The Diversity of Pre-Supernova Evolution and Mass Loss of Massive Stars

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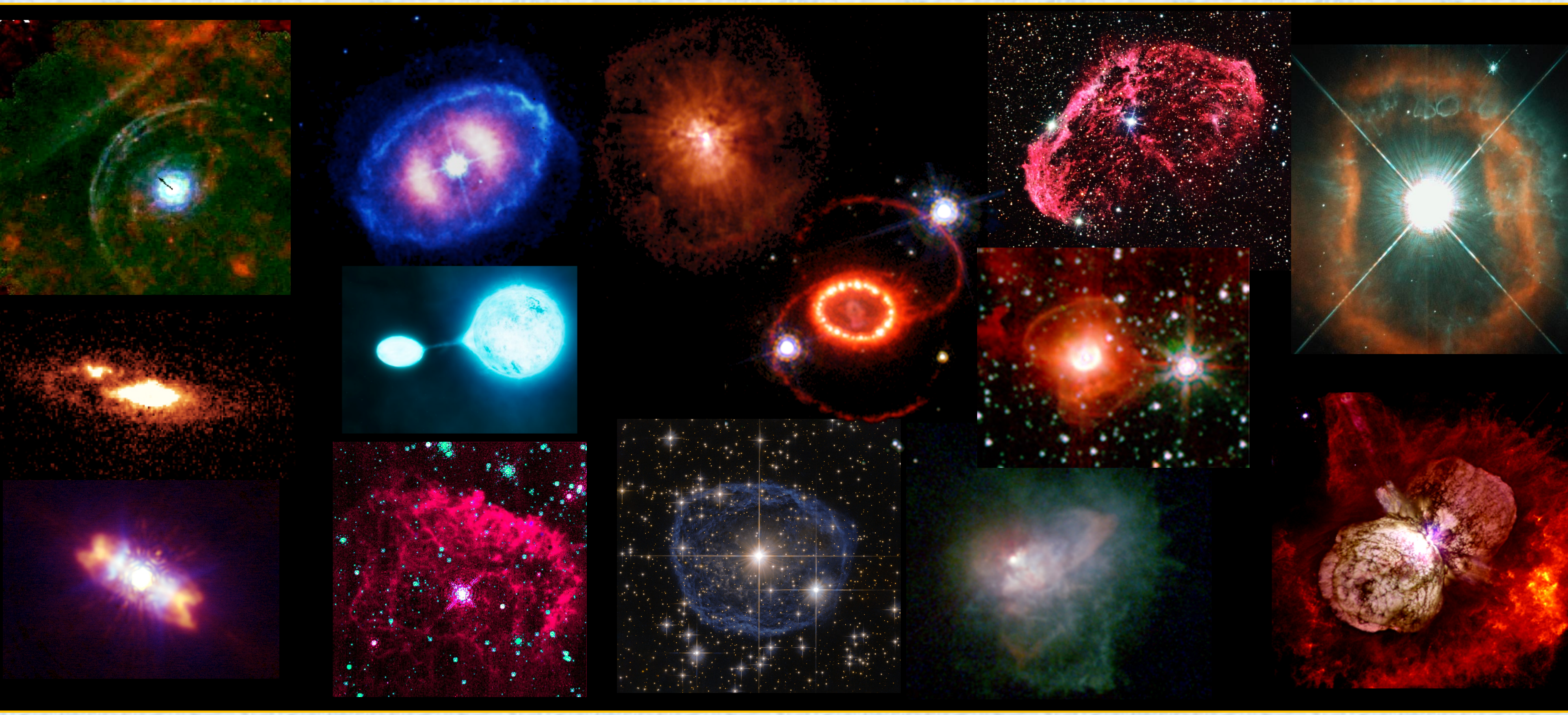


OUTLINE

Diversity in Evolution: Single star evolution with mass loss vs. Binary Evolution. Why the paradigm has (finally) shifted (again). Single stars, stripped primaries, mass gainers, mergers, etc.

Diversity in Pre-SN mass loss and CSM: Winds vs. Episodic pre-SN mass loss, CSM shells, etc. Implications for progenitor links and explosions.

for reference, see my review on mass loss (Smith 2014, ARAA, 52, 487)

Massive Star Diversity

O type:
O dwarfs, subdwarfs
O supergiants
Of, O(f), O((f))+, etc.
supergiants
Of?pe (peculiar = magnetic)

B type:
B dwarfs
B supergiants
Be
B[e] supergiants

WR:
WO, WC, WN
WNH
Ofpe/WN9
WN3/O3
He stars (no winds)

LBV:
cool or hot
giant eruptions
(Eta Car, SN impostors)
S Dor variability
microvariability
LBV candidates
CSM shells, or not

Yellow:
Yellow supergiants
Yellow hgypergiants
dense CSM (or not)

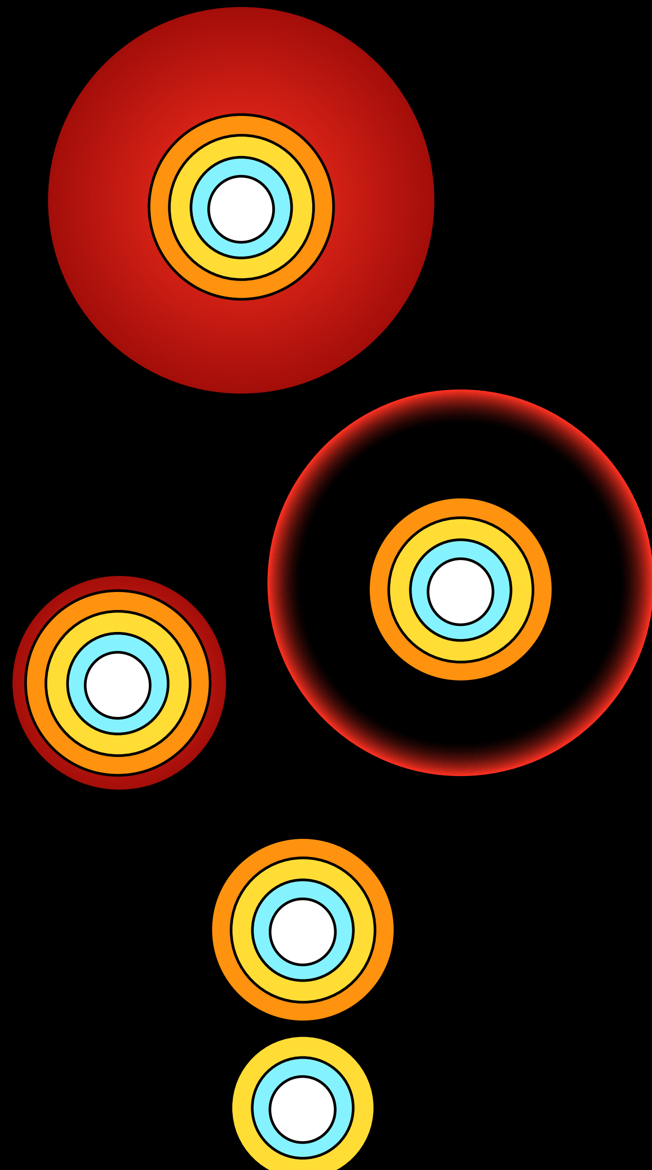
RSG:
normal RSGs
(like Betelgeuse)
extreme RSGs
(like VY CMa)
Miras
OH/IR stars
symbiotic
super-AGB

Core collapse SN Diversity

Types Ib, Ic, Ic BL, IIb (IIb-e vs IIb-c), Ibn, Ibn/IIn, GRB, SLSN Ic
Types II-P (range of peak Lum), II-L, IIn (huge variety), SLSN IIn, SLSN II

A central issue in Massive Star Evolution:
SHEDDING THE HYDROGEN ENVELOPE

Massive stars are born as H-rich O-type stars on the main sequence, and they die as:



H-rich RSGs

Type II-P/II-L SNe

(weird things in between)
YSG, BSG, LBV, other

Type IIb, II-pec, IIn, Ibn

H-free Wolf-Rayet or
lower-mass He stars

Type Ib/Ic SNe, GRBs

A central issue in Massive Star Evolution: *SHEDDING THE HYDROGEN ENVELOPE*

2 stories for how we make WR stars and stripped envelope SNe

Requires high luminosity (high M_{ZAMS})

Stronger at higher Z (line-driven or dust)

Observed classes are a monotonic time sequence of progressive mass loss:

O star → LBV or RSG → WR → SN Ibc

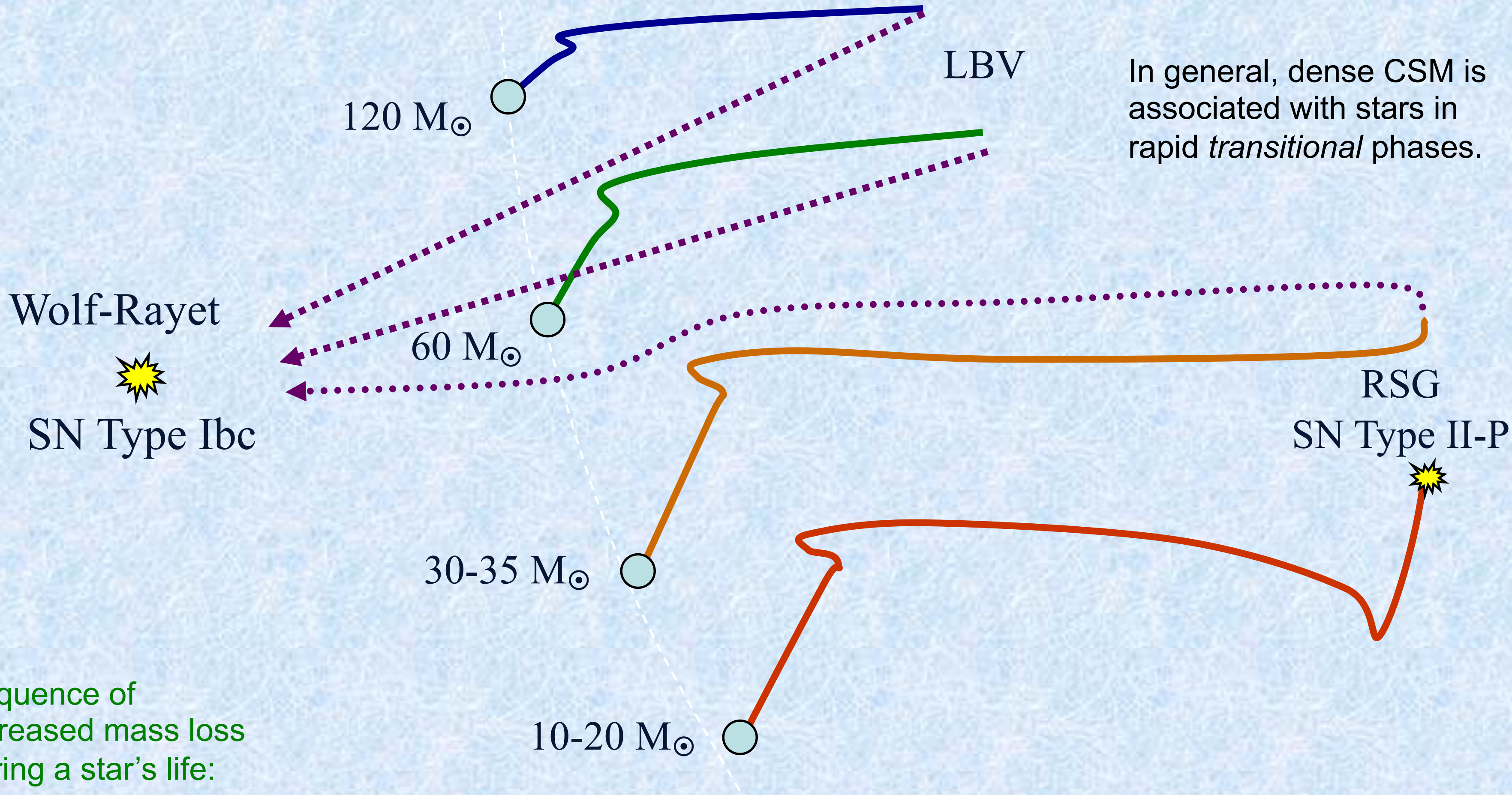
Works across all M_{ZAMS}

Can work at low Z too

Observed classes are a result of different evolutionary paths:

Mass donor, mass gainer, common env., merger, etc.

Evolution and mass loss of massive single stars



In general, dense CSM is associated with stars in rapid *transitional* phases.

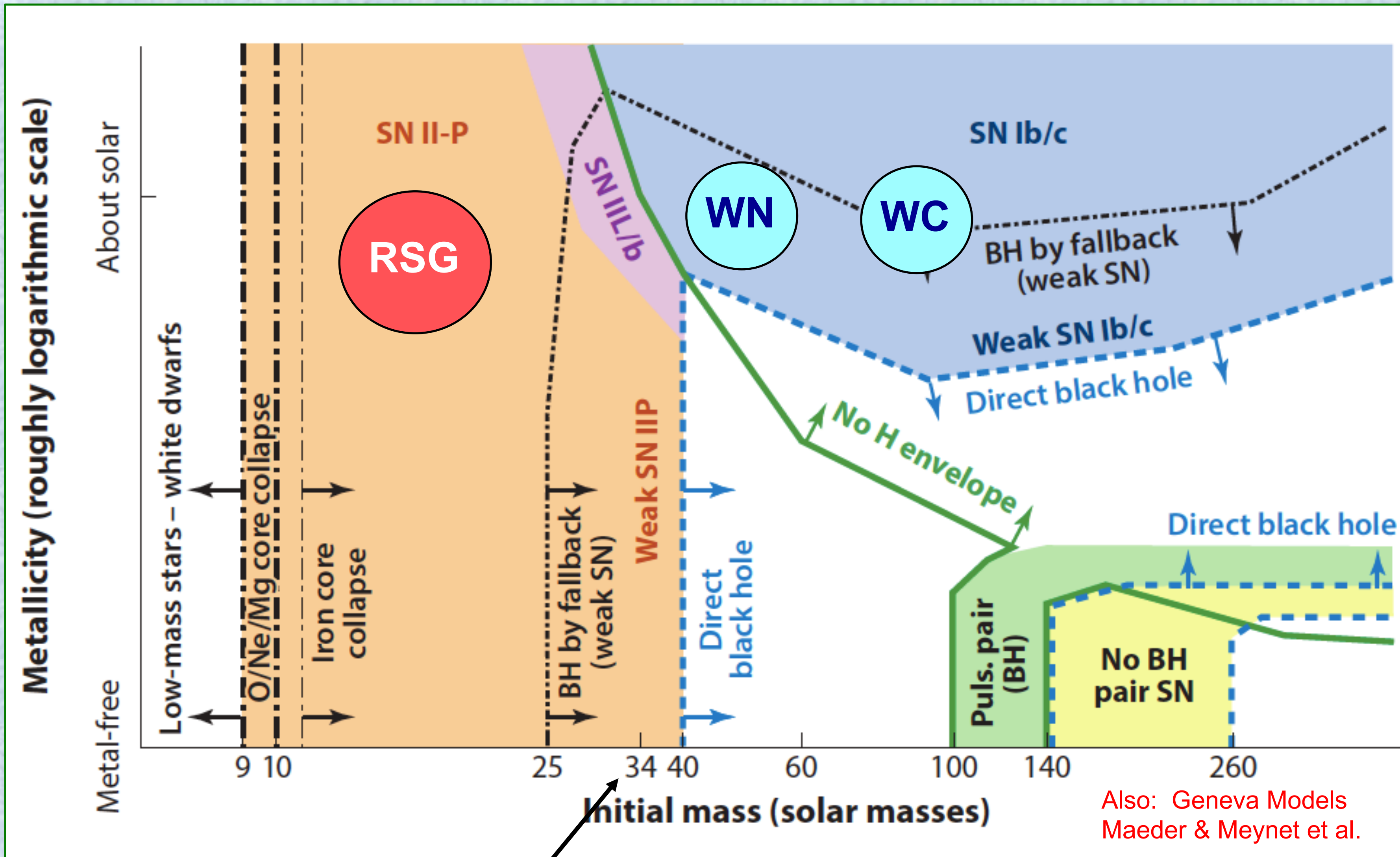
Sequence of increased mass loss during a star's life:

Early O type → LBV → WN → WC → SN Ibc

Mid O type → RSG → YHG → WN → SN Ibc (or II-L, IIn, IIb)

Late O type → RSG → SN II-P

Evolution and mass loss of massive single stars



Adapted from
Heger et al. 2003

M_{WR}

Determined by assumed mass-loss rates in a stellar evo code.

Observational problems for single-star paradigm

1. Vast majority of massive stars are actually binaries (or triples). At least 2/3 of massive stars will interact with a companion before death.

2. Depends entirely on assumed mass-loss rates: …But observed wind mass-loss rates have been revised downward by factor of ~3 due to effects of clumping. Shifts mass-loss burden to LBVs and RSGs, but…

3a. LBVs exploding as SNe IIn: LBVs are supposed to be a transitional phase ***before*** WR phase in single star view, not an end phase.

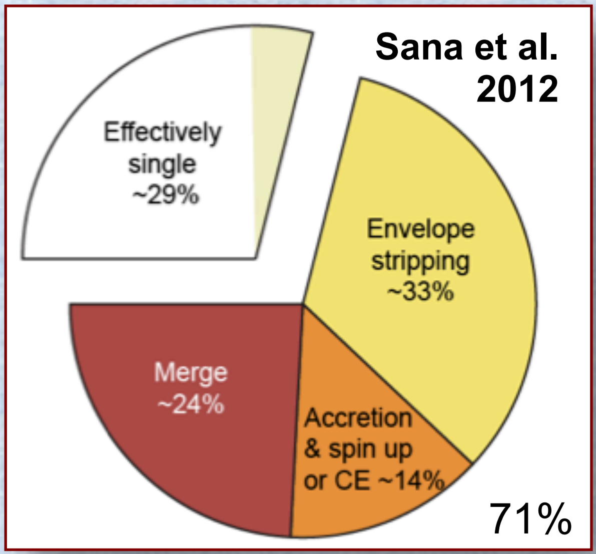
3b. LBV Environments: LBVs are too isolated from O stars – more isolated than WR stars. Their positions rule out their presumed mass-loss role in single-star evolution.

4. Relative fractions of SN types: Far too many stripped envelope SNe.

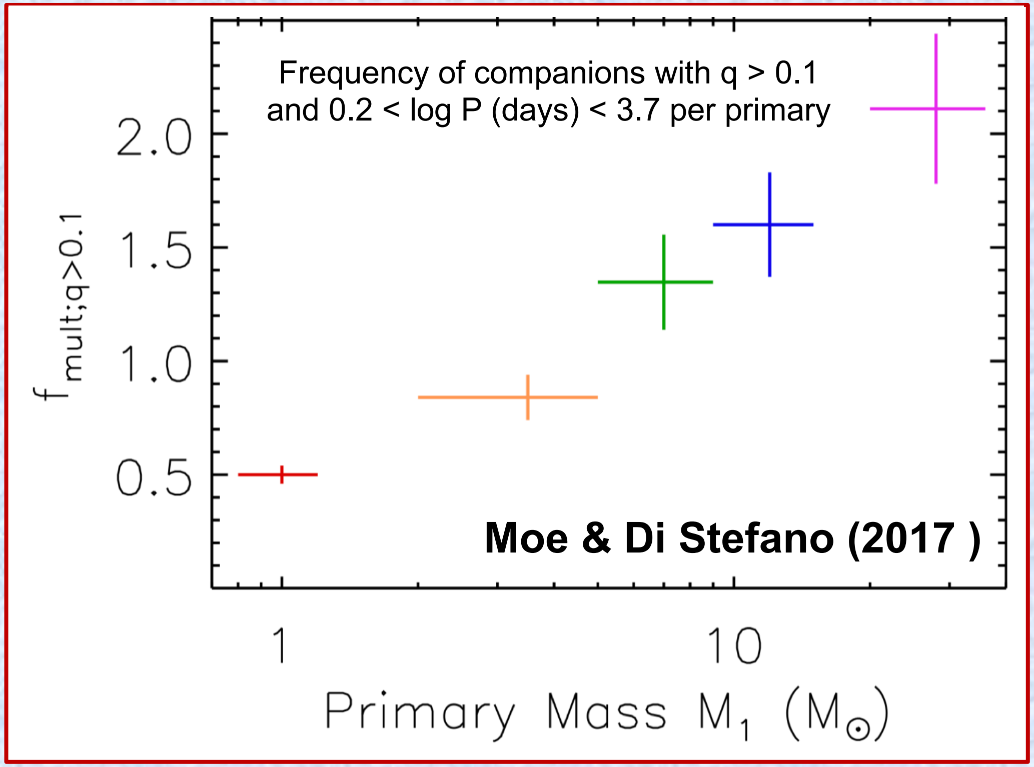
5. SN ejecta mass and progenitors: Very low ejecta masses for stripped envelope SNe. No massive WR progenitors of stripped envelope SNe (yet).

