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Low-Mass Failed Supernovae Explain the 10-Solar-Mass Peak in Merging Black Holes, Physical Review D Study Finds

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Every textbook diagram of massive stellar evolution ends with a violent core-collapse supernova: an iron core gives way under gravity, a shockwave blasts the star's outer envelope into interstellar space, and a neutron star or black hole remains behind. Yet a November 10, 2026 study published in Physical Review D (Vol. 114, 103023) by Caltech and University of Illinois Urbana-Champaign astrophysicists Isaac Legred, Jacob Golomb, and Katerina Chatziioannou demonstrates that gravitational-wave observations point to a quieter pathway. Analyzing 257 binary black hole mergers recorded by the LIGO-Virgo-KAGRA (LVK) network, the researchers show that the sharpest feature in the merging black hole mass distribution -- a prominent pileup near 10 solar masses (10 M) accompanied by a steep drop-off between roughly 12 and 16 M -- is naturally explained by "failed supernovae," in which stars between roughly 12 and 14 M with tightly compact cores collapse directly into black holes without exploding.

Roughly 75 percent of the merging binary black hole pairs analyzed in the dataset feature a primary black hole clustered right around 10 M . For nearly a decade, explaining why nature preferentially manufactures 10-solar-mass merging black holes -- while producing far fewer mergers just slightly heavier at 12 to 16 M -- remained one of the central puzzles of gravitational-wave astrophysics . By connecting relativistic core-collapse compactness theory directly to hierarchical Bayesian population modeling of LVK events, Legred, Golomb, and Chatziioannou bridge stellar-structure physics and gravitational-wave astronomy.

The 10-Solar-Mass Peak in LIGO-Virgo-KAGRA Merger Catalogs

Since the first direct detection of gravitational waves in 2015, the LIGO, Virgo, and KAGRA interferometers have transformed black holes from rare X-ray binary curiosities into a statistical population. Rather than forming a smooth, featureless power-law curve tapering from 5 M up to the pair-instability gap near 50 M , the observed primary-mass spectrum exhibits distinct substructure. Across 257 binary black hole mergers modeled in the Physical Review D analysis (extending earlier 153-event subsets), the dominant feature is a sharp, narrow overdensity centered at approximately 10 M .

Immediately above that peak, the merger rate drops precipitously across the 12 to 16 M mass interval before rising again toward a secondary broad bump near 30 to 35 M . Standard monotonic initial-to-final mass relations -- which assume that heavier zero-age main-sequence stars always leave heavier compact remnants after shedding mass through stellar winds and supernova explosions -- struggle to carve such a sharp spike at 10 M followed immediately by a deficit at 12 to 16 M without fine-tuned binary mass-transfer assumptions.

Core-Collapse Physics and the Stalled Neutrino Shock

To understand how a star can implode into a black hole without a supernova, one must follow the final milliseconds of iron -core collapse. Once silicon burning builds an iron-group core exceeding the effective Chandrasekhar mass limit (~1.4 M), electron degeneracy pressure can no longer support the core against self-gravity. Photodisintegration of iron nuclei and rapid electron capture on protons accelerate catastrophic infall, driving the inner core to nuclear saturation density (~2.7 x 10 14 g/cm 3) within fractions of a second.

At nuclear density, the strong nuclear force stiffens the equation of state abruptly, causing the inner core to rebound and launch an outward hydrodynamic shockwave. However, as that shock plows outward through the overlying iron and silicon shells, it loses enormous energy dissociating heavy nuclei into free nucleons and stalls within ~100 to 200 kilometers of the center. In a successful core-collapse supernova, intense fluxes of electron neutrinos and antineutrinos streaming out of the proto-neutron star deposit roughly 1 percent of their energy in a "gain region" behind the stalled shock, heating the plasma, driving turbulent convection , and reviving the explosion within a few hundred milliseconds.

Whether the shock revives or fails depends on a delicate duel between outward neutrino heating and the inward ram pressure of infalling stellar layers. As Evan O'Connor and Christian D. Ott demonstrated in their foundational 2011 Astrophysical Journal paper, Black Hole Formation in Failing Core-Collapse Supernovae , the outcome is governed largely by the star's core compactness -- the ratio of enclosed mass to radius at the onset of collapse. A high-compactness core places dense silicon and oxygen shells close to the center, generating overwhelming inward mass accretion and ram pressure that chokes the stalled shock before neutrino heating can unbind the star.

| Astrophysical Regime | | Progenitor / Core Trait | | Collapse Outcome & Remnant |

| Standard Exploding Massive Stars | | Lower core compactness; shock revives via neutrinos | | Bright core-collapse supernova; neutron star remnant |

| Low-Mass Failed Supernova Window | | ~12-14 M progenitors with tightly compact cores | | Shock fails; direct quiet collapse into ~10 M black hole |

| Adjacent Higher-Mass Regime | | Non-monotonic shell burning lowers compactness | | Explosion resumes; creates 12-16 M black hole deficit |

| High-Mass Direct Collapse | | Very massive, high-compactness cores | | Forms heavier black holes (~30-35 M subpopulation) |

Non-Monotonic Explodability and the 12-14 Solar-Mass Island

Crucially, stellar core compactness does not increase smoothly with a star's birth mass. During late-stage carbon , neon , oxygen, and silicon burning, subtle shifts between convective and radiative core burning -- driven by nuclear reaction rates such as 12 C(alpha,gamma) 16 O and shell-merging episodes -- create a jagged, non-monotonic "island of explodability." Certain narrow progenitor mass windows develop unusually dense, compact cores while slightly lighter and slightly heavier stars retain fluffier density profiles that explode readily.

