Eta Carinae and the Pre-Supernova Circumstellar Material of Massive Stars

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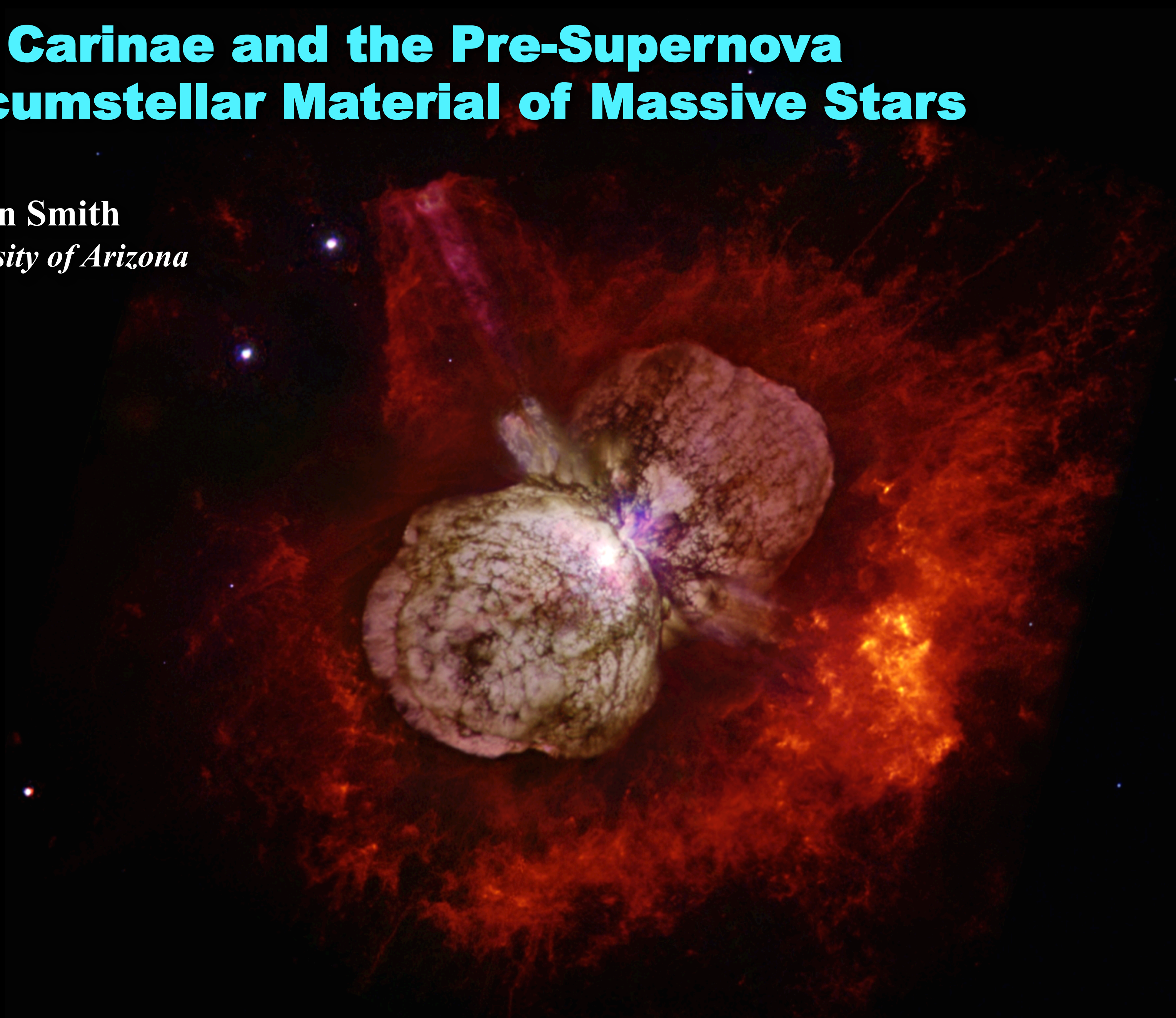

A&A 435, 1043–1061 (2005)
DOI: 10.1051/0004-6361:20041395

Astronomy & Astrophysics

The sub-arcsecond dusty environment of Eta Carinae★

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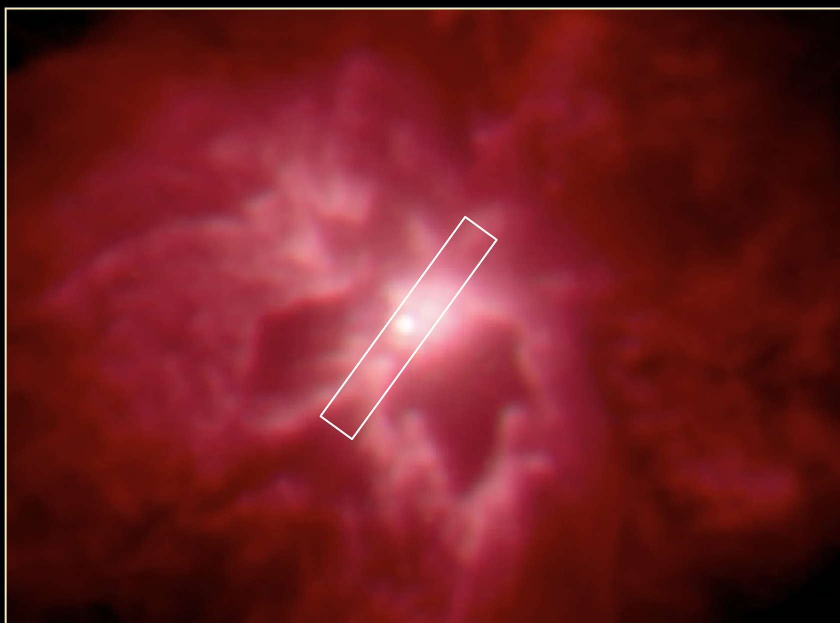
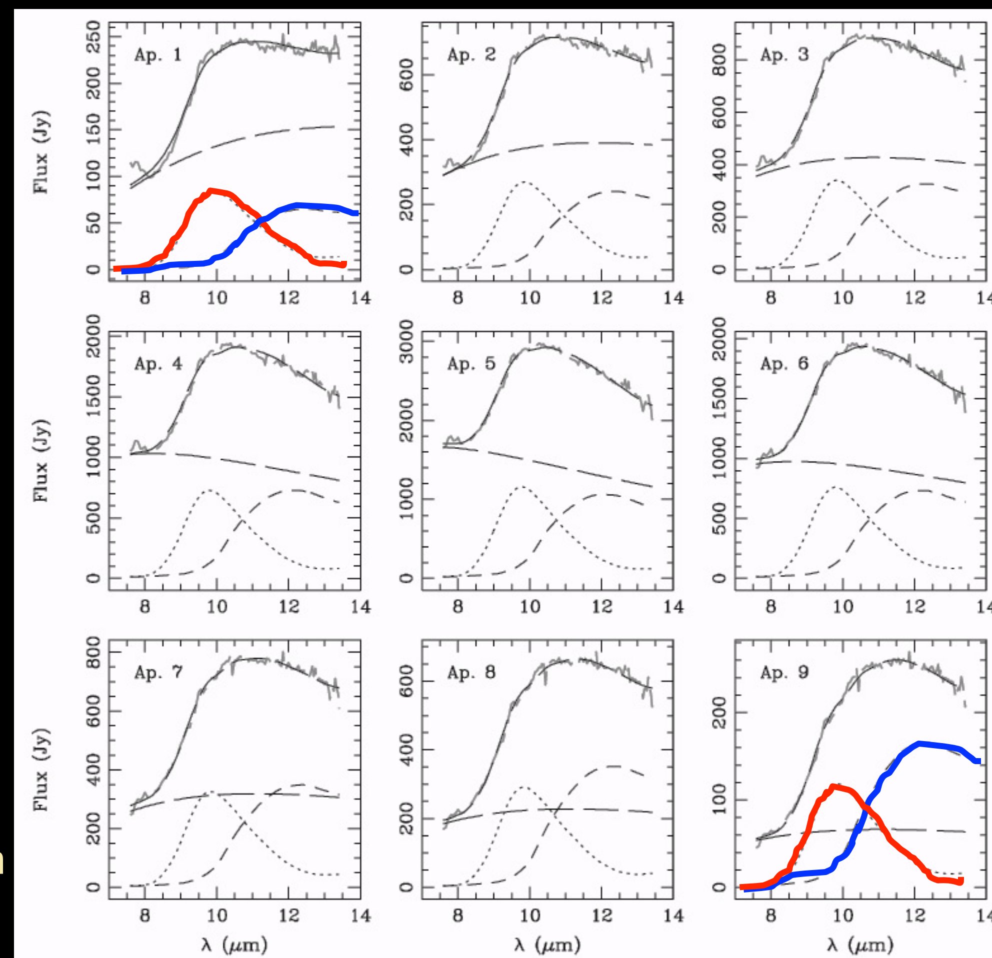
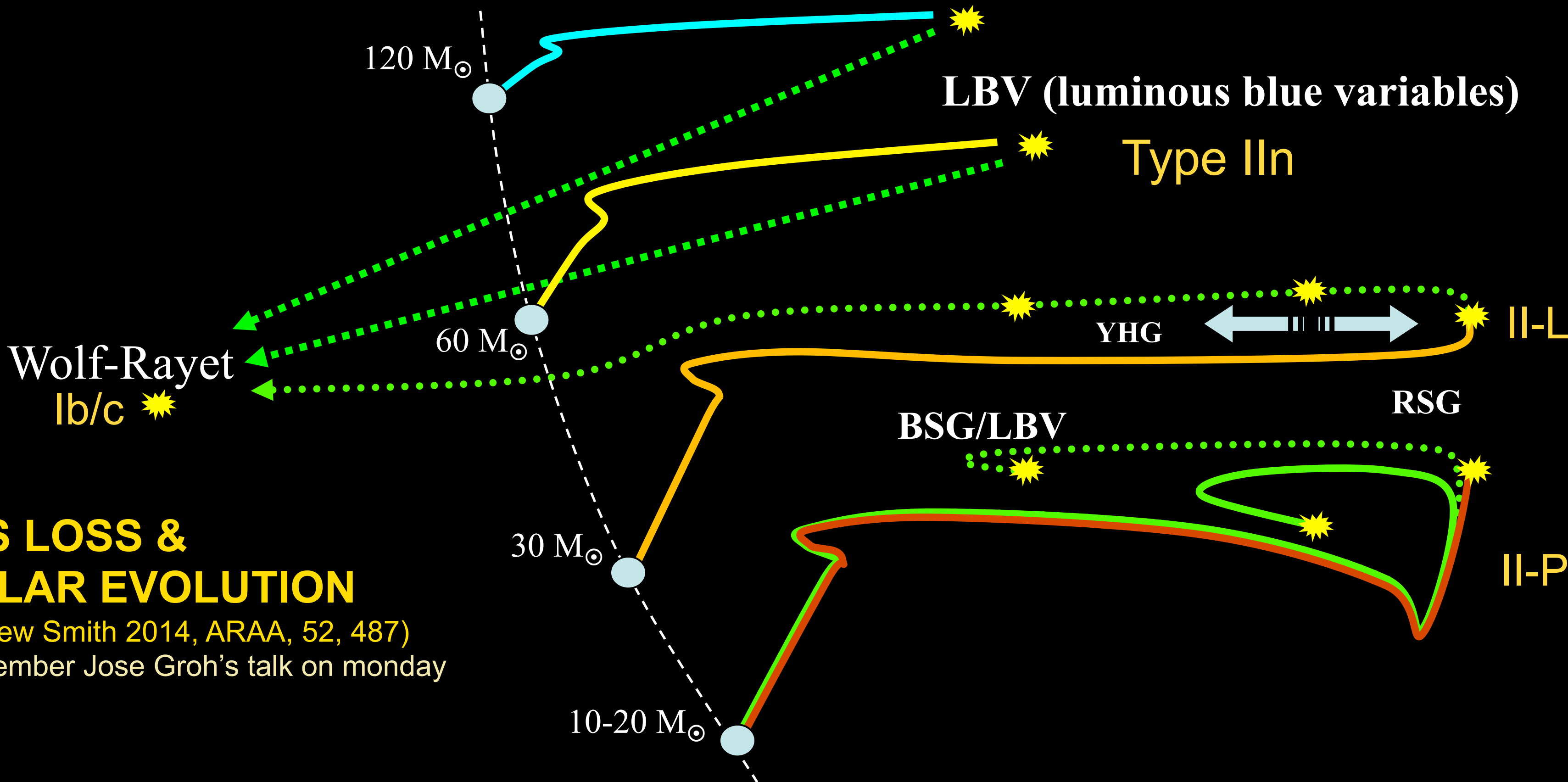


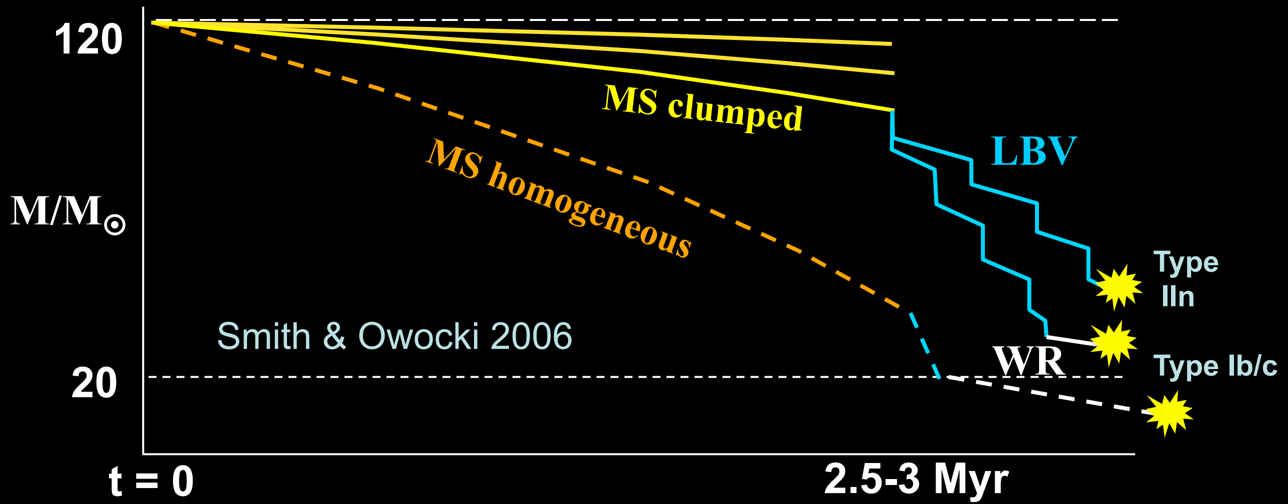


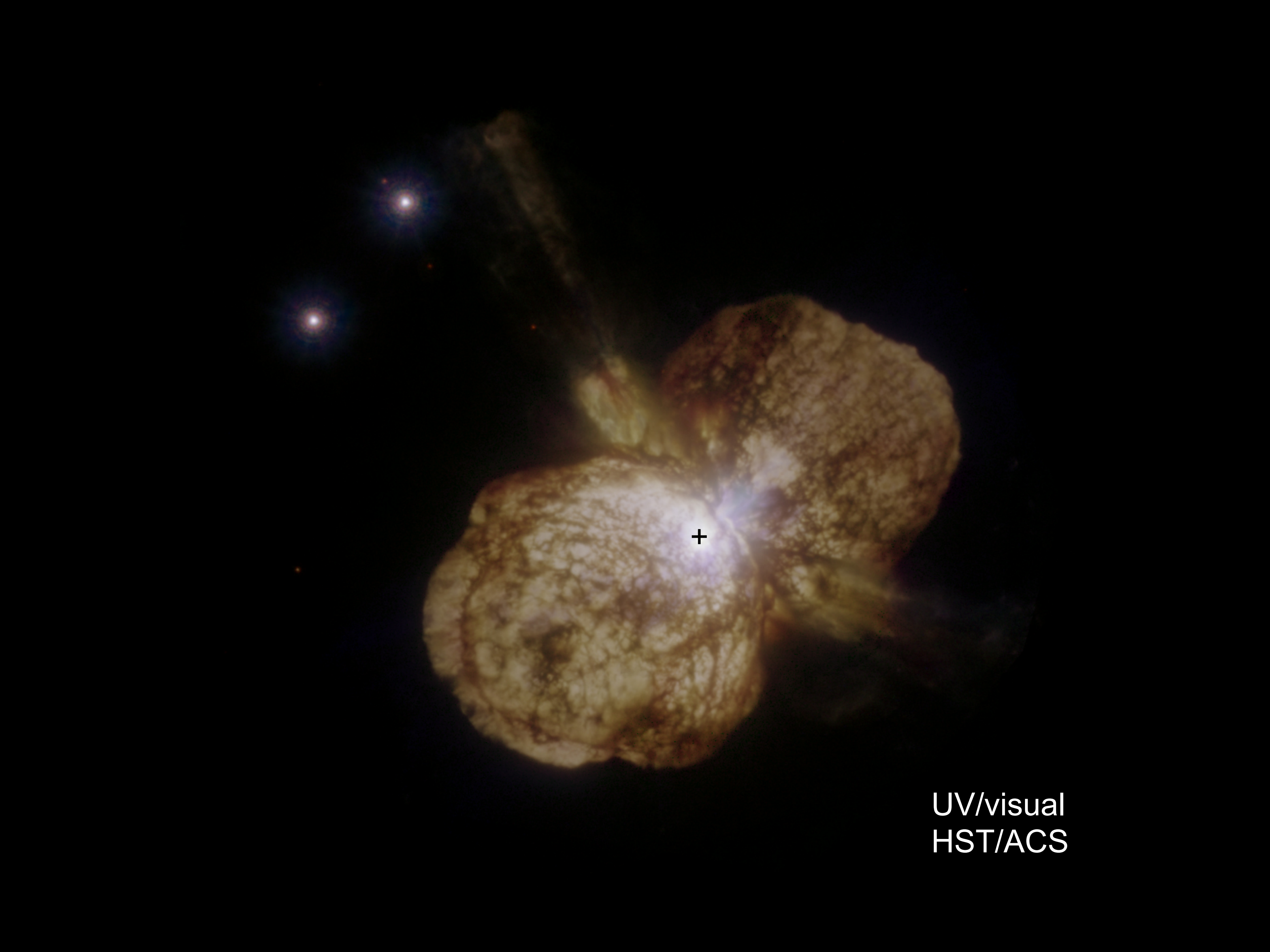
- Highest resolution near-IR images of Eta Car obtained so far.
- MIDI: Differences in dust composition on very small spatial scales.

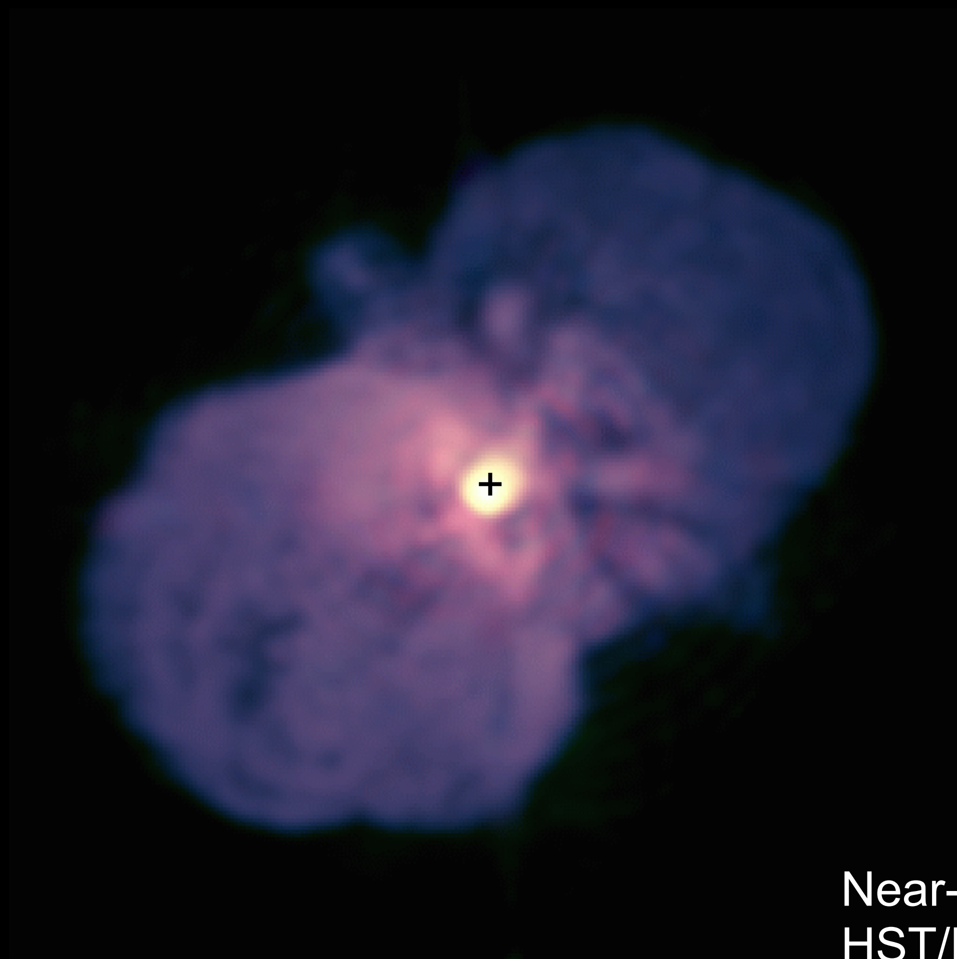


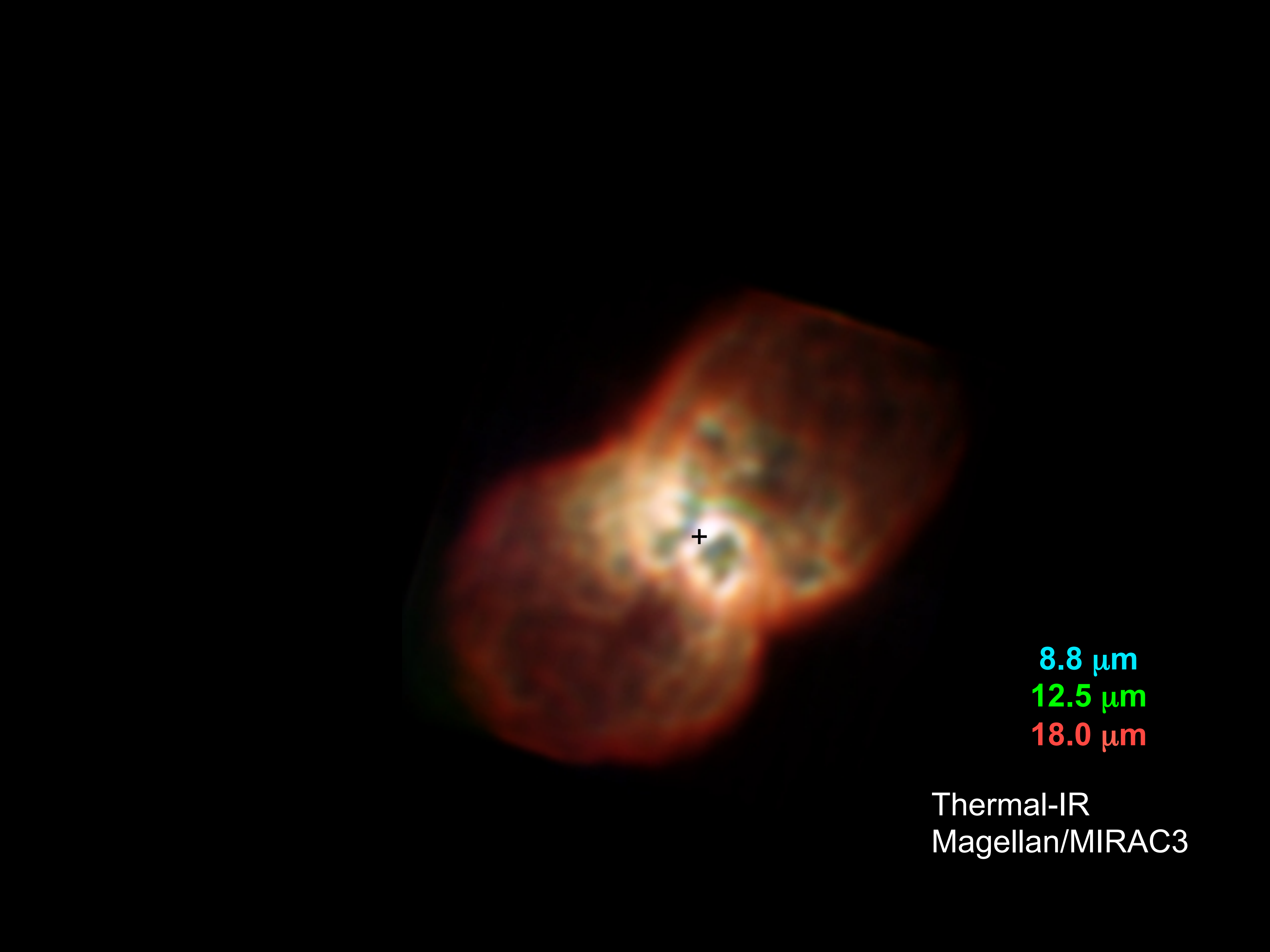
MASS LOSS & STELLAR EVOLUTION

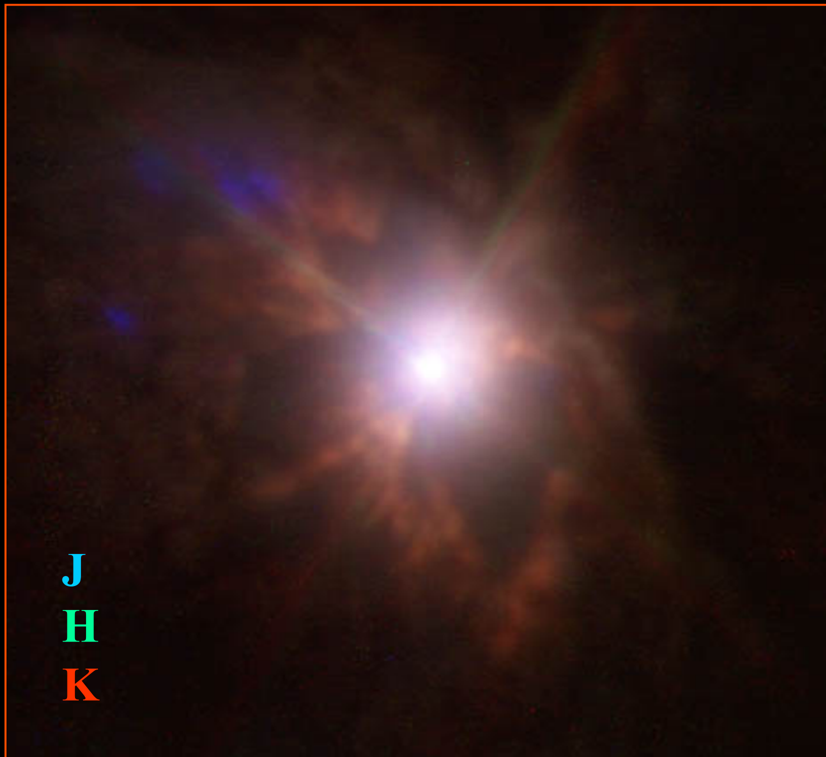
(see review Smith 2014, ARAA, 52, 487)
and remember Jose Groh's talk on monday