Observational problems for single-star paradigm

1. **Vast majority of massive stars are actually binaries (or triples).**



This is for young O-type stars.
More than 2/3 will interact.



Multiplicity is the rule, not the exception.

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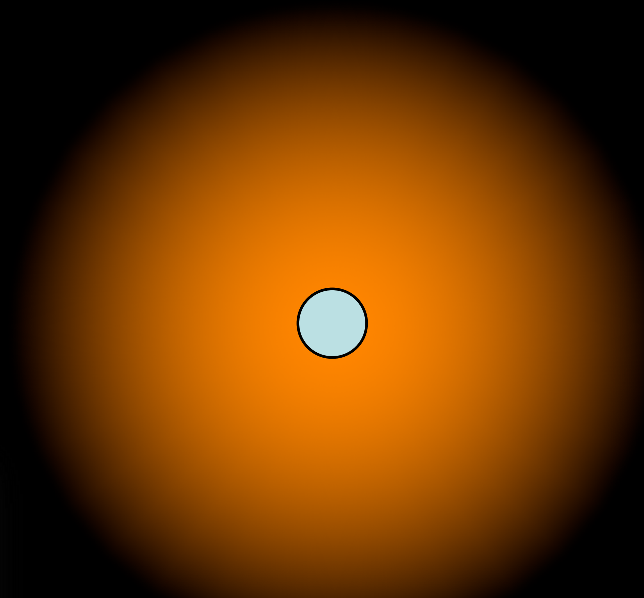
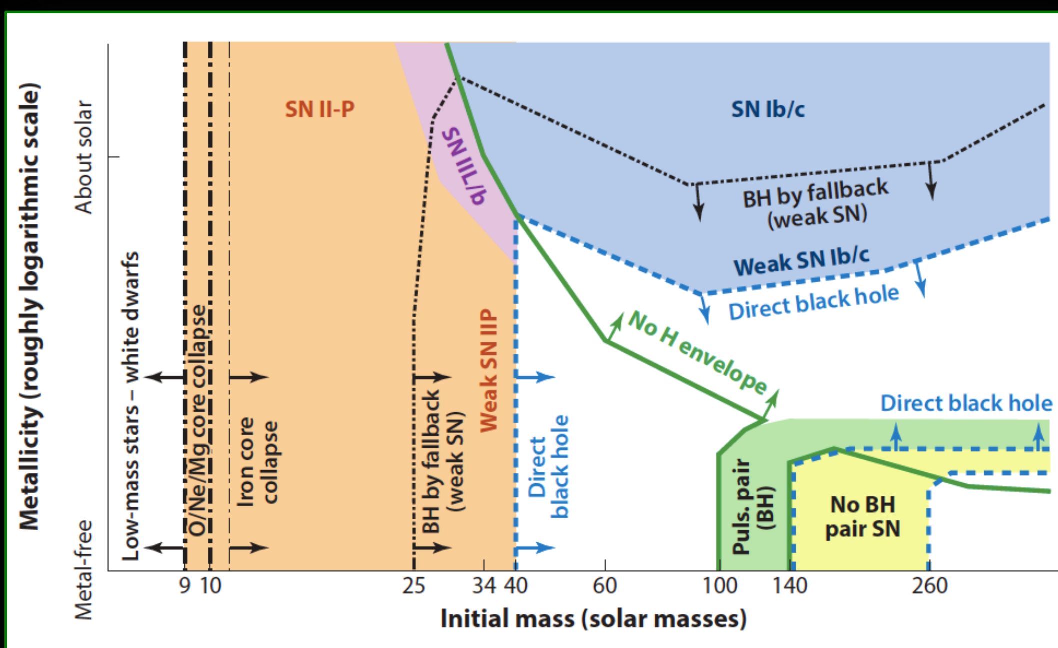
Stellar Winds. Weaker than you think.

Early/mid-2000s, several studies showed that hot-star winds (O, BSG, WR) are highly clumped, forcing observational mass-loss rates down.

- Fullerton et al. (2006); factors of 10-20 reduction in Mdot.
- Bouret et al. (2005); factors of >3.
- Puls et al. (2006); median of 5, but as much as 10x lower
- see also Crowther et al. 2003; Hillier et al. 2003; Massa et al. 2003; Evans et al. 2004.





Most studies require reduced mass-loss rates by at least a factor of 3. This fundamentally changes massive star evolution.

Shifts burden of mass loss to LBVs and RSGs.

(see Smith 2014, ARAA review)

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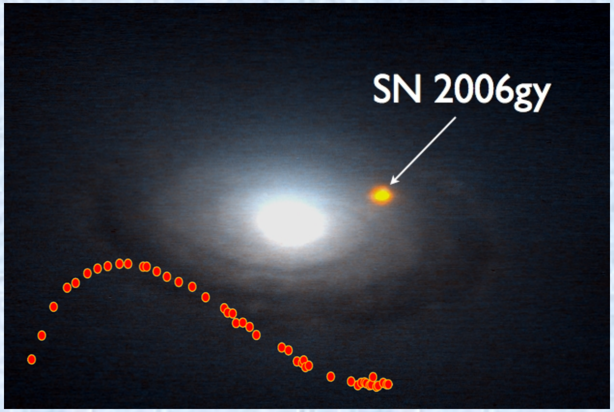
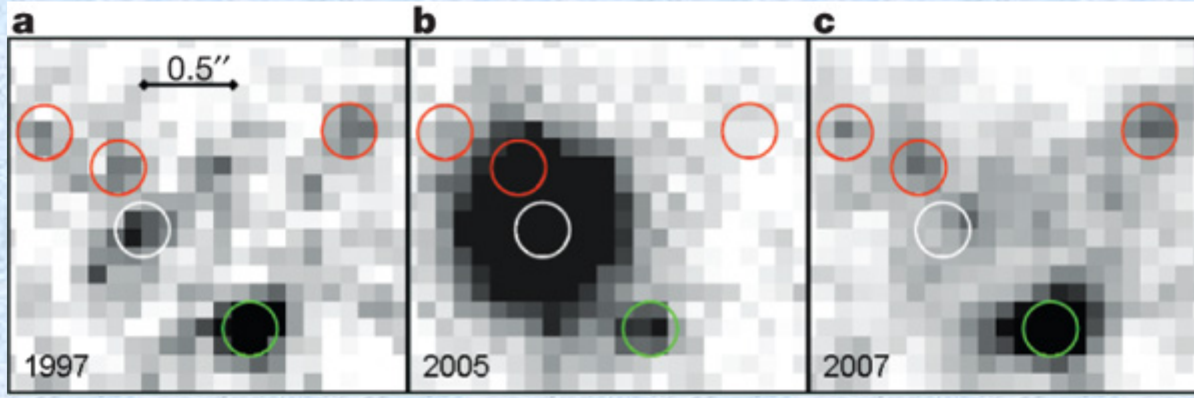
LBVs as Possible Supernova Progenitors





Gal-Yam & Leonard (2009)

- Very luminous SNe IIn require high mass of CSM
  - some require >10 $M_{\odot}$ ejected in decade before core collapse (SN2006gy, 2005tf, et al.).

- Modulation of wind density & speed (Kotak & Vink 06; Trundle+08)

- Direct detections of SN progenitors (or host cluster)
  - SN 2005gl $M_0 \approx 50\text{-}60\ M_{\odot}$ (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. 2012; Fox et al. 2017)
  - SN 2009ip $M_0 \approx 50\text{-}80\ M_{\odot}$ (Smith+2010, Foley+11)
  - SNhunt275/2015bh – (Elias-Rosa+16; Thone+16)

But caution: LBVs are bright, easy to detect in eruption…not the only IIn progenitors

- Pre-SN outbursts – SN2009ip, SN2015bh, and friends

  (Ofek+13; Bilinski+15; Fraser+13; Pastorello+07,+13; Smith+10; Mauerhan+13, and more)

LBVs exploding fundamentally contradicts predictions of single-star evolution models. (Need them to precede WR phase.)

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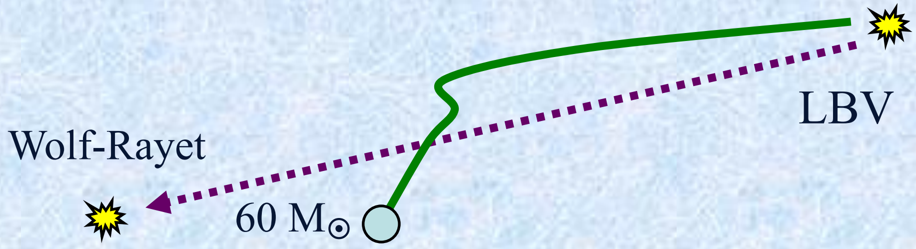
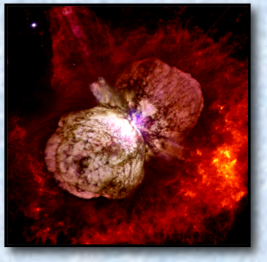
O stars behave as expected. More massive ones are more clustered.

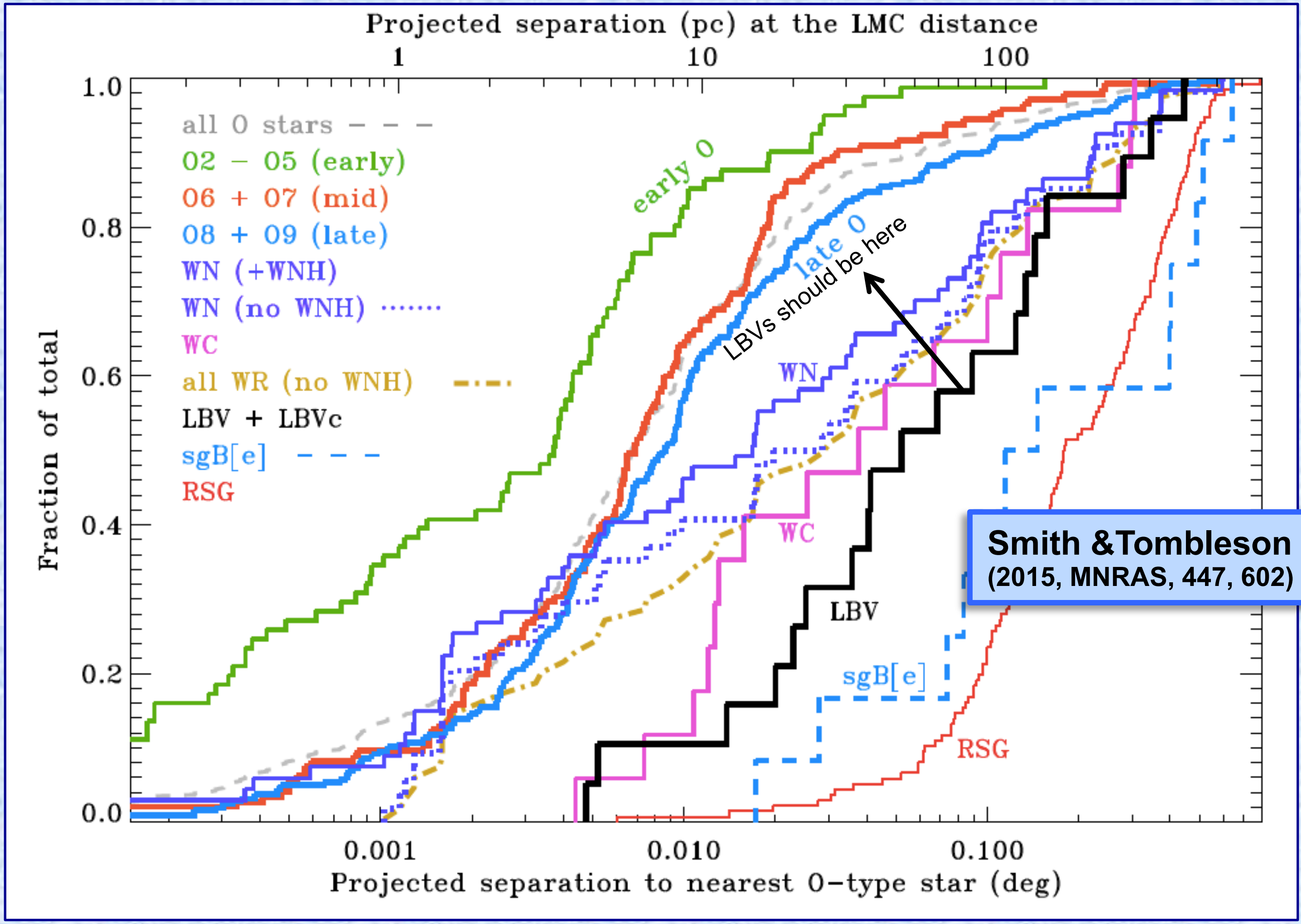
WR stars are evolved and skewed to right – as expected.

LBVs don't behave as expected. They should be in between O stars & WN… but they are more dispersed than WC stars.

Models of dispersing clusters give typical ages of 10 Myr, initial masses around 20 $M_\odot$ – way to old and low mass for LBV's current luminosity if single (Aghakhanloo +17).





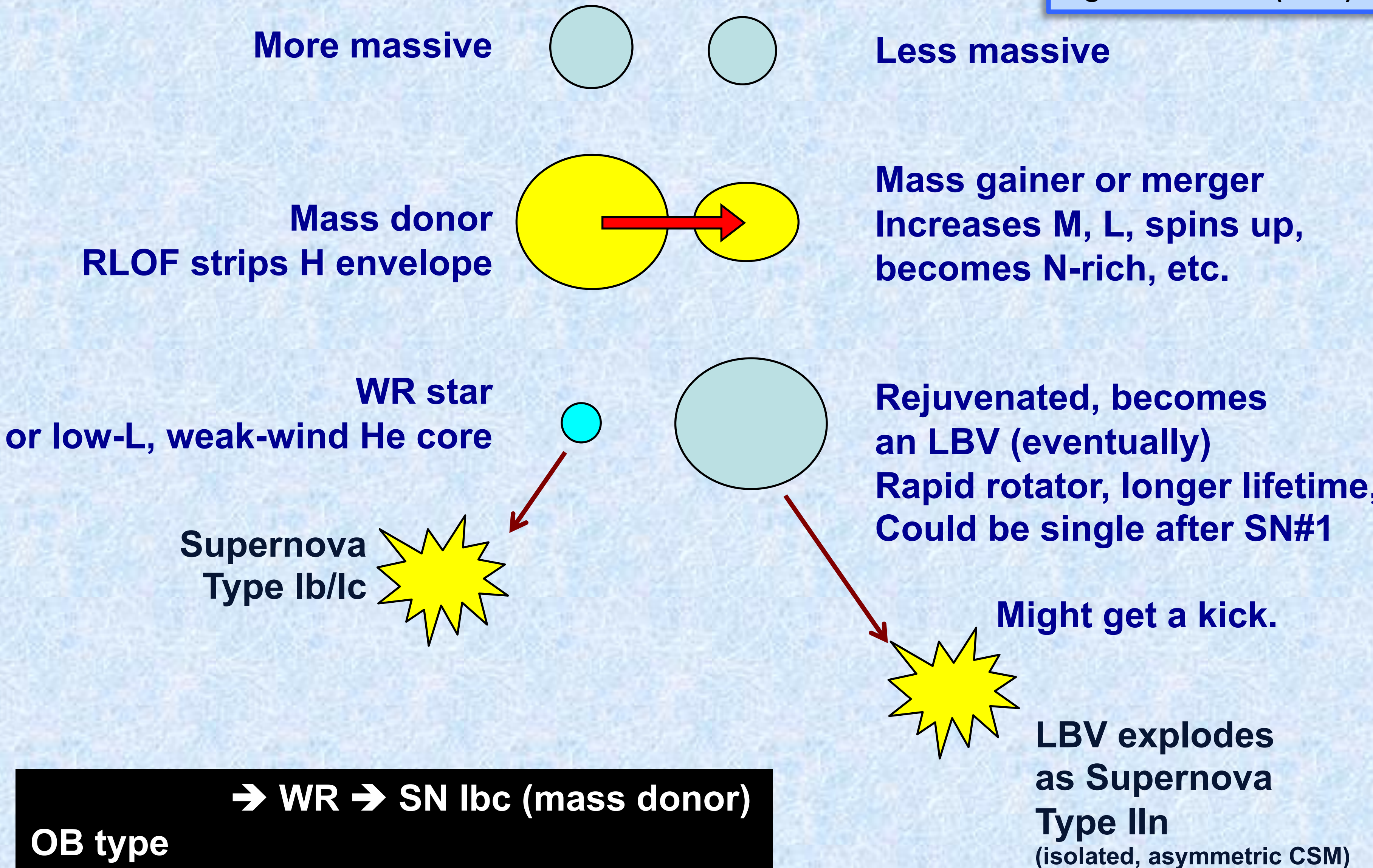


THIS PARADIGM IS WRONG: **Early O type → ~~LBV~~ → WN → WC → SN Ibc**

LBVs need long lifetimes for their L (>>3Myr). How can this be?

Smith &Tombleson
(2015, MNRAS, 447, 602)

Aghakhanloo + (2017)



OB type ➔ WR ➔ SN Ibc (mass donor)

OB type ➔ LBV ➔ SN IIn (mass gainer)

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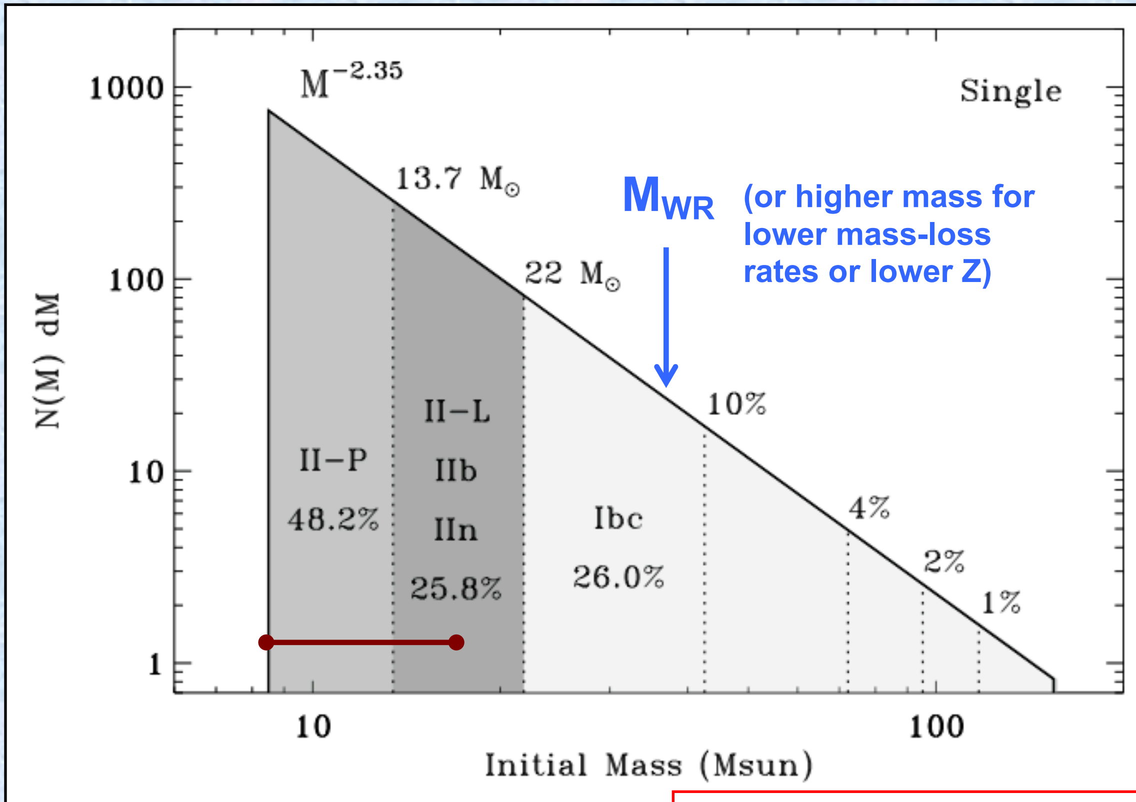
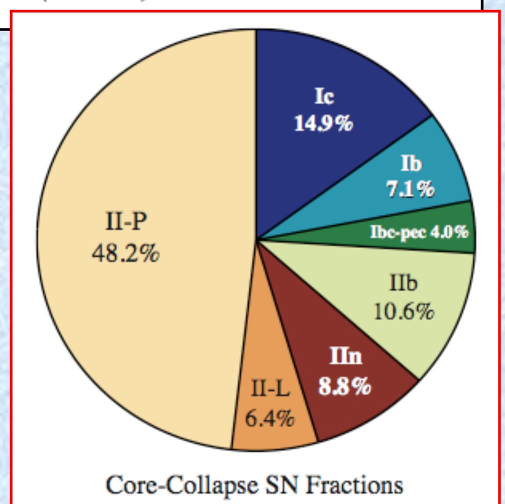


Way too many stripped-envelope SNe (even worse if you include SNe IIb…or if mass-loss rates are lower … or if high mass stars have failed SNe).

