The Most Massive Stars

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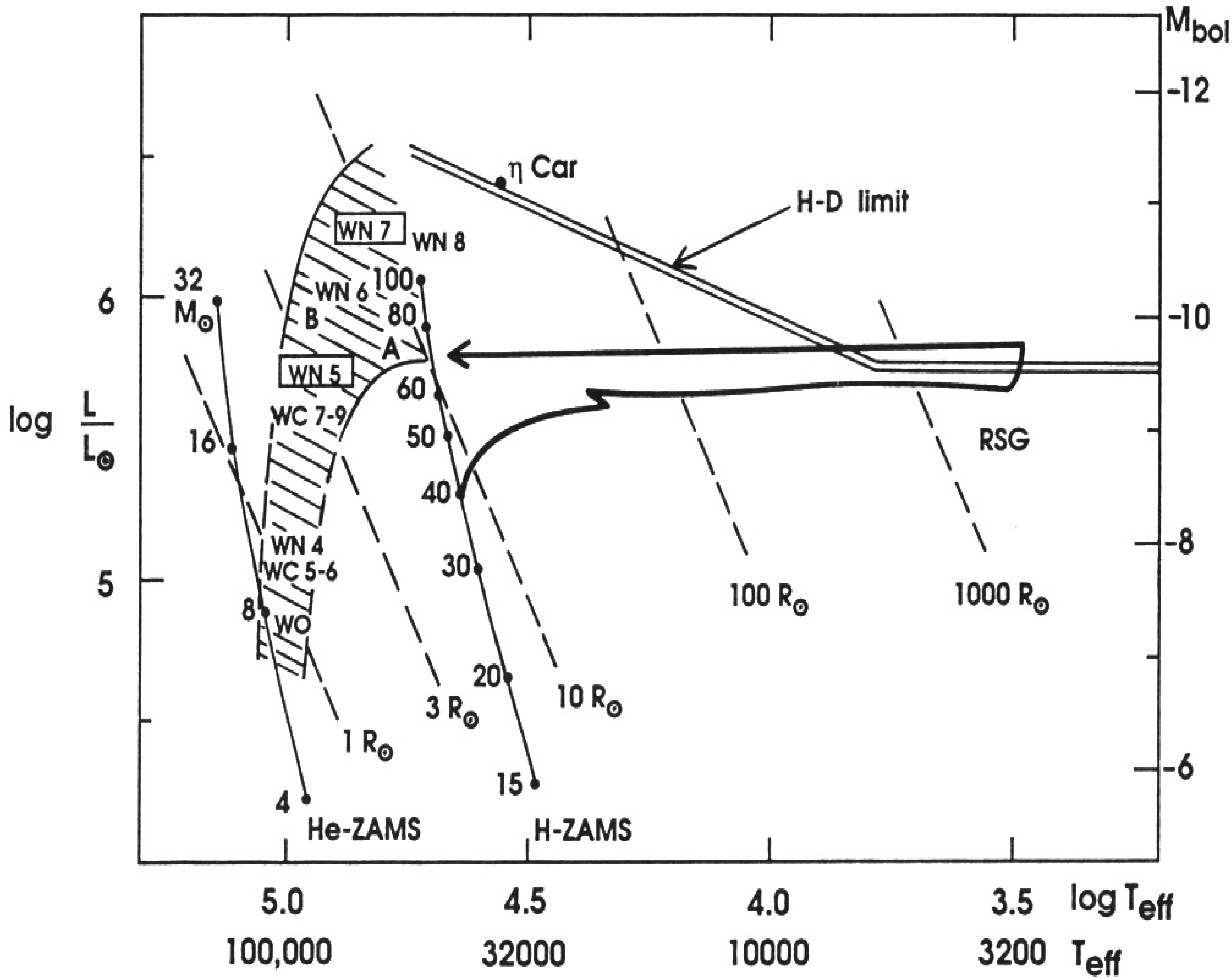
Massive Stars: What are they?

- **Definition:** reaches Fe/Ni core ($M_{init} > 8\ M_\odot$), but here: Concentrate on **O-type stars with $M_{init} > 25\ M_\odot$**
- Populate the upper-left part of HRD
  - Hot: Teff > 30 kK on ZAMS
  - Luminous: logL/Lsol > 5.0
- High Eddington factors (L/M ratios), close to radiative instability. If Eddington limit exceeded: **LBV (e.g. η Car)**
- Mass-loss through radiatively-driven stellar winds; affects stellar evolution (but depends on metallicity)



From Moffat+ 1989)

Massive Stars: Why bother? (1)

- very rare, yet they dominate the light of their host galaxies (cf. FUV/UV at high redshifts!)
- lifetimes < 5 Myr make for quick turn-over (1000's of generations of massive stars since Big Bang!)
- important for galactic ecology (early Universe!):
  - chemical enrichment: winds, SN explosion
  - mechanical feedback: winds, SN explosion; galaxy-wide superwinds can trigger star formation
  - ionization radiation: star formation, cosmology...
- kinematics of star clusters: gas expulsion via stellar winds and SN explosion; interaction with massive binaries

Massive stars: Why bother? (2)

- end their lives as core-collapse SNe (Type Ib,c)
- Type Ic SNe possible progenitors of GRBs
- form neutron stars and black holes...
- the most massive stars today are the best link to the supposedly ultra-massive Pop III stars

“Todays upper limit was yesterday's lower limit!”

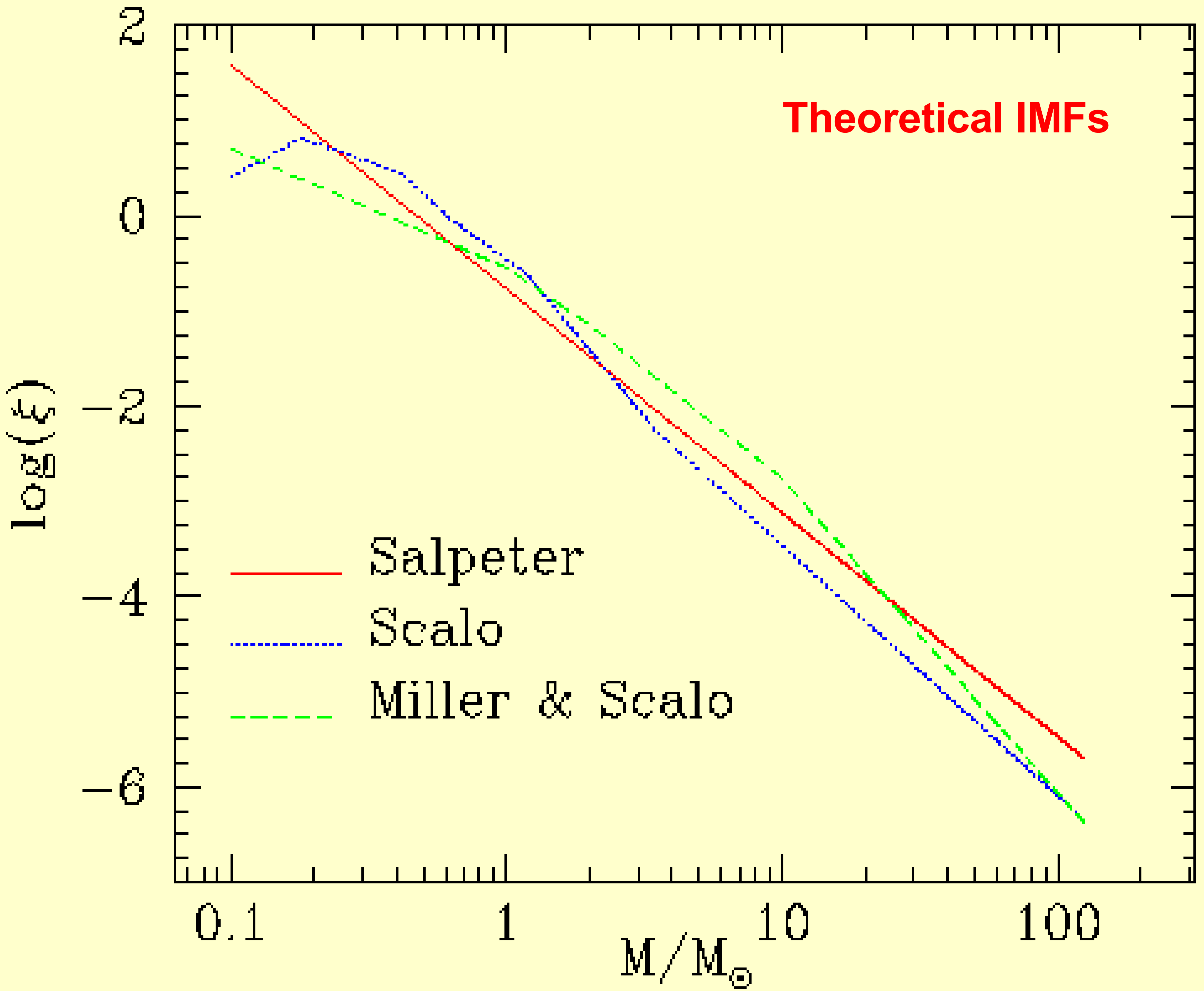
- one big question in massive-star formation research:

How massive can a star get? Is there an upper cut-off of the initial-mass function?

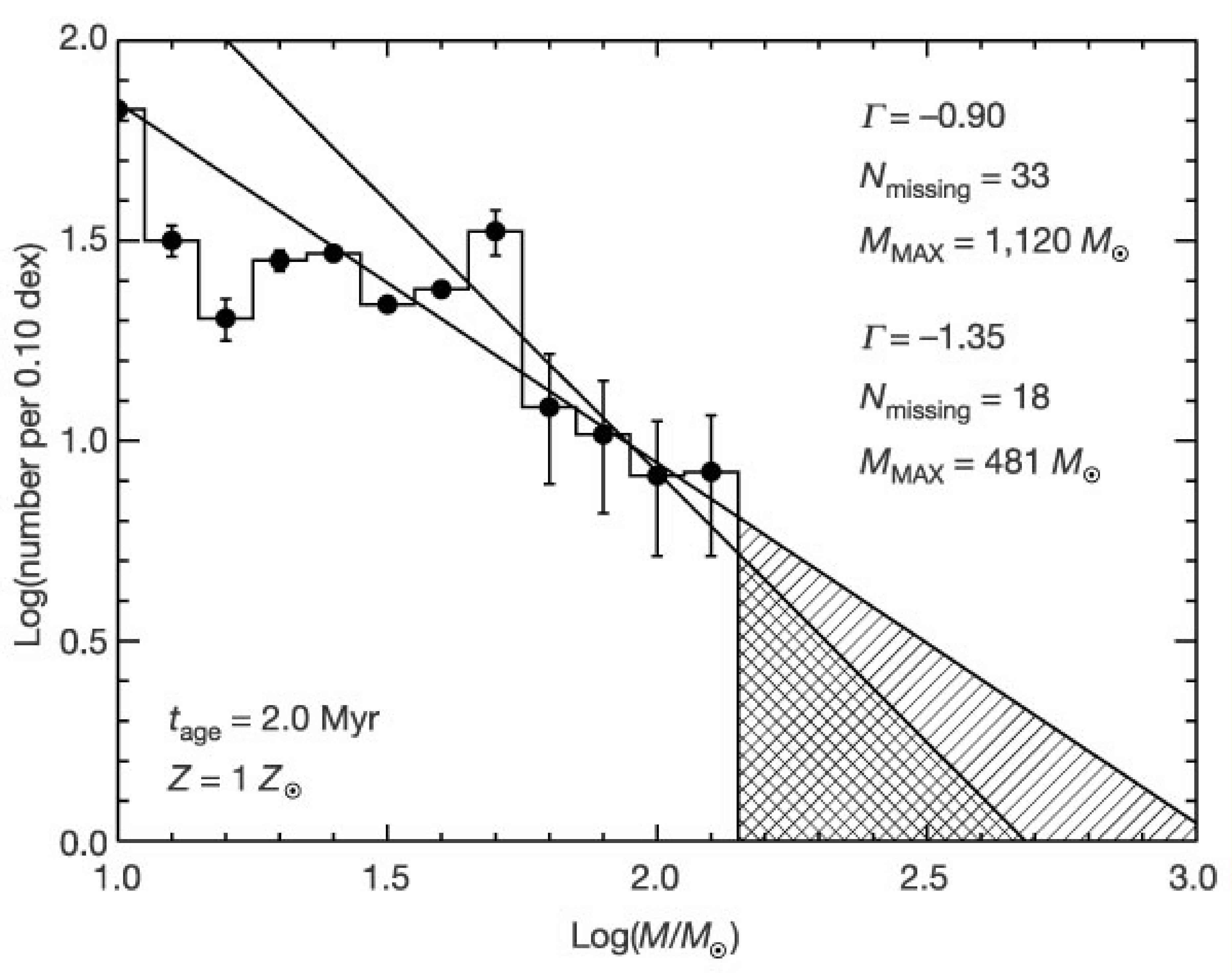
How massive are the most massive stars known?

