Dark Matter reconstruction

from stellar orbits in the Galactic Centre

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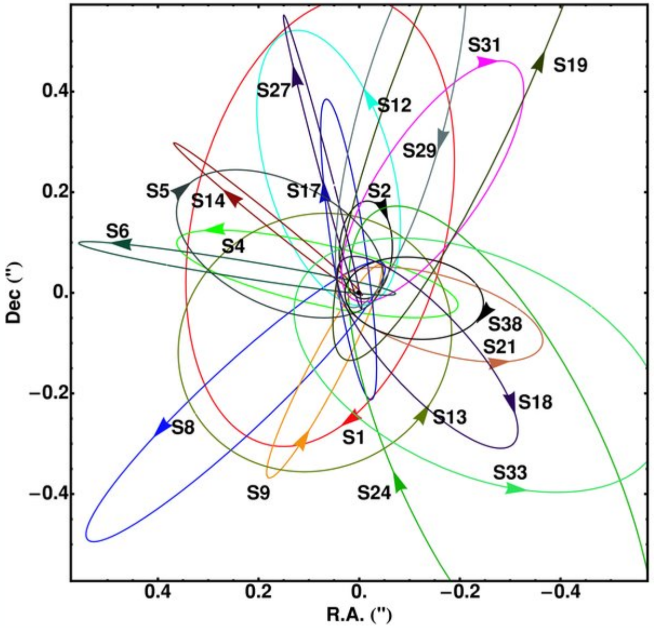
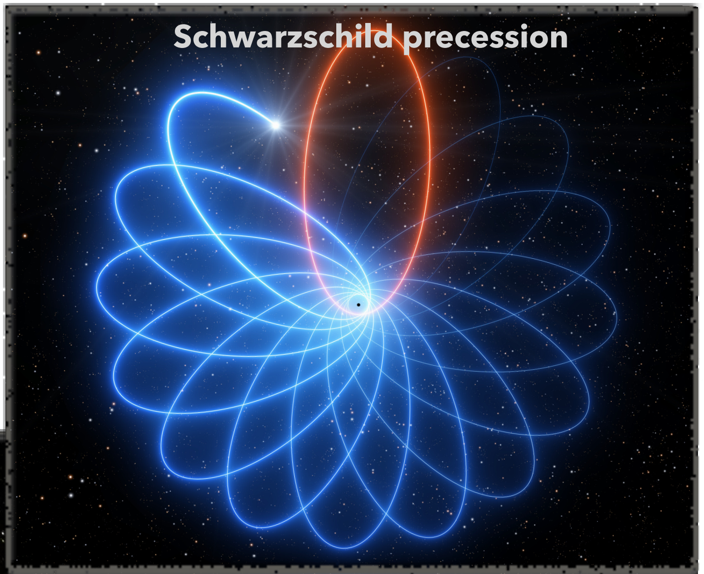
Introduction

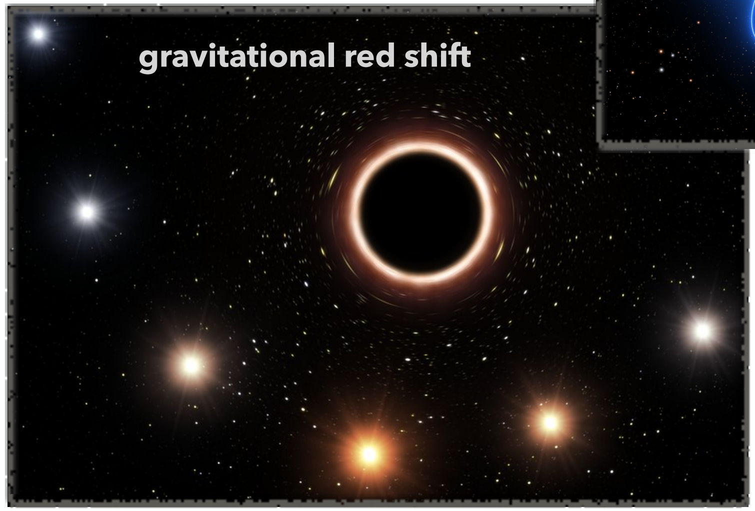
- **Stellar orbits in the galactic centre.**
  - ➡ Infrared observations revealed **compact object** of **4 Mio. solar masses**.
    - ½ of 2020 Nobel prize (Genzel & Ghez. Other ½ Penrose)
  - ➡ Focus shifted to **observation of relativistic effects** in stellar orbits (S2)
    - **Gravitational redshift** by GRAVITY Collab. et al. (2018) & confirmed by others
    - **Schwarzschild precession** by GAVITY Collab. et al. (2020, 2022*)



