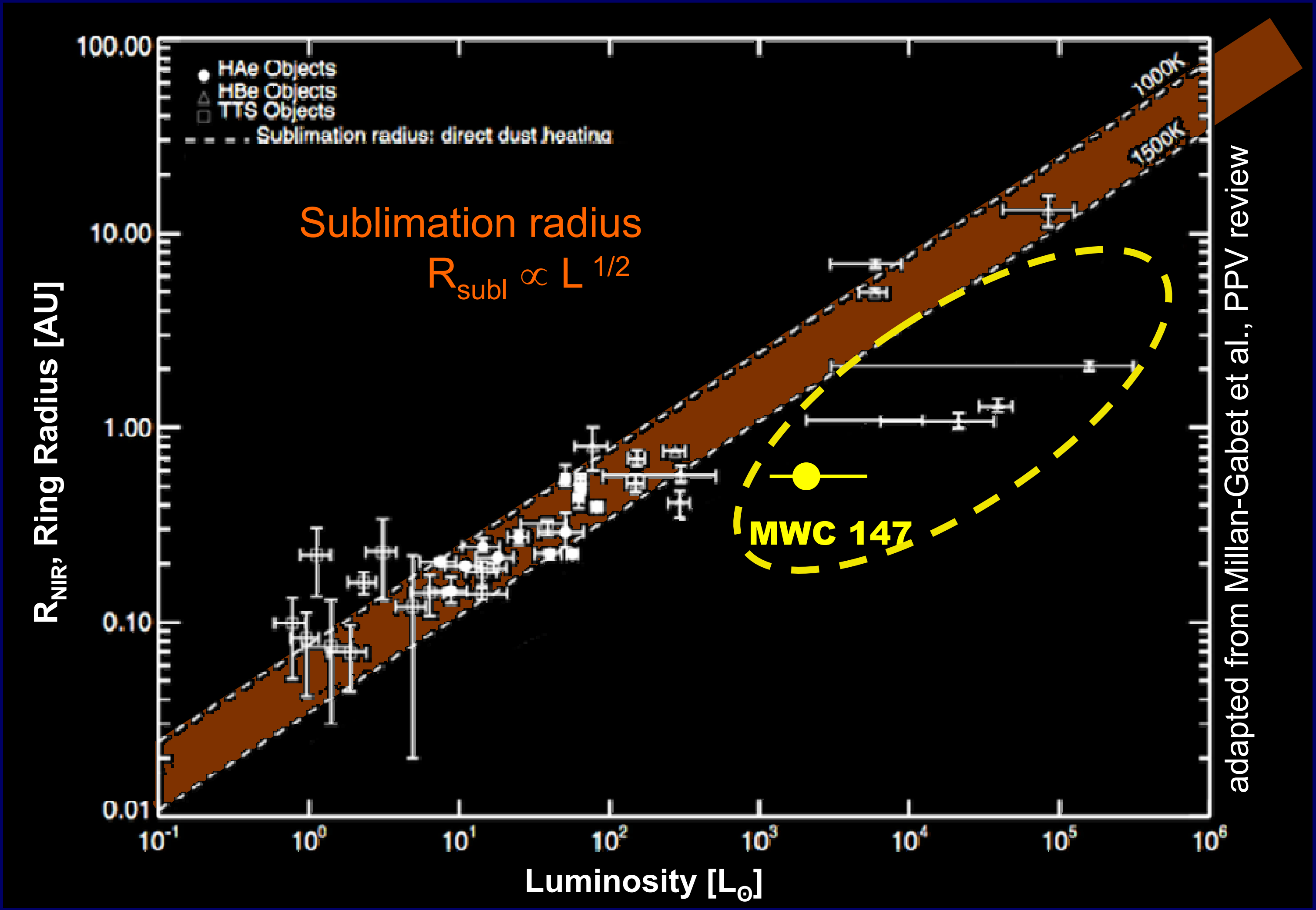


→ looks like a simple ring



adapted from Millan-Gabet et al., PPV review

In most objects, the near-infrared emission comes from hot dust near the inner edge of the dusty disk at the dust sublimation radius

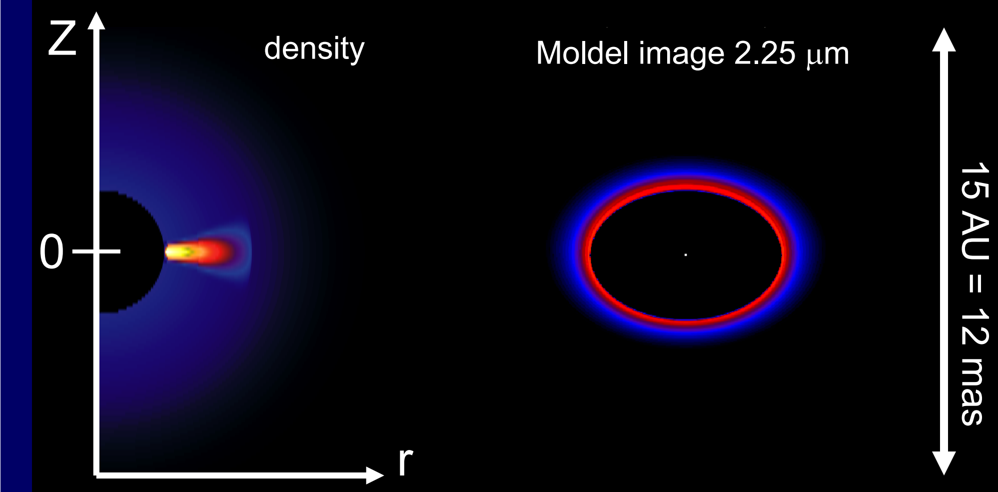


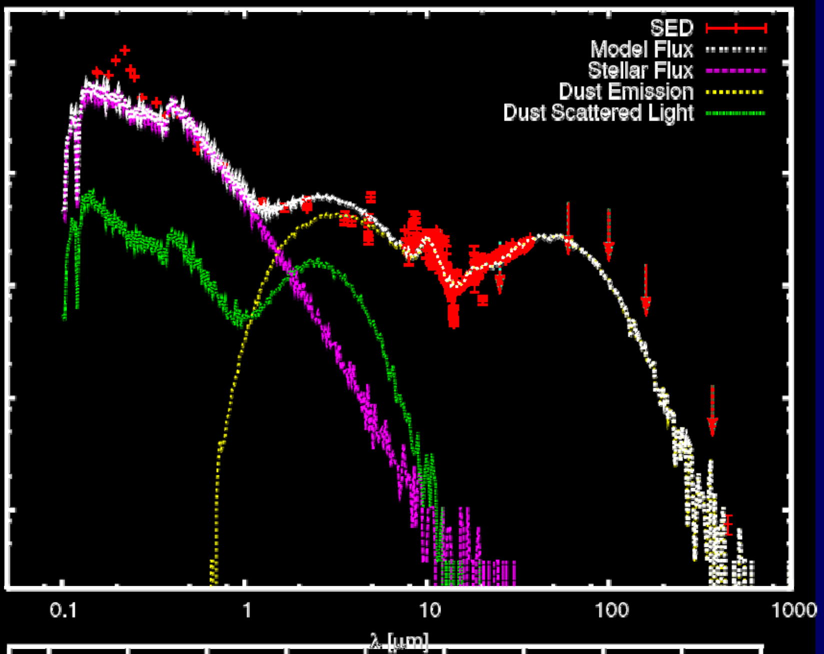
adapted from Millan-Gabet et al., PPV review

