Mass and Angular Momentum Transformations in Massive Binary Stars

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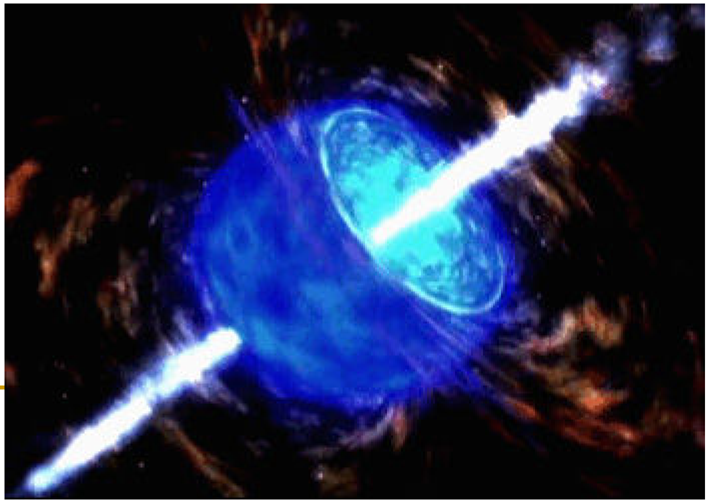
Theme: *mass and angular momentum allotments in massive binaries play critical roles over lives*

- Progenitors of the Long Gamma Ray Bursts
- Binary Star Surveys
- Early Stages of Interacting Binaries
- High Angular Resolution of Be Star Disks with the GSU CHARA Array Interferometer
- Later Stages of Interacting Binaries
- Summary and Speculations

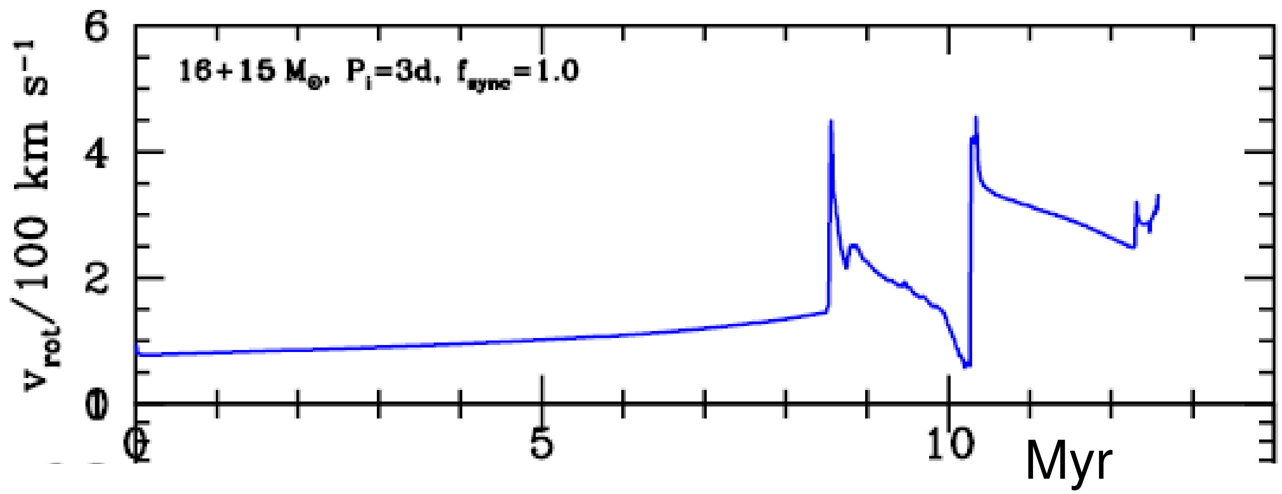
Progenitors of Long Gamma Ray Bursts

- Collapsar model (Woosley 1993): core of a massive, fast rotating star collapses into a black hole
- An accretion disk is formed around the black hole if the core has enough specific angular momentum
- Remainder of the core is accreted onto the black hole and a highly relativistic collimated outflow is produced which releases a large amount of energy
- Duration consistent with collapse of star with no H envelope
- Need rapidly rotating WR stars



How to achieve rapid rotation?

- Massive stars lose angular momentum by stellar winds (driven by metal spectral transitions so less in low metallicity regions)
- Binaries may help (Langer et al. 2008):
  - mass transfer and spin up
  - mass loss at critical rotation and spin down
  - spin-orbit coupling (spin down and spin up)

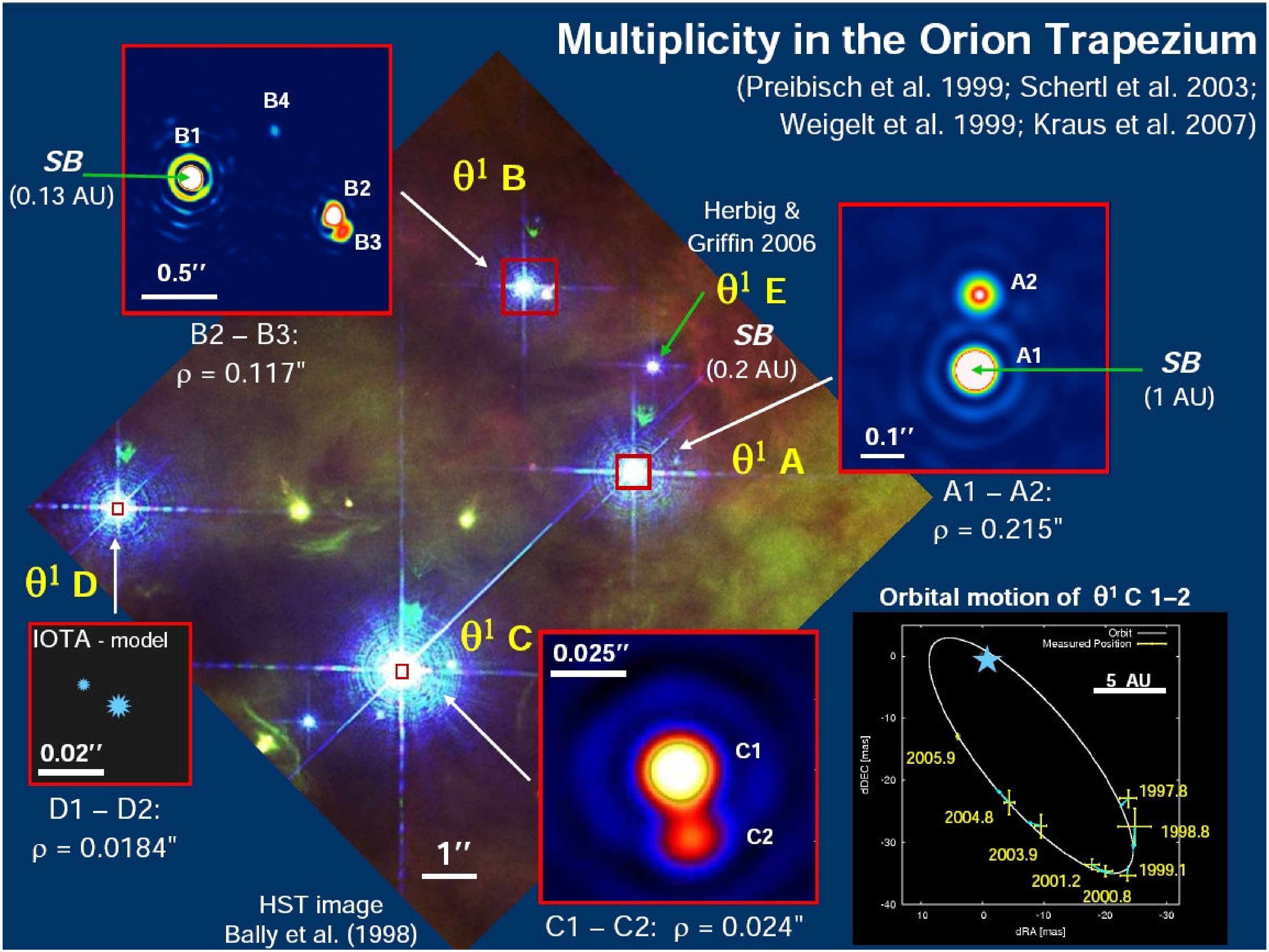


Difficult to find successful binary models

- Detmers et al. (2008) show that spin orbit coupling may yield a rapidly rotating WR if companion is compact (black hole) and in close orbit
- Most common outcome is WR+BH merger, and predicted rates are similar to estimated LGRB rates
- Cantiello et al. (2007):
  - gainer spin up by mass transfer
  - runaway star (gainer+BH) created by SN
  - travels ~200 pc and maintains fast spin
  - gainer explodes as collapsar, GRB (by merger?)
- Nearby GRBs observed ~100 pc from young clusters (Hammer et al. 2006)

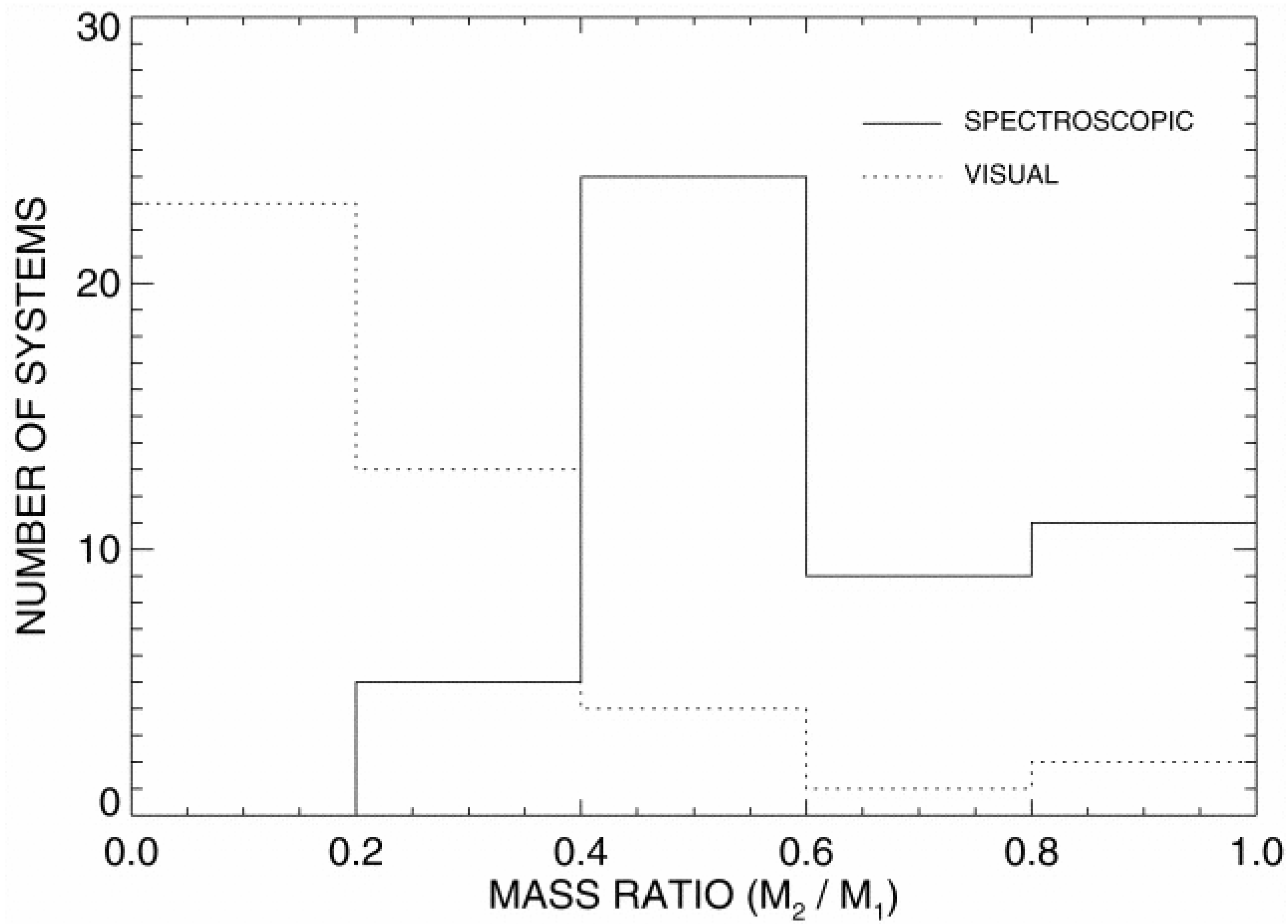
Need to study these binary processes in relatively nearby environments and in earlier stages in the lives of binaries.

Lots of examples!

