Models of Episodic Mass Loss from Massive Stars

Episodic	1-10 yr every 10^{3-4} yr
Mass Loss	0.1-10 $M_\odot$ / episode
Massive	> 40 $M_\odot$

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AST 541

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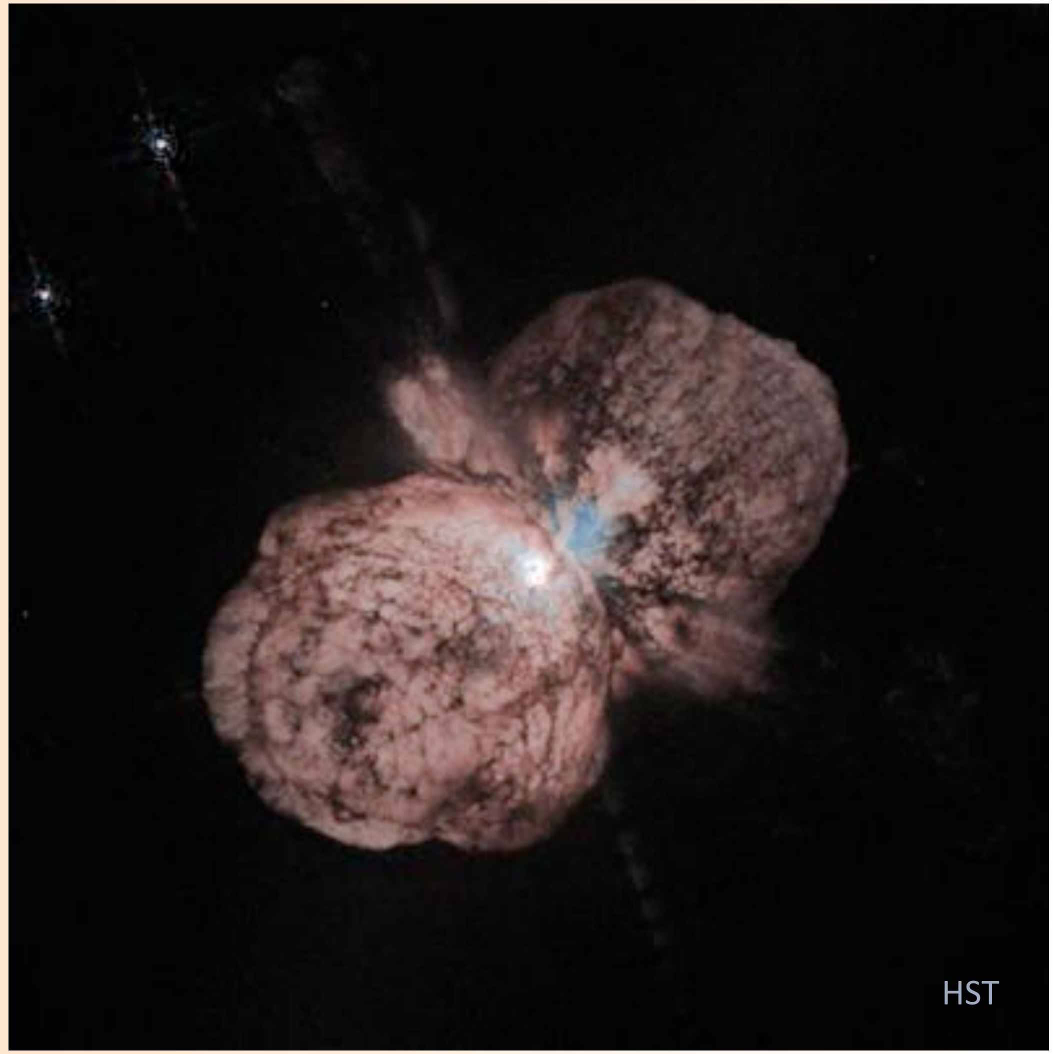
Eta Carinae—Luminous Blue Variable

- The Great Eruption (GE) — 1830-1860, 10-20 $M_{\odot}$ expelled (Humphreys, Davidson 1994, HD94)
- 10^{50} ergs in homunculus (almost SN!) (Smith, 2003)
- The Lesser Eruption (1890), < 1 $M_{\odot}$ expelled (HD94)



Luminous Blue Variables (LBVs)