- statistically, most massive star **$< 200\ M_\odot$** (Oey & Clarke 2005), but study used somewhat questionable approach
- from Arches cluster: IMF cut-off at **$\sim 150\ M_\odot$** (Figer 2005), but only used ill-known mass-luminosity relation to figure out stellar masses
  - for solar-type stars: $L \sim M^{4.7}$
  - for $10 < M < 25\ M_\odot$ $L \sim M^{2.5}$
  - for $M > 25\ M_\odot$ $L \sim M^{1.75}$
- utter lack of stars with directly confirmed $M > 40\ M_\odot$

Direct observations are required to calibrate the models!

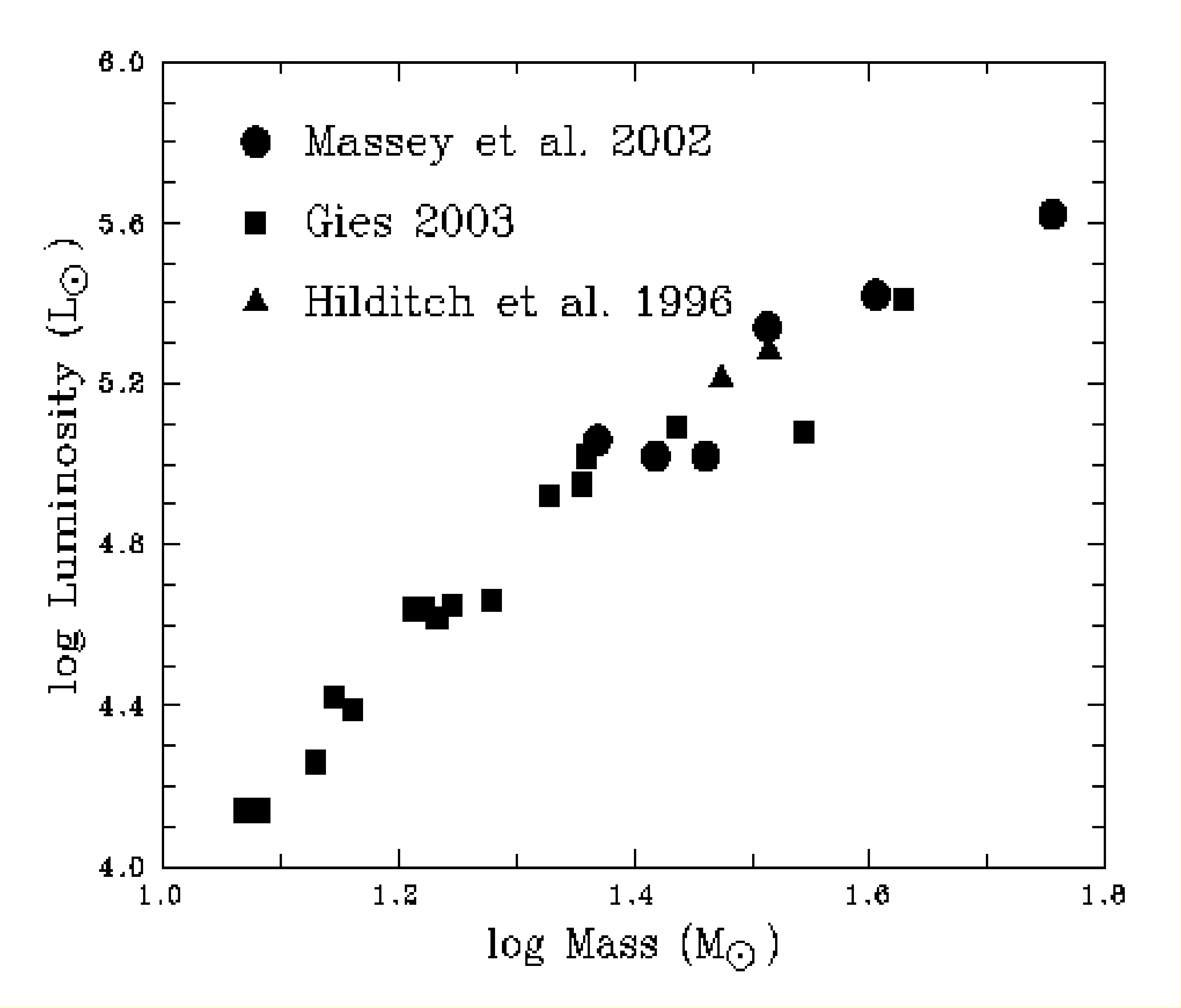


Theoretical IMFs
Salpeter
Scalo
Miller & Scalo
log(ξ)
M/M⊙
2
0
−2
−4
−6
0.1
1
10
100



Arches cluster IMF (Figer 2005, Nature)

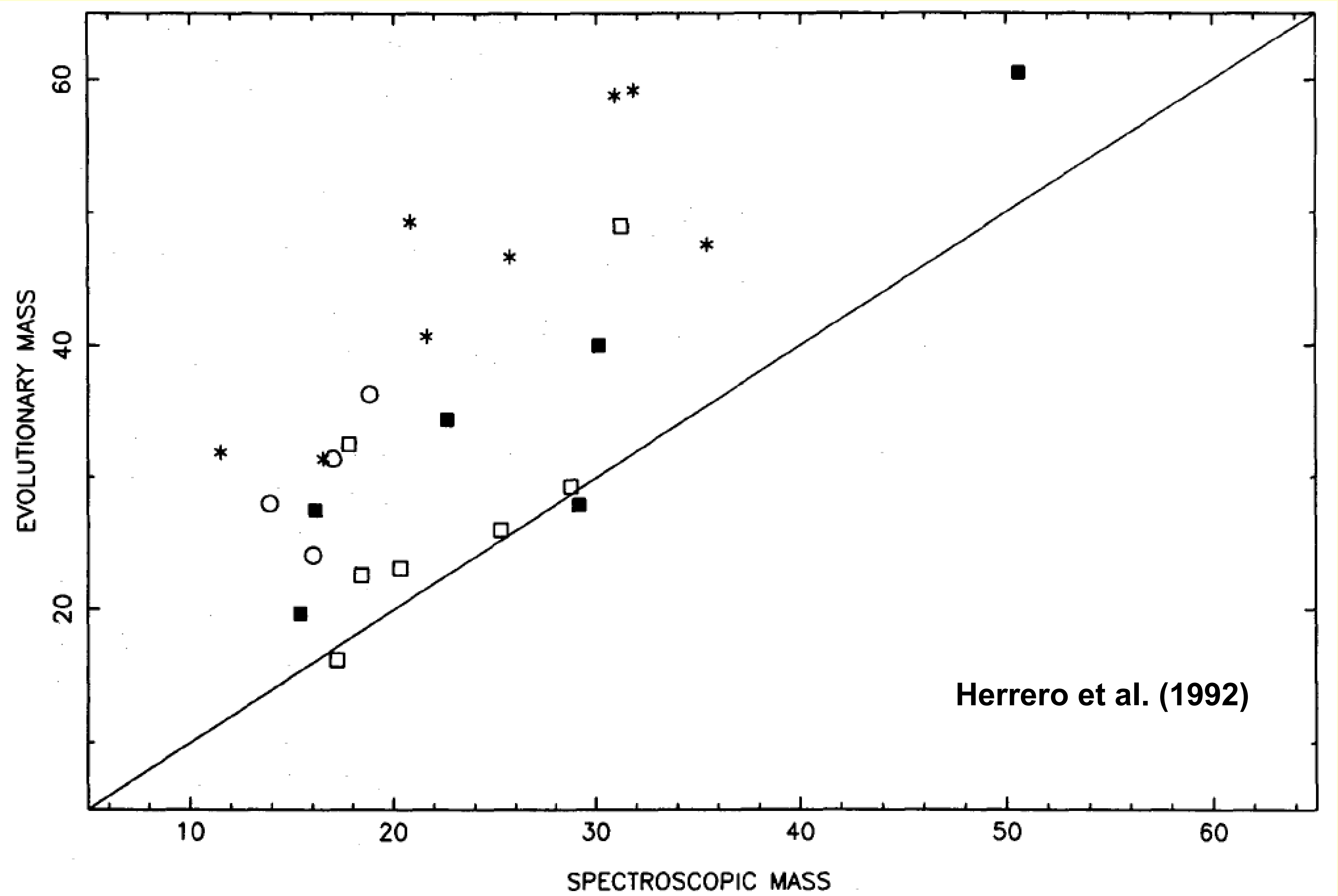
Mass-luminosity relation (log-log) for massive stars: Is it really flattening out toward very high masses?



How to “weigh” a star

- Use atmosphere models (spectroscopy) to obtain stellar parameters L, M, R, Teff, g, etc.
- Very challenging if stellar wind optically thick: non-LTE...
- Models are NOT self-consistent!
- Evolutionary (internal structure) masses and spectroscopic masses don't match!: **“mass discrepancy”** (Herrero+ 1992)
- Model quality paramount: input physics!
  - “mass dispcrepency” somewhat remedied by latest models (inclusion of iron in opacity data)
- Good calibrations required: observations!
  - … and at the high end of the IMF...?

The "mass discrepancy" (old atmosphere models for O stars)



OK, how to <u>really</u> weigh a star...

- Keplerian orbits in binaries yield the least model-dependent stellar masses! **BUT:** need orbital inclination (model!)
- surprising result: **O-type stars peter out at ~60 $M_\odot$**
- **Why?** More massive stars are luminous enough to drive optically thick wind, therefore:
  - display emission-line spectrum!
  - **look like Wolf-Rayet stars!**
- invariably from luminous subtype of WN stars: **WN5-7h/ha**

(Yeah, but I've learned that WR stars are evolved objects...?!)

What are Wolf-Rayet Stars?

- Spectrum of WR star is dominated by strong, broad emission lines of highly-ionized elements
- Stellar wind: fast (100-6000 km/s), massive (few 10^{-5} $M_{\odot}$/yr), dense and optically thick!
- Continuum from wind: hydrostatic surface is veiled!
- Emission from recombination (**square-density dependent!**)
- Little indication of physics in underlying star, but:

  classical WR stars are He-burning cores of evolved O stars!
- However, just like SNe: **definiton is purely morphological!**
- WR stars come in two flavors: WN, WC