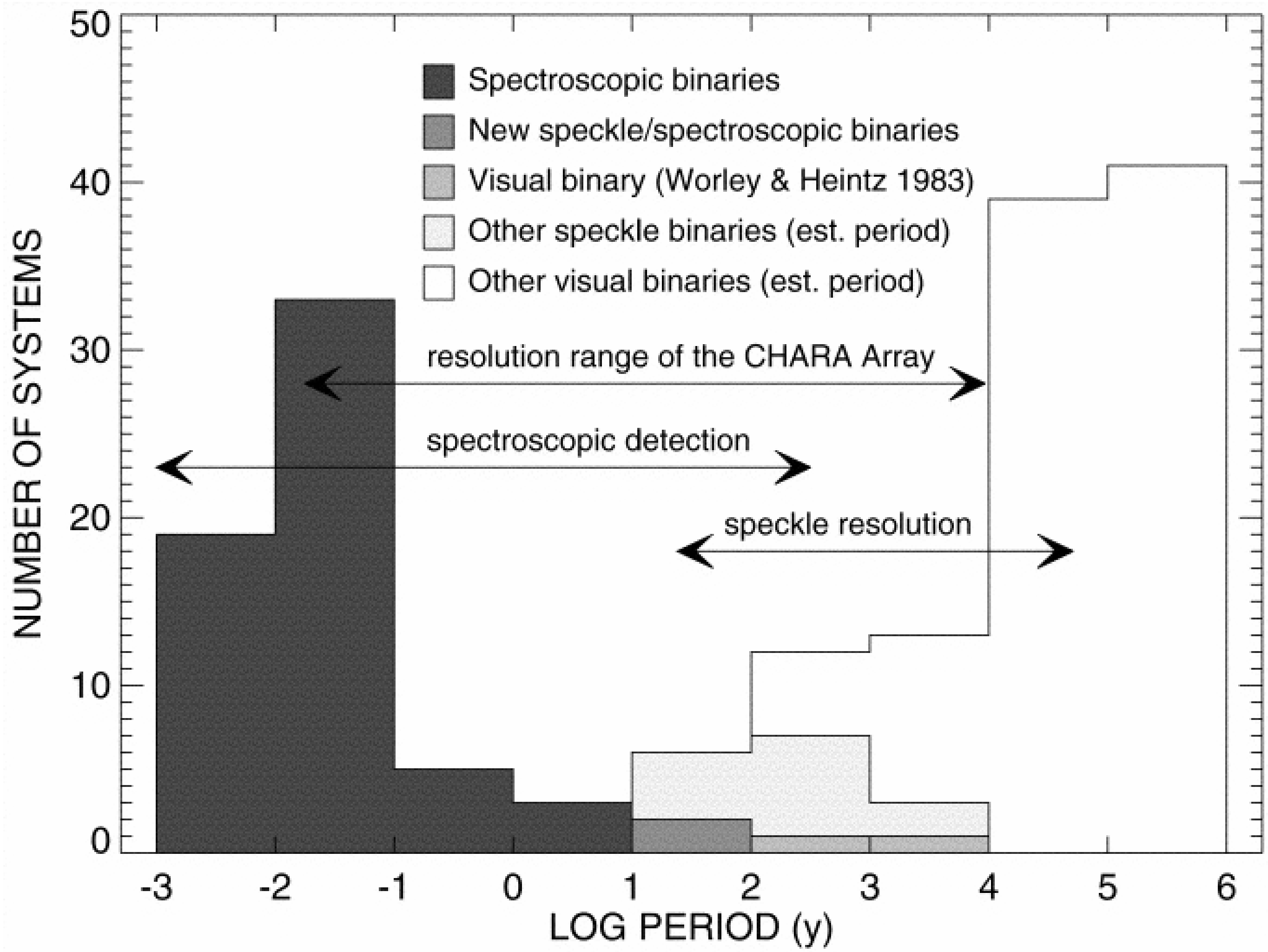

Multiplicity in the Orion Trapezium
(Preibisch et al. 1999; Schertl et al. 2003;
Weigelt et al. 1999; Kraus et al. 2007)
SB
(0.13 AU)
B4
B1
B2
B3
0.5″
B2 – B3:
ρ = 0.117"
θ1 B
Herbig &
Griffin 2006
θ1 E
SB
(0.2 AU)
A2
A1
SB
(1 AU)
0.1″
θ1 A
A1 – A2:
ρ = 0.215"
θ1 D
IOTA - model
0.02″
D1 – D2:
ρ = 0.0184"
θ1 C
0.025″
C1
C2
C1 – C2: ρ = 0.024"
1″
HST image
Bally et al. (1998)
Orbital motion of θ1 C 1–2
Orbit
Measured Position
5 AU
2005.9
2004.8
2003.9
2001.2
2000.8
1997.8
1998.8
1999.1
dDEC [mas]
dRA [mas]

Binary Star Surveys: Speckle Interferometry

- Orion: high incidence of binaries and multiples among the high mass stars (Schertl et al. 2003; Kraus et al. 2007) compared to the low mass stars (Köhler et al. 2006)
- Speckle survey of Galactic O-stars: sep.> 30 mas, Δm< 3, KPNO/CTIO 4 m (Mason et al. 1998)
- Included results on spectroscopic/visual binaries
- Binaries are common:
  >59% have companions among O-stars in clusters and associations (fewer in field and runaway stars)
- New survey (10 years later) by Mason et al. (2009) finds 23% visual binary frequency (14 new binaries)



- Companion masses:
  similar to IMF sampling for wide binaries;
  more comparable masses in close binaries



- Period gap due to observational bias
- If distribution is flat in log *P* then <u>most O-stars have companions</u>

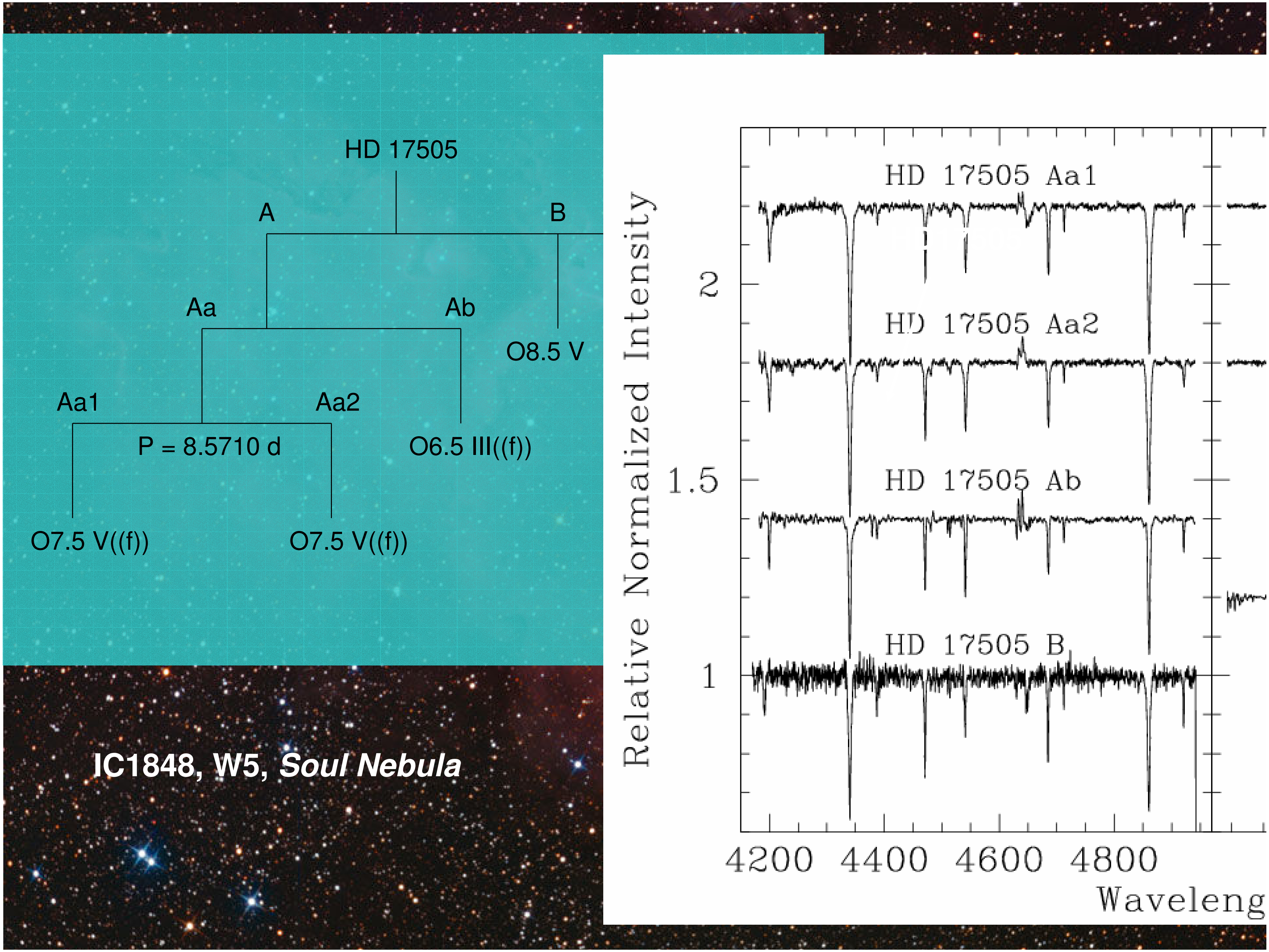
Binary Star Surveys: Adaptive optics imaging

AEOS 3.67m telescope

- Selects long period and potentially faint companions (best nearby)
- Difficult to distinguish physical companions from field stars at faint limit ($\Delta m > 8$)
- B-star survey (70): 23±6% binary (*I*-band; Roberts et al. 2007)
- O-star survey (116): 29±5% binary (for delta *I*<8; Turner et al. 2008)

Binary Surveys: Spectroscopic Binaries

- Measurements difficult because of stellar rotation, pulsation, emission
- Need many observations, long term programs
- Favors close, massive binaries with orbital planes close to line of sight
- NGC 6231: 63±20% spectroscopic binary (Sana et al. 2007)
- Cas OB6: 50±19% spectroscopic binary (Hillwig et al. 2006; Doppler tomography)



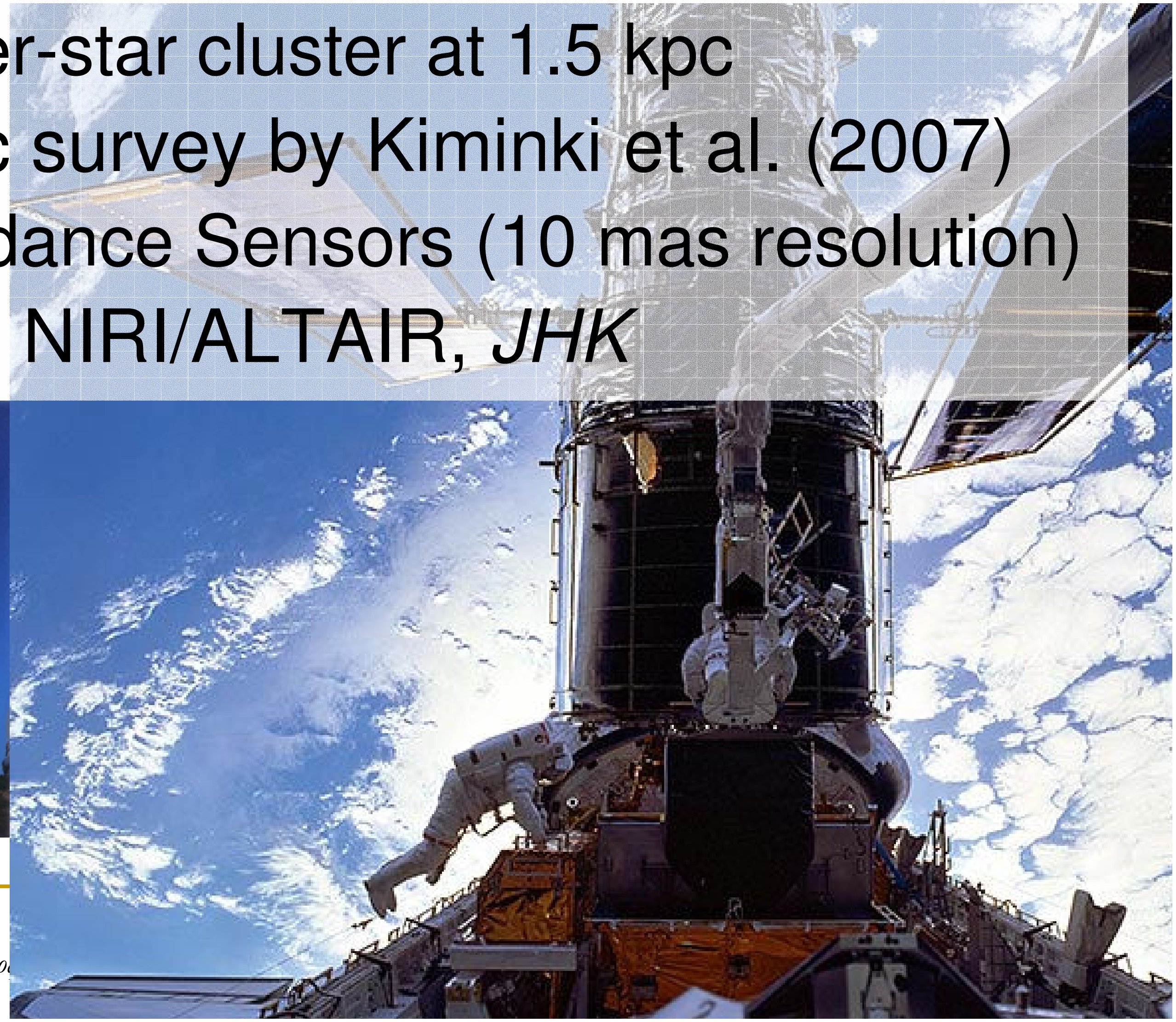
HD 17505
A
B
Aa
Ab
O8.5 V
Aa1
Aa2
P = 8.5710 d
O6.5 III((f))
O7.5 V((f))
O7.5 V((f))
IC1848, W5, *Soul Nebula*
HD 17505 Aa1
HD 17505 Aa2
HD 17505 Ab
HD 17505 B
Relative Normalized Intensity
2
1.5
1
4200
4400
4600
4800
Waveleng

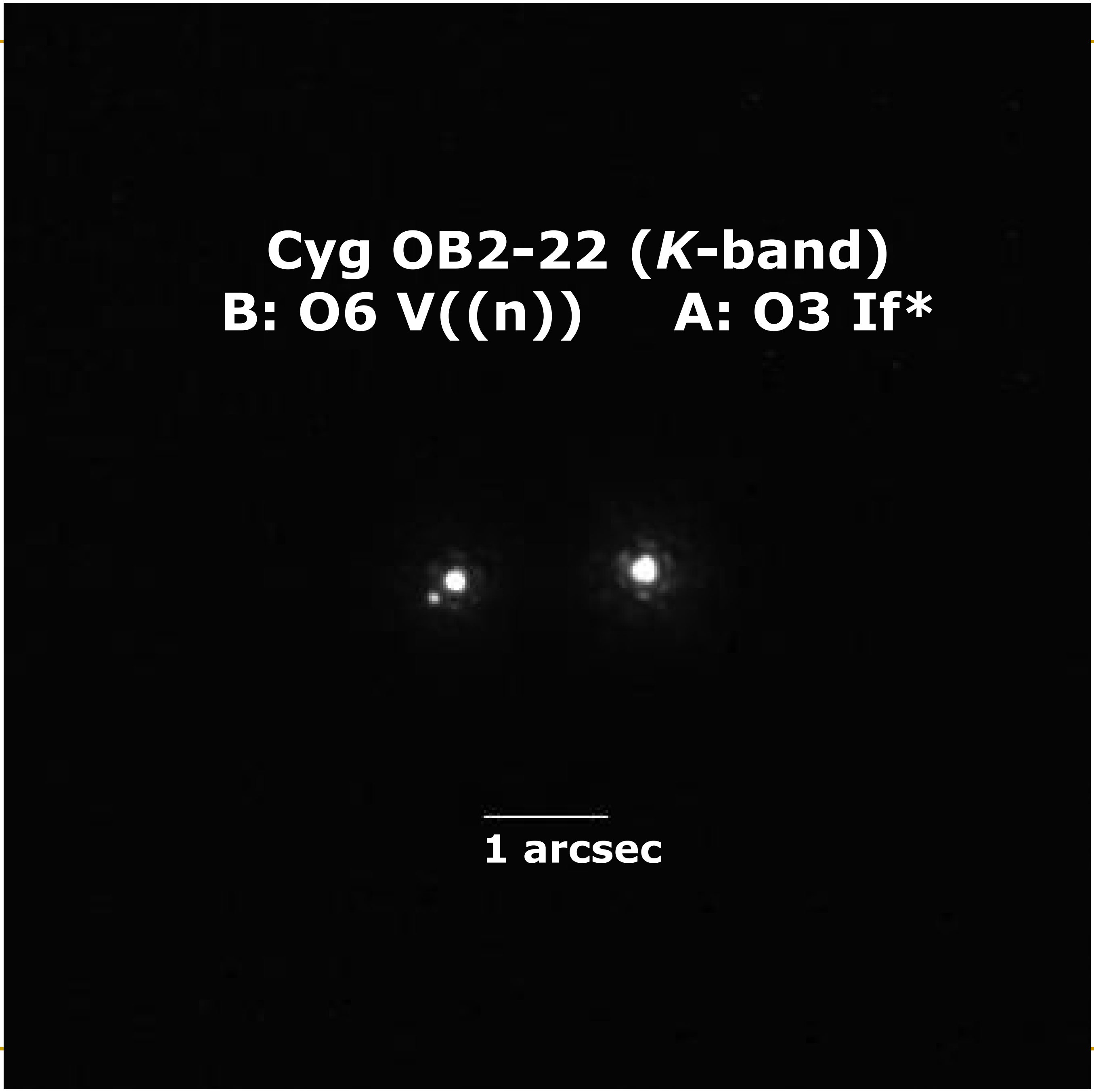
Binary Surveys: Combining results with biases

- These methods select only certain kinds of binaries, so the total binary frequency remains unknown
- Kouwenhoven et al. (2007) developed Monte Carlo simulations of how observational programs of RV and AO measurements sample the binary population in Sco OB2 (intermediate mass sample, $d = 130$ pc)
- Binary fraction is about 100% among A, B stars
- "… *multiplicity is a fundamental parameter in the star forming process*."

