Massive star cluster in the SMC NGC 602 HST (A.Nota)/Chandra (L. Oskinova)

Massive stars on their way to GRBs

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Long γ-ray bursts (LGRBs)

Associated with H/He-poor broad-line SNe Ic

Host galaxy metallicities $0.1Z_{\odot} < Z < 1\ Z_{\odot}$

Concentrated in the brightest regions of star-forming dwarfs

Common events (rates $\sim$ to massive star SFR)

- **Core collapses of evolved stars with $M_{initial}$ >40$M_{\odot}$**

Short γ-ray bursts (SGRBs)

No SNe but kilonovae (r-nucleosynthesis)

No association with star formation

Variety of galaxy hosts and locations

- **The binary compact object merger scenario**

Stanek+ 03, Cano+ 11, Modjaz+ 08, Bloom+ 98, Nakar+ 07, Berger+ 14, Tanvir+ 13

- **Collapsar**

Woosley 93, MacFadyen & Woosley 99

collapse of a WR star ($M_i > 40 M_\odot$)
BH high accretion rate, strong LGRB
afterglow: WR circumstellar medium

- **Helium Merger**

Fryer & Woosley 98, Zhang & Fryer 01

inspiral of BH/NS into a RSG He-core
long-lived central engine
afterglow: dence common envelope

- **WD+NS/BH Merger**

Fryer+ 99, Belczynski+ 02

low accretion rate
weak and long duration GRBs
afterglow: ISM

- **NS+BH/NS Merger**

Paczynski+ 86, Narayan+ 92

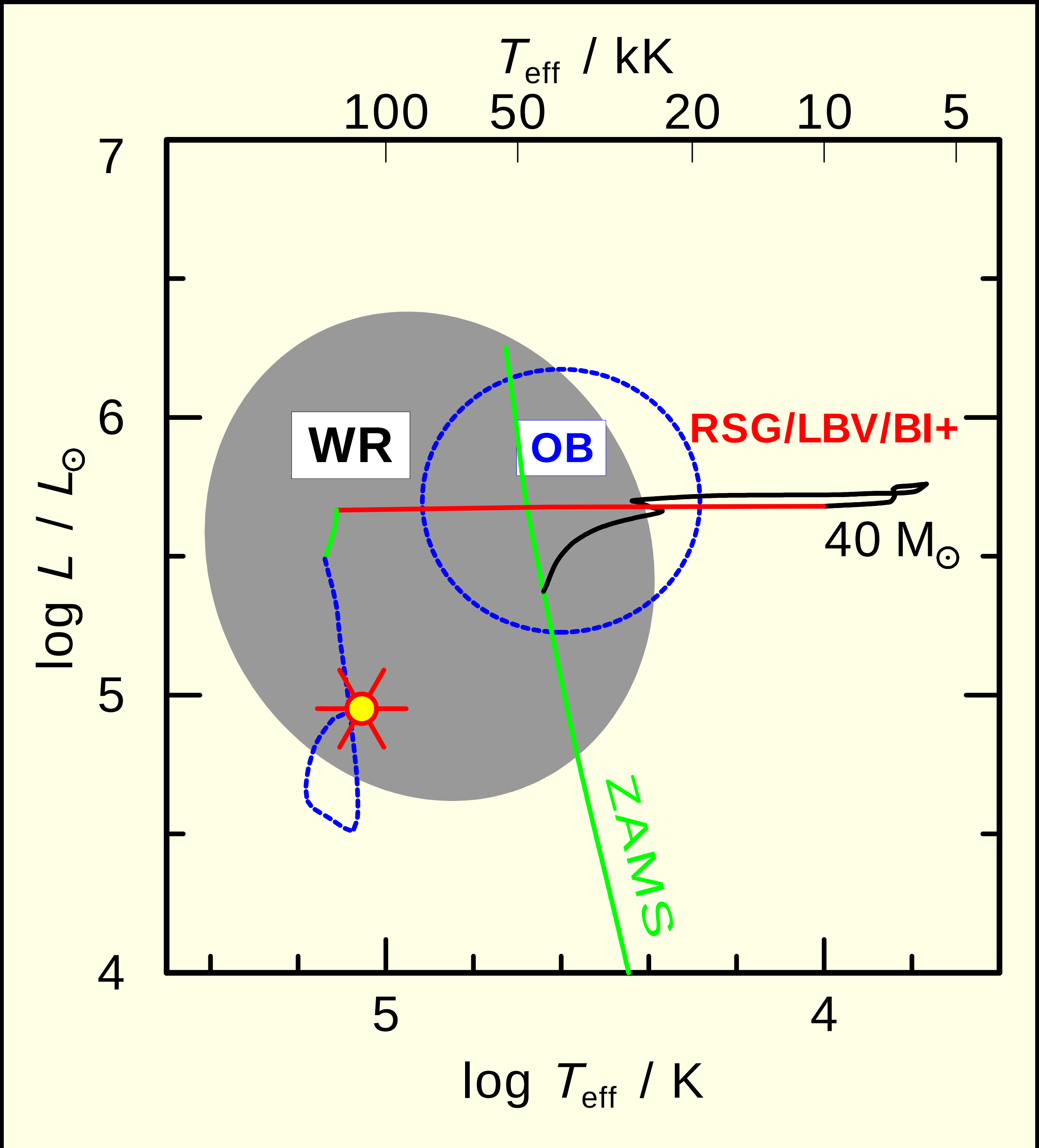
low fuel, low angular momentum
high-accretion rate, SGRB
afterglow: ISM

- **Magnetar**

Usov 92, Duncan & Thompson 92

gravitational collapse of accreting WD
spin-down of magnetized NS
afterglow: ISM, , ultralong GRBs (?)

Stellar wind: principal physics connecting Z and evolution



Wind mass loss ~ mass consumption in fusion

$$\dot{M}(Z, t)$$

a critical parameter of stellar evolution

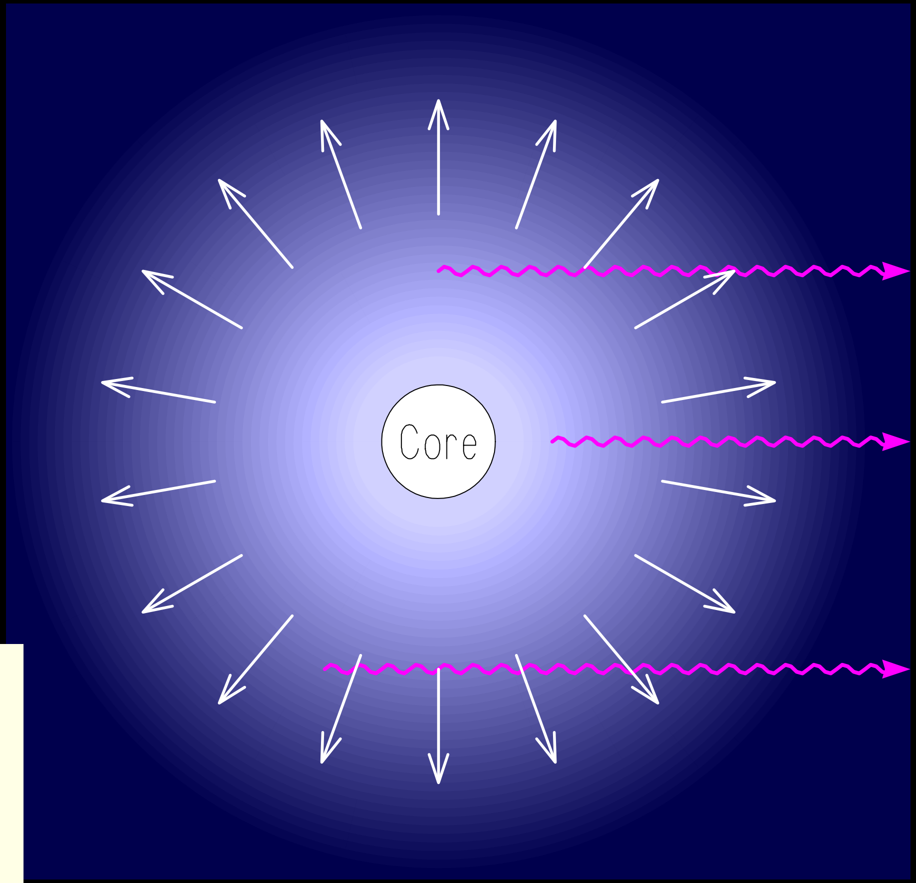
mass prior core collapse
spin prior core collapse
circumstellar environment

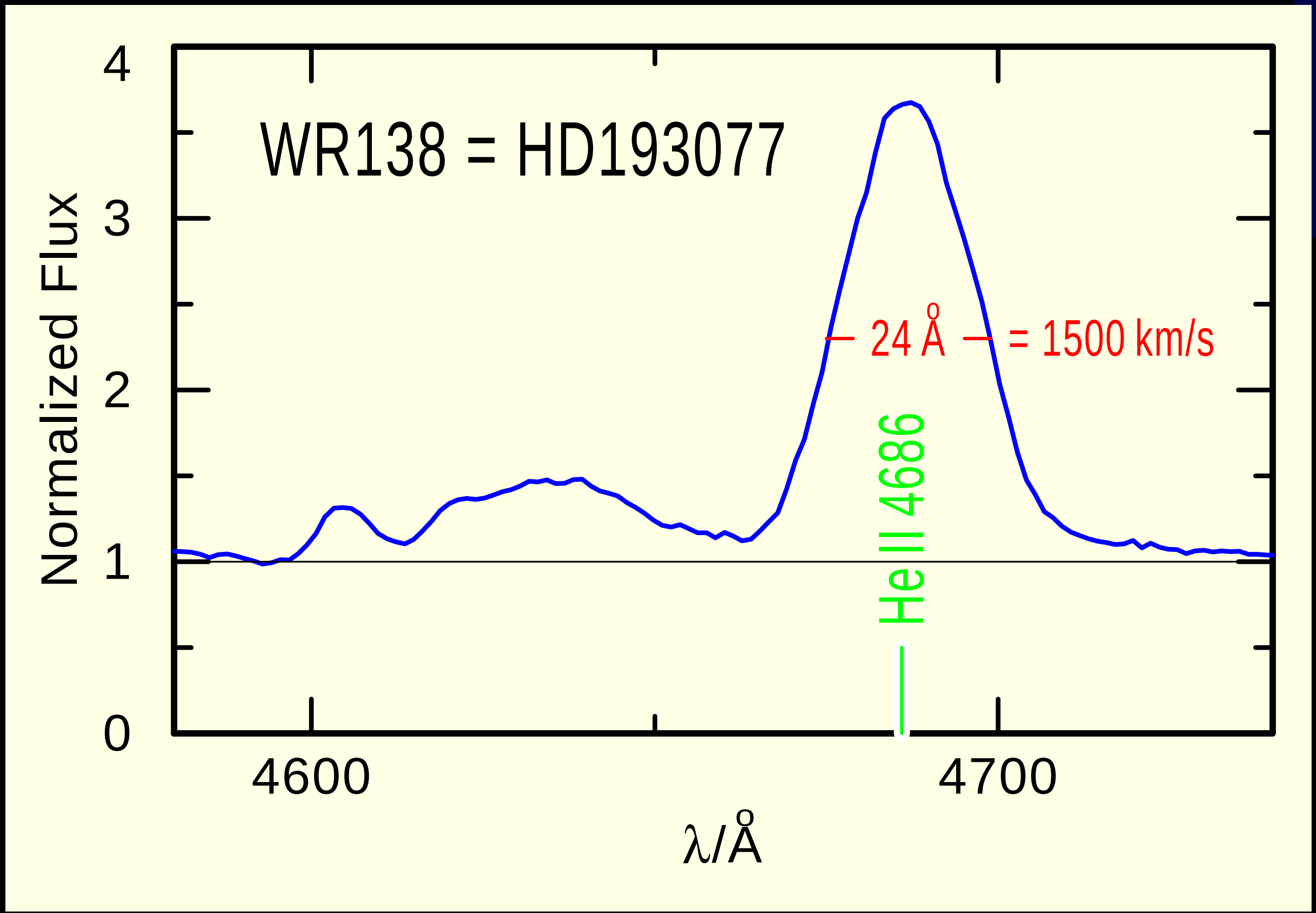
Collapsar: LGRB-SNIc produced by H-free, fast rotating WR-stars

WR emission-line spectra

Qualitative explanation (Beals 1929):

"... continuous ejection of gaseous material from the star. ... the star is surrounded by an expanding envelope..."





