Mixing of Pair-Instability Supernovae

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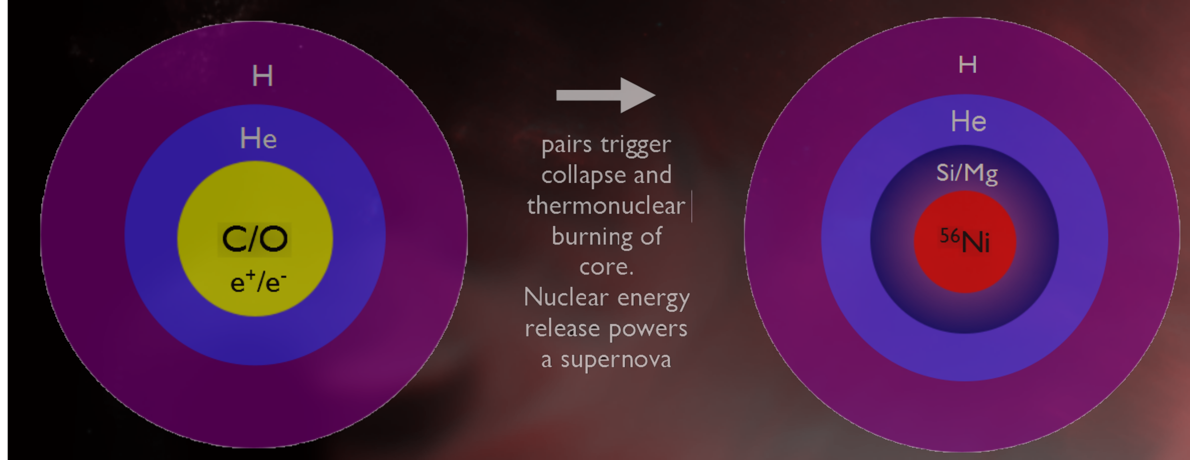
Abstract

We present results from multidimensional simulations of the supernovae from the early universe with a new radiation-hydro code, CASTRO. For carrying out our simulations, we develop a new perturbation-seeding scheme based on stellar convective physics and several nuclear reaction networks for calculating the energetics and nucleosynthesis of the explosion. Our models capture all explosive burning and follow the explosion until the shock breaks out from the stellar surface. When the shock reaches the hydrogen envelope, a strong reverse shock forms that rapidly develops Rayleigh-Taylor instabilities. In red supergiant progenitors, the amplitudes of these instabilities are sufficient to mix the supernova's ejecta and alter its observational signature.