Binary Star Survey: Cyg OB2 association - Space interferometry, AO, spectroscopy

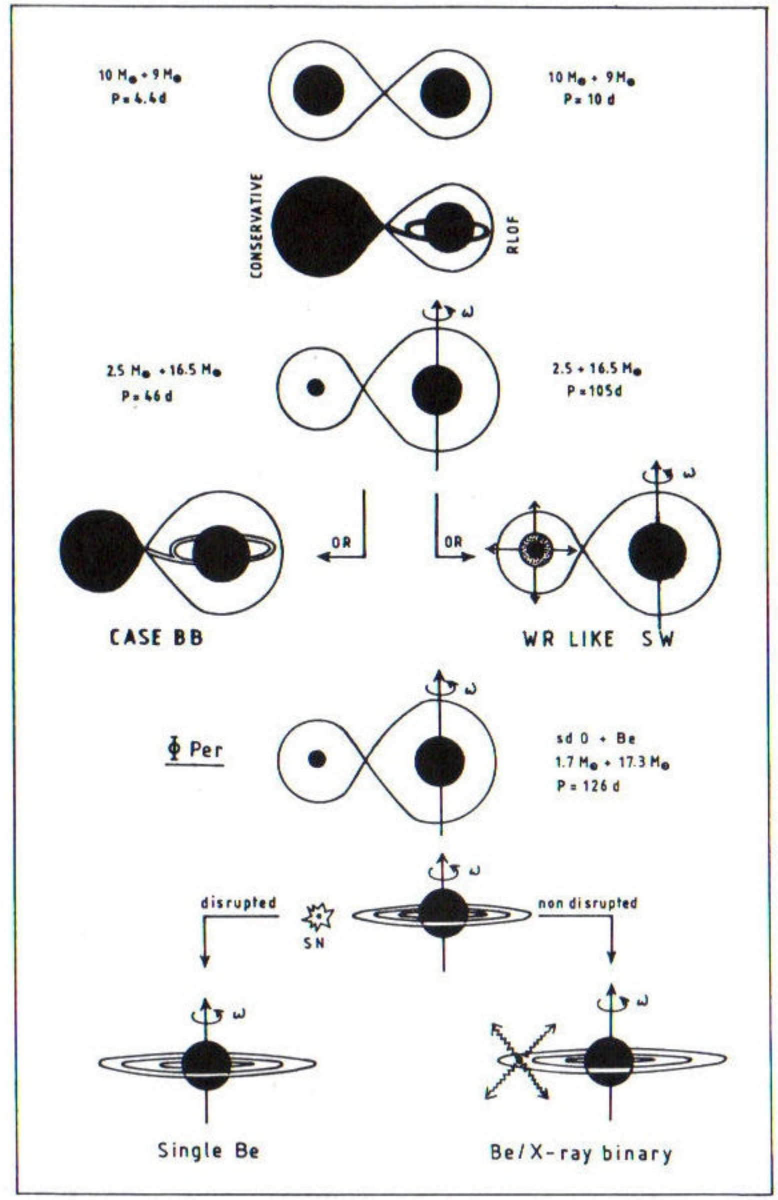
- Cyg OB2 super-star cluster at 1.5 kpc
- Spectroscopic survey by Kiminki et al. (2007)
- *HST* Fine Guidance Sensors (10 mas resolution)
- Gemini North, NIRI/ALTAIR, *JHK*




Cyg OB2-22 (*K*-band)
B: O6 V((n))
A: O3 If*
1 arcsec

Early Stages of Interacting Binaries

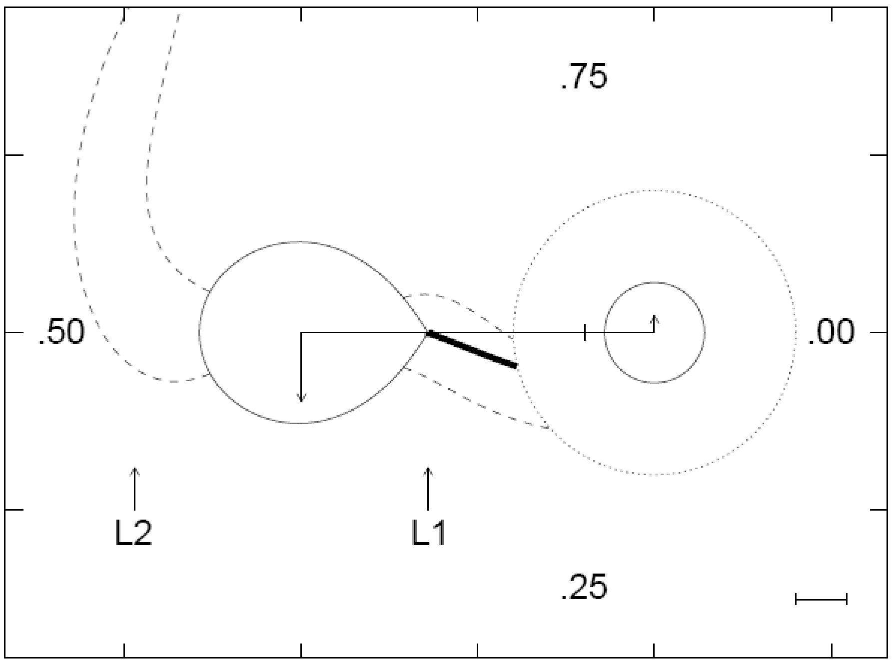
- 50% of O-stars are binaries that will interact during lifetime (*P*<10 y)
- Mass transfer occurs during episodes of growth in radius
- Mass transfer will shrink orbit until mass ratio reversed (gainer larger)
- Continued mass transfer will enlarge orbit



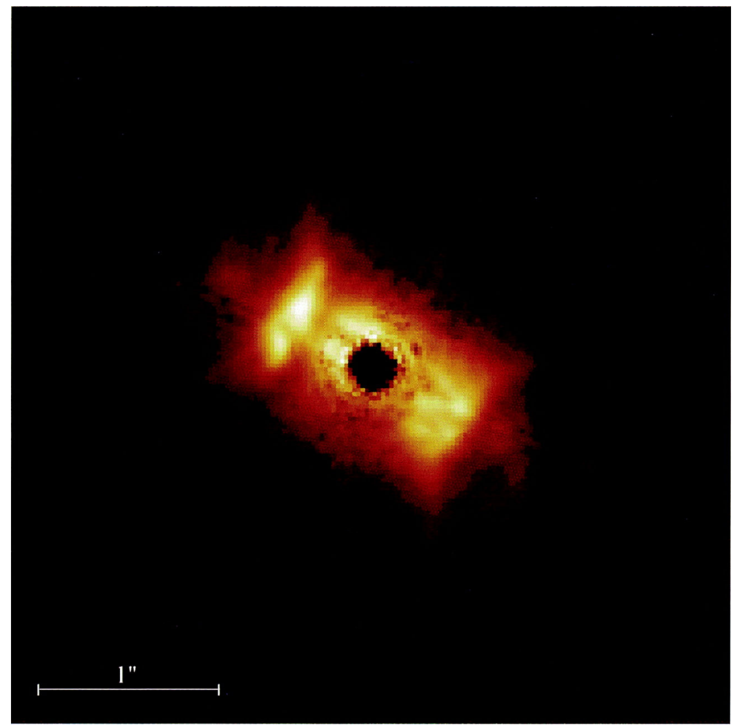
Rapid mass transfer stage: W Serpentis stars

(Beta Lyr and RY Scuti; Grundstrom et al. 2007)

- 7 M_{sun} (O9.7 Ibpe) + 30 M_{sun} (B0.5 I = torus)
- Circumbinary outflow into nebula (Smith et al. 1999)



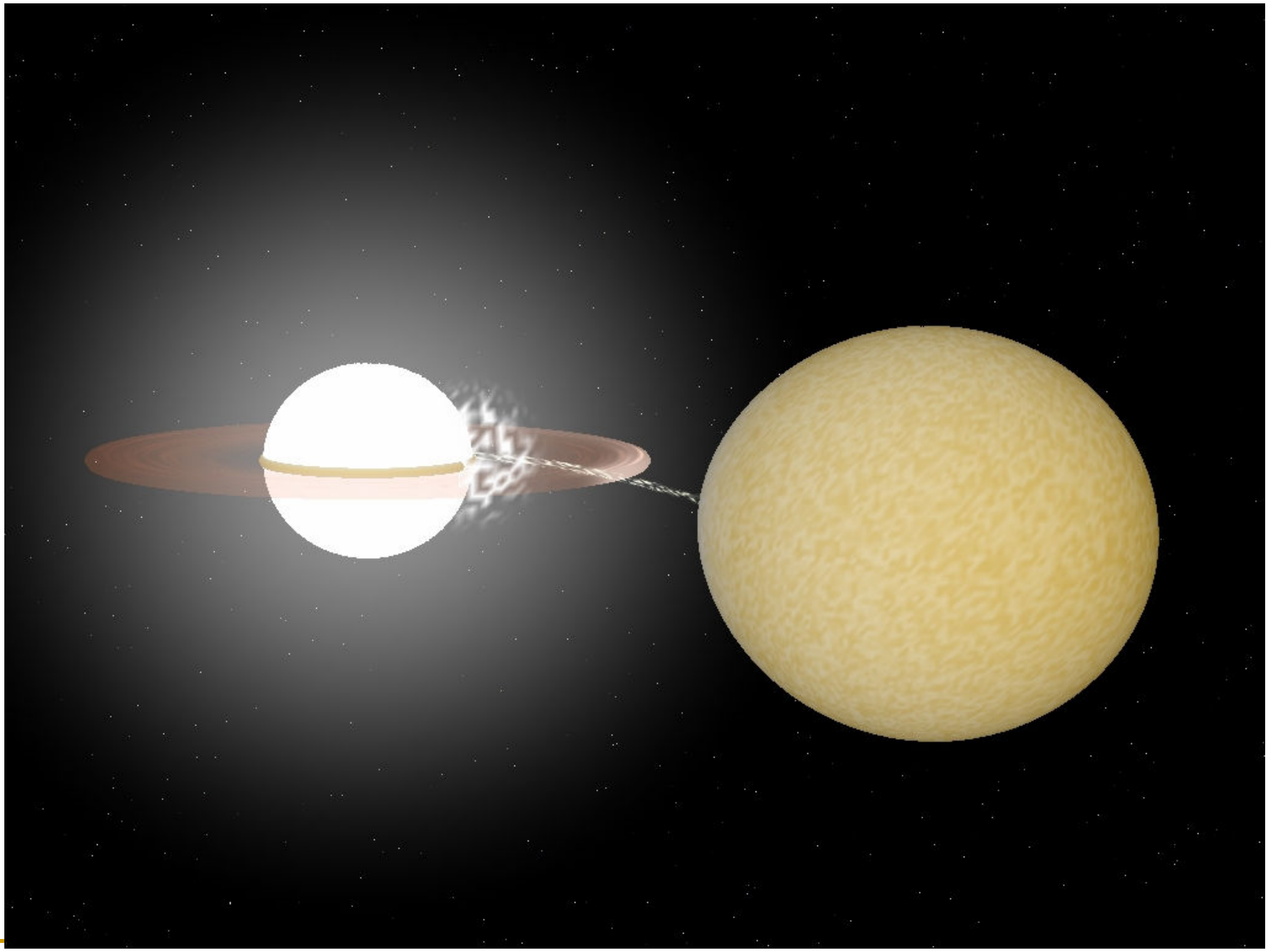
1 AU

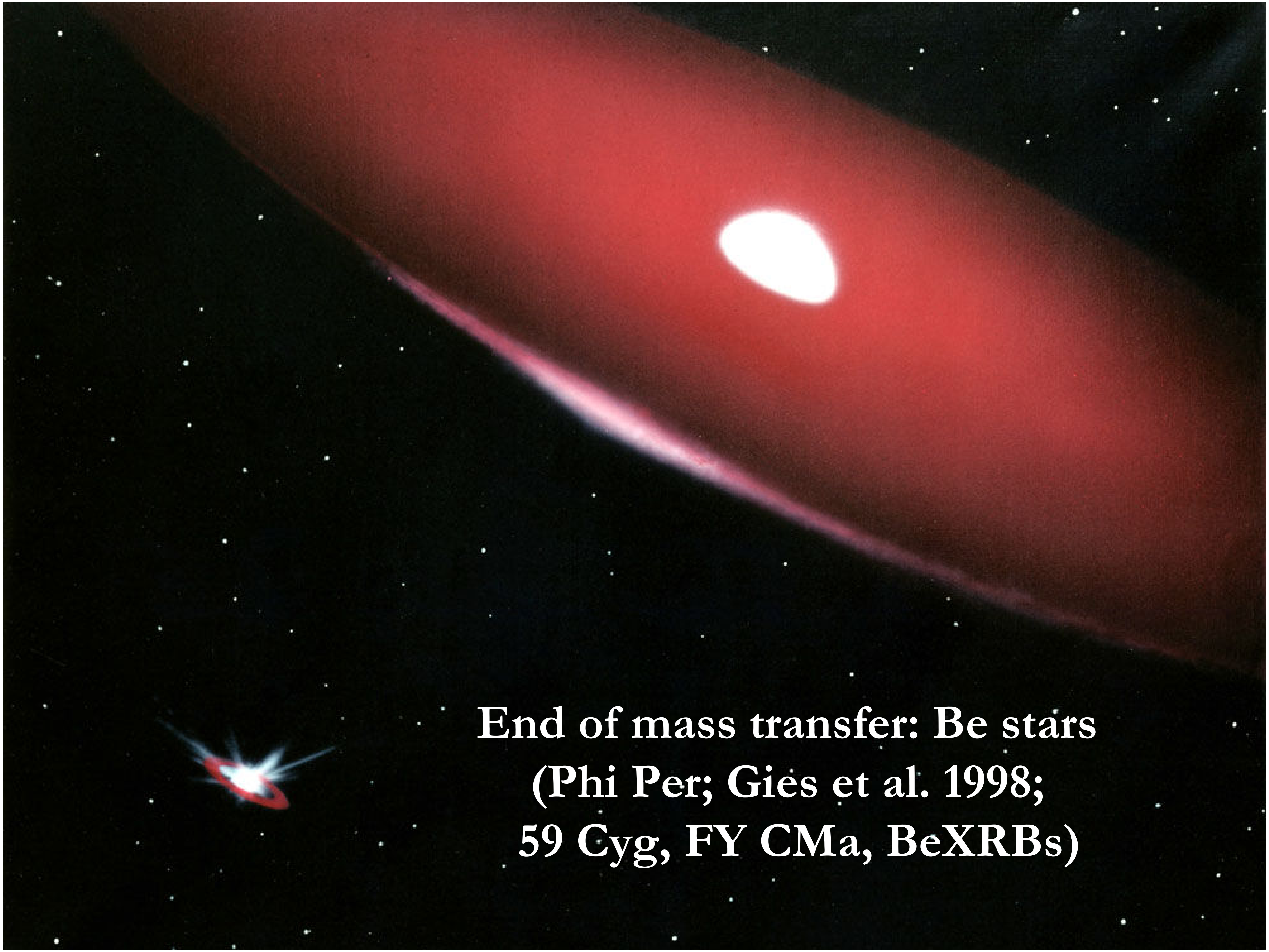


2000 AU

Slow mass transfer stage: Algols
(RY Per; Barai et al. 2005)

