The multiplicity of young OB stars revealed by interferometry

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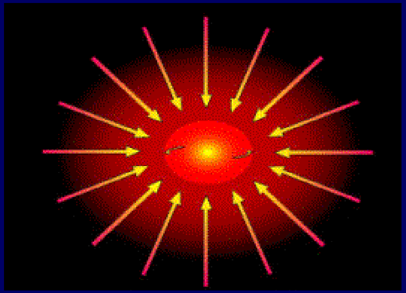
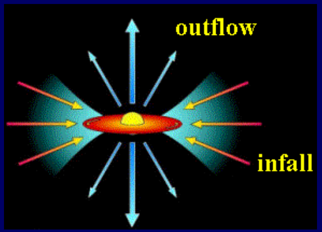
How to form high-mass stars ?

- The well established picture of *low-mass star formation:*



monolithic collapse



disk accretion

- *High-mass star formation:* Problems:

1) No good evidence for massive pre-stellar cores

2) Dense packing of high-mass stars

3) Radiation pressure versus accretion

4) No good evidence for disks around massive protostars

suggest fundamental differences to low-mass stars formation scenario.

Bonnell, Bate, et al: **Stellar interactions in massive star formation**

1) Competitive accretion

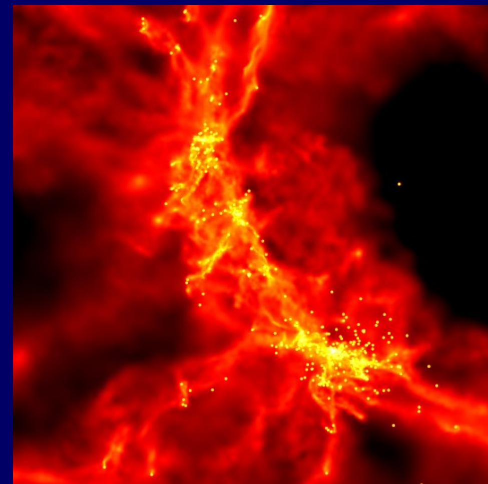
2) Cluster contraction

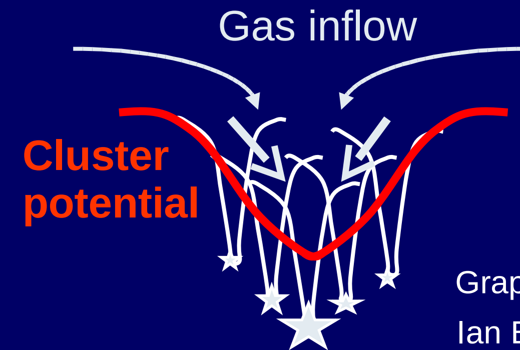
→ very high densities

$n \geq 10^7$ stars pc^{-3}

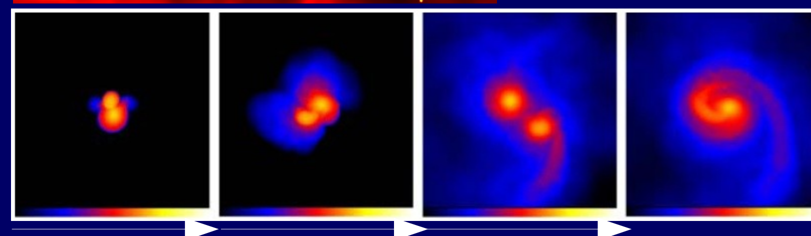
3) Proto-stellar collisions, captures & mergers

→ ***High multiplicity of massive stars***



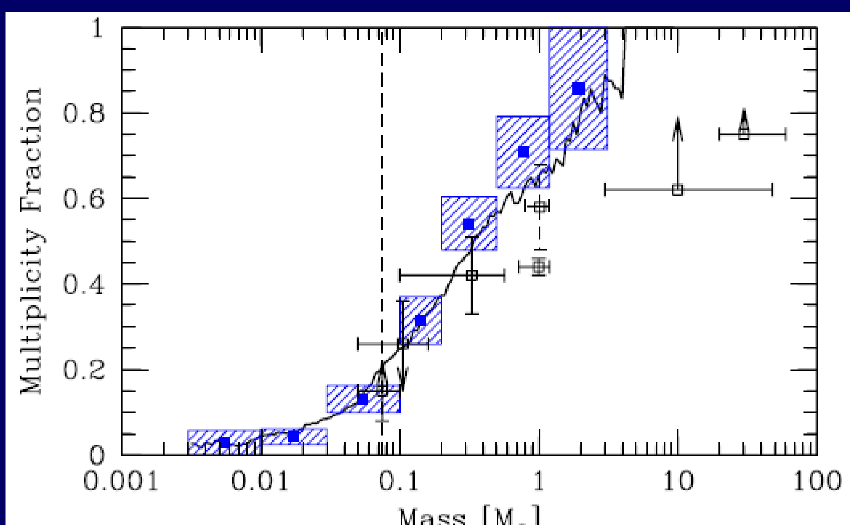


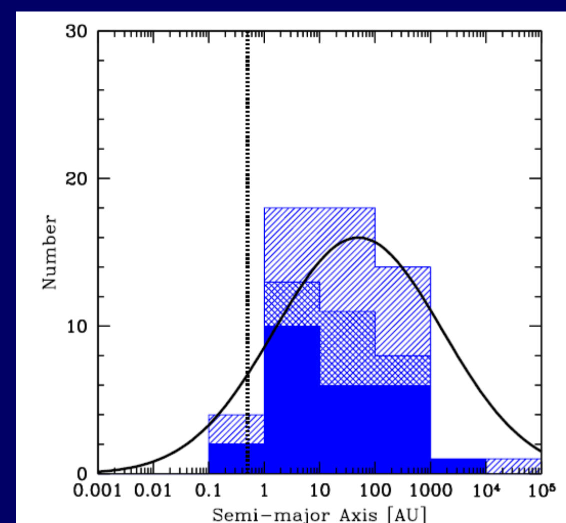
Graphic by Ian Bonnell



Davies et al. 2006, MNRAS 370,2038

close binary



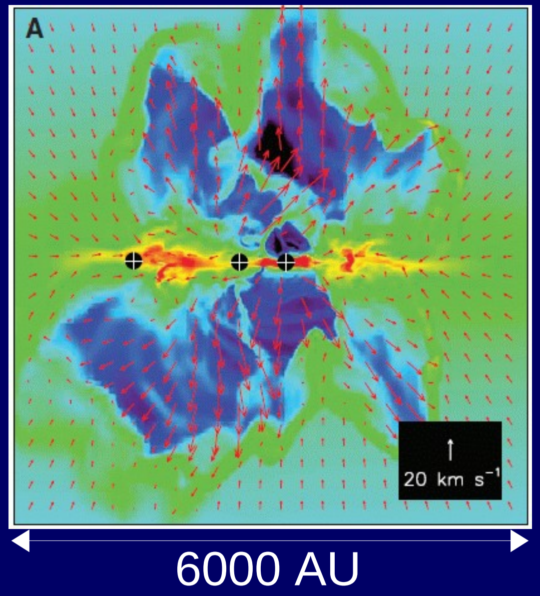


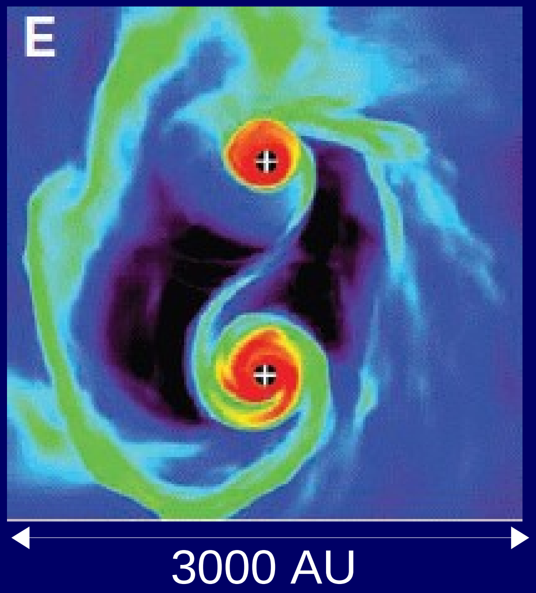
Bate 2011: arXiv:1110:1092 500 $M_\odot$ cloud → ~ 200 stars

