Inferring the Nature of Mass Distribution Near the Galactic Center Black Hole Using Precession of Stellar Orbits

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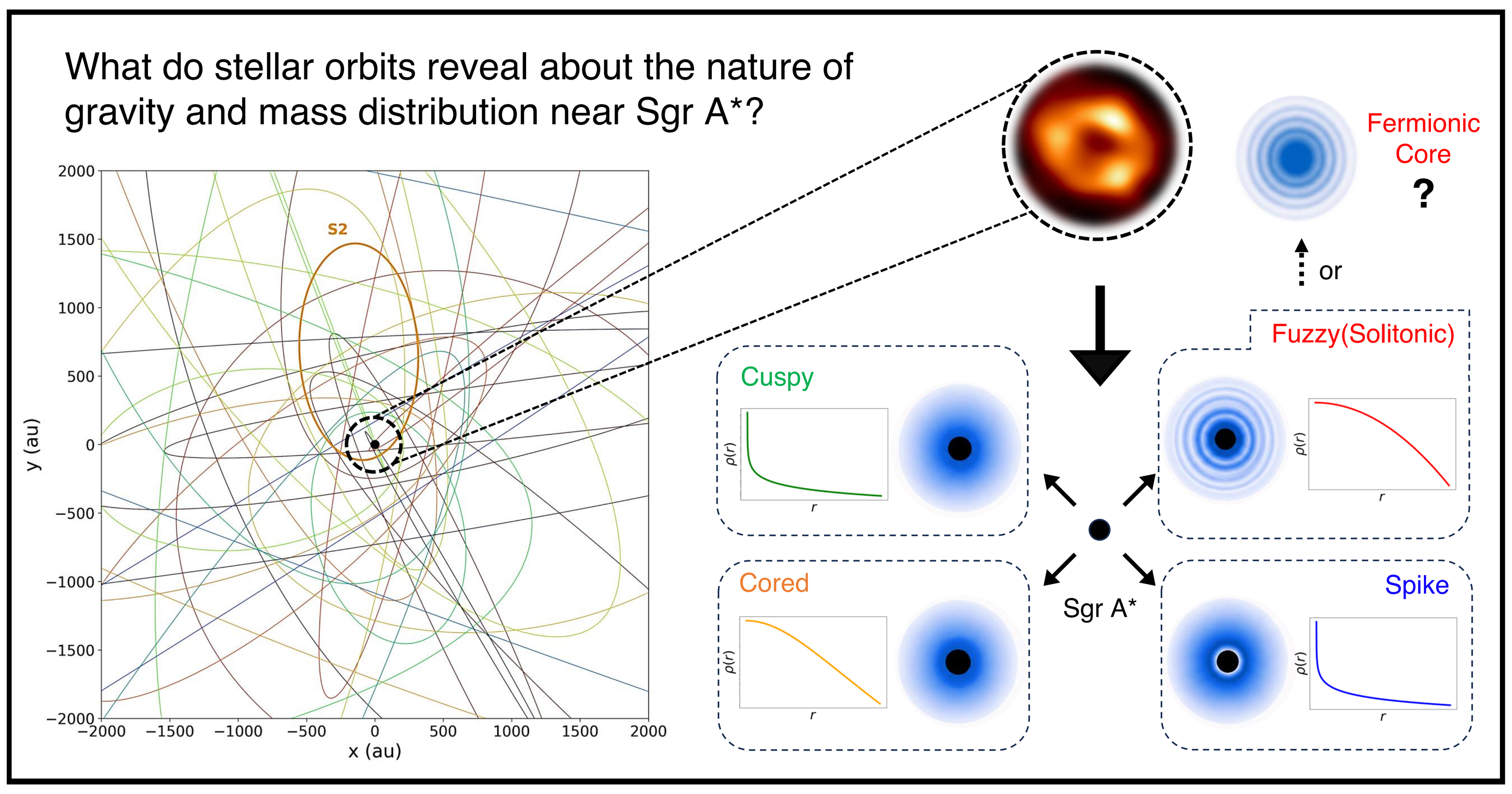
1. Introduction

Gaining insights into the mass distribution near the Galactic Center black hole is crucial for understanding the spacetime structure, formation history of the black hole and its interaction with the surrounding environment.

