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Antineutrino star model of the big bang and dark energy

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ABSTRACT

A new model of cosmology is proposed, where the state of high energy density commonly associated with the big bang is generated by the collapse of an antineutrino star that has exceeded its Chandrasekhar limit. To allow the first neutrino stars and antineutrino stars to form naturally from an initial quantum vacuum state, matter and antimatter are assumed to gravitationally repel. In this scenario, a degenerate antineutrino star in effective hydrostatic equilibrium has a density that is similar to the dark energy density of the ΛCDM model. When viewed from the core, such a star could today accelerate matter radially and emit the isothermal cosmic microwave background radiation, which addresses the horizon and flatness problems. This model and the ΛCDM model are in similar quantitative agreement with supernova distance measurements. The presented model is also in qualitative agreement with observed large-scale anisotropy and inhomogeneity, which distinguishes it from the ΛCDM model.

Keywords: Cosmology: Theory · Gravitation · Early universe · Dark energy · Large-scale structure of universe · Cosmic background radiation · Neutrinos

1. INTRODUCTION

Almost a century ago, observations showed for the first time that the distribution of matter in our universe is expanding (Hubble 1929; Slipher 1917). The big bang model describes not only this expansion, but also the abundance of light elements and the distribution of radiation and matter in the universe. It assumes that the universe is homogeneous and isotropic on large scales, which is known as the cosmological principle. Mathematically, the Friedman-Lemaître-Robertson-Walker (FLRW) metric upholds the cosmological principle by uniformly changing the metric of space with a scale factor that varies in time. In our apparently flat universe, the scale factor depends on the fractional matter density (Ω_m) and fractional dark energy density (Ω_Λ). Dark energy is commonly thought to be the constant energy density of the quantum vacuum. Physically, the matter density decelerates the inertial expansion of the metric after the big bang and dark energy accelerates it. Twenty years ago, observations of type Ia supernovae (SNe Ia) showed an accelerating expansion of matter (Riess et al. 1998; Schmidt et al. 1998; Perlmutter et al. 1999). Today, a concordance

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from various observations defines the ΛCDM model, which parameterizes the flat FLRW metric with $\Omega_m = 0.31$ and $\Omega_\Lambda = 0.69$ (Ade et al. 2016). This corresponds to a *dark energy density* of $\rho_\Lambda \approx 6 \times 10^{-30}\mathrm{g/cm}^3$, which is 10^{120} times smaller than expected (Weinberg 1989). Thus we do not yet understand what makes up the majority of the observable universe. Alternative models include a repulsive interaction between matter and antimatter (Benoit-Lévy and Chardin 2012; Dopita 2012; Villata 2013; Hajdukovic 2011b, 2012b, 2014) and relic neutrino condensation (Fardon et al. 2004; Hoon 2013). Despite these alternatives, the ΛCDM model is so far our most successful description of the late universe.

The ΛCDM model does not address several key puzzles associated with the early universe. For example, when we trace the expansion of all observable matter ($\sim 10^{55}$ g) backwards in time, we encounter a state of *high energy density* commonly associated with the big bang. The origin of this state is an open question of cosmogony (Khoury et al. 2001) and may motivate a big bounce (Brandenberger and Peter 2017). Another puzzle arises when we assume that this state initially contained equal amounts of matter and antimatter, while unequal amounts are observed in the universe today. To account for this matter-antimatter asymmetry, a mechanism for *baryogenesis* is necessary (Sakharov 1991). Additionally, the initially hot and dense matter cooled sufficiently to become transparent to radiation $\sim 10^5$ years after the big bang. In the ΛCDM model, this matter emits the cosmic microwave background (CMB) radiation (Penzias and Wilson 1965). However, the CMB is more isotropic than expected, which is known as the *horizon problem*. The theory of cosmological inflation addresses this by introducing a period of exponentially accelerating expansion up to 10^{-32} s after the big bang (Guth 1981; Linde 1982; Albrecht and Steinhardt 1982). This could allow any two regions of the CMB to become thermalized in the early universe. This also addresses the question of why our expanding metric appears to be spatially flat, known as the *flatness problem*. However, inflation suffers from problems such as the entropy problem (Penrose 1989) or the multiverse problem (Ijjas et al. 2014). Moreover, the ΛCDM model interpretation of CMB data gives an expansion rate of the universe (H_0) that is in tension with cosmology-independent measurements of H_0 at the 3.7σ level (Aghanim, N. et al. 2016; Riess et al. 2018). This motivates a search for new models, with the ΛCDM model as the benchmark.