Legred, Golomb, and Chatziioannou show that stars in a specific ~12 to 14 M regime (characterized by tightly compact cores) sit inside one of these failed-supernova islands. Because their stalled shock cannot overcome the intense ram pressure of infalling shells, the proto-neutron star accretes matter past the Tolman-Oppenheimer-Volkoff maximum mass limit (~2.1 to 2.3 M) and collapses inside an event horizon. Without a revived shockwave to eject the outer stellar envelope, the entire remaining core and envelope fall inward -- or shed only a tiny, weakly bound fraction of the outer hydrogen envelope -- producing a black hole clustered tightly near 10 M .

Just above that ~12 to 14 M island, stellar structure shifts back toward lower core compactness, allowing stars in the adjacent mass range to explode successfully as supernovae! Because a successful explosion blasts away most of the outer envelope and leaves behind a neutron star (or, if fallback occurs, a low-mass remnant), fewer stars in that neighboring mass band form black holes in the 12 to 16 M range. That non-monotonic flip between direct collapse and successful explosion simultaneously creates both the sharp 10 M peak and the adjacent 12 to 16 M merger-rate valley observed by LIGO-Virgo-KAGRA.

Why Quiet Direct Collapse Favors Merging Binaries

Forming a 10 M black hole is only half of the gravitational-wave story; to merge within the 13.8-billion-year age of the Universe, two black holes must also remain bound in a tight binary orbit whose semi-major axis is small enough for gravitational radiation to shrink the orbit within a Hubble time. Here, failed supernovae enjoy a decisive dynamical advantage over violent explosions.

In a standard asymmetric core-collapse supernova, neutrino emission anisotropies and hydrodynamic instabilities impart a strong "natal kick" to the newborn compact object -- often hundreds of kilometers per second -- while sudden ejection of more than half the system's total mass triggers the Blaauw recoil effect. Both effects frequently unbind binary star systems or widen their orbits so severely that the remnants can never merge via gravitational waves.

By contrast, a failed supernova undergoes near-spherical, quiet direct collapse with minimal mass ejection and negligible natal kick. Because the binary loses very little total mass and experiences almost no asymmetric impulse, the newly formed ~10 M black hole stays tightly bound to its companion star. Later, after common-envelope evolution or stable mass transfer brings the two remnants close together, those surviving binaries become prime progenitors for the 10 M binary black hole mergers dominating LVK catalogs.

Electromagnetic Silence and Disappearing Supergiants

If stars between roughly 12 and 14 M routinely collapse into black holes without supernovae, why did astronomers take decades to recognize them? The answer lies in observational selection bias: core-collapse supernovae outshine entire host galaxies for weeks, making them effortless to spot in wide-field optical surveys, whereas a failed supernova emits almost no optical firework.

Instead, a direct-collapse event manifests electromagnetically only as a faint, cool infrared transient -- caused by the weak ejection of the loosely bound outer

hydrogen envelope -- followed by the permanent disappearance of a massive progenitor star from archival Hubble or ground-based imaging. Monitoring campaigns targeting nearby galaxies within ~10 megaparsecs have searched specifically for vanishing red supergiants, providing independent optical evidence that not every massive star ends its life in a bright explosion.

Neutrino Bursts, Spin Signatures, and Future LVK Tests

As gravitational-wave detectors expand sensitivity in ongoing and upcoming observing runs, Legred, Golomb, and Chatziioannou's failed-supernova hypothesis offers sharp, falsifiable predictions across multi-messenger astrophysics. First, expanding binary black hole catalogs beyond 257 events will test the exact width, skewness, and redshift evolution of the 10 M peak and the 12 to 16 M gap across cosmic metallicity histories -- since lower-metallicity stars in the early Universe experience weaker stellar winds and shifted core-compactness islands.

Second, gravitational-wave spin measurements provide an independent consistency check. Quiet direct collapse without strong tidal spin-up or asymmetric explosion kicks should preserve predictable spin-orbit alignment distributions relative to dynamically assembled clusters. Finally, if a Galactic or Local Group star in the 12 to 14 M failed-supernova window collapses during the lifetime of Super-Kamiokande, Hyper-Kamiokande, or DUNE, astronomers would observe a dramatic signature: a sudden, intense burst of core-collapse neutrinos lasting roughly one to two seconds that abruptly truncates into silence -- the unmistakable death cry of a proto-neutron star vanishing behind an event horizon without a supernova.

References & Primary Sources

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