Electron-Capture Supernovae and Accretion-Induced Collapse

Philipp Podsiadlowski (Oxford)

Ken Nomoto (1982, 1984): The progenitors of electron-capture supernovae and the progenitor of the Crab supernova

- renewed interest in e-capture supernovae in recent years

I. Electron-Capture Supernovae

II. Ken's Original Work

III. Recent Simulations

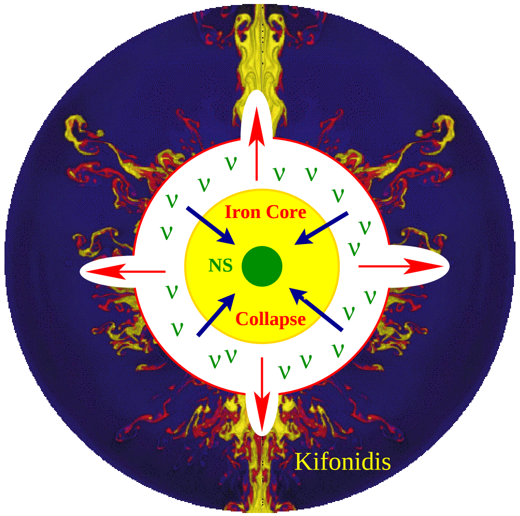
IV. Implications (Kicks, EoS)

V. Accretion-Induced Collapse

VI. Merger-Induced Collapse

Electron-Capture Supernovae

- classical core collapse: inert iron core ($> M_{Ch}$) collapses
  - ▷ presently favoured model: delayed neutrino heating to drive explosion



- electron-capture supernova in degenerate ONeMg core
  - ▷ at a critical density ($4.5 \times 10^9\,\mathrm{g\,cm^{-3}}$), corresponding to a critical ONeMg core mass ($1.370 \pm 0.005\,M_\odot$), electron captures onto ^{24}Mg removes electrons (pressure support!)

$\rightarrow$ triggers collapse to form a low-mass neutron star

note: essentially the whole core collapses

$\rightarrow$ easier to eject envelope/produce supernova

$\rightarrow$ no significanct ejection of heavy elements

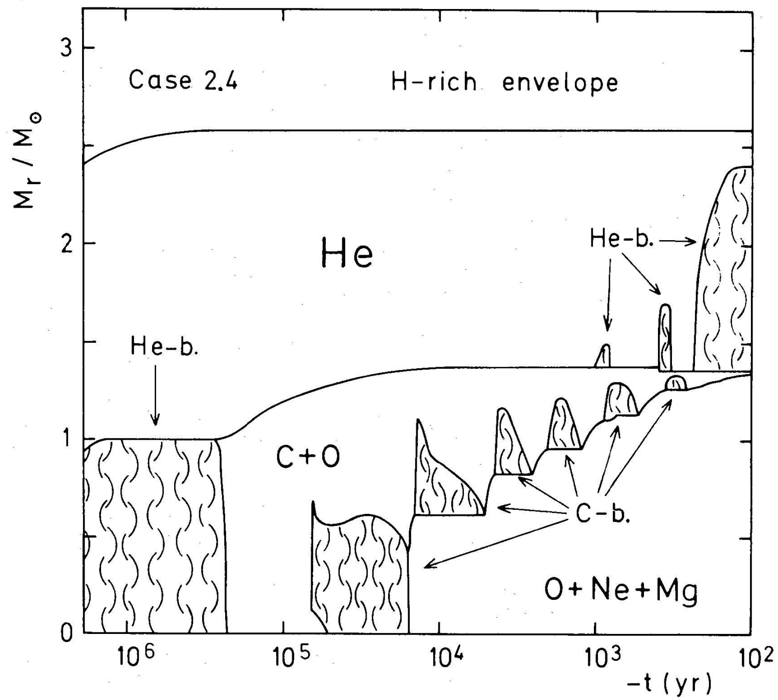
The Progenitors of E-capture Supernovae
(Nomoto 1982, 1984)