In the present Letter, a new model of cosmology is proposed that addresses all of the above puzzles, barring baryogenesis. A degenerate self-gravitating gas of neutrinos, which we will call a neutrino star, collapses when its mass exceeds the Chandrasekhar limit, $\mathcal{M}_{\nu_e} \propto 1/m_{\nu_e}^2$ (Chandrasekhar 1931, 1935). The small neutrino mass (m_{ν_e}) guides the ansatz that the collapse of an antineutrino star created the state of high energy density in the early universe. In this scenario, the universe is initially in a quantum vacuum state of minimal entropy. This state is gravitationally unstable and organically forms spatially separated neutrino stars and antineutrino stars when we assume that matter and antimatter gravitationally repel. After a 'neutrinonova' as described below, a fraction of the antineutrino gas eventually returns to effective hydrostatic equilibrium. Viewed from the core, it could today emit isothermal radiation and accelerate matter radially.

Both the new model and the ΛCDM model describe supernova distance measurements with comparable quantitative accuracy. The density of the antineutrino star is similar to the dark energy density of the ΛCDM model and the neutrino mass is constrained to high statistical precision. The new model is qualitatively consistent with CMB anisotropies and large-scale structures that challenge the cosmological principle of the ΛCDM model.

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Although there are strong theoretical arguments against repulsive gravity (for a review, see Nieto and Goldman (1991)), there have not yet been any conclusive direct tests. Several tests with antihydrogen are currently underway at CERN (Charman et al. 2013; Pérez et al. 2015; Brusa et al. 2017). While the hypothesis of repulsive gravity may prove incorrect, we will show that it offers an explanation for cosmogony and dark energy. Moreover, repulsive gravity has been proposed as origin of CP violation (Chardin and Rax 1992), which is one of the requirements for baryogenesis, and as alternative to dark matter via vacuum polarization (Hajdukovic 2011c, 2012a, 2014; Penner 2016). It also predicts antimatter emission from matter inside black holes, which will be briefly discussed (Hajdukovic 2011a; Villata 2015).

2. ANTINEUTRINO STAR MODEL OF THE EARLY UNIVERSE

2.1. *Chandrasekhar limit*

When a white dwarf star exceeds the Chandrasekhar limit, its own gravitational pressure overwhelms the degeneracy pressure of electrons and it collapses in a supernova (Chandrasekhar 1931). Similarly, the limiting mass of a degenerate gas of electron neutrinos is

$$\mathcal{M}_{\nu_e} = \frac{\omega_3^0\sqrt{3\pi}}{2}\left(\frac{\hbar c}{G}\right)^{3/2}\left(\frac{1}{m_{\nu_e}}\right)^2 , \tag{1}$$

where $\omega_3^0 \approx 2.018236$ is part of a numerical solution to the Lane-Emden equation, m_{ν_e} is the effective electron neutrino mass and other variables take their usual meaning. The most stringent experimental constraint to date on the electron neutrino mass of $m_{\nu_e} < 2.05\ \mathrm{eV/c^2}$ was found by Aseev et al. (2011) and gives a lower limit of $\mathcal{M}_{\nu_e} > 2.39 \times 10^{51}$ g. This lower limit is only four orders of magnitude below the mass content of the universe at the time of the big bang ($\sim 10^{55}$ g) (Ade et al. 2016). The collapse of an antineutrino star can thus create the state of high energy density commonly associated with the big bang with a minimum of new physics.

