THE PHYSICS OF CORE-COLLAPSE SUPERNOVAE

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Two kinds of supernovae:

Type Ia: the thermonuclear explosions of accreting white dwarf stars

- white dwarf reaches Chandrasekhar mass 1.38Msun through accretion from binary companion
- SN energy ~1e51Msun, v~10,000 km/s
- pressure is provided by degenerate electrons — almost constant
- carbon burning and convection, which eventually covers most of the star
- runaway effect as nuclear reaction produces more energy and convection lagging behind to spread it.
- temperature reaches 9e9K in a fraction of sec
- the flame does not stop until the whole star is disrupted

Type II which happen when the iron core of a massive star collapses to a neutron star or black hole.

- SN_energy ~ 1e51 ergs in the form of kinetic energy if debris.
- M_main_sequence > 9Msun
- Life-time on main sequence > 10Myrs
- Explosion is driven by neutrinos
- No explosion for M=30-80Msun — not enough energy to blow off the whole star.

Observationally, Type Ia is defined by a lack of hydrogen lines in its spectrum, lines that Type II has.

Type Ia supernovae happen in all types of galaxies with no preference for star-forming regions, consistent with their origin from an old or intermediate age stellar population.

The rest happen only in star-forming regions where young massive stars are found. Here we will discuss just the latter variety, so- called core-collapse supernovae — the most frequent kind of supernovae in nature.

About 10^{53} erg s^{-1} is released as neutrinos from a ‘core-collapse’ supernova, which is as much instantaneous power as all the rest of the luminous, visible Universe combined.

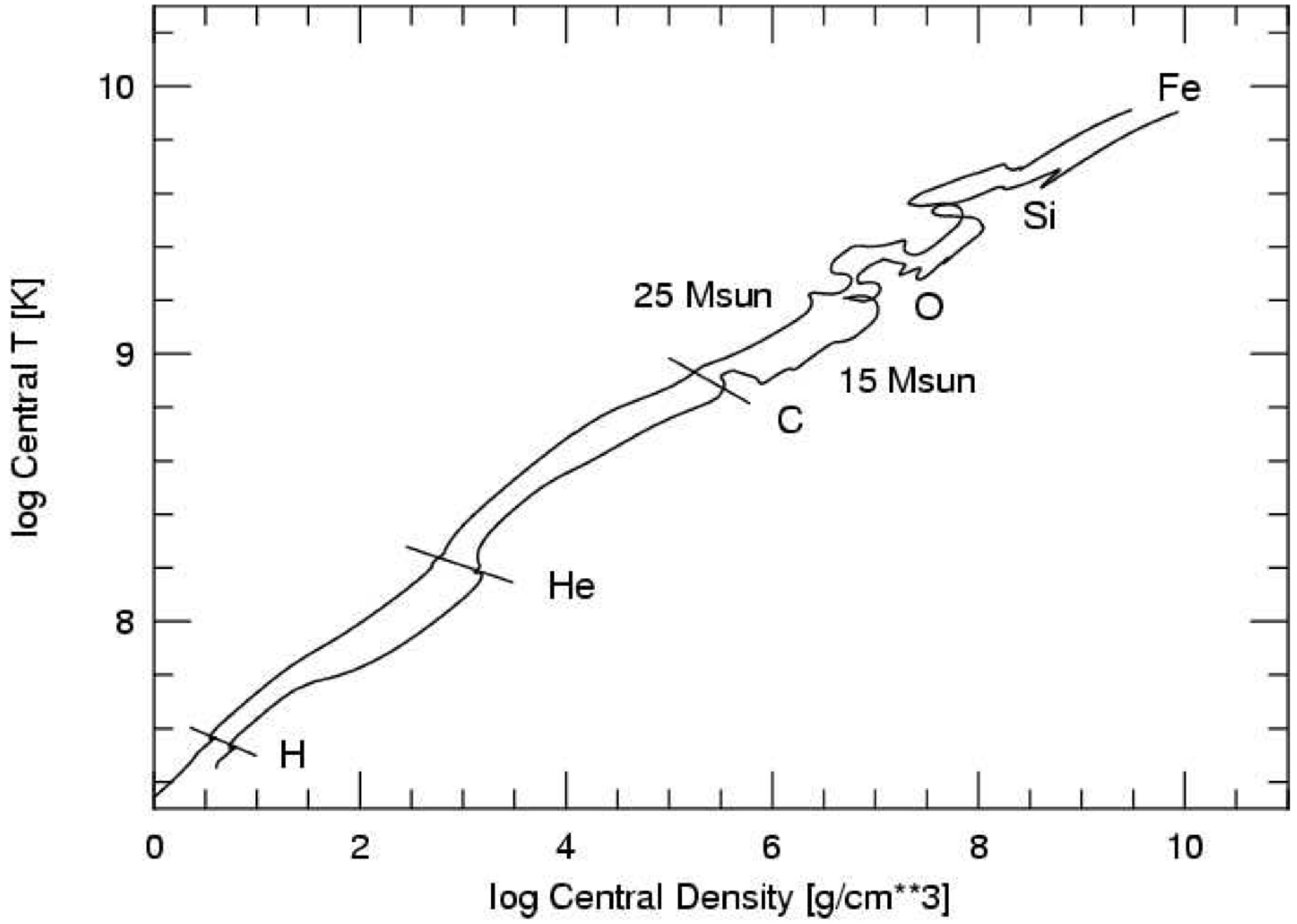
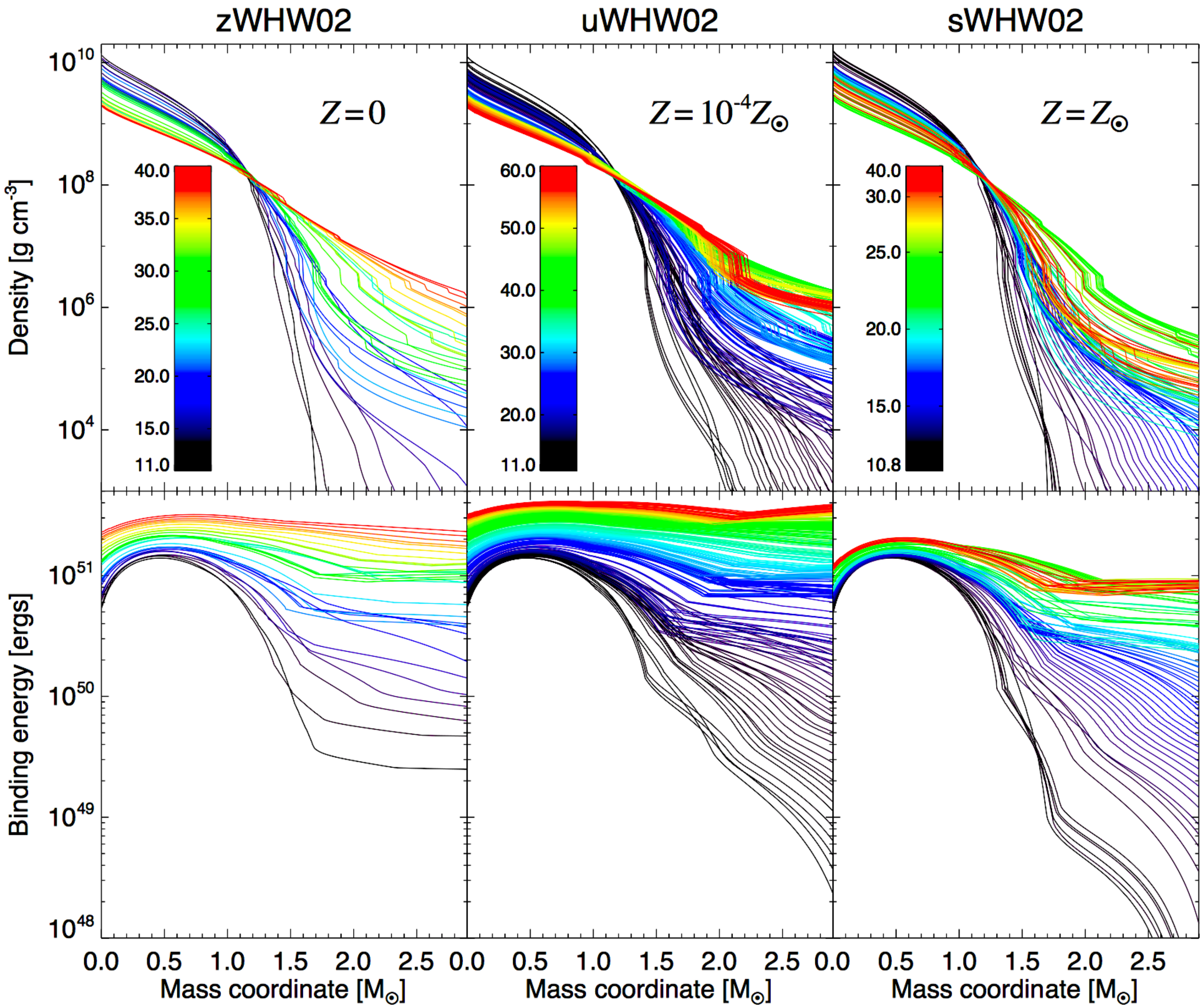


