Stellar Death and Supernovae 2009

Hydrodynamical He Shell Burning in AM CVn Systems: SNe .Ia

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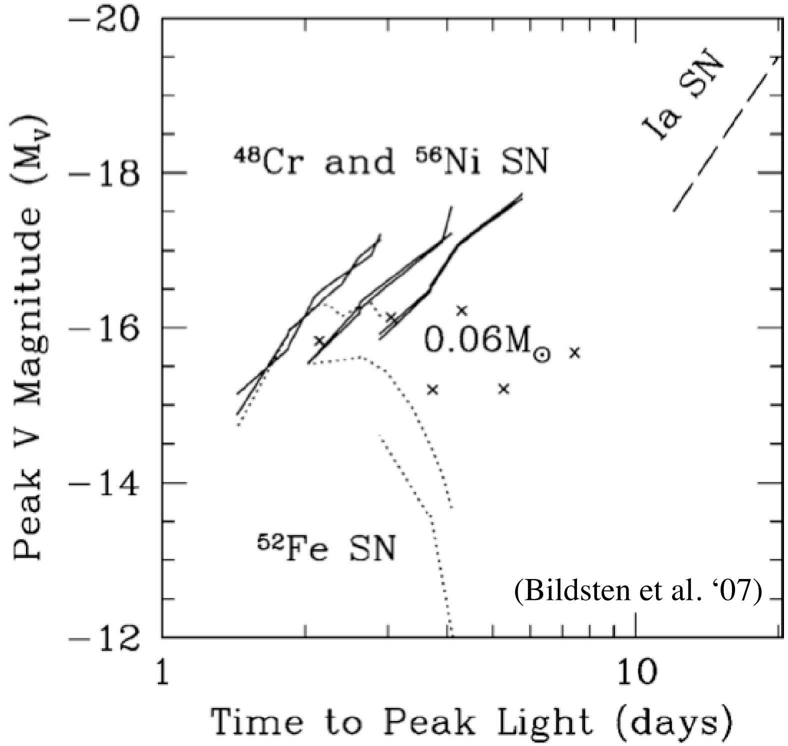
Bildsten, Shen, Weinberg, & Nelemans ‘07, ApJL
Shen & Bildsten ‘09, ApJ
Shen et al. ‘09, in prep.

SN .Ia overview

(Bildsten, Shen, Weinberg, & Nelemans '07)

- AM CVn evolution naturally yields unstable He-burning shells of ~ 0.1 $M_\odot$
- Hydrostatic calculation shows these shells burn hydrodynamically, potentially yielding He detonations with short-lived radioactive products (^{48}Cr, ^{52}Fe, ^{56}Ni)
- Small ejecta mass → short rise times (2–8 days), ~10% as bright as SNe Ia
- AM CVn birth rate → SN .Ia rate is few percent of Ia rate in an old stellar population

