Constraining regular black holes with S2 star data

Speaker: Mauro Oi

Based on: [arXiv:2211.11585]

In collaboration with:
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Why regular black holes?

Observations are compatible with the presence of Kerr black holes

[EHT Collaboration (2019) & (2022)]
[LIGO and Virgo Collaborations (2016)]
[C. Bambi (2011)]
[A. Tripathi et al. (2022)]

GR black holes are, however, endowed with an inevitable singularity at their core

[R. Penrose (1965)]
[S. W. Hawking and R. Penrose (1970)]

A (still lacking) convincing quantum theory of gravity is expected to solve the singularity

Why regular black holes?

[J. M. Bardeen (1968)]
[S. A. Hayward (2006)]
[E. Franzin et al. (2022)]
[A. Simpson and M. Visser (2019) – (2022)]

Bottom-up approach: build regular metrics and check their phenomenology

No underlying theory!

[I. De Martino et al. (2021) – (2022)]
[EHT Collaboration (2022)]
[Z. Younsi et al. (2016)]

Can be tested with orbits and imaging

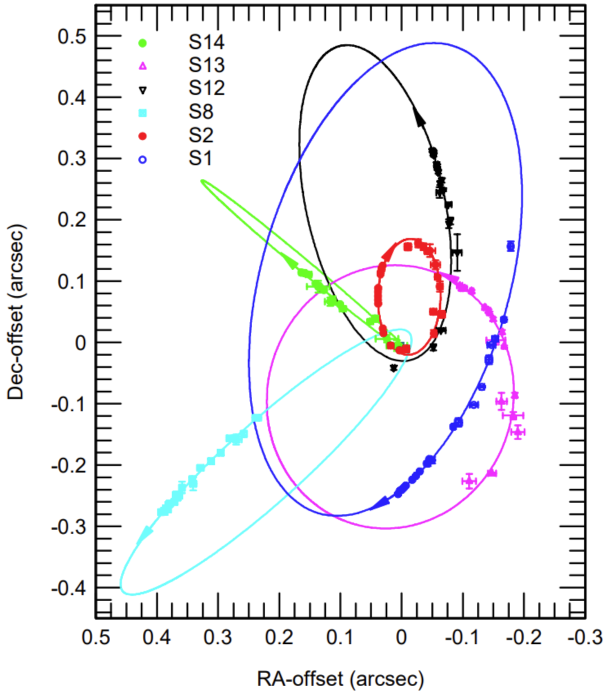
Why S2 star data?

[F. Melia and H. Falcke (2001)]
[R. Genzel et al. (2010)]

The galactic center exhibits the presence of a point-like supermassive source (Sgr A*)

Observations are compatible with the presence of a supermassive black hole

The motion of the S2 star can been used to constrain different models (modified gravity, wormholes, RBHs)



[F. Heisenhauer et al. (2005)]

[M. De Laurentis et al. (2018)]
[I. De Martino et al. (2021)]
[R. Della Monica et al. (2021)]
[M. Guerrero et al. (2021)]
[K. Jusufi et al. (2021)]

The model

$$ds^2 = -f(r)dt^2 + f^{-1}(r)dr^2 + r^2 d\Omega^2$$

We start from a spherically symmetric ansatz (spin corrections are negligible)

$$f(r) = 1 - \frac{2GMr^2}{(r+\ell)^3}$$

$$f(r \to 0) \simeq 1 - \frac{2GM}{\ell}\frac{r^2}{\ell^2}$$

$$f(r \to \infty) \simeq 1 - \frac{2GM}{r} + \frac{6GM}{\ell}\frac{\ell^2}{r^2}$$

We require a de Sitter core, and we look for the strongest corrections to the Schwarzschild metric at $r \gg GM$

It belongs to a more general class of RBH models, and can also be derived from nonlinear-electrodynamics

[M. Cadoni, **MO**, A. P. Sanna (2022)]
[C. Lang and Y.-F. Lang (2022)]

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Additional length scale

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[M. Cadoni, **MO**, A. P. Sanna (2022)]
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The model – horizons