Figure 1: *The evolution of the temperature and density for the centre of two massive stars, 15 and 25 times heavier than the Sun. Labels show the location where the star pauses to burn a given fuel (Table 1). Overall, the evolution of a massive star is a continued contraction to higher density and temperature, a contraction that only ends when a neutron star or black hole is formed. During most of the evolution the density is proportional to the cube of the temperature, as expected for an ideal gas in hydrostatic equilibrium, but there are deviations caused by nuclear burning and the partial quantum mechanical degeneracy of the electrons.*



Progenitor structure of the Woosley et al. (2002) pre-supernovae stellar models. The upper panels show the density profiles as a function of enclosed mass, while the lower panels display the absolute value of the binding energy above a particular mass coordinate. The binding energy is calculated by correcting the gravitational binding energy for the thermal energy of the progenitors. Each column displays progenitors with different metallicity and the color encodes the initial progenitor mass.

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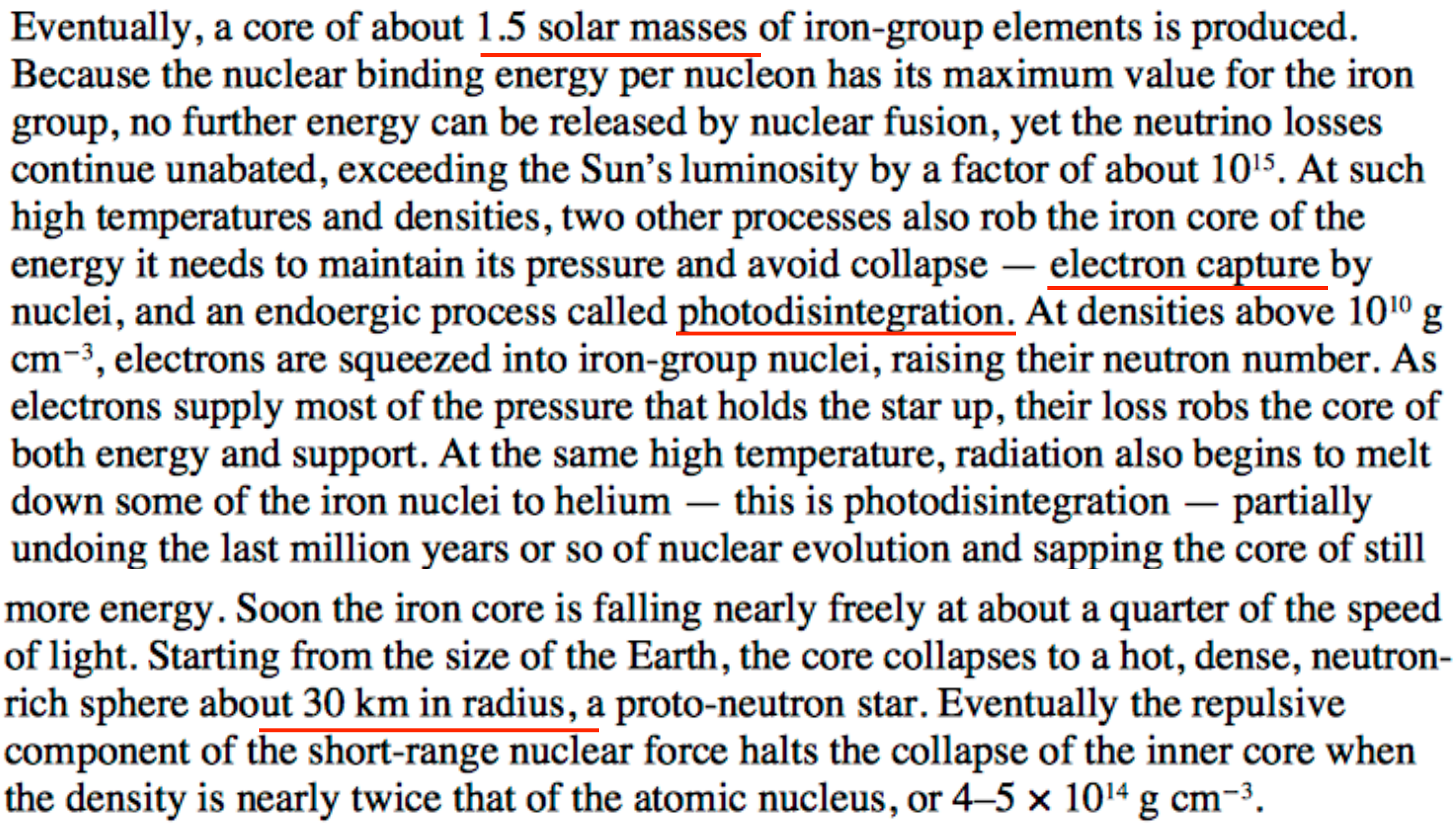
TABLE 1 Evolution of a 15-solar-mass star.

Stage	Time Scale	Fuel or Product	Ash or product	Temperature (10^9 K)	Density (gm/cm^3)	Luminosity (solar units)	Neutrino Losses (solar units)
Hydrogen	11 My	H	He	0.035	5.8	28,000	1800
Helium	2.0 My	He	C,O	0.18	1390	44,000	1900
Carbon	2000 y	C	Ne,Mg	0.81	2.8×10^5	72,000	3.7×10^5
Neon	0.7 y	Ne	O,Mg	1.6	1.2×10^7	75,000	1.4×10^8
Oxygen	2.6 y	O,Mg	Si,S,Ar, Ca	1.9	8.8×10^6	75,000	9.1×10^8
Silicon	18 d	Si,S,Ar, Ca	Fe,Ni, Cr,Ti,...	3.3	4.8×10^7	75,000	1.3×10^{11}
Iron core collapse[a]	~1 s	Fe,Ni, Cr, Ti,...	Neutron Star	> 7.1	$>7.3 \times 10^9$	75,000	$>3.6 \times 10^{15}$

