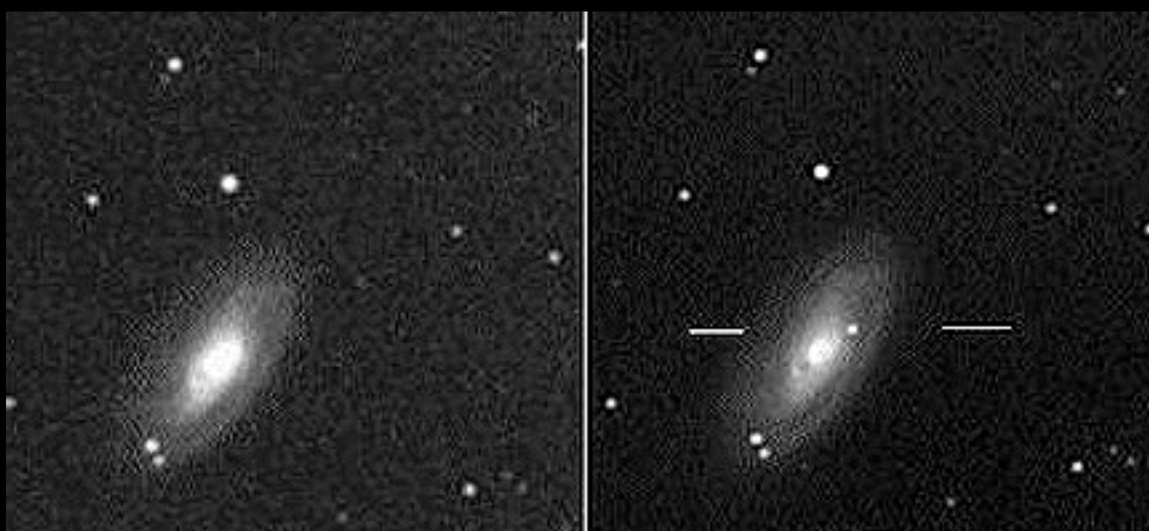
Luminous Supersoft X-Ray Sources as Type Ia progenitors

Are there enough of them?



Rosanne Di Stefano
KITP
20 March 2007

With help from my friends…

- Population synthesis and evolution: S.A.Rappaport, L. Nelson, J.D. Smith, T. Wood, W. Lee
- Observations: J. Greiner, A.K.H. Kong, F.A. Primini, M.R. Garcia, S. Murray, P. Barmby, M. Orio, T. Nelson, B. Patel, T. Russo, S. Scoles, S. Curry

See also workshop presentations by
E. Van den Heuvel and L. Nelson

SSSs: phenomenological definition
Early 1990's edition

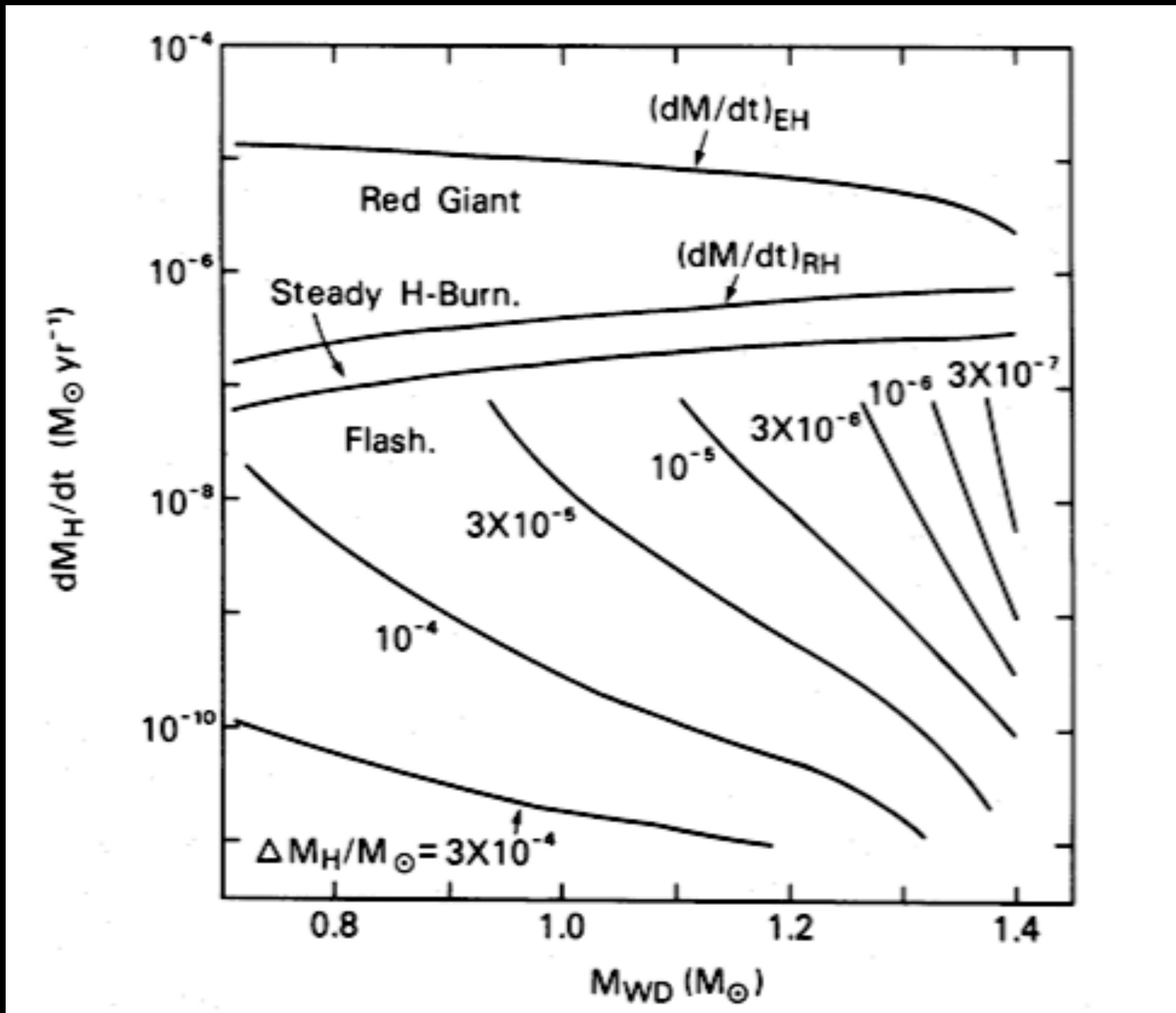
- kT : 10 eV - 100 eV
- L : 10^{37} - 10^{38} erg/s

SSSs: physical nature
Early 1990's edition

- 1/2 of the observed sources have counterparts with hot WDs: recent novae, symbiotics.
- 1/2 have counterparts which are close binaries: 0.4 d < P < 1 d.