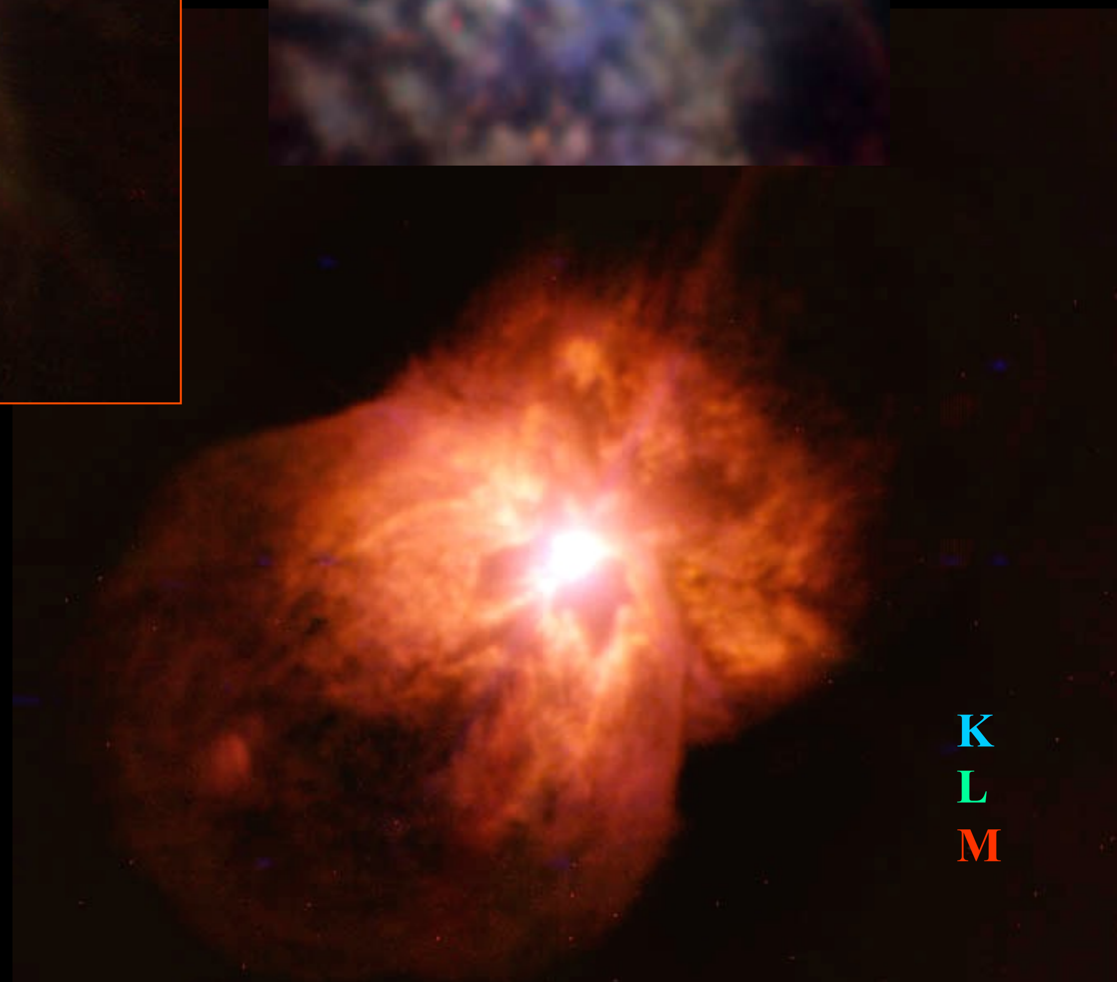

UV/visual
HST/ACS


Near-IR
HST/NICMOS


8.8 μm
12.5 μm
18.0 μm
Thermal-IR
Magellan/MIRAC3

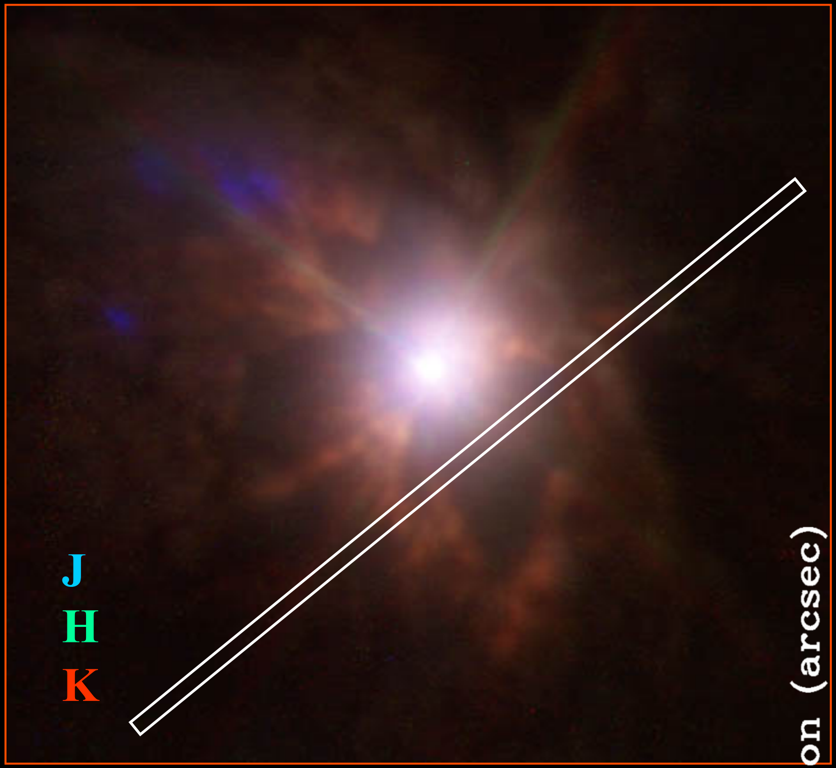


HST
ACS/HRC



VLT AO imaging
NAOS/CONICA

VLT images made
by Olivier
(Chesneau + 2005)



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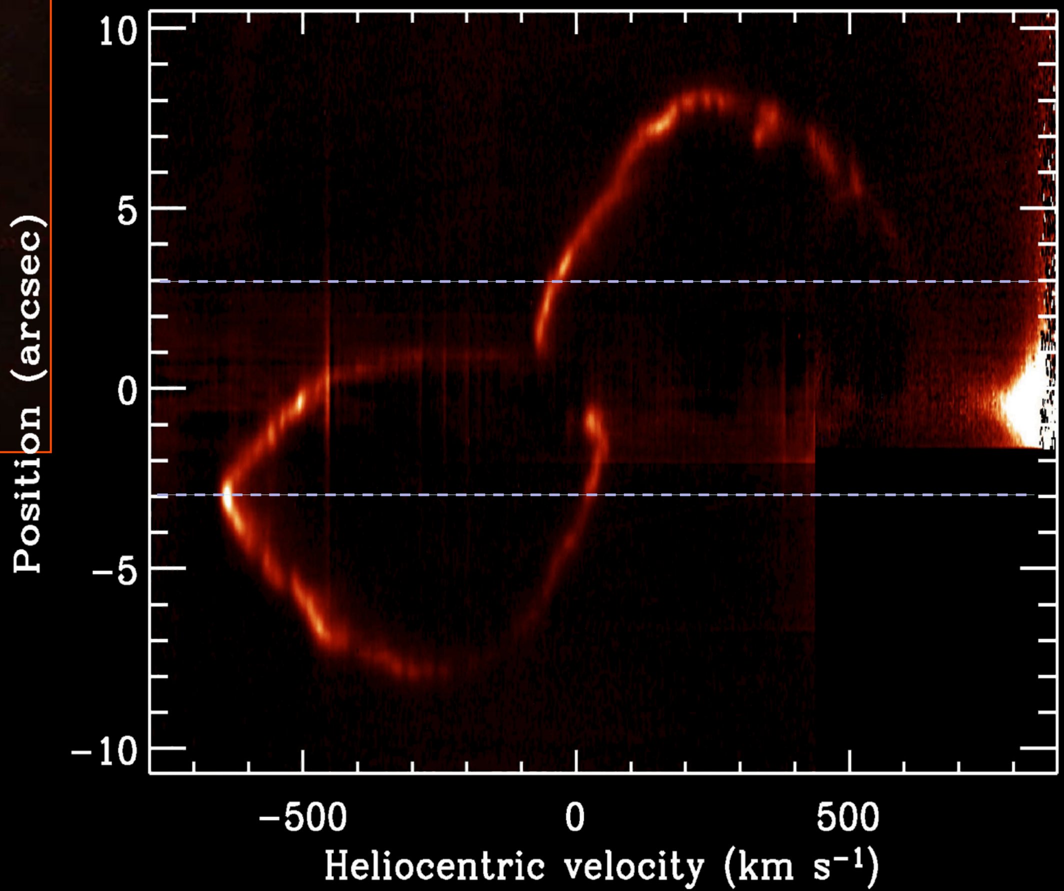
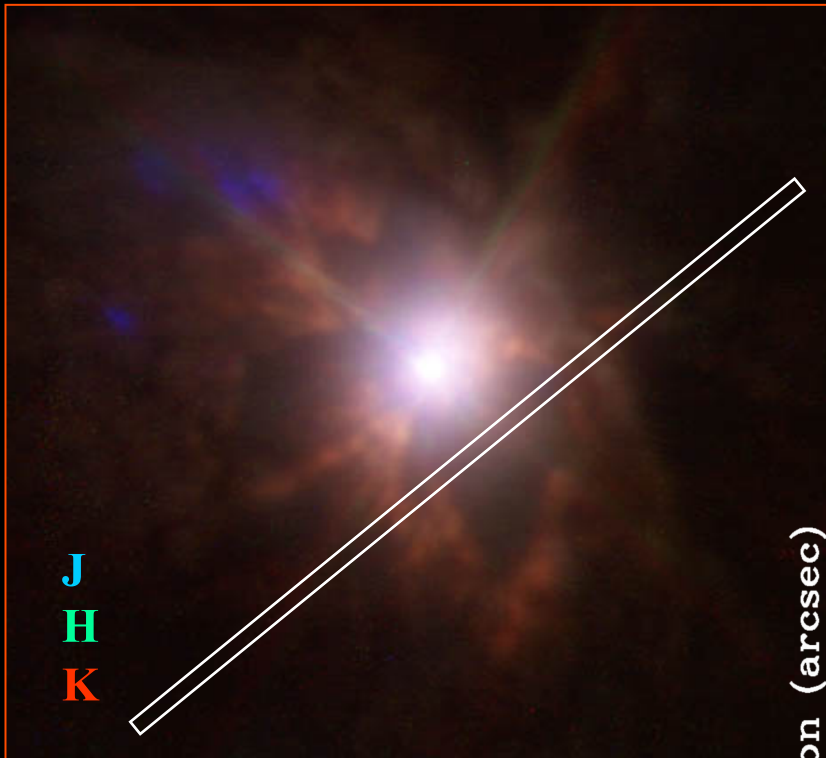
Gemini South/Phoenix
R=60,000
(Smith 2006)



2.122 µm H_2 1-0 S(1)



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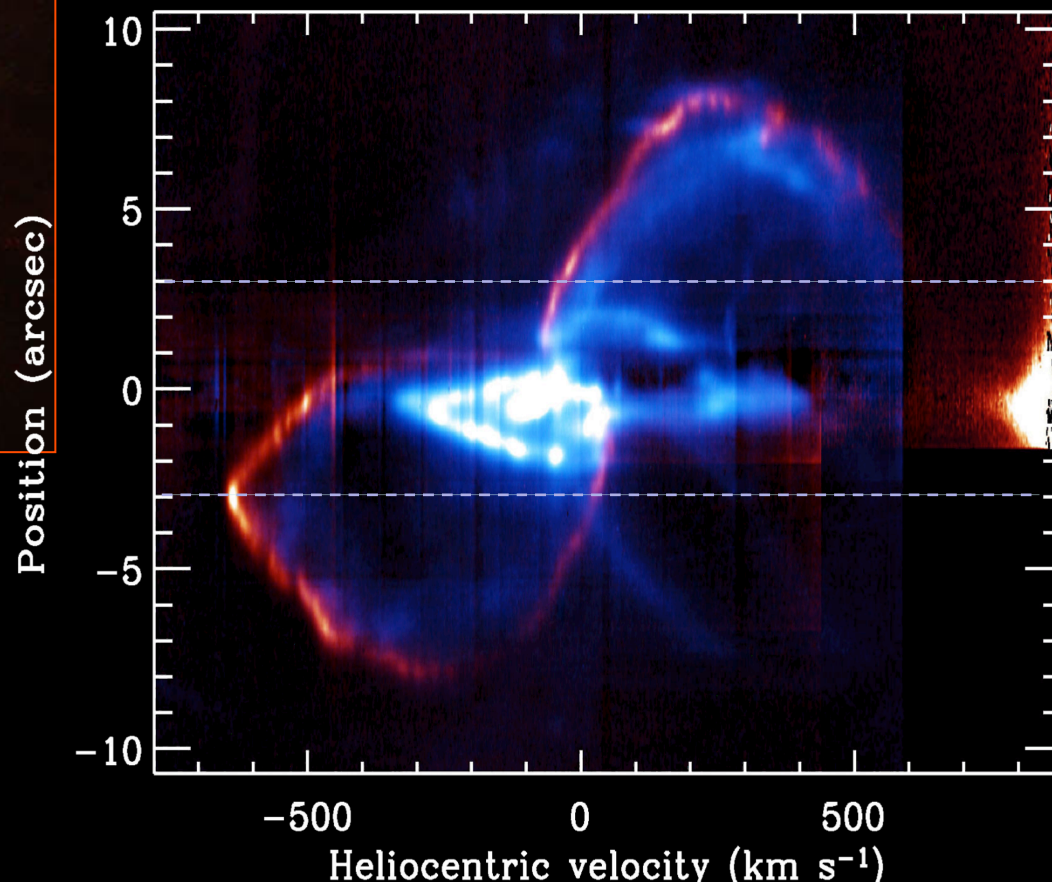
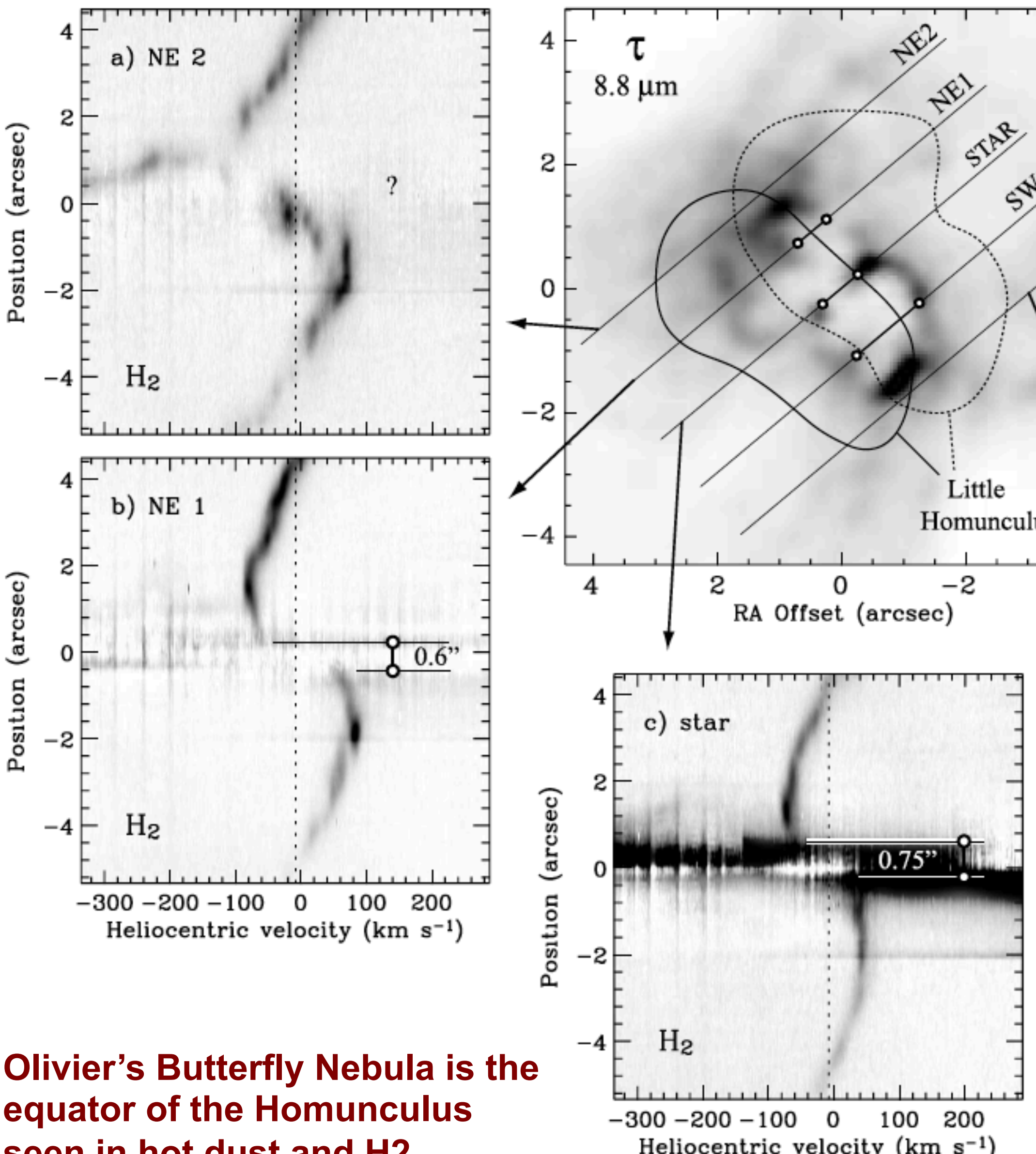
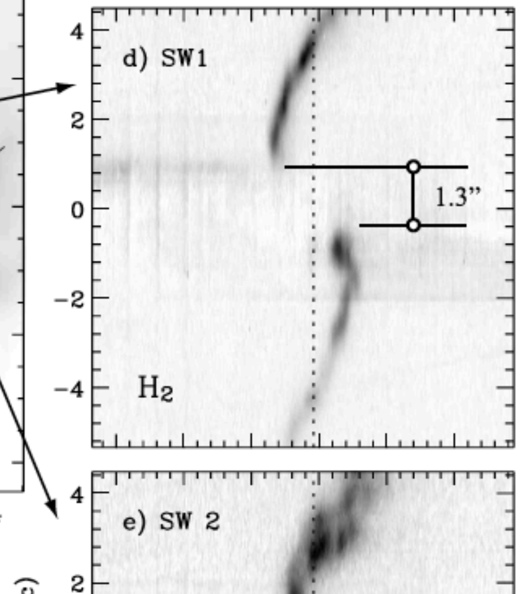
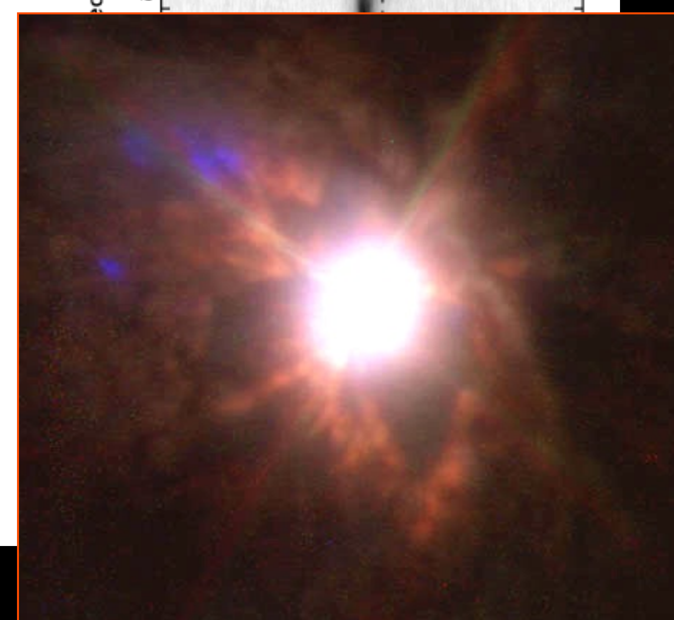


2.122 μm H_2 1-0 S(1)
1.644 μm [Fe II]



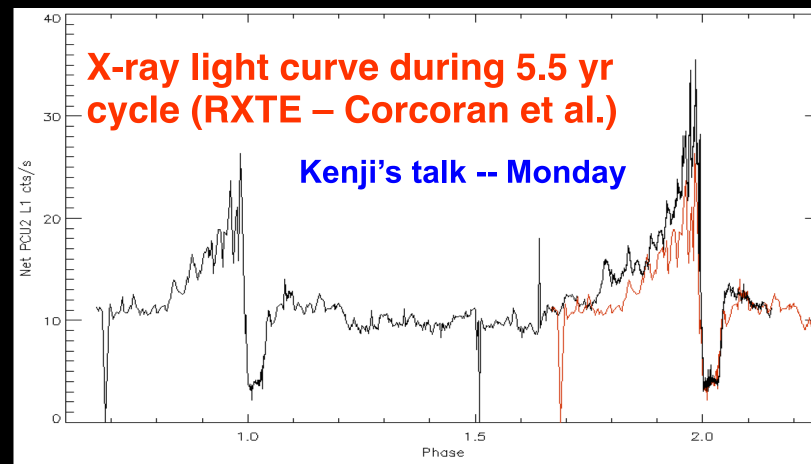


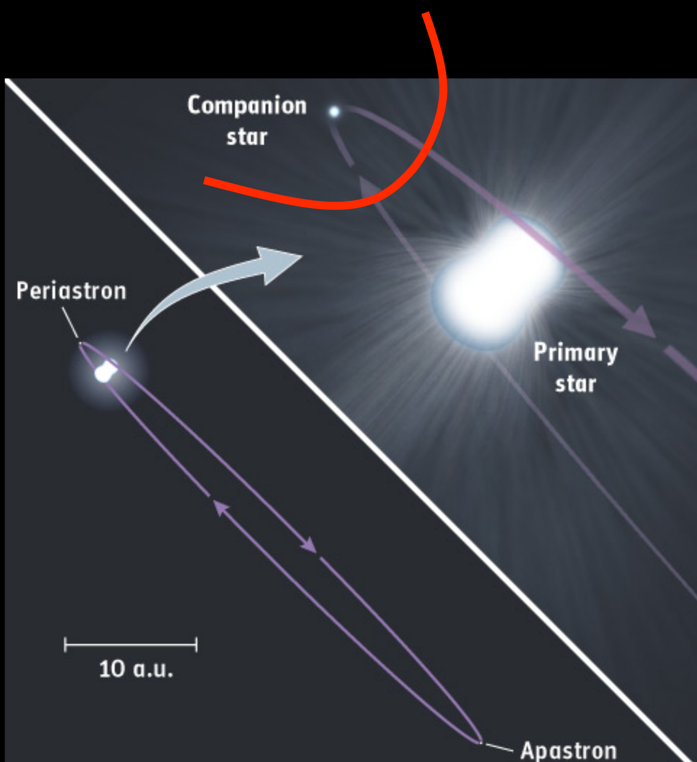


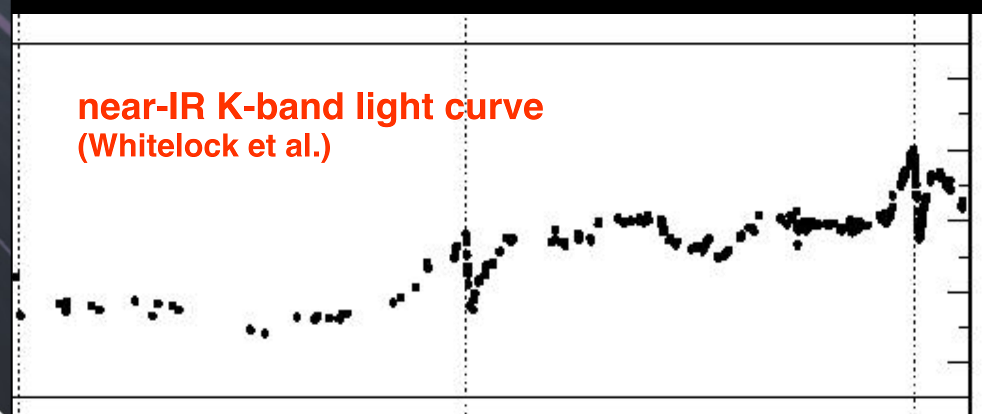
Olivier's Butterfly Nebula is the equator of the Homunculus seen in hot dust and H2.

Episodic dust formation in Eta Car:
(Smith 2010, MNRAS, 402, 145)

Eccentric colliding-wind binary with X-rays and hot dust at periastron.



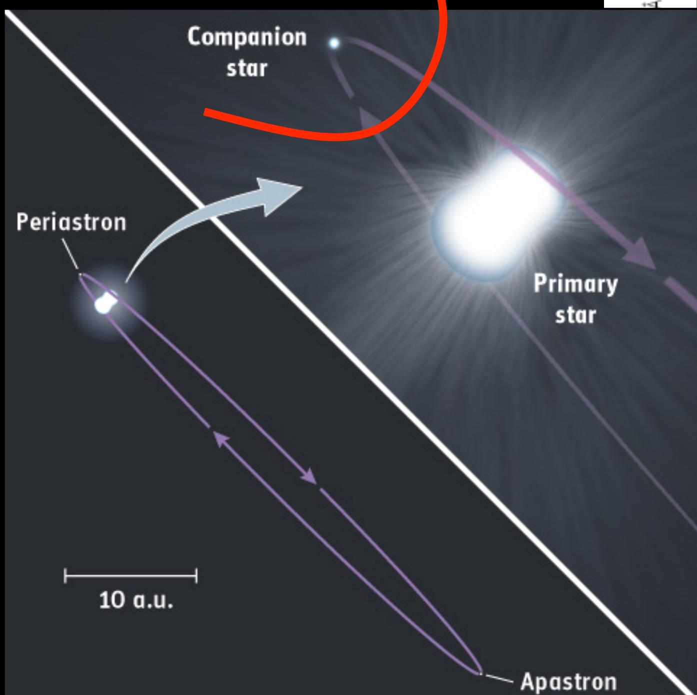


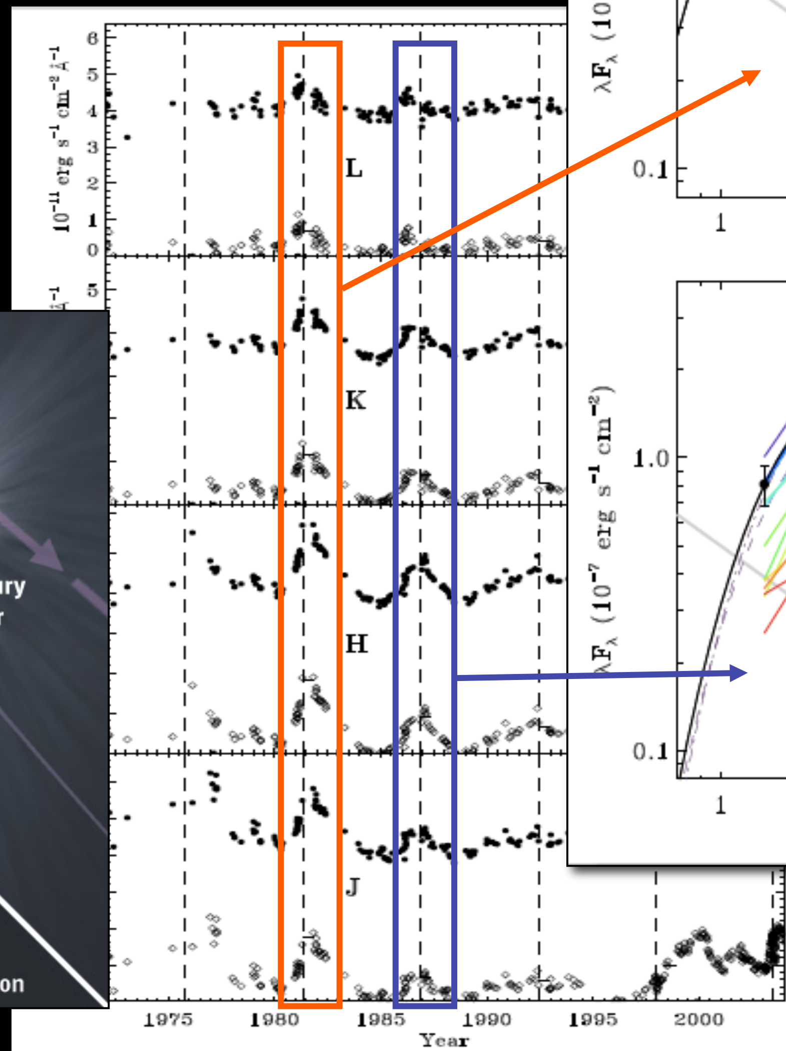


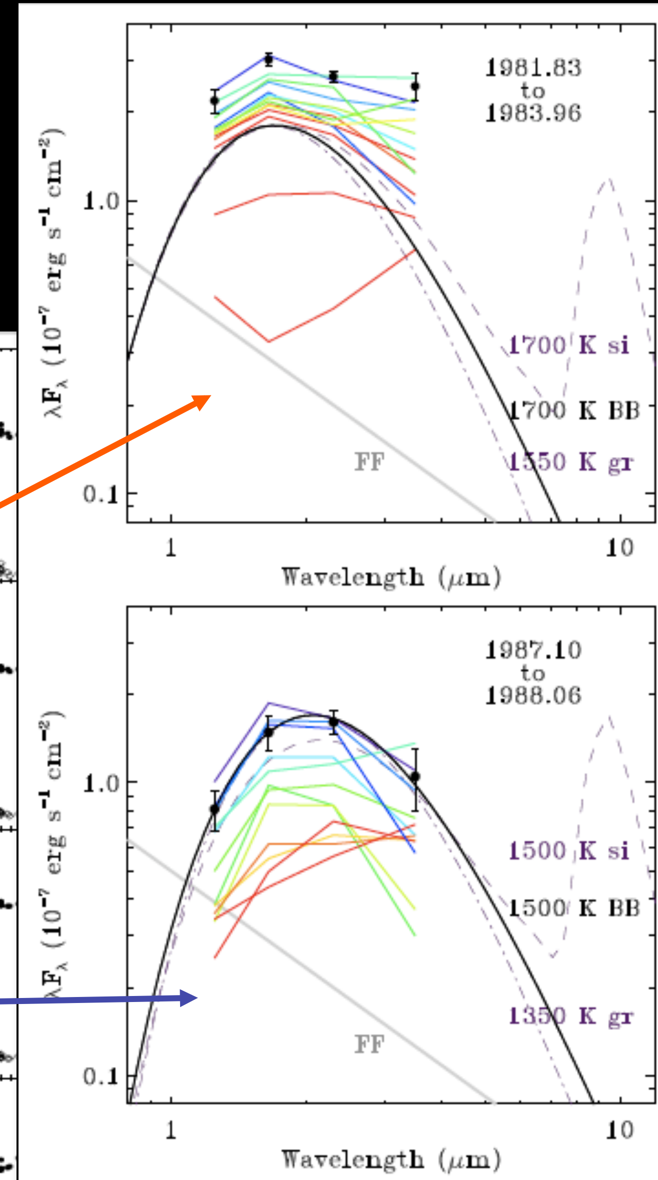
Episodic dust formation in Eta Car:
(Smith 2010, MNRAS, 402, 145)

Peaks in near-IR light curve have SED of hot dust at 1500-1700 K.

