ブラックホール形成時の放出ニュートリノで探る高密度・高温物質の物理

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Stars more massive than $\sim$10 solar masses ($M_\odot$) are known to make a gravitational collapse at the end of their lives. Especially, stars with $M \lesssim 25M_\odot$ are thought to end their lives as type II supernovae. On the other hand, stars with $M \gtrsim 25M_\odot$ will form a black hole. Observationally these black hole progenitors have two branches, namely, a hypernova branch and a faint supernova branch [1]. This trend may suggest us that the strongly rotating massive stars result in the hypernova branch while non-rotating massive stars result in the faint supernova branch. Moreover, non-rotating very massive stars with $\gtrsim 40M_\odot$ may not be able to make a supernova explosion and merely form a black hole silently. In this case, the collapse is bounced once due to the nuclear force but the star becomes unstable again because its mass exceeds maximum mass by the accretion of outer region. Since matter becomes hot and dense, meson condensation, hyperon appearance and quark deconfinement are thought to occur at the moment of black hole formation affecting the equation of state (EOS).

In this study, we investigate numerically the stellar core collapse and black hole formation taking into account the EOS's involving quarks and/or pions. Since enormous emission of neutrinos is thought to accompany stellar collapse, features of the neutrino signal from black hole formation reflects the properties of hot and dense matter. Therefore we compute the neutrino emission with hydrodynamics. Further details of this study can be found in our lately submitted paper [2] and core collapse simulations involving hyperon populations are reported in a separate paper [3].

Setups— In order to compute the neutrino signal from black hole formation, we use the numerical code of general relativistic ν-radiation hydrodynamics which solves the Boltzmann equation for neutrinos together with Lagrangian hydrodynamics under spherical symmetry [4, 5, 6]. As an initial condition, the stellar model with $40M_\odot$ and solar metallicity from the evolutionary calculation [7] is adopted. We utilize the EOS's including the hadron-quark phase transition and effects of the thermal pions in finite temperature [8]. Note that, the original EOS without pions and quarks is taken from Shen et al. (1998) [9], which is based on the relativistic mean field theory. The MIT bag model of the deconfined 3-flavor strange quark matter [10] is used for the quark EOS. In the following, we refer to the EOS without pions and quarks (the original Shen EOS), EOS without pions and with quarks, EOS with pions and without quarks and EOS with pions and quarks as OO, OQ, PO and PQ, respectively.

Results— In Figure 1(a), we show the time profiles of the central baryon mass density. These models have a bounce owing to nuclear force at the saturation density ($\sim 3 \times 10^{14}$ g cm^{-3}) and then recollapse to a black hole. We can also see that the effect of quarks

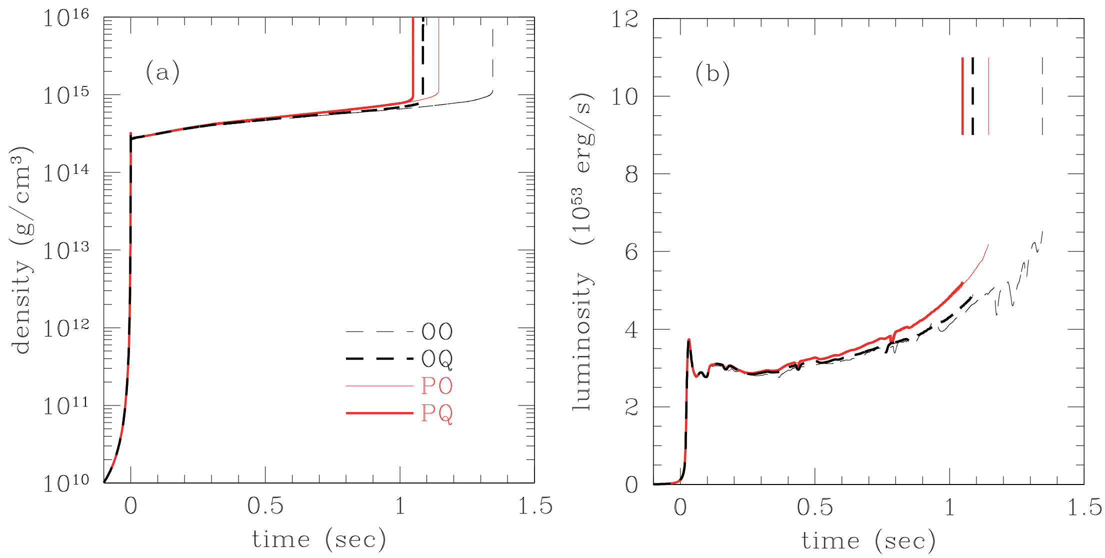

図 1: *(a)* Time evolutions of the central baryon mass density for the collapse. *(b)* Time evolutions emitted neutrino luminosities summed over all species, where vertical lines represent the end point of the neutrino emission. In both panels, thin dashed, thick dashed, thin solid and thick solid lines correspond to the models with EOS OO, OQ, PO and PQ, respectively. The time is measured from the point at bounce.

begins to work suddenly at the transition density whereas that of pions does gradually. This is because the thermal pions appear before the pion condensation. Since the EOS becomes softer and the maximum mass for the stable configurations of proto–neutron stars gets lower due to the contribution of quarks and pions, the interval time from the bounce to the black hole formation becomes shorter. In fact, the interval times are 1.049 s, 1.086 s, 1.145 s and 1.345 s for the models with EOS's PQ, OQ, PO and OO, respectively, while the maximum masses of the "cold" neutron stars are $1.8M_\odot$, $1.8M_\odot$, $2.0M_\odot$ and $2.2M_\odot$ in the same order [8]. Since the mass accretion rate, $\dot{M}$, does not differ among the EOS models, a soft EOS leads to a reduction of the interval time and our results are roughly consistent with this trend.

We show the time evolutions of total luminosity of emitted neutrinos in Figure 1(b). Note that, a duration of the neutrino emission is almost the same as the interval time from the bounce to the black hole formation. We can see again that the hadron-quark phase transition makes a difference for very late phase and these EOS's are identical in the low density regime. On the other hand, pions make differences gradually increasing the luminosity of neutrinos. Roughly speaking, neutrinos are emitted from the neutrino sphere, where the optical depth becomes 2/3 for neutrinos with a typical energy, and the neutrino luminosity is given by the accretion luminosity $L_\nu^{\rm acc} \sim GM_\nu\dot{M}/R_\nu$, where R_ν and M_ν are the radius of the neutrino sphere and the mass enclosed by R_ν, respectively. Since the EOS becomes soft and the inner core contracts due to the pion appearance, R_ν becomes smaller and T_ν gets higher. Therefore the neutrino luminosity increases due to pions. Using these differences of the interval time and luminosity, we may be able to probe observationally the EOS of hot and dense matter in future.

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