Collapse starts when iron core reaches the Chandrasekhar mass

two additional processes accelerate the collapse

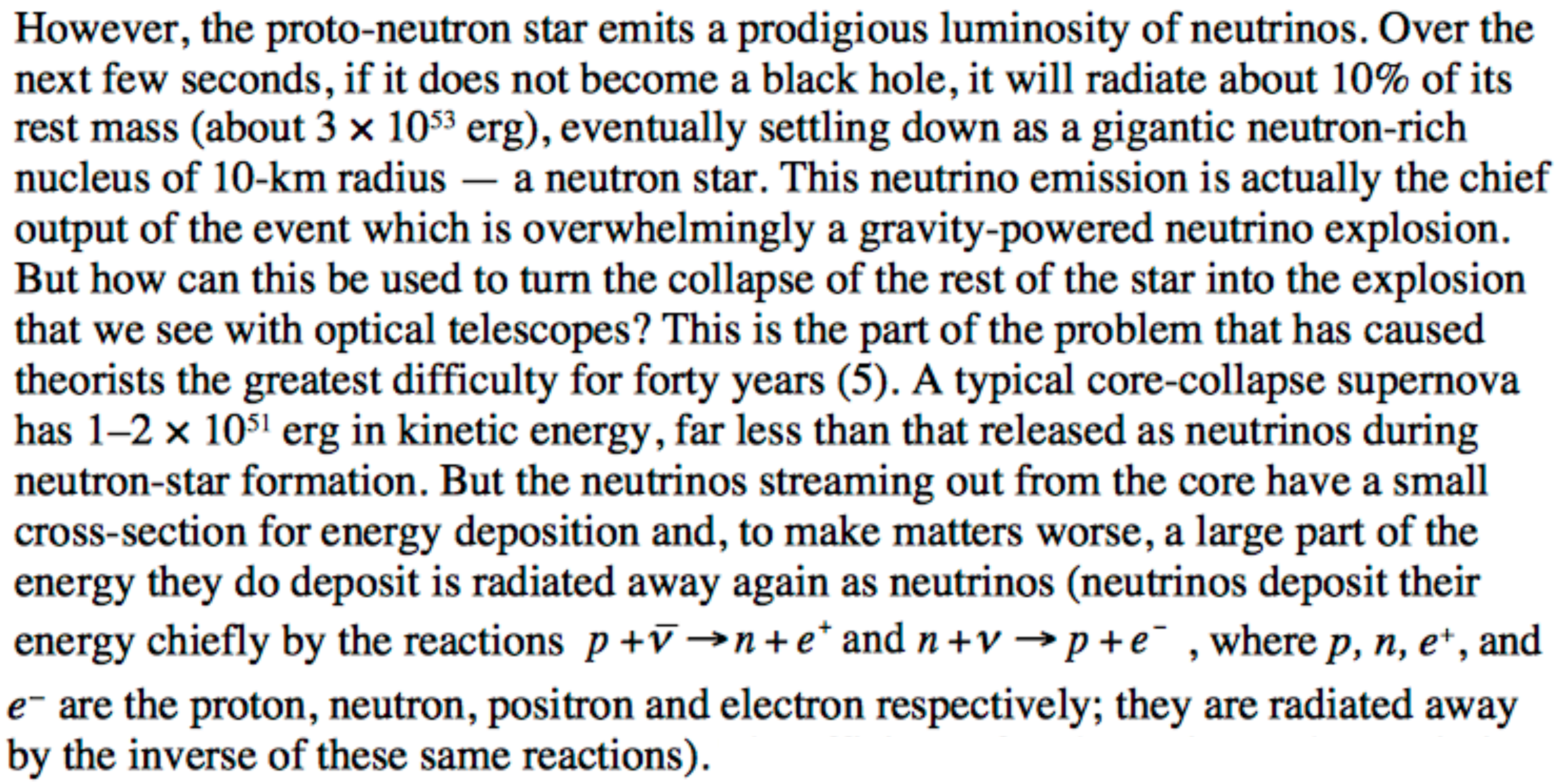
collapse to NS



Eventually, a core of about 1.5 solar masses of iron-group elements is produced. Because the nuclear binding energy per nucleon has its maximum value for the iron group, no further energy can be released by nuclear fusion, yet the neutrino losses continue unabated, exceeding the Sun's luminosity by a factor of about 10^{15}. At such high temperatures and densities, two other processes also rob the iron core of the energy it needs to maintain its pressure and avoid collapse — electron capture by nuclei, and an endoergic process called photodisintegration. At densities above 10^{10} g cm^{-3}, electrons are squeezed into iron-group nuclei, raising their neutron number. As electrons supply most of the pressure that holds the star up, their loss robs the core of both energy and support. At the same high temperature, radiation also begins to melt down some of the iron nuclei to helium — this is photodisintegration — partially undoing the last million years or so of nuclear evolution and sapping the core of still more energy. Soon the iron core is falling nearly freely at about a quarter of the speed of light. Starting from the size of the Earth, the core collapses to a hot, dense, neutron-rich sphere about 30 km in radius, a proto-neutron star. Eventually the repulsive component of the short-range nuclear force halts the collapse of the inner core when the density is nearly twice that of the atomic nucleus, or 4–5 × 10^{14} g cm^{-3}.

