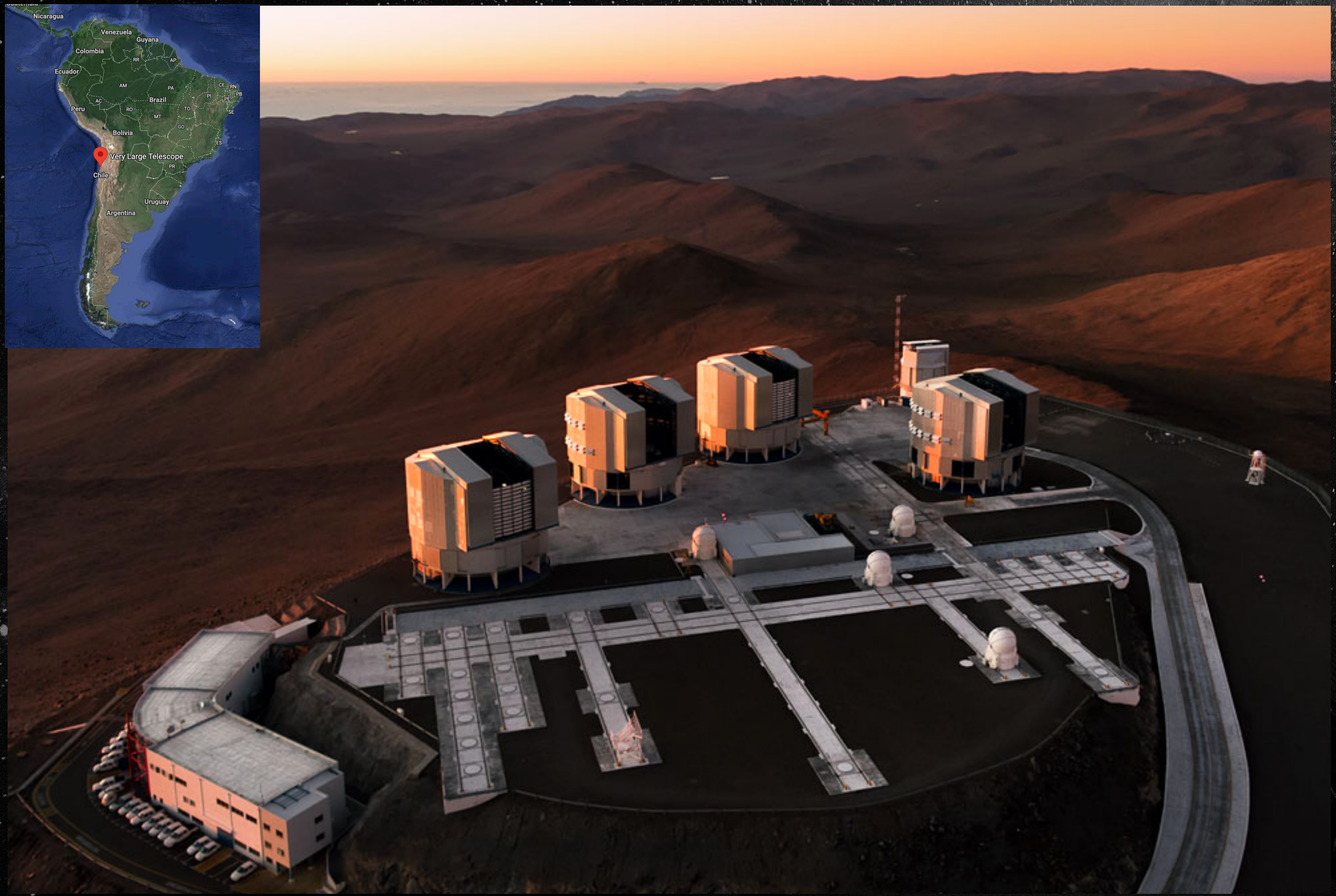
The Galactic center with GRAVITY(+) and the ELT: what can we learn before LISA flies?

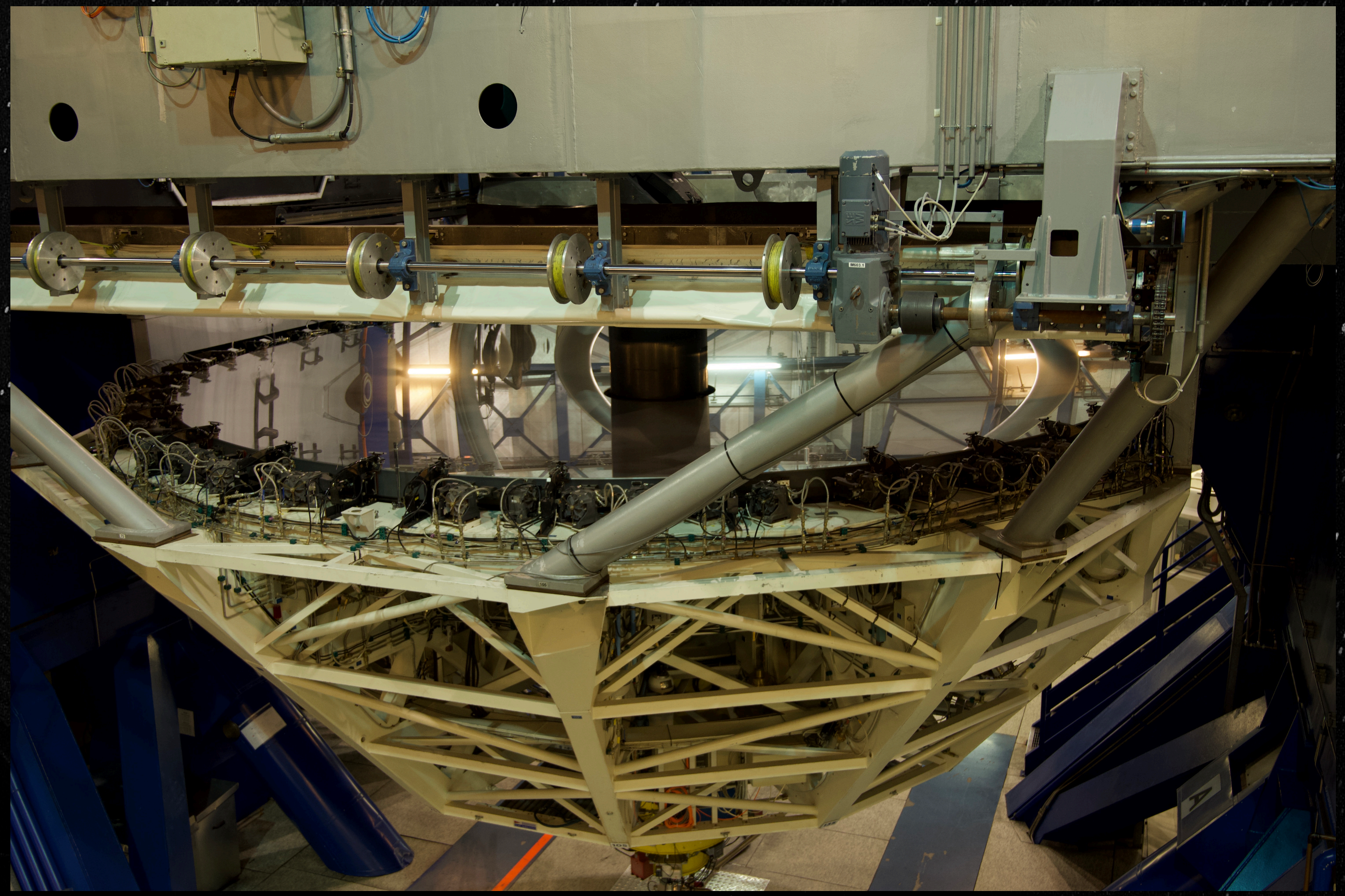
Matteo Sadun Bordoni
Max Planck Institute for Extraterrestrial Physics
GRAVITY Collaboration

"Ten years to LISA",
JPL, Pasadena, April 3rd 2025

The GRAVITY interferometer

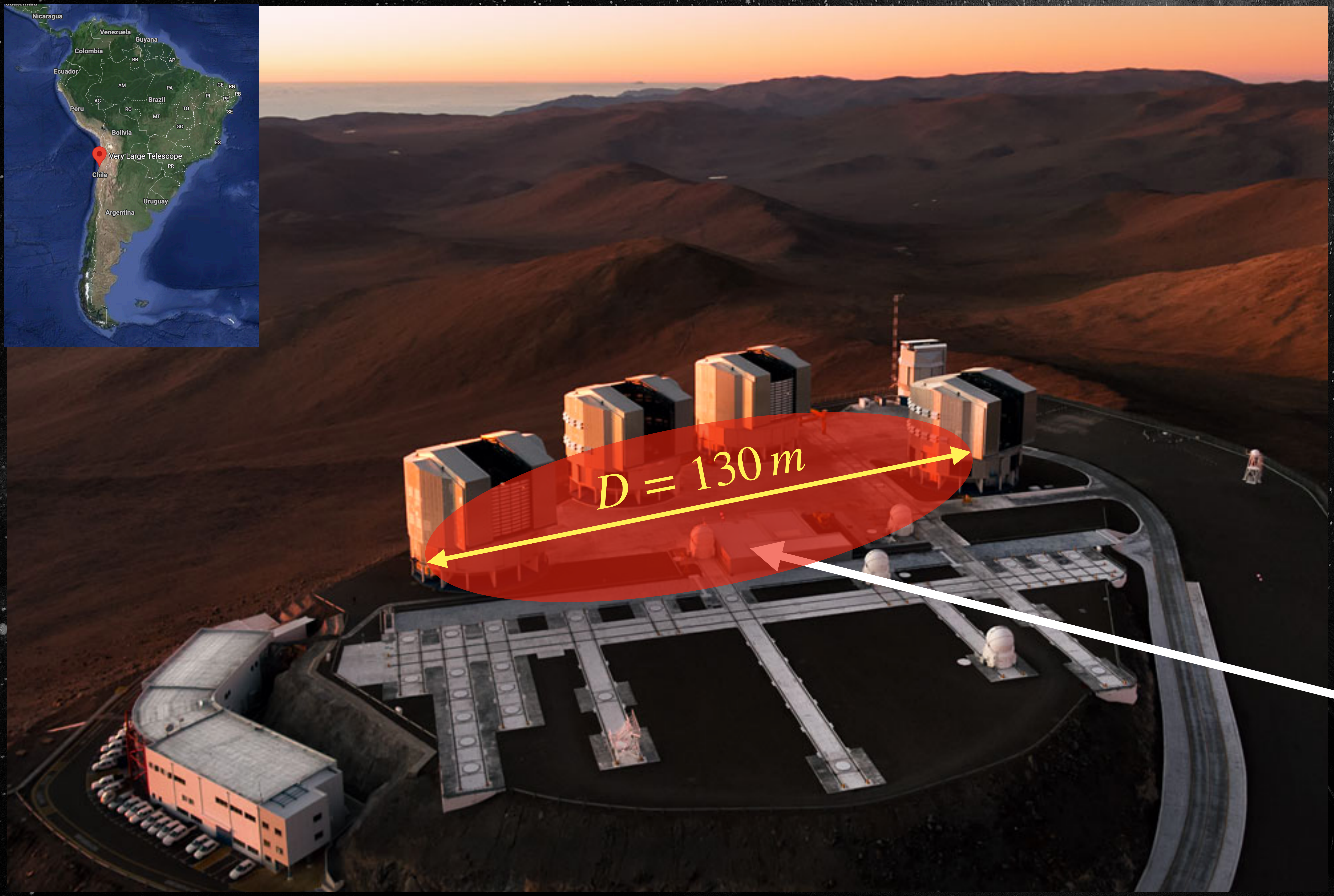


Very Large Telescope Interferometer (VLTI),
Paranal Observatory



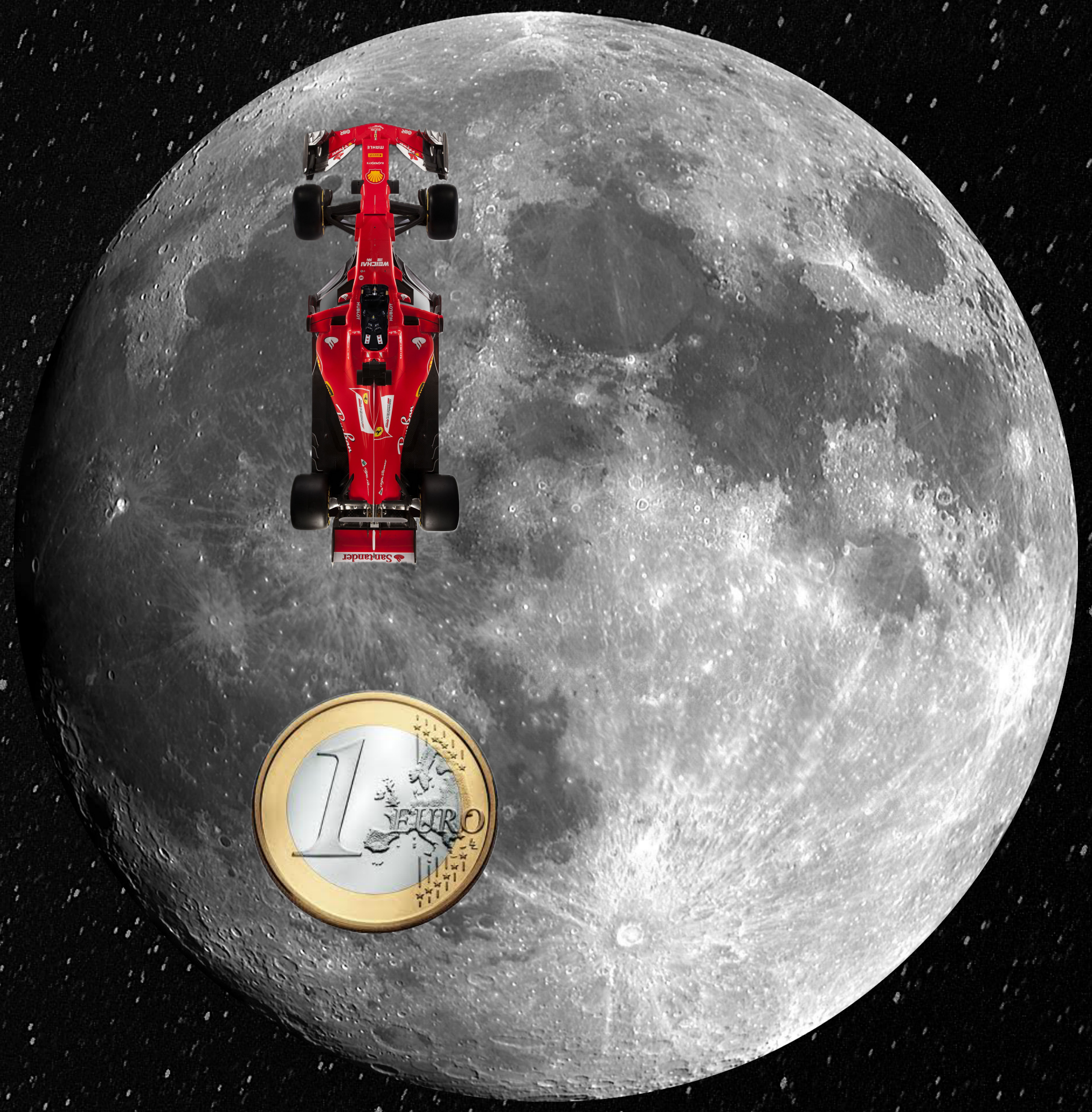
Primary mirror of each telescope:
diameter of 8.2 meters

The GRAVITY interferometer



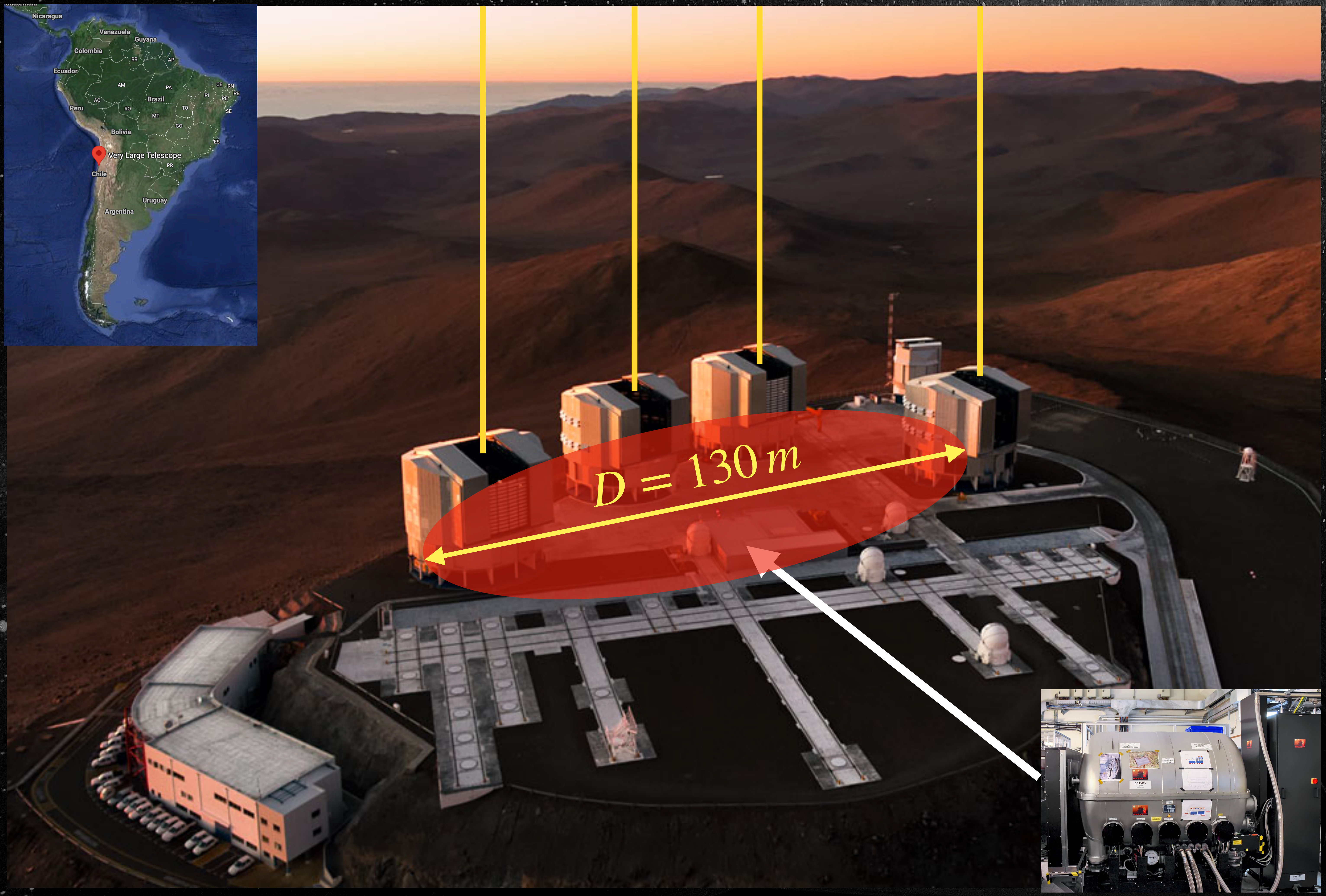
Very Large Telescope Interferometer (VLTI),
Paranal Observatory

- 4 mas angular resolution
- $30\,\mu as$ astrometric accuracy



GRAVITY, Near-Infrared Interferometer

The GRAVITY+ interferometer



Very Large Telescope Interferometer (VLTI),
Paranal Observatory

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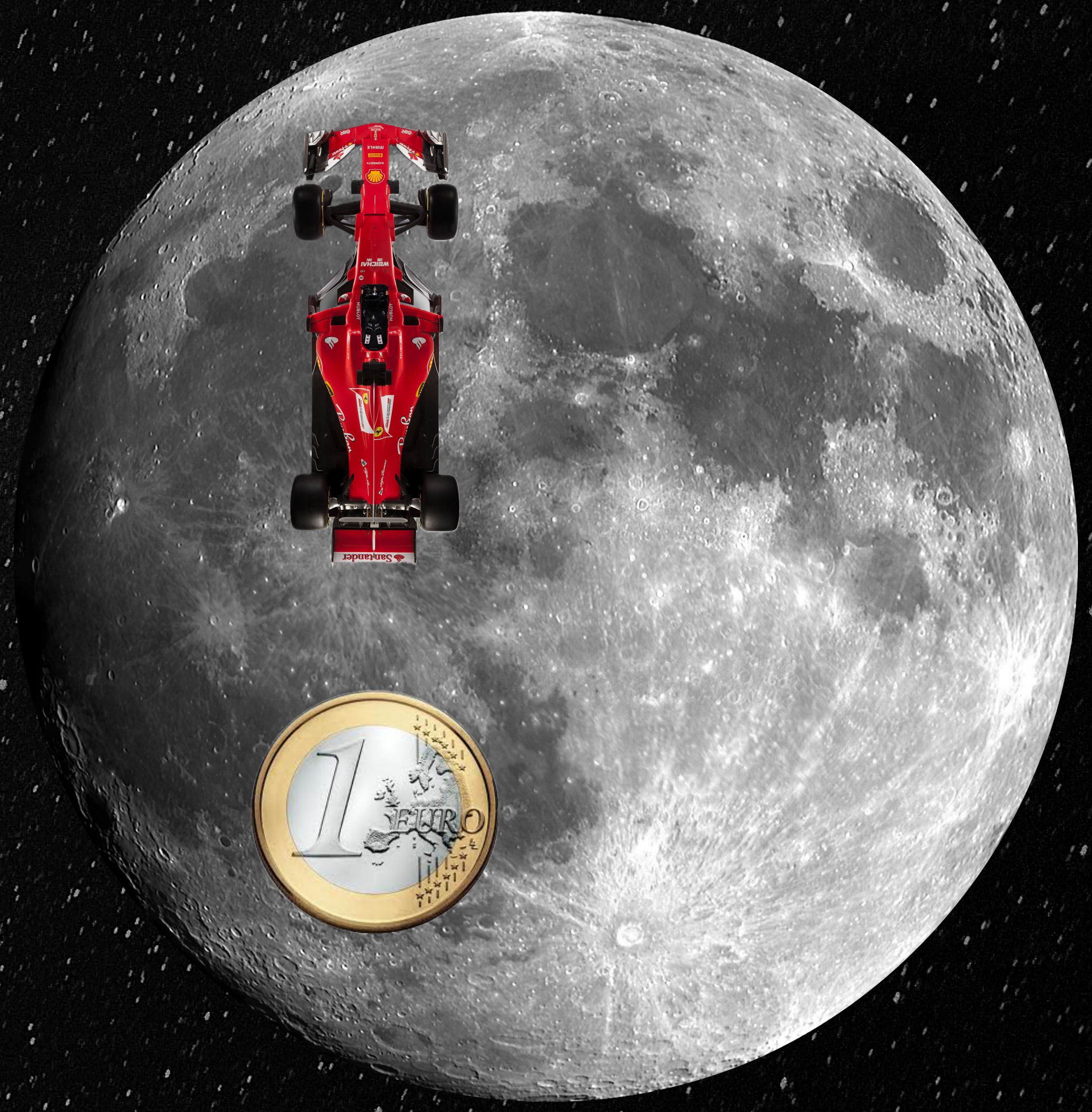


- GRAVITY+ upgrade completed by 2026: factor 10-100 improvement in sensitivity

The Galactic center

Credit: ESO

The S-Stars in the Galactic center

1 pc

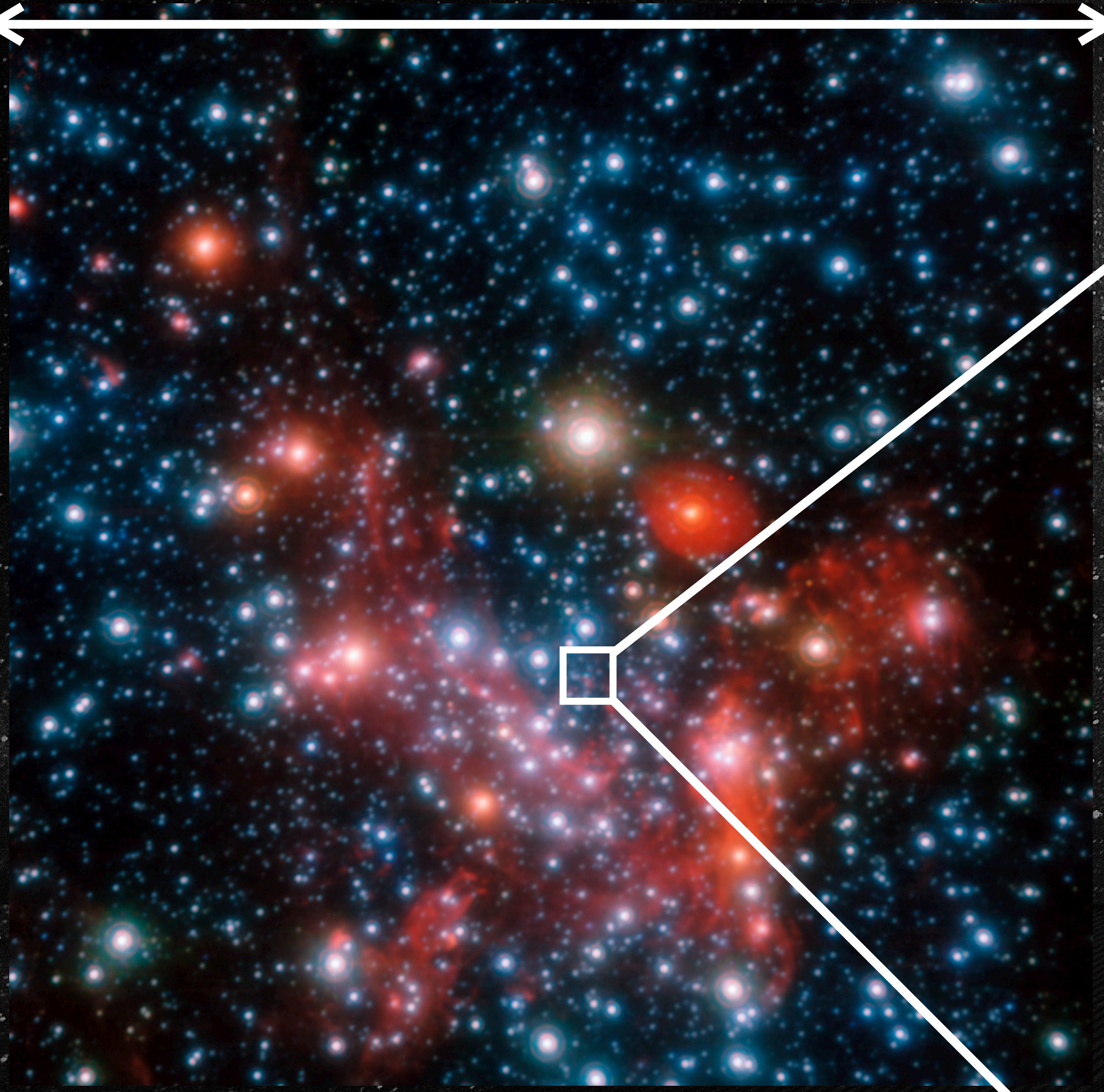
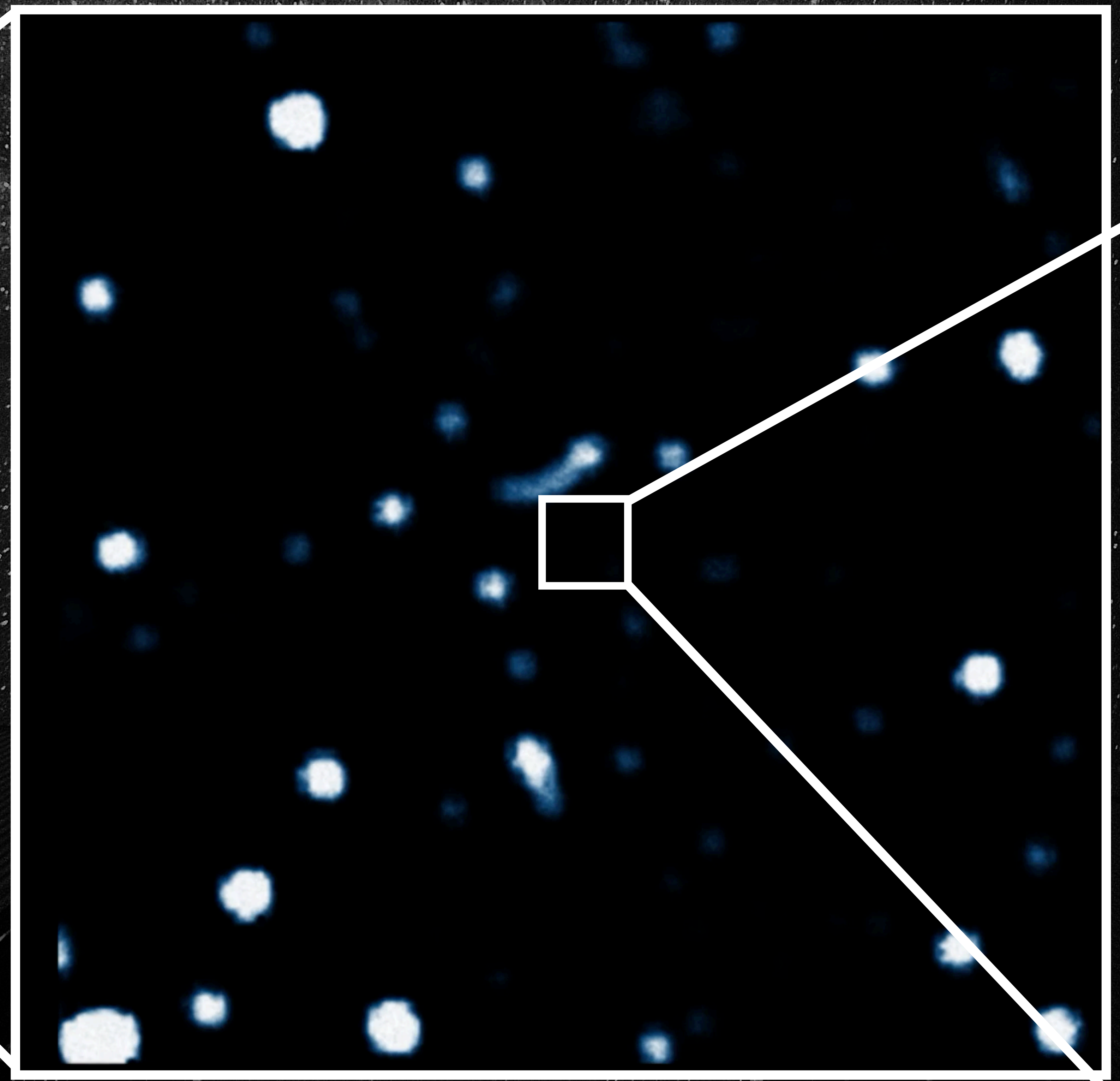