- aka S Doradus stars (LMC), Hubble-Sandage variables, SN impostors (e.g. η Car, P Cygni)
- $L \approx 10^6 L_\odot$, close to Eddington limit $L_{\rm Edd} = \frac{4\pi c G M}{\kappa}$
  - η Car $L/L_{\rm Edd.} \approx 0.9$ (Owocki & Smith 2006)
- Lifetime ≈ 10,000 – 100,000 yrs (HD94)
- Highly variable
- Quiescent mass loss (HD94): $\dot{M} \approx 10^{-4}\ M_\odot\ {\rm yr}^{-1}$
- Eruptive mass loss (HD94): $\dot{M} \gtrsim 10^{-2}\ M_\odot\ {\rm yr}^{-1}$

Evolution to LBV (m > 40 $M_\odot$)

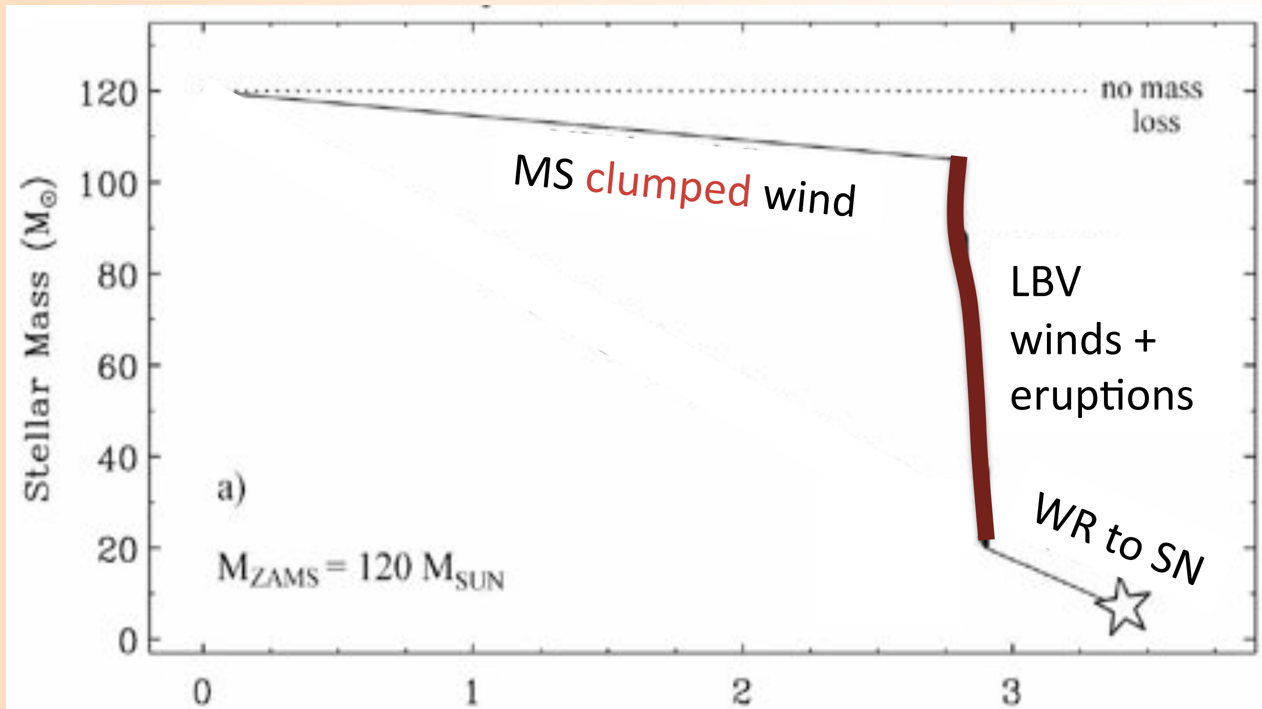
O star (wind mass loss)

LBV (red SG at low masses?)

Wolf-Rayet (10-20 M_{SUN})

SN I b/c

Conti, 1976; Massey, 2003



Time (Myr)

Smith, 2006

Favored evolutionary track; requires large mass loss from LBVs to make WR star

Nebulae around known/suspected LBV stars

Episodic mass loss models:

Ejecta: 1-10 $M_\odot$

Timescale:1-10 yrs

Independent of L

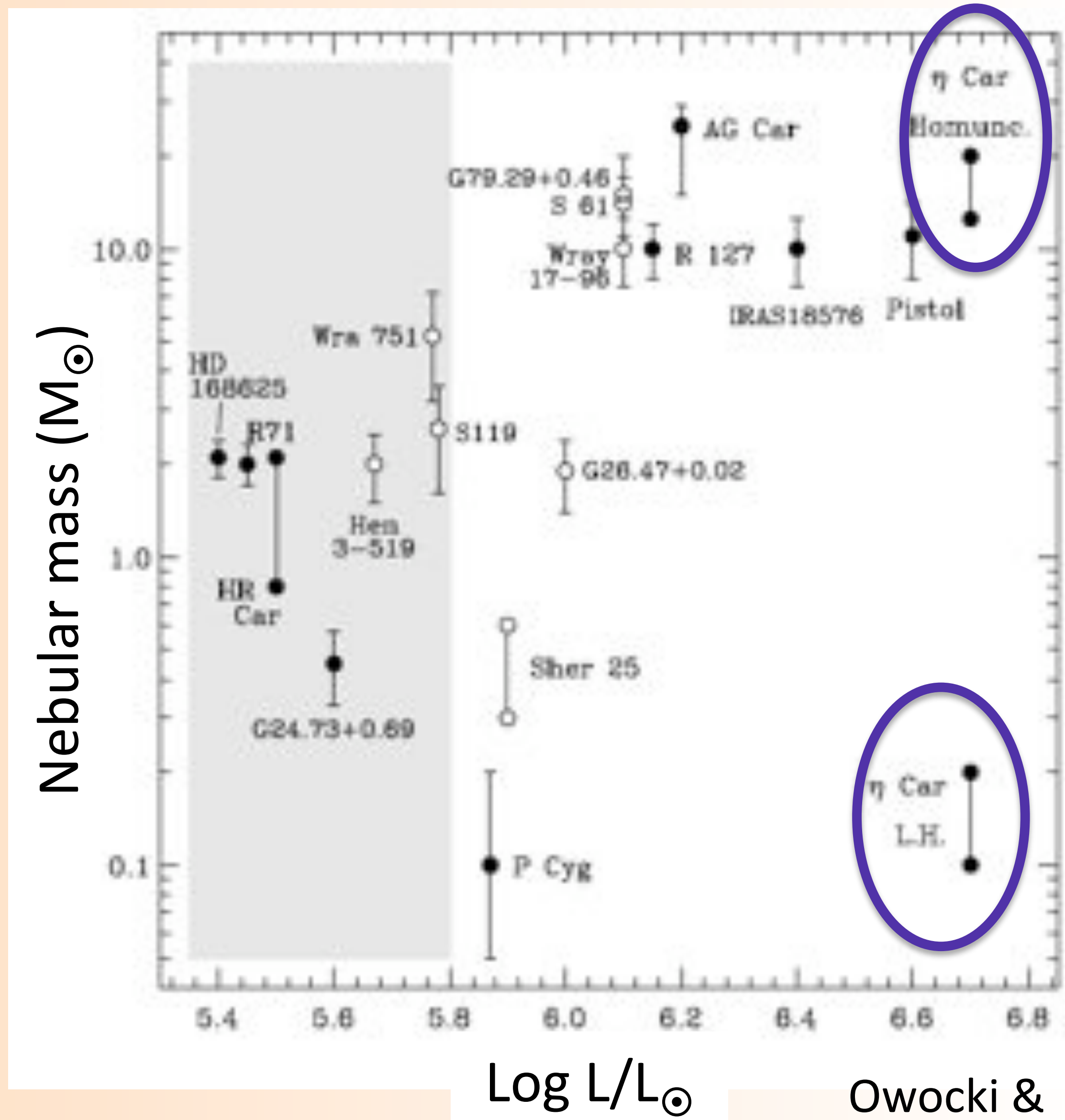
Wind speed > 100 km s^{-1}

Options:

Wind-driven

Pulsation

Thermonuclear



Owocki & Smith, 2006

Mass Loss—Winds?

