

Mass Loss and the Death of Very Massive Stars



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Mist of Mass Loss

- Rotation: Georges, Norbert, Thomas, Ilya, Pablo
- Convection: Raphael, Stan, Matteo, Eliot
- Simulation: Yan-Fei, Matteo
- SN: Thierry, Ryan, Nathan, Ken Nomoto, ...

Mass Loss

Death of Fat Stars

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Mass Loss

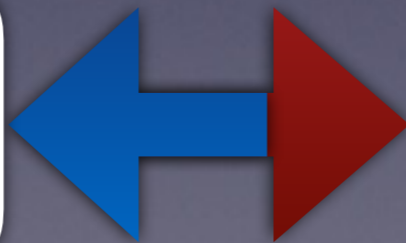


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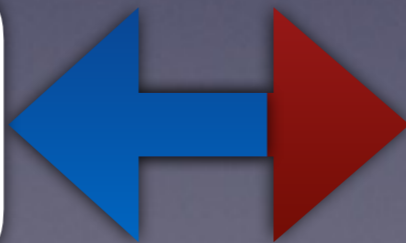


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Mass Loss



Death of Fat Stars

Who pays the bill for mass loss or giant eruptions?

Death of Non-rotating Massive Stars

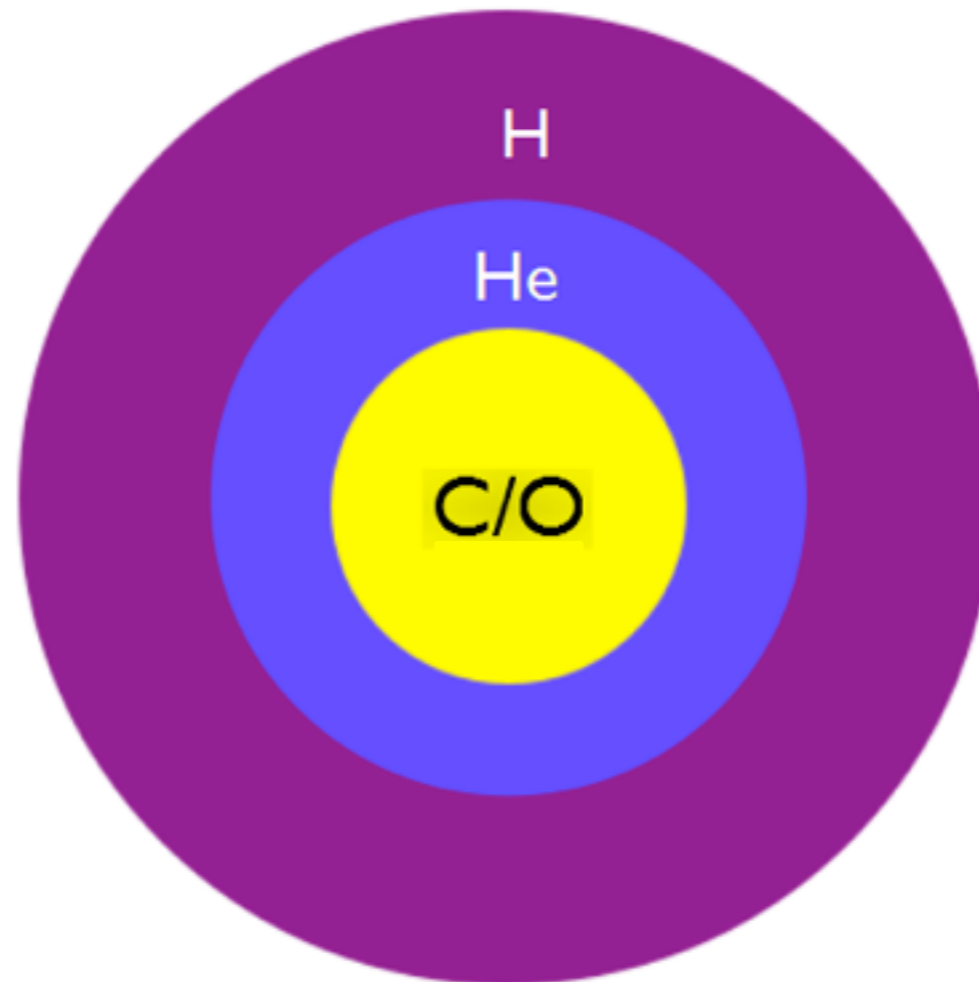
Woosley, Heger, & Weaver (2002)

MS Mass	He Core	Supernova Mechanism
Poorly known	Well known	
$10 \leq M \leq 85$	$2 \leq M \leq 32$	Fe core collapse to a neutron star or black hole
$80 \leq M \leq 150$	$35 \leq M \leq 60$	Pulsational pair instability followed by core (PPSN)
$150 \leq M \leq 250$	$60 \leq M \leq 133$	Pair instability supernova (PSN)
$250 \leq M$	$133 \leq M$	All BH or any Bang??

Mass Unit: solar mass ☉

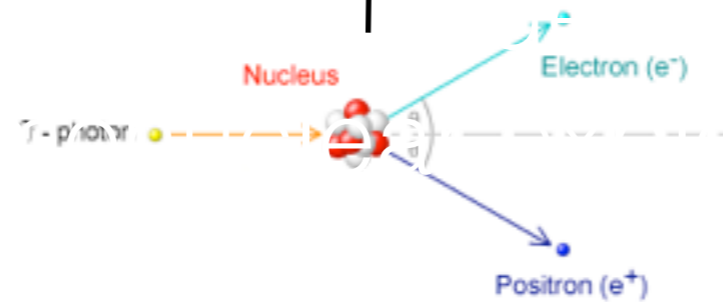
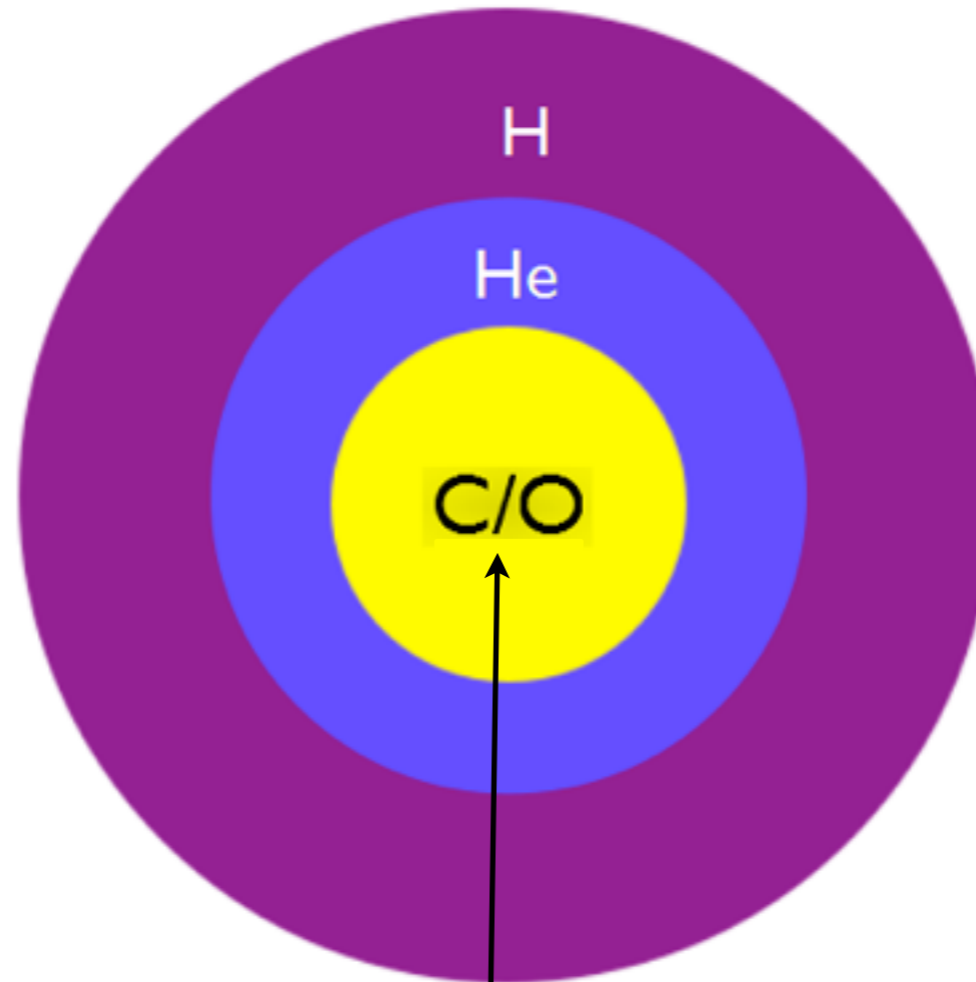
Fate of Very Massive Stars