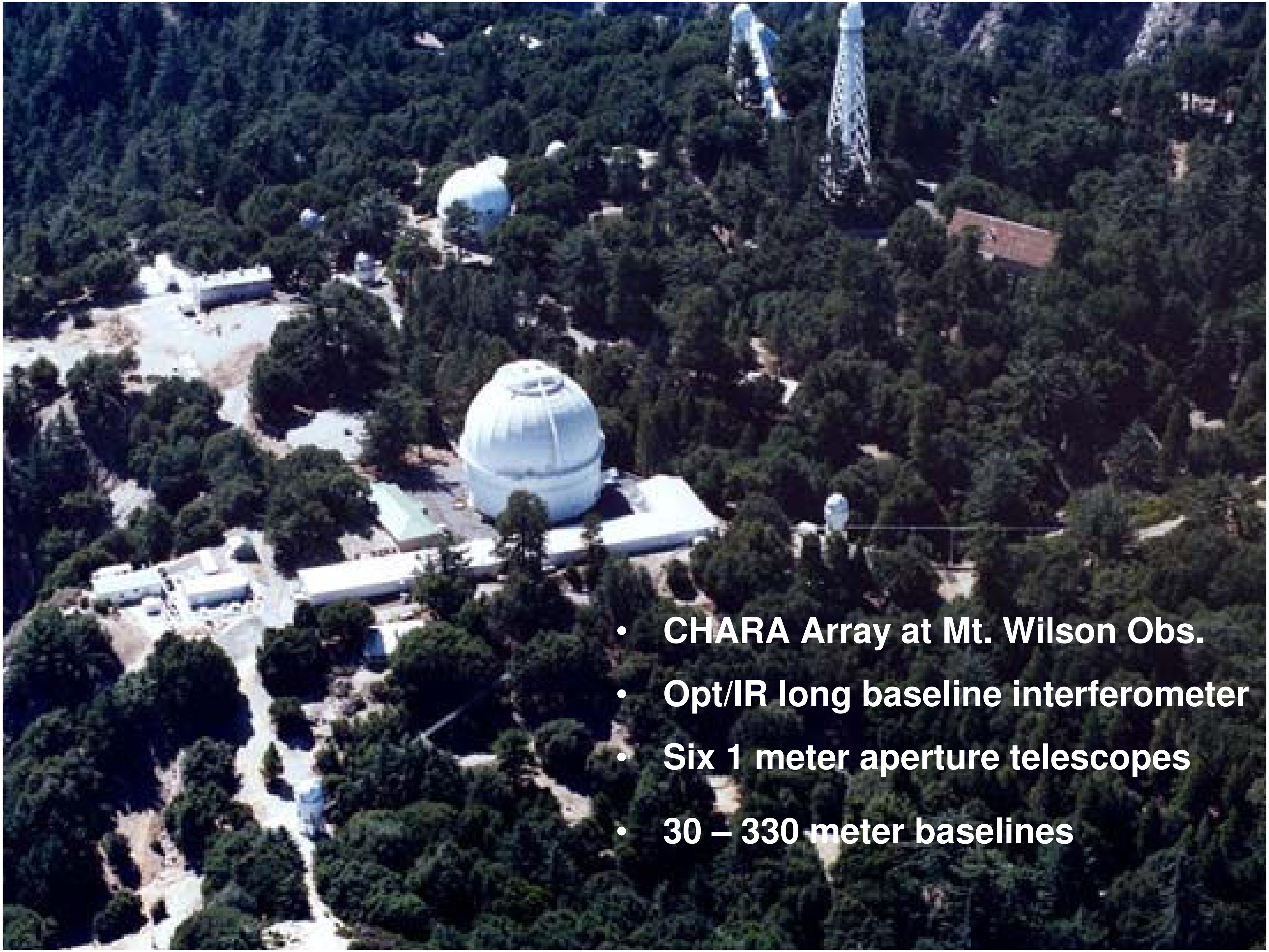
- Gas stream torque; spin up of mass gainer



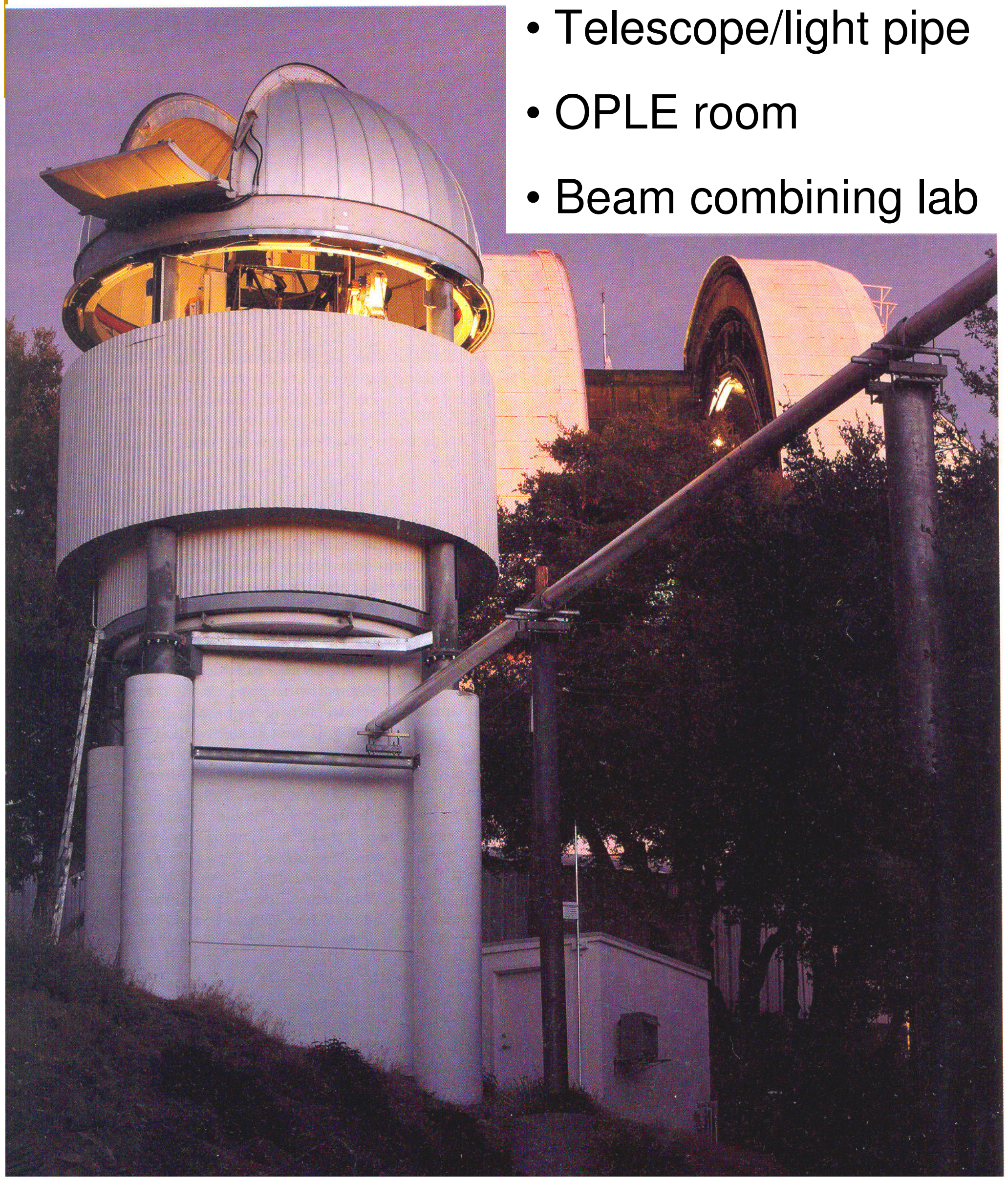

End of mass transfer: Be stars
(Phi Per; Gies et al. 1998;
59 Cyg, FY CMa, BeXRBs)

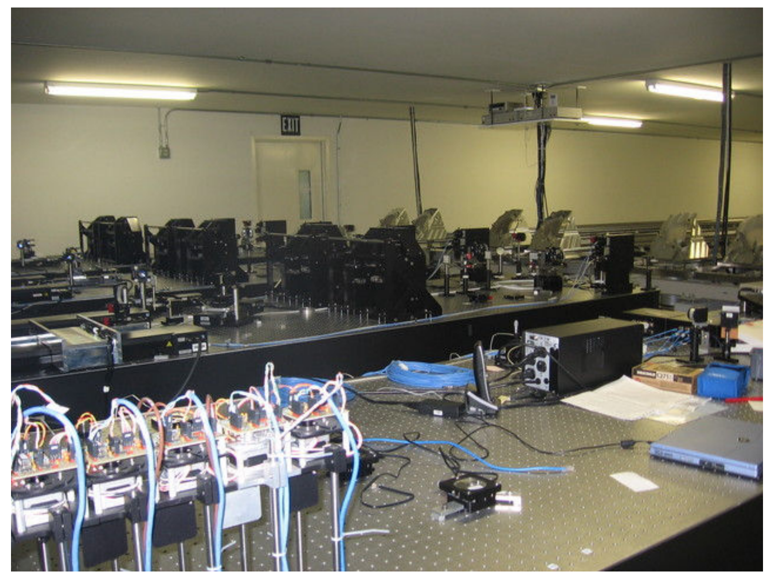
High Angular Resolution of Be Star Disks with the CHARA Array Interferometer

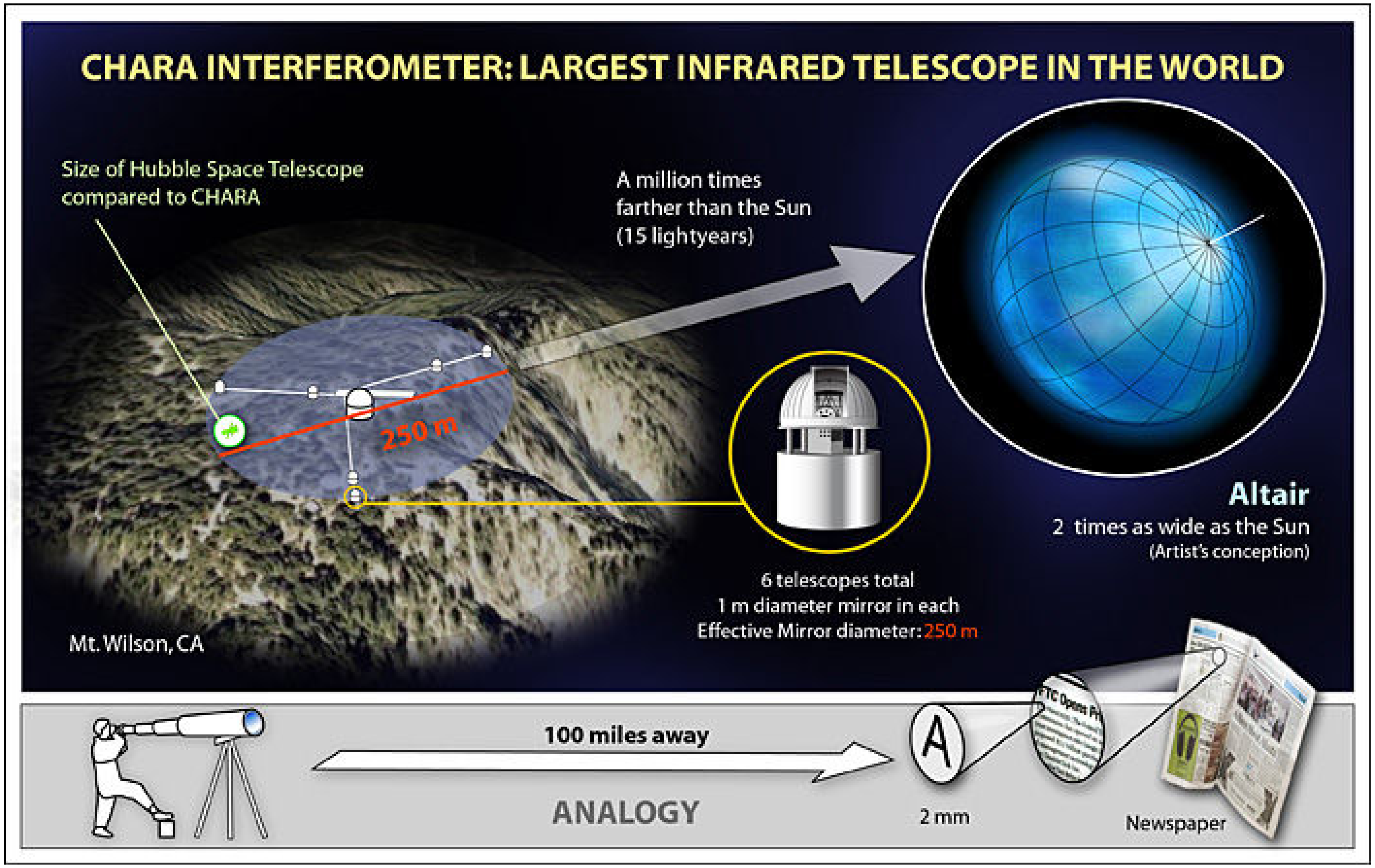
- B-type, rapid rotators (> 80% critical velocity)
- ***Circumstellar gas disks*** revealed by *emission lines* (hydrogen Balmer series), *infrared excess* continuum emission, and *linear polarization* (of scattered star light)
- Disk features inherently time variable:
  B → Be → B …(months to decades)