The horizons are located at $f(r) = 0$

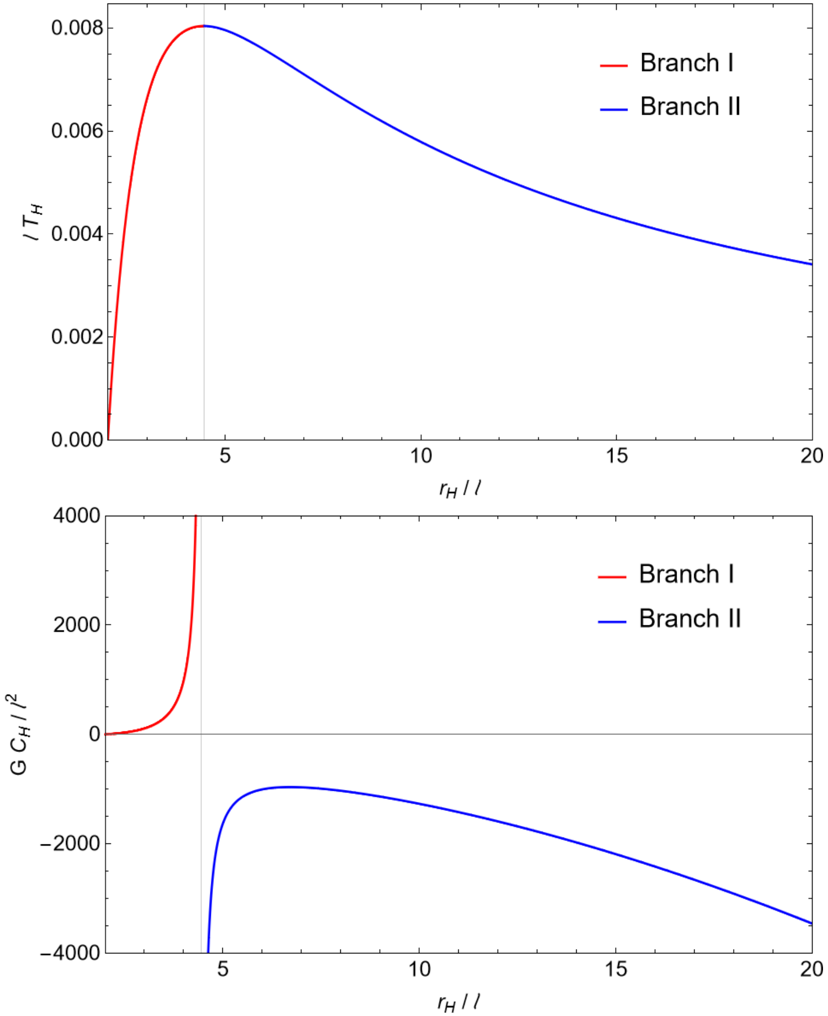
There exist a critical value ℓ_c

$\ell < \ell_c$: two horizons
$\ell = \ell_c$: extremal, two coinciding horizons
$\ell > \ell_c$: no horizons

$$f(r) = 1 - \frac{2GMr^2}{(r+\ell)^3}$$

$$\ell_c = \frac{8}{27}GM \to r_{H,extr} = 2\ell_c$$

Thermodynamical analysis



The thermodynamical behavior is common to the general class of dS-core RBHs the model belongs to

[M. Cadoni, **MO**, A. P. Sanna (2022)]

Configurations with $0.245GM < \ell < \ell_c$ (Branch I) are thermodynamically stable

Orbits

The orbits can be studied using standard methods

$$\dot{r}^2 + f(r)\left(\epsilon^2 + \frac{L^2}{r^2}\right) = E^2$$

Three conserved quantities:
Angular momentum L
Energy E
$\epsilon = 0, \pm 1$

$$\xi''(\phi) + \xi(\phi) - 1 = \sigma\left[3\xi^2(\phi) - 6\tilde{\ell}\xi(\phi)\right]$$

$$\sigma = \left(\frac{GM}{L}\right)^2, \qquad \xi = \frac{GM}{\sigma}\frac{1}{r}, \qquad \tilde{\ell} = \frac{\ell}{GM}$$

Correction to orbital precession!