- He cores with $M_{He} = 2.0 - 2.5\,M_\odot$ lead to e-capture supernova ($M_{MS} = 8 - 10\,M_\odot$)
- significant fraction of neutron stars (NSs) produced in e-capture supernova
- Crab pulsar:
  - ▷ can explain low kinetic energy of ejecta ($\lesssim 10^{50}$ erg)

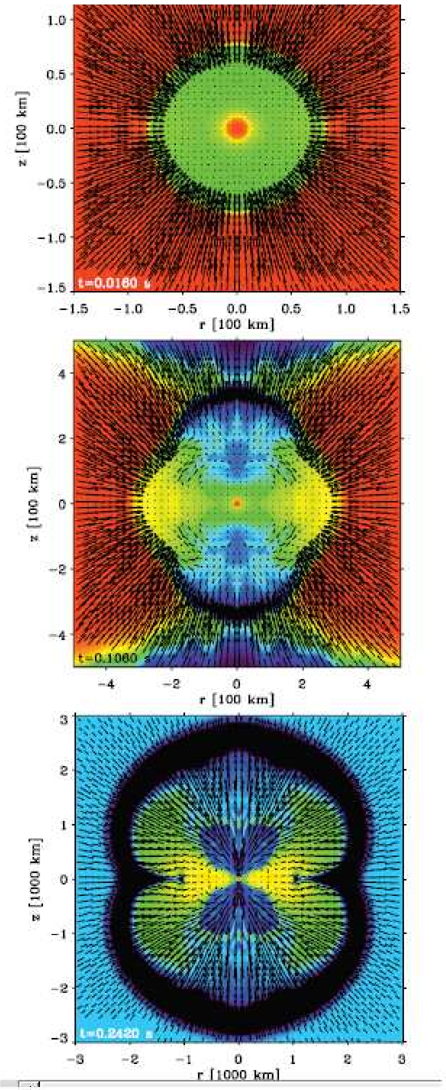
  but: no hydrogen

  → loss of H-rich envelope by binary interaction?

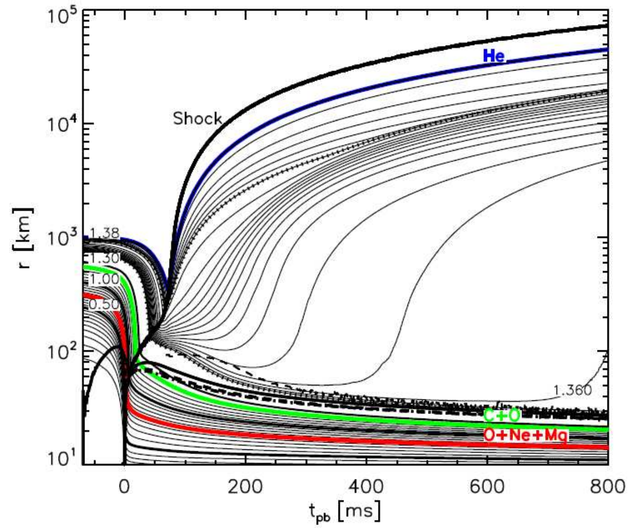
  → requires reverse evolution + binary break-up (→ space velocity?) (Pols, Nomoto)



Simulations of E-capture Supernovae



Dessart et al. (2006)



Kitaura, Janka, Hillebrandt (2006)

