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Testing the nature of Sgr A* with the S-2 star orbit data

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Resumen / Las estrellas del cúmulo S que orbitan alrededor del centro Galáctico, proveen uno de los mejores observables astrofísicos para inferir el potencial gravitatorio generado por la fuente central Sgr A*, tradicionalmente asumida como un Agujero Negro (BH). Un modelo alternativo para Sgr A* es el de Ruffini-Argüelles-Rueda (RAR), basado en un sistema autogravitante de fermiones neutros en el marco de la Relatividad General. Este predice la existencia de un núcleo denso de fermiones altamente degenerados capaz de imitar al BH, el cual está rodeado por una atmósfera mas diluida que es consistente con el halo de materia oscura (DM) de la Galaxia. En este trabajo estudiamos la dinámica de la estrella mas importante del cúmulo S, asumiendo que la misma se mueve alrededor del núcleo compacto de DM predicho por el modelo RAR. Por primera vez realizamos en el marco de este modelo un ajuste de los parámetros orbitales de la estrella S-2 con la técnica de Markov Chain Monte Carlo (MCMC), y comparamos con los resultados que se obtienen en el paradigma del BH.

Abstract / The stars of the S-cluster orbiting the Galactic center provide one of the best astrophysical observables to infer the gravitational potential generated by the central source Sgr A*, traditionally assumed to be a Black Hole (BH). An alternative model for Sgr A* is the Ruffini-Argüelles-Rueda (RAR) model, based on a self-gravitating system of neutral fermions in the framework of General Relativity. It predicts the existence of a dense core of highly degenerate fermions able to mimic the BH, which is surrounded by a more dilute atmosphere that is consistent with the dark matter (DM) halo of the Galaxy. In this work we study the dynamics of the most important star in the S-cluster, assuming that it moves around the compact DM core predicted by the RAR model. For the first time we fit the orbital parameters of the S-2 star with a Markov Chain Monte Carlo (MCMC) technique, and compare the results with the ones obtained in the BH paradigm.

Keywords / Galaxy: center — dark matter

1. Introduction

The RAR dark matter model characterizes DM halos on galaxy scales. These configurations are composed of fermionic particles governed by a most probable distribution function (DF) of the Fermi-Dirac type, that arises from an entropy maximization principle Chavanis (1998). The DM distribution develop a morphology known as *compact core-dilute halo*, where the central component provides an alternative to the BH paradigm at the center of galaxies, while the outer component can explain their circular rotation curves Ruffini et al. (2015); Argüelles et al. (2018); Becerra-Vergara et al. (2020). In particular for the Milky Way halo, a family of RAR solutions can be found given halo boundary conditions Argüelles et al. (2018). The density profiles shown there present an inner and compact core governed by quantum degeneracy of the DM fermions, followed by an intermediate region with a sharply decreasing density distribution and a Boltzmannian density tail. RAR dark matter configurations with fermion masses in the range $mc^2 = 48$–378 keV are in agreement with the Milky Way observables and provide at the same time, an alternative for the central Black Hole paradigm Argüelles et al. (2018); Becerra-Vergara et al. (2020).
In this work we will test the nature of Sgr A* with the S-2 orbit data using MCMC techniques.

2. Geodesics

For a test particle moving in a spherically symmetric space-time given by $ds^2 = g_{00}(r)c^2dt^2 - g_{11}(r)dr^2 - r^2d\Omega^2$ the equations of motion are given by $\dot{t} = E/(g_{00}(r)c^2)$; $\dot{\phi} = L/r^2$; $\ddot{r} = [-g'_{00}(r)c^2\dot{t}^2 - g'_{11}(r)\dot{r}^2 + 2r\dot{\phi}^2]/(2g_{11}(r))$, where E and L are the particle's energy and angular momentum per unit mass and c the light velocity. The overdot accounts for affine parameter derivative whilst ($'$) corresponds to radial derivative on the metric function components. This system of equations is solved numerically with appropriate initial conditions.

2.1. S2 star

In the central milliparsec of our galaxy resides a small star cluster called S-Cluster Eckart & Genzel (1996); Ghez et al. (1998). Because of its brightness and quality of astrometric data, the S2 star is the most important of the hole S cluster. It completes one orbit around the galactic center in ~ 16 yr. With the most recent and publicly available data from Do et al. (2019), we perform a MCMC statistical sampling of the S2 orbit in the plane of the sky using *emcee* Foreman-Mackey et al. (2013). We applied this for two different models; *i)* a RAR configuration for DM particle mass of $mc^2 = 56$ keV and *ii)* a Schwarzschild Black Hole (SBH) model

Oral contribution

of central mass $M_{BH} = 4.075 \times 10^6 M_\odot$. For the *priors* we use the orbital parameters given in Becerra-Vergara et al. (2020) and show the *posteriori* probability and correlations between the orbital parameters in Figure 2 for the RAR model and Figure 3 for the SBH case. In Table 1 are listed the most probable set of parameters (maximum of the likelihood function) for both models.