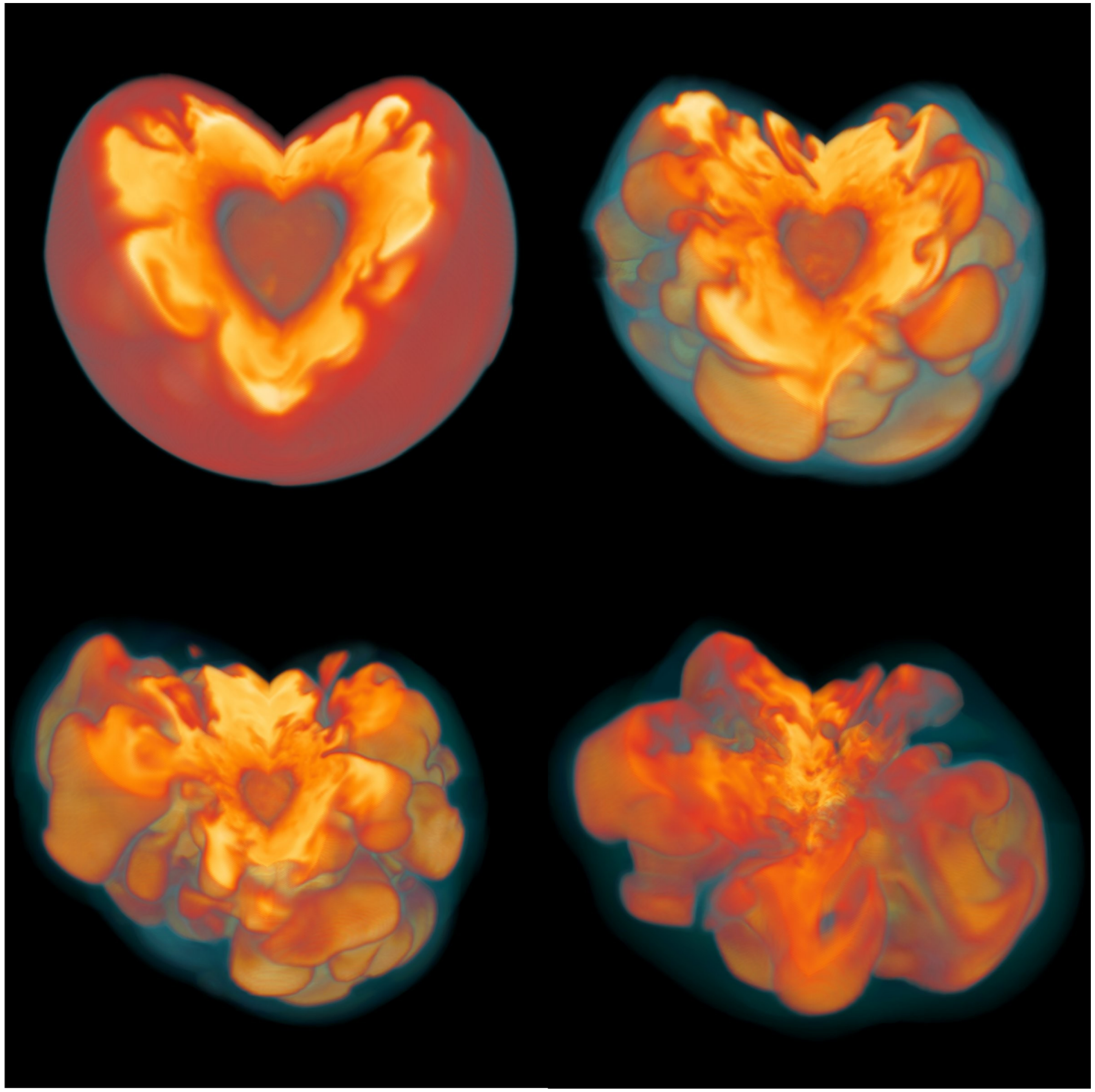
Neutrinos

Neutrinos drive the explosion

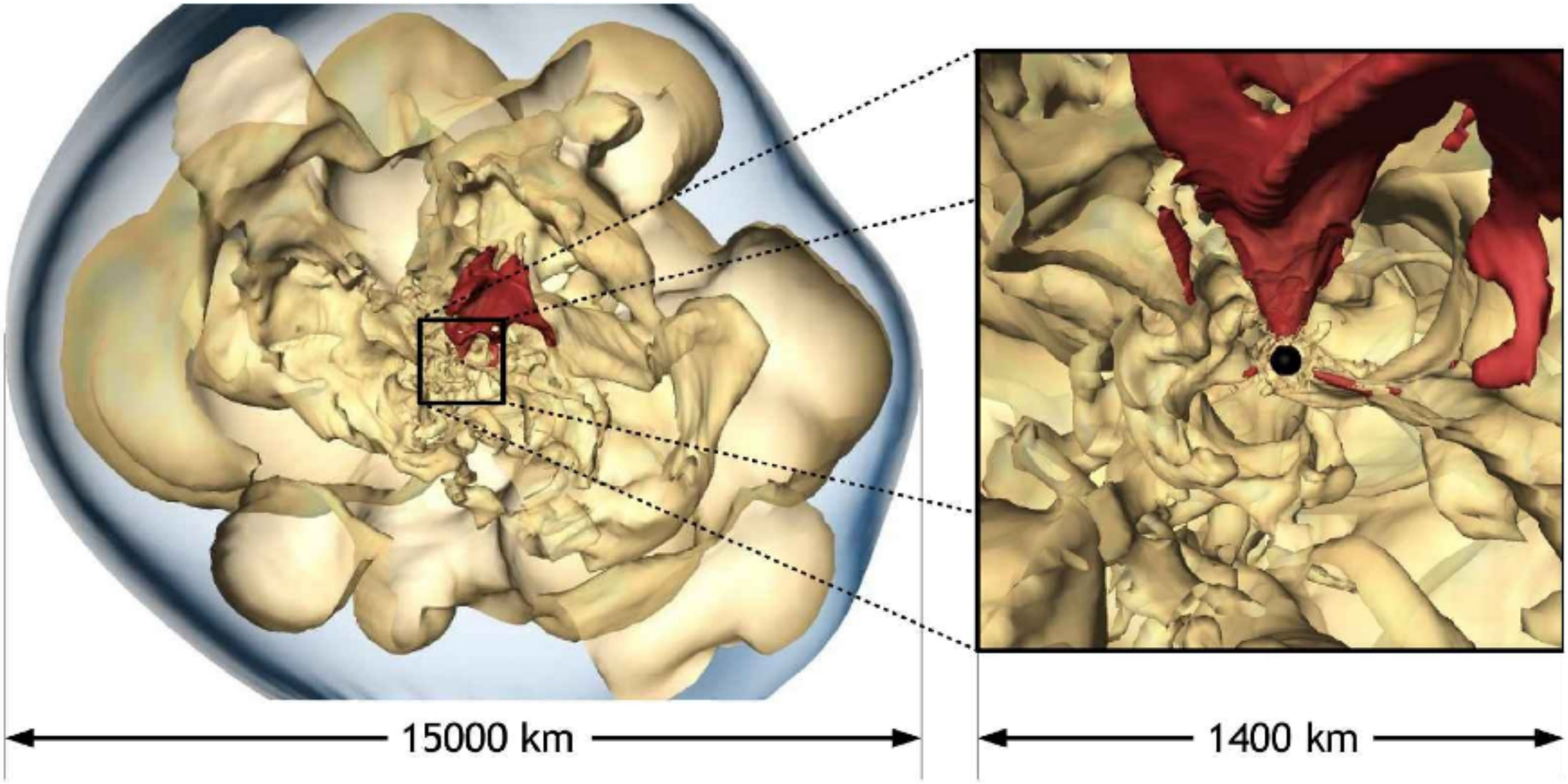


However, the proto-neutron star emits a prodigious luminosity of neutrinos. Over the next few seconds, if it does not become a black hole, it will radiate about 10% of its rest mass (about 3×10^{53} erg), eventually settling down as a gigantic neutron-rich nucleus of 10-km radius — a neutron star. This neutrino emission is actually the chief output of the event which is overwhelmingly a gravity-powered neutrino explosion. But how can this be used to turn the collapse of the rest of the star into the explosion that we see with optical telescopes? This is the part of the problem that has caused theorists the greatest difficulty for forty years (5). A typical core-collapse supernova has $1–2 \times 10^{51}$ erg in kinetic energy, far less than that released as neutrinos during neutron-star formation. But the neutrinos streaming out from the core have a small cross-section for energy deposition and, to make matters worse, a large part of the energy they do deposit is radiated away again as neutrinos (neutrinos deposit their energy chiefly by the reactions $p+\bar{\nu} \rightarrow n+e^{+}$ and $n+\nu \rightarrow p+e^{-}$, where p, n, e^{+}, and e^{-} are the proton, neutron, positron and electron respectively; they are radiated away by the inverse of these same reactions).

If the actual proto neutron star (PNS) neutrino luminosity evolves above this critical neutrino luminosity (Lcrit), a supernova explosion results. The critical luminosity Lcrit is a function of PNS mass, radius, and mass accretion rate through the shock forming a critical curve or manifold in these parameters.