Not free-free or reddened starlight.



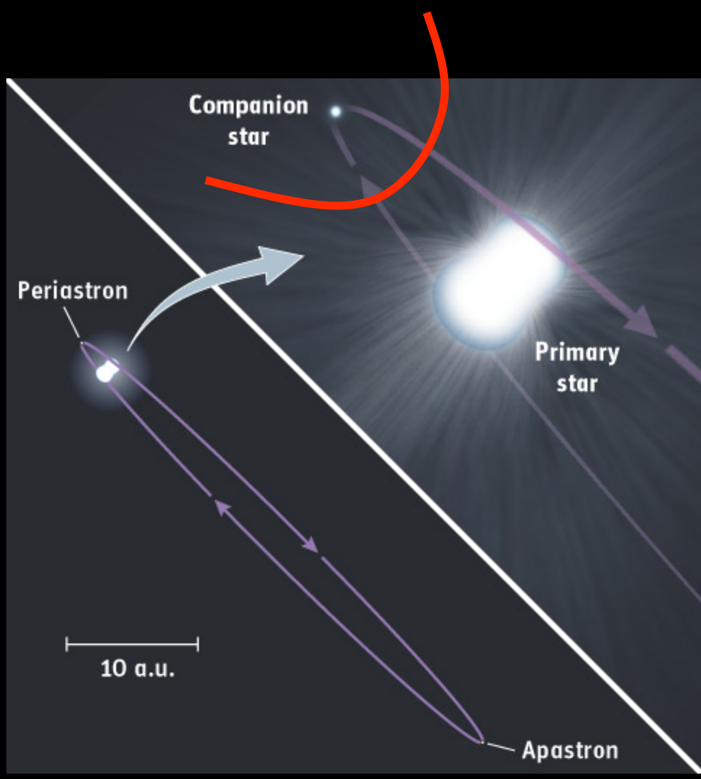


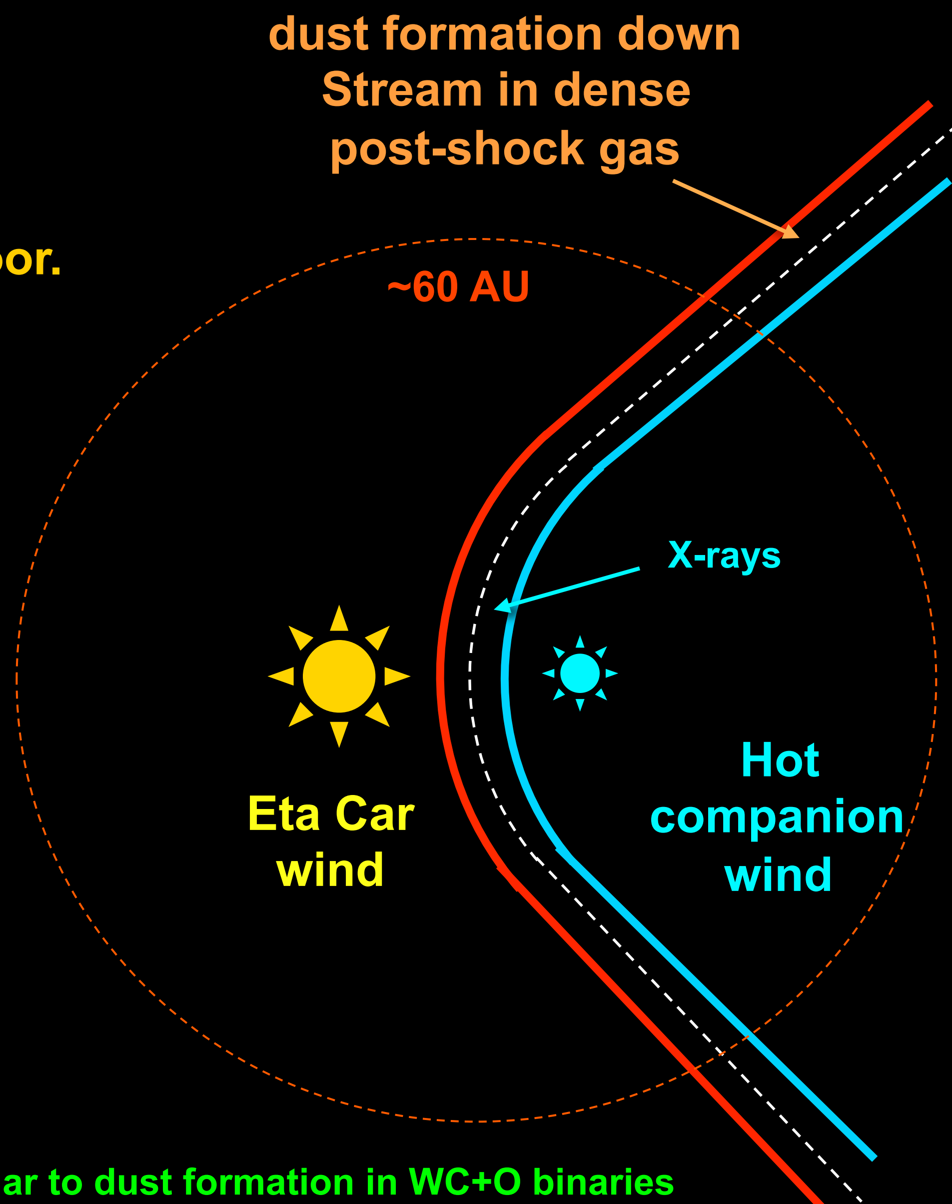


Episodic dust formation in Eta Car:
(Smith 2010, MNRAS, 402, 145)

Dust temp is too hot for silicates.

Probably corundum (Al_2O_3; alumina), since gas around Eta Car is very C-poor. Condenses at 1700 K.





Similar to dust formation in WC+O binaries (Tony Moffat's talk), but probably not C rich.

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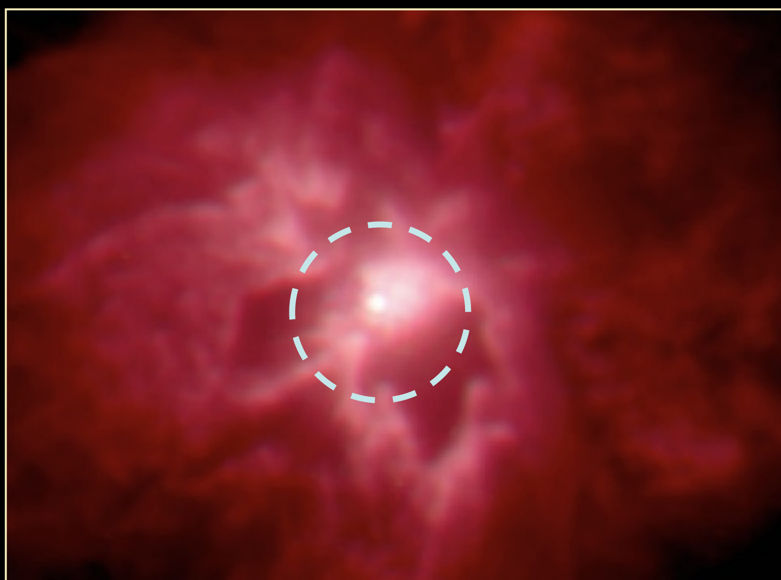
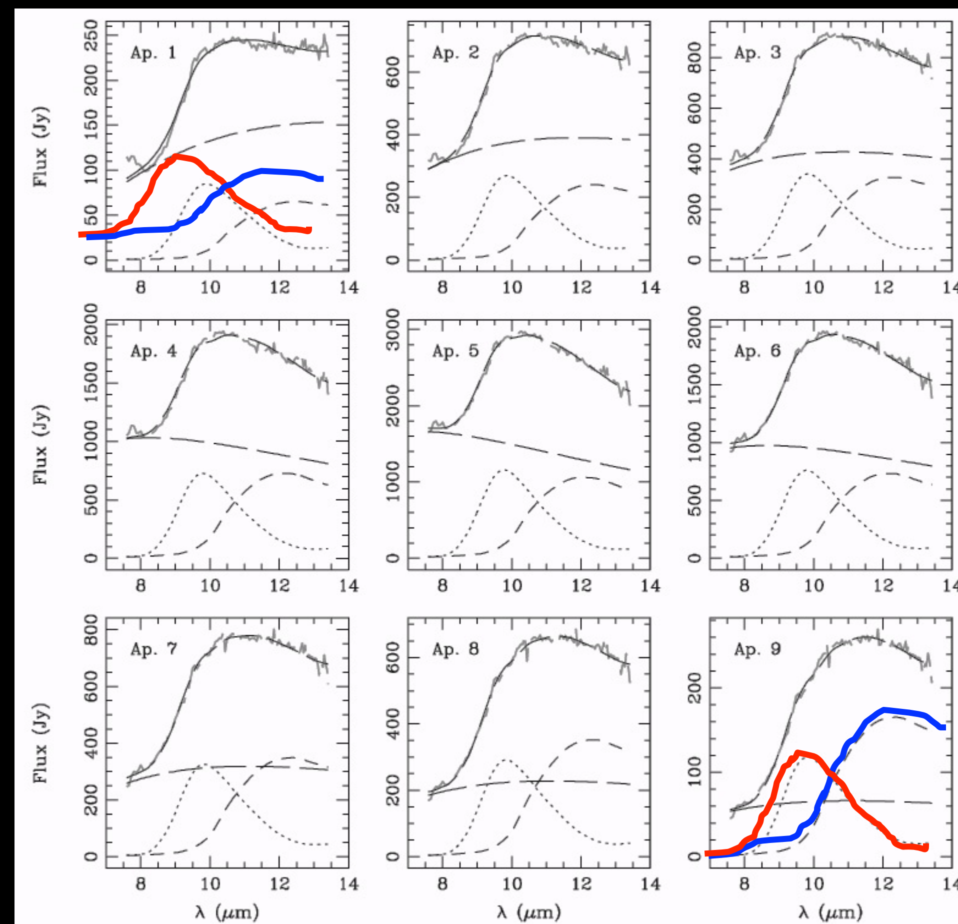
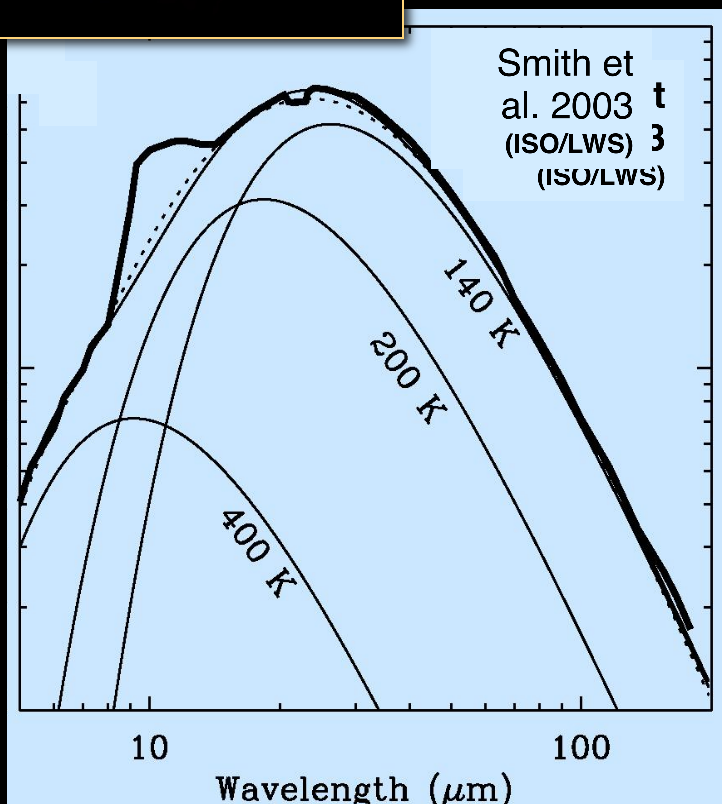




- Silicates are in Homunculus walls
- Corundum from new dust formed in wind-wind collisions fills the central region

DUST TEMPERATURES
(from color temp in images)

DUST MASS (from the ISO spectrum)



Total IR luminosity $4.3 \times 10^6\ L_\odot$

<u>100 x M(dust)</u>		
400K	200K	140K
$0.02\ M_\odot$	$1.5\ M_\odot$	$11\ M_\odot$

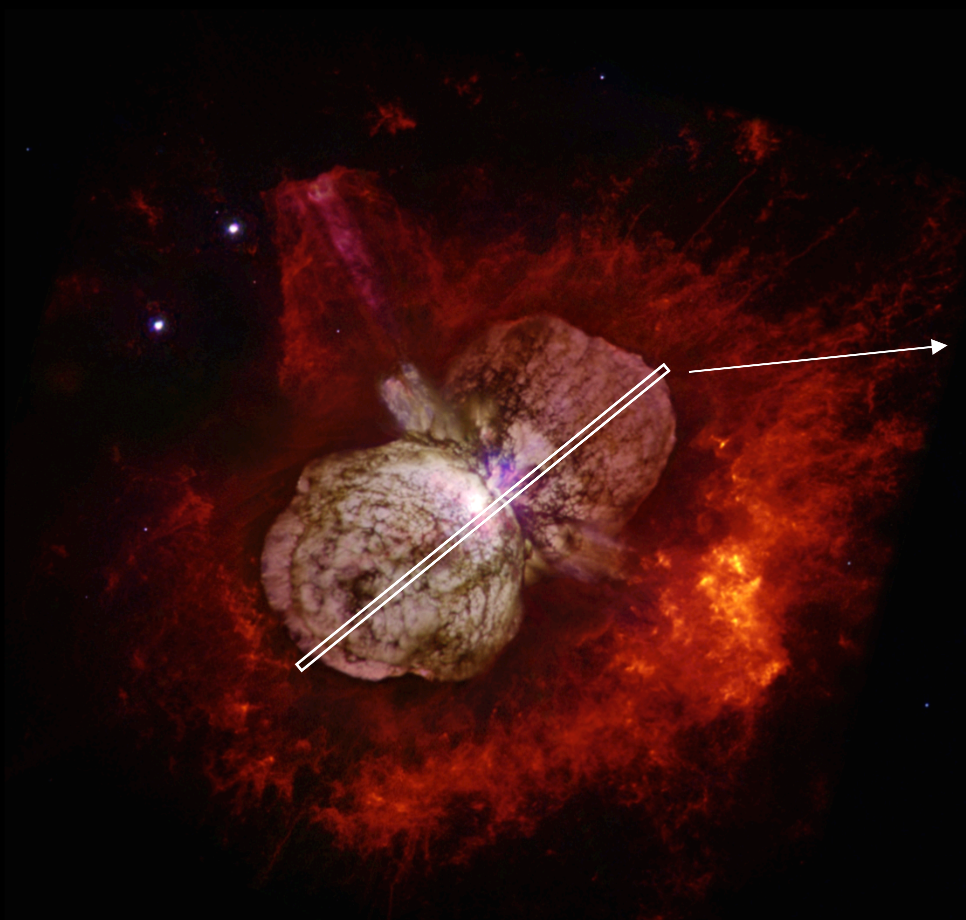
Total = $12.5\ M_\odot$

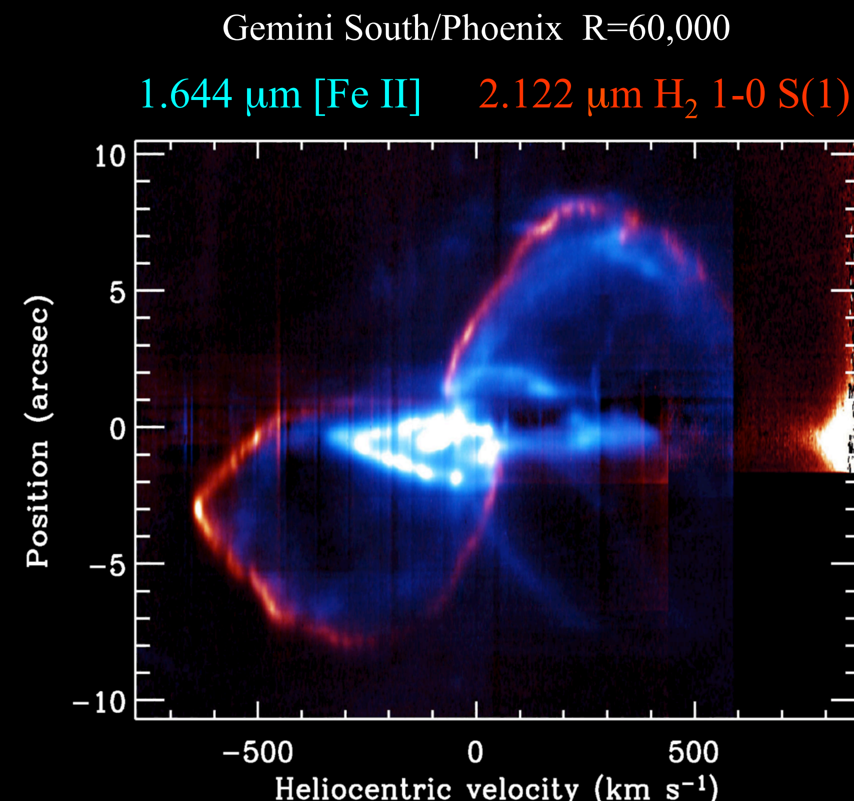
Previous estimates from λ=2-12 μm typically gave 2-3 $M_\odot$.

Higher mass comes from cool dust emitting at $\lambda > 12\ \mu$m. Smith et al. 2003

Cloudy models of gas excitation in nebula suggest 17 $M_\odot$ or more.

Smith & Ferland 2007





Smith (2006) ApJ, 644, 1151

Range of Ejecta
Speed = 40 - 650 km/s

Follows a Hubble law

Eta Carinae's
1843 eruption:

Ejected mass = 10-15 $M_\odot$
KE = $10^{49.6}$ - 10^{50} erg
E_{rad} = $10^{49.7}$ erg

← $KE/E_{rad} \approx 1$

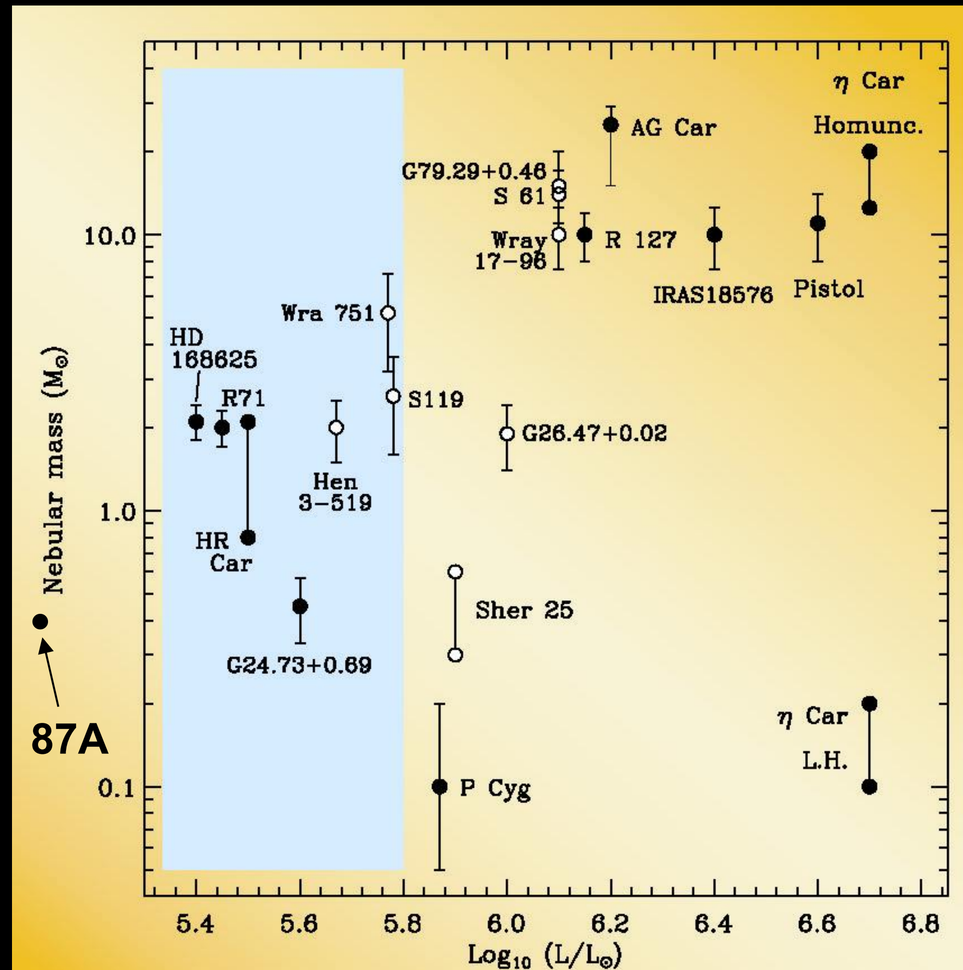
Wind or Explosion?

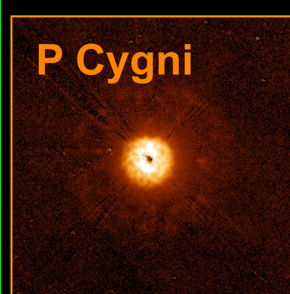
OBSERVED MASSES OF LBV NEBULAE

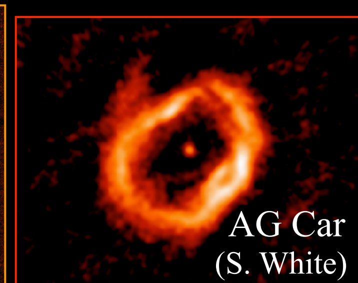
In circumstellar shells around LBVs, a mass of ~10 $M_\odot$ is typical for $L_* > 10^6 L_\odot$.

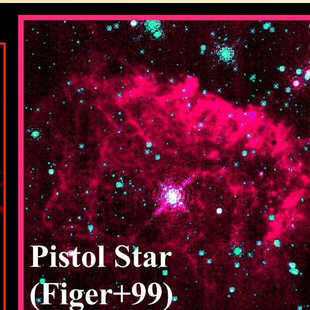
Less massive shells also seen, indicating a **variety** of outburst energy and mass.

Smith & Owocki (2006)
ApJ Letters, 645, L45

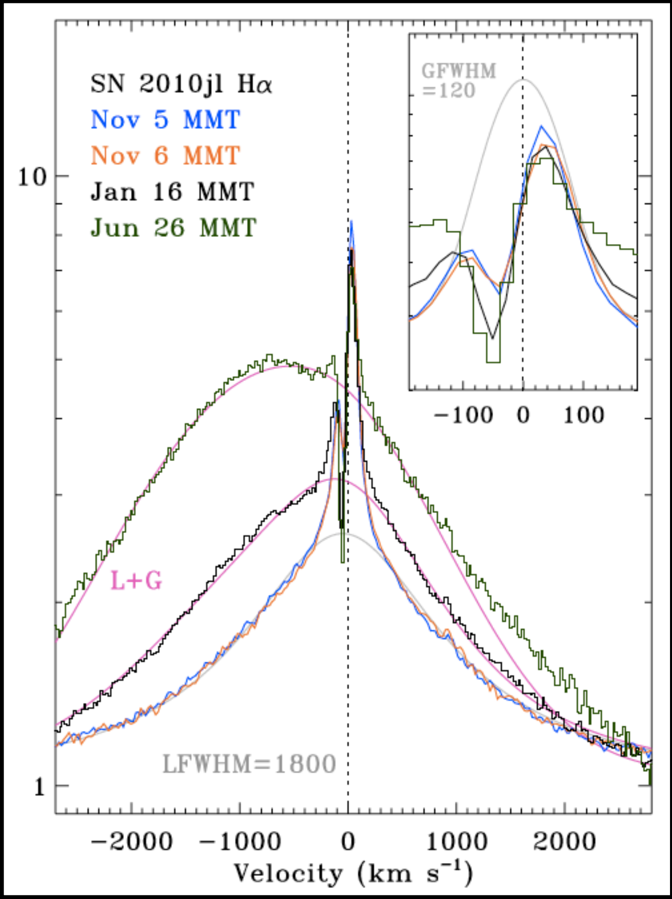


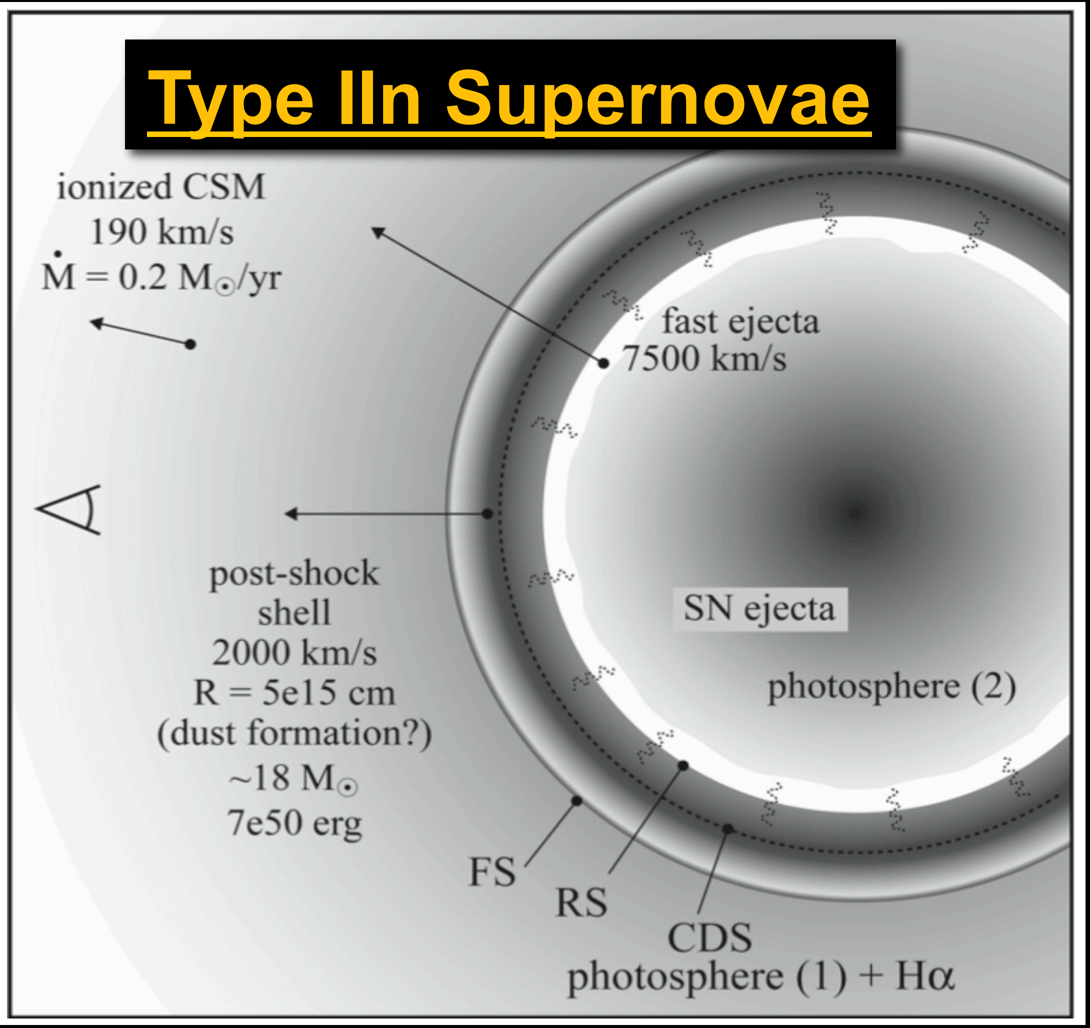






CSM Interaction





$$L = \frac{1}{2} w V_{SN}^3 = \frac{1}{2} \dot{M} \frac{V_{SN}^3}{V_w}$$

Efficient conversion of KE → Light

We can observe V_{SN}, V_w and L, and thus constrain CSM mass.

