The life of the massive stars seen through optical/near-infrared interferometry

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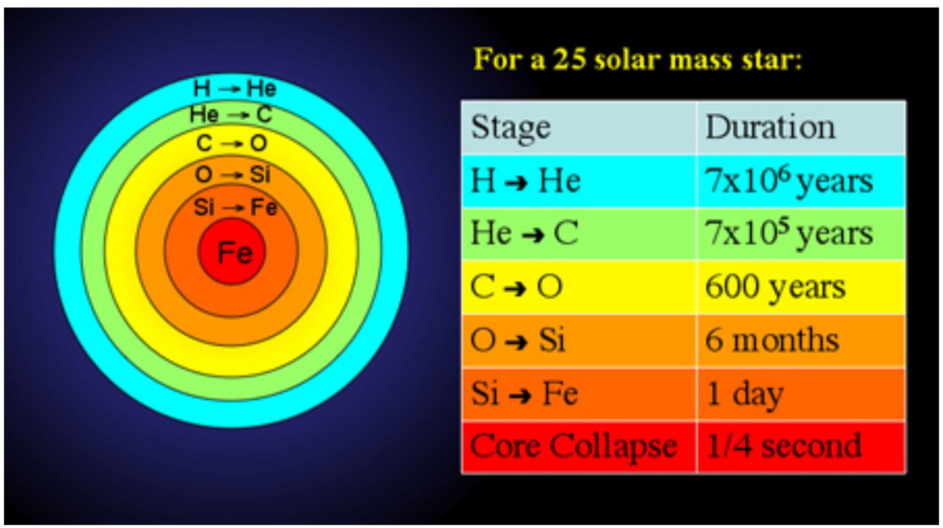
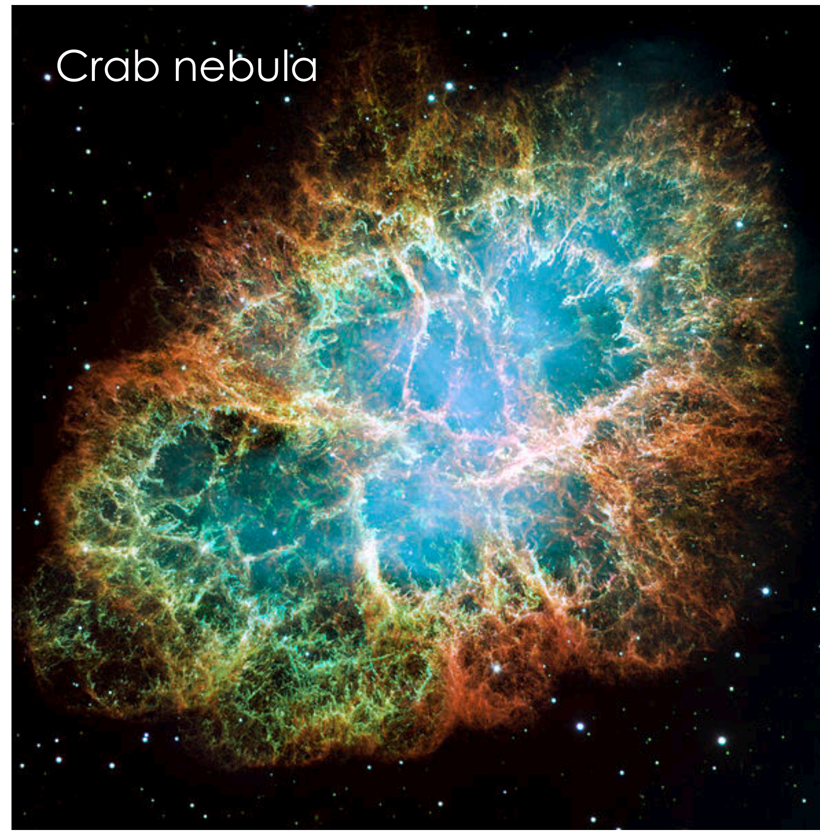
The importance of massive stars

- Important to the chemical evolution of the galaxies
- Principal UV-radiation sources
- Progenitors of the heavier chemical elements
- Strong stellar-winds and deaths in the form of supernovae



For a 25 solar mass star:

Stage	Duration
H → He	7×10^6 years
He → C	7×10^5 years
C → O	600 years
O → Si	6 months
Si → Fe	1 day
Core Collapse	1/4 second



Massive stars birthplaces

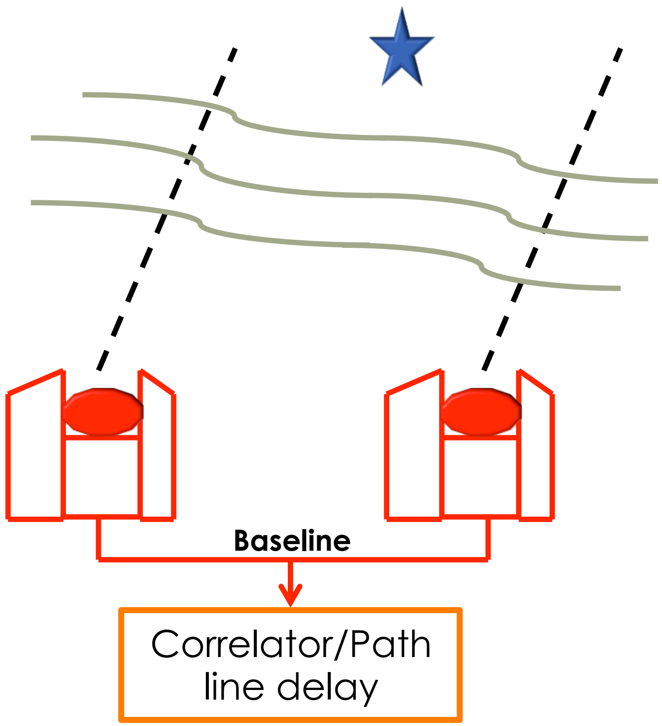
- Rare (IMF)
- Born on the main sequence
- Short life-times (≈Ma)
- Born in very dense clouds

High angular resolution techniques

- Multiplicity
- Interaction of massive stars with the CSM and ISM.
- Morphology in Massive Young Stellar Objects (MYSOs)

- Near-IR Long-baseline interferometry (AMBER/VLTI)
- Speckle Imaging (NACO/VLT)
- Near-IR Fizeau Interferometry (NACO-SAM/VLT)
- Spectro-Astrometry (CRIRES/VLT)

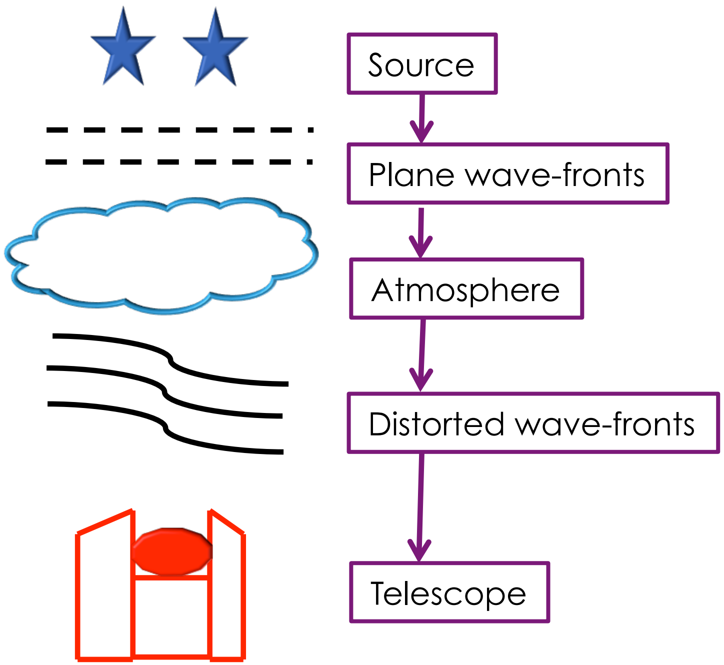
Optical/IR vs Radio Interferometry



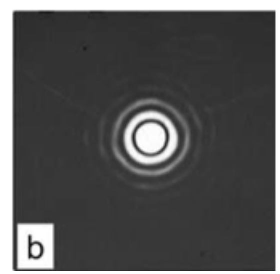
- Visibilities are complex quantities
- They have **AMPLITUDE** and **PHASE**

- Optical wavelengths are significantly shorter than radio wavelengths (10^4-10^7)
- More important atmospheric effects at infrared wavelengths.
- The properties of the received radiation are very different between RADIO and OPTICAL/IR wavelengths.

Optical/IR vs Radio Interferometry

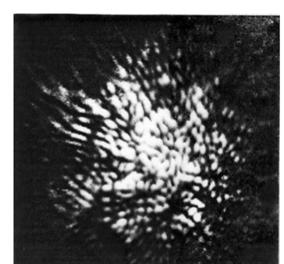


	Radio	Optical/IR
Wavelength	1.3 cm	2.2 μm
Coherence time	≈10 minutes	20 milliseconds
Fried's parameter	15 km	1 m



$D<r_0$

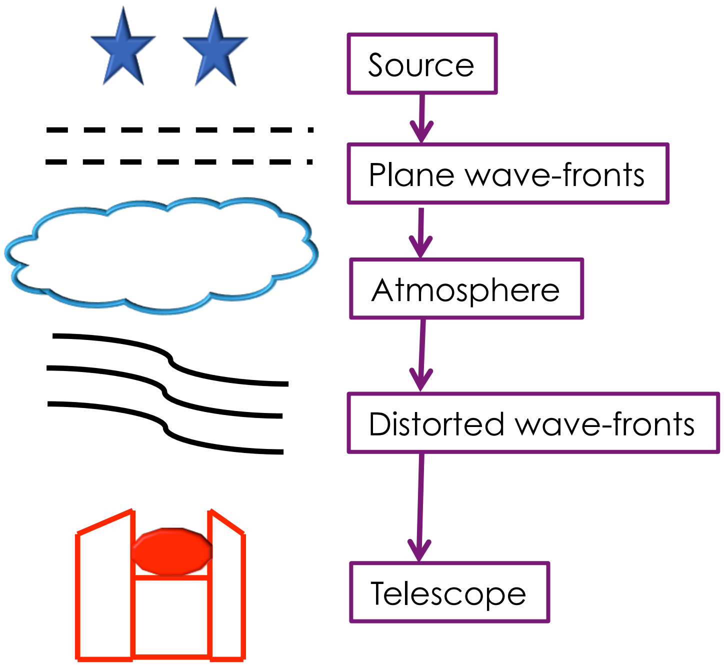
$$\Theta = \lambda / D$$



$D>r_0$

$$\Theta = \lambda / r_0$$

The atmospheric effect



- The atmosphere introduces temporal and spatial anomalies in the wave-front
- **Fried's parameter:** The circular aperture size over which the mean wave-front error is 1 rad^2. $r_0 \approx \lambda^{6/5}$. Large telescopes requires **Adaptive Optics** to achieve diffraction-limited resolution.
- **Coherence time:** Time over which the mean wave-front error changes by 1 rad^2. $t_0 \approx \lambda^{6/5}$

	Radio	Optical/IR
Wavelength	1.3 cm	2.2 μm
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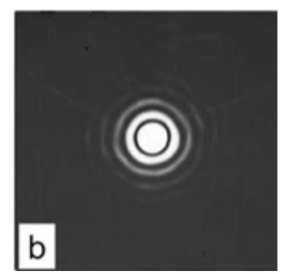
Fried's parameter	15 km	1 m