Gillessen et al. (2009)



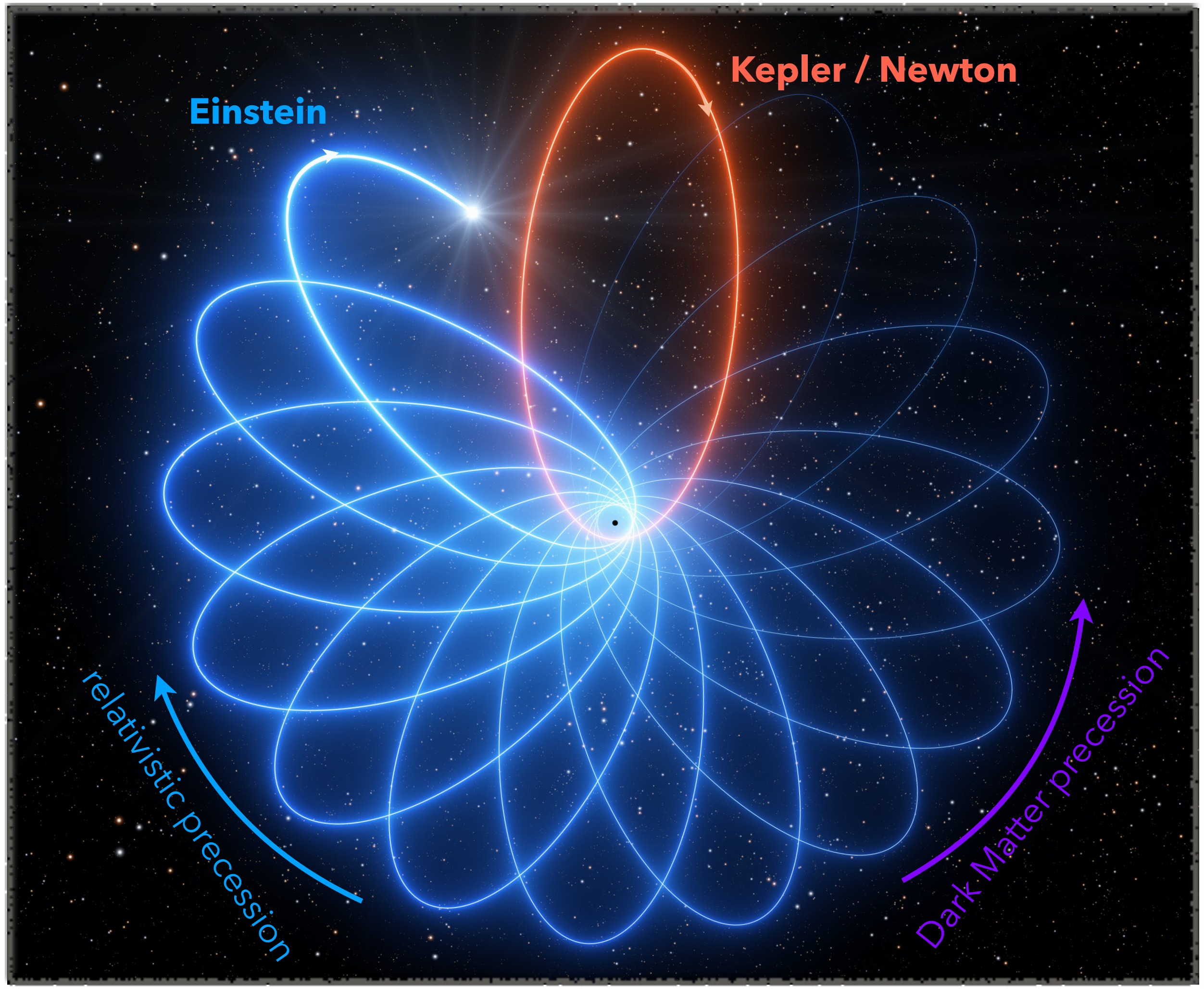
ESO



MPG

Stellar dynamics around a massive black hole

LESIA l'Observatoire de Paris esa



$$\ddot{\mathbf{r}} = -\frac{GM}{r^2}\hat{\mathbf{r}}$$

$$\ddot{\mathbf{r}} = -\frac{GM}{r^2}\hat{\mathbf{r}} + (\text{post-Newtonian})$$

$$\ddot{\mathbf{r}} = -\frac{GM}{r^2}\hat{\mathbf{r}} + (\text{post-Newtonian}) + (\text{Dark Matter})$$

