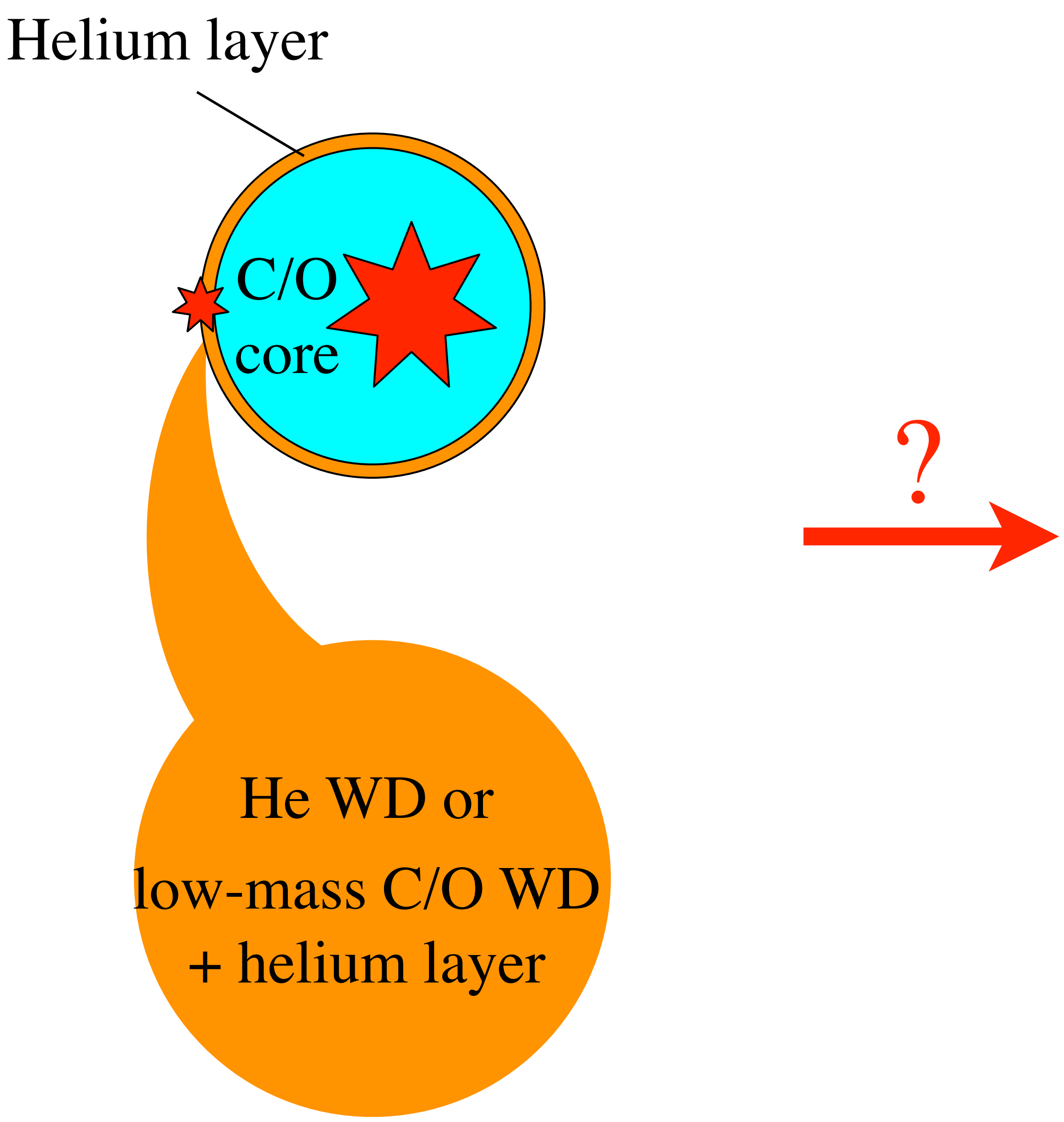
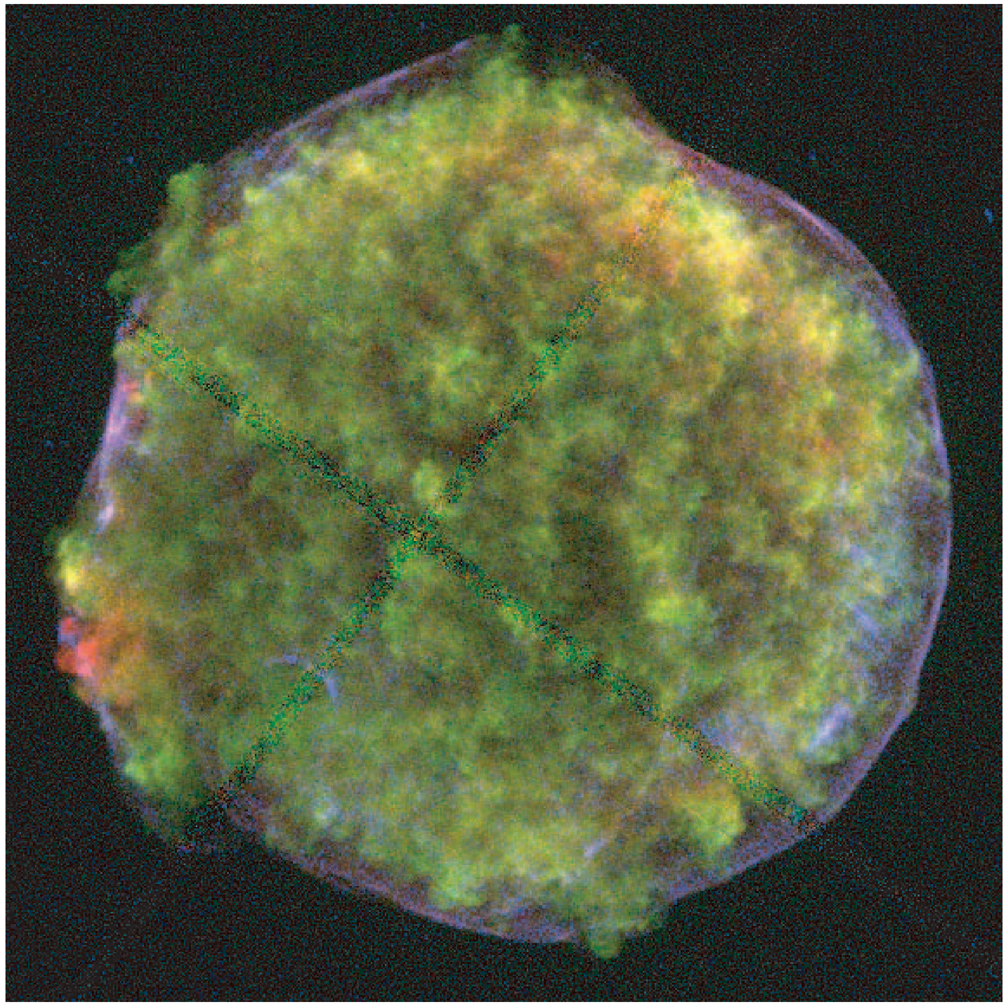
Carnegie / 05 August 2015

Double detonations in double white dwarf binaries

Ken Shen (UC Berkeley)

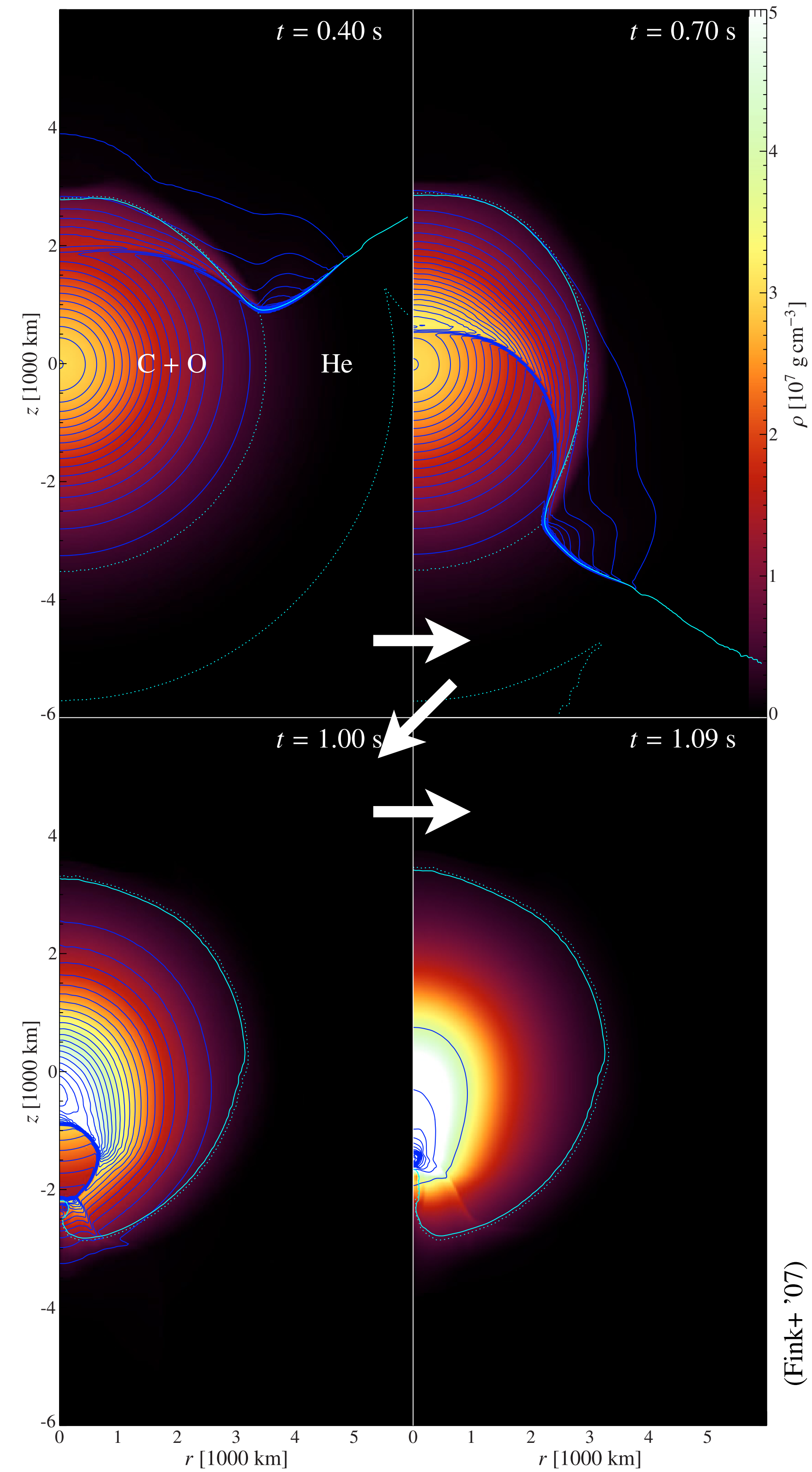




(Warren+ '05)