$$\Delta\phi_{prec} \simeq \sigma(1 - \ell/GM)$$

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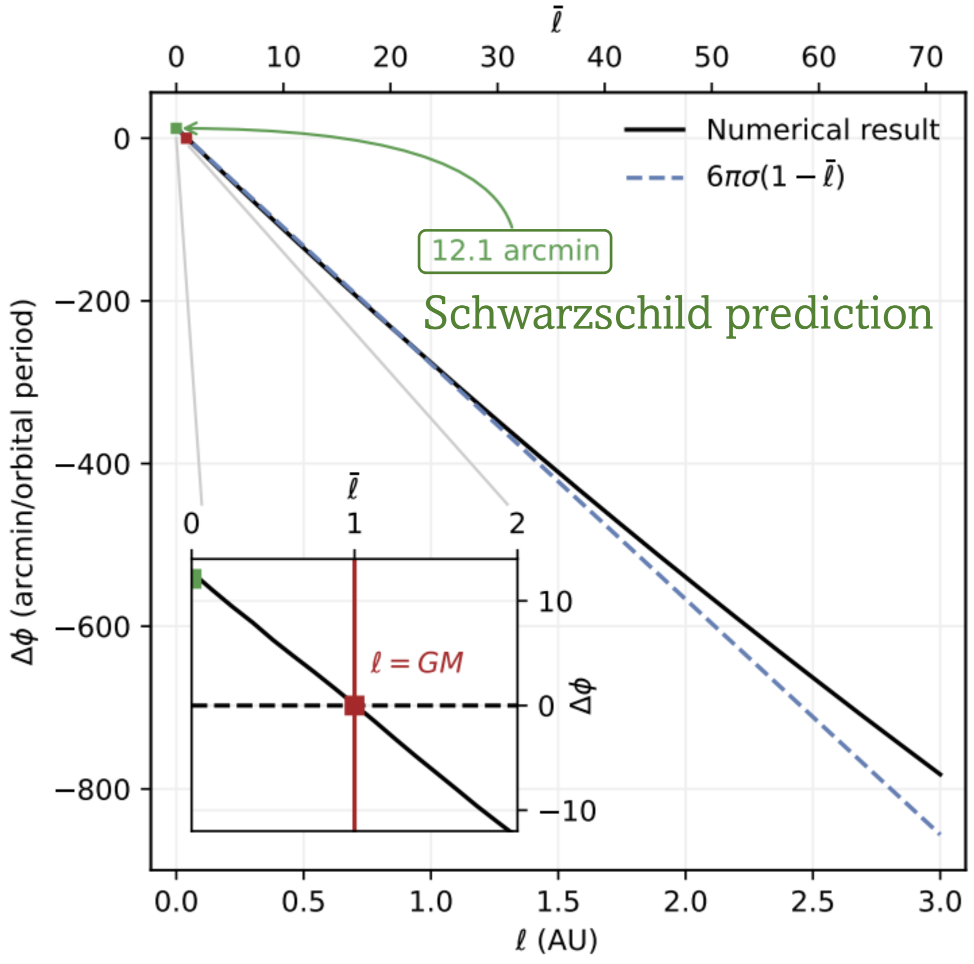
Testing the metric with S2 orbits



We can recast the energy and the angular momentum in terms of the classical Keplerian elements (a, e, T)

We numerically confirm the theoretical prediction for $\Delta\phi_{prec}$

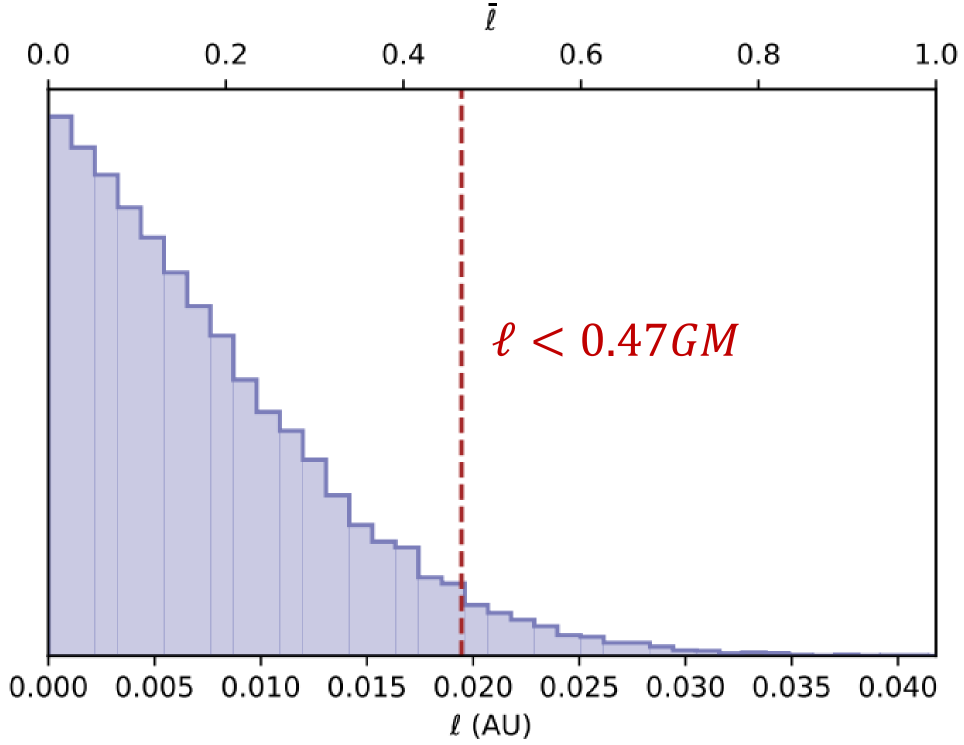
Testing the metric with S2 orbits

We exploited publicly available near/infrared astrometric positions and radial velocities and GRAVITY precession measurement

[I. De Martino et al. (2021)]
[GRAVITY Collaboration (2020)]

We have been able to cast an upper bound $\ell < 0.47GM$ at 95% c.l., keeping all the other parameters within 1σ from known results

The upper bound does not exclude thermodynamically-stable configurations



Conclusions

We developed a regular black-hole model, and we studied its phenomenological properties

The proposed spacetime has the strongest possible corrections w.r.t Schwarzschild at great distances

We tested the model with S2-star orbits obtaining an upper limit $\ell < 0.47GM$ at 95% c.l.

We expect to improve our upper limit on ℓ of roughly a factor 10

Thanks for your attention!