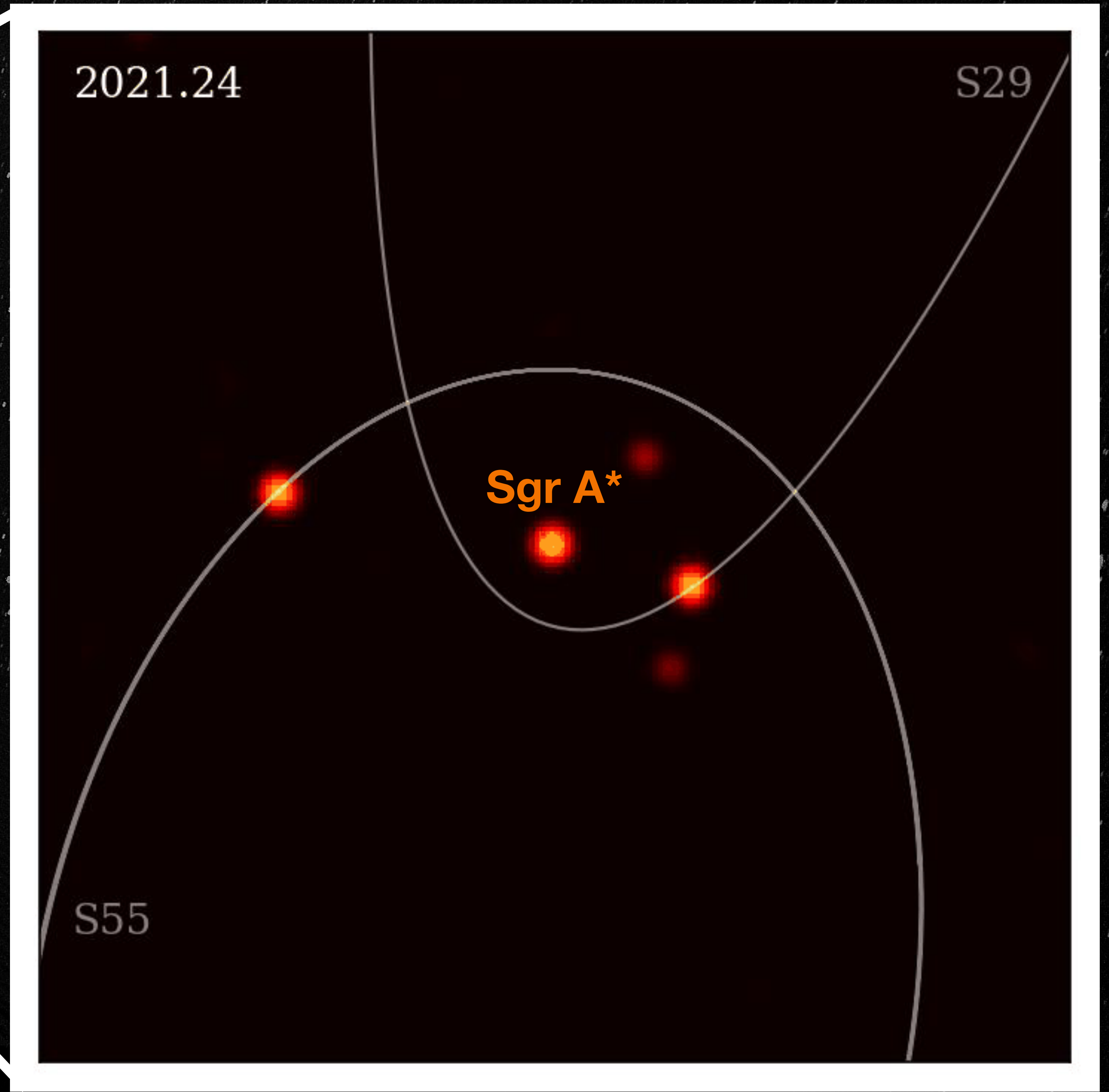
Image of the central parsec of the Galaxy, with single 8m telescope

1.5 arcsec ≈ 60 mpc



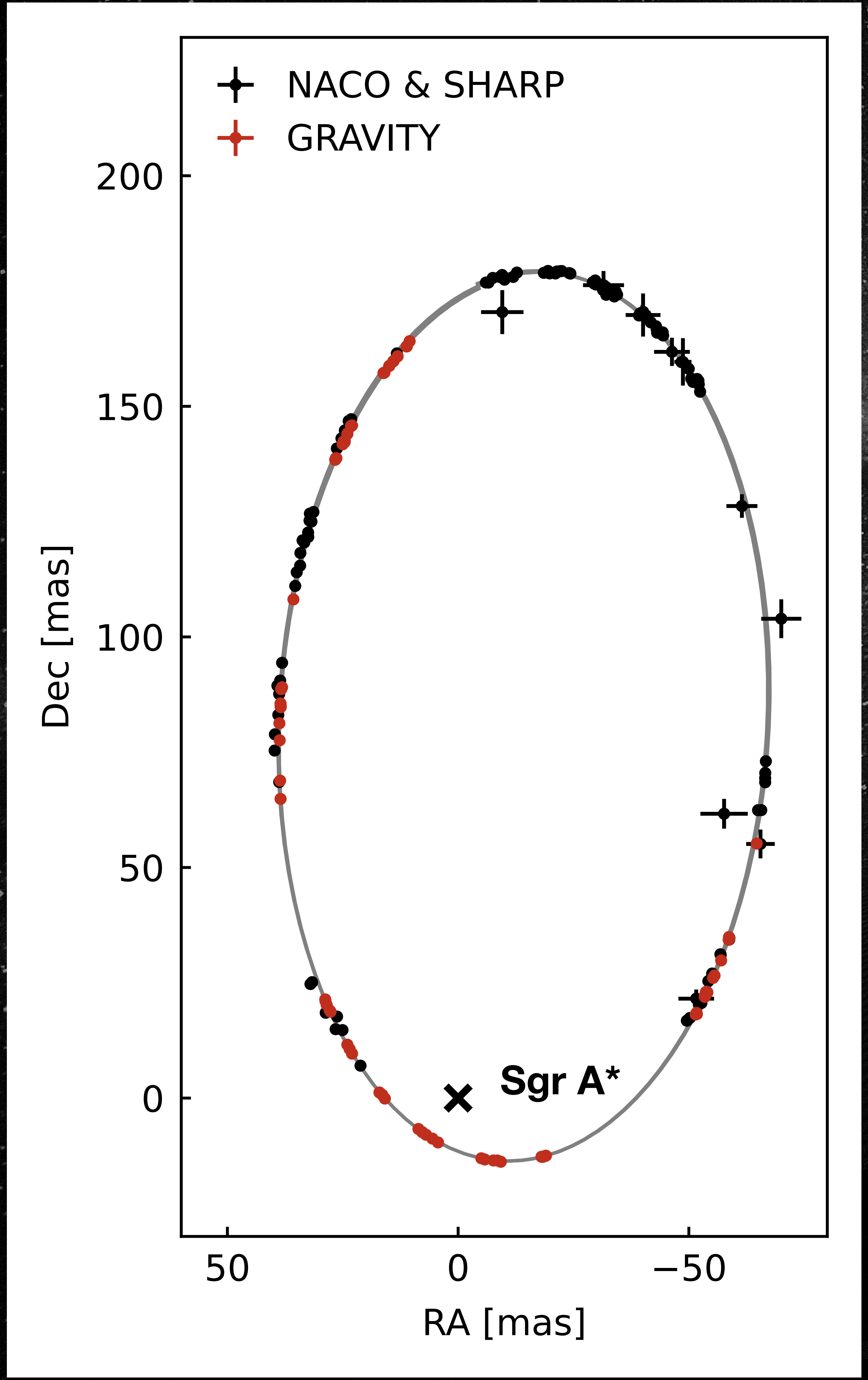
Time-lapse of stars orbiting Sagittarius A* over 20 years, with single 8m telescope

0.15 arcsec ≈ 6 mpc



2 years of GRAVITY data (reconstructed images)

The S2 star



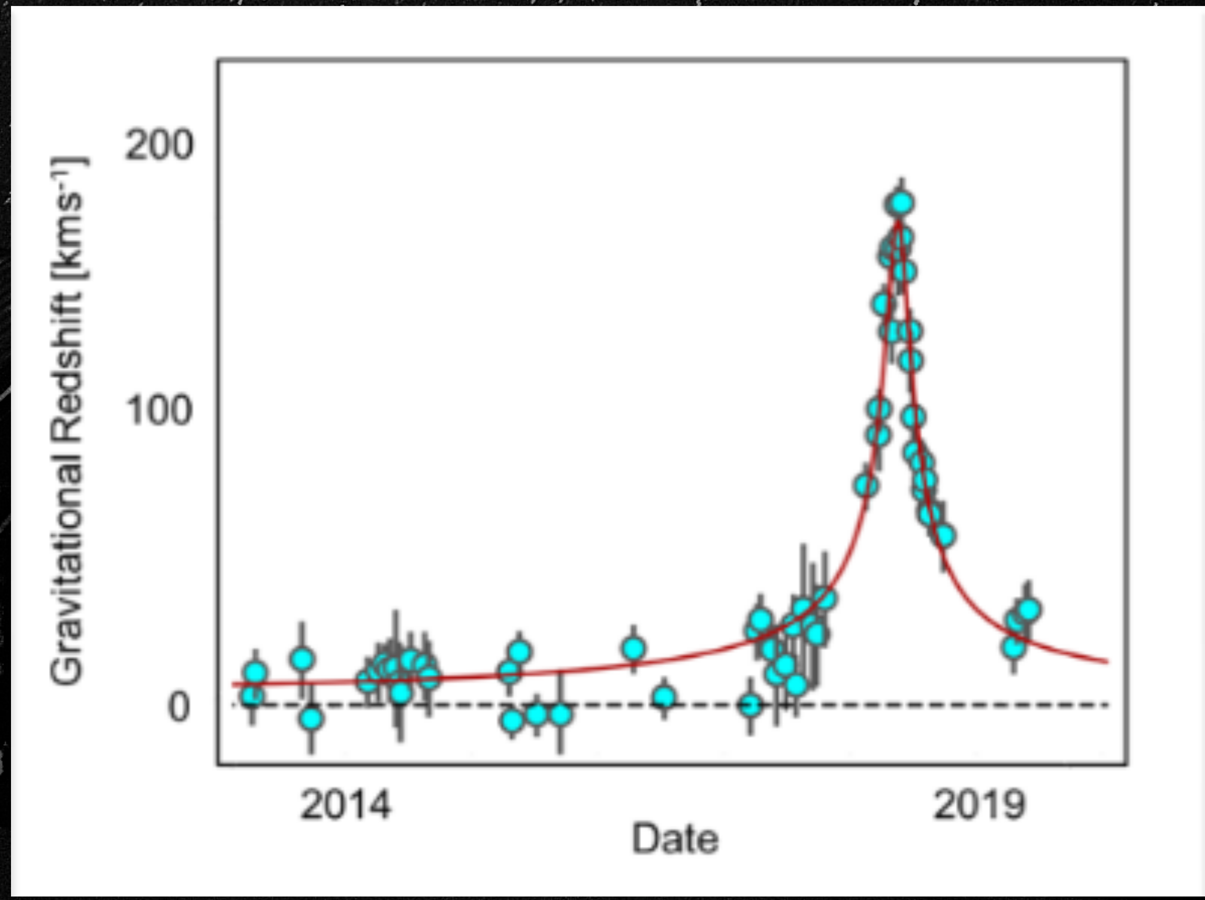
Orbit of S2 around Sagittarius A*

- **Allowed determining that Sgr A* is a SMBH and measuring its mass and distance:**

$$M_\bullet = 4.3 \times 10^6\, M_{sun}\,, \quad R_0 = 8.3\, kpc$$

- **Allowed testing General Relativity: 1PN effects detected**

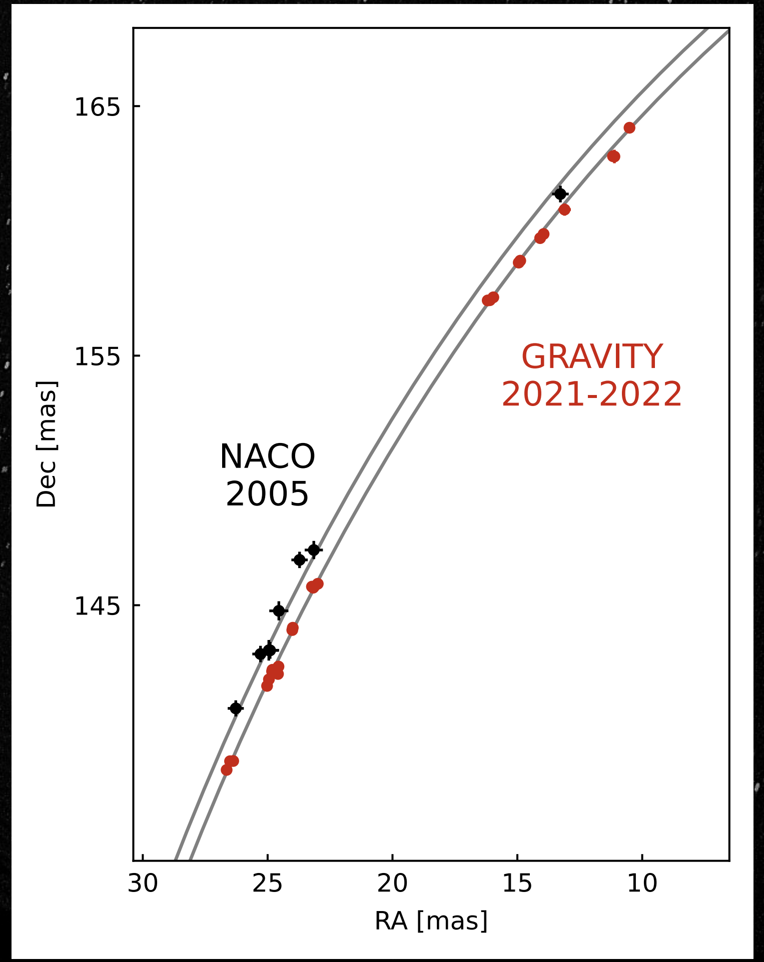
Gravitational redshift



GRAVITY Collaboration 18,19, Do et al. 19

≈20σ detection

Schwarzschild precession



GRAVITY Collaboration 20,22,24

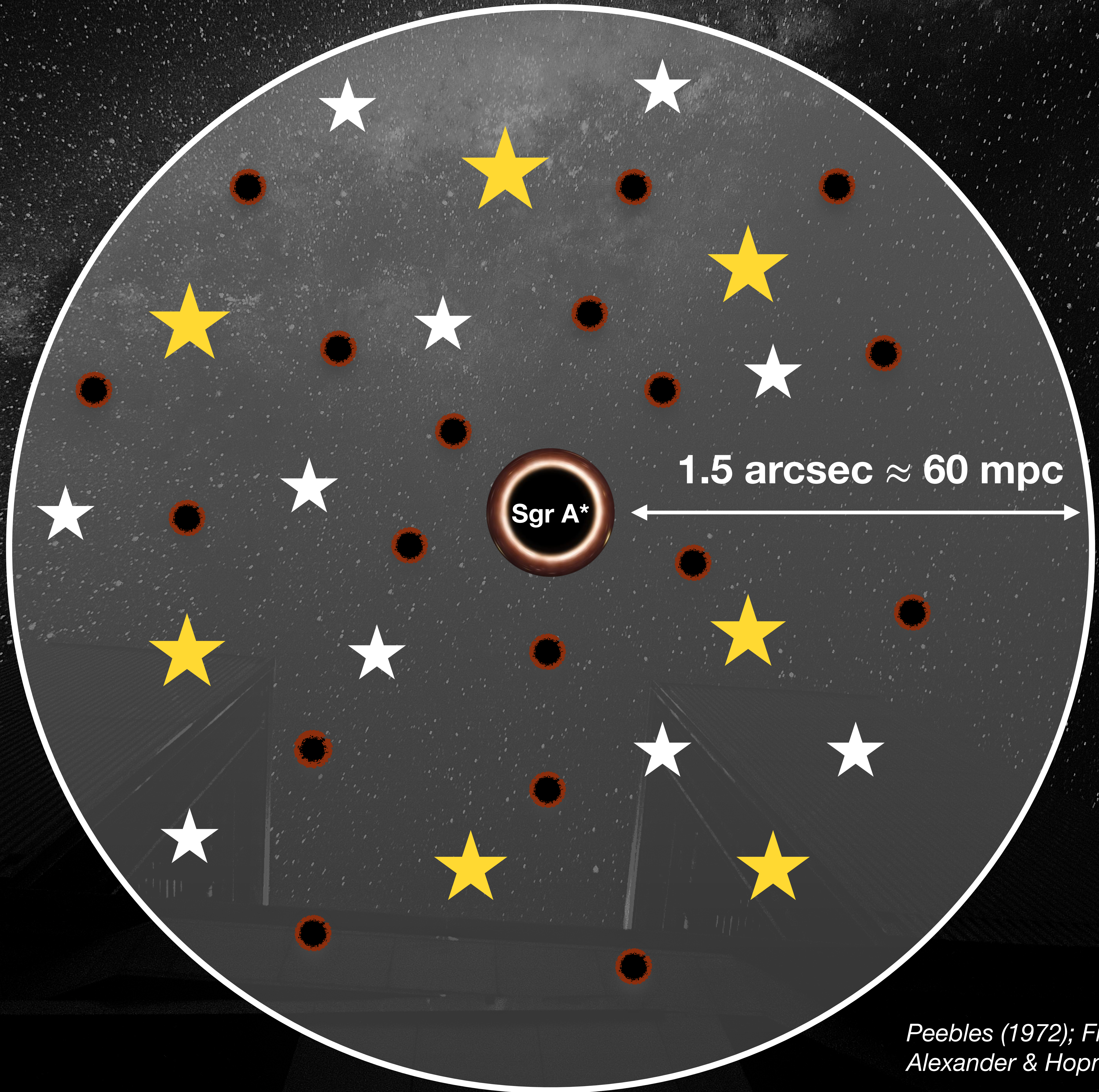
≈10σ detection

The extended mass distribution in the GC
"Dark mass" within the orbits of S-stars

Dynamically relaxed cusp of old stars and stellar remnants is predicted to exist in the GC

$$\rho(r) \propto r^s$$

→ Formation of EMRIs



Dark matter could be accreted by the SMBH to form a dense spike

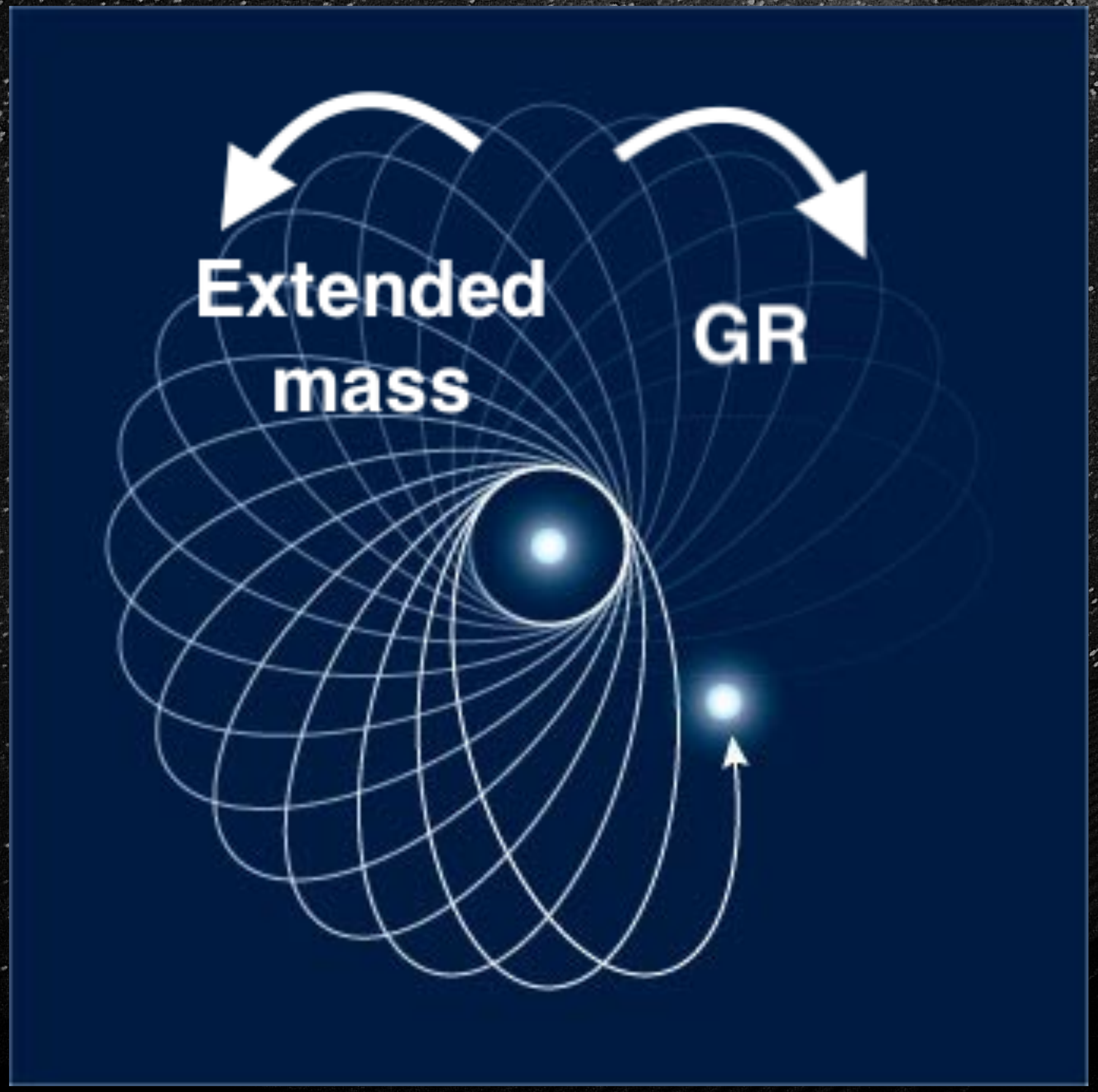
- S-Stars: O/B young, massive stars
- Compact remnants
- Faint, low-mass stars
- Dark matter spike

Peebles (1972); Frank & Rees (1976); Bahcall & Wolf (1976 & 1977); Alexander & Hopman (2009); Preto & Amaro-Seoane (2010);

Gondolo & Silk (1999); Shen et al. (2024);

Effect of an extended mass distribution

A spherically symmetric distribution of matter with density $\rho(r)$ causes a retrograde precession of the star's orbit



- GR: prograde precession $\delta\varphi > 0$
- Extended mass: retrograde precession $\delta\varphi < 0$

Constraining an extended mass distribution:
How much "dark mass" lies within the S2 orbit?

- **Assume a smooth density distribution of matter:**
  - **Power-law profile**

$$\rho(r) = \tilde{\rho}\left(\frac{r}{r_0}\right)^{s}$$

with $-3 < s \leq 0$

  - **Plummer profile**

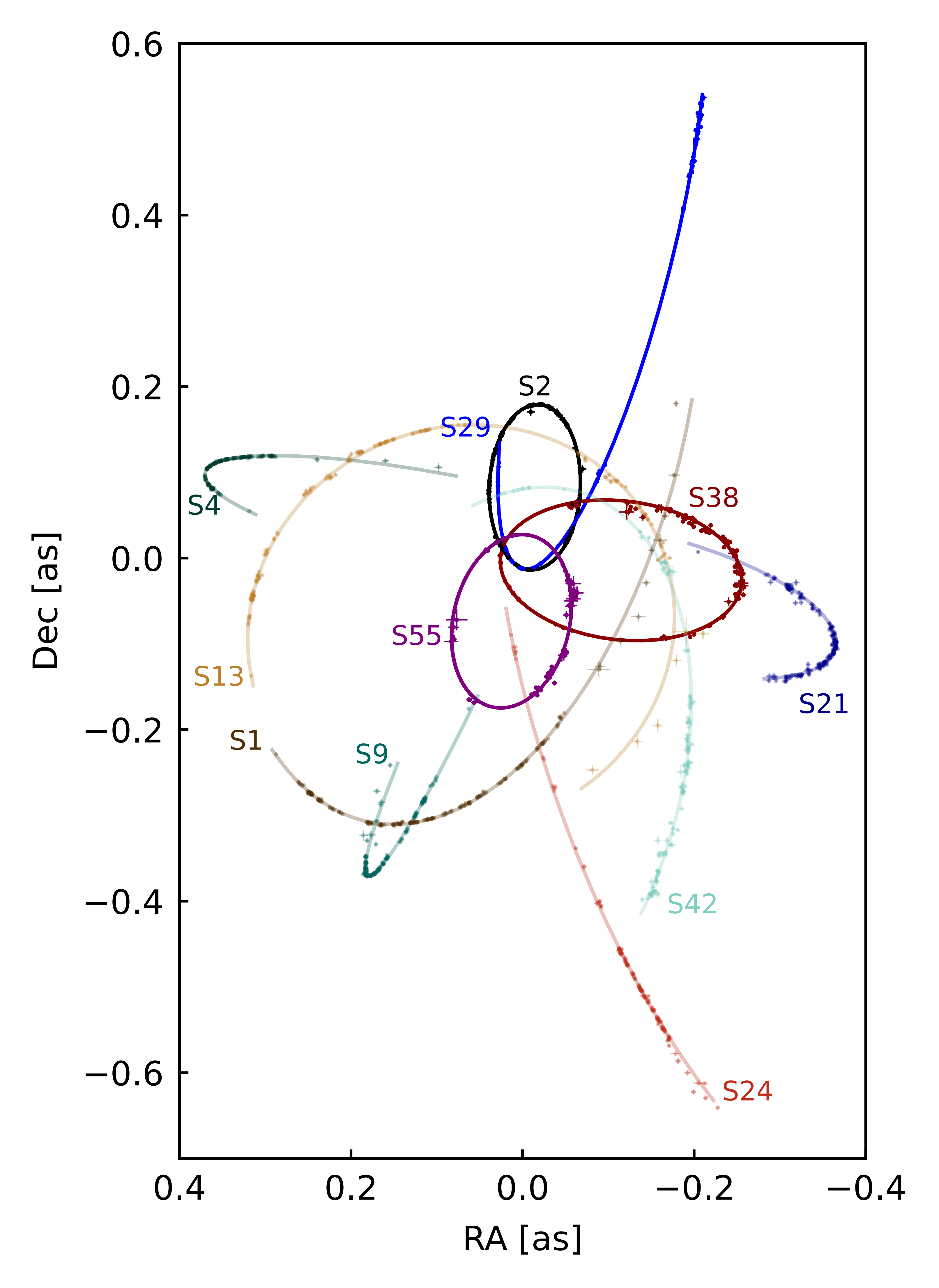
$$\rho(r) = \rho_0\left[1 + \left(\frac{r}{a}\right)^2\right]^{-5/2}$$

with $0 < a \leq 40$ mpc

Fit data of S2, S29, S38 and S55 for parameters $\rho_0, \tilde{\rho}$

Obtain enclosed mass within S2 orbit

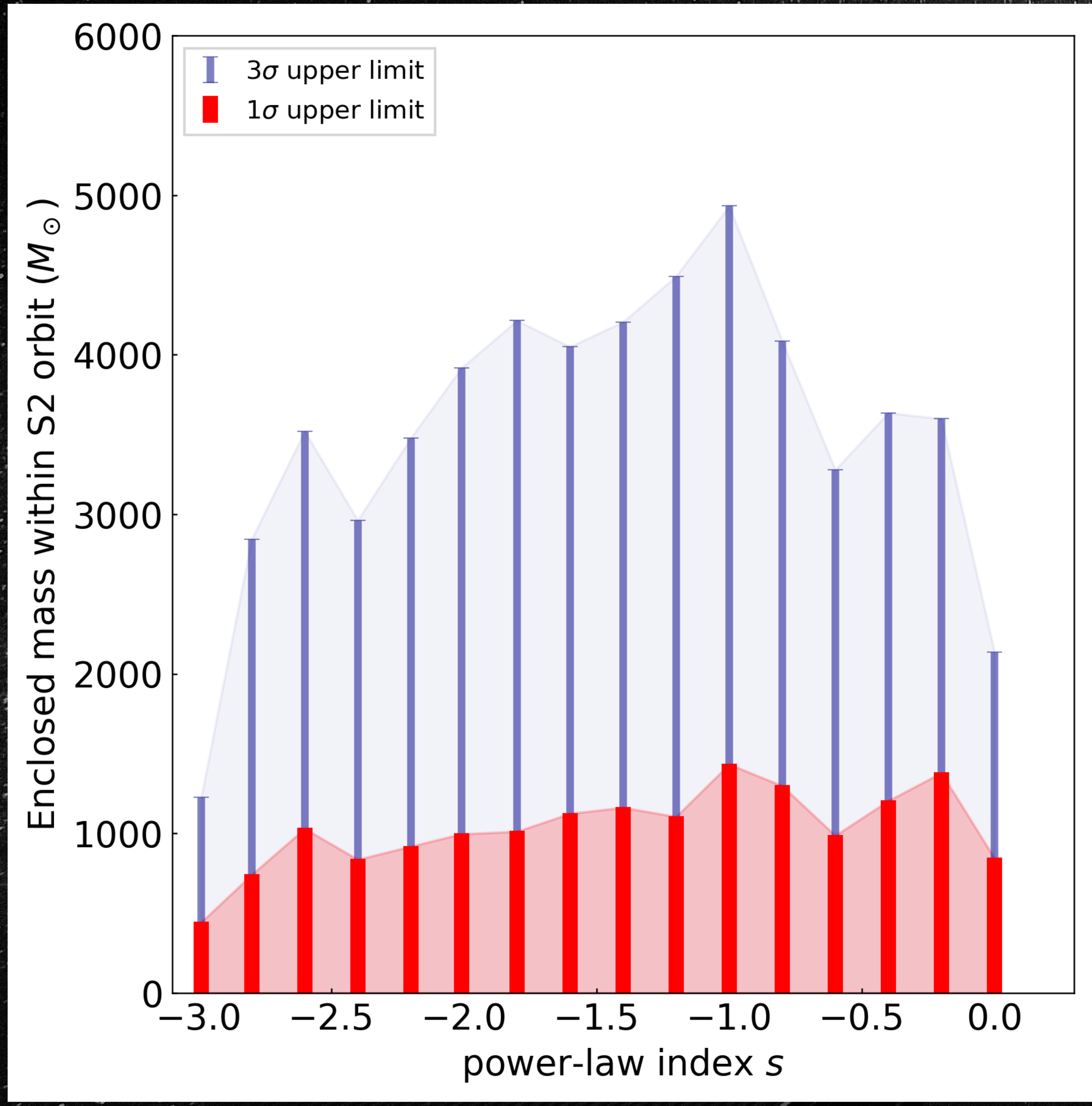
(Within the central ≈ 10 mpc of the Galaxy)