Double detonations: Overview

- Taam / Nomoto / Woosley+ / Livne+ in 1980s-1990s
- MPA / Woosley & Kasen / etc. in 2000s-2010s
- Helium shell detonation → inward converging shock wave → carbon core detonation
- Pure detonations of ~1.0 Msol C/O WDs: decent match to SNe Ia (Shigeyama+ '92, Sim+ '10, Kromer+ '10)



(Fink+ '07)

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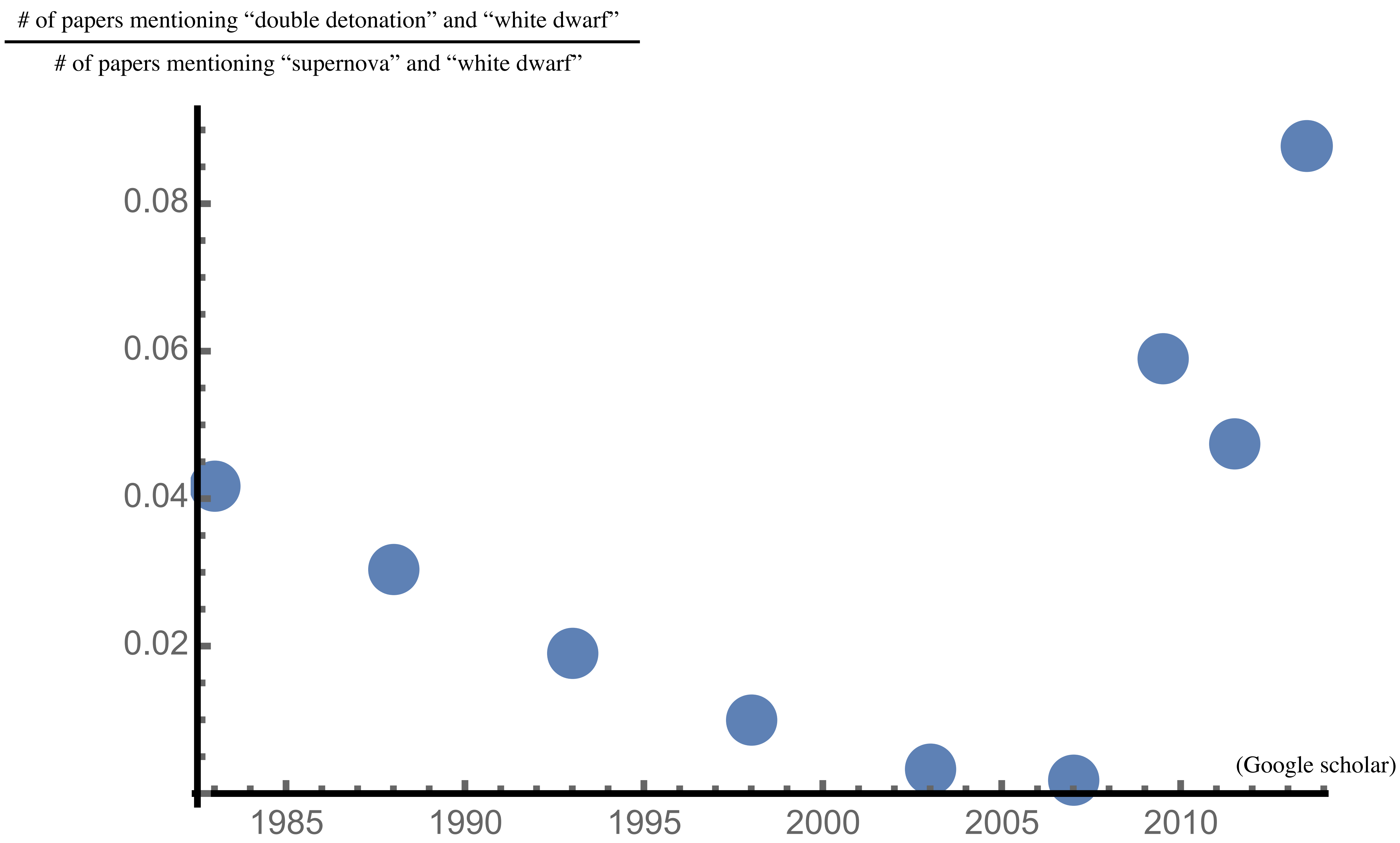
Double detonations: Overview



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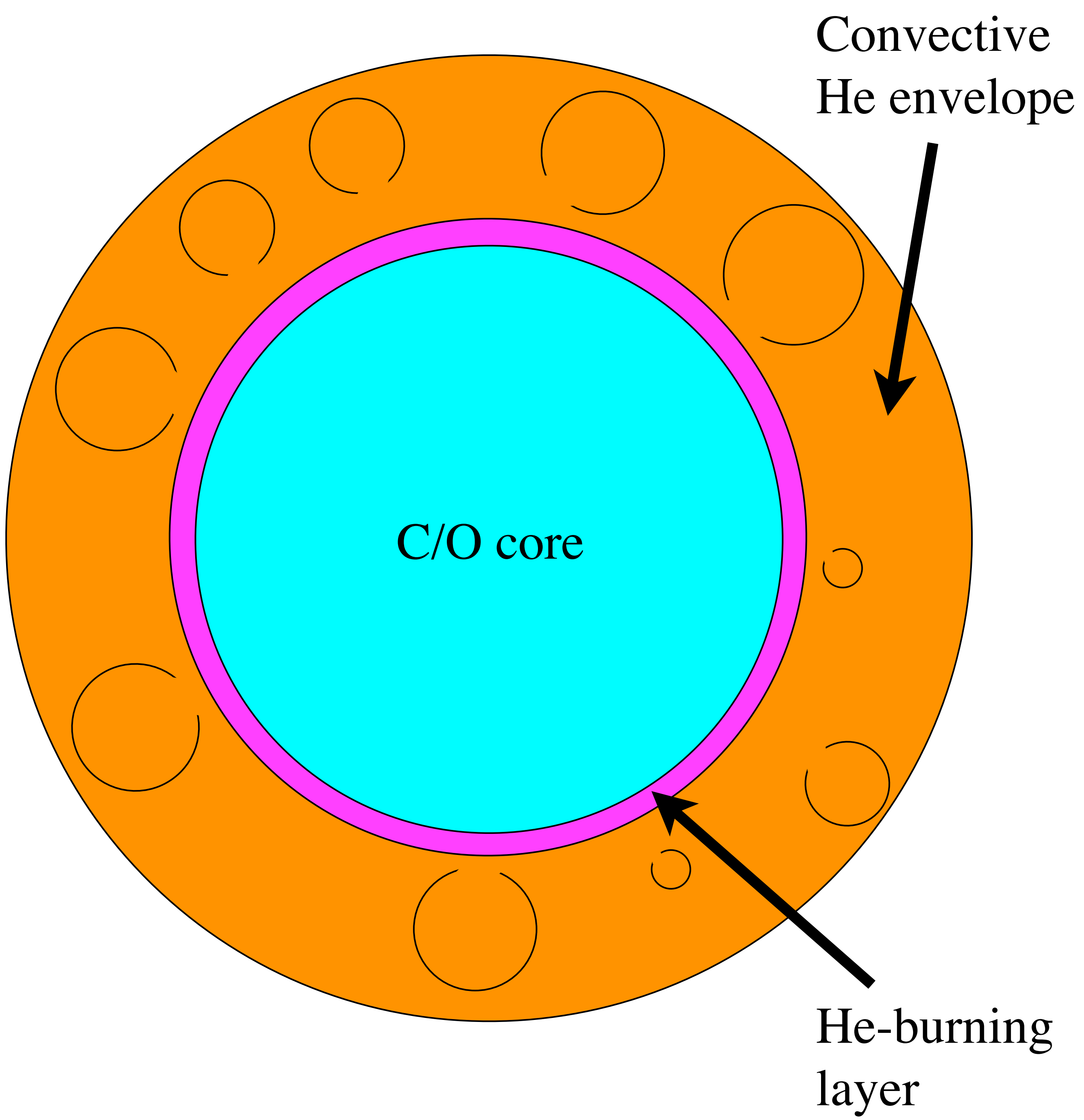
He detonations via stable accretion and convection (~10^6 yr)…

- 1980s-1990s (Nomoto / Woosley / et al.): *stable H-burning or He MS donor* (sdB/sdO)
- Late 2000s (Bildsten, Shen, et al.): *low-mass He WD donor* (low mass ratio, pre-AM CVn)
- For “large enough” He shell, convective transport is inefficient → strong turbulent fluctuations



