Constraining Scalar-Tensor gravity models by S2 star orbits around the Galactic Center

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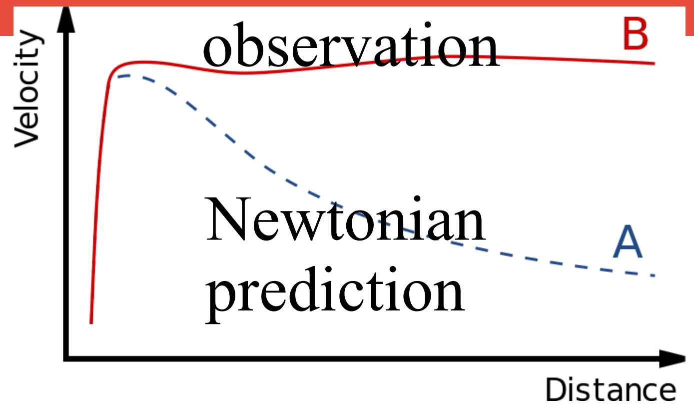
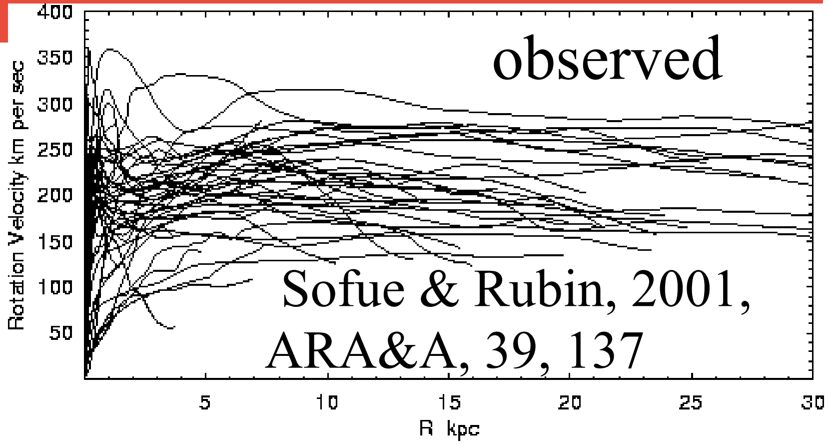
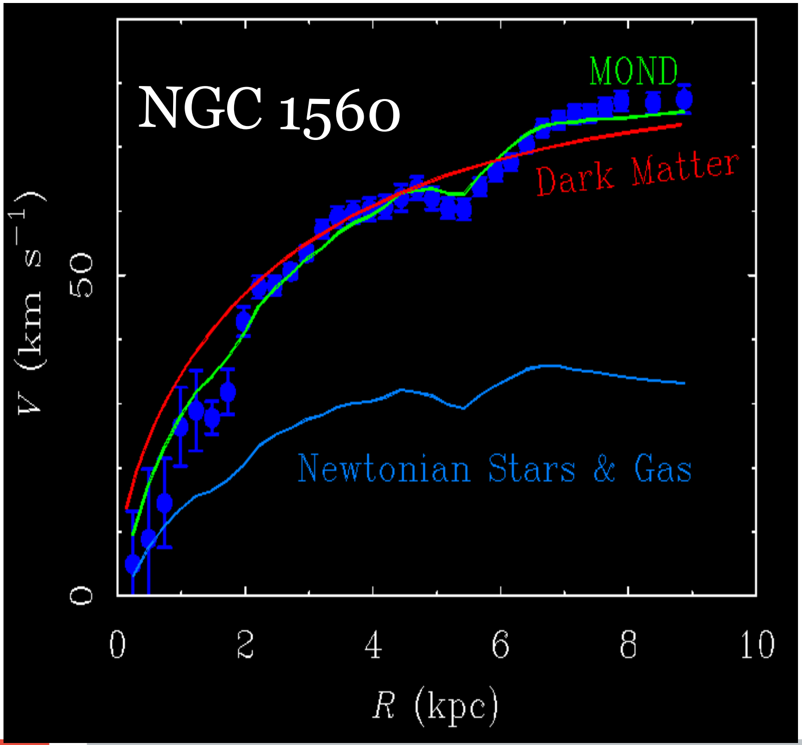
Outline of the talk