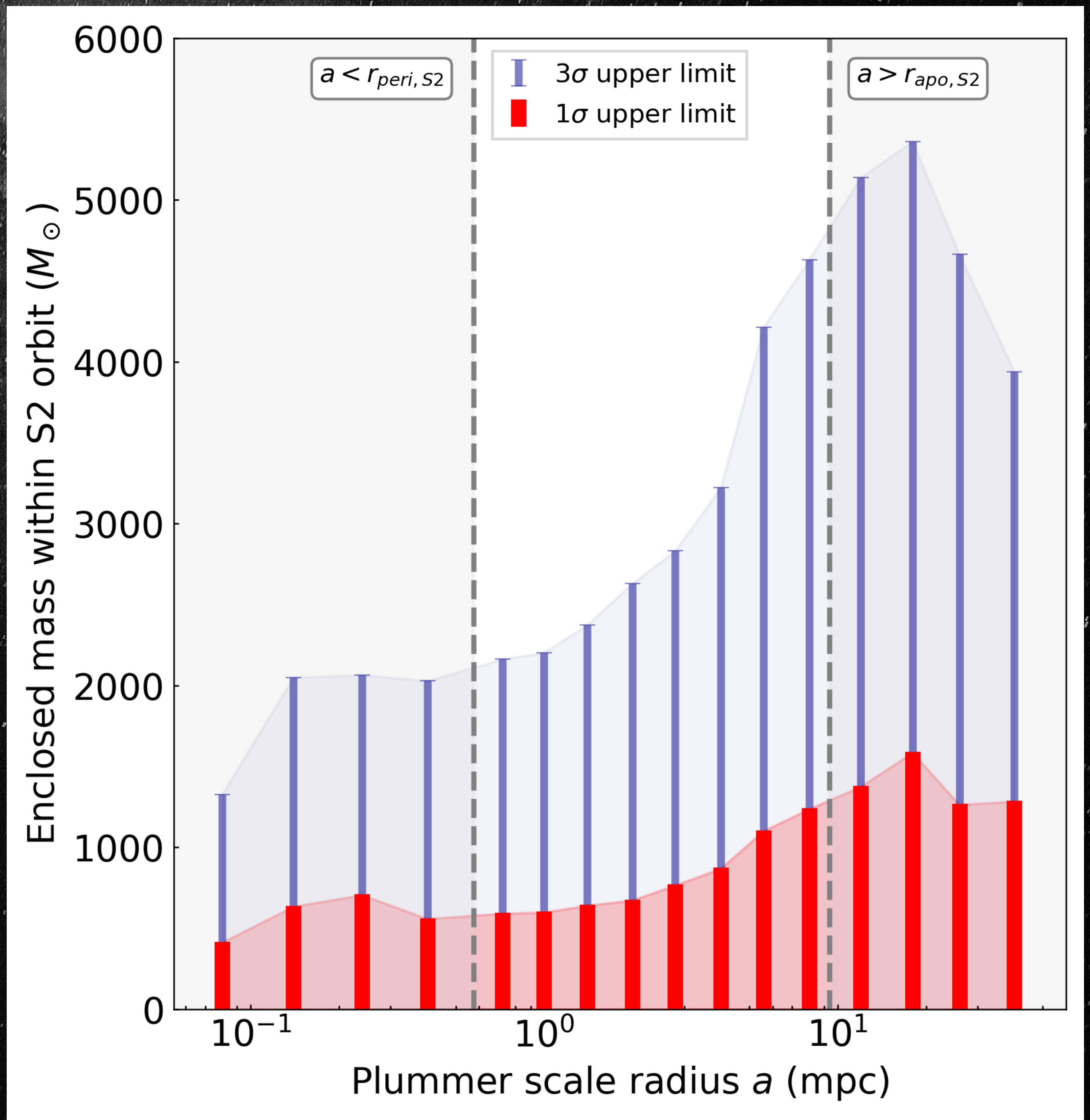
Orbits of a set of S-stars

(M. Sadun Bordoni & GRAVITY Collaboration, 2024)

Constraining an extended mass distribution:
Upper limit on “dark mass” within S2 orbit



Power-law profile



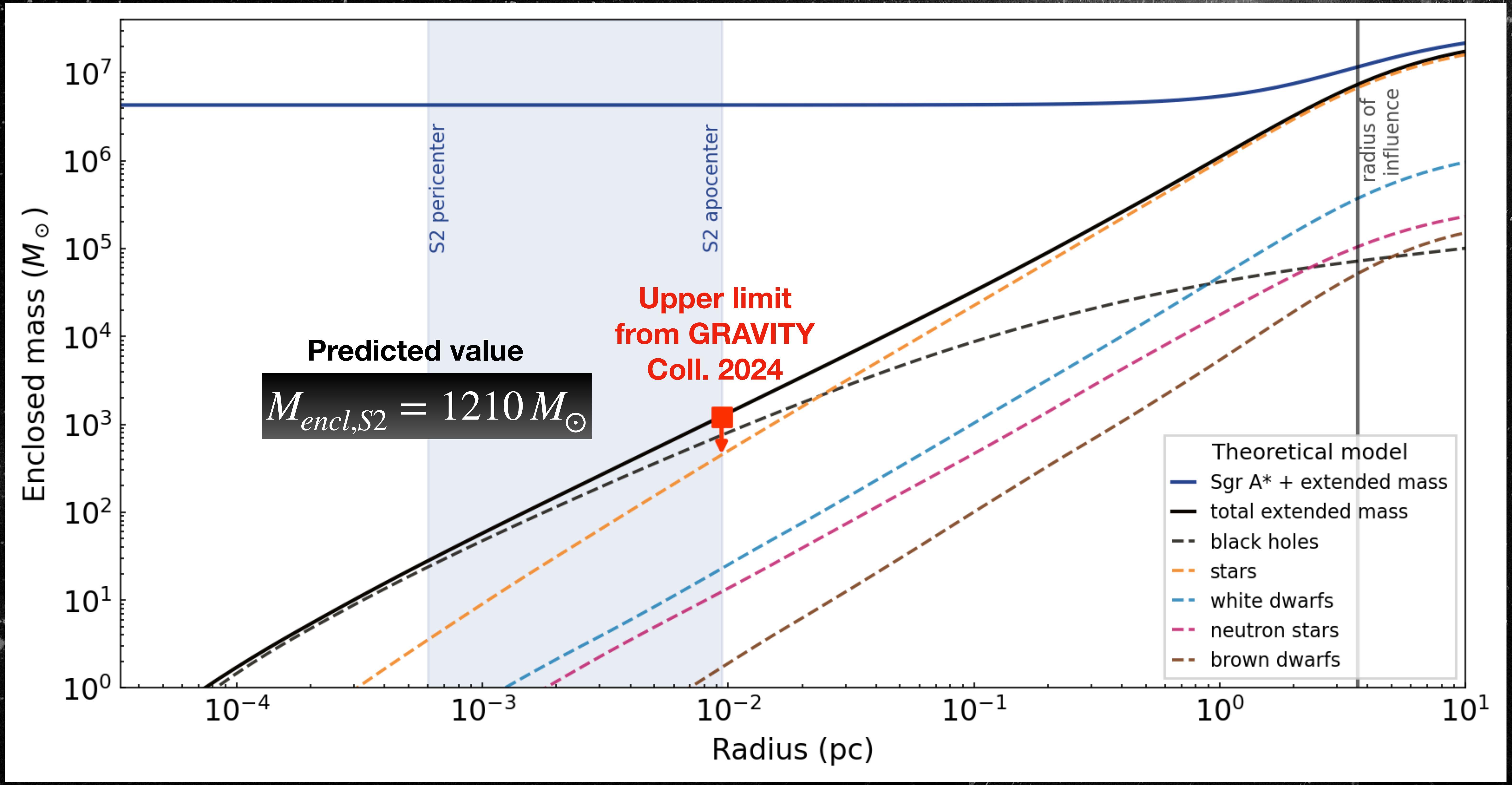
Plummer profile

$M_{encl,S2} \lesssim 1200\, M_\odot\ (1\sigma)$ independent of density profile

Retrograde precession $\lesssim 1'$ *per orbit* subdominant with respect to prograde, relativistic precession ($\delta\varphi \sim 12'$ *per orbit*)

(M. Sadun Bordoni & GRAVITY Collaboration, 2024)

Comparison with theoretical models for the stellar cusp



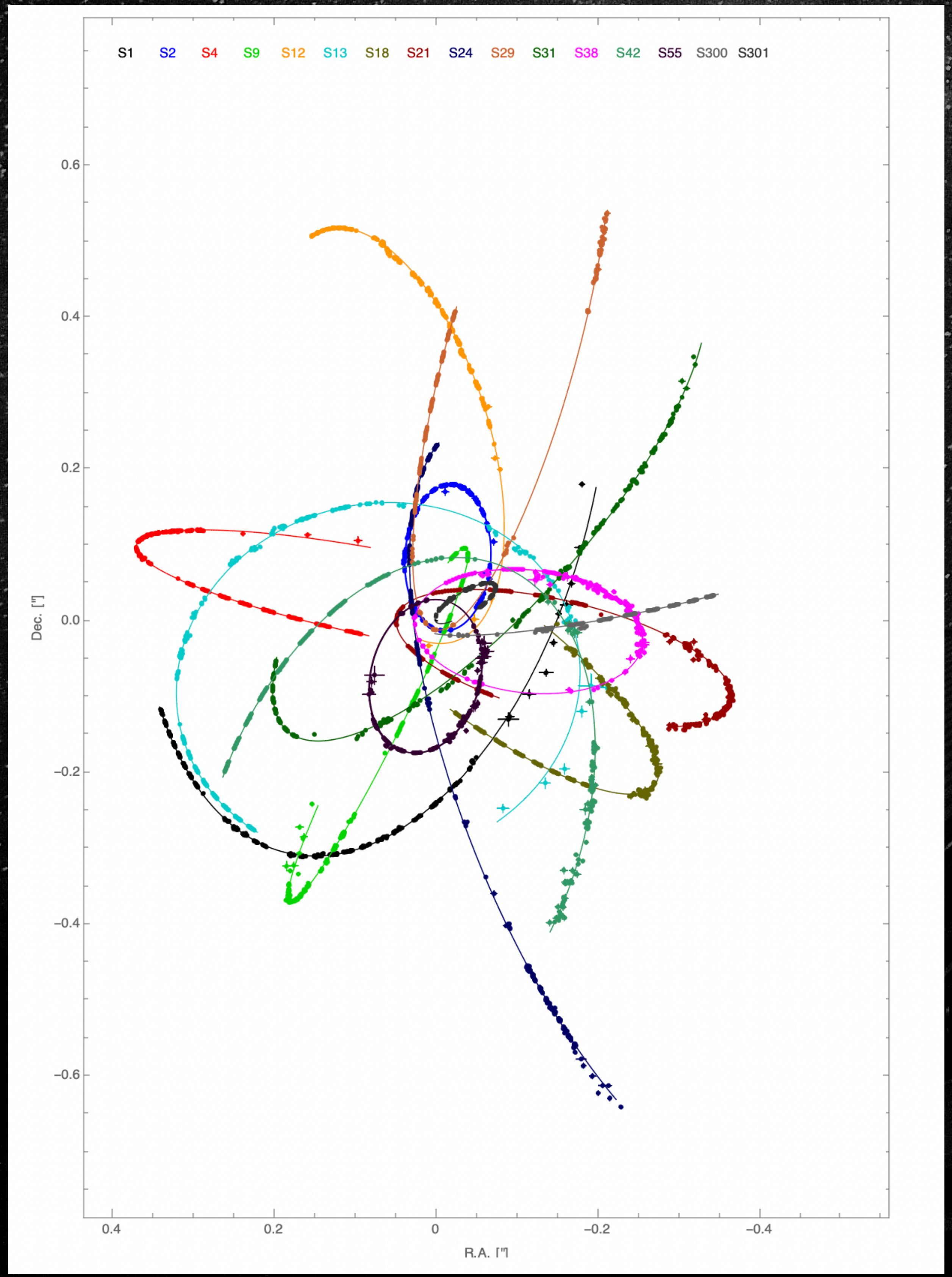
Enclosed mass profile for a stellar cusp in the Galactic center from numerical simulations *(Zhang & Amaro-Seoane 2025)*

- Upper limit very close to predicted value
- No evidence of a dark matter spike
- Most of the enclosed mass is made of stellar-mass black holes

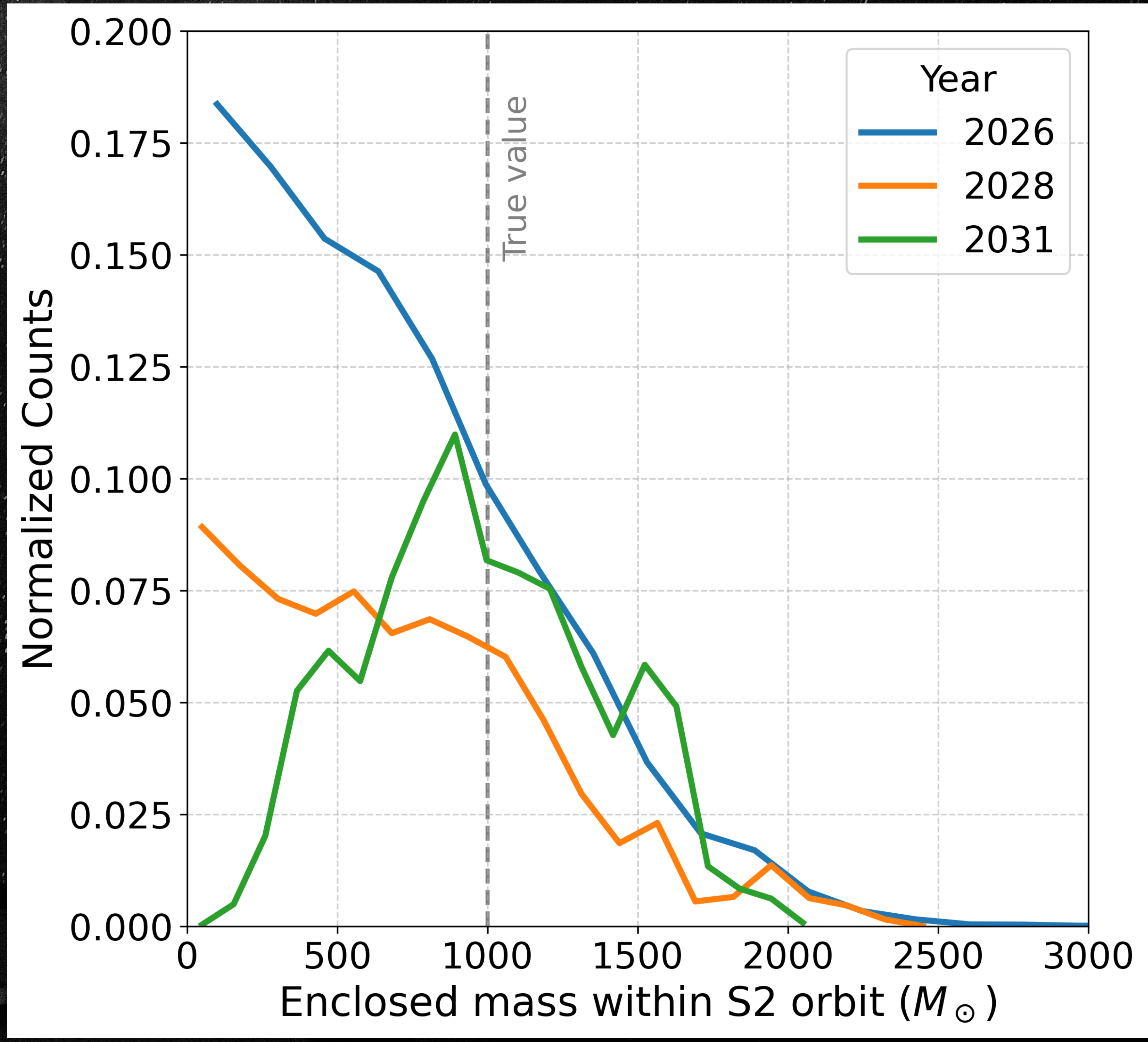
(M. Sadun Bordoni & GRAVITY Collaboration, 2024)

Constraining the extended mass distribution within S2 orbit:
Future improvements with GRAVITY+

Assuming a smooth, extended mass distribution around Sgr A*: we will measure it by 2031, tracking >10 stars with GRAVITY(+)



Mock data for a set of S-stars until 2031



Posterior distribution on the enclosed mass within S2 orbit

The granularity of the mass distribution:
Scattering of the S2 orbit by stellar-mass black holes

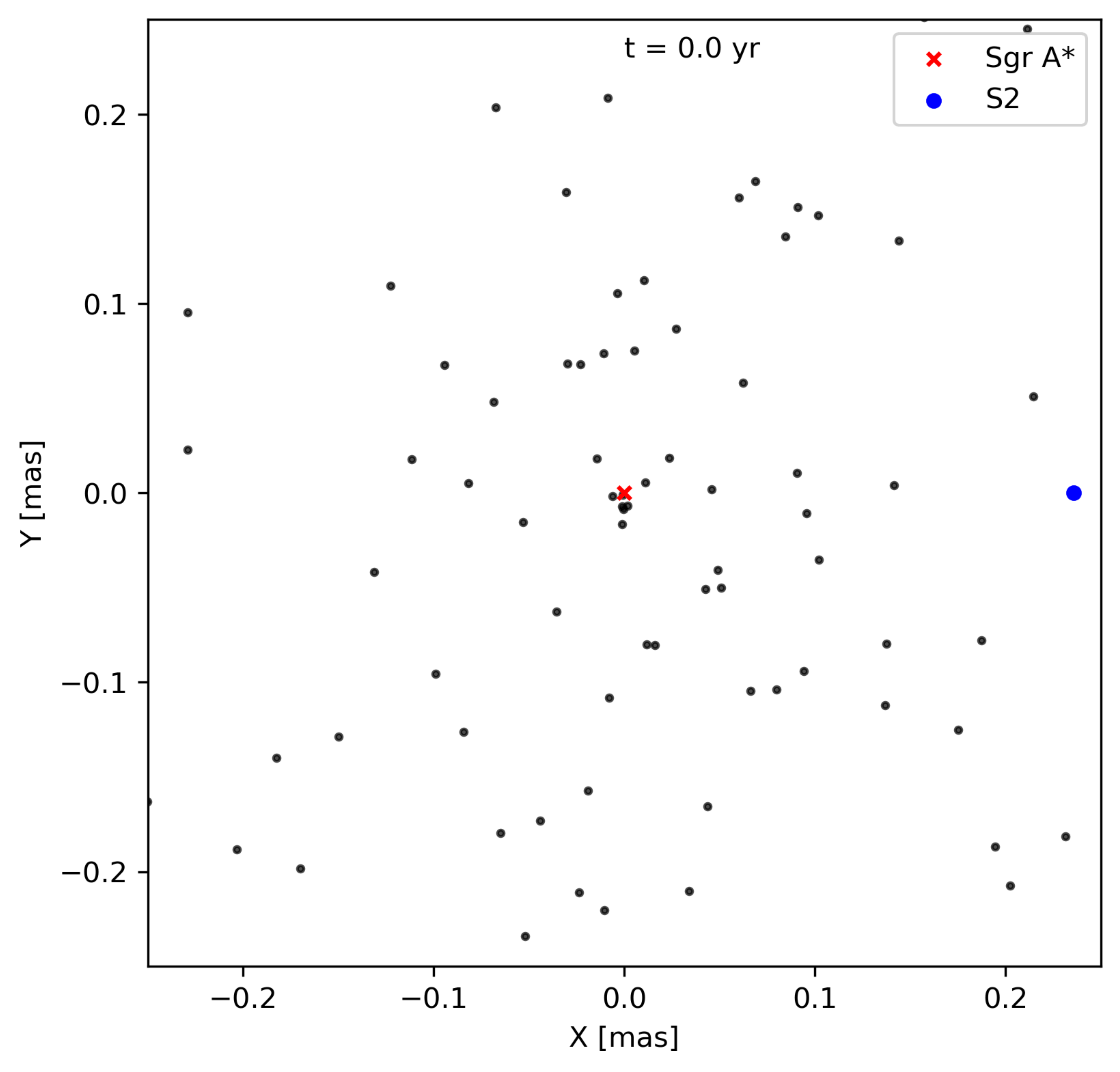
- **Full N-body simulations of the orbit of S2, assuming the mass distribution is made of a <u>cluster of stellar-mass black holes of equal mass:</u>**

  - 50 objects of $20\,M_\odot$
  - 20 objects of $50\,M_\odot$
  - 10 objects of $100\,M_\odot$

$$M_{encl,S2} = 1000\,M_\odot$$

→ **What's the impact on the orbit of S2?**

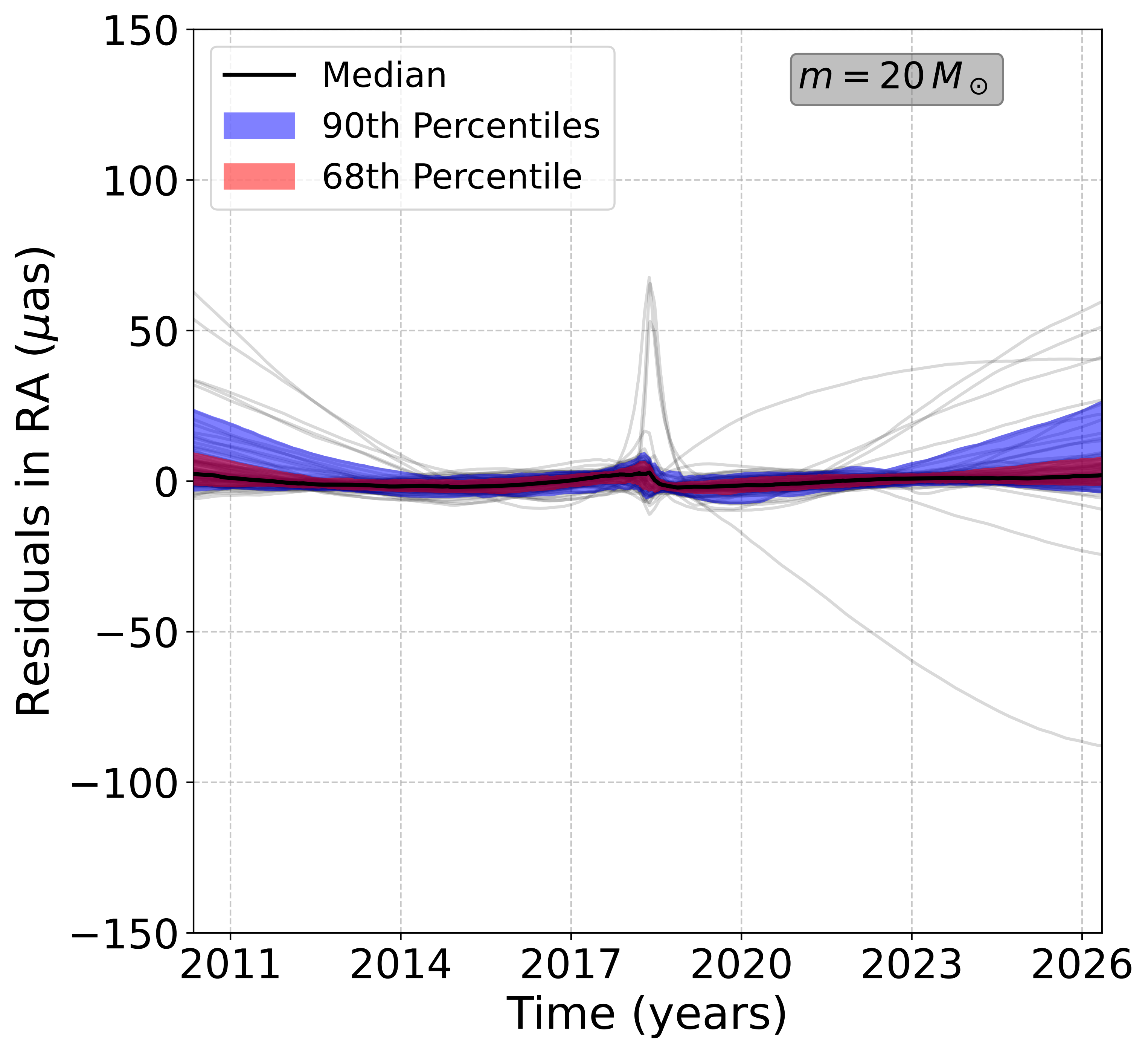
→ **Is a smooth mass distribution a good approximation in this region?**

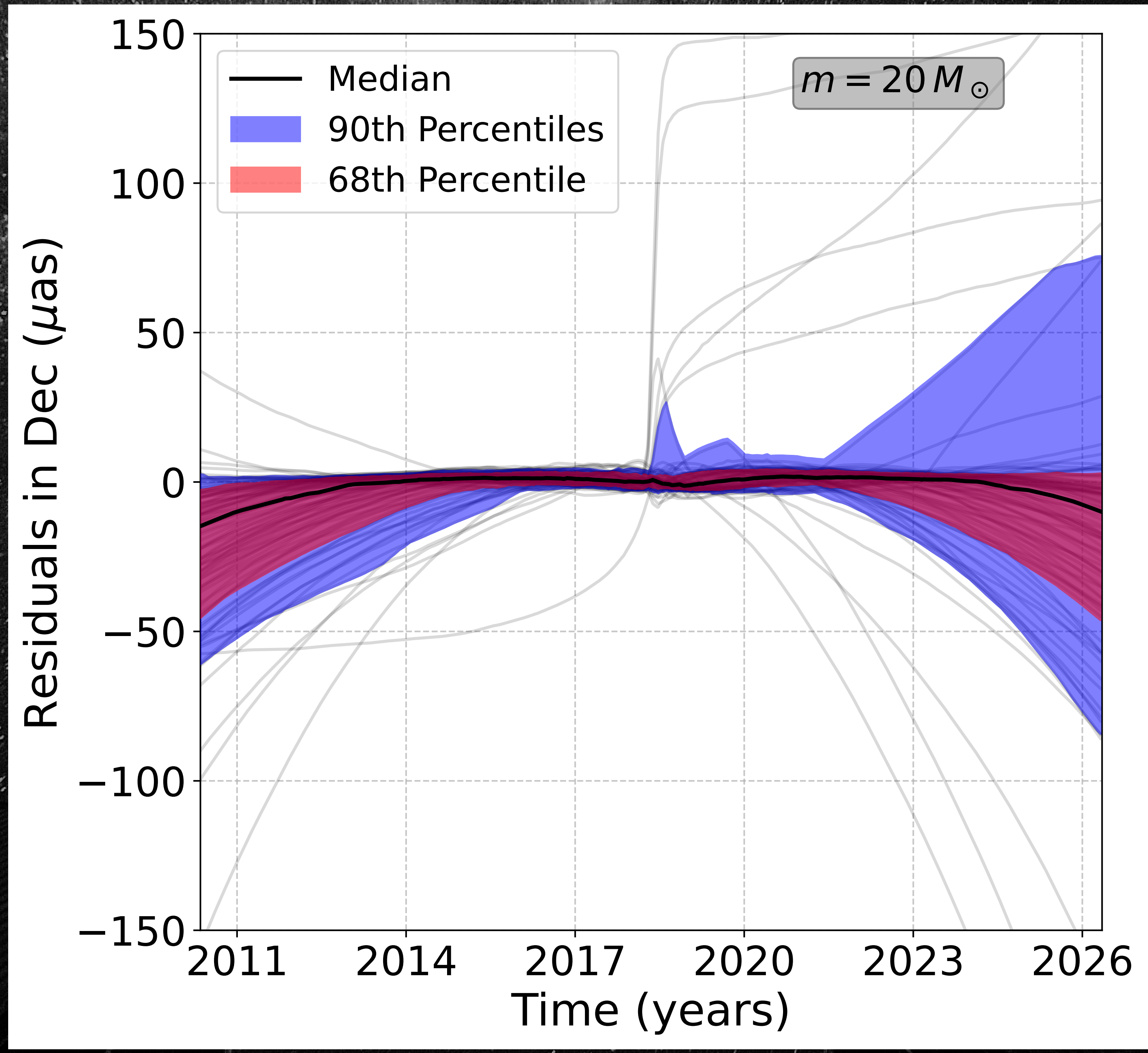


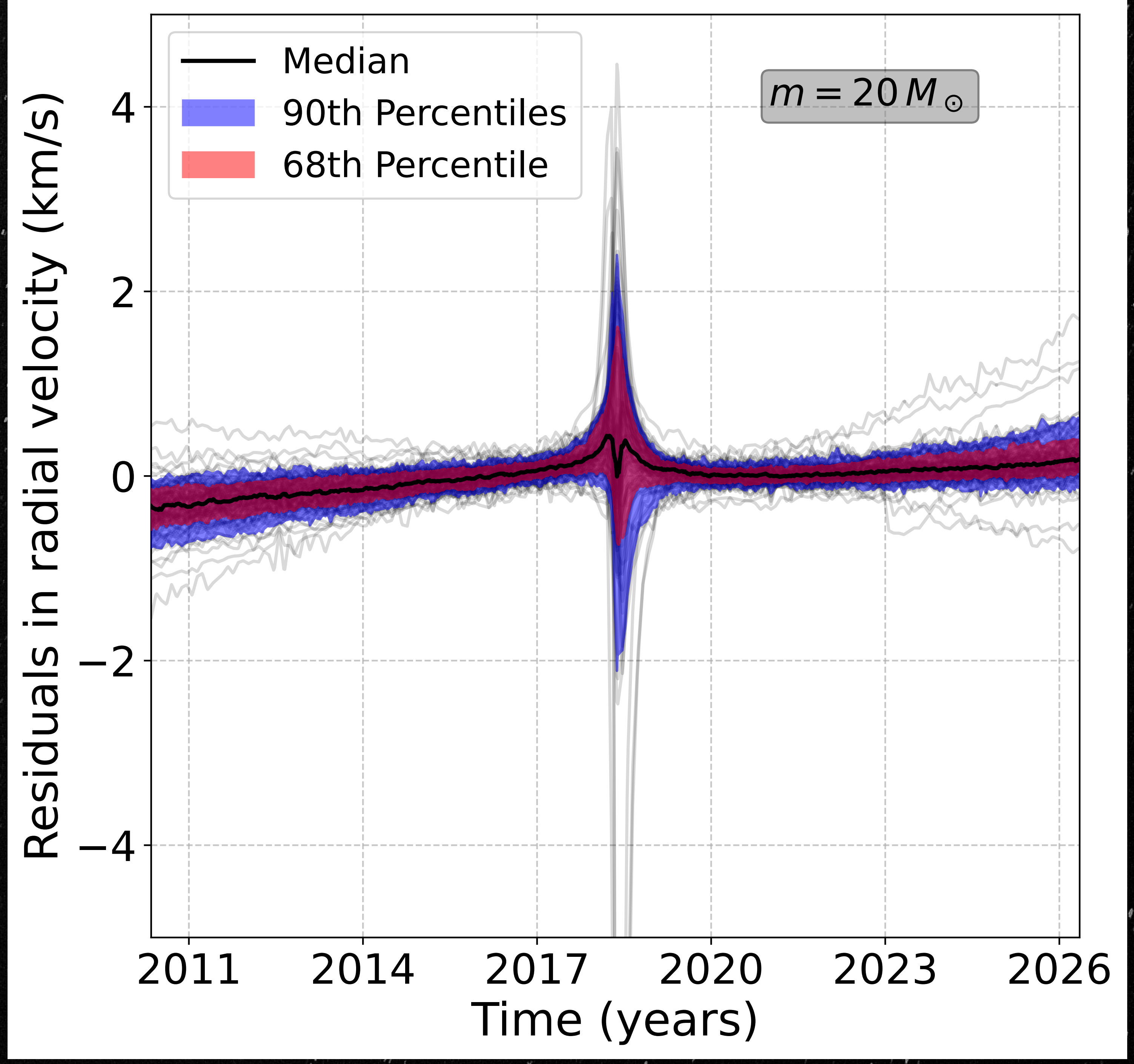
(M. Sadun Bordoni et al. 2025, submitted to A&A)

The granularity of the mass distribution:
Scattering of the S2 orbit by stellar-mass black holes

- **Mock data analysis: residuals of simulation data with respect to best-fit relativistic orbit, without additional granular potential**







- **At apocenter: residuals in declination larger than accuracy of GRAVITY ($\approx 30\,\mu as$) in 35-60% of the simulations**

→ We could detect this effect in the upcoming years!