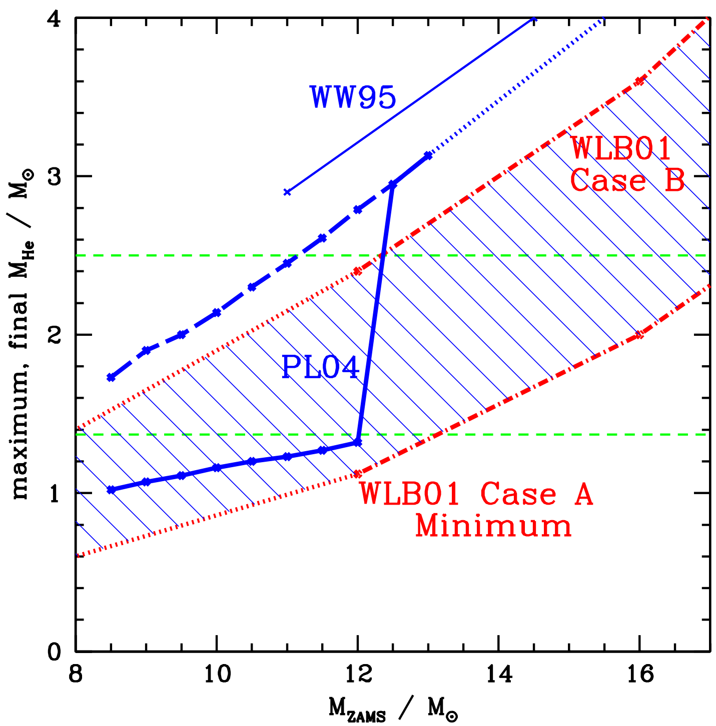
Recent simulations confirm

- successful explosion by delayed neutrino mechanism
- low explosion energy: $\lesssim 10^{50}$ erg (low binding energy; also Crab!)
- few metals ejected
- fast explosion: $100 - 200$ ms

  $\rightarrow$ low neutron-star kick

  ▷ “best” present model for NS kick: standing accretion shock instability (Blondin, Mezzacappa, Foglizzo, Janka) requires slow explosion ($\gtrsim 500$ ms) for instability to grow

Binary Evolution Effects



- **dredge-up in AGB phase may prevent ONeMg core from reaching M_{crit} → ONeMg WD instead of collapse**
- **can be avoided if H envelope is removed by binary mass transfer**

→ **dichotomous kick scenario (P. et al. 2004)**

- ▷ **e-capture SN in close binaries → low kick**
- ▷ **iron core collapse → high kick**

- **can explain**
  - ▷ **all single pulsars seem to have received large kicks (Hobbs, Lyne, Lorimer)**
  - ▷ **but need low kicks in some X-ray binaries (e.g. X Per) with low eccentricity (Pfahl)**
  - ▷ **retention of neutron stars in globular clusters (Pfahl, Ivanova, Belczyński)**
  - ▷ **double neutron star properties (v.d. Heuvel, Dewi), specifically the double pulsar**

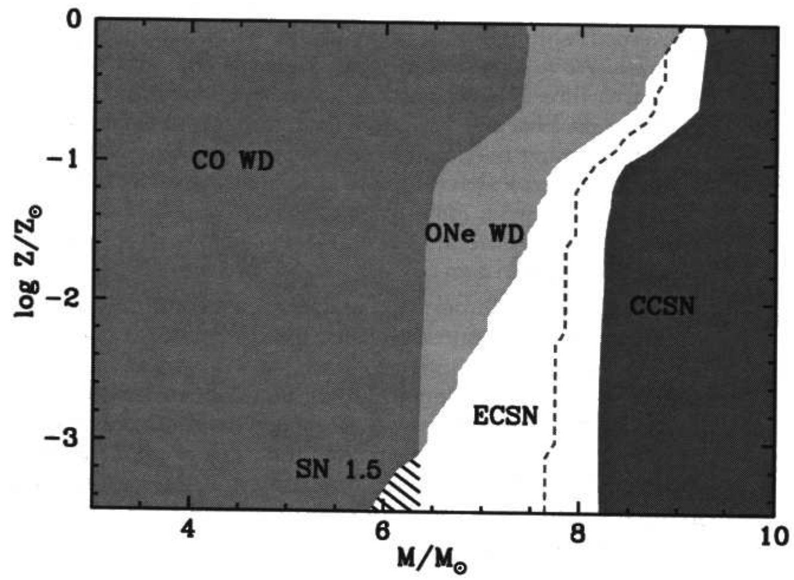
Recent Work

Arend Jan Poelarends (PhD Thesis):