Different Model: Krumholz et al. 2009, Science 323,754

Formation of massive stars by accretion

$M = 100\ M_\odot$
$r = 0.1$ pc
cloud core



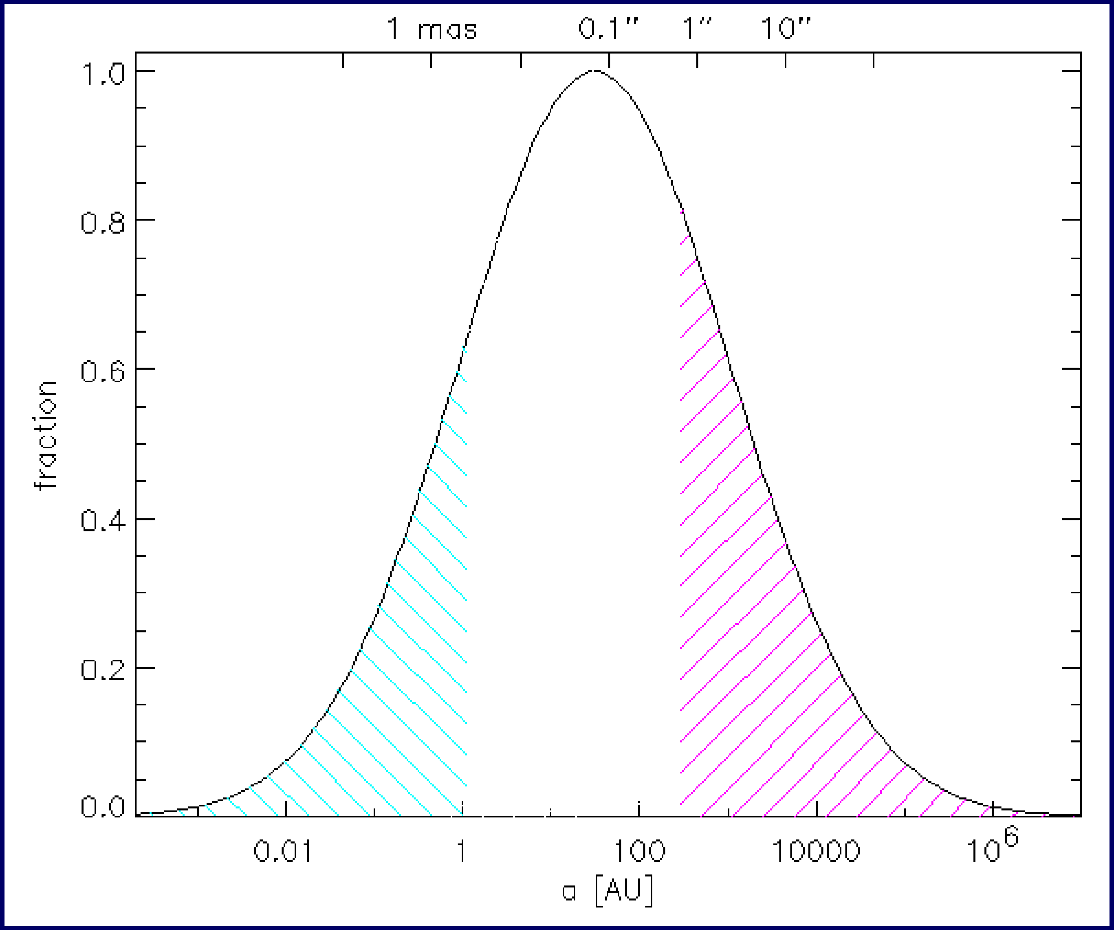


→ wide binaries
a > 600 AU

Observational information on the multiplicity of massive stars can provide very important constraints for the different theoretical models of massive star formation.

Orbit Distribution

@ ~ 450 pc



15%

20%

Detection Methods

Visual companions

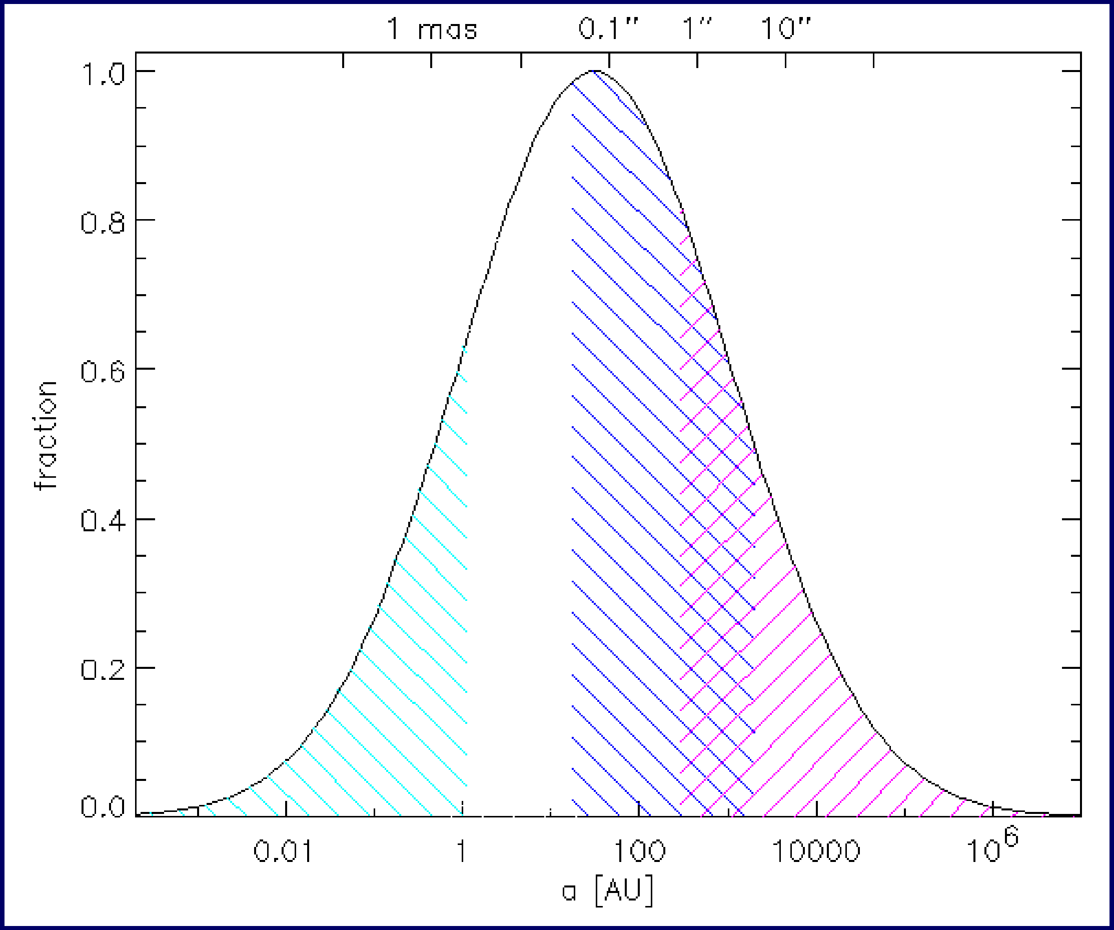
seeing limit ~ 0.5" ... 1"

Spectroscopic companions

mostly $P_{orbit} \leq 1$ yr

Orbit Distribution

@ ~ 450 pc



15%   40%   20%

Detection Methods

Visual companions

seeing limit ~ 0.5" ... 1"