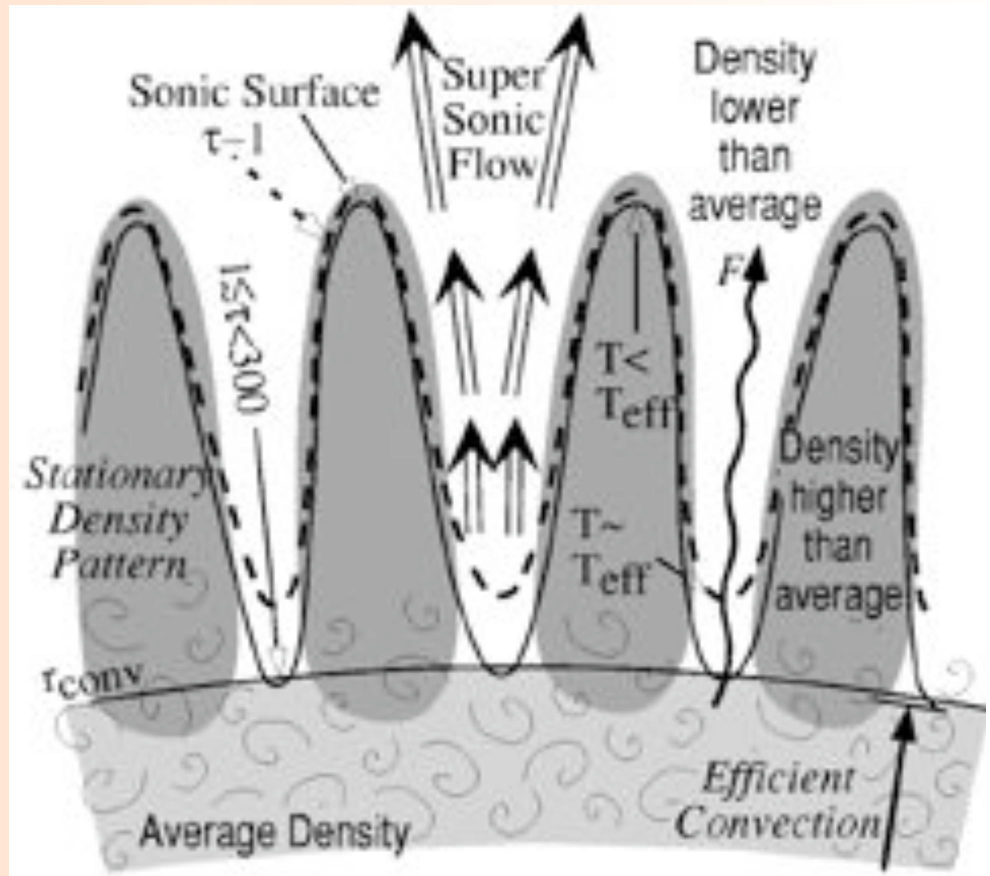
- Main sequence mass loss rates: 0.2-20 x 10^{-6} $M_\odot$ yr^{-1}
- Winds driven by radiation pressure
- Photon momentum transferred to wind by scattering in metal lines (Castor, Abbott, & Klein 1975)
  - in range of SMC-solar *Z*, $\dot{M} \propto Z^{0.5-0.7}$

$$\dot{M}_{\rm CAK} \lesssim 1.4 \times 10^{-4} \left(\frac{L}{10^6 L_\odot}\right) M_\odot \ {\rm yr}^{-1}$$

- Eruptives state mass loss is *not* driven by same mechanism as O star winds

Eruption Mechanisms (1)

- Steady-state, continuum driven (e^- scattering) wind (Owocki et al. 2004)
- Super-Eddington ➔ porous medium (Shaviv, 2000; Shaviv, 1998)
- Wind/Radiation flow out of low density pockets