$D < r_0$

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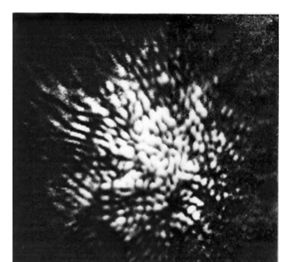


$D > r_0$

$$\Theta = \lambda / r_0$$

The quantum effect

- **Ocupation number :** The average mean energy of a source divided by the energy of a photon

$$\bar{n} = \frac{1}{e^{\frac{h\nu}{kT}} - 1}$$

- **Radio:** (1cm), T=2.7 K, <n>≈1.4

  (2cm), T=5000 K, <n>≈7000

- **Optical:** (0.5 μ m), T=5000 K, <n>≈0.003

  (2 μ m), T=1500 K, <n>≈0.008

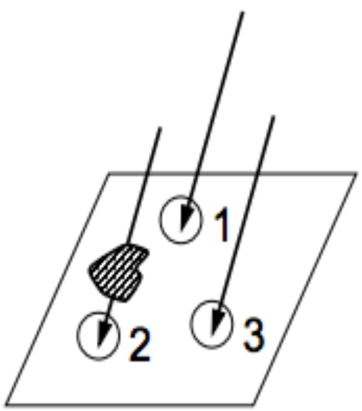
- **n>>1, rms ≈n**
- **n<<1, rms ≈sqrt(n)**

- **S/N≈V^2*N**
- **S/N<<1**

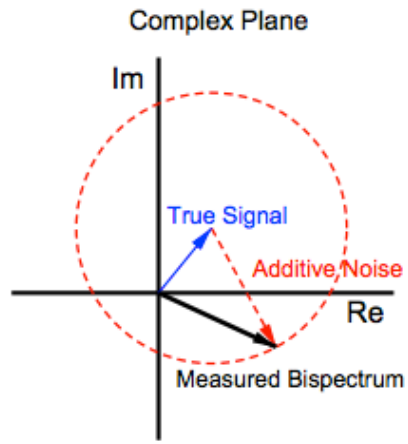
Interferometric Observables

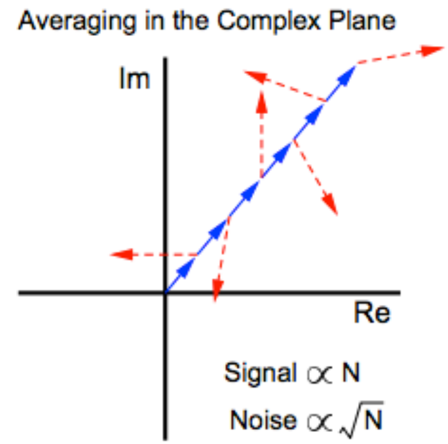
- In radio interferometry the observables are the **amplitude of the visibility (V)** and the **phase.**

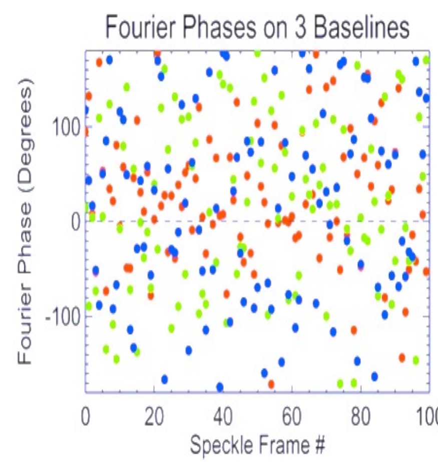
- In optical/IR interferometry we use the **modulus of the visibility (V^2)** and the **closure phases.**

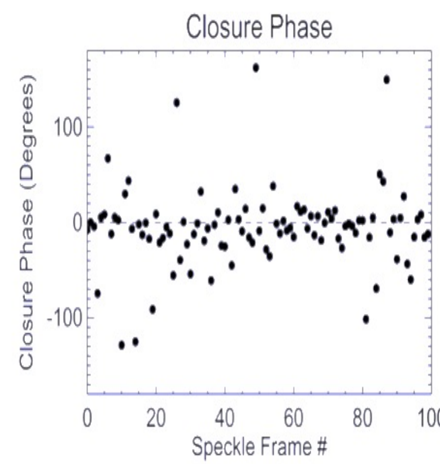


Observed	Intrinsic	Atmosphere
$\Phi(1\text{-}2) =$	$\Phi_0(1\text{-}2) +$	$[\phi(2)\text{-}\phi(1)]$
$\Phi(2\text{-}3) =$	$\Phi_0(2\text{-}3) +$	$[\phi(3)\text{-}\phi(2)]$
$\Phi(3\text{-}1) =$	$\Phi_0(3\text{-}1) +$	$[\phi(1)\text{-}\phi(3)]$





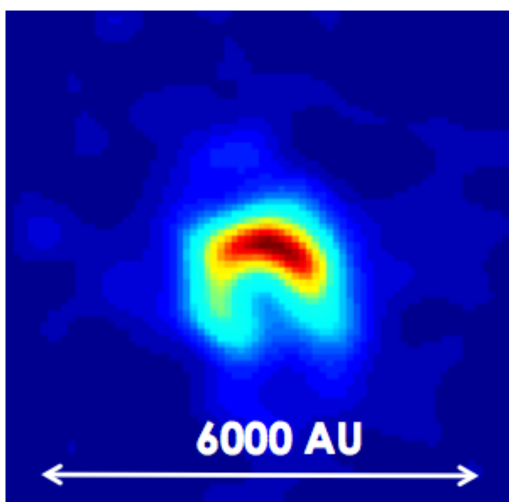


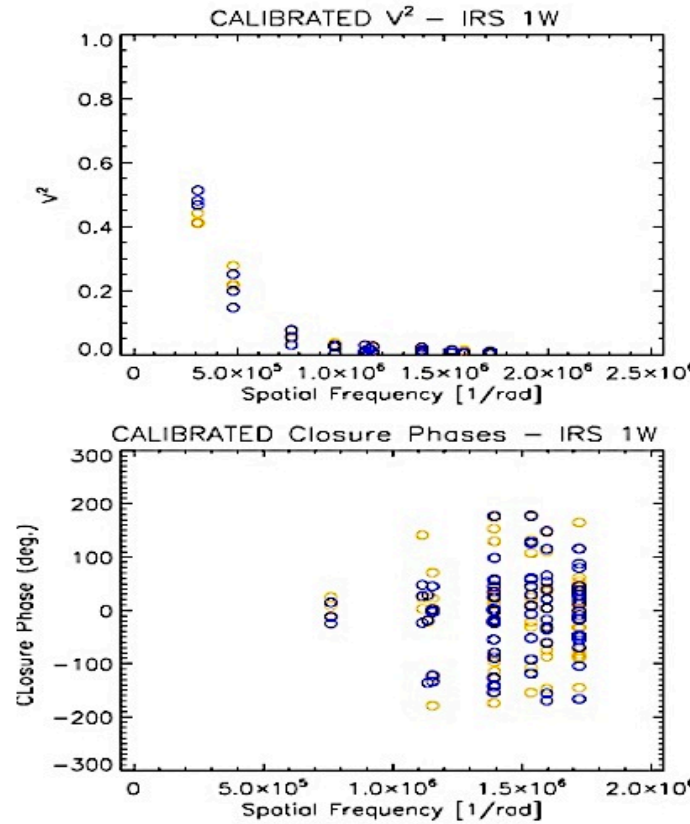


- **Closure phases:** Argument of the product of three visibilities produced by a closed triangle of baselines.

Calibration and Imaging

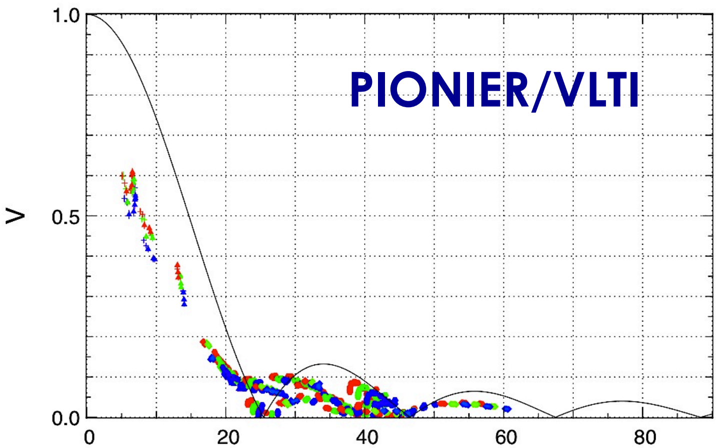
- Interwoven observations of Calibrator and target are required.
- Calibrators should be point-like sources with similar magnitudes and spectral types as the targets
- Calibrators located at few deg. from targets
- At least three software packages available bases on bispectra maximum entropy methods (BSMEM, MIRA, MACIm)