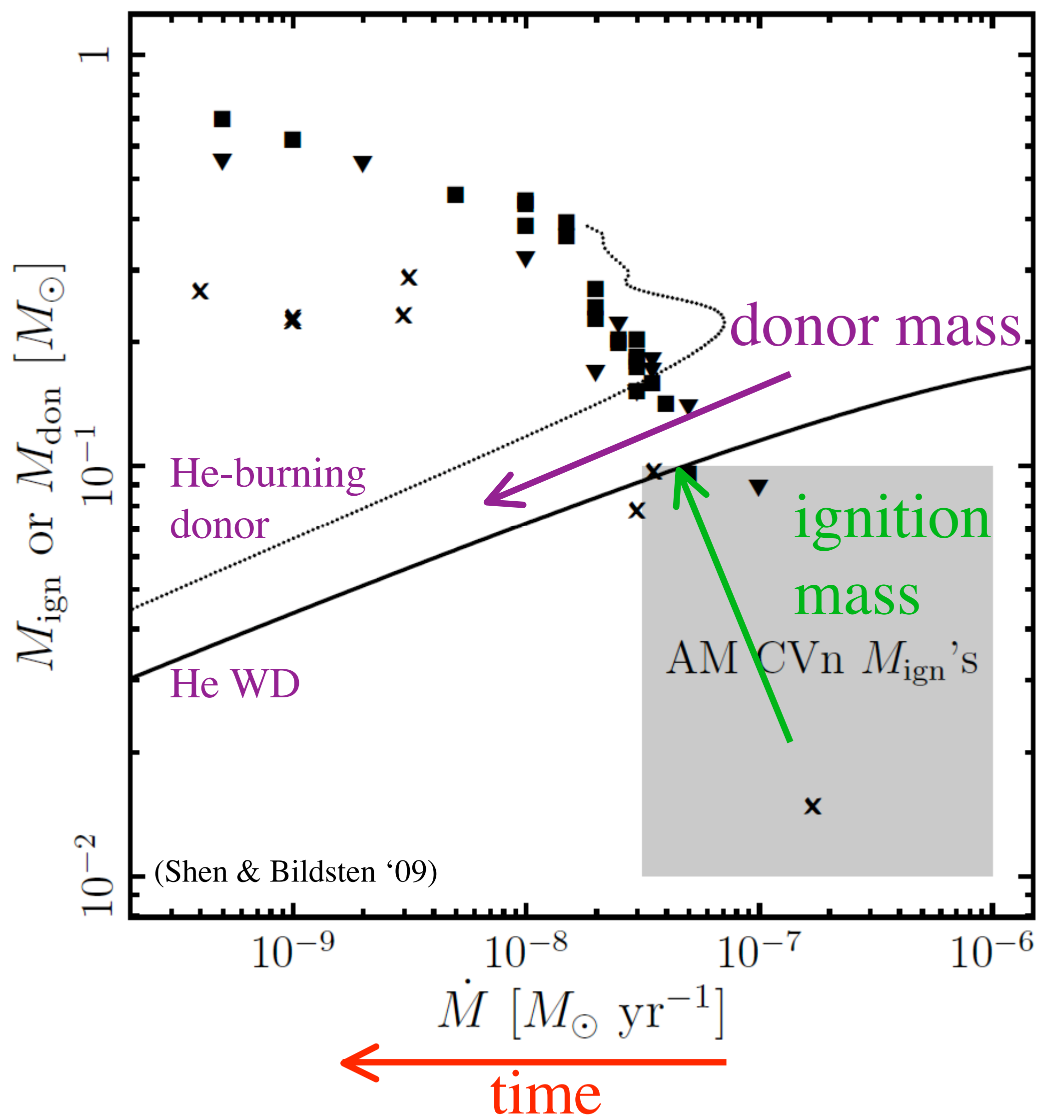


- PTF (R = 21; 2700 deg^2; 5 day cadence): ~ few per yr
- PS-1 medium-deep survey (V = 24; 50 deg^2; 4 day cadence): ~ few per yr

AM CVn evolution and He-burning

(Warner '95; Nelemans '05; Gijs's talk)

- Ultracompact binary with low-mass He donor + C/O or O/Ne WD accretor
- WD donor: initially, very high Mdot > $10^{-6}\ M_\odot$/yr: stable He-burning supersoft sources (Tutukov & Yungelson '96; Shen & Bildsten '07)
- Binary evolves to lower Mdot: ~10 unstable helium flashes (Iben & Tutukov '89)
- Eventually, $M_{donor} < M_{ign}$:
  - No flashes < $10^{-8}\ M_\odot$/yr and P_{orb} > 10 min, just He accretion
  - Last flash has largest $M_{ign} \sim 0.1\ M_\odot$