2.2. *Instability of the quantum vacuum*

As initial condition for the universe we choose an infinite volume of quantum vacuum due to its low number of degrees of freedom. The quantum vacuum contains a sea of virtual particle-antiparticle pairs going into and out of existence. The universe today is no longer in this low-entropy quantum vacuum state. To explain this, we assume that matter and antimatter gravitationally repel, such that the quantum vacuum is gravitationally unstable. Short-lived perturbations in the particle-antiparticle density create a weak and fluctuating gravitational field on small scales. By the Schwinger mechanism, this field has a *non-zero* probability of creating real particles by separating virtual ones before they can annihilate (Schwinger 1951; Hajdukovic 2014). For example, the pair creation rate per unit volume and time in a constant local gravitational field gradient, $\boldsymbol{g}$, is

$$\frac{dN}{dtdV} = \frac{m^4c^5}{4\pi\hbar^4}\left(\frac{\hbar\,|\boldsymbol{g}|}{\pi mc^3}\right)^2 \sum_{n=1}^{\infty}\frac{1}{n^2}\exp\left(-n\frac{\pi mc^3}{\hbar\,|\boldsymbol{g}|}\right) . \tag{2}$$

The exponential dependence on effective mass (m) strongly favors creation of neutrino-antineutrino pairs compared to other particles of the Standard Model (Hajdukovic 2014; Greiner et al. 1985). It also favors cold neutrinos over hot neutrinos, which allows them to bind gravitationally. Thus, repulsive gravity enables the gradual formation of mutually repulsive neutrino stars and antineutrino stars.

2.3. *Qualitative description of neutrinonova*

Whenever an antineutrino star exceeds its limiting mass due to accretion from either the Schwinger mechanism or a merger event, it collapses in a "neutrinonova" (NN). At sufficiently high temperatures and densities, antineutrinos could transform most of their kinetic energy via high-energy collisions into equal amounts of baryonic matter and antimatter. Repulsive gravity and thermal pressure could subsequently halt the collapse and initiate expansion in a big bounce. During the expansion, baryonic matter and antimatter start to annihilate faster than they are created, with baryogenesis invoked to leave a small remnant of baryonic matter (Sakharov 1991). The surviving antineutrinos and matter evolve as an adiabatic ideal gas initially in thermal equilibrium. During adiabatic expansion, the temperature (T) decreases with an increase in volume (V) as $T \propto V^{-1/3}$ for a relativistic gas and $T \propto V^{-2/3}$ for a non-relativistic gas. Thus, baryonic matter undergoes nucleosynthesis until temperature and density decrease sufficiently to "freeze out" certain reactions. This process is qualitatively similar to big bang nucleosynthesis (BBN) (Alpher et al. 1948). Since baryonic matter is much more massive than neutrinos, it becomes non-relativistic at a much higher temperature than the gas of antineutrinos. It thus begins structure formation in a much smaller volume than the gas of antineutrinos. Newly formed galaxies are subsequently gravitationally repelled from initial proximity to the center of the antineutrino gas. A fraction of the original antineutrino gas eventually re-forms into a degenerate self-gravitating gas, and re-establishes thermal equilibrium a sufficient time $t \gg R/c$ afterwards. Observers close to the center of this isothermal star would detect isotropic black body radiation, which we identify as the CMB. We call this the "ATLAS (AnTineutrino mass-Limited gAS)" model[1] and refer to the antineutrino star as ATLAS-1.

3. ANTINEUTRINO STAR MODEL OF THE LATE UNIVERSE

3.1. *Antineutrino star is defined by two parameters*

To characterize a degenerate antineutrino gas in effective hydrostatic equilibrium, we first make two assumptions. First, we ignore thermal or radiation pressure of the antineutrino gas by assuming it is highly degenerate with temperature $T/T_\mathrm{F} \ll 1$, where T_F is the Fermi temperature. Second, we assume that all neutrino-antineutrino pairs created from the quantum vacuum are electron flavored pairs with effective inertial mass m_{ν_e}. Note that due to neutrino oscillations (Fukuda et al. 1998; Ahmad et al. 2002), free electron neutrinos have an effective mass $m_{\nu_e} = \sum_i |U_{ei}|^2 m_i$, where U_{ei} are the Pontecorvo-Maki-Nakagawa-Sakata leptonic mixing matrix elements and m_i are eigenstates of definite mass ($i = 1, 2, 3$, respectively). This second assumption is reasonable in the context of the Schwinger mechanism if the electron neutrino mass m_{ν_e} is much less than the muon (m_{ν_μ}) or tau (m_{ν_τ}) neutrino masses.