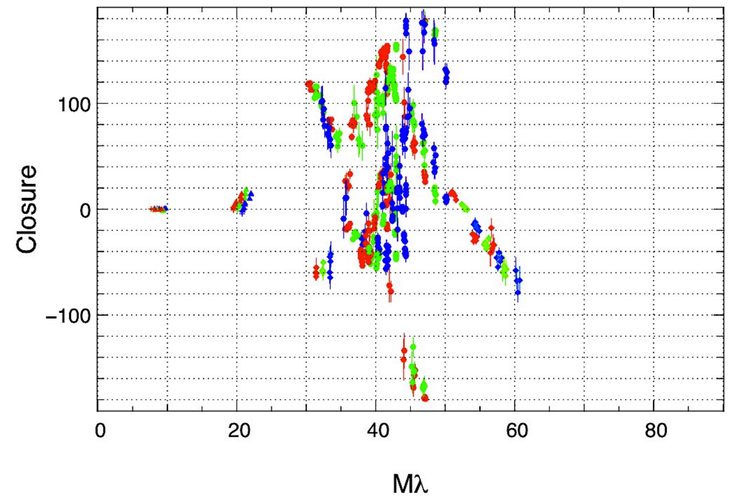


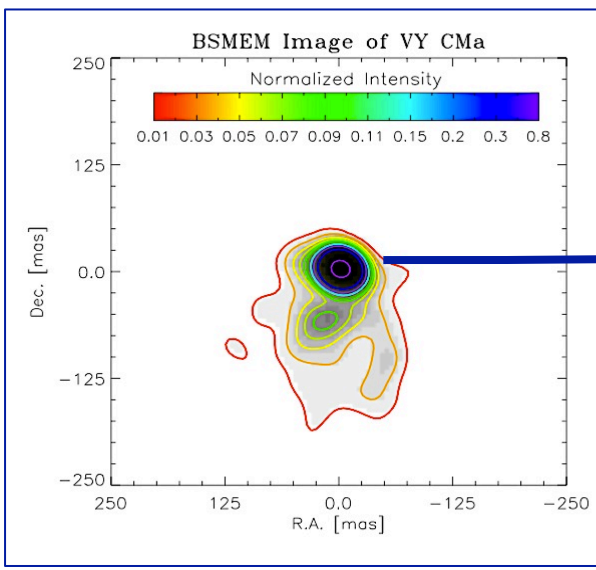


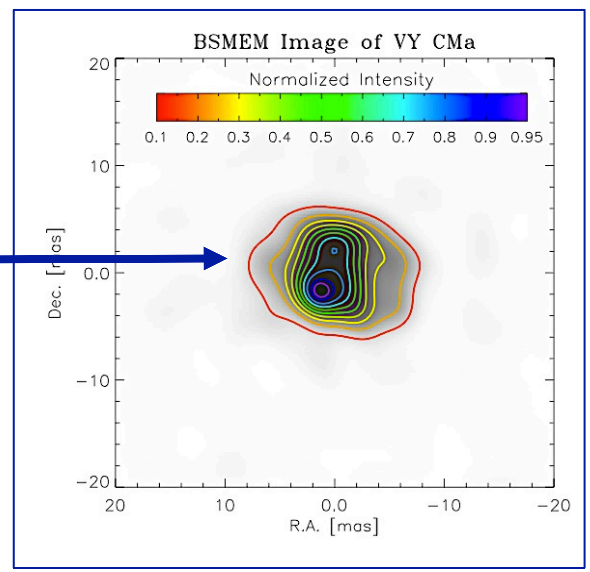
Sanchez-Bermudez et al., 2014

The Beauty Contest









W I N N E R S

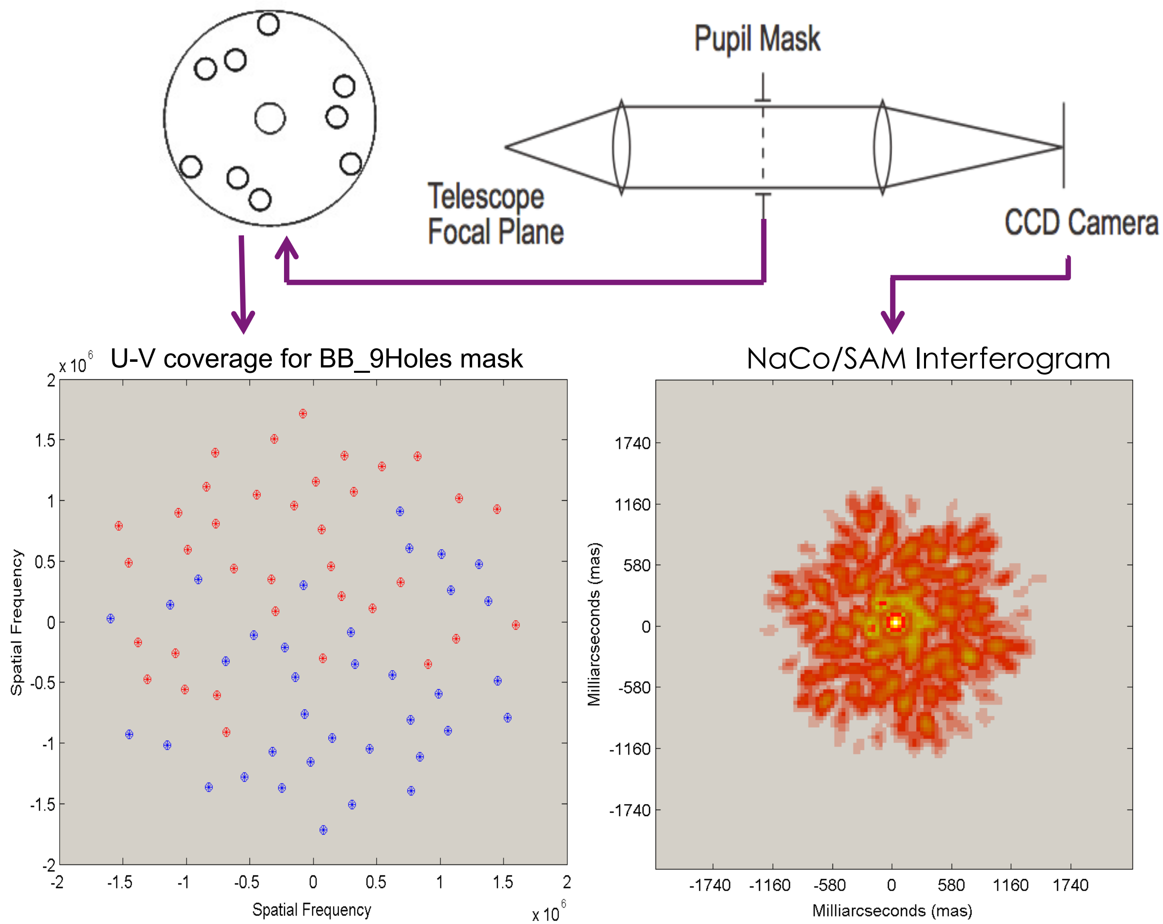
Monnier et al., 2014

Sparse aperture masking interferometry

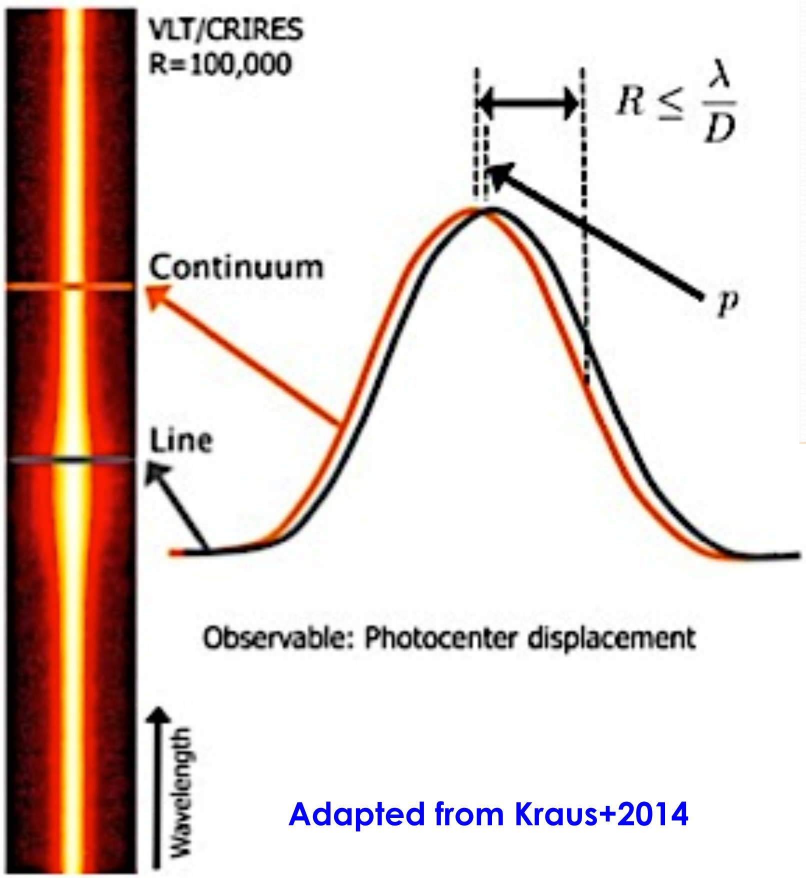
SAM Interferometry Characteristics:

- Well defined PSF calibration
- SAM cut-off most of the atmospheric noise signal
- The technique is constrained to bright sources
- SAM at VLT is suitable for sources with 4-12 mag
- SAM at VLT offers 4 masks.

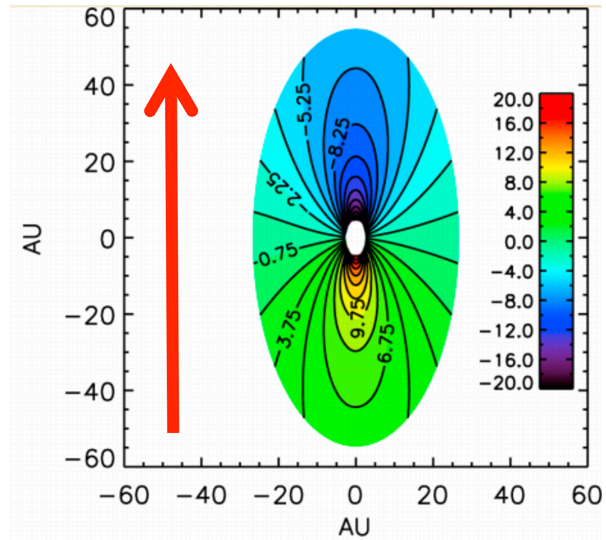
$$\theta \approx \frac{\lambda}{2D} \rightarrow$$ **Resolution**