Parameter	RAR	BH
e	0.8862	0.8860
a [mas]	124.95	125.30
T [yr]	16.049	16.049
ω [°]	66.70	66.48
i [°]	134.45	134.38
Ω [°]	228.01	228.01
X_{off} [mas]	-1.69×10^{-1}	-9.63×10^{-2}
Y_{off} [mas]	2.59	2.38
t_p [yr]	2018.38	2018.38
$\Delta\phi$ [arcmin]	-2.78	11.95

Table 1: Best fit parameters for the S2 star, where e: eccentricity; a: semi-major axis; ω: argument of the pericenter; i: inclination; Ω: position angle of the ascending node; T: orbital period; t_p: epoch of pericenter passage; $\Delta\phi$: precession angle per orbital period; X_{off}, Y_{off} correspond to offsets of the central object in R.A. and declination respectively.

3. Results

The compact shape of the posterior probability sample supports the assumption of an 8-dimensional gaussian distribution, where the mean is nearly similar to the best fit parameters given in Table 1. Between the two models implemented, the set of parameters are in accordance (bellow 1% of relative error), and in well agreement with other works Do et al. (2019); Gravity-Collaboration (2020). The main difference arises in the prediction of the angle precession per orbital period which is retrograde in the case of the RAR dark matter model and prograde for the SBH model. Since RAR configurations are an extended distribution of matter, there is a competition between the effects of prograde precession generated by the central core, and retrograde precession generated by the extended mass Argüelles et al. (2022). Furthermore, the value of the angle precession is strongly dependent on the DM particle mass, which as increases, tends to the value predicted by SBH. Given the current precision in astrometric data, it is not yet possible to discriminate between the two models Argüelles et al. (2022).

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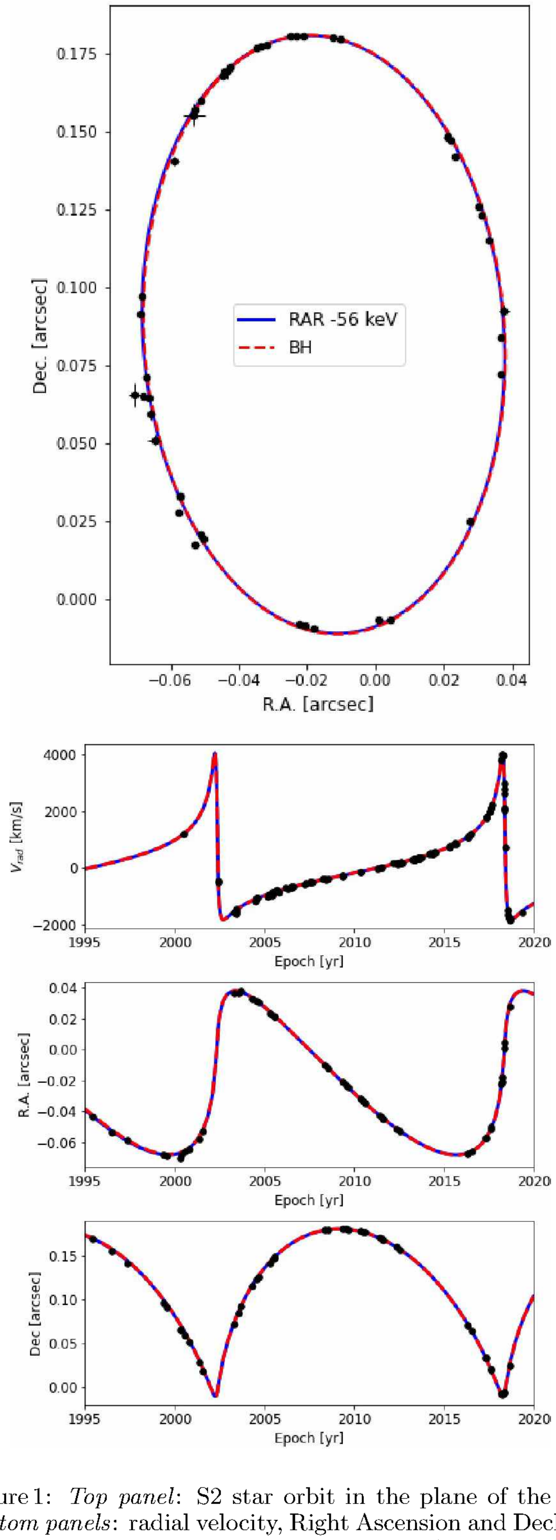

Figure 1: *Top panel*: S2 star orbit in the plane of the sky. *Bottom panels*: radial velocity, Right Ascension and Declination respectively, as a function of time for RAR dark matter model of $mc^2 = 56$ keV (solid blue) and Schwarzschild BH model of $M_{BH} = 4.075 \times 10^6 M_\odot$ (dashed red). The astrometric data were taken from Do et al. (2019).

