

## DARK MATTER CONCENTRATION IN THE GALACTIC CENTER

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### ABSTRACT

It is shown that the matter concentration observed through stellar motion at the Galactic center is consistent with a supermassive object of  $2.5 \times 10^6$  solar masses composed of self-gravitating, degenerate, heavy neutrinos. This result is opposed to the alternative black hole interpretation. According to the observational data, the lower bounds on possible neutrino masses are  $m_\nu \geq 12.0 \text{ keV}/c^2$  for  $g = 2$  or  $m_\nu \geq 14.3 \text{ keV}/c^2$  for  $g = 1$ , where  $g$  is the spin degeneracy factor. The advantage of this scenario is that it could naturally explain the low X-ray and gamma-ray activity of Sgr A\*, i.e., the so-called blackness problem of the Galactic center.

*Subject headings:* black hole physics — dark matter — elementary particles — Galaxy: center

### 1. INTRODUCTION

The idea that some of the galactic nuclei are powered by matter accreted onto supermassive black holes is based on strong theoretical arguments (Salpeter 1964; Zeldovich 1964; Lynden-Bell 1969, 1978; Lynden-Bell & Rees 1971; see Blandford & Rees 1992 for reviews) and observation of rapid time variability of the emitted radiation, which implies relativistic compactness of the radiating object. However, so far there is no compelling proof that supermassive black holes actually do exist, since the spatial resolution of current observations is larger than  $10^5$  Schwarzschild radii. The standard routine in the investigation of the nature of the dark mass distribution at the centers of active galaxies is to observe stellar dynamics and gas dynamics. However, gas dynamics is usually regarded as less conclusive since it is responsive to nongravitational forces, such as, e.g., magnetic fields.

As an alternative to the black hole scenario, Moffat (1997) considered general relativistic models of stellar clusters with large redshifts, and he investigated whether such objects are long lived enough from the point of view of evaporation and collision timescales and stability criteria. He then showed that, in certain cases, stellar clusters with masses  $\geq 10^6 M_\odot$  could mimic the behavior of supermassive black holes. A good unprejudiced review on the subject can be found in the paper by Kormendy & Richstone (1995).

The identification of a central supermassive object in the Milky Way has been a source of continuous debate in the literature. The crucial issue is whether the center of our Galaxy harbors a supermassive black hole or any other compact dark matter object. Theoretical papers that are exclusively devoted to the black hole explanation of the Galactic center include Lynden-Bell & Rees (1971), Rees (1987), Phinney (1989), and de Zeeuw (1993). However, even within this theoretical framework, there is no full agreement; the general consensus is that the supermassive black hole should have mass of  $\sim 10^6 M_\odot$ , while Ozernoy (1992) and Mastichiadis & Ozernoy (1994) argue that the black hole mass can be as low as  $\sim 10^3 M_\odot$ . The main motivation for a  $\sim 10^3 M_\odot$  black hole at the Galactic center is that it would emit less X-rays and gamma rays than a  $\sim 10^6 M_\odot$  black hole, behaving basically like a scaled-down active galactic nucleus. Although earlier observations (Gehrels & Tueller 1993; Watson et al. 1981; Skinner et al. 1987; Hertz

& Grindlay 1984; Pavlinsky, Grebnev, & Sunyaev 1994) have shown that the central region actually does emit X-rays and gamma rays, the supposed true center, usually assumed to be Sgr A\*, does not emit strongly, at least up to energies of 30 keV (Skinner et al. 1987; Hertz & Grindlay 1984; Pavlinsky et al. 1994). Sgr A\* radiation emission data at higher energies have been presented by Goldwurm et al. (1994). They find no source associated with Sgr A\*, and the inferred upper bound implies that the hard X-ray luminosity of Sgr A\* is less by a factor of  $4 \times 10^7$  than that expected for a black hole of  $\sim 10^6 M_\odot$  that is accreting matter at the maximum stable rate. An unavoidable source of accretion is the wind from IRS 16, a nearby group of hot, massive stars. Since the density and velocity of the accreting matter are known from observations, the accretion rate is basically a function of the assumed black hole mass only. This value represents a reliable lower limit to a real rate, given the other possible sources of accreting matter. Based on this and on the theories about shock acceleration in active galactic nuclei, Mastichiadis & Ozernoy (1994) have estimated the expected production of relativistic particles and their hard radiation. Comparing their results with available X-ray and gamma-ray observations, which show that Sgr A\* has a relatively low activity level, the authors tentatively conclude that an assumed black hole in the Galactic center cannot have a mass greater than approximately  $6 \times 10^3 M_\odot$ .