The dark mass signature in the orbit of S2

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

- Considered **perturbed Kepler problem**

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

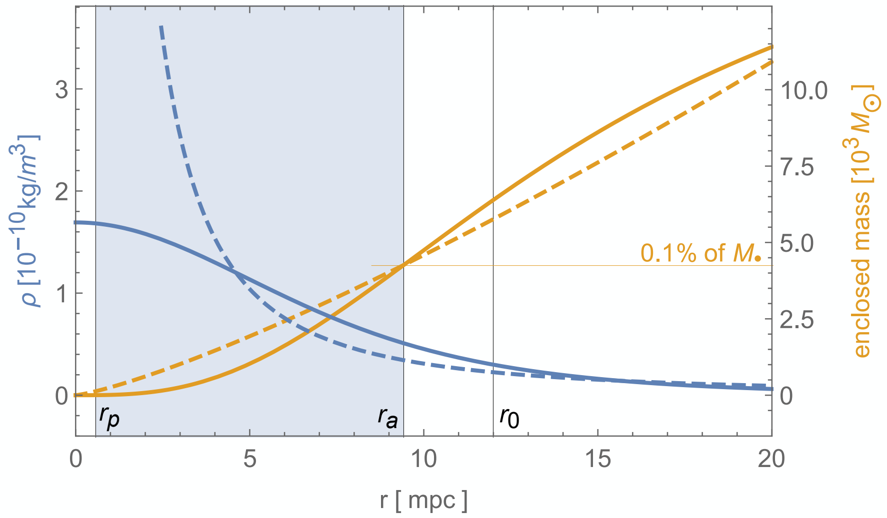
- $\mathbf{a}_{\mathrm{DM}}$ generated by **density profile**

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

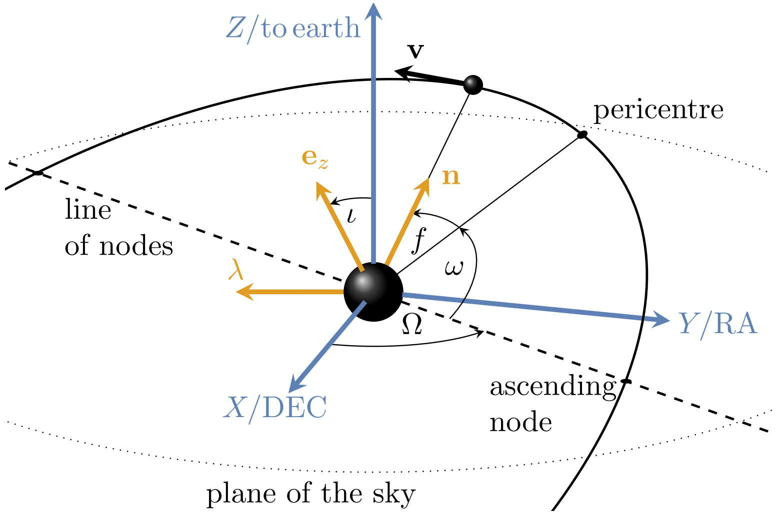
- OOGRE code integrates **osculating equations**

$$\partial_t(p, e, \iota, \Omega, \omega, f) = \mathbf{f}(p, \ldots, f, \mathbf{a}_\mathrm{p})$$