- Velocities: up to $v_\infty \approx$ 3000 km/s = 0.01 c
- Mass-loss rates: up to $\dot{M} \approx 10^{-4}\ M_\odot$/yr

State of the art model atmospheres

- Non-LTE with complex model atoms
- Spherical stellar winds
- Full comoving-frame radiative transfer
- Wind + photosphere photospheres
- Pressure broadening of lines
- Iron line blanketing (10^7 lines)
- Applicable for any hot star (WR, OB, LBV)

PoWR stellar atmosphere model

WR and **O star** models -> download

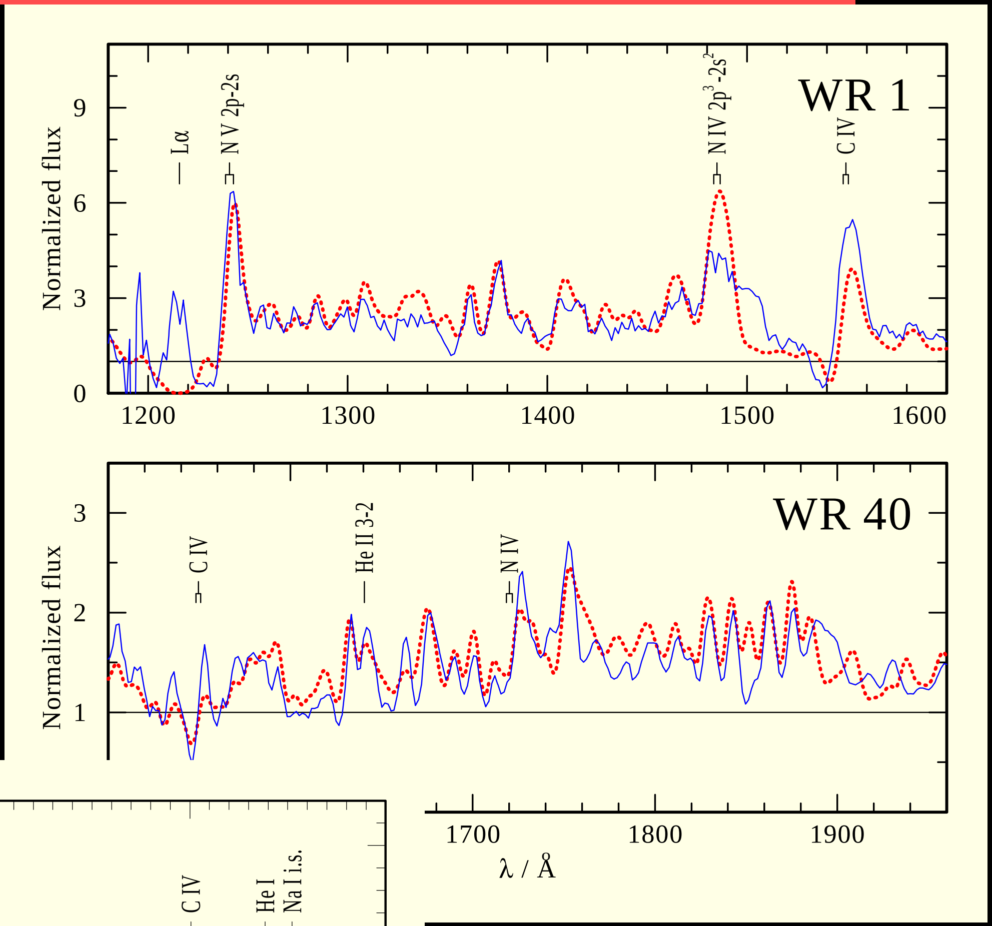
`http://www.astro.physik.uni-potsdam.de/PoWR.html`

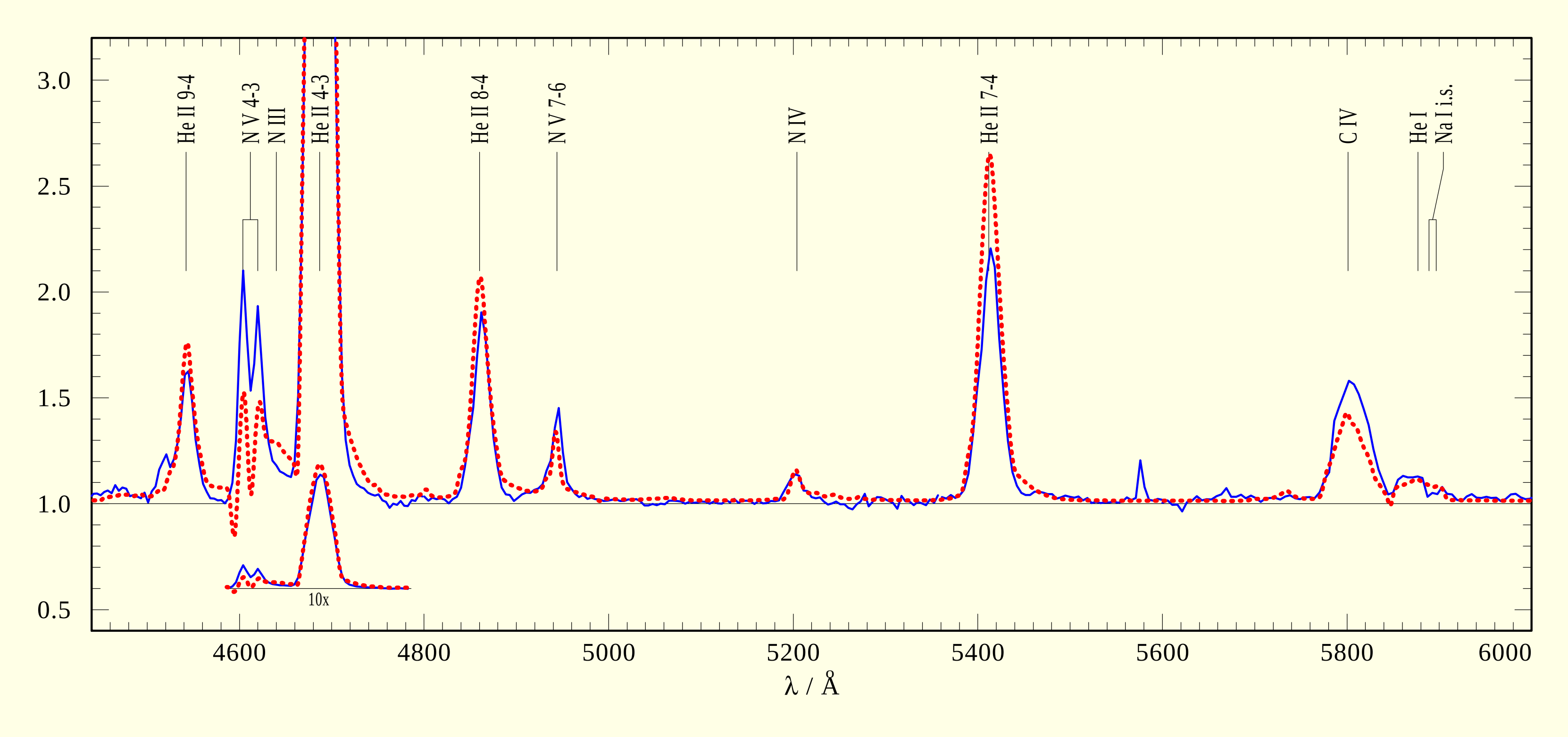
Models vs Observations → stellar and wind parameters