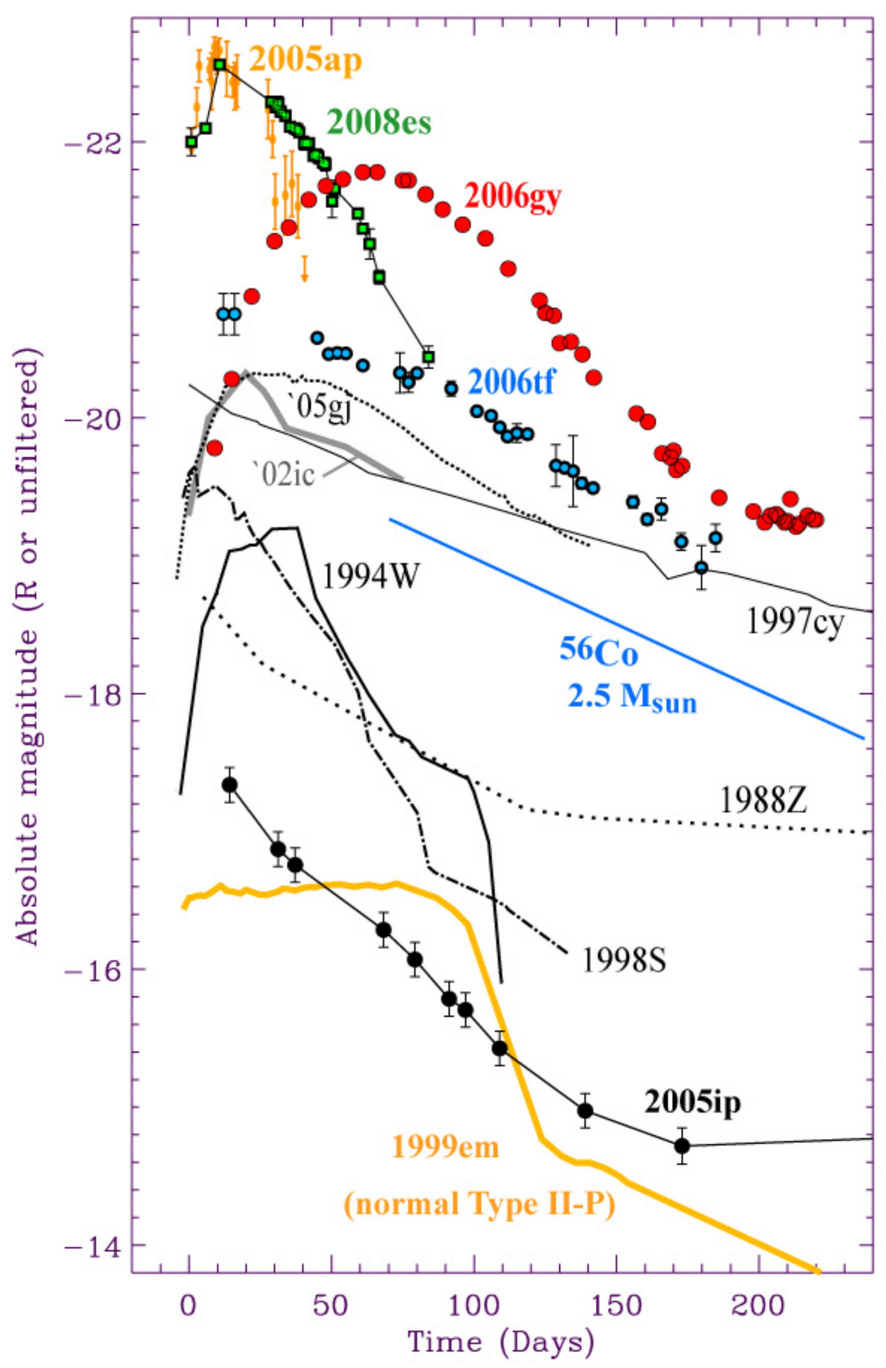
SNe IIn require several $M_\odot$ of CSM ejected only a few years before core collapse.

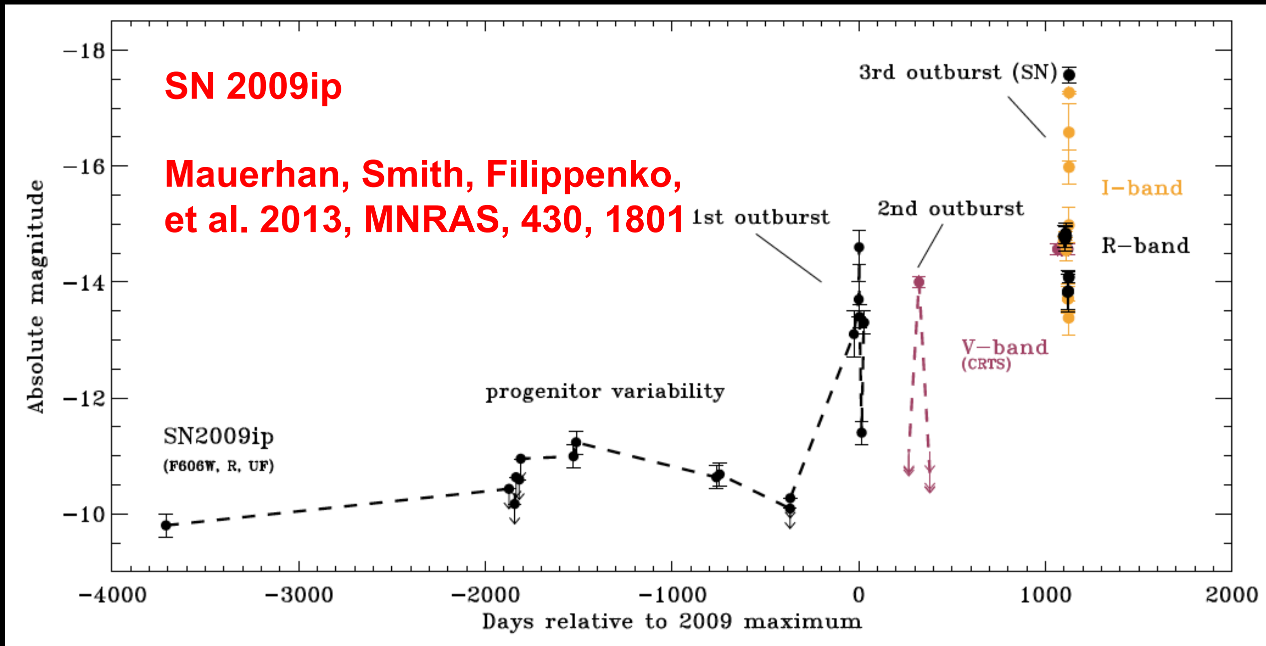
Diversity of SN IIn luminosity:
Increasing CSM mass

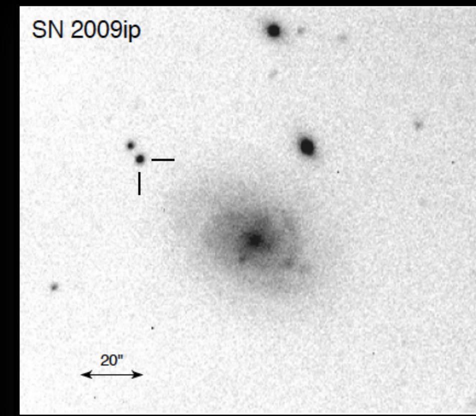
Efficient conversion of
KE ⟶ Light

A range of circumstellar shell mass provides a huge observed range of luminosity for SNe IIn.

- Very luminous SNe IIn (rare) require massive LBV-like eruptions before core collapse.
  - Observed CSM expansion speeds of 100-600 km/s
- Lower luminosity (most common IIn) can be extreme red supergiants or LBVs.
  - Observed CSM expansion speeds of 20-500 km/s







LBVs and Type IIn SNe:

- Very luminous SNe IIn require high mass of CSM
  - some require >10 $M_\odot$ ejected in decade before core collapse .

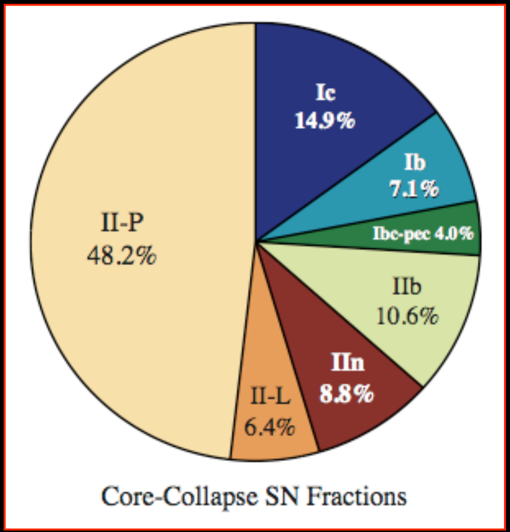
- 5 direct detections of SN progenitors (or host cluster)
  - SN 2005gl $M_0 \approx$ 50-60 $M_\odot$ (Gal-Yam & Leonard 2009)
  - SN 1961V $M_0 \approx$ 100 $M_\odot$ (Smith et al. 2011, Kochanek 2011)
  - SN 2010jl M_0 > 30 $M_\odot$ (Smith et al. 2011)
  - SN 2009ip $M_0 \approx$ 50-80 $M_\odot$ (Smith+2010, Mauerhan+13)
  - SNhunt275 – preSN eruptions (still going)

(see summary in Smith 2014, ARAA)

This was forbidden in standard single star models

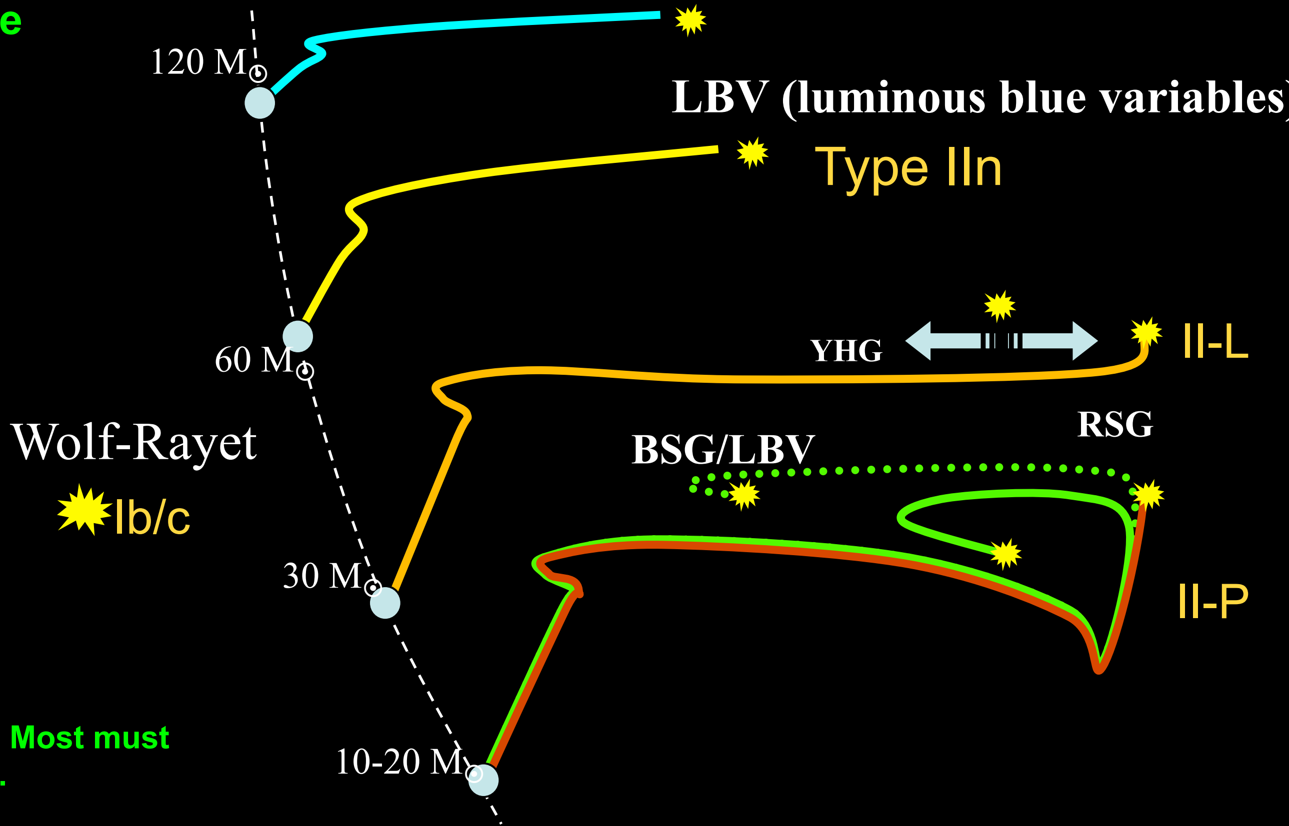
But caution: LBVs are bright, easy to detect

If LBVs explode, where do we get WR stars and SNe Ibc?



Smith et al. (2011) MNRAS, 412, 1522

Also, SN Ibc ejecta masses are too low. Most must come from binaries (Dessart et al. 2012).



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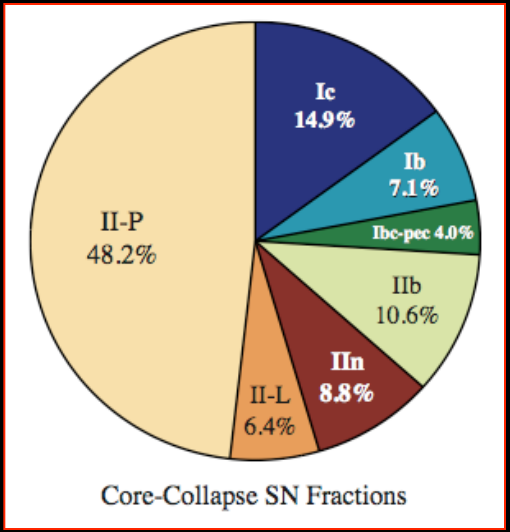

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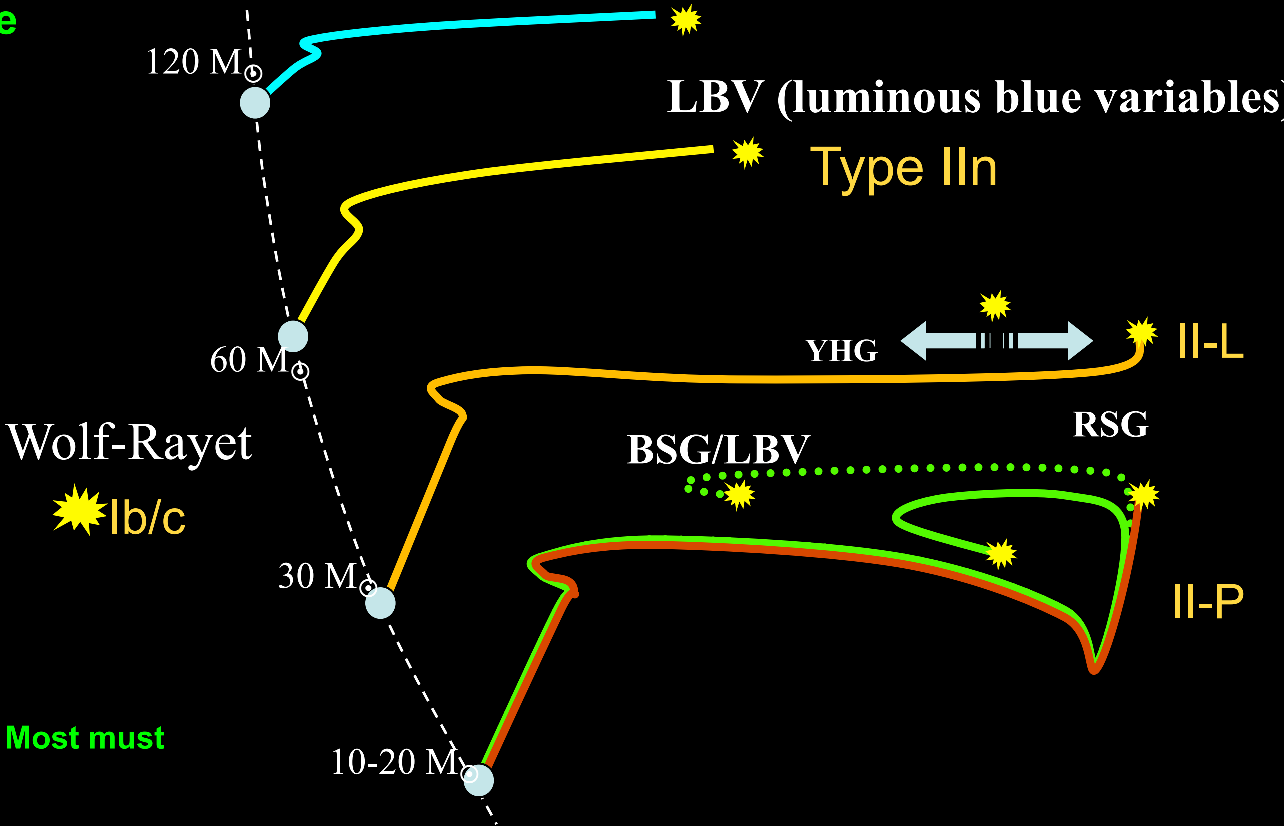

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Paczynski + 67; Podsiadlowski + 92, de Mink + 2013

Binary-star mass-transfer
(*ROCHE LOBE OVERFLOW*)

Only 3 massive star binaries caught in brief RLOF phase with spatially resolved CSM.

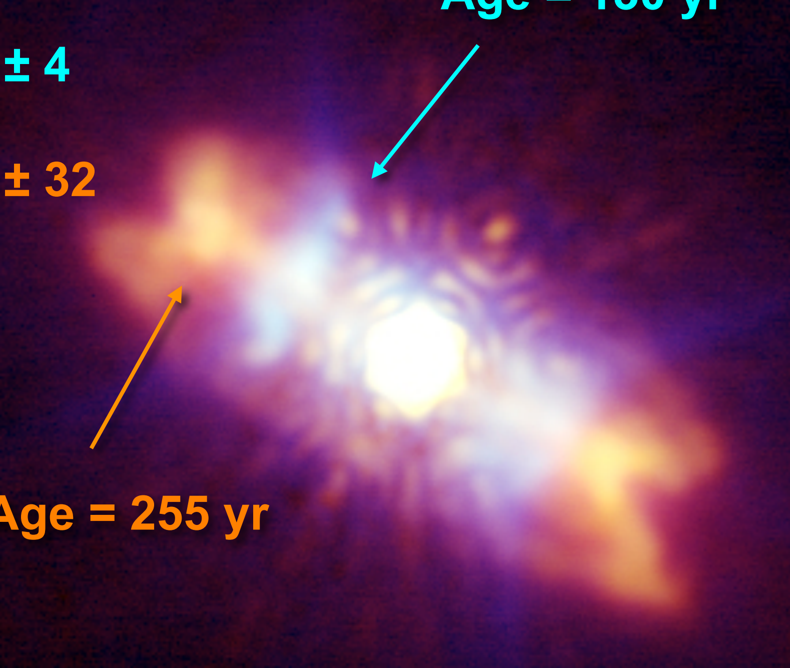
RY Scuti: eclipsing massive binary system in transition to WR+O via RLOF.

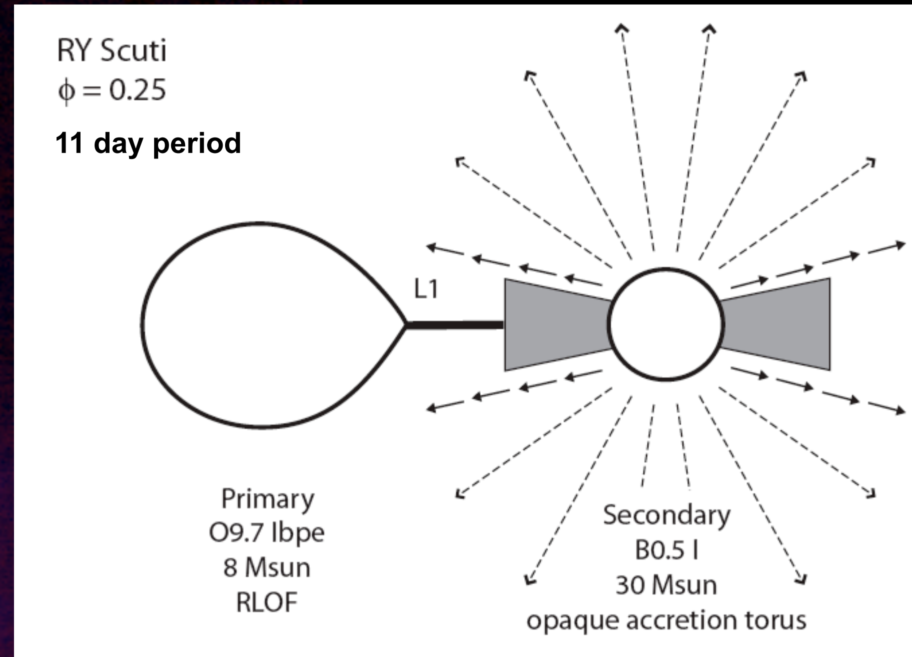
A more massive analog of β Lyrae (J. Nemravova talk)

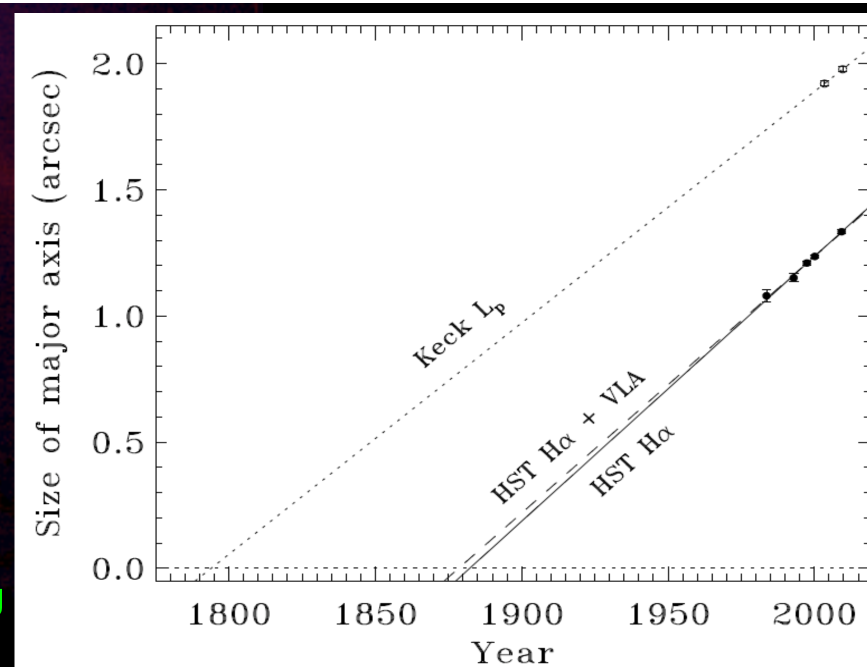
Two separate ejections.

1881 ± 4

1754 ± 32







HST/WFPC2 Hα

Keck/NIRC2-AO Lp

Smith et al. (2011)

[See poster outside by Gehrz, Smith, & Shenoi]

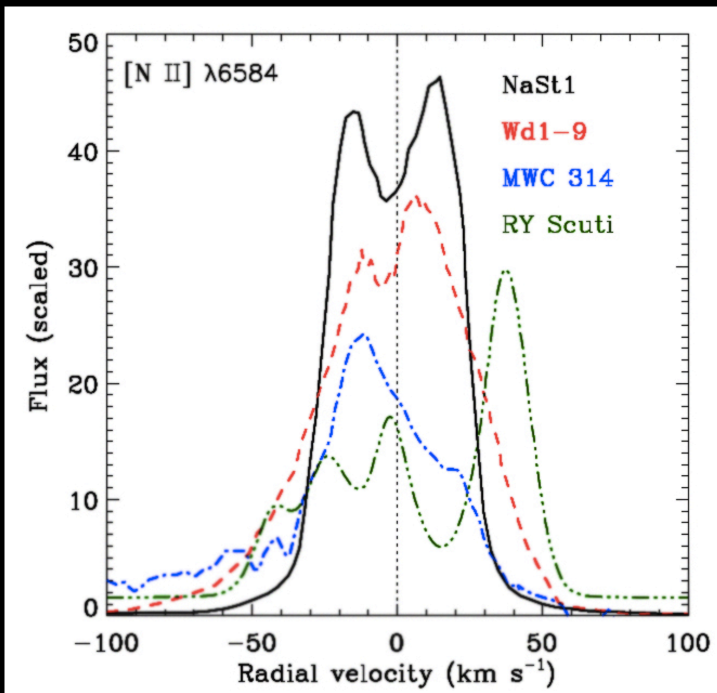
Mass donor:
Will be a WR

Mass gainer:
Will be a rapidly rotating O star, B[e], or LBV?