• CHARA Array at Mt. Wilson Obs.
• Opt/IR long baseline interferometer
• Six 1 meter aperture telescopes
• 30 – 330 meter baselines

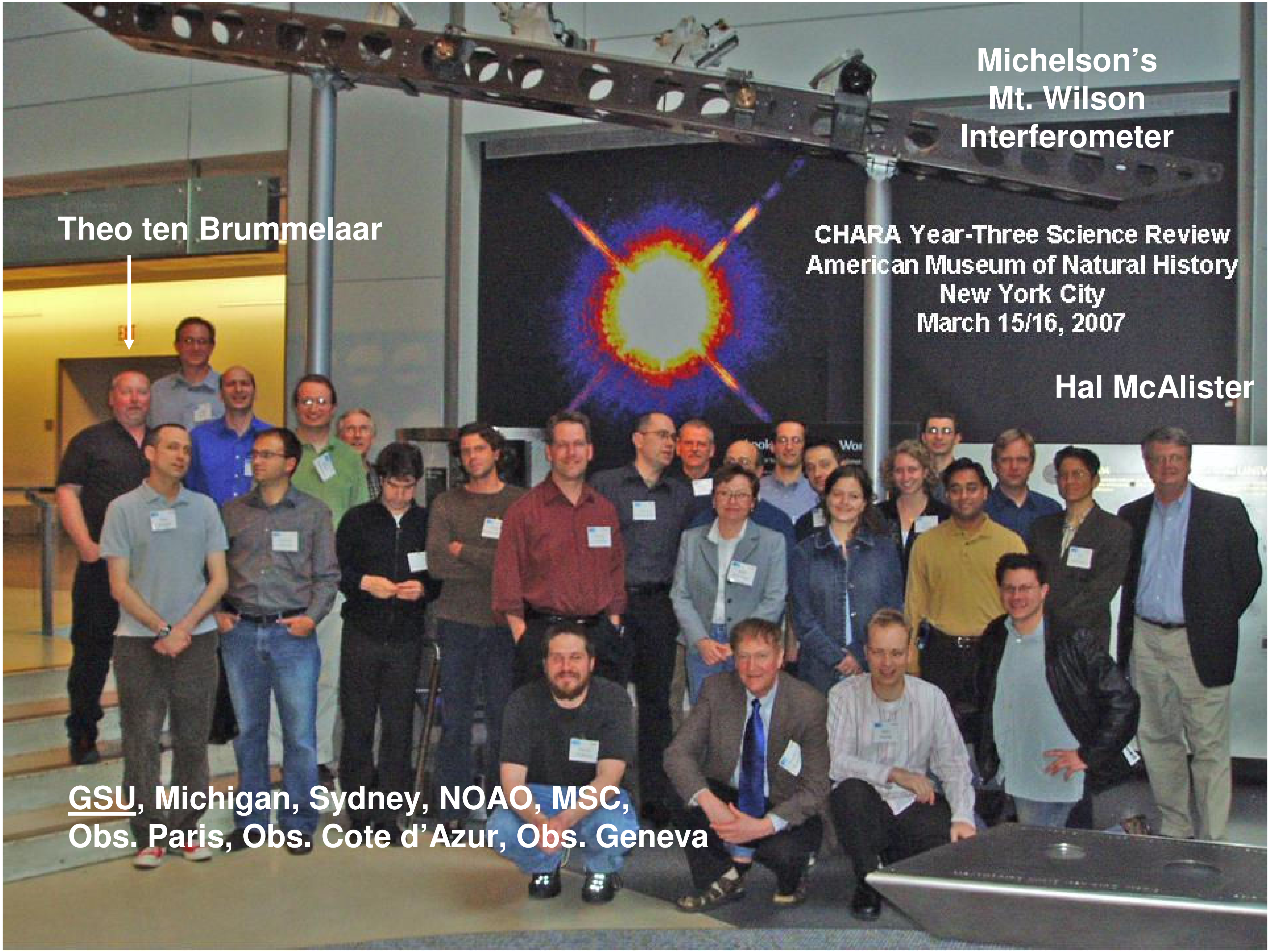
- Telescope/light pipe
- OPLE room
- Beam combining lab







- Resolve objects as small as 0.2 milliarcsec
- Huge potential for stellar fundamental properties, interior structure and evolution, pulsation, surface features, companions, mass loss and environs


Michelson's
Mt. Wilson
Interferometer
Theo ten Brummelaar
CHARA Year-Three Science Review
American Museum of Natural History
New York City
March 15/16, 2007
Hal McAlister
GSU, Michigan, Sydney, NOAO, MSC,
Obs. Paris, Obs. Cote d'Azur, Obs. Geneva

CHARA Array: Be stars (Gies et al. 2007)

- *K*-band interferometric observations of four bright Be stars (2003 – 2005)
- CHARA Classic beam combiner (pair-wise)
- Observations interposed with calibrator stars with known angular diameter in order to transform *instrumental* fringe visibility into *absolute* visibility V
- V = Fourier transform of angular image

Models of *K*-band Visibility

- Uniform disk star with set angular diameter
- Disk geometry (Hummel & Vrancken 2000)

  $$\rho(R,Z) = \rho_0 \, R^{-n} \exp[-0.5(Z/H(R))^2]$$

  ρ_0 = base density (g cm^{-3})

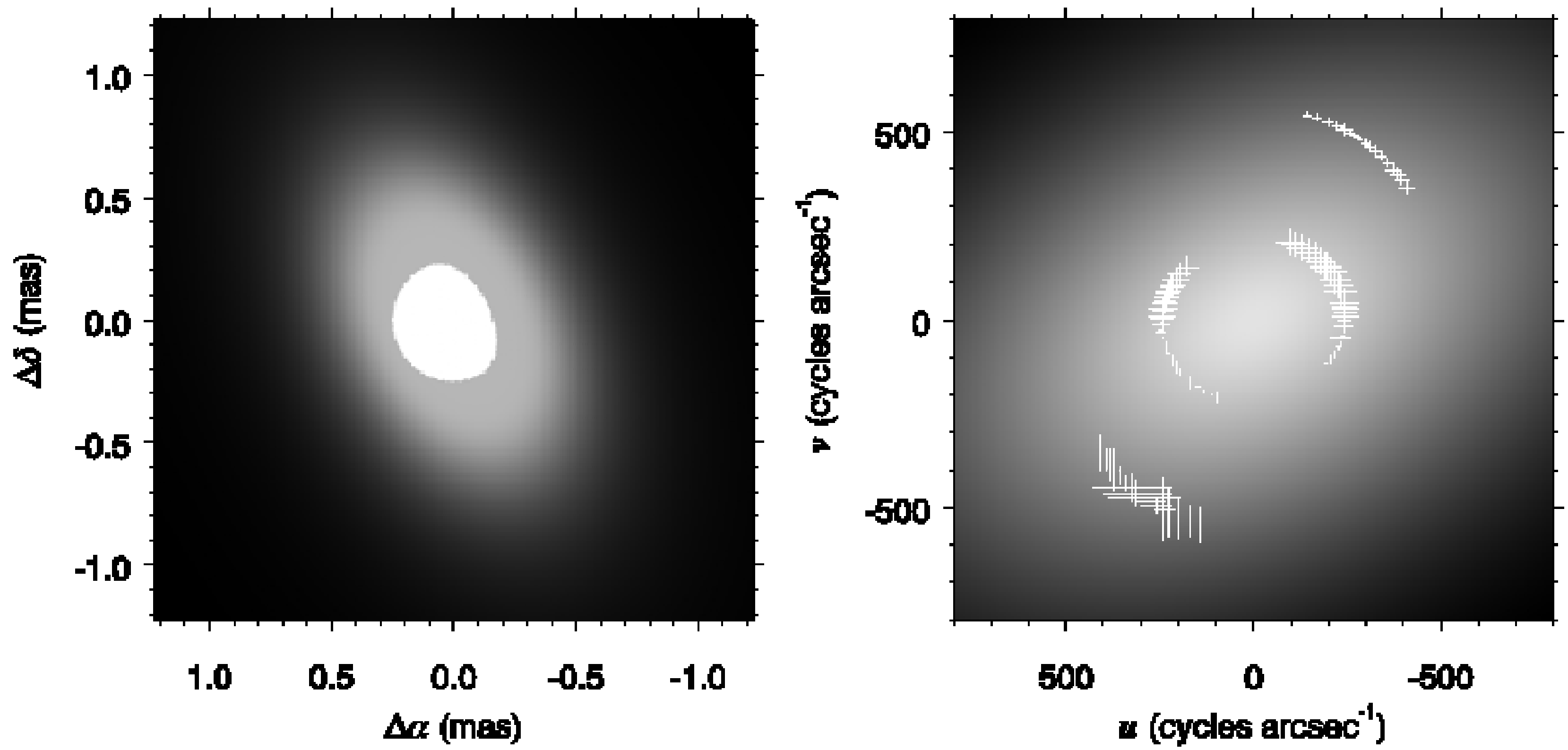
  n = radial density exponent
- Observer parameters

  i = inclination of disk normal

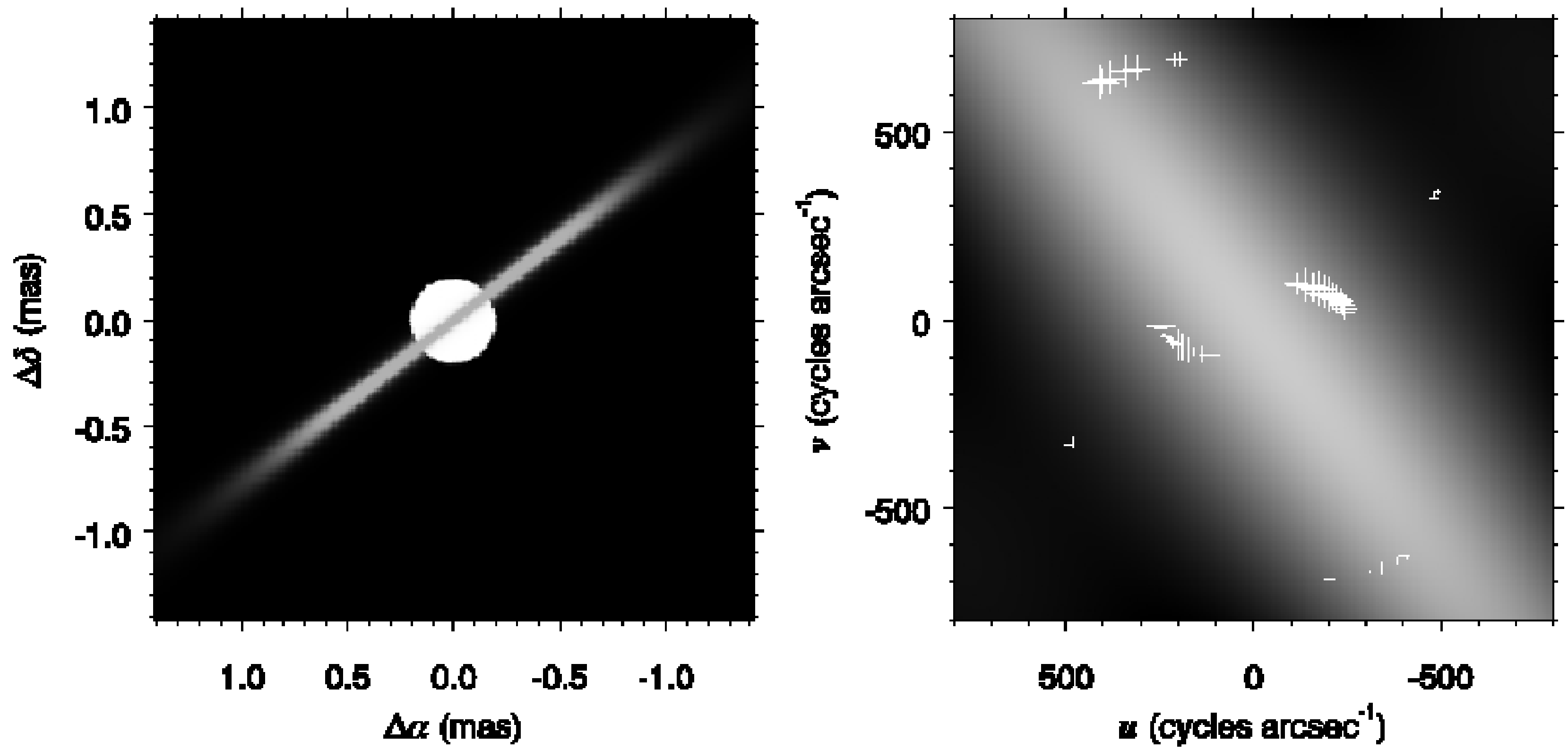
  α = position angle (E from N) of disk normal

γ Cas: single star fit

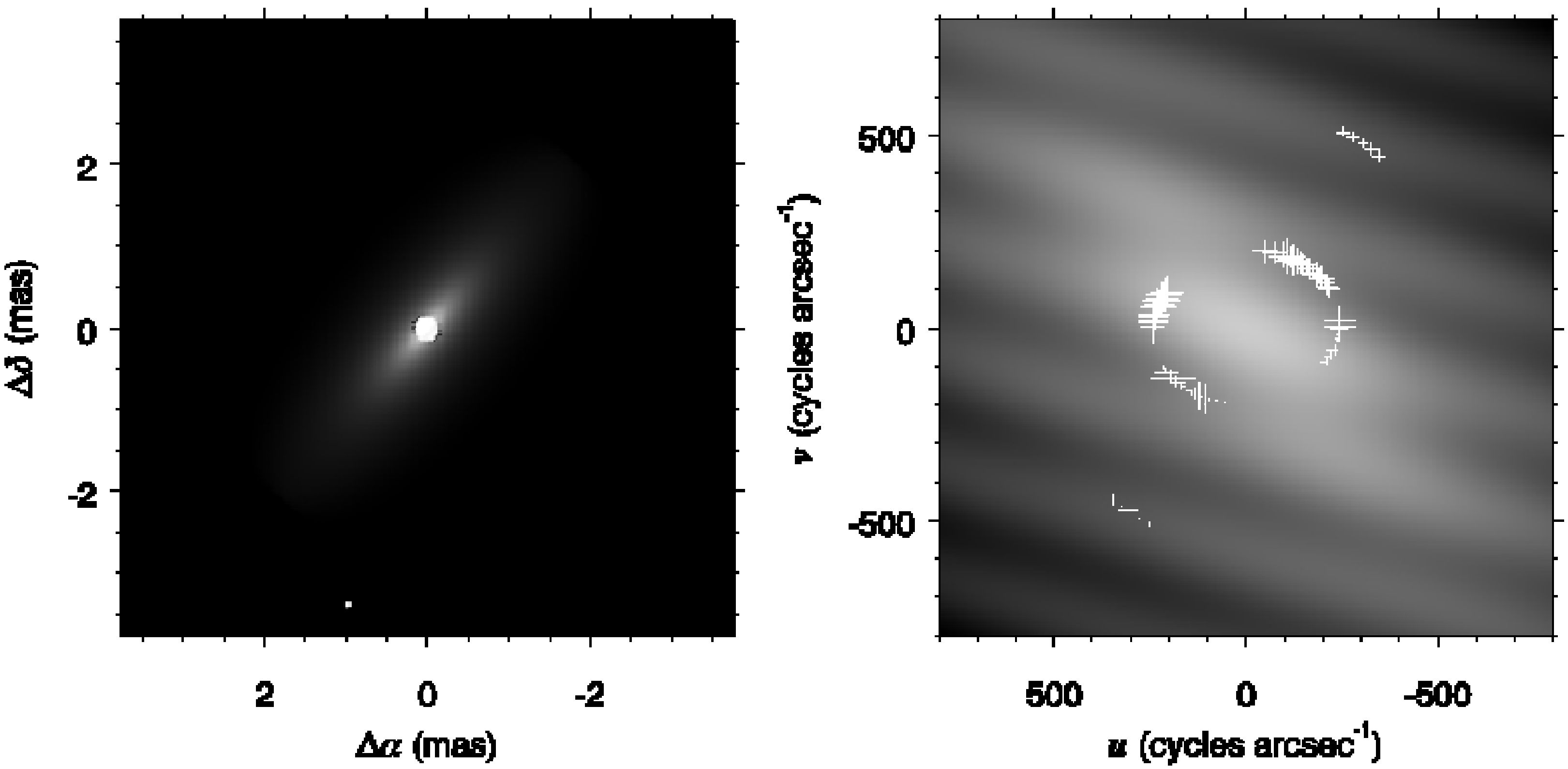
$\alpha=116^{o}$, $i=51^{o}$, $\rho_0=7x10^{\;\;11}$, $n=2.7$