NOT TO SCALE

Shaviv, 2000

Continuum Wind + Porosity Model

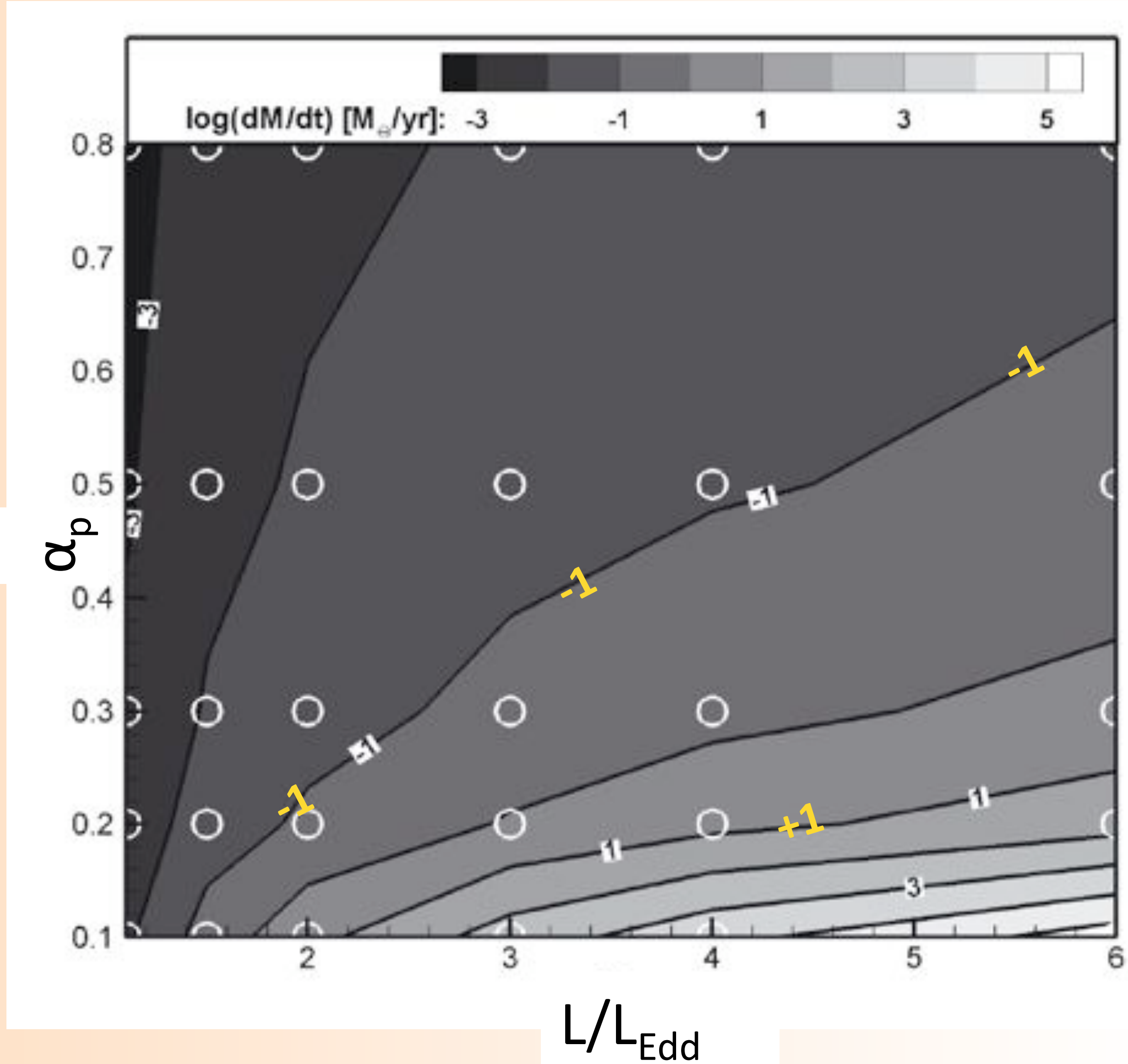
Clump optical depth (τ) distribution:

$$\tau \frac{\mathrm{d}F}{\mathrm{d}\tau} \propto \tau^{\alpha_p} e^{-\tau}$$

(Owocki et al, 2004)

1D hydrodynamic numerical simulations (ZEUS) (van Marle et al, 2008)