- examined conditions for e-capture SNe on metallicity, wind mass loss, dredge-up efficiency in AGB stars
- best model: no e-capture SN at solar Z

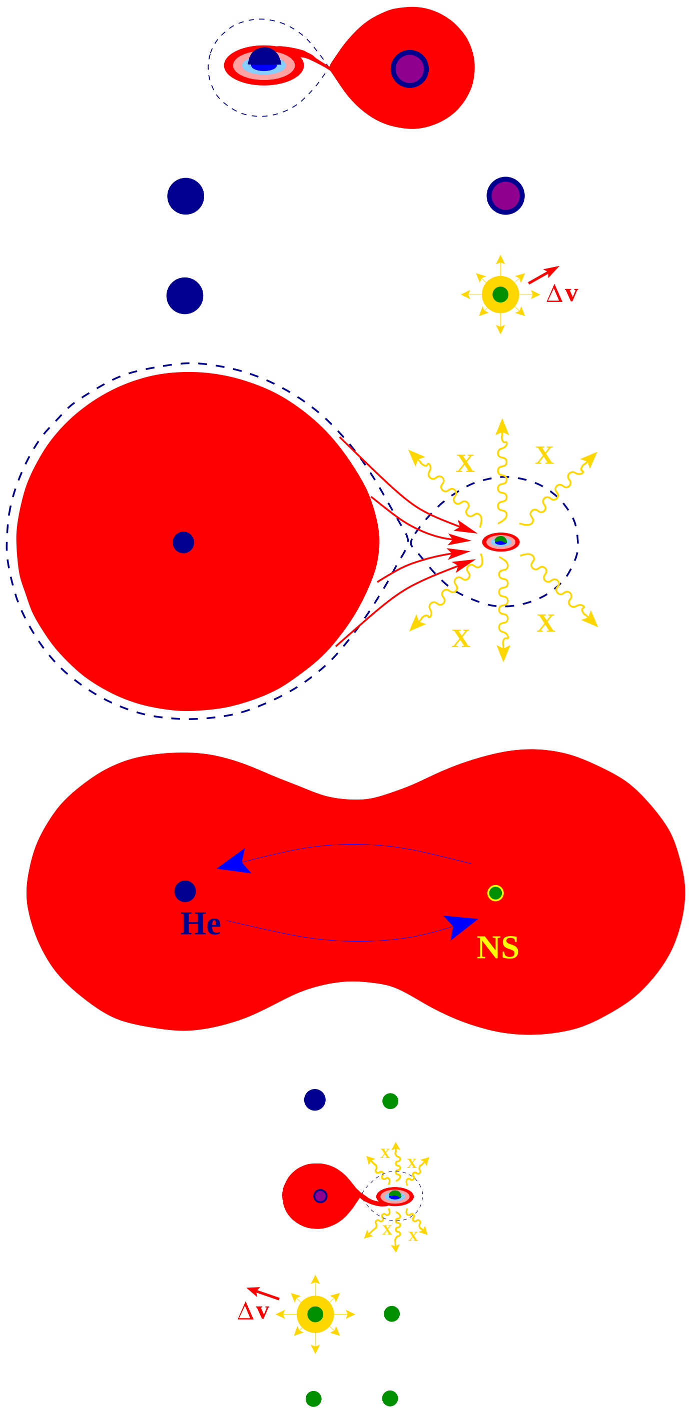
Pols: mass transfer in He-star binaries may prevent e-capture SN → reduced parameter space

- but: possibility of binary break-up (Crab?)