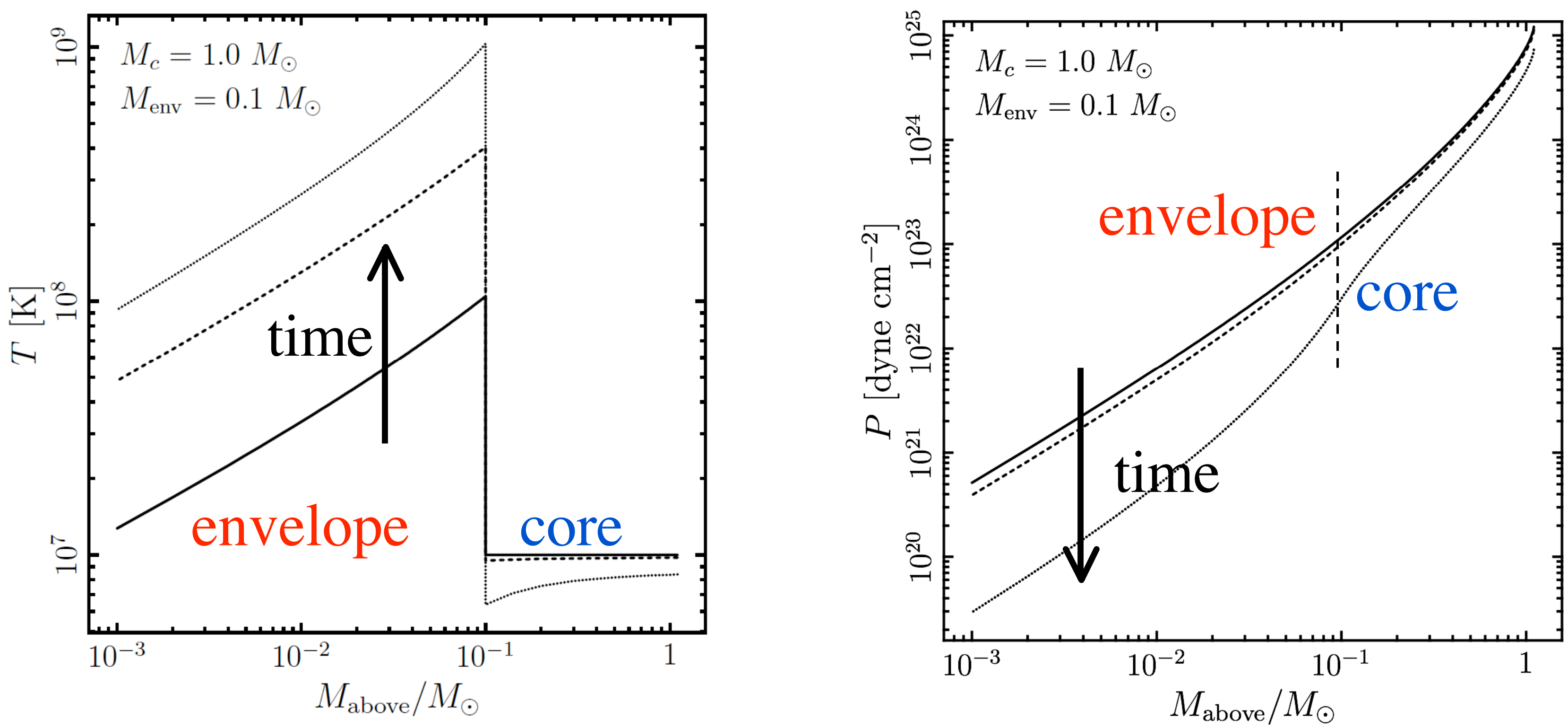


Evolution of the convective phase

- Radiative diffusion becomes inefficient at transporting heat → convection
- He-burning injects entropy into the convective (isentropic) shell, raising T:

$$Tds = du + Pd(1/\rho)$$

- Initially no expansion work done because shell is geometrically thin (i.e., $P_b \sim GM_cM_{\rm env}/4\pi R^4$), but eventually $T_b \sim T_{\rm virial}$



Small $M_{\rm ign}$: He nova
Large $M_{\rm ign}$: He detonation(?)

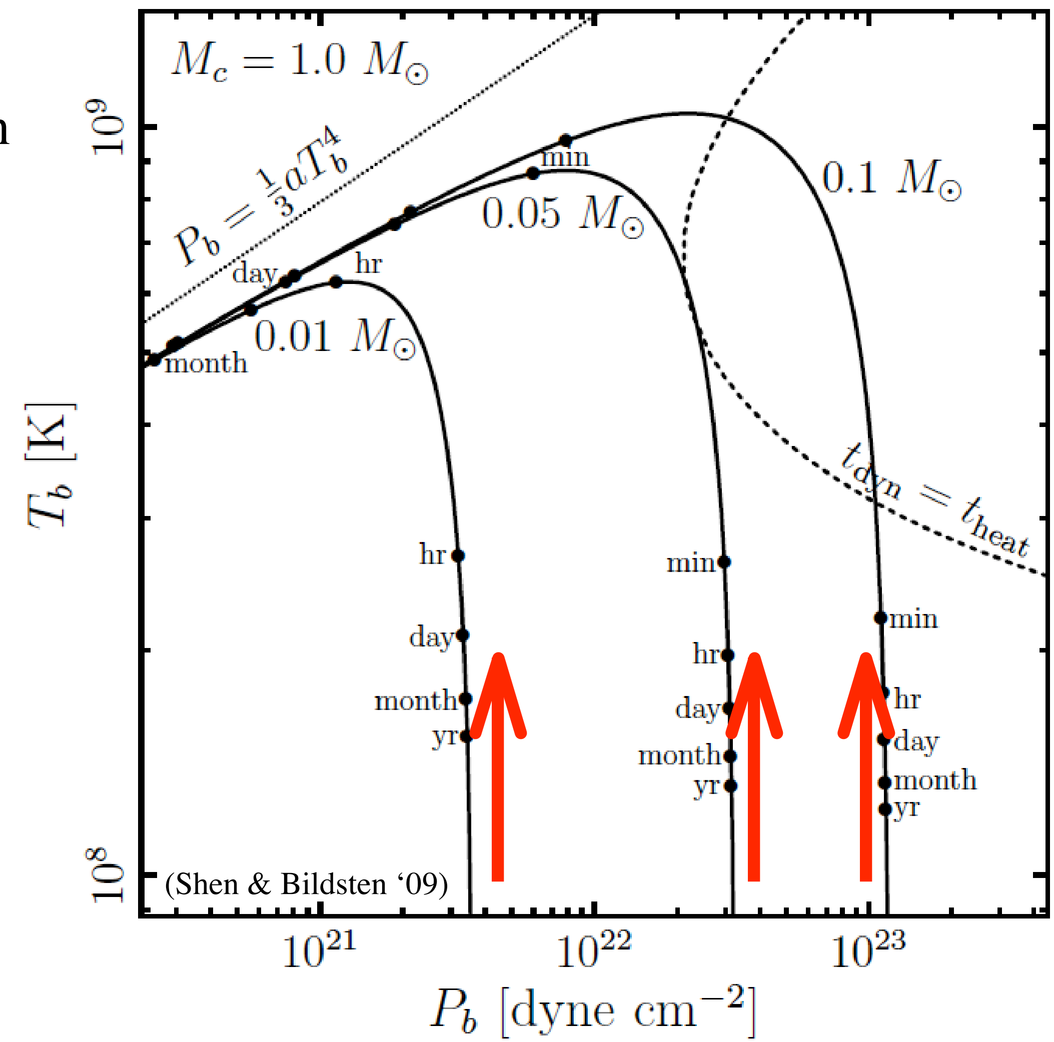
- For smaller envelopes < $10^{-2}\ M_\odot$, entropy increase eventually leads to expansion, like a hydrogen classical nova in a regular CV: He nova (e.g., V445 Pup)