The stellar orbits near the Galactic Center black hole provide a unique probe:

- for understanding the nature of mass distribution.
- for carrying out tests of gravity.

From the observation of S-stars, any extended mass within the apoapsis of S2 $\lesssim 1200 M_\odot$. (GRAVITY Collaboration et al. 2024)



Conceptual framework of the presented work

2. Methodology

Any extended mass distribution produces a gravitational potential, which has the form

$$\Phi_{ext}(r) = -G\int_r^\infty \frac{M(r')}{r'^2}dr' \qquad (1)$$

This potential acts as a small perturbation to the total potential of the system

$$\Phi_{total}(r) = \Phi_N(r) + \Phi_{ext}(r) \qquad (2)$$

Where, $\Phi_N(r) = -GM/r$. Hence, the perturbed potential can be expressed as,

$$V(r) = \Phi_{total}(r) - \Phi_N(r) = \Phi_{ext}(r) \qquad (3)$$

The rate of precession caused by this perturbed potential is expressed as (Adkins & McDonnell 2007),

$$\boxed{\Delta\theta = -\frac{2L}{GM_{bh}e^2}\int_{-1}^{1}\frac{z\,dz}{\sqrt{1-z^2}}\frac{dv(z)}{dz}} \qquad (4)$$

where, r is related to z as $r = L/1+ez$ and $L = a(1-e^2)$ is the semi-latus rectum of the orbit.

3. Dark matter profiles considered in this work

Cored Profiles

3.1. Plummer Profile

$$\rho(r) = \rho_0\left(1+\frac{r^2}{r_0^2}\right)^{-5/2}$$

3.2. Self Interacting Dark Matter (SIDM)

r^2 Model

$$\rho(r) = \frac{\rho_0 r_0^2}{r^2+r_0^2}$$

r^3 Model

$$\rho(r) = \frac{\rho_0 r_0^3}{r^3+r_0^3}$$

3.3. Fuzzy Dark Matter (FDM)

$$\rho(r) = \frac{\rho_0}{(1+Ar^2)^8}$$

Cuspy Profiles

3.4. Gnedin–Primack Cusp

$$\rho(r) = \rho_0\left(\frac{r}{r_{\rm bh}}\right)^{-3/2}$$

3.5. Bahcall–Wolf Cusp

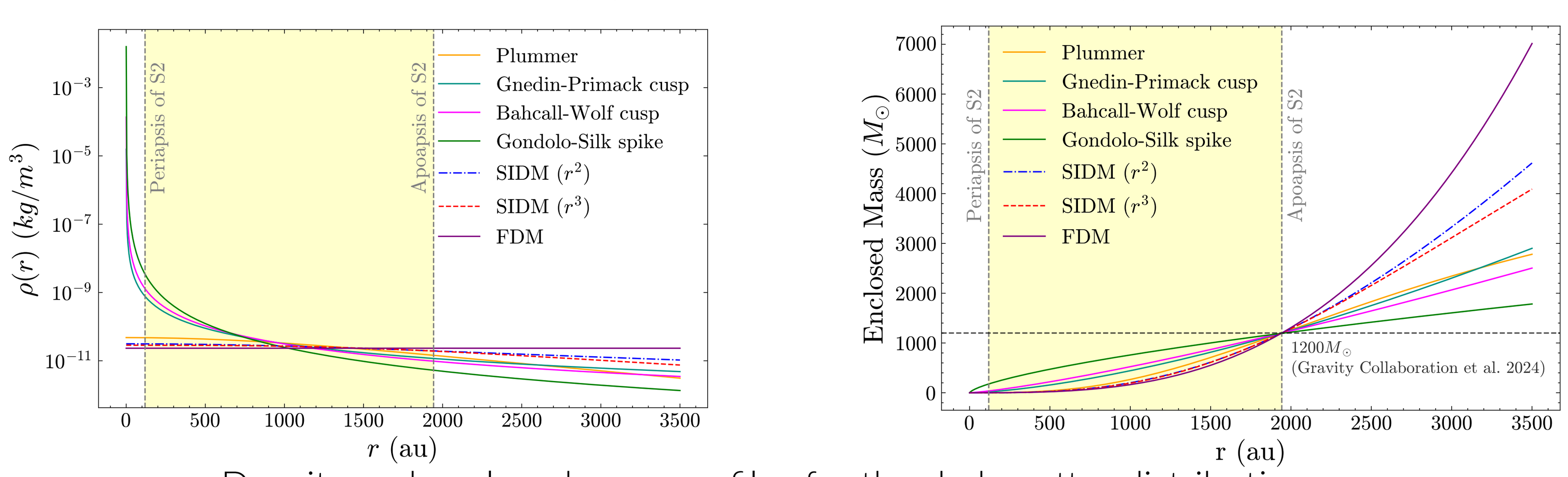
$$\rho(r) = \rho_0\left(\frac{r}{r_0}\right)^{-7/4}$$