Cannot make enough with single-star mass loss. Most SNe Ibc+IIb must be from binaries. (Smith et al. 2011)

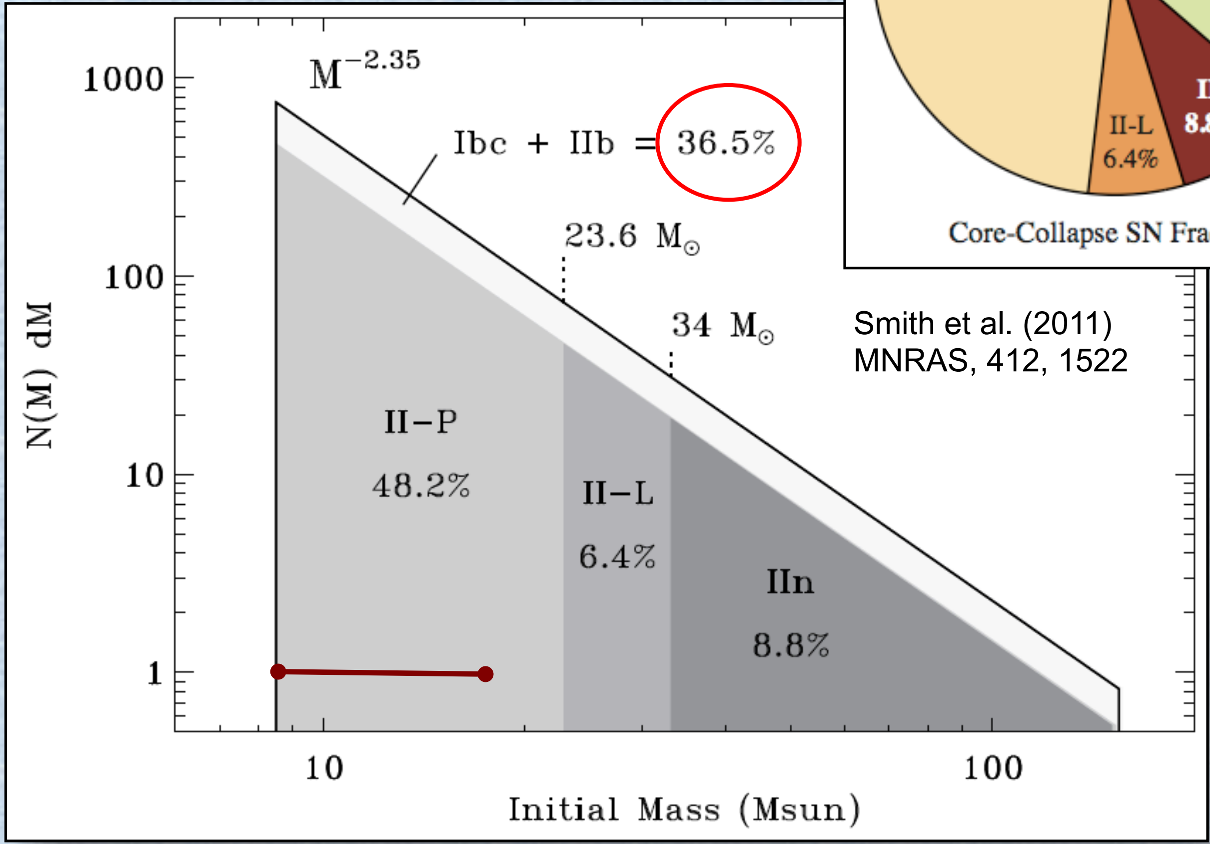
SN subtype fractions from the Lick Observatory Supernova Search

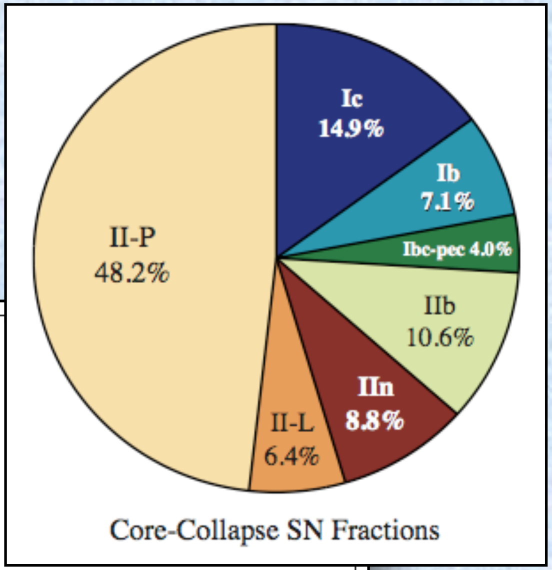


Smith et al. (2011) MNRAS, 412, 1522

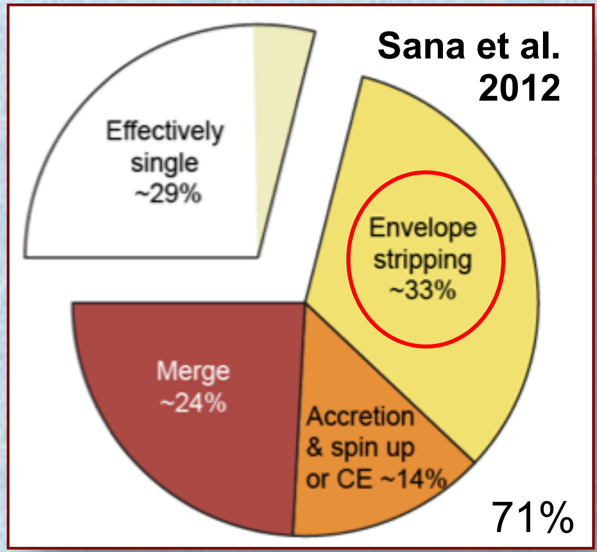
Large galaxies, roughly $Z_\odot$

SN subtype fractions





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



Main dichotomy in SNe (H envelope or not) can be explained mostly by binaries.

Not much wiggle room for single stars to make SNe Ibc (low mass-loss rates!).

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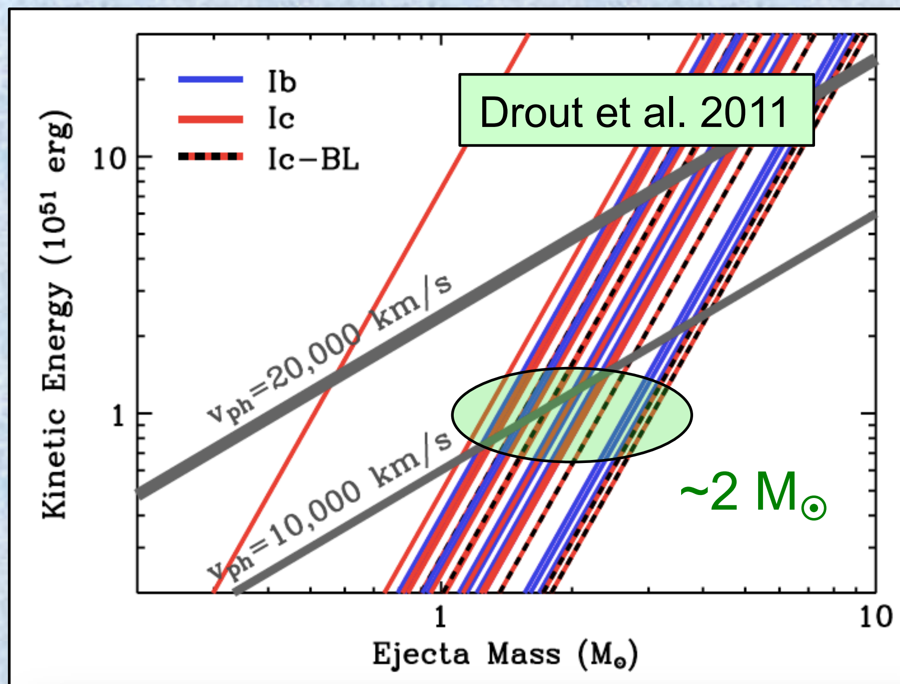
LOW EJECTA MASS

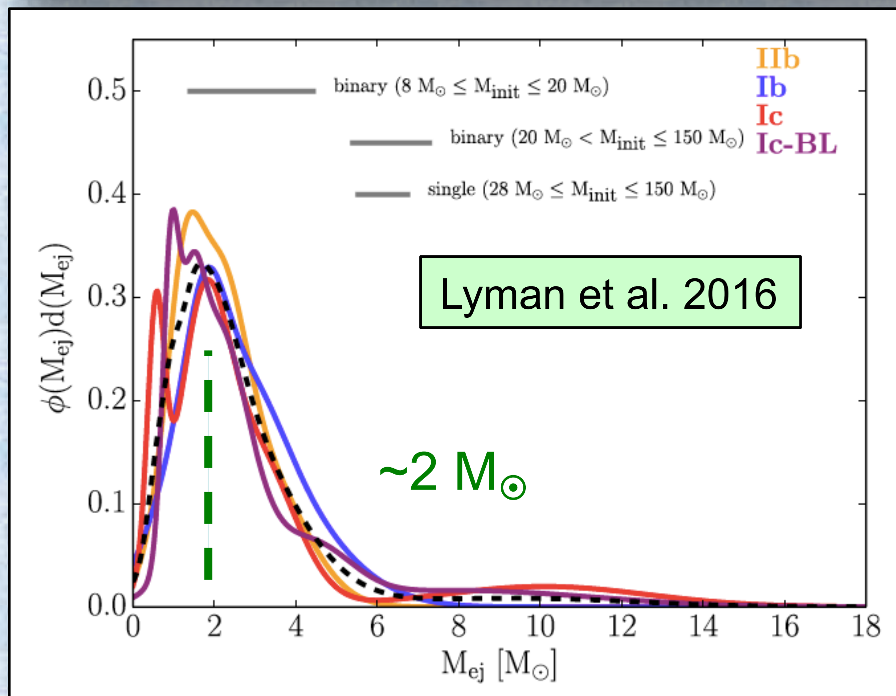
- Samples of stripped envelope supernovae (Types IIb, Ib, Ic, Ic-BL) show ejecta masses mostly around 2 $M_\odot$.

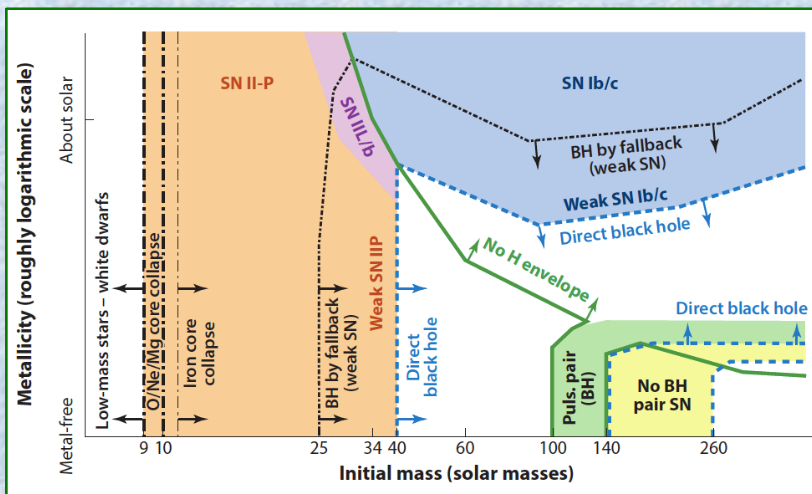
- Roughly the same for Types IIb, Ib, & Ic.

With NS, that's 3-4 $M_\odot$.
➔ He cores of M_{ZAMS} = 8-18 $M_\odot$ stars.
➔ Single stars can't do that with winds.
Requires binary stripping.

Type IIb particularly interesting…







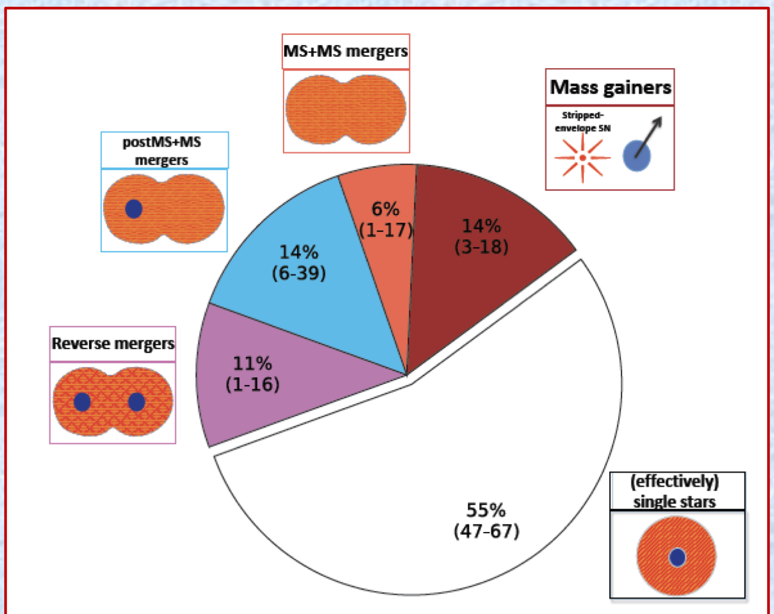
Binary Population Synthesis

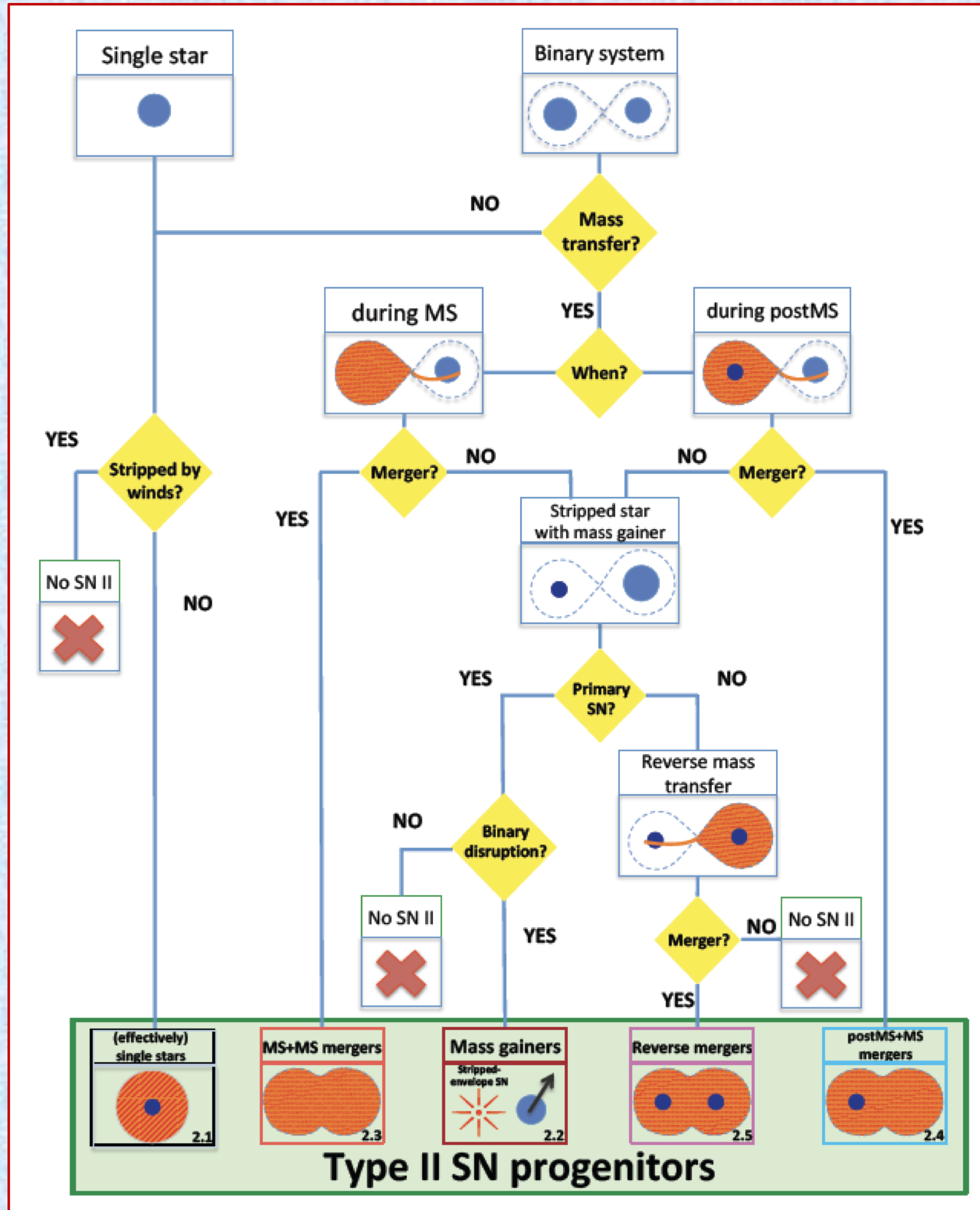
Given initial orbital periods of O type stars, models predict:

~1/3 of massive stars are stripped primaries (WR stars, SNe Ibc, IIb)
(Sana+12, de Mink+2013, Gotberg+2017)

~1/3 (or 1/3 of Type II) are effectively single

~1/3 (or half of Type II) are mass gainers & mergers.





from PhD thesis of Manos Zapartas (Zapartas et al. 2019)

OUTLINE

Diversity in Evolution: Single star evolution with mass loss vs. Binary Evolution. Why the paradigm has (finally) shifted (again). Single stars, stripped primaries, mass gainers, mergers, etc.

Main take-home point: Diversity in binary evolutionary paths dominates the diversity of stars and SNe, not monotonic scaling of mass-loss with M_{ZAMS}.

Wide diversity in evolutionary paths, even from 8-20 $M_{\odot}$ (single or wide binary, stripped primaries, mass gainers, mergers, mass ratios, orbital period, etc).

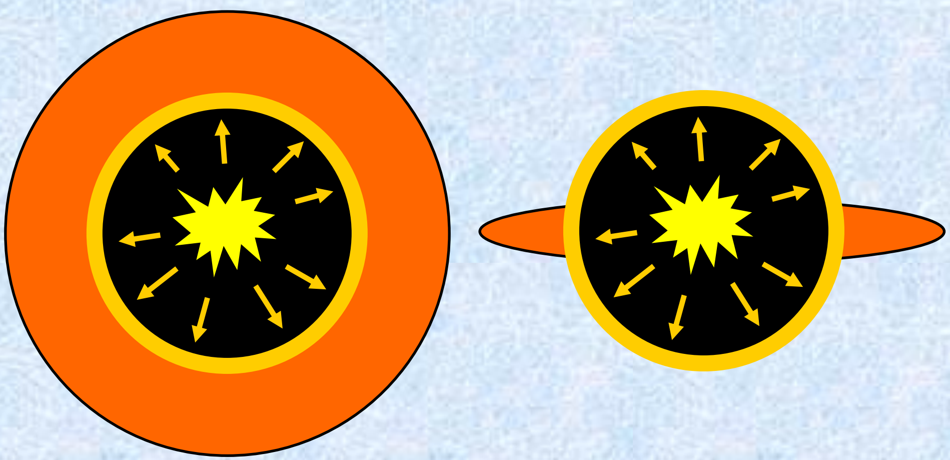
Diversity in Pre-SN mass loss and CSM: Winds vs. Episodic pre-SN mass loss, CSM shells, etc. Implications for progenitor links and explosions.