Star $> 80 M_{\odot}$



Fate of Very Massive Stars

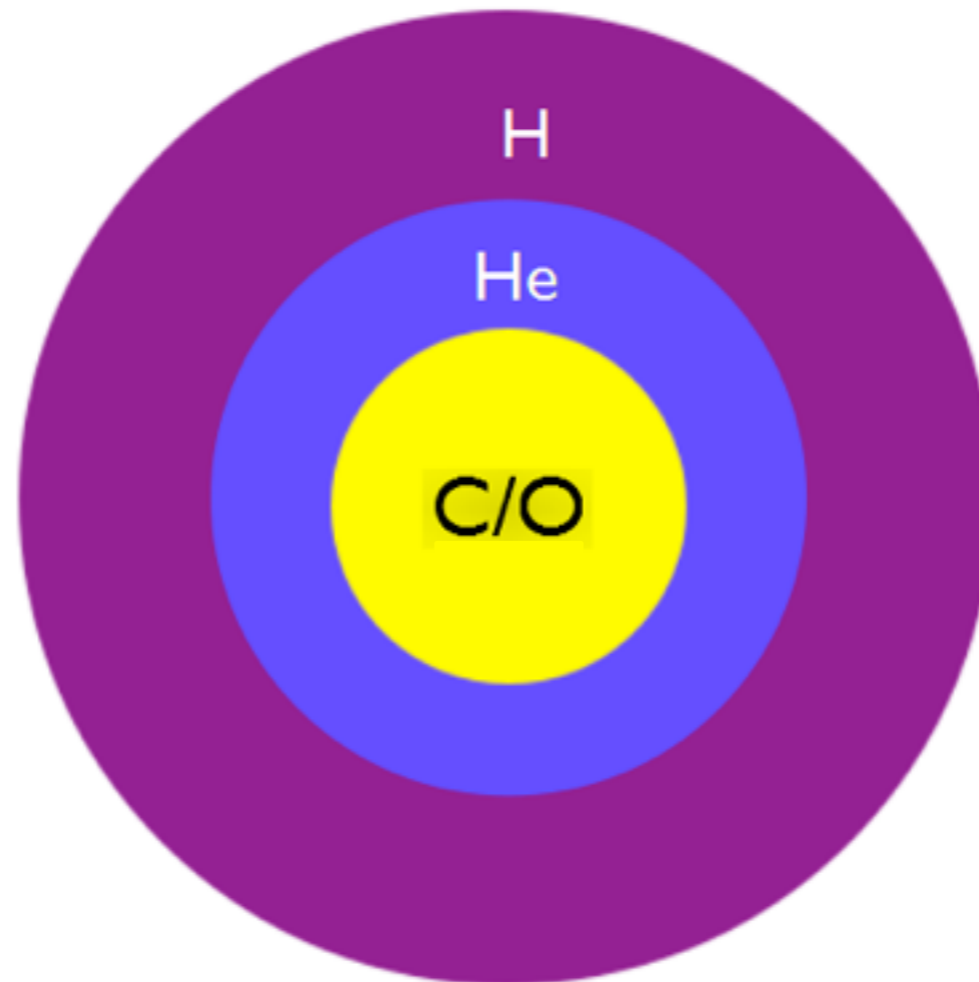
Star $> 80 M_{\odot}$



$E_{\gamma} > 2m_0c^2$, where m_0 is the electron rest mass

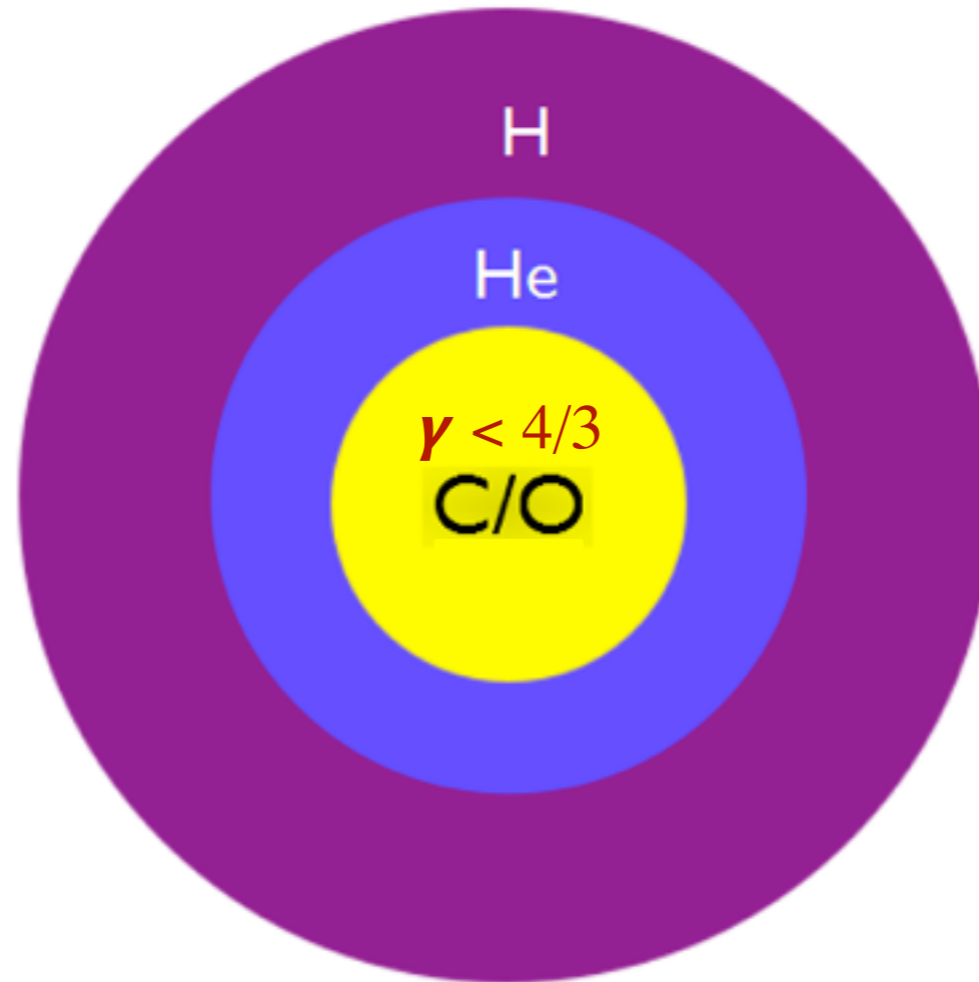
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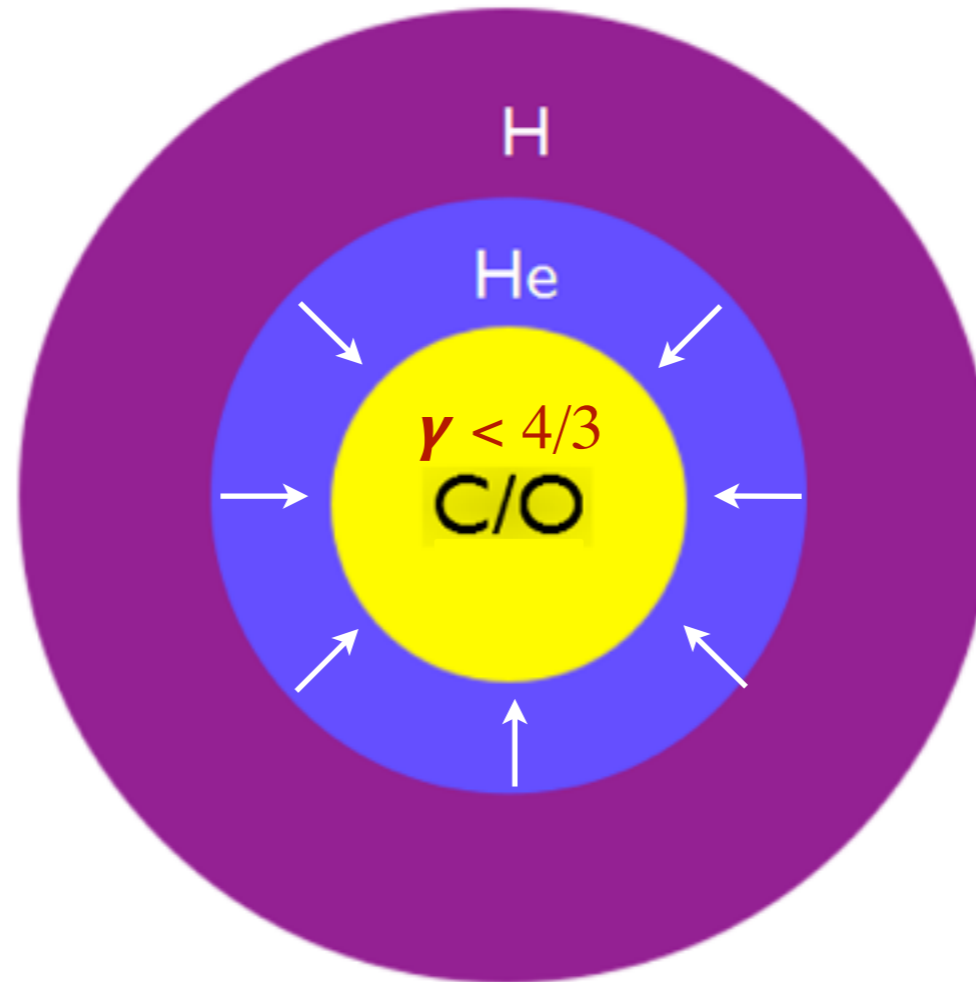
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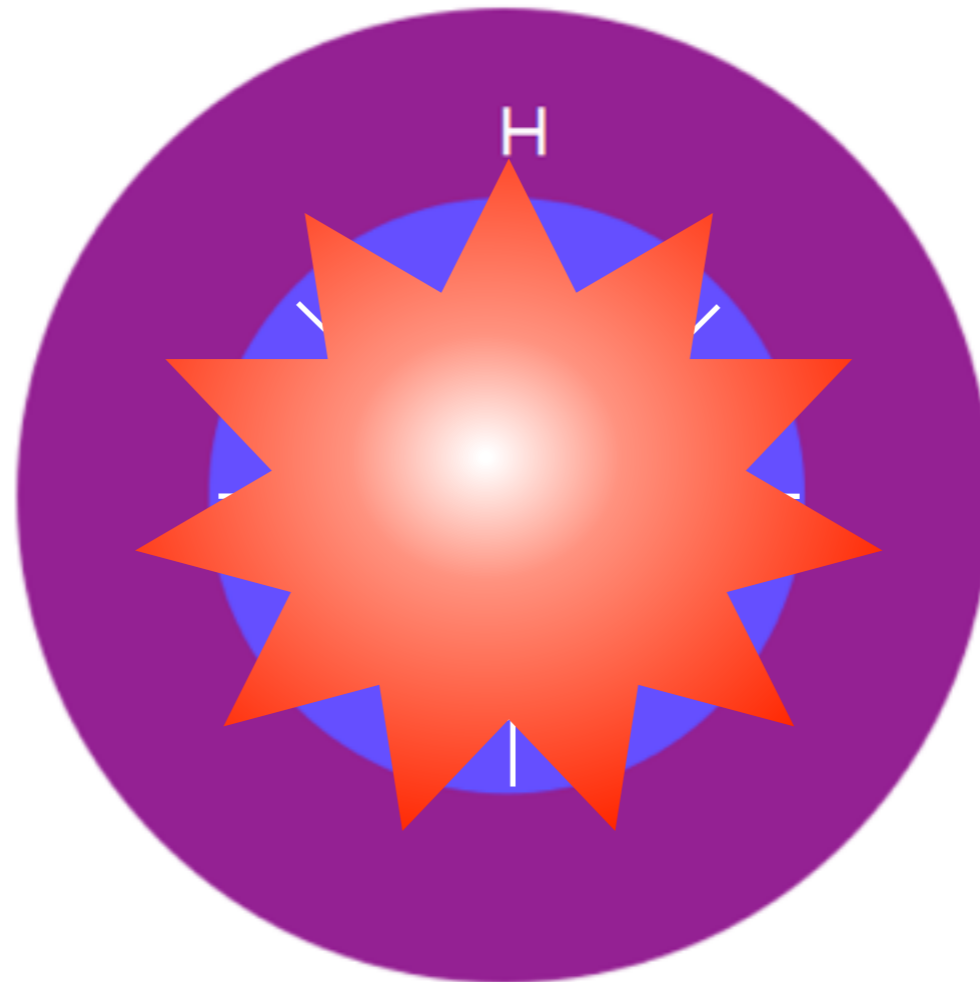
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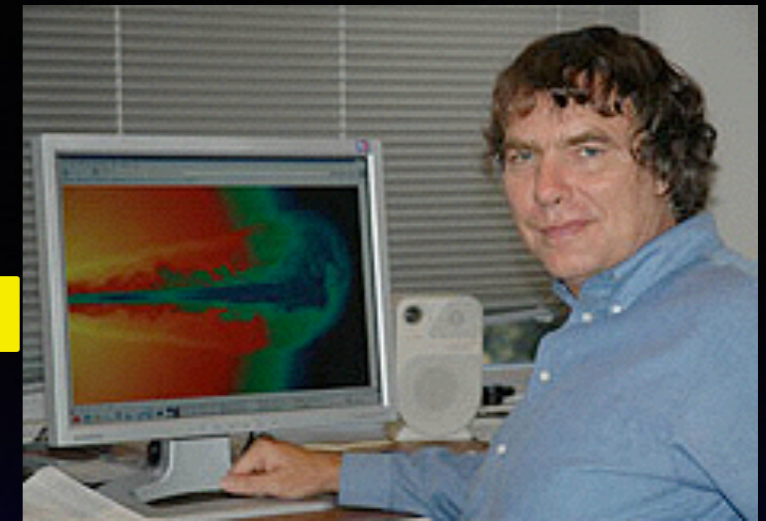
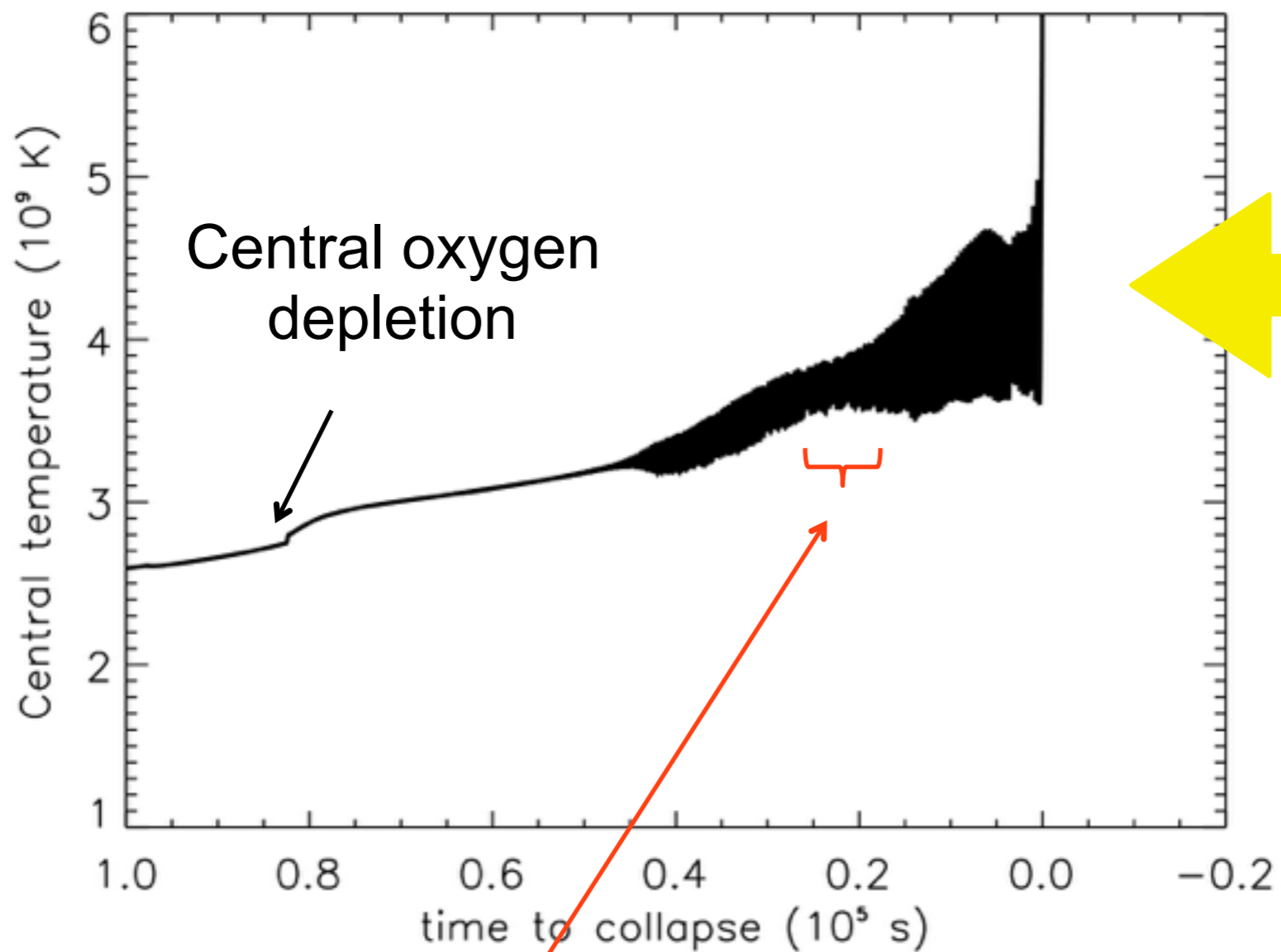
Fate of Very Massive Stars