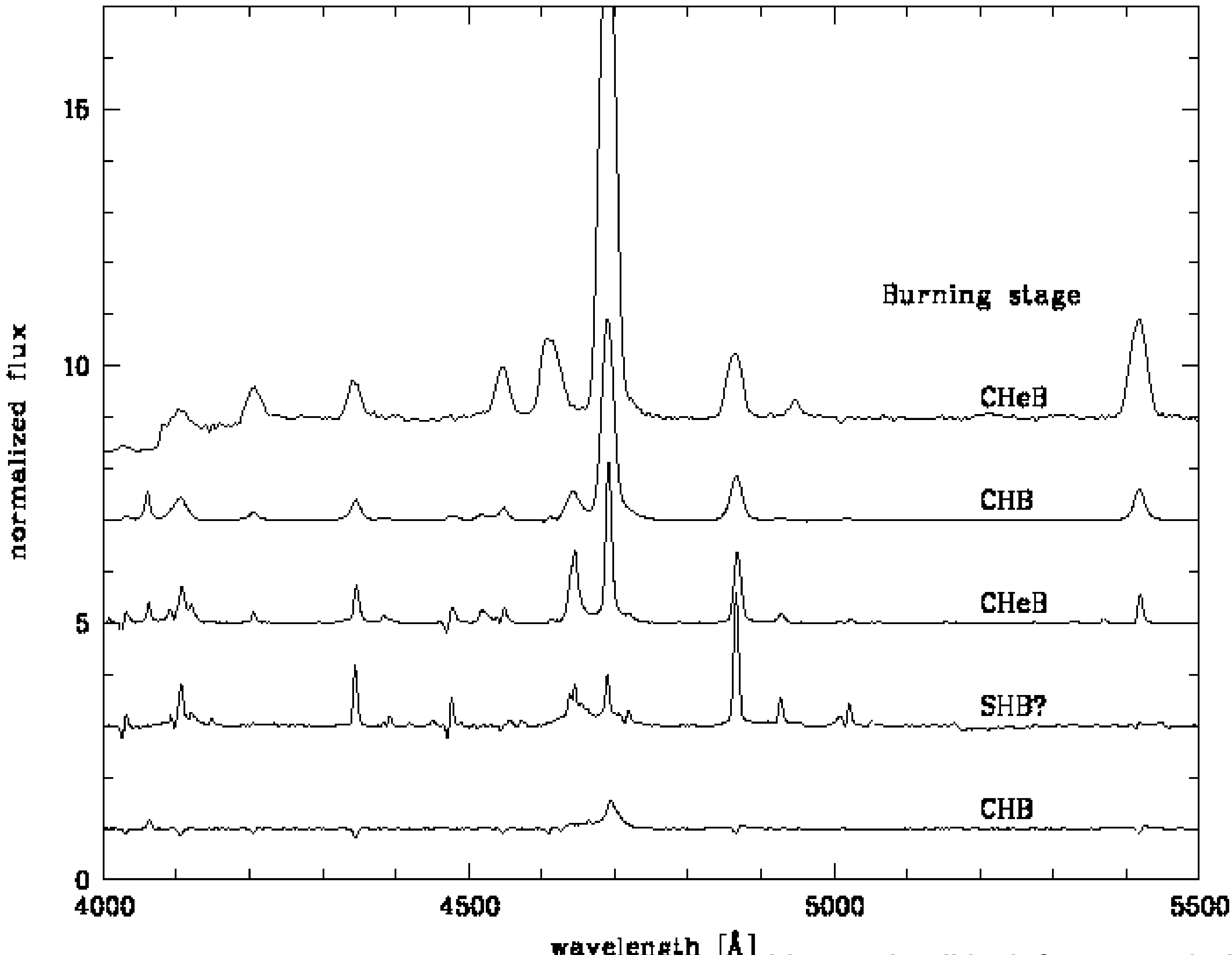
The Wolf-Rayet Zoo: WN stars

- **WN stars:** enriched with CNO elements (He,N), **all Pop I**
  - very late-type (WN10/11): shell-H burning objects with link to quiescent LBVs (S Dor variables)...
  - classical WN: core-He burning objects, with or without H, CNO in equilibrium
    - Type Ib (no H) SN progenitors?
  - luminous WN5-7h: core-H burning, most extreme O stars ("super-Of stars"); enriched, but not in CNO-equilibrium
  - H content between 30 and 75% by mass.

The Wolf-Rayet Zoo: WC stars

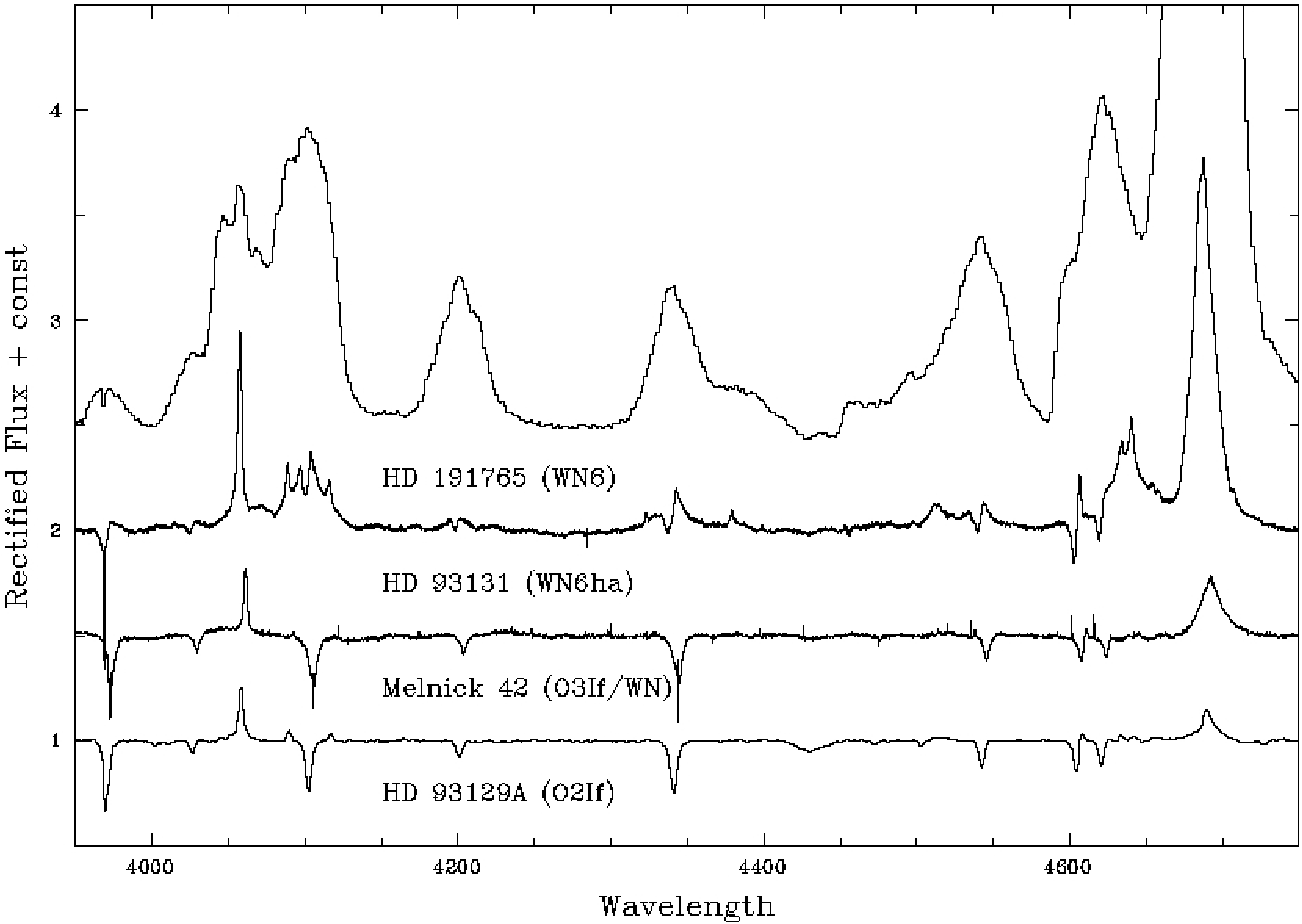
- **WC stars:** enriched with 3α elements (C,O)
  - classical WC/WO: advanced CHeB (evolved WN stars?)
    - Type Ic (no He) SN progenitors: GRBs!
    - Have fastest steady winds known: 6000 km/s
  - CSPNe: [WC], links to AGB and wD (Pop II);
    - [WN] elusive so far, can't exist?

Spectral appearance of WN stars vs. evolutionary state



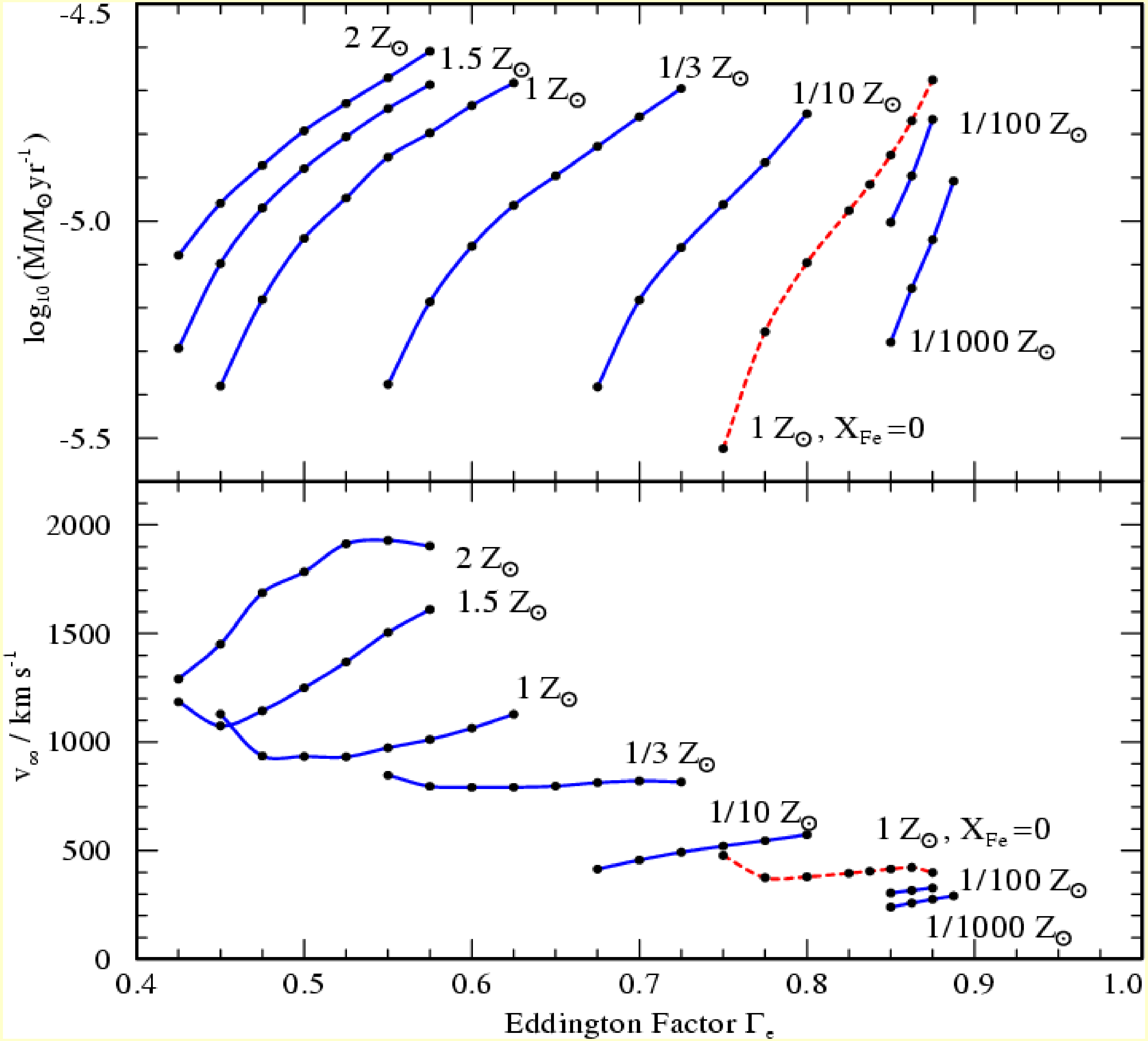
You can't tell jack from morphology!

Core-hydrogen burning (CHB) stars with different wind densities



Recombination rate depend on densities of both electron and ion: **squared-density effect!**

Mass-loss rates as function of Eddington factor and Z



Graefener & Hamann (2008)

Inventory: The most massive stars known (O/WN)

Name	SpecType	$M\sin^3 i$	i(°)	$M(M_\odot)$	Reference
R136-38	O3V+O6V		90	56+23	Massey+ (2002)
WR22	WN7ha+O	55+27	90?	55+27	Schweickhardt+ (1999)
WR25	WN6ha+O	75+27	37?	344+124	Gamen+ (2006)
WR20a	WN6h+WN6h		90	83+82	Rauw+ (2004,2005)
					Bonanos+ (2004)
WR21a	Of/WN+O	87+53	?	n/a	Niemela+ (2008)

Are there stars more massive than that?
If yes: where can we find them?

Where are the most massive stars?

- In clusters, there's a relation between the total mass of the cluster and the mass of the most massive cluster member (Weidner & Kroupa 2006): **The most massive stars are likely to be found in the most massive clusters!**
- **Mass segregation** (most massive stars in the cluster core)
  - either primordial or
  - happens dynamically in less than ~1 Myr
- **Thus, expect to find the most massive stars smack in the core of the most massive, young, unevolved clusters!**
- Goldilock problem: Not too young (molecular cloud), not too old (stellar evolution)

Best candiates in the Local Group

- LMC: **R136a**, the central cluster of the 30 Dor GHIIR
- Galaxy: **NGC3603**, a perfect clone of R136a's core;
  Arches cluster at the GC

Cluster	R136a	NGC 3603	Arches
location	LMC	MW (Carina)	MW (GC)
d (kpc)	50	8	8
M (Msol)	2×10^4	7×10^3	1×10^4
ρ_{core} (Msol/pc^3)	6×10^4	6×10^4	3×10^5
age (Myr)	2--3	1--2	2–3

First stop: NGC 3603

- Only starburst cluster in Milky Way outside the GC region
- Only visible Giant HII region in the Milky Way
- core is HD 97950
  - resembles closely the core of R136a (“perfect clone” of inner 1 pc)
  - but 7 times closer: spatial resolution!
  - extremely dense core: most massive stars are there!

