Nuclear cluster, dark matter or both?

Constraints on distributed matter in the innermost galactic centre from stellar orbits.

Gernot Heißel, Dark Matter and Stars, Lisbon May 3-5 2023

LESIA l'Observatoire de Paris | PSL

Laboratoire d'Études Spatiales et d'Instrumentation en Astrophysique

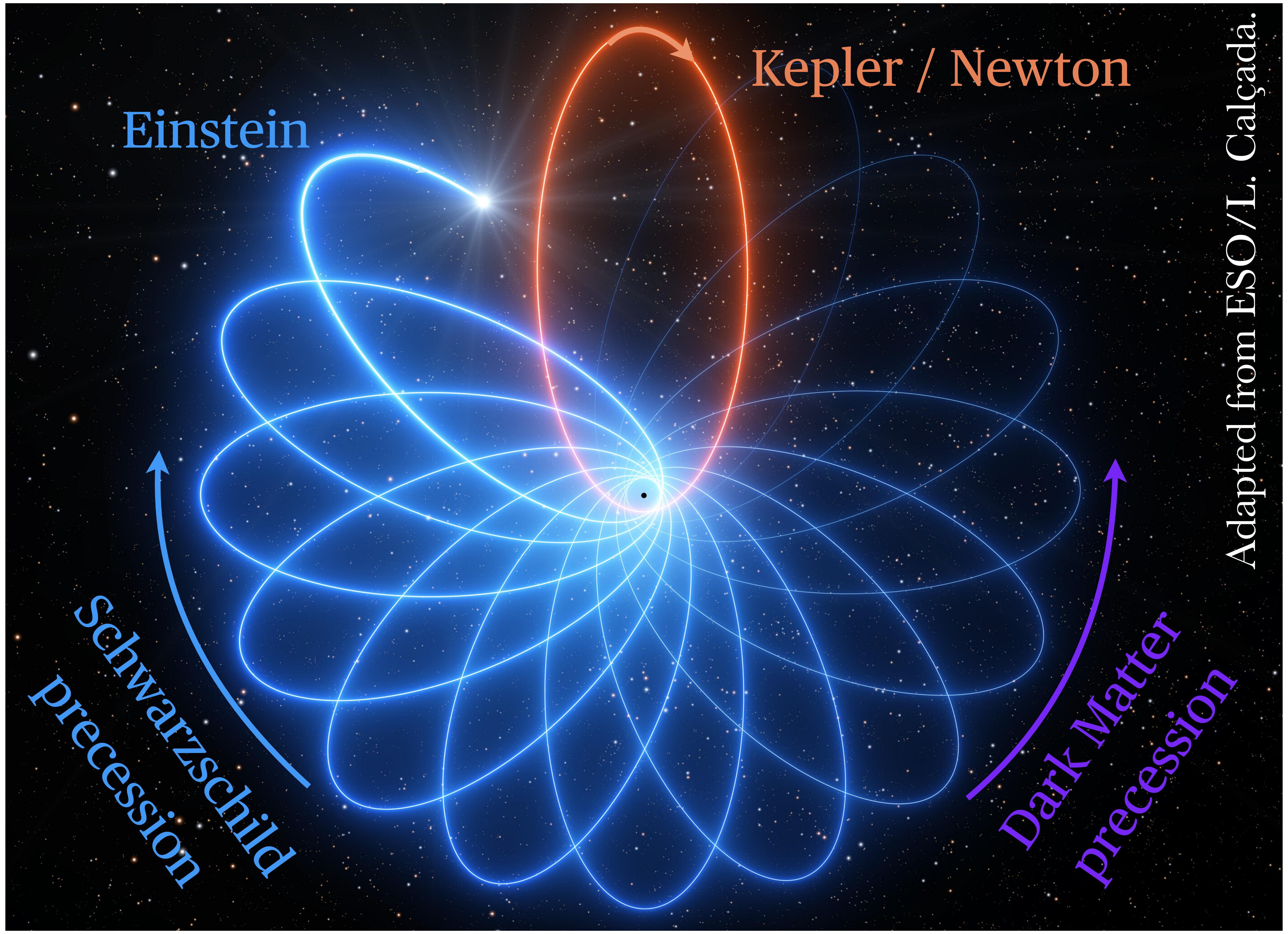
1. The dark mass signature in the orbit of S2.

G Heißel, T Paumard, G Perrin, F Vincent A&A 660, A13 (2022)

Background

Extreme mass ratio **two-body problem**: Sgr A* + star at distances $> 1400\, R_{\text{Schwarzschild}}$

$$\ddot{\mathbf{r}} = -\frac{GM_\bullet}{r^2}\frac{\mathbf{r}}{r} + \mathbf{a}_{1\text{PN}} + \mathbf{a}_{\text{DM}}$$



Candidate generators of $\mathbf{a}_{\text{DM}}$

- **Cluster of faint stars** and stellar remnants (bhs, neutron stars, …)
- **Dark Matter** (yet undiscovered particles or fields)
- **Or both!**

Effects of $\mathbf{a}_{\text{DM}}$ on stellar orbit

A. **Secular** (over several orbits): **retrograde in-plane precession** → determined by **amount of DM**

B. **Non-secular** (within each orbit): depends on the distribution → determined by **nature of DM**

Methods

Model for astrometric and spectroscopic observations, based on

$$\ddot{\mathbf{r}} = -\frac{GM_\bullet}{r^2}\frac{\mathbf{r}}{r} + \mathbf{a}_{1\mathrm{PN}} + \mathbf{a}_{\mathrm{DM}}$$