Spectroscopic companions

mostly $P_{orbit} \leq 1$ yr

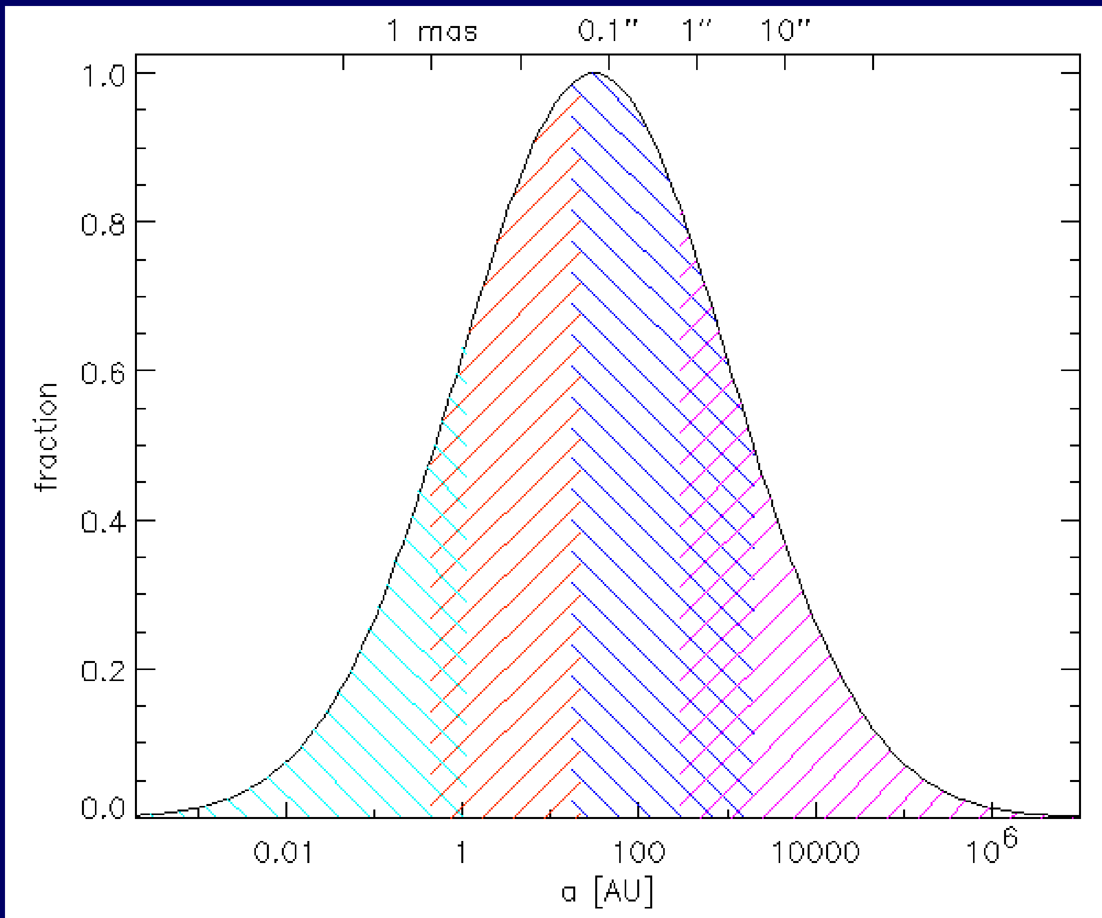
Speckle / Adaptive Optics

diffraction limit ≈ 0.04"

(for λ= 1.2 μm, D = 6 m)

Orbit Distribution

@ ~ 450 pc



15% 30% 40% 20%

Detection Methods

Visual companions

seeing limit ~ 0.5" ... 1"

Spectroscopic companions

mostly $P_{orbit} \leq 1$ yr

Speckle / Adaptive Optics

diffraction limit ≈ 0.04"

(for λ= 1.2 µm, D = 6 m)

Long-baseline Interferometry

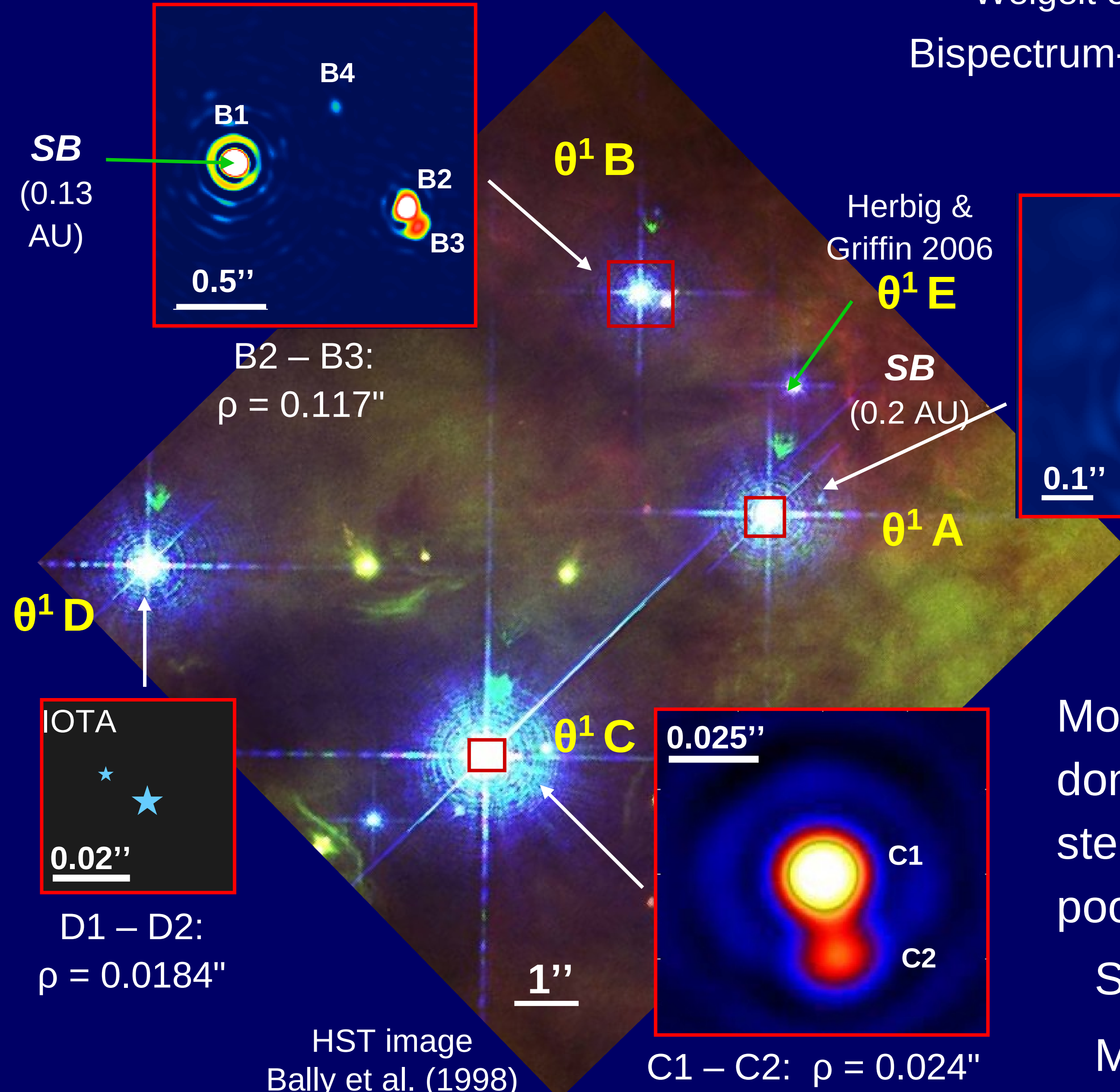
λ / B ≈ 0.002"

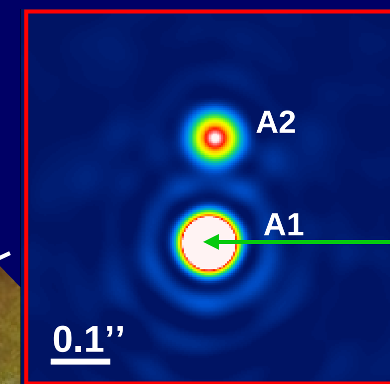
(for λ= 1.6 µm, B = 200 m)

Multiplicity in the Orion Trapezium

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

Bispectrum-Speckle Interferometry





SB
(1 AU)

A1 – A2:
ρ = 0.215"