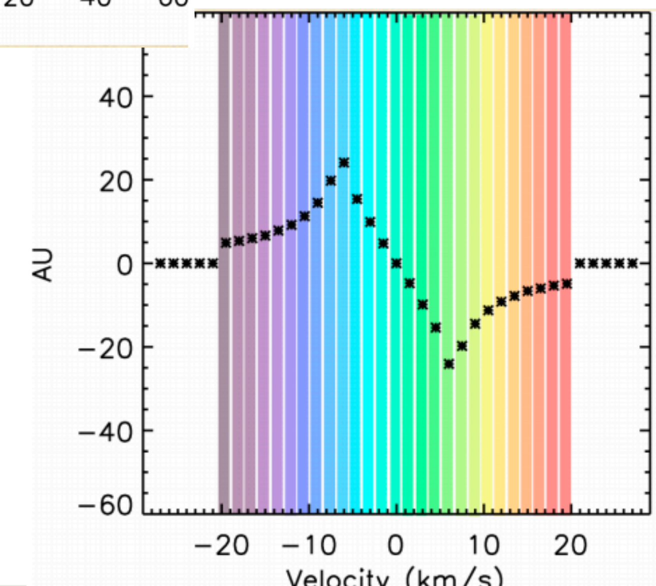
Spectroastrometry



Adapted from Kraus+2014



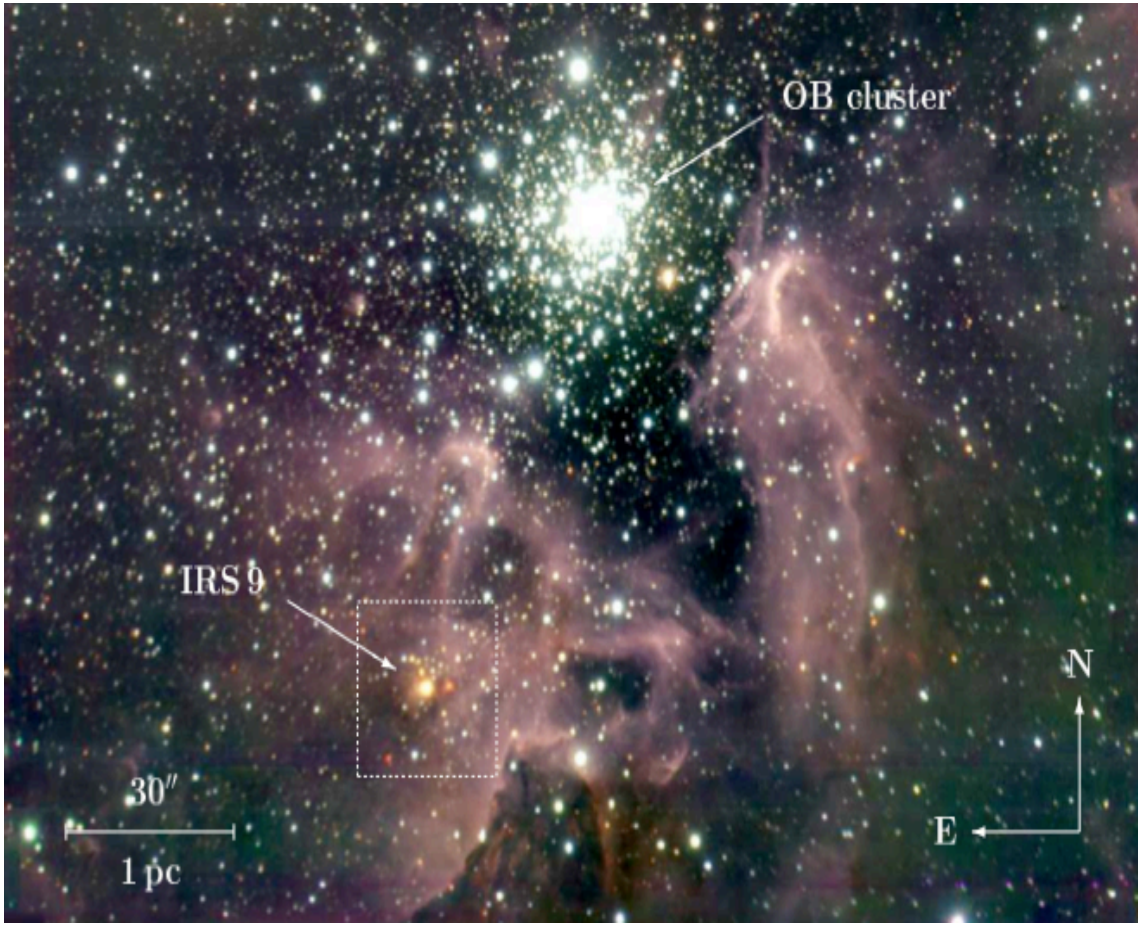
Adapted from Troutman+2009



Massive stars at their early stages (NGC3603 IRS9A)

IRS9A in context:

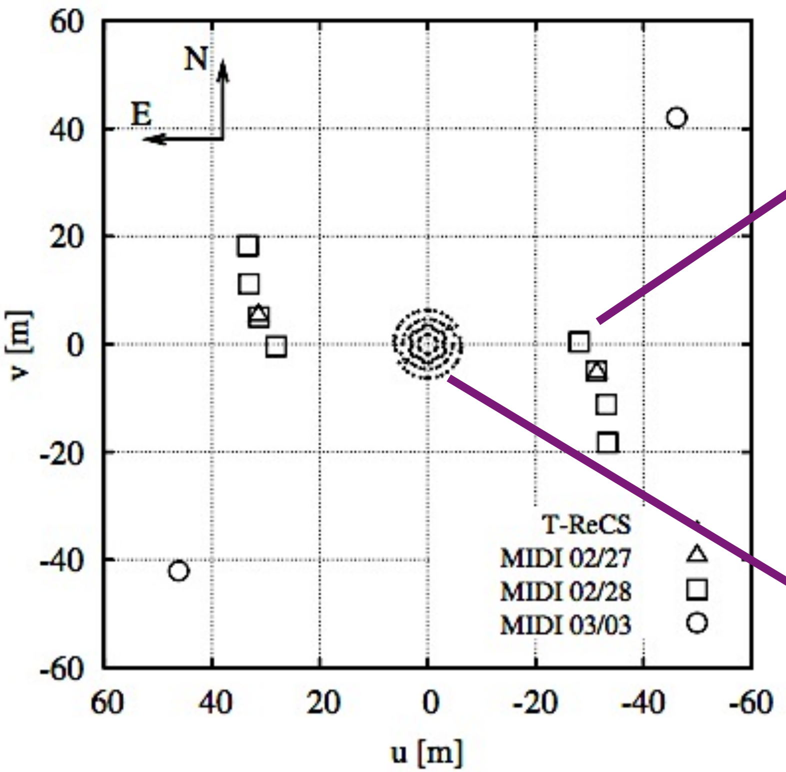
- Very luminous source ($2.3 \times 10^5\ L_\odot$)
- Spectral index $\alpha_{2.2\text{-}10\,\mu m}=1.37$
- Mass: 30-40 $M_\odot$
- Extinction: 4-5 mag

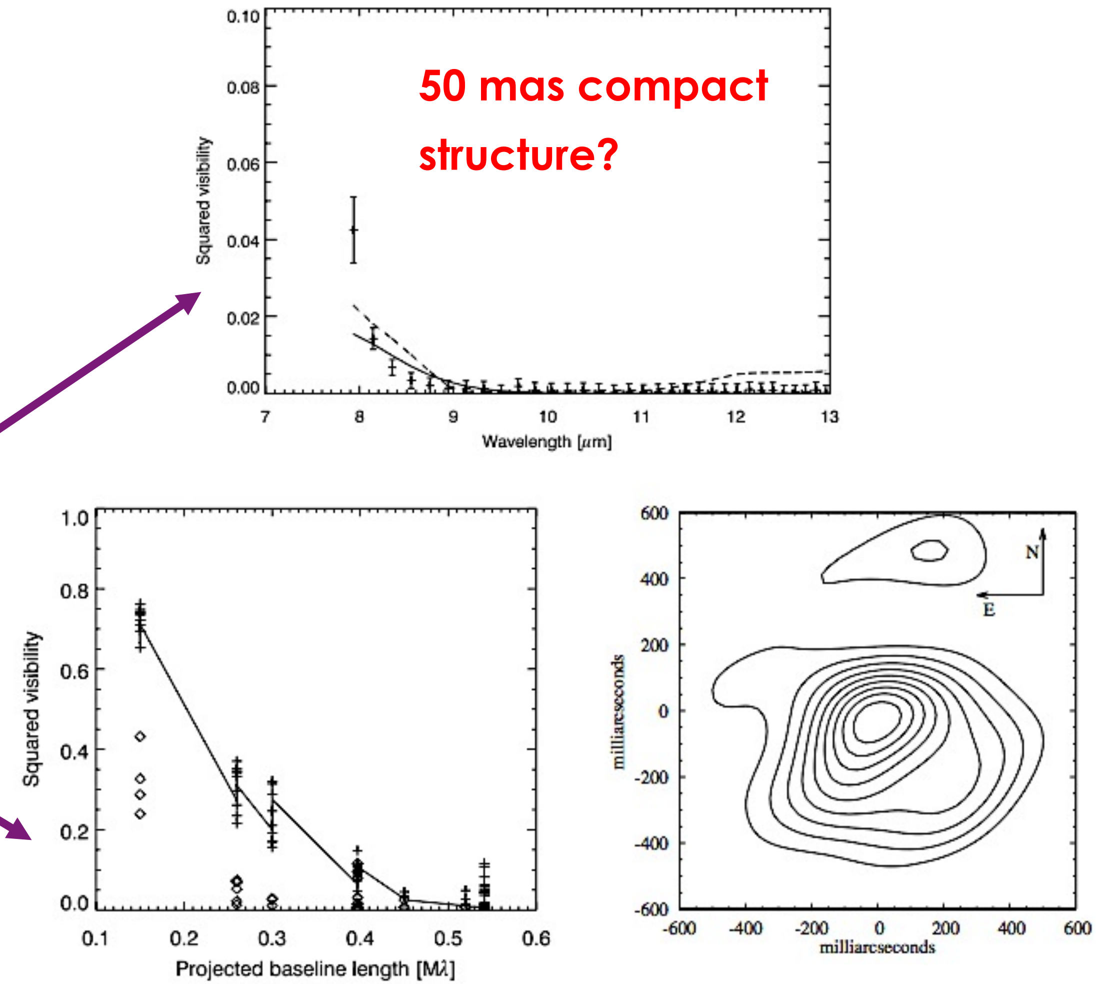


Mid-infrared interferometric observations of IRS9A

MID-IR Observations:

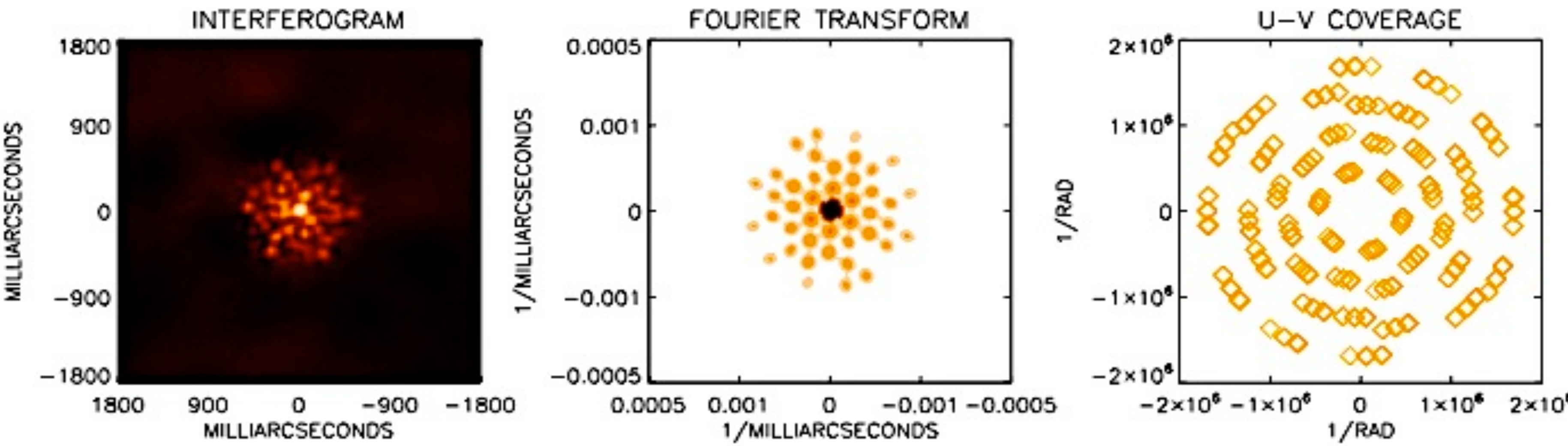
- MIDI (9-13 μm)
- T-ReCS (11.7 μm)