Other scenarios used to explain the low X-ray and gamma-ray activity of Sgr A\* include so-called advection-dominated models (Narayan, Yi, & Mahadevan 1995; Narayan et al. 1997; Mahadevan, Narayan, & Krolik 1997), which can exist with a  $\sim 10^6 M_\odot$  black hole that accretes matter at a realistic accretion rate of  $\dot{M} \sim 10^{-5} M_\odot \text{ yr}^{-1}$ . However, most of the energy released by viscosity is carried along with the gas and lost into the black hole, while only a small fraction is actually radiated.

The purpose of this paper is to present an alternative model, based on the idea that the dark matter concentration in the Galactic center could be a ball of degenerate, self-gravitating heavy neutrinos, a scenario that is consistent with the present observational data.

### 2. THE MODEL

In the recent past, Viollier and coworkers have argued that massive, self-gravitating, degenerate neutrinos,

arranged in balls where the degeneracy pressure compensates self-gravity, can form long-lived configurations that could mimic the properties of dark matter at the centers of galaxies (Viollier 1994; Viollier et al. 1992, 1993). Tsiklauri & Viollier (1996) demonstrated that a neutrino ball could play a similar role as a stellar cluster in the 3C 273 quasar, revealing its presence through the infrared bump in the emitted spectrum. Tsiklauri & Viollier (1997a) further investigated the formation and time evolution of neutrino balls via two competing processes: annihilation of the particle-antiparticle pairs via weak interaction and spherical (Bondi) accretion of these particles. Bilić & Viollier (1997a) showed how the neutrino balls could form via a first-order phase transition of a system of self-gravitating neutrinos in the presence of a large radiation density background based on the Thomas-Fermi model at a finite temperature. They find that by cooling a nondegenerate gas of massive neutrinos below a certain critical temperature, a condensed phase emerges, consisting of quasi-degenerate supermassive neutrino balls. General relativistic effects in the study of the gravitational phase transition in the framework of the Thomas-Fermi model at finite temperature were taken into account in Bilić & Viollier (1997b). A theorem was proved by Bilić & Viollier (1997c) that in brief states that the extremization of the free energy functional of the system of self-gravitating fermions, described by the general relativistic Thomas-Fermi model, is equivalent to solving Einstein's field equations.

The basic equations that govern the structure of cold neutrino balls have been derived in the series of papers (Viollier 1994; Viollier et al. 1992, 1993; and Tsiklauri & Viollier 1996); here we adopt the notations of Tsiklauri & Viollier (1996). In this notation, the enclosed mass of the neutrinos and antineutrinos within a radius  $r = r_n \xi$  of a neutrino ball is given by

$$M(\xi) = 8\pi\rho_c r_n^3 \left[ -\xi^2 \frac{d\theta(\xi)}{d\xi} \right] \equiv 8\pi\rho_c r_n^3 (-\xi^2 \theta'), \quad (1)$$

where  $\theta(\xi)$  is the standard solution of the Lane-Emden equation with polytropic index  $\frac{3}{2}$ ,  $r_n$  is the Lane-Emden unit of length, and  $\rho_c$  is the central density of the neutrino ball. In this paper, we use the length scale 1 pc instead of  $r_n$ , resulting in a trivial rescaling of the standard Lane-Emden equation.