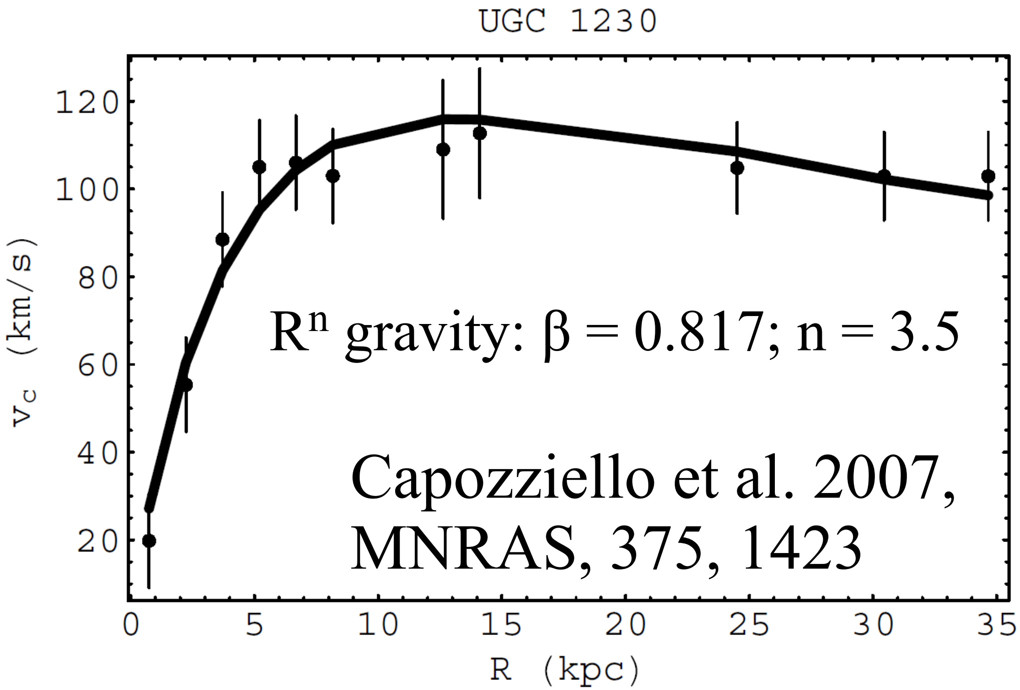
- Object and goal: to test Scalar-Tensor (ST) gravity models using kinematics of S-like stars
- Motivation: using ST gravity, as well as the other modifications of standard Einstein's gravity, some observed phenomena may be explained without dark matter and dark energy
- Data: NTT/VLT telescope, Gillessen et al., ApJ 692, 1075 (2009)
- Method: ST is analyzed using observed orbits of S-stars around Galactic Center and also using two-body simulations
- Results: we review the various consequences of the ST gravity parameters on stellar dynamics and investigate their constraints from the observed S-star orbits
- Conclusions
- References

Modified gravity and rotation curves of spiral galaxies









Scalar-Tensor (ST) theory of gravity

- both the metric tensor $g_{\mu\nu}$ and a fundamental scalar field φ are involved
- it contains two arbitrary functions of the scalar field: the coupling $F(\varphi)$ and the interaction potential $V(\varphi)$

$F(\varphi)$ – underlines a non-minimal coupling between the scalar field and the geometry

$V(\varphi)$ – implies a self-interaction of the field

In our study we take the action of the form:

$$S = S_M + \frac{1}{2\kappa^2} \int d^4x \sqrt{-g} [F(\phi) R + \frac{3}{2\phi} g^{\mu\nu} \phi_{,\mu} \phi_{,\nu} - V(\phi)].$$

We choose a specific form for $F(\varphi) = \xi\varphi^m$, $V(\varphi) = \lambda\varphi^n$, where ξ is a coupling constant, λ gives the self-interaction potential strength, m and n are arbitrary parameters (S. Capozziello, R. de Ritis, C. Rubano, P. Scudellaro, *La Rivista del Nuovo Cimento* 19, 1 (1996)).

Parameters of ST gravity

The ST gravitational potential in the weak field limit can be written in the form (D'Addio et al. 2018 & Gravina et al. 2018, in Publ. AOB):

$$U_{ST} = \frac{\widetilde{G}}{\xi\varphi_0^m}\frac{M}{r} - \frac{\lambda}{4\xi}\varphi_0^{n-m}r^2 - \frac{\widetilde{G}m^2M}{3(1-m^2\varphi_0^{m-1}\xi)}\frac{e^{-pr}}{r}.$$

Parameters:

ξ - a coupling constant

λ - parameter which gives the self-interaction potential strength

m,n - arbitrary integer numbers, for which it stands: $n \neq 2m$, $n \neq 0$

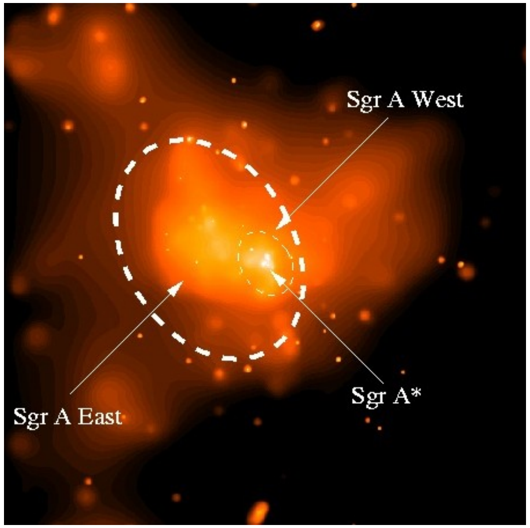
p - function of the ST gravity parameters ξ, λ, m, n

φ_0 - positive real number, close to 1

In order to constrain these parameters observationally, we simulated orbits of S2 star in the modified gravitational potential, and then we compared the results with the set of S2 star observations obtained by the Very Large Telescope (VLT).