Their effective radii, and the association with nova, symbiotics, and one planetary nebula suggest:

SSSs are nuclear-burning white dwarfs (NBWDs).



Nomoto 1982; Iben 1982

The connection between SSSs and Type Ia SNe

- Are Type Ia progenitiors SSSs?

  At some point in their evolution, virtually all progenitors are NBWDs that can potentially be observed as SSSs. SSS behavior can help to identify Type Ia progenitors.

In single-degenerate models, SSS behavior could occur during the epoch of mass increase.

This is the epoch of interest to us here: are the progenitors detectable as SSSs during the epoch of maximum mass gain?

In the early 1990's it was established that galaxies, such as M31 and the Milky Way have large SSS populations. (RD & Rappaport 1994)

For ellipticals, the population could only be estimated based on diffuse emission. (Fabbiano, Kim and collaborators)

This was independent of the nature of the sources.

Based on observations

- Modeling galactic gas distributions; ``seeding" galaxies with SSSs from:
  (a) observations
  (b) simulations
- Result: ~1000 in M31 and in the Milky Way (Di Stefano & Rappaport 2004)
- Interstellar gas hides most SSSs--whatever their basic nature.
- Could be many more with low L and/or T.

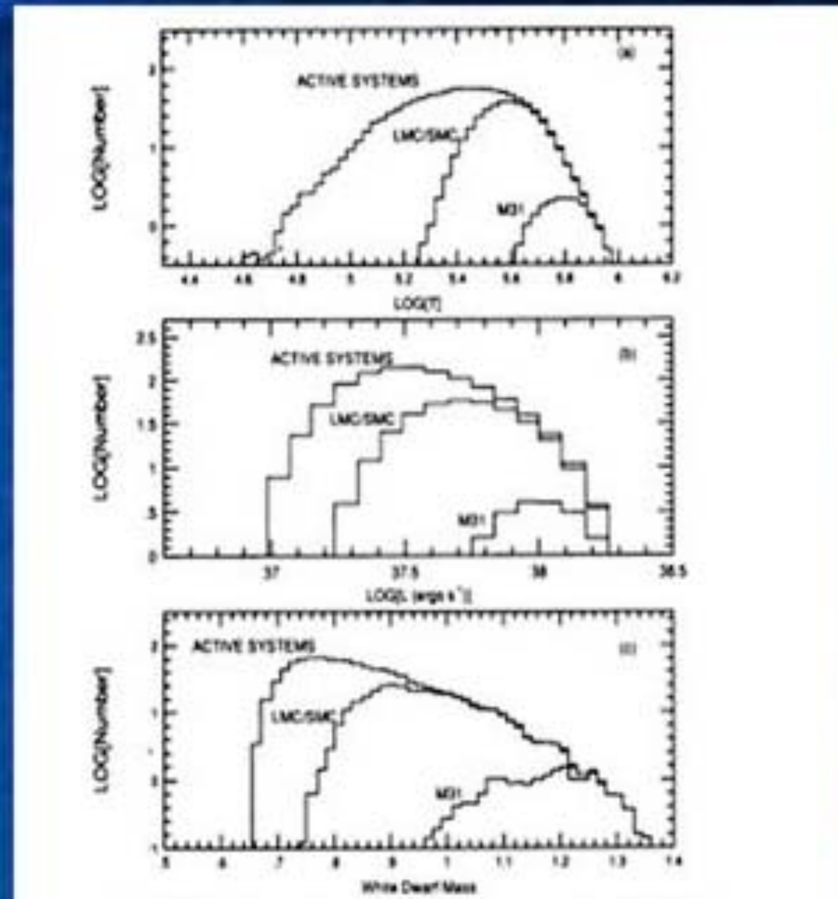


FIG. 3.—Calculated properties of supersoft X-ray sources that should be detected with *ROSAT*. In each panel the uppermost curve, which encompasses

- NBWDs require high rates of mass transfer.

- This can happen in close binaries and wide binaries; through Roche-lobe overflow or through winds.

Close-Binary SSS model (CBSS)