To model the mass distribution, usually the first moment of the collisionless Boltzmann equation (also referred to as the Jeans equation) is used (Binney & Tremaine 1987):

$$\frac{GM(R)}{R} = v_{\text{rot}}(R)^2 - \sigma_r(R)^2 \left[ \frac{d \ln n(R)}{d \ln R} + \frac{d \ln \sigma_r(R)^2}{d \ln R} \right], \quad (2)$$

where  $n(R)$  is the spherically symmetric space-density distribution of stars,  $M(R)$  is the total included mass,  $\sigma_r(R)$  is the nonprojected radial velocity dispersion, and  $v_{\text{rot}}$  is the rotational contribution. In order to apply equation (2) to the observational data, one should relate the intrinsic velocity dispersion to the projected one via the following Abel integrals:

$$\Sigma(p) = 2 \int_p^\infty n(R) R dR / \sqrt{R^2 - p^2}, \quad (3a)$$

$$\Sigma(p) \sigma_r(p)^2 = 2 \int_p^\infty \sigma_r(R)^2 n(R) R dR / \sqrt{R^2 - p^2}, \quad (3b)$$

where  $\Sigma(p)$  denotes surface density and  $p$  is the projected distance. One further needs some parameterization for  $\sigma_r(R)$  and  $n(R)$ , and after numerical integration of equations (3a) and (3b), the free parameters appearing in  $\sigma_r(R)$  and  $n(R)$  should be varied in order to obtain the best fit of  $\sigma_r(p)$  and  $\Sigma(p)$  with the observational data. Following Genzel et al. (1996), we use the parameterization

$$n(R) = \frac{(\Sigma_0/R_0)}{1 + (R/R_0)^\alpha} \quad (4)$$

as a model for  $\Sigma(p)$ .  $R_0$  is related to the core radius through  $R_{\text{core}} = b(\alpha)R_0$ , where  $b = 2.19$  for  $\alpha = 1.8$ . Genzel et al. (1996) find that the best-fit parameters for the stellar cluster are a central density of  $\rho(R=0) = 4 \times 10^6 M_\odot \text{ pc}^{-3}$  and a core radius of  $R_{\text{core}} = 0.38 \text{ pc}$ . Thus, for the mass distribution, Genzel et al. (1996) obtain a black hole of  $2.5 \times 10^6 M_\odot$  plus a stellar cluster with the above-mentioned physical parameters. As mentioned earlier, we argue here that a neutrino ball composed of self-gravitating, degenerate neutrinos within a certain mass range could mimic the role of a black hole. This can be seen in Figure 1, where the mass distribution of the neutrino ball (using the rescaled eq. [1]), with a neutrino mass in the range of 10–25 keV/ $c^2$  for  $g = 1$  and 2 plus the stellar cluster are plotted. For comparison, the  $2.5 \times 10^6 M_\odot$  black hole plus stellar cluster and pure stellar cluster are also shown. We gather from the graph that in the case of  $m_\nu = 12.013 \text{ keV}/c^2$  for  $g = 2$  and  $m_\nu = 14.285 \text{ keV}/c^2$  for  $g = 1$  (note that these two curves actually do overlap), the mass distribution is marginally consistent with the observational data. It is clear that for larger neutrino masses (with a corresponding degeneracy factor  $g$  and with the same total mass), the neutrino ball would be more compact and, therefore, also consistent with the observational data. It is worthwhile to note that precise values of masses of the neutrinos are essential since the radius of the neutrino ball, which actually sets the neutrino mass constraints, scales as  $\propto m_\nu^{8/3}$ . To investigate what an impact the replacement of the black hole by a neutrino ball would have, we also calculated  $\sigma_r(p)$  for both mass distributions: a

