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Core-collapse supernova simulations[1]

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Core-collapse supernovae, the deaths of massive stars, are among the most spectacular phenomena in astrophysics: Not only can supernovae outshine their host galaxy for weeks; they are also laboratories for the behavior of matter at supranuclear densities, and one of the few environments where collective neutrino effects can become important. Moreover, supernovae play a central role in the cosmic matter cycle, e.g., as the dominant producers of oxygen in the Universe. Yet the mechanism by which massive stars explode has eluded us for decades, partly because classical astronomical observations across the electromagnetic spectrum cannot directly probe the supernovae "engine". Numerical simulations are thus our primary tool for understanding the explosion mechanism(s) of massive stars. Rigorous modeling needs to take a host of important physical ingredients into account, such as the emission and partial reabsorption of neutrinos from the young proto-neutron star, multi-dimensional fluid motions, general relativistic gravity, the equation of state of nuclear matter, and magnetic fields. This is a challenging multi-physics problem that has not been fully solved yet. Nonetheless, as I shall argue in this talk, recent first-principle 3D simulations have gone a long way towards demonstrating the viability of the most popular explosion scenario, the "neutrino-driven mechanism". Focusing on successful explosion models of the MPA-QUB-Monash collaboration, I will discuss possible requirements for robust explosions across a wide range of progenitors, such as accurate neutrino opacities, stellar rotation, and seed asymmetries from convective shell burning. With the advent of successful explosion models, supernova theory can also be confronted with astronomical observations. I will show that recent 3D models come closer to matching observed explosion parameters (explosion energies, neutron star kicks) than older 2D models, although there are still discrepancies.

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