Stellar dynamics in a Fuzzy Dark Matter Halo

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(1) Background

Wave dark matter (ψDM) is a candidate theory of dark matter which proposes that dark matter particles have a small enough mass to where they can collectively be described as a wave. ψDM solves two major problems that the current standard cosmology Λ cold dark matter (ΛCDM) cannot: 1) the cuspy halo problem, where the dark matter density distributions of low-mass galaxies are predicted to steeply increase at low radii whereas flattening is observed and 2) the satellite halo problem, where ΛCDM over-predicts low-mass dark matter halos while ψDM suppresses these structures. Fuzzy dark matter (FDM) studies the case of ψDM where the particle mass $m \sim 10^{-22}$ eV, so the system can be studied entirely using wave mechanics. [1]

(2) Goals + Motivation

In past research, FDM halo gravitational potentials were approximated as the potential contribution from a static, spherically symmetric density profile. But this does not include wave interference effects that have been theorized to produce various phenomenology. [2]

Our research explores FDM by including wave interference effects in the FDM halo's evolution. We also used a more efficient method for evolving the FDM halo over time. Here, we present a more efficient method for calculating the gravitational potential of an, on average, spherically symmetric FDM halo. This will provide more accurate simulations at a lower computational cost.

(3) Methods

To calculate the gravitational field, we first decomposed the FDM density profile ρ into spherical harmonics

$$\rho(r,\theta,\phi) = \sum_{l=0}^{l_{max}} \sum_{m=-l}^{l} \rho_{lm}(r) Y_{lm}(\theta,\phi), \qquad \text{where } Y_{lm} \text{ are the spherical harmonics.} \tag{1}$$

We determined the amplitudes via the Schwarzschild method. Then, we calculated the spherical harmonic amplitudes of the gravitational potential generated by this density profile [3]:

$$\Phi_{lm}(r) = -\frac{4\pi G}{2l+1}\left[r^{l}\int_{r}^{\infty} R^{1-l}\rho_{lm}(R)dR + r^{-(l+1)}\int_{0}^{r} R^{2+l}\rho_{lm}(R)dR\right] \tag{2}$$

We reconstructed $\Phi(r,\theta,\phi)$ using the inverse Fourier transform. To determine the gravitational field, we will calculate