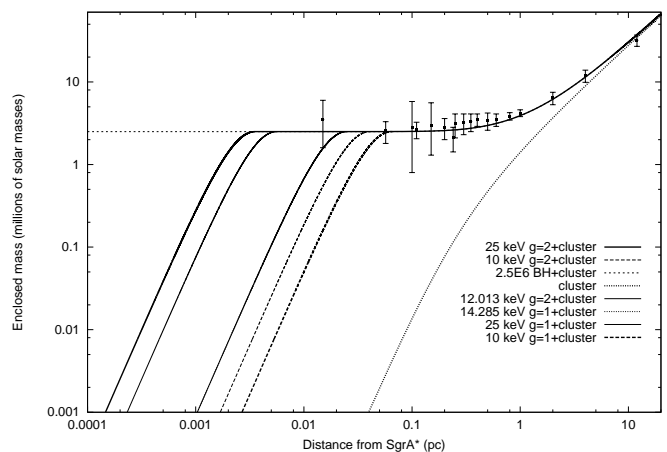


FIG. 1.—Different models for the enclosed mass: neutrino balls (using rescaled eq. [1]) with the neutrino mass in the range 10–25 keV/ $c^2$  for  $g = 1$  and 2 plus the stellar cluster;  $2.5 \times 10^6 M_\odot$  black hole plus the stellar cluster; and stellar cluster only. Note that mass curves for  $m_\nu = 12.013 \text{ keV}/c^2$  for  $g = 2$  and  $m_\nu = 14.285 \text{ keV}/c^2$  for  $g = 1$ , which go through the innermost error bar, do overlap. Data points are taken from Eckart & Genzel (1997) and Genzel et al. (1996 and references therein).

$2.5 \times 10^6 M_\odot$  black hole plus a stellar cluster and a neutrino ball composed of  $m_\nu = 12.0 \text{ keV}/c^2$  for  $g = 2$  or  $m_\nu = 14.3 \text{ keV}/c^2$  for  $g = 1$  neutrinos with the same total mass plus stellar cluster. First, we fitted the observational data taken from Eckart & Genzel (1997) and Genzel et al. (1996 and references therein) via numerical integration of the following expression for  $\sigma_r(R)$ :

$$\sigma_r(R)^2 = \sigma(\infty)^2 + \sigma(2'')^2 (R/2'')^{-2\beta},$$

where we use the Abel integrals from equations (3a) and (3b). For the fit parameters we obtain  $\sigma(\infty) = 59 \text{ km s}^{-1}$ ,  $\sigma(2'') = 350 \text{ km s}^{-1}$ , and  $\beta = 0.95$ , and for the distance to Sgr A\* we took 8 kpc. The resulting  $\sigma_r(p)$ -values for both mass distributions are plotted in Figure 2, which shows that the difference is rather small. It is worthwhile to point out that the actual fit parameters do not play an important role, since the aim of the graph is to demonstrate that the substitution of the  $2.5 \times 10^6 M_\odot$  black hole by a neutrino ball of the same mass, which is composed of self-gravitating, degenerate neutrinos with masses of  $m_\nu = 12.0 \text{ keV}/c^2$  for  $g = 2$  or  $m_\nu = 14.3 \text{ keV}/c^2$  for  $g = 1$ , produces a very tiny effect in the projected velocity dispersion. Only further theoretical input (e.g., the use of the Jeans equation) makes it possible to discriminate between different density distribution models. In fact, our results are in accordance with the similar conclusion by McGregor, Bicknell, & Saha (1996), where the authors calculated the projected velocity dispersions by integrating the Jeans equation with enclosed mass profiles that combine the Saha, Bicknell, & McGregor (1996) mass model with inward extrapolation with  $M(r) \propto r$  and central black holes of masses of  $(0-1.5) \times 10^6 M_\odot$ .

### 3. CONCLUSIONS

We have shown that a neutrino ball of total mass  $2.5 \times 10^6 M_\odot$ , which is composed of self-gravitating, degen-

erate neutrinos and antineutrinos of mass  $m_\nu \geq 12.0 \text{ keV}/c^2$  for  $g = 2$  or  $m_\nu \geq 14.3 \text{ keV}/c^2$  for  $g = 1$ , surrounded by a stellar cluster with a central density of  $\rho(R=0) = 4 \times 10^6 M_\odot \text{ pc}^{-3}$  and a core radius of  $R_{\text{core}} = 0.38 \text{ pc}$ , is consistent with the currently available observational data. As far as the current observational data is concerned, a neutrino ball with the above-mentioned physical parameters would be virtually indistinguishable from a black hole with the same mass.