- **Residuals in radial velocity always smaller than current accuracy ($\approx 7\,km/s$ for S2)**

(M. Sadun Bordoni et al. 2025, submitted to A&A)

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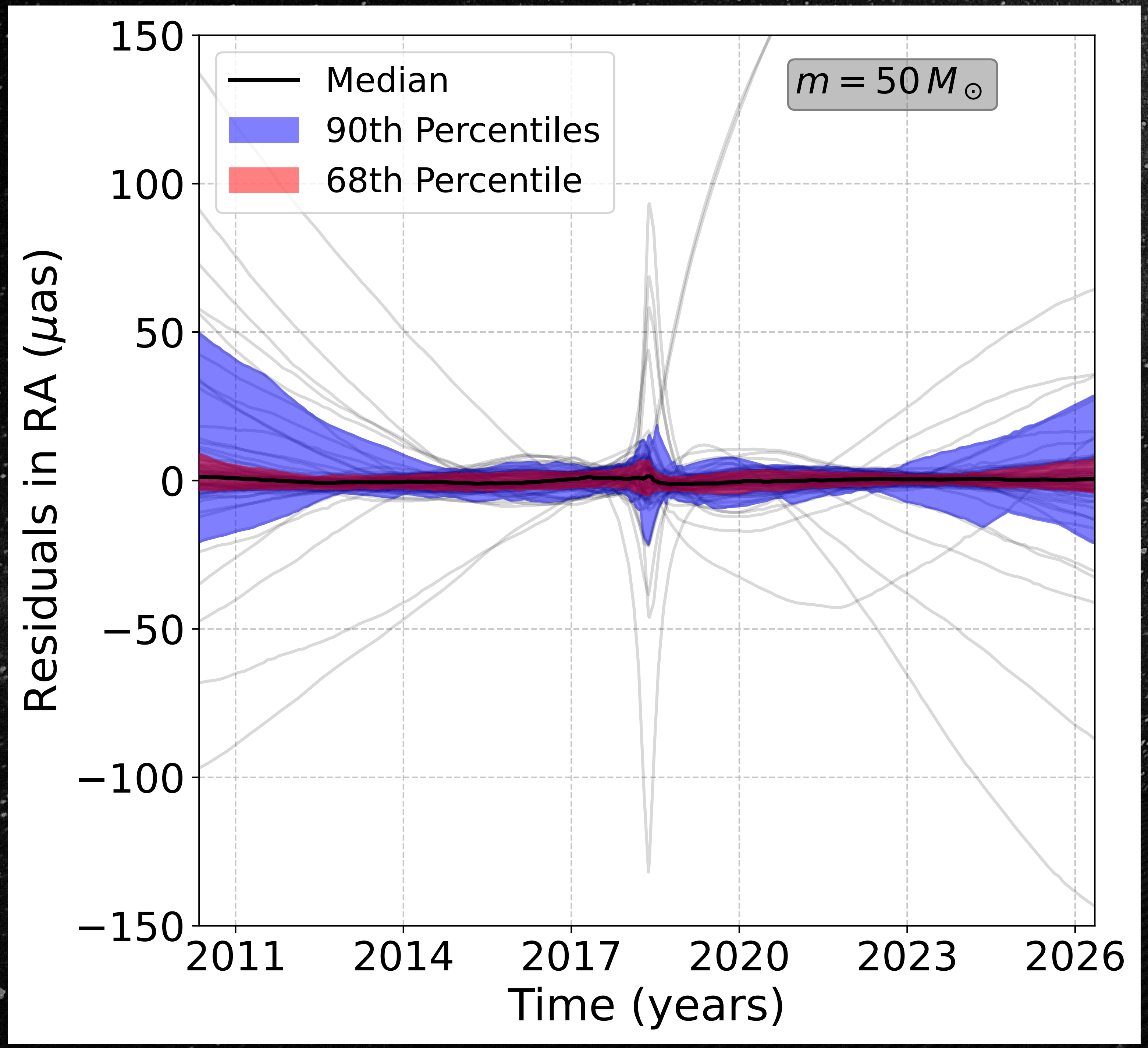

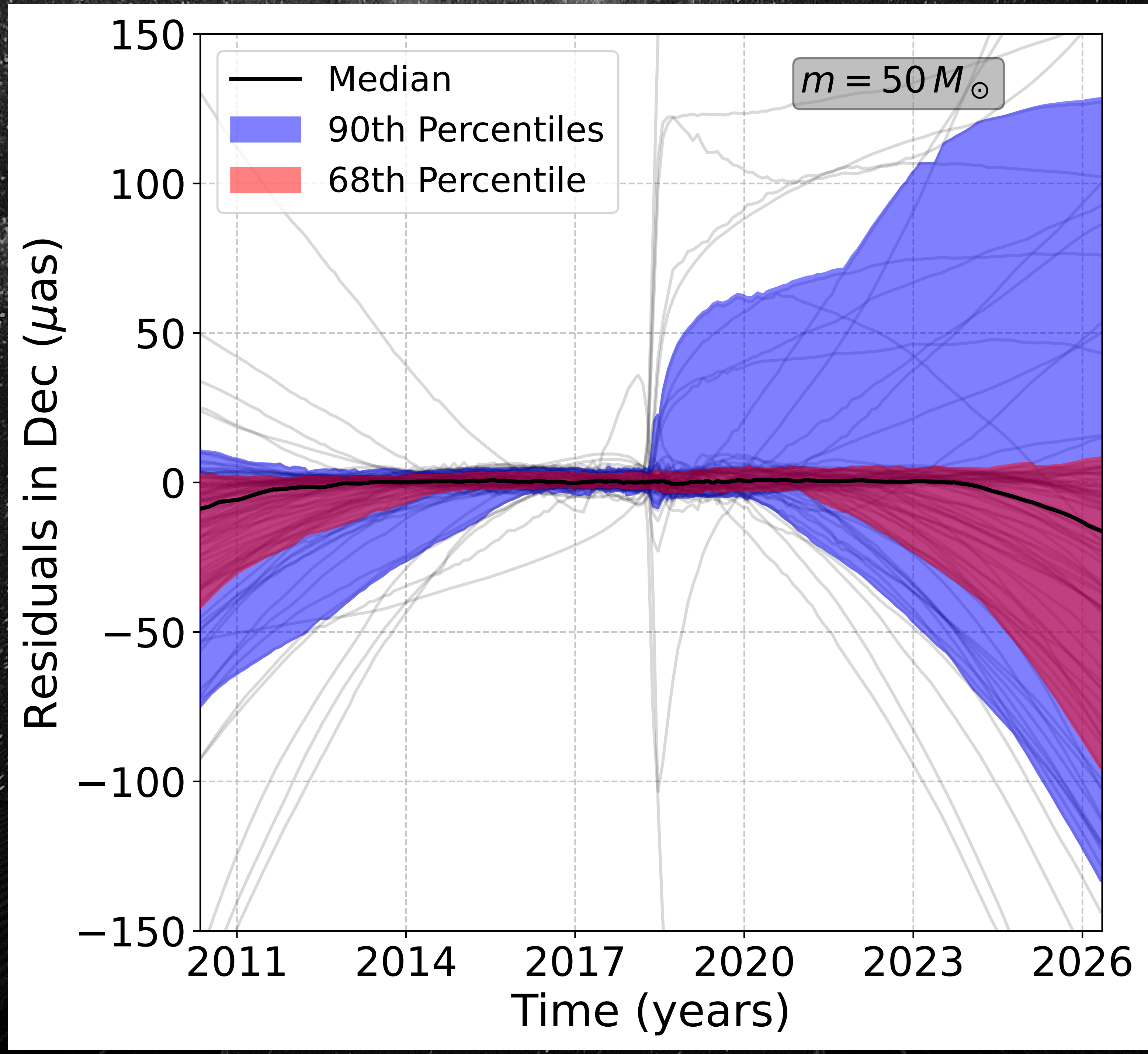

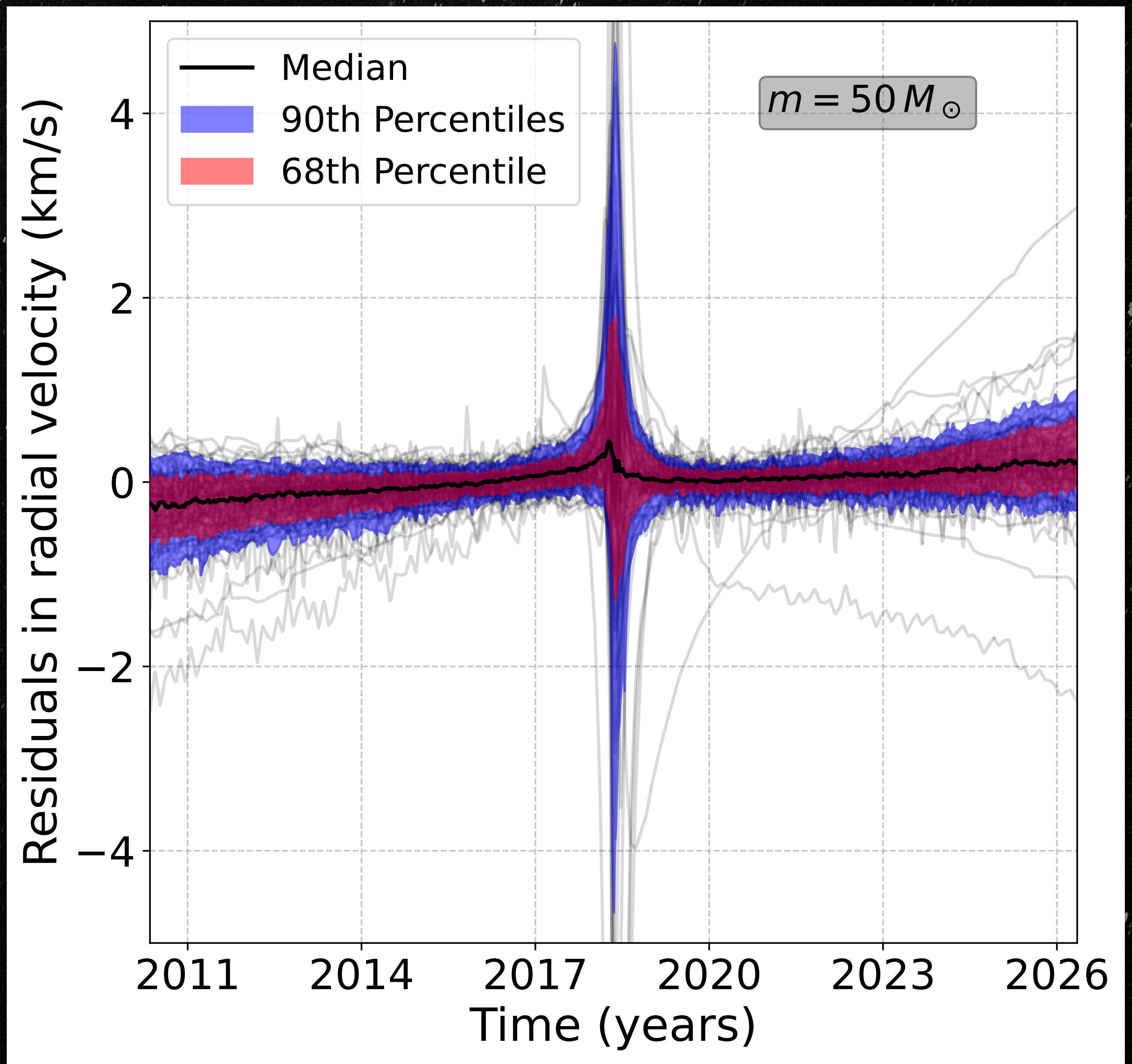

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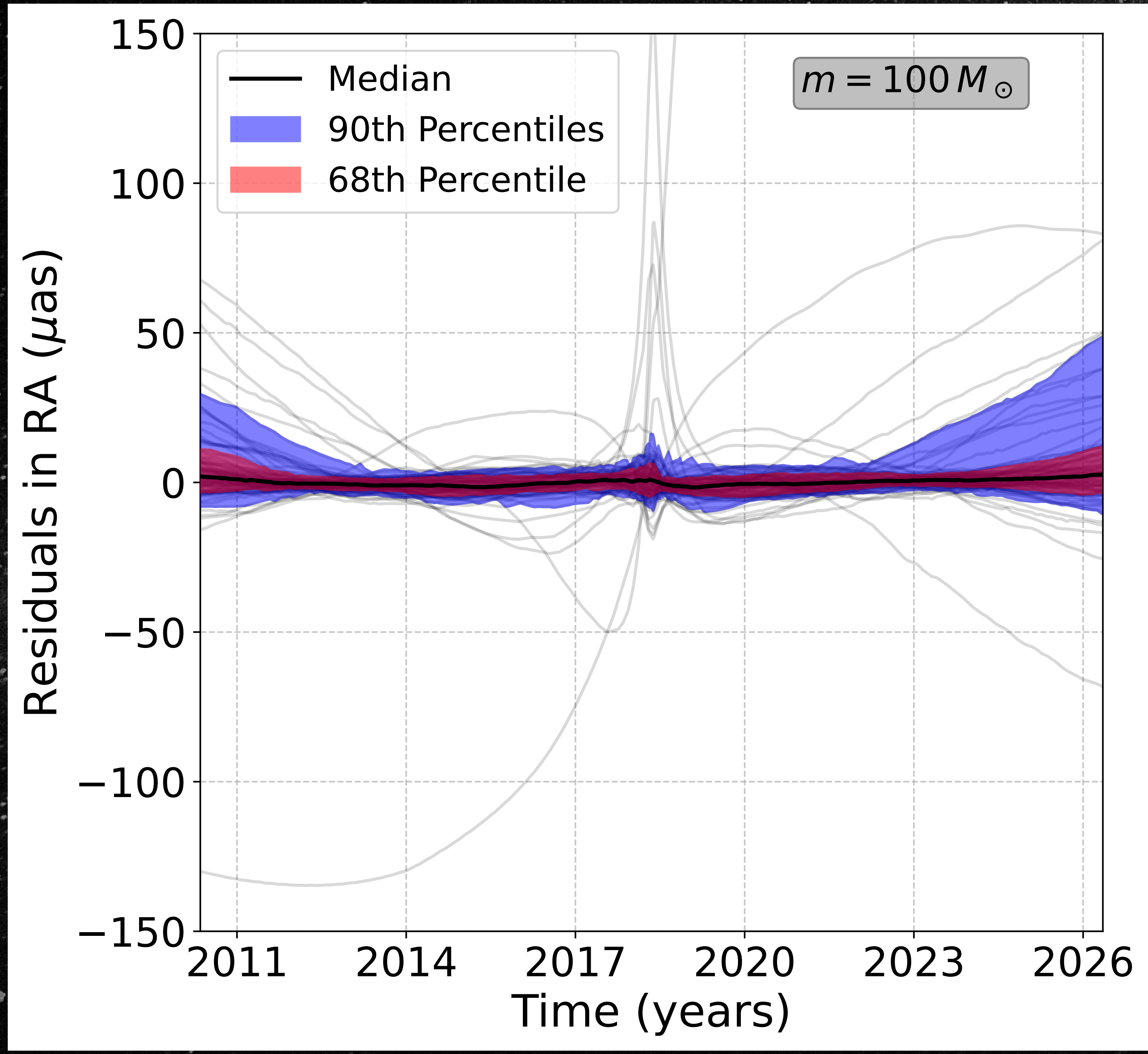

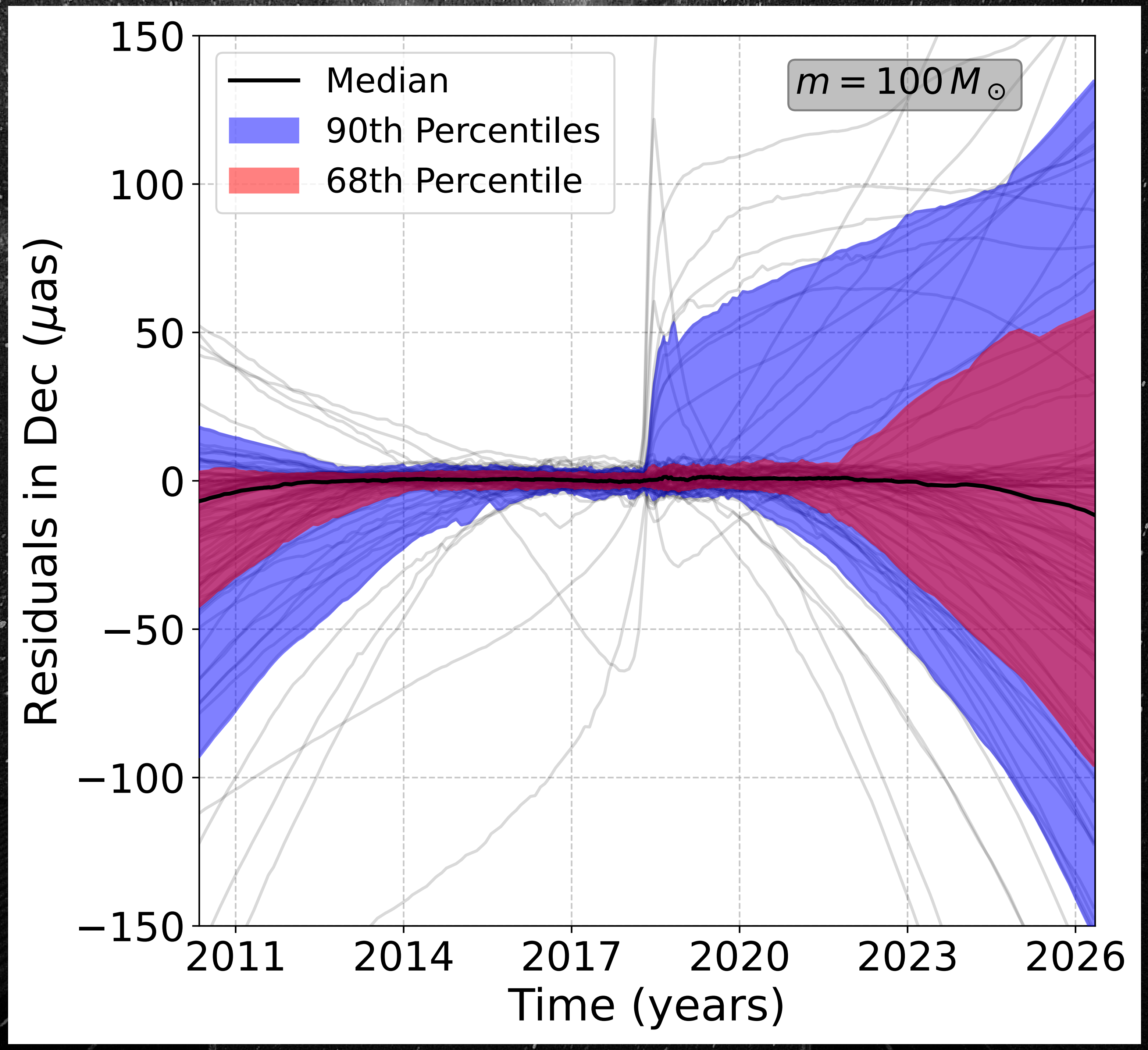

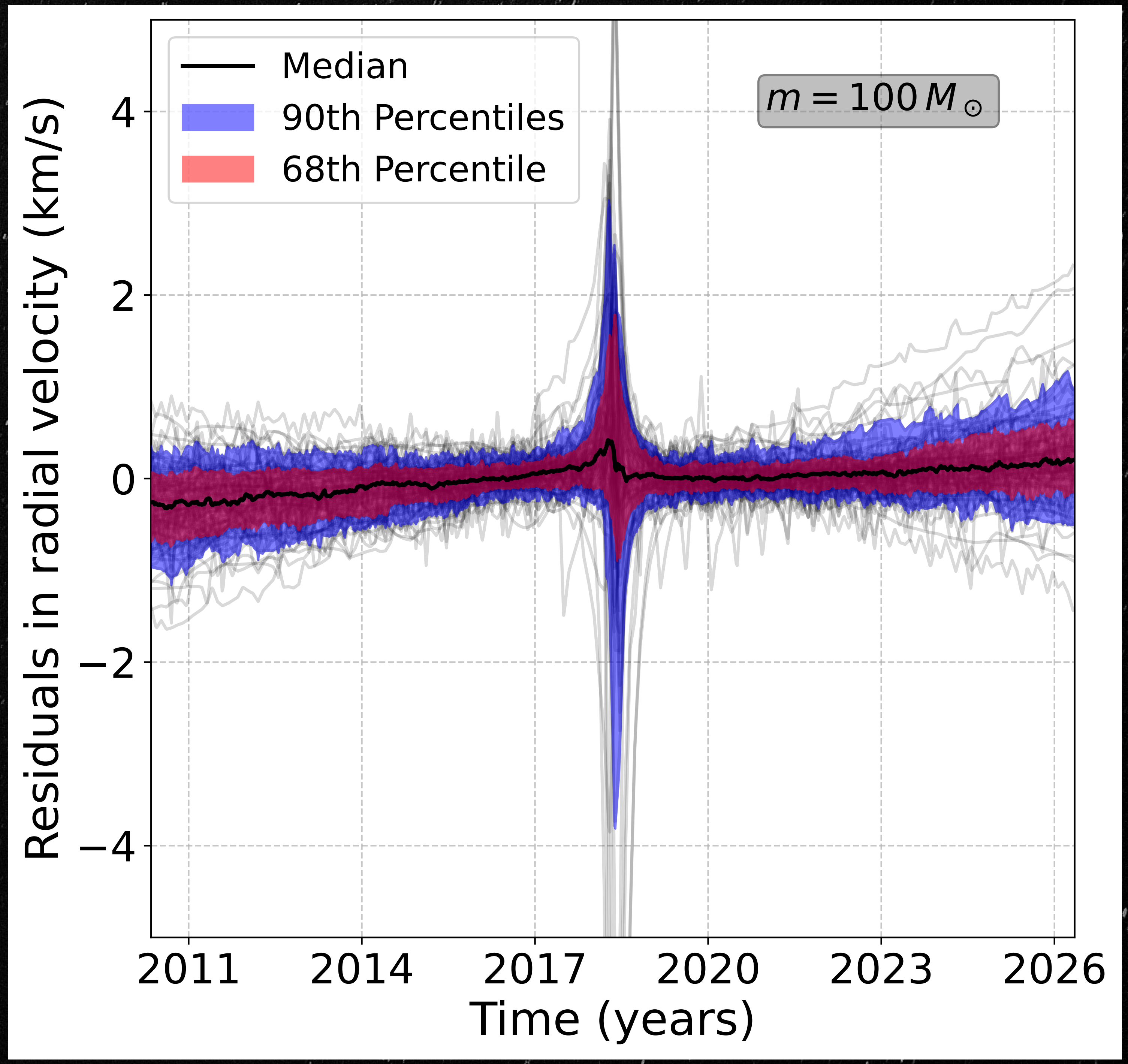

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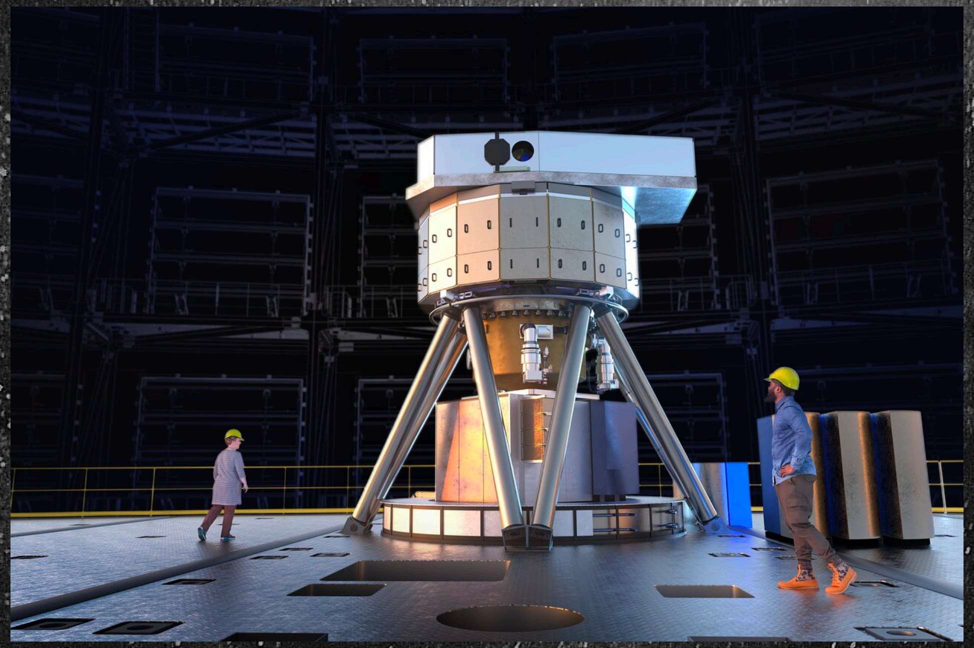
(M. Sadun Bordoni et al. 2025, submitted to A&A)

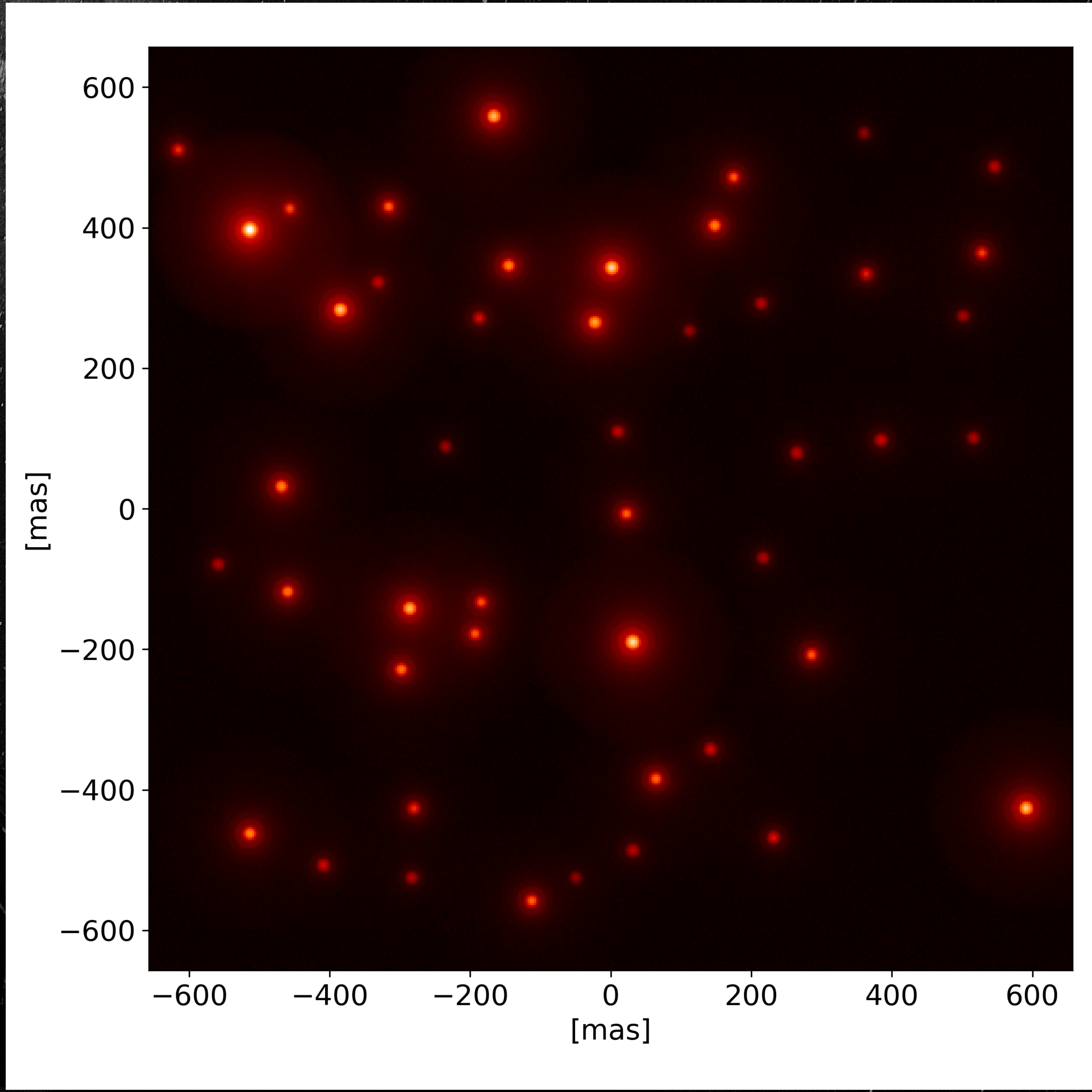
Detecting fainter stars:
The Extremely Large Telescope

ELT under construction, time-lapse
(Credit: ESO)



Model of MICADO:
Multi-AO Imaging Camera
for Deep Observations
(Credit: ESO)