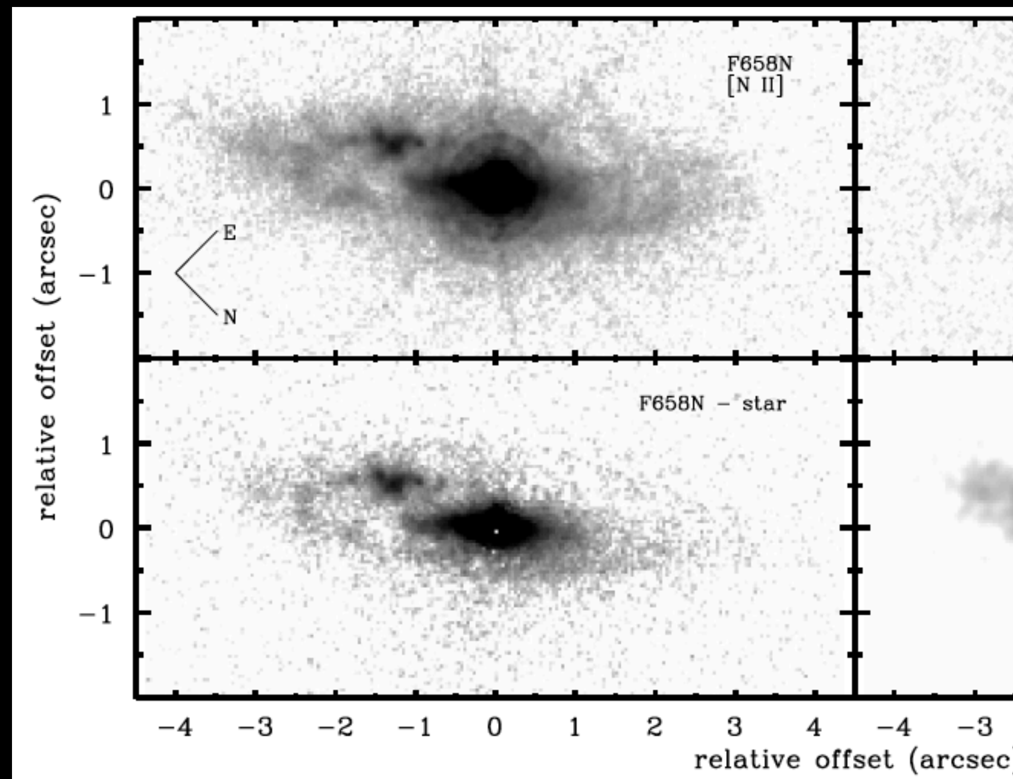
Multiwavelength observations of NaSt1 (WR 122): Equatorial mass loss and X-rays from an interacting Wolf-Rayet binary

arXiv:1502.01794 (MNRAS in press)

Jon Mauerhan[1⋆], Nathan Smith[2], Schuyler D. Van Dyk[3], Katie M. Morzinski[2], Laird M. Close[2], Philip M. Hinz[2], Jared R. Males[2], and Timothy J. Rodigas[4]



Slow outflow
V ≈ 20 km/s
Even though wind speeds are several 10^2 km/s



Equatorial mass loss reminiscent of low-mass symbiotics (talk by Shazrene M.)

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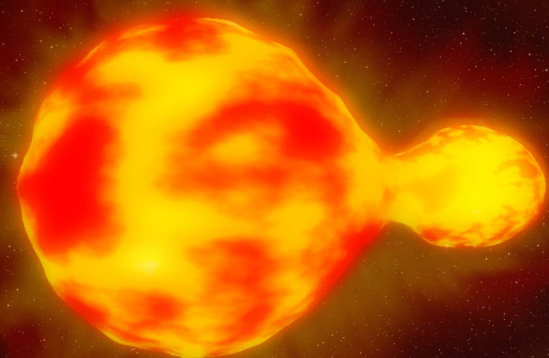
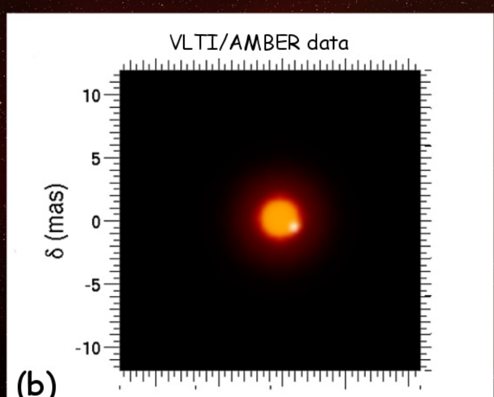
Astronomy & Astrophysics

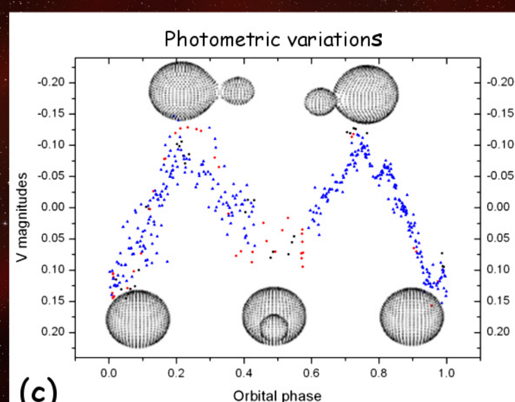
The yellow hypergiant HR 5171 A: Resolving a massive interacting binary in the common envelope phase⋆,⋆⋆

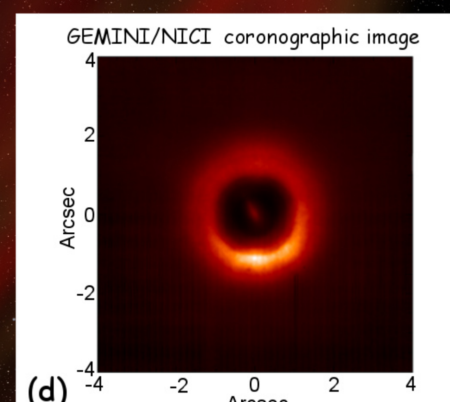
O. Chesneau[1], A. Meilland[1], E. Chapellier[1], F. Millour[1], A. M. van Genderen[2], Y. Nazé[3], N. Smith[4], A. Spang[1], J. V. Smoker[5], L. Dessart[6], S. Kanaan[7], Ph. Bendjoya[1], M. W. Feast[8,15], J. H. Groh[9], A. Lobel[10], N. Nardetto[1], S. Otero[11], R. D. Oudmaijer[12], A. G. Tekola[8,13], P. A. Whitelock[8,15], C. Arcos[7], M. Curé[7], and L. Vanzi[14]

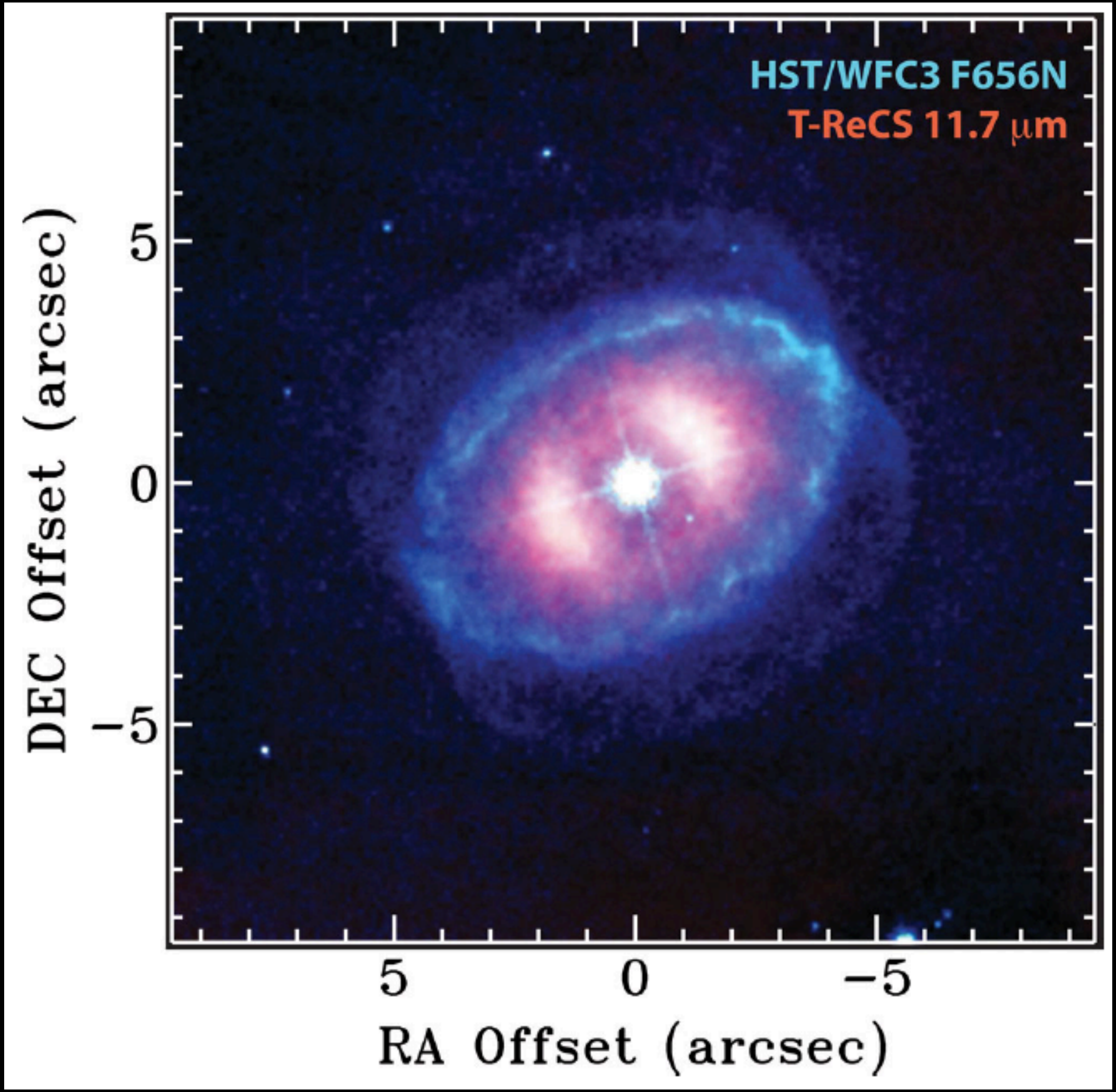


- 1304d eclipsing contact binary
- Resolved 2 stars with VLTI (1st ever)
- Undergoing RLOF
- May evolve to B[e] or LBV / WR



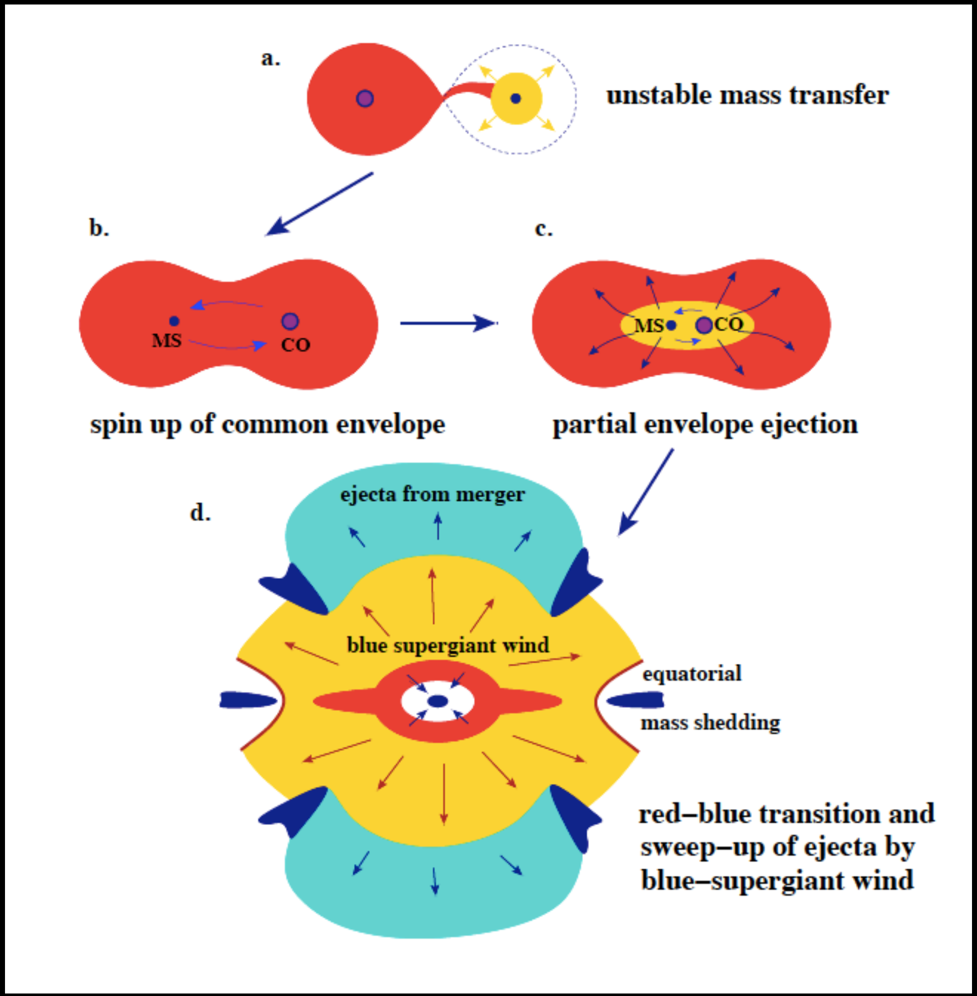


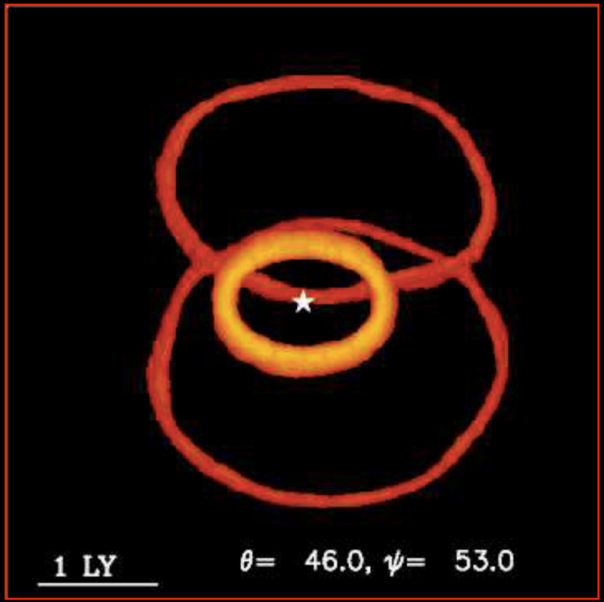



HST/WFC3 F656N
T-ReCS 11.7 μm
DEC Offset (arcsec)
5
0
−5
RA Offset (arcsec)

We require the ejection of a very slow & dense equatorial ring. How?

1. MERGER. Morris & Podsiadlowski 2007, 2008, etc.





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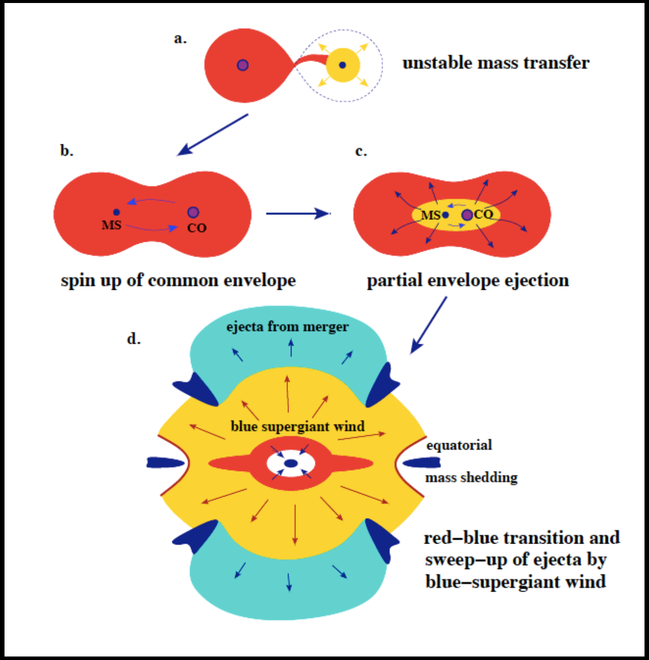
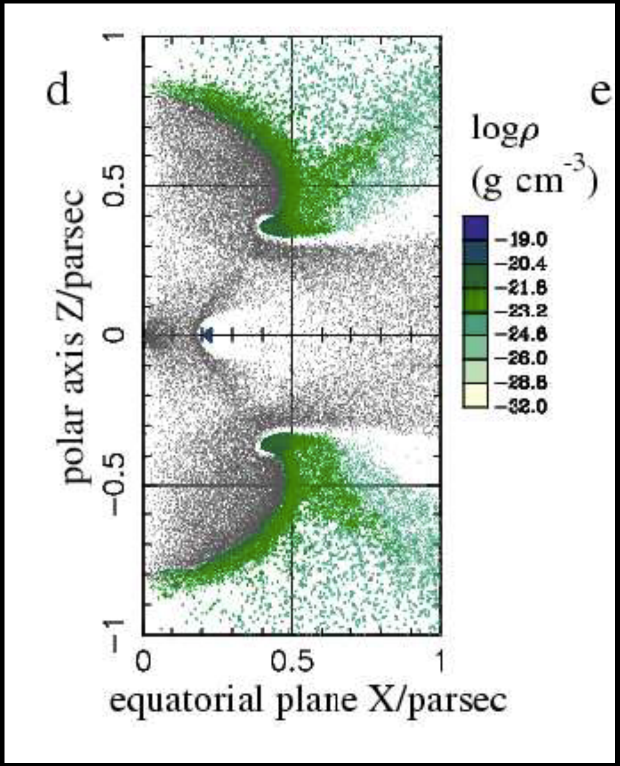


Some problems/objections:

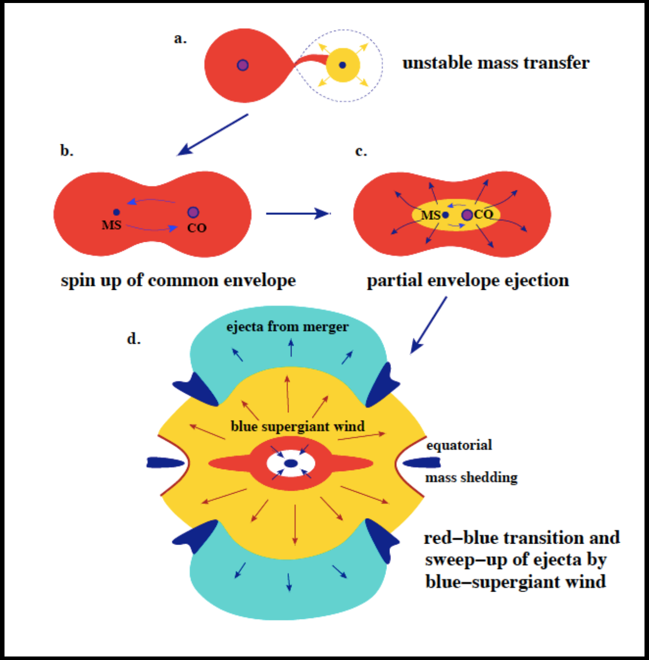
- Predicts filled polar caps and empty equator. Observations suggest opposite.



By now, these polar caps would have been hit 5-10 yrs ago by the fastest ejecta going 35,000 km/s.

We require the ejection of a very slow & dense equatorial ring. How?

1. MERGER. Morris & Podsiadlowski 2007, 2008, etc.



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- **For successful merger, equatorial mass shed is at least 4-5 $M_{\odot}$. This seems high for SN1987A's ring, and is too high for SBW1 ($M<1\ M_{\odot}$).**

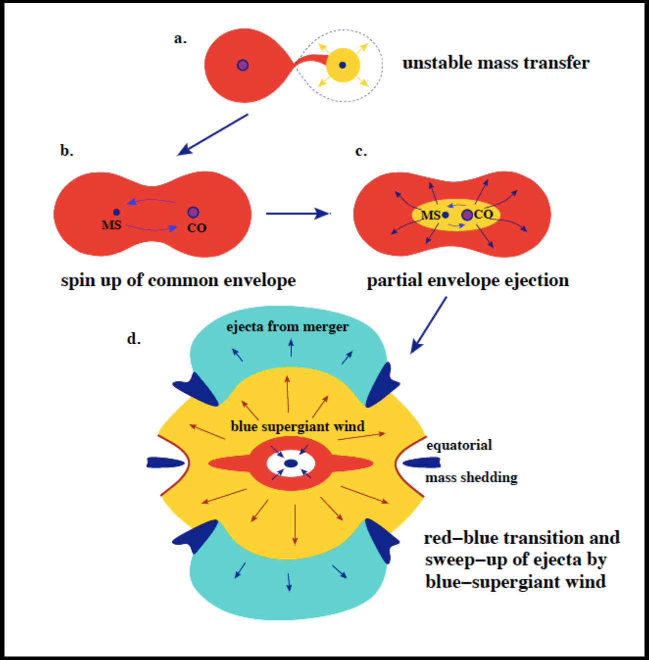
The equatorial outflow occurs as the envelope loses angular momentum during the blue loop. The total mass lost can be estimated from angular momentum conservation

$$M_{ER} = \frac{\Delta L}{\sqrt{GM_{\star}R_{\star}(1-\Gamma)}} \sim 4\,M_{\odot} \quad (4)$$

if the mass is lost near critical rotation (as suggested by the low expansion velocity of the ring of around $10.3\,\mathrm{km\,s^{-1}}$). Here ΔL is the excess angular momentum that needs to be lost, i.e. is the difference between the post-merger angular momentum in the envelope and the maximum angular momentum for a stable blue supergiant ($\sim 4\times10^{54}$ erg s). We assume an Eddington factor of $\Gamma = 0.4$ and that the envelope must lose $\sim 6\times10^{54}$ erg s at a radius of roughly 6000 $R_{\odot}$. This is likely to be a lower limit unless magnetic processes in the excretion disk can increase

We require the ejection of a very slow & dense equatorial ring. How?

1. MERGER. Morris & Podsiadlowski 2007, 2008, etc.



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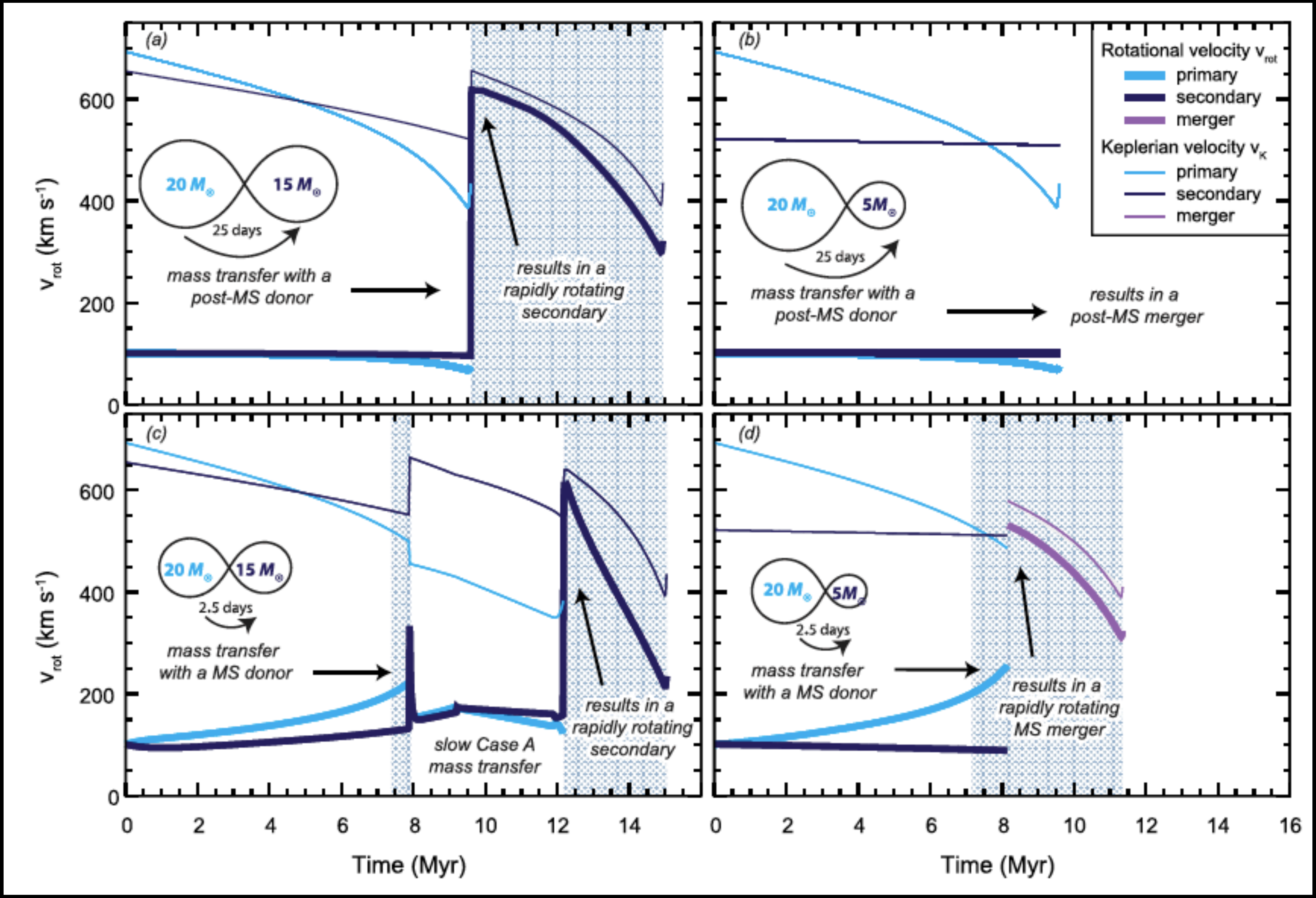
- For successful merger, equatorial mass shed is at least 4-5 $M_{\odot}$. This seems high for SN1987A's ring, and is too high for SBW1 ($M<1\ M_{\odot}$).
- The resulting BSG merger product is rotating at critical rotation, and takes several Myr to spin down with the low inferred wind mass-loss rate. Age of equatorial ring is only 1-2e4 yr.

Mergers produce rapid rotators

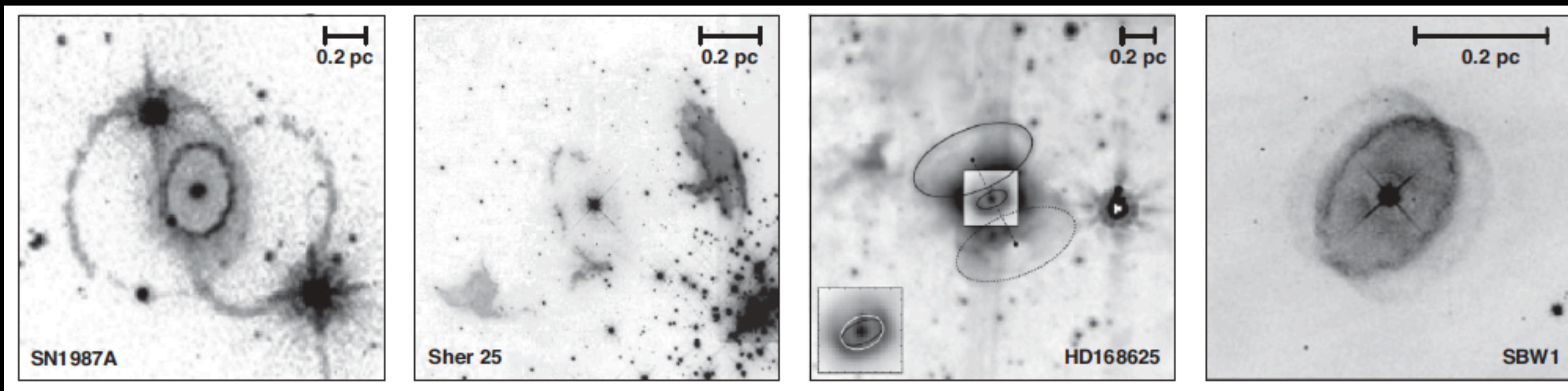


de Mink et al. (2013)

MNRAS 442, 1483–1490 (2014) doi:10.1093/mnras/s

Sher 25: pulsating but apparently alone

William D. Taylor,[1★] Christopher J. Evans,[1] Sergio Simón-Díaz,[2,3] Hugues Sana,[4] Norbert Langer,[5] Nathan Smith[6] and Stephen J. Smartt[7]



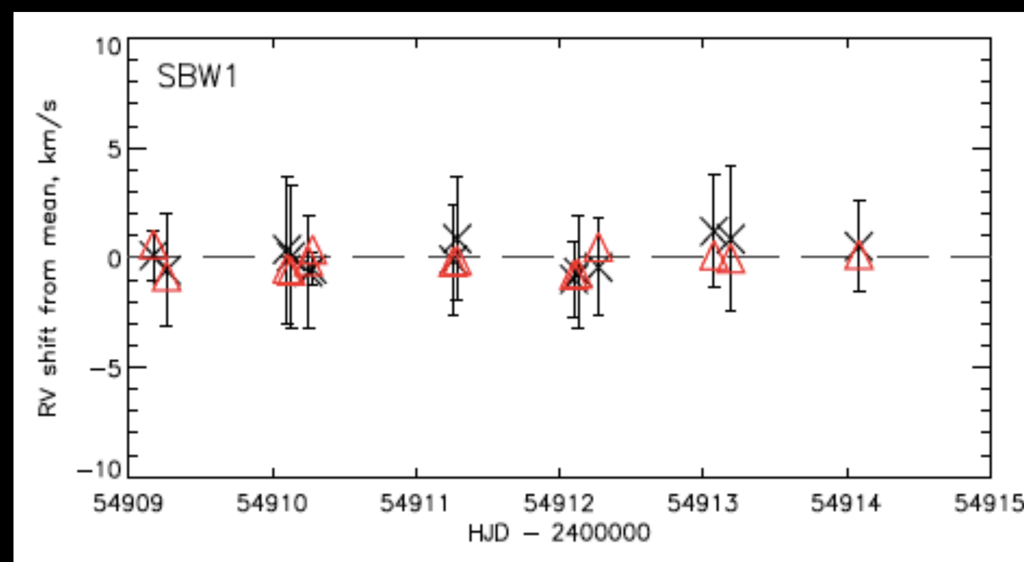
FEROS/ESO2.2m – echelle spectra

SBW1:

Lack of radial velocity variation rules out a close massive companion. Might allow low-mass (<1 Msun) wide (P=yrs) companion or highly eccentric orbit.