Many models were put forward to explain the low X-ray and gamma-ray emission of the Sgr A\*. Another possible solution to this “blackness problem” could be the presence of a neutrino ball, which is consistent with current observational data, instead of the supermassive black hole. In fact, in the neutrino ball scenario, the accreting matter would experience a much shallower gravitational potential, and therefore less viscous torque would be exerted. The radius of a neutrino ball of total mass  $2.5 \times 10^6 M_\odot$ , which is composed of self-gravitating, degenerate neutrinos and antineutrinos of mass  $m_\nu = 12.0 \text{ keV}/c^2$  for  $g = 2$  or  $m_\nu = 14.3 \text{ keV}/c^2$  for  $g = 1$ , is  $1.06 \times 10^5$  larger than the Schwarzschild radius of a black hole of the same mass. In this context, it is important to note that the accretion radius  $R_A = 2GM/v_w^2$  for the neutrino ball, where  $v_w \simeq 700 \text{ km s}^{-1}$  is the velocity of the wind from the IRS 16 stars, is approximately  $0.02 \text{ pc}$  (Coker & Melia 1997), which is slightly less than the radius of the neutrino ball, i.e.,  $0.02545 \text{ pc}$  (for  $m_\nu = 12.0 \text{ keV}/c^2$  for  $g = 2$  or  $m_\nu = 14.3 \text{ keV}/c^2$  for  $g = 1$ ). The accretion radius is the characteristic distance from the center within which the matter is actually gravitationally captured. Therefore, in the neutrino ball scenario, the captured accreting matter will always experience a gravitational pull from a mass less than the total mass of the ball. We do not discuss this issue any further, since the direct comparison of the emitted X-ray spectra with the black hole or with the neutrino ball instead would require going into

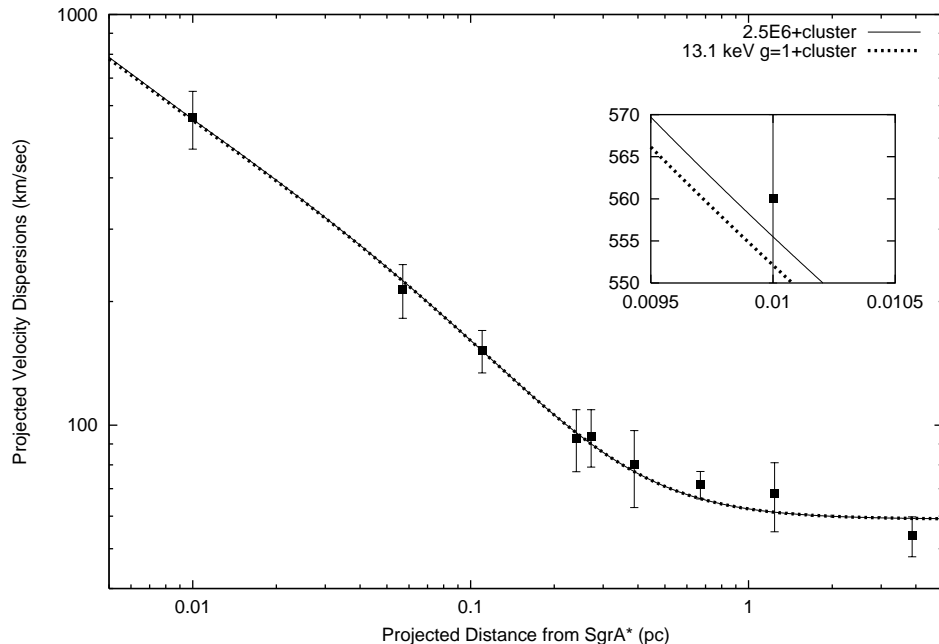


FIG. 2.—Projected velocity dispersions for different mass models:  $2.5 \times 10^6 M_\odot$  black hole plus the stellar cluster and neutrino ball with the same total mass and with  $m_\nu = 12.013 \text{ keV}/c^2$  for  $g = 2$  or  $m_\nu = 14.285 \text{ keV}/c^2$  for  $g = 1$  plus the stellar cluster. Note the tiny difference between these two curves, as emphasized in the inserted window, which is a zoomed region around the innermost error bar. The data points are taken from Eckart & Genzel (1997) and Genzel et al. (1996 and references therein).

the details of current models of X-ray emission from a compact object. The ultimate goal of this paper was to demonstrate that our model of the mass distribution at the Galactic center is consistent with the current observational data.