Star $> 80 M_{\odot}$



A large, powerful thermonuclear explosion is shown as a massive mushroom cloud rising from the ocean. The cloud is bright orange and yellow, with a thick, dark column of smoke and debris rising from the base. The background is a dramatic sunset or sunrise over the ocean, with a bright glow on the horizon and dark, silhouetted clouds. The overall scene is one of immense power and destruction.

We have a better understanding of
Thermonuclear explosion



Based on Stan's Model

Woosley+ 2007, Woosley+ 2016

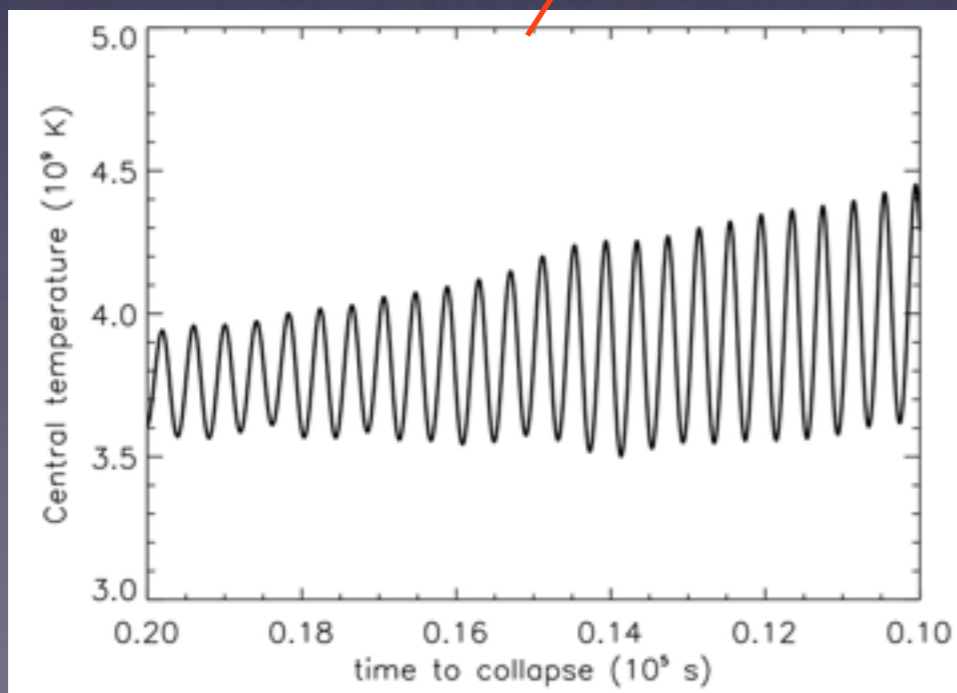
Woosley Priv. Comm.

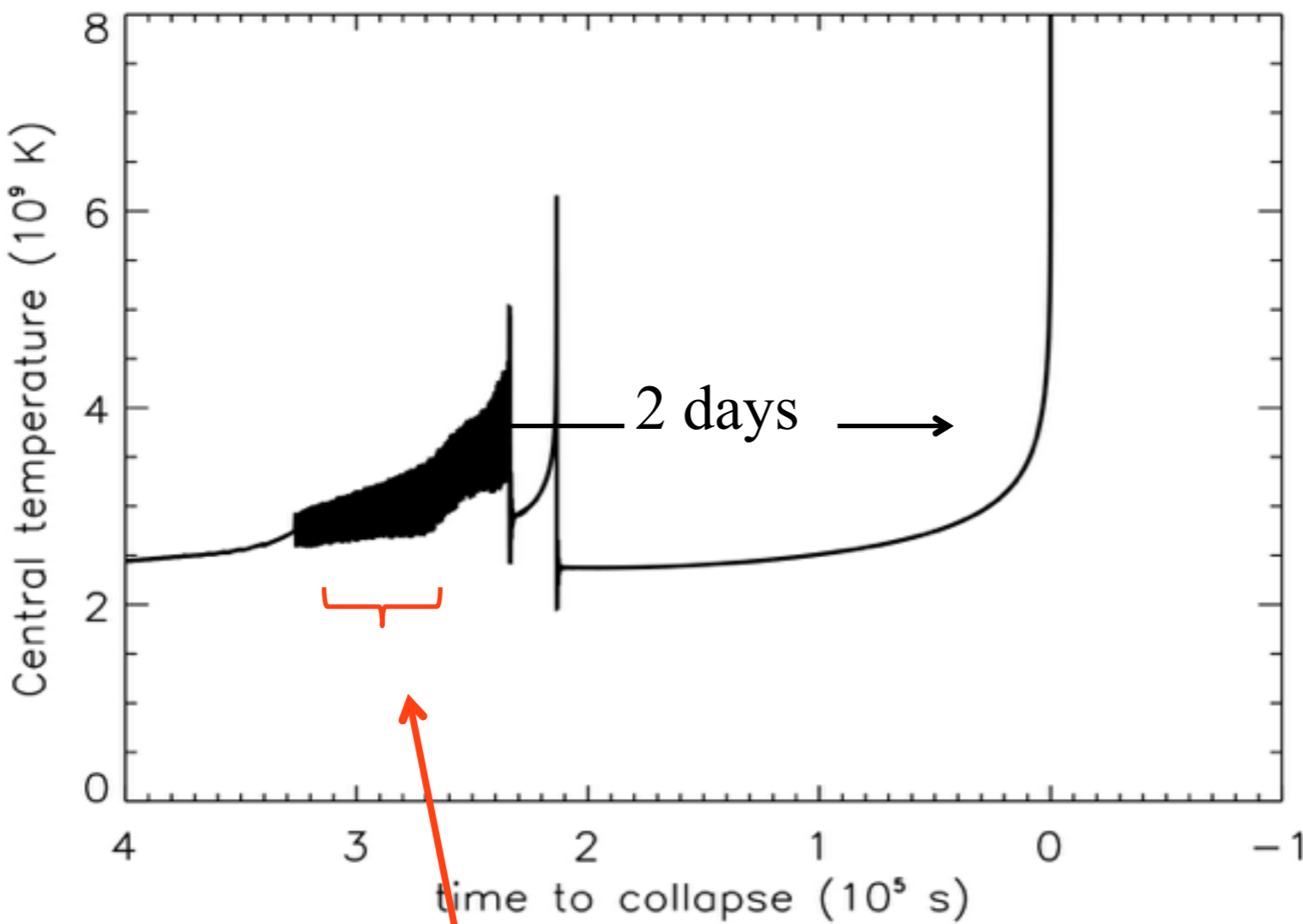
80 M_{\odot} Helium core 35.7 M_{\odot}

Pulsational instability begins shortly after central oxygen depletion when the star has about one day left to live ($t = 0$ here is iron core collapse).

Pulses occur on a hydrodynamic time scale for the helium and heavy element core (~ 500 s).

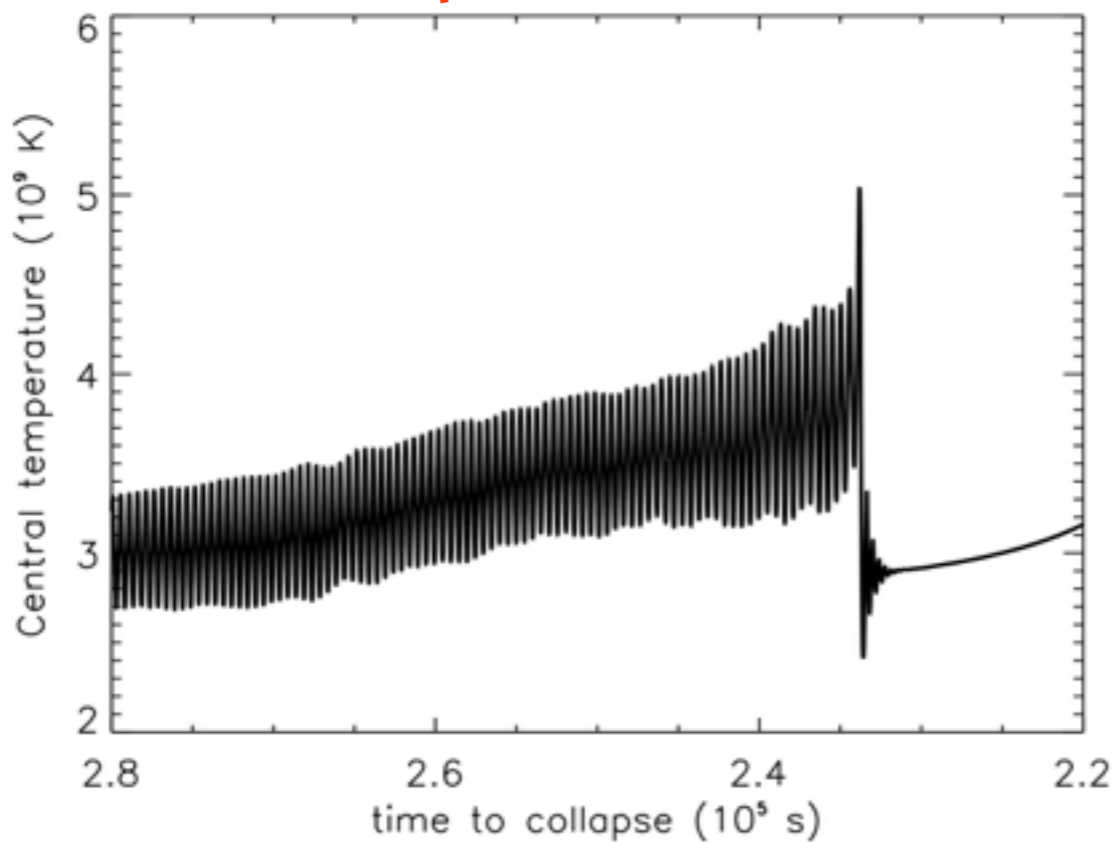
For this mass, there are no especially violent single pulses before the star collapses. Nevertheless, there may be mass ejection.