The Double Pulsar (PSR J0737-3039)

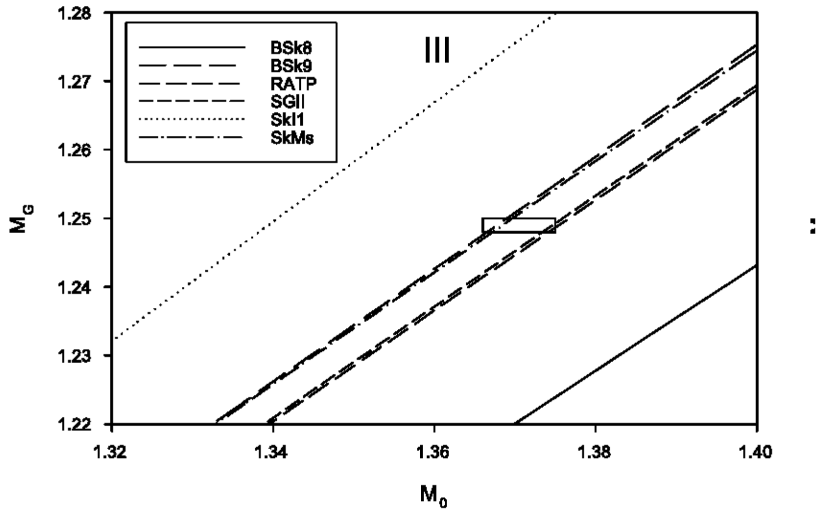
- $P_{orb} = 2.4\,h$, $M_A = 1.338\,M_\odot$ ($P_A = 22.7\,ms$), $M_B = 1.249\,M_\odot$ ($P_B = 2.77\,s$)
- lower-mass pulsar formed in e-capture supernova?
- circumstantial evidence:
  - ▷ low mass of $1.249\,M_\odot$ close to expected mass from e-capture SN
  - ▷ evidence for low kick: low eccentricity, low space velocity, Pulsar A spin aligned with orbital axis (no geodetic precession)



Testing the Equation of State of Nuclear Matter
(P. et al. 2005)

- critical density for e-capture in ONeMg core → critical collapse mass: $M_{crit} = 1.370 \pm 0.005\, M_\odot$ (Lesaffre) (no rotation!)
- post-SN NS mass = pre-collapse core mass – binding energy
- binding energy depends on the equation of state

complications: core mass loss in explosion (a few $10^{-3}\, M_\odot$)



(Newton, Miller, Stone)

Accretion-Induced Collapse (AIC)

Nomoto & Iben (1985): for high accretion rate
($\dot{M} > 0.2\,\dot{M}_{Edd} \simeq 4 \times 10^{-6}\,M_\odot$ [$M_{WD} = 1M_\odot$])

$\rightarrow$ carbon shell flash

$\rightarrow$ series of C shell flashes at successively smaller mass shells

$\rightarrow$ conversion of CO WD into ONeMg WD

$\rightarrow$ core collapse rather than thermonuclear explosion

- formation of neutron stars in LMXBs by AIC
(e.g. Her X-1; v.d. Heuvel, Grindlay)
  - ▷ to produce ms pulsars with low B (alternative to recycling scenario)
  - ▷ NS with low kicks (retention in GCs, etc.)
- rate estimate: $10^{-6} - 10^{-4}\,\mathrm{yr}^{-1}$ (Yungelson)

Merger-Induced Collapse (MIC)