Looking into the heart of a supernova. Four snapshots show the vigorous boiling of the neutrino-heated, convective region around the nascent neutron star. Buoyant bubbles of hot matter moving outwards appear bright red and yellow. These are bounded by a shock wave, which expands outwards, disrupting the star. The images, from top left to bottom right, show the structure at 0.1, 0.2, 0.3, and 0.5 seconds after the shock is born. At these times, the shock has an average radius of about 200, 300, 500, and 2,000 kilometers, respectively.



Accretion onto the nascent neutron star shows a dipolar character. Cool matter (visible in red in the blow-up on the right) falls and is funnelled onto one side of the neutron star (black circle at the center), while neutrino-heated, hot ejecta flows out on the other. This ‘jet engine’ can accelerate the neutron star to velocities of several hundred kilometres per second within the first second of its life.

At that same time, the supernova shock wave (blue, enveloping surface) is already well on its way through the exploding star (left panel), being pushed by the buoyant bubbles of neutrino-heated gas. Although the calculation was followed in three spatial dimensions, the initial model was spherically symmetric and was not rotating.

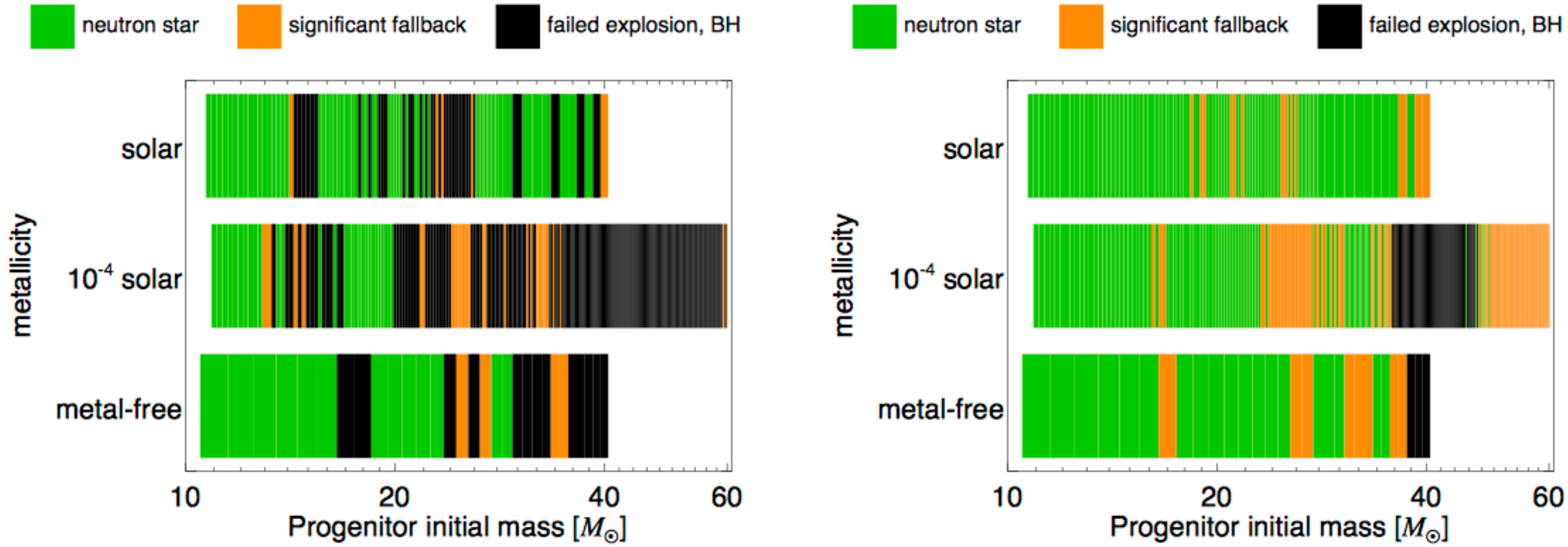


FIG. 12.— Outcomes of core collapse as a function of initial progenitor mass and progenitor metallicity for WHW02 progenitors for parameterizations (a) (left panel) and (b) (right panel). We show successful explosions leaving behind neutron stars (green), successful explosions with significant fallback leaving behind either massive neutron star or a black hole (orange), and failed explosions leaving behind a black hole (black). Our results are very different from the picture