- For larger envelopes, the heating timescale can become shorter than the dynamical timescale, yielding hydrodynamical burning:

$$t_{\rm heat} = \frac{c_P T}{\epsilon_{\rm nuc}}$$

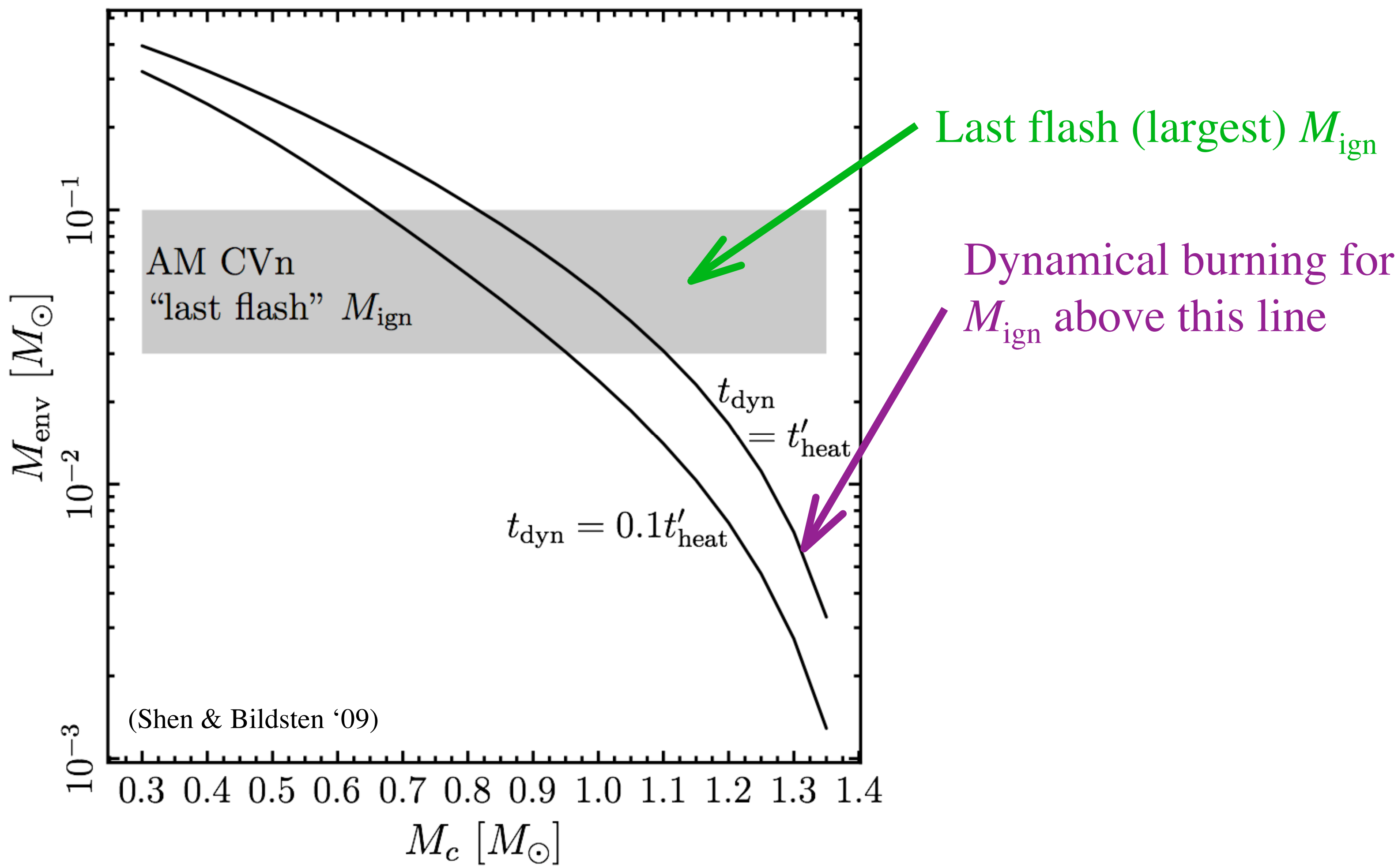
$$t_{\rm dyn} = \frac{H}{c_s} = \sqrt{\frac{P}{\gamma \rho g^2}}$$

- There is a minimum $M_{\rm env}$ that achieves hydrodynamical burning and could detonate