Also, narrow lines indicate a SLOW equatorial rotation speed of only 41 km/s.

(In fact, all 3 are relatively slow rotators)



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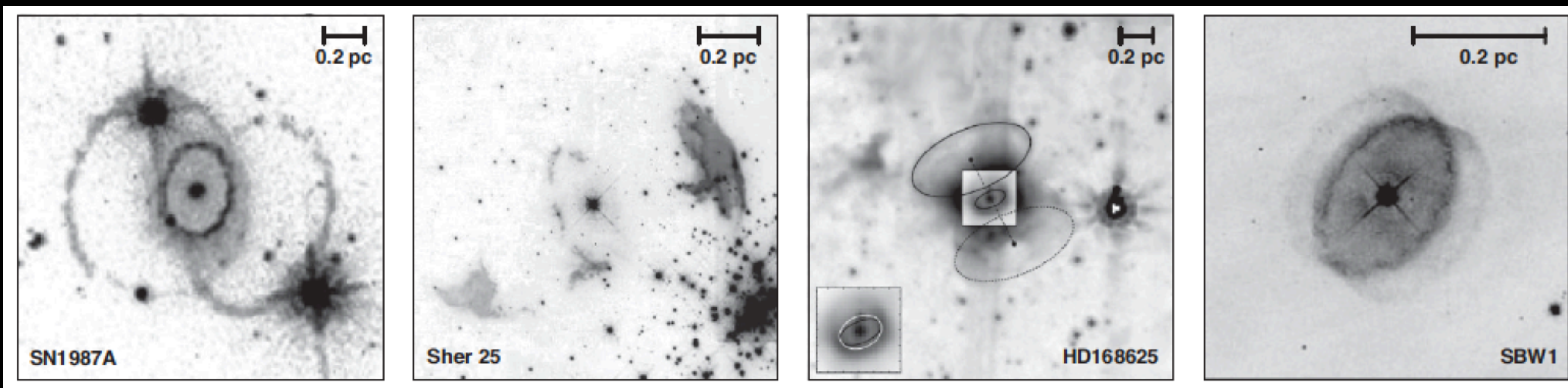

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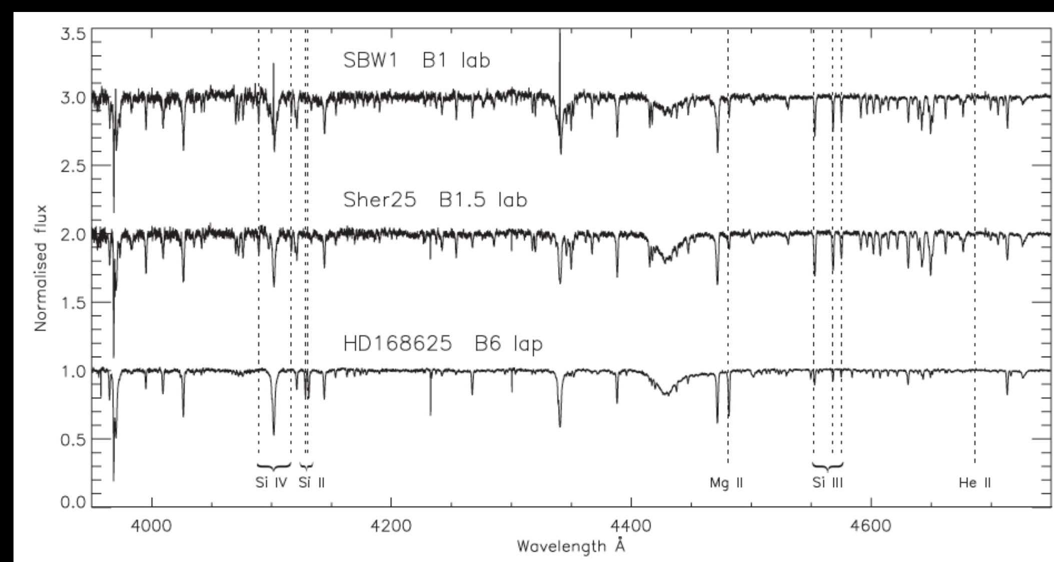
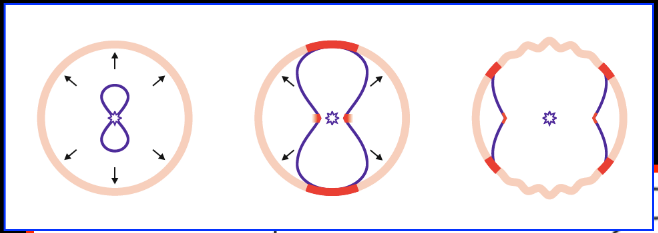
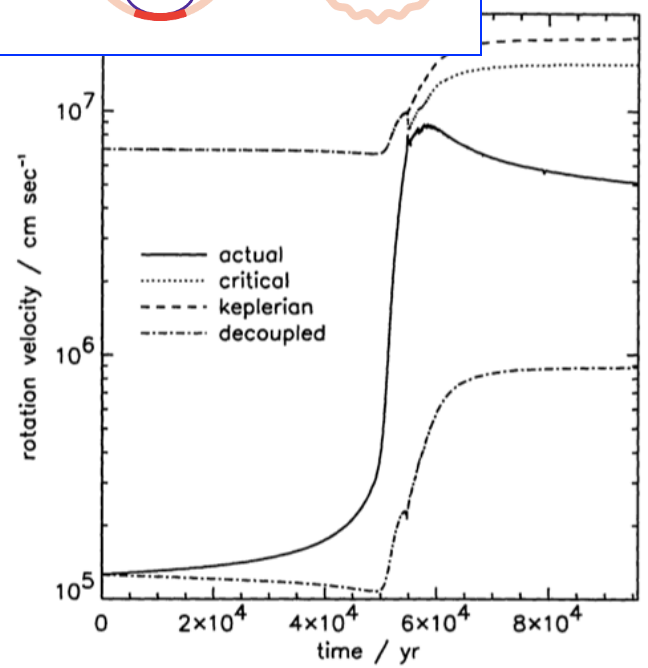


We require the ejection of a very slow & dense equatorial ring. How?

2. RSG – BSG contraction and spin up.

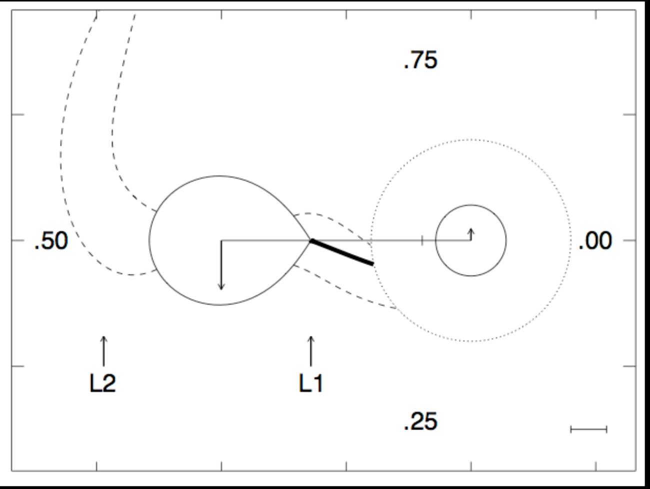




Langer et al. (1998)

Figure 3. Equatorial rotation velocity as a function of time (solid line) of a model 12 $M_\odot$ rotating star during the transition from the red-supergiant branch to the blue-supergiant stage during core helium burning ($t = 0$ is arbitrary). It is compared to the Keplerian (dashed

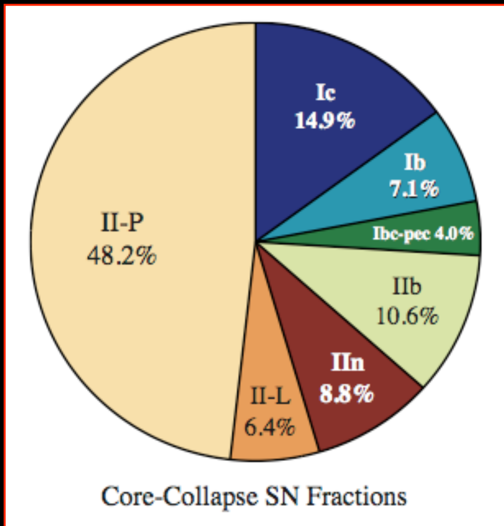
3. RLOF event in wider binary. Short duration (few 1000 yr) mass-transfer phase. Produces very slow equatorial outflow Through L2.



Is the (low-mass?) companion still there?

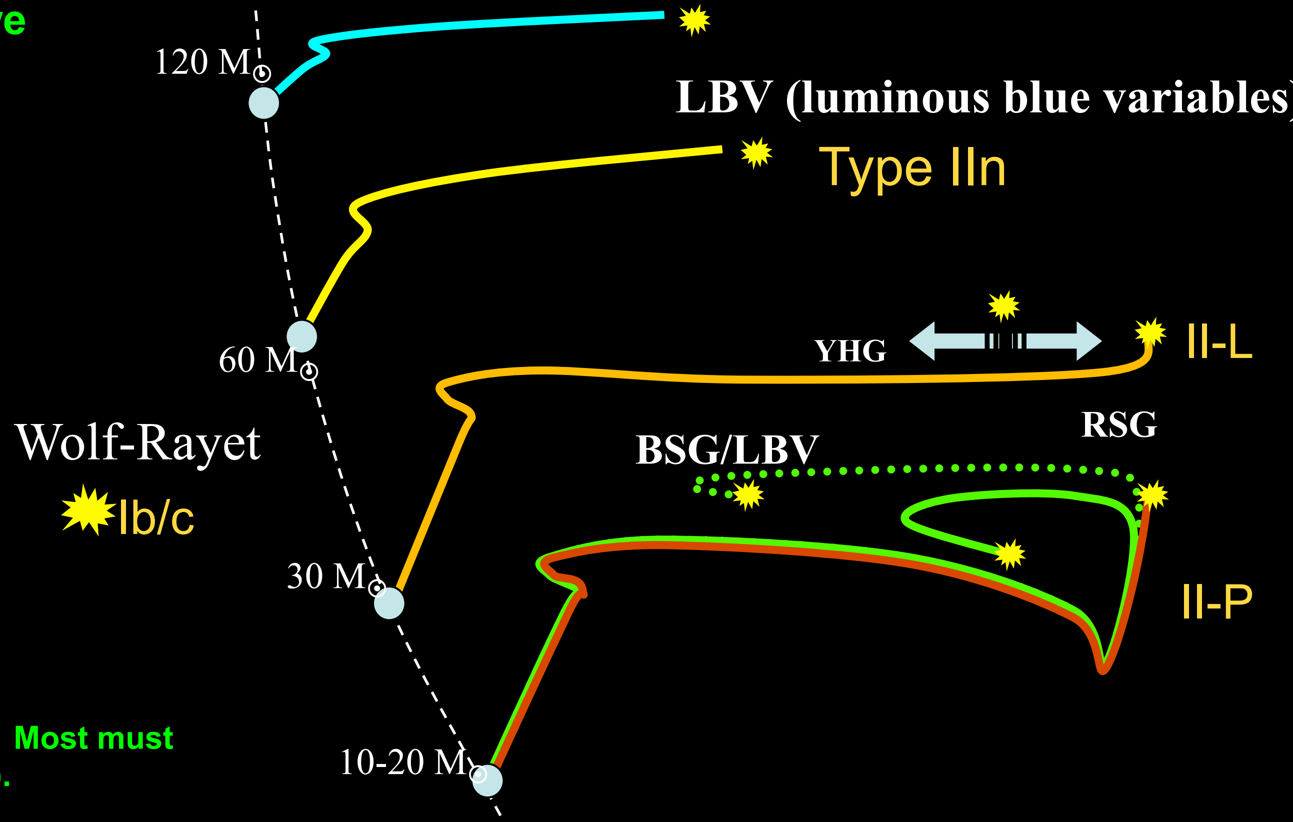
Why did this happen right before SN?

If LBVs explode, where do we get WR stars and SNe Ibc?

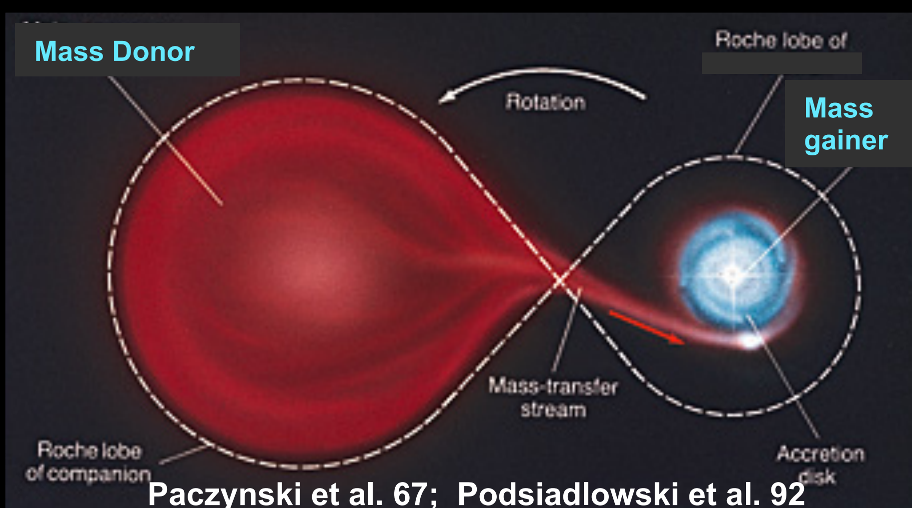


Core-Collapse SN Fractions

Smith et al. (2011) MNRAS, 412, 1522



Also, SN Ibc ejecta masses are too low. Most must come from binaries (Dessart et al. 2012).



Paczynski et al. 67; Podsiadlowski et al. 92

Binary-star mass-transfer (*ROCHE LOBE OVERFLOW*)

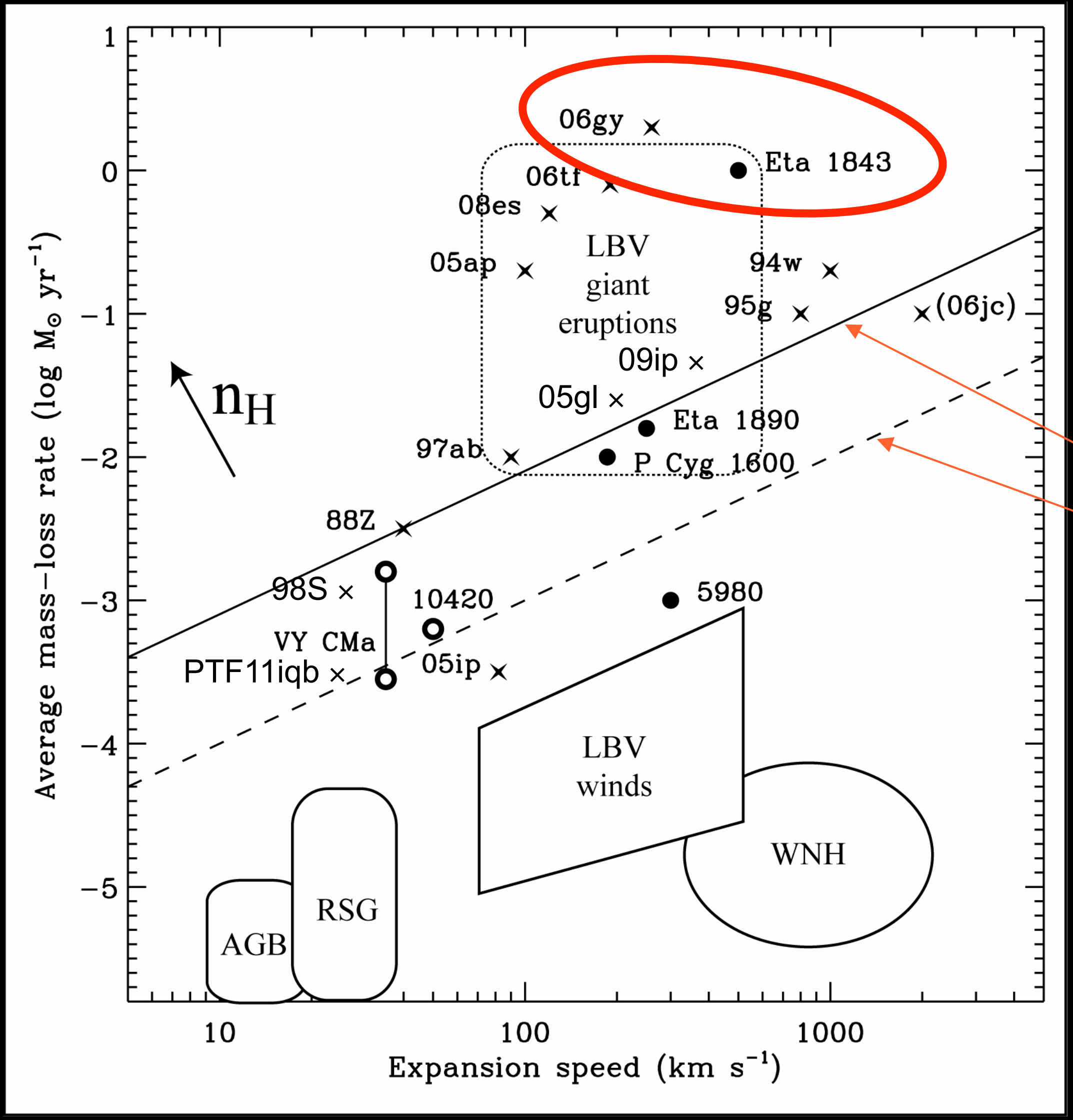
Only 3 massive star binaries caught in brief RLOF phase with spatially resolved CSM.

WHICH KNOWN H-RICH STARS HAVE HIGH-ENOUGH MASS-LOSS RATES TO BE Type IIn SUPERNOVAE?

$\langle \dot{M} \rangle$

For Type IIn SN progenitors:

$$\dot{M} = 2Lv_w/(v_{SN})^3$$



Minimum $\dot{M}$ needed to be observed as a Type IIn for:

$L=10^9\ L_\odot$

v_{SN}=5000 km/s

$v_{SN}=10^4$ km/s

Smith (2010) in prep.

RY Scuti: eclipsing massive binary system in transition to WR+O via RLOF.

(Smith et al. 2011, arXiv:1105.2329)

Repeated equatorial ejections every 120 years (cyclical?).

WHY?

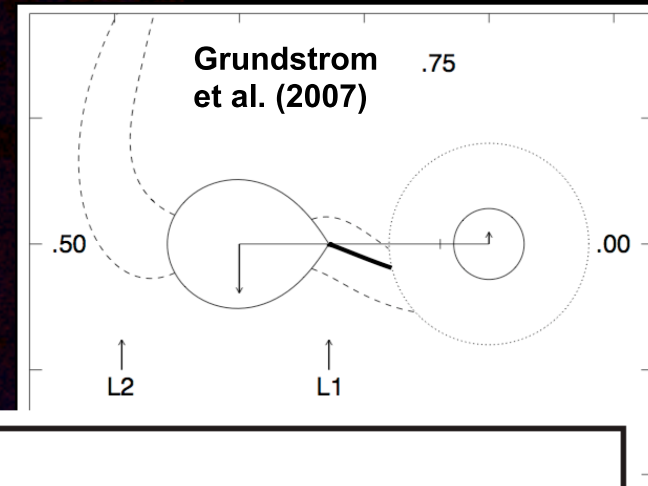
RLOF…

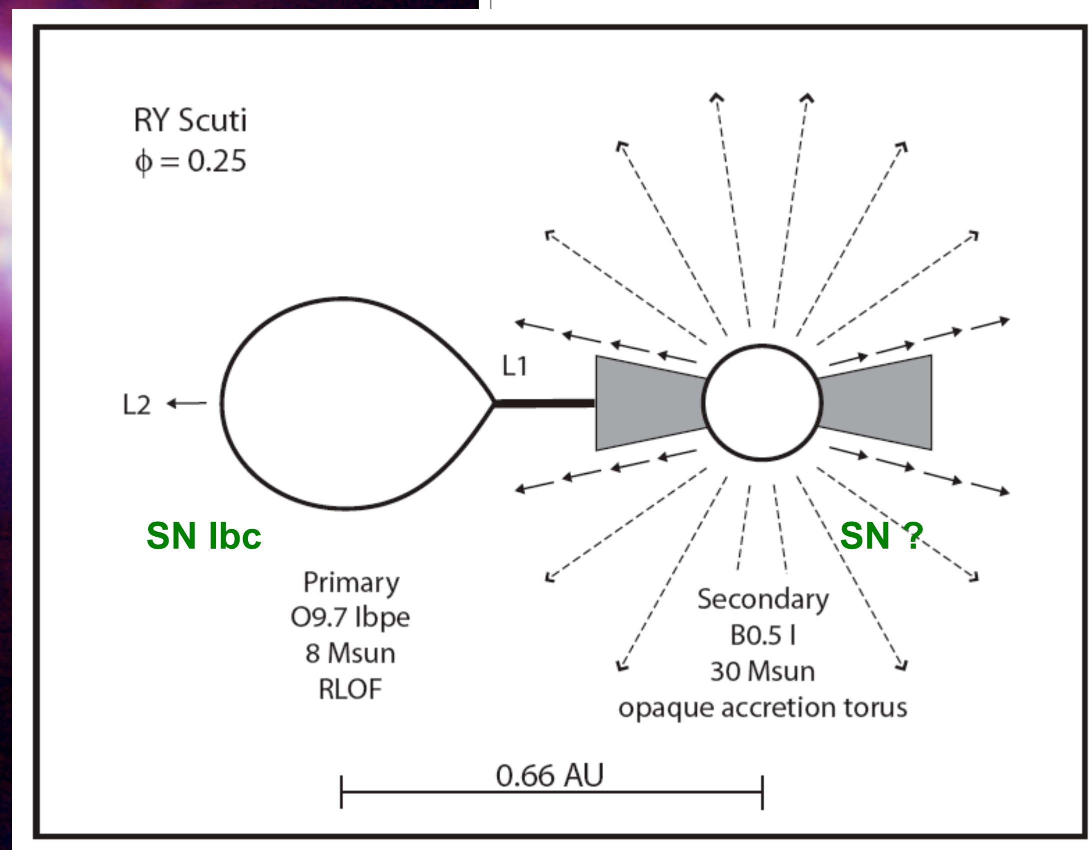
Accretion onto mass gainer companion:

Overluminous
Out of thermal equilibrium
Critical rotation

(LBVs, Be stars, B[e]sg…?)

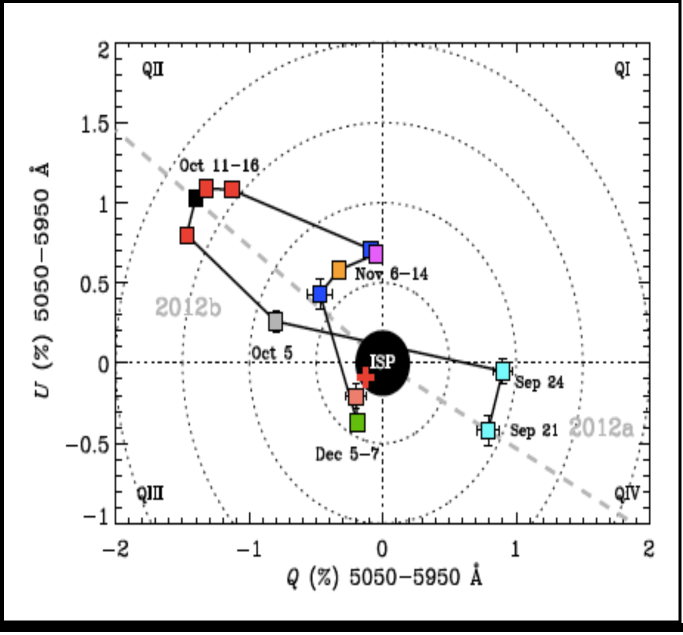
What about the mass gainer's SN?