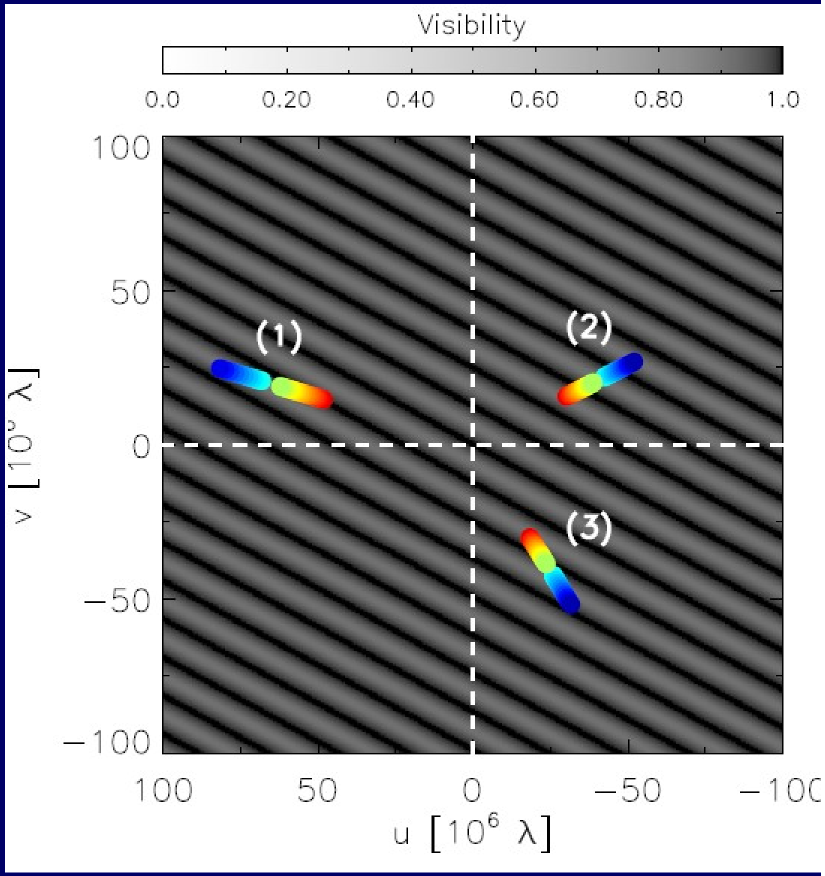
Most massive member; dominates UV output; stellar parameters only poorly known:

SpT ≈ O5 … O7

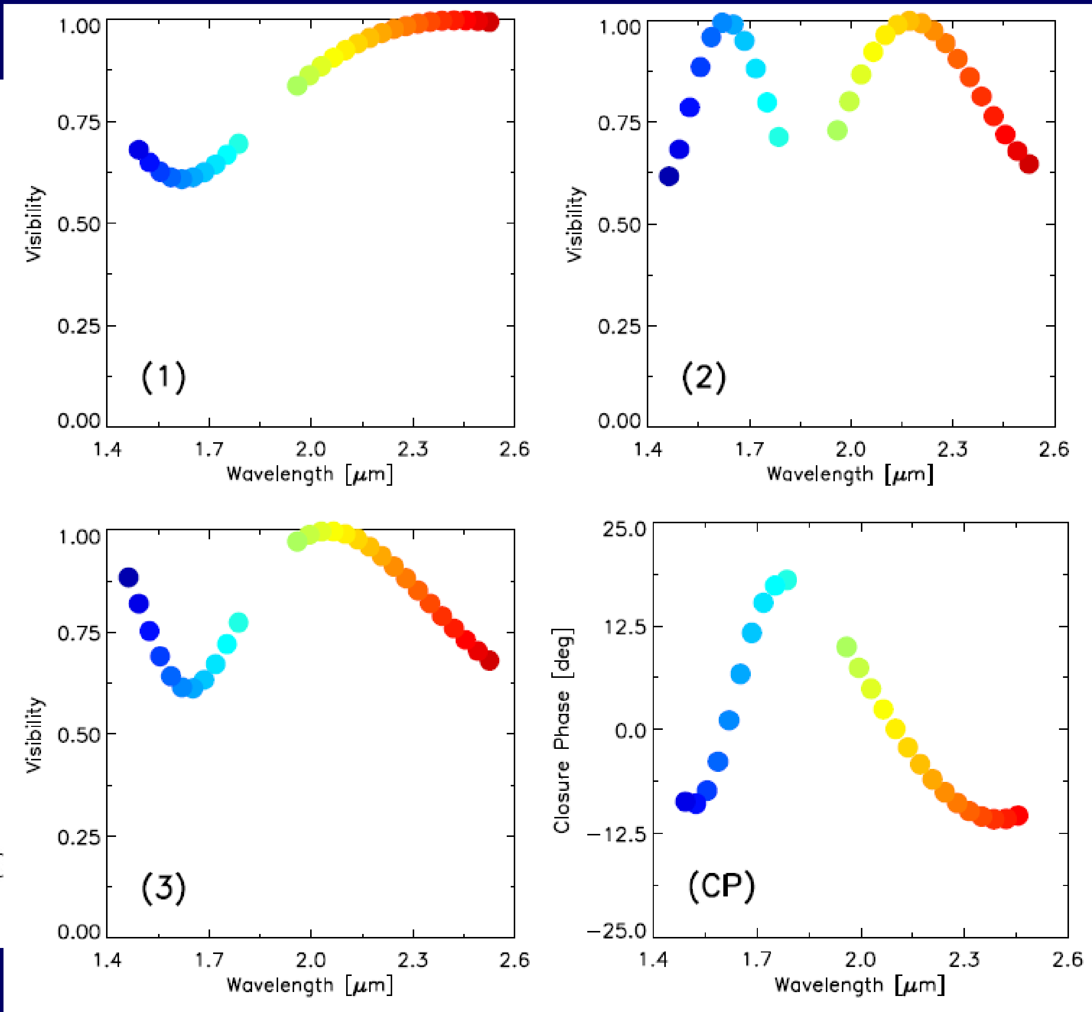
M ~ 30 … 60 $M_\odot$

Long-baseline Interferometry: Differential visibilities of binary systems

Model binary with ρ =19 mas and P.A. = 241 deg
observed with 3 telescopes in spectral channels from 1.4 μm to 2.4 μm

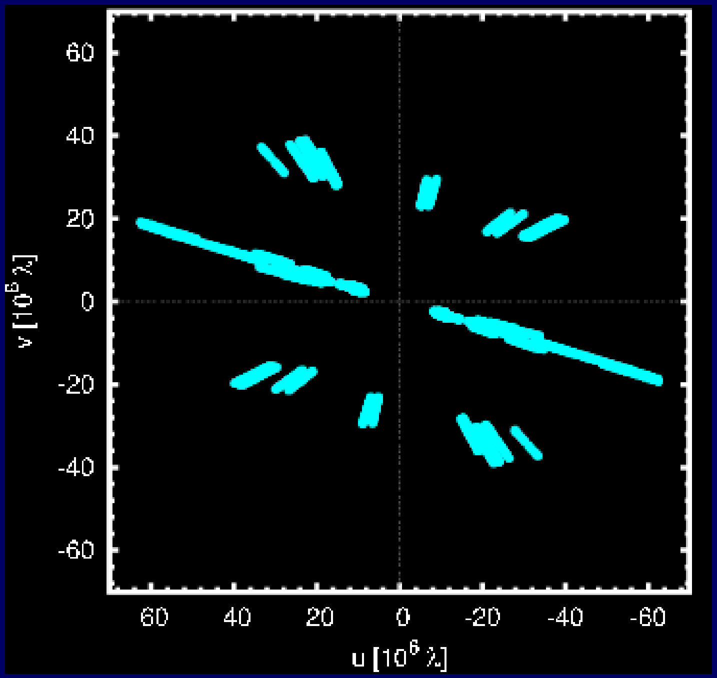


Sampling of the (u,v)-plane

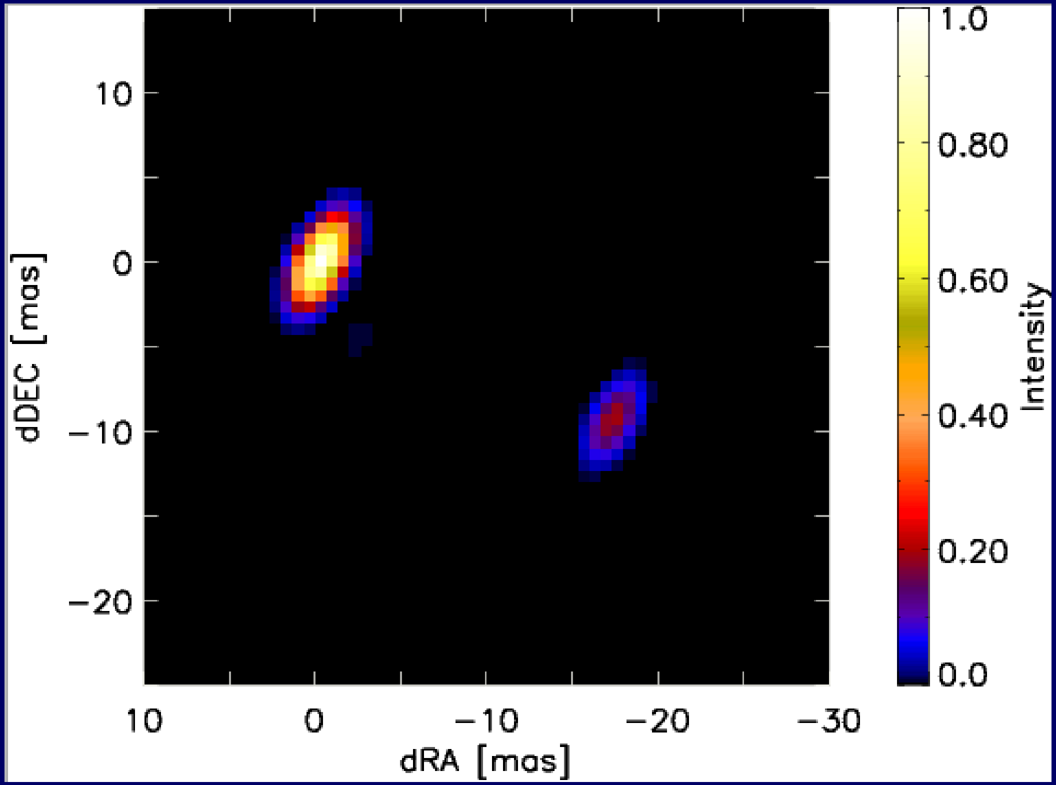


Expected wavelength variation of visibility

First aperture synthesis image reconstructed from AMBER data:



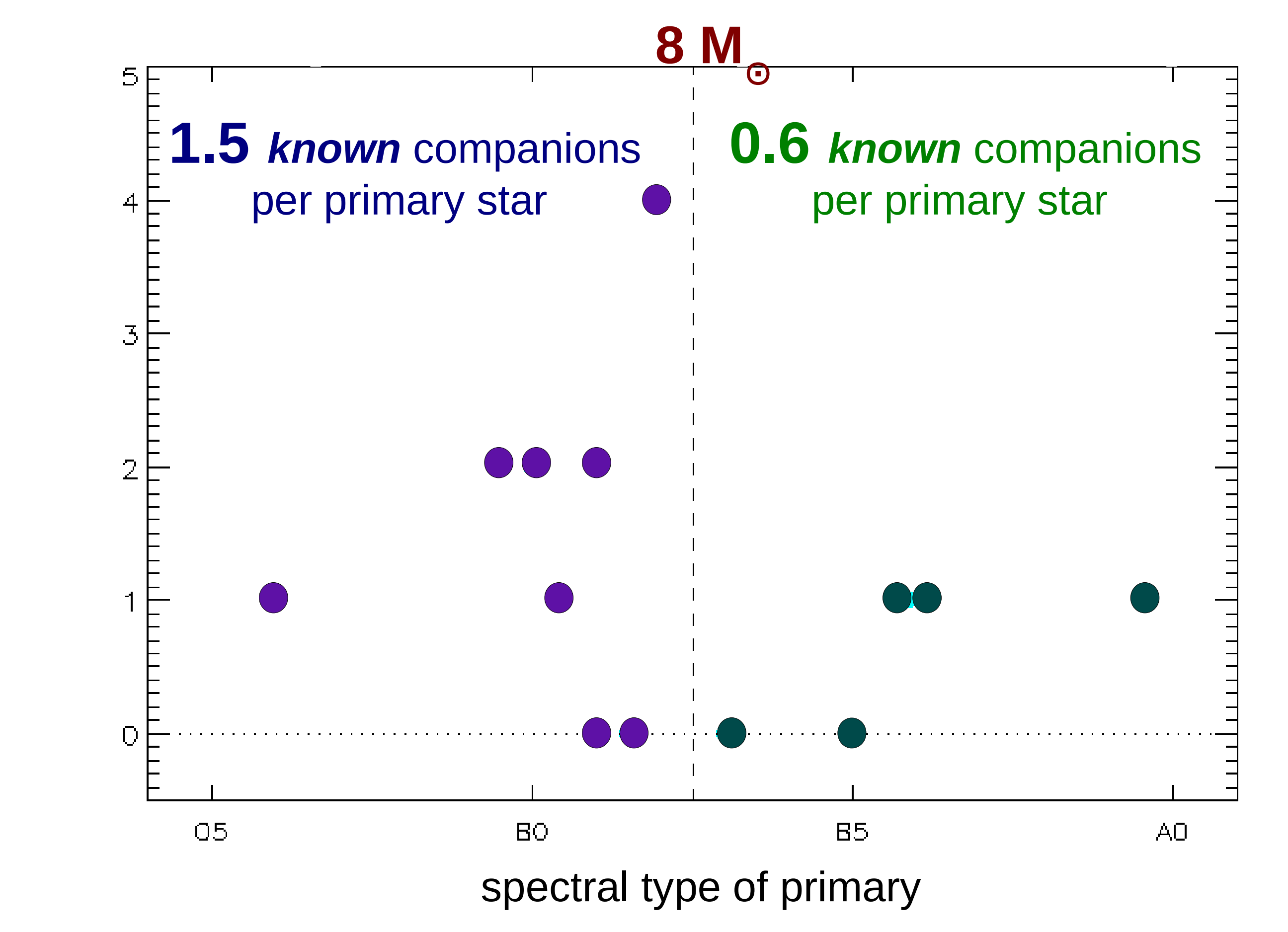
Kraus et al. 2009
A&A 497, 195



Binary star θ^1 C Ori
effective resolution ~ 2 mas

Multiplicity statistics

Multiplicity as a function of spectral type (stellar mass)