Some intermediate / high - mass objects deviate from the relation

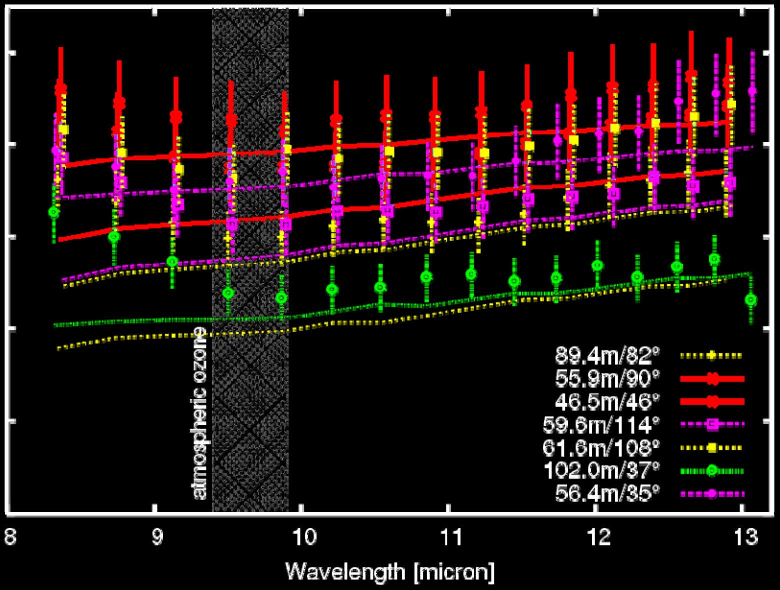
Dusty circumstellar disk model

$\chi_r^2 = 42$

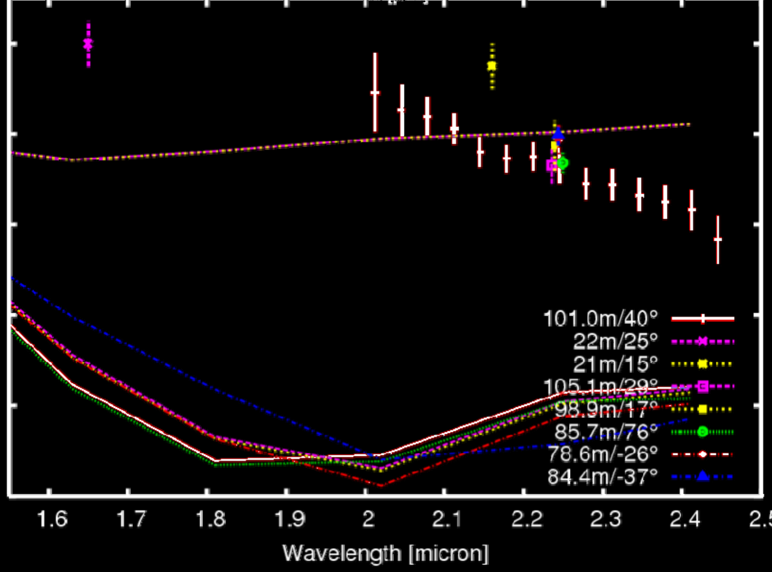




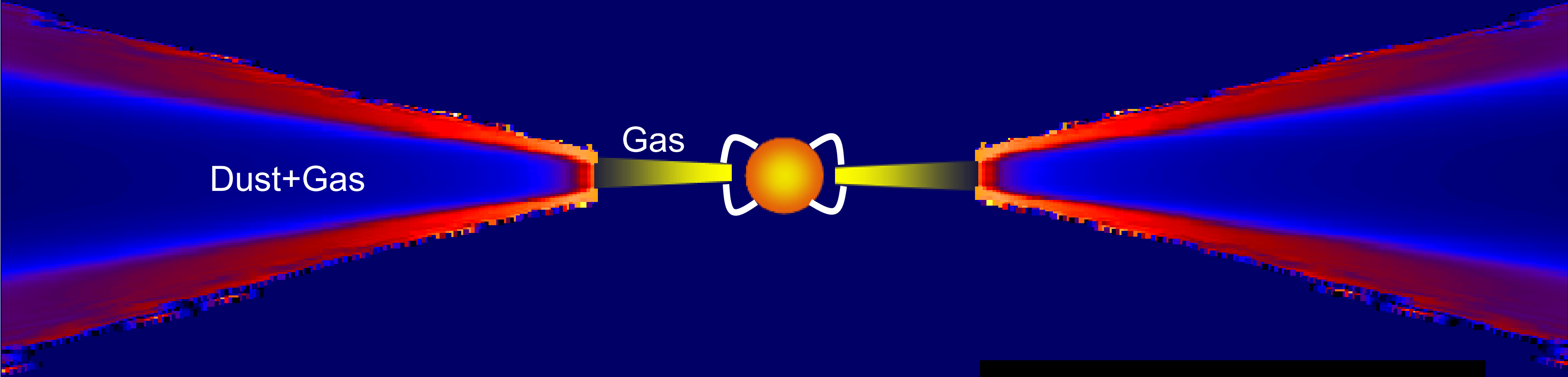
MIR visibilities



NIR visibilities

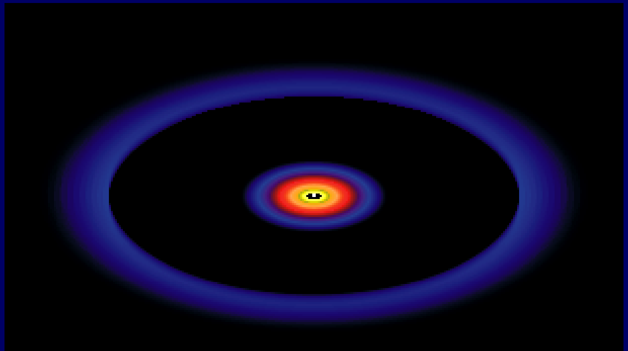


Solution: **Emission from gas in the inner disk**



Muzerolle et al. 2004:

Emission from gas in the inner accretion disk can dominate near-infrared emission for accretion rates ≥ 10^{-6} $M_\odot$ / yr



K-band model image

→ We model the gas in the inner accretion disk to be

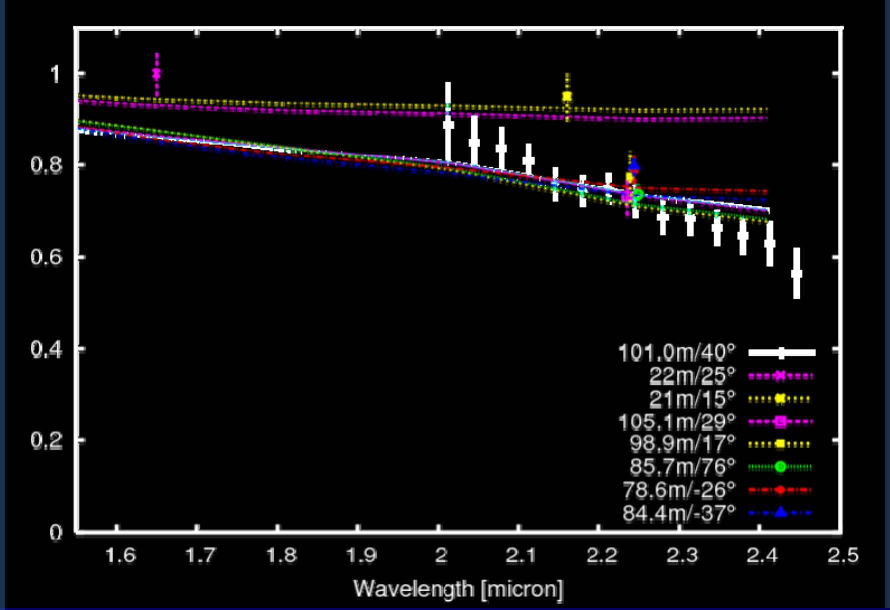
- geometrically thin
- extend from R_{corot} (~ 3 $R_\star$) to R_{subl} (~2.5 AU)
- follow the temperature-profile from Pringle (1981)

$$T^4_{\mathrm{gas}}(r) = \left(\frac{3GM_\star\dot{M}}{8\pi\sigma r^3}\right)\left(1-\sqrt{R_\star/r}\right)^{1/2}.$$