van den Heuvel et al. 1992

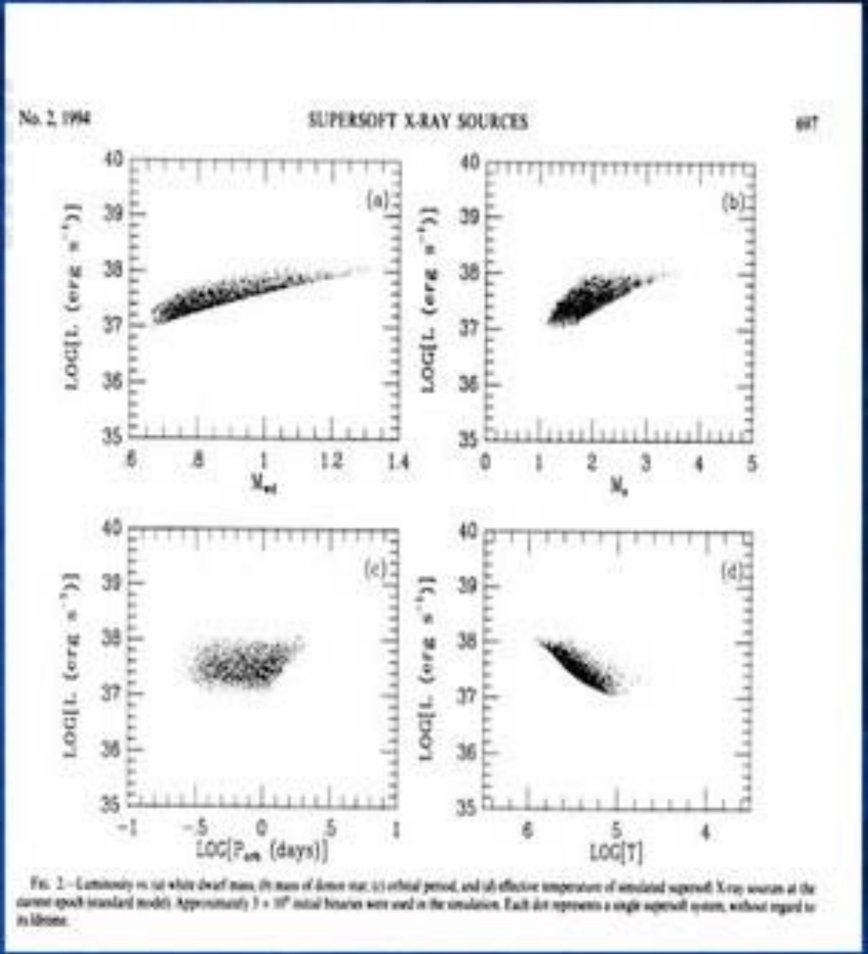
M_dot ~ 10^-7 m_sun/yr

To produce the high accretion rate, the donor must be more massive than the WD and/or slightly evolved.

The luminosity is caused by the nuclear burning of accreted hydrogen.

Population synthesis

- How many CBSSs are predicted from first principles?
- Result: ~1000 in M31 and in the Milky Way (Rappaport et al. 1994)
- Verified by Yungelson et al. (1995), who predicted about half as many.



First predictions of the rate of Type Ia due to SSSs (Rappaport, Di Stefano, \& Smith 1994)

- M_dot in recurrent nova range:
- M_dot in or above steady-burning region
- M_dot in steady-burning range

- 0.6 per century
- 0.3 per century
- 0.008 per century

- To refine the calculations, need to conduct binary evolution calculations. (Di Stefano, Nelson, Rappaport, Wood, & Lee 1996; Di Stefano & Nelson 1996)

Following 3 slides from Nelson's KITP workshop talk.

Rate of Mass Transfer

$$\frac{\dot{R}_L}{R_L} = -\frac{\dot{M}_2}{M_2}\left(\frac{5}{3} - 2\beta q - \frac{2}{3}(1-\beta)\frac{q}{1+q}\right) + 2\frac{\dot{J}_{\rm dis}}{J} - 2\alpha(1-\beta)(1+q)\left(-\frac{\dot{M}_2}{M_2}\right)$$

↑ internal J redistribution <0 **OR** >0

↑ dissipation <0

↑ systemic J loss <0

If the system remains in contact $\Rightarrow$ $R_L(t) = R_2(t)$

$$\frac{\dot{R}_L}{R_L} = \frac{\dot{R}_2}{R_2} \simeq \xi_{ad}\frac{\dot{M}_2}{M_2} + \frac{\dot{R}_{2,nuc}}{R_2} + \frac{\dot{R}_{2,th}}{R_2}$$

where

$$\xi_{ad} \equiv \left[\frac{d\ln(R)}{d\ln(M)}\right]_{ad}$$

The equations describing the mass-transfer can be approximated as follows:

$$-\frac{\dot{M}_2}{M_2} \simeq \frac{\dot{R}_{2,nuc}/R_2 + \dot{R}_{2,th}/R_2 - 2\dot{J}_{\rm dis}/J}{D(\alpha,\beta,q,\xi_{ad})}$$