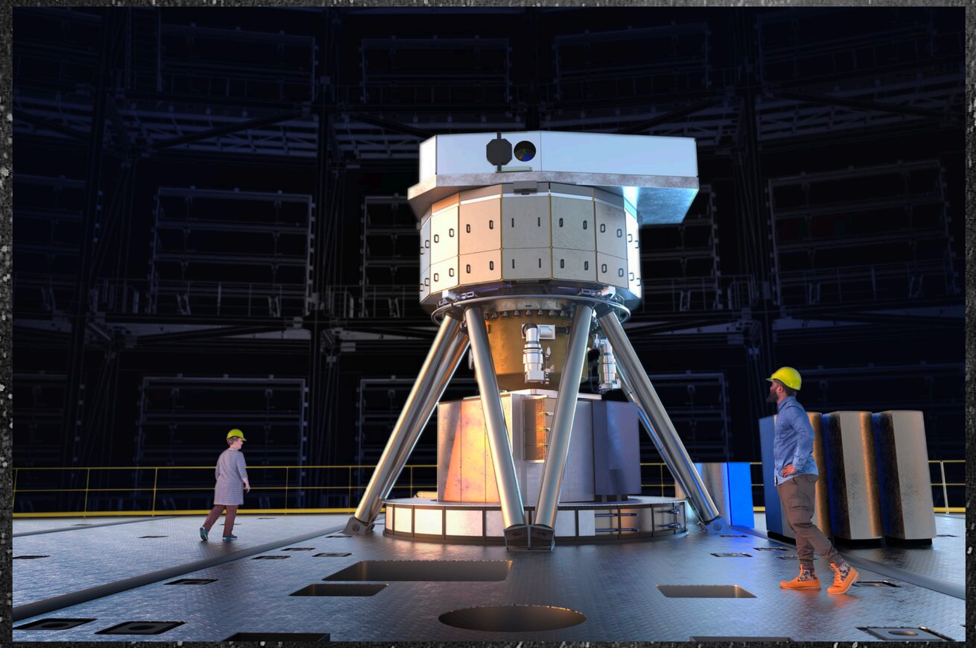
- **Main mirror of 39 meters**
- **Improvement in sensitivity of factor >100 compared to GRAVITY+, but lower angular resolution**



Mock image of the GC with MICADO,
With the known S-stars

Detecting fainter stars:
The Extremely Large Telescope

ELT under construction, time-lapse
(Credit: ESO)



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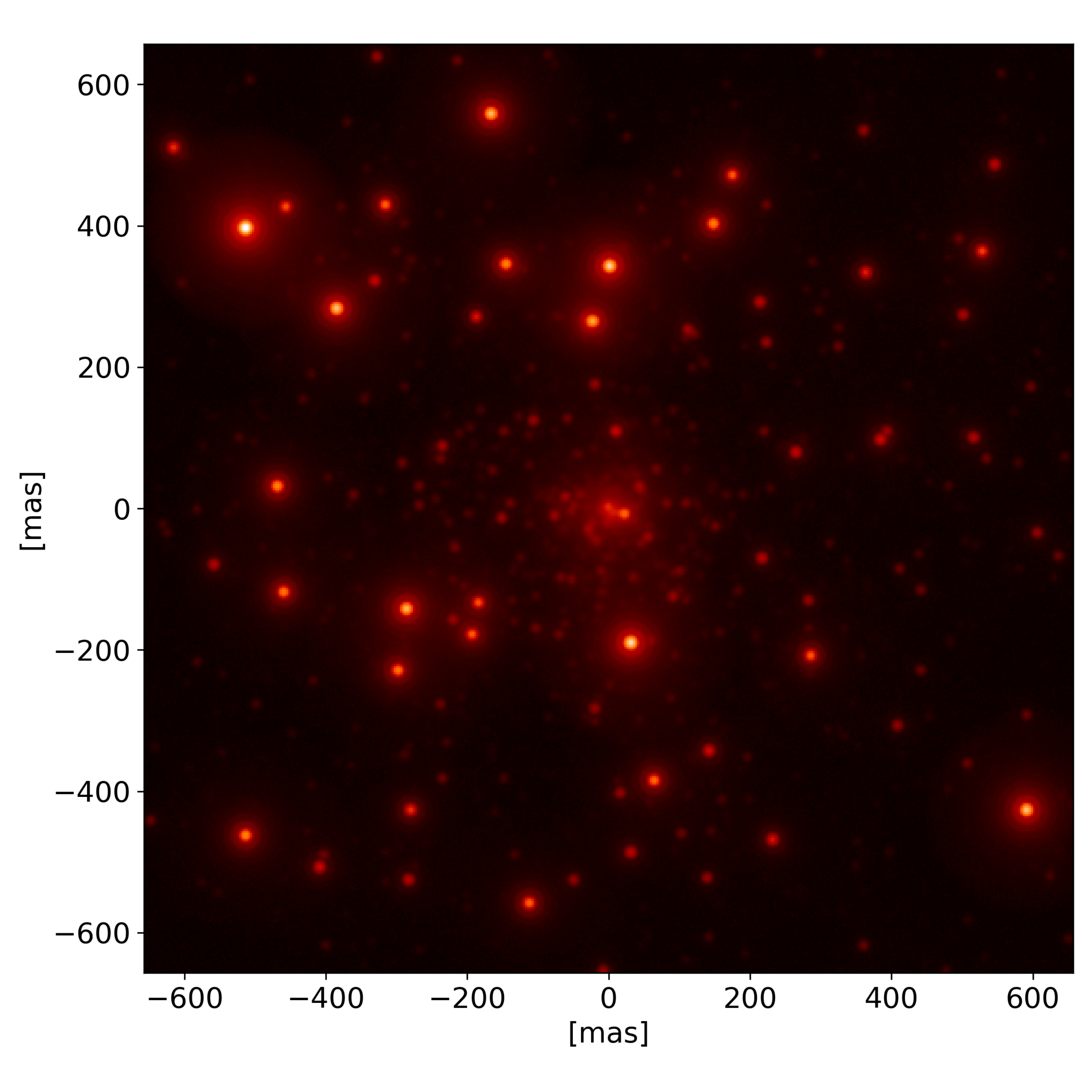


Mock image of the GC with MICADO, including potential fainter stars following a power-law cusp

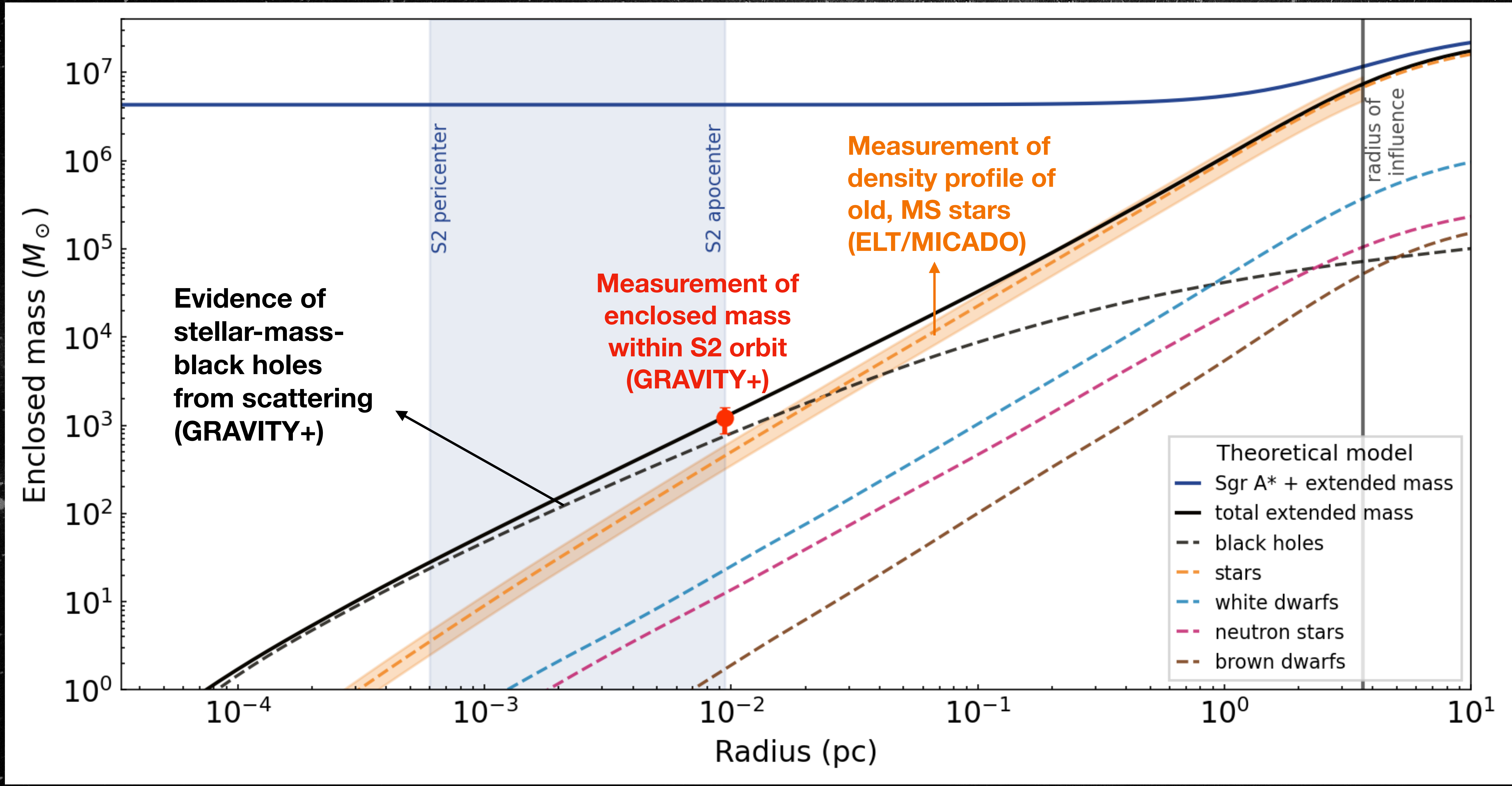
- **Main mirror of 39 meters**
- **Improvement in sensitivity of factor > 100 compared to GRAVITY+, but lower angular resolution**
- **Detect the fainter, main-sequence stars of $m \lesssim 1.5\, M_{\odot}$ and measure their density profile**

→ **Is there a dynamically relaxed stellar cusp in the GC?**

(Baumgardt, Amaro Seoane et al. 2018, Schödel et al. 2018, Gallego-Cano et al. 2018)

The mass distribution in the Galactic center:
What can we learn before LISA flies?

The Milky Way is a standard galaxy for LISA: what can we learn from our own Galactic center about the mass distribution around SMBHs?



Enclosed mass profile for a stellar cusp in the Galactic center from numerical simulations
(Zhang & Amaro-Seoane 2025)

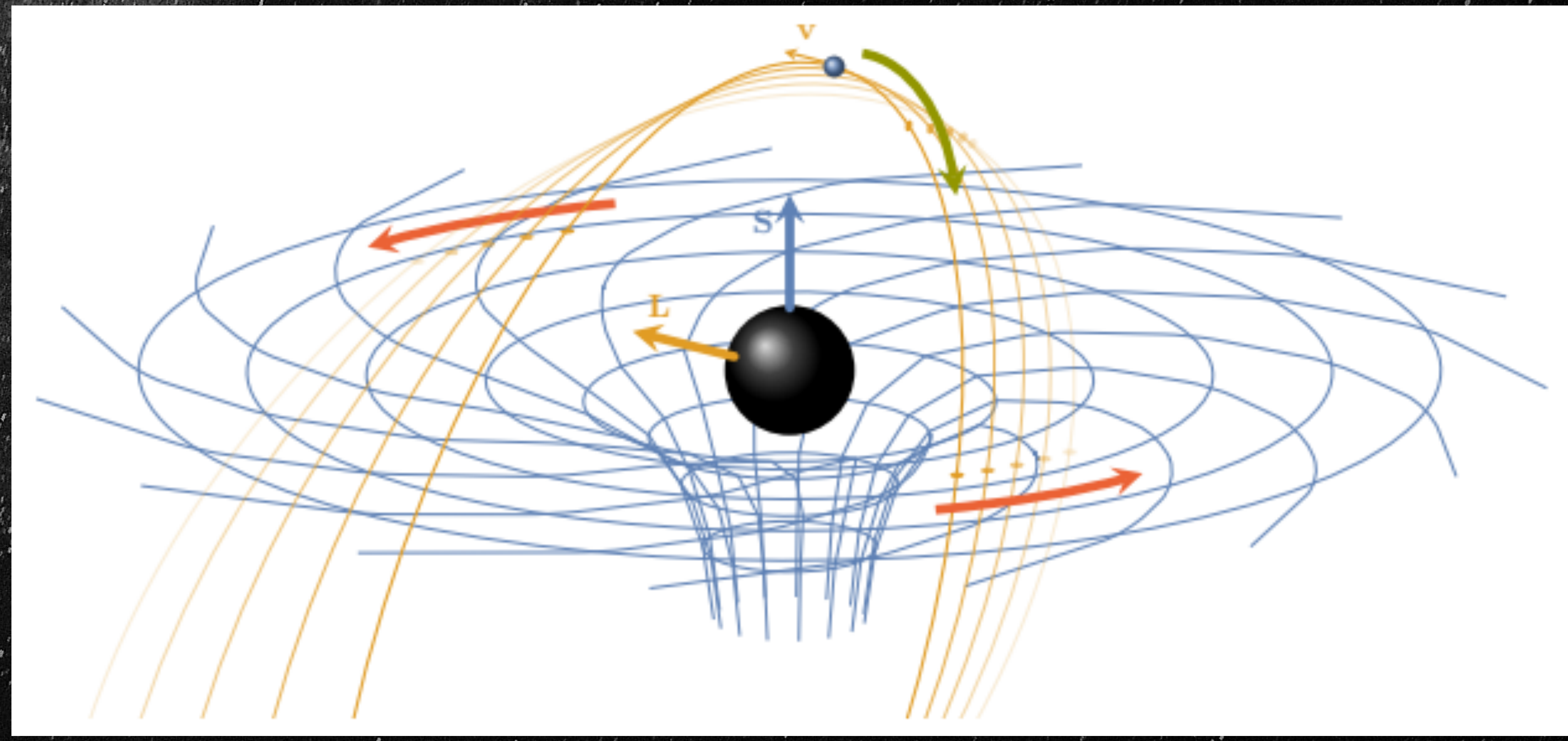
- **Is there a dynamically relaxed stellar cusp in the GC?**
- **What is the EMRI rate in a Milky Way—like Galaxy?**
- **Will we observe early EMRIs and XMRIs in the GC?**

(Amaro Seoane 2019, Amaro Seoane et al. 2025)

Towards the measure of the spin of Sgr A*
The Lense-Thirring precession

- **Lense-Thirring effect is orders of magnitude smaller than the Schwarzschild precession:**

$$\delta\Phi_{LT} = 4\pi\chi\left(\frac{R_S}{2a(1-e^2)}\right)^{3/2} \sim 0.1' \; \textit{per orbit} \text{ for S2}$$



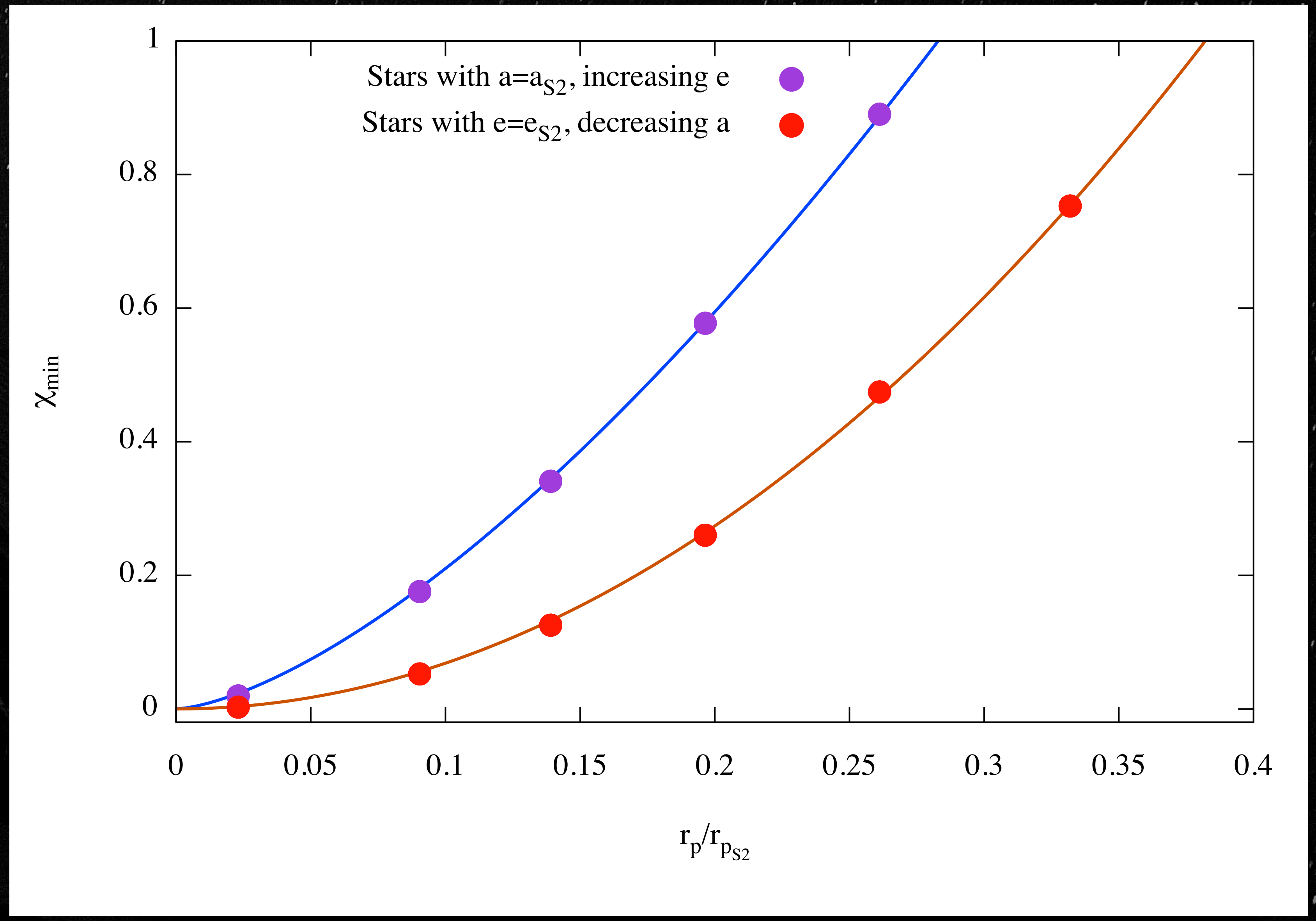
Lense-Thirring effect

- **Too small to be detected with S2: need a star with pericenter distance at least 3 times smaller**

ELT Spectroscopy

+

GRAVITY+ astrometry

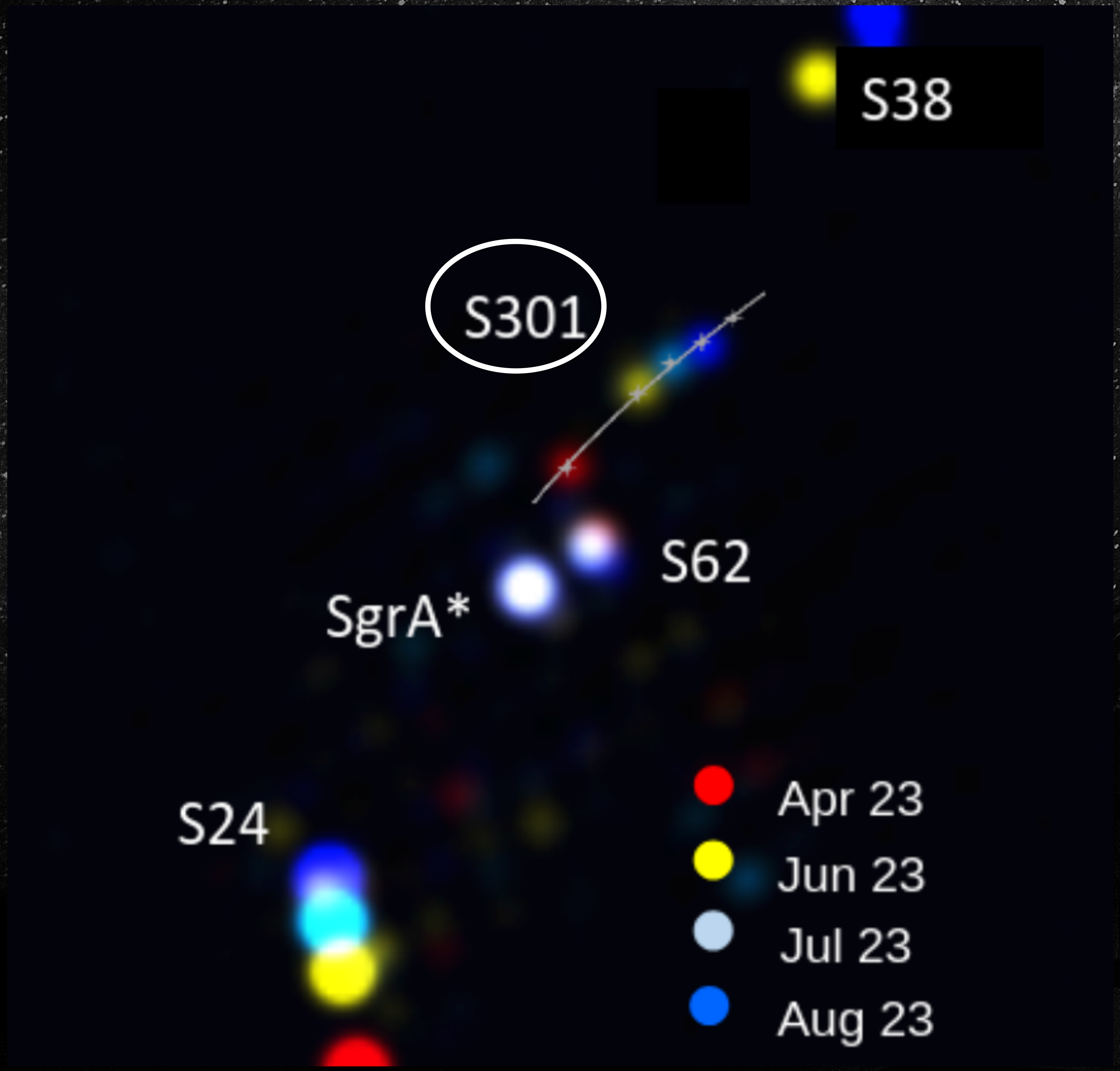


Minimum value of the spin detectable in function of pericenter distance *(Capuzzo-Dolcetta & Sadun-Bordoni, MNRAS 2023)*

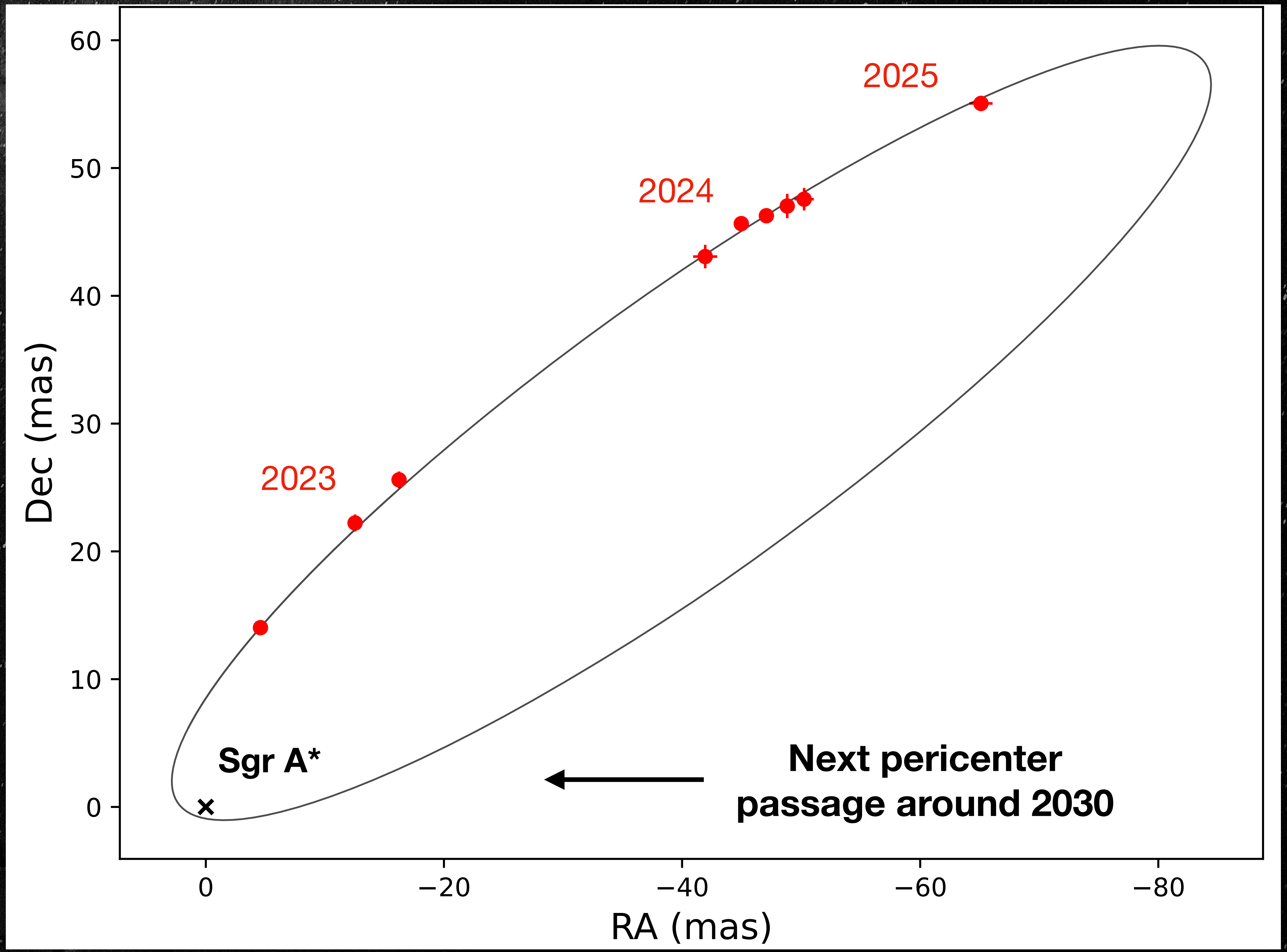
Towards the measure of the spin of Sgr A*
S301: A possible candidate

- **Faintest star detected so far with GRAVITY**
- **Pericenter distance 3-5 times smaller than S2**

→ **Observing it at the next pericenter passage might give us the spin of Sgr A***



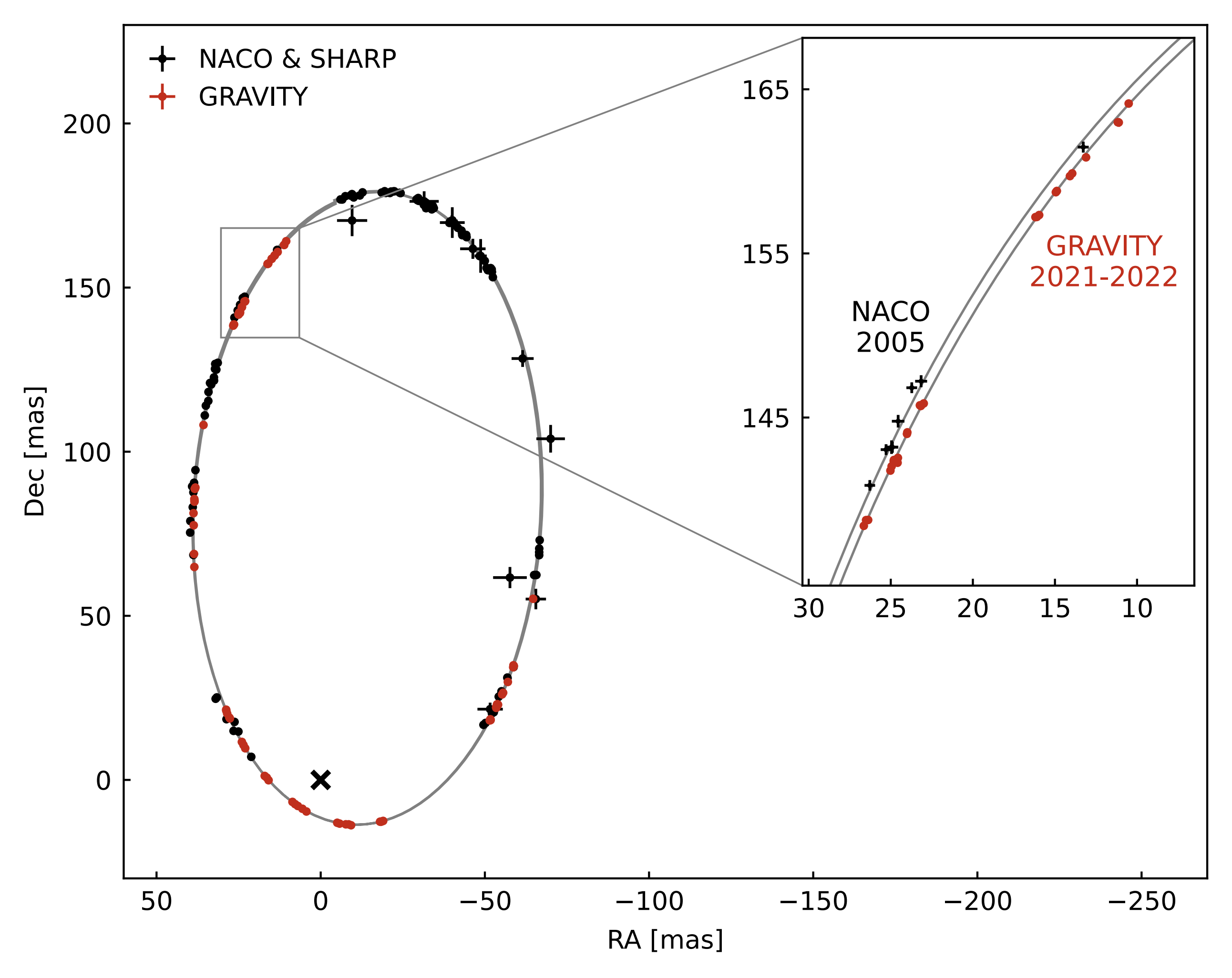
Reconstructed images of the Galactic center in 2023
(F. Mang & GRAVITY+ Collaboration 2025, in prep.)