S2 star orbits in ST and Newtonian potential

The massive black hole Sgr A* at the Galactic center is surrounded by a cluster of stars orbiting around it: S-star cluster.
S2 star is one of the brightest among S-stars, with the short orbital period and the smallest uncertainties in determining the orbital parameters: a good candidate for this study.



- we compare the obtained theoretical results for S2-like star orbits in the ST potential with the available set of observations of the S2 star

- we draw orbits of S2 star in ST and Newtonian potential.

Modified: $\Phi_{ST}(r) = C_1 \cdot (1/r) + C_2 \cdot r^2 + C_3 \cdot exp(-p \cdot r)/r$

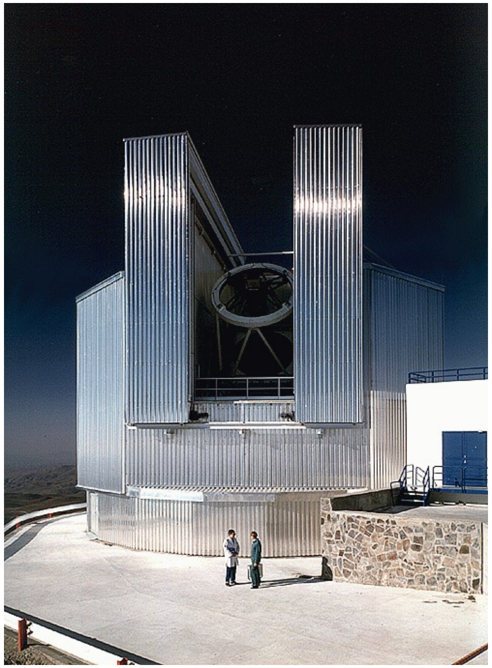
$C_1 = C_1(\xi, m)$, $C_2 = C_2(\xi, \lambda, m, n)$, $C_3 = C_3(\xi, m)$, $p = p(\xi, \lambda, m, n)$

Newton: $\Phi_N(r) = - GM/r$

Observations and method

- observations collected between 1992 and 2008 at the ESO (European Southern Observatory): NTT/VLT optical telescopes
- data publicly available as the supplementary online data to the electronic version of paper Gillessen et al., ApJ 692, 1075 (2009)

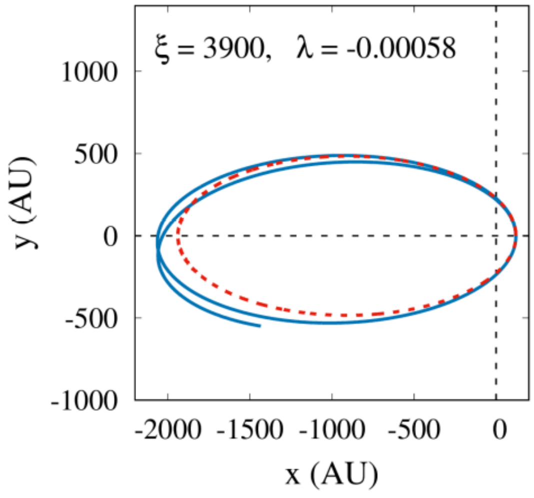
New Technology Telescope (3.6 m) *La Silla Observatory, Chile*