CSM Interaction and IIn Diversity

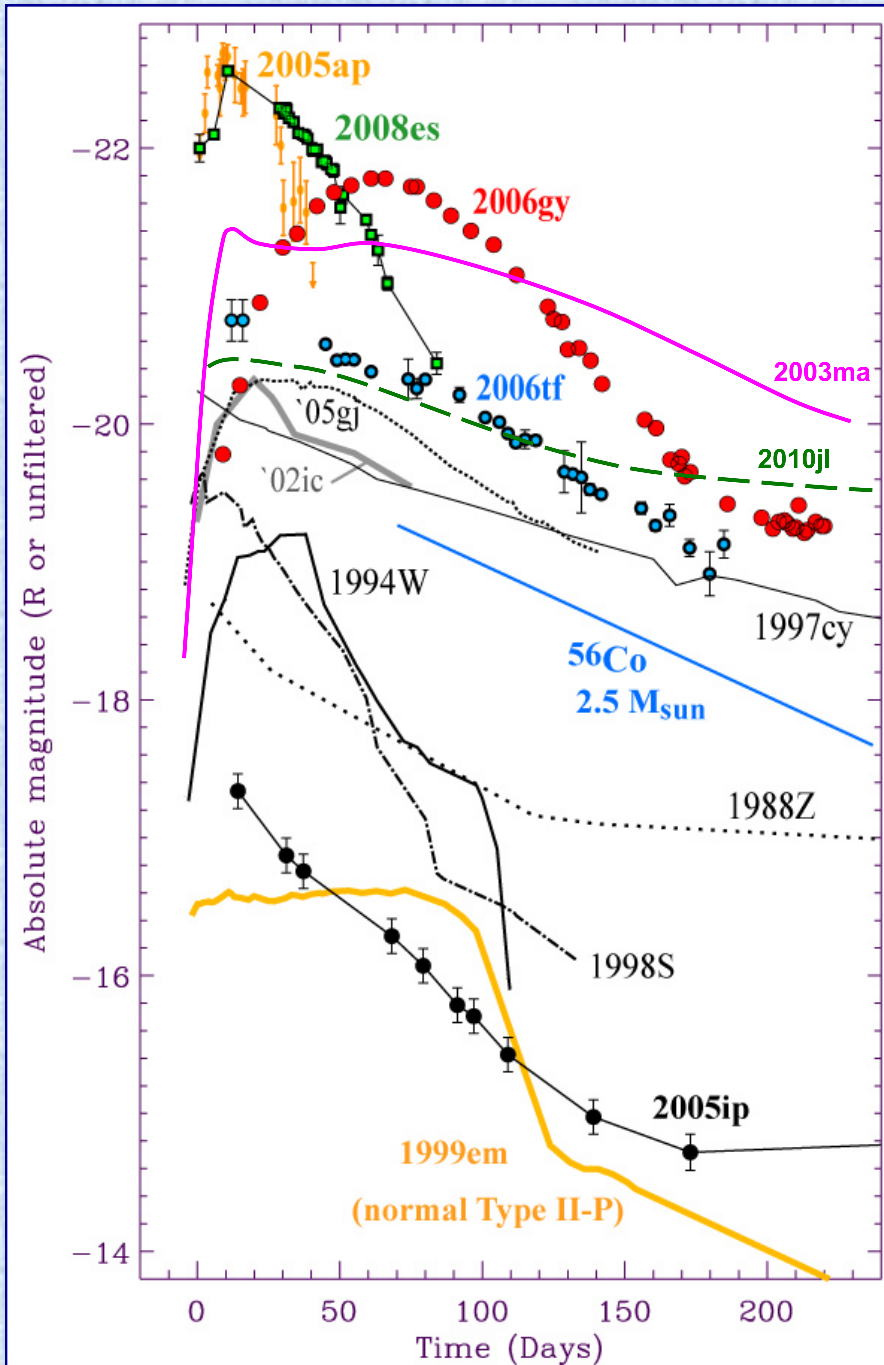
Huge diversity in light curves of SNe IIn; wide variation in peak L and duration. CSM interaction can provide this with differences in:

- CSM mass/density/radial extent
- Explosion energy
- Geometry

To match a light curve is easy. To consistently explain light curves and spectra is a little harder.



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



Observed mass-loss rates of various types of stars vs. SNe IIn

Mass-loss rates are too high for normal winds.

Mass-loss rate doesn't capture diversity. Also:

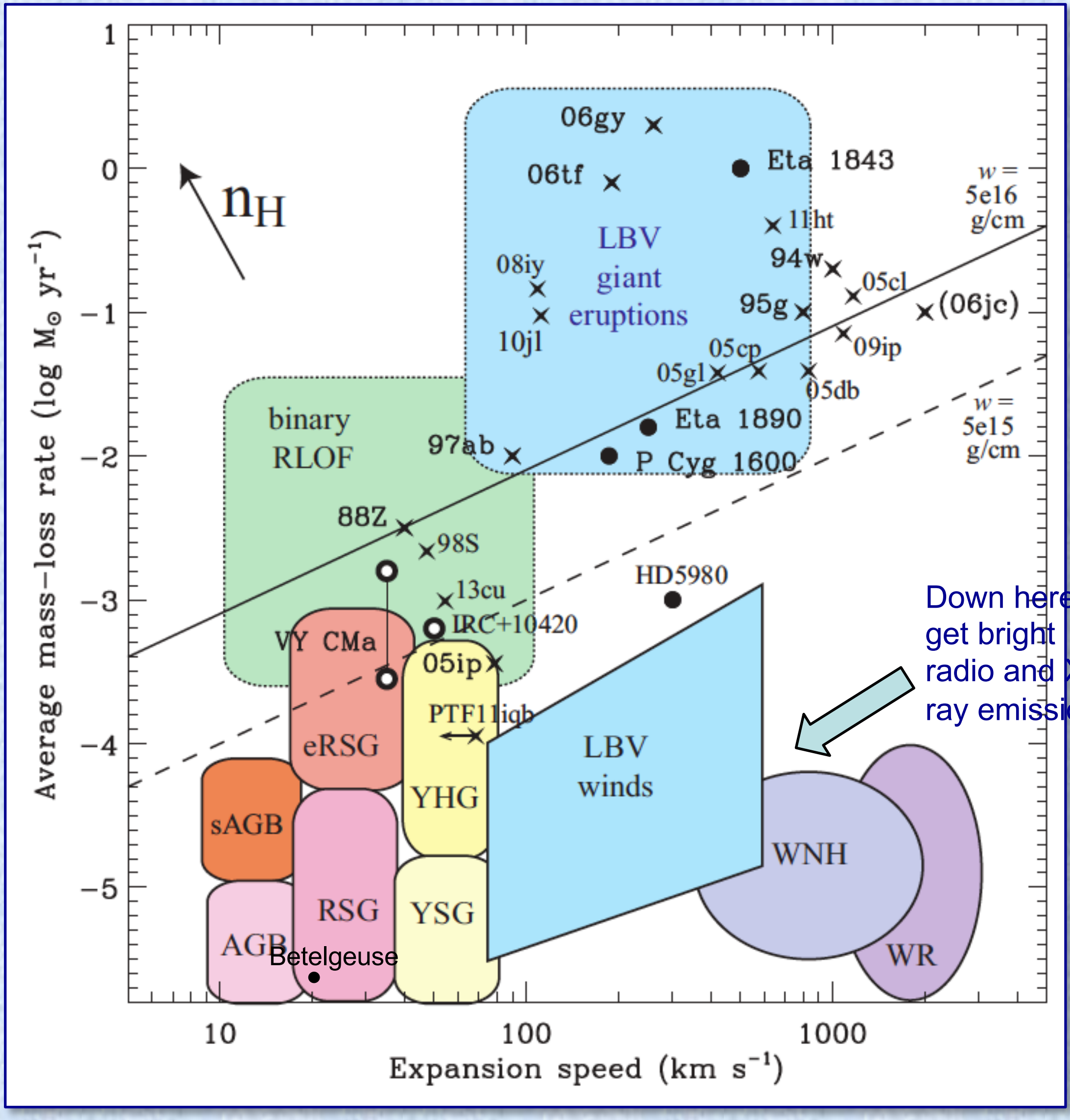
Total mass (0.01-25 $M_{\odot}$)

Duration of mass loss (months to 10^4 yr).

CSM speed (10-2000 km/s).

Geometry (filled or thin hollow shell, clumpy or smooth).

Asymmetry (bipolar, disk, 1-sided, etc.).



Down here we get bright radio and X-ray emission.

Figure from Smith (2016) in Handbook of Supernovae

Some pre-SN mass loss is explosive, not windy (shocks, not radiation pressure)

Exceptionally fast ejecta seen in light echoes of Eta Carinae's Great Eruption

MNRAS, 480, 1457

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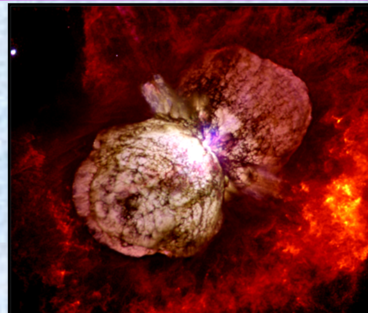
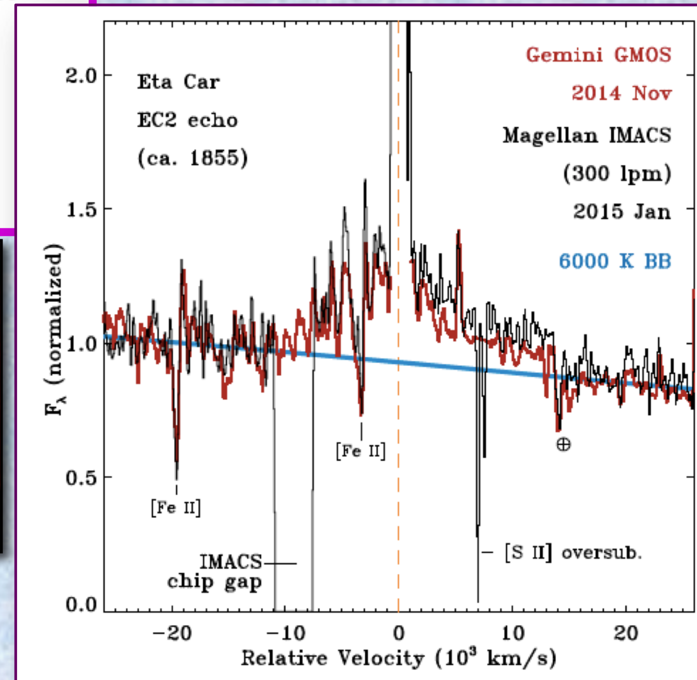
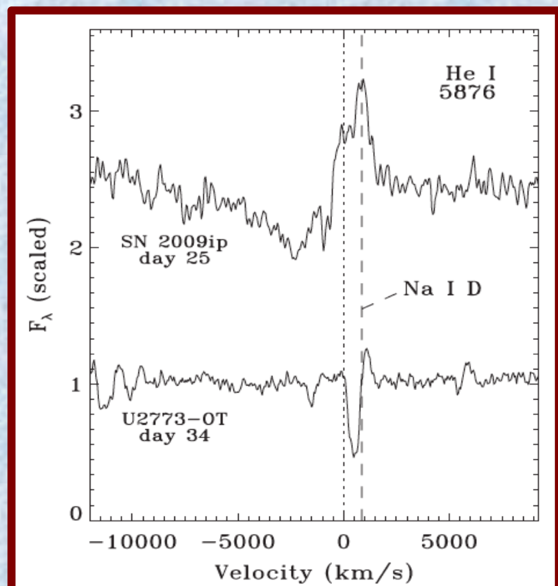




Expansion speeds of ≳10,000 km/s suggest explosive mechanism in Eta Car's eruption. (see A.Rest's poster)

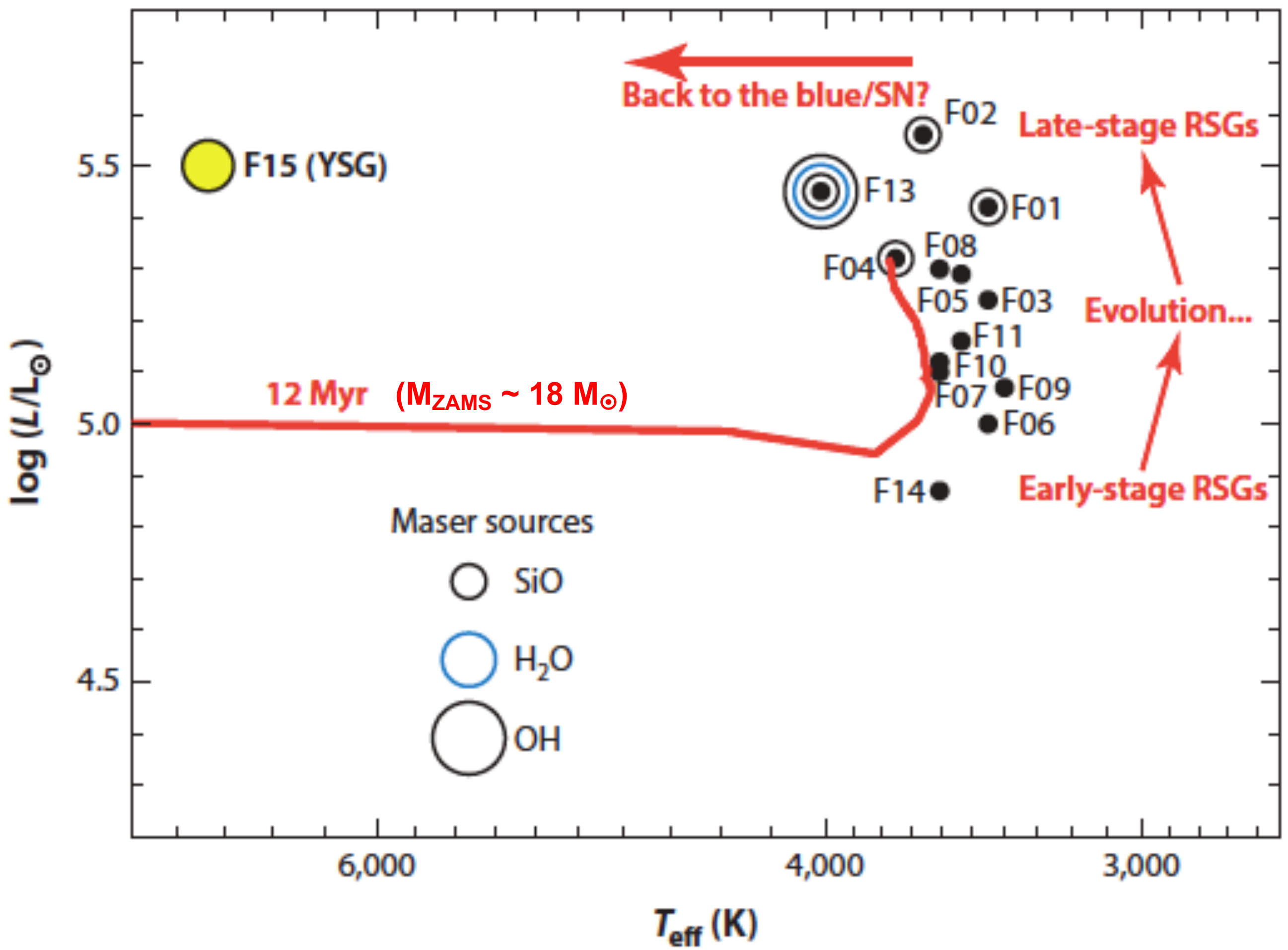
Bulk expansion speed was only 600 km/s, but had KE=1e50 ergs.



Similar to some pre-SN explosions/eruptions:

SN 2009ip: progenitor outbursts showed small mass of fast material, 7000 km/s (Smith+10; Foley+11; Pasorello+13). Most mass (H-alpha line width) expanding at 600 km/s.

RSG mass-loss rates probably ramp up in last few 10^3 yr of evolution due to high L/M ratio (not for entire RSG phase).



Davies et al. (2008)

Davies et al. have studied several different RSG clusters, which have multiple RSGs in a single cluster (same age).

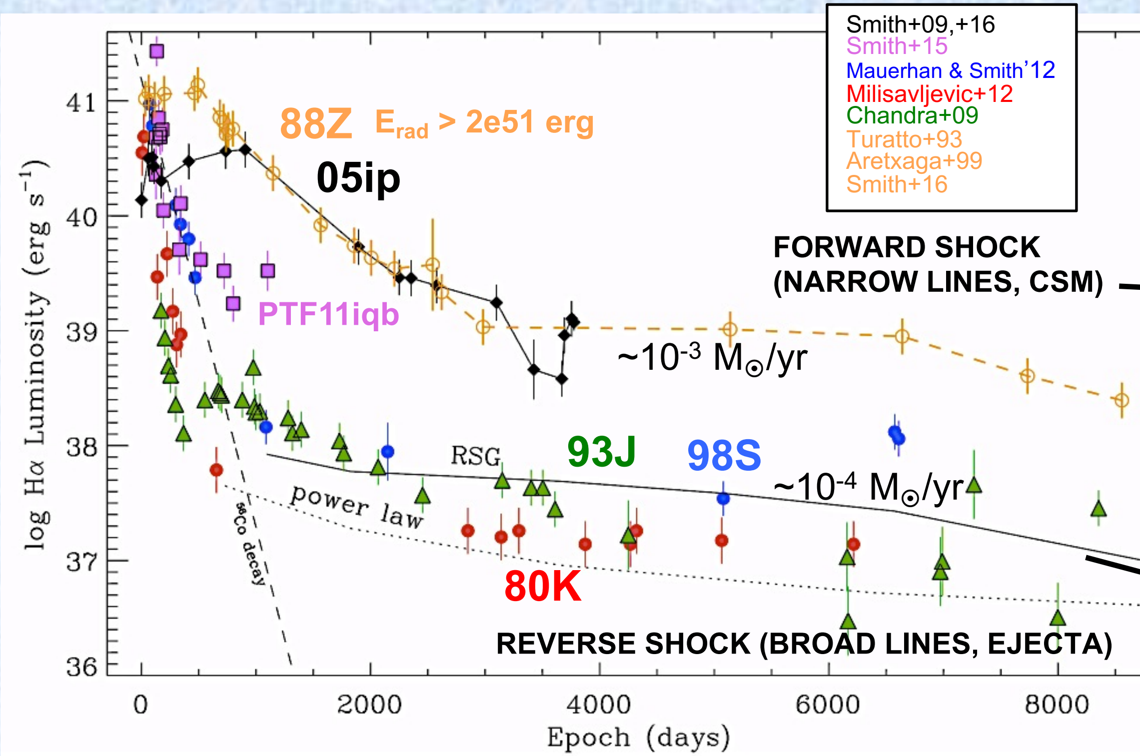
Self-obscured, optically faint, OH masers (i.e. luminous OH/IR stars) are always at the top of the RSG branch.

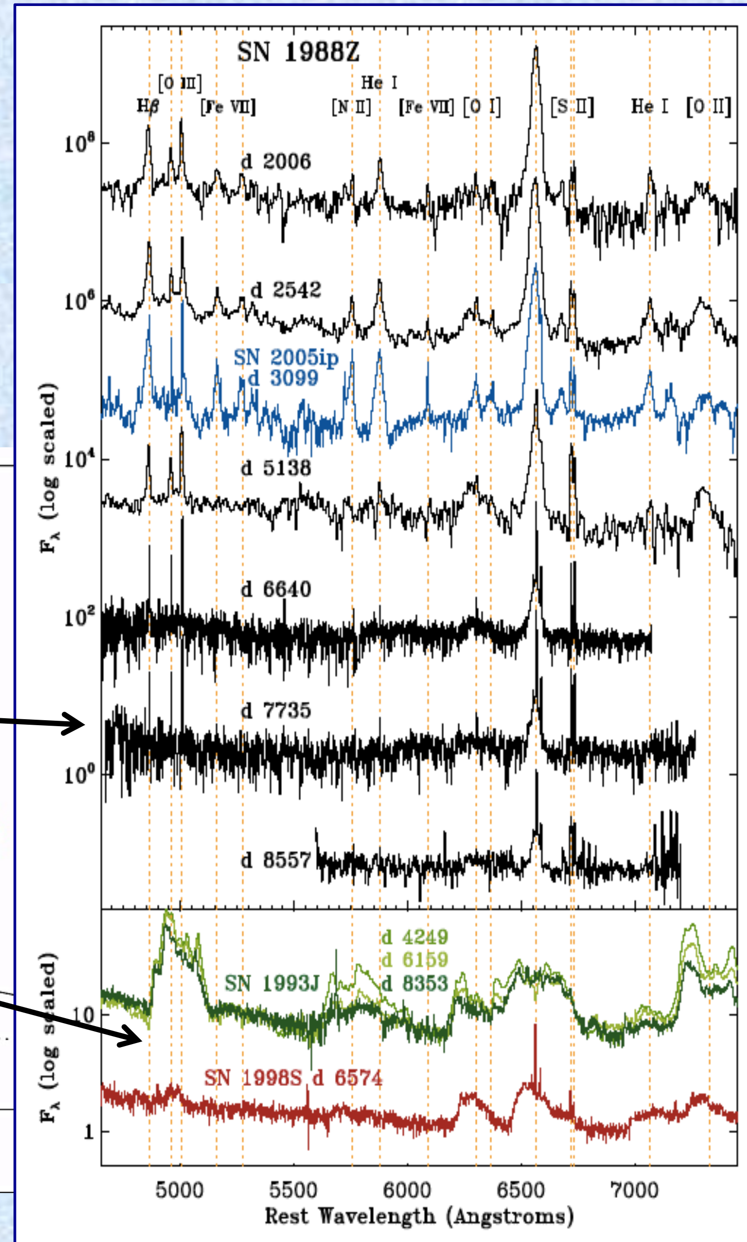
Mass lost rates start low but ramp up at end (see also Beasor & Davies 2017)

CSM interaction for decades after SN traces mass loss 1,000-20,000 yr before death.

