

Sterile neutrinos and the rapid formation of supermassive black holes

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Abstract. The most massive black holes, lurking at the centers of large galaxies, must have formed less than a billion years after the big bang, as they are visible today in the form of bright quasars at redshift $z \gtrsim 6$ [1]. Their early appearance is mysterious, because the radiation pressure, generated by infalling ionized baryonic matter, inhibits the rapid growth of these black holes from stellar-mass black holes [2]. Here we show that the supermassive black holes may, instead, form timeously through the accretion of degenerate sterile neutrino dark matter onto stellar-mass black holes [3].

1. Sterile neutrino dark matter

The abundance of sterile neutrinos of $\sim 15 \text{ keV}/c^2$ mass, mixed with an active neutrino at the level of $\theta \sim 10^{-6.5}$, is consistent with that of non-baryonic matter, as determined by WMAP [4] if the initial active neutrino asymmetry is $\sim 10^{-2}$. On the scale of the age of the universe, these right-handed sterile neutrinos are quasi-stable, and they can be embedded in a renormalizable extension of the standard model of particle physics, dubbed the ν MSM [5]. They are produced mainly through MSW-resonant [6], and to a lesser extent, non-resonant scattering of active neutrinos at temperatures around 330 MeV/k $2.3 \mu\text{s}$ after the big bang. MSW-resonant scattering yields quasi-degenerate, while non-resonant scattering yields warm sterile neutrino dark matter.

2. The symbiotic scenario

Our symbiotic scenario relies, firstly on the formation of neutrino balls from quasi-degenerate sterile neutrino matter through gravitational cooling [8] between 640 and 830 Myr after the big bang. Secondly, it requires the formation of stars of mass $\sim 25 M_\odot$ at the center of the neutrino balls. The supernova explosion taking place after ~ 3 million years, sparks the rapid growth of the seed black hole of 3 to 4 M_\odot through accretion of sterile neutrino dark matter from the surrounding neutrino ball until the supplies dry up. Thus the observed lower and upper limits of the supermassive black

holes, are given by the corresponding limits of the preformed neutrino balls. On the one hand, the lower mass limit of $\sim 10^6 M_\odot$ is due to the minimal mass that may undergo gravitational collapse, i.e. the mass contained within the free-streaming length at matter-radiation equality. On the other hand, the upper mass limit of $\sim 3 \times 10^9 M_\odot$ is given by the maximal mass that the degeneracy pressure can support, i.e. the Oppenheimer-Volkoff limit [9]. Both mass limits strongly depend on the neutrino mass.

3. Anti-hierarchical formation of the supermassive black holes

The anti-hierarchical pattern of the formation of the supermassive black holes, i.e. the fact that the large black holes are observed earlier than the smaller ones [10], may be explained by the vastly different escape velocities from the center of the neutrino balls, ranging from 1700 km/s, for a $3 \times 10^6 M_\odot$ neutrino ball of 25 light-days radius, to the velocity of light, for a $2.8 \times 10^9 M_\odot$ neutrino ball of 1.4 light days radius [11]. Thus a low-mass neutrino ball will have a much harder time attracting a molecular hydrogen cloud, that may form a massive star of mass $\gtrsim 25 M_\odot$, which can deliver the required 3 to 4 solar mass black holes, after a supernova explosion. In fact, for a low-mass neutrino ball, there may be many failed attempts, over a period of several Gyr, until a black hole is formed, while a 3×10^9 solar-mass neutrino ball may produce this required stellar-mass black hole on its first attempt within 10 Myr.

4. Degenerate sterile neutrino matter accretion

The time needed for a 3 to 4 M_\odot seed black hole to swallow a neutrino ball of arbitrary mass can be calculated using Bondi's accretion theory [12], and it turns out to be less than 5 Myr. Thus, the most massive black holes may form, in this scenario, between 650 and 840 Myr after the big bang.

We, therefore, conclude that supermassive neutrino balls, with stellar-mass black holes at their center, offer an intriguing symbiotic scenario, in which baryonic matter conspires with degenerate sterile neutrino dark matter, to form these galactic supermassive black holes, with masses between 10^6 and $3 \times 10^9 M_\odot$ rapidly and efficiently.

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