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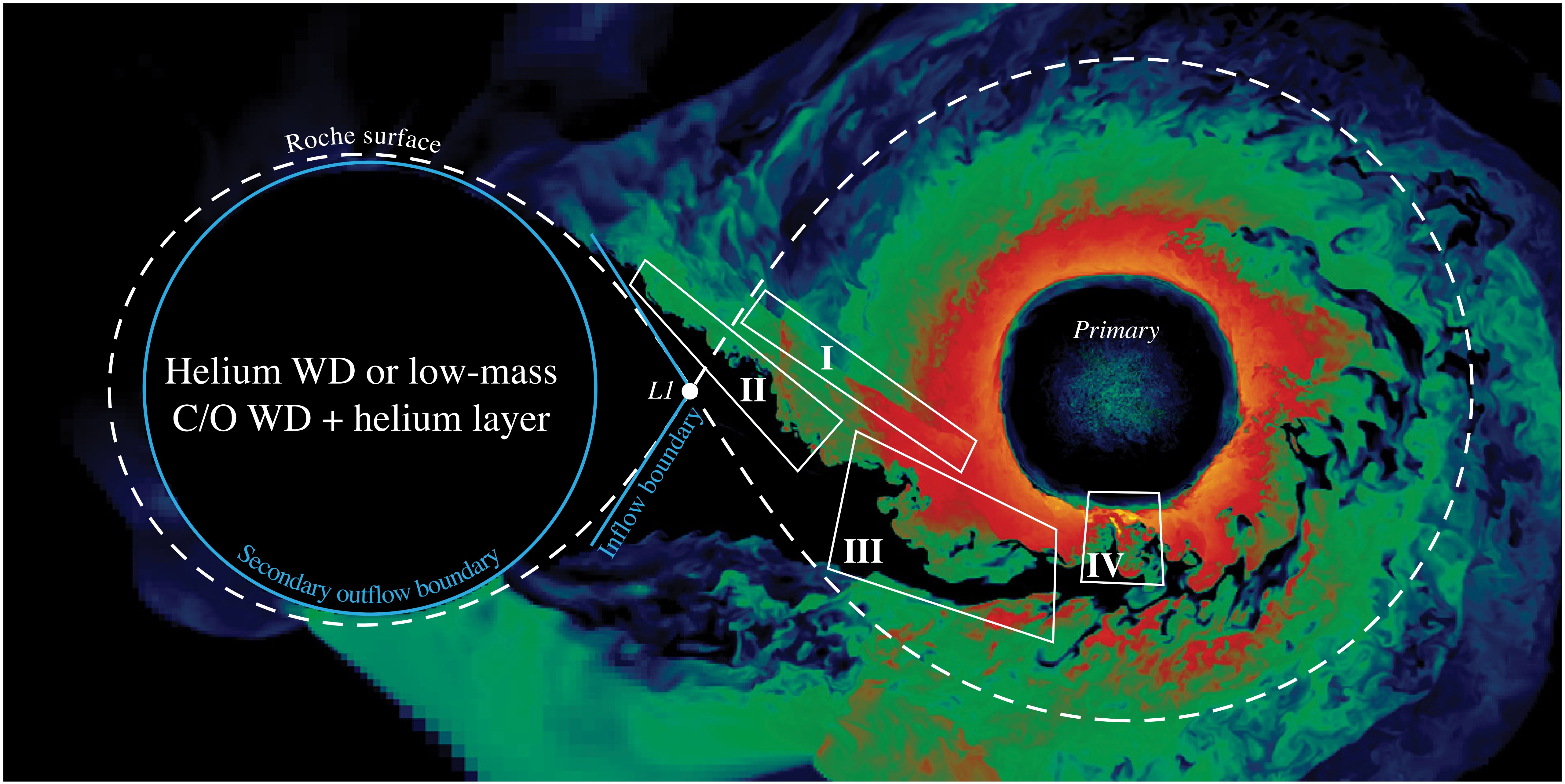
…Or He detonations via dynamical accretion (~100 s)

- 2010s (Guillochon / Dan / Raskin / Pakmor):
  Dynamical processes during He + C/O or C/O + C/O WD merger
- Especially if all double WD binaries merge (Shen ’15a)



(Guillochon+ ’10)

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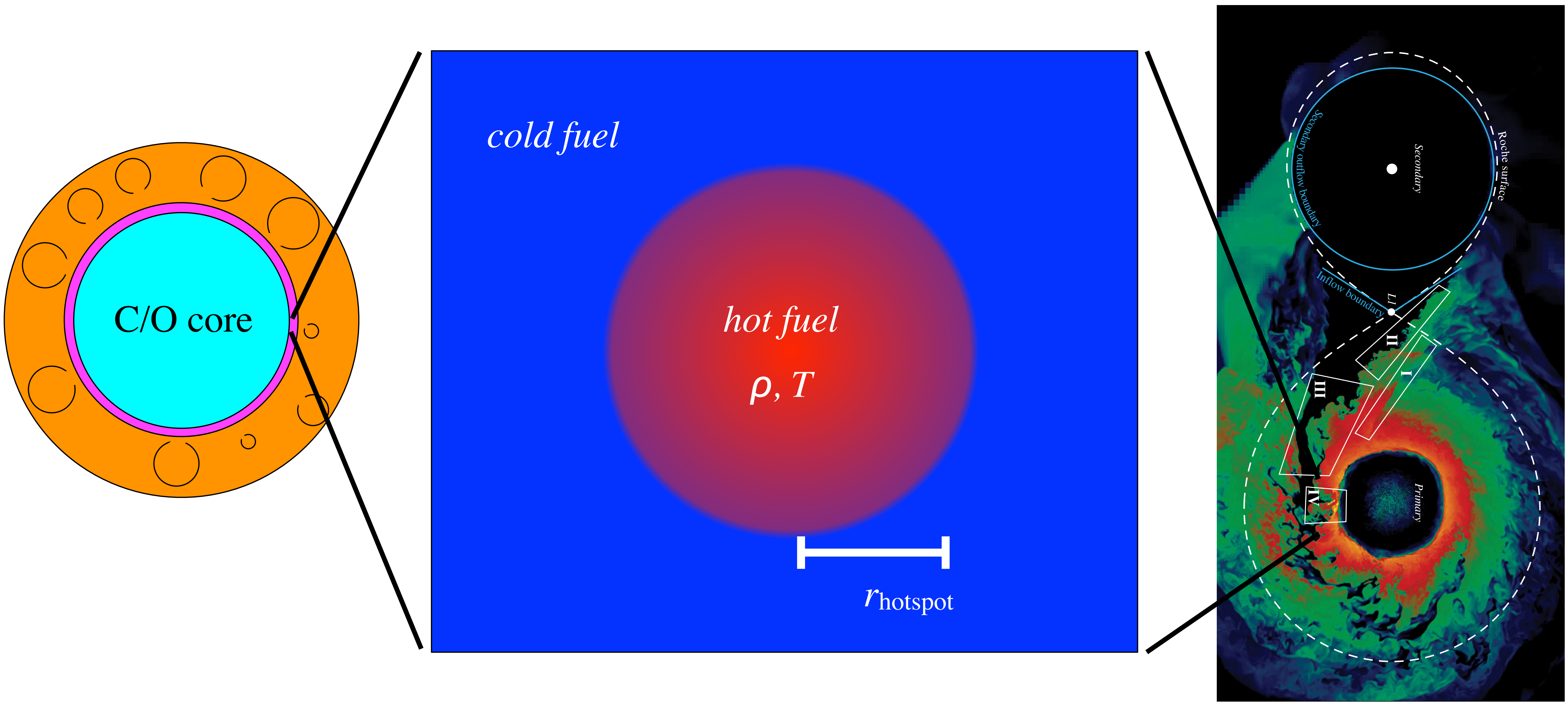
First detonation: Does the helium ignite? Likely yes



- Spontaneous initiation via Zel'dovich gradient mechanism → minimum r_{hotspot}
- Hotspot expectations: $T \sim 10^9$ K, $\rho = 10^5$ - 10^6 g/cm^3
- Shen & Moore '14: Small CNO pollution + complete nuclear network
  → **Minimum r_{hotspot} < 10-100 km, helium detonation easy to ignite**