argument of pericentre

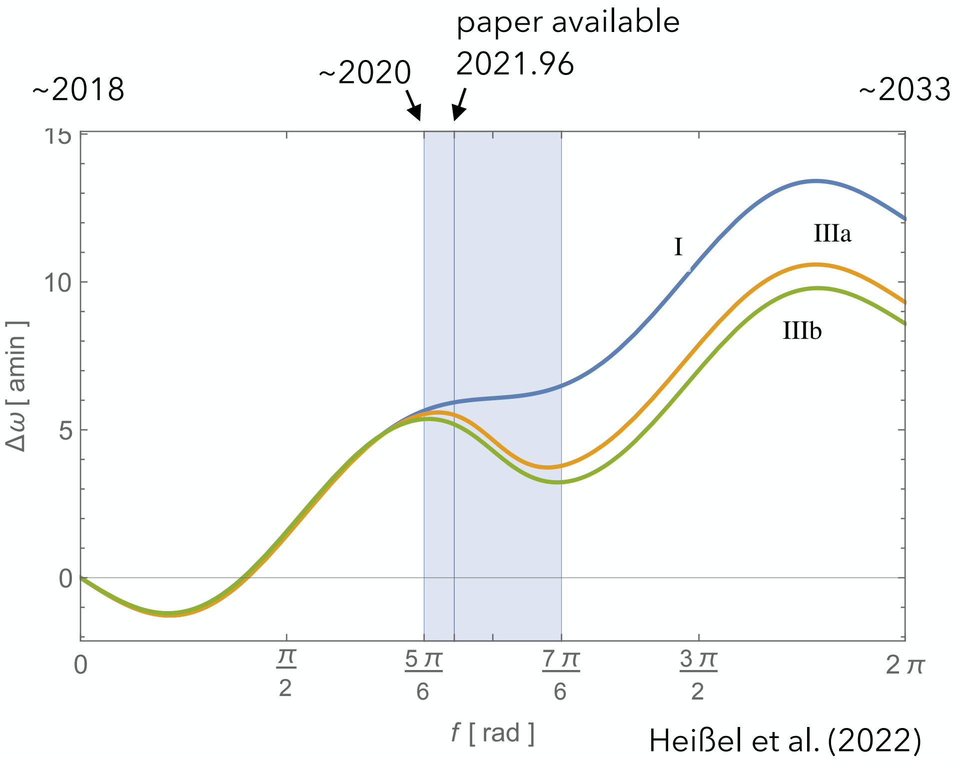


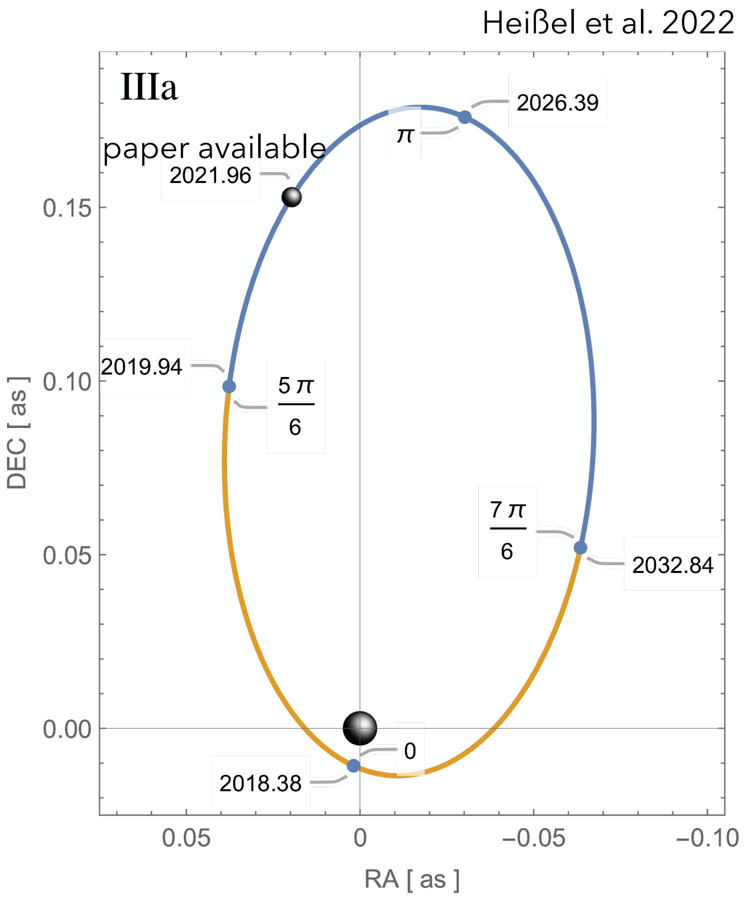
Heißel et al. 2022

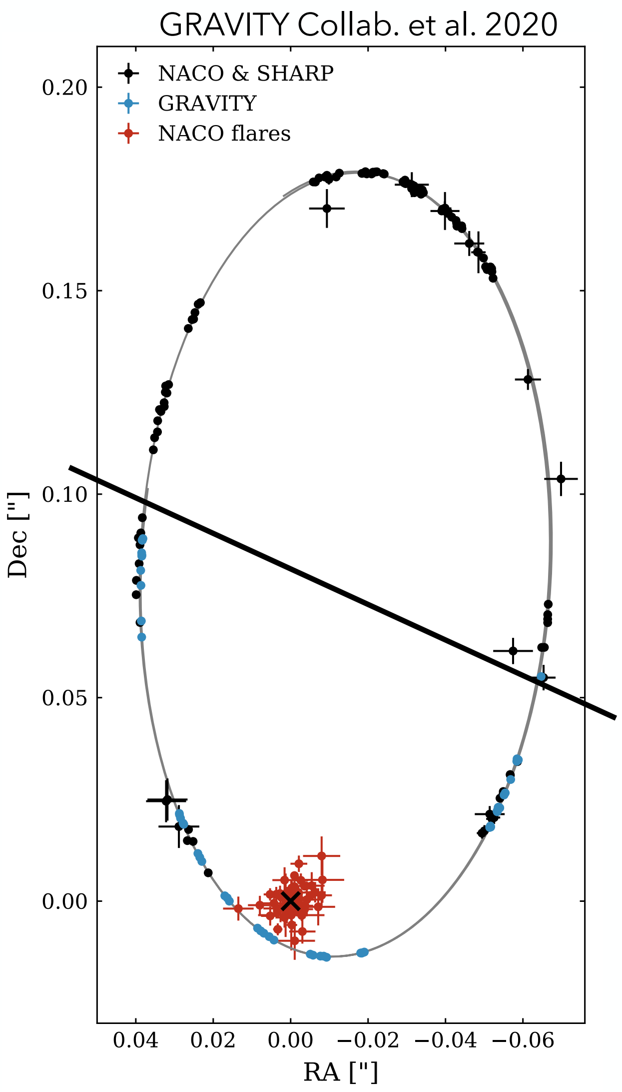


Heißel et al. 2022