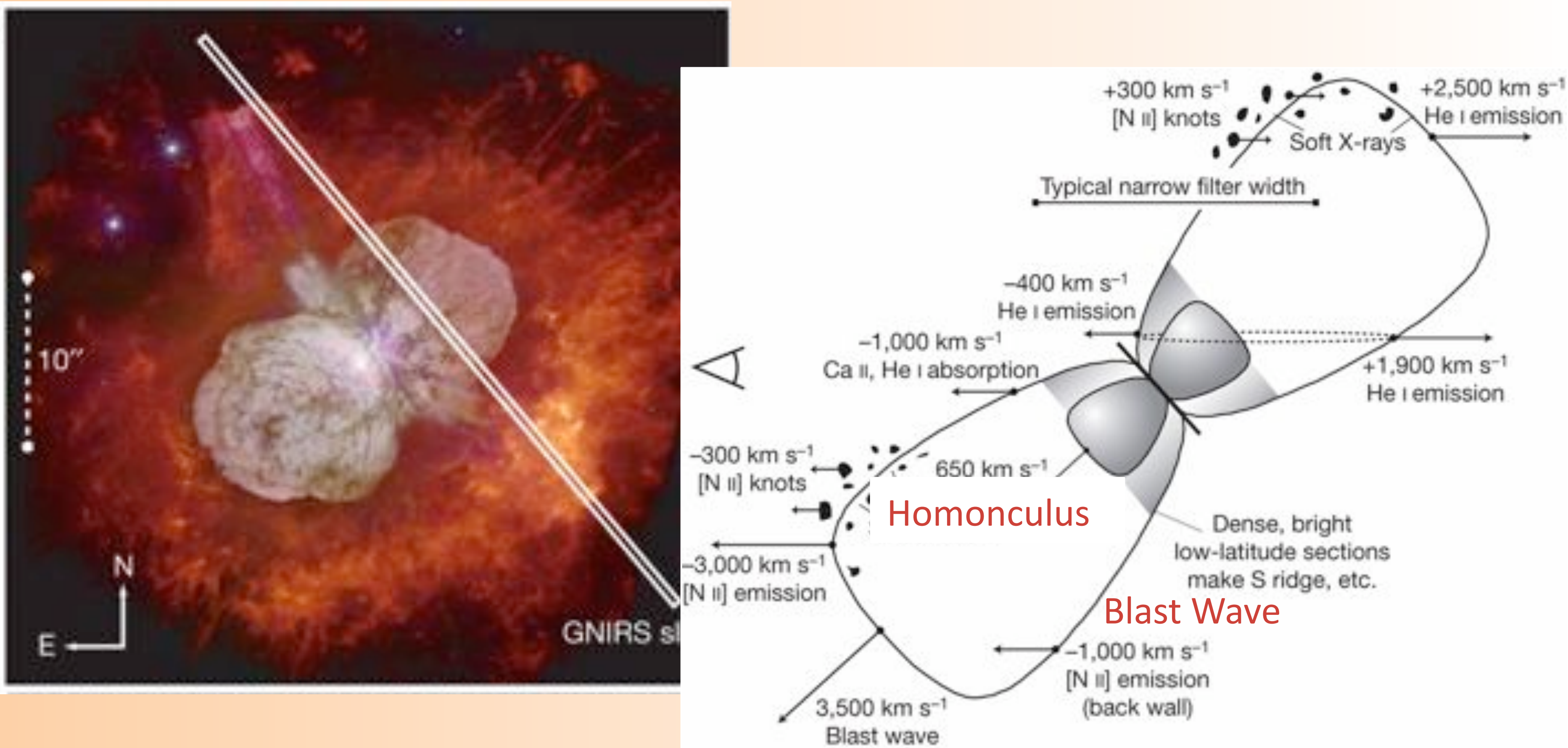
Marginally enough mass loss for eruptive LBV state



van Marle et al, 2008

Eruption Mechanisms(2)

Fast outflow ahead of η Car homunculus suggest shocked ejecta, hydrodynamic event (Smith, 2008)



Eruption Mechanisms(2)

Young, 2005, Arnett et al. 2005

- Wave-mixing gives larger core, lower density envelope
- $T \approx 10^{5.5}$ metal line opacity bump moves inwards, lowers local Eddington luminosity→unstable
- Depth of instability: 5 $M_{\odot}$

Glatzel, 1999 & 2005

- Strange modes: Acoustic waves btw photosphere & an opacity maximum
- Instability requires high P_{rad}, low heat capacity /density
- Possibly drive mass loss, $v \approx 100$ km s^{-1}

Eruption Mechanisms(2)

Guzik, 2005

- g modes form in radiative H/He region outside He core
- Shearing action of modes ➔mix H into core ➔thermonuclear explosion

Pair Instability Pulsations (Woosley et al, 2007)

- e^--e^+ pair creation ➔ core contraction ➔ thermonuclear burning
- H-envelope binding energy ≈ 10^{49} ergs < pair instability explosion energy
- Shortly precedes (10 yr) SN