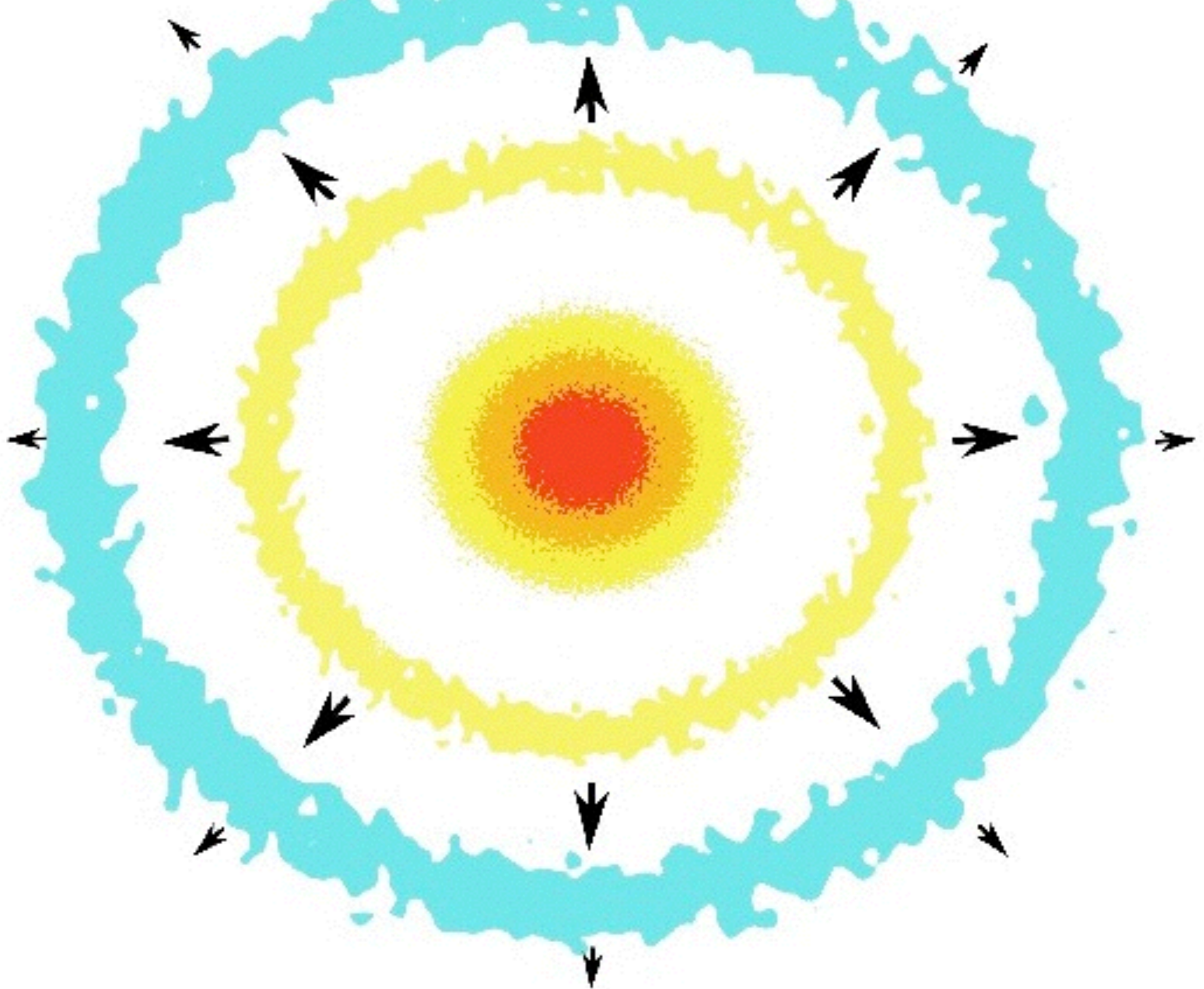


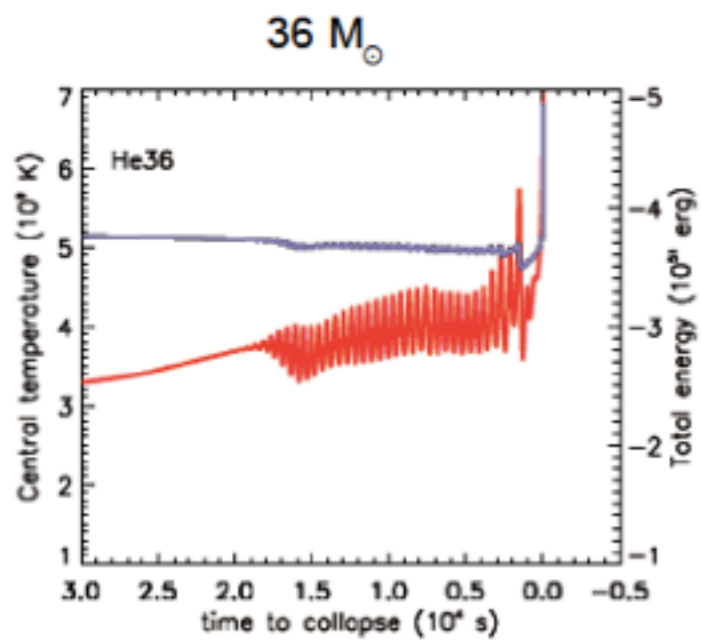
90 M_⊙
Helium core 41.3 M_⊙

Pulses commence again after central oxygen depletion, but become more violent. Two strong pulses send shock waves into the envelope. Two days later the iron core collapses.

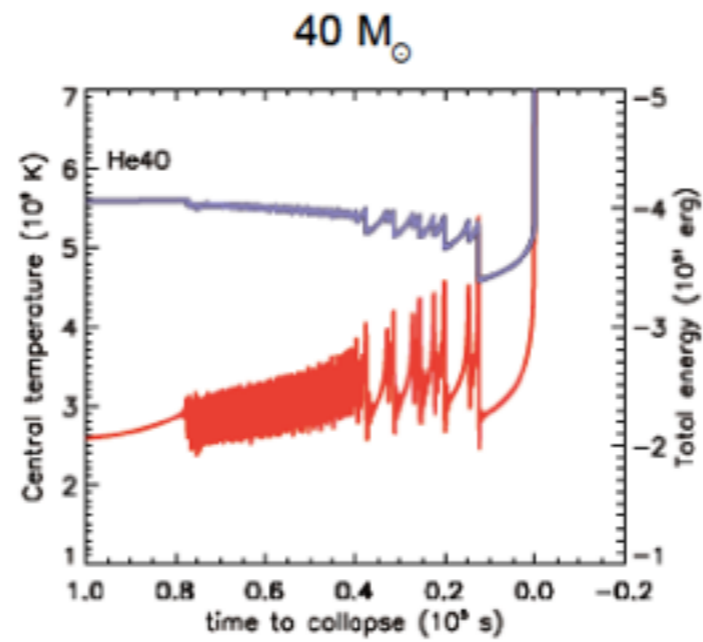


For still larger helium cores, the pulses become more violent and the intervals between them longer. Multiple supernovae occur but usually just one of them is very bright.