Vehoff et al., 2010

Near-infrared interferometric observations



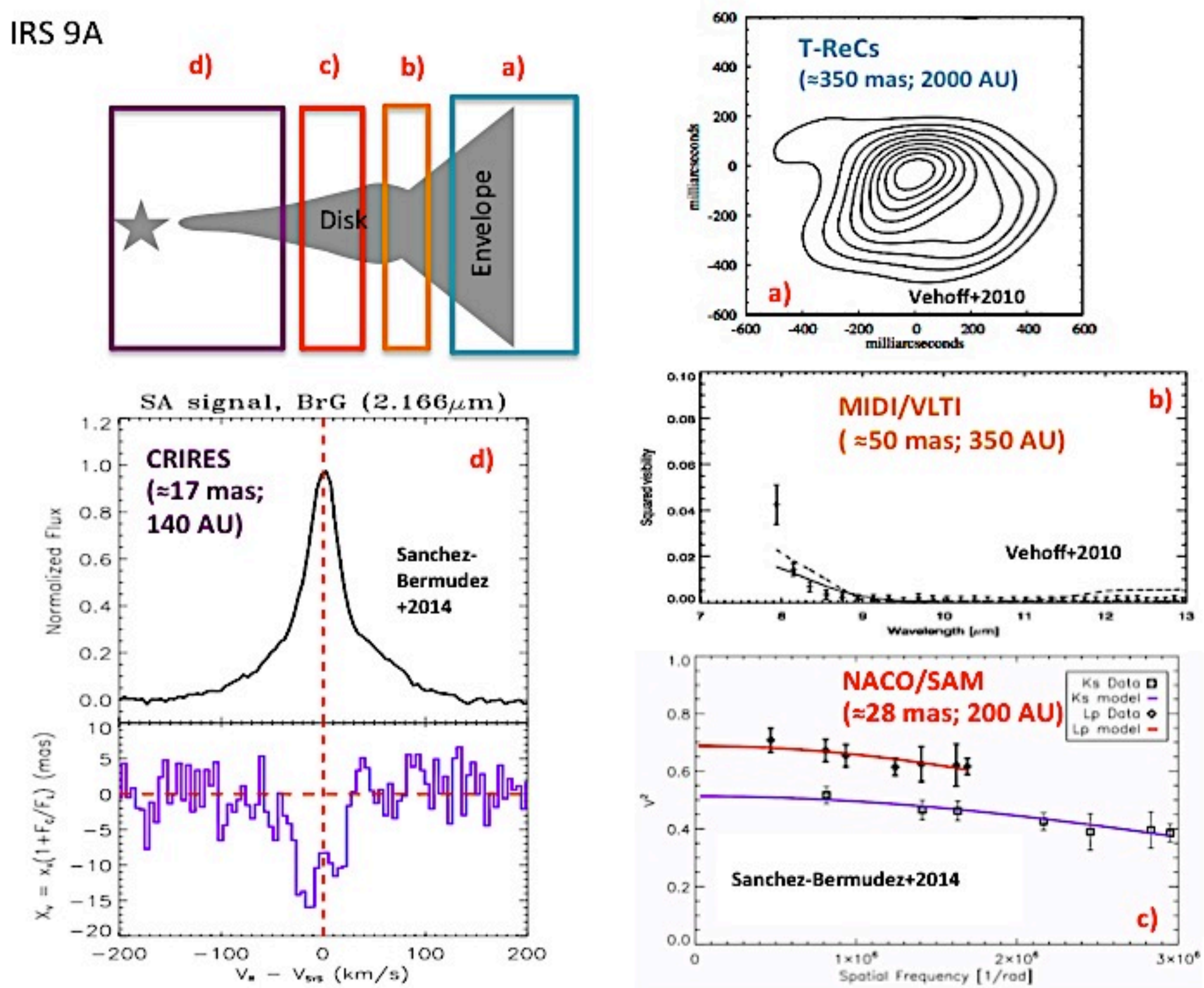
NACO setup:

- 7holes mask (faint object ≈ 9 mag)
- Ks, Lp and M
- Standard SCI-CAL-SCI sequence
- Cube mode/pupil tracking
- NDIT=50seg

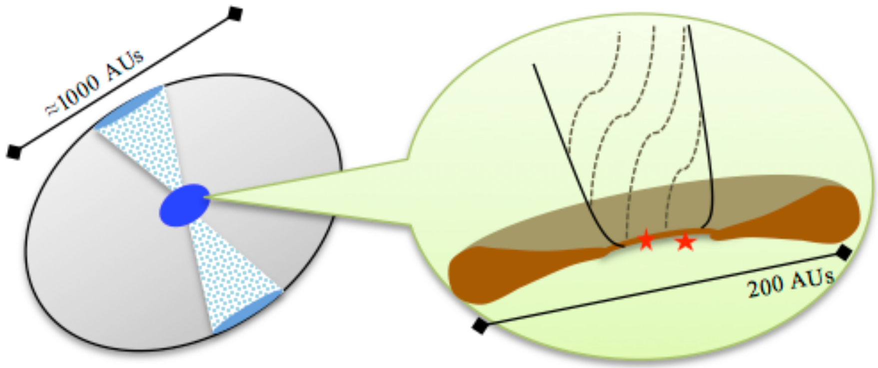
CRIRES setup:

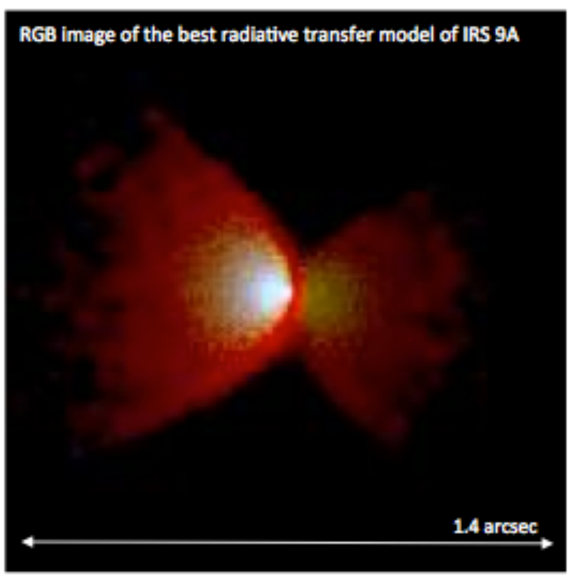
- H2 (2.121 μm) and BrG (2.166 μm) emission lines
- 6" slit width; R≈33000; 1.5 km/s
- 3 position angles (0°, 90°, 128°)
- NDIT=60 seg
- Ks, Lp and M

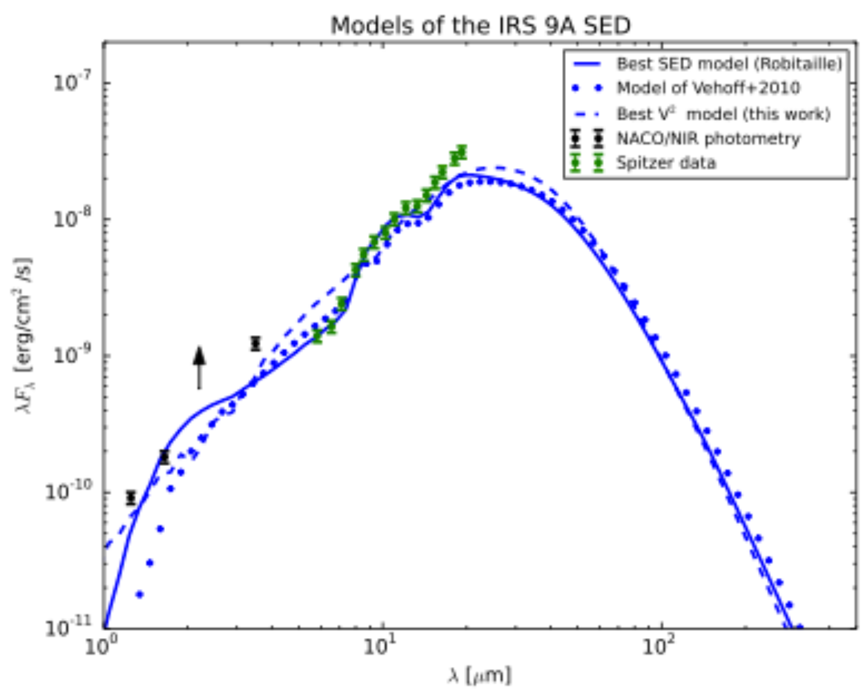
The morphology of IRS 9A



A complete view of IRS9A (1)