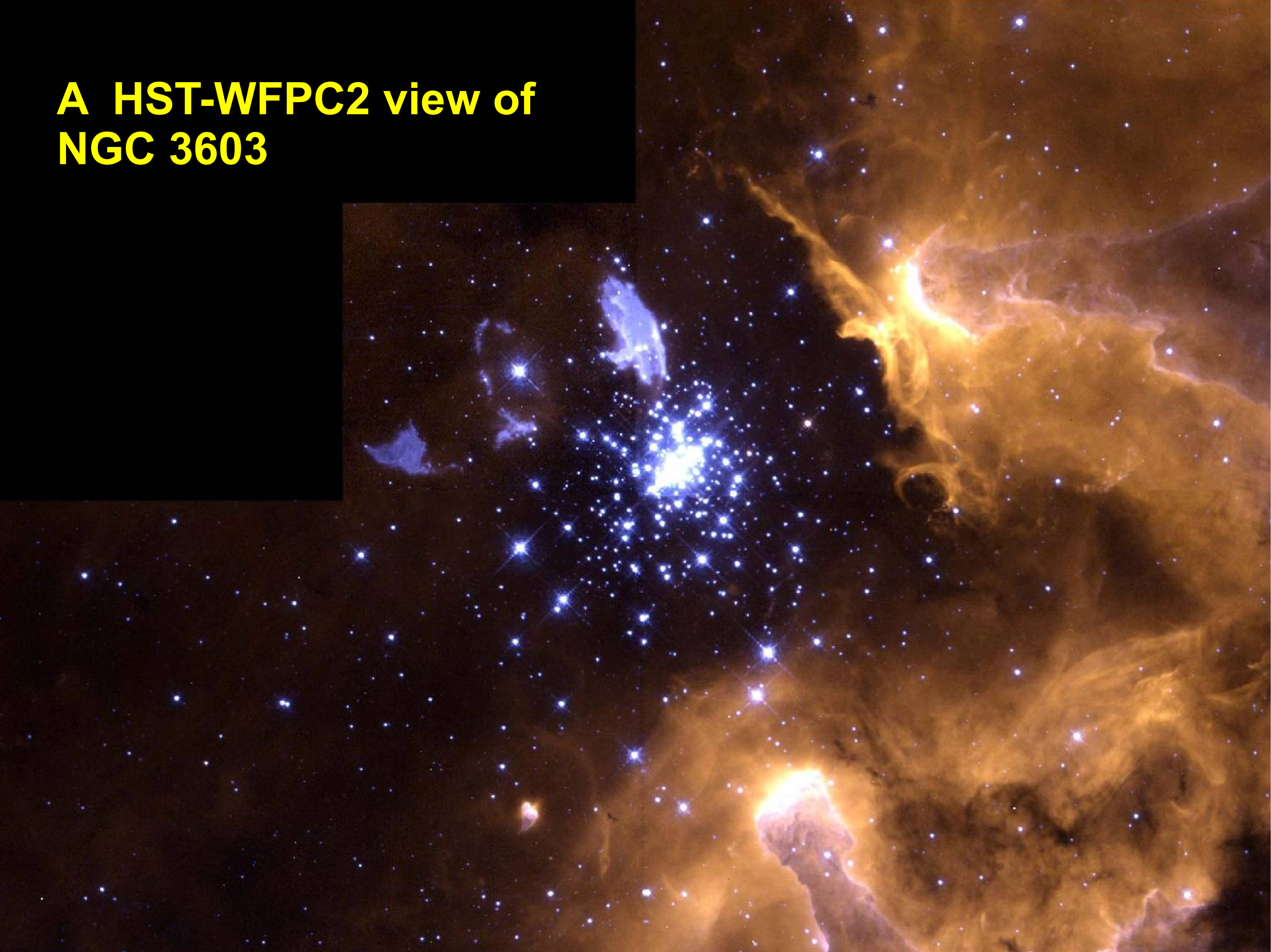
HD 97950 and its WNh content

Three WN6h stars A1, B, C in its core:

- A1 is intrinsically one(!) magnitude brighter than WR20a, which has a confirmed Keplerian mass of ~80 $M_\odot$!
- A1 is a 3.8-day binary and double-eclipsing (Moffat et al. 2004), i.e. with known orbital inclination angle!
- C is one of the brightest X-ray sources known among all WR stars: colliding-wind binary?

In order to obtain absolute masses for A1, just obtain radial velocities of <u>both</u> components!

A HST-WFPC2 view of NGC 3603



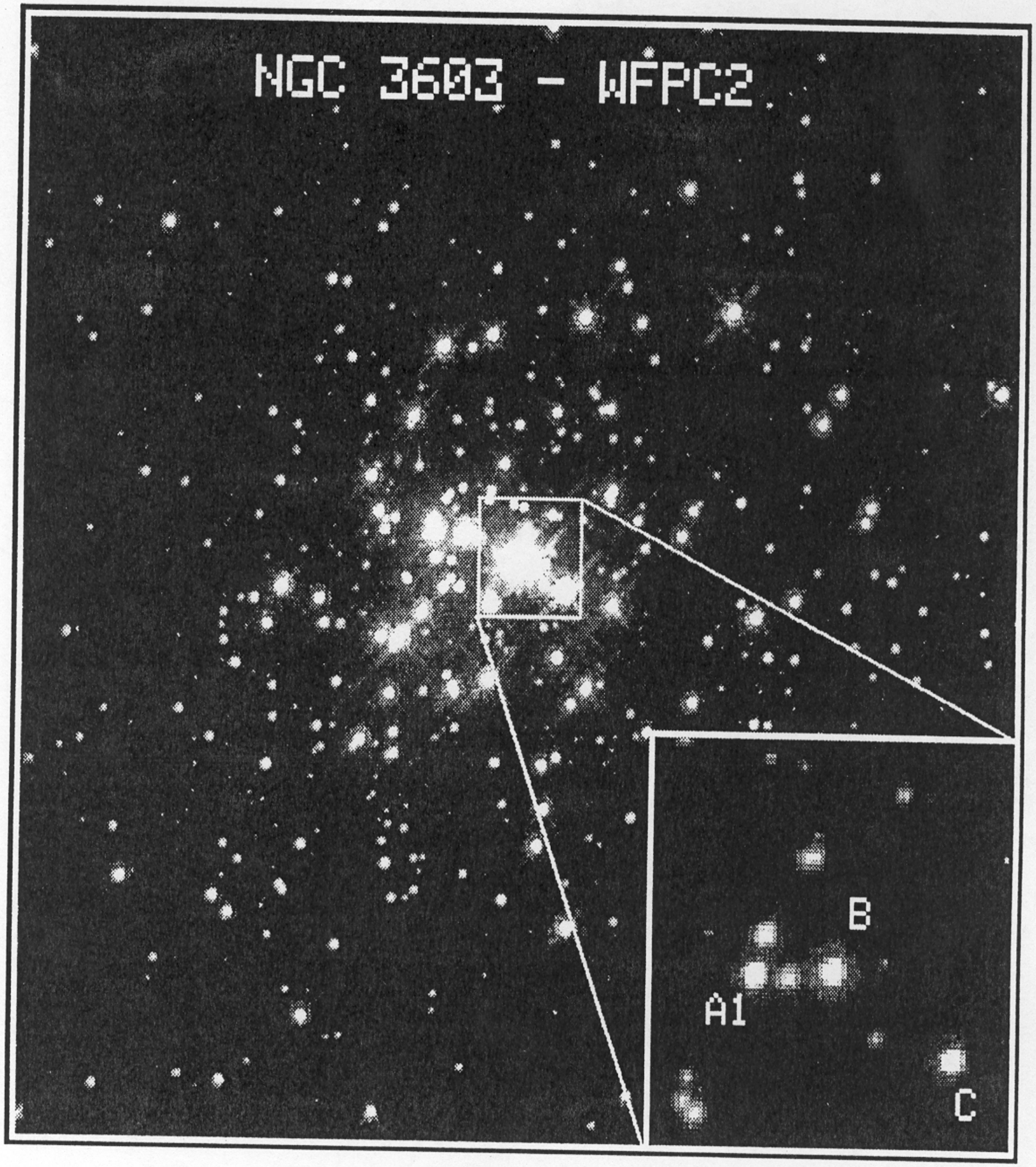


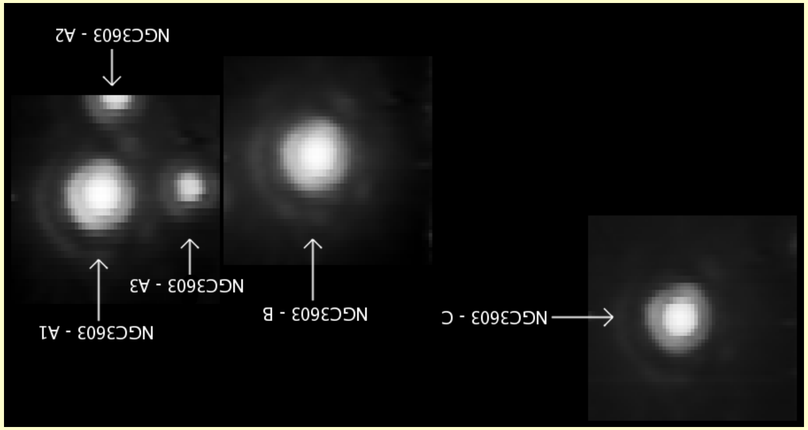
Figure 1. *HST*-WFPC2 *I*-band (F814W) image of NGC 3603. The image is 25″ × 25″ (0.8 pc × 0.8 pc). The insert shows the three WR stars.

To resolve individual stars in NGC3603 use:

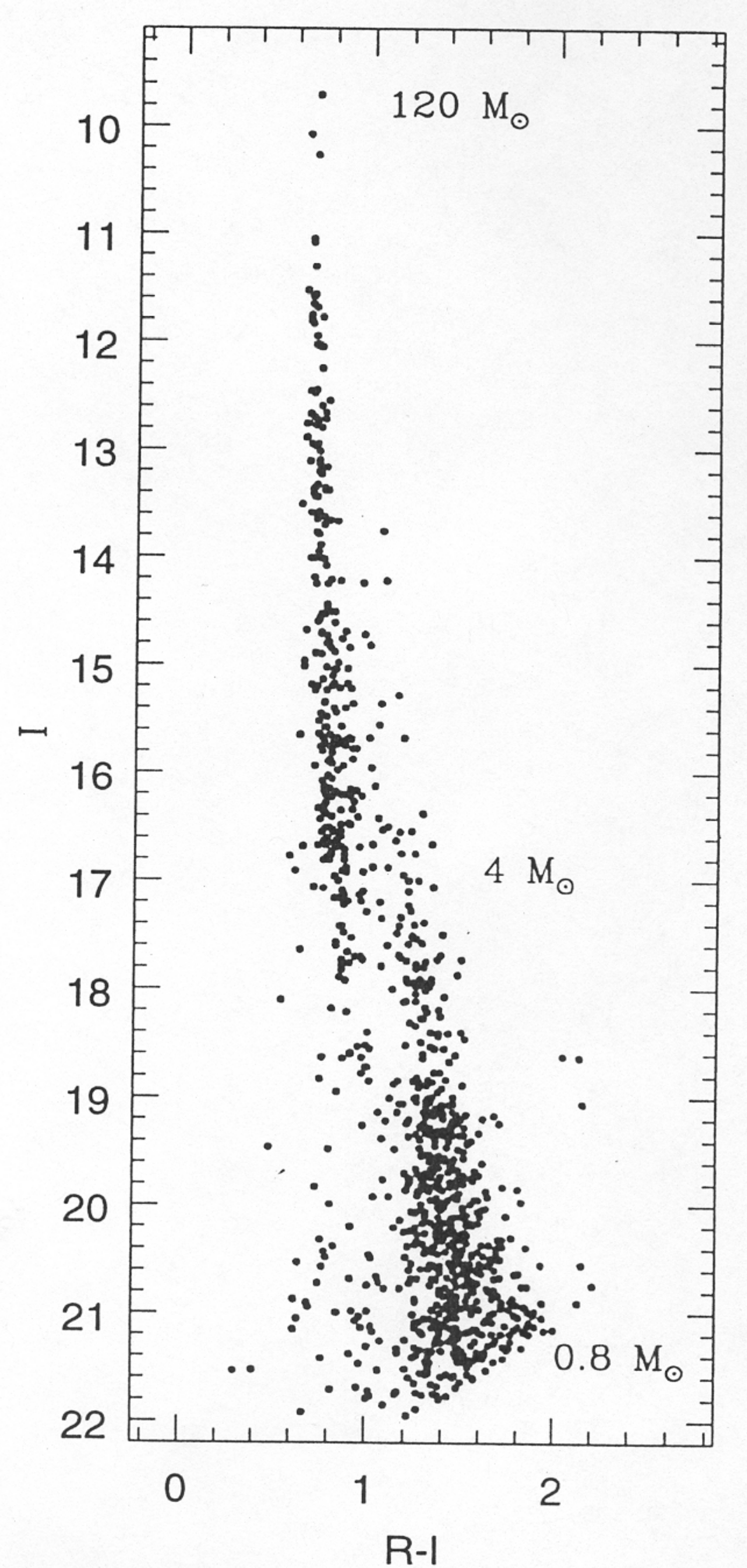
HST-WFPC/STIS

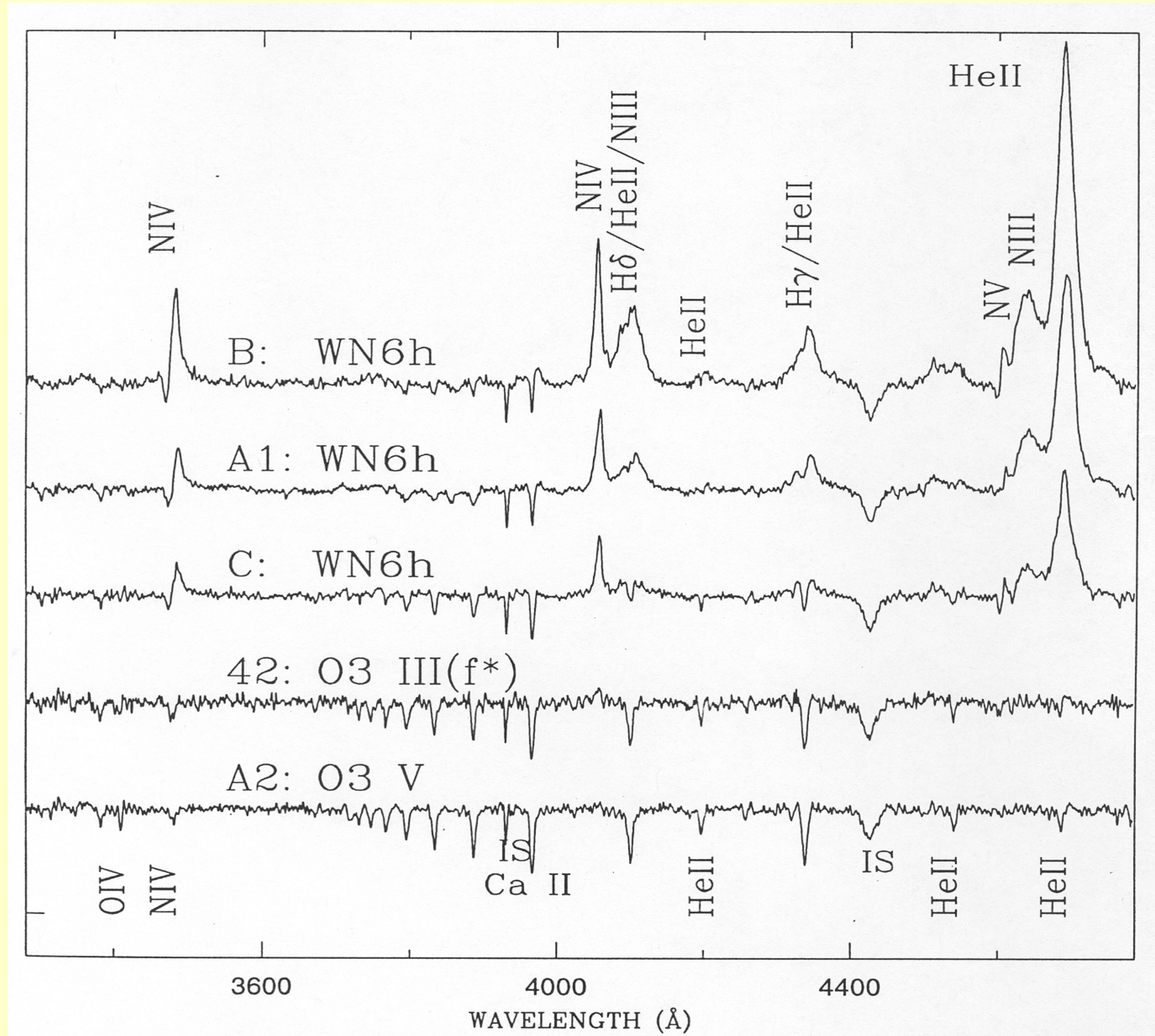
or

VLT/SINFONI + AO

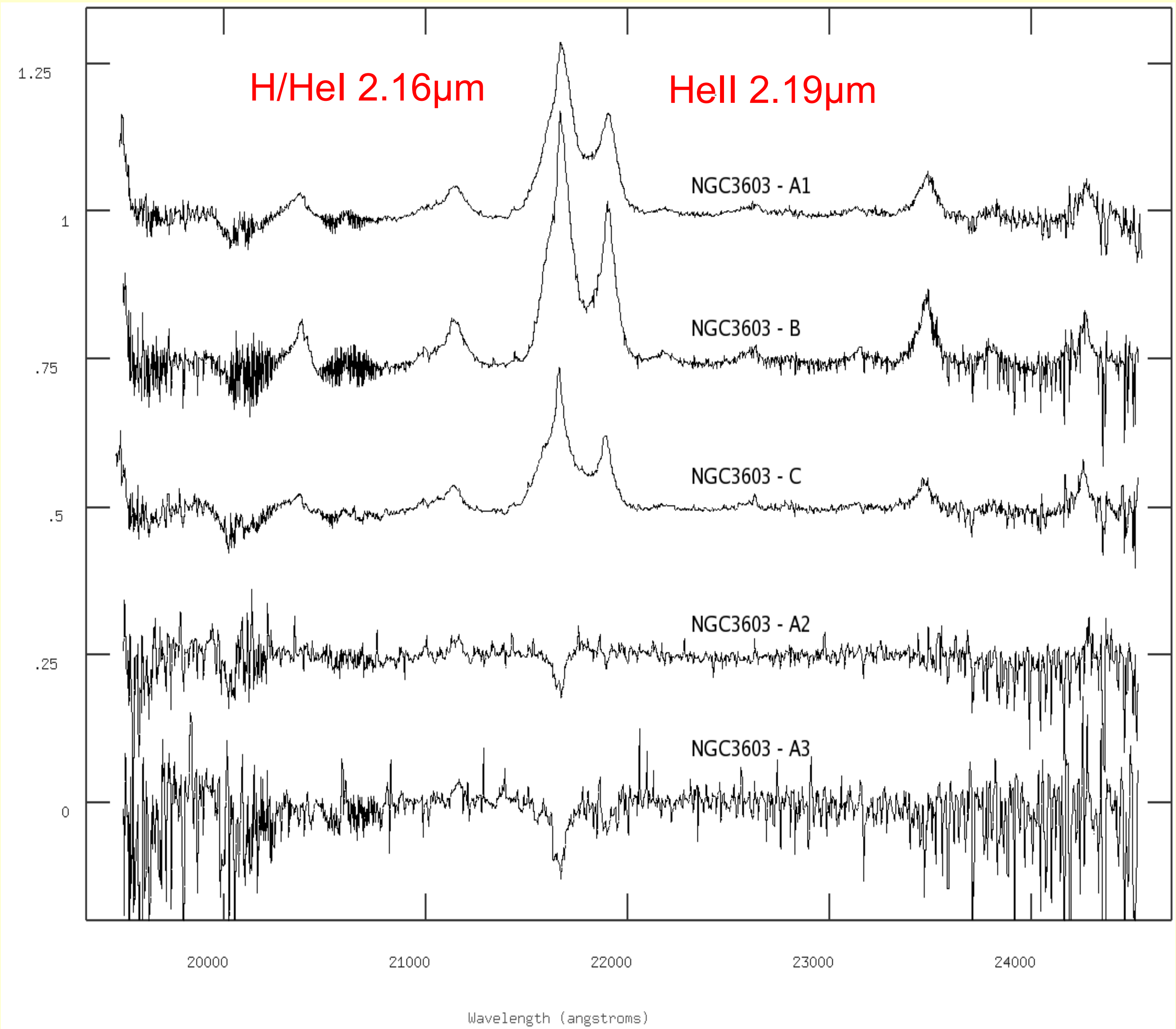


NGC3603: CMD (I vs. R-I) and HST-FOS optical spectra of the three central WN6h stars (Drissen 1999).



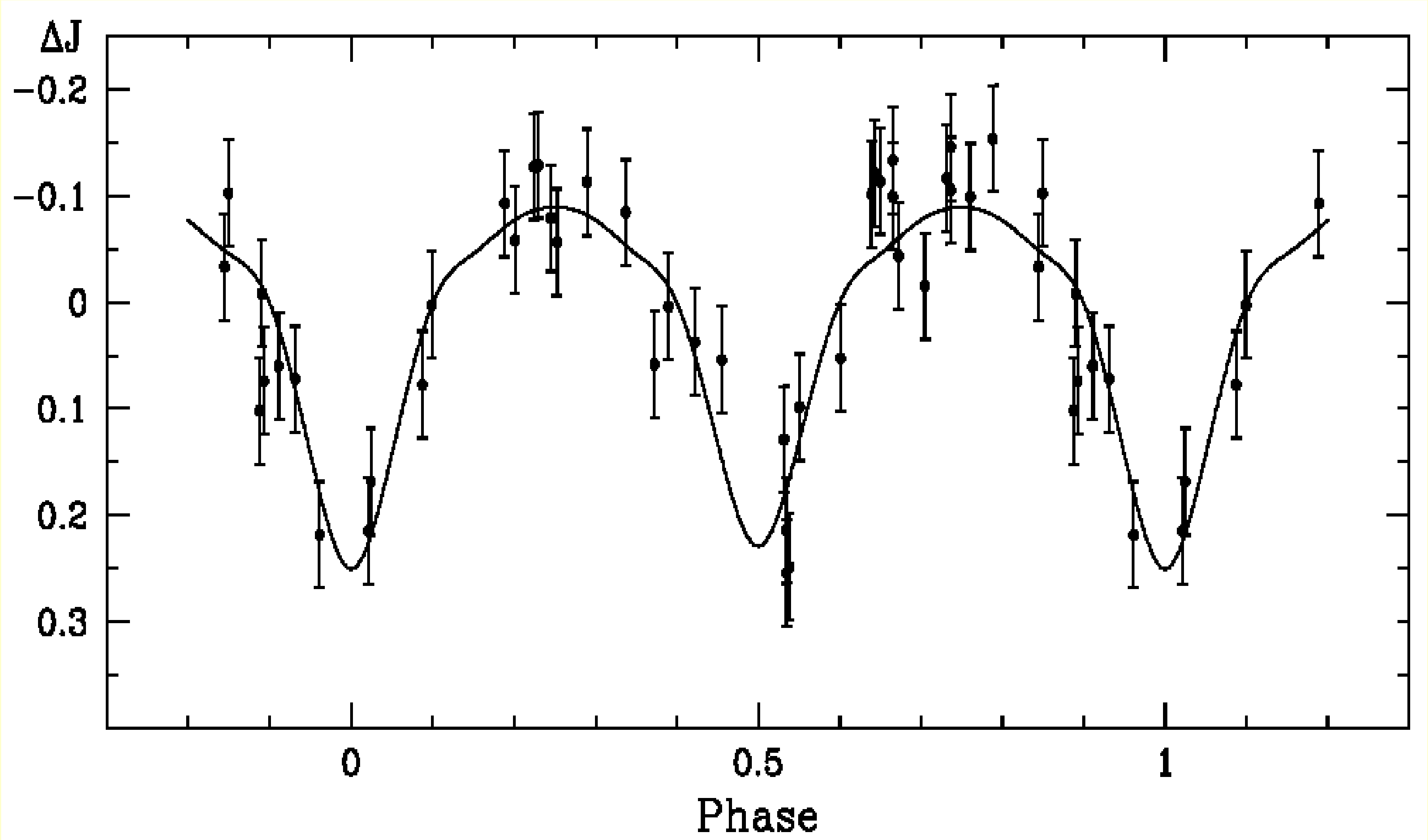


Obtain AO-assisted, spatially resolved, repeated spectroscopy with VLT/SINFONI in K-band