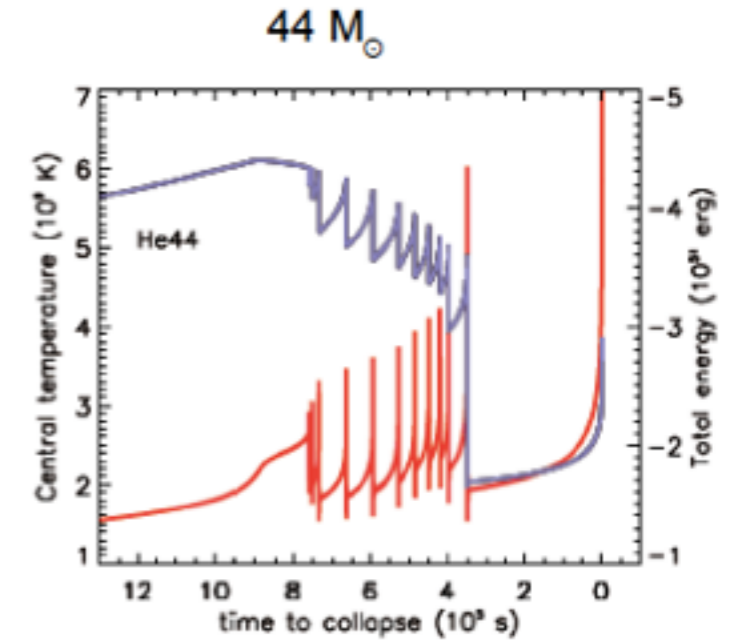




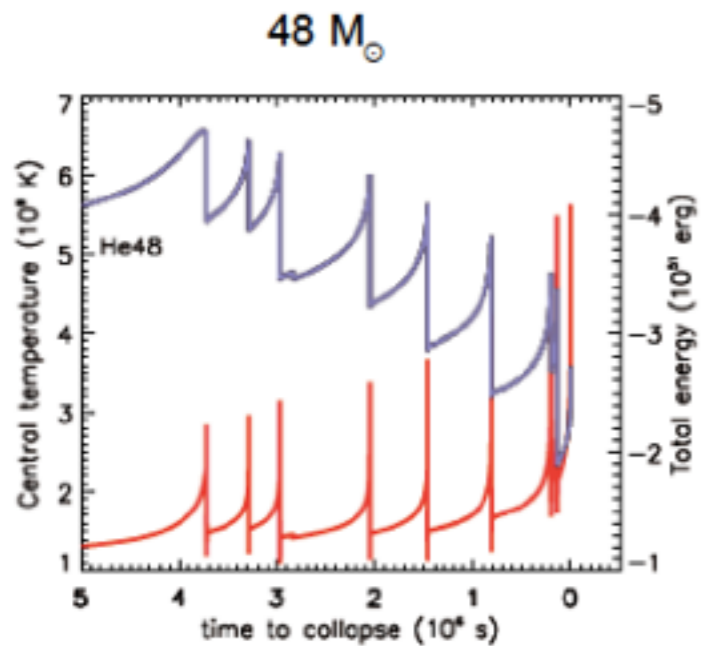
10^4 s



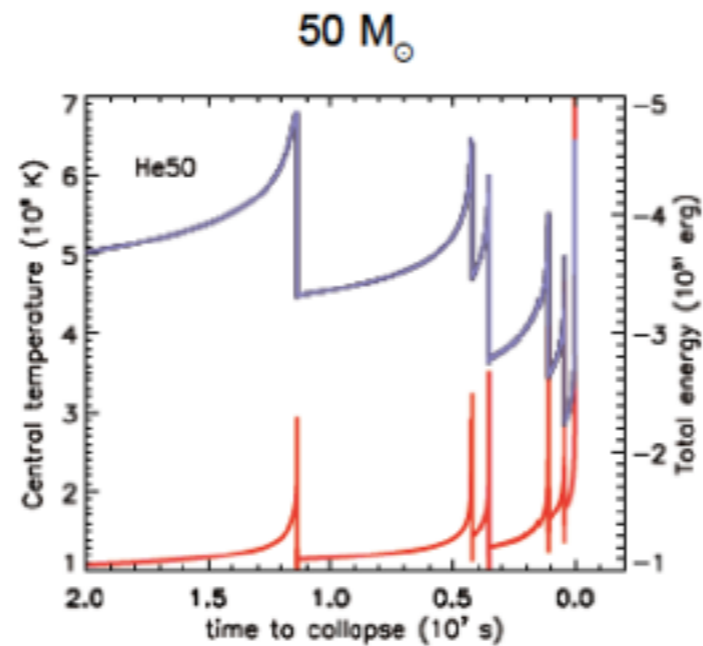
10^5 s



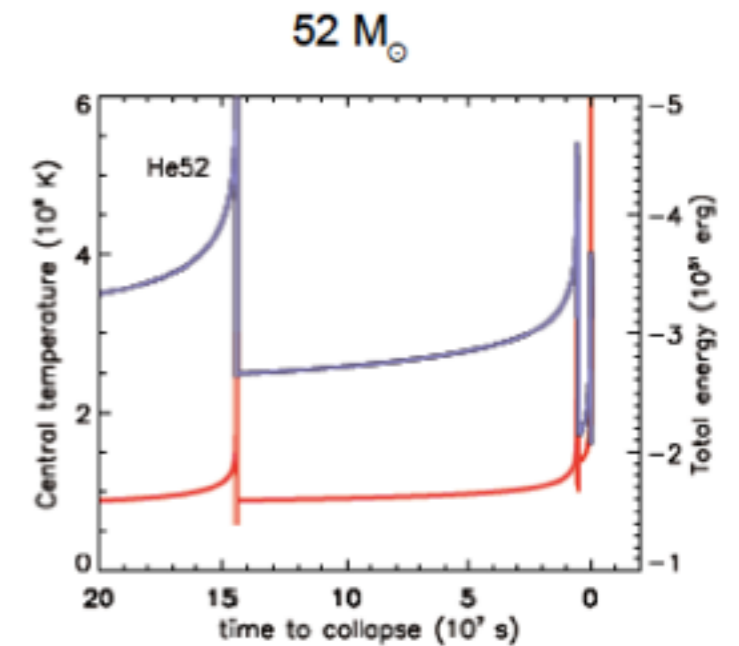
10^5 s



10^6 s



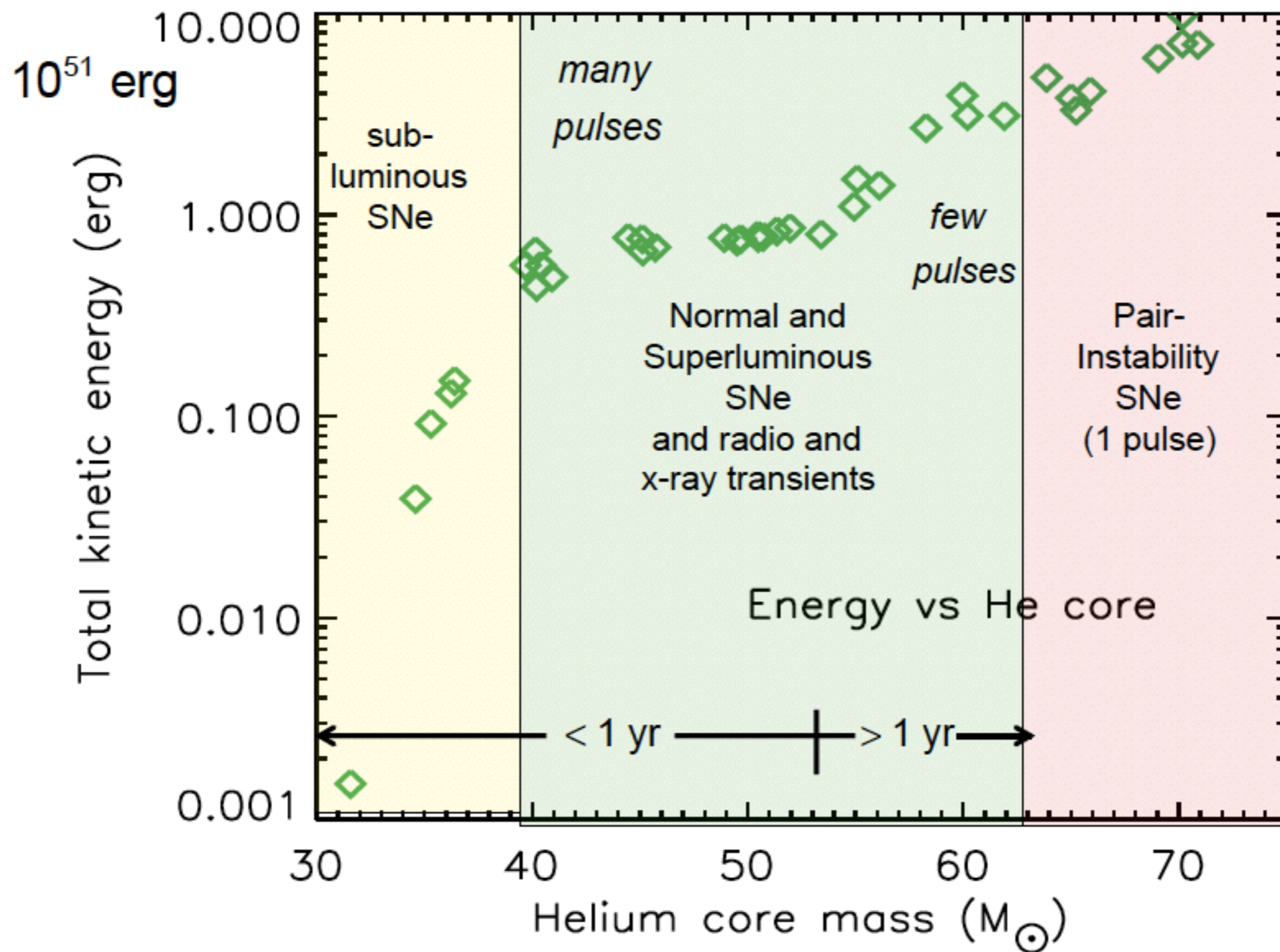
10^7 s



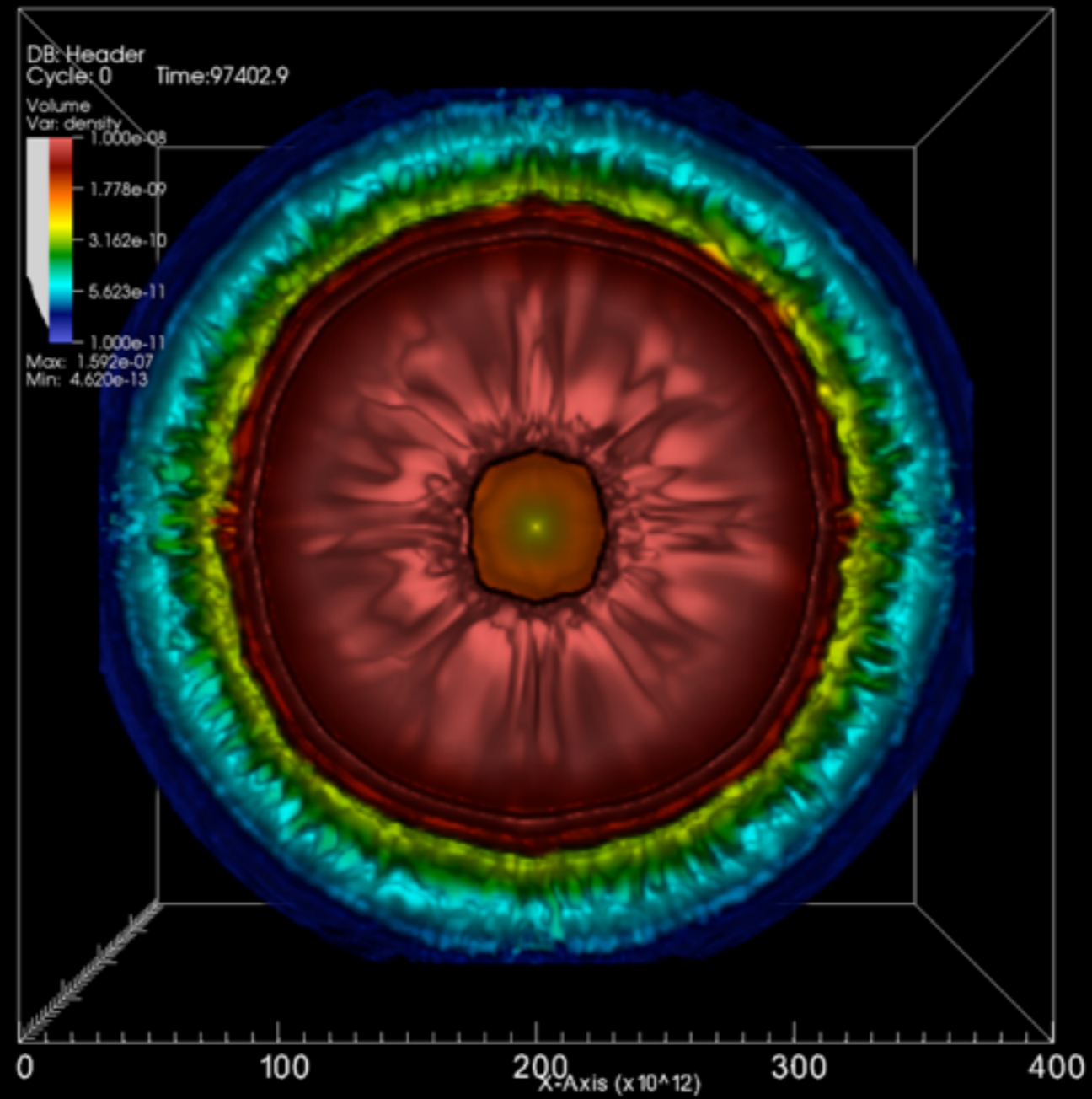
10^7 s

Total ejected mass from 0.1 M_{\odot} to 8 M_{\odot} depending on the helium core mass

TOTAL ENERGY IN PULSES



Mult-D Simulations of PPSNe



Chen+ ApJ 792 28 (2014)

Core of 110 M_⊙ star



Time=0 s



-3.0e+08

-1.0e+08

1.0e+08

3.0e+08

(cm/s)

Core of 110 M_⊙ star



Time=0 s



-3.0e+08

-1.0e+08

1.0e+08

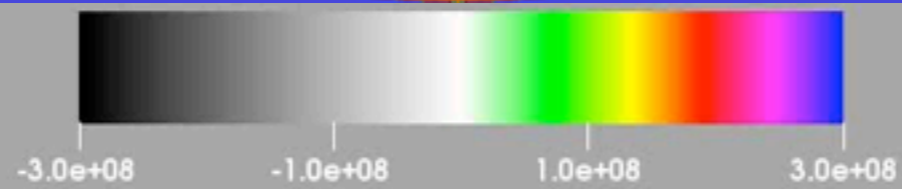
3.0e+08

(cm/s)