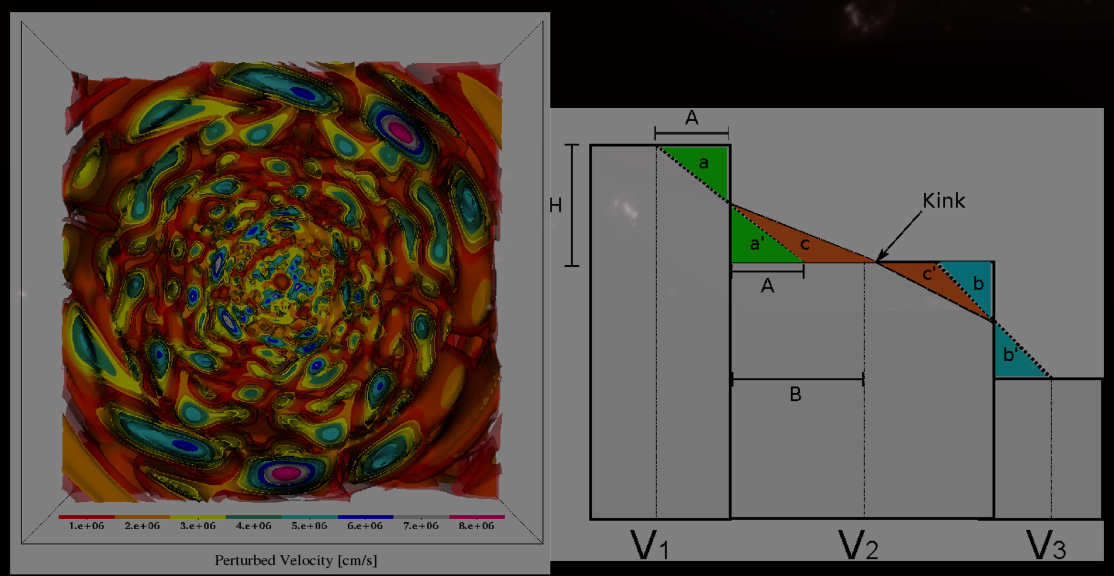
Explosive Fate of Very Massive Stars



Recent observations find the evidence of massive stars with masses greater than 100 M⊙. Based on stellar physics, the stars with an initial mass of 150 - 250 M⊙ may die as energetic thermonuclear supernovae, known as pair instability super-novae (PSNe).

Computational Approach

The early stages of the star's life until oxygen burning are simulated using KEPLER, a one-dimensional spherically-symmetric Lagrangian code. We follow the evolution of star until about hundreds of seconds before the maximum compr-ession of the core. Then we map the resulting 1D profiles into multidimensional grids, where they serve as the initial conditions for CASTRO, a new, massively parallel, multi-dimensional Eulerian, adaptive mesh refinement (AMR), radiation-hydrodynamics code for astrophysical applications. Multi-D simulations are so complex that they require the computational power, memory, and storage equivalent to hundreds or thousands of "regular" desktop computers; they require supercomputers.



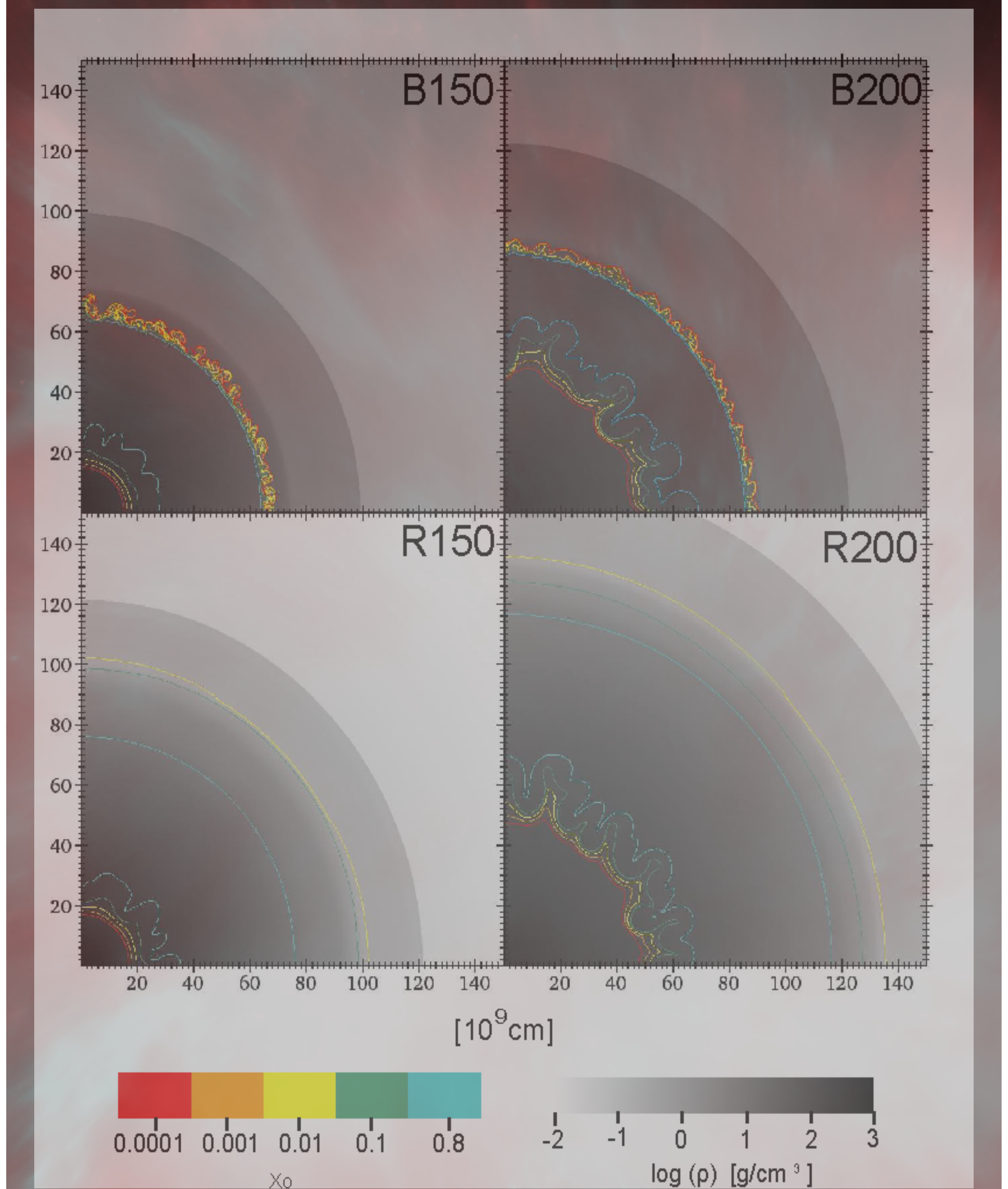
We introduce a new mapping technique for initializing multi-D simulations of stellar explosions with 1D stellar evolution models and imprint them with velocity perturbations that reproduce the Kolmogorov energy spectrum expected for highly turbulent convective regions in stars. Our simulations considering nuclear burning can calculate the nucleosynthesis and energetic during the explosion.