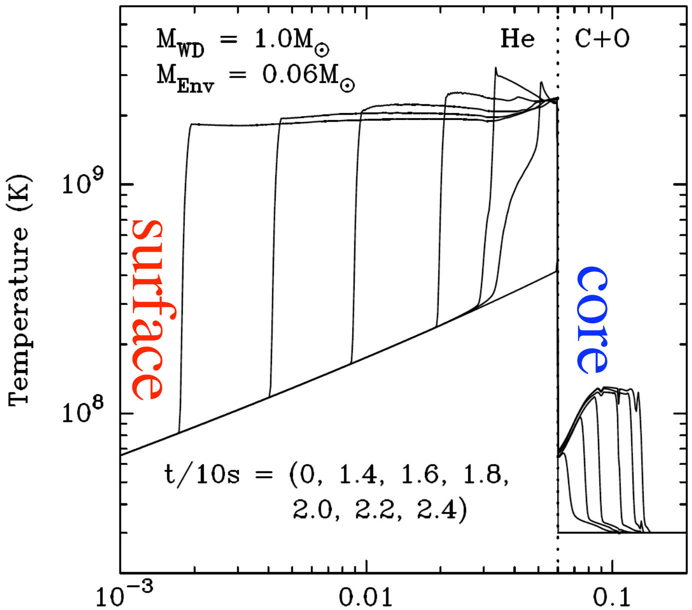


Many AM CVn's could undergo He detonations

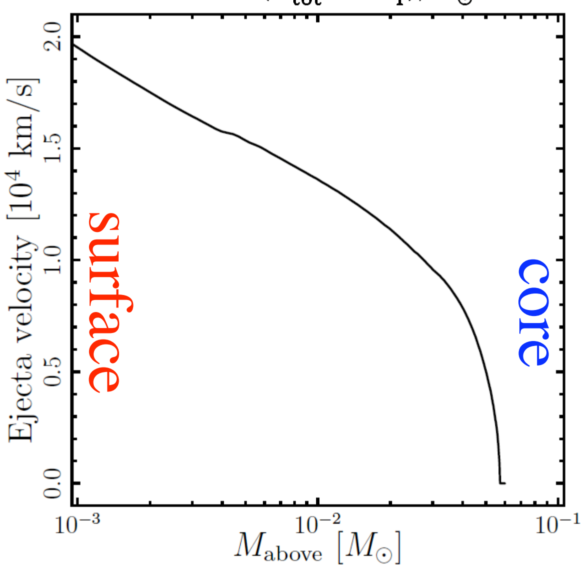
- Last flash for each system is the biggest
- For $M_c > 0.8\ M_\odot$, last flash should be dynamical / detonation



Outcome of 1D radially propagating detonation: 0.06 + 1 $M_\odot$



(Shen et al. '09)



- 1D spherically symmetric detonation initiated at interface between 0.06 $M_\odot$ He envelope and 1.0 $M_\odot$ C/O core
  - This is a *single* example; different M_{ign}, M_{WD}, composition will yield a *range*
  - Actual detonation geometry could be different (e.g., tangentially propagating)

- Edge of C/O core not detonated by shock (but maybe focusing could do it in the center; Woosley & Weaver '84; Livne & Glasner '90, '91; Fink et al. '07)