Strong CSM interaction indicates 0.2-20 $M_\odot$ lost in relatively short time intervals before core collapse in some cases.

Many cases suggest disk-like CSM (double-peaked profiles).



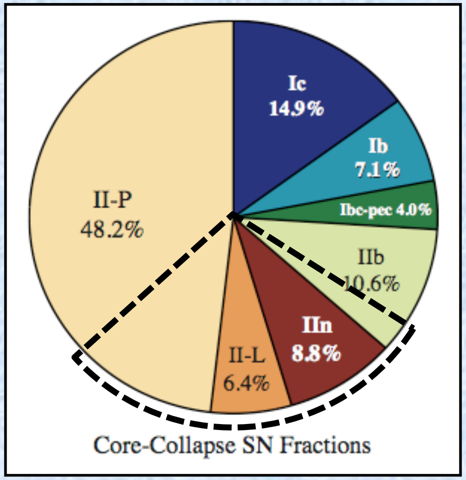


Smith +16

$$t_{\rm wind} = t_{obs} \times \frac{V_{shock}}{V_{CSM}}$$

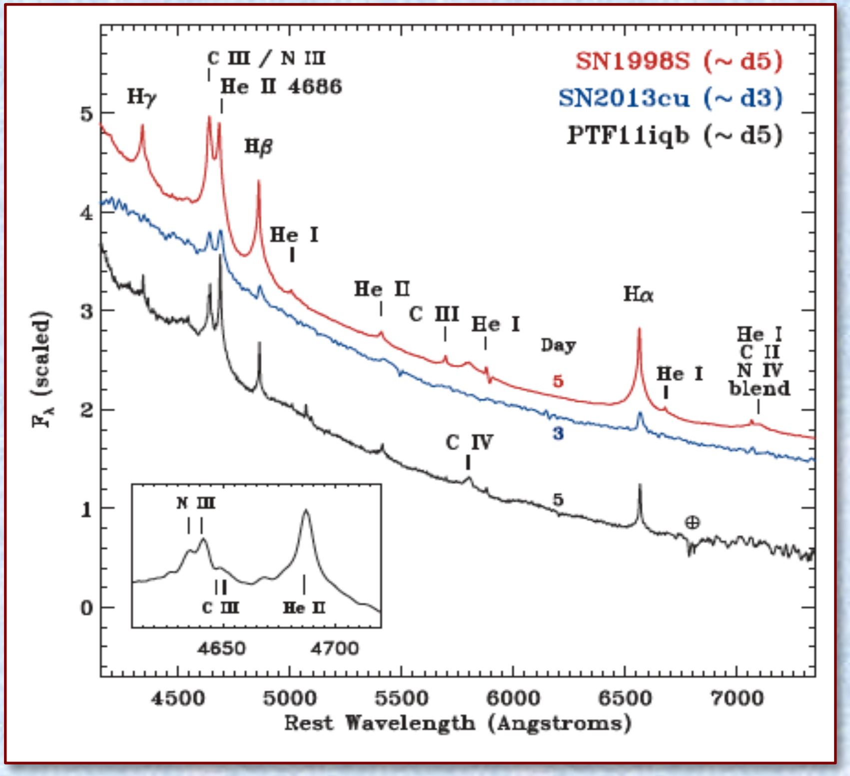
$$t_{\rm wind} \approx 20\,{\rm yr} \times \frac{1e4\ \ {\rm km/s}}{10\,{\rm km/s}}$$

Sometimes CSM interaction is *fleeting*, lasting for only for a few days after explosion. Heavy mass loss for months to years before explosion.



SN 1983K (Type II; Niemala+85)
SN 1993J (Type IIb; Benetti+94; Matheson+00)
SN 1998S (Type II-L/IIn; Leonard+00; Shivvers+16)
SN2006bp (Type II-P; Quimby+07)16)
PTF11iqb (Type II-P/IIn; Smith+15)
SN 2013fs (Type II-P/IIn; Yaron+17, Bullivant+18)
SN 2013cu (IIb) and a number of other recent PTF objects
(Gal-Yam+14; Groh+15; Khazov+16)

These 4 also showed very strong continued CSM interaction at late times, some with double-peaked profiles (and specpol in 98S).

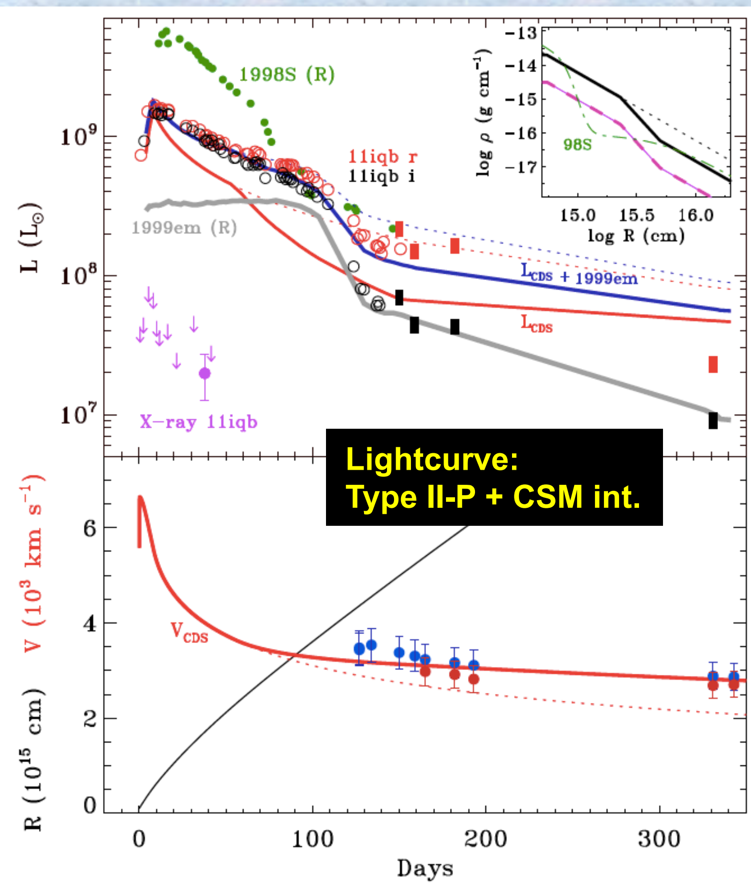


Interpreted as either early CSM interaction or flash ionized CSM. Either case requires strong pre-SN mass loss with 1e-3 $M_\odot$/yr for a year or so before cc.

PTF 11iqb: A Type IIn from a RSG progenitor

How to HIDE signs of CSM interaction:

Disk-like geometry of CSM gets *enveloped* by SN photosphere. (Smith+15)

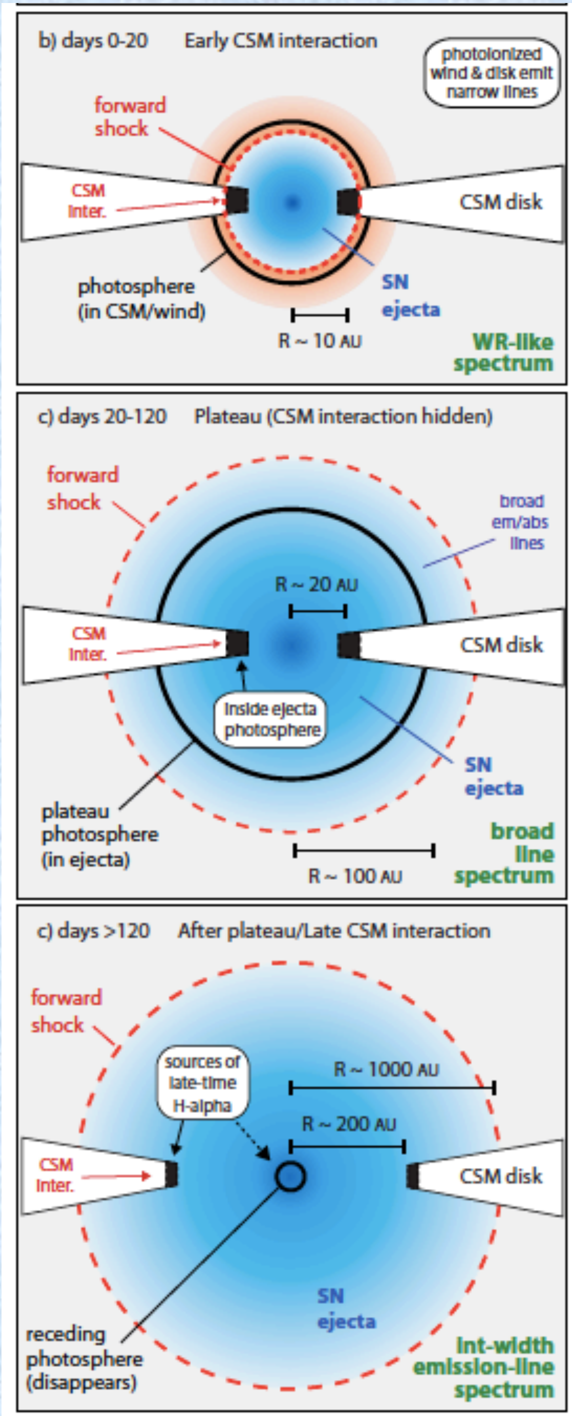


Spectroscopic evolution through 3 main phases:

1. Early CSM interaction (WR-like spectrum) in thick inner wind at ~10 AU.

2. SN photosphere expands to ~100 AU and engulfs CSM interaction (*not because wind recombines or is obliterated*). CSM interaction luminosity (re)heats ejecta.

3. SN continuum photosphere recedes and exposes CSM interaction again (multi-peaked asymmetric Hα).



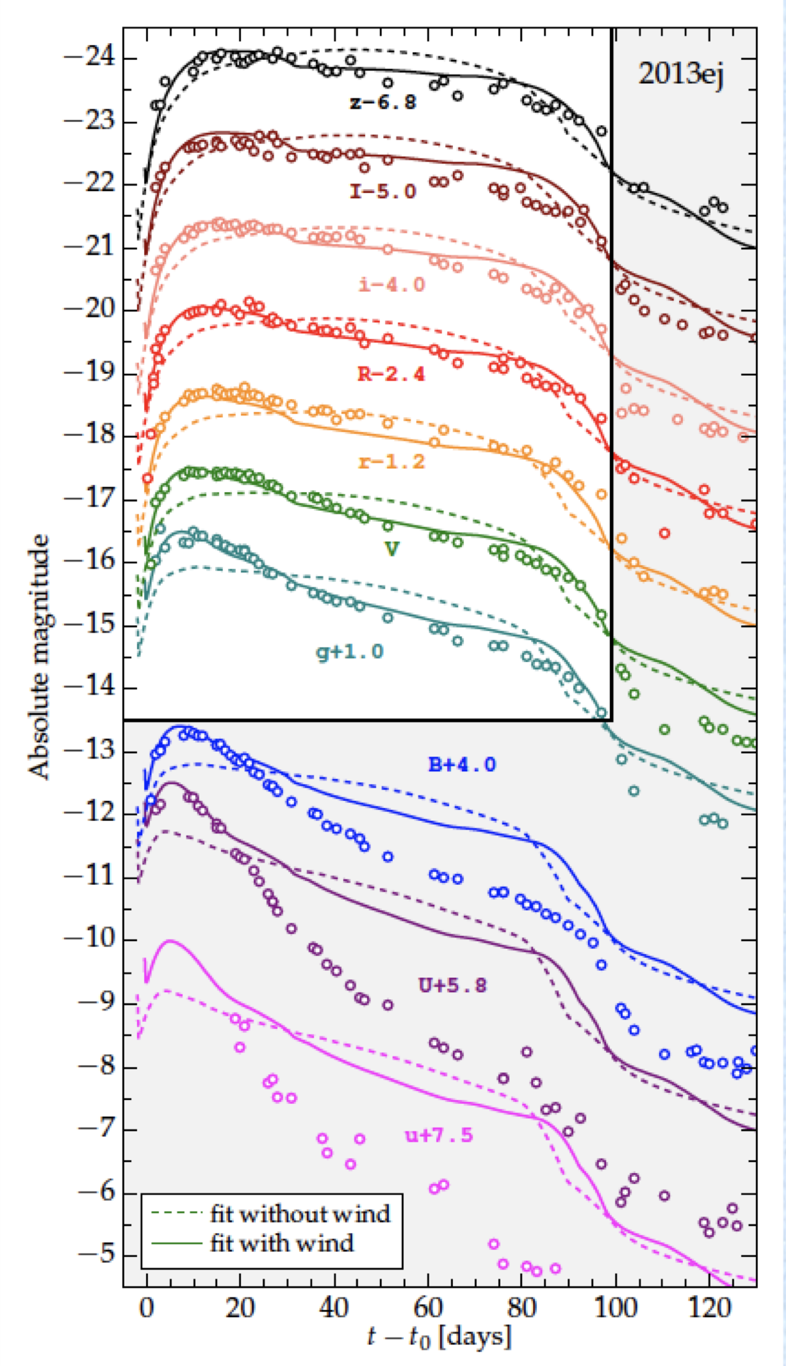
Probably relevant for many SNe II-P and II-L light curves.

Brief CSM interaction even in normal SNe II-P with no narrow lines (not IIn)

Morozova et al. (2016, 2017, 2017) model light curves of normal SNe II-P with SNEC code, finding that CSM interaction is needed to match the early peaks of many.

In sample of 20 well-observed nearby SNe II-P and II-L, they find that 70% need CSM shells with masses of 0.2-0.8 $M_\odot$ (mostly within ~10 AU).

Implies strong mass loss of 0.01-0.1 $M_\odot$/yr in just few years before explosion.



Multiple Eruptions in Eta Car

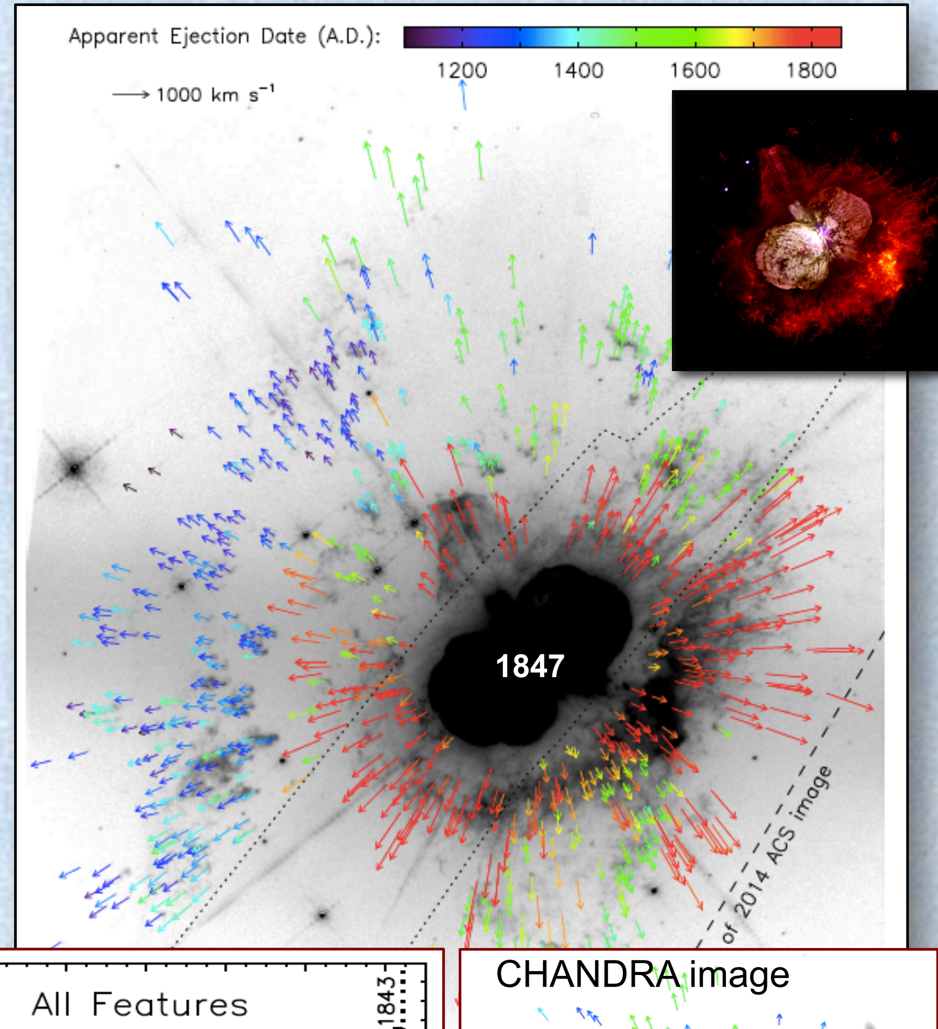
Kiminki, Reiter, & Smith (2016)

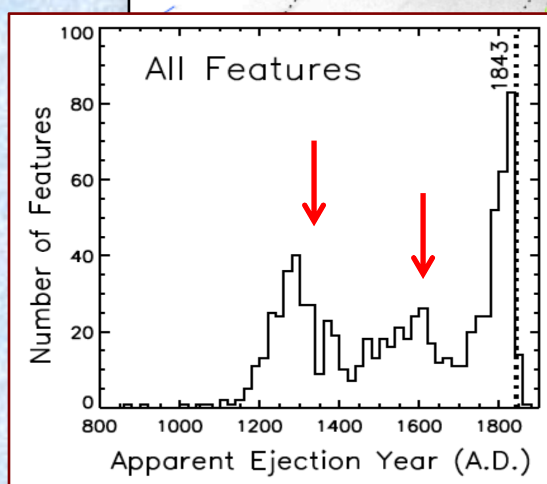
Proper motions in HST images. Color coded vectors show speed and ages as function of locations.

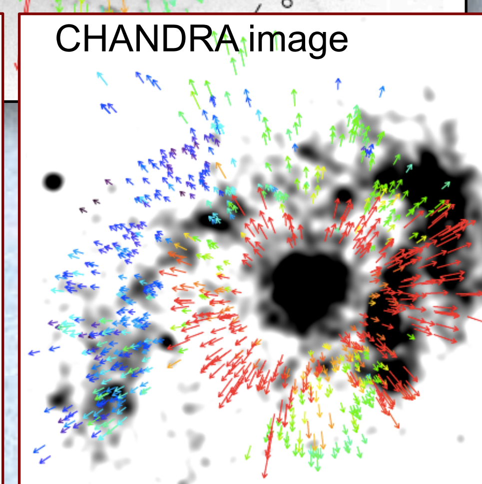
Major eruptions before the 1843 eruption:

- Red = early 19th century
- Green = mid 16th century.
- Blue = mid 13th century.

Seems to have very different geometry in previous eruptions.