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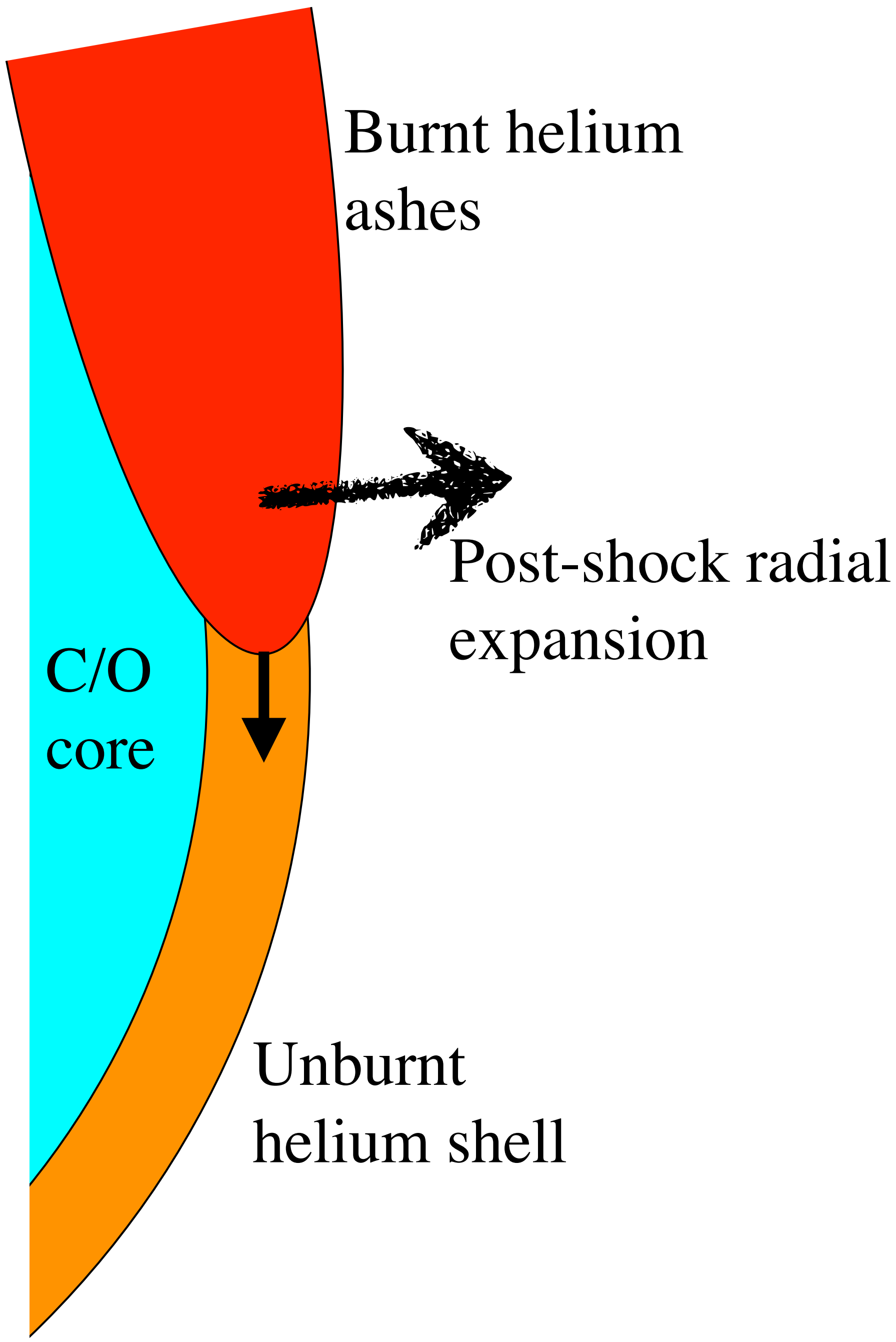
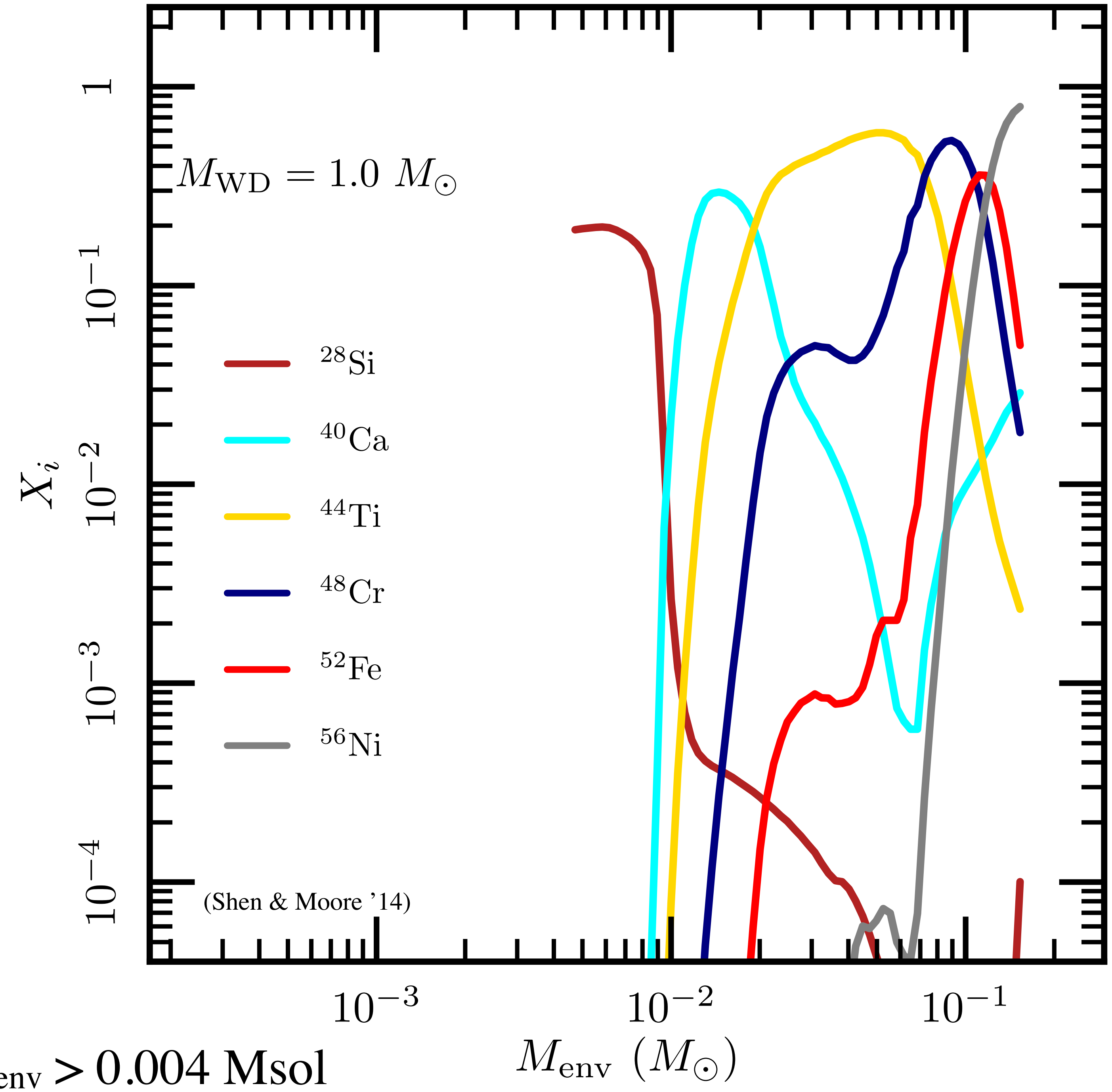
Does the helium detonation propagate? Yes, even for small shells





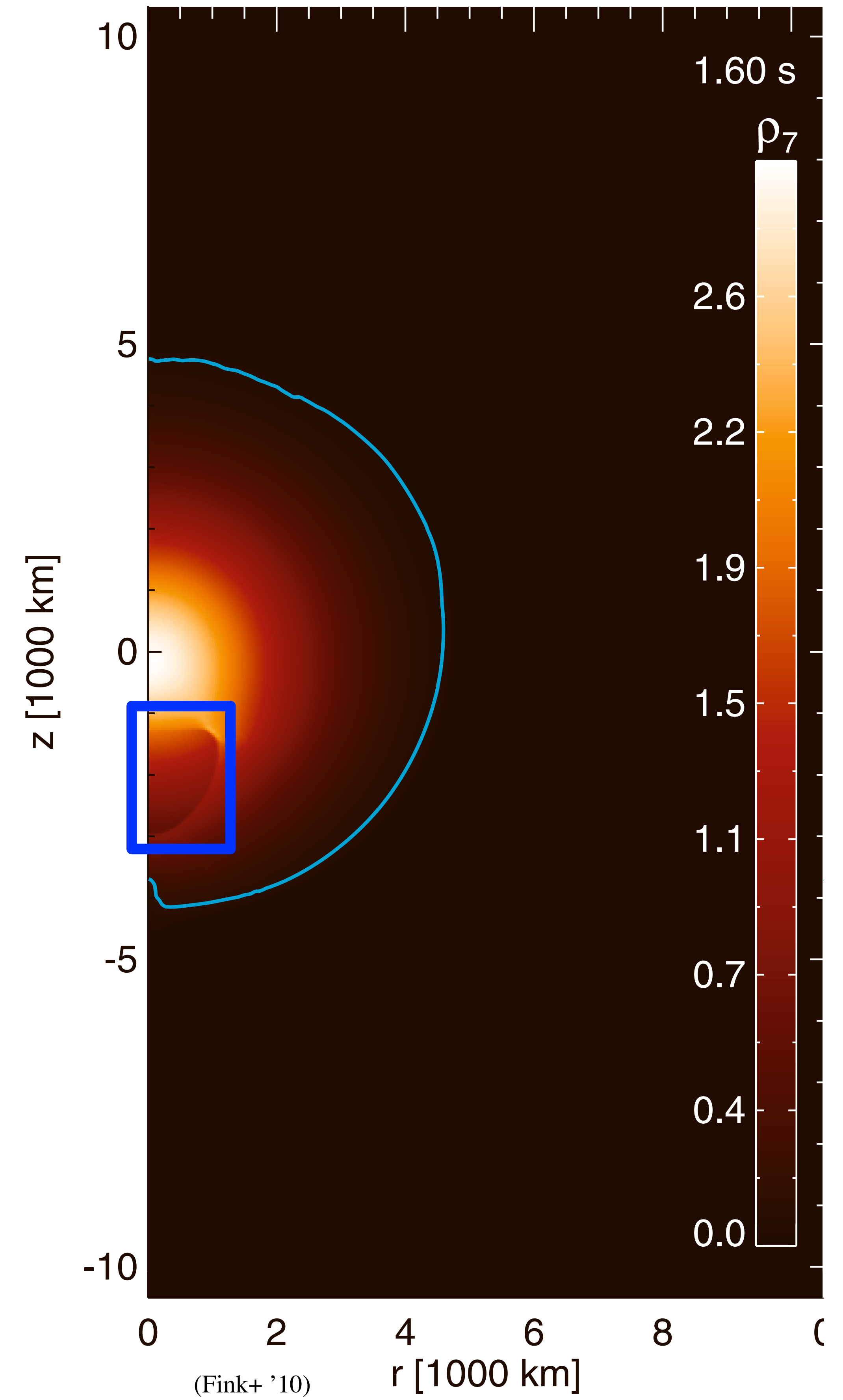
- Helium detonation propagates for $M_{\rm env} > 0.004$ Msol
  - 0.7 Msol C/O WD donor has ~0.01 Msol He layer
- Smallest (first) helium detonations → **^{28}Si + ^{40}Ca + unburnt ^{4}He**
  - No IGE
  - High velocity features? Asymmetry (accretion stream, point explosion, etc.)?