with $\mathbf{a}_{\mathrm{DM}}$ generated by

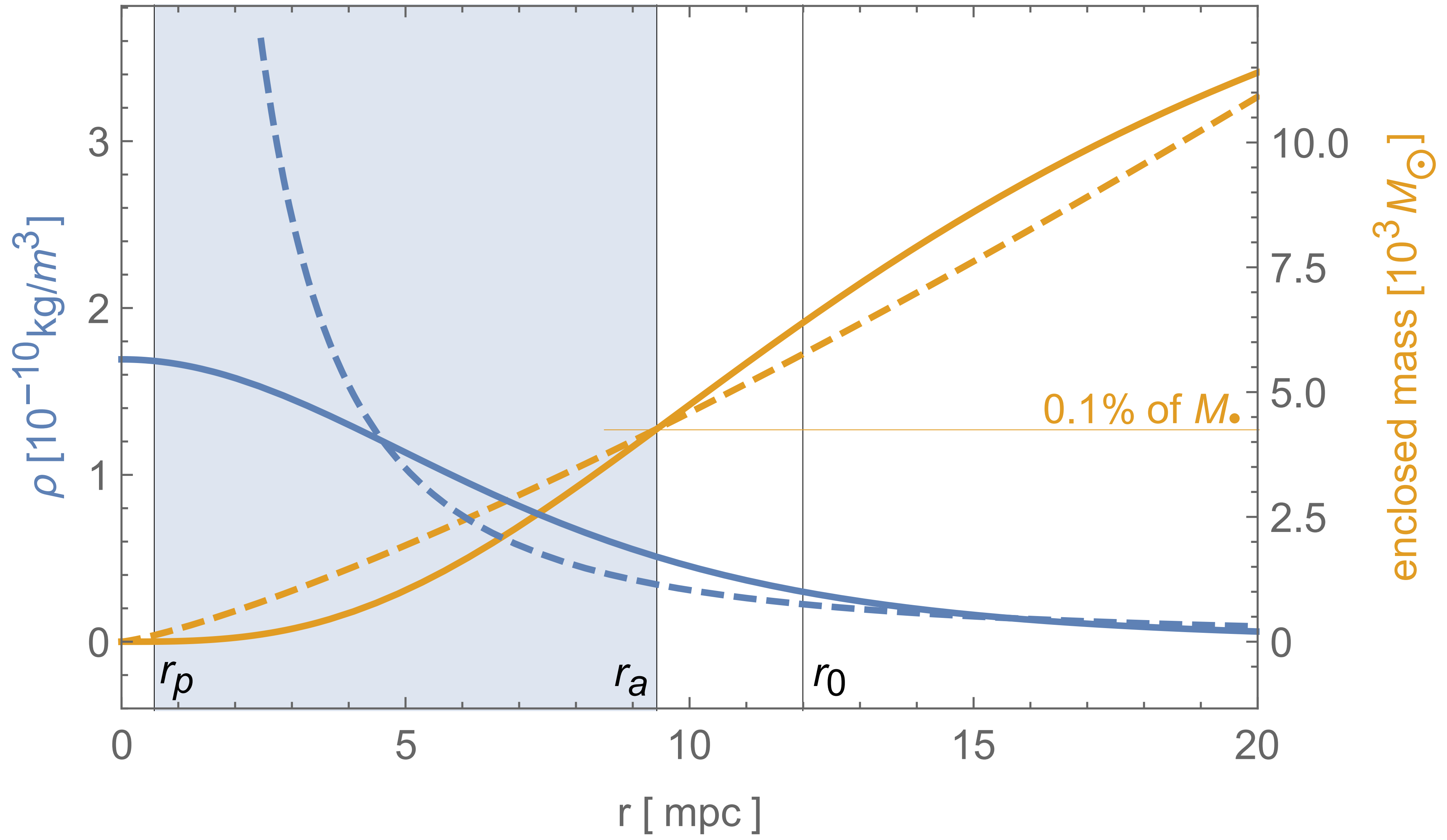
$$\rho(r) = \begin{cases} \rho_0 \left(1 + \frac{r^2}{r_0^2}\right)^{-5/2} & \text{Plummer} \\ \rho_0 \left(\frac{r}{r_0}\right)^{-7/4} & \text{Bahcall-Wolf cusp} \end{cases}$$

which model **relaxed stellar clusters** and nuclear clusters respectively → ordinary matter.

However, Bahcall-Wolf cusp also example for **DM spike** of adiabatic growth models proposed by **Gondolo & Silk (1999)**.

Performed two types of analyses:

- **Compared S2 model orbits** with and without distributed matter.
- **Fits of the model to mock data**.



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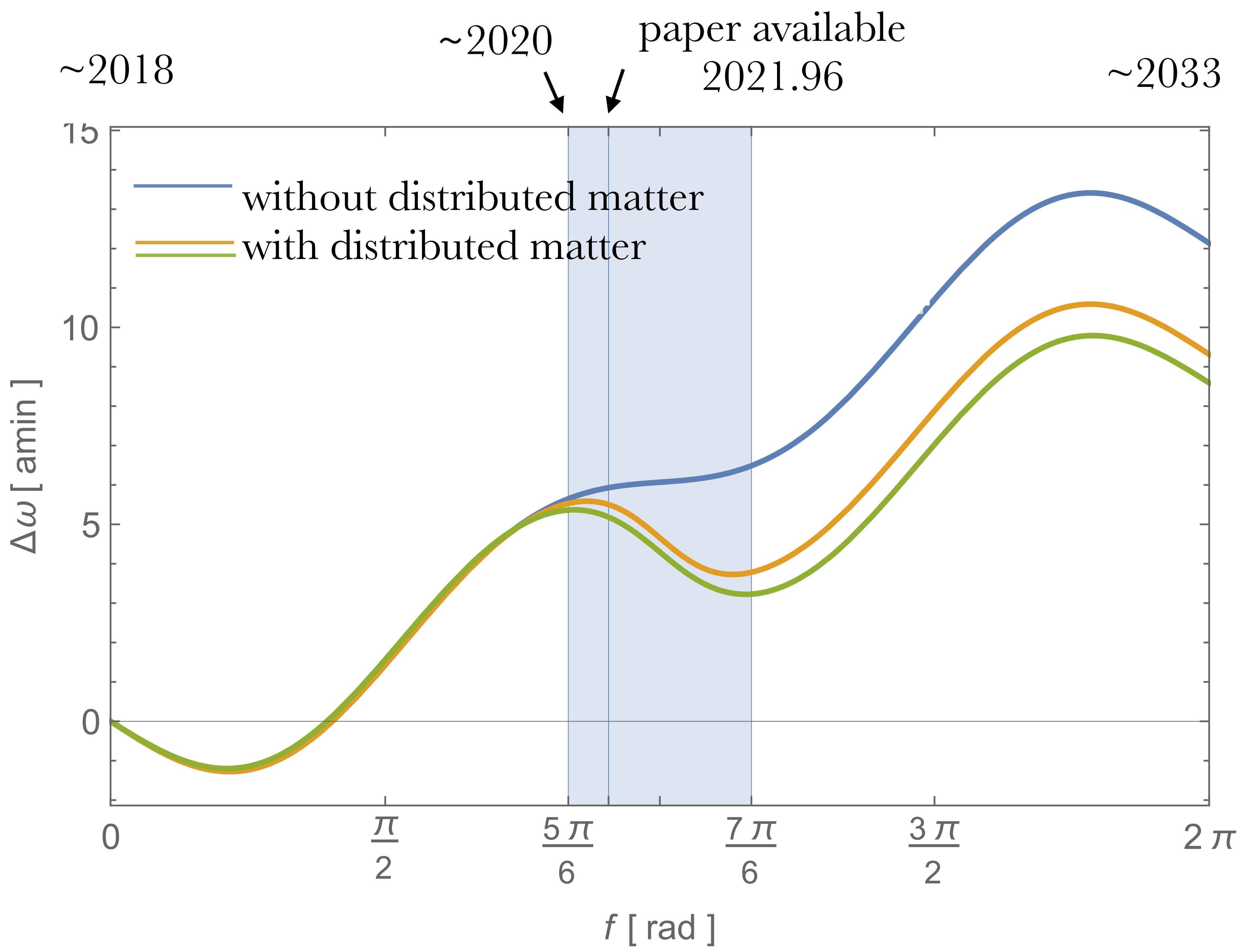
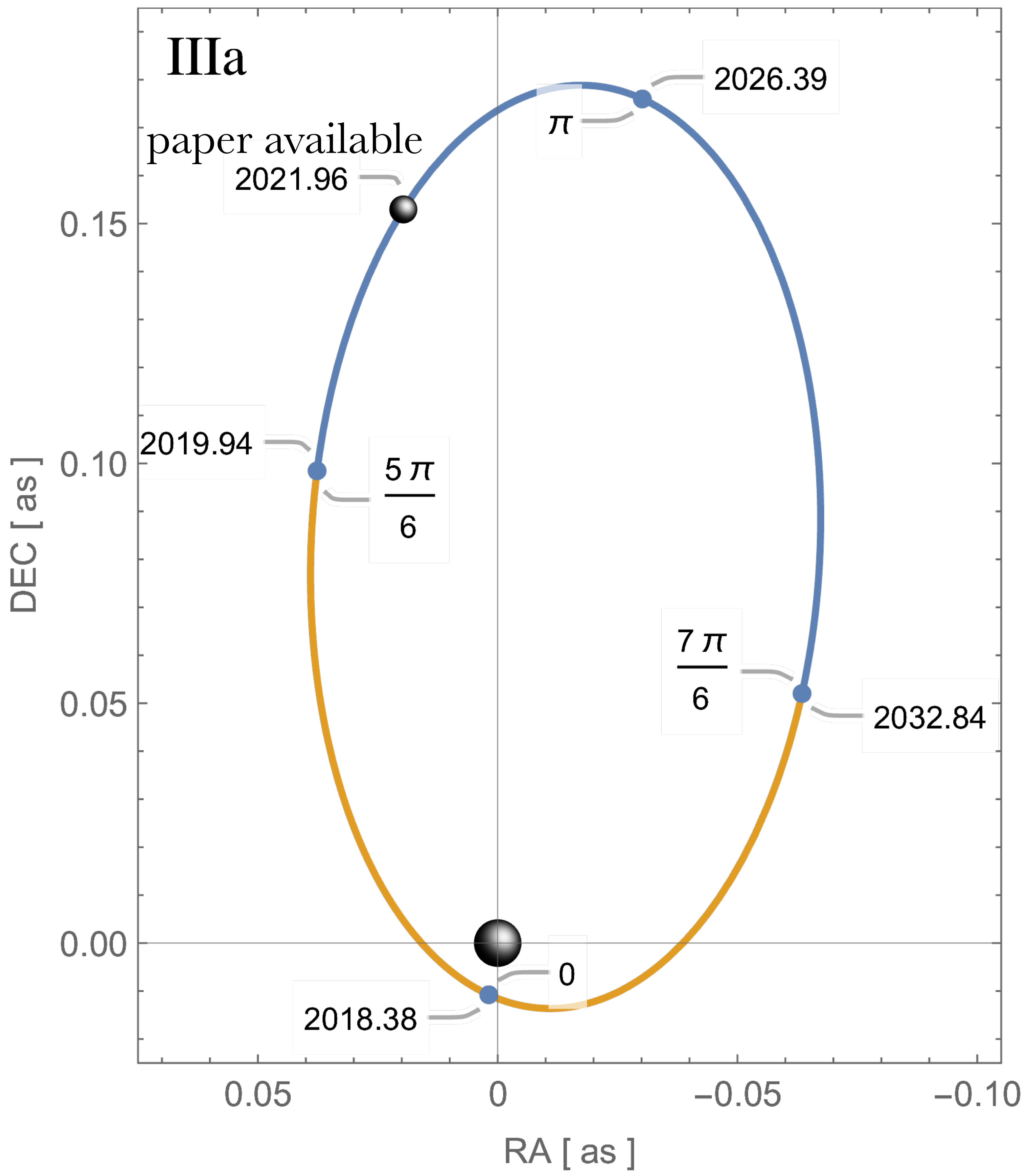
Results





