Exercises for Experimental methods in Astroparticle Physics

Universität Heidelberg | 18. December 2019 | **Hand in:** 8. January 2020

Sheet 8

1. **Supernovae explosion**

   Core-collapse supernovae are the final stage of stars with a mass above about eight solar masses. Figure 1 shows a representation of the evolution of a massive star from the onset of collapse (A) to shock formation (C), propagation of the prompt shock (D), shock stagnation and revivial (E). The core collapses (B) to a proto-neutron star (PNS) within a fraction of a second. The dynamical state is shown with arrows indicating the flow of stellar fluid. The neutron star is initially very extended and contracts to a more compact configuration while more matter accretes (D). The subsequent cooling and neutronization of the remnant is driven by emission of neutrinos of all flavors (E).

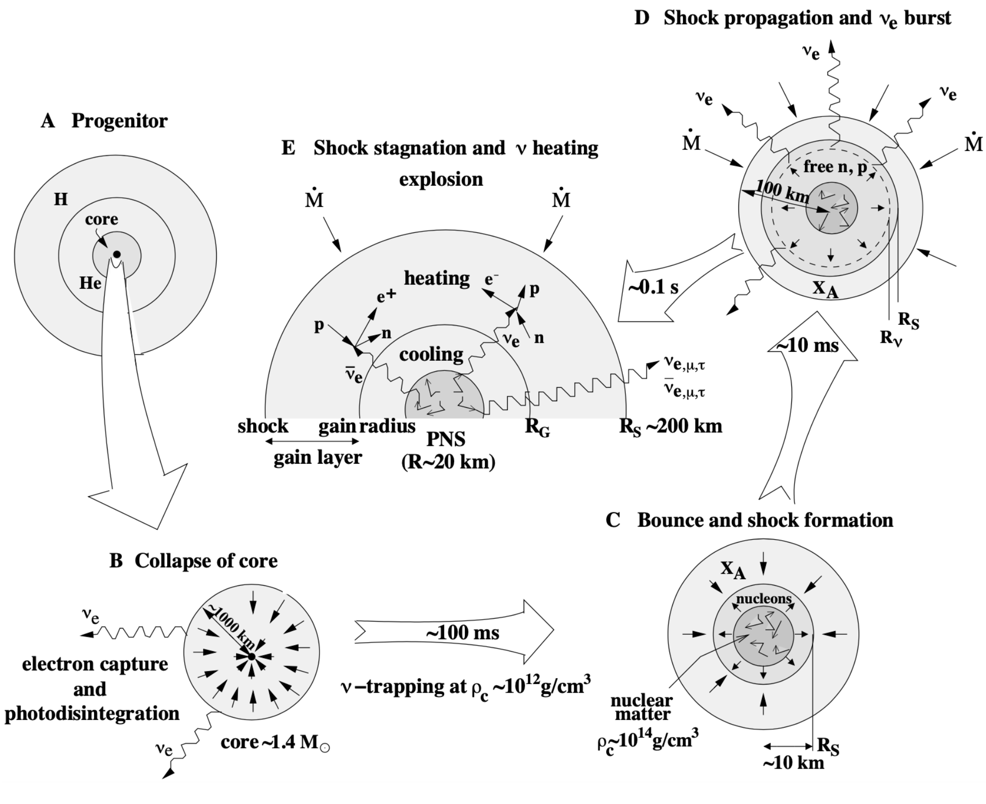

Figure 1: Representation of the evolution of a massive star. R_S is the shock radius, R_{gain} is the gain radius, and R_ν is the neutrinosphere radius. (F. Kitaura)

   (a) Estimate the gravitational energy released by the core collapse, taking into account the energy of the core before and after the collapse. Take from the figure the necessary numerical data.

   (b) The observed explosion energy (kinetic energy + radiation energy) is only about 10^{51} erg (kinetic $\mathcal{O}(10^{51}\,\mathrm{erg})$, radiation $\mathcal{O}(10^{49}\,\mathrm{erg})$). That is only $\sim 1\%$, and the rest of the binding energy is radiated away by neutrinos (99%). To find the neutrino flux at the time of explosion, one has to carry out an involved hydrodynamic calculation including neutrino transport. Nevertheless, an estimation is still meaningful. Calculate the total neutrino flux using the released energy found before, taking into account that the average neutrino energy is $\epsilon_\nu \approx 10\,\mathrm{MeV}$ ($1\,\mathrm{MeV} = 1.602\,03 \times 10^{-6}\,\mathrm{erg}$).

(c) If a supernova occurs at the center of the Galaxy ($d \approx 10\,\mathrm{kpc}$), what is the expected neutrino flux on Earth?

(d) Using a $20\,\mathrm{kt}$ scintillator detector ($C_{16}H_{18}$), the reaction with the largest cross section to detect neutrinos is:

$$\bar{\nu}_e + p \rightarrow e^+ + n, \quad \sigma = 93.0 \times 10^{-43} (\mathrm{E}_\nu / 10\,\mathrm{MeV})^2 \mathrm{cm}^2 \tag{1}$$

Detecting a supernova means detecting at least 10 neutrino events. Would it be possible to detect the supernova from (c)? (Use only the protons from the hydrogen for neutrino capture! $\rho = 0.985\,\mathrm{g/cm}^3$, molecular weight = $210.3\,$a.m.u.)

(e) On 23 Februrary 1987, a supernova SN1987a exploded in the Large Magellanic cloud. The Kamiokande collaboration detected 11 neutrino events from this supenova. Why is this number of events so different to the one calculated in this problem?

2. Detection techniques for neutrinos originating from Supernovae

In order to detect neutrinos originating from a Supernova (SN) explosion scintillation detectors, water Cherenkov detectors, and time projection chambers among others. Read the paper in Nuclear and Particle Physics Proceedings, Vol. 265, p. 233 titled "HALO, a supernova neutrino observatory" by K. Zuber (link here) and go through your lecture notes to answer on the following questions:

(a) What is the physics case for constructing the HALO detector?

(b) What is the detection principle of HALO and in which sense is it complementary to existing detectors which are sensitive to SN explosions? Why is lead a good choice as the active material for the detector?

(c) Why is the identification of ν_e and $\bar{\nu}_e$ important? What are the additional information which could be obtained comparing with the SN1987a explosion?

(d) Experiments meant to detect dark matter, such as XENONnT can also be used to measure SN neutrinos. Why are these relatively small detectors (tons vs. kilotons) relevant?

Consider that the HALO detector is not yet ready to record data:

(e) If a SN explosion occurs the 31st of December 2019, which operating detectors are expected to be sensitive this event?

(f) If 10.000 events are detected due to inverse double beta decay, how many events would be expected due to $\nu_e - e$ scattering in the detector material?