Second detonation: Does the C/O ignite? Likely yes

- Impossible to resolve ignition in full-star 2D sim (burning lengthscale ~ 0.1-1 cm ; $R_{WD} \sim 10^{8\text{-}9}$ cm)

- Shen & Bildsten '14: zoom in on the inner $10^3 - 10^5$ cm around focal point in 1D spherical symmetry
  - **C/O easy to ignite via converging shocks**
  - O/Ne very difficult (high primary mass cutoff)
  - Lower densities difficult (low primary mass cutoff)

- Also the possibility of "edge-lit" detonation
  - Not well-studied yet



(Fink+ '10)

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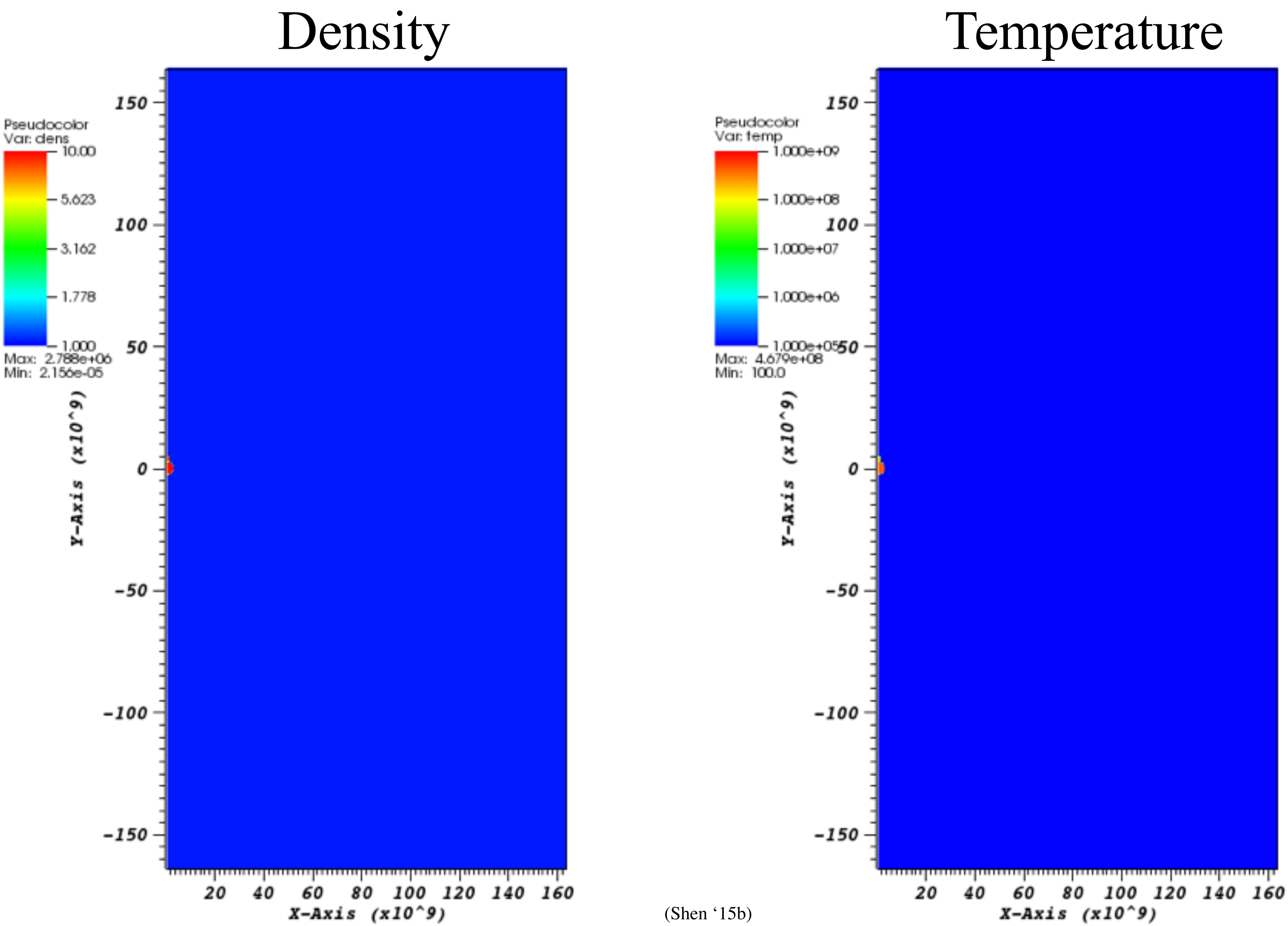
How does a surviving companion influence the remnant?

- If it survives, RLOF companion (non-degenerate or WD) casts shadow



(Shen '15b)

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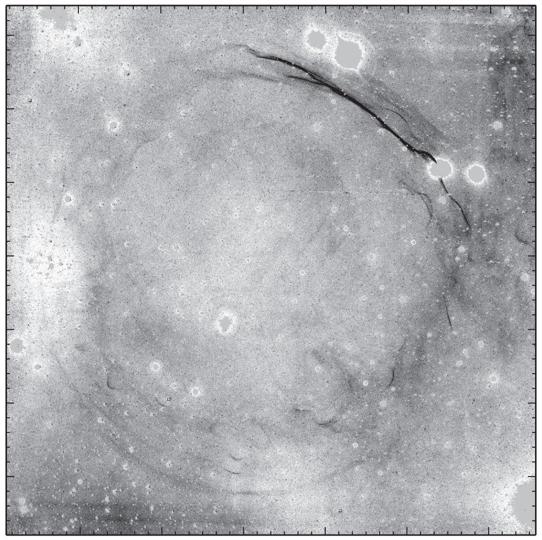
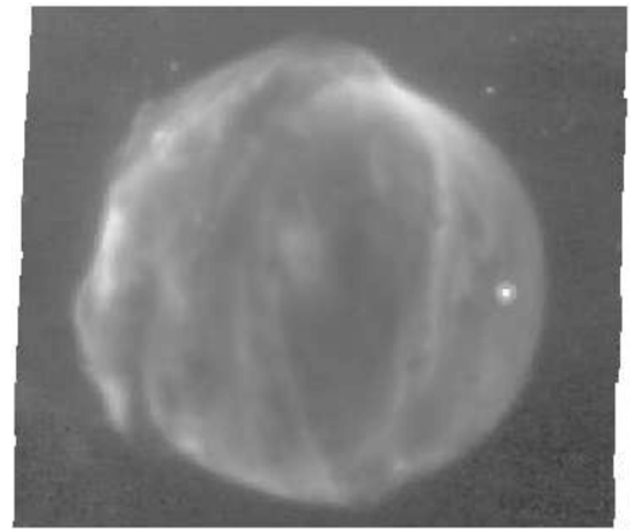
SNR forward shock is usually spherical (more or less)

SN 1006, Hα



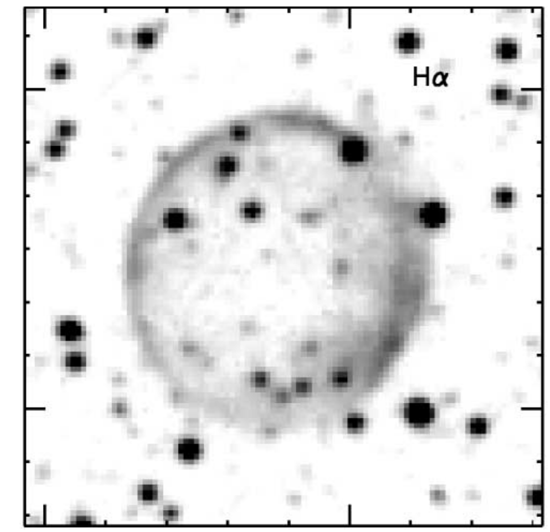
(Winkler+ '14)

Tycho, 24 μm



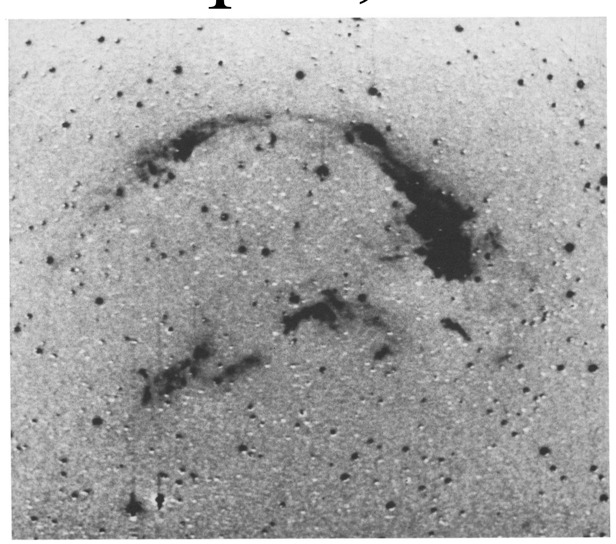
(Williams+ '13)

LMC 0509, Hα



(Warren & Hughes '04)

Kepler, Hα



(Blair+ '91)

RCW 86, Hα

(Smith '97)

- Almost certainly dominated by ISM inhomogeneities, but could mask ejecta asymmetry