ζ Tau: single star fit
$\alpha=38^o$, $i=90^o$, $\rho_0=2\text{x}10^{10}$, $n=3.1$



φ Per: binary with P = 126.7 d
α=49°, i=69°, ρ_0=1x10^{11}, n=1.8

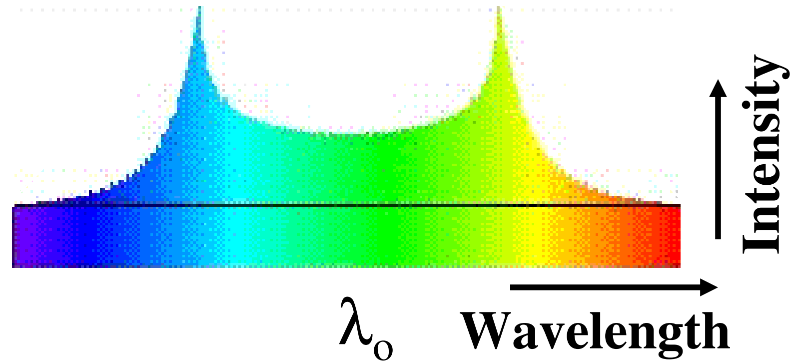


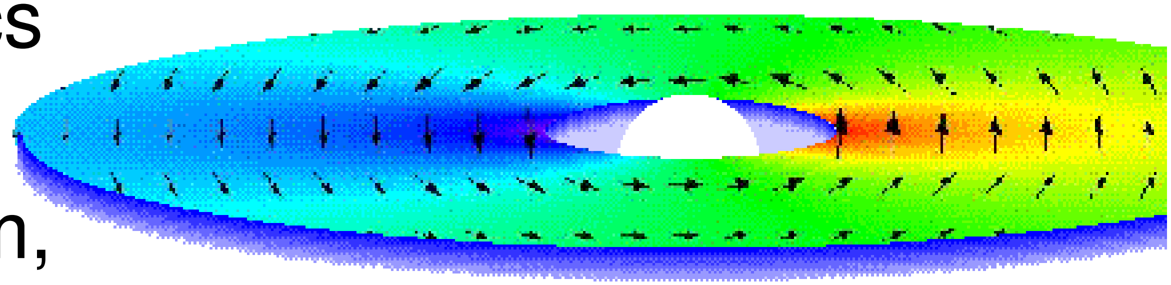
Results

- Disks appear smaller in *K*-band than in H-alpha but have similar geometric appearance (NPOI: Tycner et al. 2006)
- Total disk mass of 10^{-7} to 10^{-6} solar masses
- For disk filling time ≈ 1 year, angular momentum loss sufficient to spin-down stars during main sequence

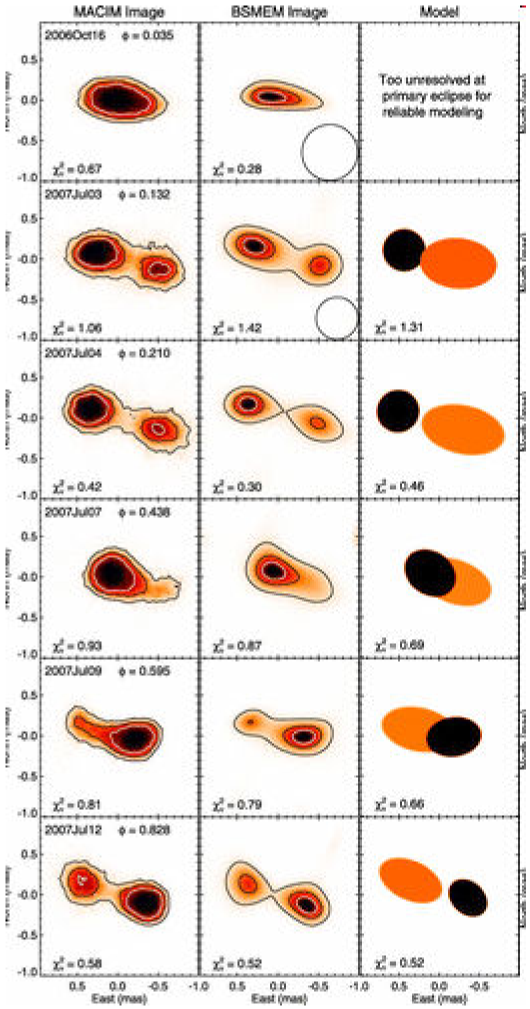
Upcoming for CHARA

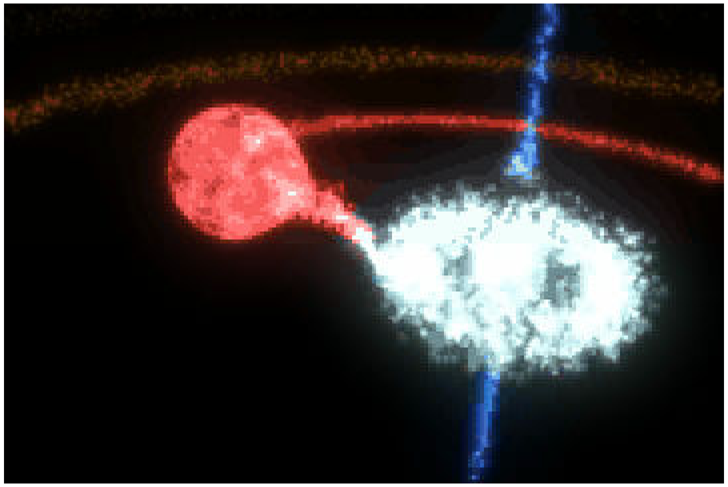
- FLUOR: precise *V* (Merand,Touhami)
- VEGA: spectral dispersion in optical for disk kinematics (Mourard, Stee)
- MIRC: multi-beam, *V* + phase for imaging (Monnier, Zhou)





Beta Lyr with CHARA MIRC (*H*-band)



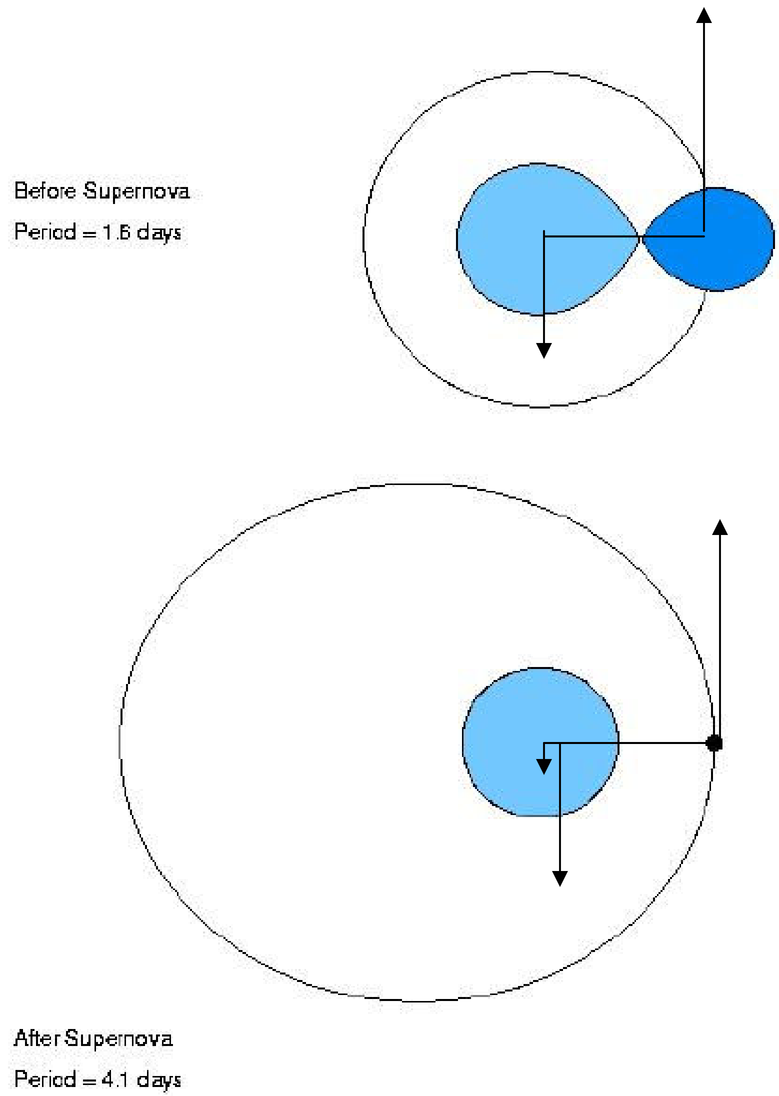


P **= 13 d**

Zhao et al. (2008)

Later Stages of Interacting Binaries: After the SN

- Donor usually less massive at SN
- Depending on SN "kick", binary may break up <u>or</u> survive with remnant in orbit
- Runaway star, speed ~ orbital velocity before SN

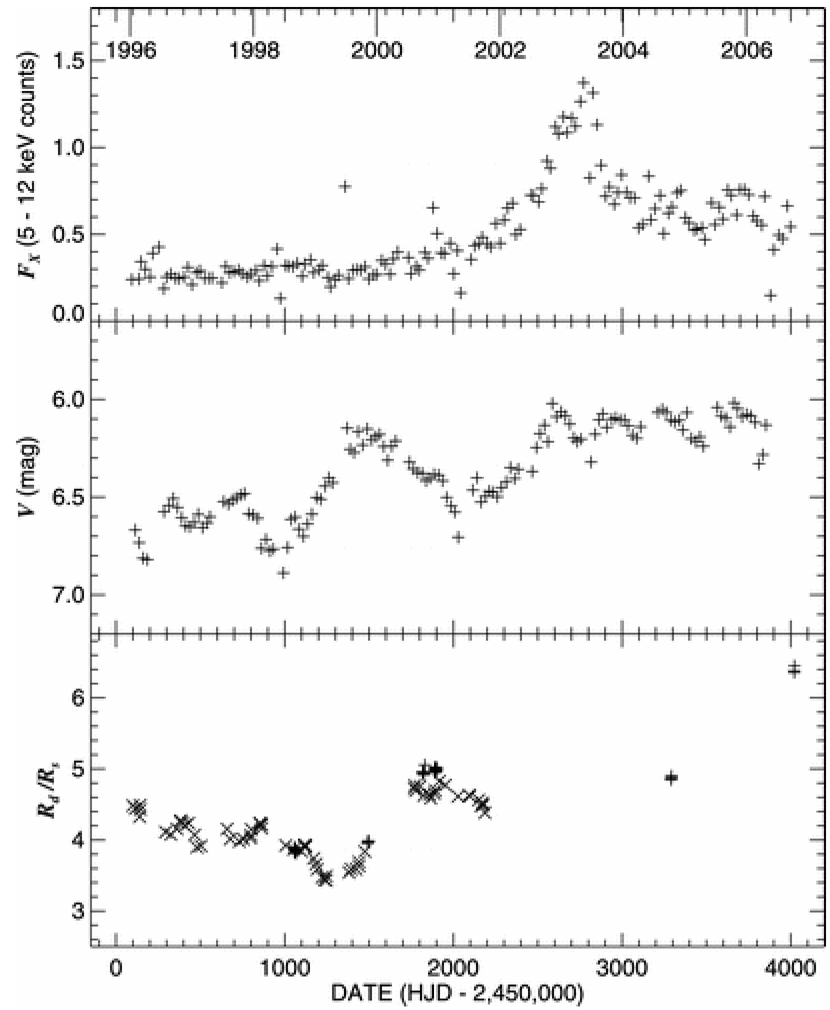


Later Stages of Interacting Binaries: OB Runaway Stars

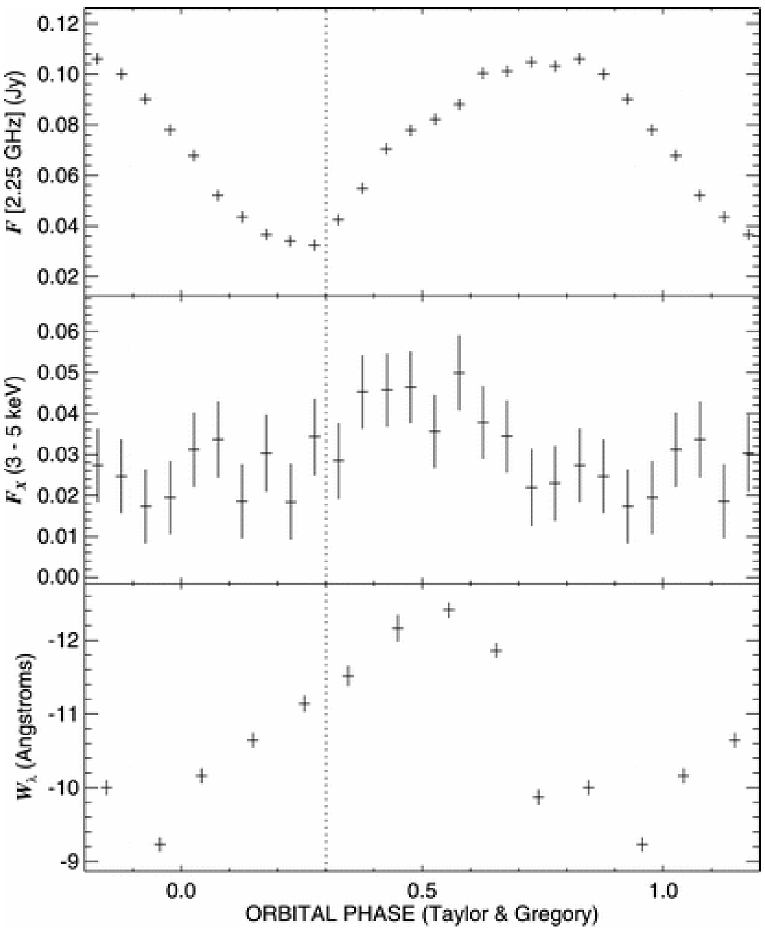
- Most are single (Gies & Bolton 1986) and rapid rotators (Blaauw 1993)
- Some were ejected by close encounters with binaries in dense clusters
- Some are SN survivors that remain bound with NS/BH companions:
  LS5039 (McSwain et al. 2004):
  P = 4 d; microquasar and TeV GR source
  HD14633 (Boyajian et al. 2005):
  P = 15 d; X-ray “quiet” binary