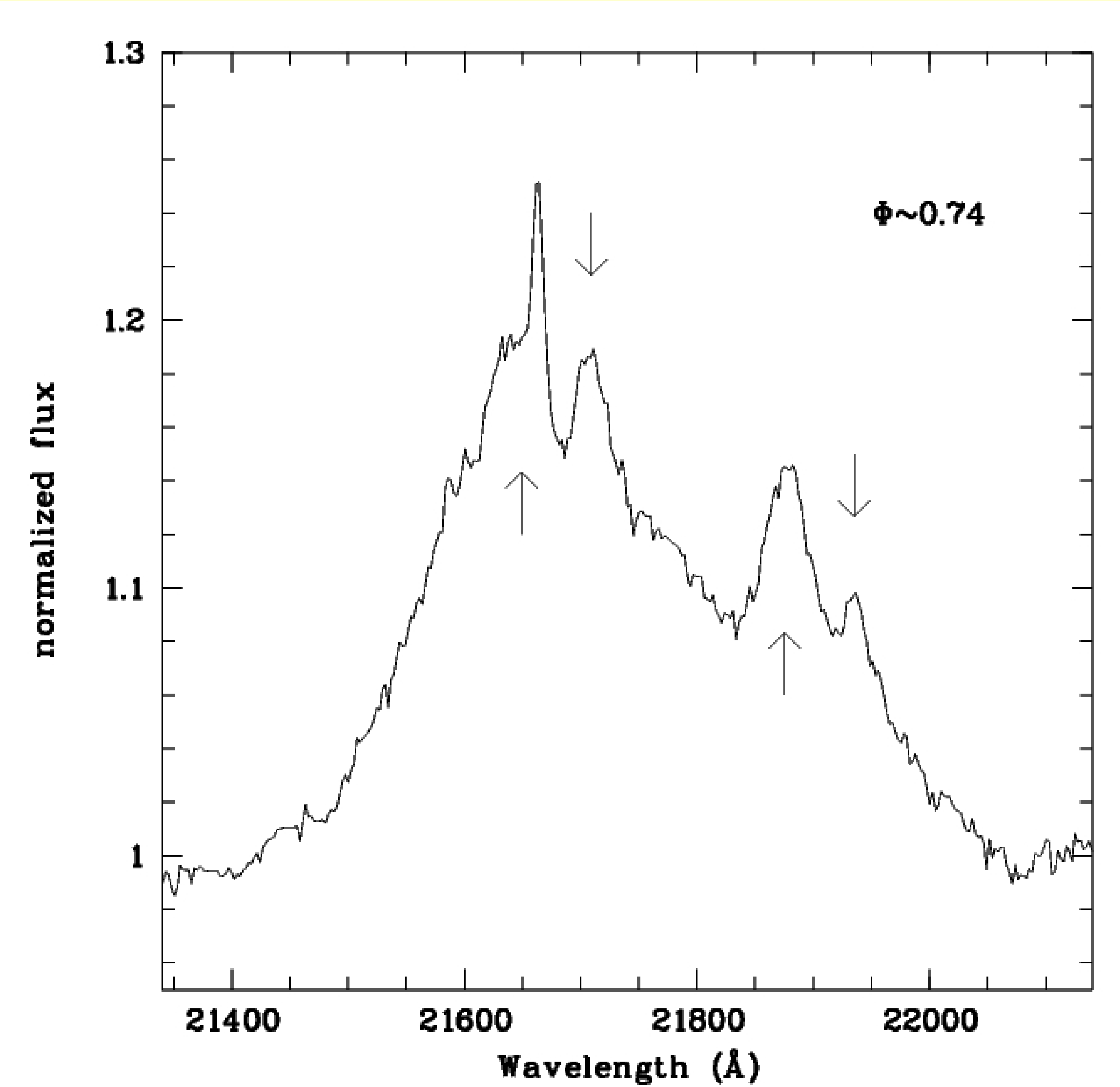
(Schnurr+, 2008a)

HST/NICMOS photometry in J-band of NGC3603-A1



Orbital inclination angle: $i = 71^{o} \pm 6^{o}$ (Moffat et al. 2004)

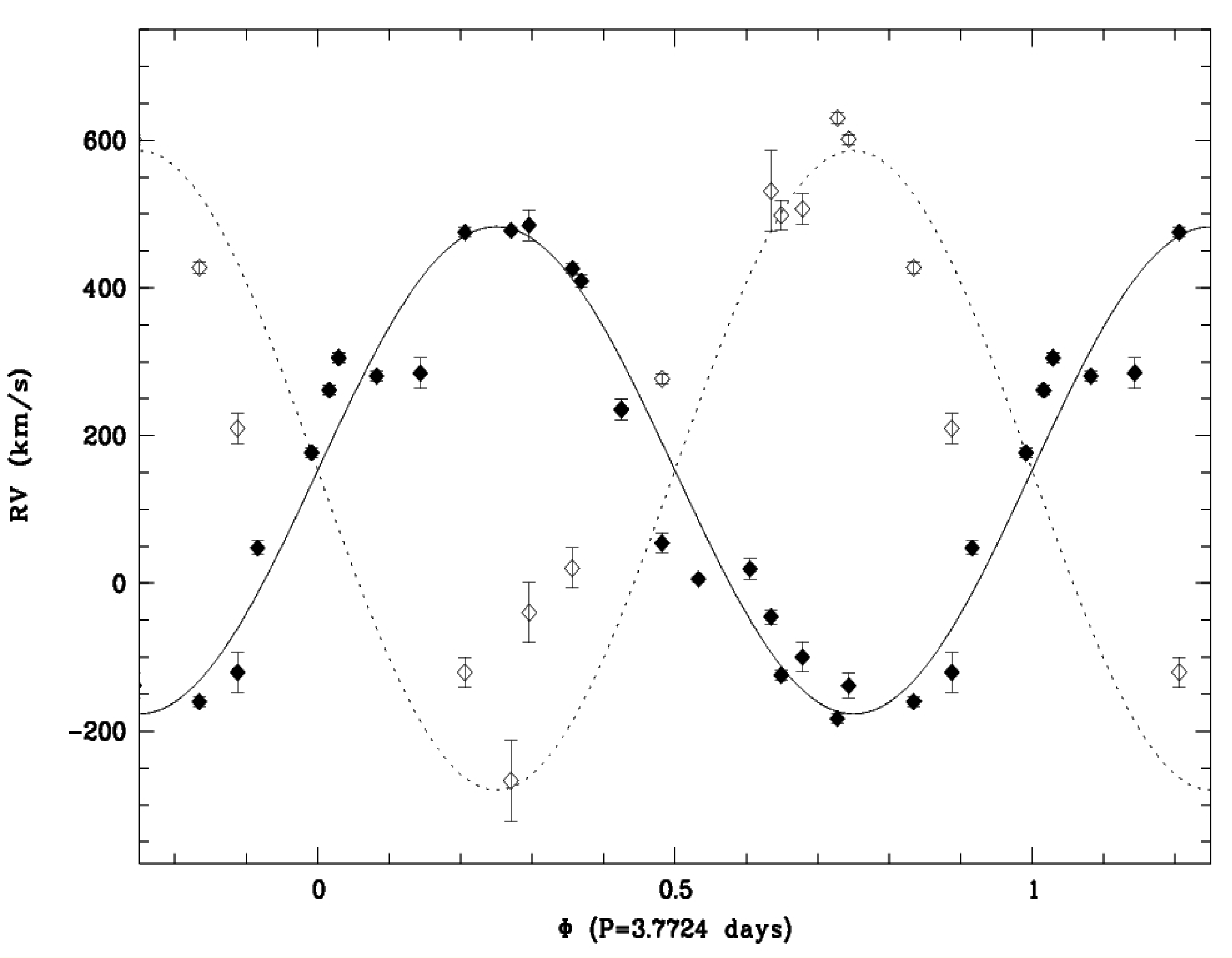
NGC3603-A1 consists of two emission-line stars!



WN6h+WN6:h:

(confirmation in optical required)

Trace both components over the orbital cycle...



$K_1 = 333 \pm 20$ km/s

$K_2 = 431 \pm 53$ km/s

P = 3.7724 d

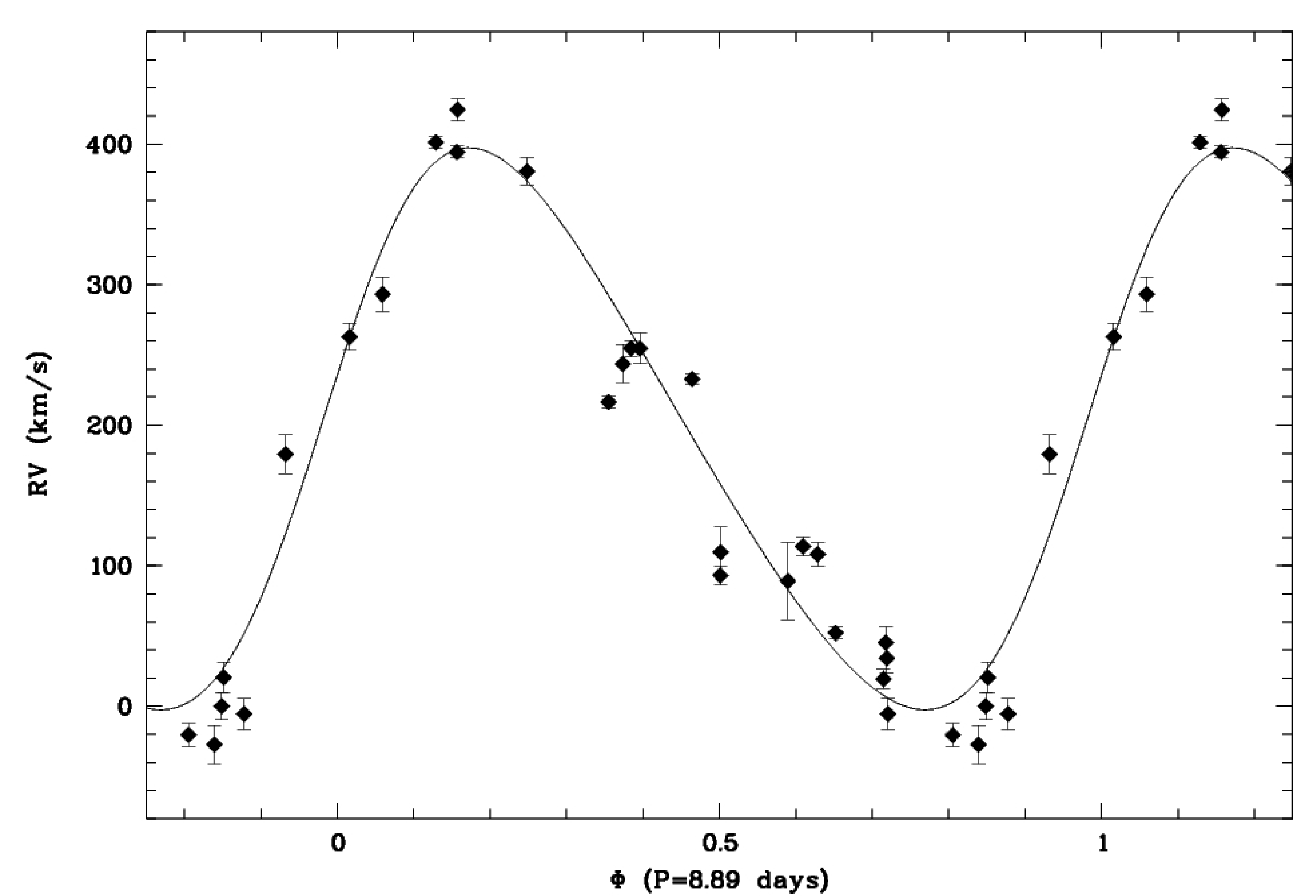
i = 71°

... and obtain their absolute masses:

$M_1 = 116 \pm 31$, $M_2 = 89 \pm 16\ M_\odot$

Most massive stars known to date!