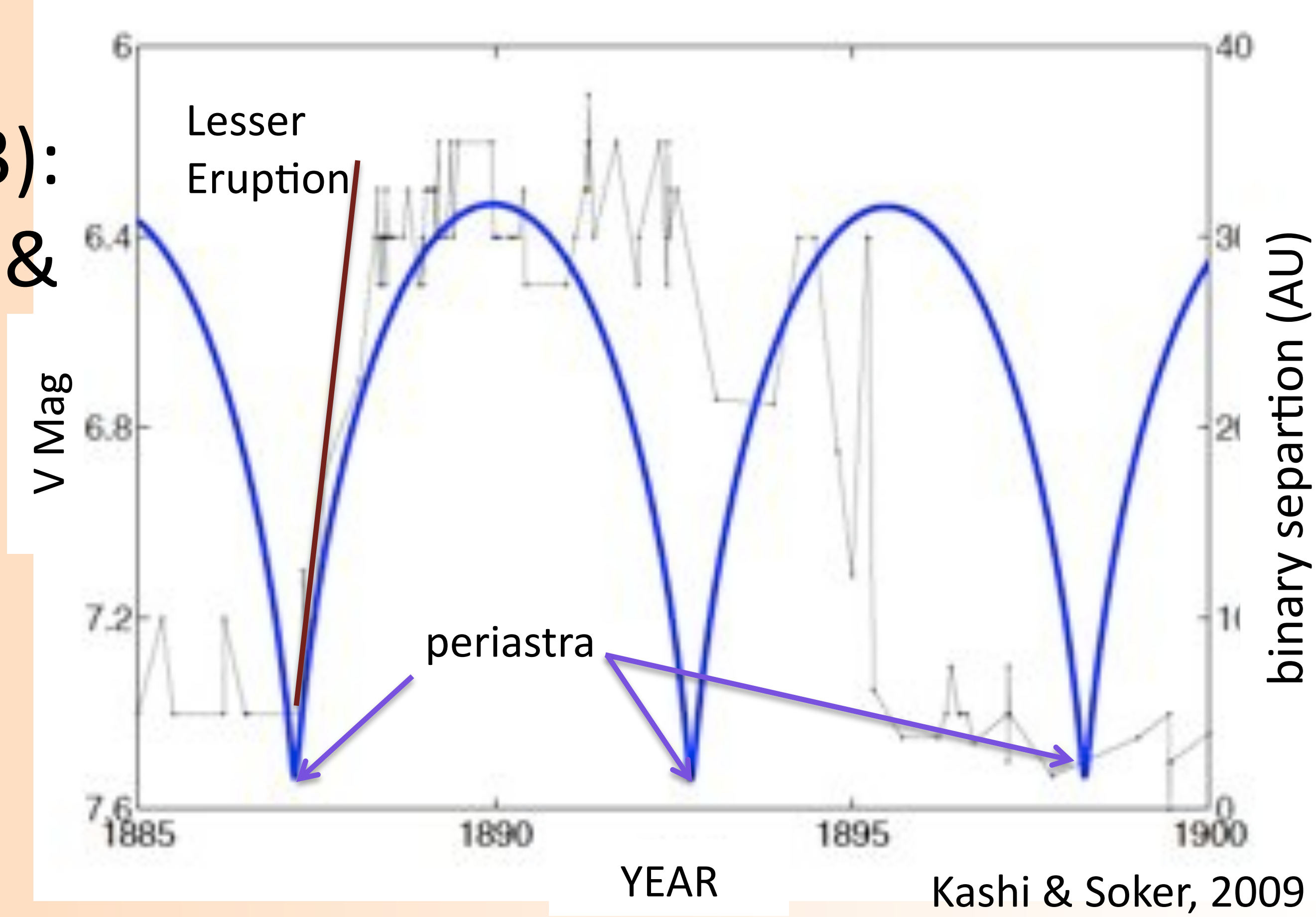
Eruptions Mechanisms (3): Binarity (Kashi & Soker 2009)

η Car:

M_1=120-170 $M_\odot$

M_2= 30-90 $M_\odot$

P = 5.54 yr



Kashi & Soker, 2009

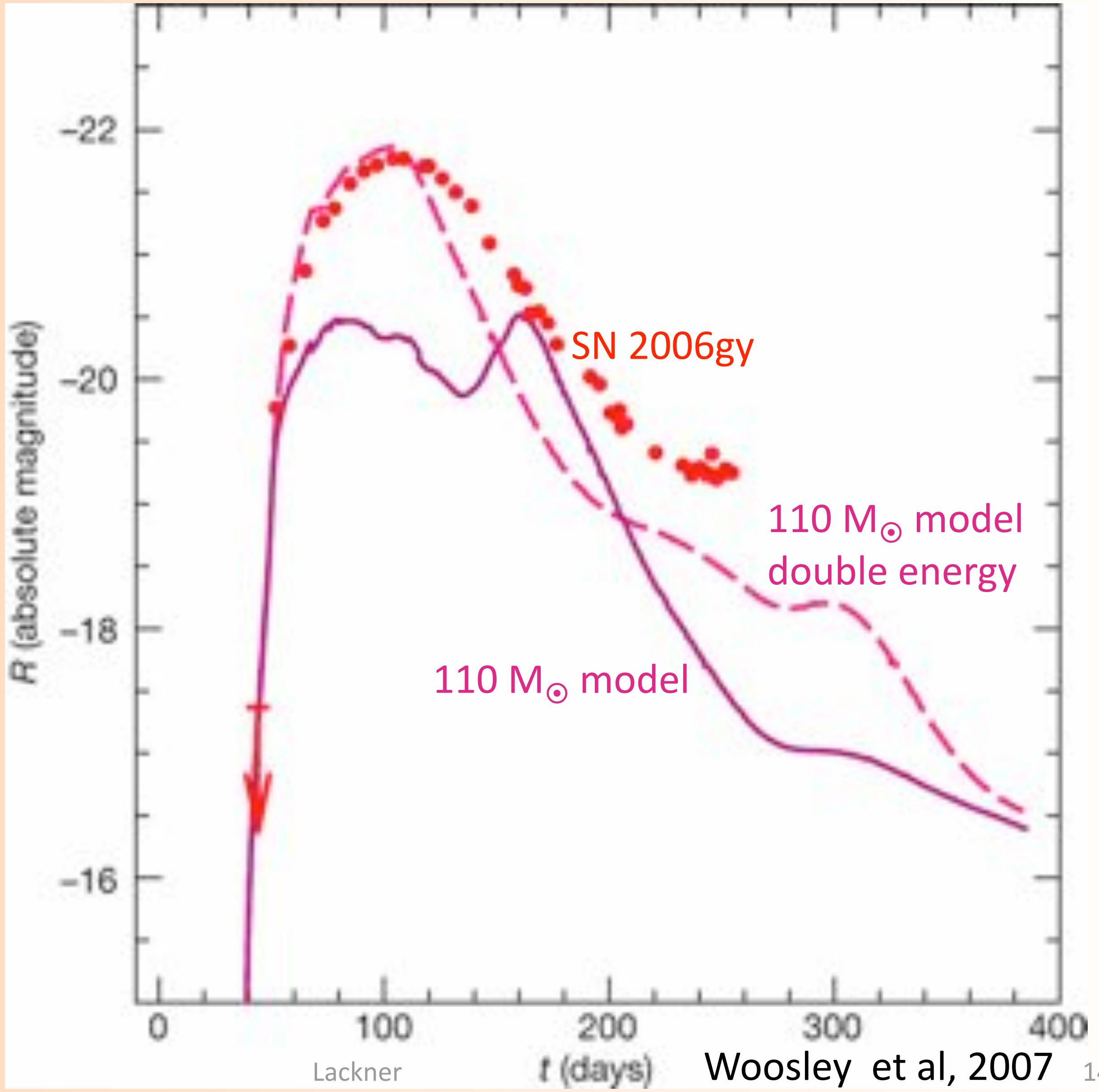
- Can only be modeled for GE because mass loss changes orbital period
- Soker, 2004 suggest component of η Car GE luminosity explained by accretion onto companion

LBVs & SNe

- SN/GRBs with massive circumstellar nebulae: SN1988Z (15 $M_\odot$) (Aretxaga, 1999)
- Radio modulations of light curves = shock passing expelled matter shells? (Kotak & Vink, 2006)
- SN 2006jc (type Ib)—preceded by *observed* LBV outburst (Foley, 2007)
- SNe IIn (eg SN2006gy) require bursts of mass loss before exploding
  - P Cyg profiles of Hα lines suggest wind of 200 km s^{-1} (LBV)
- New evolution scenario? O➔WN(H rich)➔LBV➔SN

SN2006gy Light curve—Future of Eta Carinae?

Light curve powered by collision of shock with previously expelled material (Smith, 2007; Woosley et al, 2007)



Woosley et al, 2007

Aside—First Stars

- Eruption of LBVs, many possible mechanisms are independent of Z
- Large mass loss events for the first (massive) stars:
  - Alter initial ISM pollution and subsequent IMF
  - Changes yields remnant (NS/BH) yields
- Models of the first stars should include mass loss

Summary

- Episodic mass loss seems necessary
  - Stars like η Carinae exist (SNe imposters)
- LBV phase provides potential for high mass loss, but mechanism (wind-like, hydrodynamic, magnetic, binary-induced) remains unknown
- Close association with mass loss and SNe suggest some LBV progenitors for SN