WR 1 (WN5-s): T_* = 141 kK;
"iron forest" < 1500 Å ← Fe V, Fe VI

WR 40 (WN8): T_* = 45 kK
"iron forest" 1500 - 2000 Å ← Fe IV

Optical range **WR 44** (WN4)
T_* = 63 kK

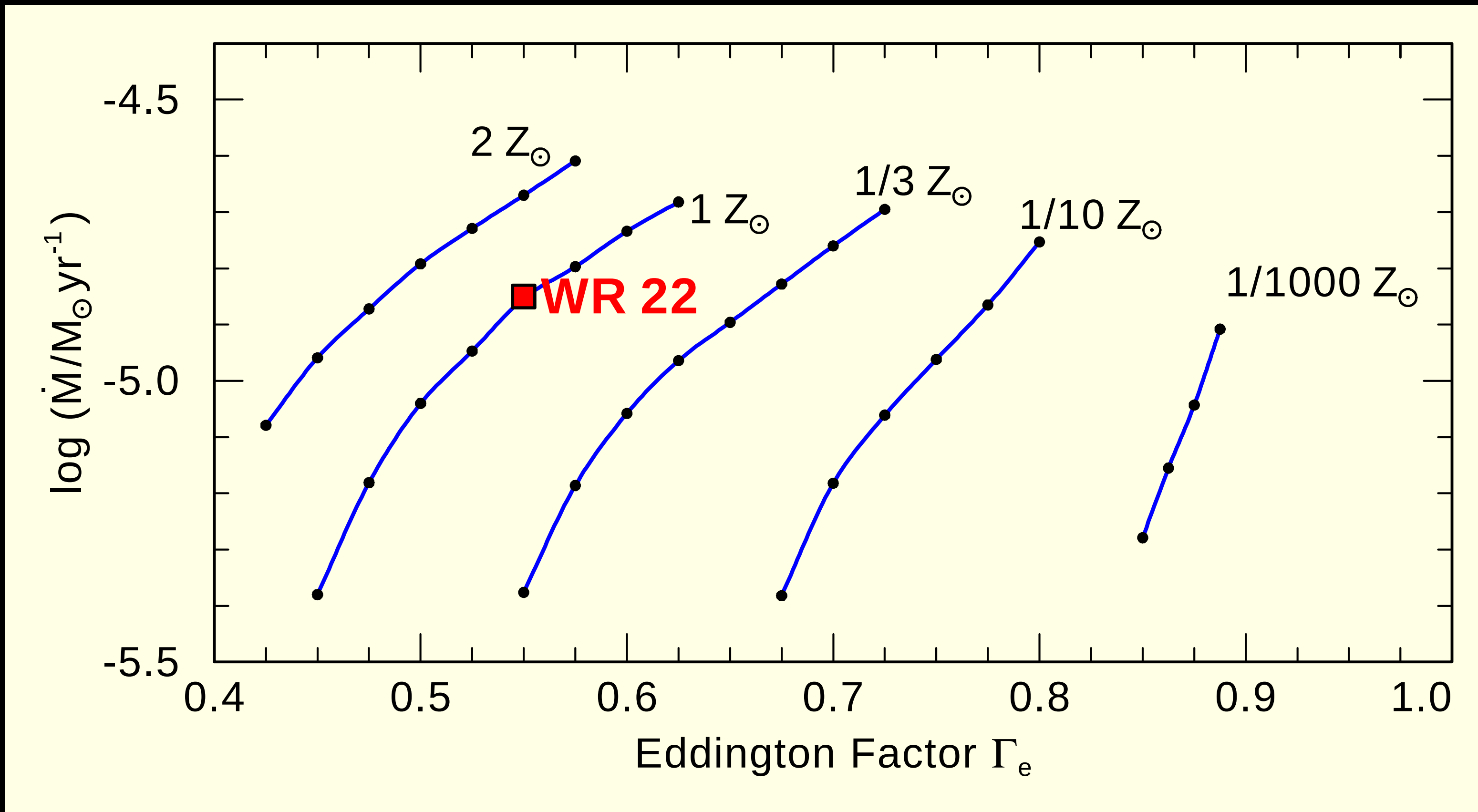




M, T, L, Z

→ $\dot{M}, v_{\rm wind}$

Hydrodynamically consistent WN models: parameters



Eddington Limit:
$\Gamma_e = 1$
radiation pressure on free electrons balances gravity

← Gräfener & Hamann (2008)

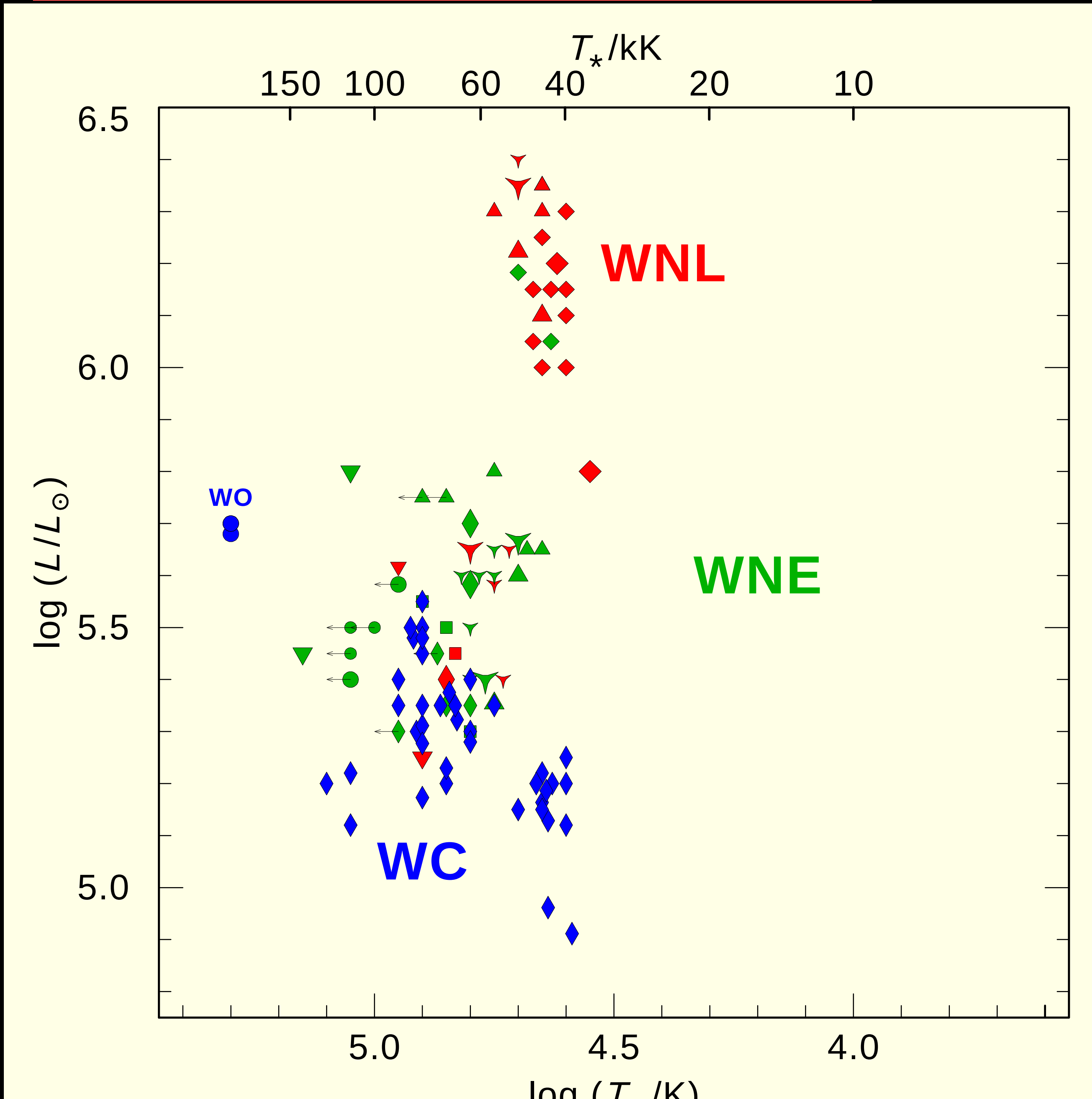
Why WR stars have $\approx 10\times$ stronger winds than O stars ?

- They are closer to the Eddington limit (higher L/M), being
  - extremely massive and luminous hydrogen burners
  - helium burners of relatively low current mass

Even at low Z, WR winds are driven if L/M is sufficiently high

New generations of hydrodynamically consistent models
Muijres+ 12, Noebauer & Sim 15, **Sander+ 17, Krticka & Kubat 17**

Wolf-Rayet stars: subclasses



WN sequence: WN 2 … 11

WNL "late": WN7 …

- Very luminous
- Atmosphere:
  - H 20 … 55 %
  - He 45 … 80 %
  - N ~1 %; C, O low

→ H burning (?)

WNE "early": WN2 … 6

- log $L/L_\odot$ < 6
  - no H
  - He 98 %
  - N ~1 %; C, O low

→ He burning

WC Carbon sequence

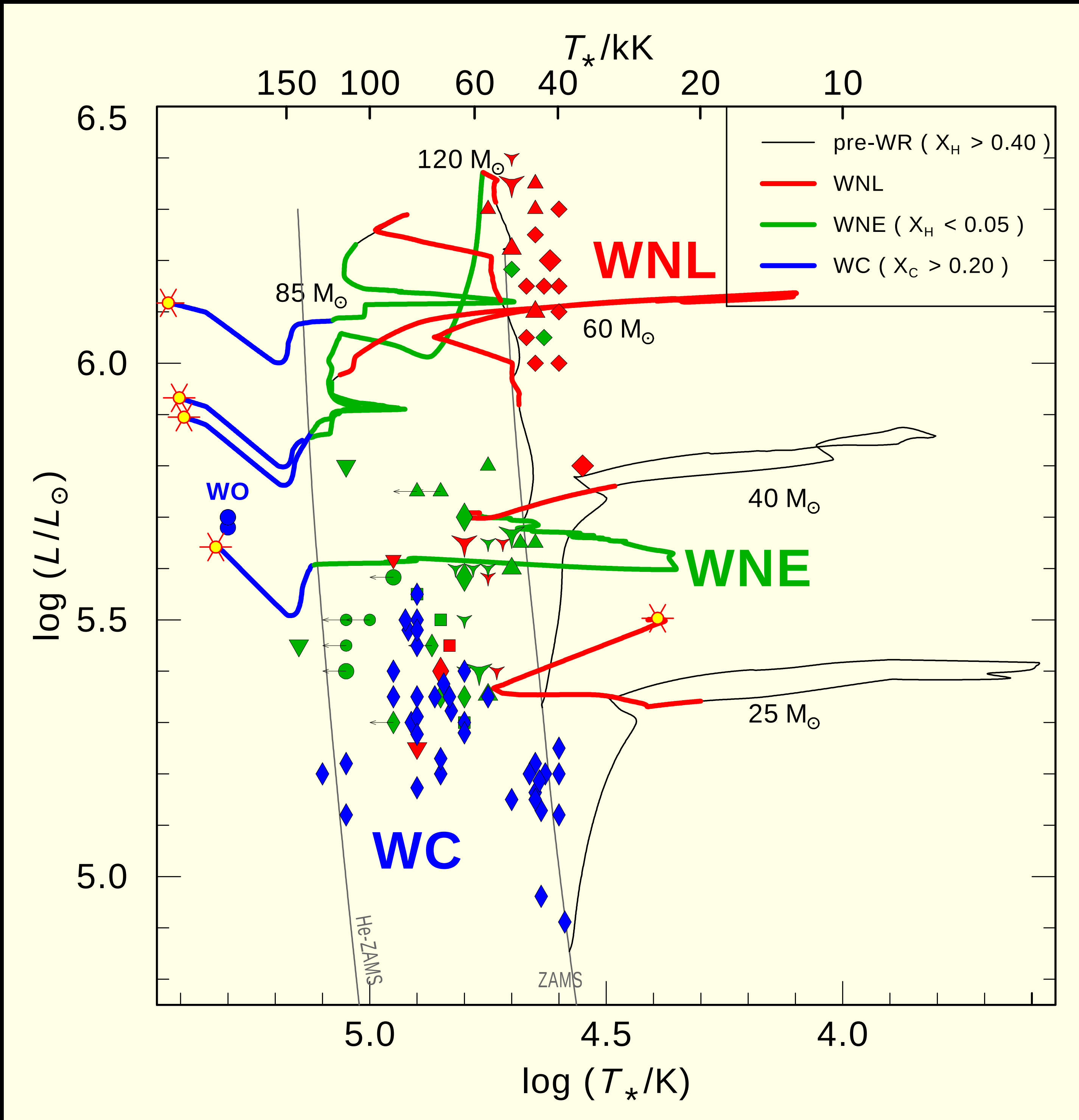
- log $L/L_\odot$ < 6
  - He:C:O = 55:40:5