Mass transfer is ONLY stable if numerator and denominator > 0

N.B.: If D < 0 then the binary system is dynamically unstable

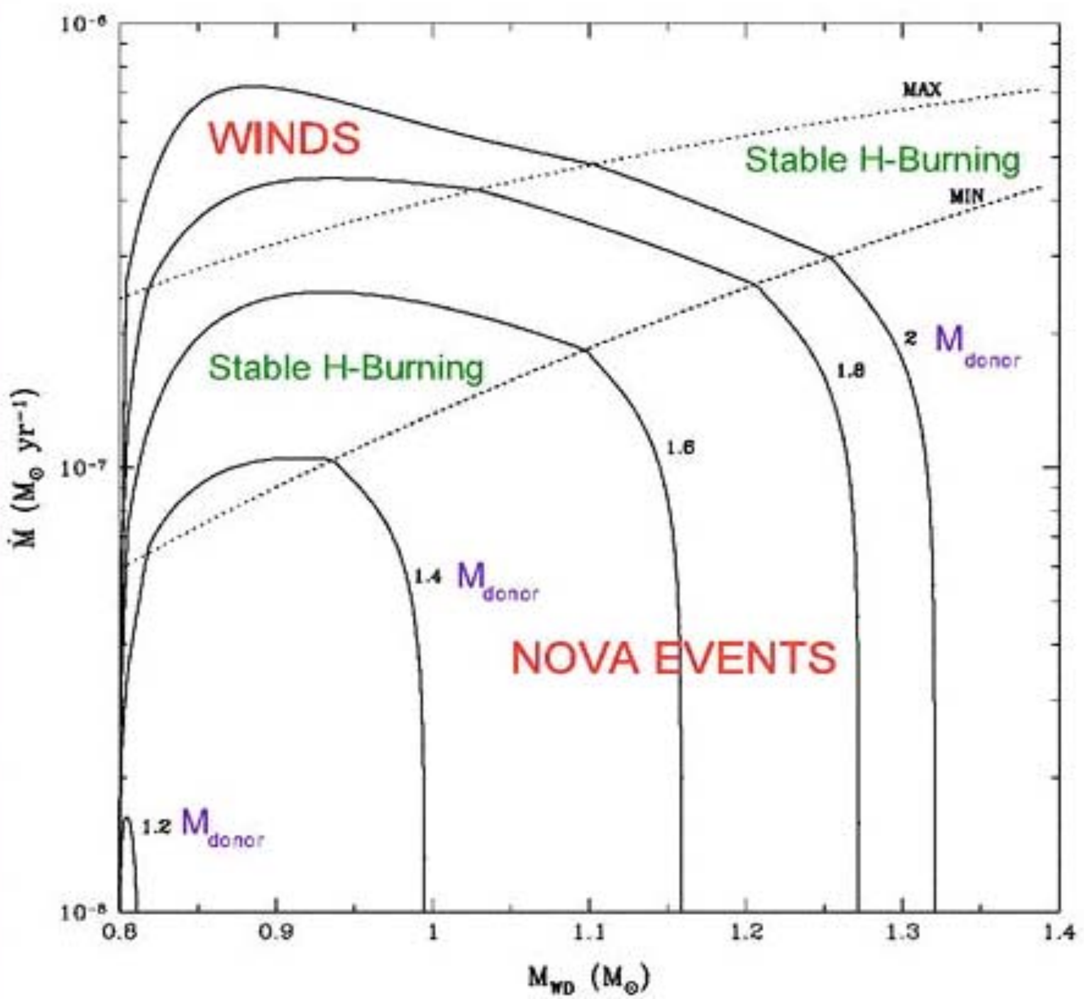
⇒ CE phase/merger

$$D(q,\alpha,\beta,\xi_{ad}) = \left[\frac{5}{3} + \xi_{ad} - 2\beta q - \frac{2q(1-\beta)}{3(1+q)} - 2\alpha(1-\beta)(1+q)\right]$$

Sign of *D* very much depends on the value of α

Importance wrt Type Ia SNe was noted by Di Stefano, Nelson, Rappaport, Lee and Wood (1995); Han and Podsiadlowski (2004)

Temporal Evolution of Supersofts



SSXSs can be regarded as "Super CVs"

Van den Heuvel et al. (1991) developed the model of steady H burning on the surface of WDs

Di Stefano & Nelson 1996

- Result:

  If there are winds which carry modest angular momentum per unit mass, common envelopes can be avoided for many progenitors.

  The rate is comparable to the needed rate.

  The winds are energetically possible.

Progress

Winds: Hachisu, Kato, & Nomoto (1996) found them to be viable.

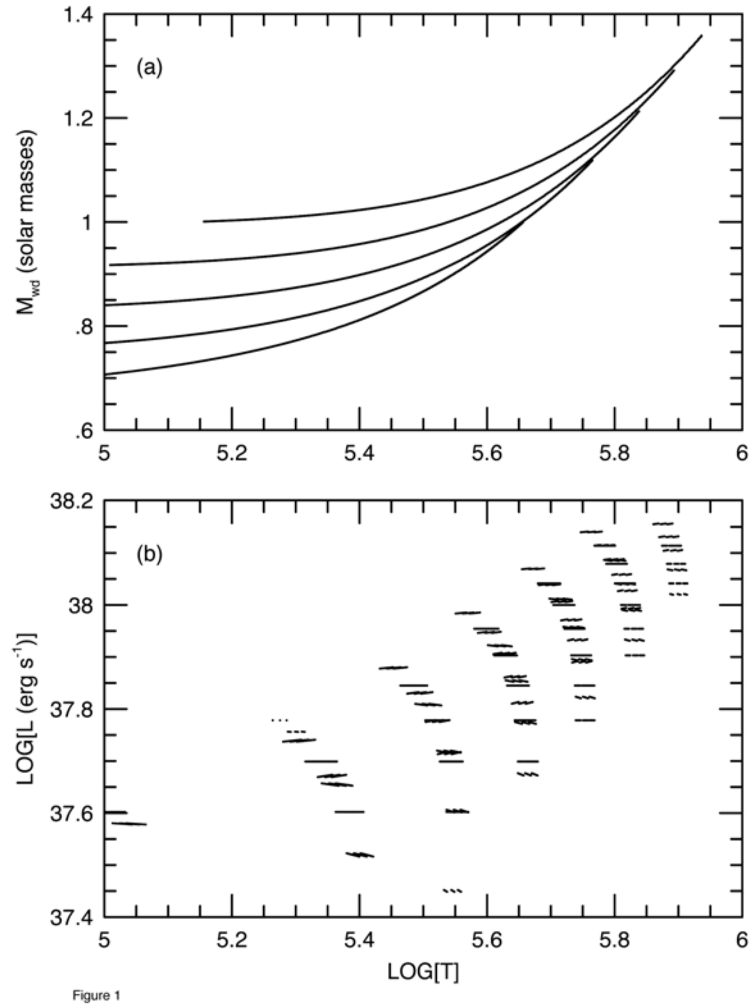
Wide-binary SSSs have been considered (Hachisu, Kato, Nomoto 1999).

Radiative-driven winds from the donor (van Teeseling & King 1998)

More comprehensive population synthesis (Yungelson 2005)

CBSS calculations with winds (Han & Podsiadlowski 2004)

The result still holds: It is possible that accreting NBWDs are the primary class of progenitors.



Massive NBWDs are the hottest and the most luminous.