With these assumptions we can use Chandrasekhar's equation of state for degenerate matter, derived from hydrostatic equilibrium of gravitational and degeneracy pressures (Chandrasekhar 1935). This equation of state does not take into account general relativistic effects, which we can ignore for simplicity if the radius of the star is much larger than its Schwarzschild radius, $R_S/R \ll 1$. Using Chandrasekhar's notation, we get

$$\frac{1}{\eta^2}\frac{d}{d\eta}\left(\eta^2\frac{d\phi}{d\eta}\right) = -\left(\phi^2 - \frac{1}{y_0^2}\right)^{3/2}, \tag{3}$$

[1] In Greek mythology, Atlas is a titan who holds up the celestial spheres.

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where η is proportional to radius, $\phi(\eta)$ is proportional to the gravitational potential, and y_0 is a constant related to the central density by

$$\rho_0 = (y_0^2 - 1)^{3/2} \frac{m_{\nu_e}^4 c^3}{3\pi^2 \hbar^3} \,. \tag{4}$$

The density profile of the antineutrino star is given by

$$\rho_{\bar{\nu}_e}(\eta) = \rho_0 \frac{y_0^3}{(y_0^2 - 1)^{3/2}} \left(\phi(\eta)^2 - \frac{1}{y_0^2} \right)^{3/2} \,, \tag{5}$$

and vanishes at the star's radius, $R = \alpha\eta_1$, where

$$\alpha = \left(\frac{3\pi\hbar^3}{4cGm_{\nu_e}^4 y_0^2} \right)^{1/2} \tag{6}$$

is a scale length. We can numerically evaluate equation (3) by using as initial values the expansions of $\phi(\eta)$ and its derivative $\phi'(\eta)$ near the origin, for example

$$\phi(\eta) = 1 - \frac{q^3\eta^2}{6} + \frac{q^4\eta^4}{40} - \frac{q^5(5q^2+14)\eta^6}{7!} + \mathcal{O}[\eta^8] \,, \tag{7}$$

where we used the substitution $q^2 = 1 - 1/y_0^2$. The free parameters ρ_0 and m_{ν_e} allow us to uniquely solve Chandrasekhar's equation of state.

We assume that inertial masses (m_i) of matter and antimatter are equal and positive, and that the gravitational mass of matter is positive ($m_g/m_i = 1$) and of antimatter is negative ($m_g/m_i = -1$); for generality, we don't use overbar notation. The spherically symmetric gravitational potential $\varphi(r)$ inside and outside an antineutrino star is

$$\varphi(r) = \begin{cases} c^2 y_0[\phi(r/\alpha) - 1], & \text{if } r \le R \,, \\ \varphi(R) - GM_g \left(\frac{1}{r} - \frac{1}{R}\right), & \text{if } r > R \,, \end{cases} \tag{8}$$

where $M_g < 0$ is the gravitational mass of the antineutrino star. The gauge is fixed to zero at the star's center, $\varphi(0) = 0$, so that $\varphi(r) < 0$ everywhere else.

3.2. *Relative velocities define observational frame*

An antineutrino star establishes a background potential given by equation (8) that is the dominant contribution to the velocity of galaxies. Therefore, we can determine our approximate position empirically from our velocities relative to other galaxies and to the rest frame of the antineutrino star, that is the rest frame of the CMB. The velocities of galaxies relative to us scale approximately *isotropically* with distance at a rate of $H_0 \approx 70$ km s^{-1}Mpc^{-1} (Riess et al. 2018). The velocity of the Local Group relative to the CMB is comparably small at $v_{LG} \approx 627$ km s^{-1} (Kogut et al. 1993). These velocities suggest we are approximately at rest and near (but not at) the center of the star. This can be explained with the small potential gradient near the center, which causes matter initially close to the center to lag behind other matter in the overall expansion.

3.3. *Derivation of distance-redshift relationship*

The Schwarzschild metric is useful to determine the redshift of light emitted by a galaxy in free fall from initial proximity to the center of an antineutrino star. We may identify ourselves as Schwarzschild observers, who are by definition at rest where the gauge is fixed to zero, namely at the star's center. When allowing for repulsive gravity, we need to define two different metrics for matter and for photons.