→ He burning

WO He:C:O = 30:40:30

← Galactic WR stars

Galactic WR stars: analyses versus evolutionary models



Symbols: single (?) Galactic WR stars

WNlate WNEarly WC

Evolutionary tracks

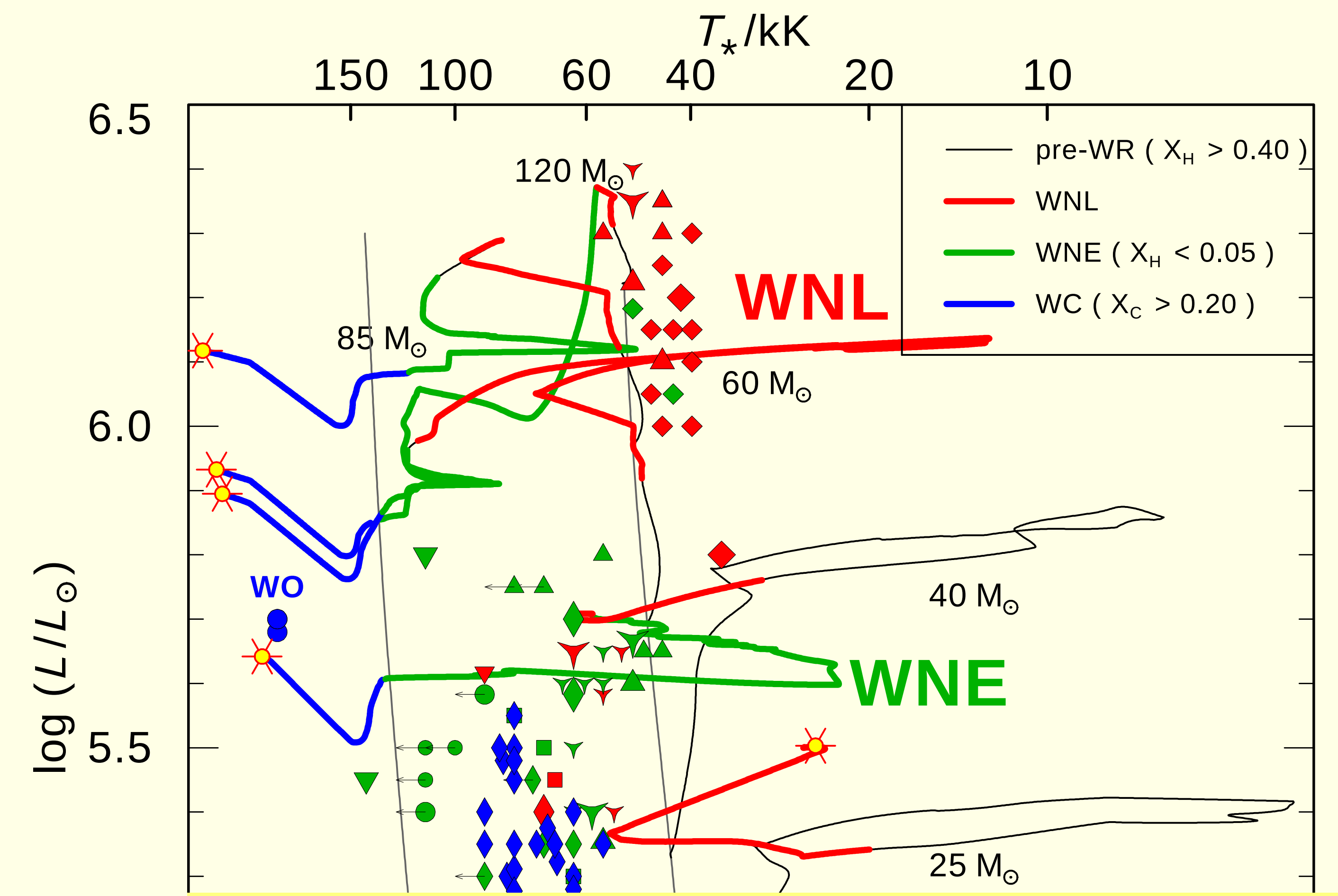
(Geneva, *with* rotation) Georgy+ 12)

→ **log L in contradiction !**

Empirical scenario:

(Sander, Hamann & Todt 2012)

Galactic WR stars: analyses versus evolutionary models



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WNlate WNEarly WC

Evolutionary tracks (Geneva, *with* rotation) Georgy+ 12)

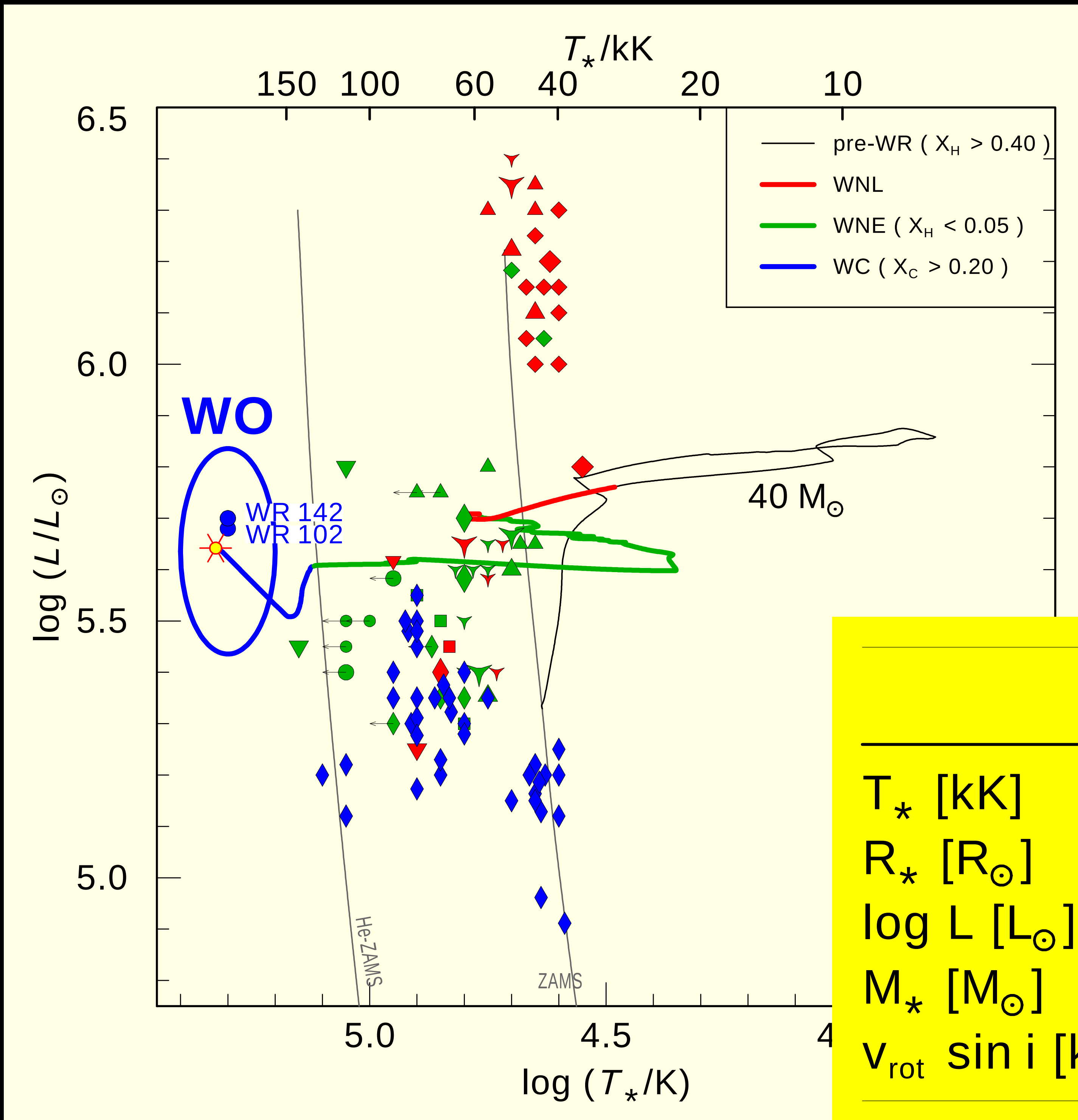
→ **log L in contradiction !**

Empirical scenario:

(Sander, Hamann & Todt 2012)

Init. Mass	Evolutionary Sequence
10 - 20	OB → RSG (→ BSG) → SN II
20 - 40	O → RSG → WN → WC → SN Ib/c
> 40	O → WNL (→ LBV) → WNE → WO → SN Ic/GRB