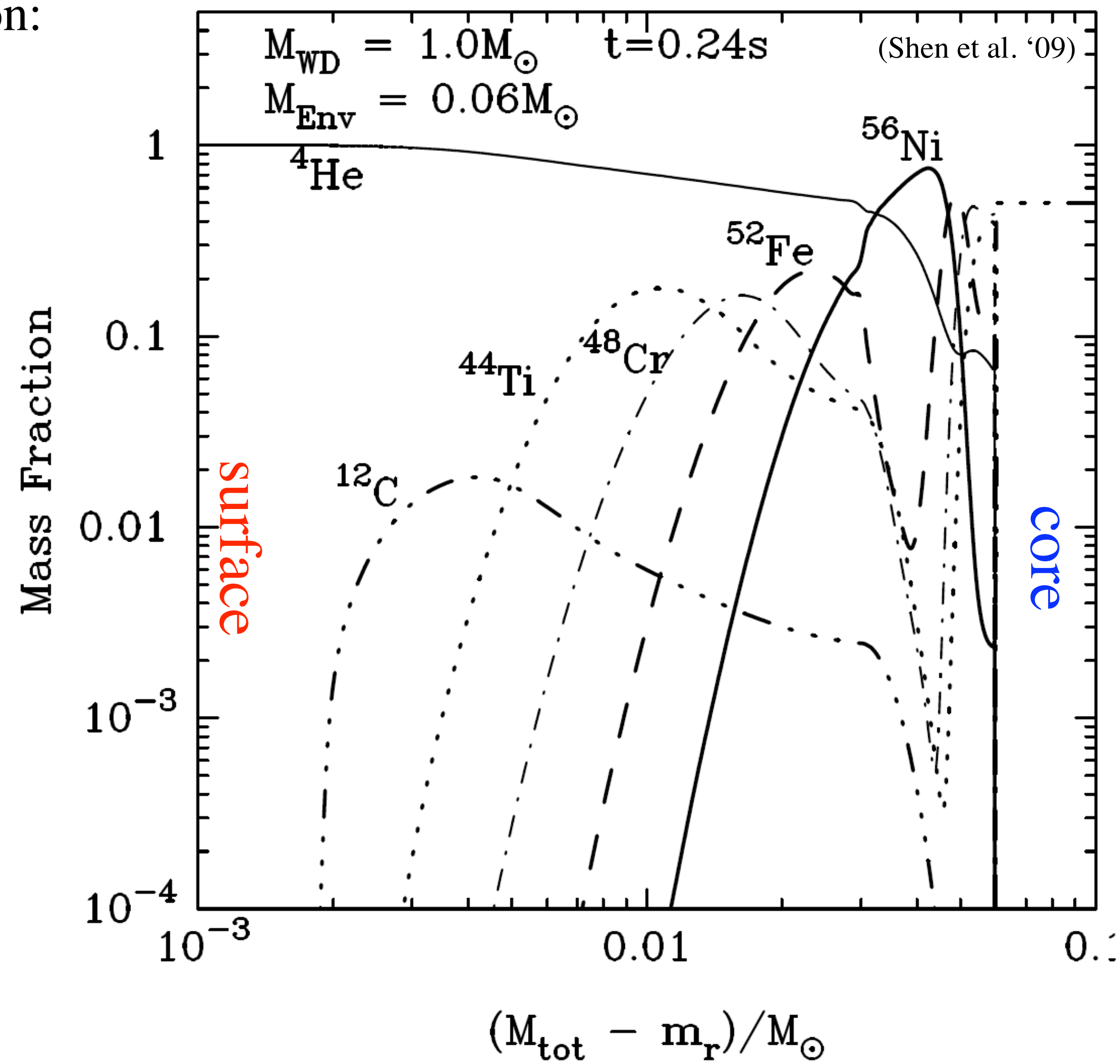
- Nearly all of the envelope ejected with $v_{ej} \geq 8000$ km/s

Nucleosynthesis

- Dominant ejecta composition:

Isotope	M $[M_\odot]$
^{4}He	0.025
^{40}Ca	0.001
^{44}Ti	0.004
^{48}Cr	0.007
^{52}Fe	0.007
^{56}Ni	0.015

- Lots of unburned He
- Everything else combined $< 10^{-3}\ M_\odot$
  - Very few IMEs



Light curves

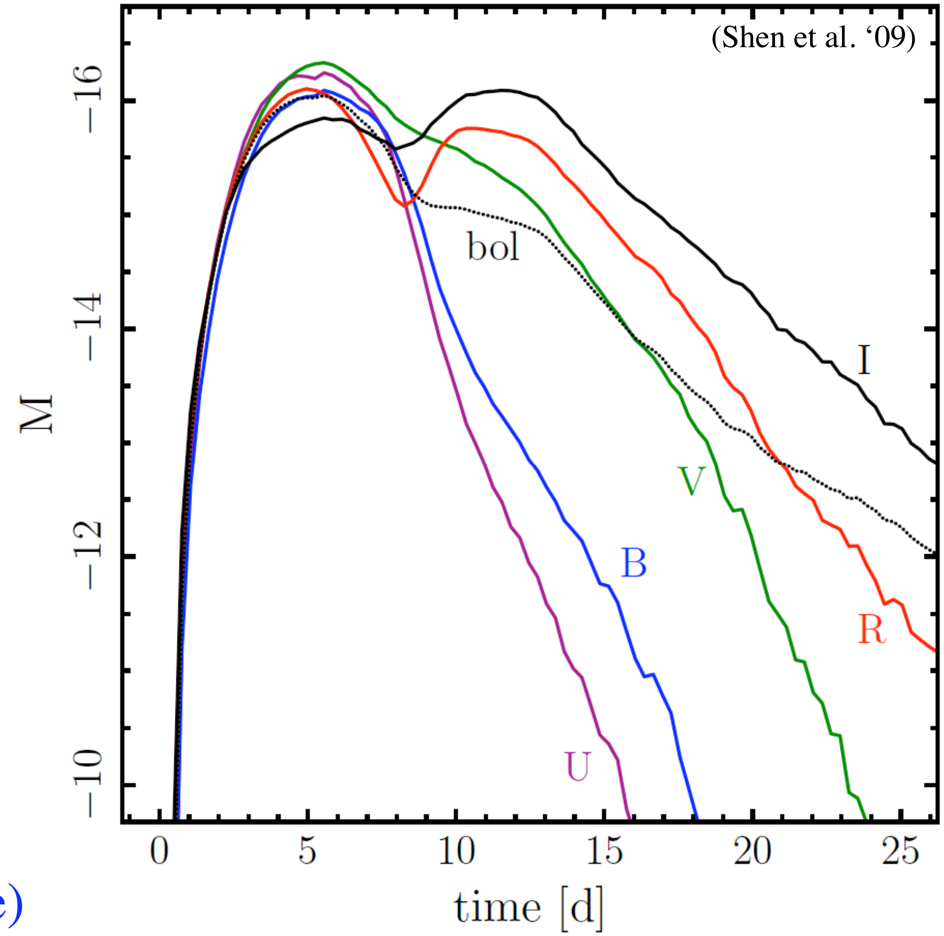
- Time to peak is when rise time equals $t_{\rm diff}$ (Arnett '82; Pinto & Eastman '00):