Matter experiences a generalized Schwarzschild metric, where the proper time τ is given by

$$d\tau^2 = \left(1 + \frac{2V(r)}{m_i c^2}\right) dt^2 - \frac{dr^2}{c^2} \frac{1}{1 + \frac{2V(r)}{m_i c^2}} - \frac{r^2 d\Omega^2}{c^2}\,, \tag{9}$$

where $V(r)$ is the gravitational potential energy of a test particle, m_i is its inertial mass, t is coordinate time, and the angular path element in spherical coordinates is $d\Omega^2 = \sin\theta^2 d\phi^2 + d\theta^2$. Note that this general expression allows matter and antimatter to experience different metrics that depend on the sign of the potential energy, $V(r)$. The time dilation factor for galaxies with average initial velocity v_0 undergoing free fall from the center of the star is found with energy conservation (Radosz et al. 2008) to be

$$\frac{d\tau}{dt} = \left(1 + \frac{2\varphi(r)}{c^2}\right) \sqrt{1 - \frac{v_0^2}{c^2}}\,, \tag{10}$$

where $\varphi(r)$ is the potential created by the antineutrino star in equilibrium and is given by equation (8). The coordinate velocity $v_s = dr/dt$ is found similarly,

$$\frac{v_s}{c} = \left(1 + \frac{2\varphi(r)}{c^2}\right) \sqrt{1 - \left(1 - \frac{v_0^2}{c^2}\right)\left(1 + \frac{2\varphi(r)}{c^2}\right)}\,. \tag{11}$$

By symmetry, we assume that photons in a gravitational potential undergo blueshift or redshift independently of the matter or antimatter nature of the gravitational source. In other words, the weak equivalence principle holds for photons but is modified for matter. We will thus use a metric for photons that is agnostic to the type of matter,

$$d\tau_\gamma^2 = \left(1 + \frac{2\varphi(r)}{c^2}\frac{M_g}{M_i}\right) dt_\gamma^2 - \frac{dr_\gamma^2}{c^2} \frac{1}{1 + \frac{2\varphi(r)}{c^2}\frac{M_g}{M_i}} - \frac{r^2 d\Omega_\gamma^2}{c^2}\,. \tag{12}$$

Since proper time is zero for photons, the velocity $v_\gamma = (dr/dt)_\gamma$ of distant photons moving in the radial direction ($d\Omega_\gamma = 0$) is

$$\frac{v_\gamma}{c} = 1 + \frac{2\varphi(r)}{c^2}\frac{M_g}{M_i}\,, \tag{13}$$

where M_g is the gravitational mass and M_i the inertial mass of the source. The above equations allow us to calculate the redshift seen by a Schwarzschild observer,

$$z = \left(\frac{dt}{d\tau}\right)\left(1 + \frac{v_s}{v_\gamma}\right) - 1\,, \tag{14}$$

which reduces to the special relativistic Doppler effect in flat spacetime (for example, at $r = 0$). Therefore, redshift is caused by a combination of apparent radial velocity v_s and time dilation of

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free-falling sources in the gravitational potential φ. The distance modulus of distant SNe Ia in receding galaxies is

$$\mu_{\rm th}(z) = 25 + \log_{10}[r(z)(1+z)]\,, \tag{15}$$

where $r(z)$ is the distance from the center of the antineutrino star in Megaparsec (Riess et al. 1998).

4. COSMOLOGICAL PARAMETERS

We can compare the theoretical distance modulus to observed distance moduli of SNe Ia for a given set of cosmological parameters, $\theta = (m_{\nu_e}, \rho_0, v_0/c)$. Goodness of fit is determined with a χ^2 statistic,

$$\chi^2_\nu(\theta) = \sum_i \frac{[\mu_{{\rm th},i}\,(z_i;\theta) - \mu_{0,i}(z_i)]^2}{\sigma^2_{\mu_{0,i}}}\,, \tag{16}$$