Galactic WO stars: the most advanced evolutionary stage

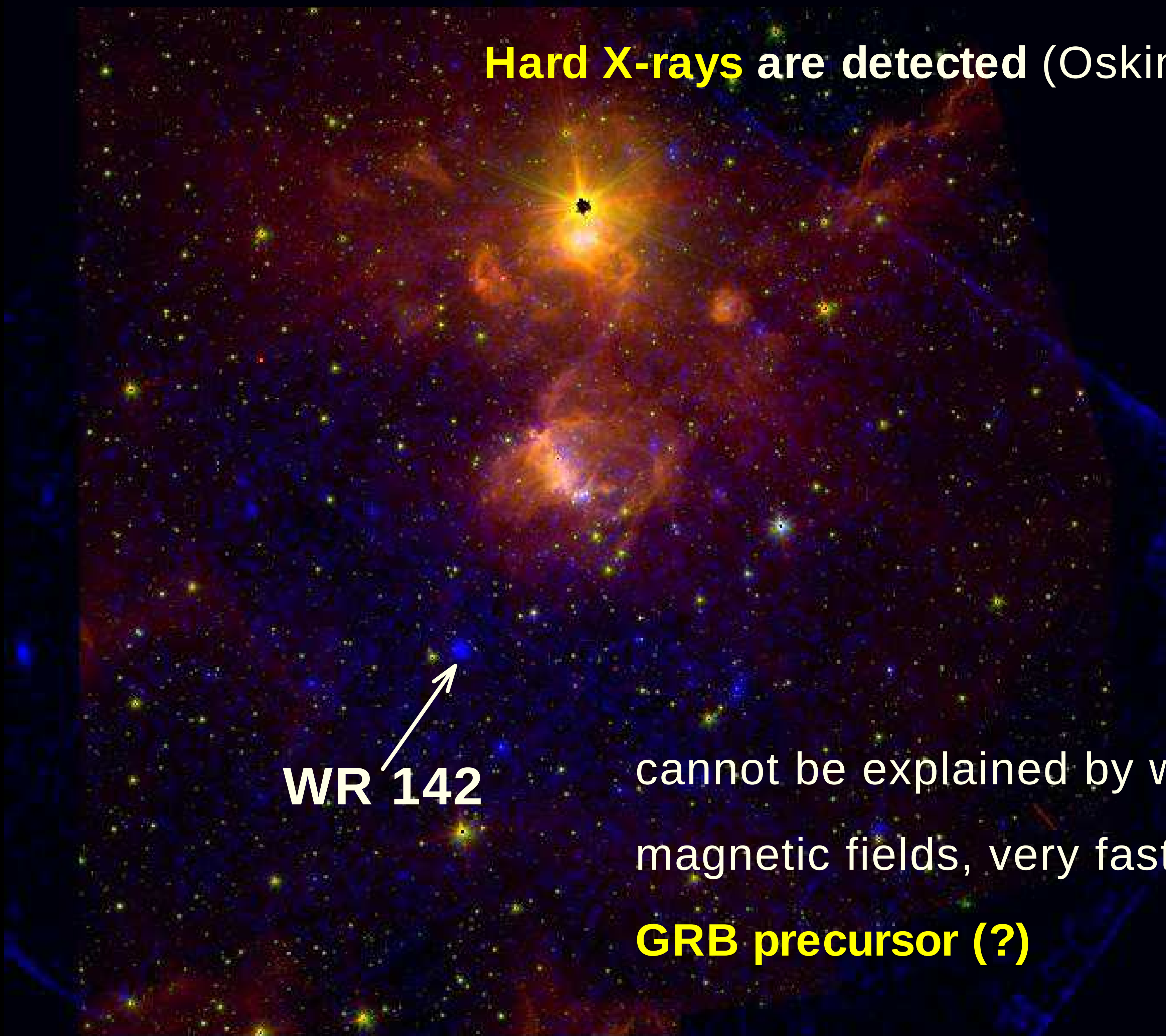


Two (out of 4) analyzed (Sander+ 12, Tramper+ 15)

- Current mass M_* estimated from luminosity L
- L depends on distance → large error: $M_* = 30\ M_\odot$ for WR 102 with alternative distance

	WR102	WR142
T_* [kK]	200	200
R_* [$R_\odot$]	0.6	0.6
log L [$L_\odot$]	5.7	5.7
M_* [$M_\odot$]	19	20
v_{rot} sin i [km/s]	~1000	~1000

Hard X-rays are detected (Oskinova + 12)



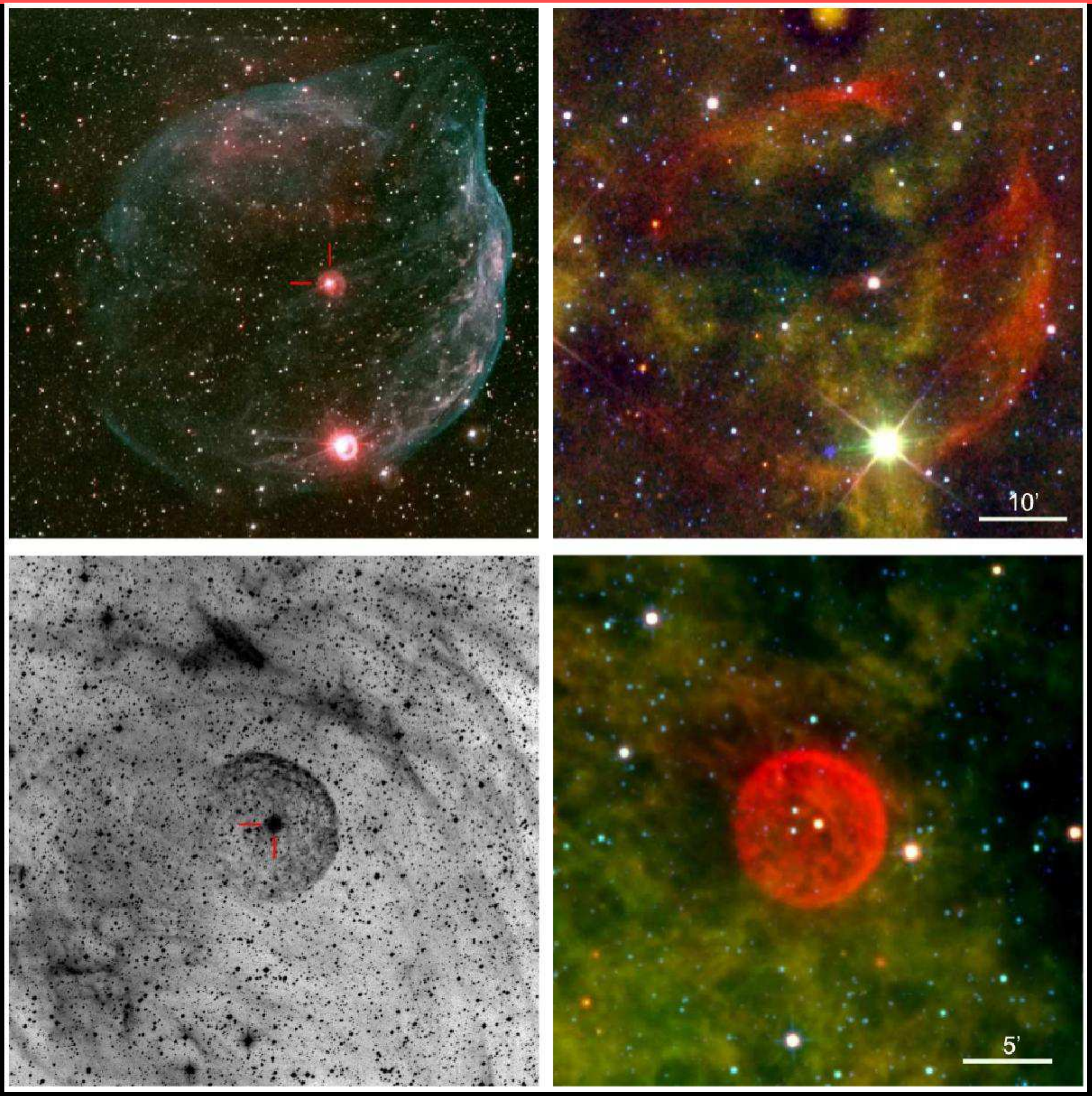
cannot be explained by wind shocks

magnetic fields, very fast rotator

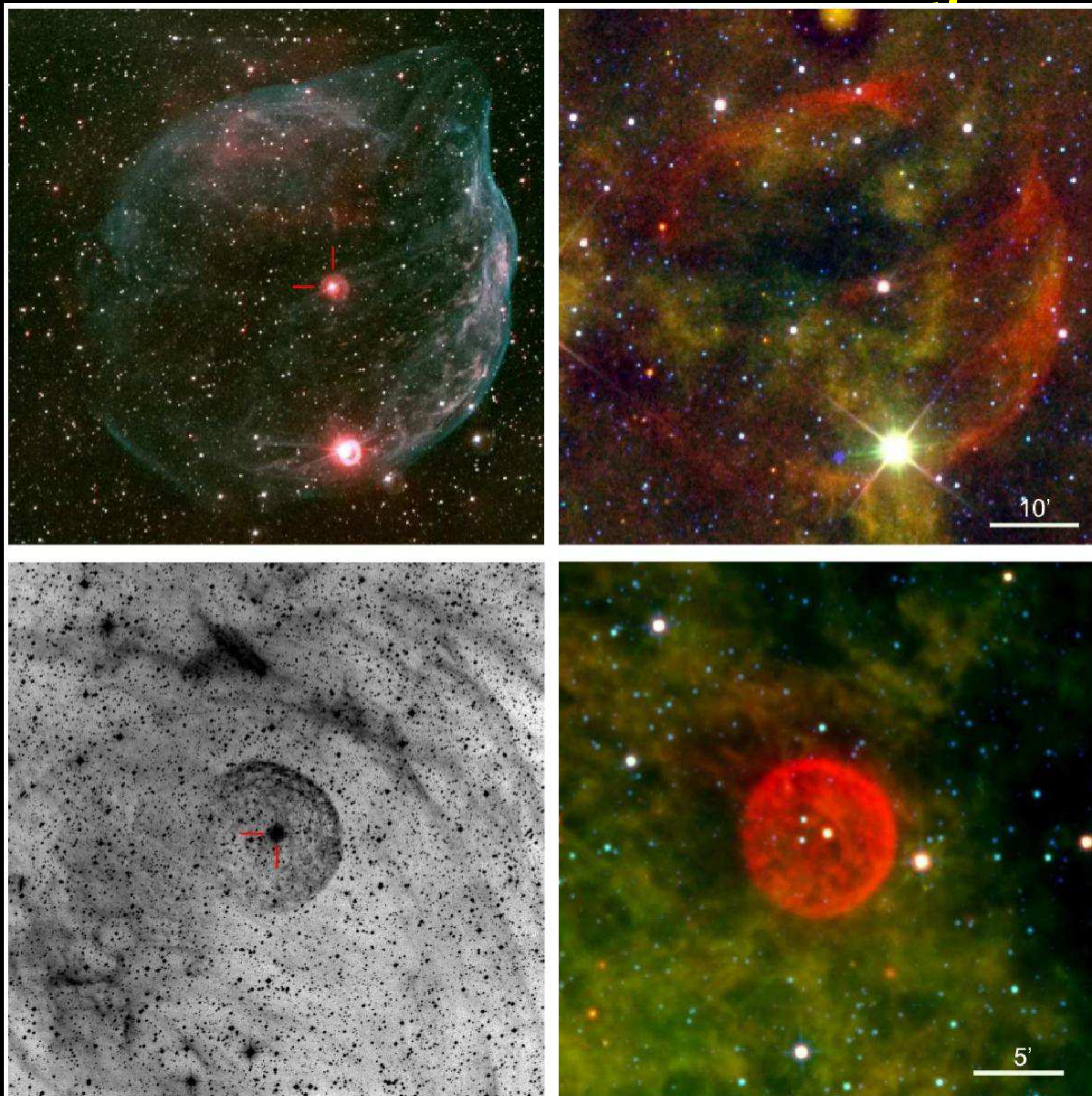
GRB precursor (?)