within S2's apocentre

	Year	Enclosed mass $[M_\odot]$	
now	2020	4261	← GRAVITY et al. (2020) limit
	2026	2828	
	2033	969	

1. Relativistic precession occurs on **pericentre half**. DM precession occurs on **apocentre half**. **Clear separation!**
2. At least **one orbit of data required** for adequate DM constraints. → Cannot isolate prec. effects by restricting dataset.
3. Given one orbit of data, the **pericentre half data are the dominant component** for constraining the DM.
4. Estimated **detection thresholds** until one full orbit of data is gathered with VLTI/GRAVITY interferometer.

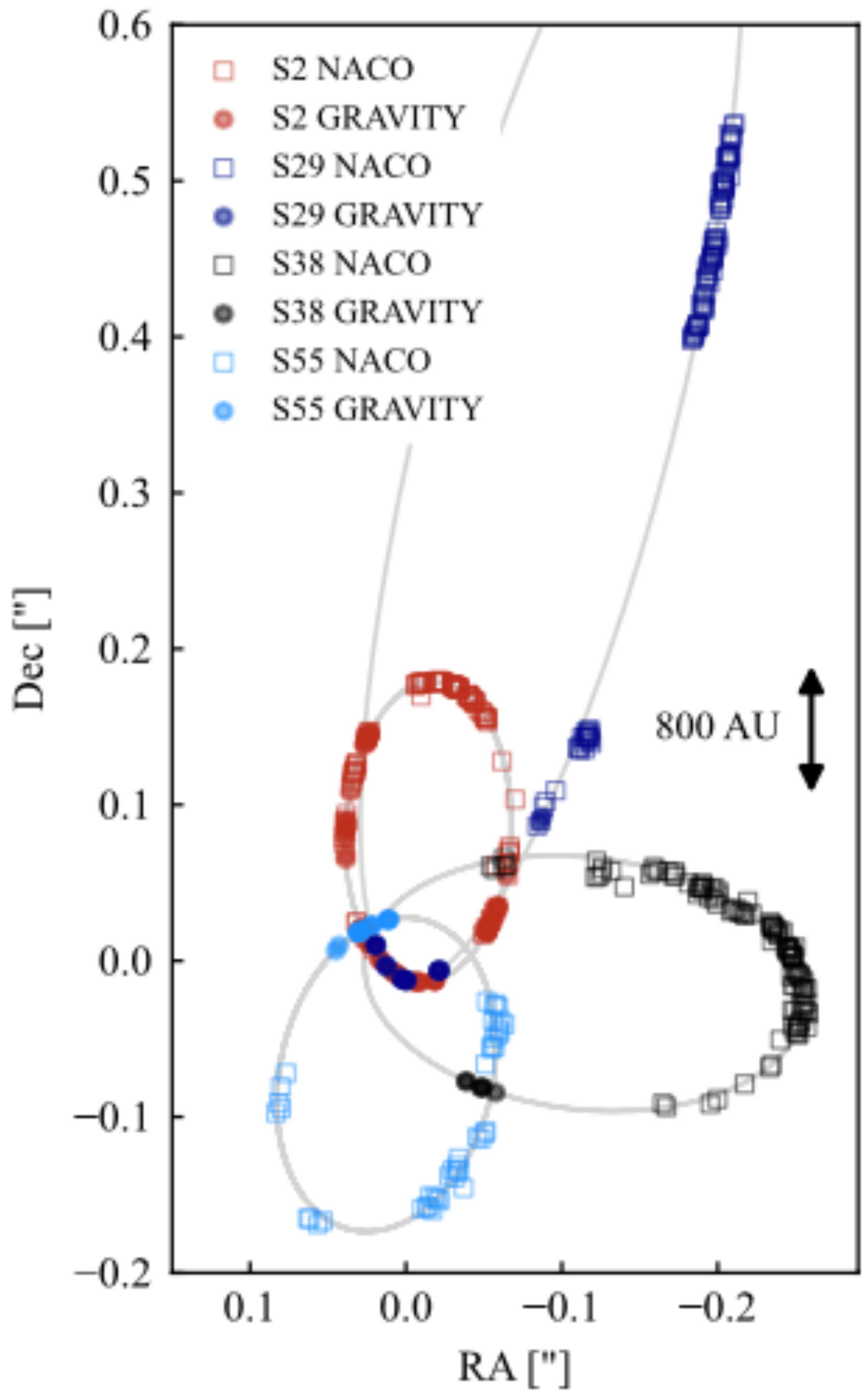
1. Mass distribution in the Galactic Centre, …

GRAVITY Collab. et al. A&A 657, L12 (2022). Corresponding: S Gillessen, F Widmann, **G Heißel**

Background

Since detection of Schwarzschild precession by GRAVITY Collab. et al. (2020), **more observations** have been made with the VLTI/GRAVITY interferometer not only for S2, but **also for other innermost S-stars**.