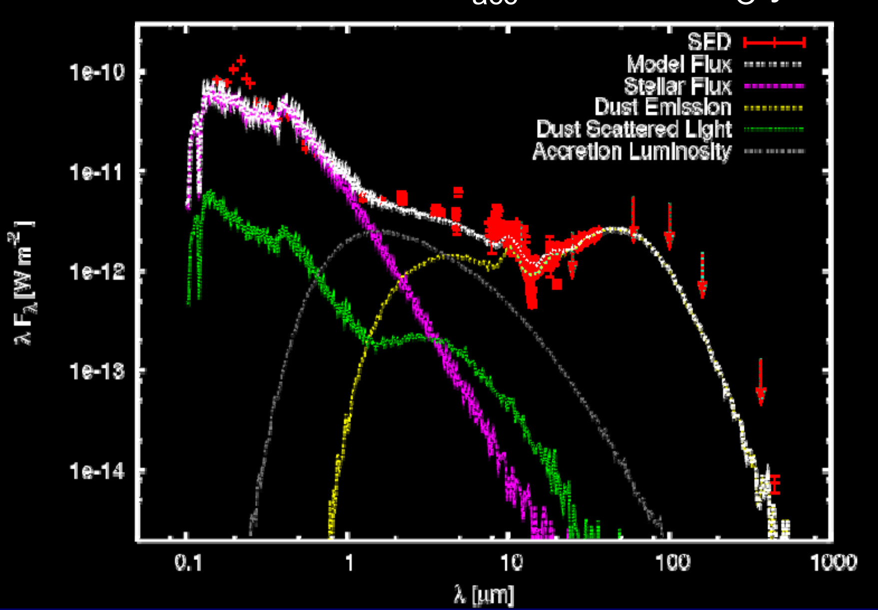
Dusty disk + inner gas disk: $\chi_r^2 = 1.28$

Inclination: 60°, $\dot{M}_{acc} = 9\times10^{-6}\ M_\odot/yr$

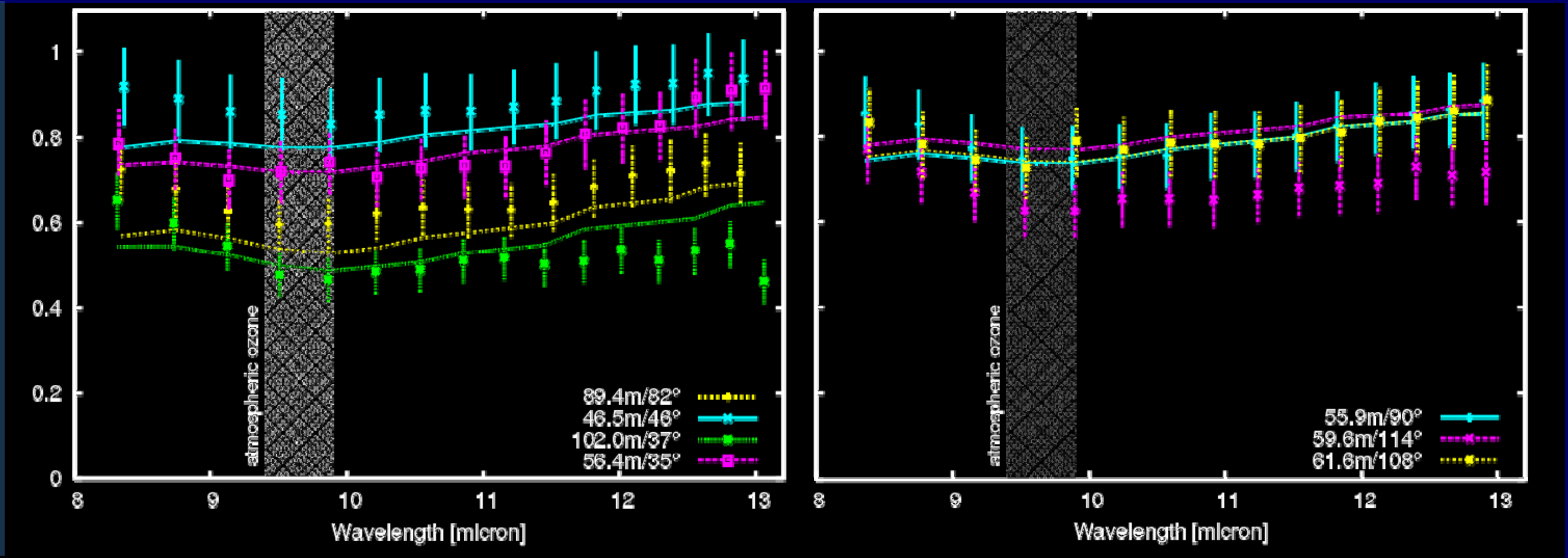
NIR visibilities

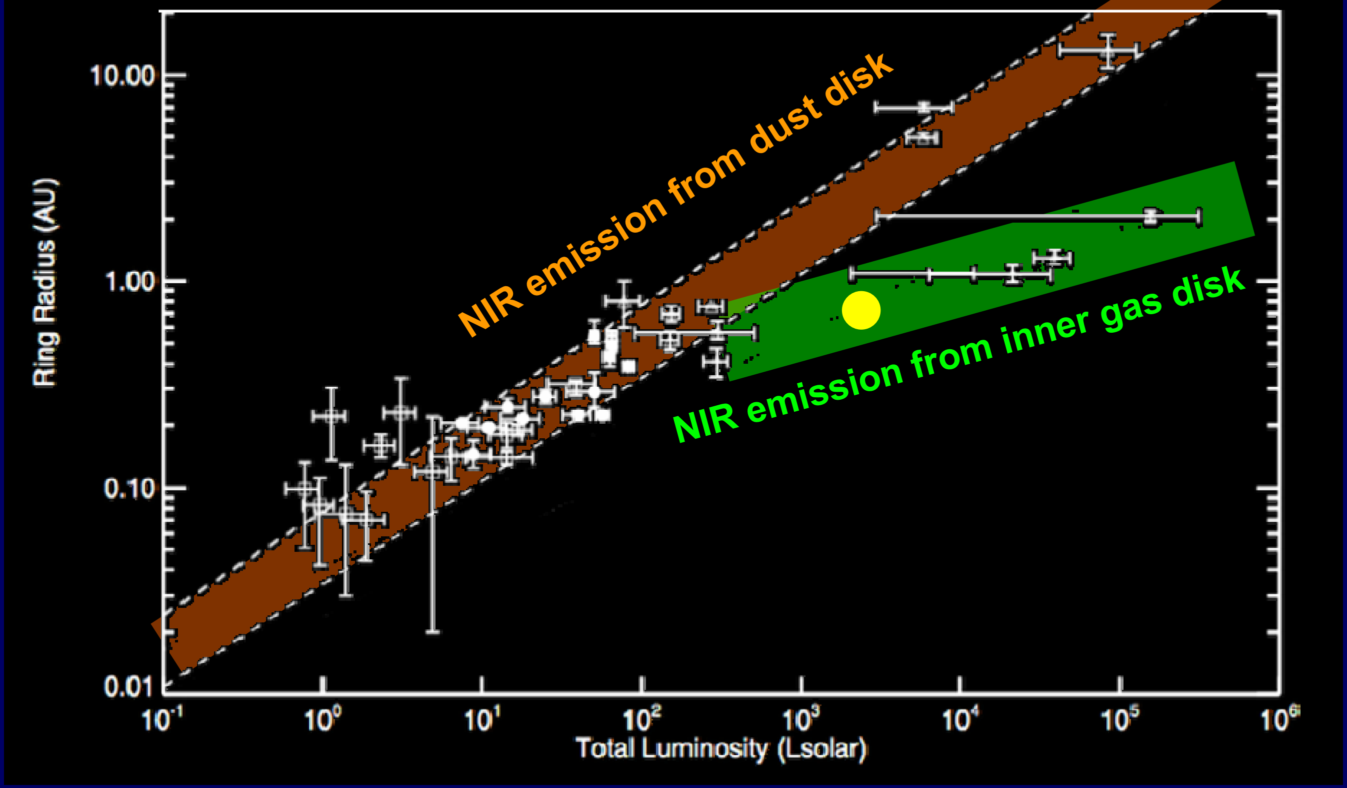


SED



MIR visibilities





adapted from Millan-Gabet et al., PPV

NIR emission of massive young stars often dominated by gas emission

(see also Monnier et al. 2005, Eisner et al. 2005, Vinkovic & Jurkic 2007)

Different accretion physics in more massive stars (?)