where $\sigma_{\mu_{0,i}}$ is the measurement uncertainty in the observed distance modulus $\mu_{0,i}$. As observational data, the "Union2.1" catalog of 580 SNe Ia is used[2] (Suzuki et al. 2012). The best-fit parameter values are $m_{\nu_e} = 7.90$ meV/c^2, $\rho_0 = 1.60\times10^{-29}$ g/cm^3 and $v_0/c = 6.38\times10^{-3}$. These give $\chi^2_\nu/{\rm dof} = 1.04$, where dof stands for a model's degrees of freedom. For reference, the ΛCDM model has a comparable fit of $\chi^2_\Lambda/{\rm dof} = 1.09$ (Ade et al. 2016). The theoretical distance modulus of the ATLAS model using the above best-fit parameters is plotted together with the Hubble diagram of type Ia supernovae in Figure 1. For comparison, the theoretical distance modulus of the concordance ΛCDM model is shown with $H_0 =$ 67.74 km s^{-1}Mpc^{-1} (Ade et al. 2016). We find that the ATLAS model can account for the motion of matter with the spatially varying density of an antineutrino star in equilibrium acting as a dark energy.

Following Riess et al. (1998), the probability density function (PDF) for a given cosmological parameter is quantified with Bayes' theorem, which gives a PDF for the electron neutrino mass of

$$p(m_{\nu_e}|\mu_0) = \frac{\int_0^c dv_0 \int_0^\infty \exp(-\chi^2/2)\, d\rho_0}{\int_0^c dv_0 \int_0^\infty d\rho_0 \int_0^\infty \exp(-\chi^2/2)\, dm_{\nu_e}}, \tag{17}$$

where μ_0 represents all measured distance moduli, which are assumed to be independent and normally distributed. This gives a mass to one standard deviation of $m_{\nu_e} = 7.90\pm0.16$ meV/c^2. Note that this uncertainty is purely due to statistical error and does not include possible systematic errors, which can be caused by model assumptions or calibration (Suzuki et al. 2012). This mass is consistent with the present experimental upper limit of $m_{\nu_e} < 2.05$ eV/c^2 (Aseev et al. 2011). Measurements of neutrino mixing angles can give the muon and tau neutrino masses; for example, the most recent best-fit values[3] by Esteban et al. (2017) give $[m_{\nu_\mu}, m_{\nu_\tau}] \approx [30.5, 26.9]$ meV/c^2.

5. DISCUSSION

The antineutrino star parameters are approximately consistent with the model's assumptions. The best-fit muon and tau neutrino masses are larger than the electron neutrino mass by a factor of $\gtrsim$ 3. This is consistent with the simplifying assumption that the antineutrino star consists only of electron neutrinos due to the Schwinger mechanism (section 3.1). The best-fit electron neutrino mass gives a Chandrasekhar limit of $\mathcal{M}_{\nu_e} = 1.61\times10^{56}$ g. The re-formed antineutrino star has

[2] http://supernova.lbl.gov/union/
[3] NuFIT 3.2 (2018), http://www.nu-fit.org/?q=node/166