Huge Explosions

Name	M_* $[M_\odot]$	M_{He} $[M_\odot]$	ρ_c $[10^6\ g/cm^3]$	T_c $[10^9\ K]$	R_* $[10^{13}\ cm]$	E $[10^{52}\ erg]$	M_{Ni} $[M_\odot]$
B150	150	67	1.40	3.25	16.54	1.29	0.07
B200	200	95	1.23	3.31	2.86	4.14	6.57
B250	250	109	1.11	3.34	23.06	7.23	28.05
R150	150	59	1.58	3.25	25.69	1.19	0.10
R200	200	86	1.27	3.31	27.68	3.43	4.66
R250	250	156	0.95	3.38	20.76	...	...

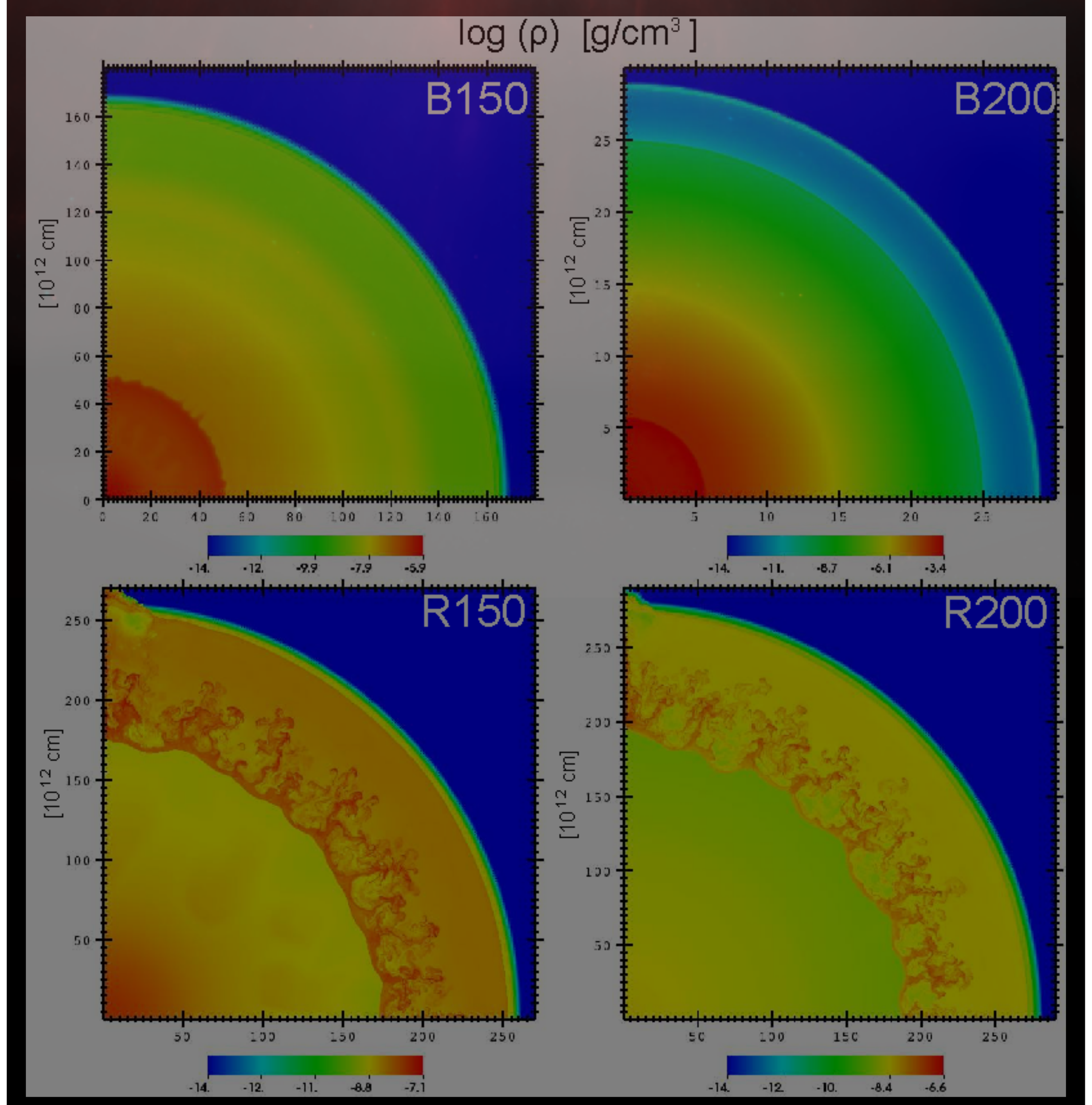