It is worthwhile noting that a possible way to distinguish between the supermassive black hole and neutrino ball scenarios is to track a single star that is moving on a bound orbit inside the radius of the neutrino ball over a significant part of the orbiting period. The star trajectory, in general, would be an open path between the classical turning points  $r_{\min}$  and  $r_{\max}$ . The trajectory would be closed only in the case of  $1/r$  (black hole) and  $r^2$  (uniform density distribution) potentials. In the case of the black hole, the star would orbit on an ellipse, with the black hole located at the focus, whereas in the case of a uniform density distribution, the center of the ellipse would coincide with the center of the ball. In the neutrino ball scenario, the trajectory of a star would be somewhat intermediate between the black hole and uniform density orbits. The period of a star on an elliptical orbit around the black hole is  $T = 2\pi(a^3/GM)^{1/2}$ , where  $a$  is the semimajor axis of the ellipse. Using  $2a \approx 2.545 \times 10^{-2}$  pc, with  $2a$  being the radius of the neutrino ball for  $m_\nu = 12.0$  keV/ $c^2$  for  $g = 2$  or  $m_\nu = 14.3$  keV/ $c^2$  for  $g = 1$  and  $M = 2.5 \times 10^6 M_\odot$ , we thus obtain  $T = 85.1$  yr. The difference between the black hole and neutrino ball scenarios is that in the case of a neutrino ball, the period will remain roughly constant for any orbit within the neutrino ball, as it is well represented by an extended object with uniform density distribution with an average density of about  $\frac{1}{6}$  the actual central density of the neutrino ball (Viollier 1994), while in the black hole scenario  $T$  would scale as  $T \propto a^{3/2}$ . In summary, future stellar proper motion studies on an appreciable fraction of this timescale may be practicable in discriminating between the two scenarios.

Another possible characteristic signature of a neutrino ball at the Galactic center would be the X-ray emission line at the energy  $\sim m_\nu c^2/2$ , which has a width of about the Fermi energy  $[E_F = p_F^2/2m_\nu = (6\pi^2/g)^{2/3}(\hbar^2/2m_\nu)n_\nu^{2/3}]$ . This X-ray emission, a direct consequence of the standard electroweak interaction theory, is due to the decay of the heavy neutrino into a photon and massless neutrino species, both with energies of  $\sim m_\nu c^2/2$  (Viollier 1994). For Dirac neutrinos, this would generate a luminosity of

$$L_\gamma = 2.27 \times 10^{31} \left( \frac{m_\nu c^2}{17.2 \text{ keV}} \right)^5 |U_{\tau\nu} U_{\tau\nu}^*|^2 \frac{M_\nu}{M_\odot} \text{ ergs s}^{-1},$$

where  $U_{\tau\nu}$  denotes the Cabibbo-Kobayashi-Maskawa matrix element and  $M_\nu$  is the mass of neutrino ball. Thus, using  $M_\nu = 2.5 \times 10^6 M_\odot$  and the experimental upper limit  $|U_{\tau\nu} U_{\tau\nu}^*|^2 \leq 10^{-3}$ , we obtain  $L_\gamma \leq 1.45 \times 10^{34}$  ergs s $^{-1}$ .

The Galactic center has been observed in the 2–10 keV range by Koyama et al. (1996). They find that the X-ray flux from inside the Sgr A\* shell (an oval region of  $\approx 2' \times 3'$ ) is approximately  $10^{-10}$  ergs cm $^{-2}$  s $^{-1}$  in the 2–10 keV band. After correcting for the observed absorption by a column of approximately  $7 \times 10^{22}$  H atoms cm $^{-2}$ , they obtain a luminosity of  $\approx 10^{36}$  ergs s $^{-1}$  for an assumed distance of 8.5 kpc to the Galactic center. To detect X-rays emitted by the neutrino ball, a much higher angular resolution is needed. It would suffice to make observations of a  $0''.6 \times 0''.6$  (about the size of the neutrino ball) region around Sgr A\*. The

diffuse luminosity expected from an area corresponding to the area of the neutrino ball would be  $(0''.6 \times 0''.6)/(2' \times 3') \times 10^{36}$  ergs s $^{-1} \approx 1.67 \times 10^{31}$  ergs s $^{-1}$ . This number could be even lower since it includes contributions from all energies from 2 to 10 keV. Thus, it seems possible to detect the X-ray line of  $E_\gamma \geq 6.0$  keV ( $g = 2$ ) or  $E_\gamma \geq 7.1$  keV ( $g = 1$ ) because of the radiative decay of the neutrino in the neutrino ball. However, it might be that the energy of the emitted X-rays is too close to the fluorescent iron lines to be detected with the current energy resolution of CCD cameras and gas-imaging spectrometers.