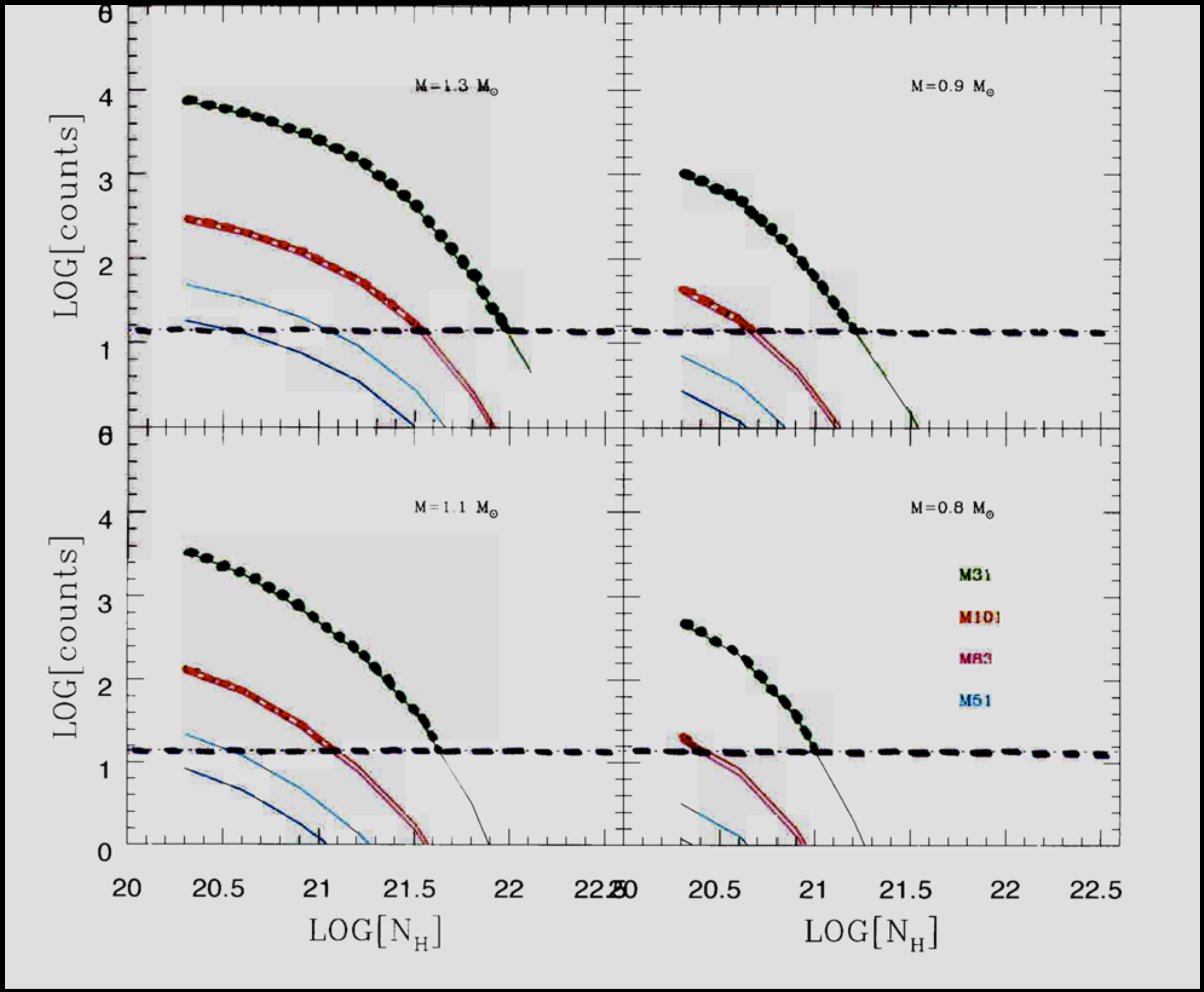
β is the fraction of the incident mass retained.

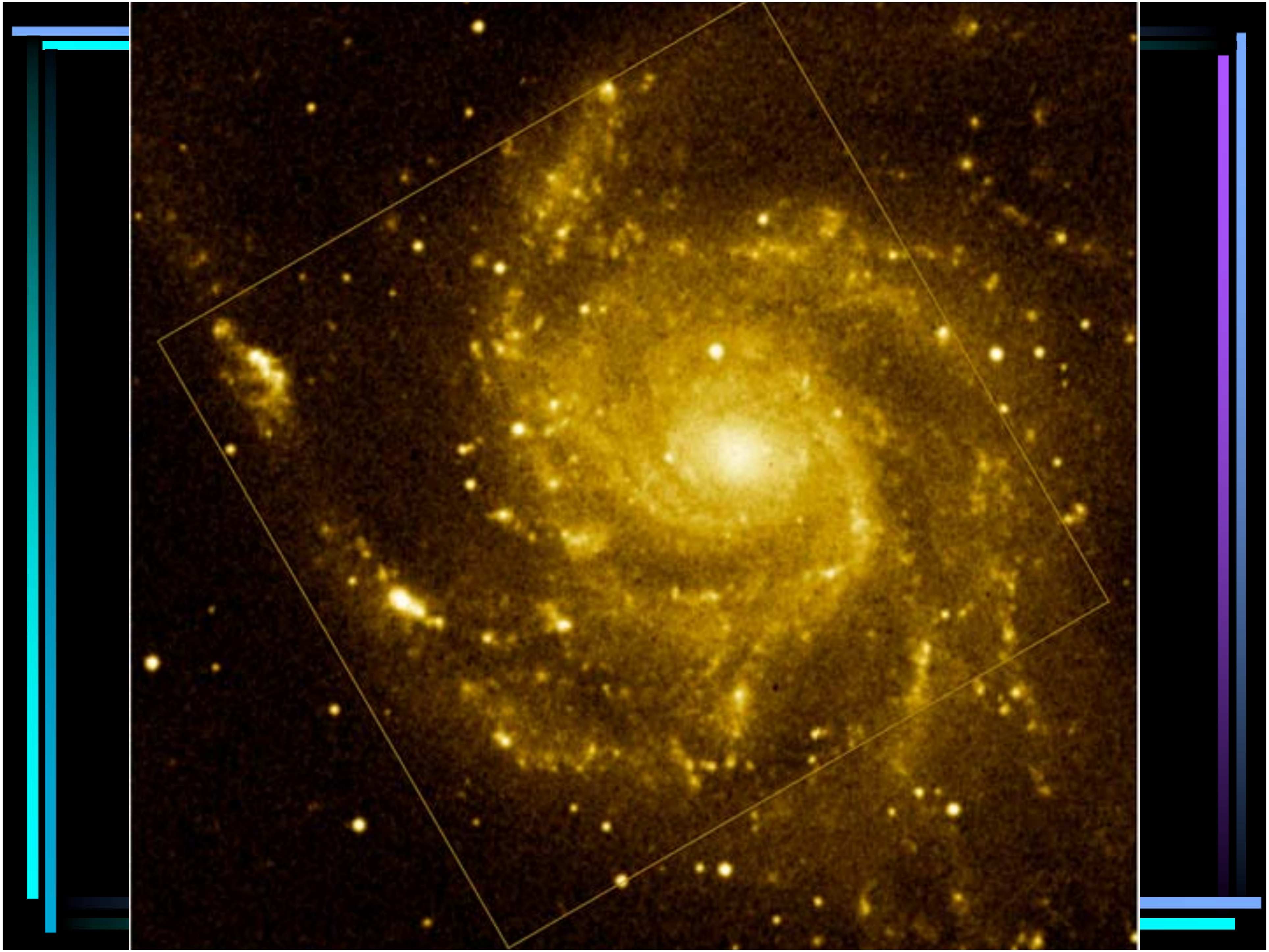
$\Delta\, M$ is the mass increase required.