Hydrogen rich nebulae around H-free WR stars

Toala+ 15



H-rich nebulae around fast rotating H-free WR stars



20% of WR stars are fast rotating (Vink+ 11)

Strong correlation between H-free fast rotating WRs and H-rich ejection nebula

Proposed LGRB progenitors

Shenar+ 14: **a sample of very fast rotating & strongly magnetic WR stars**

H-rich circumstellar nebula around H-free WR star

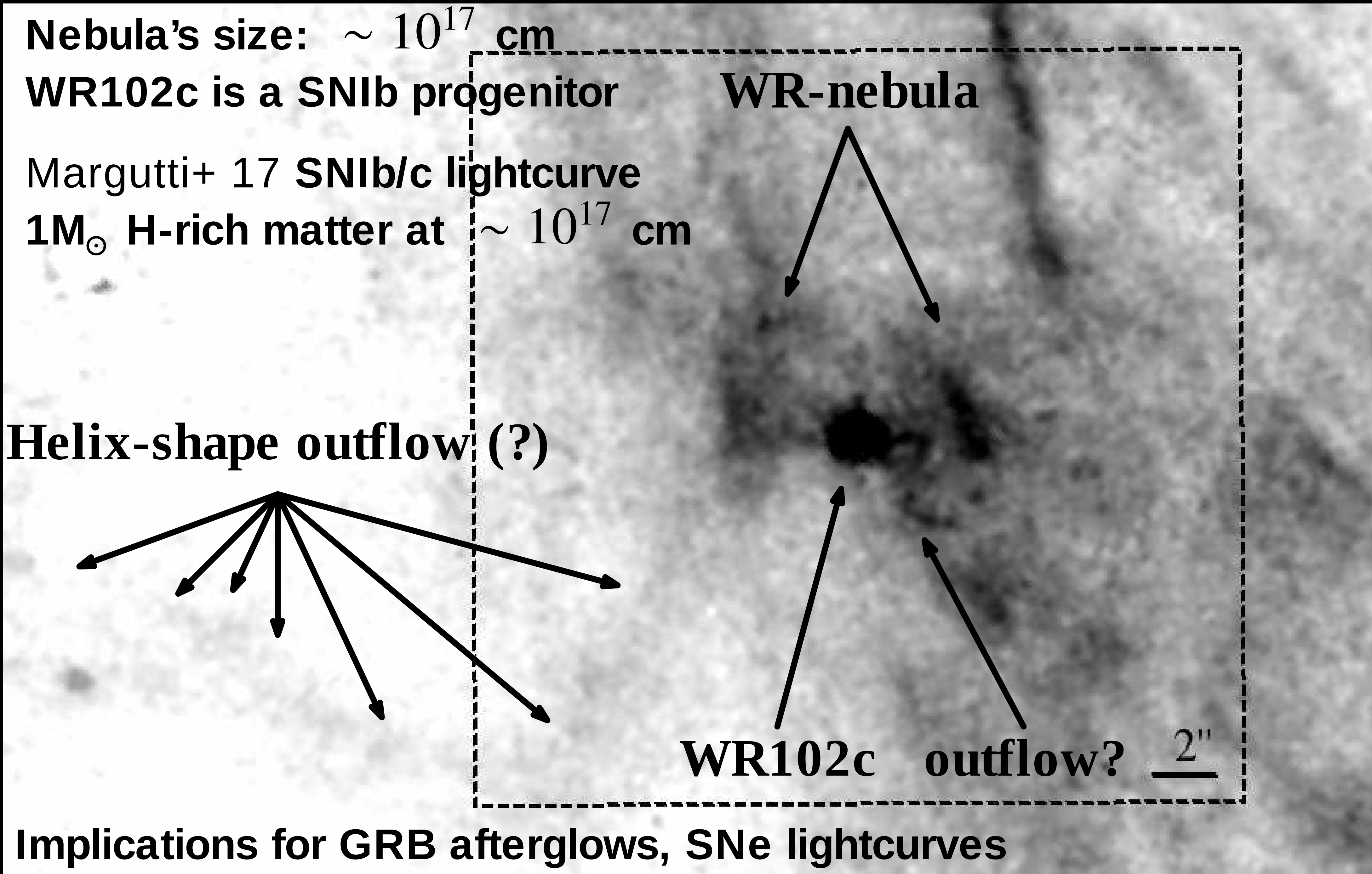
Steinke+ 16, Lau+ 16

Nebula's size: $\sim 10^{17}$ **cm**

WR102c is a SNIb progenitor

Margutti+ 17 **SNIb/c lightcurve**

1M$_\odot$ H-rich matter at $\sim 10^{17}$ **cm**



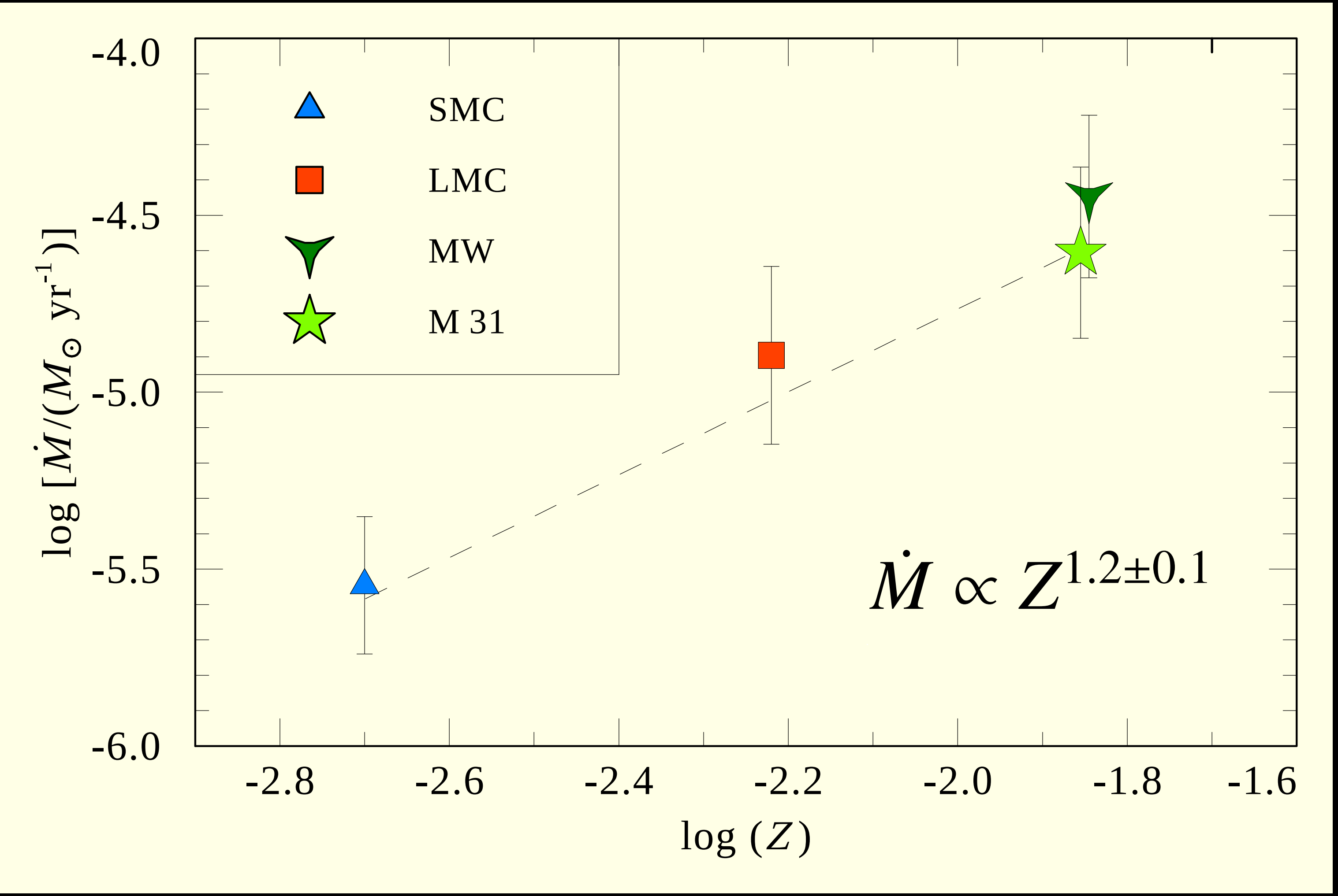
Implications for GRB afterglows, SNe lightcurves

Metallicity dependence of WR mass-loss rates

Large samples of WN stars from

- Small Magellanic Cloud (SMC)
- Large Magellanic Cloud (LMC)
- Milky Way
- Andromeda Galaxy (M31)

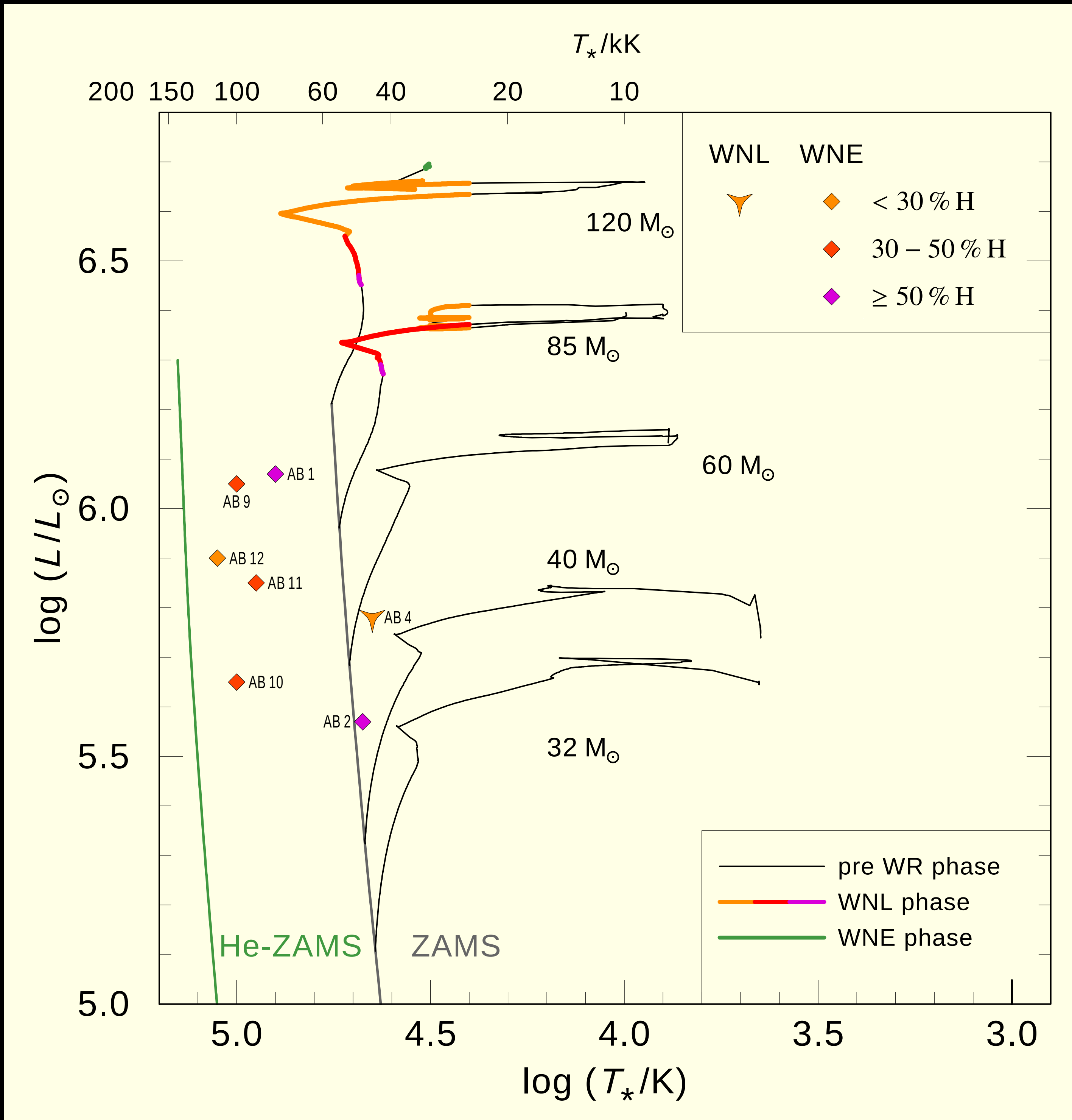
$$\dot{M}_{\rm WR} = f(L, T_*, X_{\rm He}, Z)$$