Summary of 2D models: We have simulated a suite of progenitor models, containing weak (B) and strong (R) mixing for non-rotating stars with different masses.

Explosive Burning



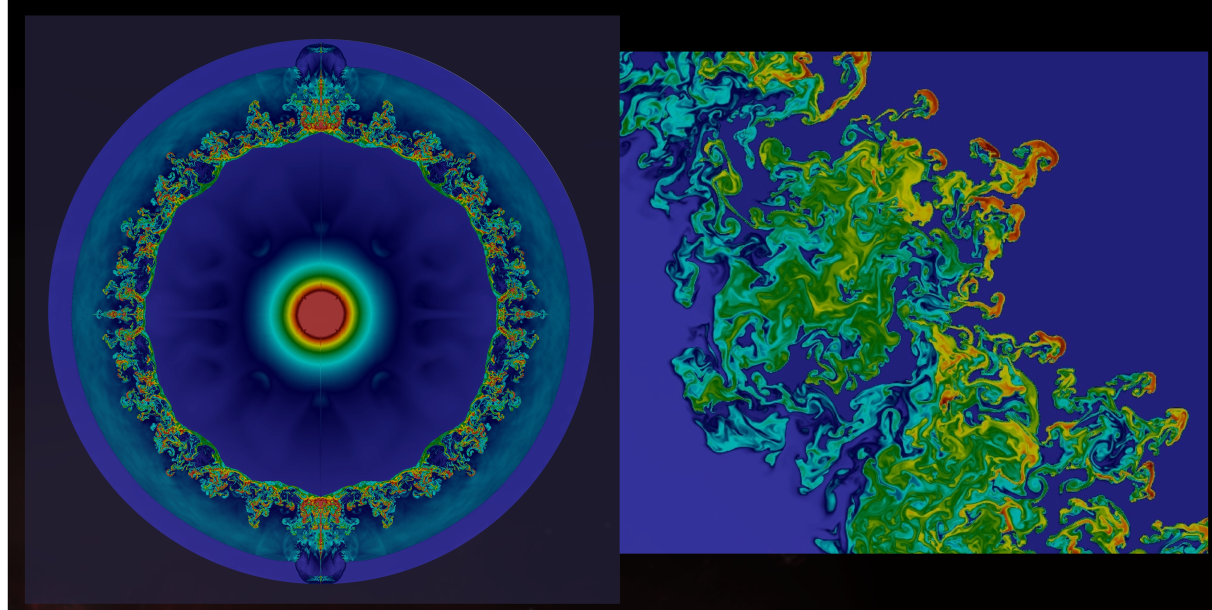
Density and oxygen mass fraction at 120 s after the shock is launched: For B models, there are some fluid instabilities driven by burning appearing at the upper boundary of the oxygen burning shell.