Star C is a single-lined binary! P = 8.89 days

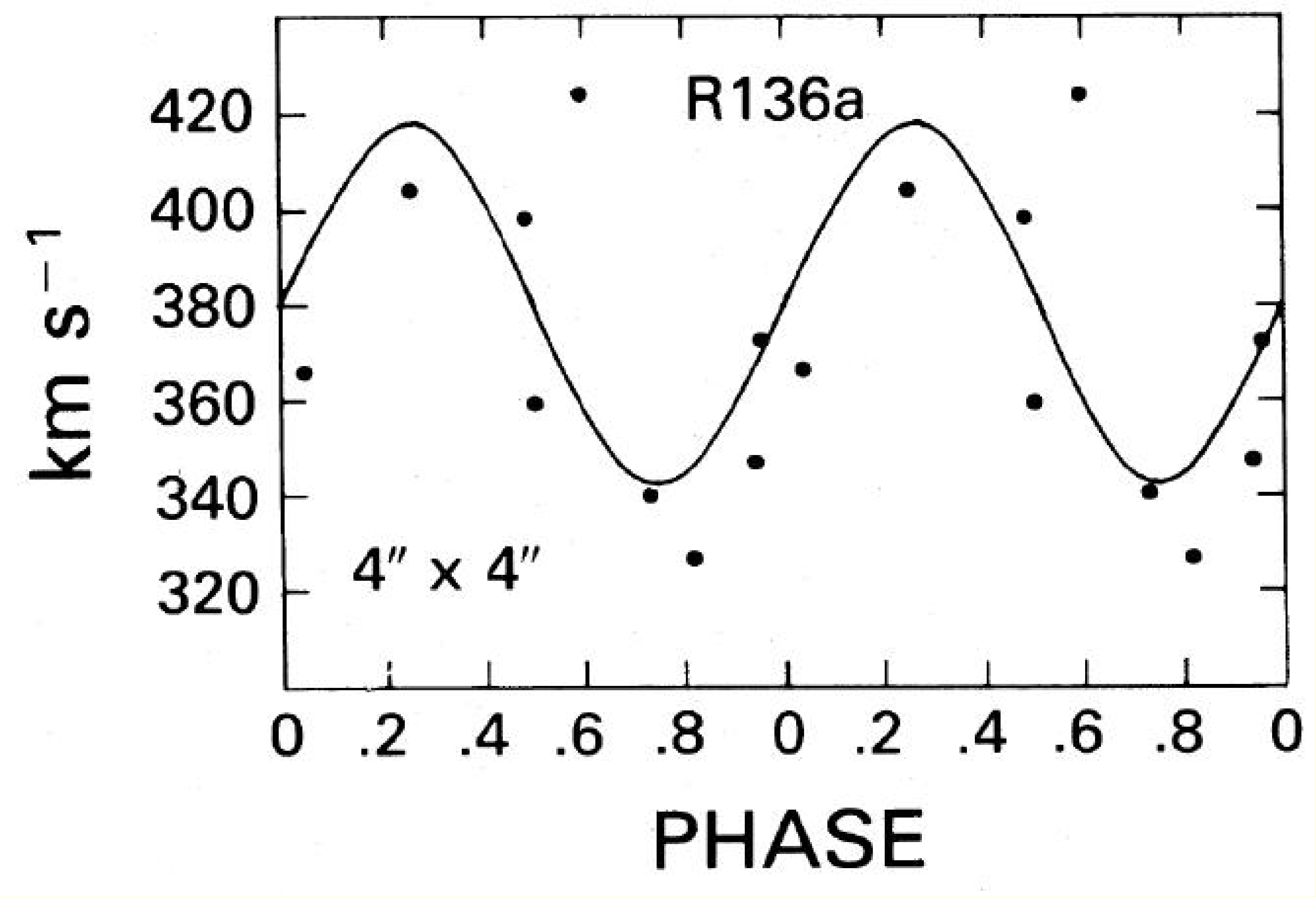


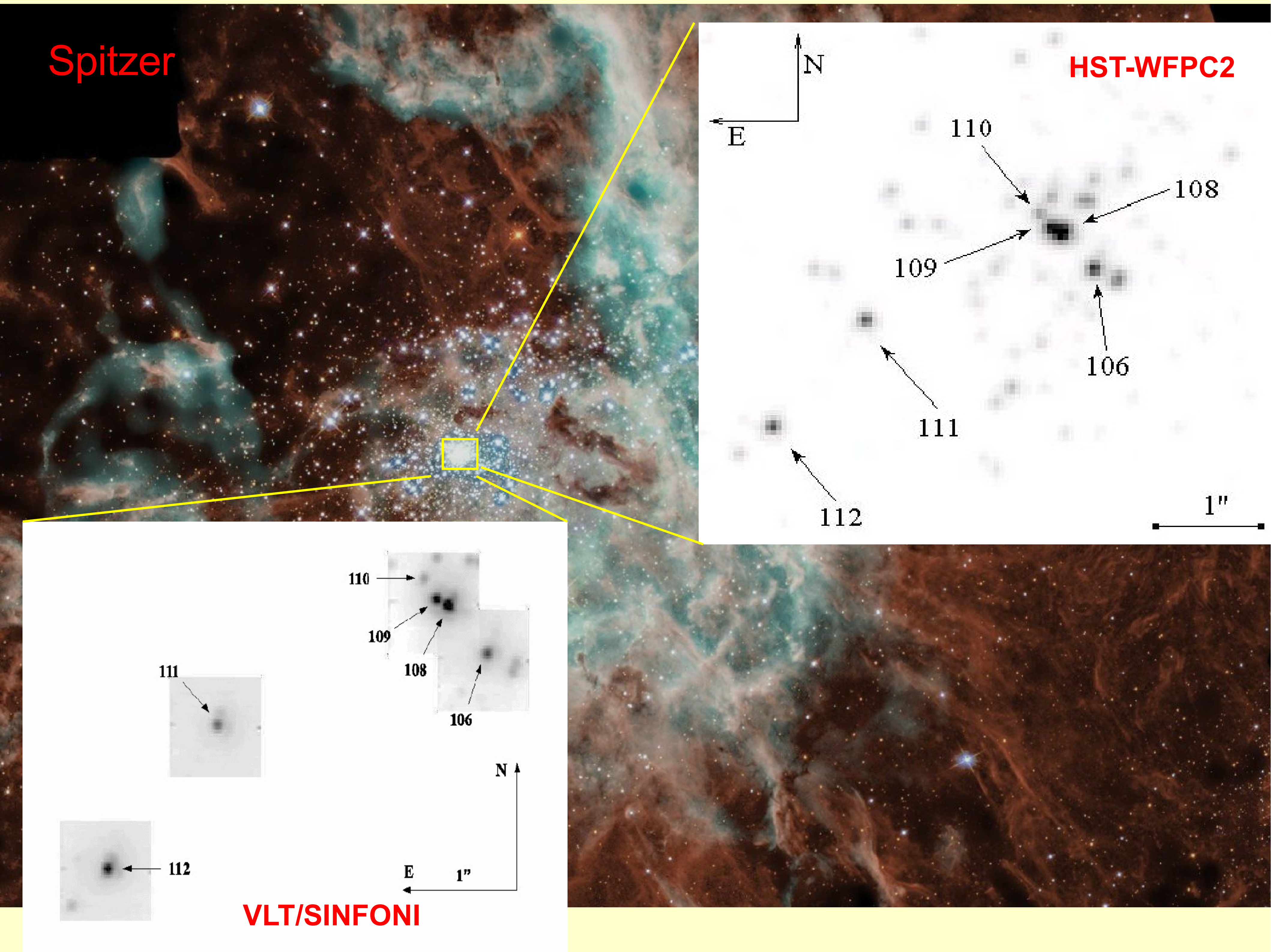
For both A1 and C, follow-up observations have been obtained (Schnurr et al., in prep)

Second stop: 30 Doradus

- Giant HII region in the LMC
- Closest starburst cluster in Local Group
- Central cluster of 30 Dor is R136 (usually the WFPC2 field)
  - Contains 100's of O stars, including the hottest known O3V stars (Massey & Hunter 1998)
- Core of R136 is R136a (central arcsecond):
  - was thought to be a single star with 1000's of Msol
  - HST resolved it into individual stars
  - extremely dense core: most massive stars are there!
  - **One suspected 4.377-day binary!**

From unresolved, ground-based, optical spectroscopy (Moffat & Seggewiss 1983; Moffat+ 1985)




Spitzer
HST-WFPC2
N
E
110
108
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1"
VLT/SINFONI
110
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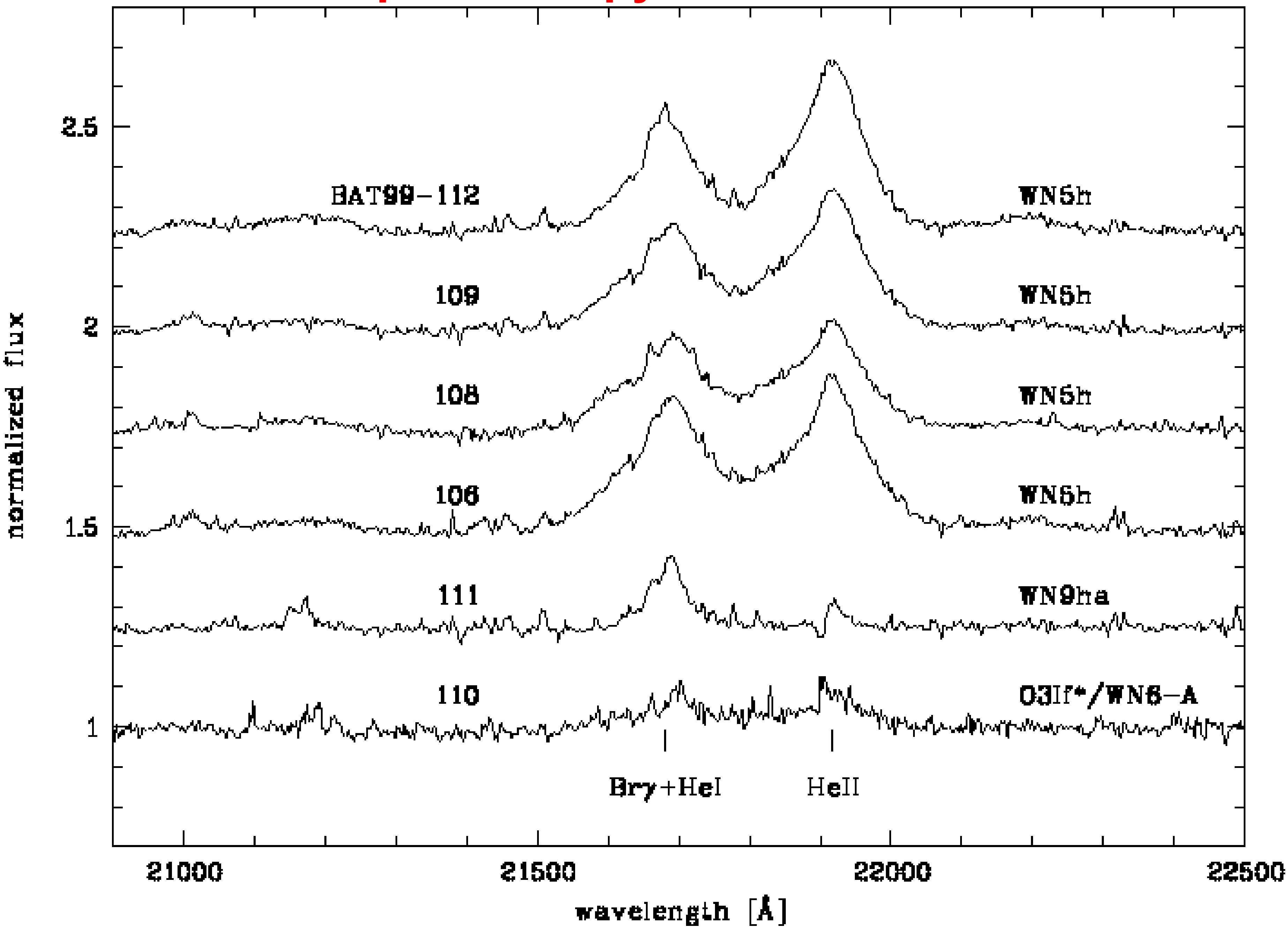
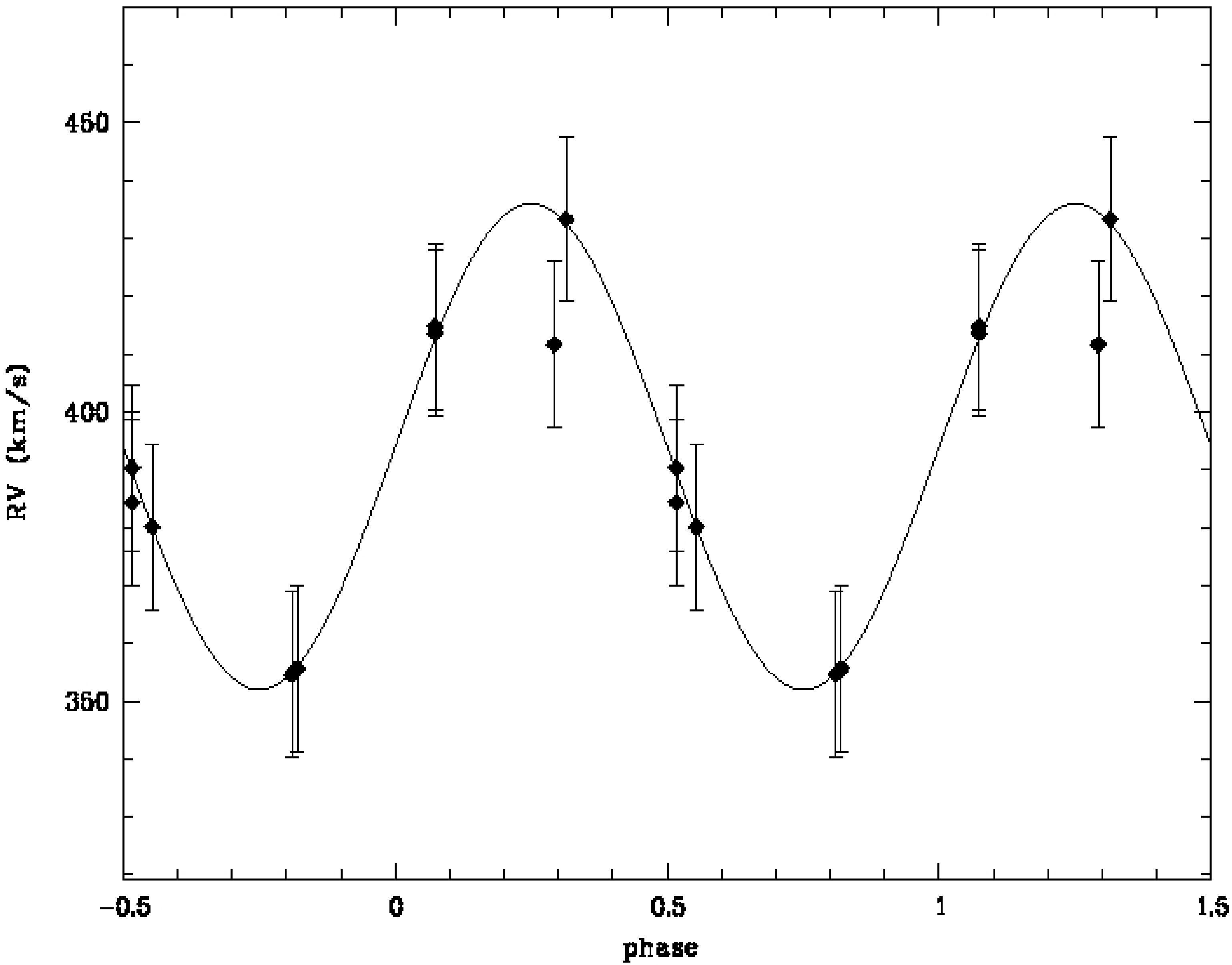
108
106
111
112
N
E
1"

SINFONI K-band spectroscopy of central WNh stars...