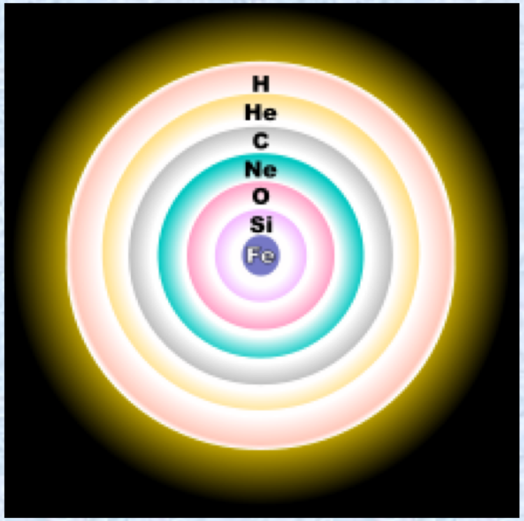




Some SNe show this too

SN 2006gy (multiple shells)
SN2009ip (multiple pre-SN eruptions)

PRE-SN OUTBURST DIVERSITY

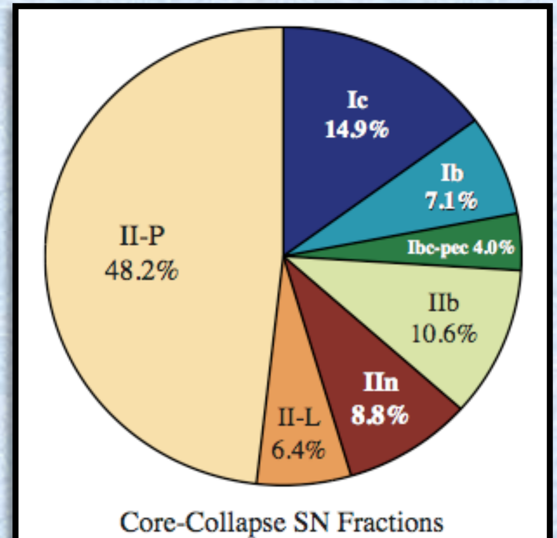


C burning ~ 1000 yr
Ne, O burning ~ few years
Si burning ~ few days

Whatever the mechanism, it needs to be fairly common (not just SNe IIn), and must provide a wide range of energy and mass loss over a wide range of timescales before collapse. Shock or wind driven. Probably wide range of initial mass.

WHAT MECHANISM(s)?

1. **Pulsational Pair Instability** Woosley (2016)
   Problem: Too rare; only very high M_{ZAMS}.
2. **Degenerate flashes (Ne)** Arnett (1974)
   Problem: Too rare; only narrow range of low M_{ZAMS}.
3. **wave-driven mass loss** Quataert & Shiode (2012)
   Problem: Too short duration; only Ne/O/Si burning (~1 yr).
4. **explosive/unsteady burning**
5. **trigger binary interaction** Smith & Arnett 2014
6. **NS+RSG merger** Chevalier (2012)



Core-Collapse SN Fractions

Smith et al. (2011)

SUMMARY

Diversity in Evolution: Single star evolution with mass loss vs. Binary Evolution. Why the paradigm has (finally) shifted (again). Single stars, stripped primaries, mass gainers, mergers, etc.

Main take-home point: Diversity in binary evolutionary paths dominates the diversity of stars and SNe, not monotonic scaling of mass-loss with M_{ZAMS}.

Wide diversity in evolutionary paths, even from 8-20 $M_{\odot}$ (single or wide binary, stripped primaries, mass gainers, mergers, mass ratios, orbital period, etc).

Diversity in Pre-SN mass loss and CSM: Winds vs. Episodic pre-SN mass loss, CSM shells, etc. Implications for progenitor links and explosions.

For many SNe and many evolved stars, steady winds are a bad approximation.

Wide diversity of pre-SN mass ejection may require diverse mechanisms (no single theory so far can account for the diversity).

Points to some instability in pre-SN star – may be important for explosion.

Estimates from fleeting IIn signatures in SNe. High rates, but for very short time.

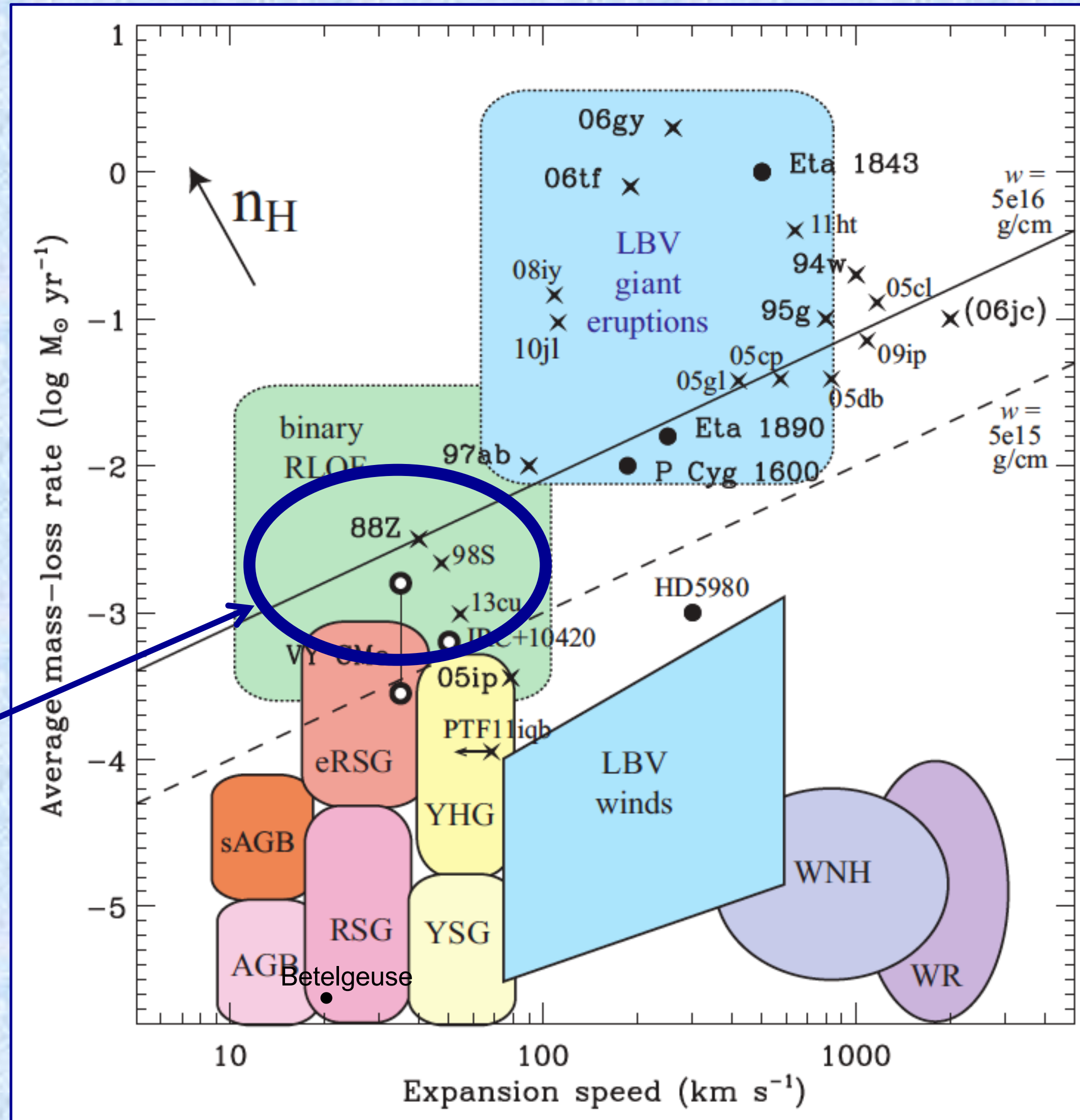


Figure from Smith (2016) in Handbook of Supernovae

SNe probe recent (temporary) mass loss phases before SN

- **Range of timescales before core collapse.** Important clues about pre-SN evolution that we can't always get from studying nearby stars.
- **Range of total CSM mass involved.** Detectable CSM and interaction requires dense CSM, but total mass and mass-loss rates vary widely (0.01-25 $M_{\odot}$).
- **Complex structures and mass-loss history.** Shells, clumps, disks, bipolar, asymmetric, different velocities... smooth R^{-2} density law is not always the best choice.

Expansion timescales at $V_{SN}=10^4$ km/s:	Pre-SN timescales at $V_W=10^2$ km/s:
1 day = 5 AU	100 days
2 days = 10 AU	200 days
10 days = 50 AU	~3 yr
100 days = 500 AU	~30 yr
1 yr = 2000 AU	100 yr
10 yr = 0.1 pc	1000 yr
100 yr = 1 pc	10^4 yr

In general:

Steady winds and constant mass-loss rates are not safe assumptions for many progenitors

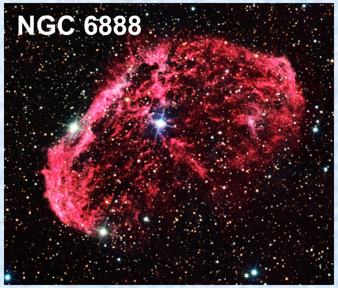
Large bubbles and shells

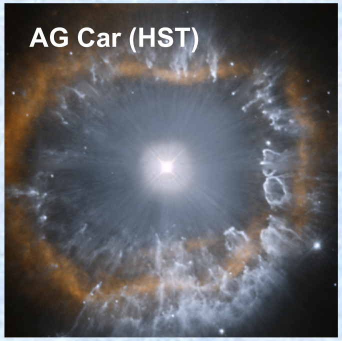
- **Fast wind sweeps into slow wind.** LBV➔WR, LBV eruption➔LBV, RSG➔BSG, blue loops, etc. Cool wind gets swept into a thin, dense shell at large radius. Cavity (fast wind) inside bubble.

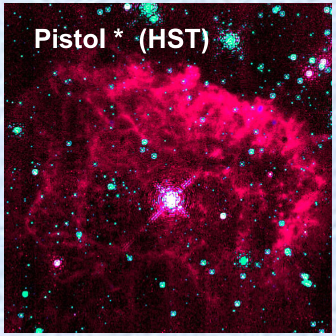
- **Stalled wind from external pressure or bow shock.** Slow cool RSG wind stalls at terminal shock due to external pressure; H II region, earlier hot wind, external photoionization. see Mackey +14,16

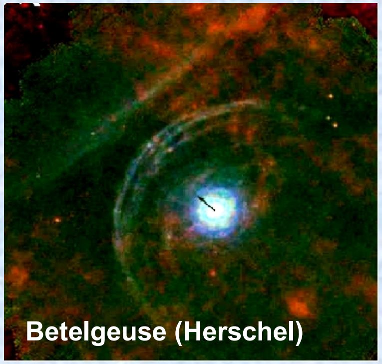
Normal SN (not Type IIn), but with interaction at very late times.

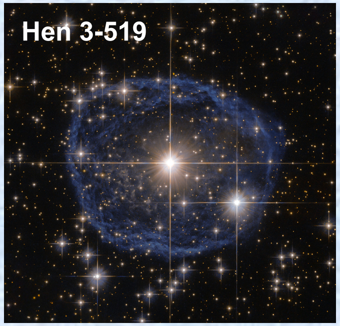
Expansion timescales at $V_{SN}=10^4$ km/s:	Pre-SN timescales at $V_W=10^2$ km/s:	Observed Examples:
1 day = 5 AU	100 days	
		Flash Spec/
2 days = 10 AU	200 days	Early bumps
10 days = 50 AU	~3 yr	Fleeting IIn (98S)
100 days = 500 AU	~30 yr	SNe IIn/SLSNe
1 yr = 2000 AU	100 yr	Late interaction (14C)
10 yr = 0.1 pc	1000 yr	87A, 88Z, 05ip, 93J
100 yr = 1 pc	10^4 yr	SNRs (Cas A)









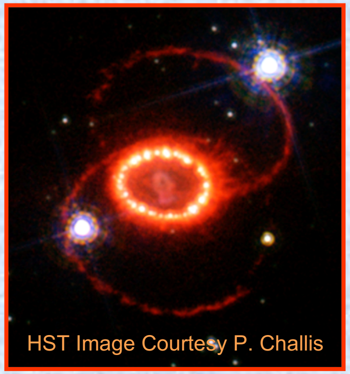


Distant CSM: bubbles, shells, bipolar, strong winds

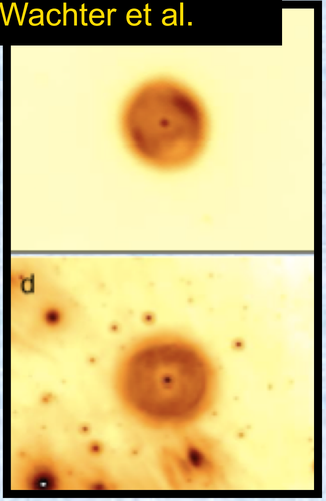
- **Fast wind sweeps into slow wind.** As for previous slide, but smaller (slower winds, more recent transition). Asymmetry in slow wind.
- **Sustained mass loss.** Extreme RSGs with strong, dense winds.
- **Past eruption or common envelope.** Coasting massive shell.

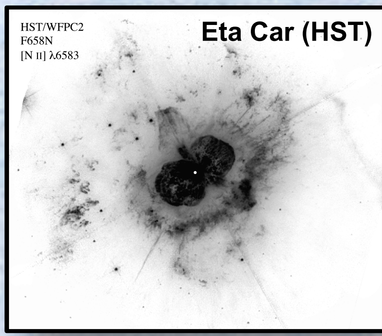
Onset of interaction (or sustained) at late times. IR echoes.

Expansion timescales at $V_{SN}=10^4$ km/s:	**Pre-SN timescales at $V_W=10^2$ km/s:**	**Observed Examples:**
1 day = 5 AU	100 days	Flash Spec/ Early bumps
2 days = 10 AU	200 days	
10 days = 50 AU	~3 yr	Fleeting IIn (98S)
100 days = 500 AU	~30 yr	SNe IIn/SLSNe
1 yr = 2000 AU	100 yr	Late interaction (14C)
10 yr = 0.1 pc	1000 yr	87A, 88Z, 05ip, 93J
100 yr = 1 pc	10^4 yr	SNRs (Cas A)



MIPS nebulae:
Gvaramadze et al.
Wachter et al.





Cocoons, young bipolar nebulae, massive disks, strong winds

- **B[e] disk/torus.** Rapid rotation or binary RLOF
- **Sustained dense winds.** Extreme RSGs/YHGs with strong winds.
- **Recent LBV eruption or common envelope.** Massive shell. Probably bipolar shape (pinched waist = early, lobes = late).

Strong interaction in main peak (Type IIn) and late times.

Expansion timescales at $V_{SN}=10^4$ km/s:	Pre-SN timescales at $V_W=10^2$ km/s:	Observed Examples:
1 day = 5 AU	100 days	
		Flash Spec/
2 days = 10 AU	200 days	Early bumps
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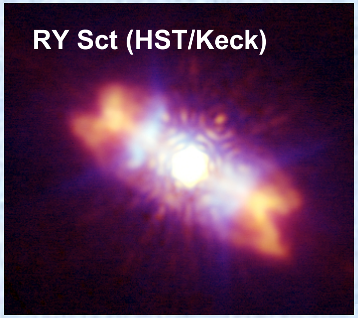

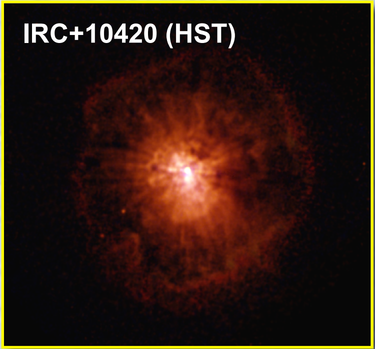

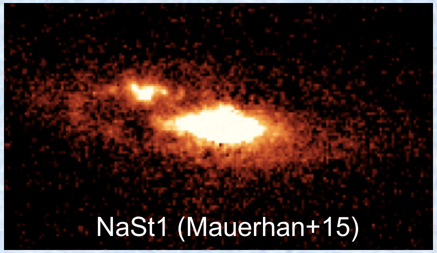

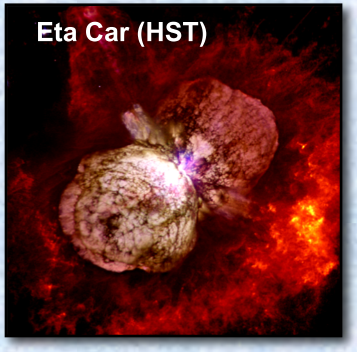

Close-in CSM, disks, cocoons. Limited to small radii.

- **Enhanced pre-SN winds.** Dense winds turn-on within few years of SN.
- **Keplerian disks / Magnetically confined disks.** Rapid rotators (Be stars), binary RLOF/L2, magnetic stars (Romanova & Owocki 2016).
- **Immediate pre-SN common envelope or binary interaction.** Probably disk-like shape, small radii (~10 AU).

Strong interaction only at early times. Possibly very asymmetric.

Expansion timescales at $V_{SN}=10^4$ km/s:	Pre-SN timescales at $V_W=10^2$ km/s:	Observed Examples:
1 day = 5 AU	100 days	
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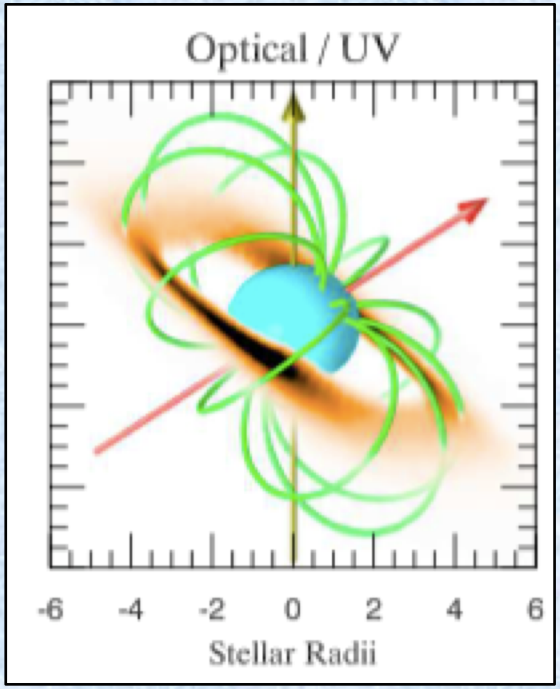
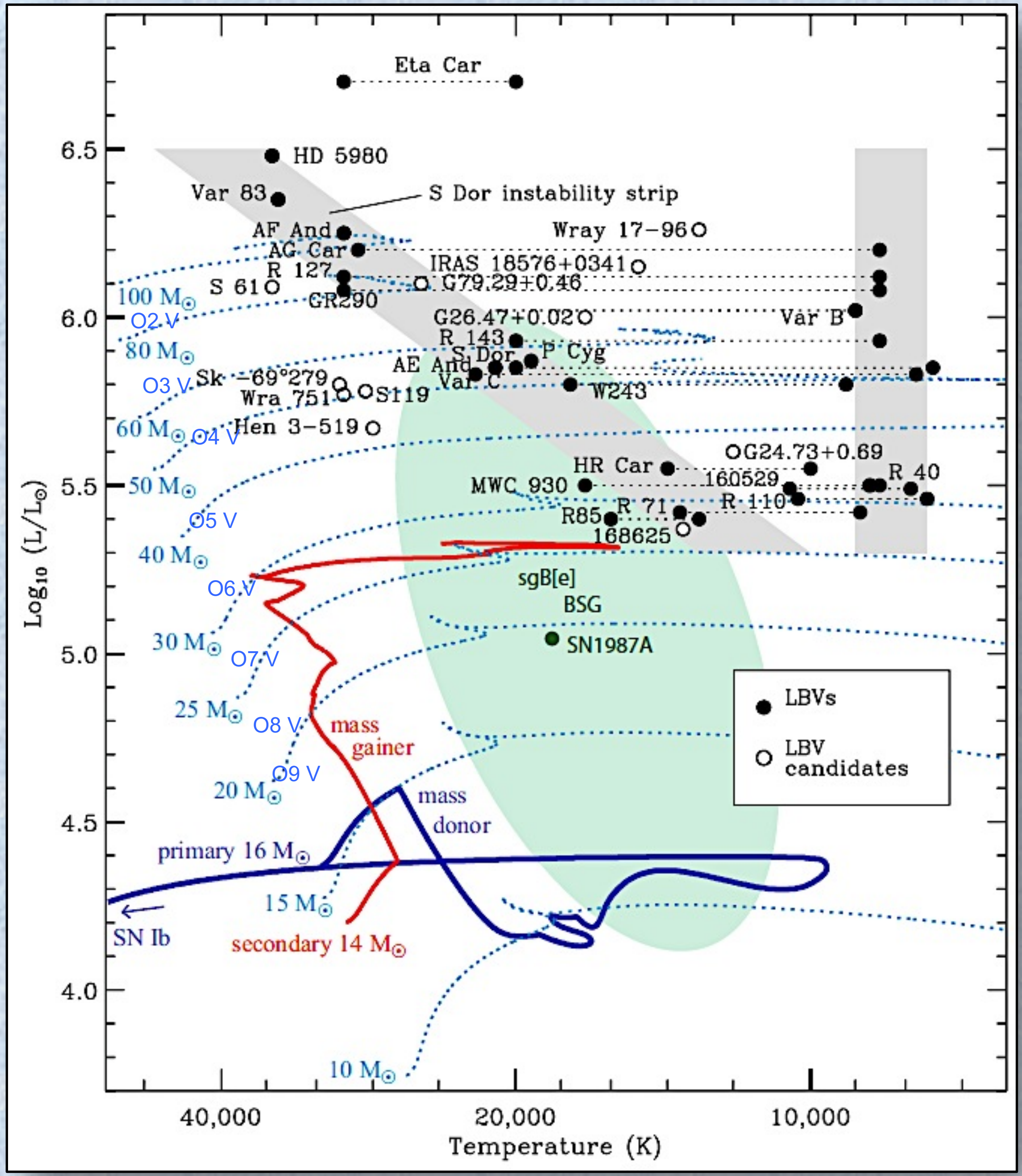


Instead, LBVs are binary products
(Kicked mass gainers, mergers…)
Companion may be faint (stripped and hot), dead, or merged.