We would like to emphasize that the idea that Sgr A\* may be an extended object rather than a supermassive black hole is not new (see, e.g., Haller et al. 1996; Sanders 1992). To our knowledge, all previous such models assume that the extended object is of a baryonic nature, e.g., a very compact stellar cluster. However, it is commonly accepted that these models face problems with stability, and it has been questioned whether such clusters are long lived enough, based on evaporation and collision timescales stability criteria (for a different point of view see Moffat 1997). It is interesting to note that in the context of a different object, the center of the NGC 4258 galaxy, and based on similar criteria, Maoz (1995) has shown that an object composed of elementary particles would be in accordance with the observational data, which agrees with our conclusions.

Finally, we would like to comment on the neutrino mass necessary for our model to work. We are particularly interested in neutrinos with masses between 10 and 25 keV/ $c^2$ , since these could form supermassive, degenerate neutrino balls, which may explain, without invoking the black hole hypothesis, some of the features observed around the supermassive compact dark objects with masses ranging from  $10^{6.5}$  to  $10^{9.5} M_\odot$ , which have been reported to exist at the centers of a number of galaxies (Kormendy & Richstone 1995) including our own (Genzel, Hollenbach, & Townes 1994; Eckart & Genzel 1997; Tsiklauri & Viollier 1997a, 1997b). A 10–25 keV/ $c^2$  neutrino is neither in conflict with particle and nuclear physics nor with astrophysical observations (Viollier 1994). On contrary, if the conclusion of the Liquid Scintillator Nuclear Detector (SND) collaboration, which claims to have detected  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$  flavor oscillations (Athanasopoulos et al. 1996a and 1996b) is confirmed, and the quadratic see-saw mechanism involving the up, charm, and top quarks (Gell-Mann, Ramond, & Slansky 1979; Yanagida 1979) is the correct mechanism for neutrino mass generation, the  $\nu_\tau$  mass may very well be in the cosmologically forbidden range between 6 and 32 keV/ $c^2$  (Bilić & Viollier 1997d). It is well known that such a quasi-stable neutrino would lead to an early matter-dominated phase, which may have started as early as a few weeks after the big bang. As a direct consequence of this, the universe would have reached the current microwave background temperature much too early to accommodate the oldest stars in globular clusters, cosmochronology, and the Hubble expansion age. It is conceivable, however, that in the presence of such heavy neutrinos, the early universe might have evolved quite differently than described in the standard model of cosmology (Kolb & Turner 1990, 1991; Börner 1988). Neutrino balls might have been formed in a local condensation process during a gravitational phase transition, shortly after the neutrino matter-dominated epoch began. The latent heat produced in such a first-order phase transition, apart from reheating the gaseous phase, might have reheated the

radiation background as well. Annihilation of the heavy neutrinos into light neutrinos via the  $Z^0$  boson will occur efficiently in the interior of the neutrino balls, since the annihilation rate is proportional to the square of the number density, which is of the order of  $10^{25}$  particles  $\text{cm}^{-3}$  at the center of neutrino ball with a mass of a few times  $10^9 M_\odot$ . Both these processes will decrease the contribution of the heavy neutrinos to the critical density today and therefore increase the age of the universe (Kolb & Turner 1991). Thus, a quasi-stable neutrino in the mass range  $10\text{--}25 \text{ keV}/c^2$  is not excluded by astrophysical arguments (Viollier 1994). In fact, it has been established in the framework of

the Thomas-Fermi model at finite temperature (Bilić & Viollier 1997a) that such neutrino balls can form via a first-order gravitational phase transition, although the mechanism through which the latent heat is released during the phase transition and dissipated into observable or perhaps unobservable matter or radiation remains to be identified. At this stage, however, it is still not clear whether an energy dissipation mechanism can be found within the minimal extension of the standard model of particle physics or whether new physics is required in the right-handed neutrino sector in order to generate this efficient cooling of the neutrino matter.

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