Core of 110 M_⊙ star

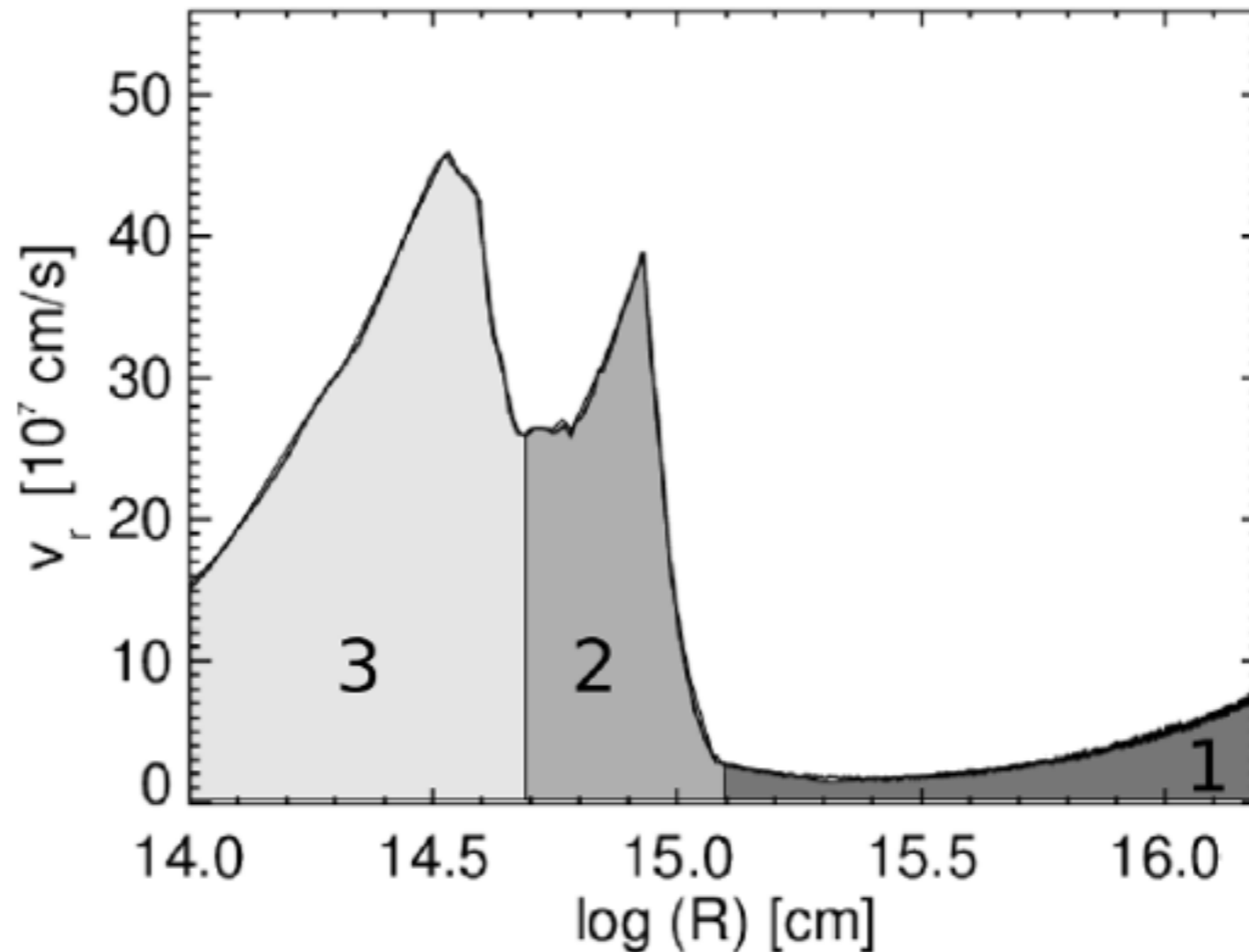


Ken Chen

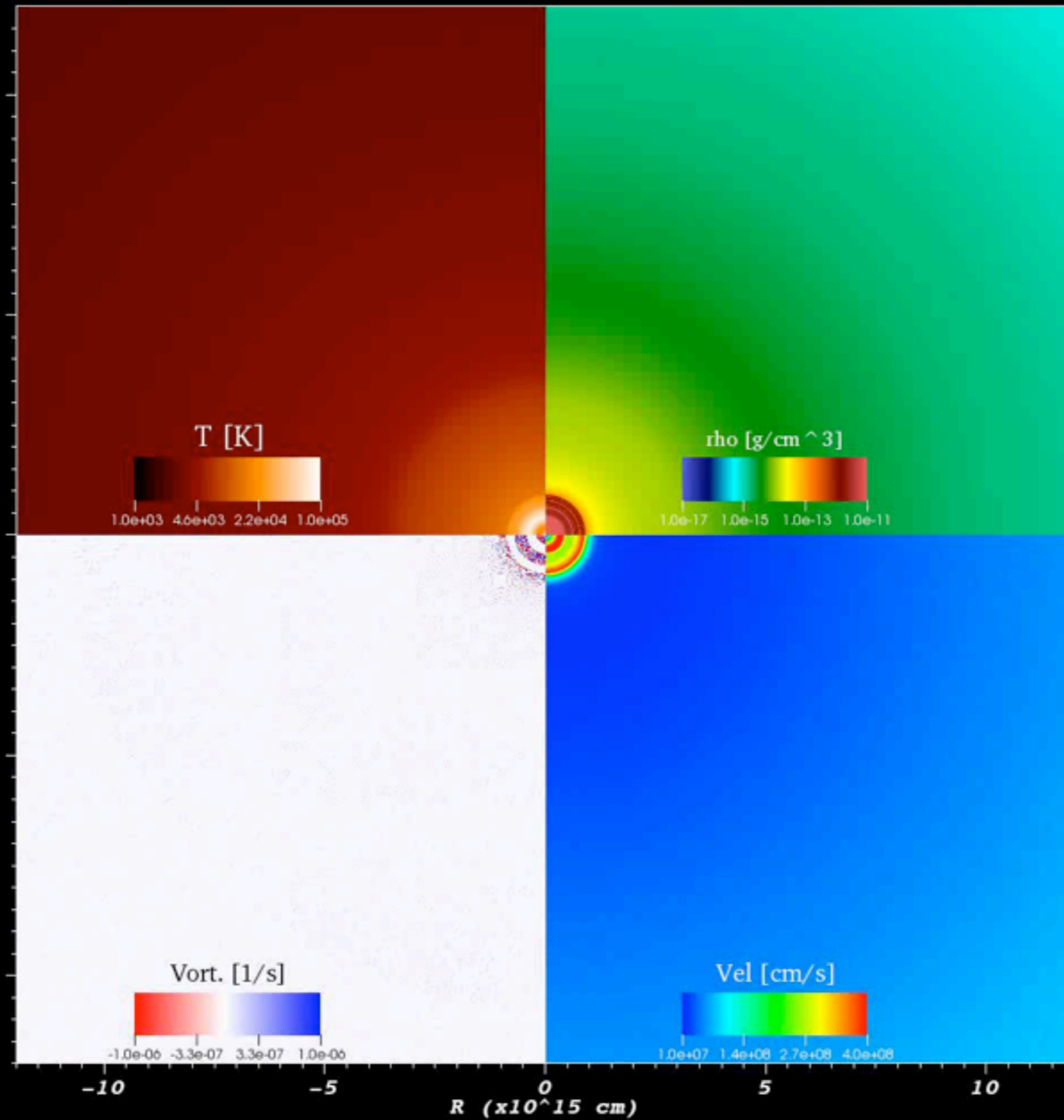


Eruption History

The star produces three violent outbursts. The first, P1, ejects most of the hydrogen envelope, making a faint Type II supernova and leaving a residual of **50.7 Msun**, just a bit more than the helium core itself. After **6.8 yr**, the core again contracts and encounters the pair instability, twice in rapid succession. The total mass of the second and third pulses (P2 and P3) is **5.1 Msun** and their kinetic energy is **6e50 erg**. P3 collides with P2 at large optical depths that are not visible to an external observer. These combined shells then overtake P1 at $1e^{15}$ cm and speeds of a few 1000 km/s.