Products of mergers and mass gainers in RLOF will be diverse (depends on initial mass, binary mass ratio, separation, transfer efficiency, etc.)

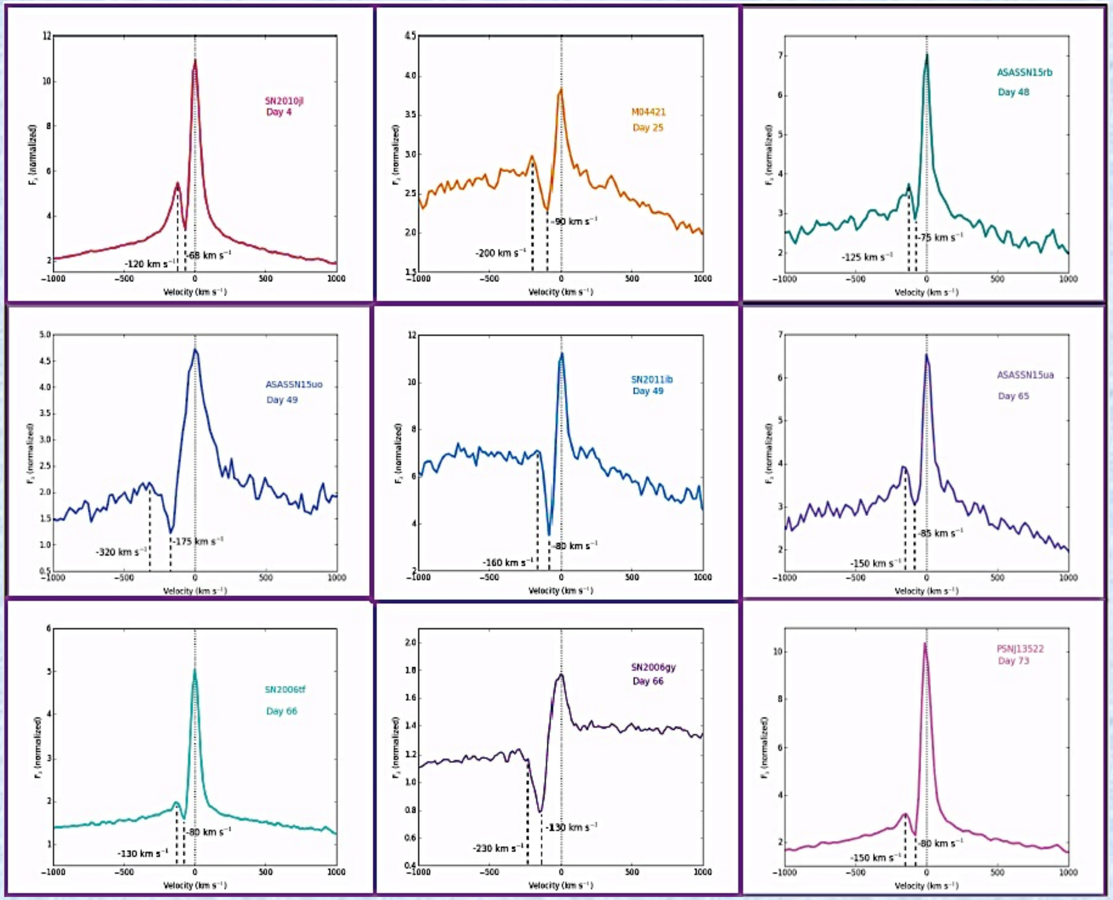
Giant eruptions / SN impostors from the merger event.



Narrow components - pre-shock CSM

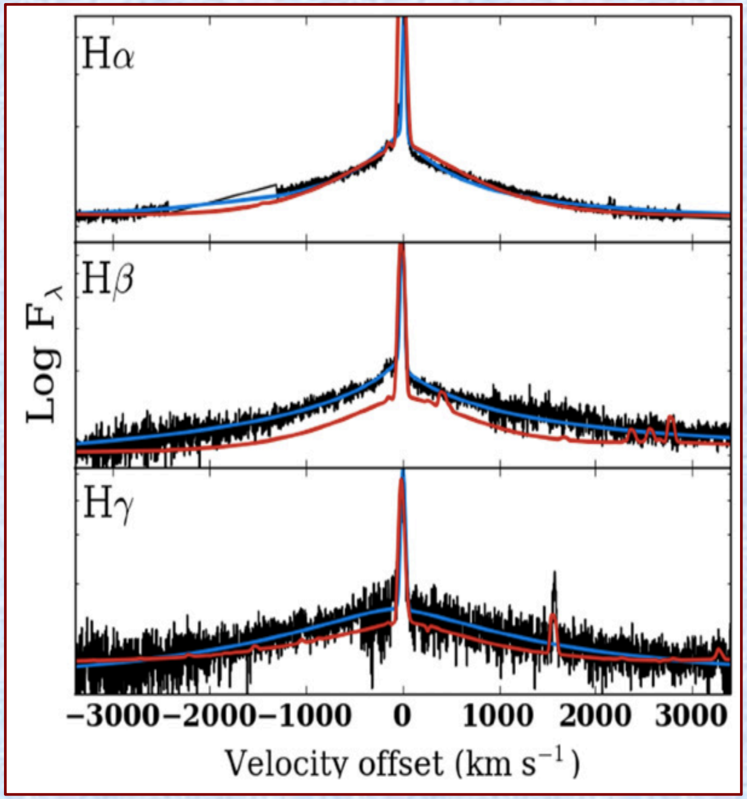
SNe IIn:

- typically show speeds of 60-200 km/s (LBVs and YHGs)
- Sometimes several 10^2 to 10^3 km/s (more massive LBVs)
- Sometimes slower (few x 10 km/s), implying ex-RSGs



J. Andrews et al. (in prep.)

SN 1998S – Shivvers +15



Echelle spectrum of SN 1998S - day 1.

Narrow component suggests RSG with slow wind of 40-50 km/s.

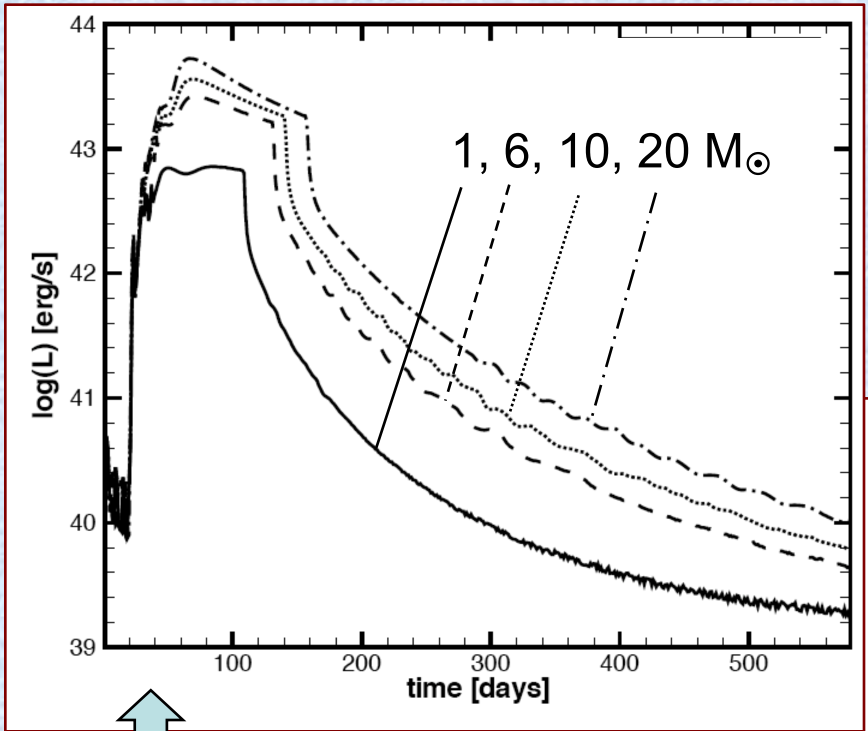
**Note: Narrow absorption can be seen or not, depending on geometry, resolution, and physics of rad tran.

CSM Interaction

Light curves from SN/shell collisions

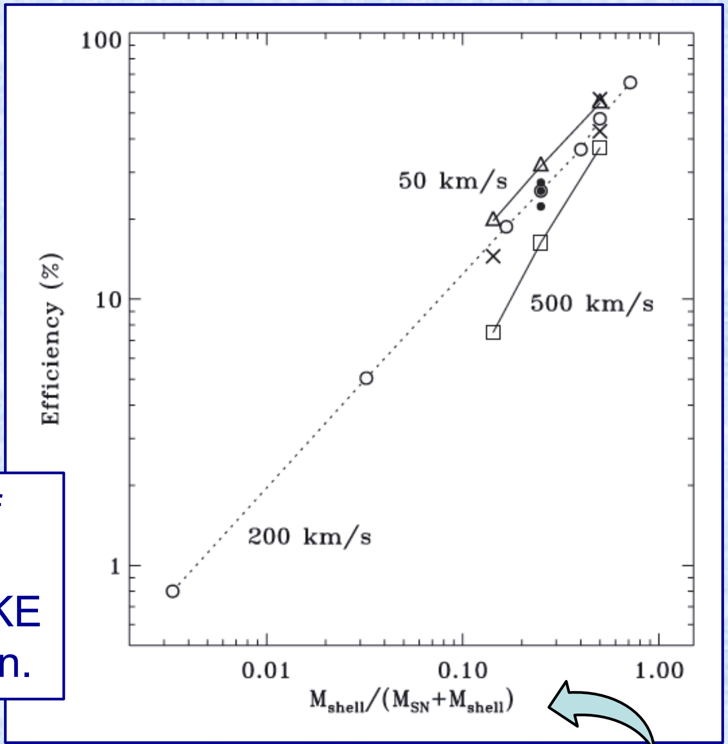
simulations using ZEUS (van Marle +10)

(see also Woosley+07; Moriya+14)

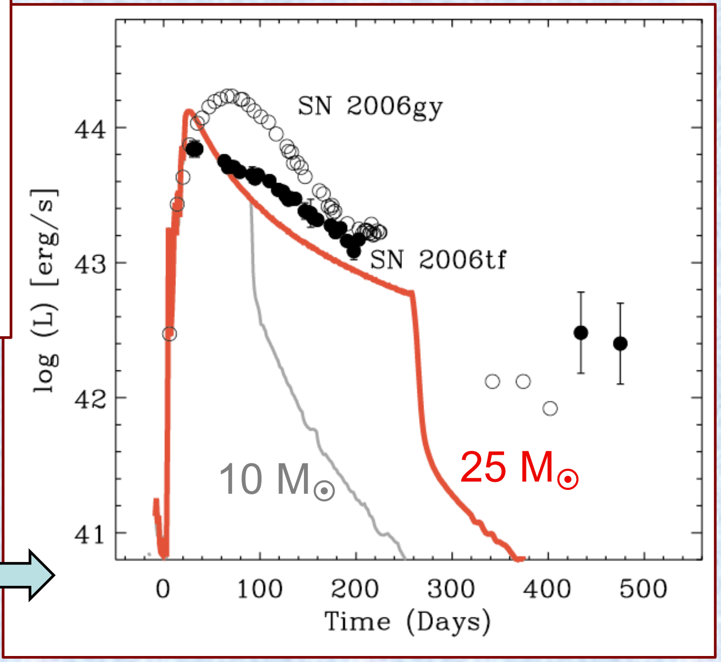


- increasing shell density (total mass) increases the peak luminosity
- increasing the outer shell radius (also increasing total M) increases duration

efficiency of 10-50% in converting KE into radiation.



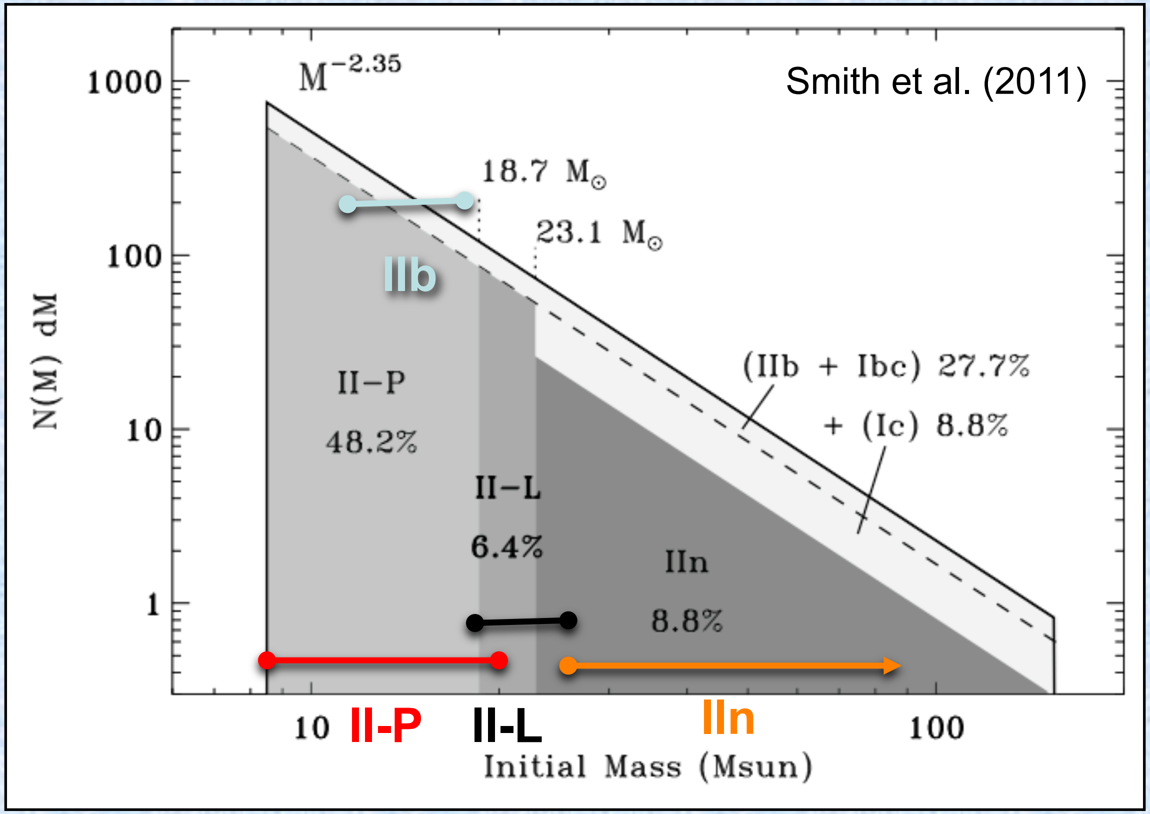
M_{CSM}/M_{Tot}



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
Maybe 1 detection, (15 upper limits)

Type IIb
13-17 $M_\odot$ binary (3)

Binary channel: mass donors in RLOF.

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

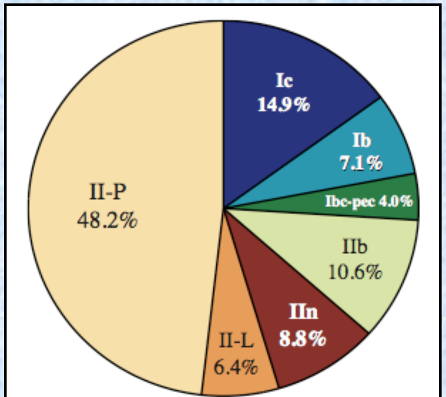
Type II-L
18-25 $M_\odot$ (2)

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

Type IIn
>30-100 $M_\odot$ (5)

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.)

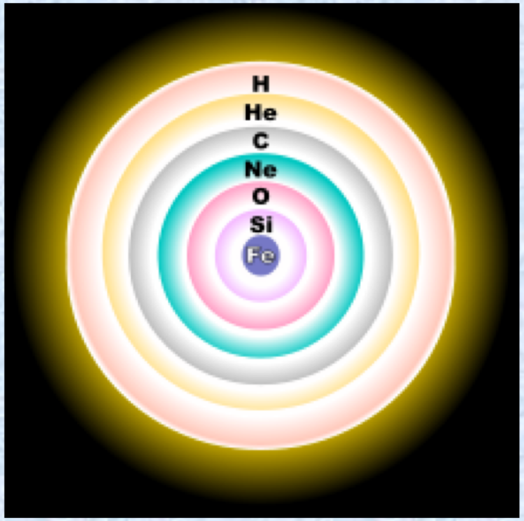


Core-Collapse SN Fractions

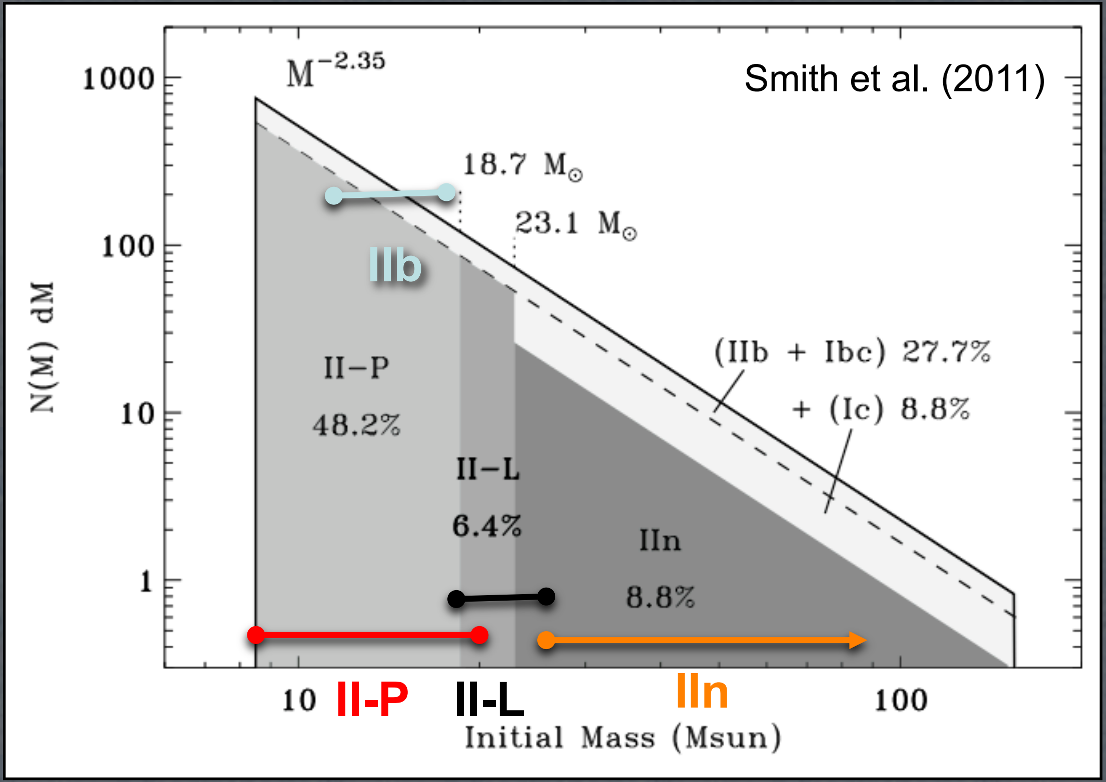
PRE-SN OUTBURSTS

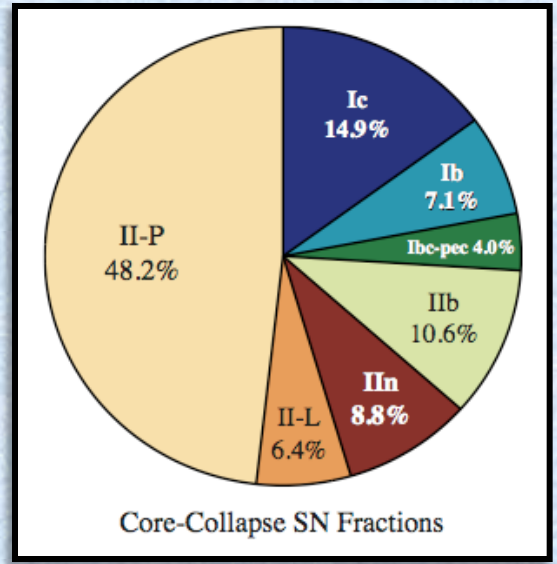
Whatever the mechanism, it needs to provide a wide range of energy and mass loss over a wide range of timescales before collapse. Probably also a wide range of initial mass (see Smith 2014; Smith & Arnett 2014).