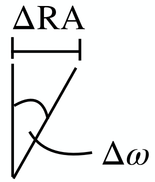
Dark Matter impact on orbital elements







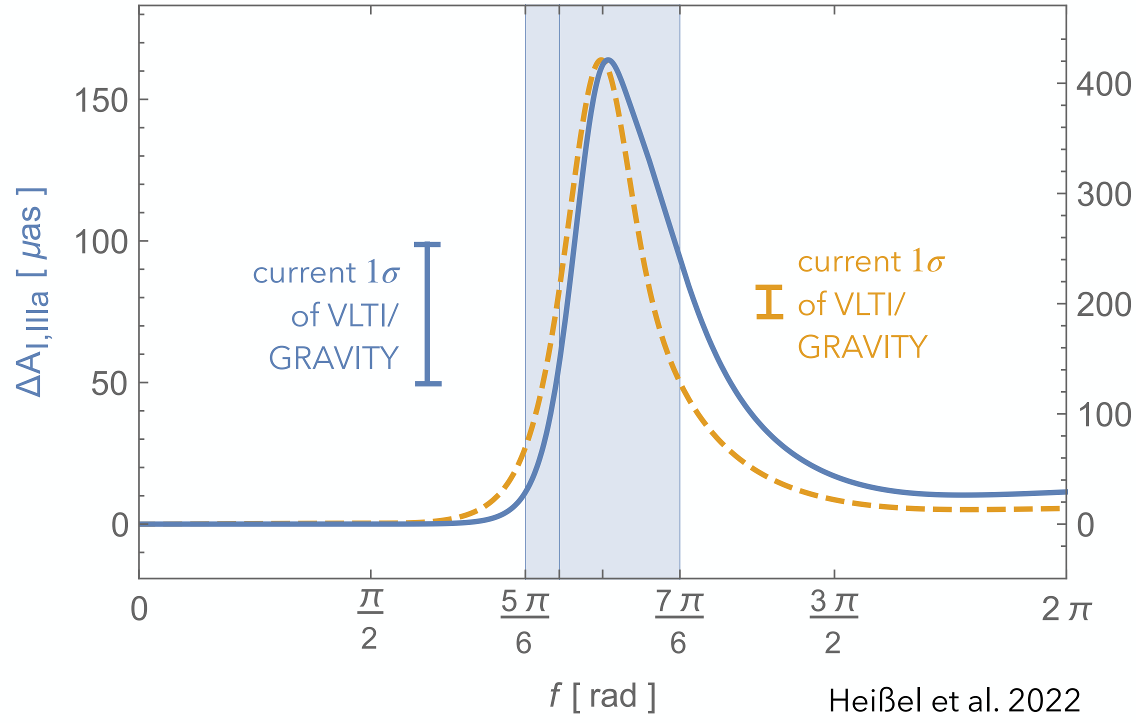
+ Estimate of astrometric impact → <191 μas in RA. < –183μas in DEC.