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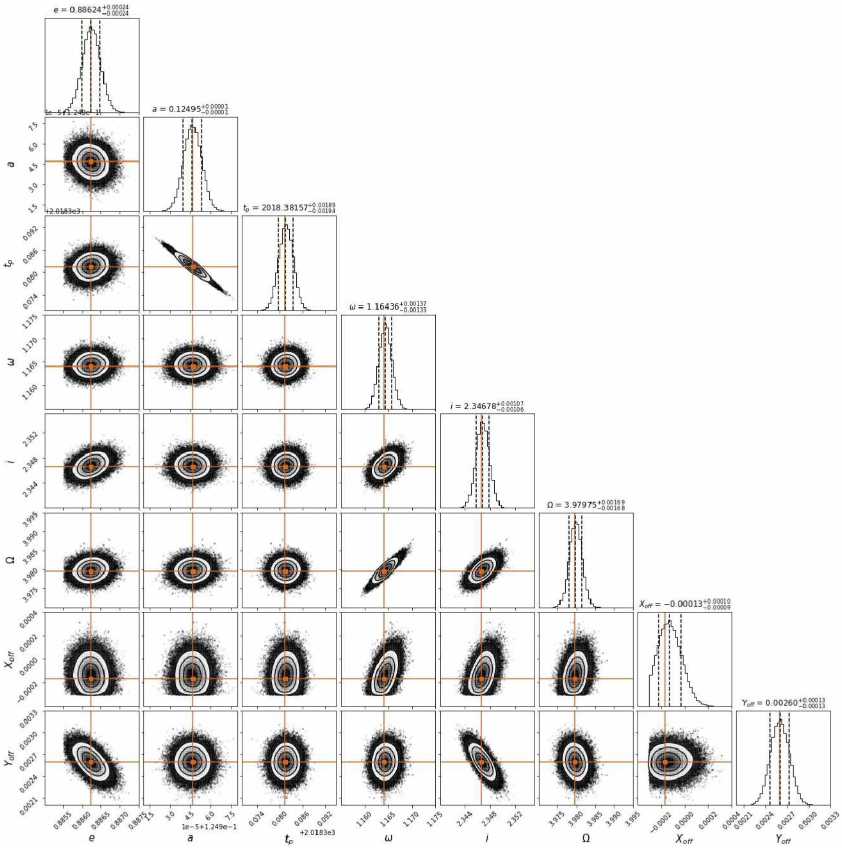

Figure 2: Corner plots corresponding to the 8-dimensional posterior probability space for the S2 star consistent with the RAR model for fermion mass of $mc^2 = 56$ keV. Solid lines correspond to the most probable set of parameters listed in Table 1 and dashed lines correspond to the mean and 1σ significance level.

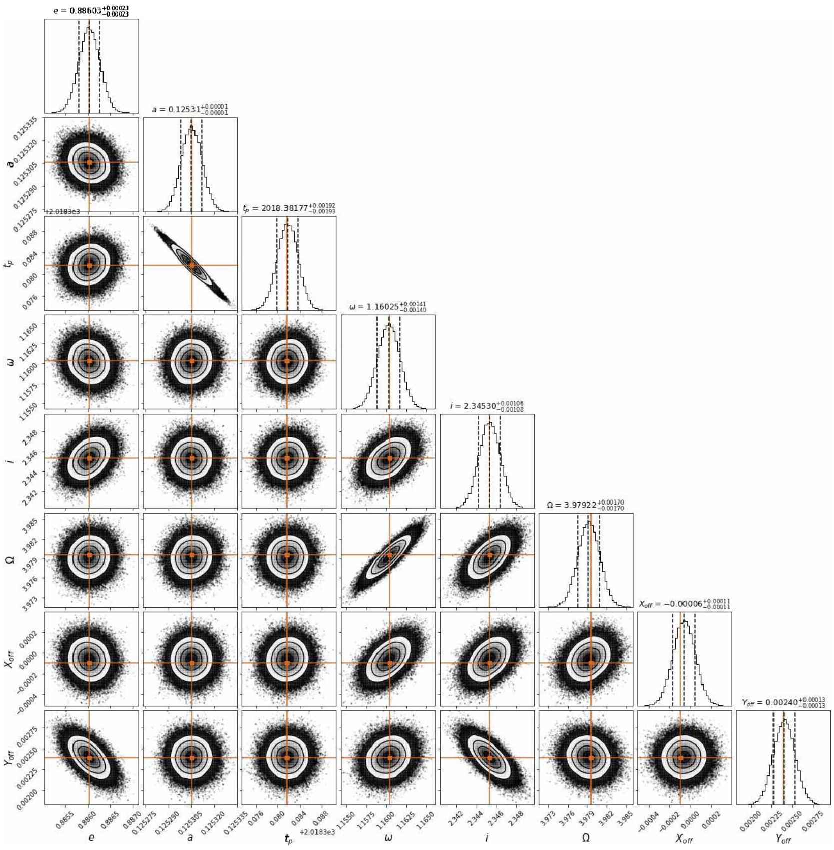

Figure 3: Analogous for the S2 star consistent with a Schwarzschild BH model for central mass of $M_{BH} = 4.075 \times 10^6 M_{\odot}$.