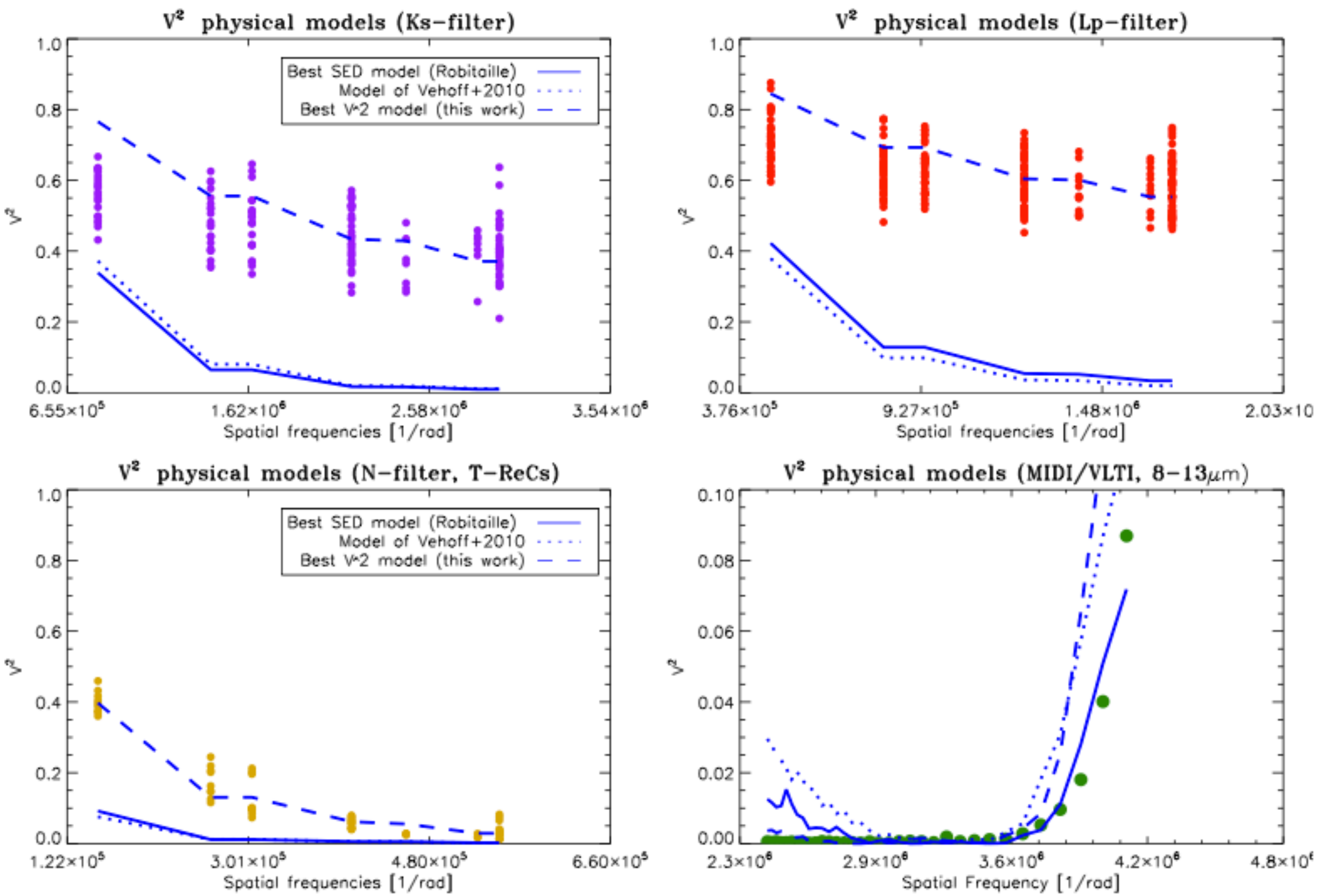




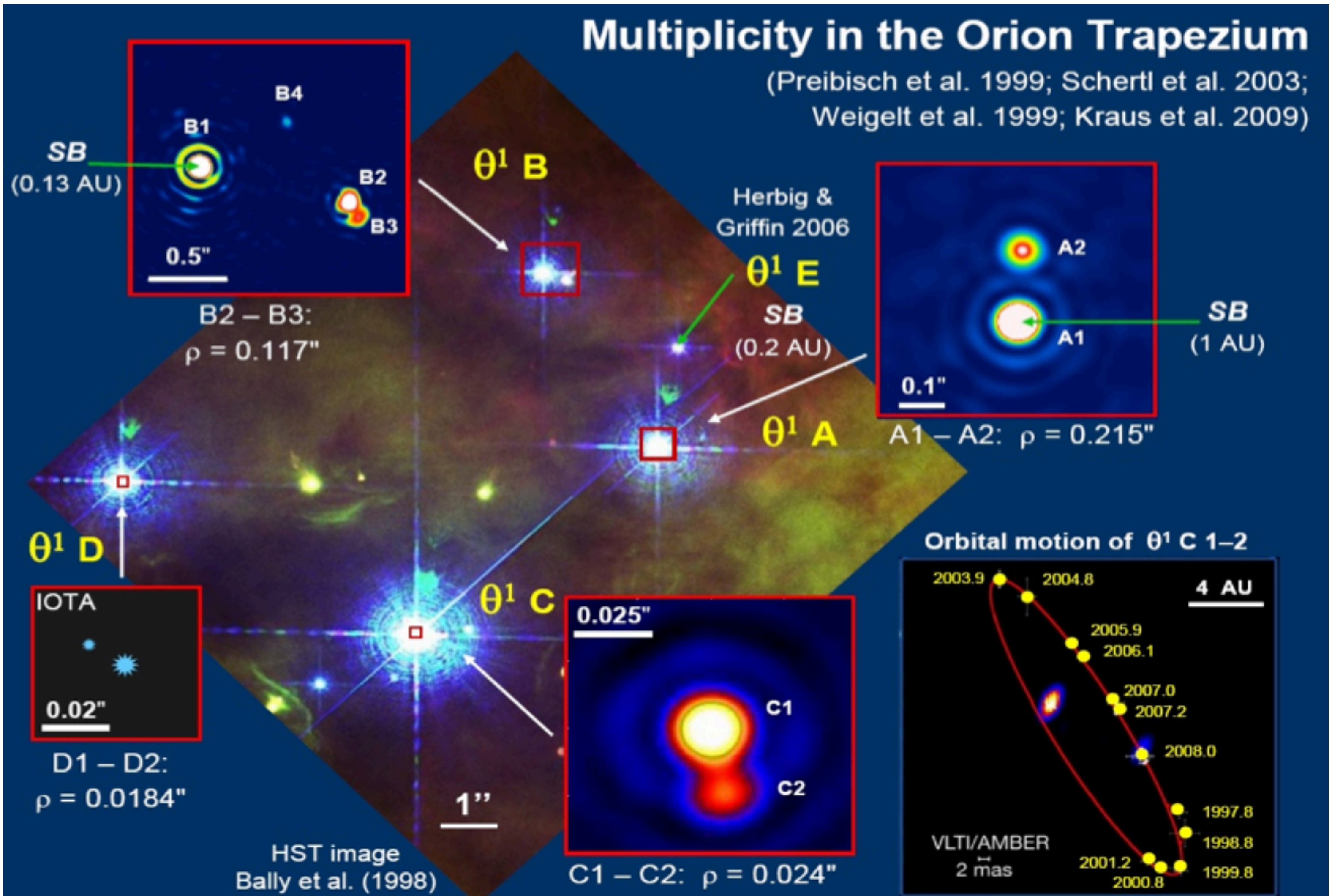


Sanchez-Bermudez et al., 2014c (in prep)

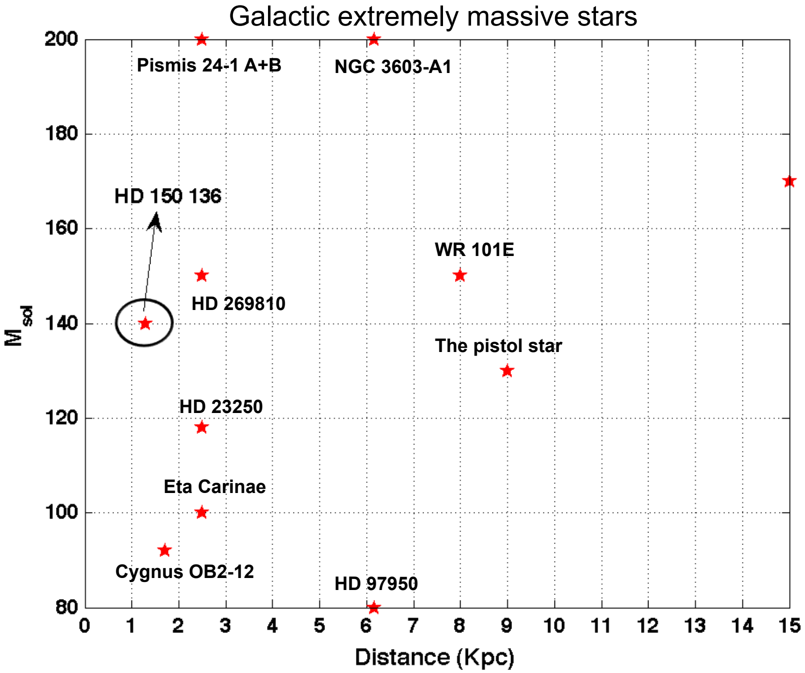
A complete view of IRS9A (2)

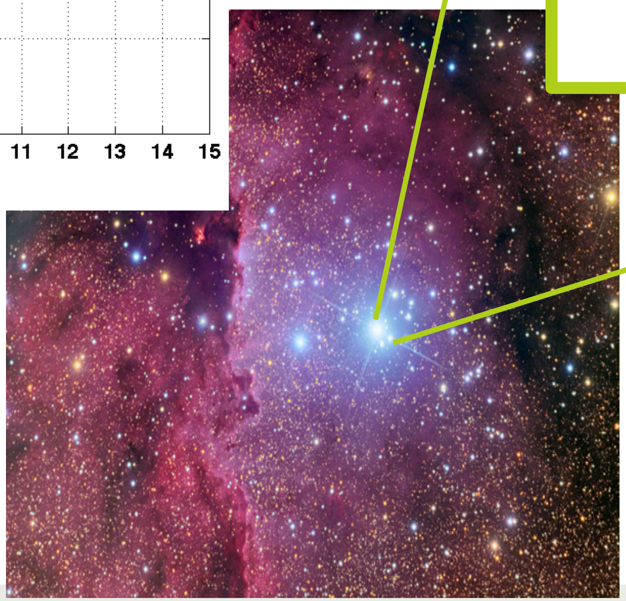


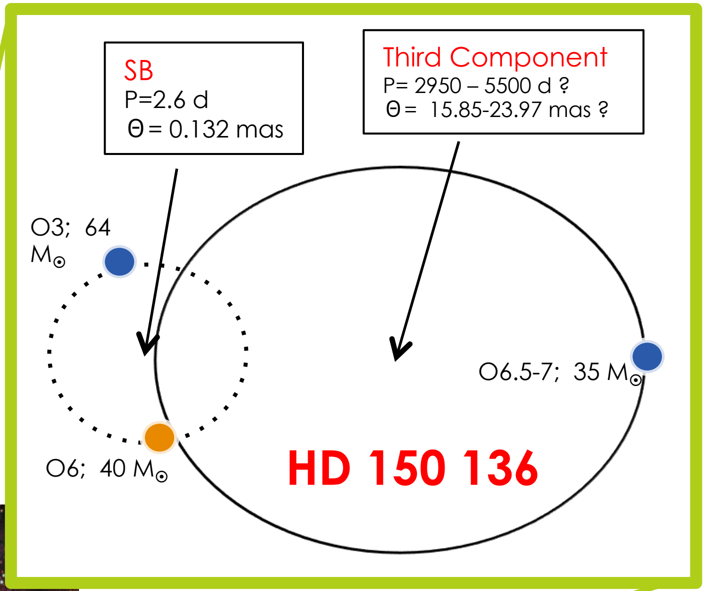
Multiplicity in massive stars



Multiplicity (HD 150136)

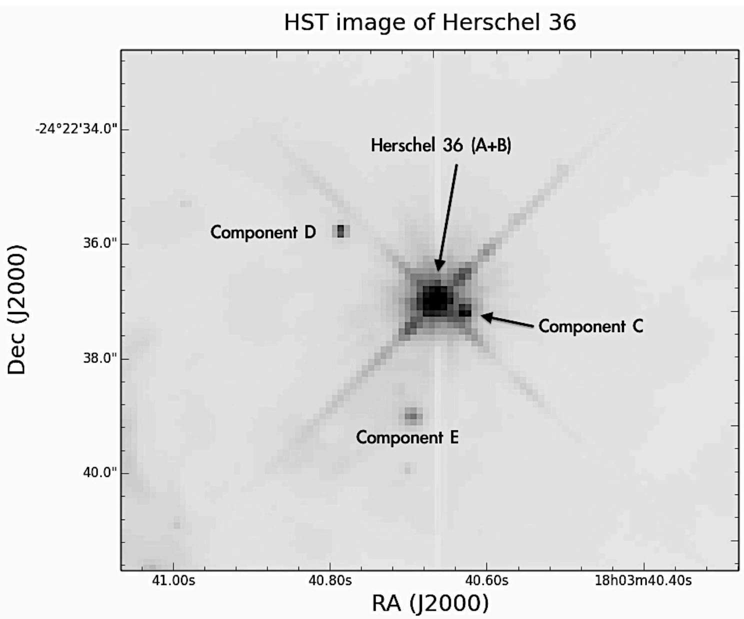


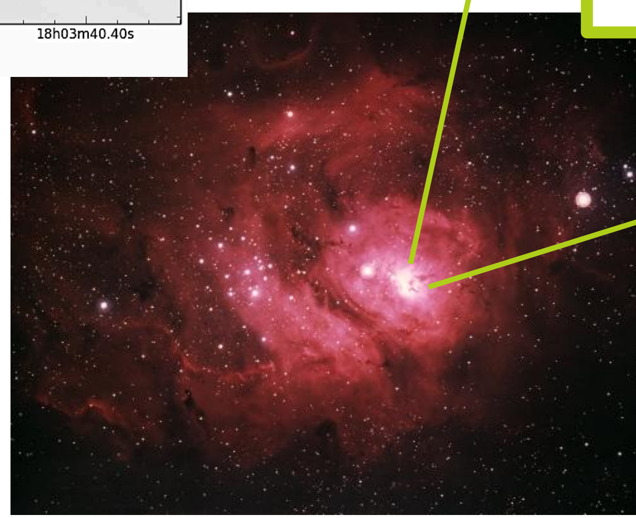


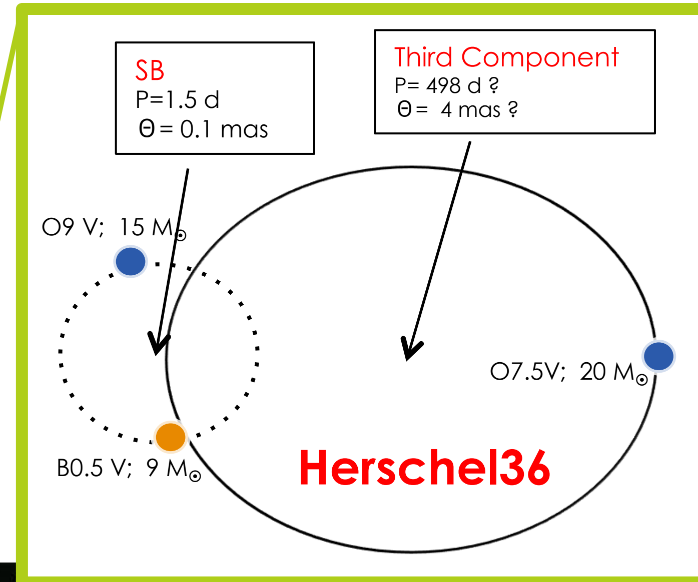


Sanchez-Bermudez+2013

Multiplicity (Herschel36)