Dark Matter impact on observables

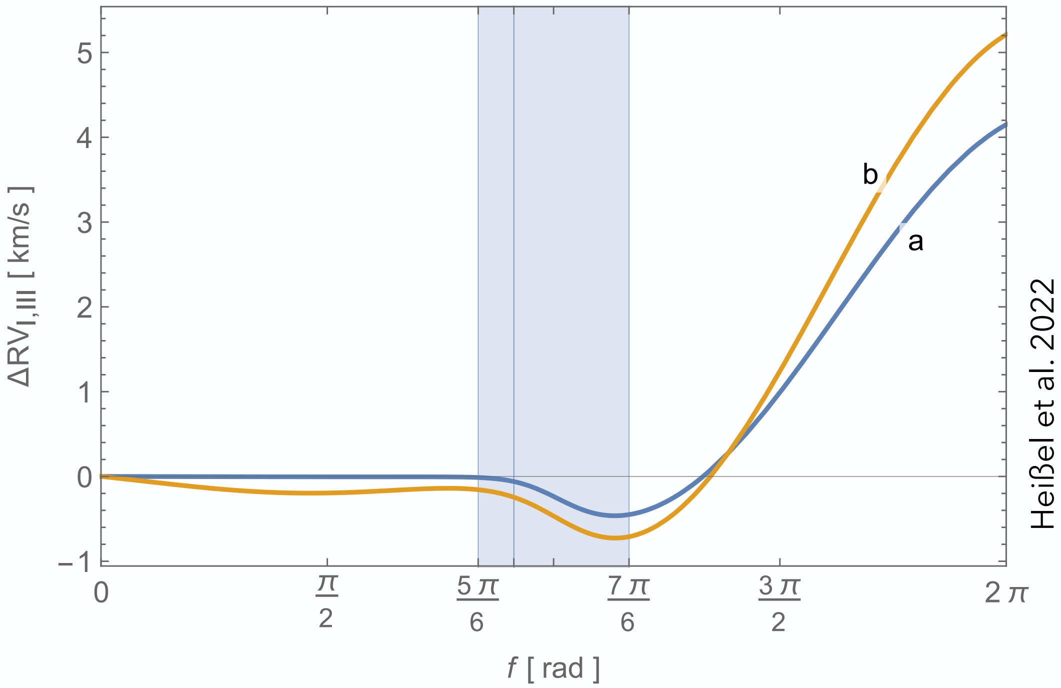
- Astrometry (RA, DEC)

$$\Delta A_{I,III}(f) = \sqrt{\Delta RA^2_{I,III}(f) + \Delta DEC^2_{I,III}(f)}$$



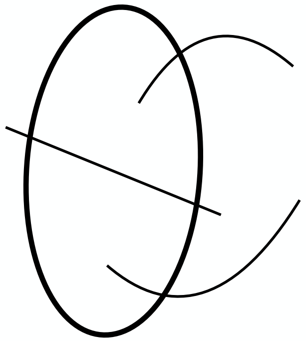
Residuals of (1PN + DM) orbit to 1PN orbit.

- Radial velocity (RV)

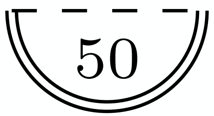


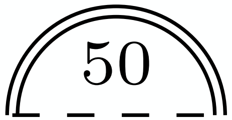
For RV focus: see Takamori et al. 2020

Mock Data analysis



- Data limited to **orbital halves**

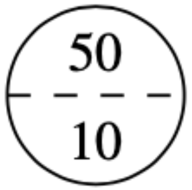


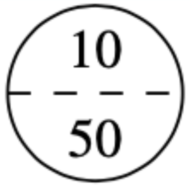


Cannot constrain DM. **Can** constrain DM.