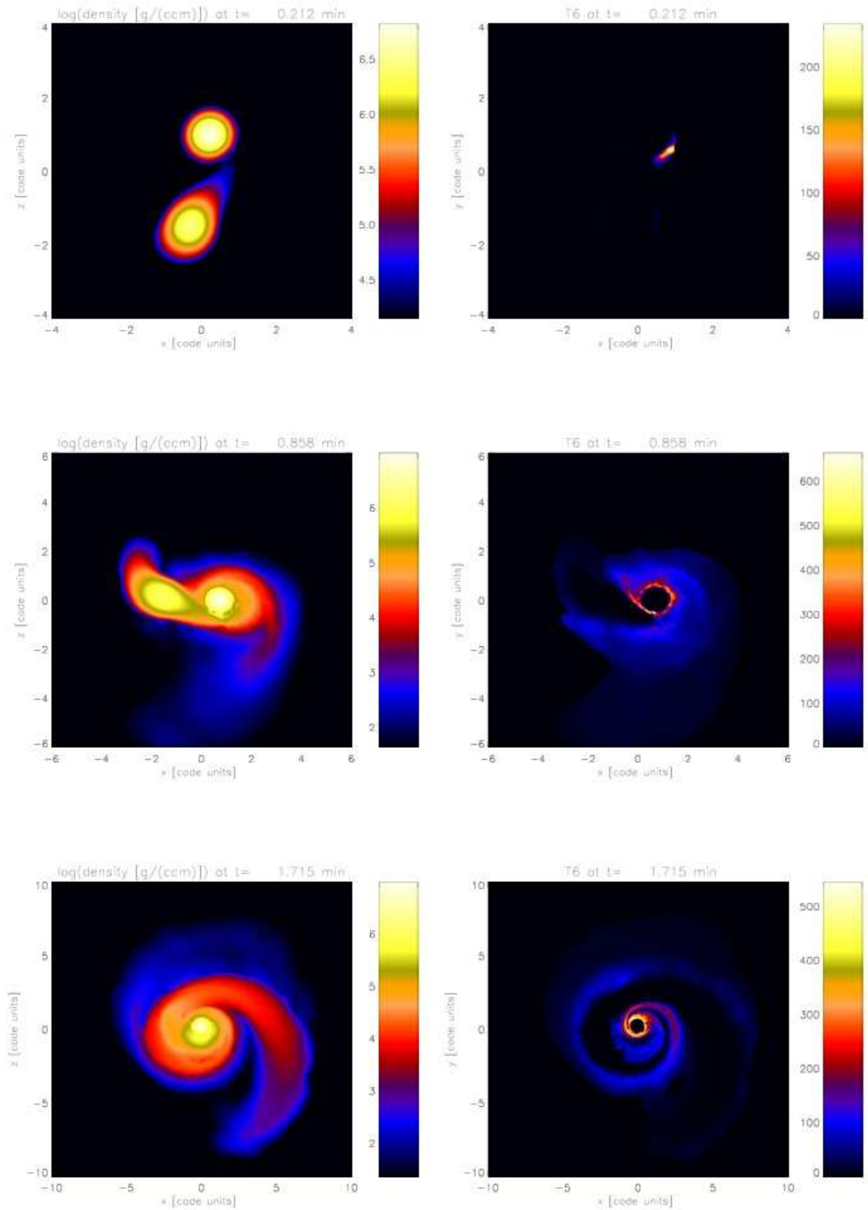
- double-degenerate mergers are prime candidates to produce NSs in an e-capture supernova
- rate $\sim$ SN Ia rate

  Theory: a few $10^{-3}\,\mathrm{yr}^{-1}$ (Iben, Yungelson, Nelemans, Han)

  Observations: SPY (Napiwotzki) probably consistent with theoretical estimate
- 10 – 20 % of all NSs?
- low kick to solve retention problem in globular clusters (Pfahl, Belczyński, Ivanova)
- Issue: MIC or SN Ia?

  ▷ fast initial accretion $\rightarrow \dot{M} > \dot{M}_{\mathrm{crit}}$

  but: initial configuration more complicated



(Rosswog 2006)