$$t_{\rm peak} \simeq \sqrt{\frac{\kappa M_{\rm ej}}{7 c v_{\rm ej}}} \sim 4 \text{ d}$$

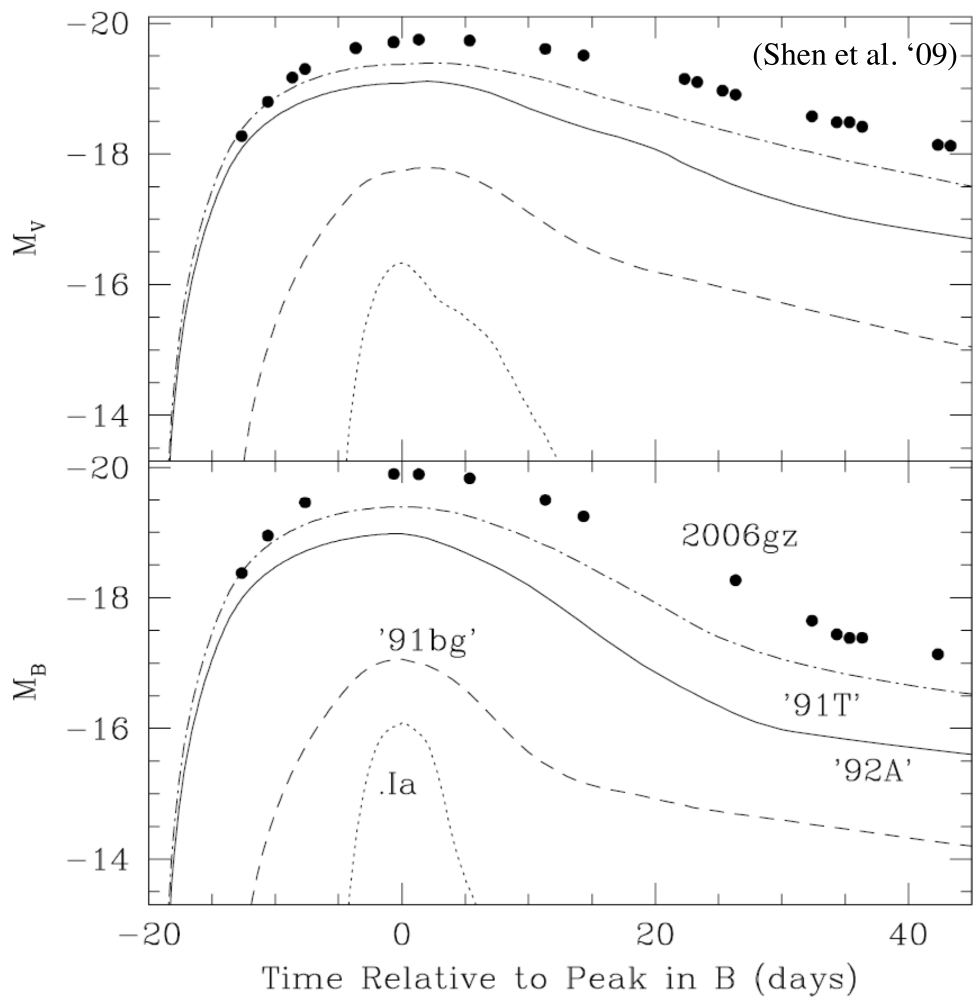
(Bildsten et al. '07)

- $L_{\rm peak}$ set by instantaneous radioactive decay: can catch quick decays of ^{48}Cr, ^{52}Fe, and ^{56}Ni
  - NB: code is missing energy input from ^{48}Cr and ^{52}Fe decays

- Secondary NIR max due to Fe-group recombination effects on UV/blue opacity (Kasen '06)
  - $M_B < -14$ for 9 d (for this example)
  - $M_R < -14$ for 17 d