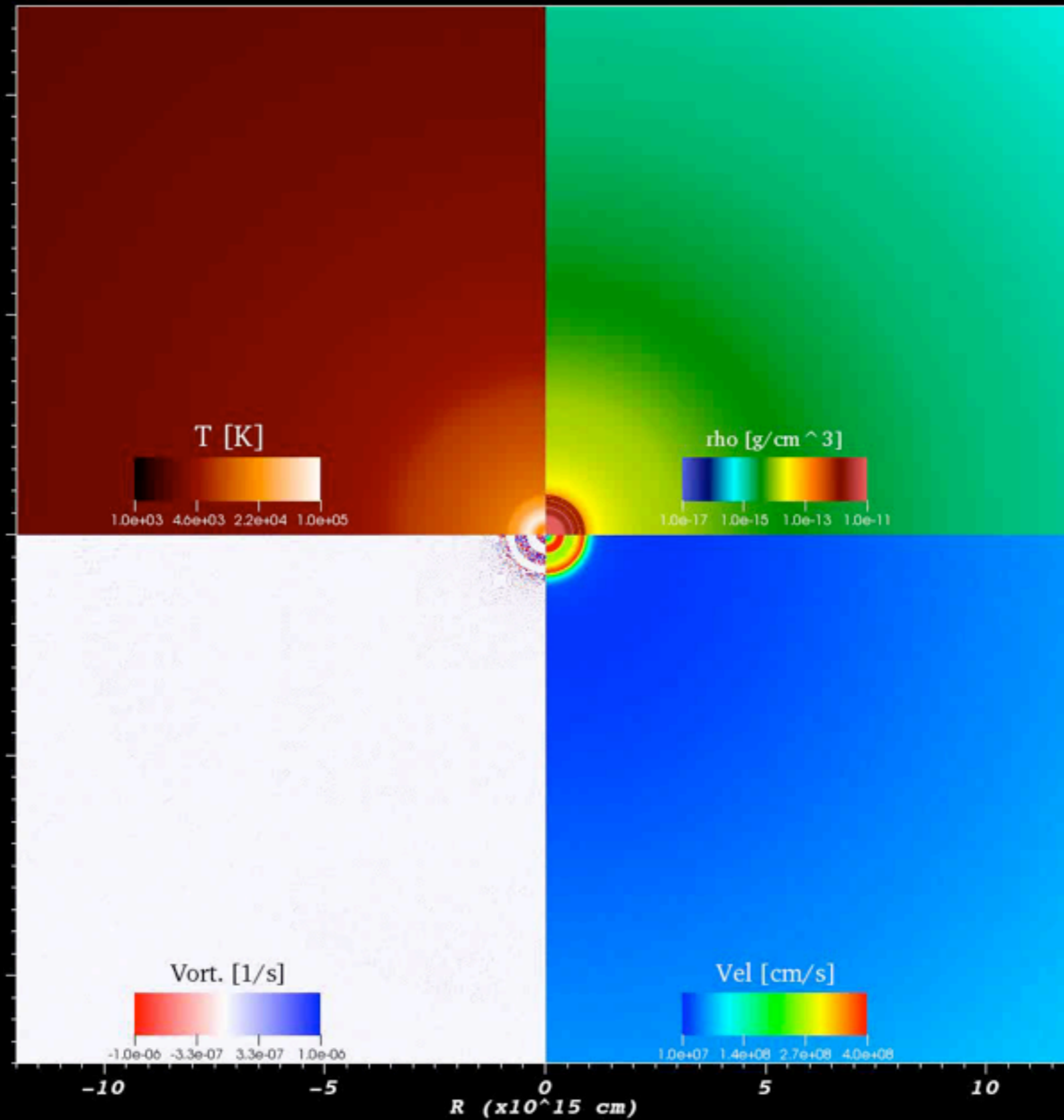


Physical Properties of Colliding Shells



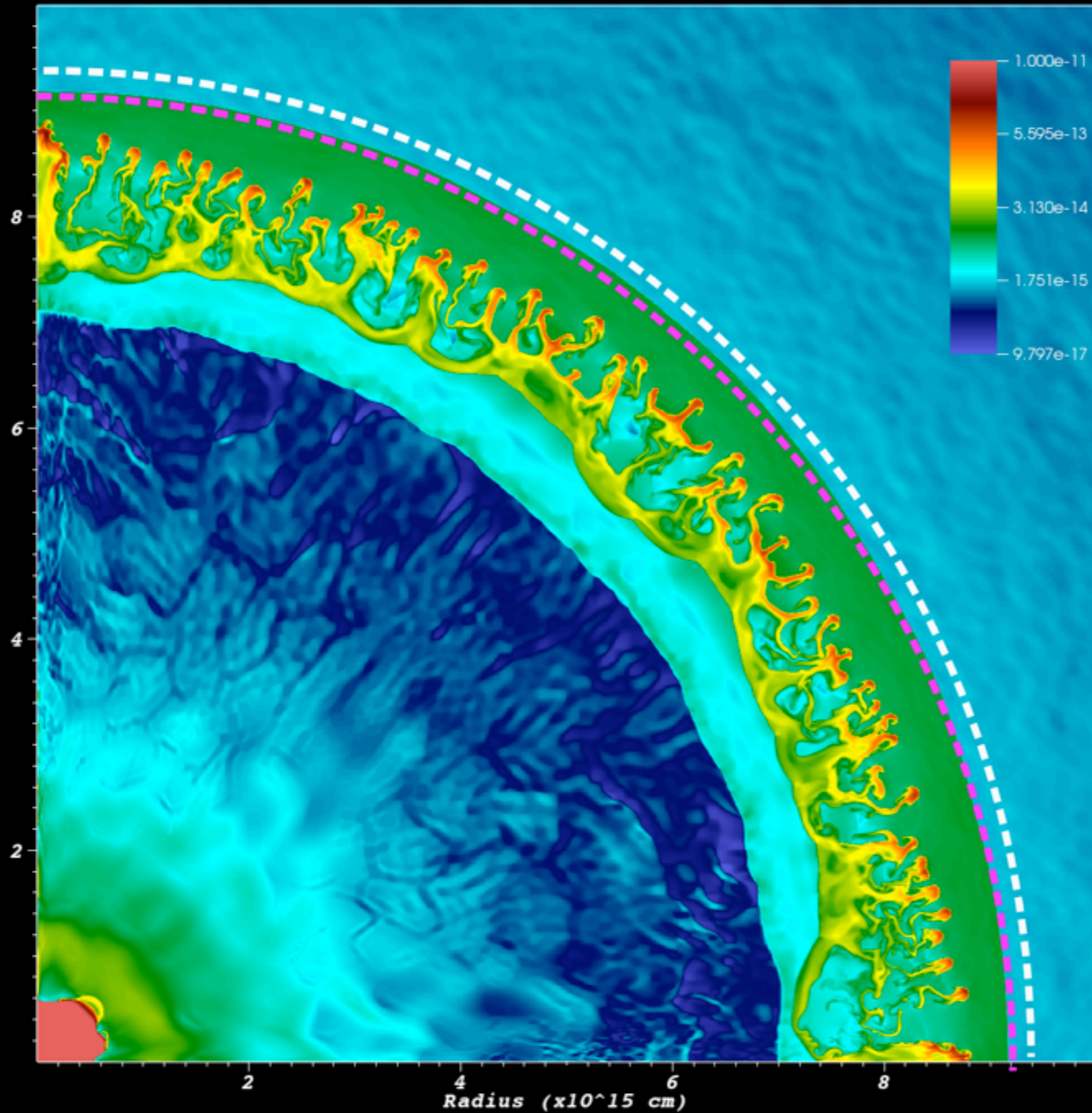
Time=0 s

Physical Properties of Colliding Shells

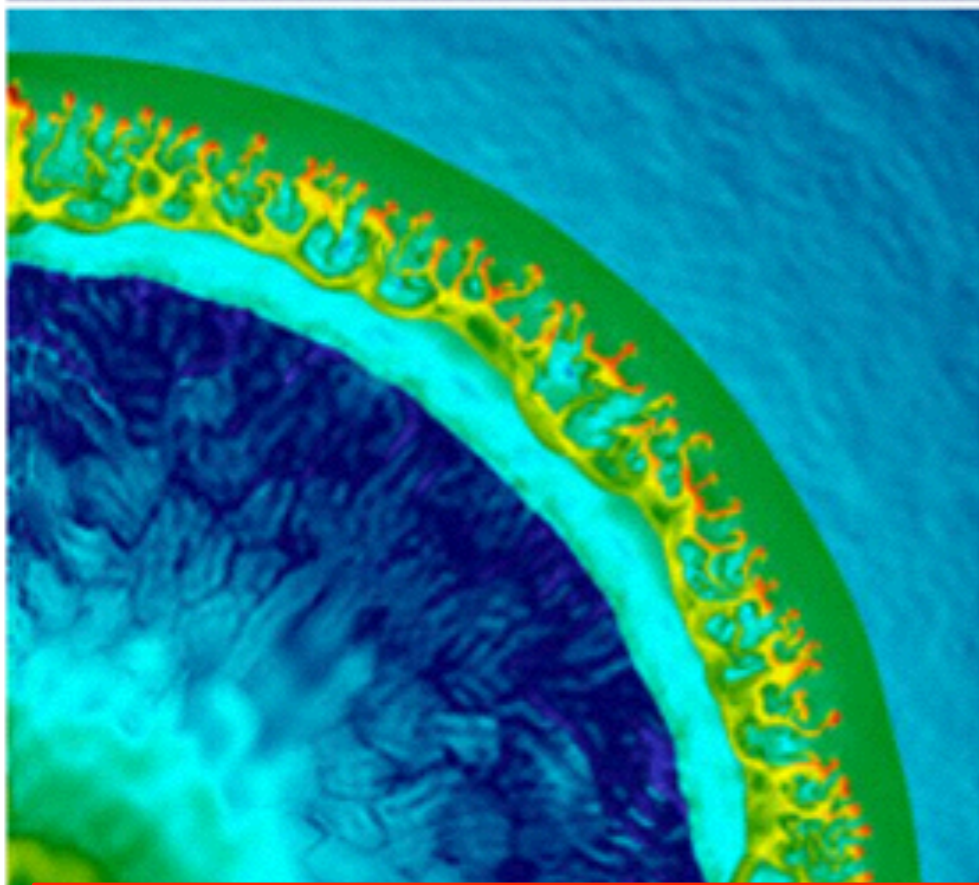


Time=0 s

Physical Properties of Colliding Shells



07 February 2013



Ke-Jung Chen/Univ. Minnesota

A dying star's massive outburst

Observations of the final weeks of a massive star, just over a month before it exploded as a supernova, are reported in *Nature* this week.

Latest news

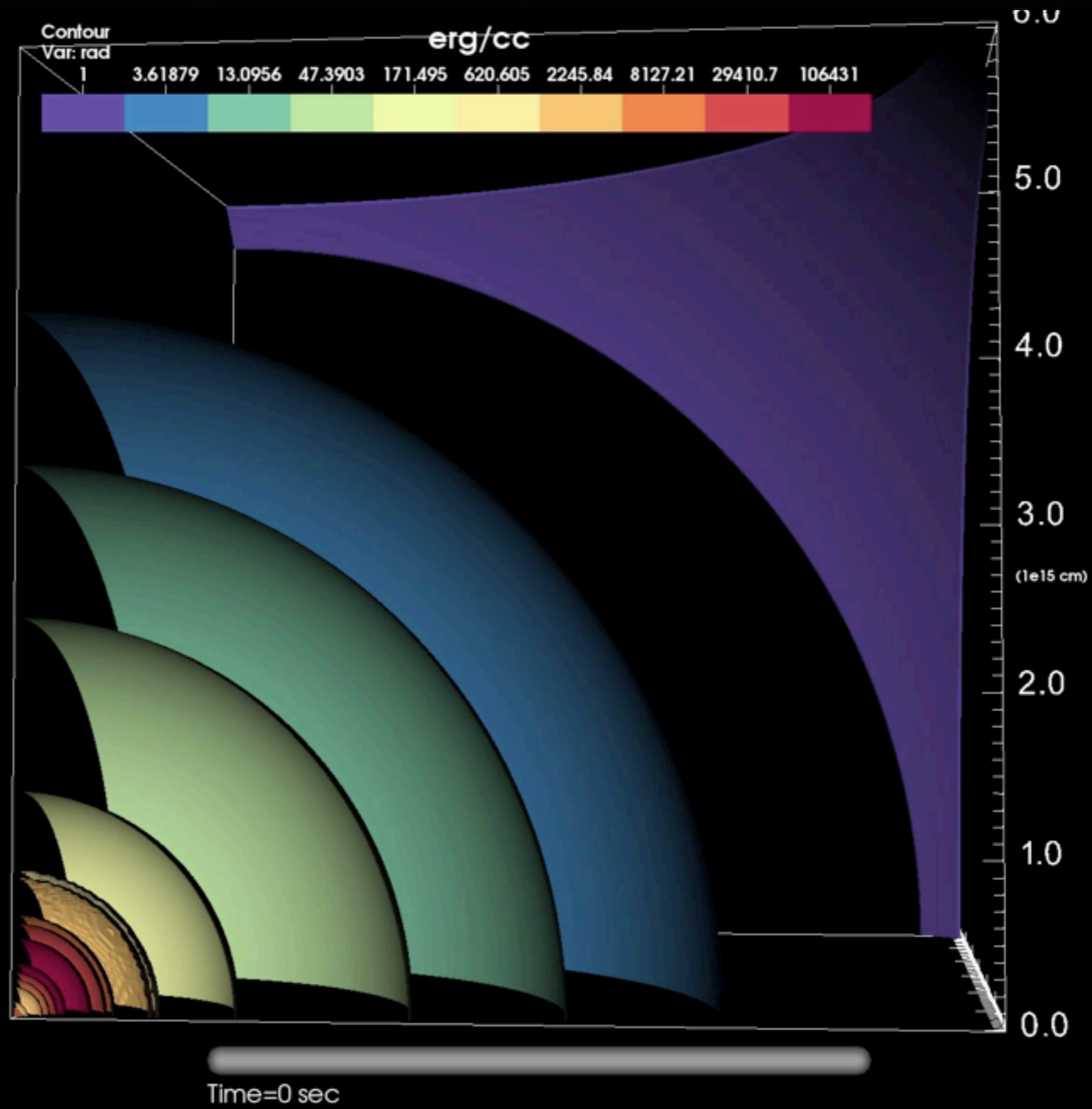
- ▶ Europe bets on drug discovery
- ▶ Seven days: 1–7 February 2013
- ▶ Landsat 8 to the rescue

Ofek, E. O., *et al.* *Nature* (2013)
Heger *Nature* (2013)