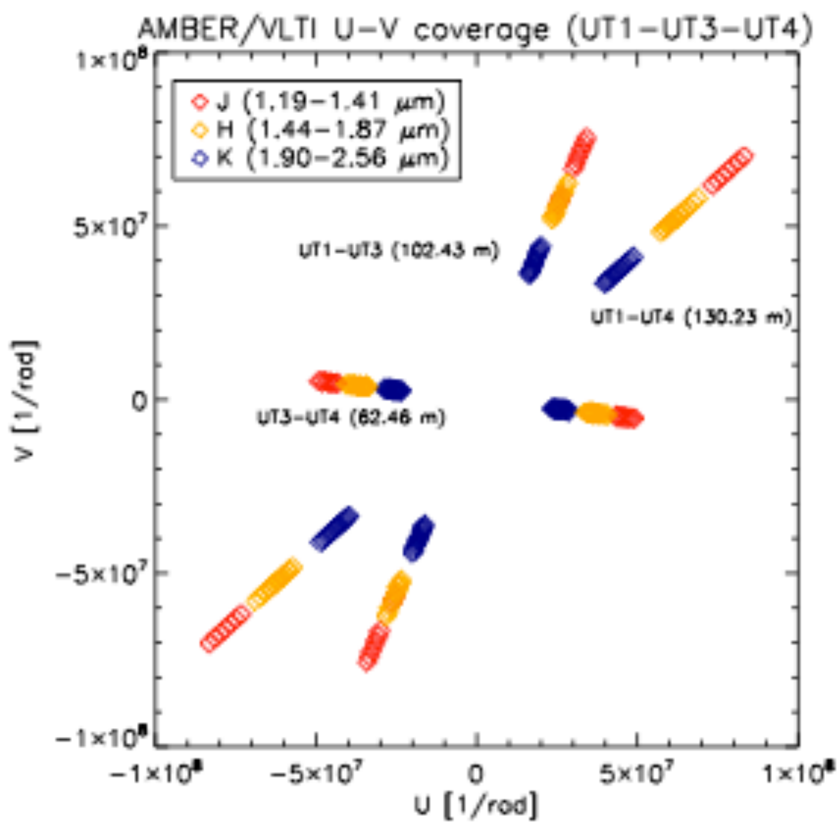


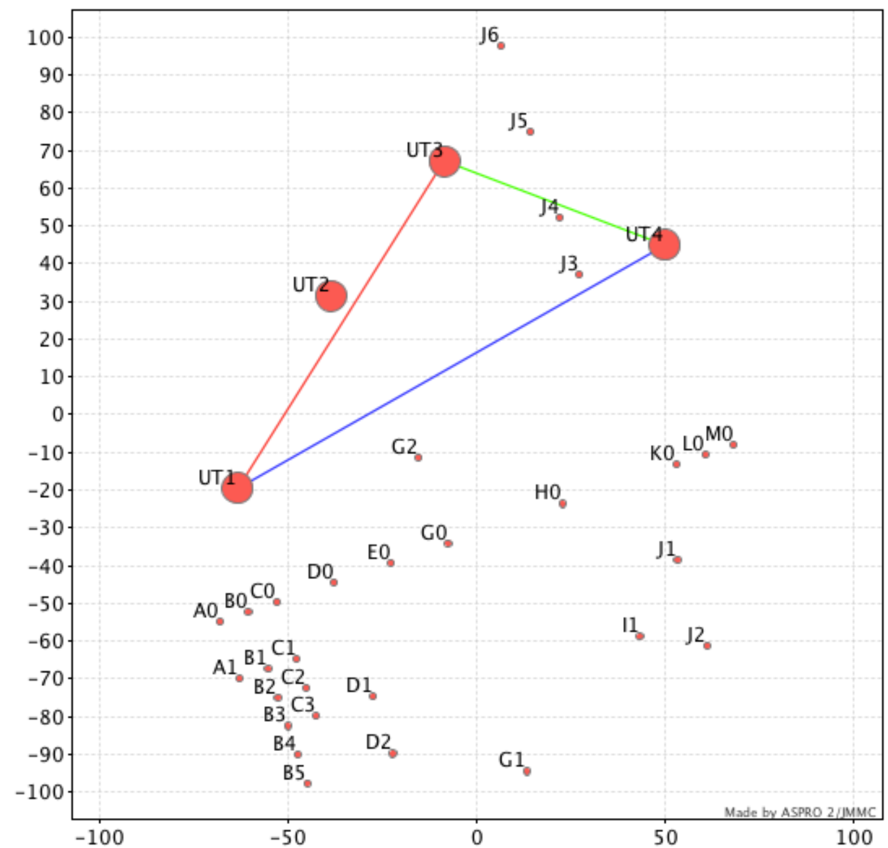


Sanchez-Bermudez et al., 2014b (submitted)

AMBER/VLTI observations (HD150136)

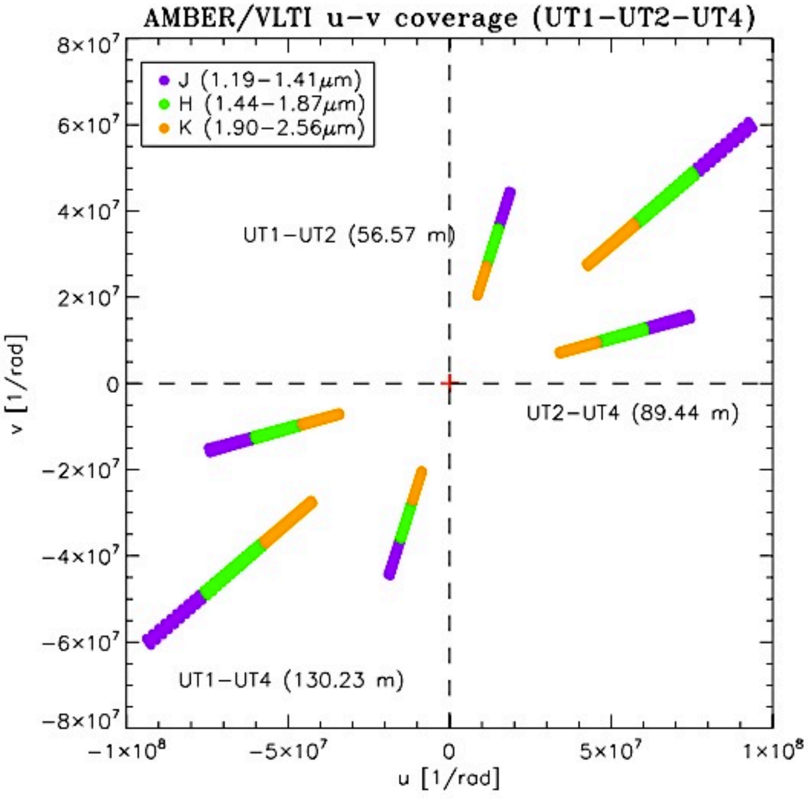
- 2 hrs in LR-JHK
- CAL-SCI-CAL

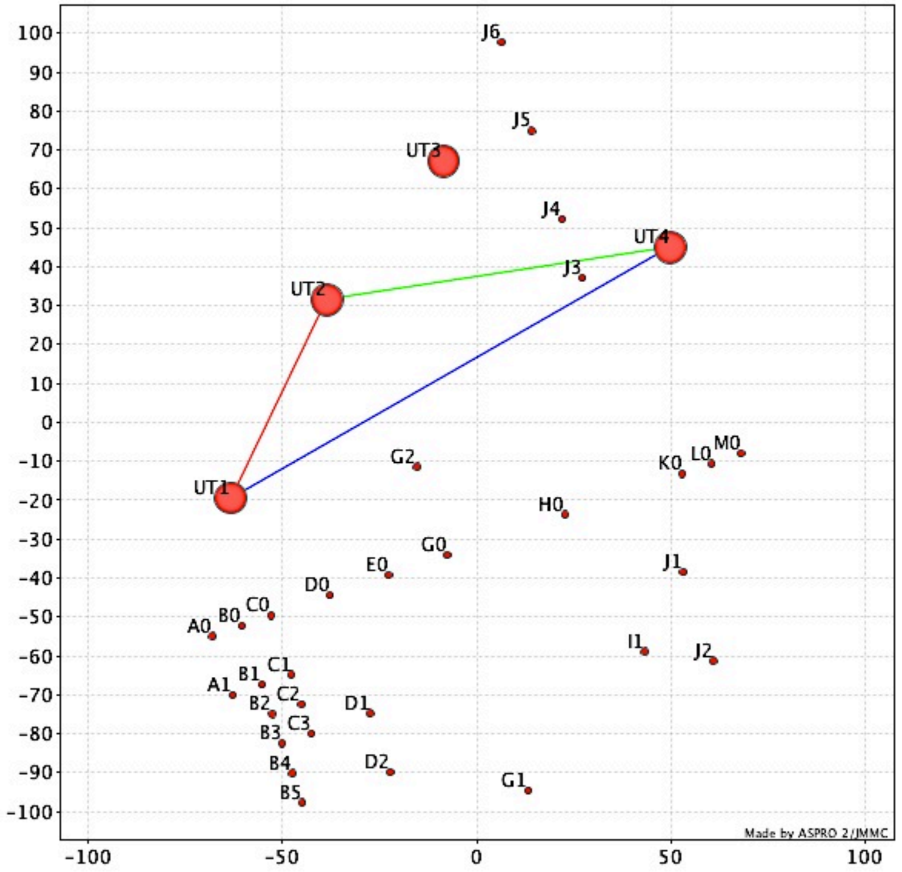




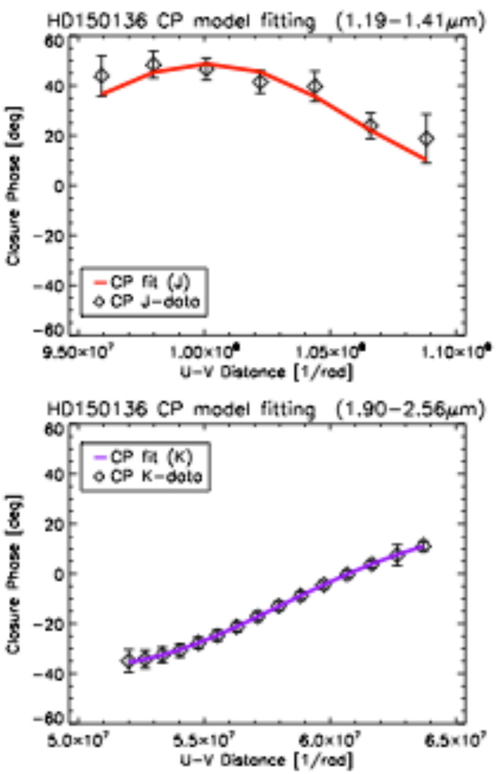
AMBER/VLTI observations (Herschel36)