Orbit of S301

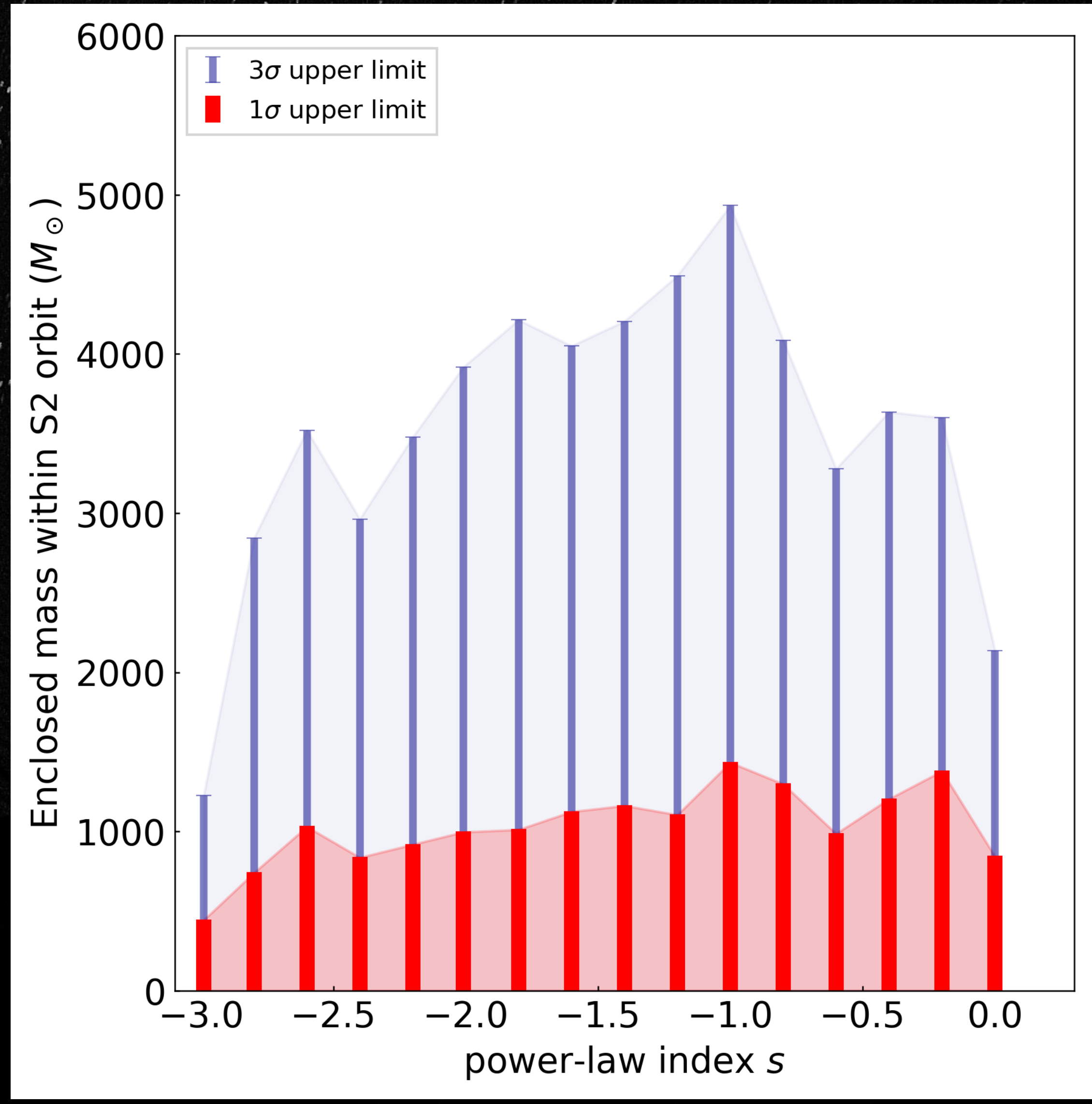
Summary:
What do we know?

- **<u>Schwarzschild precession of the S2 orbit:</u>** measured with ~10σ confidence



- **<u>Constraints on the extended mass distribution around Sgr A*:</u> upper limit of $\approx 1200\,M_\odot$ within S2 orbit** (~10 mpc), assuming smooth density profile

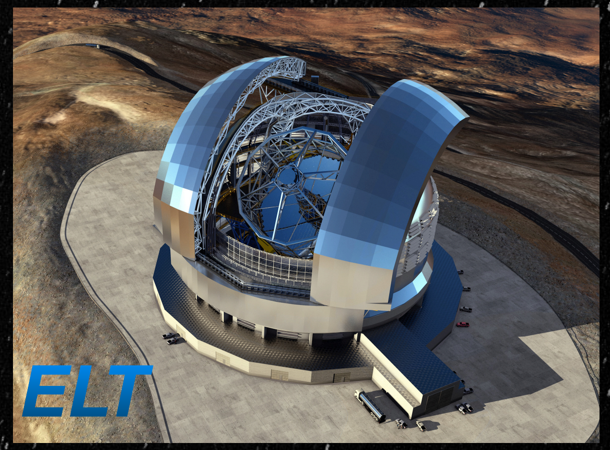
    1. Upper limit very close to theoretical predictions for the stellar cusp in the Galactic center
    2. No evidence of a dark matter spike around Sgr A*



Summary:
What can we learn before LISA flies?

- **Future goals with GRAVITY+ and the ELT:**

1. Measuring the spin of Sgr A*
2. Measuring the “dark” mass enclosed within the S2 orbit
3. Measuring scattering on the S2 orbit by stellar-mass black holes
4. Measuring the density profile of the faint, old, low-mass stars that are part of the cusp



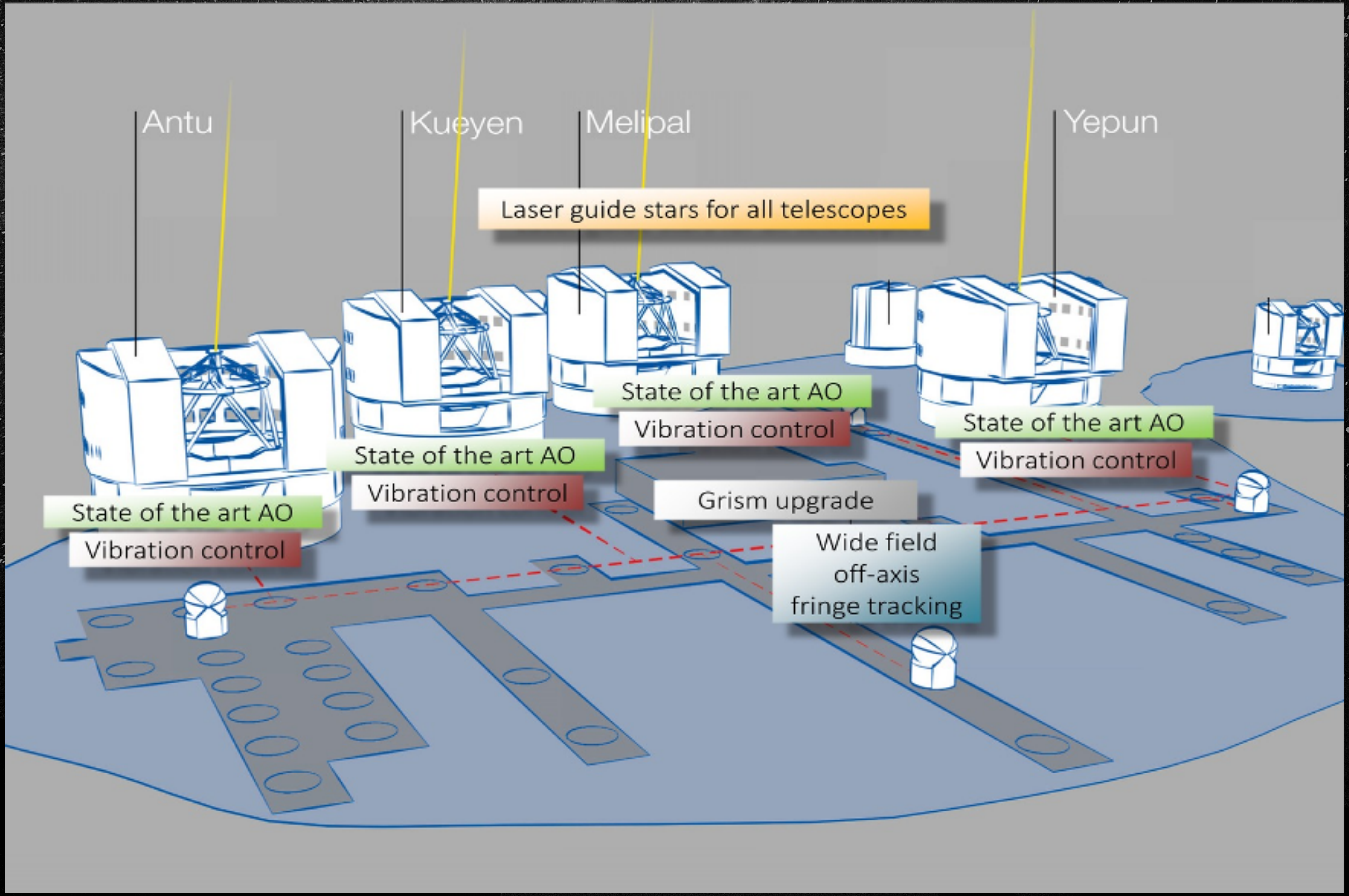
→ What is the mass distribution near MBHs in galactic nuclei? Is there a dynamically relaxed cusp?

→ What is the EMRI rate in Milky Way - like galaxies?

Backup slides

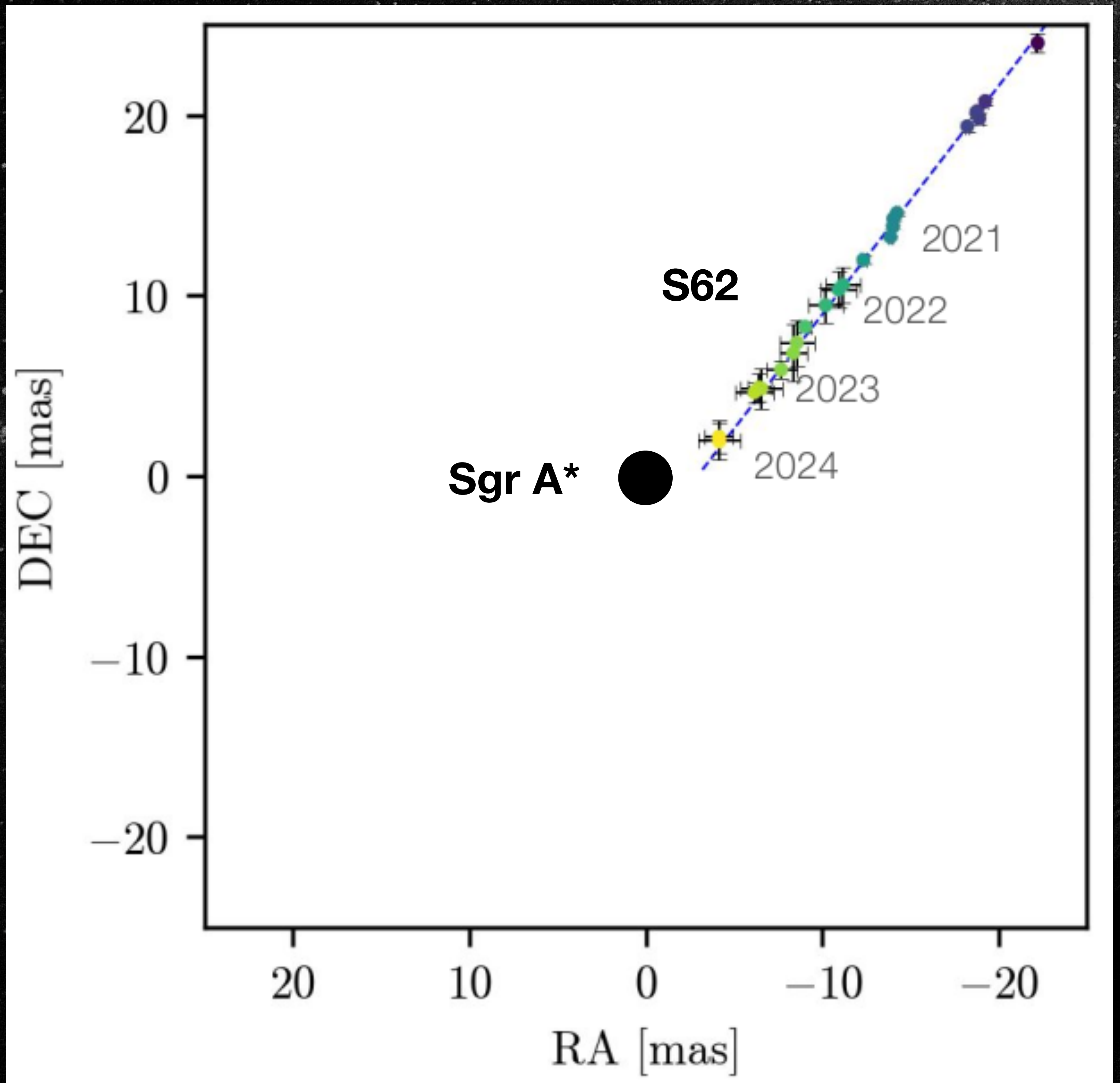
The GRAVITY+ upgrade

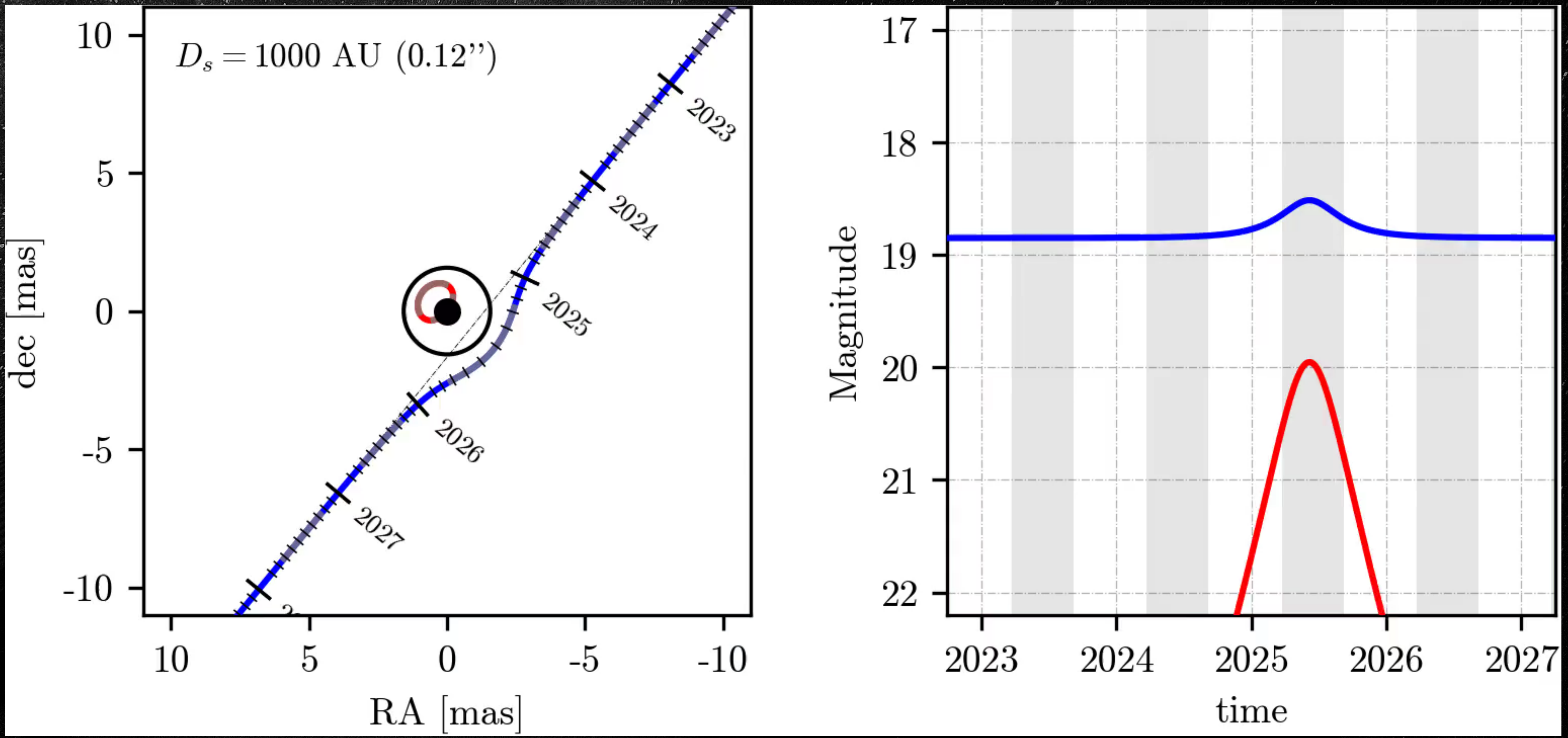
With Laser Guide Stars and new Adaptive Optics system for each telescope: improvement of factor 10-100 in sensitivity!



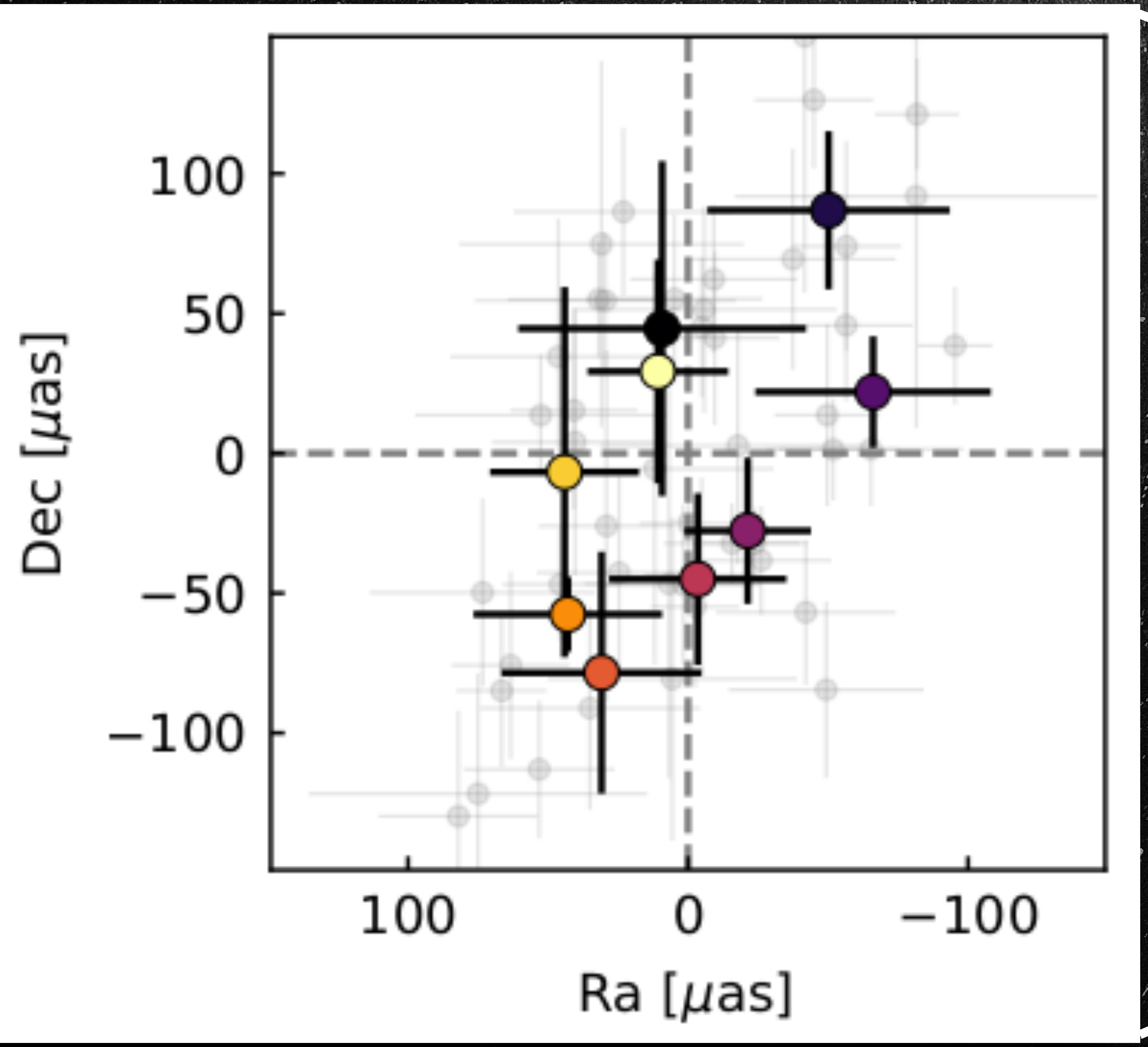
The Lensing candidate S62

Potential detection of lensing of S62 by Sgr A*: another test of GR in the GC
GRAVITY data in 2025 will be key to measure it



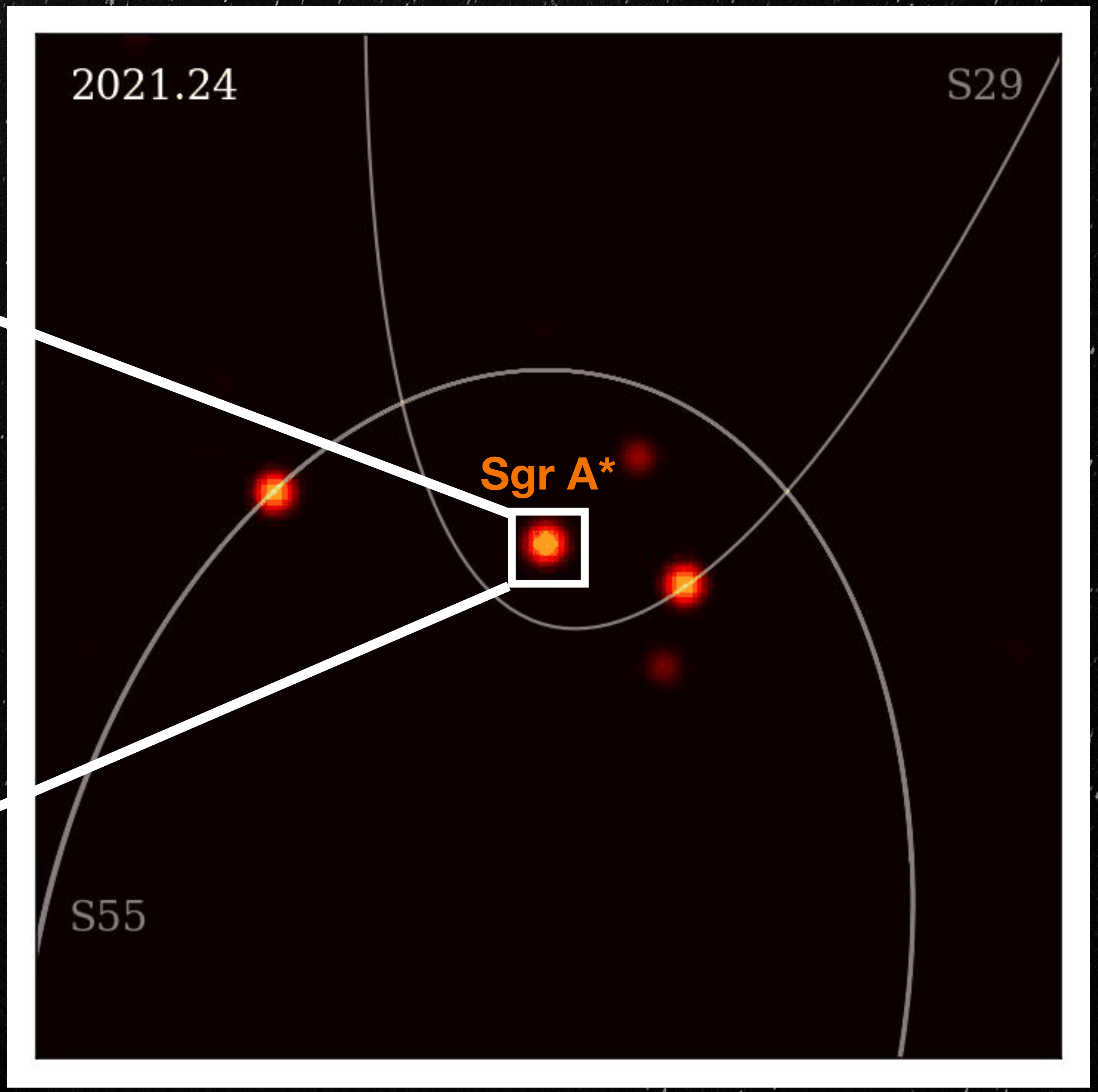


Flares of Sgr A*



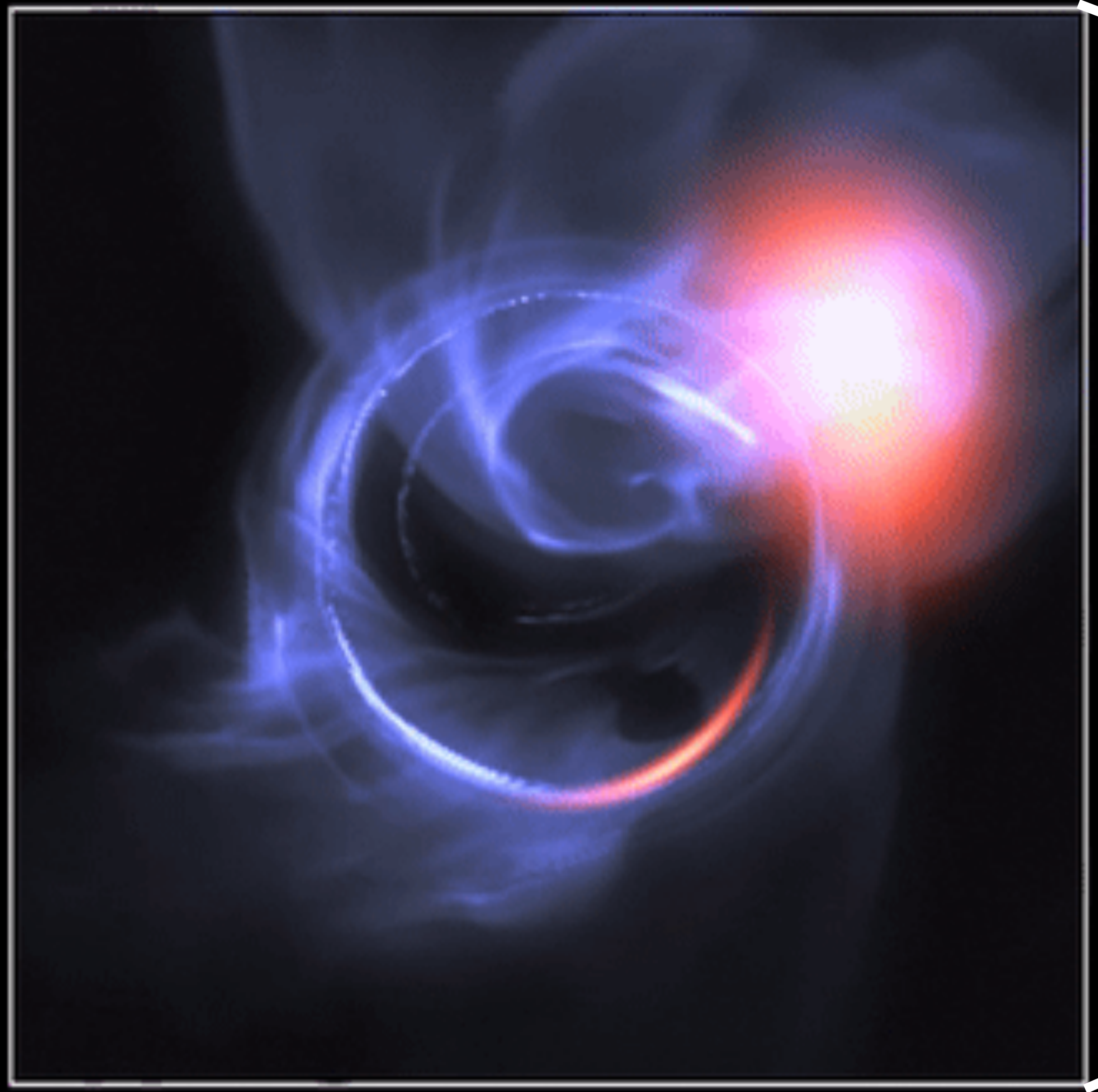
Astrometry of flares orbiting Sgr A* close to the ISCO *(GRAVITY Coll. 23)*

0.15 arcsec ≈ 6 mpc



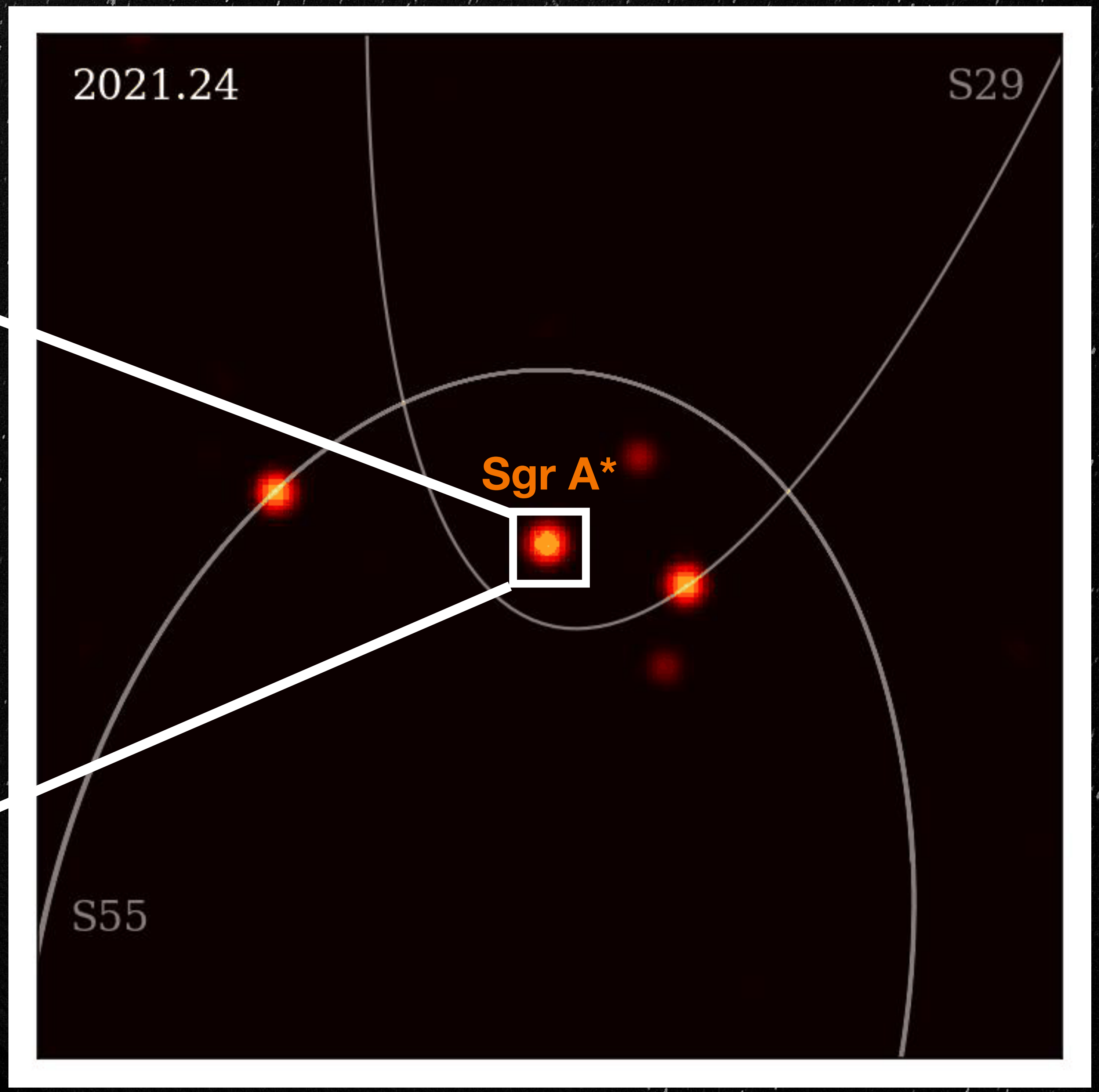
2 years of GRAVITY data (reconstructed images)