This may alter the progenitor core structure…



C burning ~ 1000 yr
Ne, O burning ~ few years
Si burning ~ few days





Smith et al. (2011)

CSM Interaction

Basic picture leads to complicated observations.

Four main zones in a simple shock:

1. Pre-Shock CSM
2. Shocked CSM - behind forward shock
   (***cooling makes this collapse in a SN IIn***)
3. Shocked ejecta - reverse shock
4. Unshocked freely expanding ejecta

CONTINUUM PHOTOSPHERE

- Moves through these zones with time.
- Can come from different zones at the same time.
- There can be no photosphere (late times, thin).

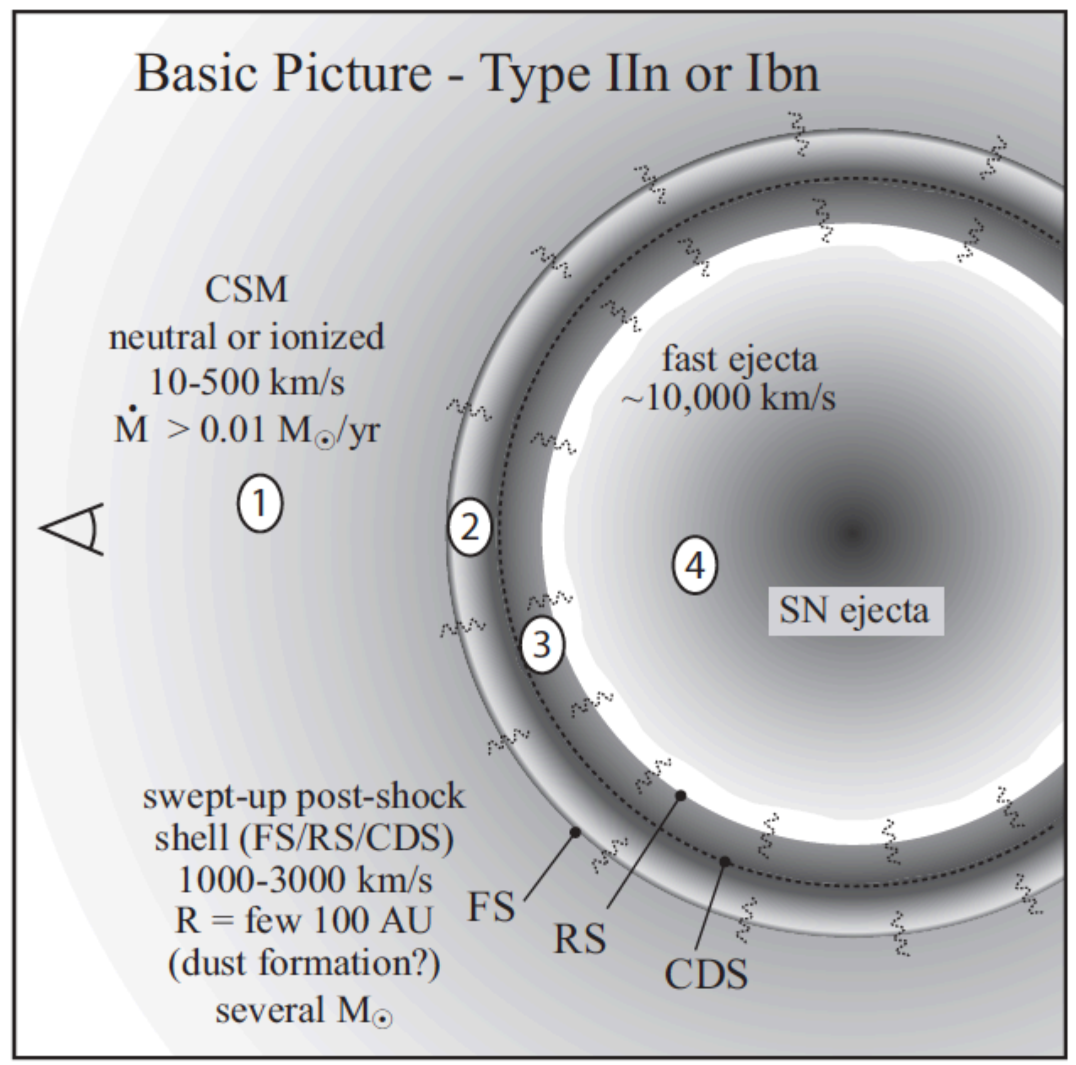
SPECTRAL LINES

- Can be seen from any or all of these zones, changing with time.
- Line profiles modified or hidden by electron scattering, occultation by photosphere, or dust.

ASYMMETRY CANNOT BE IGNORED

- CSM can be highly asymmetric (i.e.disk)
- Appearance may depend on viewing angle
- Can see multiple zones simultaneously
- Can hide narrow lines altogether
- X-rays can escape… or not

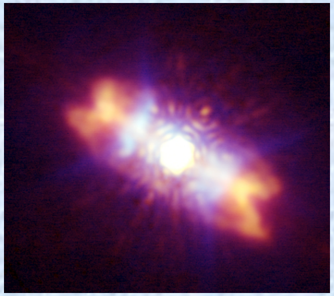
SHOCK RADIATION PROPAGATES OUTWARD AND INWARD, MODIFIES CSM AND EJECTA



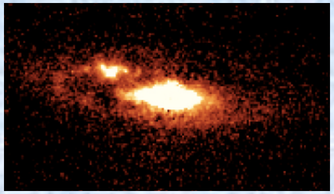
$$L = \frac{1}{2} w V_{SN}^3 = \frac{1}{2} \dot{M} \frac{V_{SN}^3}{V_w}$$

Efficient conversion of KE ⇨ Light

ASYMMETRIC CSM (Part I): DISKS, RINGS, BIPOLAR

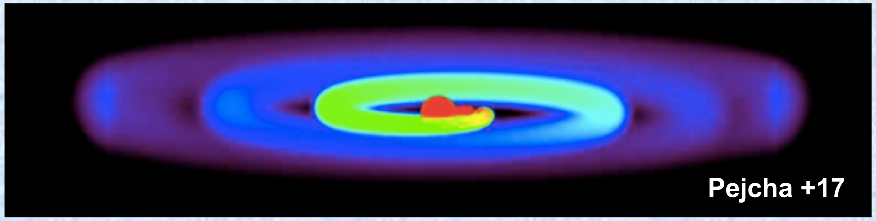


Large CSM shells are often spherical, but small (young) ones are usually asymmetric. Asymmetry gets washed out as they expand.



If it isn't spherical, then a disk is a good first approximation.

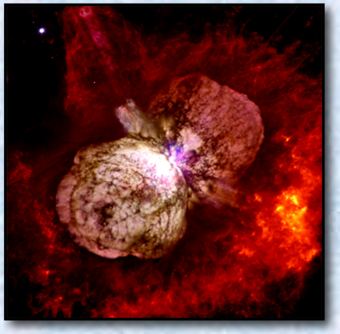
- Rapid rotators
- Magnetic stars
- Binary RLOF
- Mergers



Even bipolar lobes are "disk like" when CSM interaction begins, because of pinched waist. None of these require a RSG-to-BSG transition, although that may happen too.

Asymmetry impacts our interpretation of the SN observations.

- Energy budget (solid angle)
- Polarization and line profiles
- Multiple optical depths (X-rays can escape out poles)
- Two different photospheres can be seen simultaneously: normal SN ejecta photosphere + shocked CSM
- Added diversity due to viewing angle
- If disk has limited radius, CSM interaction can be hidden



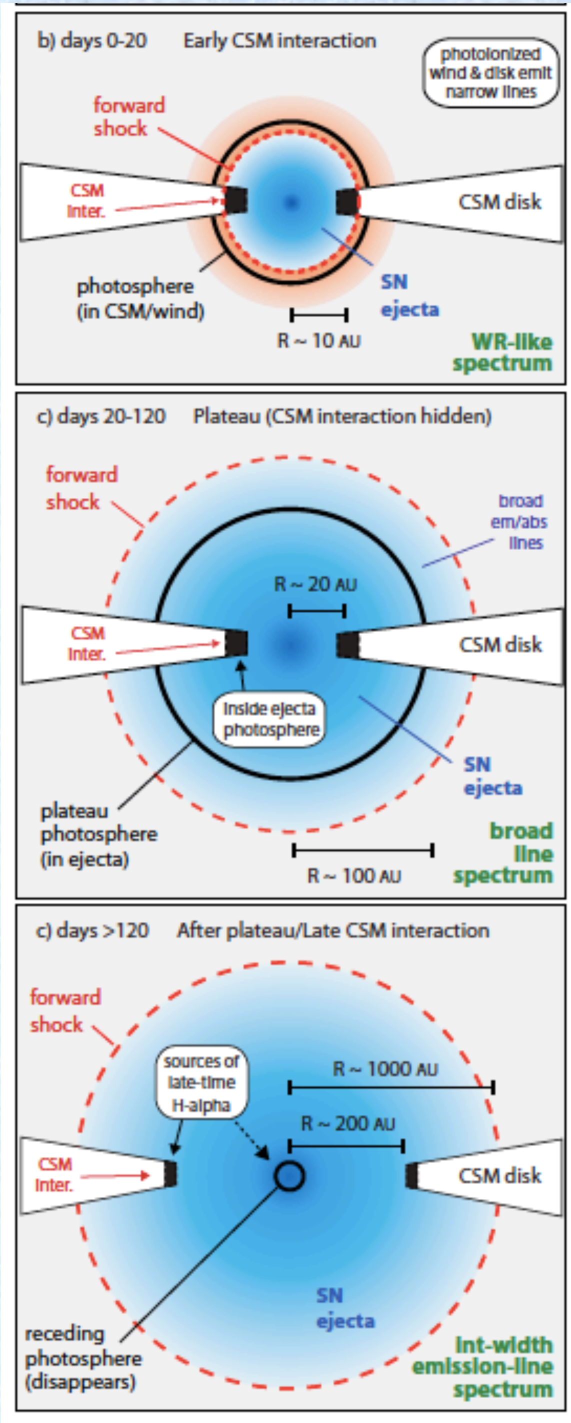
ASYMMETRIC CSM ALLOWS HIDDEN CSM INTERACTION

If the CSM is in a disk with a limited outer radius, it can be overrun and buried inside the SN ejecta, but the collision continues underneath (Smith+15; McDowell, Duffell, & Kasen 18).

- AT first, we see early CSM interaction ("Flash" spectrum) in first few days at R ~ 10 AU.
- SN ejecta sweep past the disk and engulf it within several days to weeks. Shock interaction is now buried under photosphere, inside opaque ionized SN ejecta. Interaction can add heat from the inside. Enhanced luminosity during main light curve peak, even with no direct signatures of CSM interaction (narrow lines, X-rays).
- After SN ejecta recombine, photosphere recedes and exposes CSM interaction once again. Late time-signatures of interaction.

SN 1998S and PTF11iqb are good examples of this.

The Impossible SN (PTF14hls) may be another (Andrews & Smith 18)



SN impostors are much more diverse than traditionally thought

Wide range in peak L, duration, E_{rad}, KE, v_{exp}, M_{ZAMS}, etc.

peak M = -8 to -14 mag or more

E_{tot} = 1e46 to 1e50 erg

T = weeks to decades

bulk V_{exp} = 10s to 1000 km/s

M_{ej} (nebulae) = 0.01 to 20 Msun

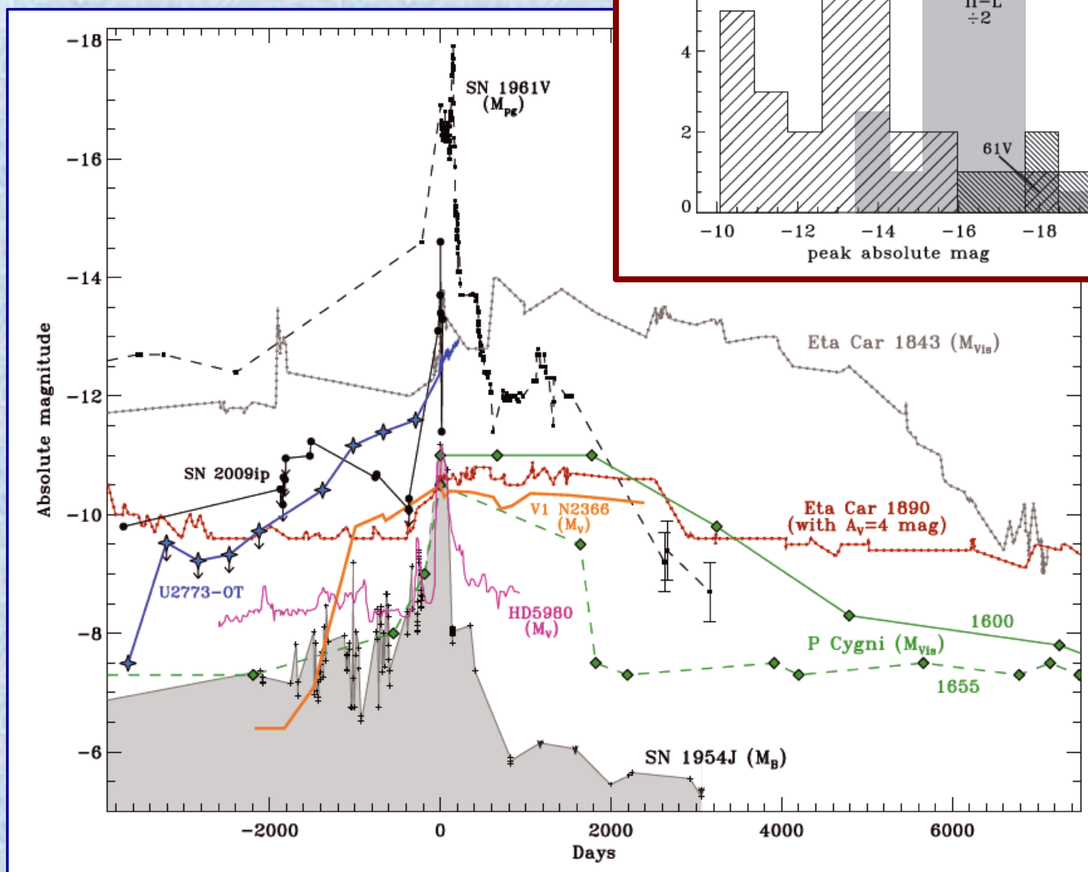
M_{ZAMS} = 10-ish to upper mass limit

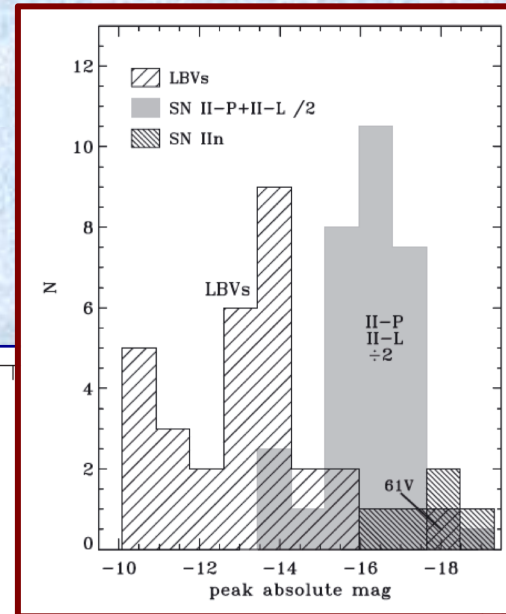
Possibly related:

V1309 Sco, V838 Mon (mergers)

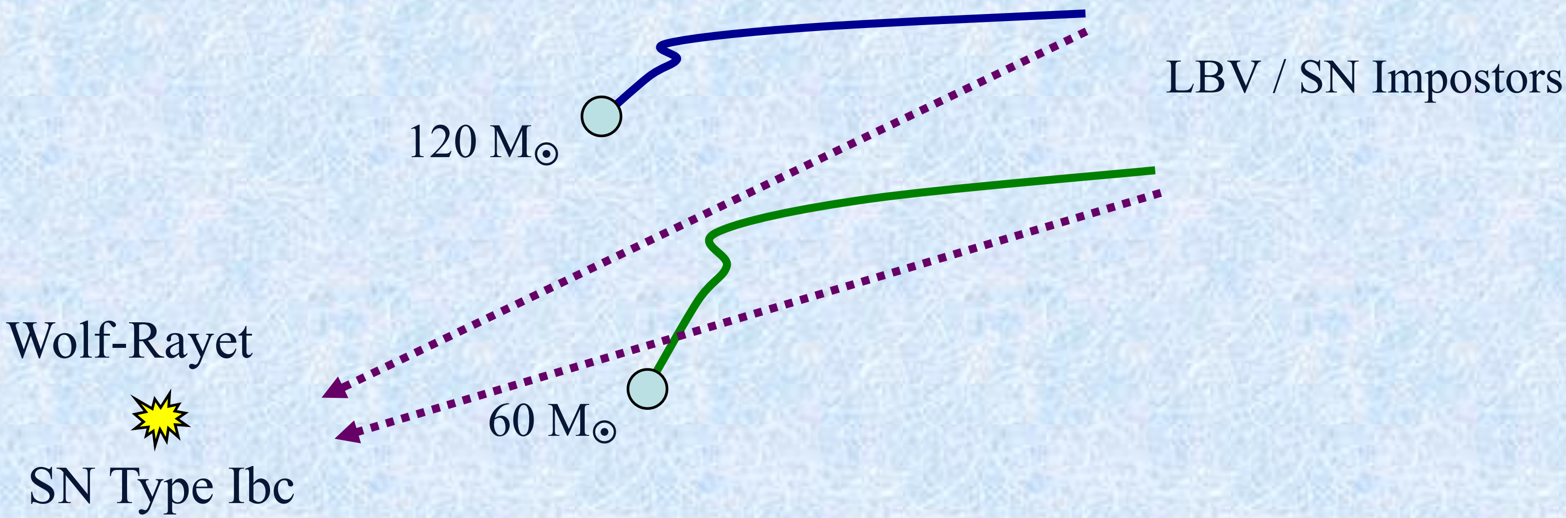
SN2008Slike (electron capture?merger? supergiant outburst?)

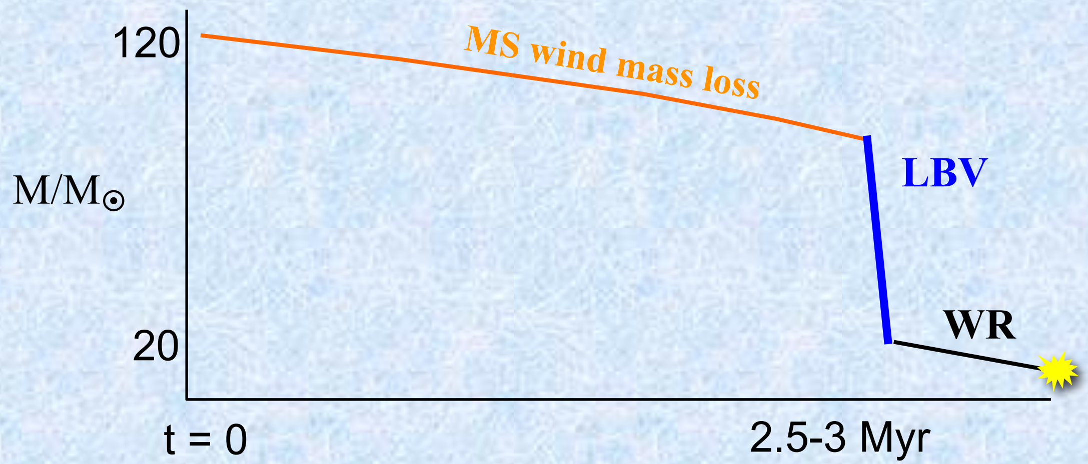
Smith, Li, Silverman, Ganeshalingam, AVF 2011 "LBV Diversity" - mostly KAIT





Luminous Blue Variables (LBVs) and their presumed role in stellar evolution





In the single star picture, LBVs are stars in *transition*. End of H burning, start of He burning.

Sequence of increased mass loss during a star's life:

Early O type → LBV → WN → WC → SN Ibc