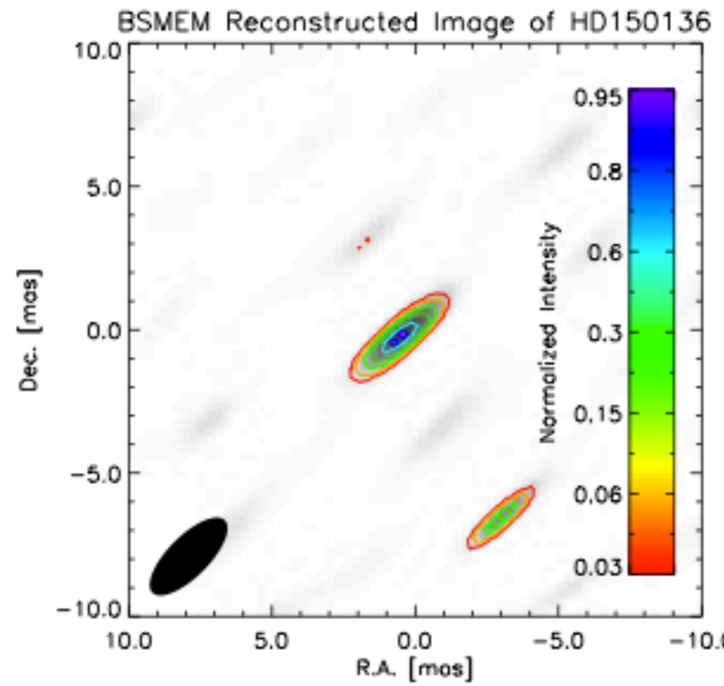
- 1 hrs in LR-JHK
- CAL-SCI-CAL



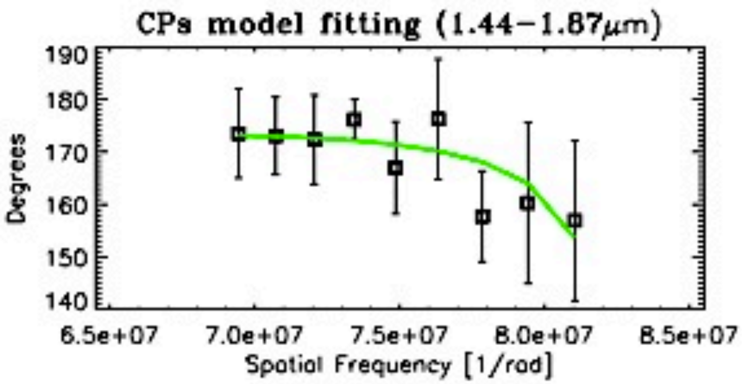


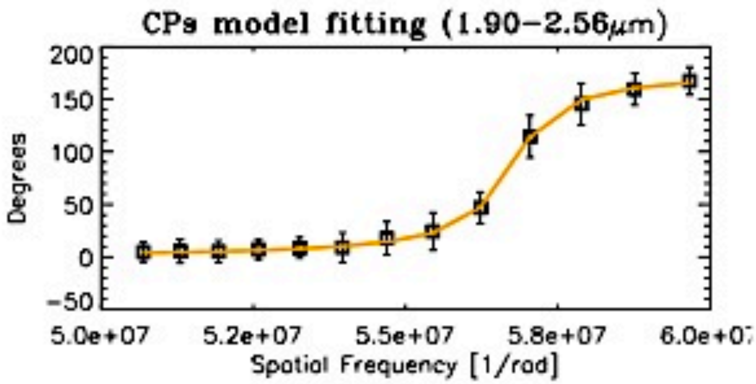
Results (HD 150136)

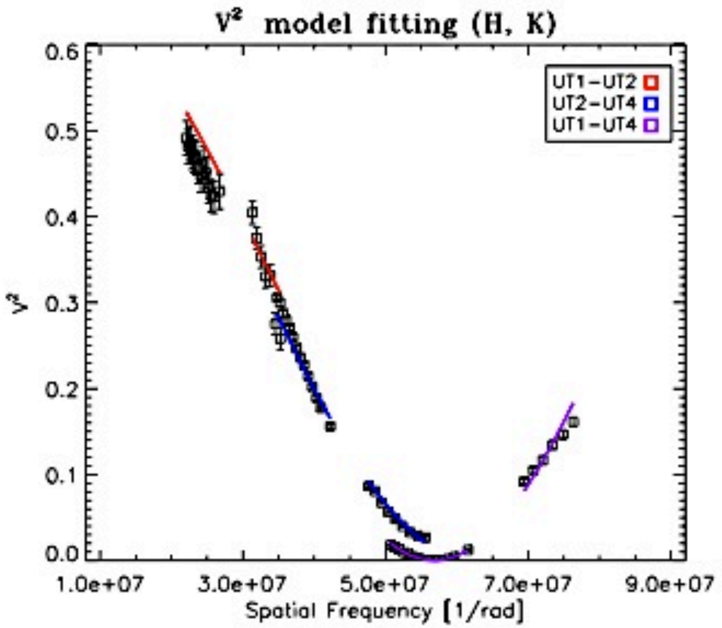


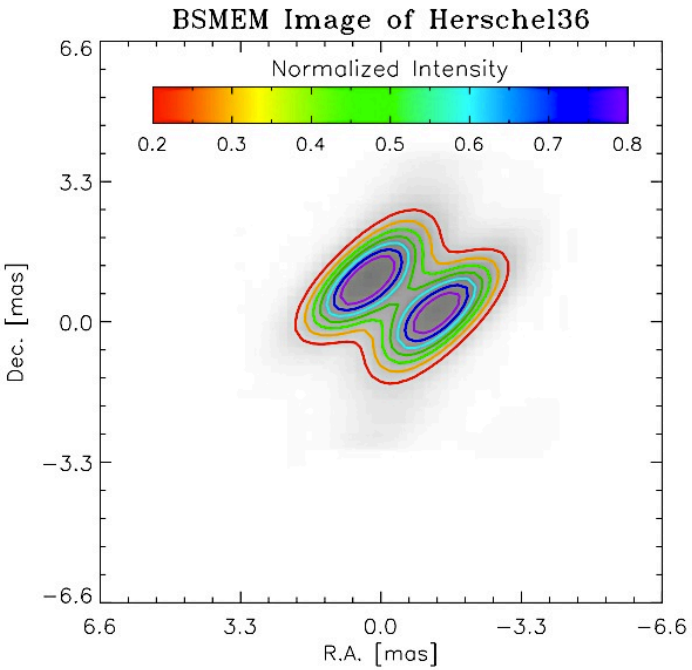


Results (Herschel36)





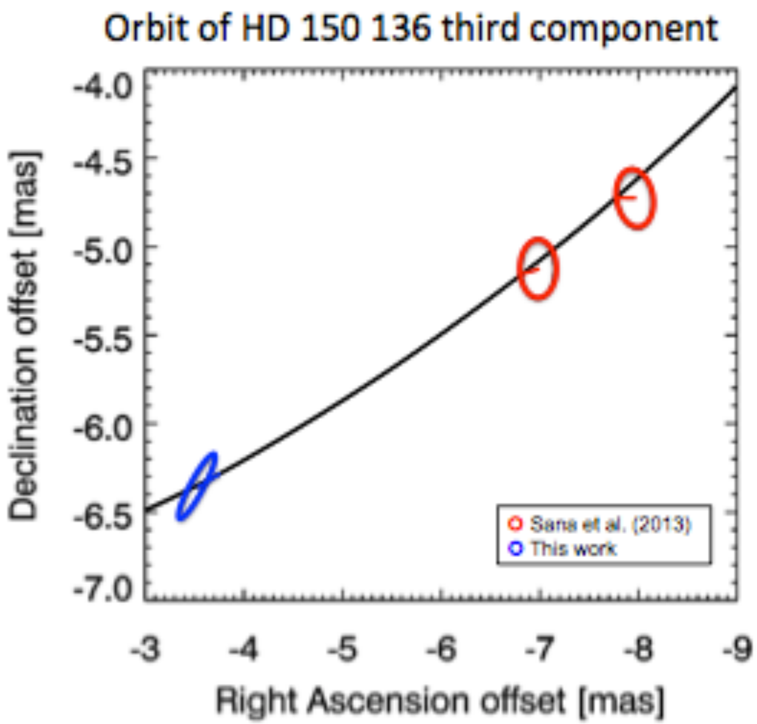


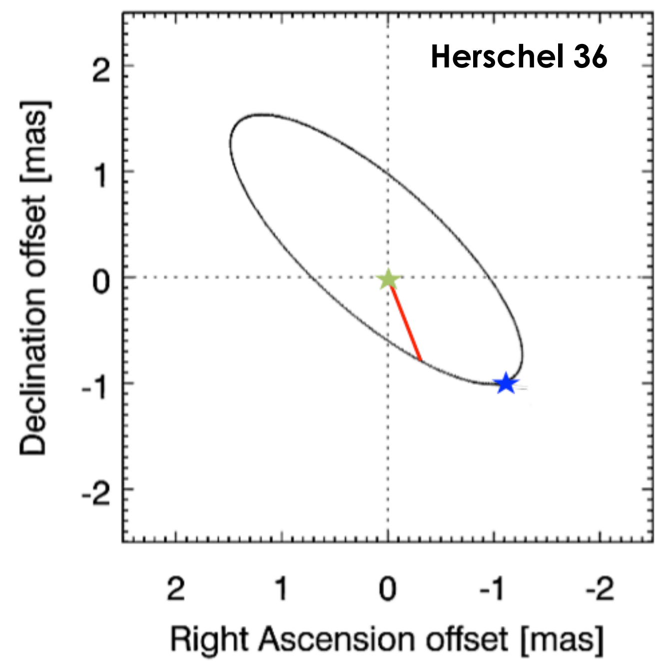


First estimate of the orbits

Parameter	Combined	J	H	K
f_{inner}[a]	0.80	0.78	0.80	0.82
f_T[b]	0.20	0.22	0.20	0.18
d [mas][c]	7.27	7.27	7.19	7.19
Φ [deg][d]	209.0	210.2	206.7	210.7

Parameter	Combined	H	K	1-σ[f]
$f_{over-resolved}$[a]	0.17	0.18	0.17	0.095
$f_{SystemB}$[b]	0.42	0.42	0.43	0.12
f_A[c]	0.41	0.40	0.40	0.12
d [mas][d]	1.82	1.80	1.81	0.03
Φ [deg][e]	234.0	214.8	217.0	10.5





To keep in mind

- Massive stars have strong impact to their surroundings.
- Our understanding of their formation and evolution is still sketchy.
- Observations of massive stars are challenging.
- VLTI has the best angular resolution to study massive stars at near and mid infrared wavelengths.
- Interferometric observations provide us unique information of some of the most important aspect of massive stars (e.g. imaging binaries, circumstellar disks, envelopes).
- The second generation of VLTI instruments will improve imaging capabilities and sensitivity (2-5 mag), opening new opportunities to study more massive stellar systems.