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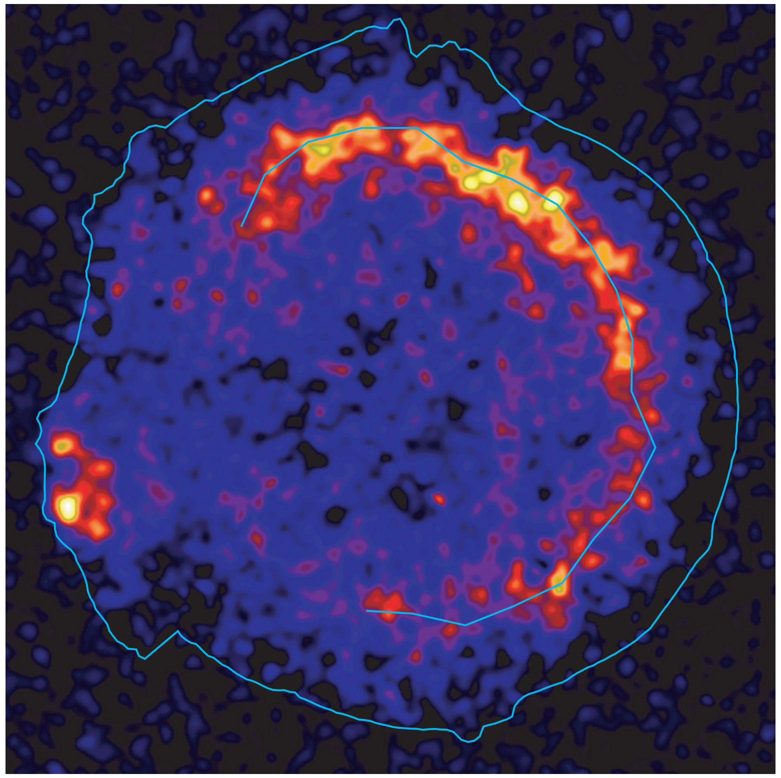
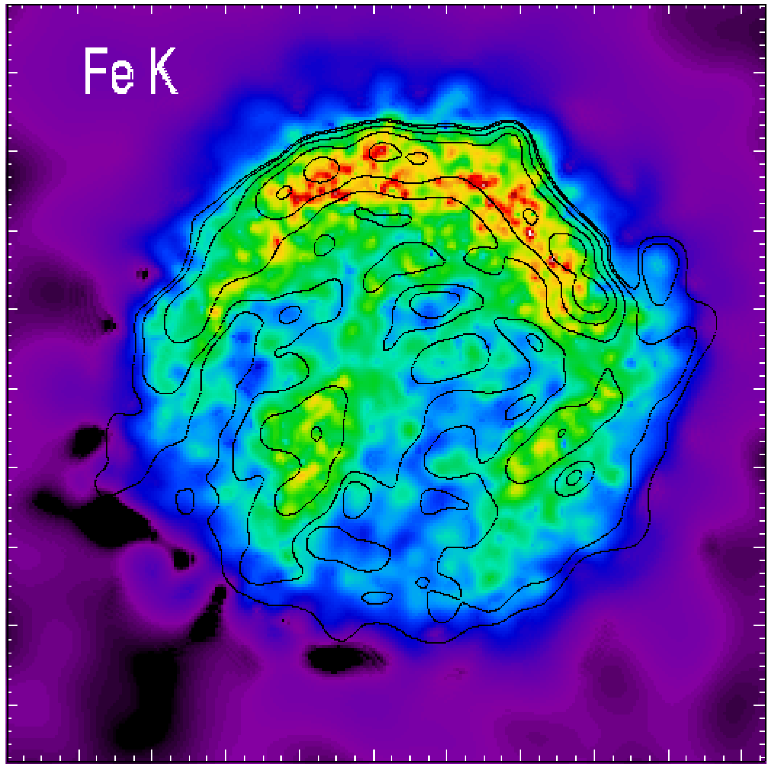
Reverse-shocked ejecta less spherical

Tycho, Fe Kα



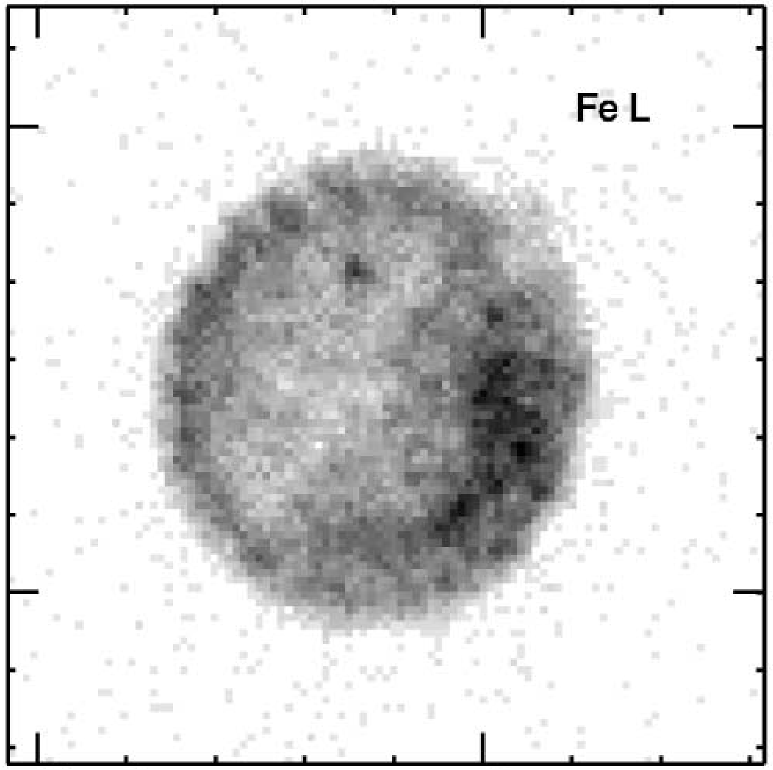
(Warren+ '05)

Kepler, Fe Kα



(Cassam-Chenaï+ '04)

LMC 0509, Fe L



(Warren & Hughes '04)