Flares of Sgr A*



Simulation of hotspot orbiting Sgr A* close to the ISCO
(Credit: ESO/Gravity Coll./L. Calçada)

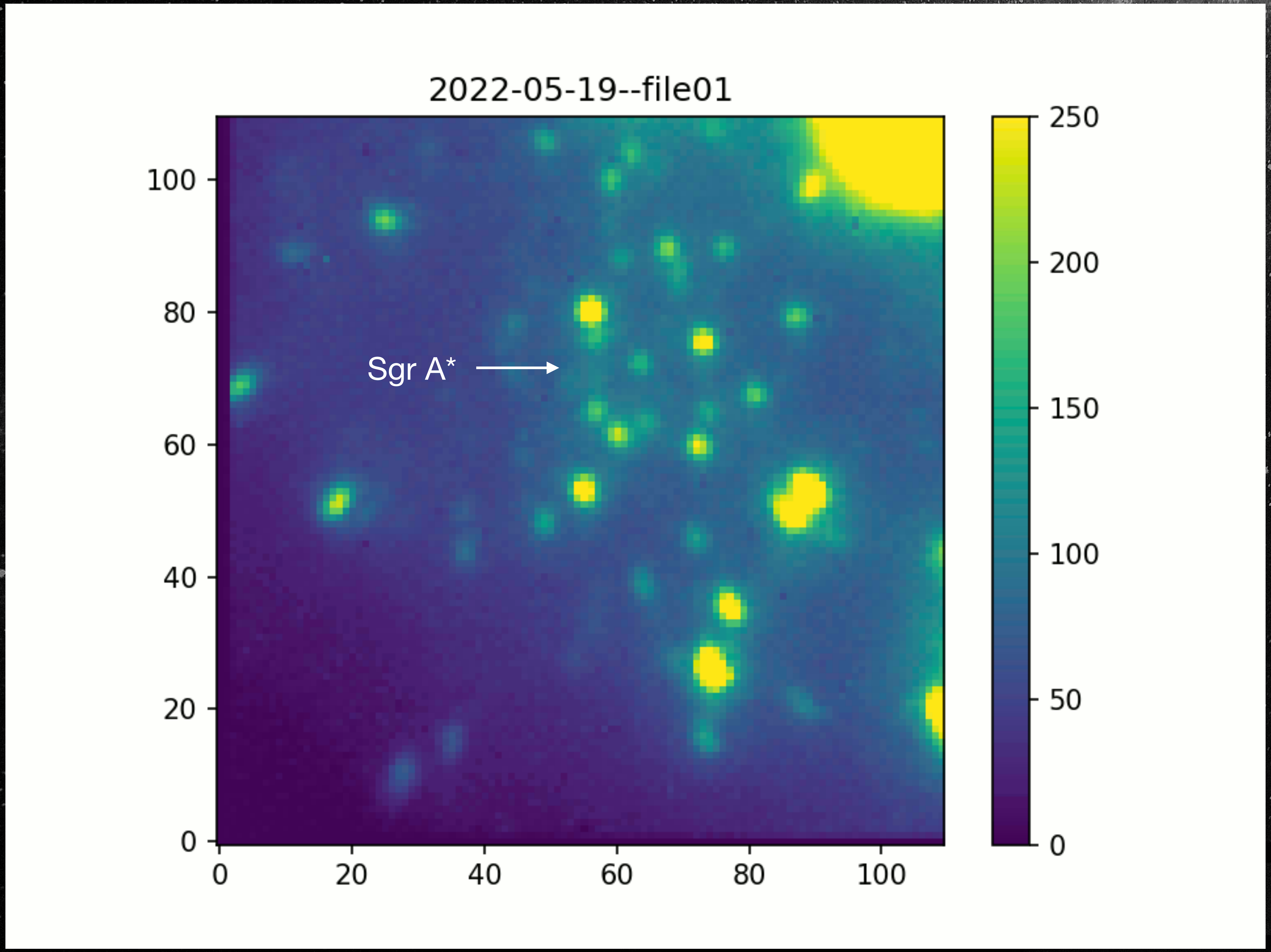
0.15 arcsec ≈ 6 mpc



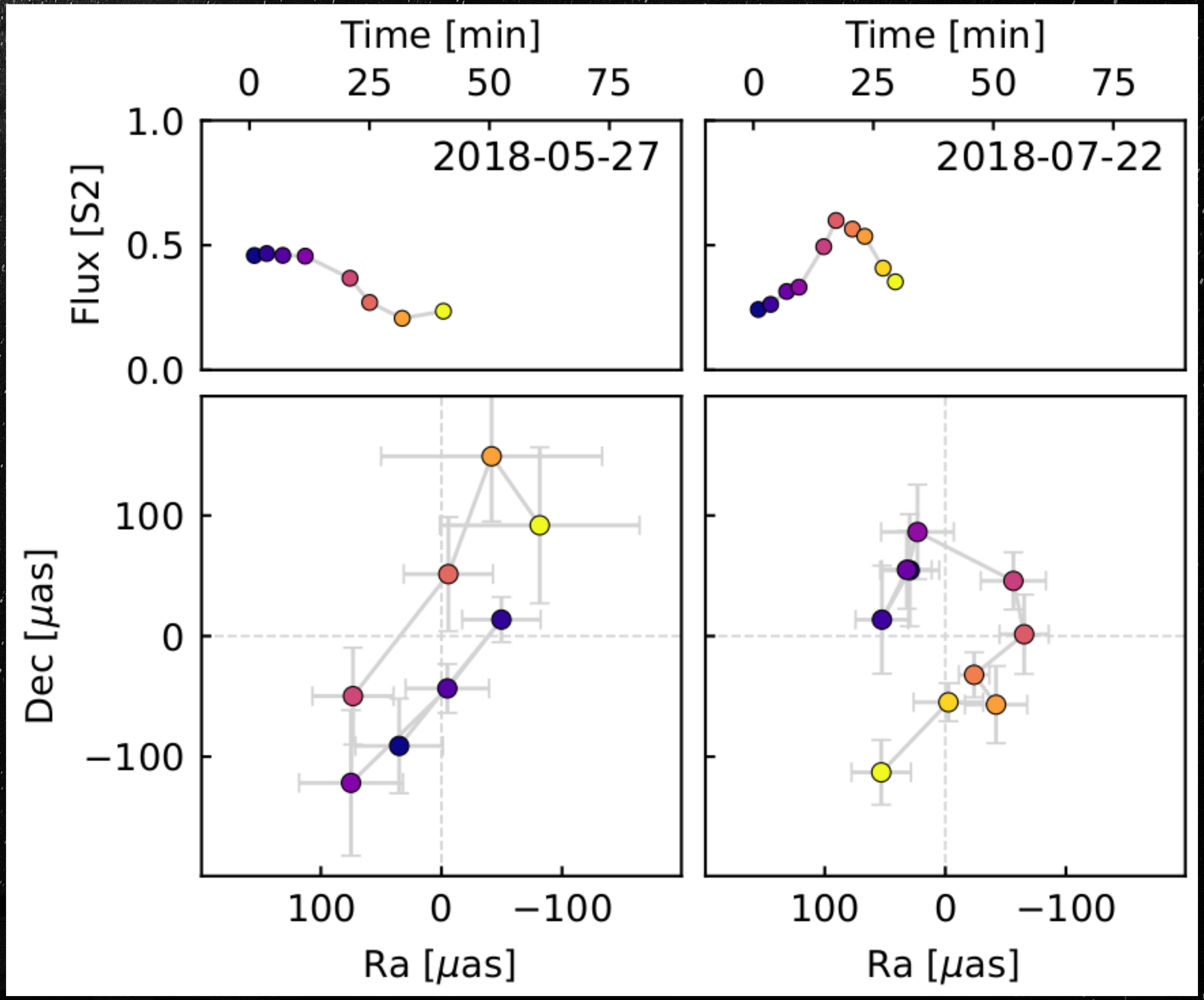
2 years of GRAVITY data
(reconstructed images)

Flares of Sgr A*

- Sudden increase in brightness in NIR emission of Sgr A*: most likely locally heated electrons emitting synchrotron radiation
- We measure the centroid motion of the emission



GRAVITY acquisition camera



Flare orbit

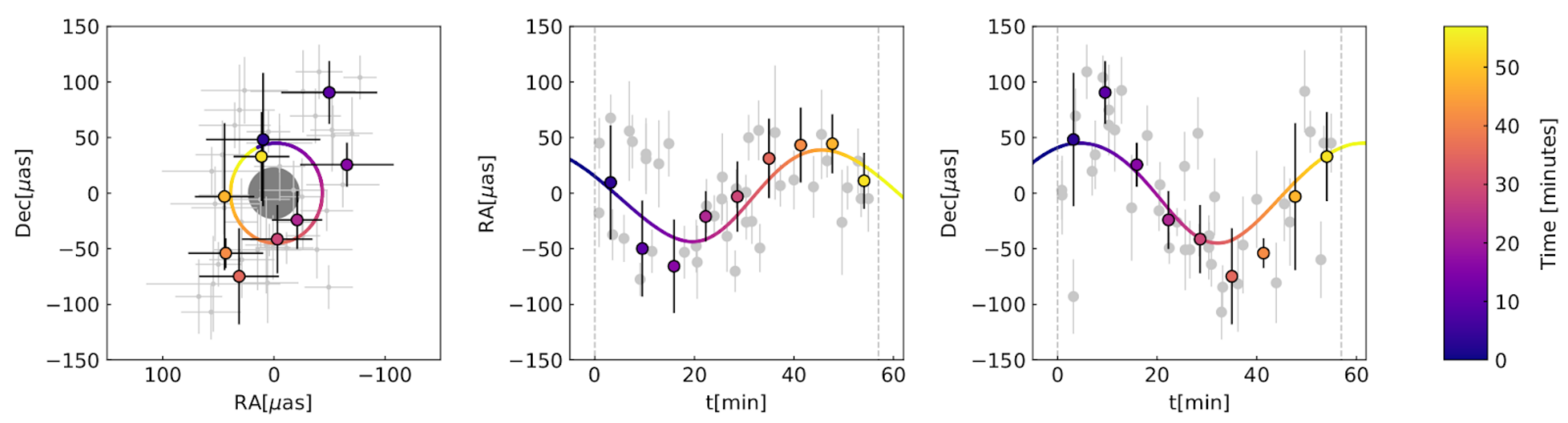
Flares of Sgr A*

- We obtained 4 astrometric orbits of flares with GRAVITY:

    1. All clockwise
    2. All similar period of few tens of minutes
    3. All similar radius of ~ 75 μas

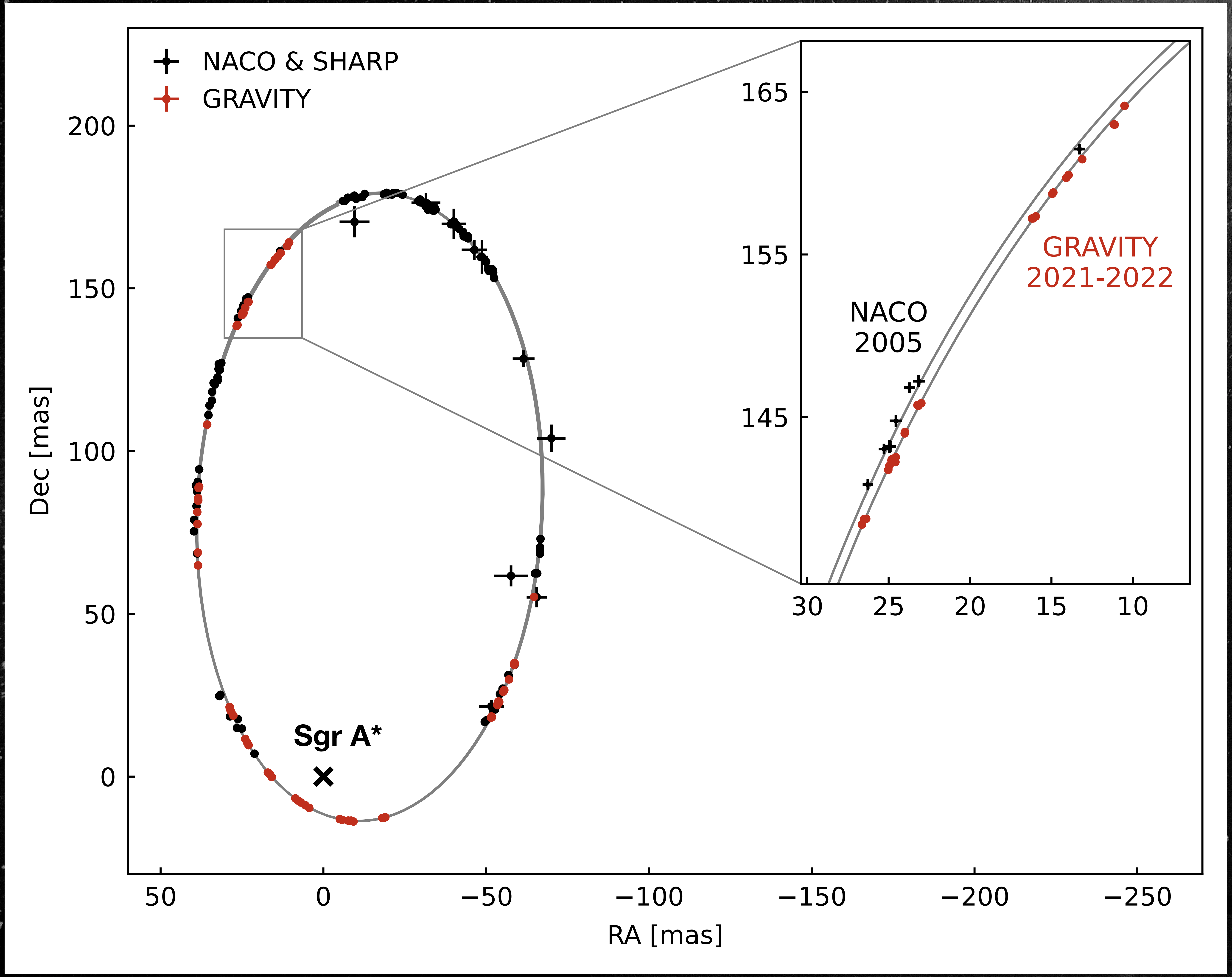
We combine the data in a single, averaged orbit and fit a relativistic hotspot model:

- Radius: $R = 8.9^{+1.5}_{-1.3} R_g$
- Inclination: $i = 154.9^{+4.6}_{-4.6}\, deg$
- Position angle $\Omega = 177.3^{+24}_{-23}\, deg$
- Enclosed mass $M_\bullet = 4.2^{+1.2}_{-0.9} \times 10^6 M_\odot$



Average of four observed flares with GRAVITY

Schwarzschild precession of S2 orbit



Orbit of S2 around Sagittarius A*

Prograde, in-plane precession of the orbit's pericenter angle, predicted by General Relativity

$$\delta\varphi_{1PN} = \frac{6\pi G}{c^2}\frac{m_\bullet}{a(1-e^2)} \sim 12' \; per\,orbit$$

Our measurement, assuming :

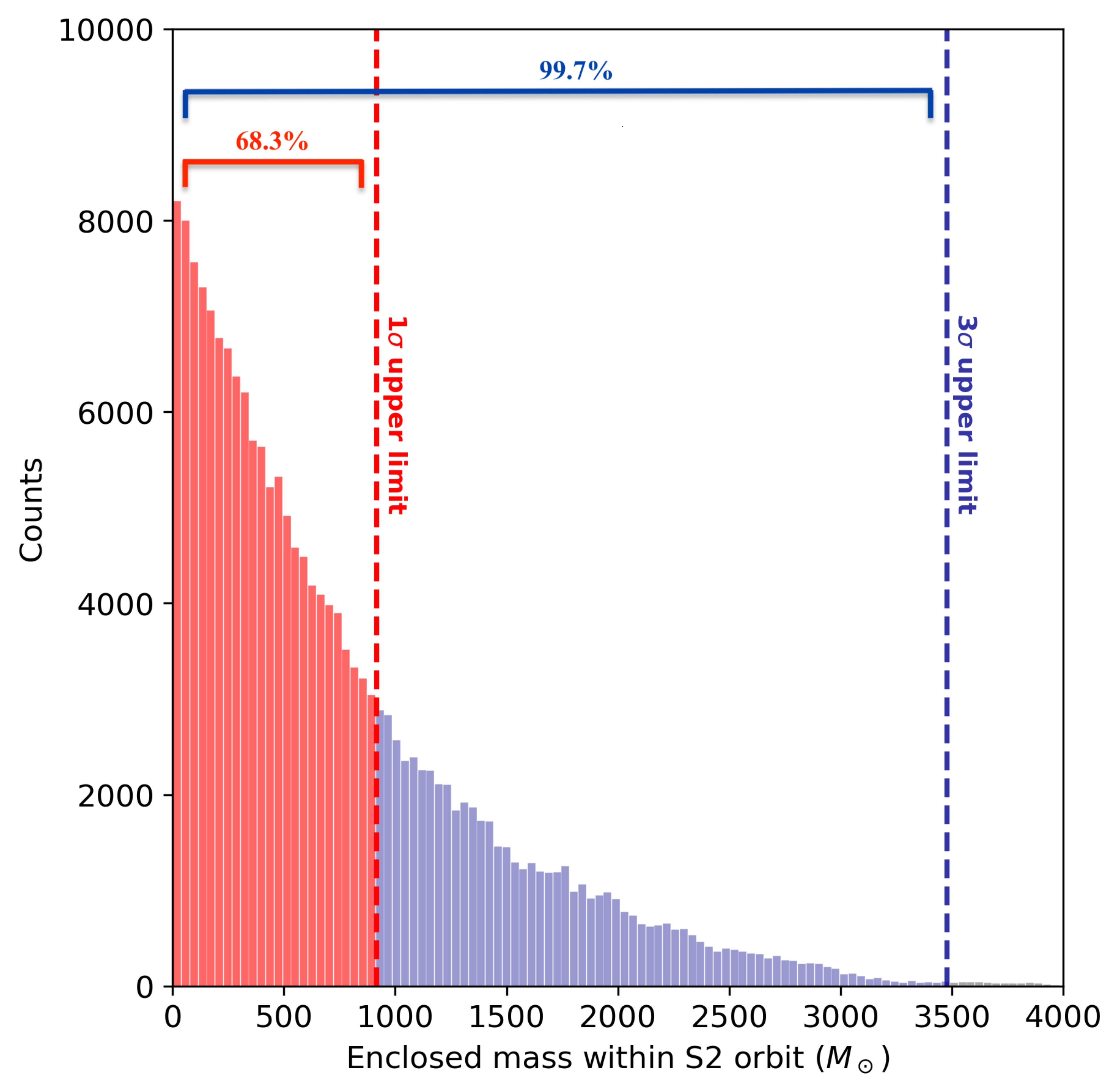
$$\vec{a}_{S2} = GM_\bullet \frac{\vec{r}}{|\vec{r}|^3} + f_{SP}\,\vec{a}_{1PN}$$

$$\rightarrow \quad \delta\varphi_{obs} = f_{SP} \times \delta\varphi_{1PN}$$

$$f_{SP} = 1.1 \pm 0.1$$

$\rightarrow$ **$\approx 10\sigma$ detection**

Constraining an extended mass distribution



Example of posterior distribution on the enclosed mass within S2's orbit, showing how the 1σ and 3σ upper limits are derived (multi-star fit, power-law with slope $s = -2.2$).

Power-law density profile

$$\rho(r) = \tilde{\rho}\left(\frac{r}{r_0}\right)^s$$

Mass profile

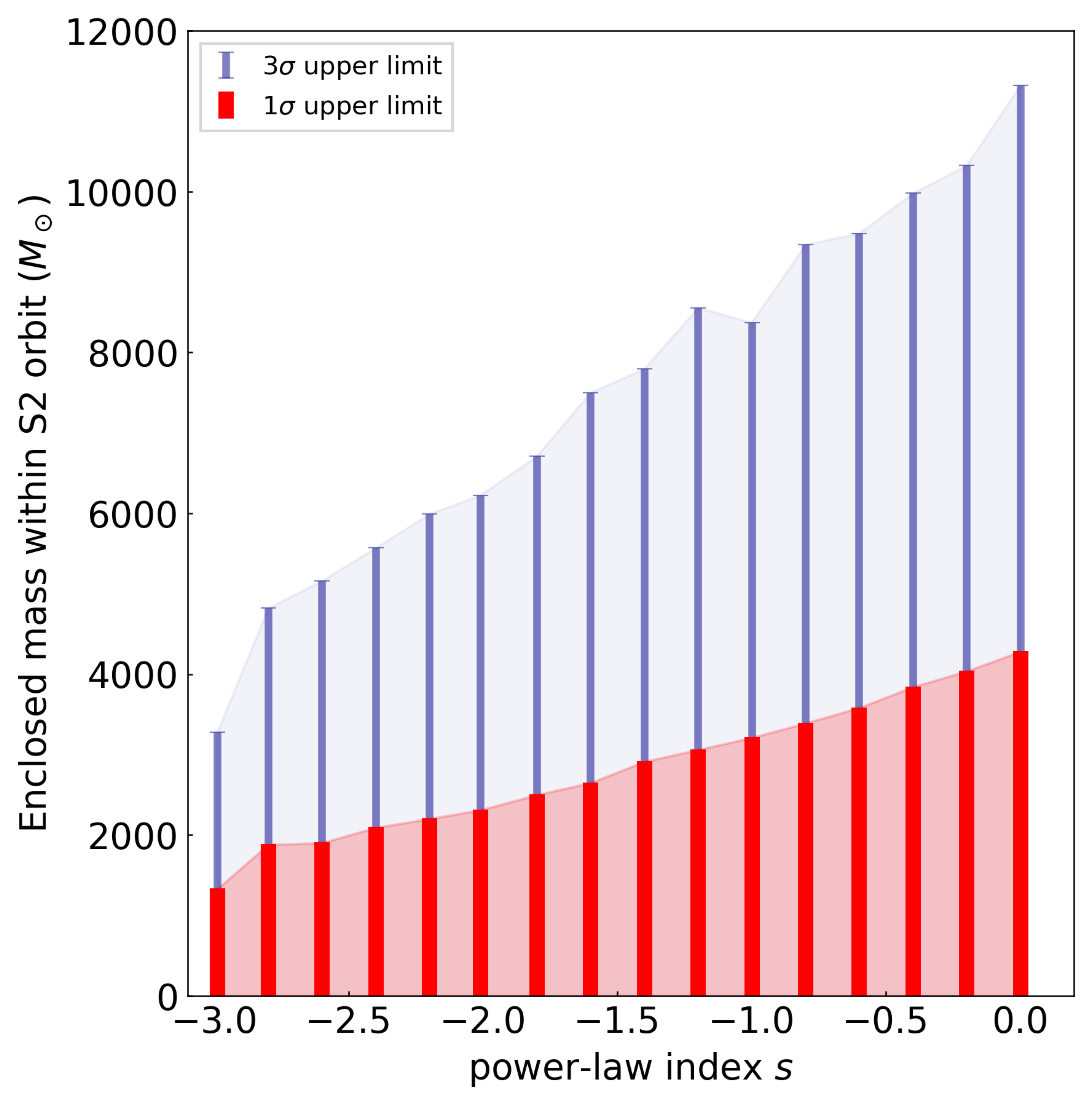
$$m(r) = \frac{4\pi\tilde{\rho}}{3+s}\left(\frac{r^{3+s}}{r_0^s}\right)$$

Assuming as a prior that $\rho(r) \geq 0$, fit for $\tilde{\rho}$ and convert the posterior distribution into a distribution on $M_{encl,S2} = m(r_{peri,S2} < r < r_{apo,S2})$

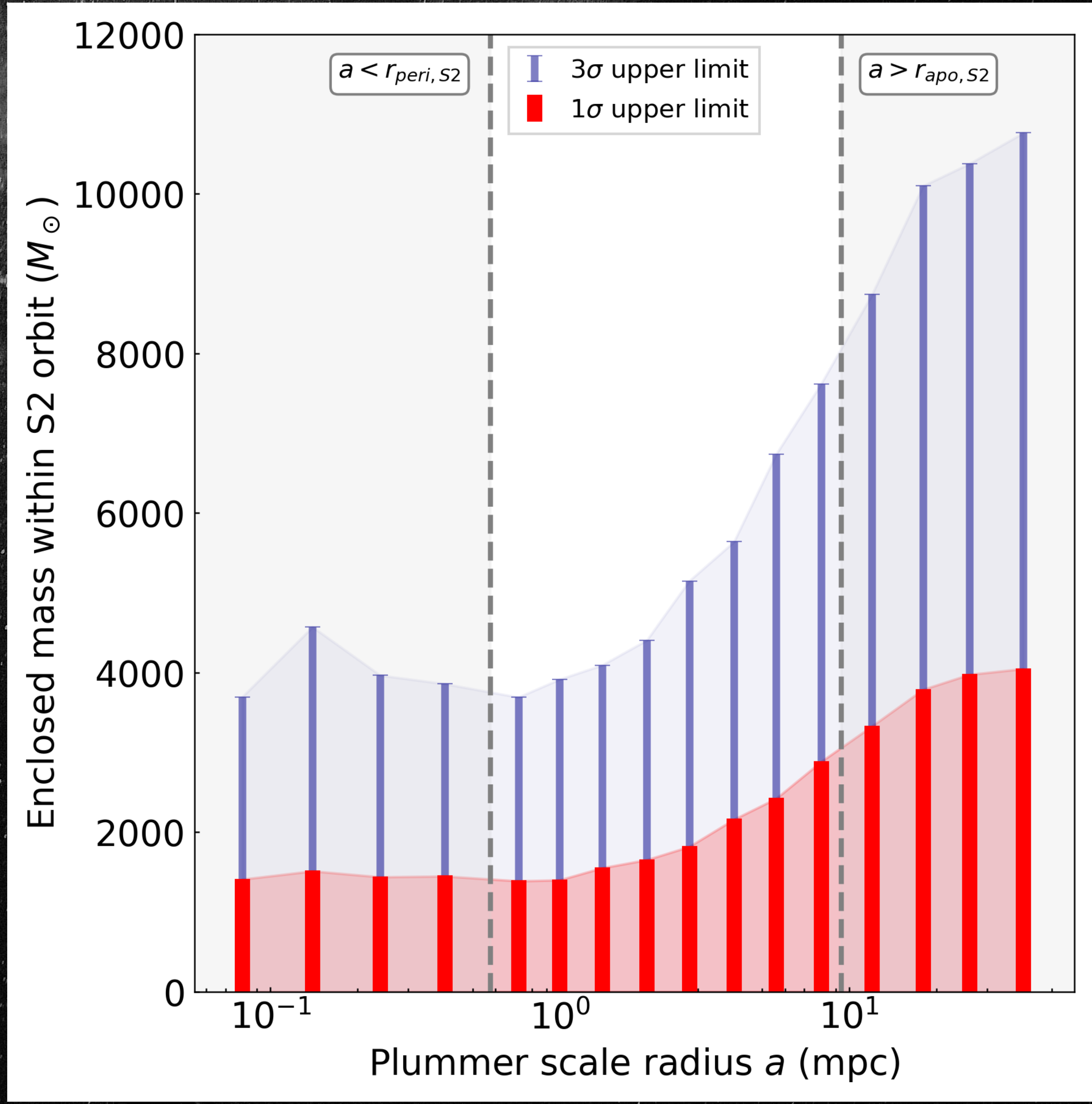
derive 1σ and 3σ upper limits

(M. Sadun Bordoni & GRAVITY Collaboration, 2024)

Constraining the extended mass distribution (S2 only fit)