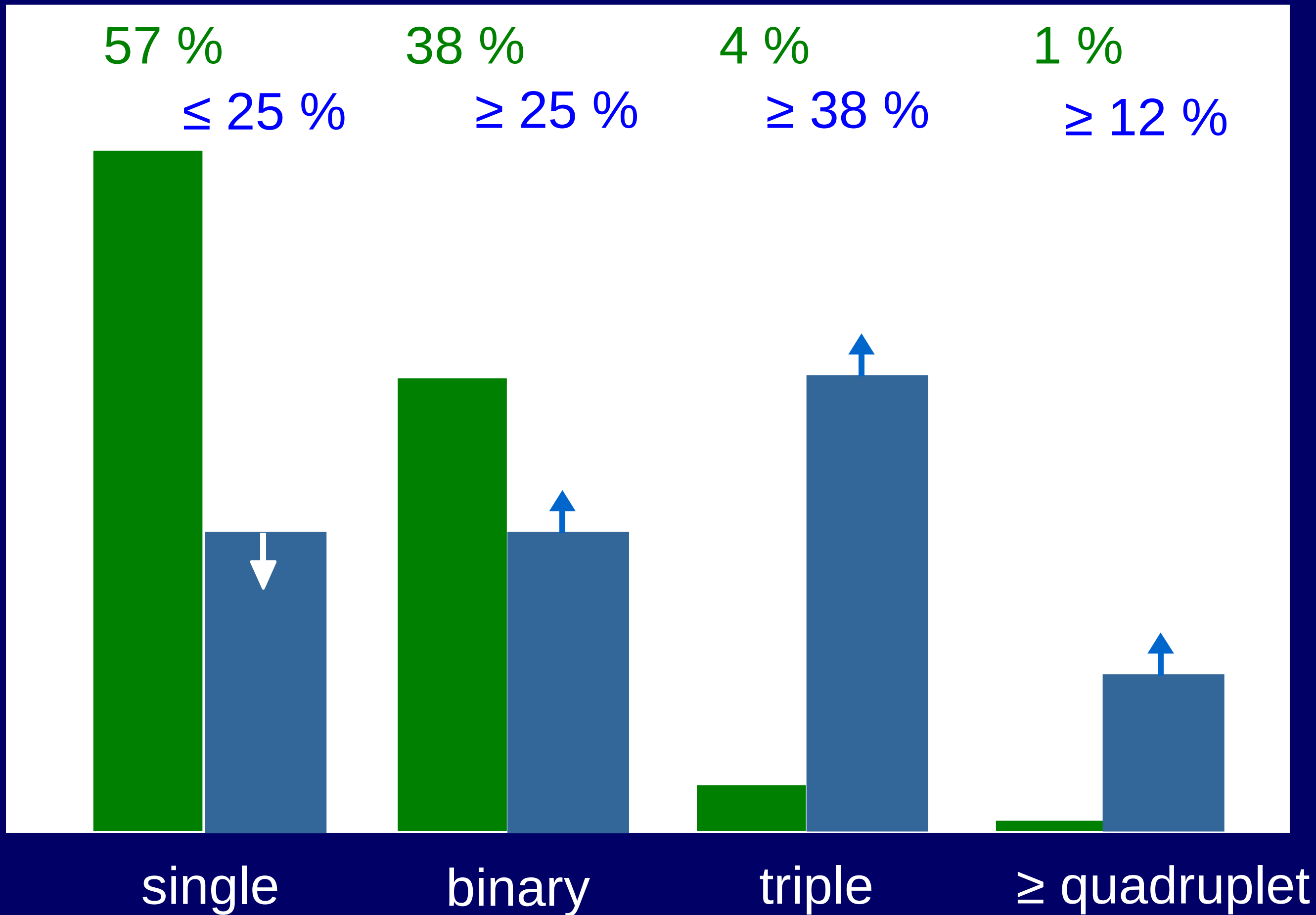
Low mass ONC stars:
~ 0.6 companions

Low mass field stars:
~ 0.6 companions

These numbers are ***strict lower limits***

→ high multiplicity of massive stars

Degree of multiplicity as a function of stellar mass



Massive ($\geq 8\ M_\odot$) ONC stars

solar-mass field stars

Duquennoy & Mayor 1991, AA 248,485

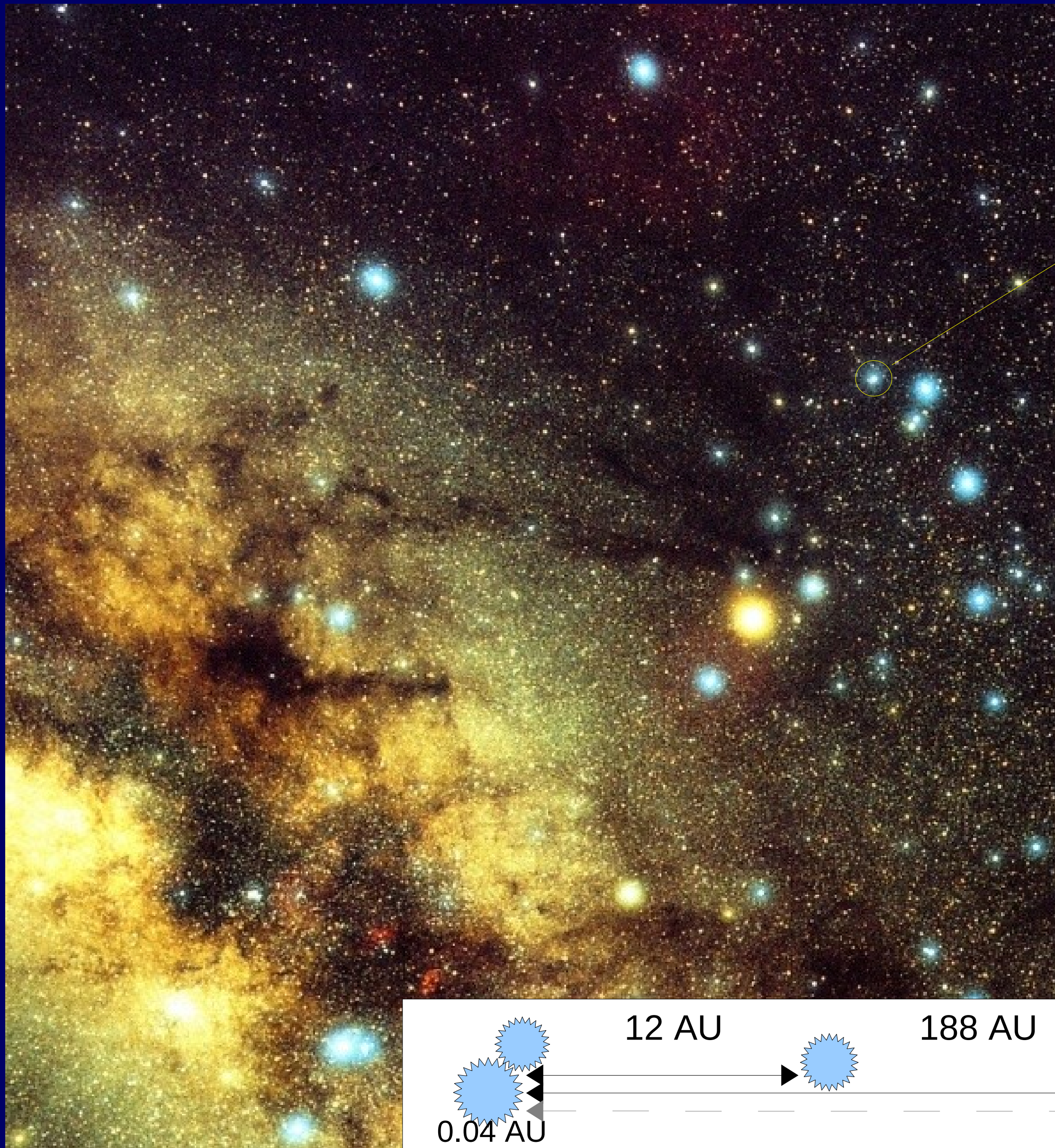
Massive stars are preferentially in higher-order multiple systems

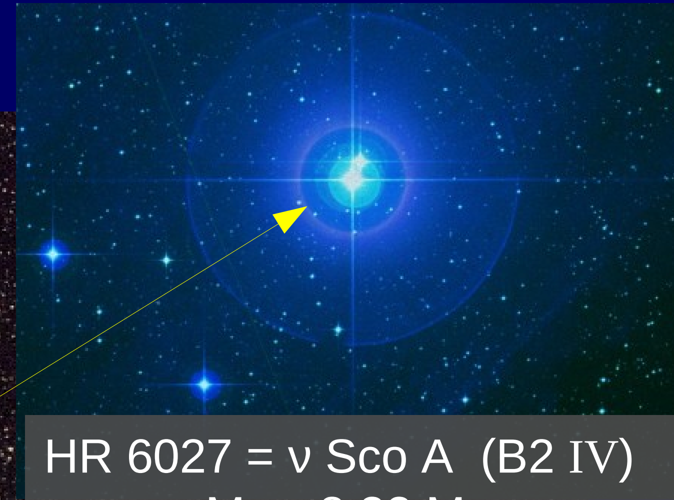
Fundamental differences between high- and low-mass stars

Multiplicity of the B-stars in Upper Scorpius

AMBER time for 14 stars granted in P85, but only 5 actually observed

Detection of a new quadruple system:





HR 6027 = ν Sco A (B2 IV)