[More news from nature](#) ▶

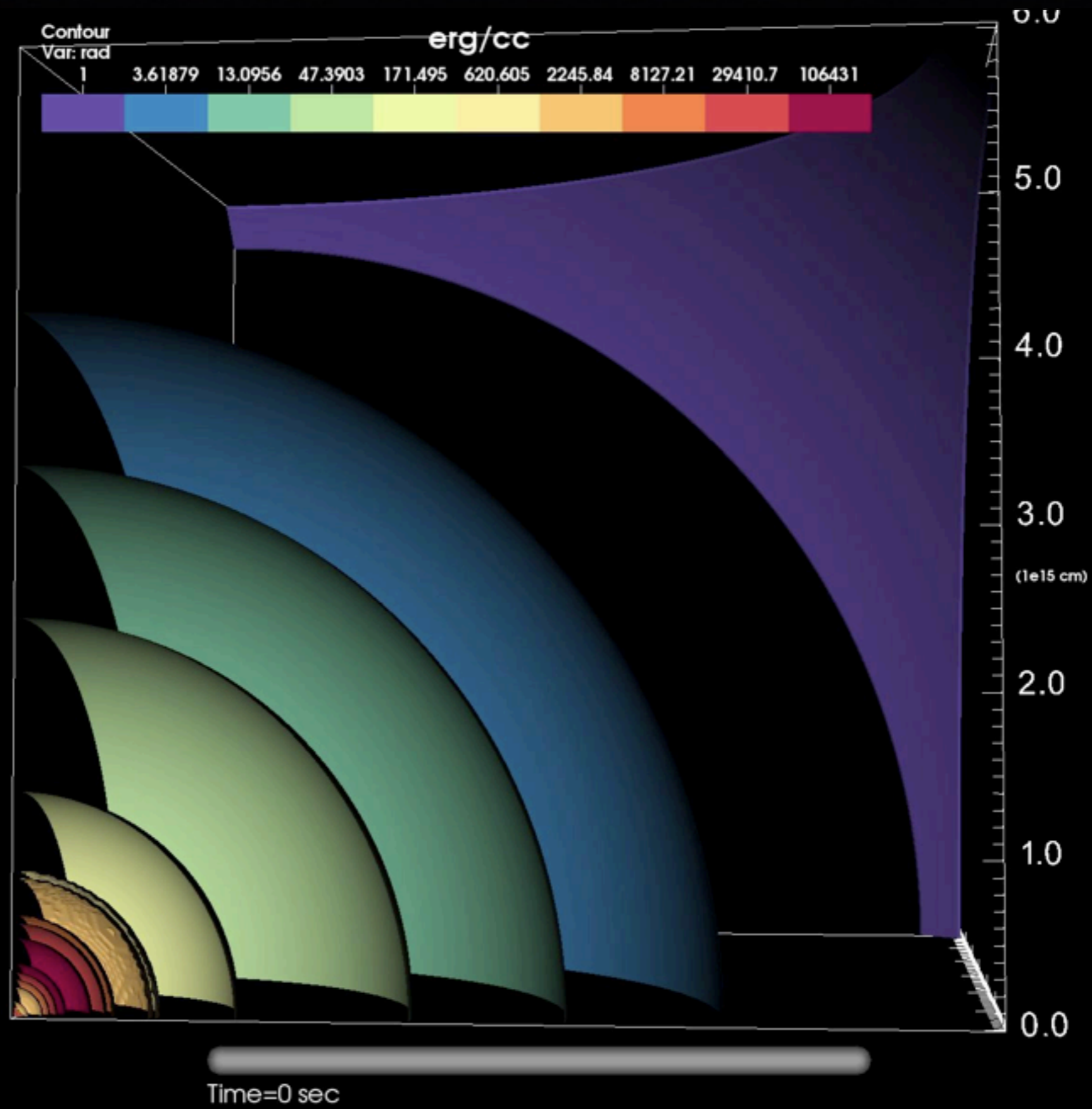
3D Radiation Transport Simulations of PPSNe

Chen, Woosley, & Zhang (In prep.)

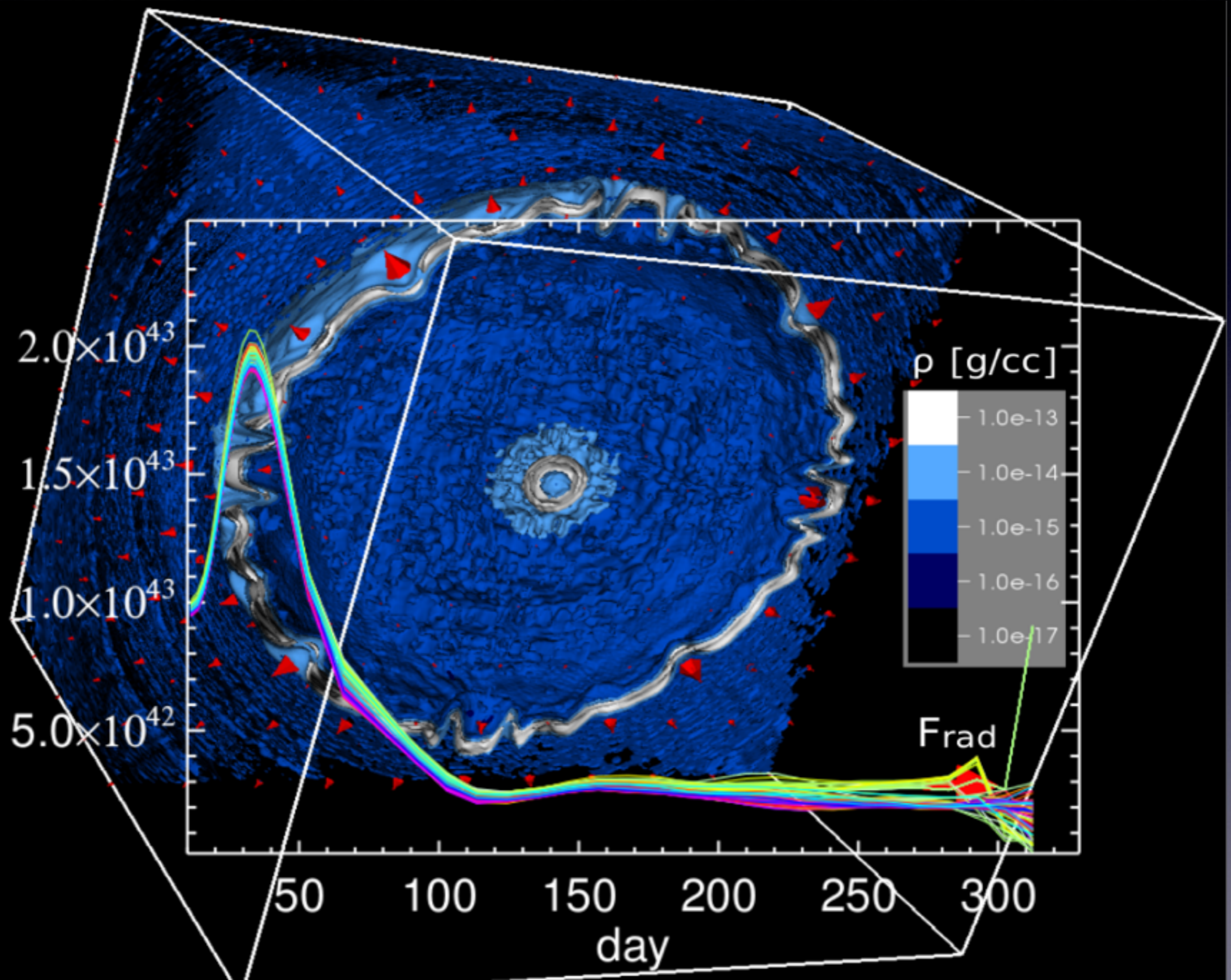


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3D Radiation Transport Simulations of PPSNe



More Bangs & Advertisement

Low Energy SNe



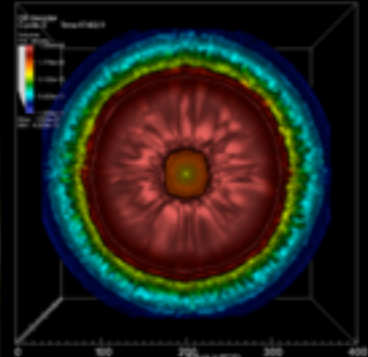
$12 M_{\odot} < M^* < 60 M_{\odot}$
 Trigger: iron core collapse
 Dynamite: G-energy and neutrino
 Characteristics:
 1. 10,000+ fainter than normal SN
 2. Almost no Ni ejecta
 3. Strong mixing during fallback
 Chen+ (arXiv:1601.06896)

Magnetar-powered SNe



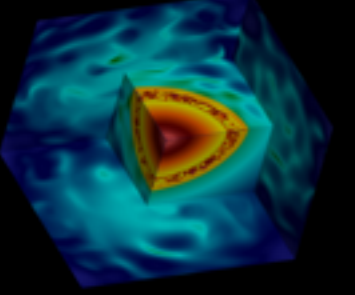
$30 M_{\odot} < M^* < 45 M_{\odot}$
 Trigger: iron core collapse
 Dynamite: magnetar energy
 Characteristics:
 1. Luminous SN or GRB
 2. $< 0.1 M_{\odot}$ Ni
 3. Radiation breakout at early on
 Chen+ (arXiv:1604.07989)

Pulsational Pair-Instability SNe



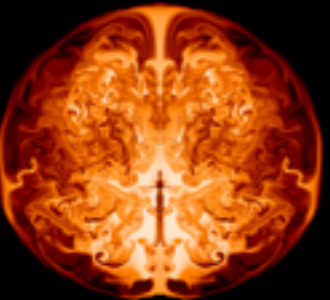
$80 M_{\odot} < M^* < 140 M_{\odot}$
 Trigger: e+/e- creation instability
 Dynamite: explosive C/O burning
 Characteristics:
 1. Several eruptions
 2. Multi-SNe (one superluminous)
 3. Mixing during shell collisions
 Chen+ ApJ 792 28 (2014)

Pair-Instability SNe



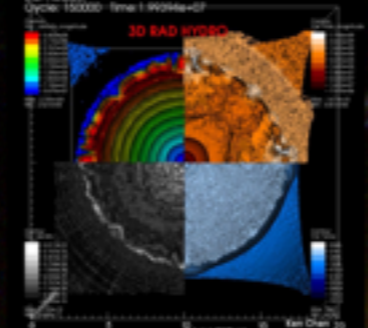
$140 M_{\odot} < M^* < 250 M_{\odot}$
 Trigger: e+/e- creation instability
 Dynamite: explosive O/Si energy
 Characteristics:
 1. faint or superluminous SN
 2. 0.2 to 30 M_{\odot} Ni
 3. Mixing by reverse shock or burning
 Chen+ ApJ 792 44 (2014)

GR Instability SNe



$54,000 M_{\odot} < M^* < 56,000 M_{\odot}$
 Trigger: GR instability
 Dynamite: explosive He burning
 Characteristics:
 1. Energetic explosion $\sim 1E55$ erg
 2. No Ni and no superluminous
 3. Mixing by burning
 Chen+ ApJ 790 162 (2014)

Radhydro models of Exotic SNe



$30 M_{\odot} < M^* < 140 M_{\odot}$
 To advance the state of the art in synthetic light curves and spectra for SNe of massive stars, we perform multidimensional radiation hydrodynamics simulations to obtain their light curves and use time-dependent monte carlo radiative transfer calculations to retrieve the detailed spectra that can be directly compared to actual data...
 Chen, Woosley, Zhang, In prep

East Asian Core Observatories Association (EACOA)



Japan



Taiwan



China



Korea

EACOA Postdoctoral Fellowship !!

- up to 5 year duration
- \$20,000+ annual research fund
- \$60,000 annual stipend (tax-free)
- \$4,000 relocation
- Fellows are free to select at least two host institutions from the EACOA member institutions and have the opportunity to access all research facilities run by the EACOA member institutes, including the LAMOST, Subaru Telescope, CFCA, ALMA, etc.