$$\tau_{acc} = 10^6 \mathrm{yr} \left(\frac{\Delta\, M}{0.4\, M_\odot} \right) \left(\frac{4 \times 10^{-7} M_\odot \mathrm{yr}^{-1}}{\langle \beta\, \dot{M}_{in} \rangle} \right)$$

$$N_{acc} = 3000 \left(\frac{\Delta\, M}{0.4\, M_\odot} \right) \left(\frac{4 \times 10^{-7} M_\odot \mathrm{yr}^{-1}}{\langle \beta\, \dot{M}_{in} \rangle} \right) \left(\frac{L_B}{10^{10} L_\odot} \right)$$

High-mass NBWDs in nearby galaxies can be detected by *Chandra*, because they have high T and L





Numbers observed

M101	SSS: 42; QSS: 21; other: 65
M83	SSS: 28; QSS: 26: other: 74
M51	SSS: 15; QSS: 21; other: 56
M104	SSS: 5; QSS: 17; other: 100
NGC4472	SSS: 5; QSS: 22; other: 184
NGC4697	SSS: 4; QSS: 15; other: 72

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- If single-degenerate Chandrasekhar-mass models are the principal channel through which most Type Ia supernova are formed, are there enough SSSs?
- We derive the answer: NO!!!!
- Existing Chandra data falsifies the hypothesis that:

  Accreting NBWDs that reach M_c are the principal progenitors AND that they are detected as SSSs during the epoch of mass gain.

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- But this result may also be consistent with winds, which seem to be required by the model.
- Photospheric effects could also come into play.
- Input assumptions could be incorrect.

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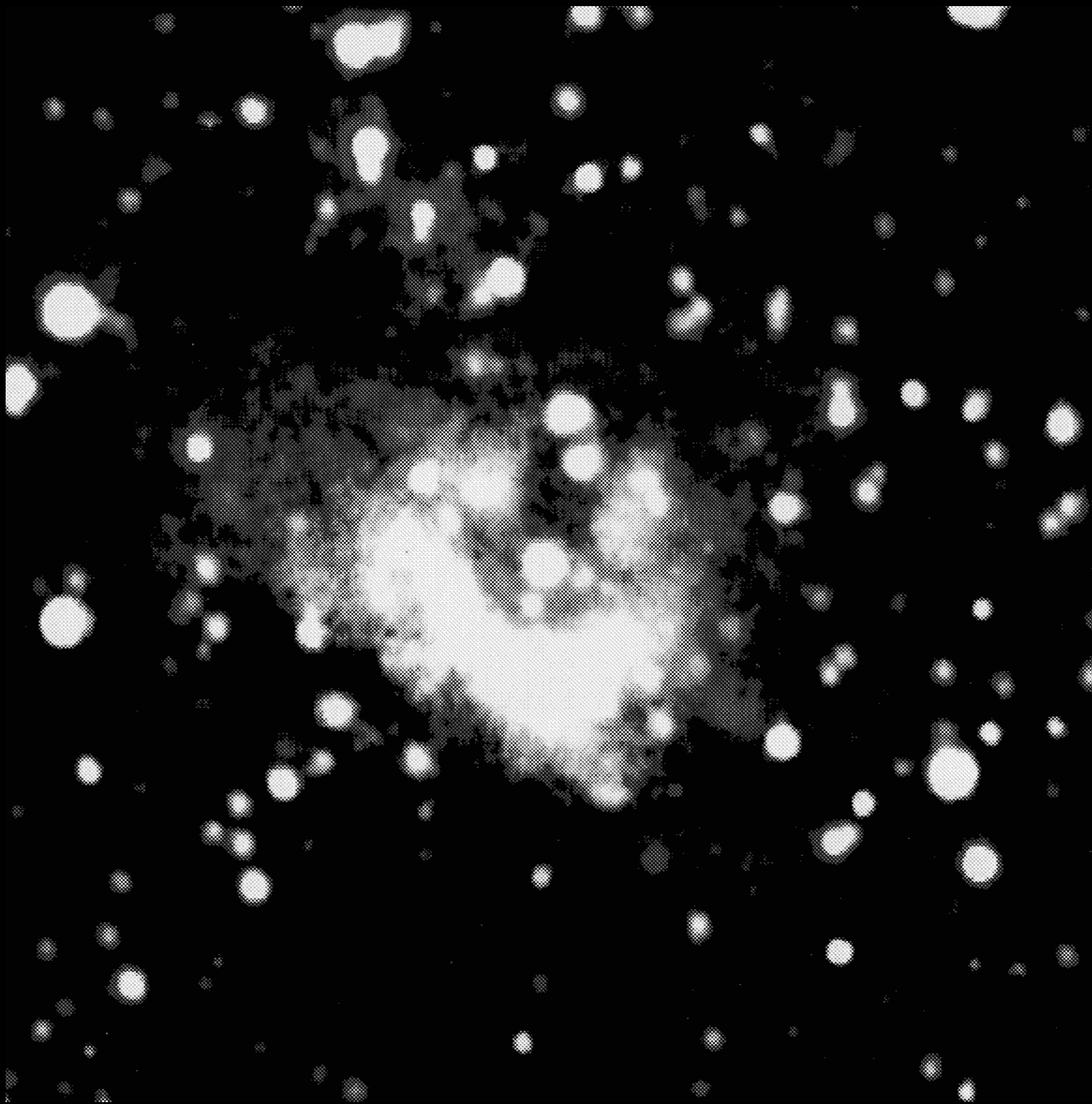
- SSS nebulae

  (RD, Paerels, & Rappaport 1995; RD 1996)



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- Post-explosion signatures..e.g., in SNR (Badenes 2007)