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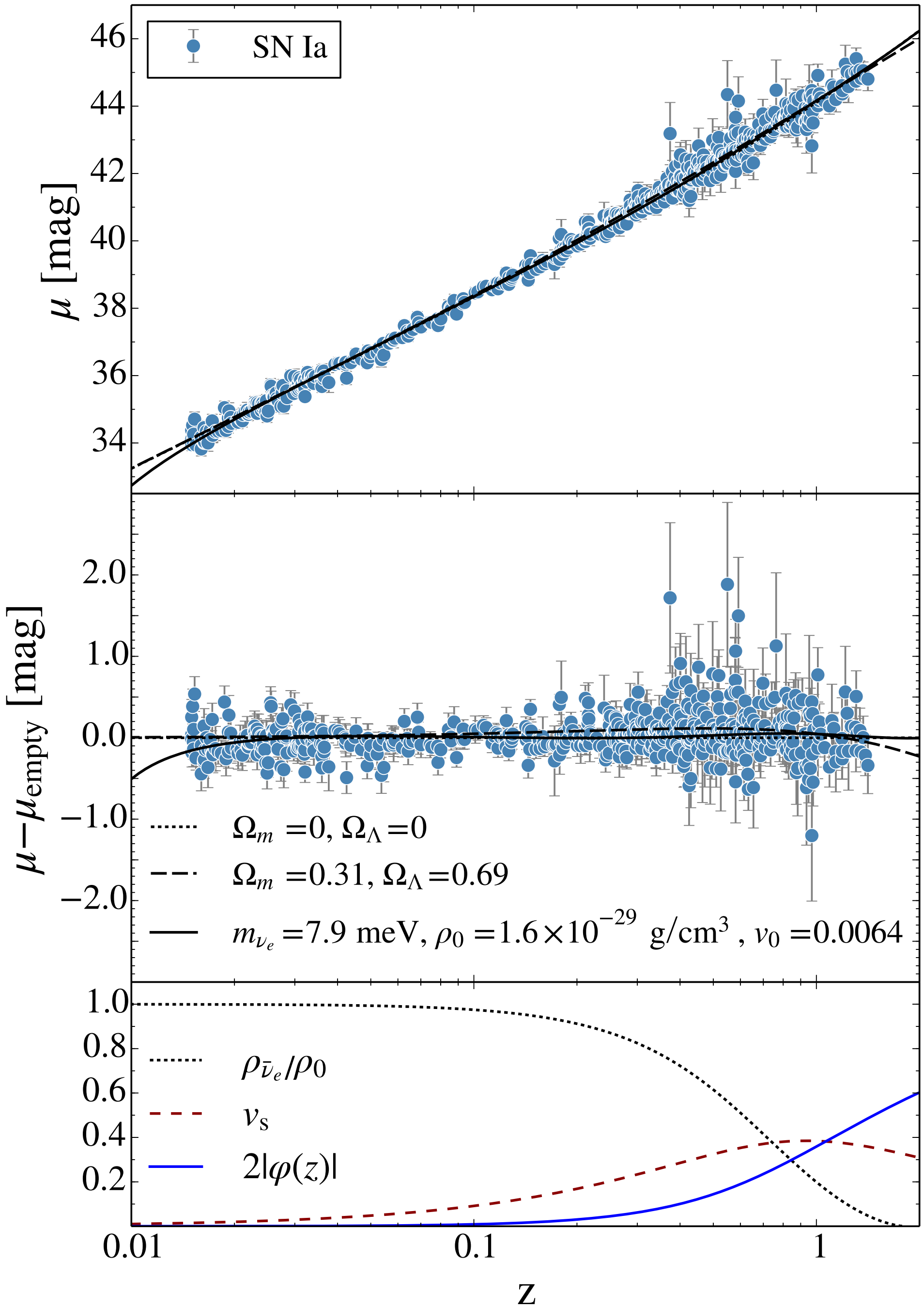

Figure 1. *Top*: Hubble diagram of SNe Ia (*blue circles*) with comparable fits by the ΛCDM model (*dashed line*) and the ATLAS Model (*solid line*). *Middle*: Hubble diagram relative to the empty universe model for a better comparison (for brevity, $c = 1$). *Bottom*: The antineutrino star's density (*dotted curve*) is comparable to the dark energy density of the ΛCDM model in the core of the star ($\rho_\Lambda/\rho_0 \approx 0.4$), and vanishes at the star's radius $R = 17.6$ Gly, where $z = 1.80$

mass $M/\mathcal{M}_{\nu_e} =$ 0.277 and radius $R = 17.6$ billion light-years (Gly) or $R_S/R = 0.398$, which is found by solving Chandrasekhar's equations using best-fit parameters. The antineutrino star is degenerate, with central Fermi temperature $T_{\rm F,0} = 26.1\,{\rm K} > {\rm T}_{\rm CMB,0} = 2.73\,{\rm K}$ (Fixsen 2009). Future work could account for the temperature ratio T/T_{F} and general relativistic effects $\mathcal{O}\left[(R_S/R)^2\right]$ to improve the accuracy of the antineutrino star model. Since these effects are small and dominate at high-z, where supernova data is still sparse, they are ignored for simplicity in the present model.