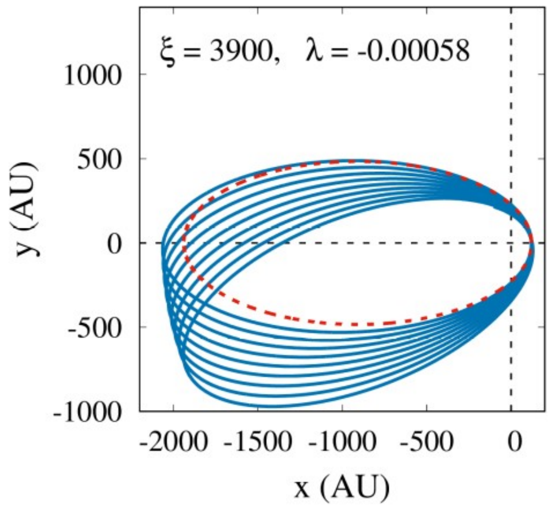


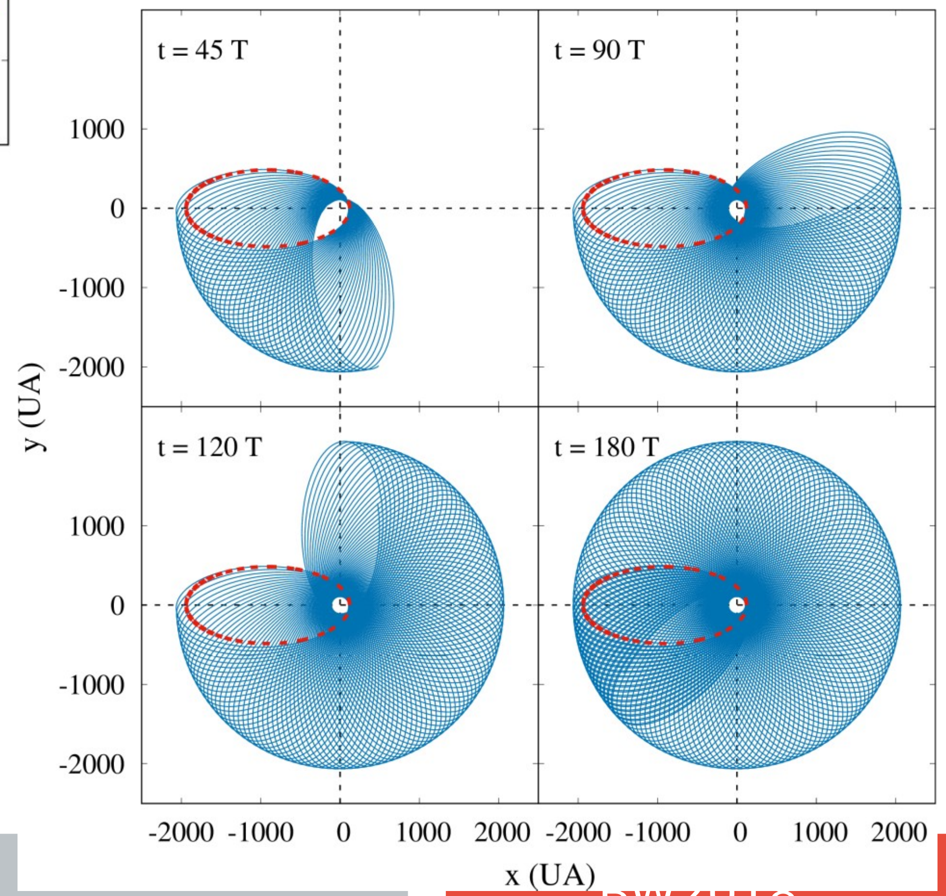
Very Large Telescope (4 x 8.2 m) *Paranal Observatory, Chile*