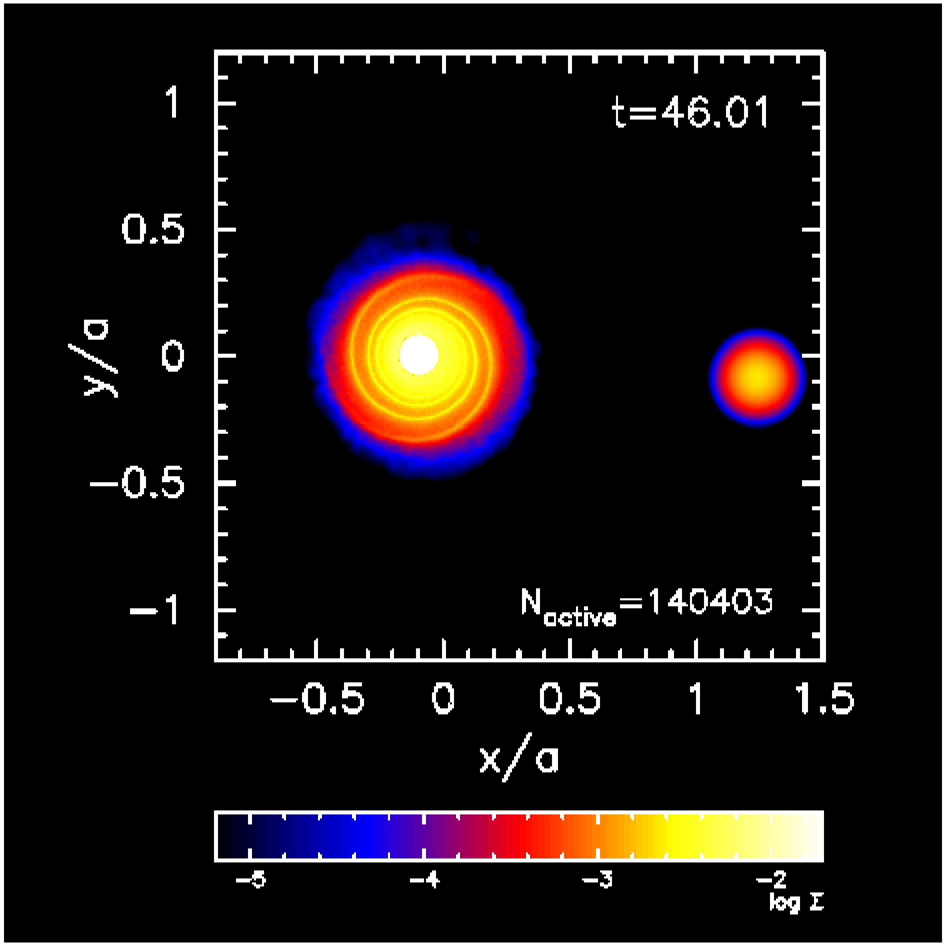
Mass "Return to Sender": Be X-ray Binaries

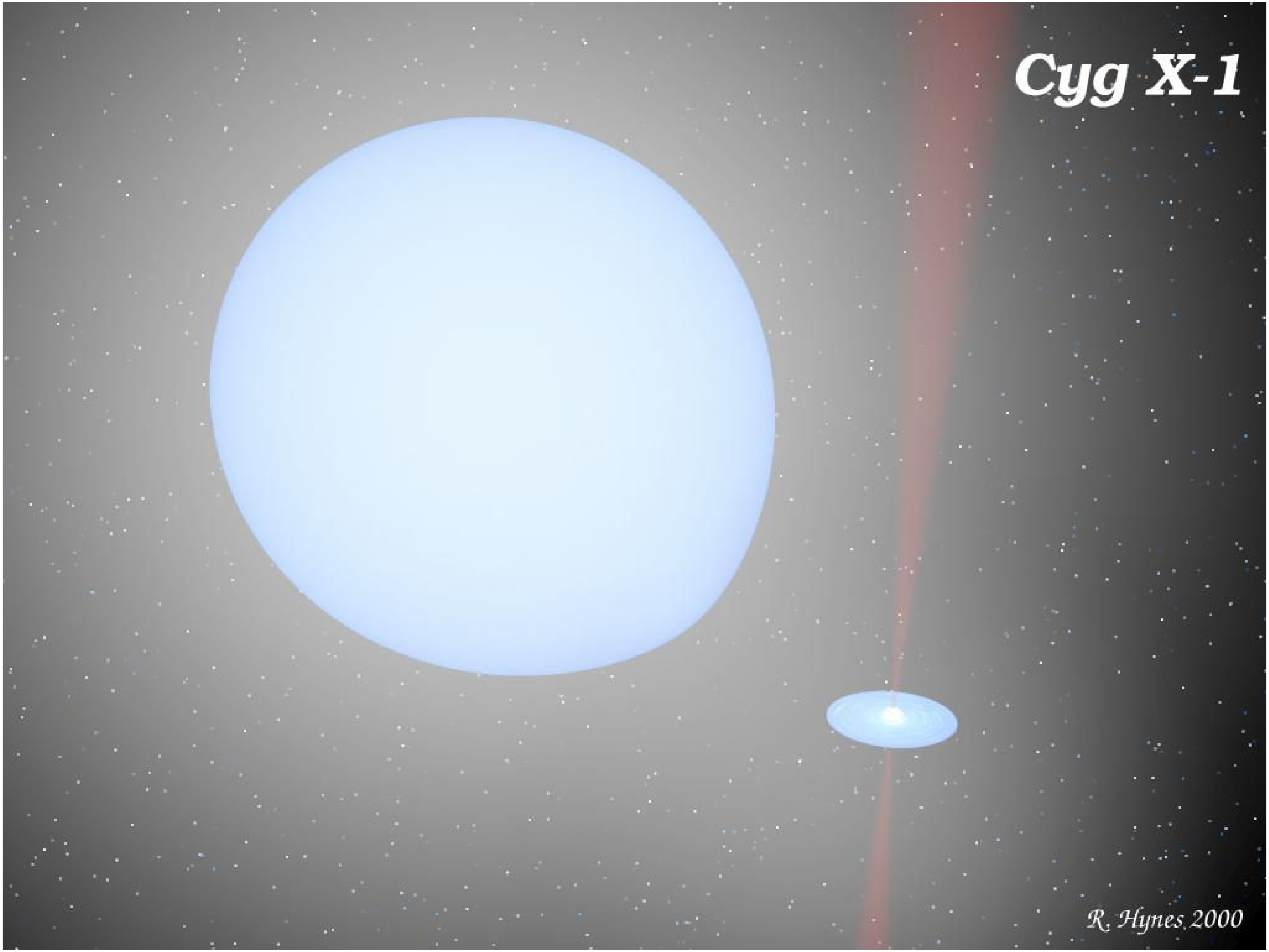
- *P* = 16 – 400 d,
  little tidal spin down
- Mass and angular momentum loss into circumstellar disk
- Disk growth promotes mass transfer to NS (X Per: see Grundstrom et al. 2007)



Disk limited by tidal resonances with NS;
Mass loss by disk spiral arms at periastron
(LS I +61 303: Grundstrom et al. 2007) (Okazaki et al. 2002)



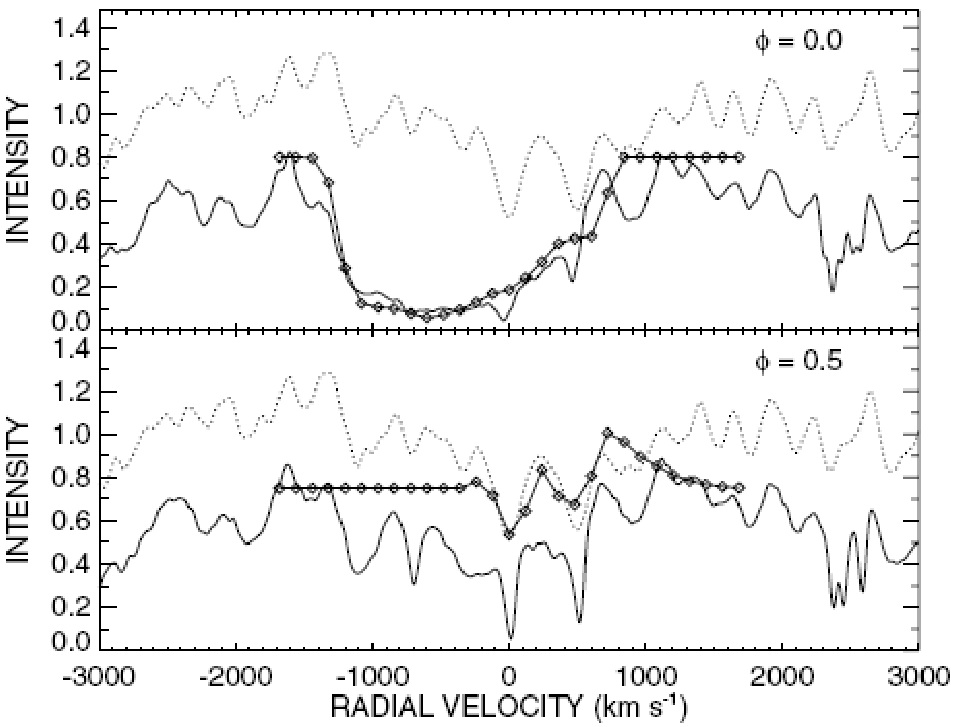


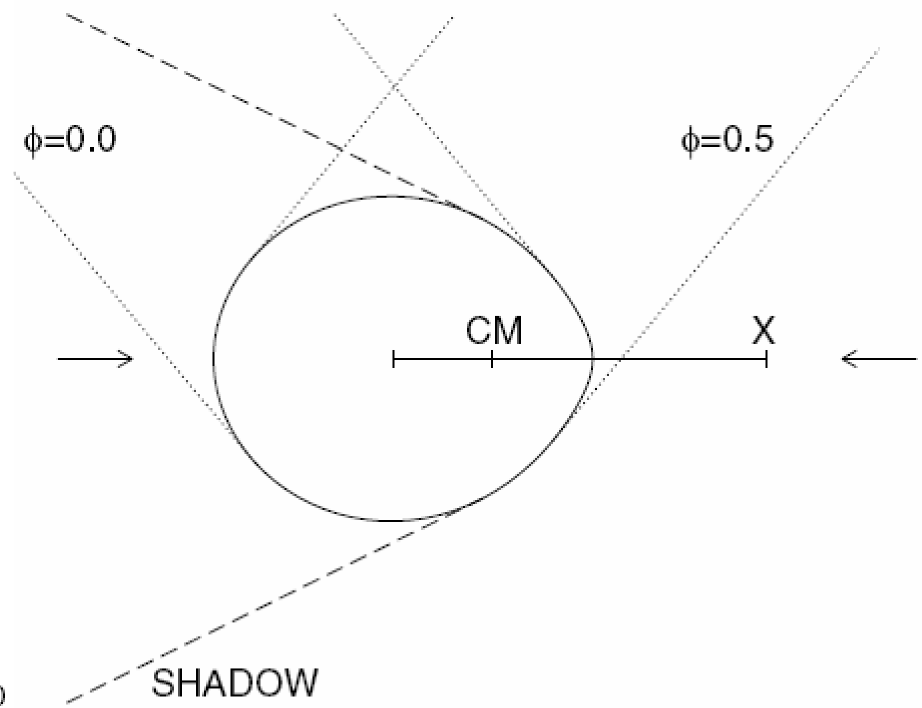

Cyg X-1
R. Hynes 2000

Evolved Roche-filling Gainers: Black Hole X-ray Binary Cygnus X-1

- O9.7 Iab + black hole, *P* = 5.6 d
- X-rays fueled by wind or stream capture?
- Gies, Bolton, et al. (2008): HST/STIS UV spectroscopy to explore mass transfer
- UV wind lines show that wind-driving atoms are fully X-ray photoionized: *shadow wind*
- He II 4686 emission suggests dense gas stream always present