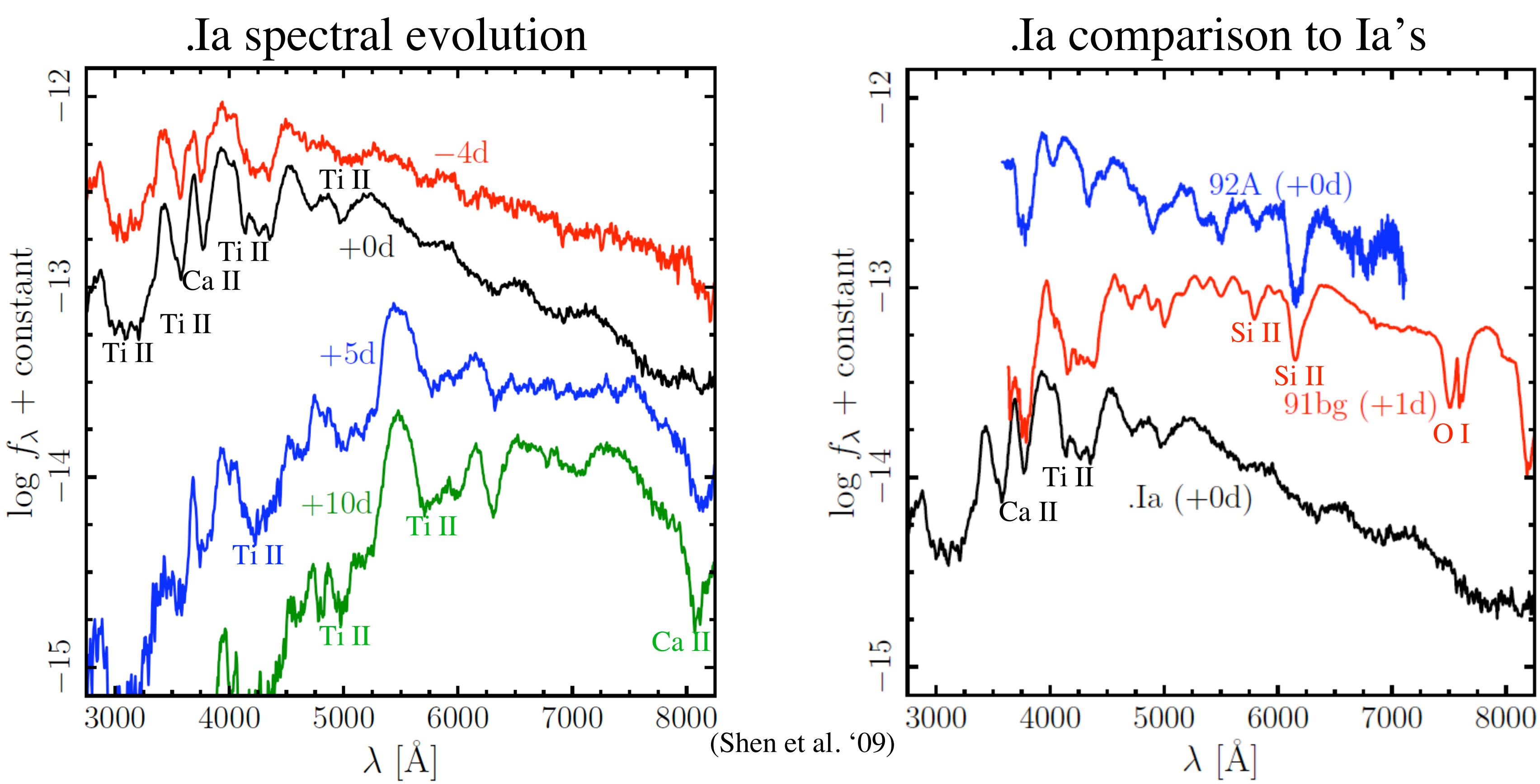


Comparison to SNe Ia



- Definitely faster than even sub-luminous Ia's
  - Hard to get around that result given small M_{ej}
- Think of magnitude as a guide:
  - Fainter than typical SNe Ia, but depending on exact nucleosynthesis, could be much dimmer or could be comparable to faint Ia's
  - I.e., don't rule out .Ia's if magnitudes don't quite match

Spectral evolution and comparison at peak



(Shen et al. '09)

- Strong Ti features as in subluminous Ia's
- But essentially no Si (only $7\times10^{-5}\ M_\odot$)

Caveats and conclusions

- AM CVn evolution leads to dynamical He shell explosions
- Does He detonation propagate?
  - ZND length (reaction width) << scale height, and accelerants like ^{12}C, ^{14}N, and ^{16}O will make it even more likely; more work in progress
- Can core be detonated by focusing of inward shocks?
  - Double detonations previously studied with larger M_{env}, but Fink et al. '07 found shock focusing and core detonation with .Ia-sized envelopes
  - O/Ne core?
  - Jury is still out, but if core is detonated, we'd definitely see those events too
- If propagating He detonation and undetonated C/O core: .Ia supernova
  - Quick rise of a few days, ~10% as long as SNe Ia, allowing short-lived radioactivity to be seen
  - Peak ~10% as bright as SNe Ia (but likely a large range)
  - AM CVn birth rate gives upper limit of a few percent of the Ia rate in E/S0
  - Upcoming (and maybe current) optical surveys could see a few every year! (And 05E, 08ha, and others [Perets et al. '09; Foley et al. '09; Dovi's talk tomorrow] are definitely interesting…)