- we performed two-body simulations in the ST gravity potential

Results I: simulated orbits of S2 star in ST gravity



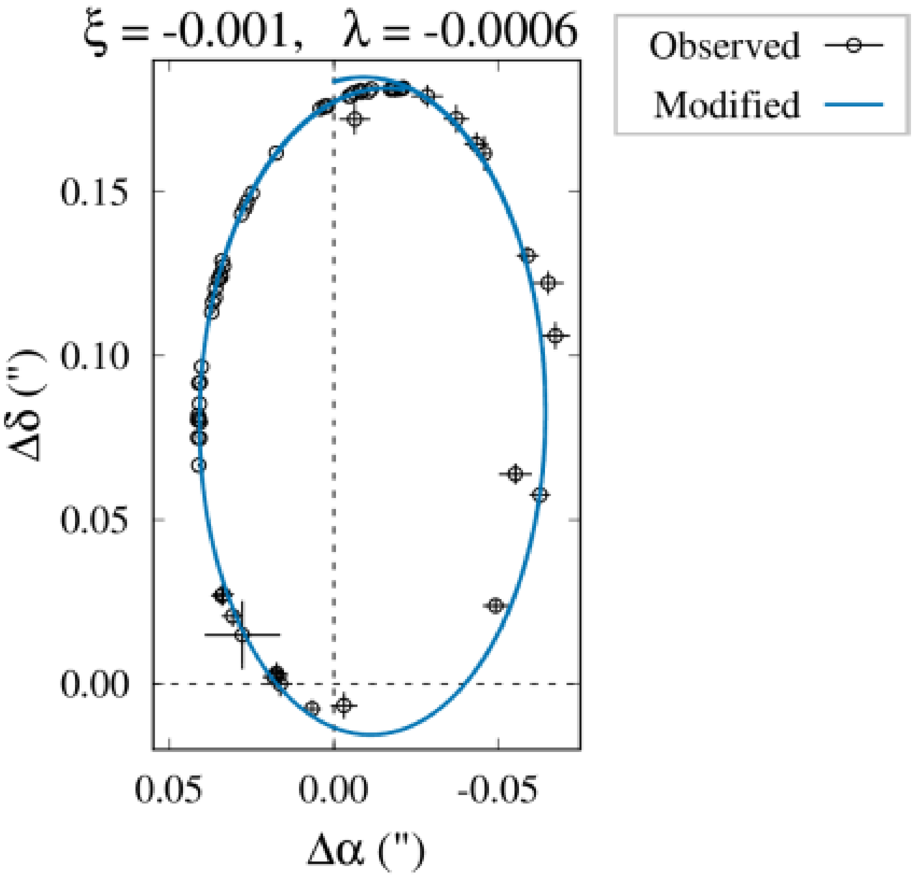




Comparison between the orbit of S2 star in Newtonian and ST potential during t = 2 T, t = 10 T and more orbital periods (t = 45, 90, 120 and 180 T).

- positive precession (as in GR)
- prograde shift that results in rosette-shaped orbits

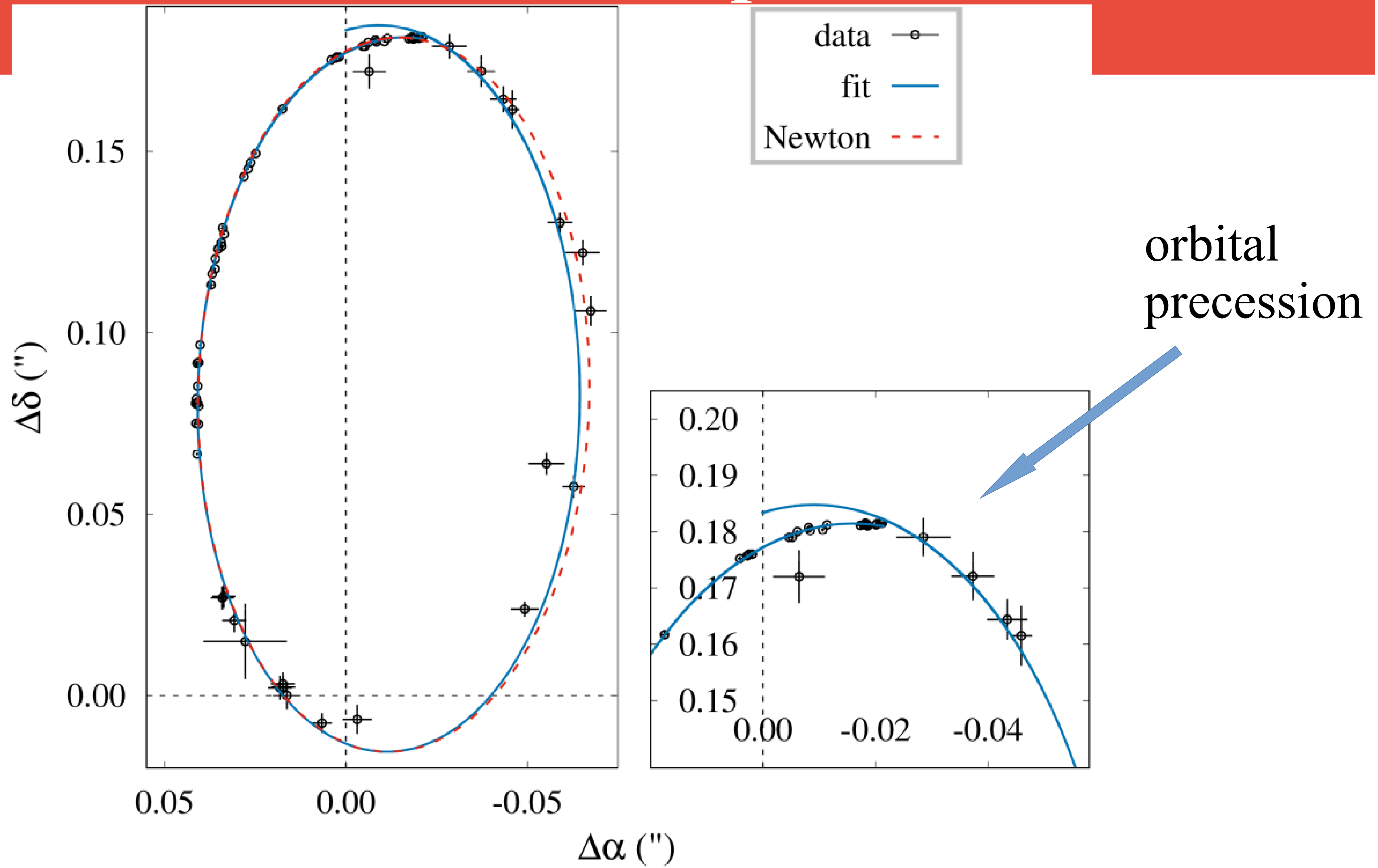
Results II: comparison between the simulated and observed orbits of S2 star