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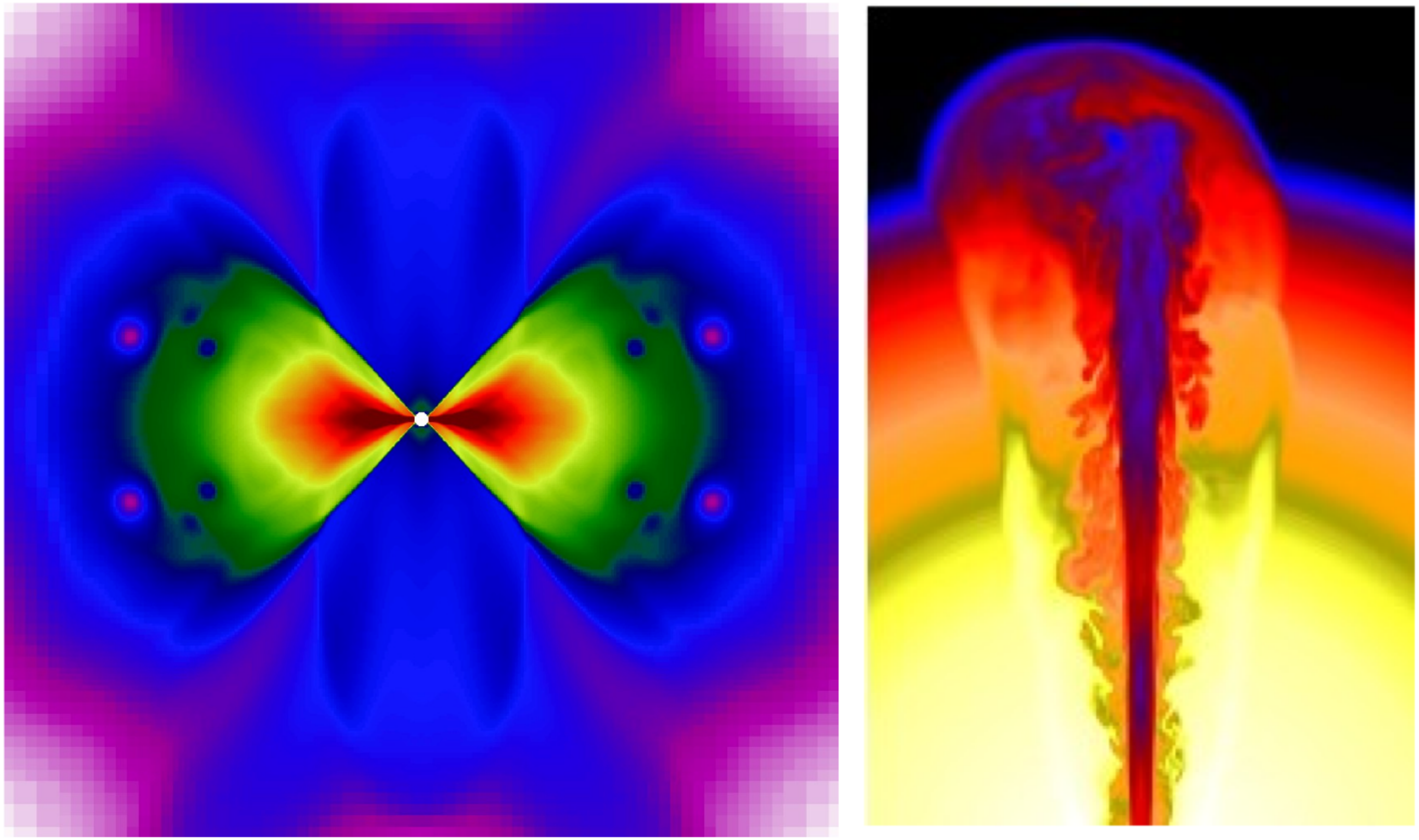
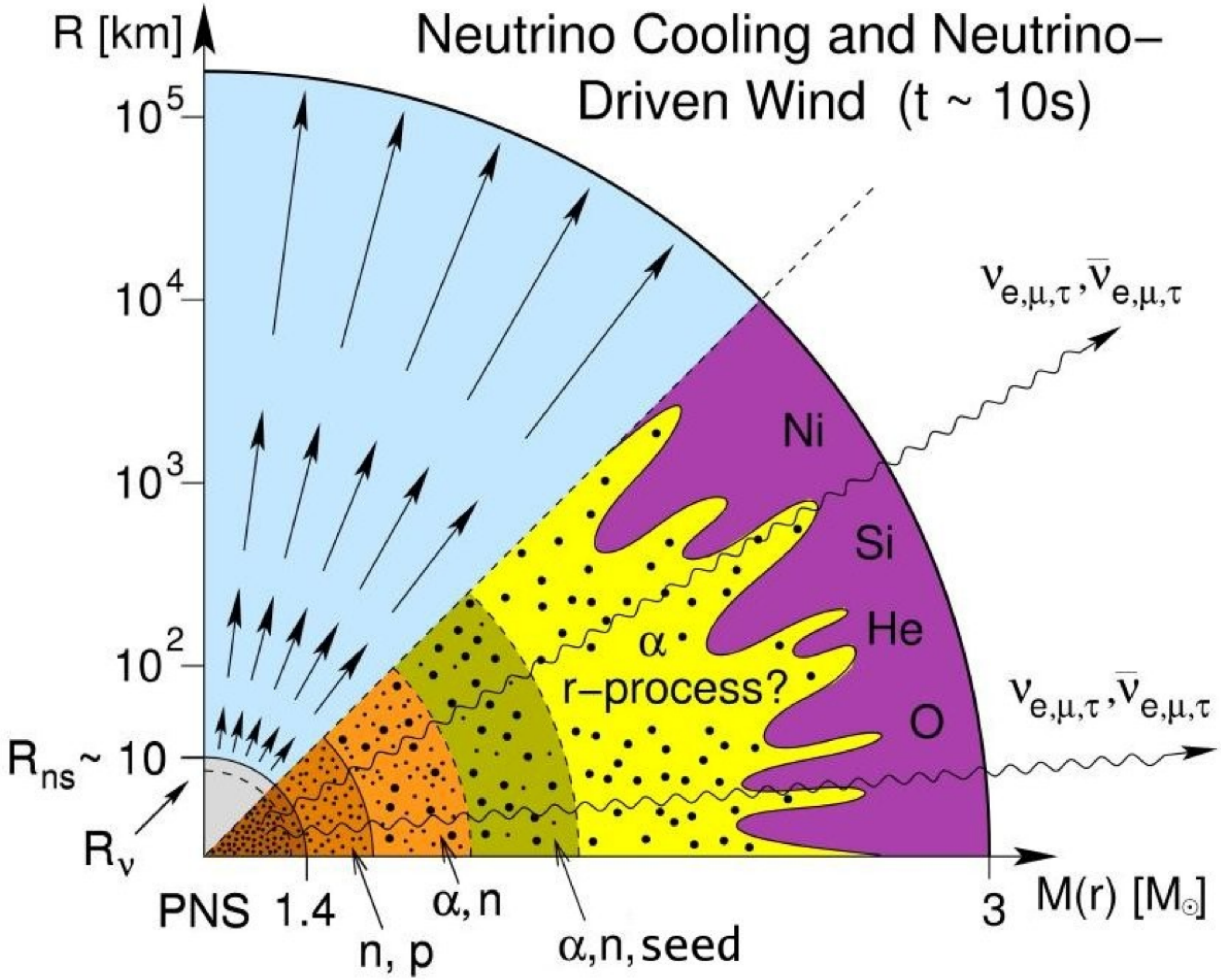
GRBs — intense flashes of gamma-rays lasting about 20 seconds and coming from cosmological distances — are produced by highly relativistic collimated outflows (with Lorentz factors, $\Gamma = (1 - (u/c)^2)^{-1/2} > 200$, where u is the outflow velocity) (36). A typical GRB involves a jet with an opening angle of about 5 degrees (37).