Spike Profile

3.6. Gondolo–Silk Spike

$$\rho(r) = \rho_{\rm halo}\left(\frac{R_{\rm sp}}{r}\right)^{\gamma_{\rm sp}}$$

where, $\gamma_{sp} = \frac{9-2\gamma}{4-\gamma} \approx 2.32$ (Z.-Q.Shen et al. 2023)



Density and enclosed mass profiles for the dark matter distributions.

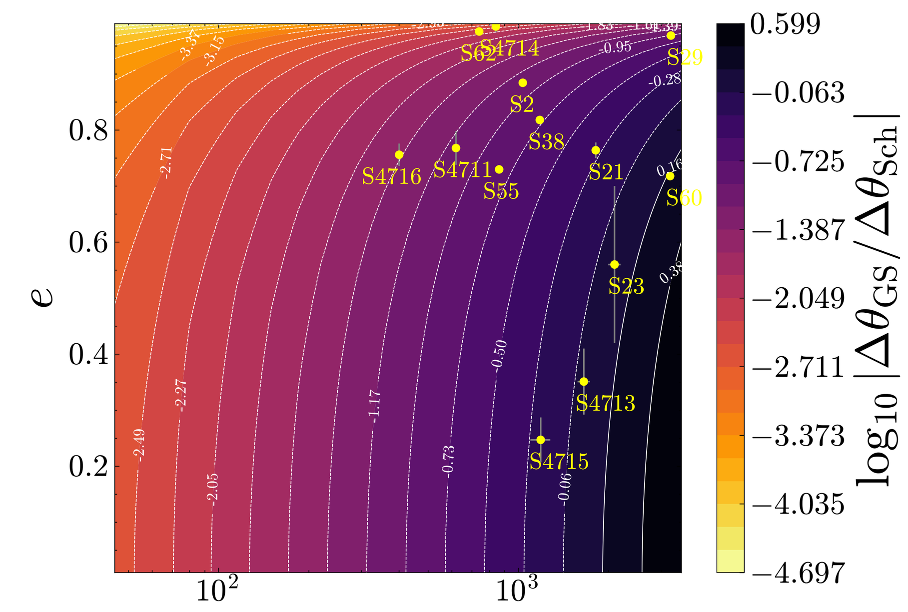
4. Dark matter induced precession

For Gondolo-Silk spike profile (Paul & Kalita 2026),

$$\Delta\theta_{GS} = -\frac{4\pi^2\rho_{\rm halo}(R_{\rm sp})[a(1-e^2)]^{3-\gamma_{\rm sp}}}{M_{\rm bh}} \times {}_2F_1\left(\frac{5-\gamma_{\rm sp}}{2}, 2-\frac{\gamma_{\rm sp}}{2}; 2; e^2\right) \qquad (5)$$