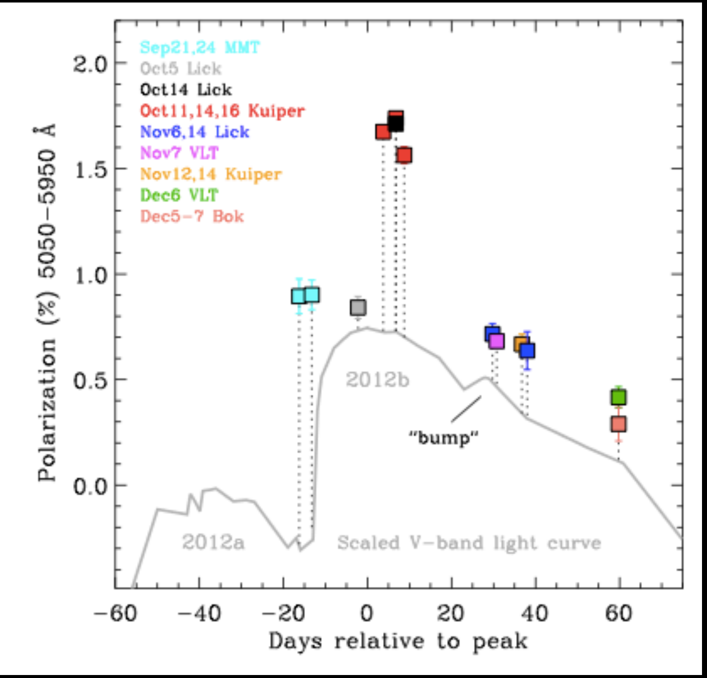




SN 2009ip   Spectropolarimetry: Direct evidence for highly asymmetric CSM

Mauerhan et al. (2014)
MNRAS, 442, 1166

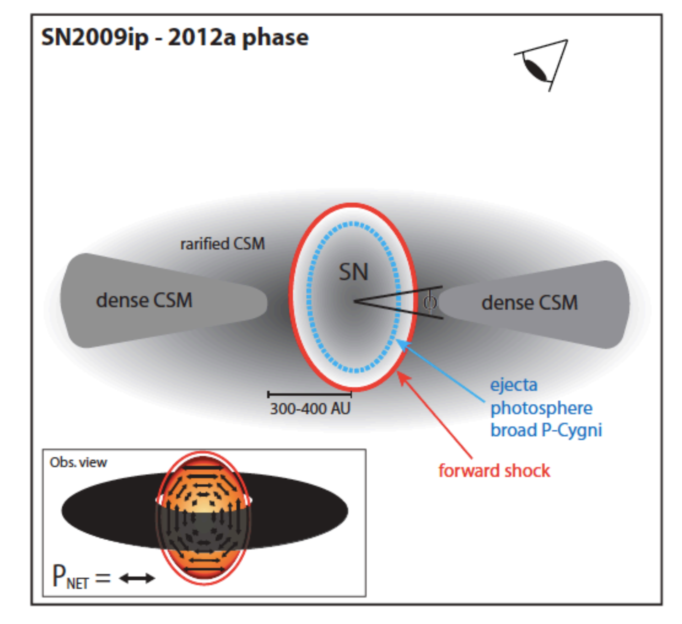


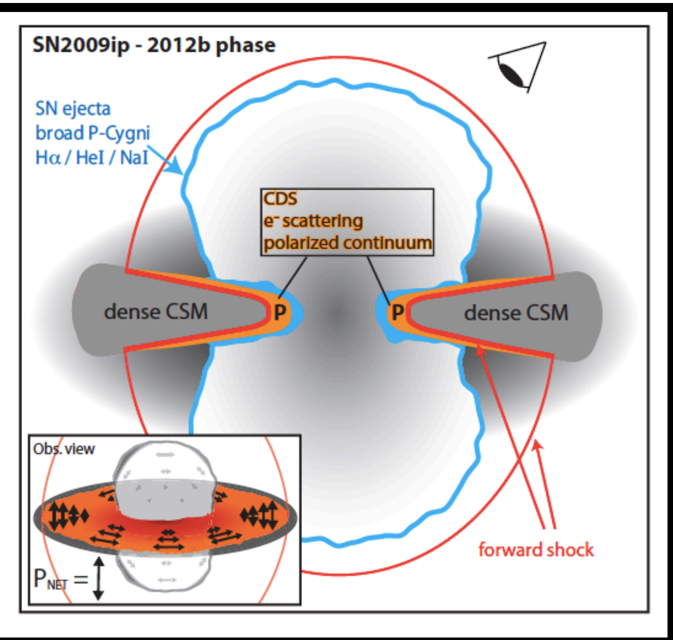


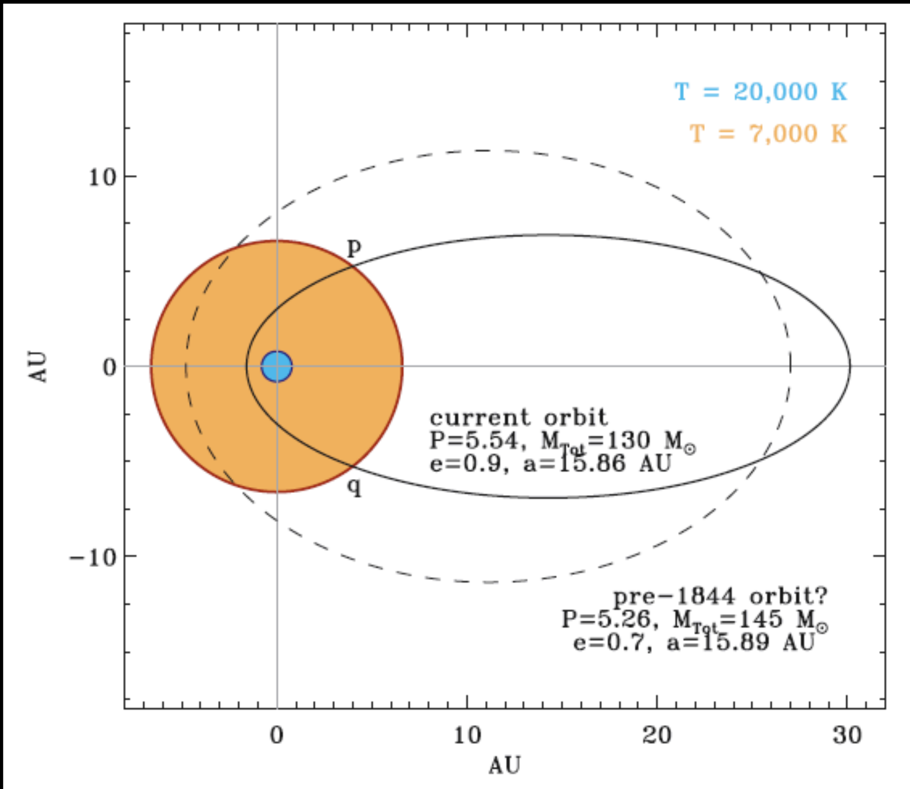
Weaker polarization (lower asymmetry) during broad-line SN photosphere phase (2012a and end of 2012b).

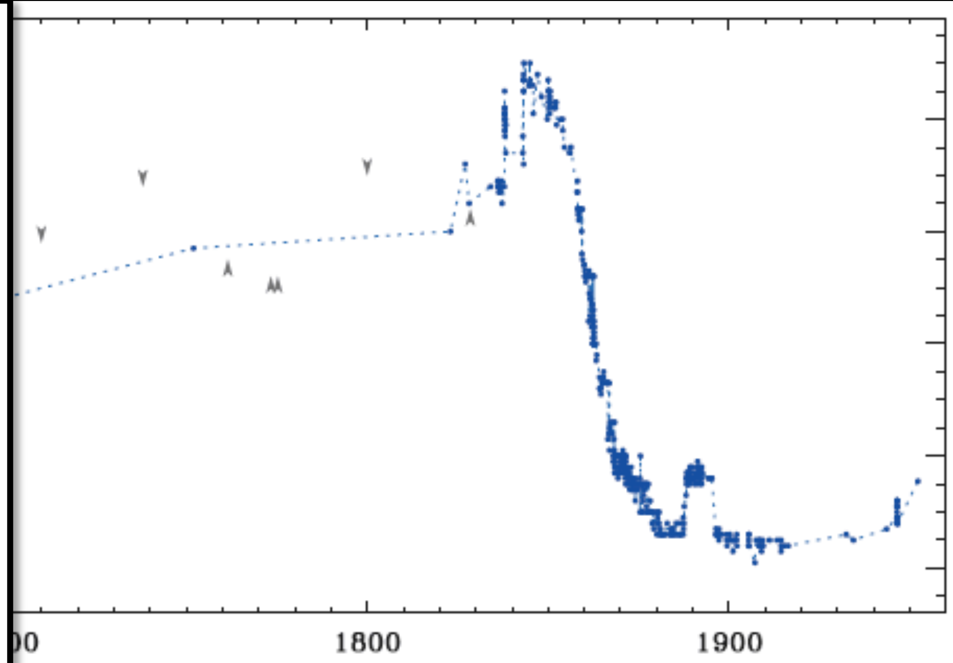
Stronger polarization (high asymmetry) in CSM-interaction dominated phase (2012b peak).

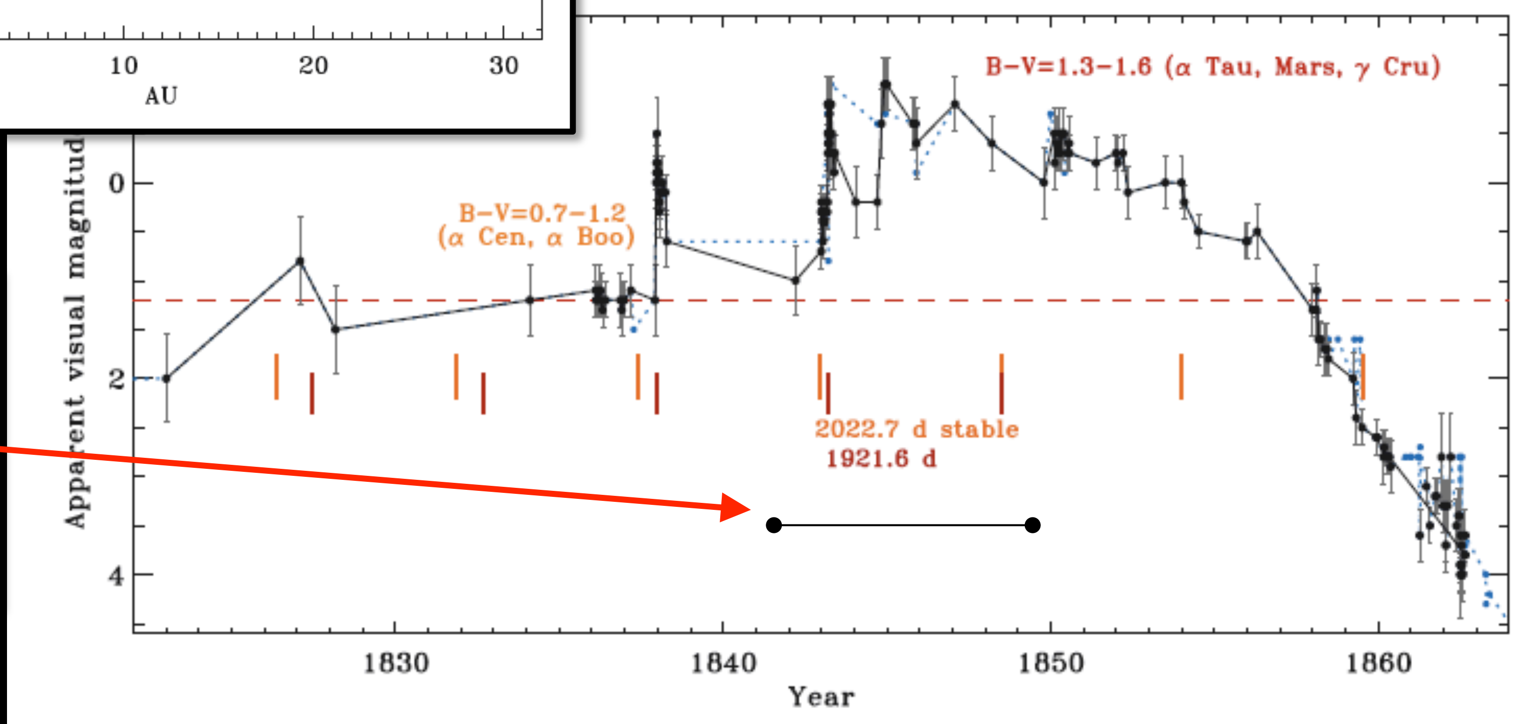
Two components are roughly orthogonal in PA.

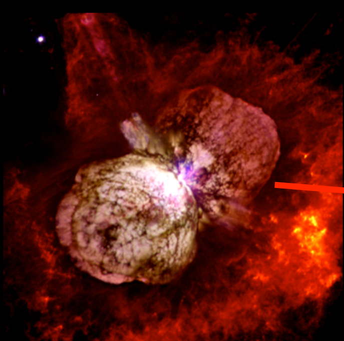












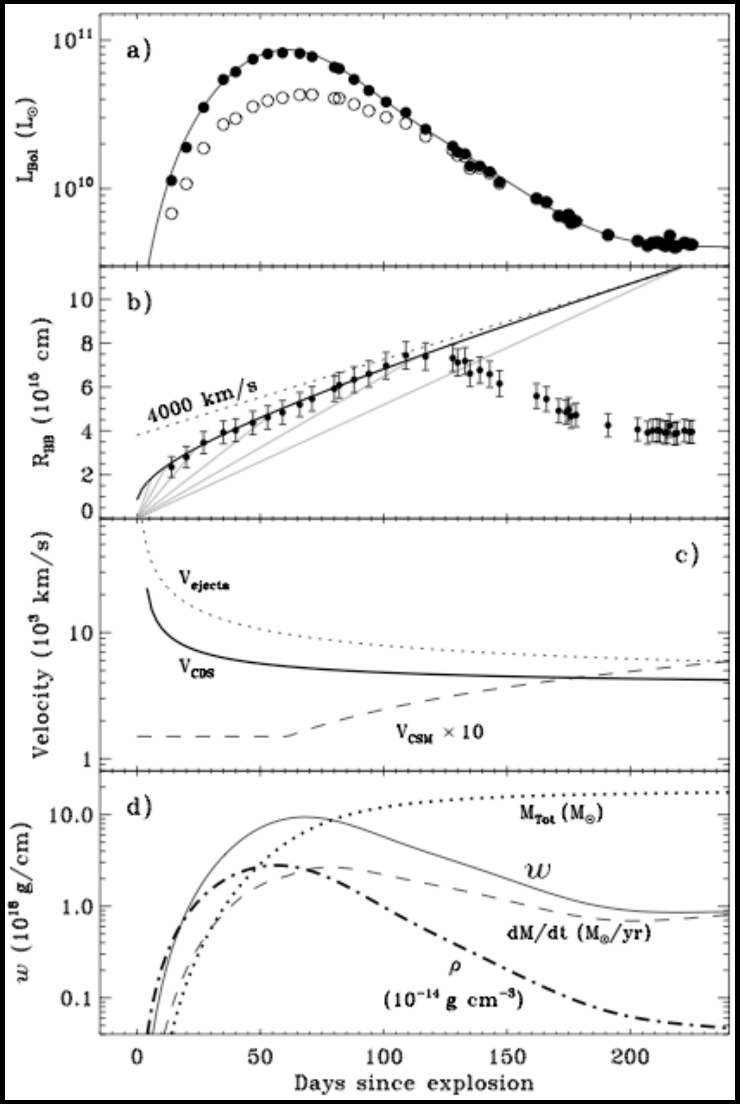
Smith & Frew (2010)

PROPERTIES OF SN2006gy's CSM

A Massive LBV-like Shell: Clues from Spectral Evolution

Time evolution of Luminosity

(Smith et al. 2010, ApJ, 709, 856) →

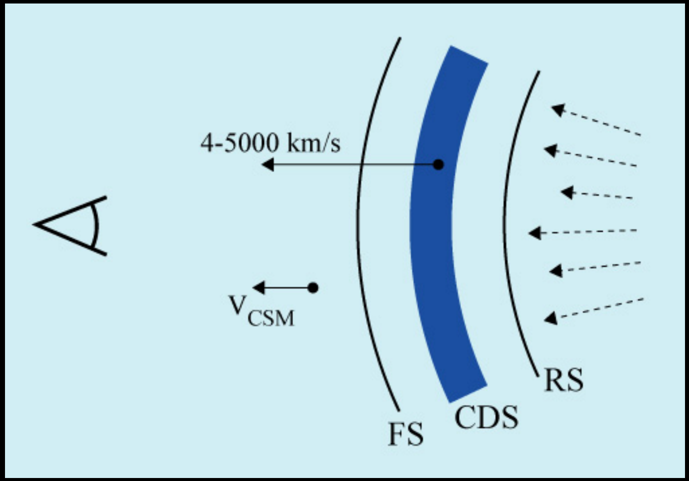


- High CSM density required to drain KE...

$$L = (1/2)\, 4\pi R^2 \rho\, V_{shock}^3$$

- Cumulative swept-up CSM mass:

$$\geq 18\ M_\odot$$



E_{rad} = 2.5e51 erg E_K = 3e51 erg

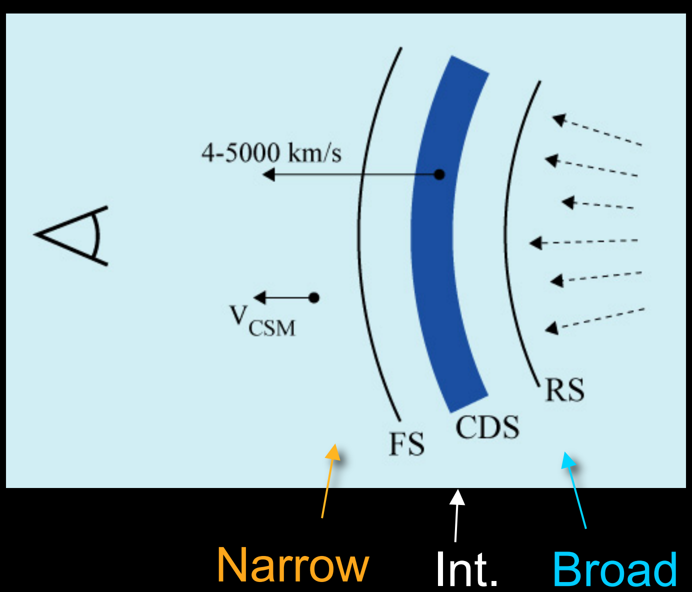
PROPERTIES OF SN2006gy's CSM

A Massive LBV-like Shell:
Clues from Spectral Evolution

Time evolution of narrow Hα

(Smith et al. 2010, ApJ, 709, 856)

- Narrow absorption gets weaker...
  …running out of CSM?
- Narrow absorption gets broader...
  …faster CSM at larger radii?



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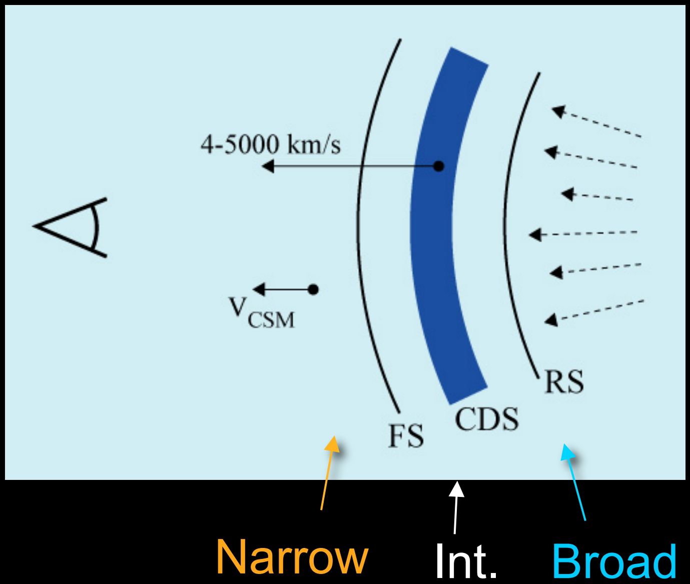
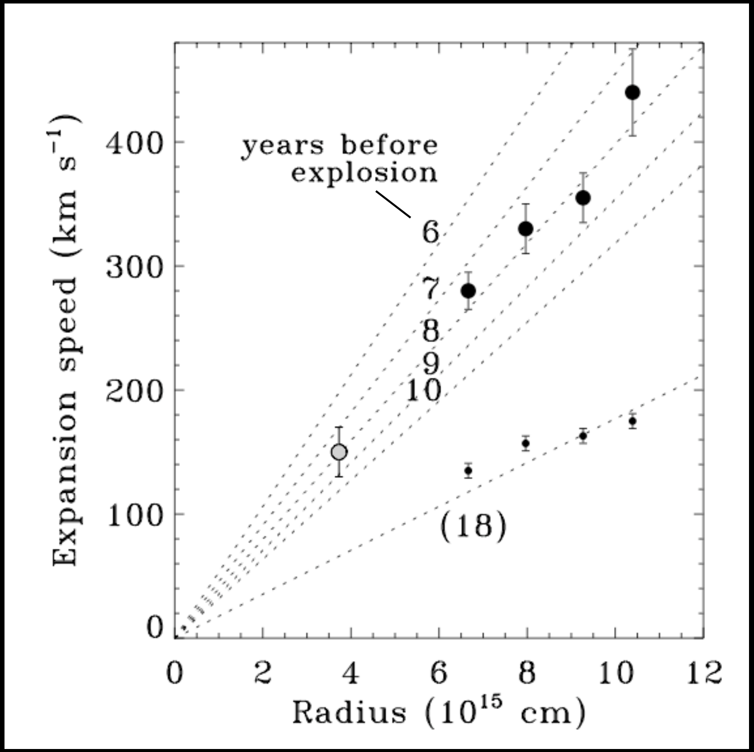




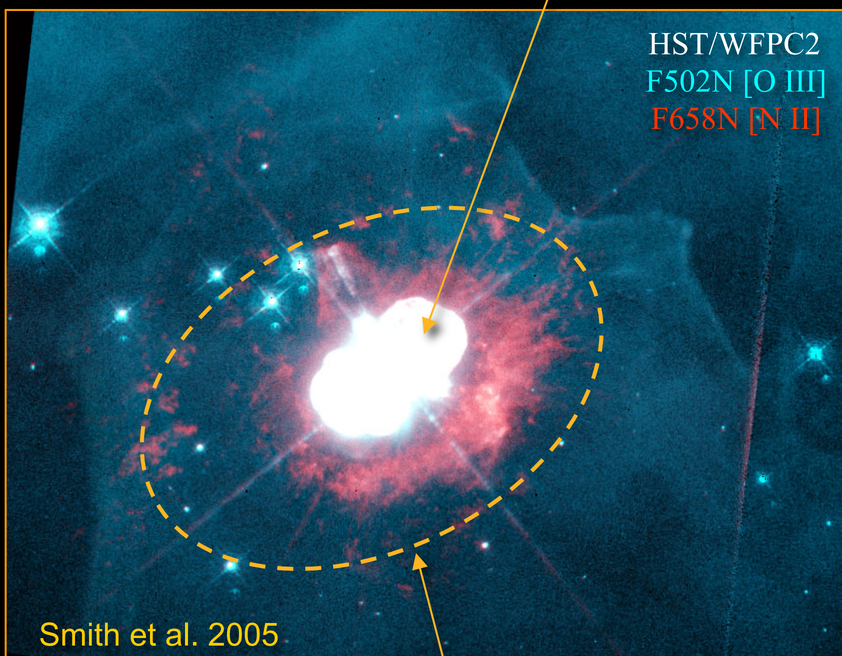
Hubble Flow at 150-500 km/s

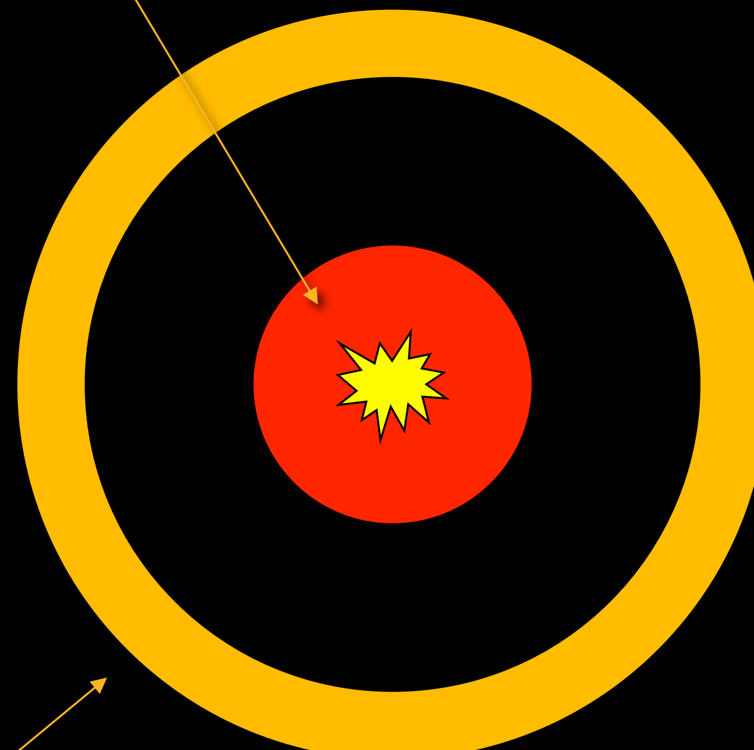
Suggests ≥10^{49} erg ejection ~8 yr before SN (fall 1998)

Comparing the CSM of Eta Carinae and SN 2006gy:

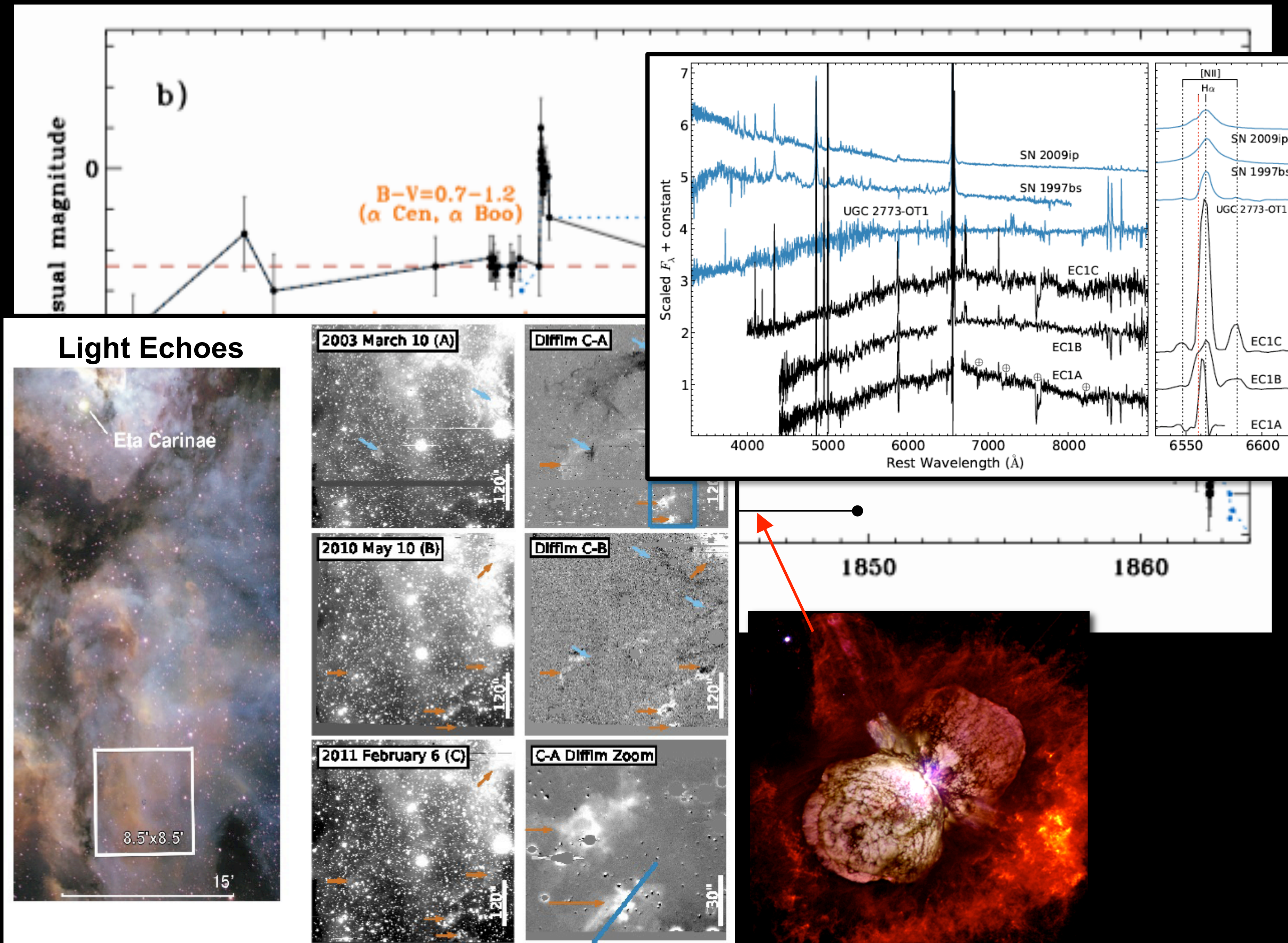
Both had multiple massive shell ejections.