A **refined analysis** of the updated dataset **sharpens the constraints** on both the relativistic precession as well as on a distributed mass component.



Methods

Updates on observational data:

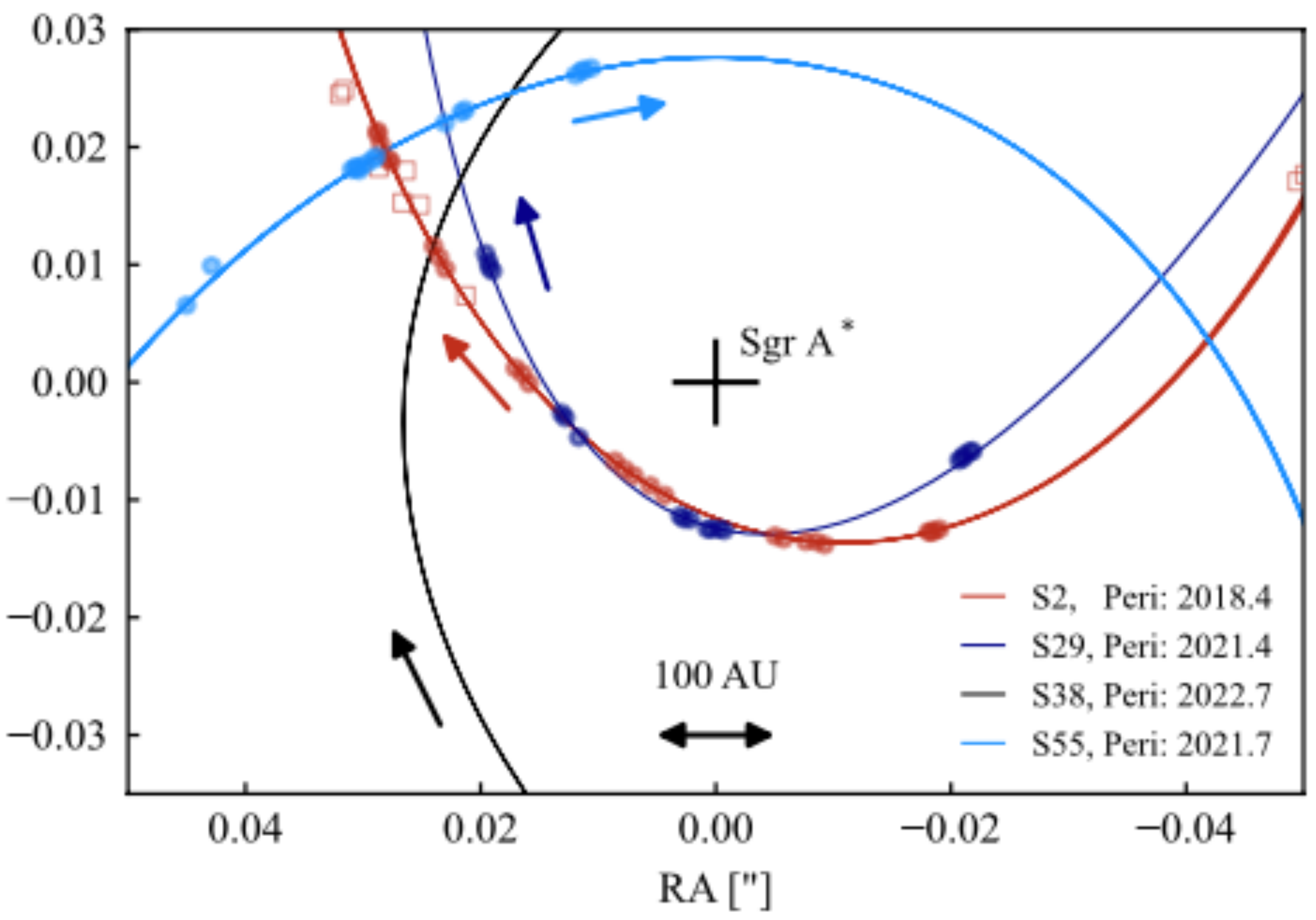
- Stars: **S2, S29, S38, S55**
- Instruments: VLT/NACO, SINFONI; **VLTI/GRAVITY**, some Keck and GEMINI/GNIRS.

Updates on data analysis:

- Discarded some near-peri NACO data where now near-peri GRAVITY data was available → to **counter source confusion** in crowded field of view.
- **Updated priors on NACO rest frame** (by better tying it to the radio reference frame following Plewa (2015))

Model fits to data:

- Model based on $\ddot{\mathbf{r}} = -\frac{GM_\bullet}{r^2}\frac{\mathbf{r}}{r} + \mathbf{a}_{1PN} + \mathbf{a}_{DM}$
- **Constrain non-Keplerian** terms $\mathbf{a}_{1PN}, \mathbf{a}_{DM}$.



Results

Update on **constraints on Schwarzschild precession**:

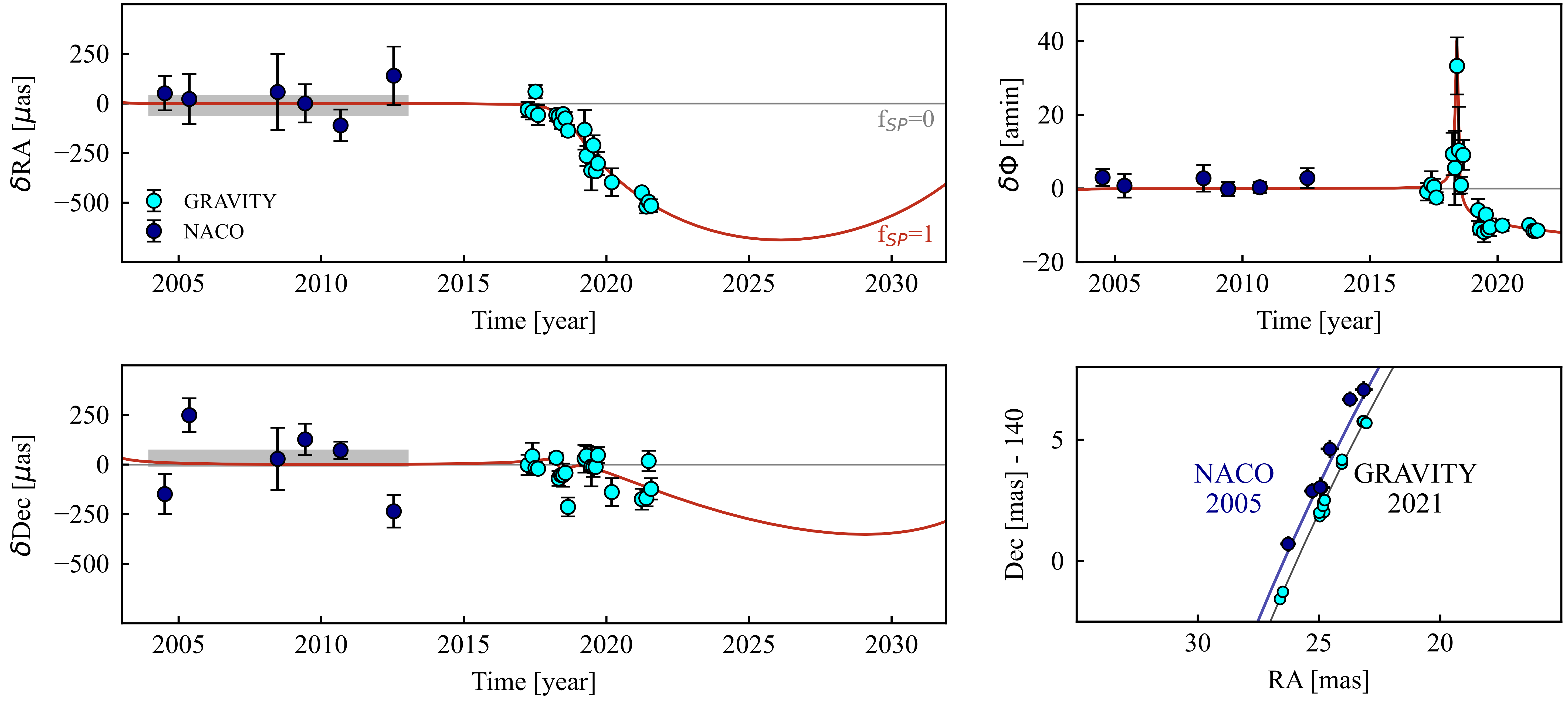
$f_{SP} = 0.997 \pm 0.144.$

This constitutes a 7σ **rejection of Newtonian physics** ($f_{SP} = 0$) and an excellent agreement with relativity ($f_{SP} = 1$). (5σ in 2020)

Update on **constraints on a DM**:

2700 ± 3500 solar masses.

constitutes a **null result** within 1σ. The upper bound is in the range predicted by Heißel et al. (2022).



within S2's apocentre

Year	Enclosed mass $[M_\odot]$
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now

← GRAVITY et al. (2020) limit

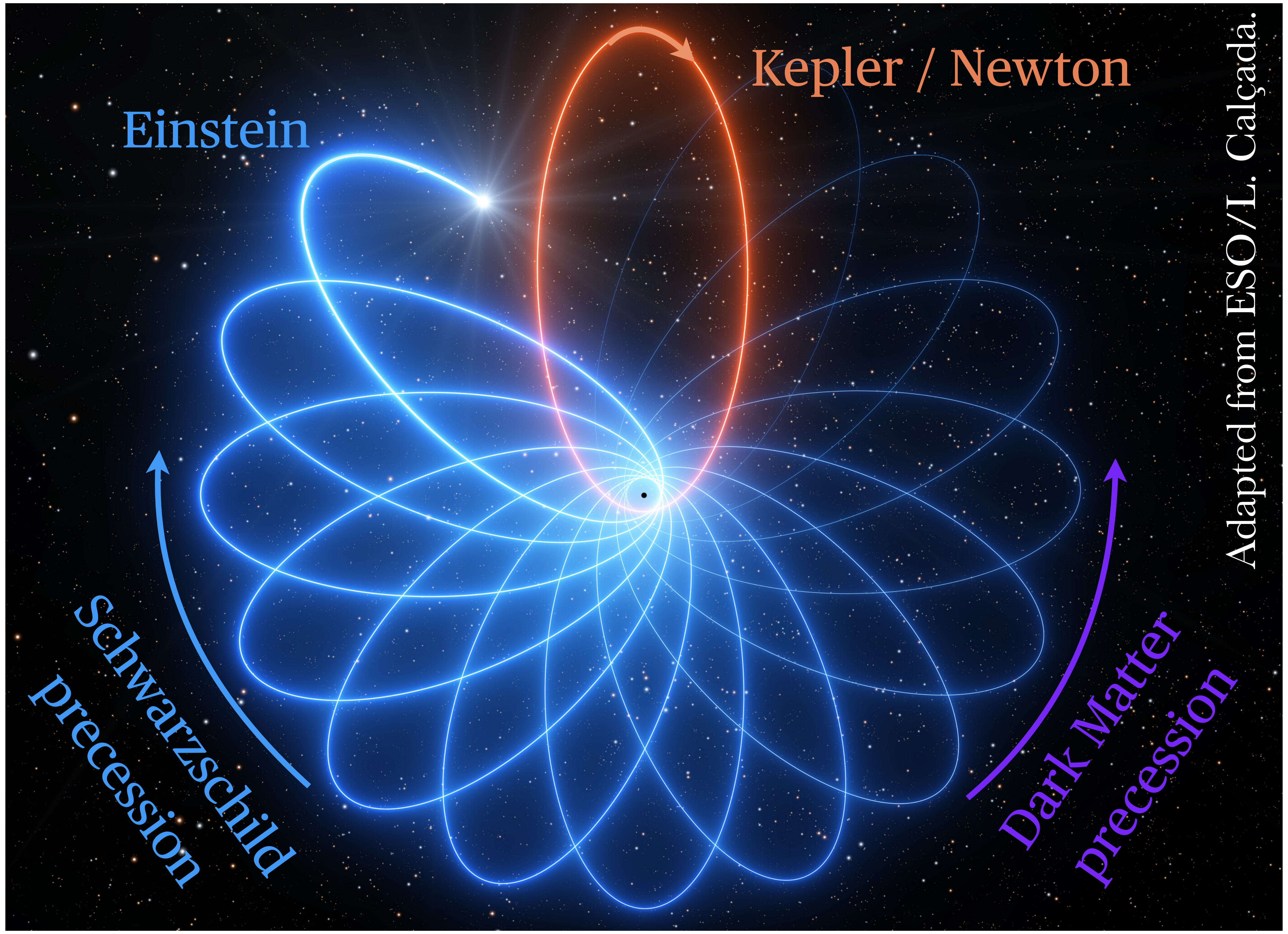
1. Dark Matter reconstruction from stellar orbits in the GC

T Lechien, **G Heißel**, J Grover, D Izzo (to be submitted to A&A)

Background

Current constraints on DM in the GC like the one above **a priori assume the functional form** of the distribution.

- Constraints are **not general**
- Assuming shape of DM → **assuming nature**
- To infer nature of DM, one would have to go through a tedious and likely intractable comparison of a **zoo of DM candidate** models.
- Models may be **superposed**!! (Hence the title of my talk.)