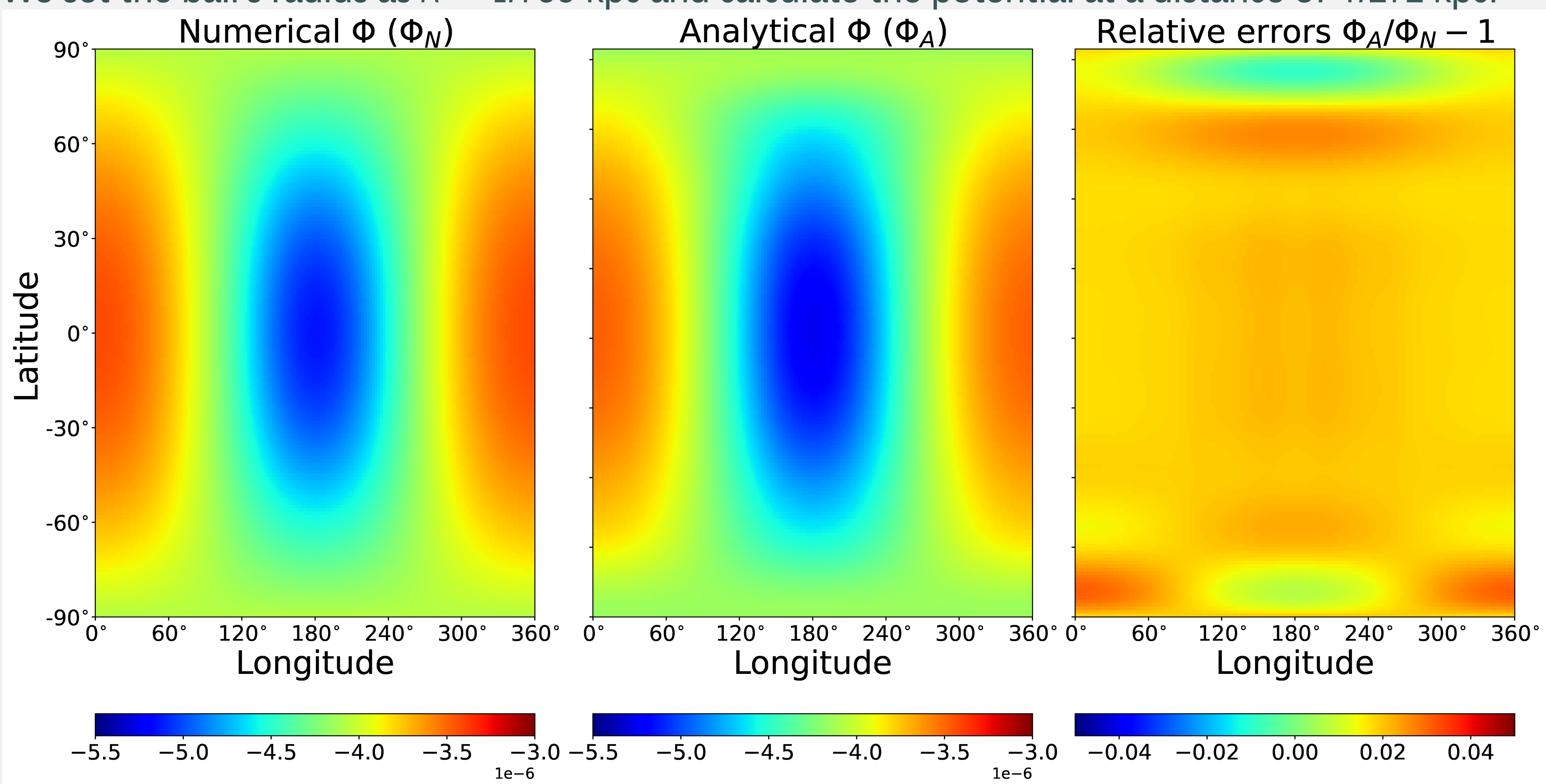
$$g = -\nabla\Phi. \tag{3}$$

(4) Results

We tested these methods against a few examples, most notable of which is the non-uniform solid ball. Parameterizing it in spherical coordinates, we assigned a 3D gaussian mass distribution

$$m(r,\theta,\phi) = a_1 \exp\left[-\frac{(r-b_1)^2}{2c_1^2}\right] + a_2 \exp\left[-\frac{(\theta-b_2)^2}{2c_2^2}\right] + a_3 \exp\left[-\frac{(\phi-b_3)^2}{2c_3^2}\right] \tag{4}$$

We set the ball's radius as $R = 1.769$ kpc and calculate the potential at a distance of 4.272 kpc.



Here, Φ_N uses the method described in section (3) while Φ_A is an analytical calculation on a 10x10 grid that was interpolated to be the same size as Φ_N (163x163).

(5) Conclusion

We find the analytical calculation of the potential matches well with the numerical method with errors on the order of 5 % at most. As this was from a highly non-uniform mass distribution, this increases our confidence in the method we used.

(6) Future work

- Fix bugs relating to the calculation of the θ and ϕ components of the gravitational field.
- Do some basic simulations with stars under the influence of this field.
- Evolve the halo over time and simulate stellar dynamics in an evolving halo.

References

[1] Hui L., 2021, arXiv e-prints, p. arXiv:2101.11735

[2] Li X., Hui L., Yavetz T.D., 2021, Phys. Rev. D, 103, 023508

[3] Dalal N., Bovy J., Hui L., Li X., 2021, J. Cosmology Astropart. Phys., 2021, 076

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