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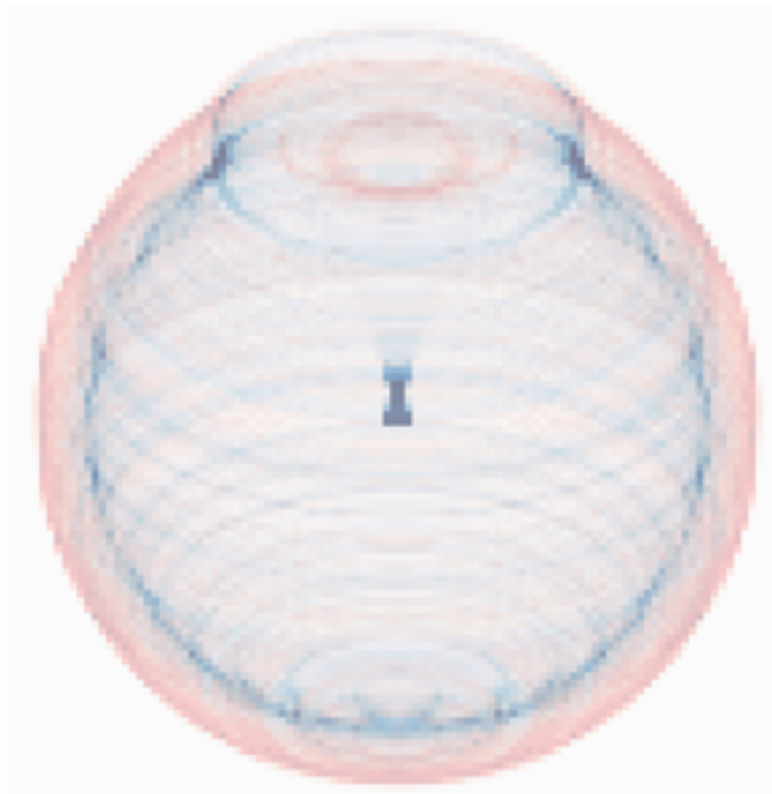
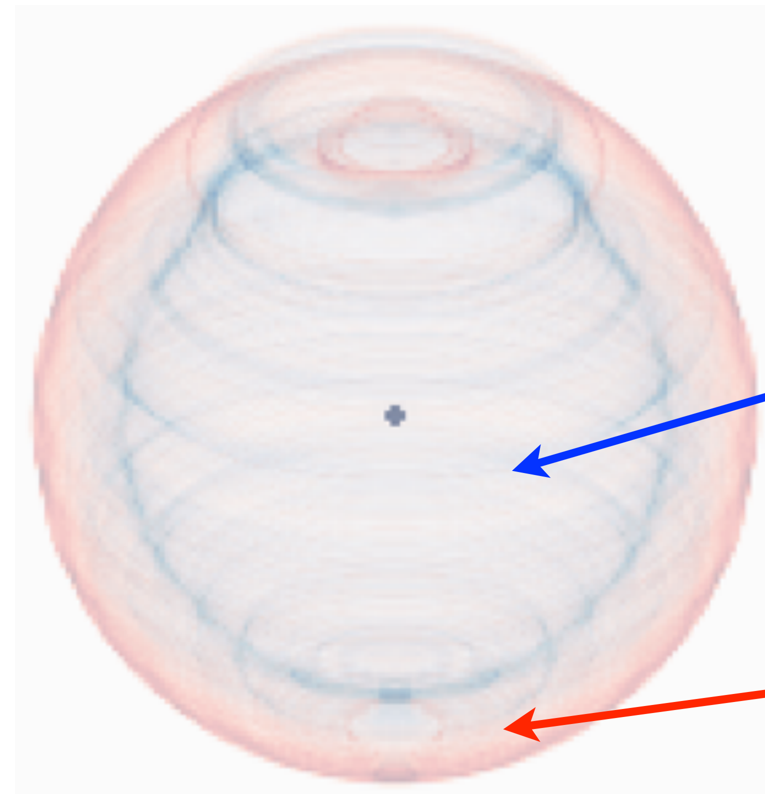
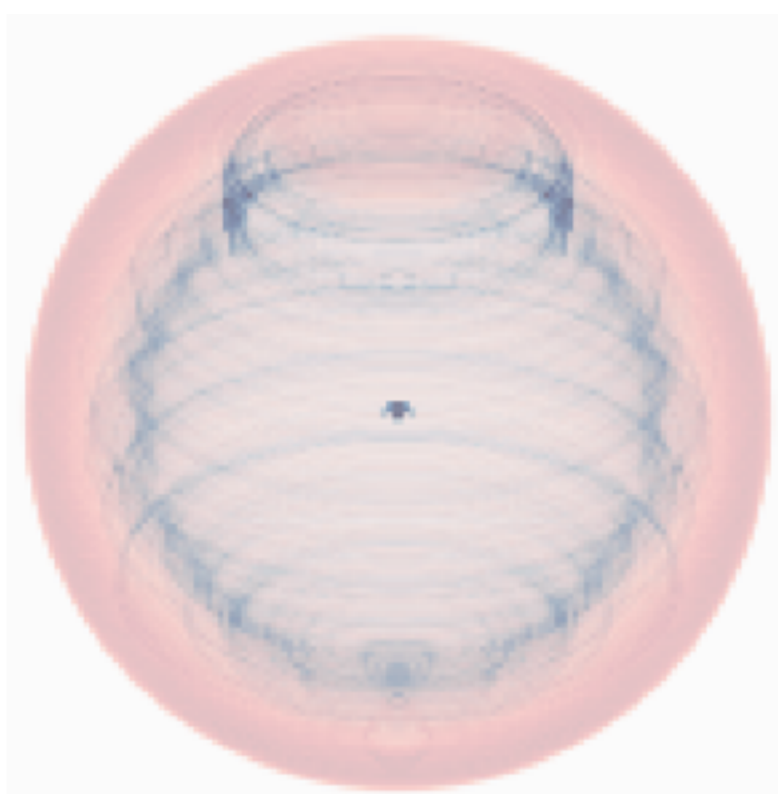
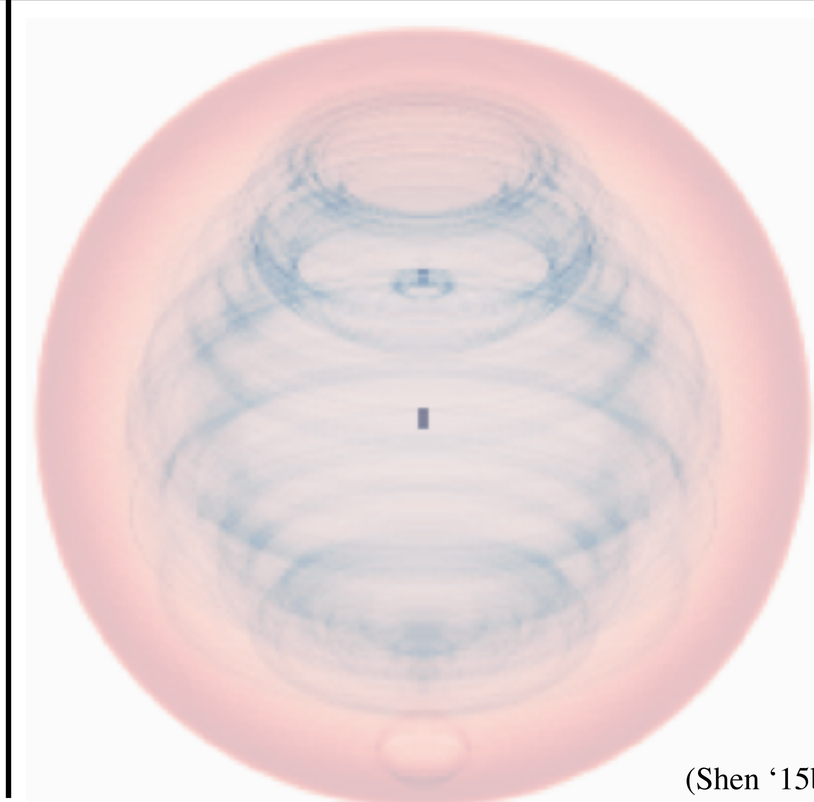
Emission maps

	$v_{\text{forward shock}} = 5000$ km/s	$v_{\text{forward shock}} = 3000$ km/s
$\gamma = 1.2$		
$\gamma = 5/3$		

Density[2] integrated along line of sight, viewed at 30°

Reverse-shocked SN ejecta

Forward-shocked ISM

(Shen '15b)

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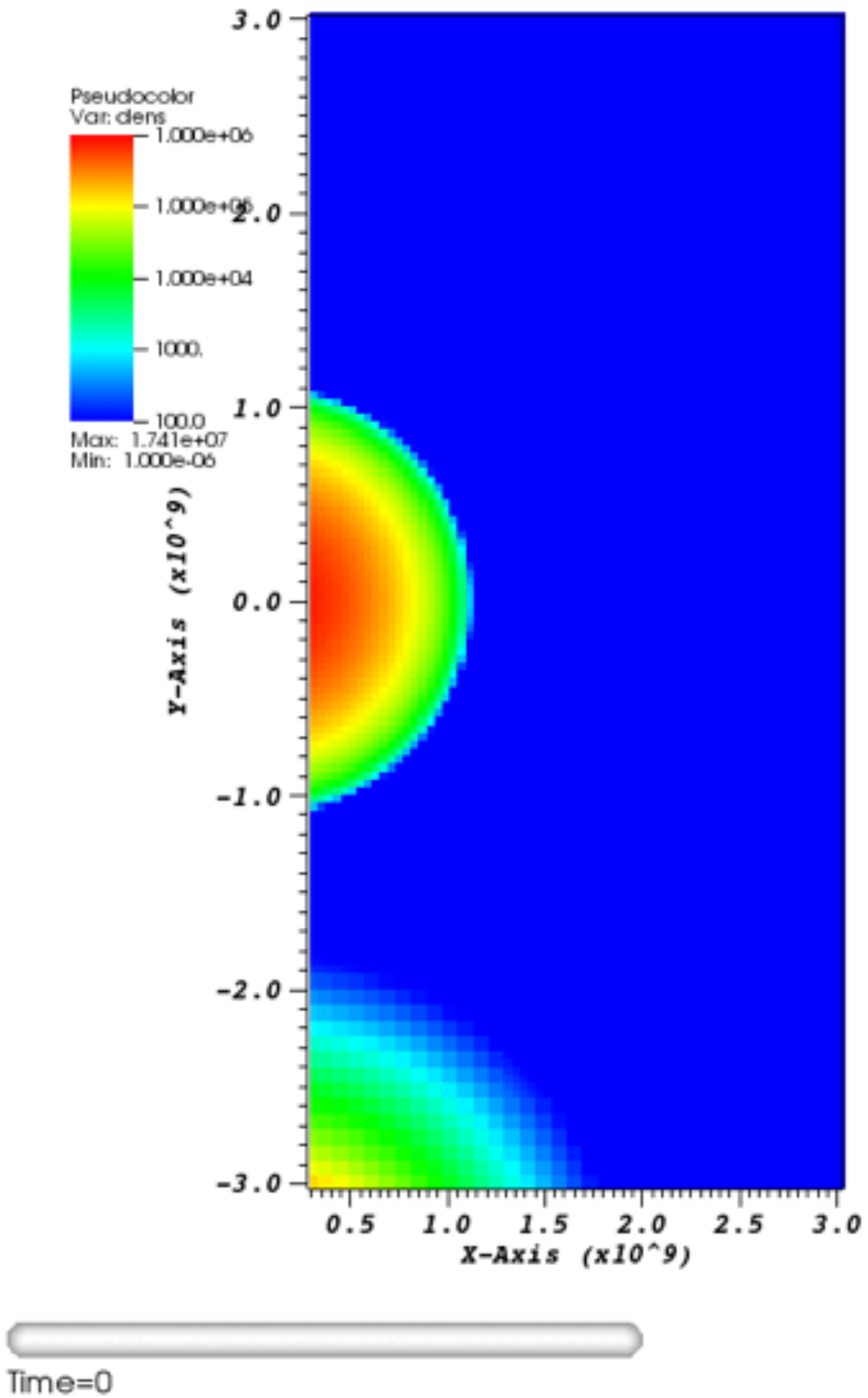
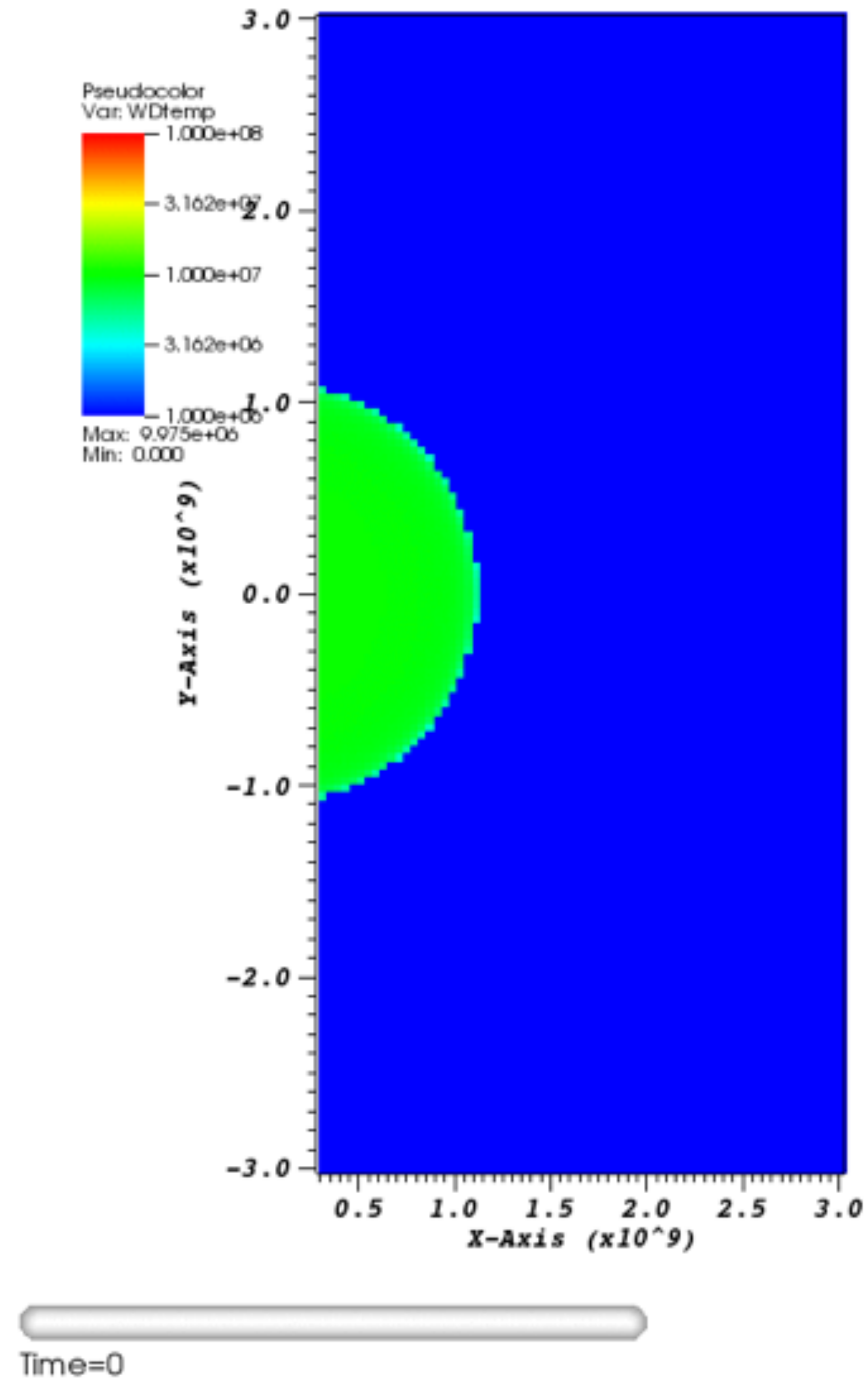
How does the ejecta influence a surviving companion WD?