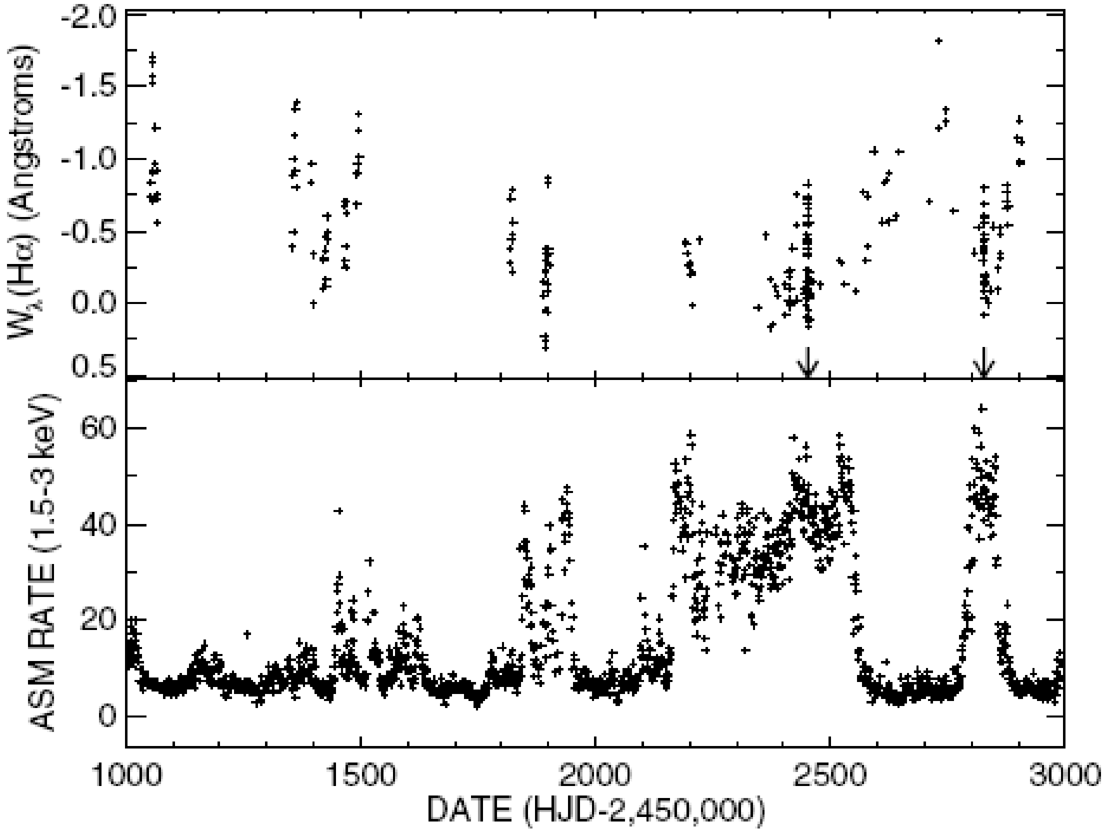
Shadow Wind in Cyg X-1

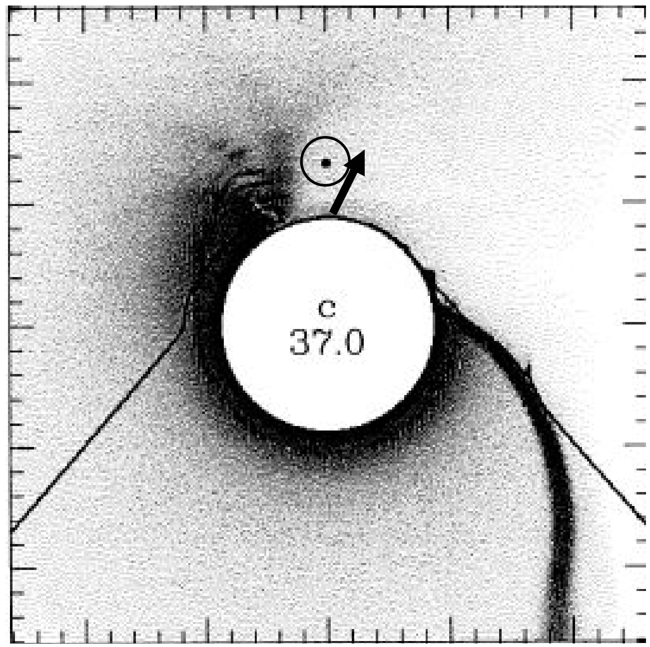




X-ray states in Cyg X-1:

Inverse H-alpha (wind) vs. X-ray (accretion) trend;
Strong shadow wind may inhibit BH mass accretion

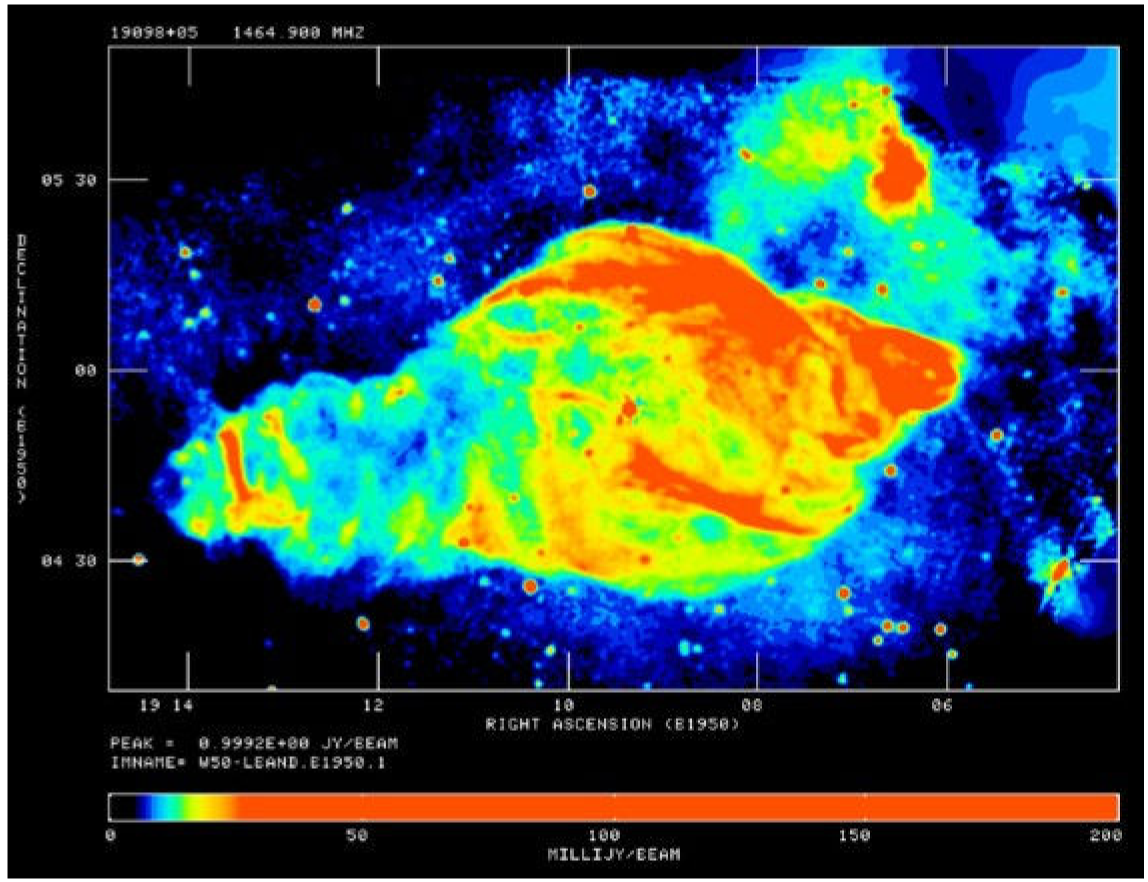




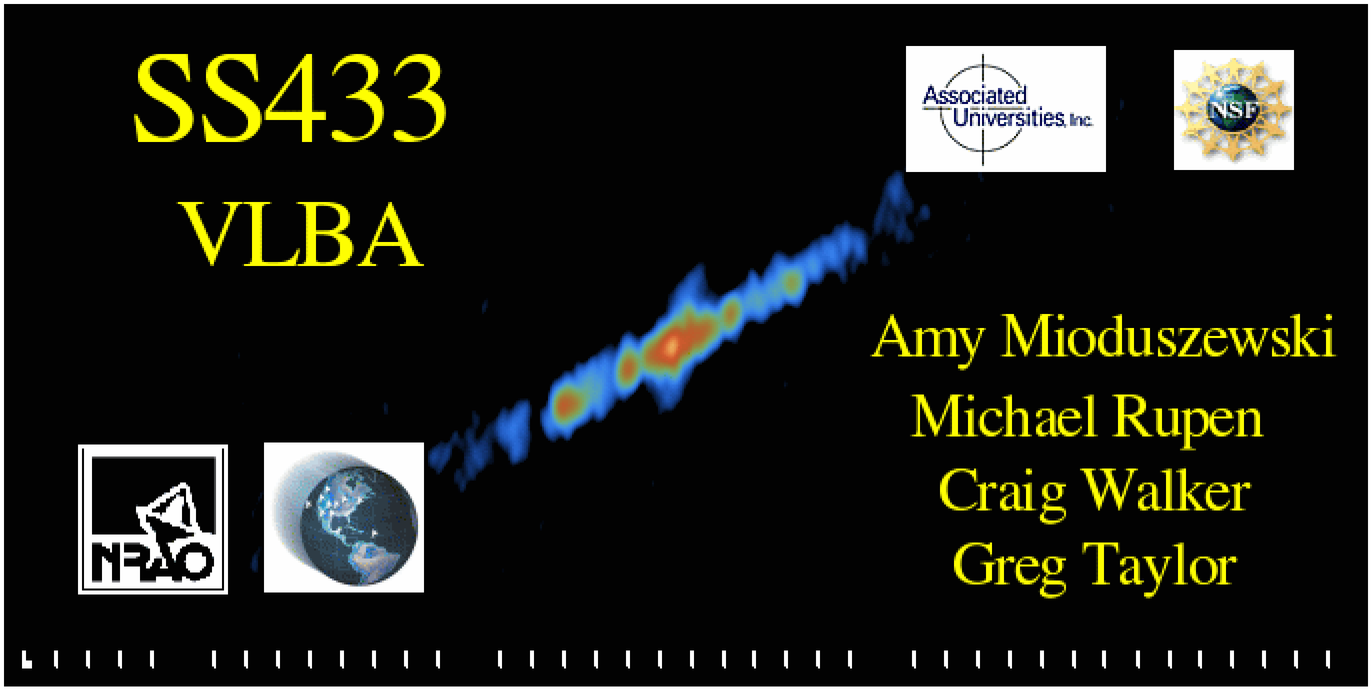
Blondin (1994)

Evolved Roche-filling Gainers: Super-Eddington Accretion in SS 433

- Example of recent SN (20,000 y old)
- Central object is a massive binary emitting relativistic jets (0.26 *c*)



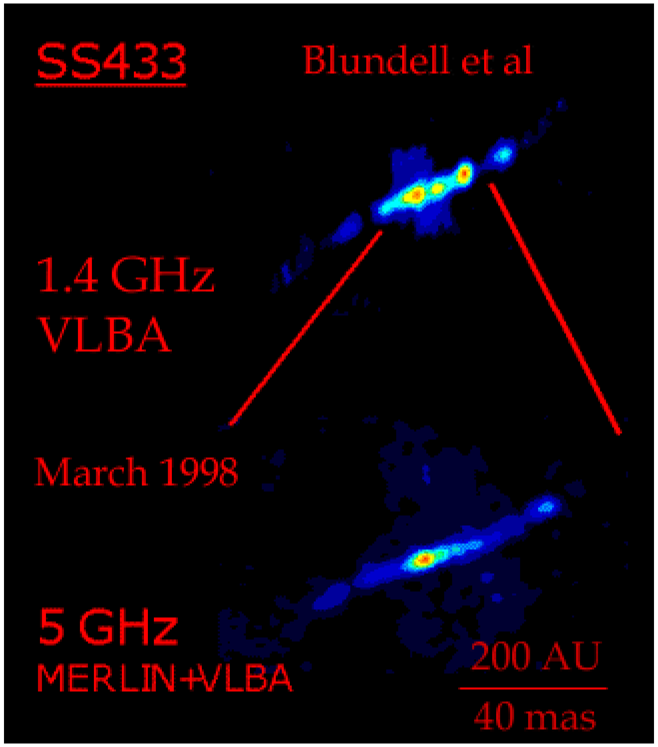
Precessing Jets in SS 433



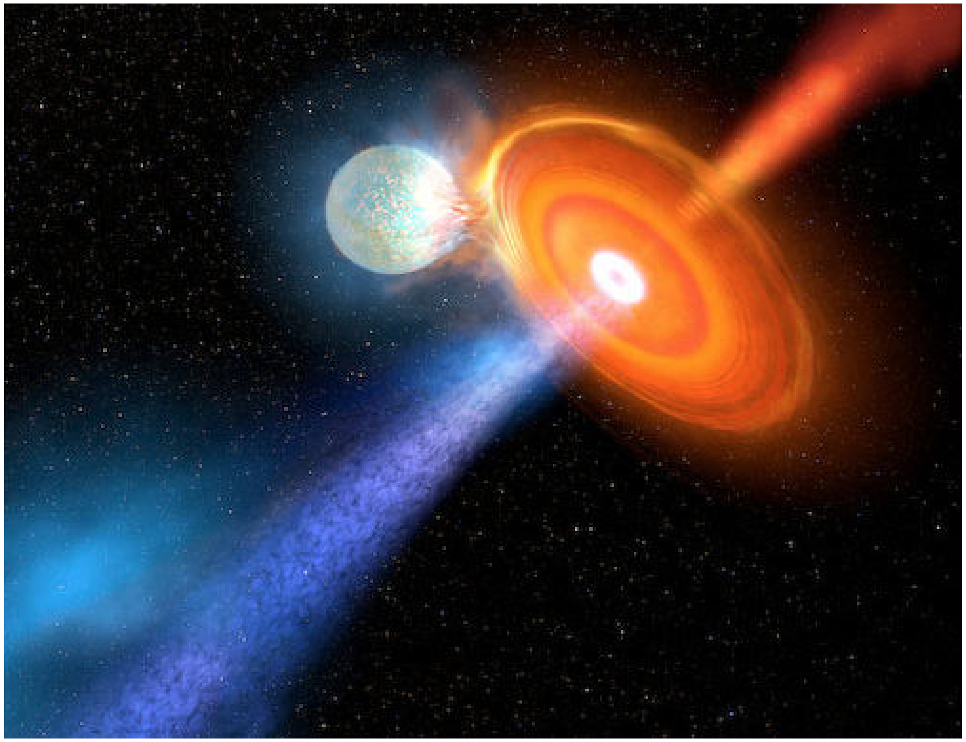
VLBA: 42 days covering roughly 1/4 of the precession period

SS 433 Mass Loss: jets and disk

- Circumbinary disk

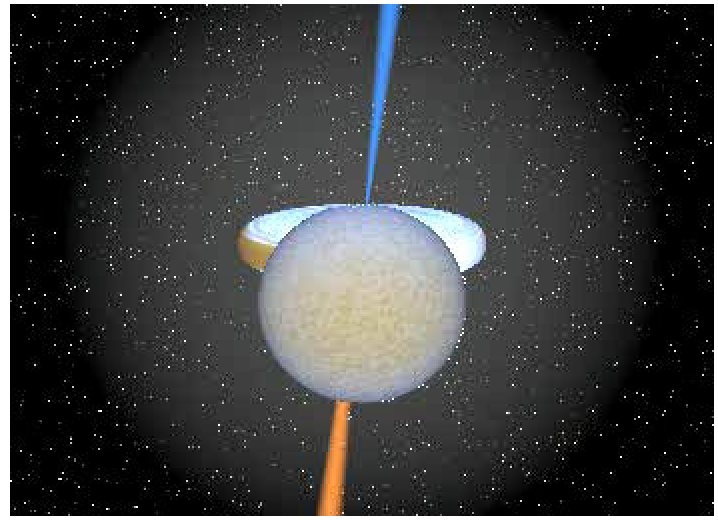


- Mass loss into jets, disk wind, CB disk



Detection of the SS 433 Donor: A-supergiant filling Roche lobe

- Best opportunity: donor in front and above disk
- Hillwig & Gies (2008): *Gemini* blue spectra, lines of A3 I star
- Radial velocity curves + jet model inclination:
  12.3 M_{sun} A-supergiant
  4.3 M_{sun} black hole



Summary and Speculations

- Mass and angular momentum losses/gains play central role in evolution of massive binaries
- Importance for first generation of stars where massive stars predominate
- Messy process: binary loss in disks, jets, winds
- Limits on masses of black holes in binaries because of prior mass loss
- Consequences for nuclear processing yields (nuclear processed gas revealed, transferred)

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