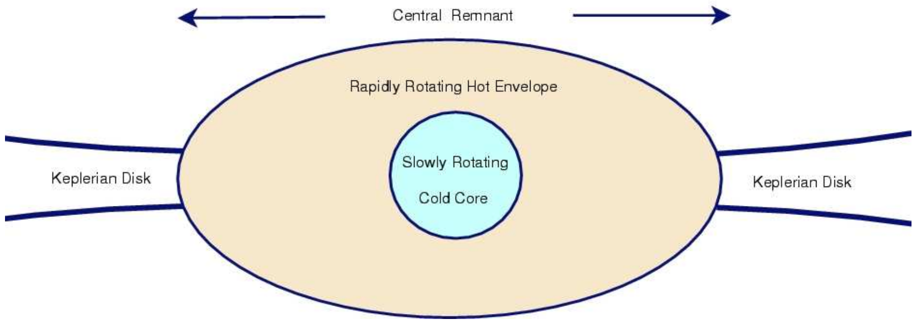
Remnant Evolution after a Double-Degenerate Merger
(Yoon, P., Rosswog 2007)

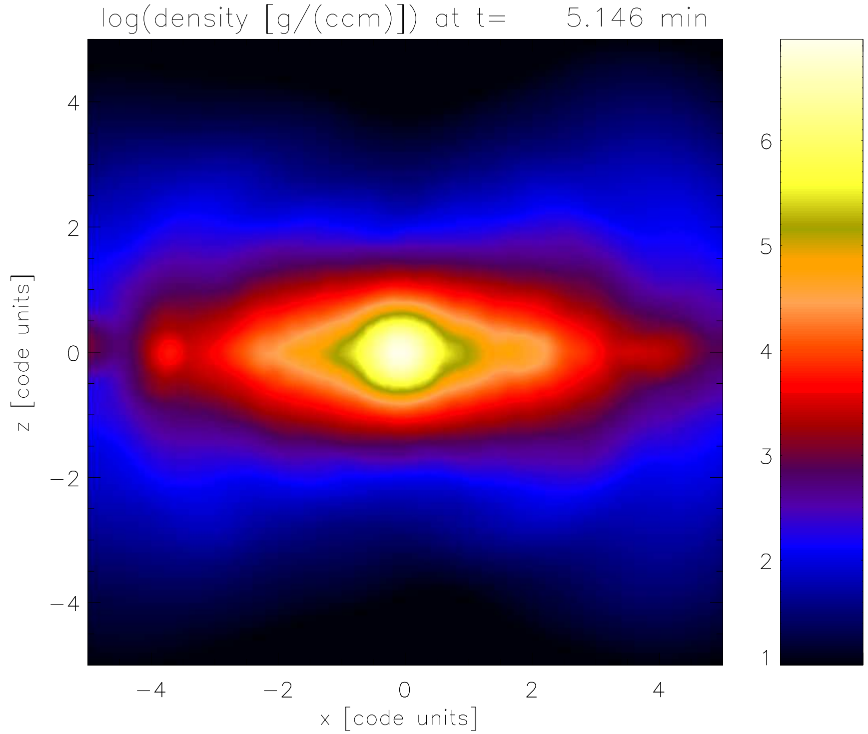
- post-merger configuration
  - ▷ not simple star+disk system
  - ▷ 1/3 to 1/2 of disrupted WD is dumped onto the massive WD dynamically
  - ▷ cold WD + high-entropy envelope + thick quasi-Keplerian disk
- post-merger evolution is governed by the evolution of the envelope controlling the effective accretion rate onto the core ($\sim 10^4$ yr)

Key result: neutrino cooling at the interface between the hot envelope and cool core can carry away the energy produced by compressional heating

→ C shell ignition may be avoided under certain conditions

→ thermonuclear explosion?





Necessary conditions for avoiding C shell ignition

- immediately after the merger, T_{max} less than the ignition temperature for C burning
- disk accretion rate less than $5 \times 10^{-6} - 10^{-5}\,M_\odot\,yr^{-1}$
- angular momentum loss timescale > neutrino cooling timescale
- depends
  - ▹ on the CO WD masses
  - ▹ the thermal state of the massive WD

Conclusions (personal)

- probably not the dominant channel for SNe Ia

but: some double-degenerate mergers could produce SNe Ia (special sub-class?)