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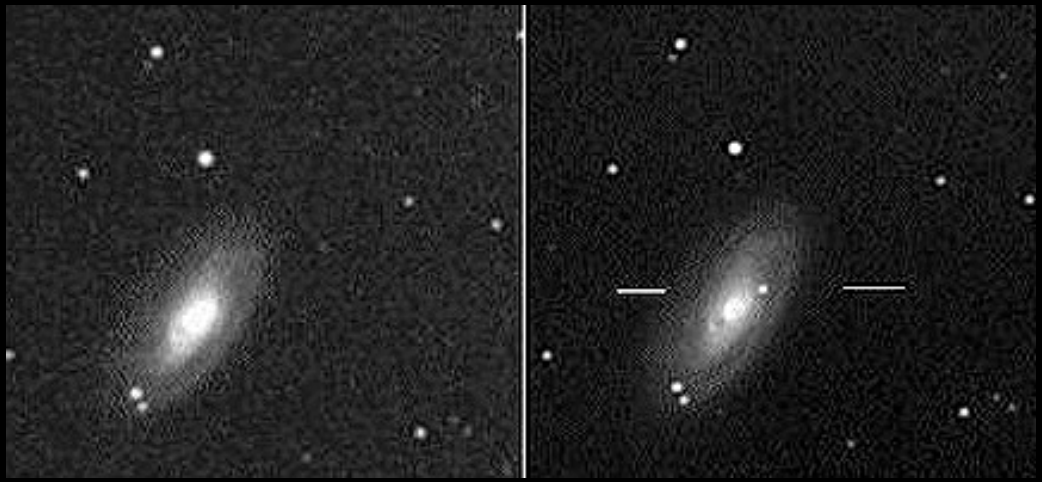
- Effects of winds on the surroundings.
- SSS nebulae
  (RD, Paerels, & Rappaport 1995; RD 1996)
- Signatures in SNRs (Badenes 2007)
- Lack of hydrogen in the post-explosion spectra.

Type Ia supernovae occur far away.



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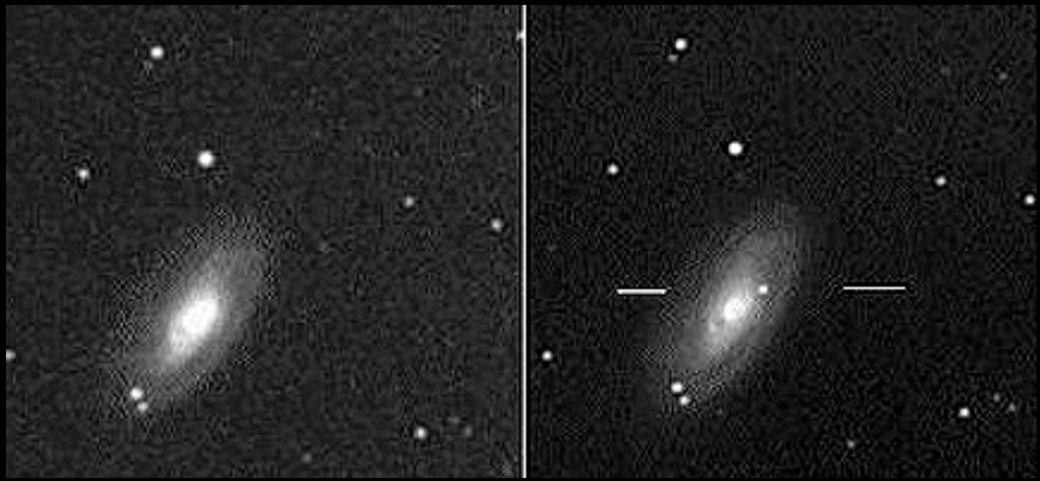

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- (10-30 with M > M_sun, within 1 kpc, if the single-degenerate model dominates.)