Power-law profile



Plummer profile

$M_{encl,S2} \lesssim 3000\, M_\odot\ (1\sigma)$

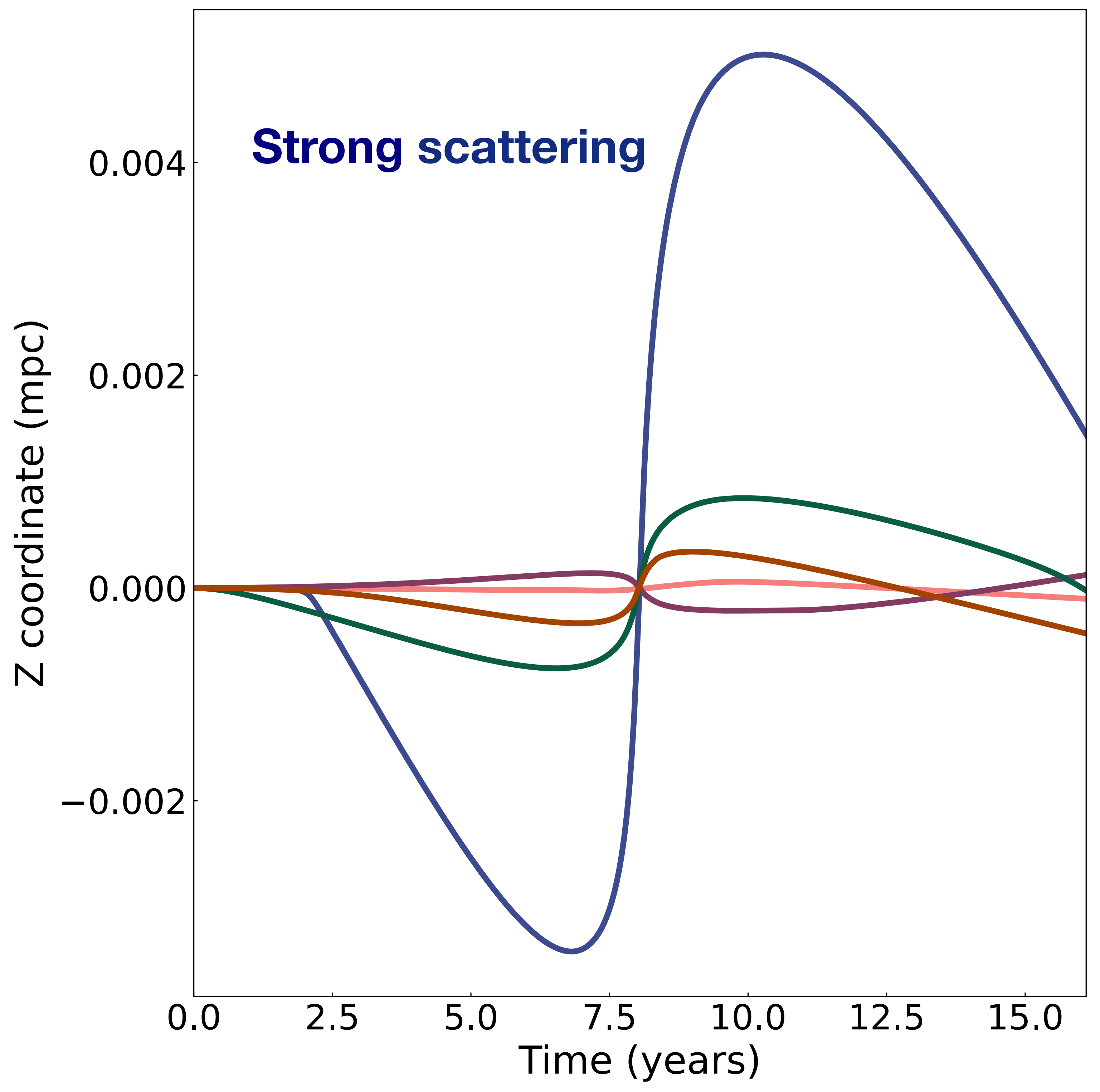
Retrograde precession $\lesssim 2'$ *per orbit*

Significantly worse constraint with respect to multi-star fit

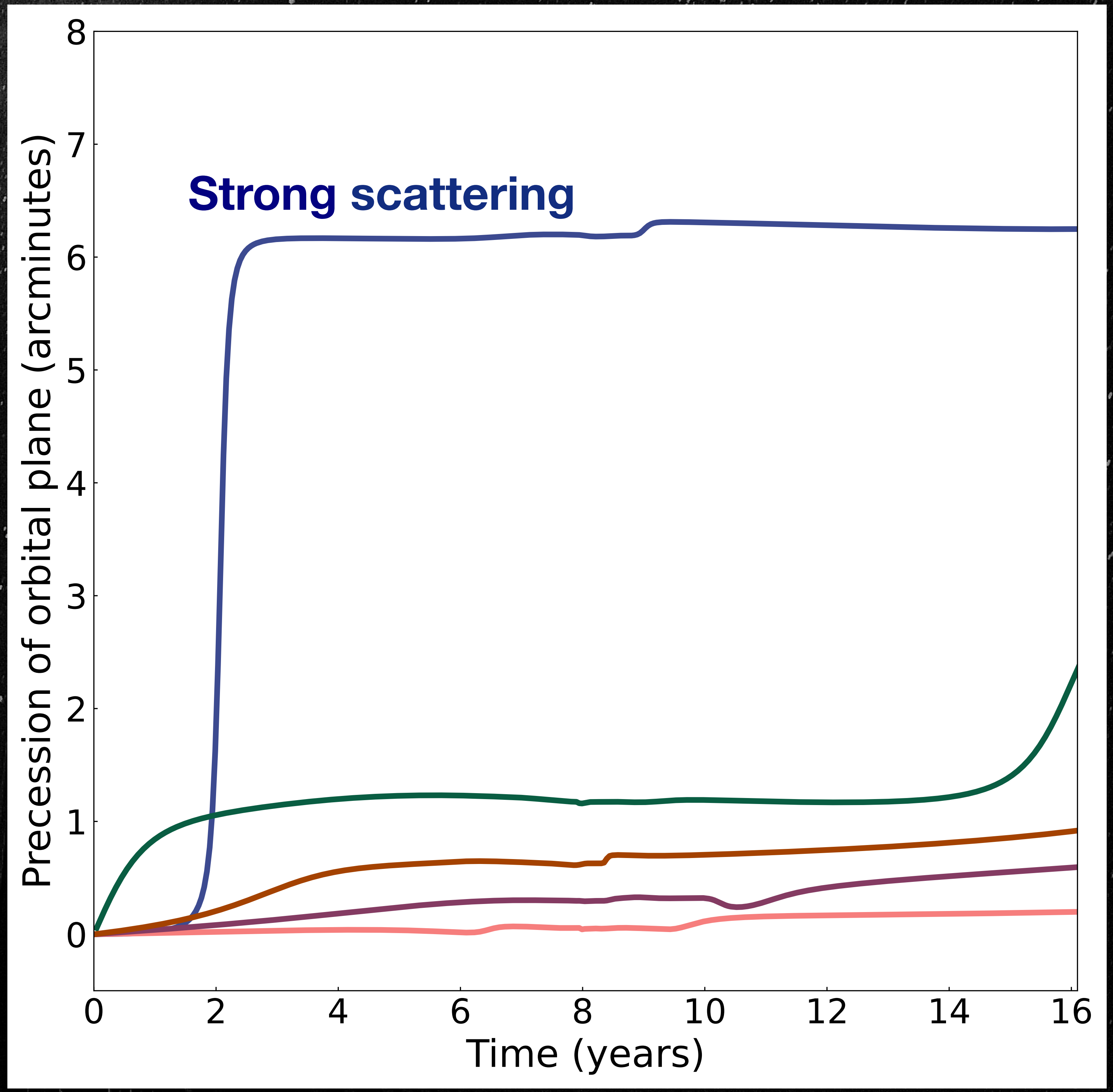
(M. Sadun Bordoni & GRAVITY Collaboration, 2024)

The granularity of the mass distribution:
Scattering of the S2 orbit by stellar-mass black holes

- **Global deviation of the potential from spherical symmetry and local scattering events with field objects**
- **Depending on the sampling, weaker or stronger scattering events can occur**



Star acquires a Z component (out of the initial orbital plane), 5 example cases



Precession of the orbital plane, 5 example cases

(M. Sadun Bordoni et al. 2025, submitted to A&A)

The granularity of the mass distribution: Simplified dynamical approach

- **Simulate at 1PN order the orbit of S2 around Sgr A* and cluster of particles of equal mass m**

Loop over total mass in particles within the apocenter of S2:
$M_{e,S2} = 100, 500, 1000, 1500\,\mathrm{M}_\odot$.
Loop over the particle mass:
$m = 1, 2, 5, 10, 20, 50, 100\,\mathrm{M}_\odot$.

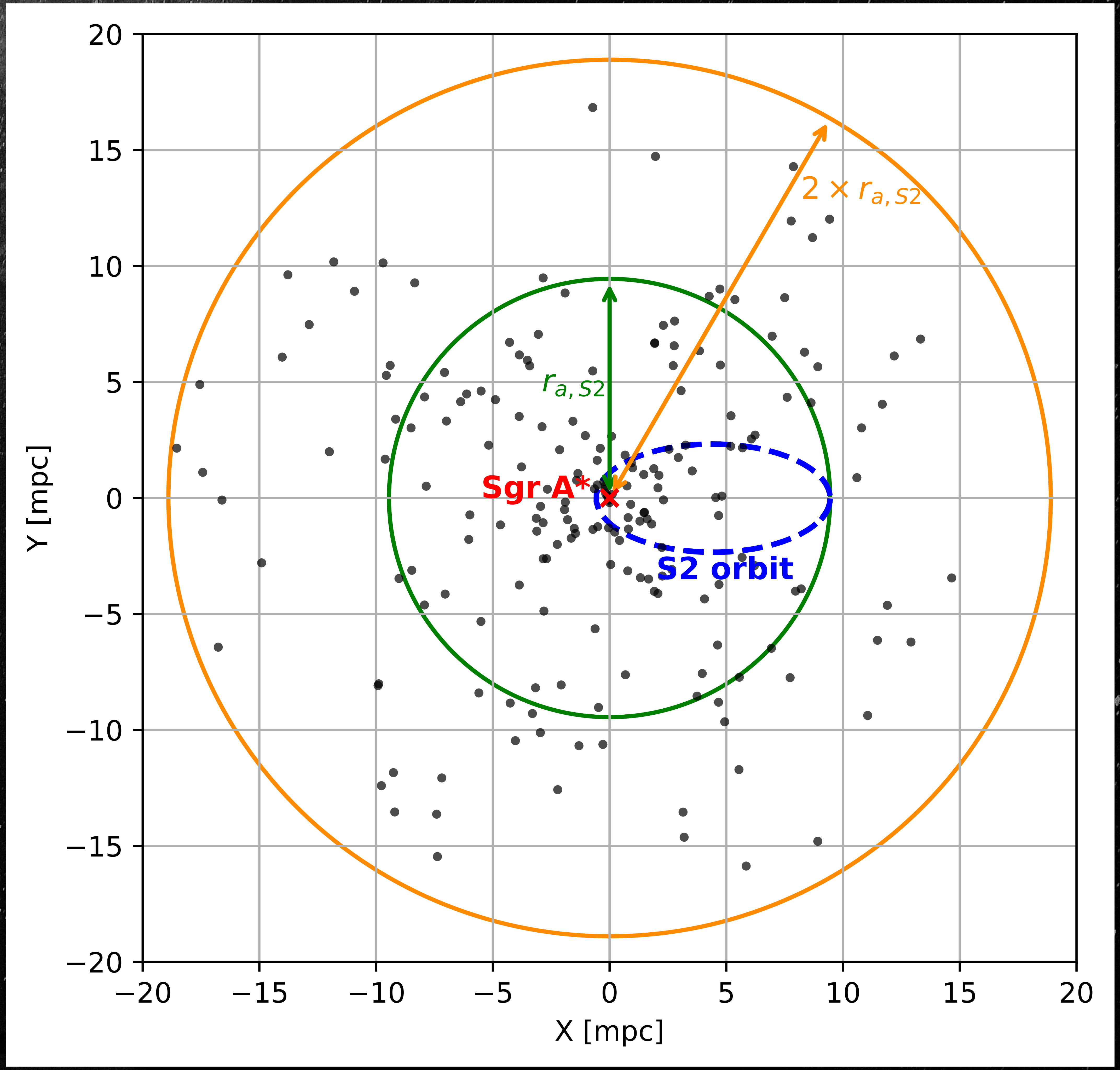
↓

100 different samplings of the positions of the particles, according to $\rho(r) \propto r^{-2}$.
Particles are assumed to be fixed in space.

↓

Simulation of the motion of S2,
for each sampling of the particle positions.

→ Statistical study unreachable with extensive full N-body simulations



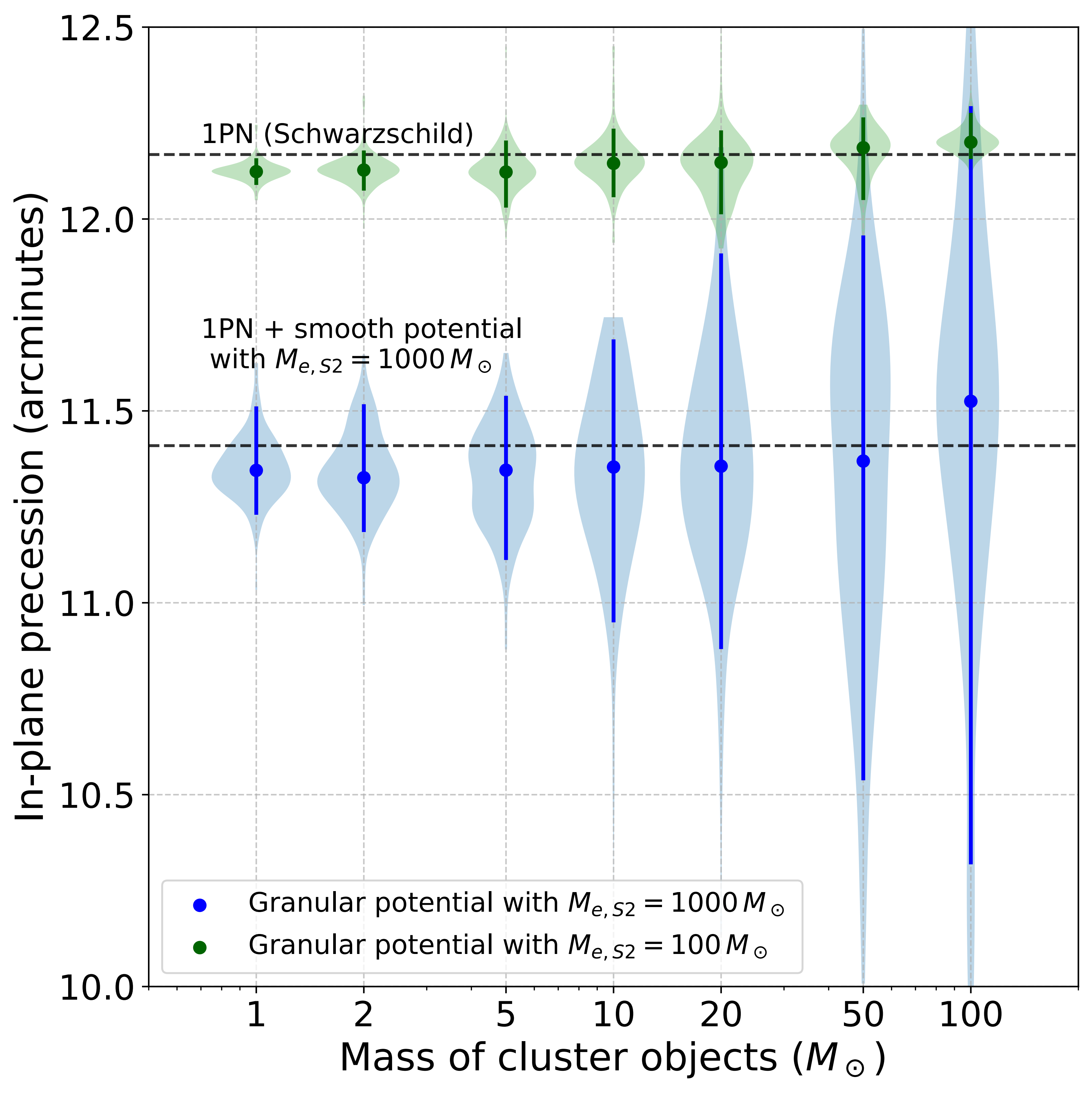
Orbit of S2 around Sgr A* and a particular realisation of the distribution of surrounding cluster objects

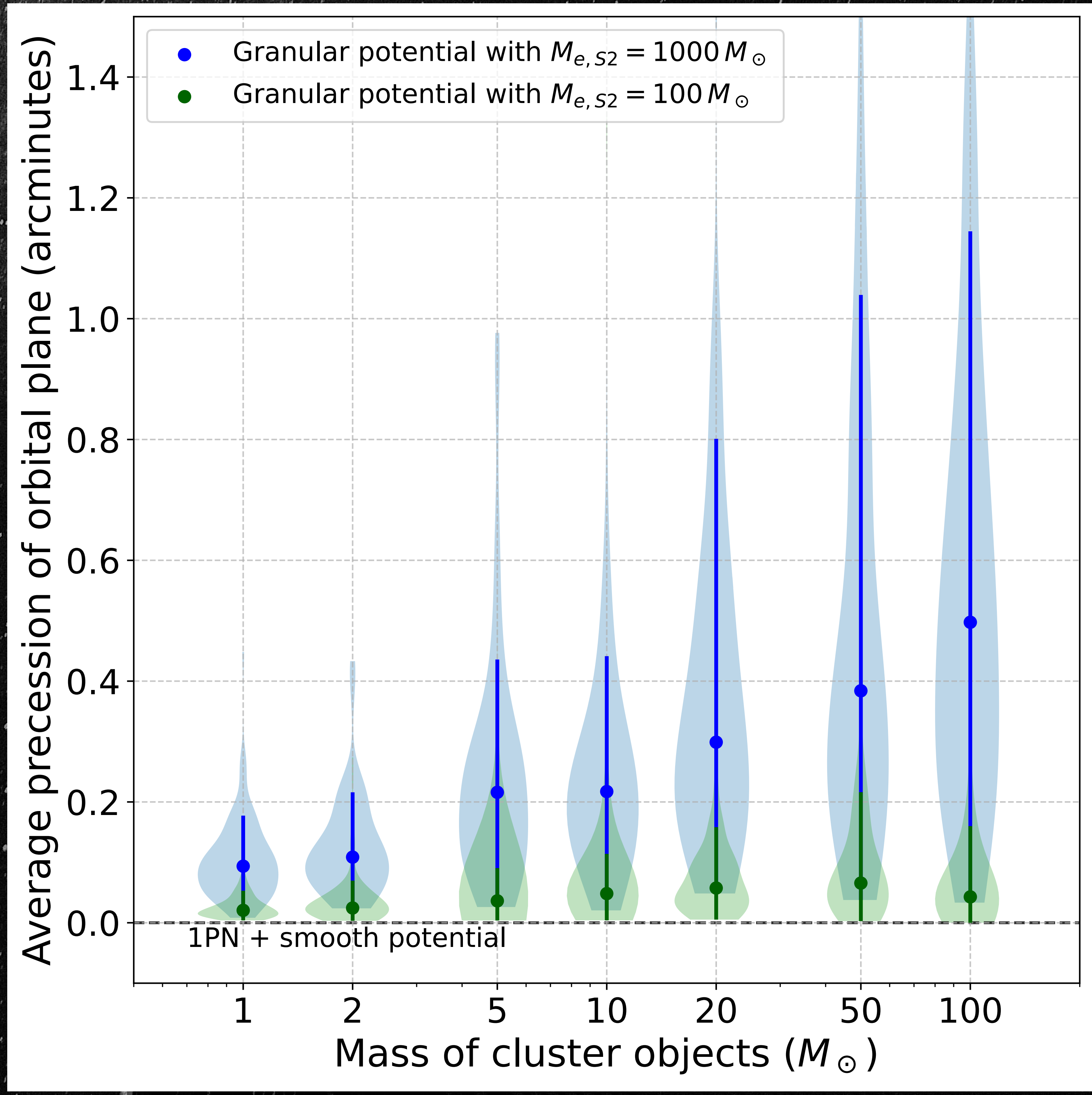
(M. Sadun Bordoni et al. 2025, submitted to A&A)

The granularity of the mass distribution: Simplified dynamical approach

(M. Sadun Bordoni et al. 2025, submitted to A&A)

- **Global asymmetry of the potential and local scattering events lead to deviations from the orbit in a smooth potential**



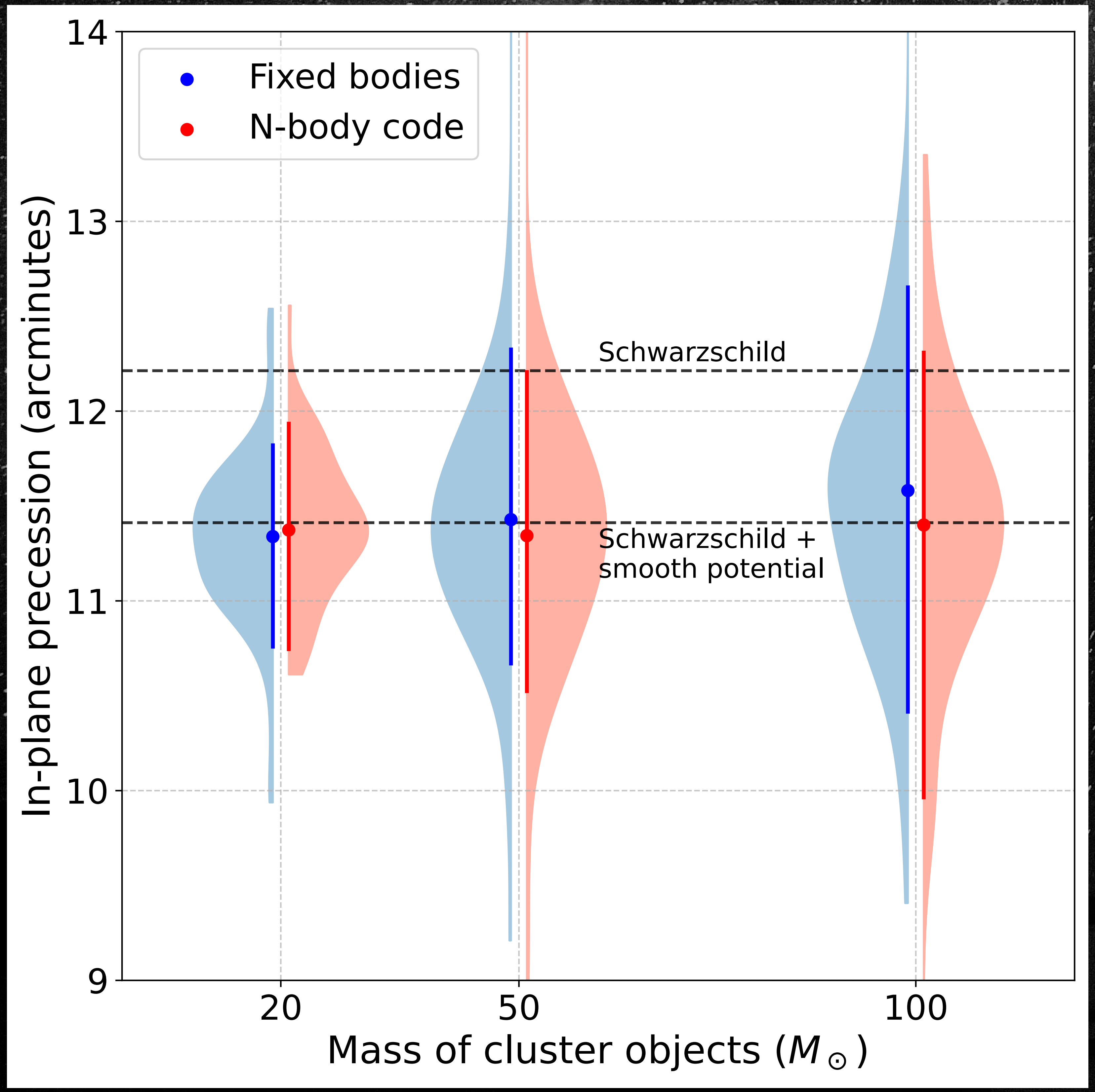


Larger deviations for larger mass of the cluster objects and larger total mass of the cluster

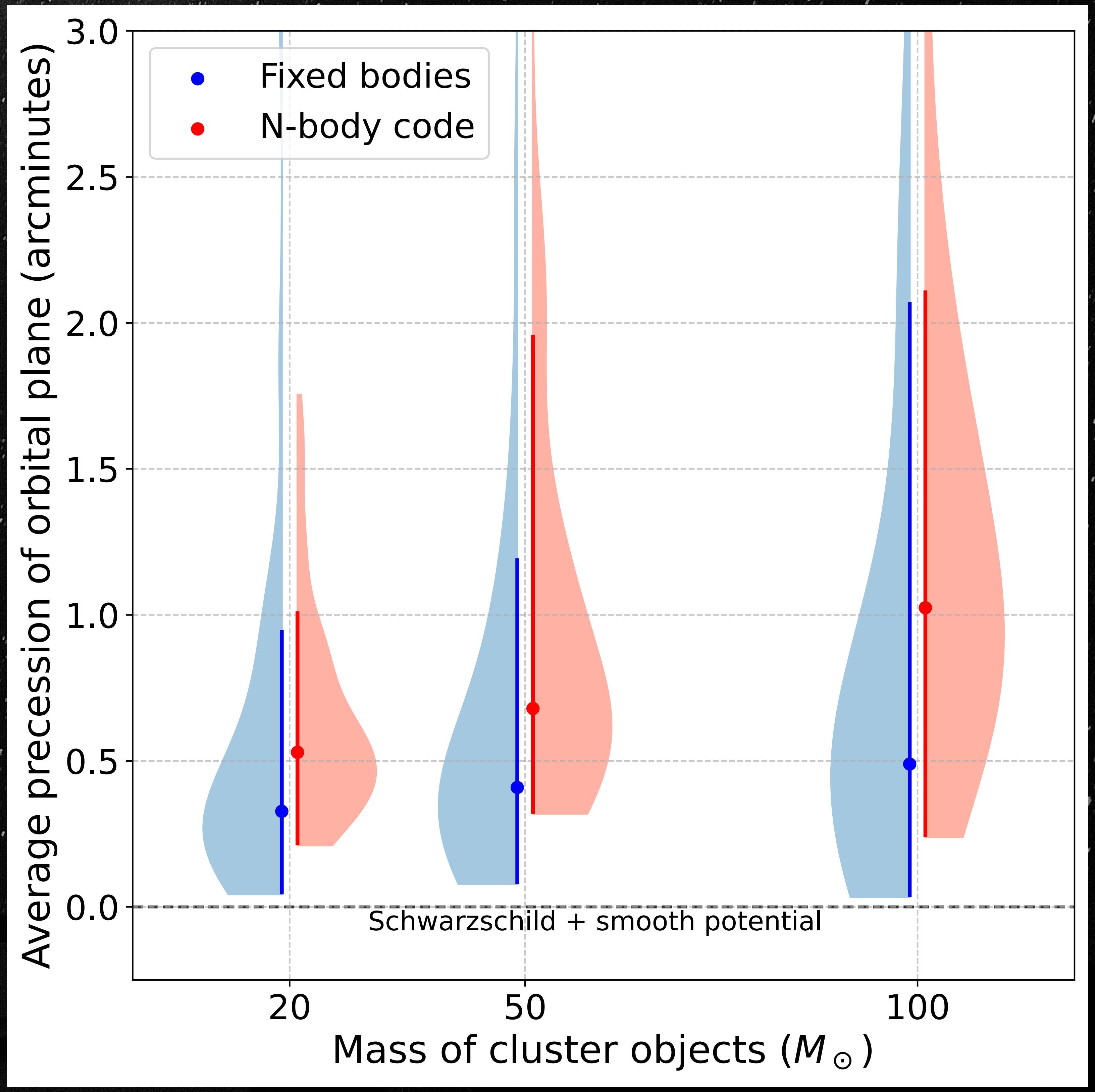
The granularity of the mass distribution:
Comparison with full N-body simulations

Global asymmetry of the potential and local scattering events lead to deviations from the orbit in a smooth potential:

• Variation of the in-plane precession



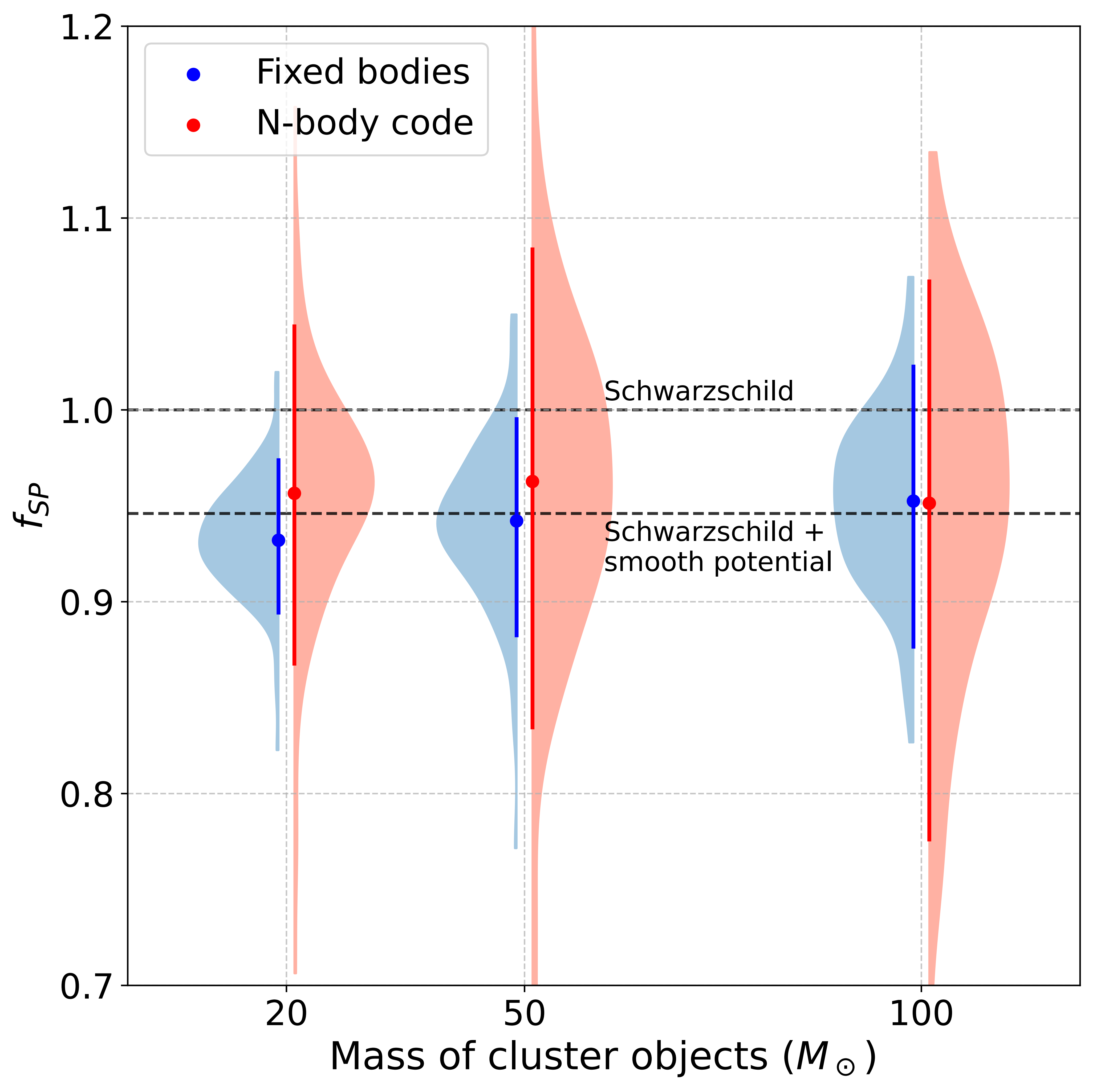
• Precession of the orbital plane



(M. Sadun Bordoni et al. 2025, submitted to A&A)

The granularity of the mass distribution:
Deviations from a Schwarzschild orbit

(M. Sadun Bordoni et al. 2025, submitted to A&A)



- **Mock data analysis: fitting the simulation data for the f_{SP} parameter**

The granularity of the mass distribution could significantly alter the S2 orbit with respect to the Schwarzschild case

(remember that the observational result, fitting the actual S2 data, is:
$f_{SP} = 1.1 \pm 0.1$**)**