$m = 2, n = 3$

- we calculate the positions of S2 star in the orbital plane (the true orbit) by the numerical integration of equations of motion
- then we project the true orbit to the observed plane (the apparent orbit)
- discrepancy between the simulated and the observed apparent orbit is estimated by the reduced χ^2

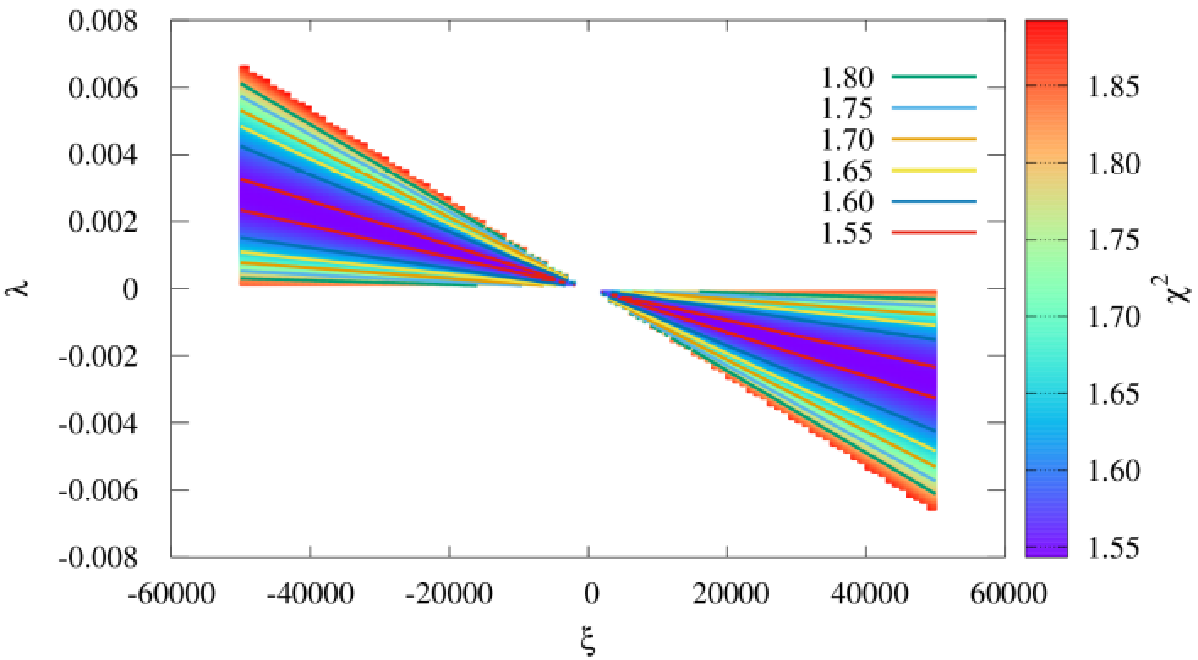
Results III: orbital precession



The comparison of the fitted orbit of S2 star and astrometric observations: $(m,n) = (2,3)$ and $(\xi,\lambda)=(-1000, 0.0006)$.

Results IVa: constraints on ST gravity parameters

- we chose some values for (m,n), and vary the parameters (ξ,λ) over some intervals, and search for those solutions which for the simulated orbits in ST gravity give at least the same (χ^2 =1.89) or better fits (χ^2 <1.89) than the Keplerian orbits
- we repeat the procedure for different combinations (m,n) $\rightarrow$ [1,10]



- for chosen:
  $\varphi_0 = 1$
  $m = 1$, $n = 4$,

parameters of the best fit are:

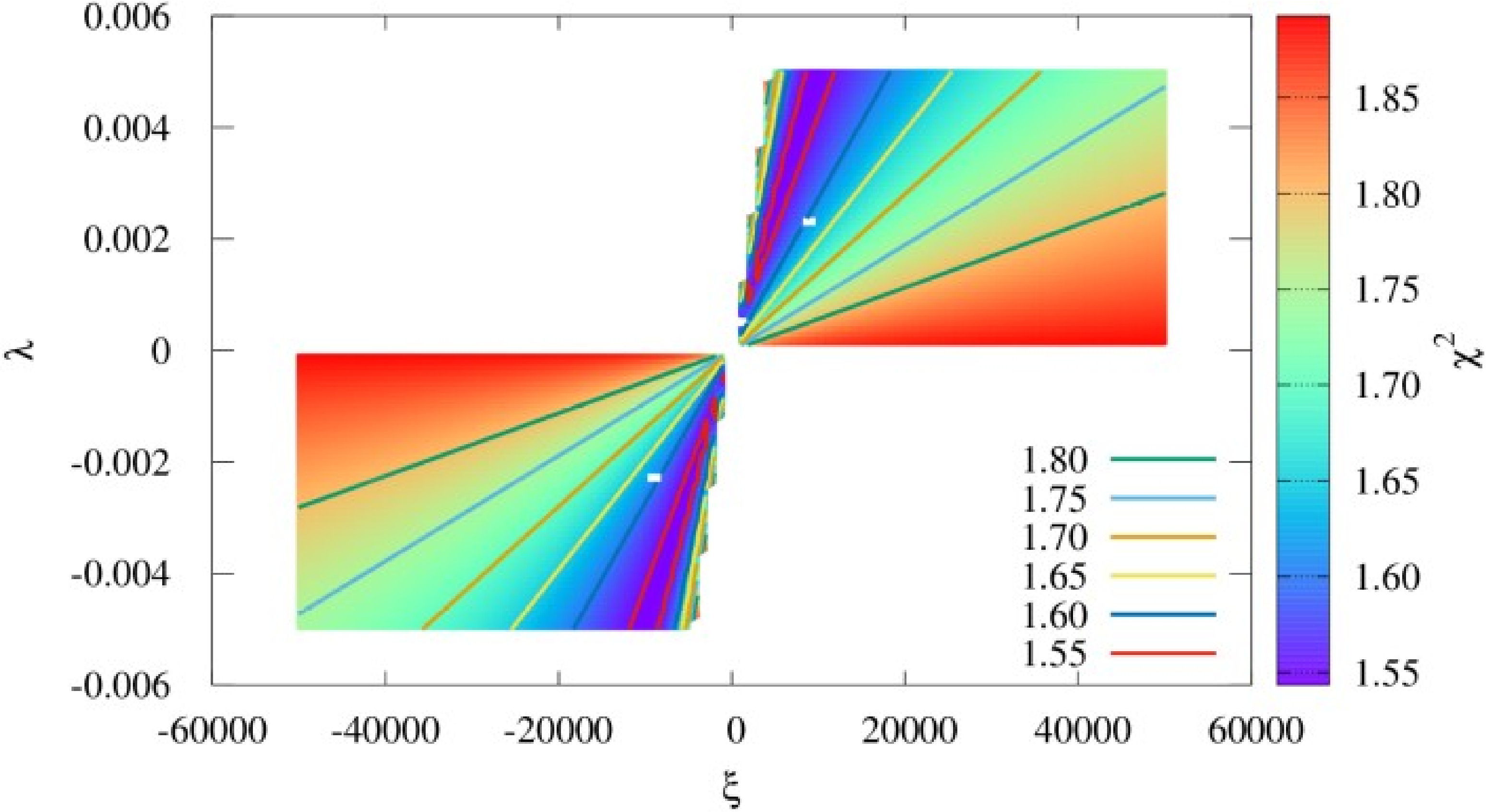
$\chi^2_{min} = 1.54$

$\xi\_{min} = 43000$

$\lambda\_{min} = -0.0024$

The map of the reduced χ^2 over the parameter space (ξ,λ) of ST gravity.

Results IVb: constraints on ST gravity parameters

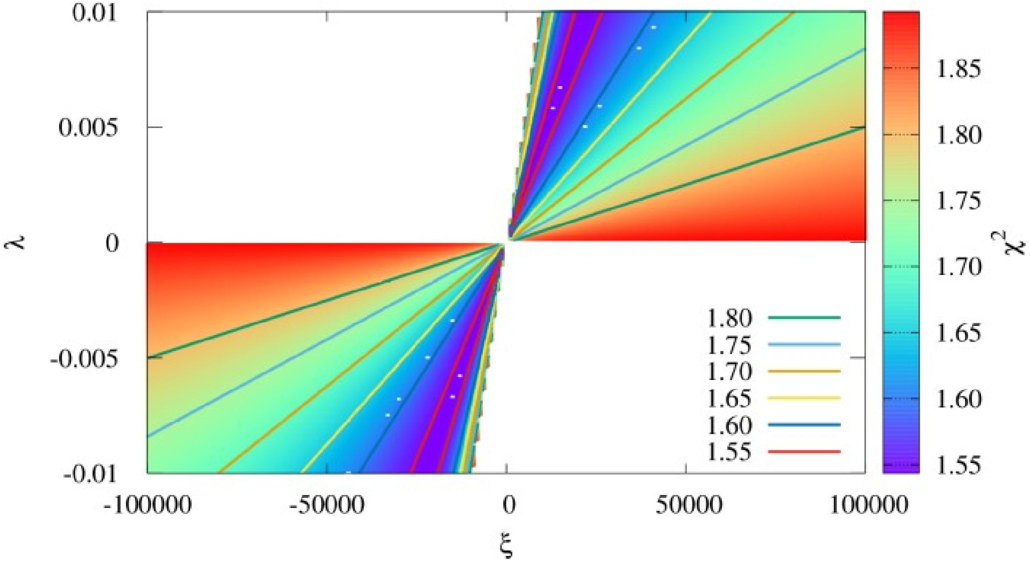


(*m*,*n*) = (3,4) $\chi^2_{min} = 1.54$; $\xi\_min = 1000$; $\lambda\_min = 0.0005$