Accetion disk models for low-mass stars may not be valid for high-mass stars

Further investigations are required

The (near) future: Interferometric imaging

combine 3 (or more) telescopes (closure phase)

→ reconstruction of images with mas resolution

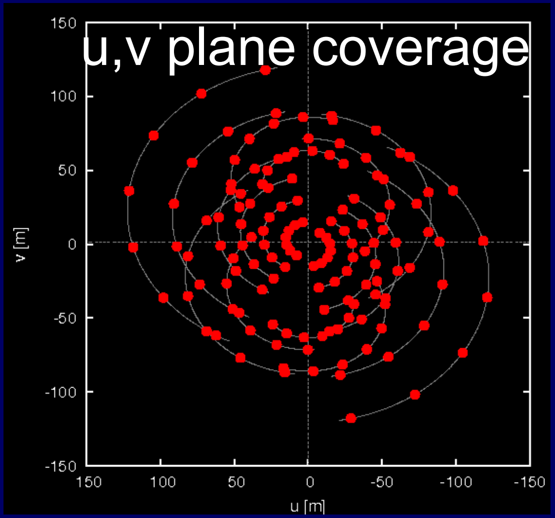
Example:

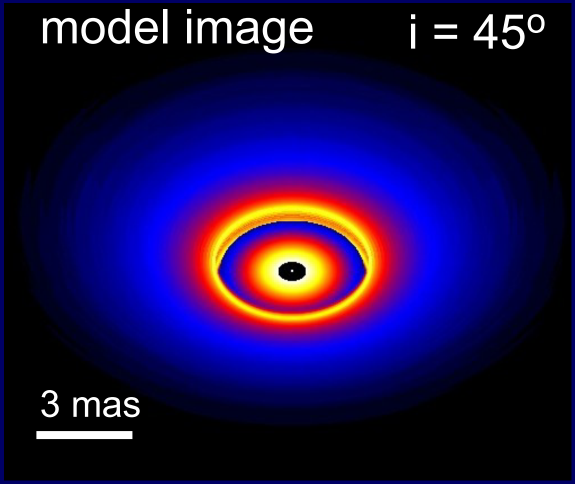
image reconstruction with

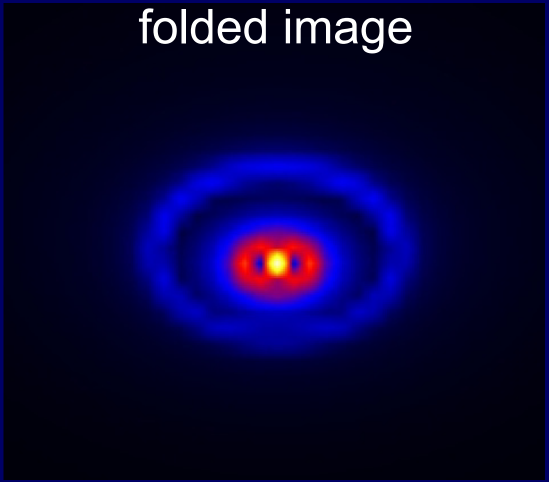
simulated VLTI / AMBER data:

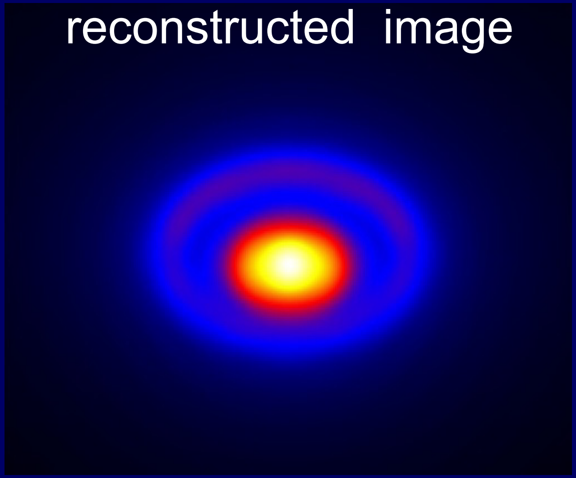
4 nights with 3 ATs

K-band, S/N = 50


u,v plane coverage

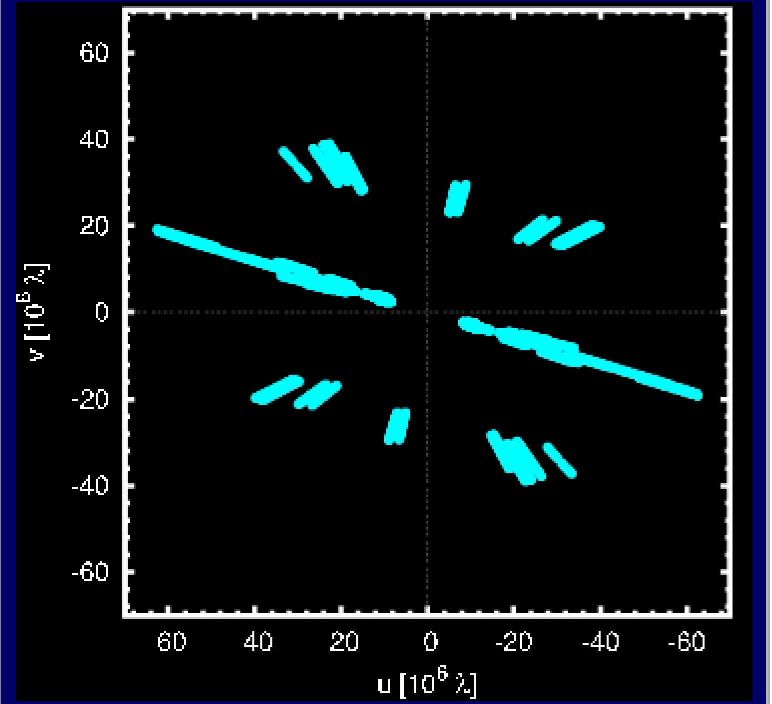

model image i = 45°


folded image

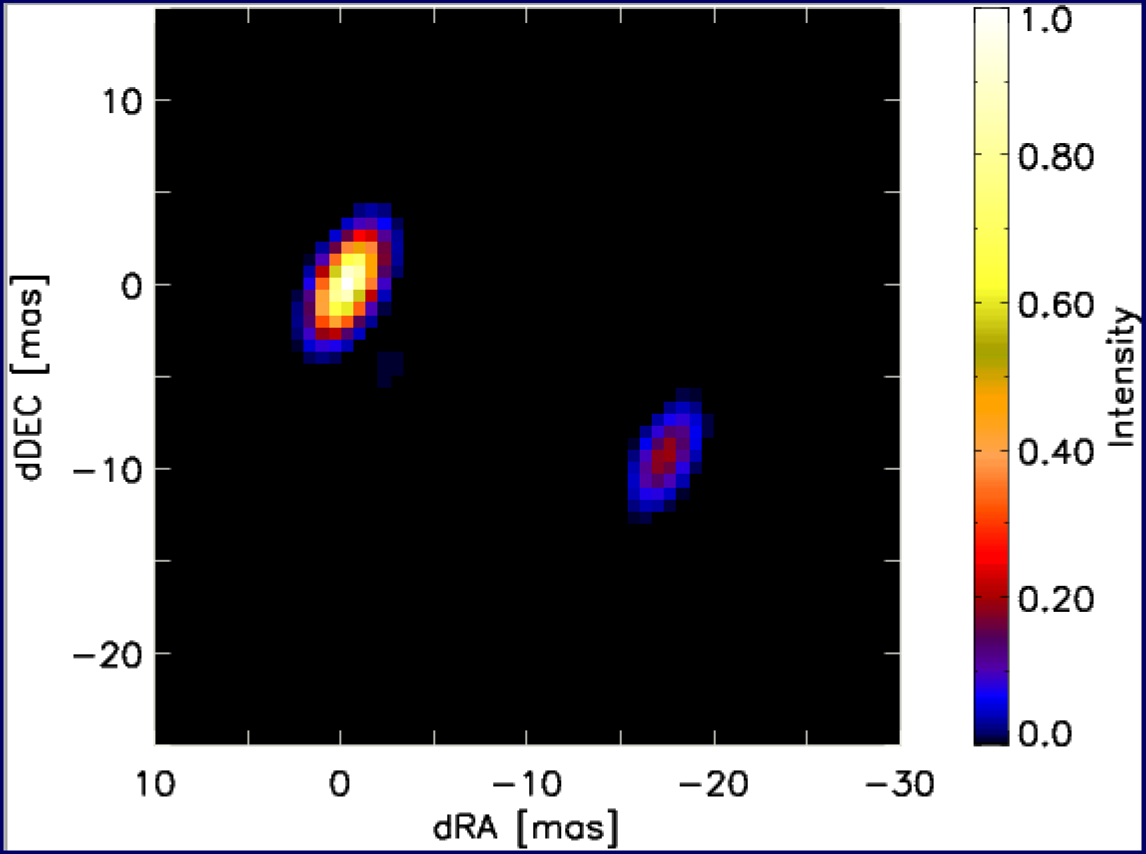

reconstructed image

simulation by K.-H. Hofmann and S. Kraus, MPIfR Bonn

First aperture synthesis image reconstructed from AMBER data:



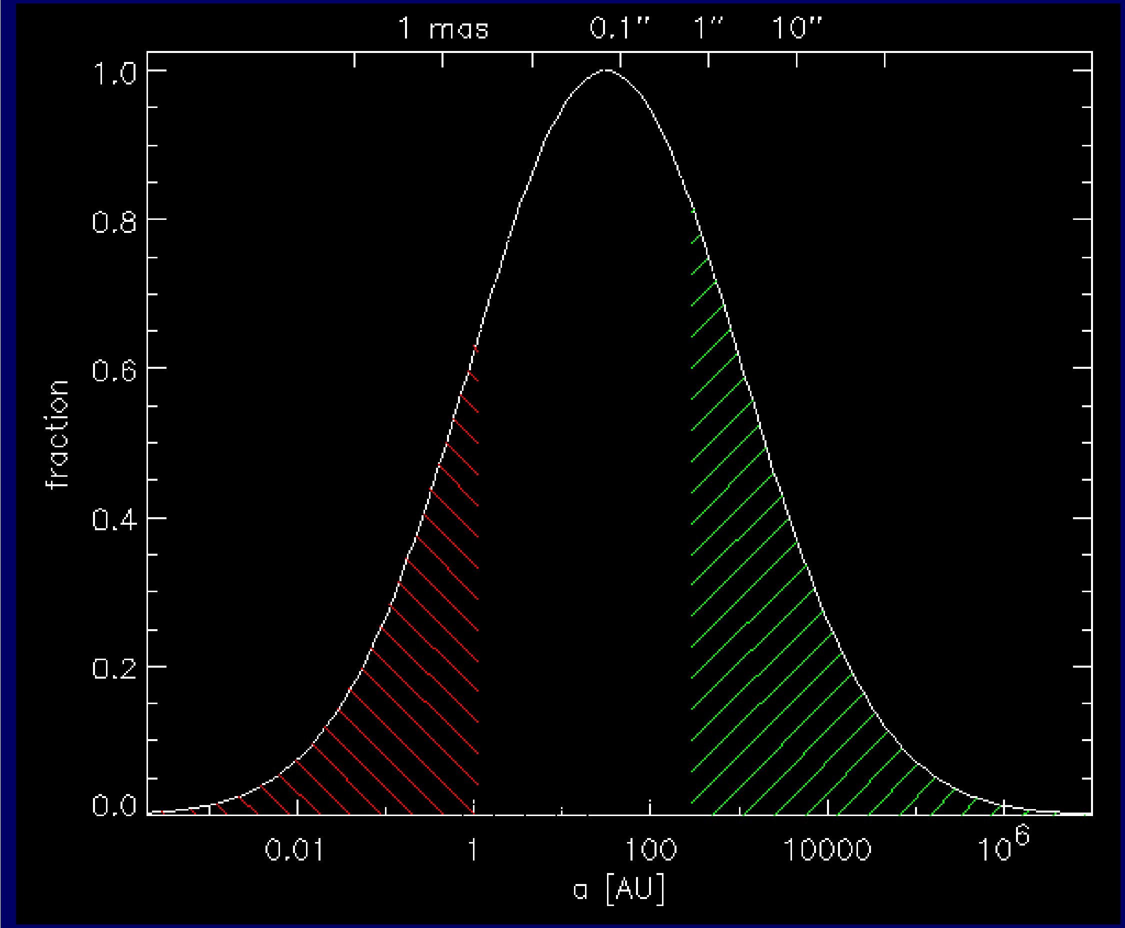
Kraus et al. 2009



Binary star θ^1 C Ori

effective resolution ~ 2 mas

Part 2: Interferometry of young multiple stars



20%

25%

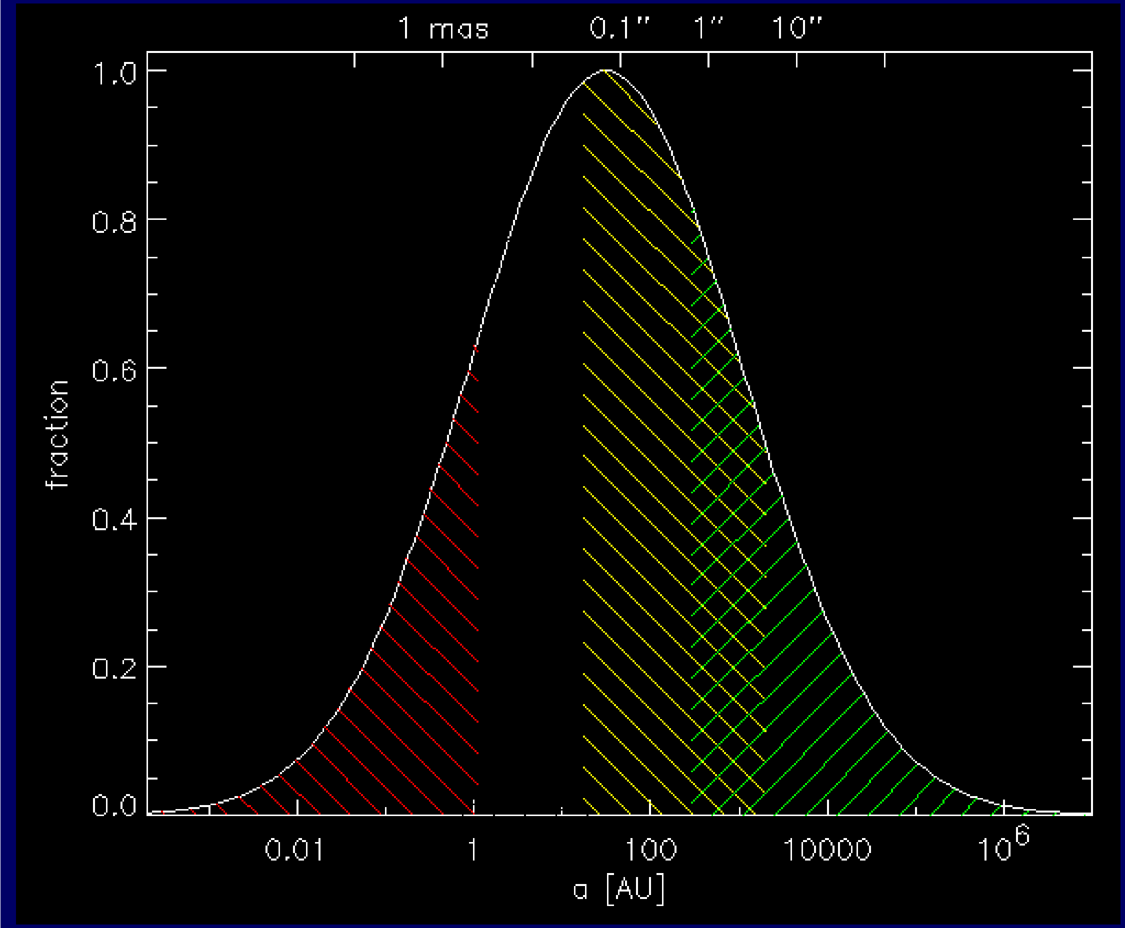
Visual companions

seeing limit ~ 0.5" ... 1"

Spectroscopic companions

mostly $P_{orbit} \leq 1$ yr

Part 2: Interferometry of young multiple stars



20% 40% 25%

Visual companions

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mostly $P_{orbit} \lesssim 1$ yr

Speckle / Adaptive Optics

diffraction limit: λ / D = 0.04"

(for λ = 1.2 μm, D = 6 m)

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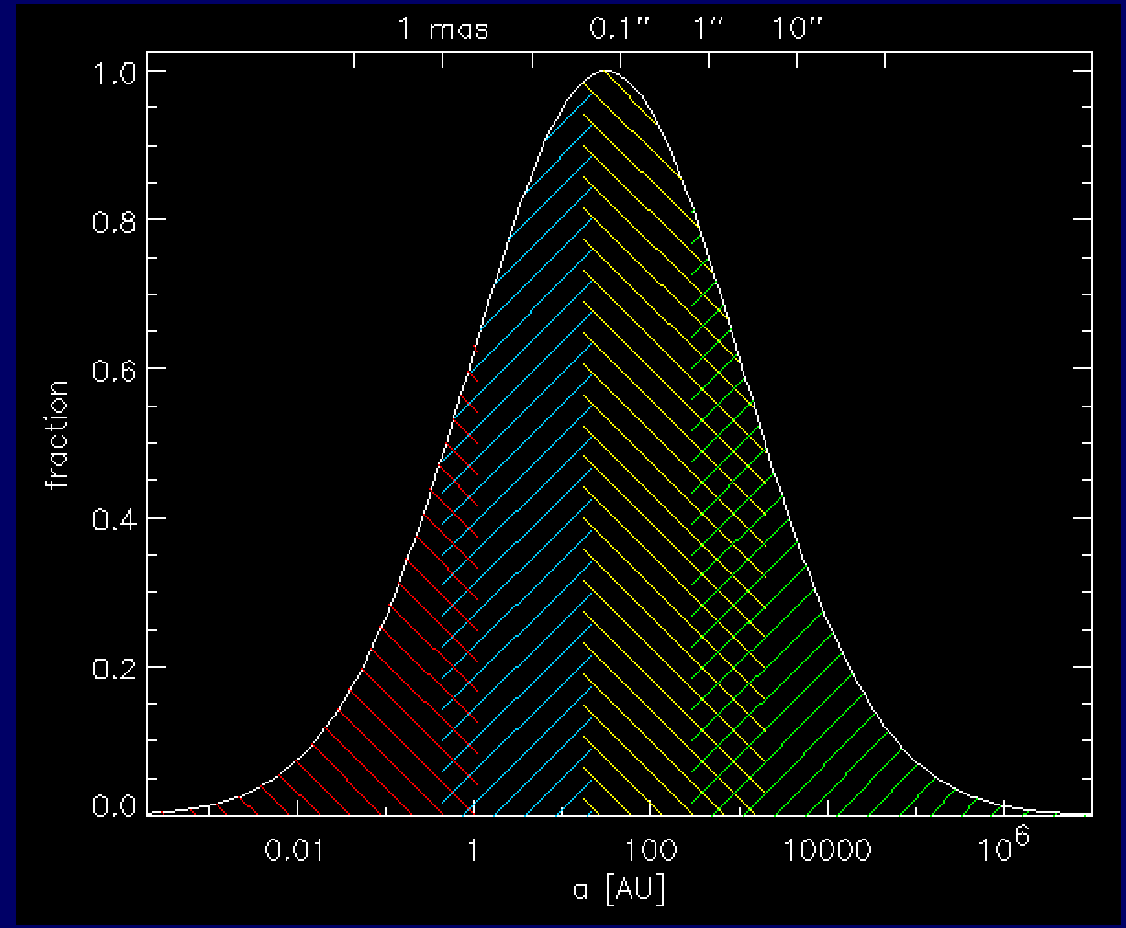


20% 30% 40% 25%

Visual companions

seeing limit ~ 0.5" ... 1"

Spectroscopic companions

mostly $P_{orbit} \lesssim 1$ yr

Speckle / Adaptive Optics

diffraction limit: λ / D = 0.04"

(for λ = 1.2 µm, D = 6 m)