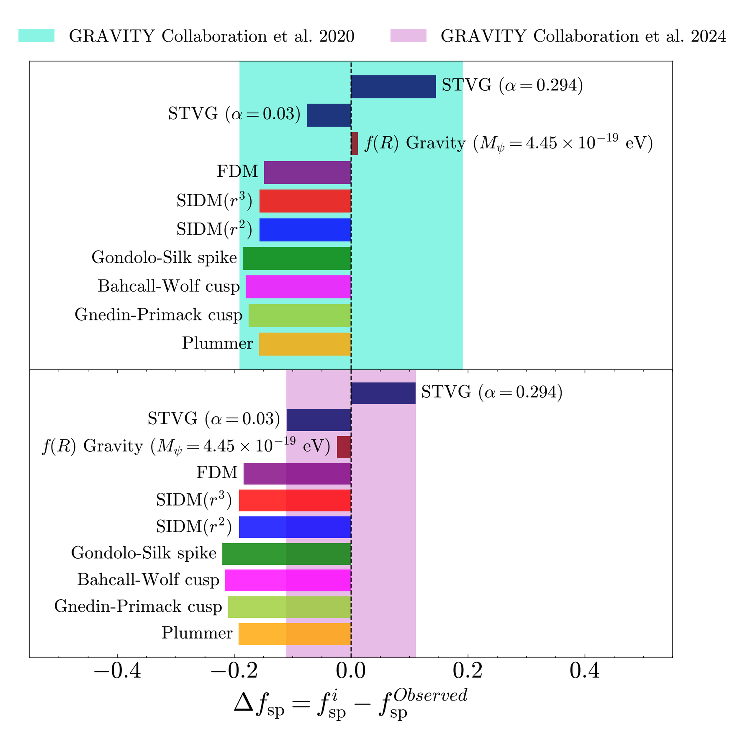
Where, ${}_2F_1(a,b;c;z)$ is the hypergeometric function.

The retrograde precession predicted by this profile is compared with prograde precession induced by GR ($\Delta\theta_{Sch} = 6\pi GM_{bh}/c^2a(1-e^2)$).



The ratio of magnitude of precession per period in different profiles to that of Schwarzschild.

5. Prospects of detection in S2's orbit



The deviation parameter f_{sp} for different DM profiles as well as modified gravity models.

A parameter f_{sp} has been introduced which is related to total precession ($\Delta\theta$) as (GRAVITY Collaboration et al. 2020)

$$\boxed{\Delta\theta = f_{sp}\Delta\theta_{Sch}} \qquad (6)$$

when $f_{sp}=0$ it is purely Newtonian gravity and when $f_{sp}=1$ corresponds to purely Schwarzschild precession. f_{sp} can be expressed as (Paul et al. 2024)

$$\boxed{f_{sp} = 1+\left[\frac{\Delta\theta_i - \Delta\theta_{Sch}}{\Delta\theta_{Sch}}\right]}; \qquad (7)$$

$$\Delta\theta_i = \Delta\theta_{Sch} + \Delta\theta_X$$

Where $\Delta\theta_X$ is the contribution from the different mass profiles/modified gravity.