All credible models of long-soft GRBs so far rely on very rapid rotation to produce either a neutron star rotating nearly at the point of centrifugal break up (39,40), or a black hole and an accretion disk (41) — a 'collapsar'. The rotational axis gives a natural preferred direction for the propagation of a jet (42) (Fig. 4). Neutrinos play a role in some of these models, but the observed supernova energy is much greater than what they are able to transport. It seems certain that long-soft GRBs are rotationally powered supernovae. However, even correcting for the fact that we only see a GRB if we are in the solid angle of its beam, GRBs are associated with but a small fraction of all supernovae, roughly a few tenths of a percent (43). The physics that drives them



The collapse of a the core of a rapidly rotating 14 solar mass helium core yields a black hole and a centrifugally supported accretion disk. **a,** This image, representing an area 1,800 km across, shows the density structure 20 seconds after the black hole has formed and begun to accrete. At this point, the black hole mass is 4.4 solar masses, corresponding to a radius of 14 km, and the accretion rate has been 0.1 solar masses per second for the last 15 seconds. The highest densities (dark red) are about 109 g cm−3; the lowest along the axis near the hole, 107 g cm−3. In this collapsar model, jets initiated either by magnetic processes in the disk or by the rotating black hole itself propagate up the axis, exit the star and eventually produce gamma-ray bursts. **b,** A jet exiting the star, which has a radius similar to that of the Sun. The time here is 8 seconds after the jet originated in the centre.



Neutrinos (νe,νμ,ντ and their anti-particles) drive a wind from the surface of the cooling proto-neutron star (PNS) creating the r-process isotopes. The wind begins as a flux of neutrons and protons lifted from the surface of the PNS (here 1.4 solar masses and 10 km in radius) by neutrinos originating at the "neutrinosphere" (Rν). As these nucleons flow out, an excess of neutrons is created by the capture of anti-neutrinos on protons. As the nucleons cool, all the available protons combine with neutrons to make α-particles until one is left, in the orange region, with a mixture of only α-particles and unbound neutrons. Further cooling leads to the assembly of a few α-particles into nuclei in the iron group ("seed") by reactions involving neutrons and α-particles (green region). As the temperature declines still further, from 3 billion K to 1 billion K, all neutrons are captured on this seed making the heavy r-process nuclei. Since the efficiency of the reactions that assemble α-particles into seed increases with the density, lower density in the wind keeps the number of seed small and makes the number of neutrons that can be captured on each larger.