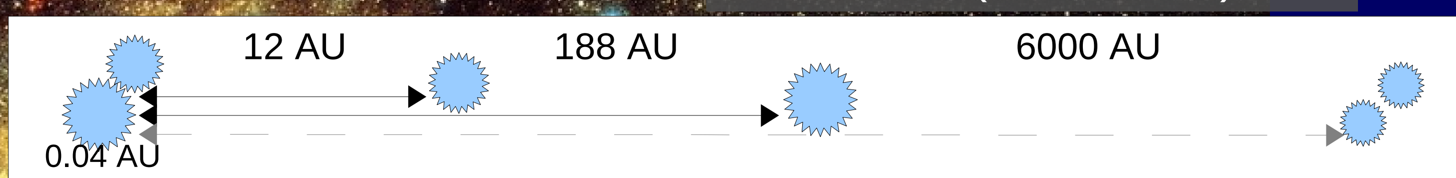
$M_1 = 8.32\ M_\odot$

- SB with P=5.3 d
- AO companion
  a = 188 AU, $M_2 = 5.47\ M_\odot$

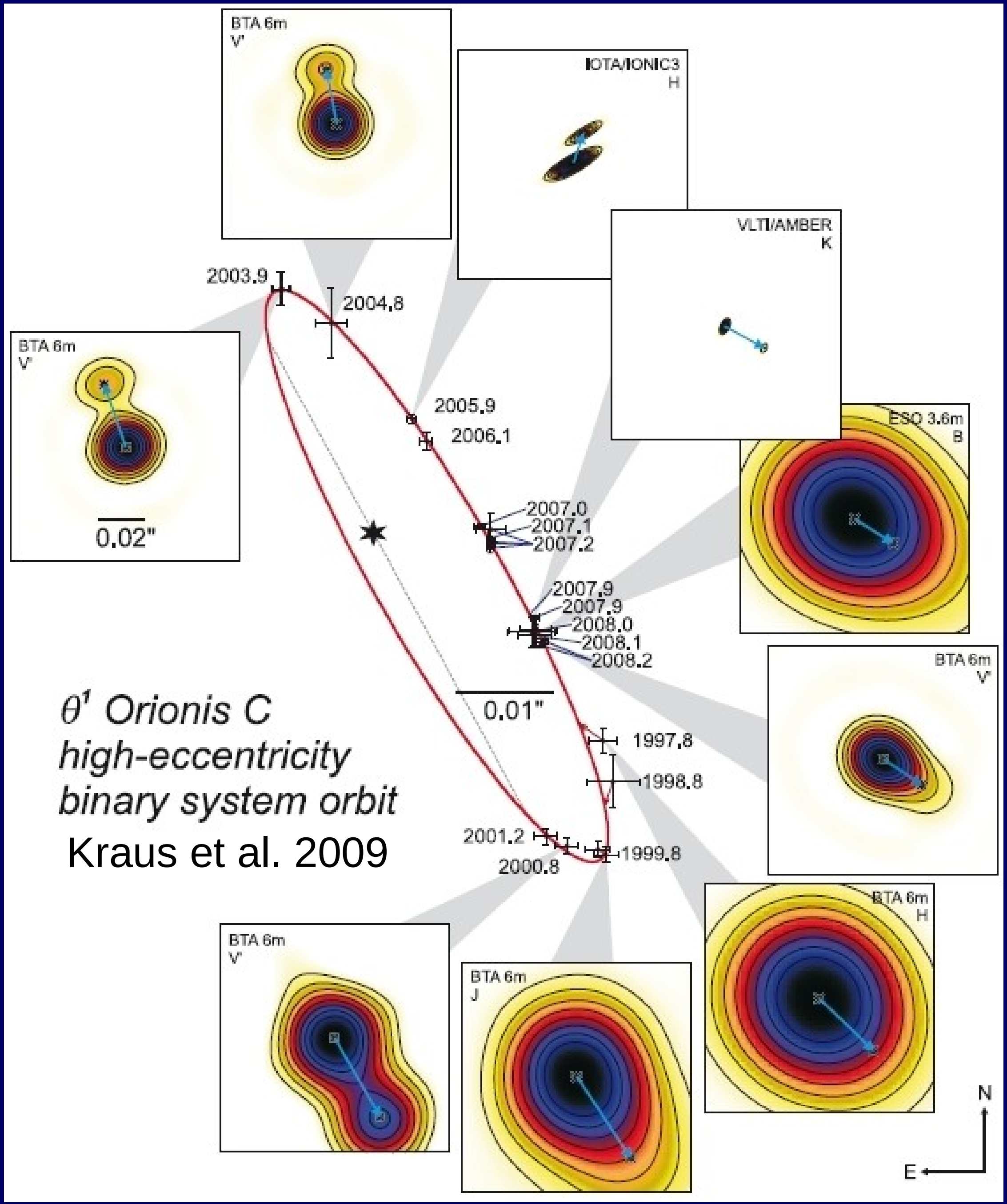
  (Kouwenhoven + 2007 AA 474,77)

- 80 mas (12 AU) companion detected with AMBER

- 41" (6000 AU) companion HR 6026 (B8V + B9V)



Part 2: Properties derived from binary orbits



θ^1 C Ori

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:

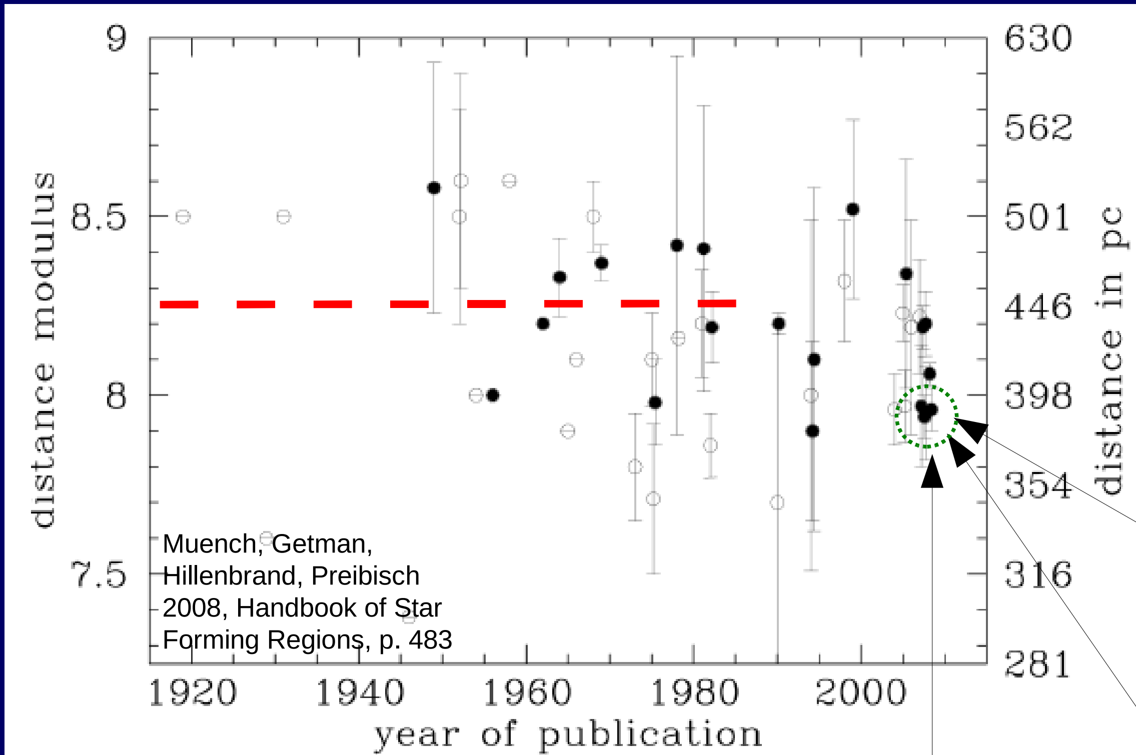
$M_1 = 39.5\ M_\odot$

$M_2 = 7.5\ M_\odot$

(~B3 star @ MS)

Orbital parallax:
D = 416 ± 12 pc

Where is the Orion Nebula Cluster ?



Until recently:
"Canonical" distance

450 pc

→ age ~ 1 Myr

Jeffries 2007:
34 stars, rotation
392 ± 32 pc

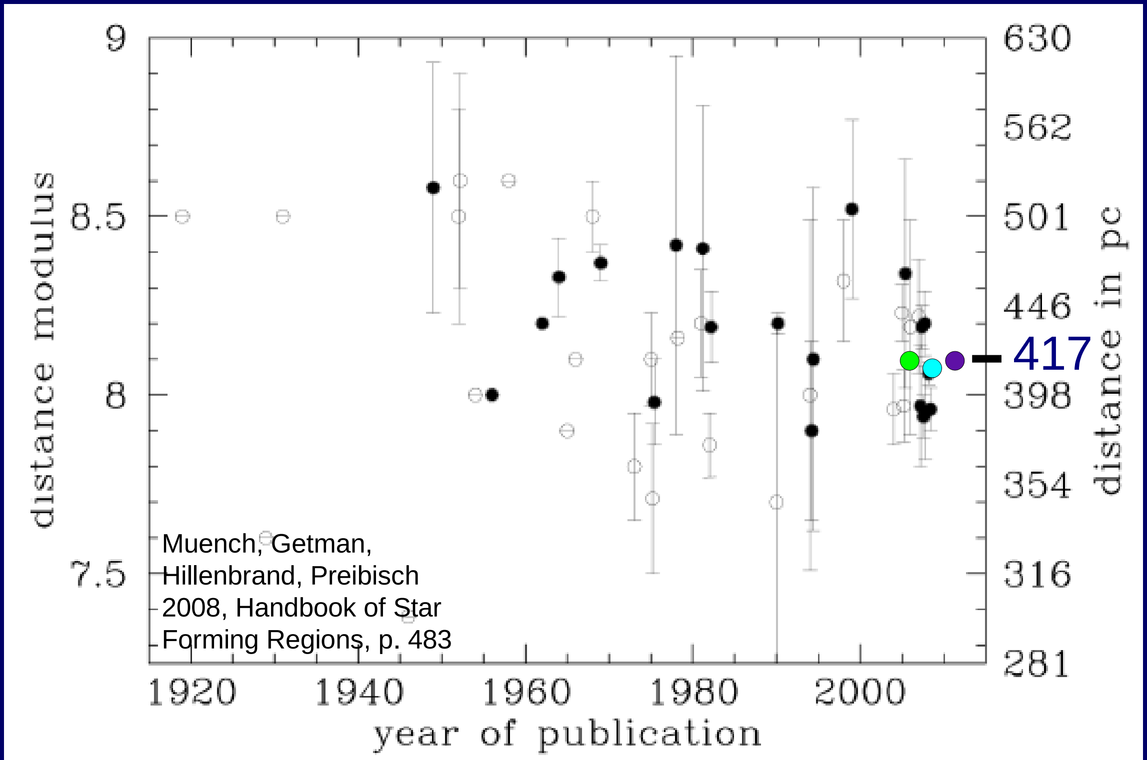
Sandstrom et al. 2007:
1 radio star
389 ± 20 pc

Mayne & Naylor 2008:
19 stars, MS-fitting
391 ± 10 pc

Δ L (390 – 450 pc) = – 25 %

→ ONC is 3 Myr old ???