Note: χ^2_{min} – minimal value

ξ_min, λ_min – not minimal, but the most probable values

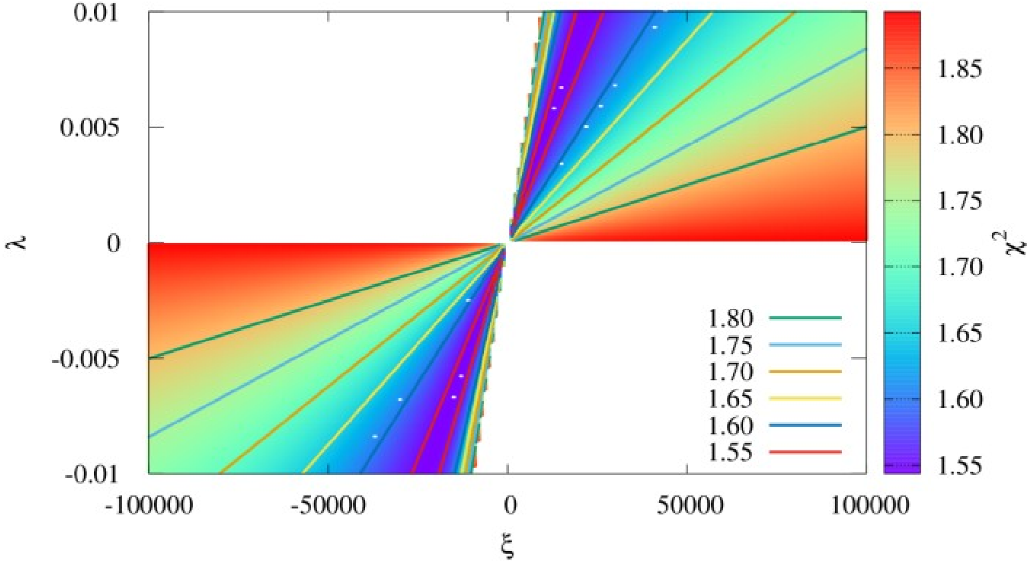
IVc: constraints on ST gravity parameters



(*m*,*n*) = (4,4)

χ^2_{min} = 1.54;

ξ_{min} = 15000; λ_{min} = 0.0067



(*m*,*n*) = (10,10)

χ^2_{min} = 1.54;

ξ_{min} = -15000; λ_{min} = -0.0067

$m = n$:

$\xi_{min,1} = \xi_{min,2}$, $\lambda_{min,1} = \lambda_{min,2}$

Results V: best fit values for ST gravity parameters

χ^2	m	n	ξ	λ
1.5434350	1	1	13000	0.0058
1.5434440	1	3	43000	-0.0064
1.5434426	1	4	43000	-0.0024
1.5434345	2	1	16000	0.0095
1.5434352	2	2	15000	0.0067
1.5434474	2	3	-1000	-0.0006
1.5434336	3	1	1000	0.0008
1.5434383	3	2	1000	0.0005
1.5434352	3	3	15000	0.0067
1.5434383	3	4	1000	0.0005
1.5434317	4	1	4000	0.0041
1.5434478	4	2	-1000	-0.0006
1.5434348	4	3	21000	0.0100
1.5434353	4	4	15000	0.0067
…	…		…	
1.5434353	10	10	-15000	-0.0067

$$\varphi_0 = 1$$
$$(m,n) \rightarrow [1,10] \quad n \neq 2m$$

With the parameter space $\{\xi,\lambda\}$ determined in this way, we calculate the simulated orbits, and then compare them with the observations.
In that way, our results enable us to test Scalar Tensor Theory at galactic scales.

Conslusions

✔ We derived a particular theory among the class of Scalar Tensor theories of gravity, and then tested it by studying dynamics of S2 star around supermassive black hole at Galactic Center.

✔ Using the observed positions of S2 star around the GC, we constrained the parameters of ST gravitational potential.

✔ To constrain these parameters, we compare the observed orbit of S2 star with our simulated orbit which we obtained theoretically with the derived potential.

✔ We obtained the most probable values for parameters λ and ξ, for different parameters m and n, and they fit better astronomy data than Keplerian orbit.

Conslusions II

✔ The precession of S2 star orbit obtained for the best fit parameter values has the positive direction (as in General Relativity).

✔ We obtained much larger orbital precession of the S2 star in ST gravity than the corresponding value predicted by general relativity.

✔ The approach we are proposing can be used to constrain the different modified gravity models from stellar orbits around Galactic Center.

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