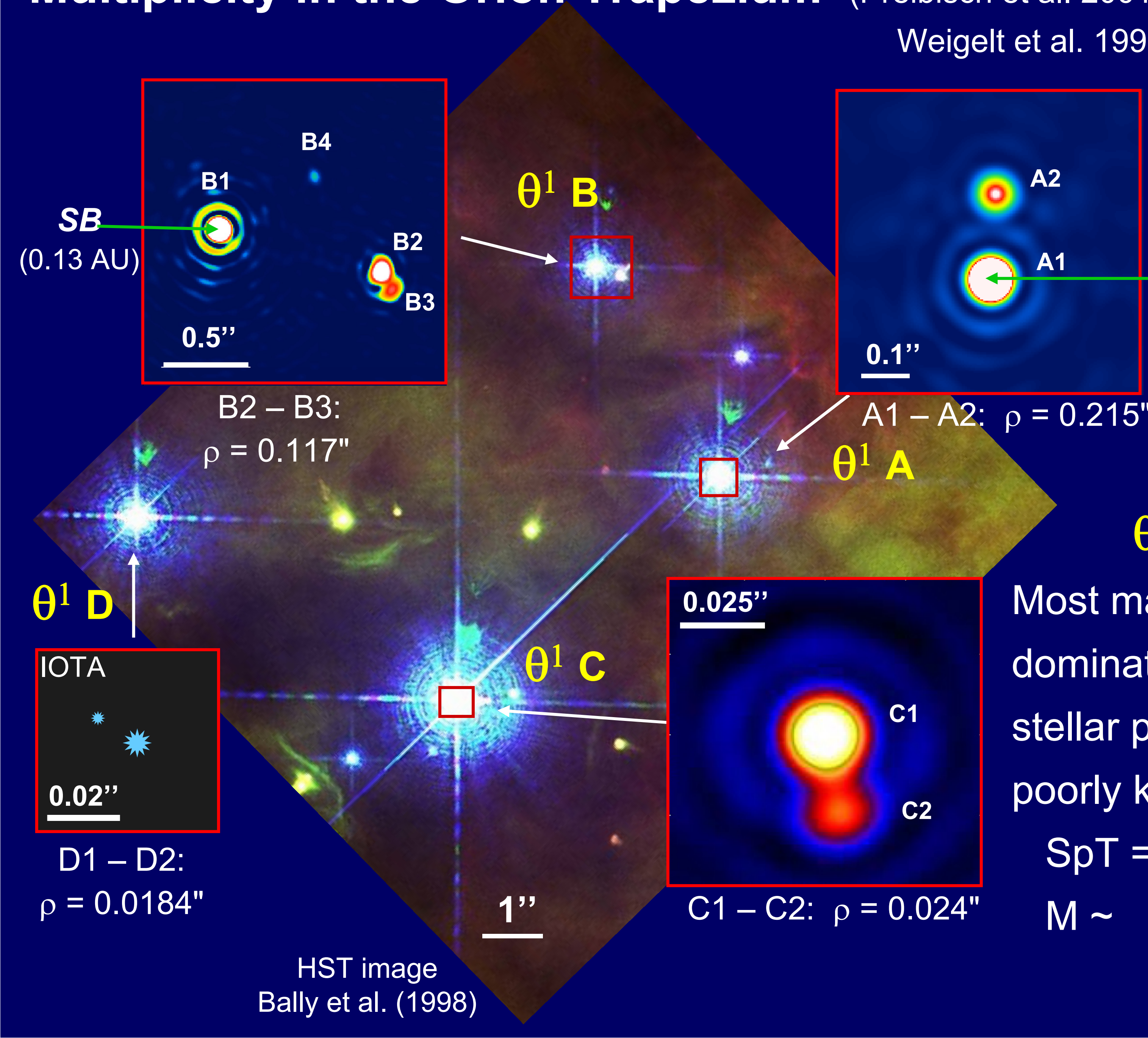
Long-baseline Interferometry

resolution λ / B = 0.001"

(for λ = 1.2 µm, B = 200 m)

Multiplicity in the Orion Trapezium

(Preibisch et al. 2001; Schertl et al. 2003; Weigelt et al. 1999; Kraus et al. 2009)



SB
(0.13 AU)

B2 – B3:
$\rho = 0.117''$

SB
(1 AU)

A1 – A2: $\rho = 0.215''$

D1 – D2:
$\rho = 0.0184''$

C1 – C2: $\rho = 0.024''$

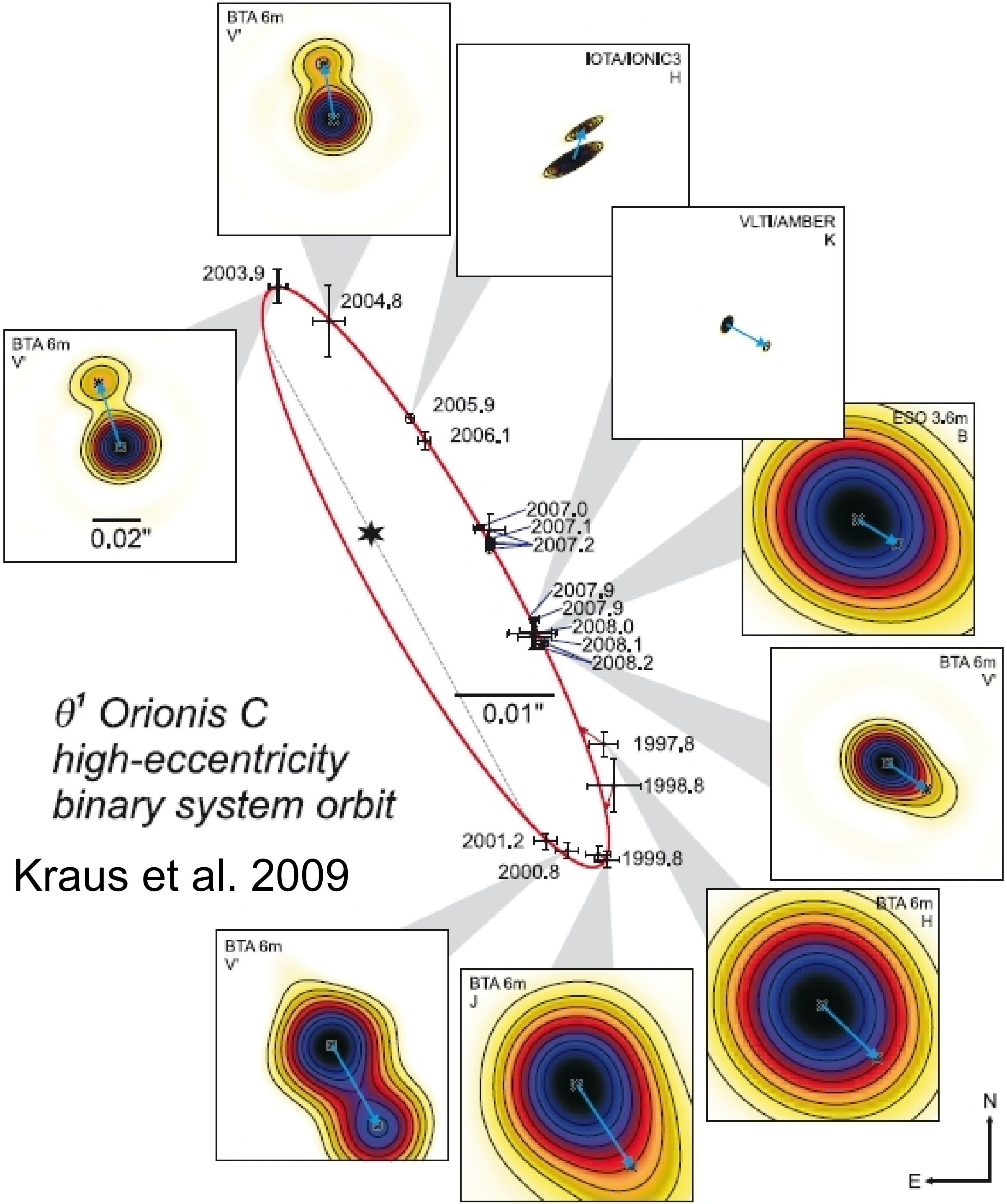
HST image
Bally et al. (1998)

θ^1 C:

Most massive member; dominates UV output; stellar parameters only poorly known:

SpT = O5…O7

$M \sim 30 \ldots 60\ M_\odot$



θ^1 Orionis C
high-eccentricity
binary system orbit

Kraus et al. 2009

Orbit:

P = 11.26 ± 0.5 yrs

a = 43.6 mas = 18 AU

e = 0.592 ± 0.07

+ radial velocity curve & B,V,J,H,K mag. difference:

→ $M_1 = 39.5\ M_\odot$

$M_2 = 7.5\ M_\odot$

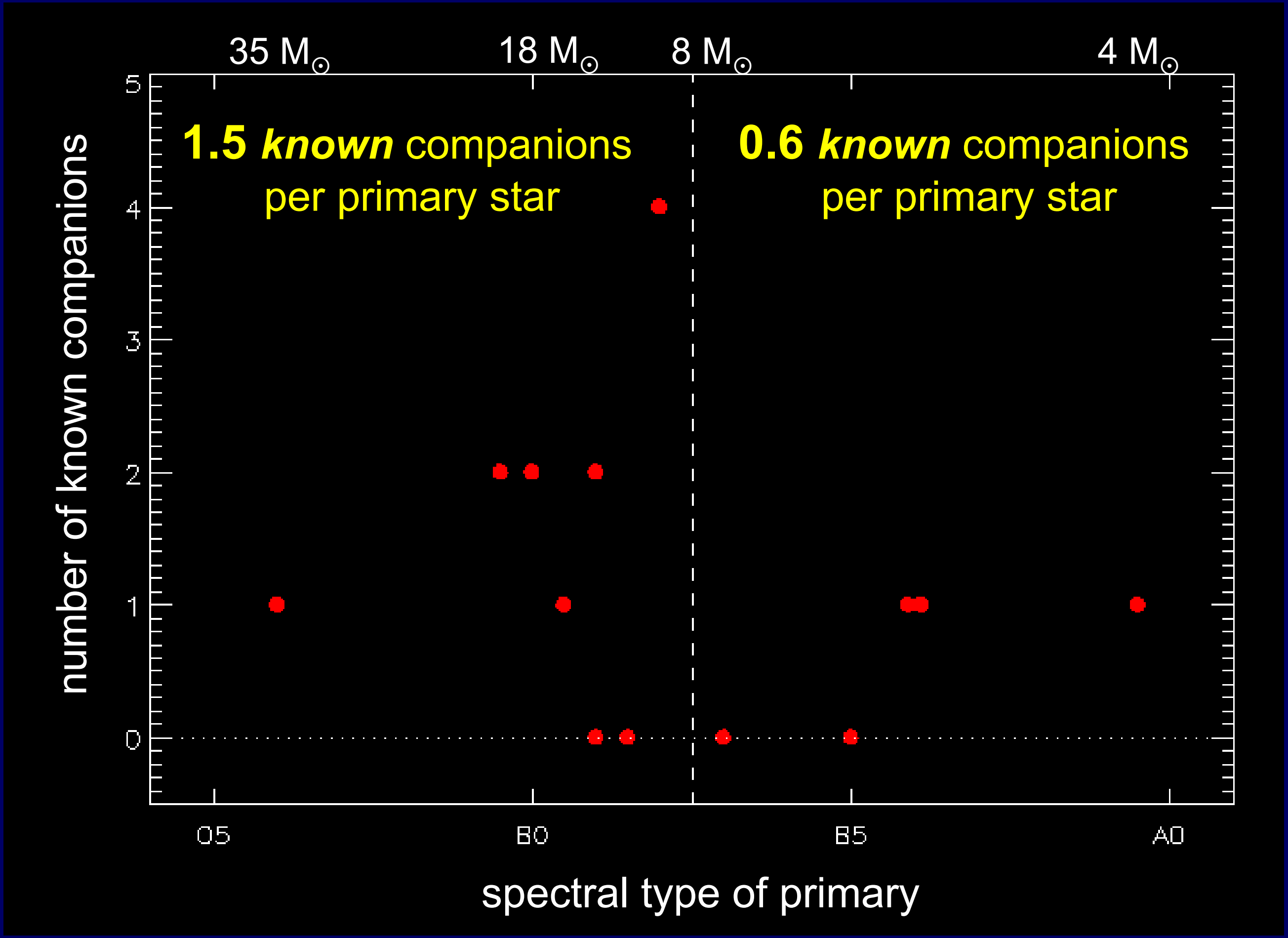
(~B3 star @ MS)

Orbital parallax:

D = 416 ± 12 pc

Menten et al. 2007:
(Trigonometric parallax)
414 ± 7 pc

Multiplicity as a function of spectral type (stellar mass)



Low mass ONC stars:
~ 0.6 companions

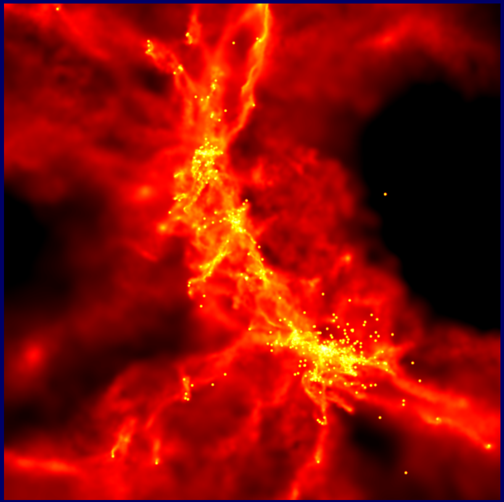
Low mass field stars:
~ 0.6 companions

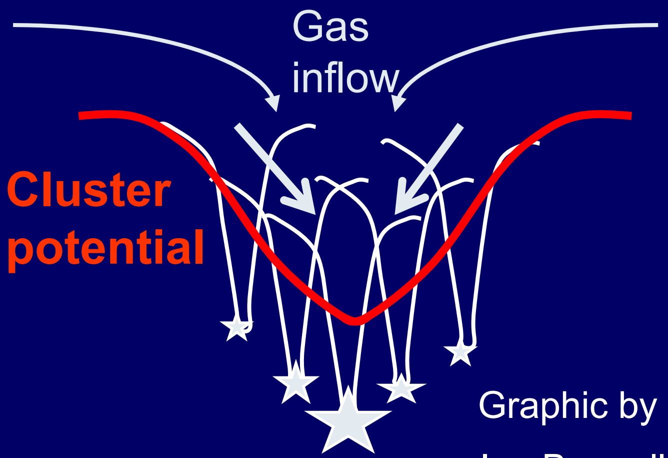
- These numbers are ***strict lower limits***
- High multiplicity of massive stars is confirmed in many other studies

VLTI multiplicity surveys will improve statistics

Stellar interactions in massive star formation

1) **Competitive accretion**



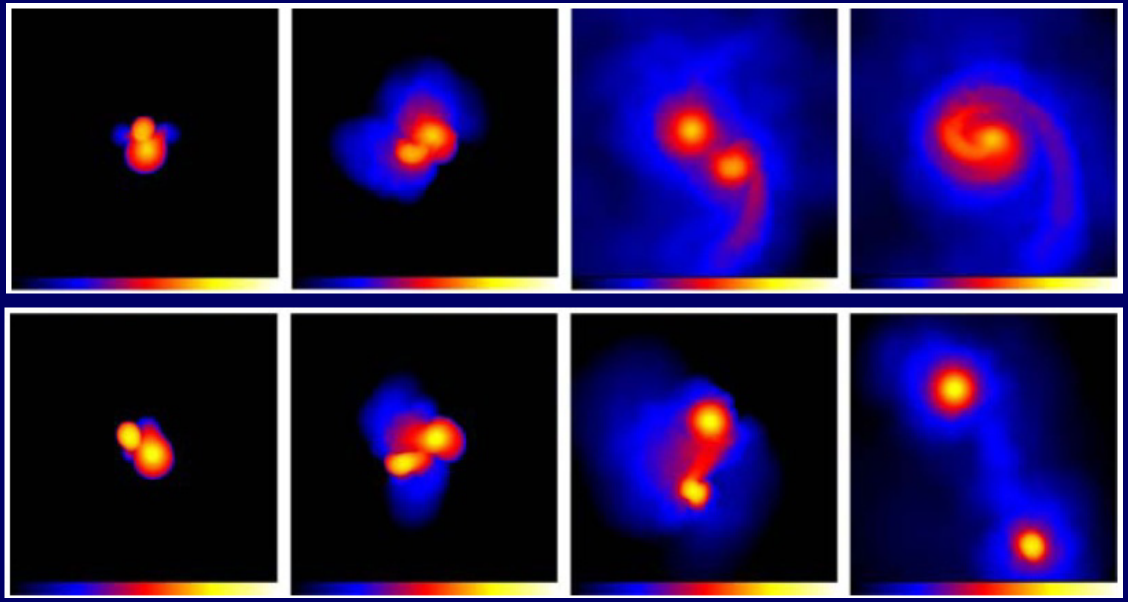


Graphic by Ian Bonnell

2) **Cluster contraction**

→ $n \geq 10^7$ stars pc^{-3}

3) **Proto-stellar collisions captures & mergers**



Davies et al. 2006, MNRAS 370,2038

→ close binary

SUMMARY & OUTLOOK: The potential of infrared interferometry

- Surveys can characterize stellar multiplicity

  → important constraints on theoretical models

- Can resolve & characterize disks around massive stars

  (if they exist)

- *Spectro-Interferometry* provides unique information about inner circumstellar disks (which are more complex than expected)

- *Interferometric imaging* is now becoming possible & feasible

  First images of young stellar objects expected this year