Hainich+ 15
Tramper+17

→ *Z-dependence much steeper than commonly assumed !*

Testing stellar evolution at low metallicity



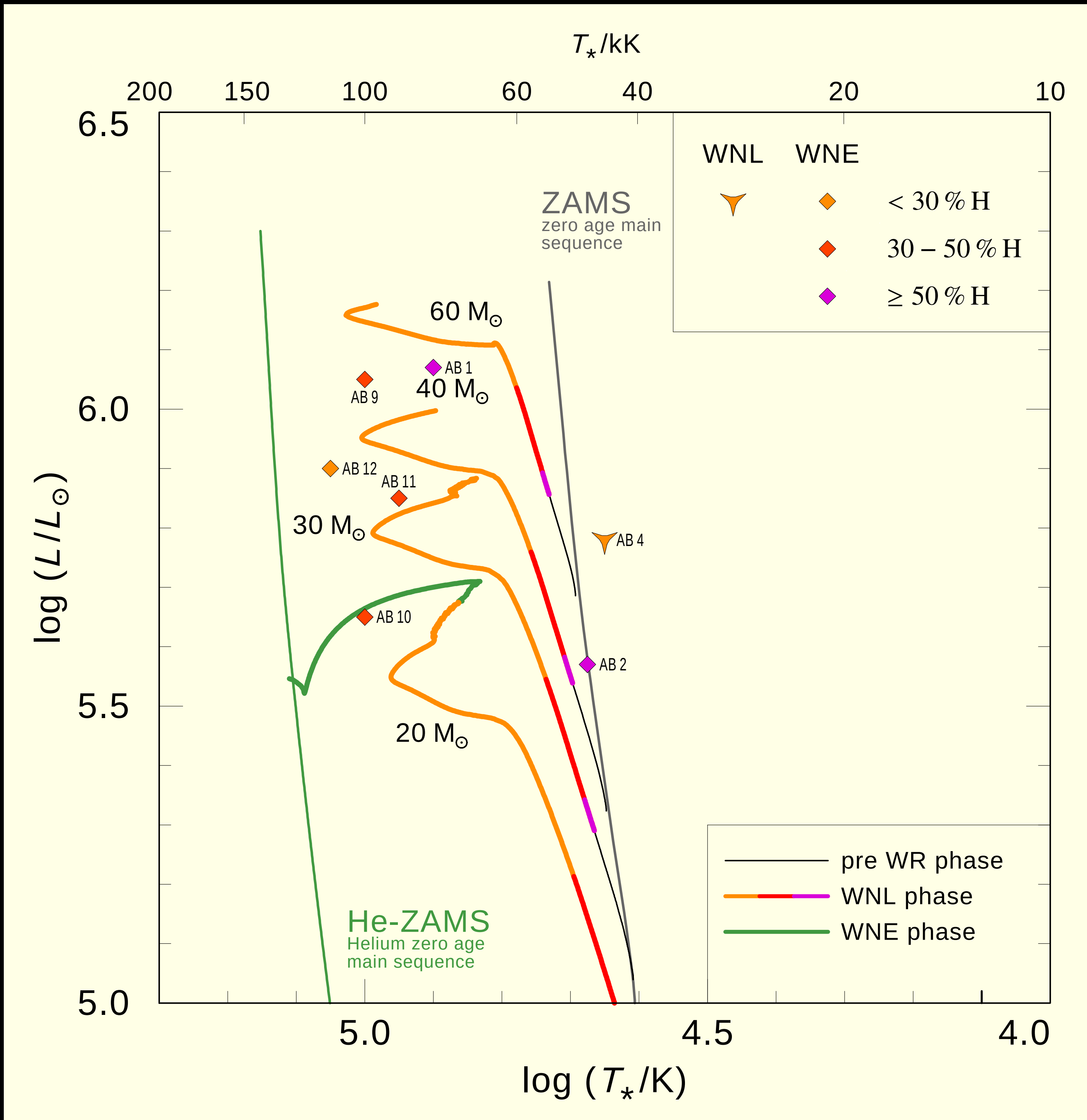
Small Magellanic Cloud (SMC)

- Discrete symbols: analyzed WR stars (Hainich+ 15)

  → SMC: *ALL* **WN stars contain hydrogen** (like Galactic WNL), but are hot and compact (like Galactic WNE)

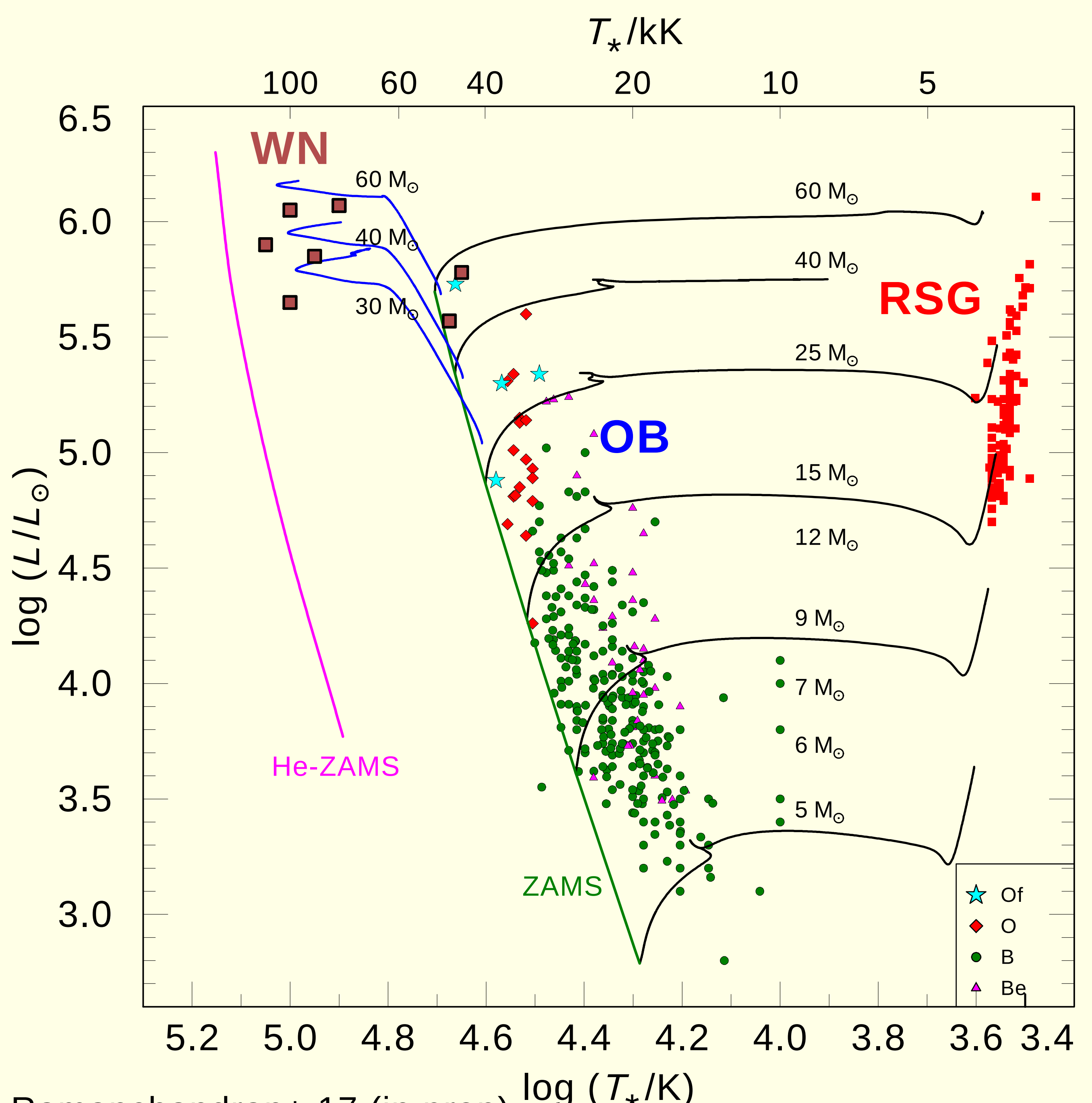
- **Evolutionary tracks** (Geneva code, with rotation, Z=0.14 $Z_\odot$) (Georgy+ 13)

Testing stellar evolution at low metallicity SMC



- Discrete symbols: analyzed WR stars (Hainich+ 15)
- WN stars in the SMC contain hydrogen but are hot and compact
- **Evolutionary tracks** (very strong rotational mixing, Z=0.14 $Z_\odot$) (Brott+ 11) →
- **quasi homogeneous evolution**

Massive stars in the SMC (spectroscopy > 500 stars, in prep)