Methods

Idea:

Assess the utility of an **unbiased approach**, without **no a priori assumption on shape** of the DM distribution.

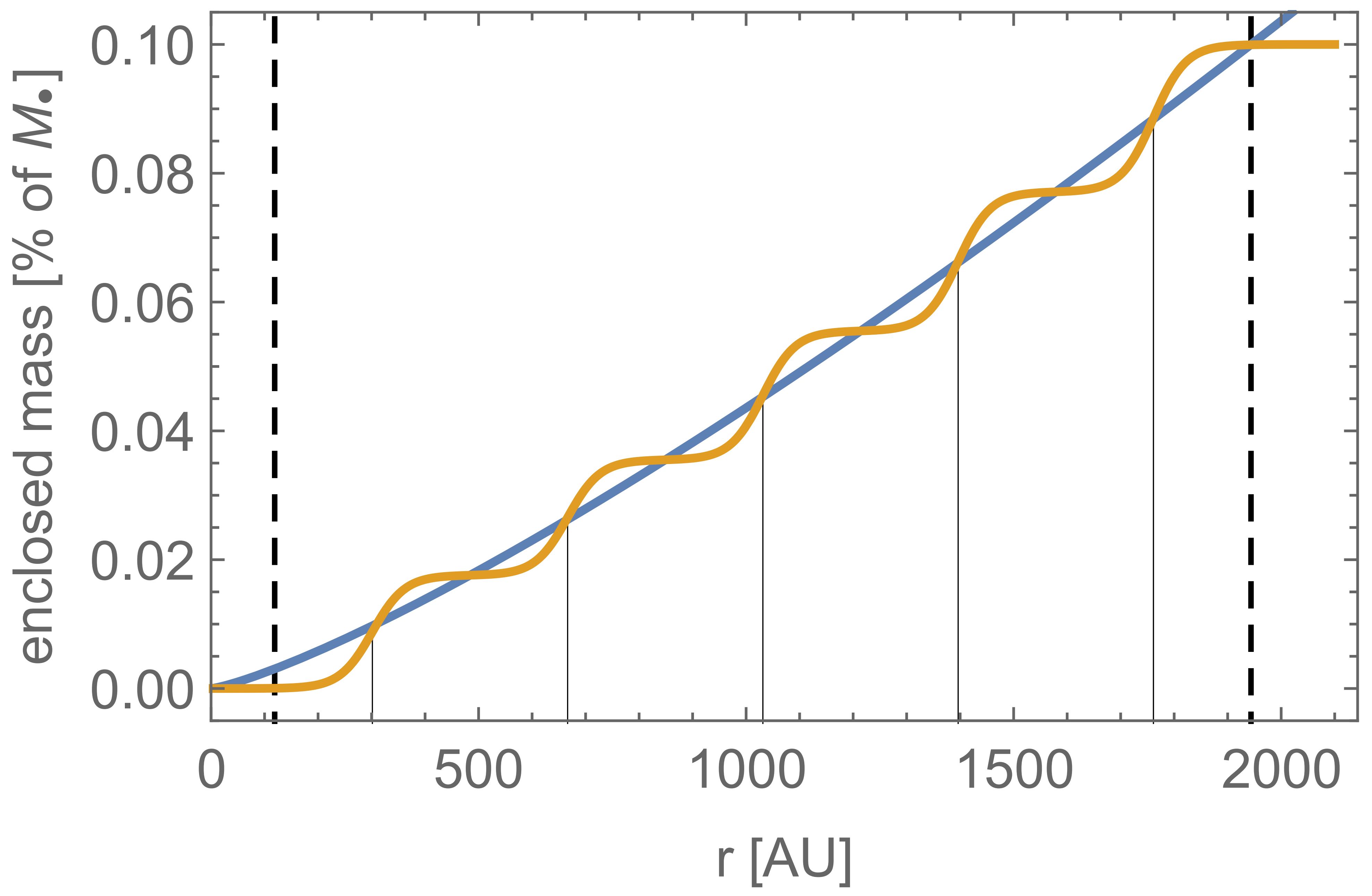
First find the distribution → then worry about what it is.

Implementation:

- Model DM via a **series of concentric mass shells**.
- Each shell is radially bell distributed → enclosed mass as function of radius increases in **smoothed out steps** (sigmoids).
- Smoothness tweaked for good adaptability of the model to physically reasonable profiles.
- The Mode **parameters are the shell masses**, i.e. the steps increments.

Analysis:

- Fits to mock data, using three different profiles as ground truths. (Plummer, Bahcall-Wolf, Zhao)
- Tweak amount and precision of data.
- Assess if ground truth profiles can be reconstructed.



Approximation of Bahcall-Wolf cusp by 5 mass shells.

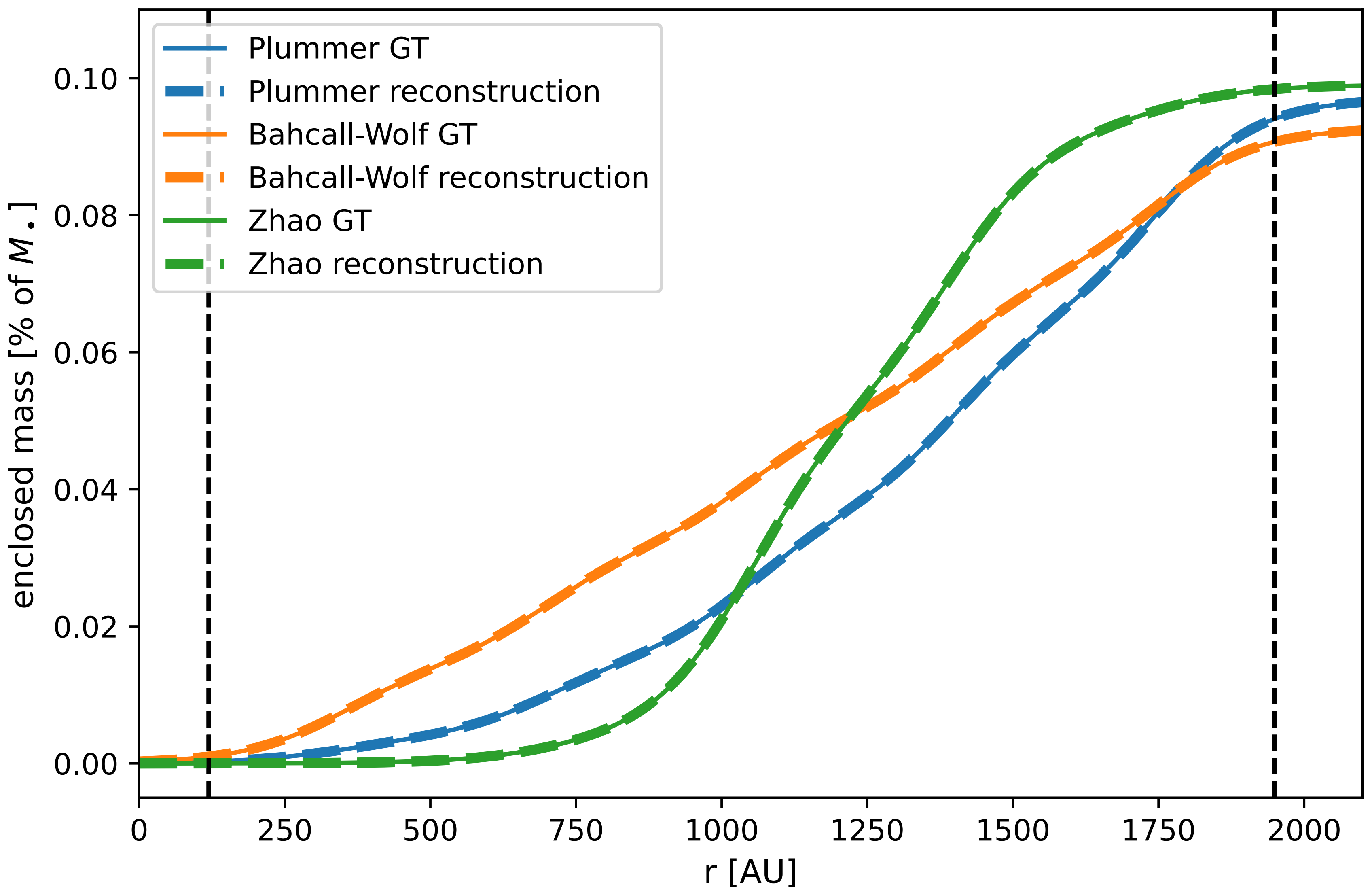
Here with coarse steps for demonstration of the model.