The ATLAS model predicts observations that challenge the cosmological principle of the ΛCDM model. First, the high isotropy of the CMB suggests that the last neutrinonova occurred $t \gg 17.6$ billion years ago. Thus, sufficient time has elapsed for the formation of large structures in the distant universe. This is qualitatively consistent with the existence of the Hercules-Corona Borealis Great Wall (Horváth et al. 2014; Balazs et al. 2015); its size of 7-10 Gly challenges the *homogeneity* assumption of the ΛCDM model, which predicts structures not larger than ~ 1.21 Gly (Yadav et al. 2010; Clowes et al. 2013). Second, the Copernican Principle would suggest that we are not *exactly* at the center of the antineutrino star. At the same time, observations of the largely isotropic Hubble expansion and CMB suggest that we are relatively close to the center. This could explain small yet statistically significant ($\sim 3\sigma$) anisotropies detected in both the distribution of radio galaxies (Singal 2011; Tiwari and Nusser 2016) and the CMB (Bennett et al. 2011; Ade et al. 2014), which challenge the *isotropy* assumption of the ΛCDM model. Note that all anisotropies are expected to disappear when viewed from the *exact* center of the star. This central region could coincide with an underdensity of matter in our cosmic neighborhood (for example, see Hoffman et al. (2017); Villata (2012)).

The ATLAS model relies on testable assumptions, in particular on the assumption of repulsive gravity. On cosmological scales, this assumption is useful for the continuity of the ATLAS model on three occasions. It explains the formation of neutrino and antineutrino stars (section 2.2), the bounce during a neutrinonova (section 2.3), and the radial acceleration of matter (see Fig. 1). This assumption may be tested on galactic and laboratory scales. On galactic scales, it predicts the emission of antimatter from matter inside the event horizon of black holes (Hajdukovic 2011a; Villata 2015). The *Fermi* bubbles are two bulbous sources of gamma rays above and below the Milky Way's galactic plane with bases converging on the galactic center. This region harbors the supermassive black hole Sgr A* with mass $M_{\mathrm{bh}} = 4 \times 10^6\ M_\odot$, where $M_\odot$ is a solar mass (Ghez et al. 2008; Gillessen et al. 2009; Boehle et al. 2016). The gamma rays emitted from the *Fermi* bubbles can be modeled as CMB photons that have scattered off high-energy charged particles of uncertain origin (Ackermann et al. 2014; Yang and Ruszkowski 2017). Future observations could investigate whether positrons and antiprotons emitted by accreting matter inside the event horizon of Sgr A* could create the *Fermi* bubbles. There also exists a positron excess in the galactic center (Weidenspointner et al. 2008) and in cosmic rays (Adriani et al. 2013; Accardo et al. 2014; Aguilar et al. 2016; Abeysekara et al. 2017), which could be emitted by accreting compact objects. More generally, repulsive gravity could provide a robust mechanism for Hawking radiation from near the event horizon in the form of antiparticles (Hawking 1974, 1975). On laboratory scales, the ALPHA, GBAR and AEGIS laboratories at CERN (Charman et al. 2013; Pérez et al. 2015; Brusa et al. 2017) are currently directly testing the assumption of repulsive gravity and thereby a key assumption of the ATLAS model.

6. CONCLUSIONS

The entropy of the universe is increasing relative to an initial state of low entropy, which is assumed to be the quantum vacuum. With the assumption that matter and antimatter gravitationally repel, which is currently being tested at CERN, this vacuum gradually decays into neutrinos and antineutrinos. The collapse of an antineutrino star is a possible explanation for the state of high energy density in the early universe. After collapse and subsequent creation of matter via baryogenesis, an antineutrino gas adiabatically expands and partially re-forms into an antineutrino star in effective hydrostatic equilibrium. Viewed from its core, this star could today emit the isothermal CMB radiation and radially accelerate matter. This addresses the problems of cosmogony and dark energy, and removes the horizon and flatness problems. The above ATLAS model is in good quantitative agreement ($\chi^2_\nu/\mathrm{dof} = 1.04$) with SNe Ia distance measurements. Supernova data constrain the electron neutrino mass as a cosmological parameter to $m_{\nu_e} = 7.90 \pm 0.16\,(\mathrm{stat.})\,\mathrm{meV/c^2}$, without taking systematic errors into account. The model is qualitatively consistent with existing observations of large structures in the distant universe and anisotropies in the Hubble flow and CMB, which help to distinguish it from the ΛCDM model.

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