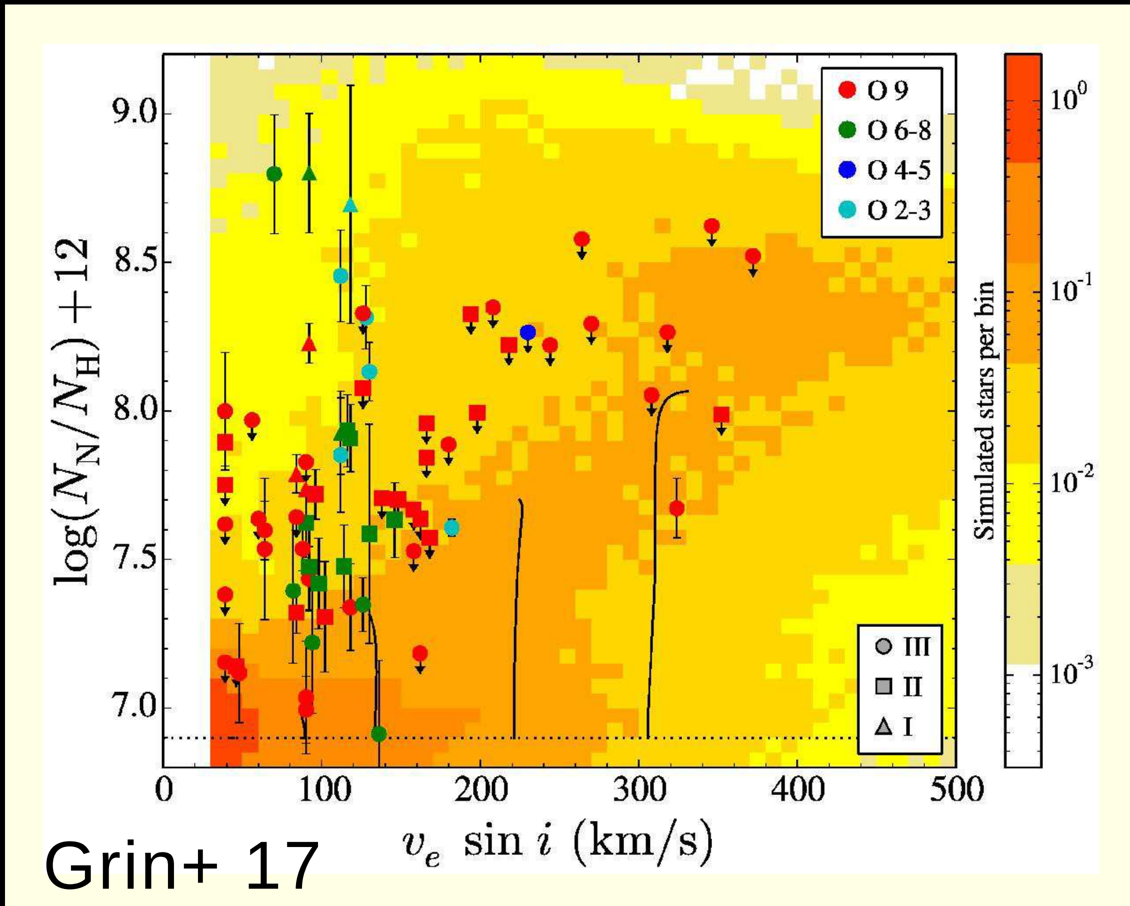


Ramanchandran+ 17 (in prep)

- Initial masses **> ~40 $M_\odot$ QHE**
- Initial masses **< ~30 $M_\odot$ evolve without full mixing**
- In some mass intervall (30 - 50 $M_\odot$) a second parameter might decide on the path: initial angular momentum? magnetic field?

RSGs: Massey & Olsen 03

Massive stars in the LMC (spectroscopic survey)



Evans+ 11

Indication for rotational mixing: N abundance vs $v \sin i$

Szecsi+ 15, at low-Z even moderate rotators evolve QCH. Implications for feedback.

Yoon & Langer 05, Woosley & Heger 06 **QHE of GRB progenitors**

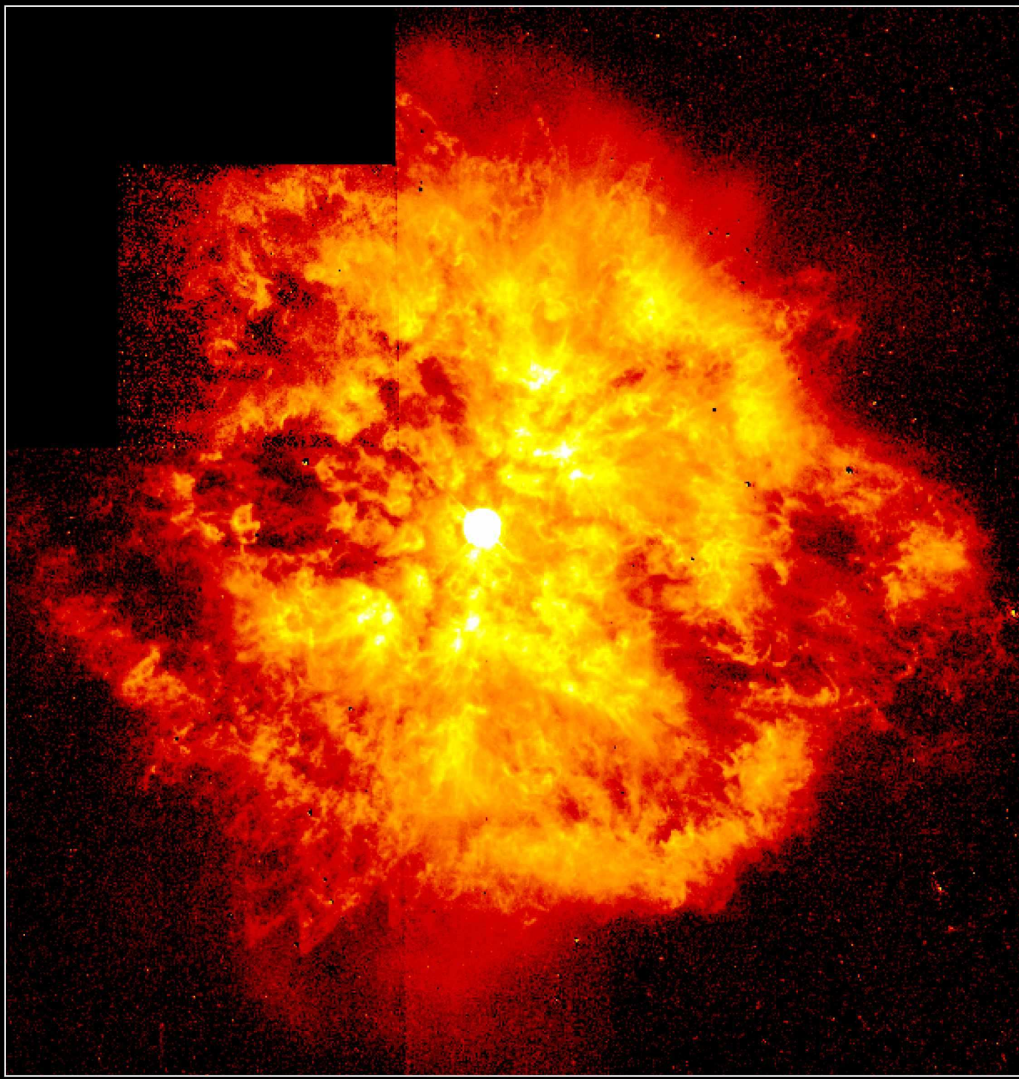
- massive fast-rotating He-stars are formed without removing H
- no giant branch phase, short time-scale for chemical mixing
- more massive cores than for non-rotating stars
- importance of the channel increases with decreasing Z

QHE of single stars is required for GRB progenitors (?)

Binary channels

Variety of mergers (Podsiadlowski 07)

- WR RLOF + NS
- He-core + NS in CE
- CO core + NS/BH
- lucky SN kick (NS/BH+ disruption)
- explosive CE ejection



Nebula M1-67 around Star WR124
Hubble Space Telescope • WFPC2

PRC98-38 • STScI OPO • Y. Grosdidier and A. Moffat (University of Montreal) • NASA

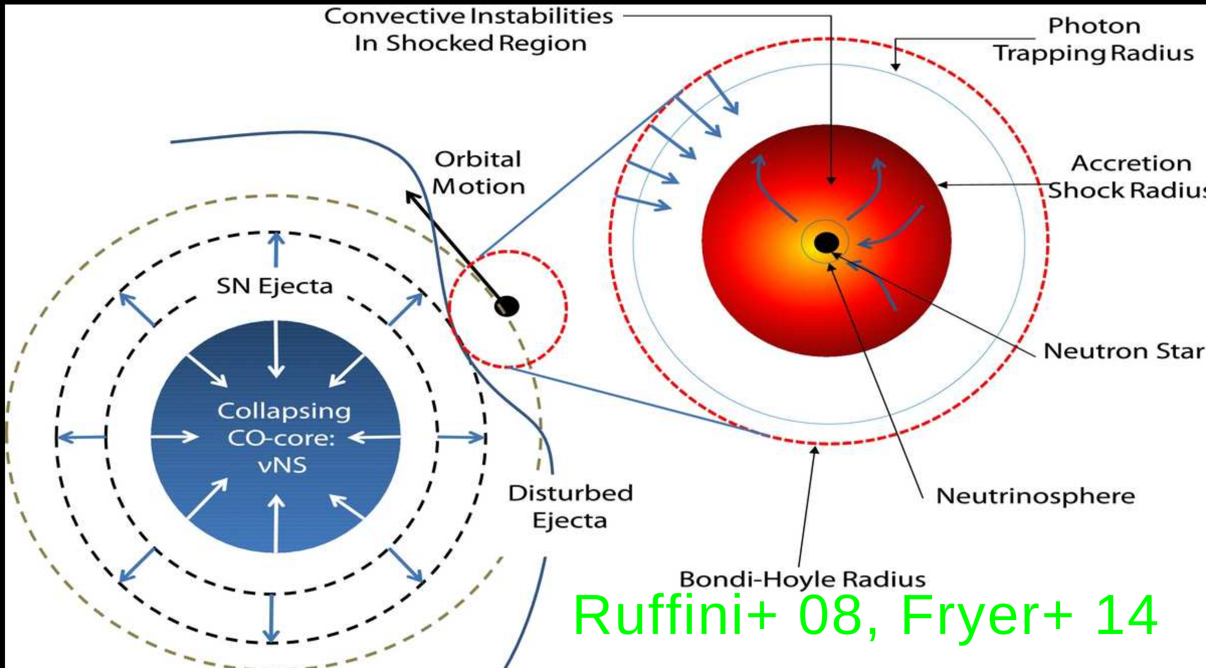
Example 1. Binary mass-transfer, the donor dies as SNIb/c (Cantiello+ 07)

- mass-gainer QHE
- Binary is disrupted by SN, the gainer becomes a runaway WR
- 7Myr later the gainer makes GRB

Three runaway WRs, among them WR148 is binary (Munoz+ 17)

X-ray observations of WR124 - soon!

Example2. The induced gravitational collapse (IGC)



Ruffini+ 08, Fryer+ 14

- Binarity: removes H-envelope, spin up the star
- tight binary after CE: massive CO star and a NS
- CO star SNIc → NS accretion → NS collapse into a BH → GRB

Observations of WR binaries

- WC/WN+O;
- Only four suggested WN+BH(?)
- Majority of HMXBs: sgOB+NS, **Be+NS**
- Neither WC/WO+NS/BH binaries nor RSG+BH

The only WO star in the SMC is a binary

Shenar+ 16: anlysis of complete set of WR binaries in the SMC

The majority of the WR stars are not chemically homogeneous

RLOF had occurred in most systems, affecting their evolution

The WR stars were initially massive: binarity is not required

AB 8: WO+O4V, 20 $M_\odot$ + 60 $M_\odot$

supergiant shell - 600 pc diameter

Hα+[OIII]+X-ray

Summary

Image: Bill Saxton, NRAO/AUI/NSF

WR stars can have strong winds even at low Z

$M > 40M_{\odot}$: O → WNL (LBV?) → WNE → WO → SNIc/GRB

H-free WR - can be fast rotators and magentic

H-rich nebulae around H-free WRs

Evidence for QHE at low-Z for stars > $40M_{\odot}$.

WR-binaries in the SMC - no QHE

Observed WR populations provide support for GRB progenitor models including single and binary channels