1. Dark Matter reconstruction from stellar orbits in the GC.
T Lechien, **G Heißel**, J Grover, D Izzo. prep. submission to A&A

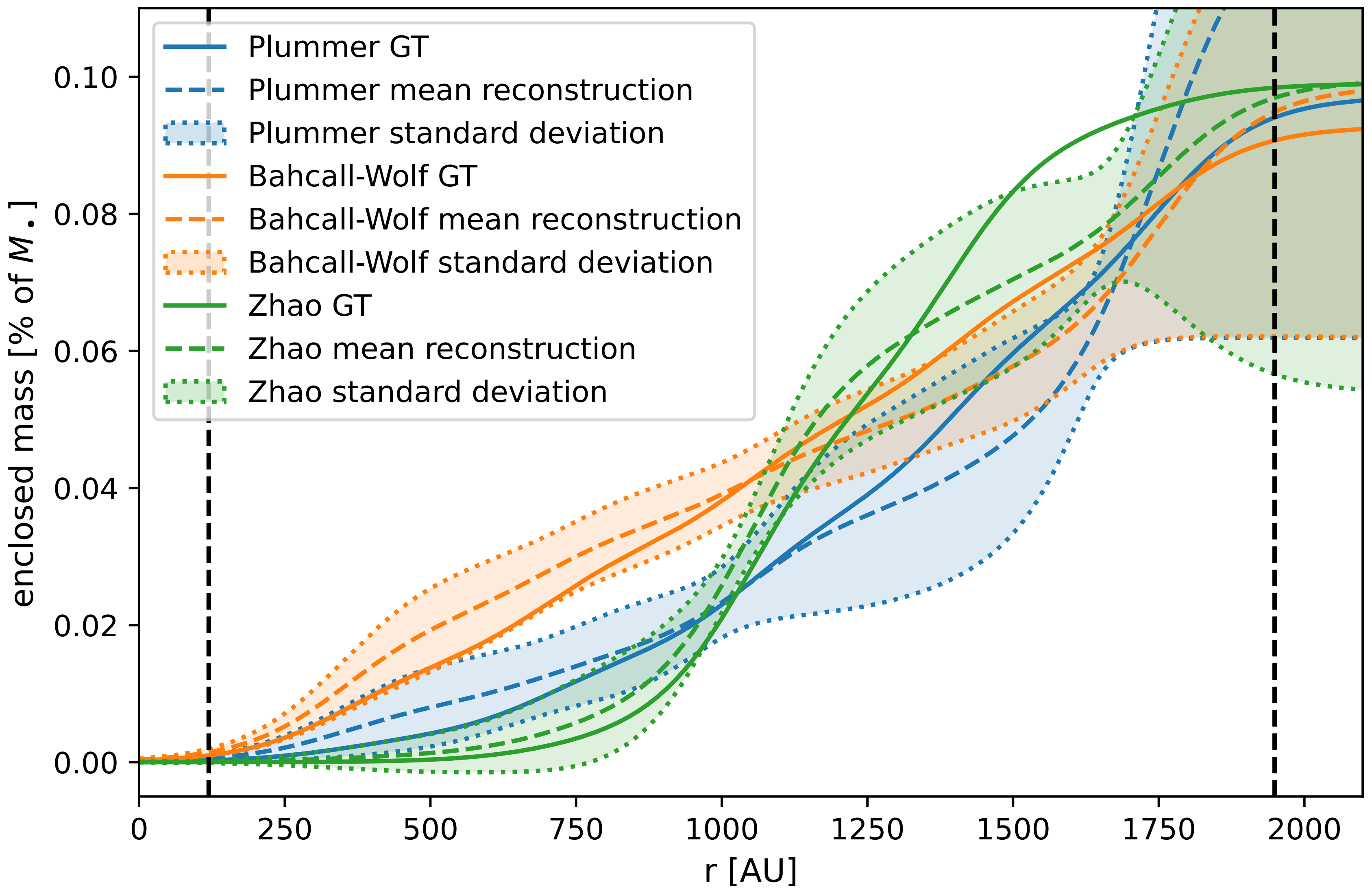
Results

- **Proof of concept**. ✔
- Problem **non-convex** with measurement uncertainties.
- Reconstructions cluster around correct ground truths for lower radii and **1/10th of current instrument precision**.
- Hopeless with **current instrument precision** when data confined to one orbit.
- 10 orbits of data **constrain total amount** of enclosed mass, but **not reliably the shape**.