Inner massive shell, H-rich, M ~ 10-20 $M_{\odot}$
ejected at 100-600 km/s, Hubble law

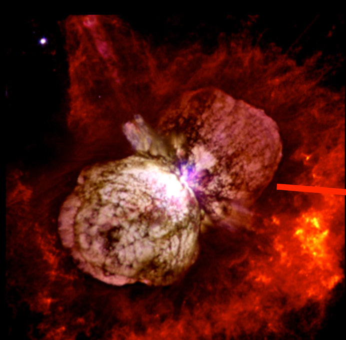




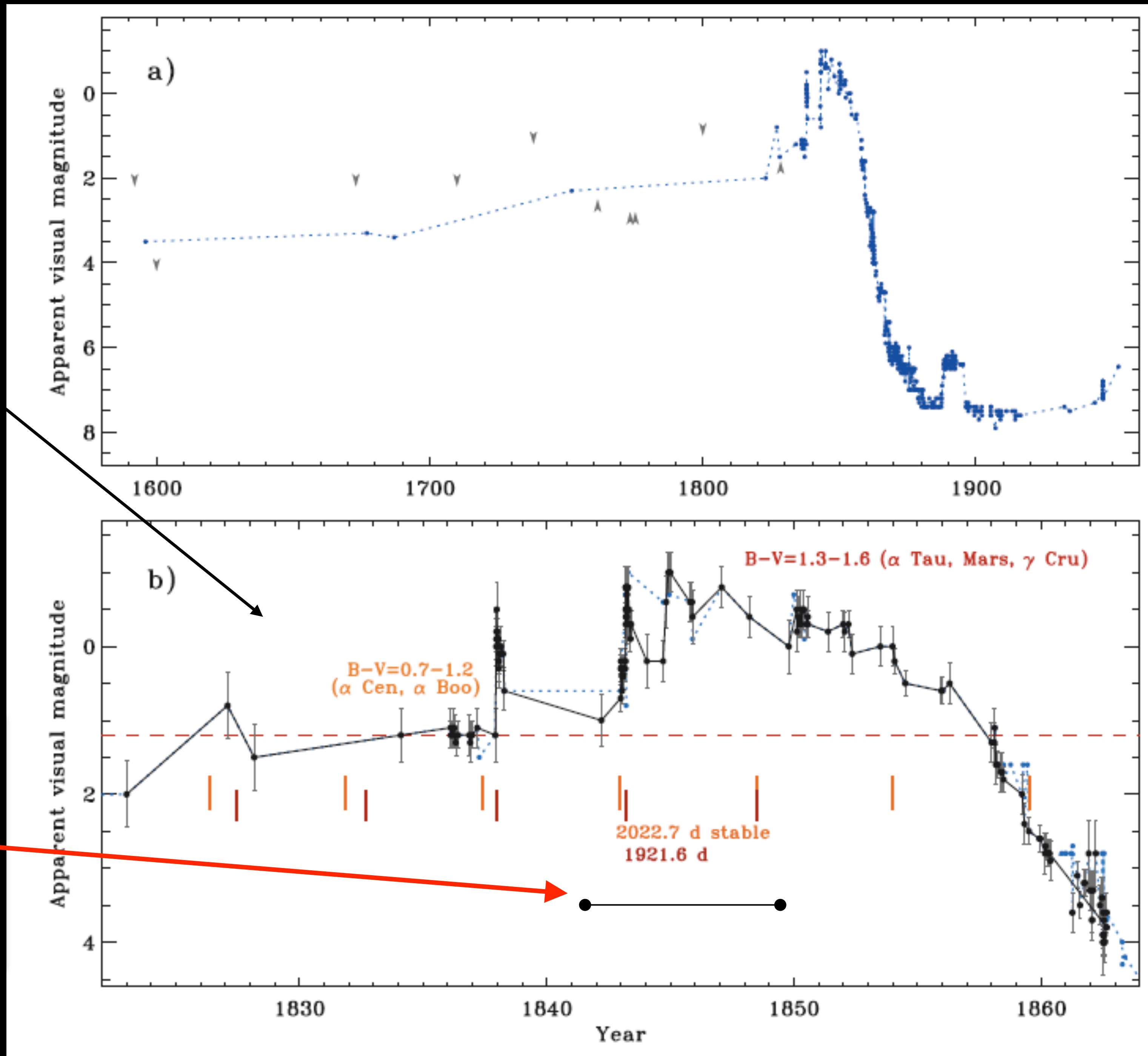
Outer massive shell, R ~ 1 ly
ejected ~1000-2000 yr earlier


b)
sual magnitude
0
B−V=0.7−1.2
(α Cen, α Boo)
1850
1860
Scaled F_λ + constant
Rest Wavelength (Å)
SN 2009ip
SN 1997bs
UGC 2773-OT1
EC1C
EC1B
EC1A
[NII]
Hα
Light Echoes
Eta Carinae
8.5'x8.5'
15'
2003 March 10 (A)
Diffim C-A
2010 May 10 (B)
Diffim C-B
2011 February 6 (C)
C-A Diffim Zoom
120"
30"

John F.W. Herschell
1792-1871



Smith & Frew (2011)

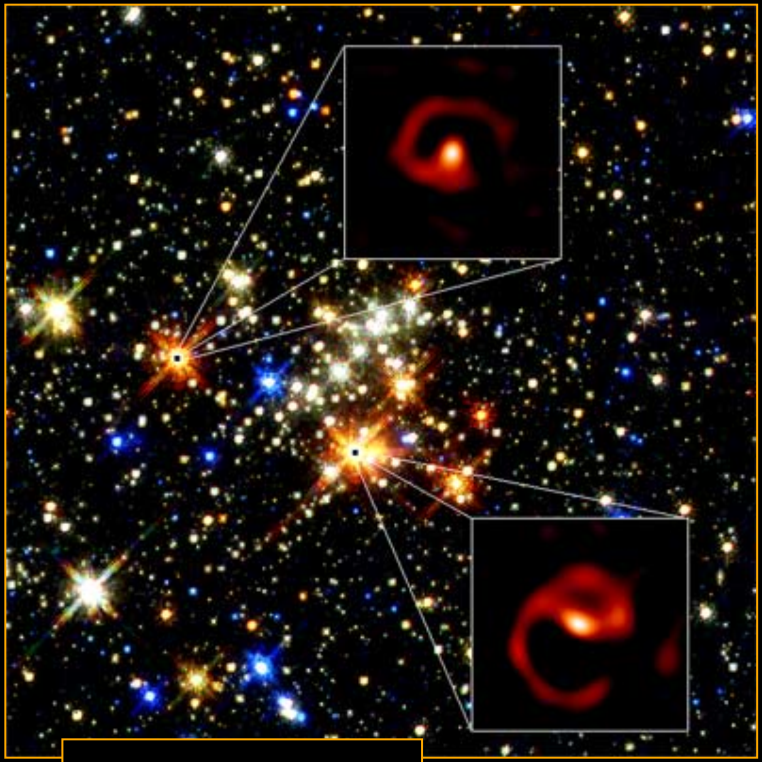


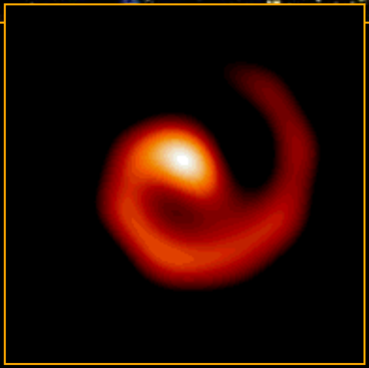
Can dust form in strong shocks?

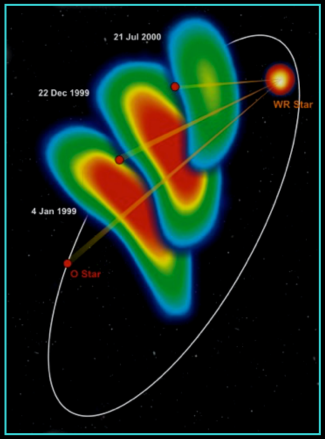
WC+O Colliding-wind binaries do it.
(they are C-rich)

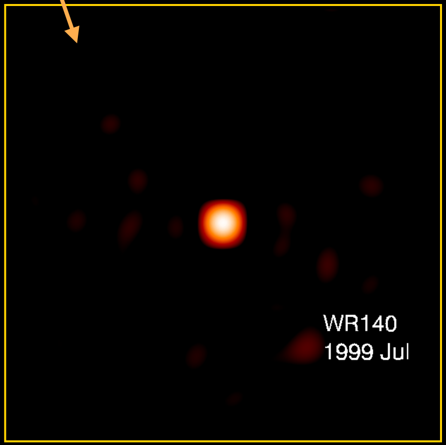
persistent dust producers
(a.k.a. "Pinwheels")

episodic dust producers
(at periastron like WR140)









Tuthill et al., Monnier et al.

END FATES of MASSIVE STARS:
What type of supernova
from which type of star?

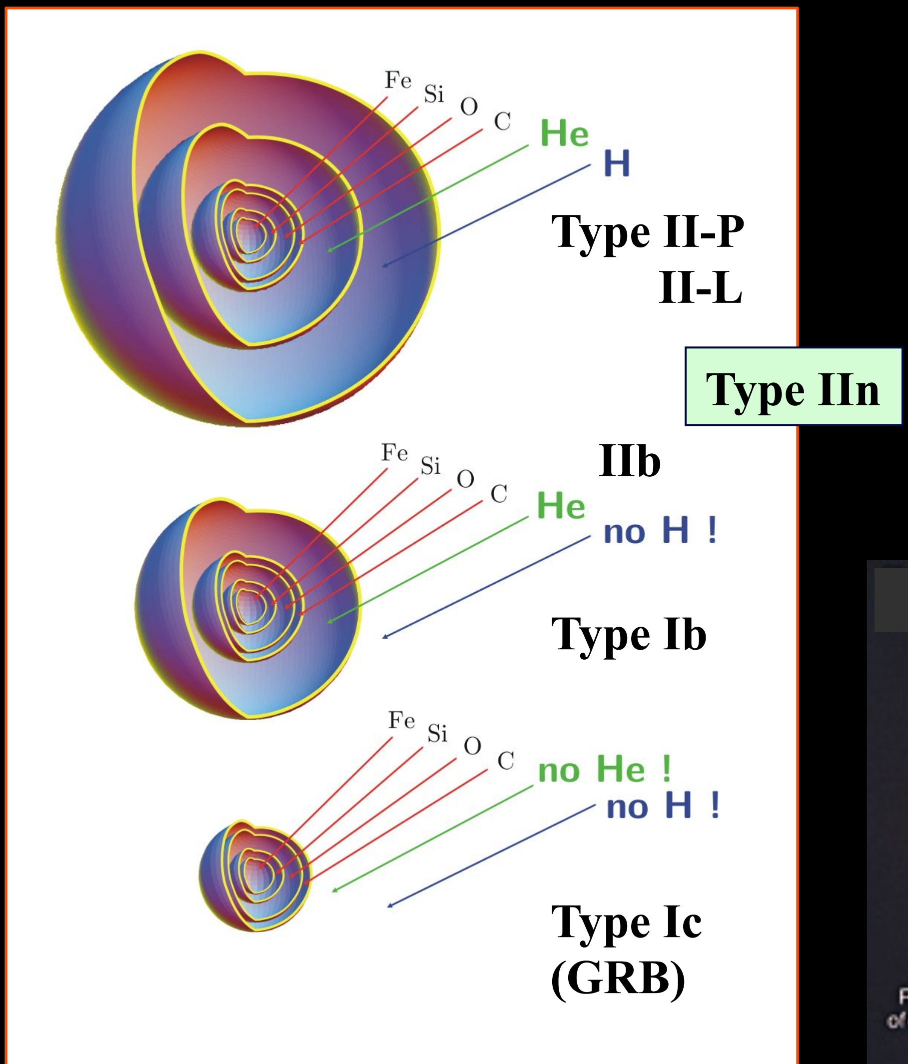
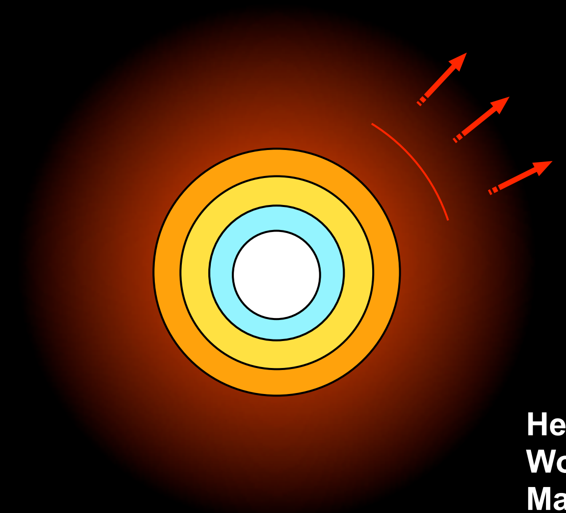


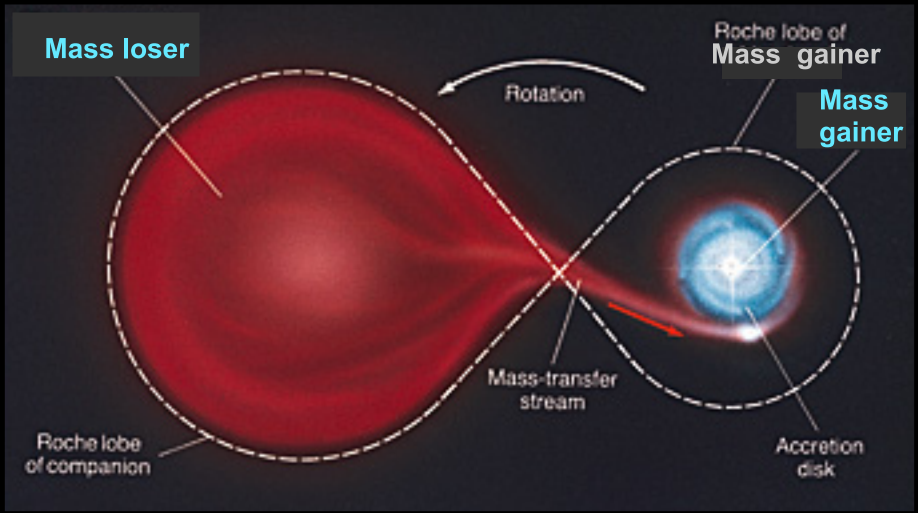
Image courtesy M. Modjaz

Single-star mass-loss
(*STELLAR WINDS and ERUPTIONS*)



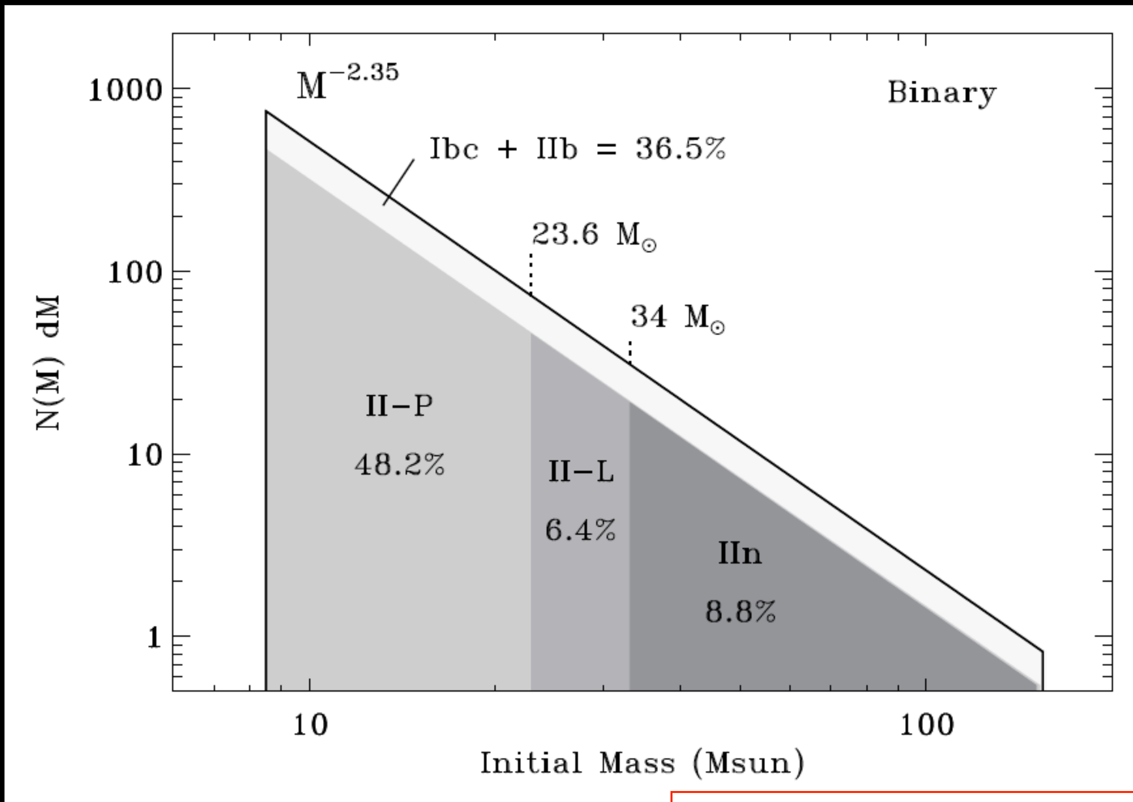
Heger et al.
Woosley et al.
Maeder & Meynet

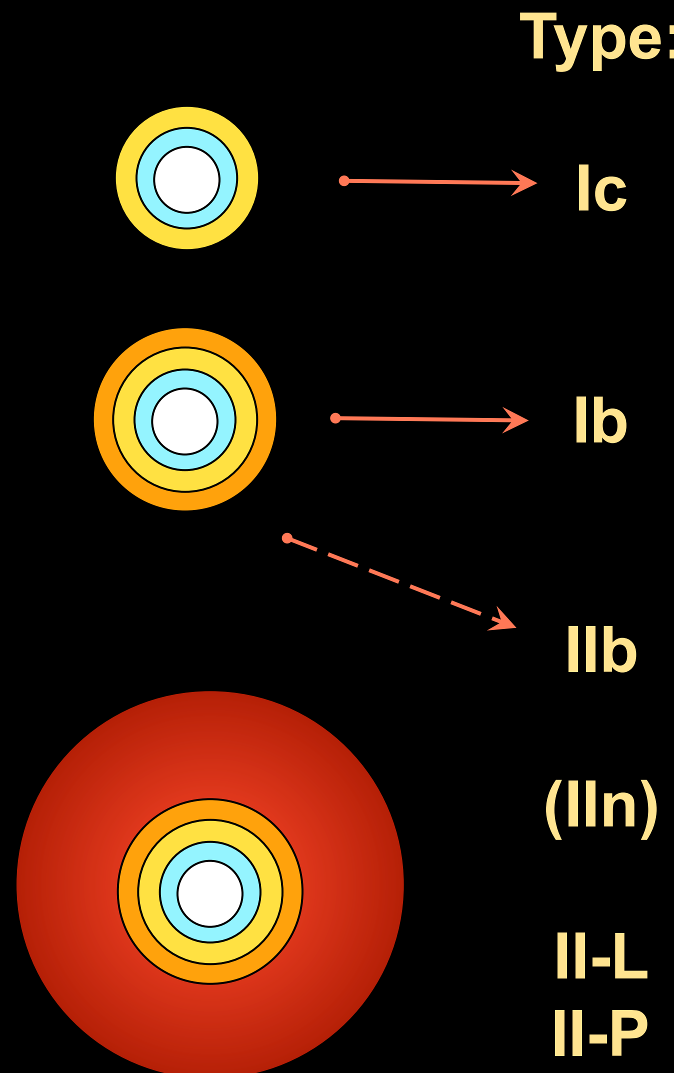
Binary-star mass-transfer
(*ROCHE LOBE OVERFLOW*)



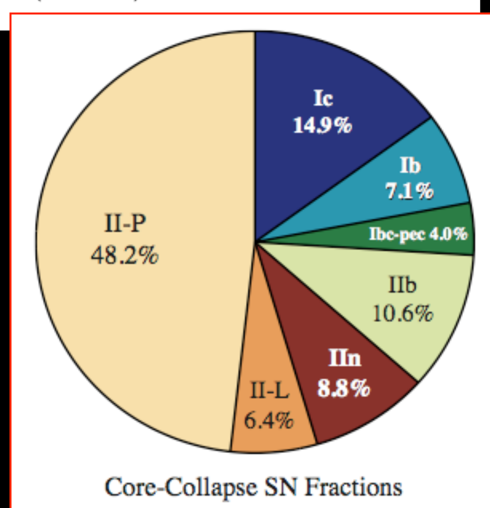
Paczynski et al. 67; Podsiadlowski et al. 92

Supernovae: SN types & initial mass.





SN subtype fractions from the LOSS (Li et al. 2011)



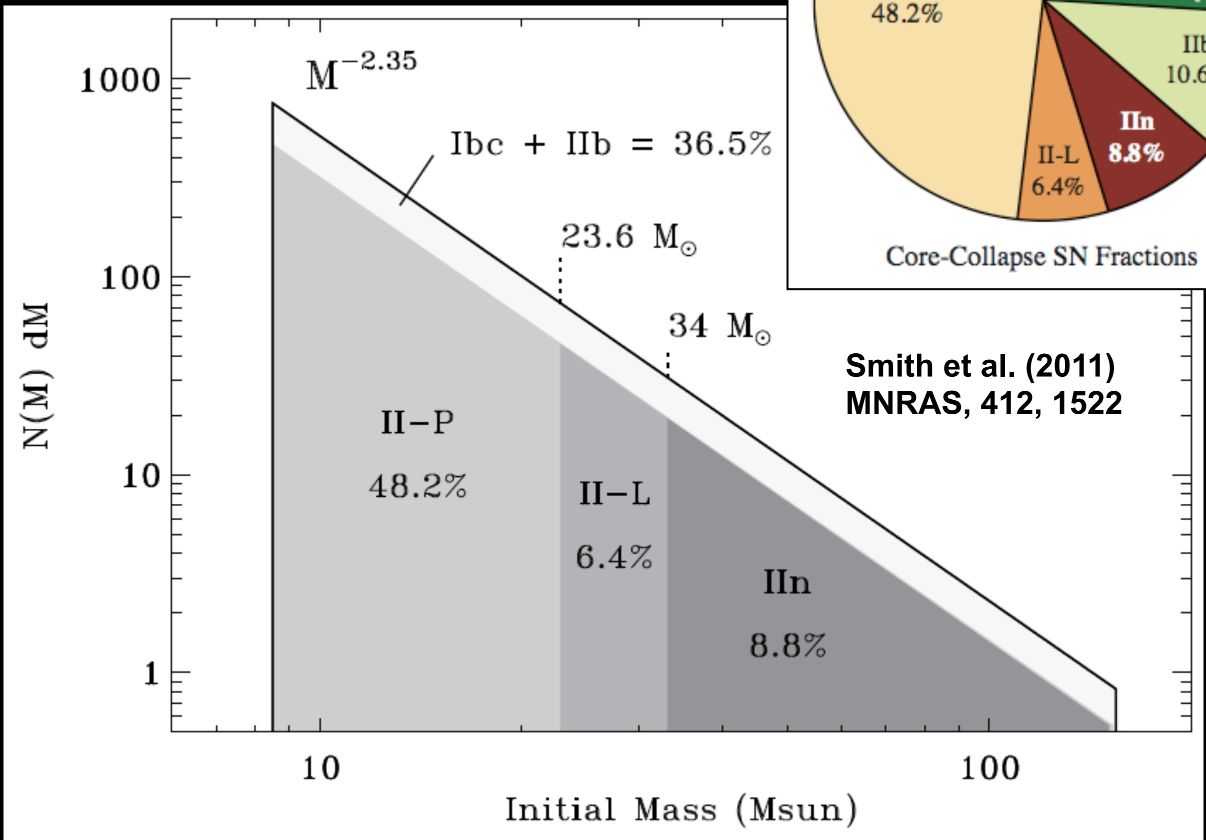
Core-Collapse SN Fractions

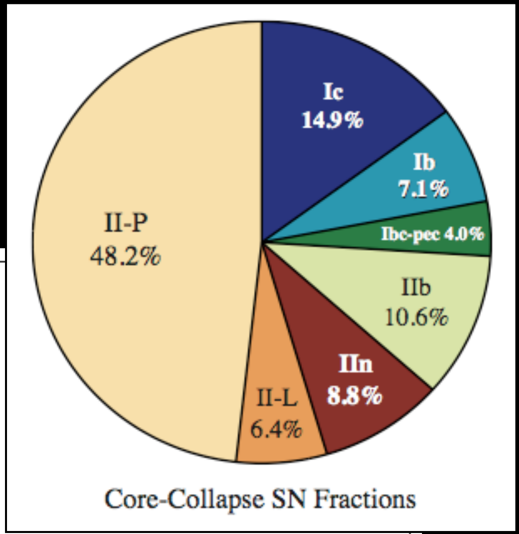
$\dot{M}$ determines SN type (initial mass, binarity)

Smith et al. (2011) MNRAS, 412, 1522

Large galaxies, roughly $Z_\odot$

SN subtype fractions





Smith et al. (2011)
MNRAS, 412, 1522

Sana et al. 2012, de Mink et al. 2013 (see also Kiminki et al. 2007,2014; Kobulnicky & Fryer, etc.):

- **Binary interaction must dominate the evolution of massive stars**
- **Roughly 2/3 of massive stars will interact & exchange mass or merge**

CONSTRAINTS FROM SUPERNOVA PROGENITOR STARS

Type II-P
RSGs with initial mass $8.5 – 20\ M_\odot$ (~12)

Most common. Single stars (or wide binaries) of low-ish mass.

Type Ibc
Zero detections, but probably mostly binary (10-15 upper lim)

Type IIb
$13\text{-}18\ M_\odot$ binary (3)

Binary channel: mass <u>donors</u> in RLOF.

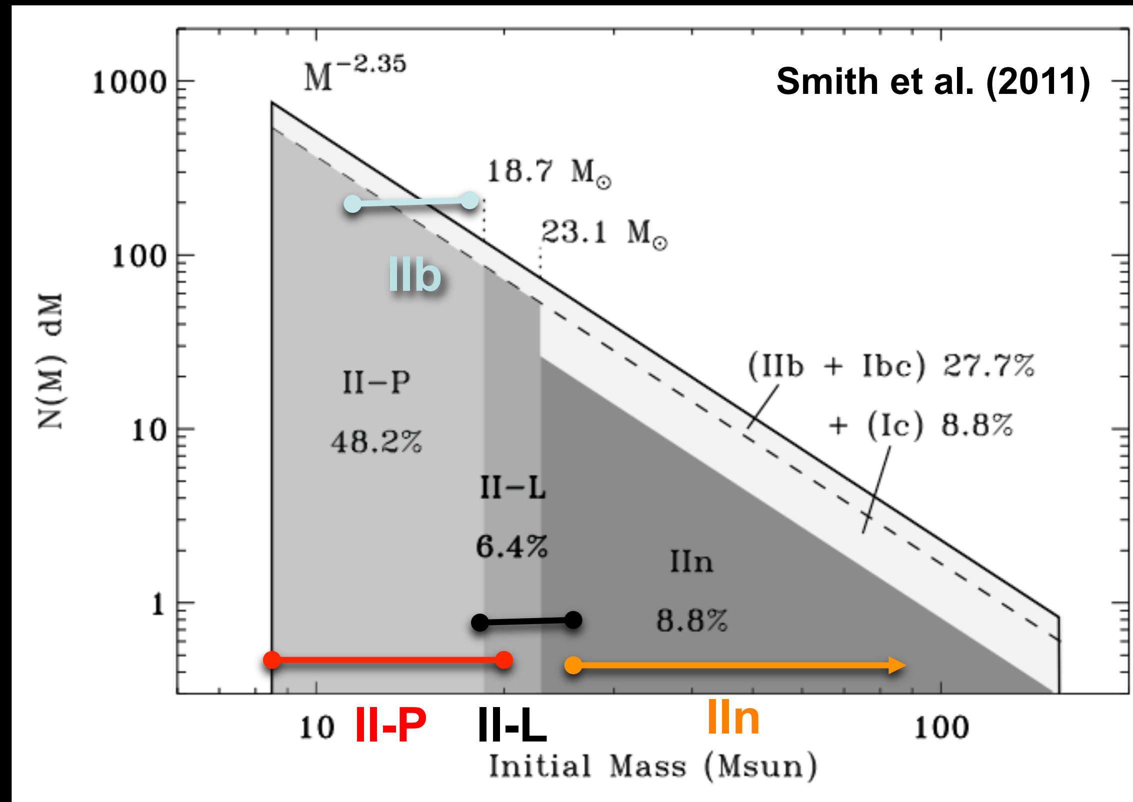
Might favor locations in clusters. Could be $8\text{-}100\ M_\odot$

Type II-L
$18\text{-}25\ M_\odot$ (2)

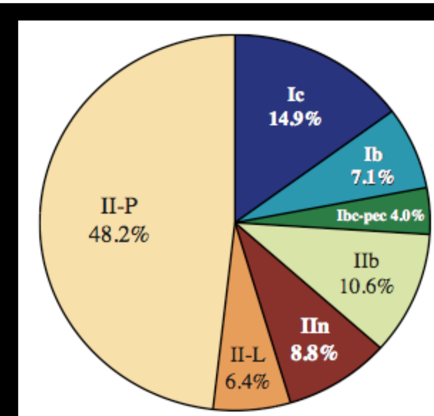
Like II-P, but a little more massive (?).

Type IIn
$>30\text{-}100\ M_\odot$ (4)

LBV-like. Some very massive stars, but weird & poorly understood.



** Also: SN ejecta masses of SNe Ibc & IIb are small (Dessart et al.; Haschinger et al.)



Core-Collapse SN Fractions