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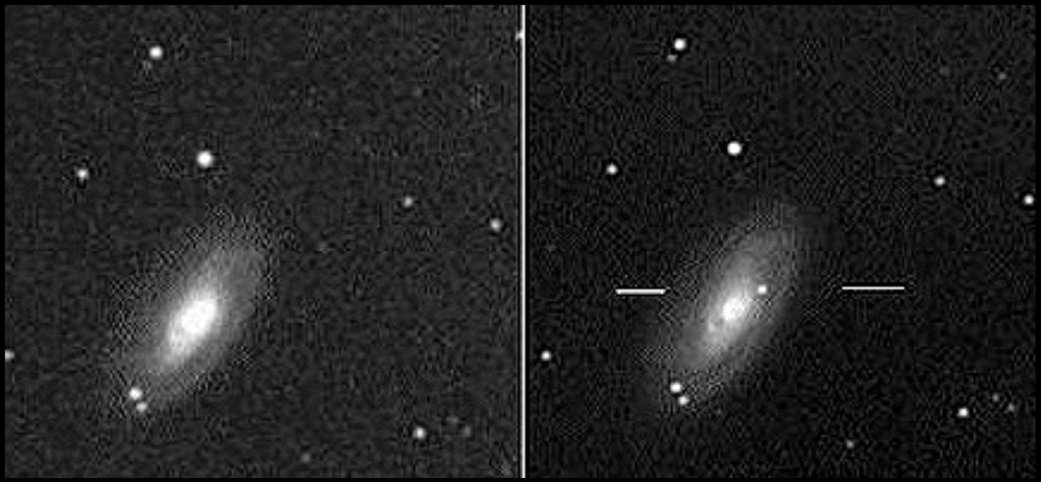
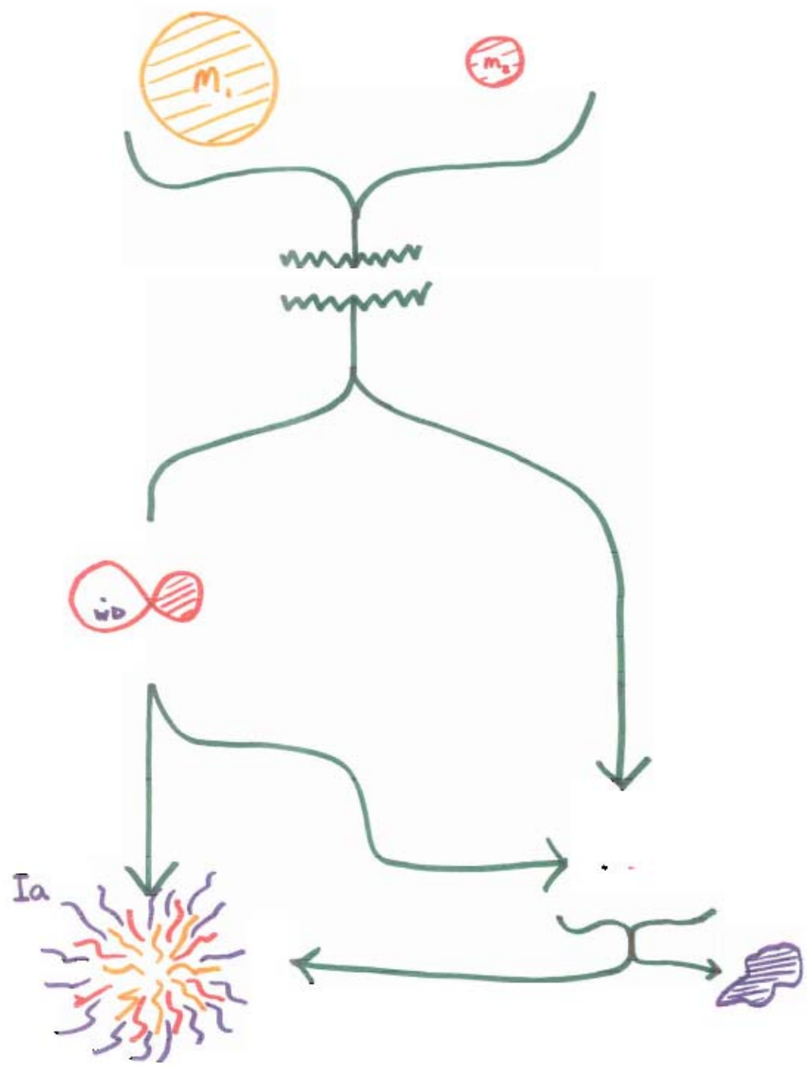
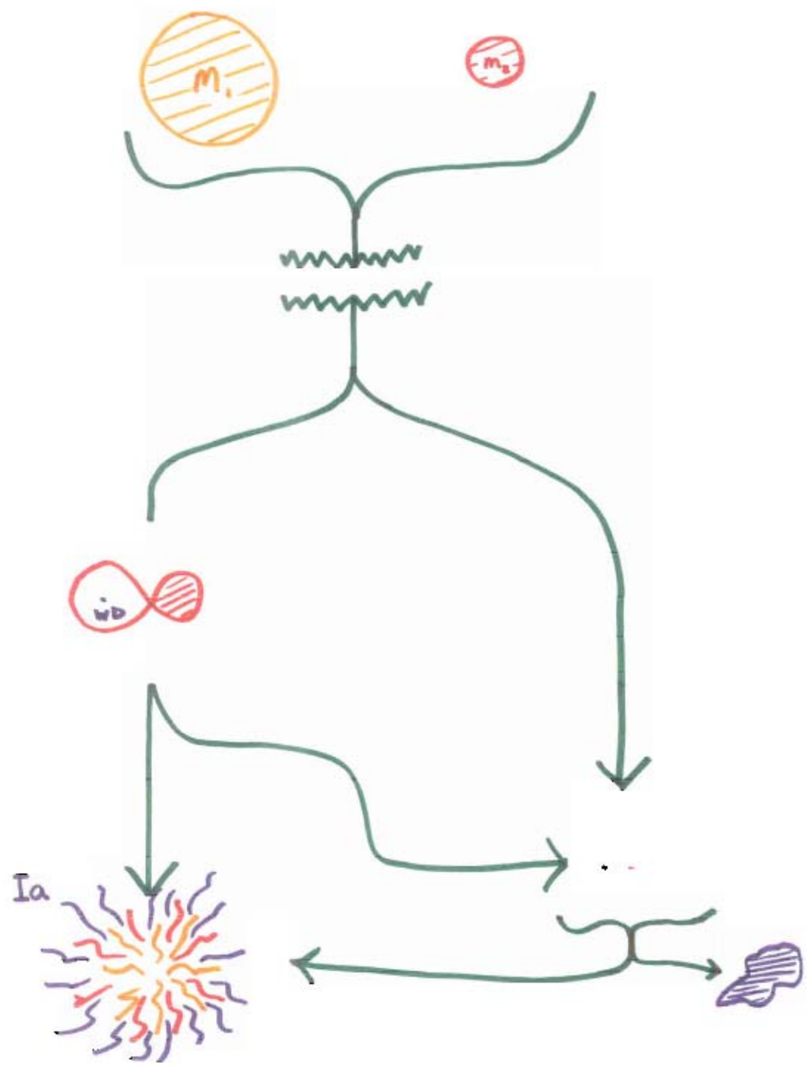


- Progenitors occur nearby.
- (10-30 with M > M_sun, within 1 kpc, if the single-degenerate model dominates.)
- These have L > 10^38 erg/s, distinctive spectra, and perhaps ionization and.or wind signatures.



Ia



Many cross-checks are possible.

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- And conduct a wealth of cross checks.

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- Could the winds needed to make this model work be responsible for absorption?
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- We can search for nearby progenitors.
- And conduct a wealth of cross checks.

Single-degenerate models with hydrogen-rich donors may face their ultimate limits from limits on hydrogen post-explosion.

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- kT: 10 eV - 100 eV
- L: 10^36 - 10^38 erg/s (low-L extension)

The connection between SSSs and Type Ia SNe

- Are Type Ia progenitiors SSSs?

  At some point in their evolution, virtually all progenitors are NBWDs that can potentially be observed as SSSs. SSS behavior can help to identify Type Ia progenitors.

- Are SSSs Type Ia progenitors?

  Some are, and some are not even WDs.

SSSs: phenomenological definition 21st century edition

- kT: 10 eV-100 eV + QSS extension
- L: 10^36 - 10^38 erg/s + ULX extension

SSSs: phenomenological definition 20th century edition

- kT: 10 eV - 100 eV + high T extension
  quasisoft sources (QSSs)

- L: 10^36 - 10^42 erg/s (high-L extension)