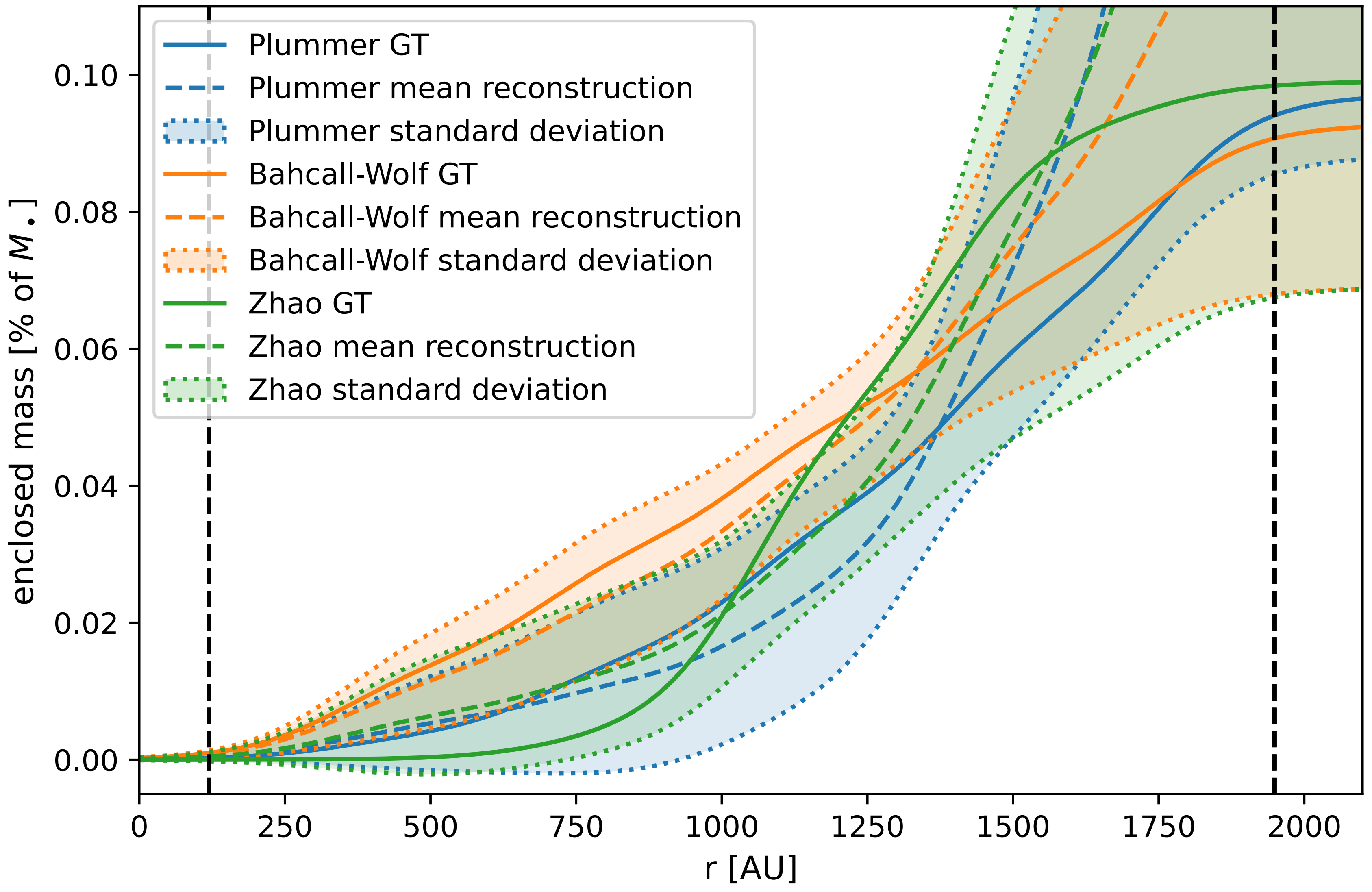
1 orbit, 300 obs, vanishing measurement uncertainties



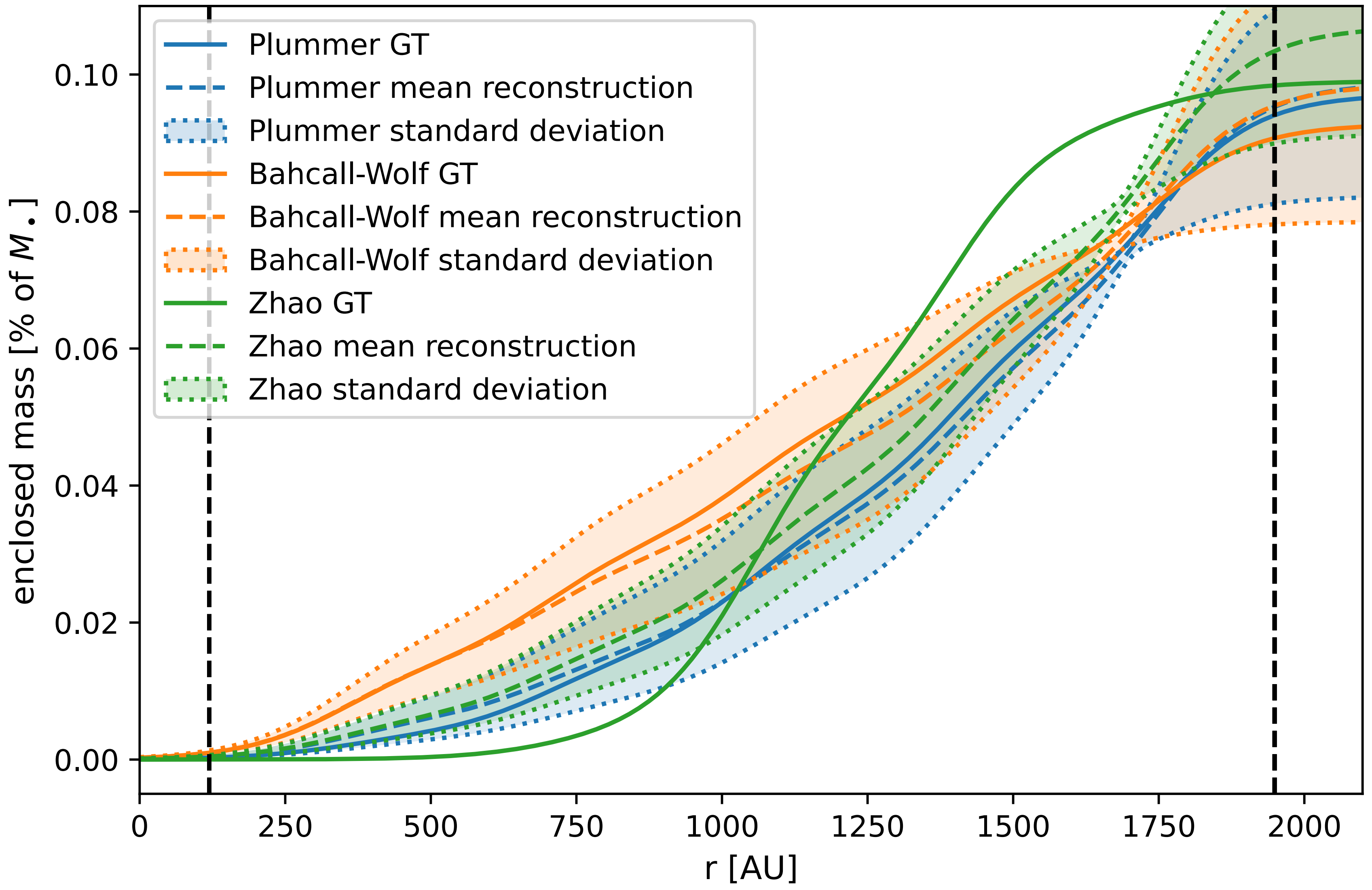
1 orbit, 300 obs, uncertainties of 5μ" and 1km/s



1 orbit, 3000 obs, uncertainties of 50μ" and 10km/s



10 orbits, 3000 obs, uncertainties of 50μ" and 10km/s



Key message

Effects of orbit

A. **Secular** (over several orbits): **retrograde in-plane precession** → determined by **amount of DM**

B. **Non-secular** (within each orbit): depends on the distribution → determined by **nature of DM**

- **Multiple orbits** of S2 data will help to **constrain A** in unbiased approach, and will therefore check and generalise the current biased constraints.
- Current instruments **not precise enough in order to constrain B**, in measuring S2.
- This is not a detriment of our model, but a **principal limitation!**