… but found no short binary (P < 45 days) in SINFONI data!

Yet another binary candidate? BAT99-112 (R136c) with P = 8.2 days



Where are the binaries in R136a?

- BAT99-112 only candidate
- Excess of hard X-rays is indication for wind-wind collisions
- **However, no signs of binarity with P < 45 days in other program stars!**
- Maybe longer-period system(s), but very difficult to observe (sampling, inclination?)
- Long-term monitoring will be proposed for P84 with ESO
- Makes for interesting cluster dynamics: mass-segregated cores should contain all hard, massive binaries...?

How about the Arches cluster?

- **Most massive starburst cluster in the Milky Way**
- Extremely dense core-region (2 x 10^5 Msol/pc^3) should make for very massive population; in particular:

  Is the reported IMF cut-off real?

- Martins+ (2008) analyzed the WNh stars:
  - most luminous members: logL ~ 6.0-6.3
  - masses around 100 $M_\odot$, but more evolved than the stars in NGC3603
- So far no study for binarity, but planned for P85 at ESO

Are the other very massive binaries outside cluster cores?

- WR20a is a hard(!), very massive binary (83 + 82 Msol)
- located **outside** of Westerlund 2 (not even in cluster)!
- … and Westerlund 2 is seemingly not such an extreme OB cluster by size, mass, or density.
- Assumption about most massive stars in cluster cores could be wrong!

So, what about other luminous, H-rich WN stars?

Massive binaries in the LMC

- Schnurr+ (2008b) surveyed all known WNL stars in the LMC to find binaries with P < 200d
- found a total of 9 WNL binaries
- 8 binaries most likely contain unevolved CHB objects
- for 6 of them, follow-up data have been obtained (in prep.)
- Are likely to fill the gap between 60 and 100 Msol...
- for one of them, **R145**, the second brightest WNh in the LMC, we have additional polarimetry to derive the inclination angle (light of O star scattered by WN wind)

R145 (WN6h), v=12.15 mag

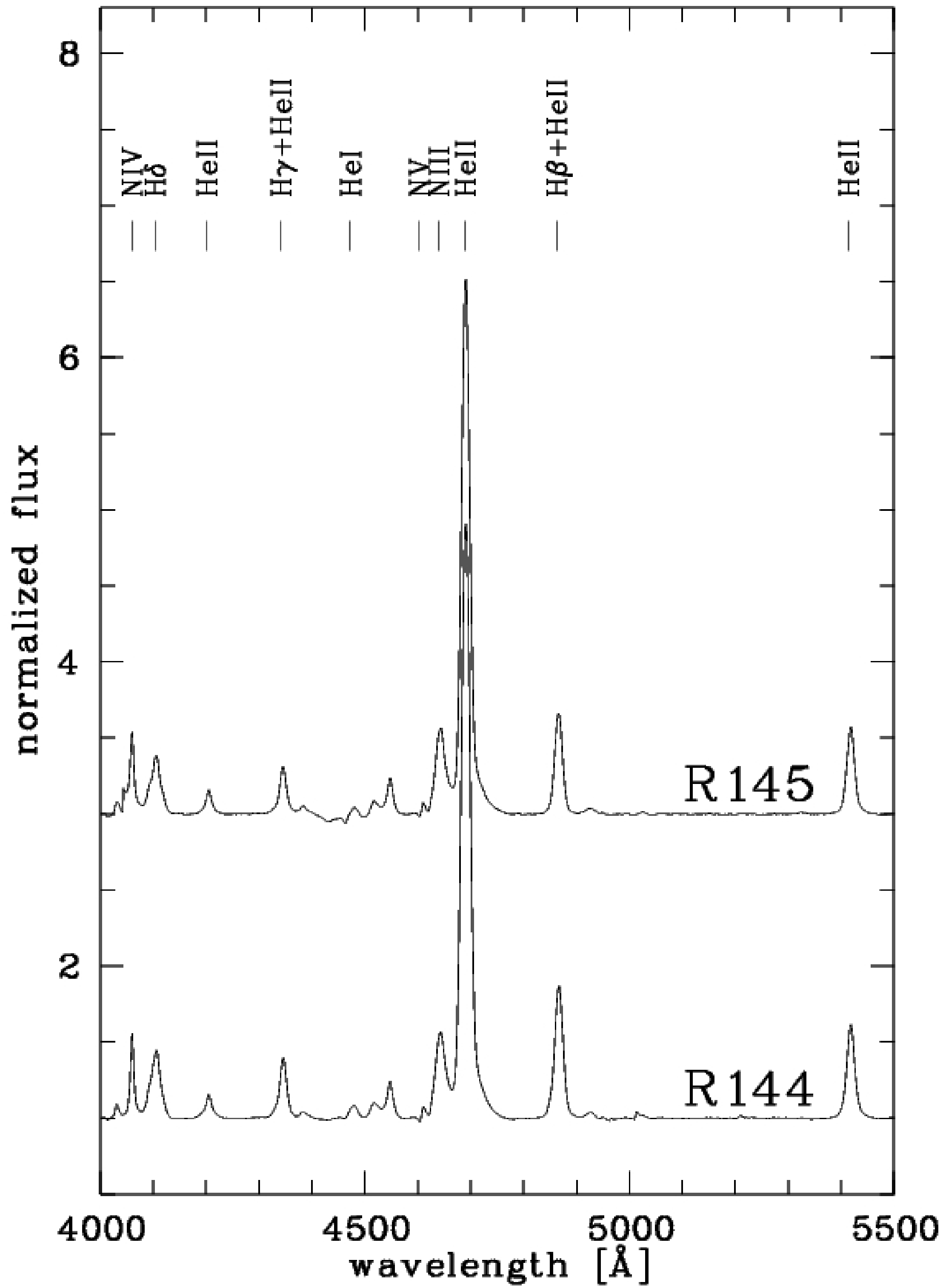
known binary, but period?

R144 (WN6h), v=11.15 mag

old models: logL = 6.34
new models: logL ~ 6.5+ est.

R144 is the most luminous WR star known in the Local Group!

unfortunately single(?), monitoring in progress



Linear polarimetry: Stokes Q,U parameters

Combining POL and SPEC data:

P = 158.8 days

***i* = 39°**

K_{WR} = 93 ± 10 km/s

With the shift & add method (poor man's tomography), we find O stars has

K_O = 219 ± 20 km/s

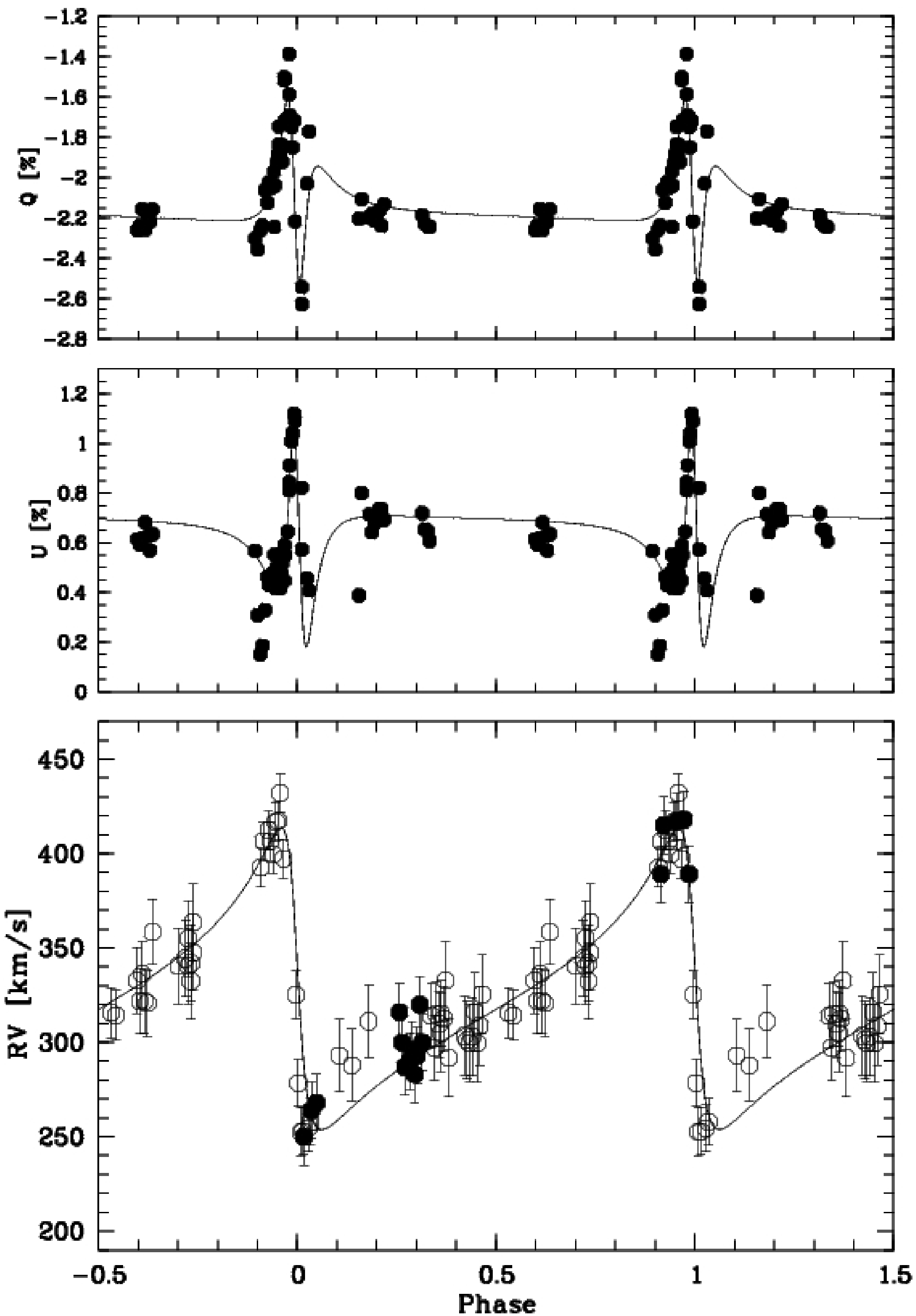
This yields

$M_{WR} \sin^3 i$ = 116 ± 33 $M_\odot$

$M_o \sin^3 i$ = 48 ± 20 $M_\odot$

but with i = 39°, ***$\sin^3 i$* ~ 4**,
which gives way too high masses!

Schnurr+ (2009)



Summary and Conclusions

- The most massive main-sequence stars known so far span a mass range from 60 to ~120 Msol
- They **all** are luminous and hydrogen-rich WN5-7h stars
- Current record holder is NGC3603-A1 with Keplerian mass of $116 \pm 31\ M_\odot$
- Equally or slightly more massive WN5-7h binaries at the horizon: NGC3603-C, R145, WR21a, WR25... Arches?
- There exist more luminous, but single(?) WNh stars: NGC3603-B, R144, …

Thus so far, the upper mass cut-off of 150 $M_\odot$ remains untested...

... but we're getting there!