Where is the Orion Nebula Cluster ?



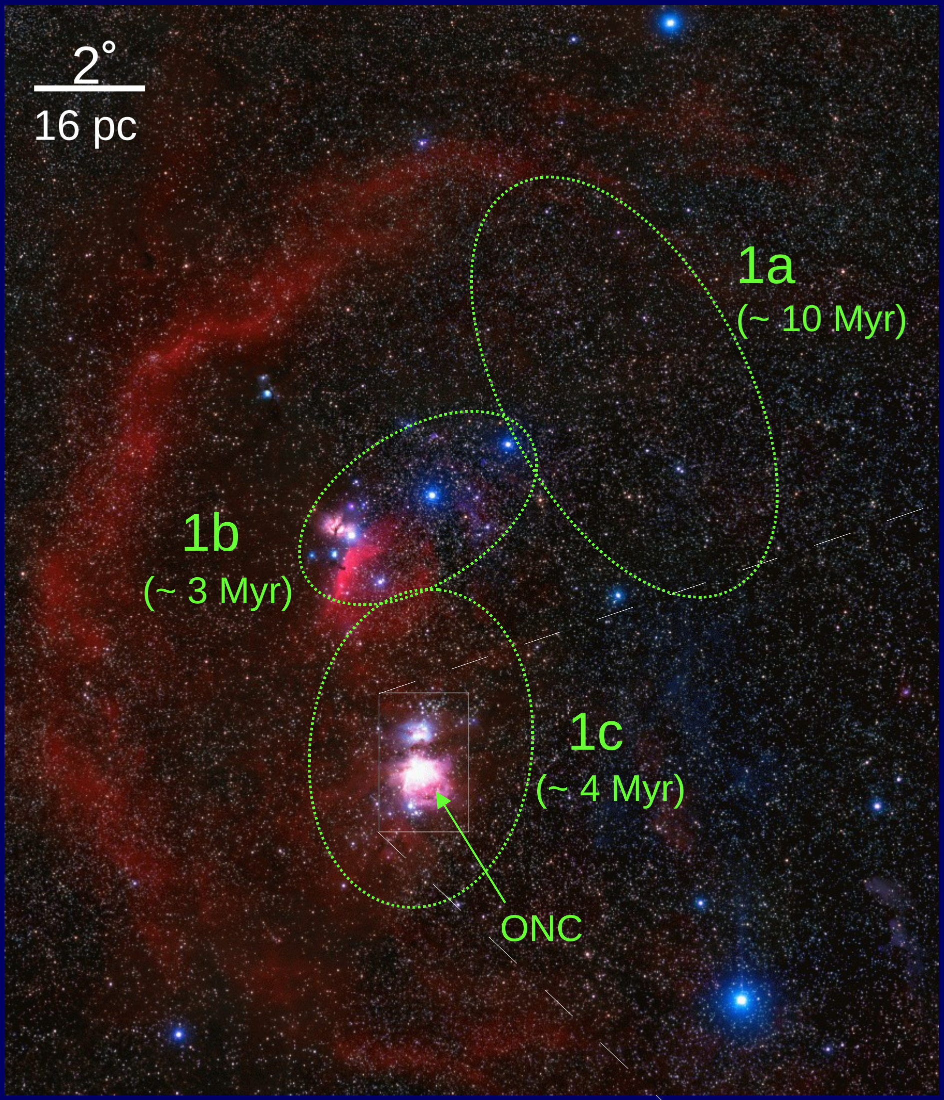
θ^1 C Ori orbital parallax:

D = 416 ± 12 pc

Menten et al. 2007:
Trigonometric parallax of 4 radio stars (incl. θ^1 A Ori)
414 ± 7 pc

Stassun et al. 2004:
Eclipsing binary (V1174 Ori)
419 ± 21 pc (8.11)

Our results strongly support a ONC distance of ≈ 420 pc



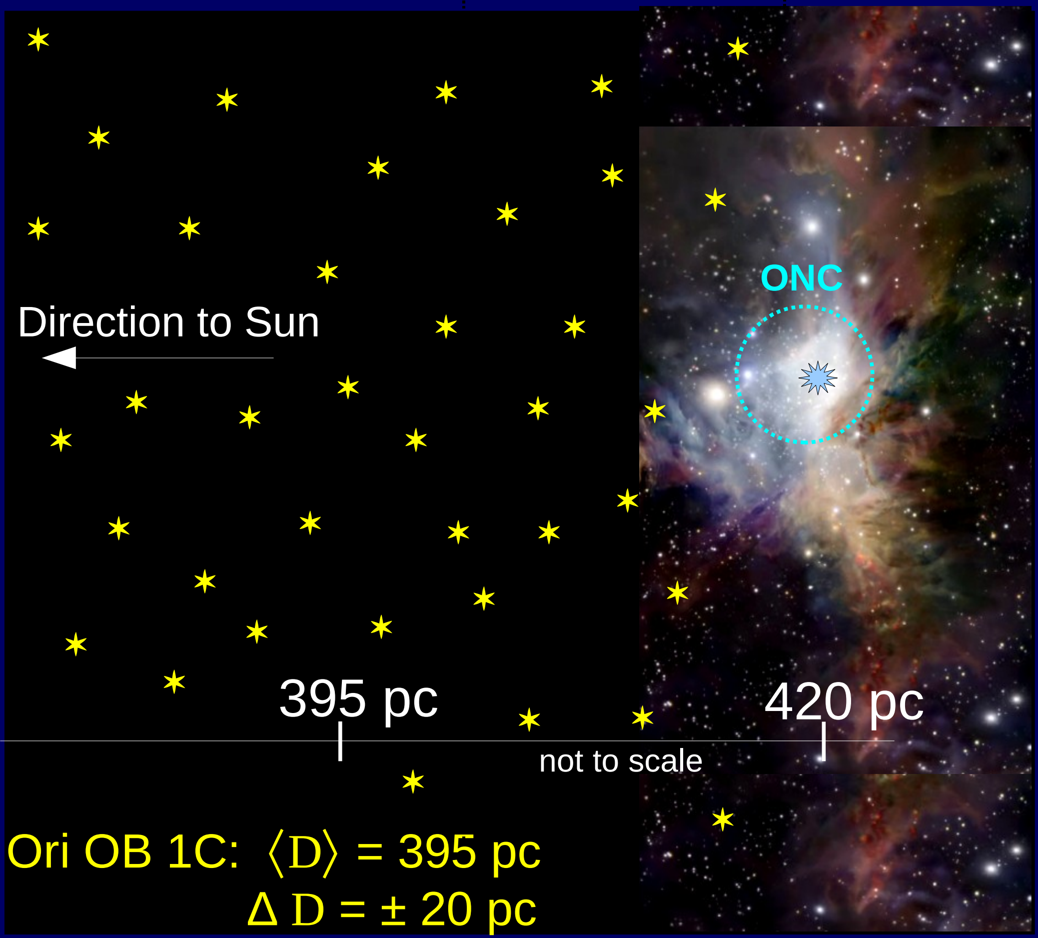
The Orion Nebula Cluster
is **part of the Ori OB 1 association.**

The ~4-6 Myr old subgroup
Ori OB 1c lies directly in front of the ONC, at D ≈ 395 pc
(Brown et al. 1994, A&A 289, 101)

Schematic side view of the ONC region

http://www.spacetelescope.org/videos/astro_bo/

Contamination by
Ori OB 1C group members
can *bias* distance estimates
for the ONC
towards *too small values*.



<u>θ^1 C Ori is surely a genuine ONC member.</u>

Therefore, the orbital parallax obviously measures the distance to the ONC, *unaffected by any foreground contamination*.

Distance of the ONC ≈ 420 pc