Shock Breakout

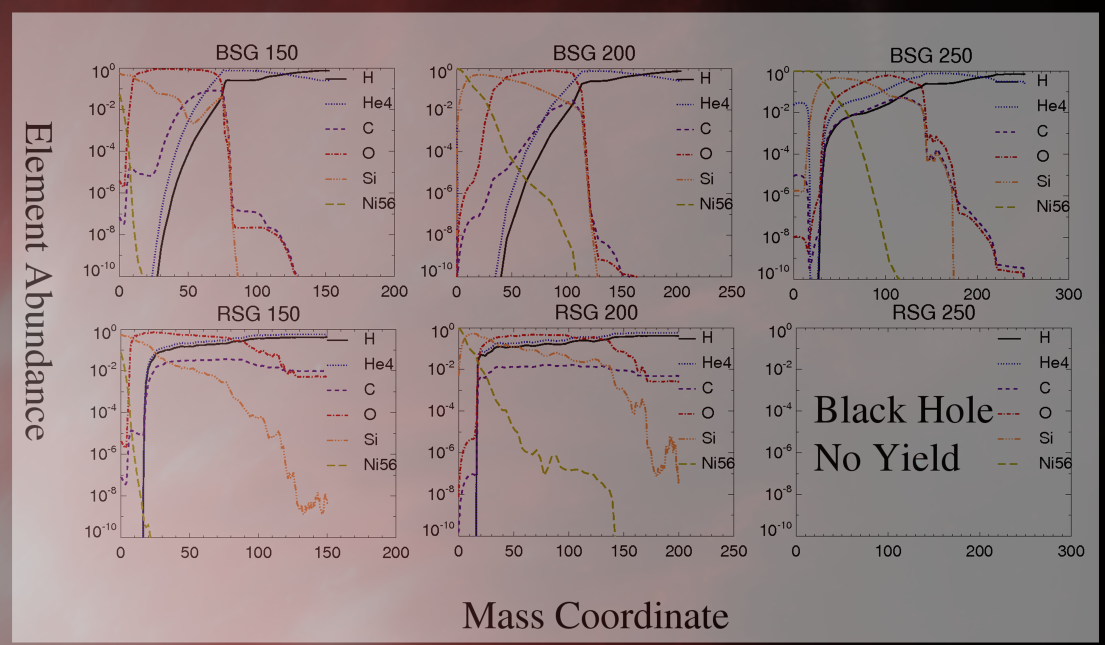


Density at shock breakout: The fluid instabilities driven by reverse-shock have evolved into large scale for R models.

Fluid Instabilities and Mixing



When the shock propagates into the hydrogen envelope, we find fluid instabilities start to grow because of the formation of a strong reverse shock that leads to Rayleigh-Taylor instabilities. They are significant enough to mix the oxygen-burning shell with the surrounding elements.



We have discovered that a large amount of Ni is made, up to 30 M ⊙, and the Ni production depends on the masses and types of the progenitors. For blue super giant progenitors, the mixing is relatively insignificant because of the weaker reverse shock.

Conclusion and Future Work

We have presented the results from the Multi-D simulations of the pair-instability supernovae using a new code, CASTRO. For simulating PSNe in Multi-D, we introduce new numerical approaches for setting up our simulations and consider the nuclear burning to study the energetic and nucleosynthesis of explosions. The formation of Rayleigh-Taylor instabilities in the explosion can lead to significant mixing of ejecta that can directly affect the observational signatures of PSNe. The future work is to process our simulations into light curves and spectra to produce observational signatures. The expected results will provide useful predictions for PSNe that might soon be examined with the JWST.

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