- If WD companion survives, will be shock heated and polluted with ^{56}Ni

Density



Temperature



(Shen '15c)

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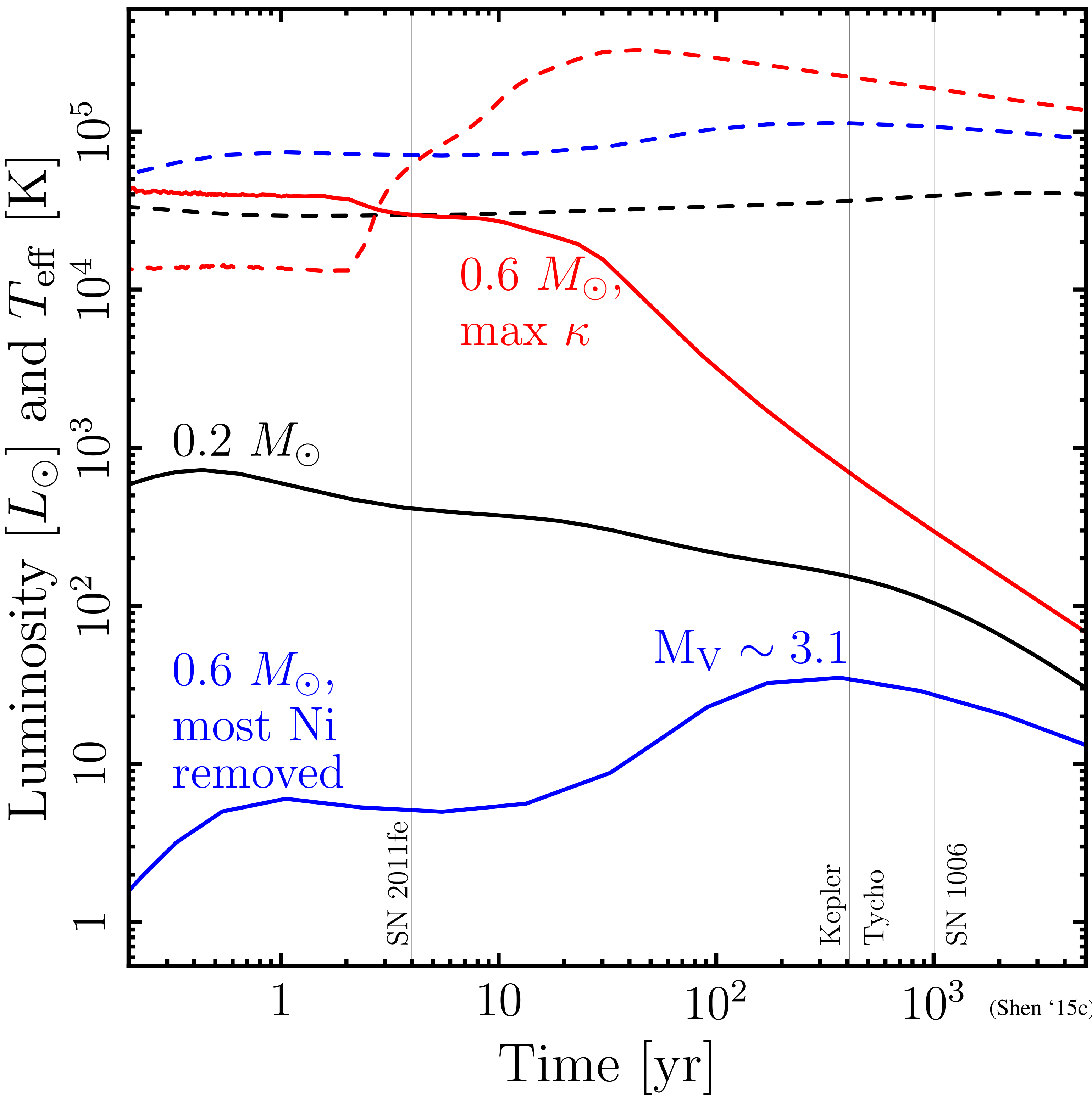
How does the ejecta influence a surviving companion WD?

- Hydro simulation with FLASH, spherically average and map to MESA for stellar evolution (e.g. Pan+, Shappee+)
- $q_{56} = 10^{17}$ erg/g $\sim$ $q_{\rm binding} \sim 10^{17}$ erg/g (for cold 0.6 Msol WD)



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Summary

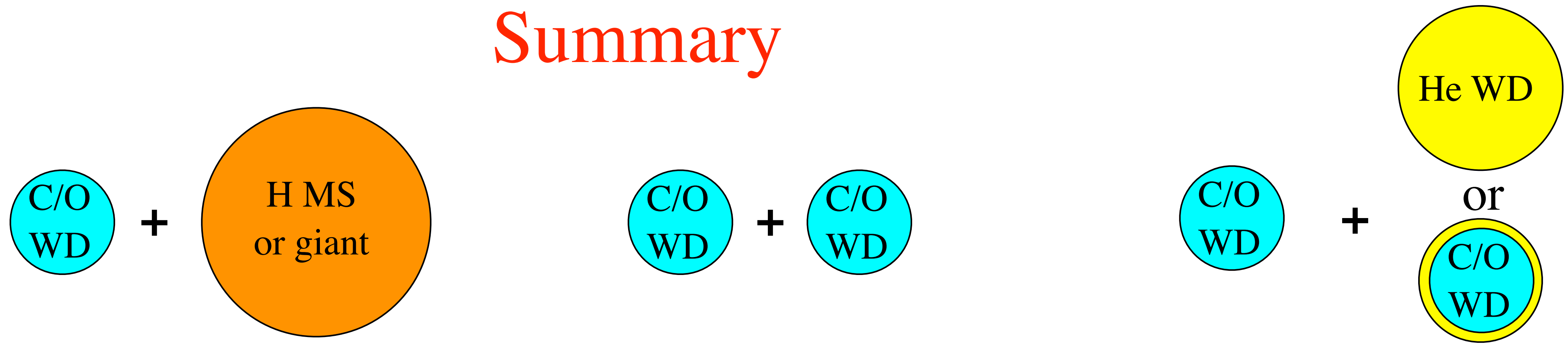
- **Merging double WD systems with primary WD mass > 0.9 Msol likely lead to detonation**
  - Companion WD < 0.7 Msol: helium triggers double detonation
  - Companion WD > 0.7 Msol: direct carbon ignition ("violent merger") can occur

- **Helium WD companion not detonated by the SN ejecta if at the proper binary separation**

- **Supernova remnant consistent with observed SNRs**
  - Forward-shocked ISM spherical
  - Reverse-shocked ejecta roughly spherical

- **Appearance of surviving WD companion**
  - Likely bright and blue, very high proper motion
  - Probably not seen in Tycho or Kepler
  - Suggests WD companion nearly or completely disrupted prior to ignition

Summary



	Single degenerate	Long-lived double degenerate merger	Detonation during double degenerate merger
Explode			
No shock interaction		Depending on timescale	
No H seen			
Nothing seen pre-explosion			
Ex-companion not seen post-Ia			
Rates			
Circumstellar absorption	Okay for some, but not for all	Depending on timescale	Depending on clumping
SN remnant			
IGE production			

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Questions

- Can IGE production problem be avoided with sub-Chandrasekhar detonations?

- If WD companion disrupted prior to ignition, is there an observable signature (polarization, SNR appearance, early-time excess)? If WD companion survives, why don't we see it?