6. Prospects of detection in S-Star orbits

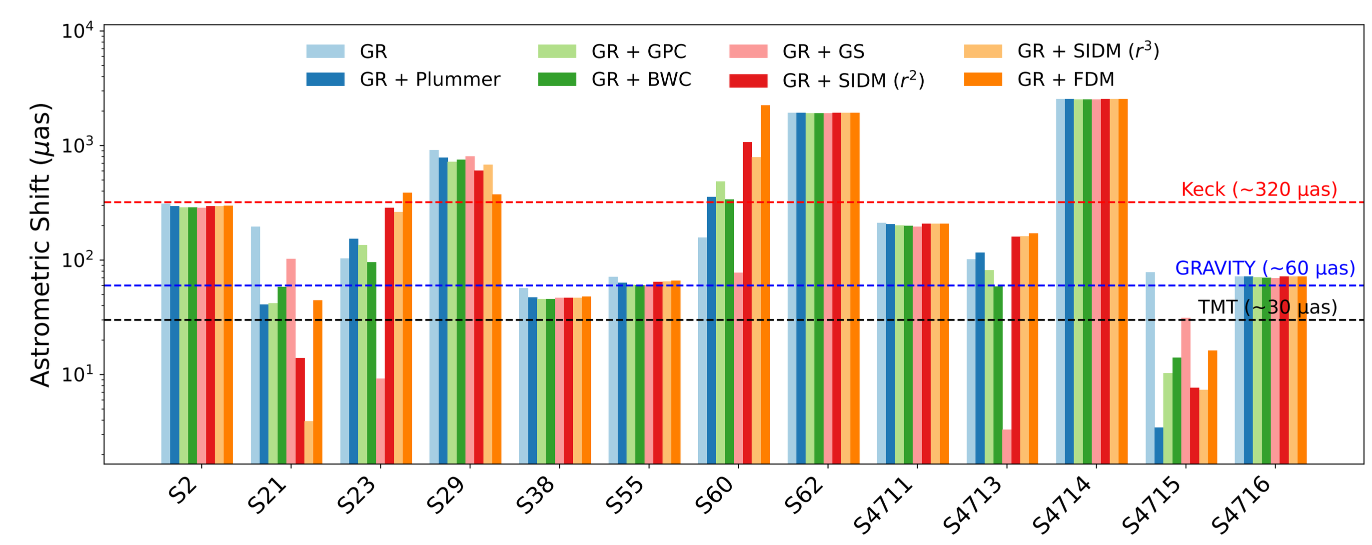
We consider 13 S-stars which have recently crossed or will cross their periapsis within the next decade.

The astrometric shift of the pericenter of any stellar orbit in the sky is estimated as,

$$\boxed{\phi = \Delta\theta \times \frac{a}{D}\sin(i)} \quad (\mu as) \qquad (8)$$

We compare this with: $\phi_{keck} = 320\ \mu as$, $\phi_{GRAVITY} = 60\ \mu as$ and $\phi_{TMT=30\ \mu as}$

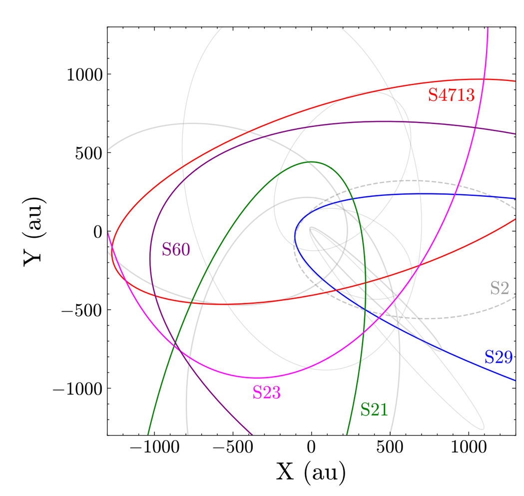
(Hees et al. 2017,Zakharov 2018,GRAVITY Collaboration et al. 2018).



Astrometric shift of S-star orbits induced by different DM profiles.

7. Summary and Furture Prospects

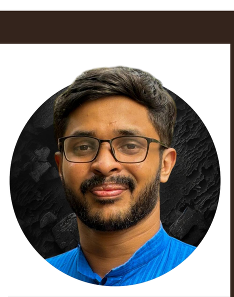
- S2's orbit is a reliable probe for testing modified gravity but not dark matter.
- We identify five S-star orbits: S21, S23, S29, S60 & S4713 as promising probes to distinguish dark matter profiles.
- Low-eccentricity & wider S-star orbits are prominent probes of dark matter–induced precession for current and upcoming facilities.



DM sensitive S-star orbits.

Future Work:

Can we detect signatures of the unknown mass from EHT shadow measurements (test of metric)?



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