➡ **Confirms** that peri half by itself is not sensitive to DM.

- Data on **full orbit** with different accuracies.

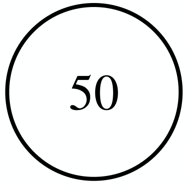


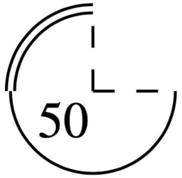


Constrains DM better.

➡ **Counterintuitive** given previous result!

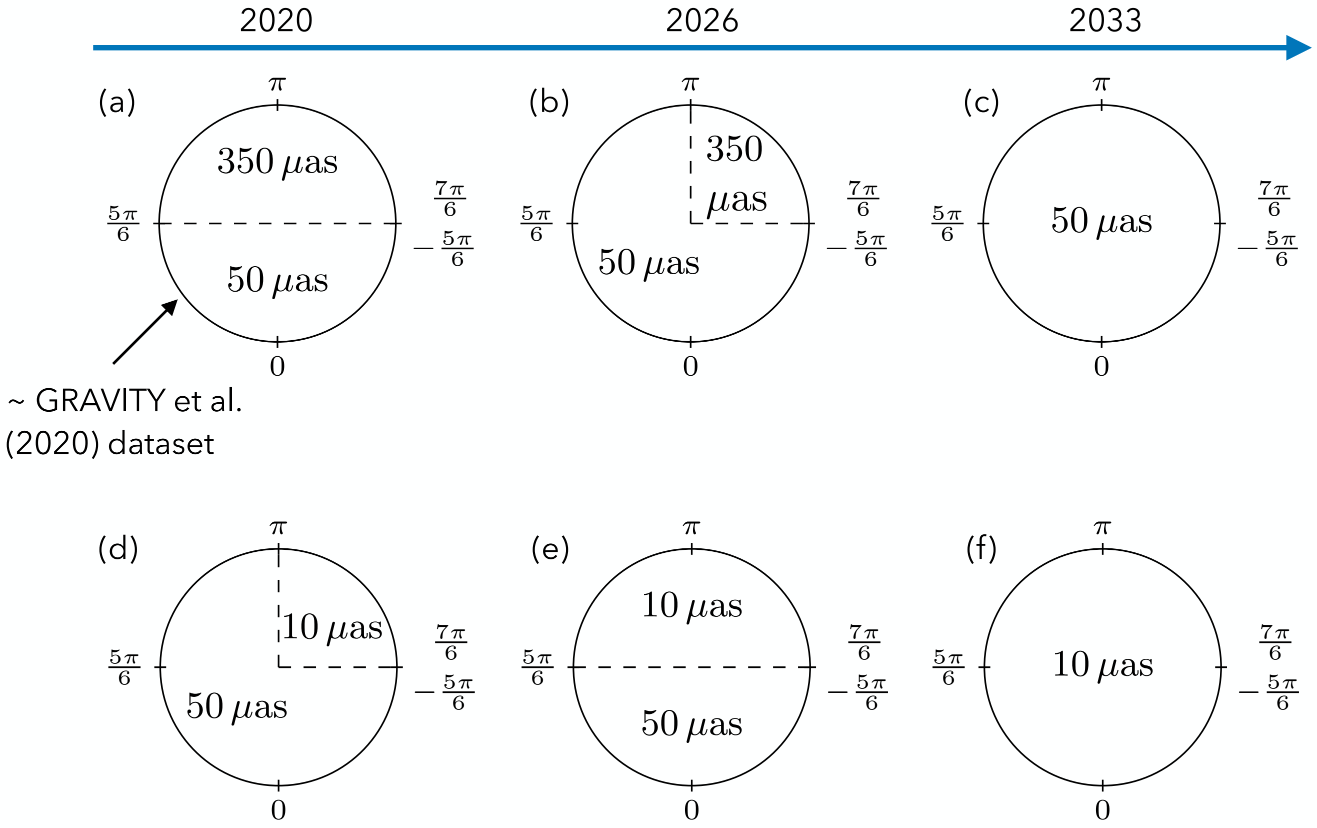
- Can **denser sampling** make up for data gap on orbit? **No!**





Constrains DM better.

Detection threshold estimates



within S2's apocentre

Case	Enclosed mass $[M_\odot]$
(a)	4261
(b)	2828
(c)	969
(d)	799
(e)	699
(f)	194

2020 / 2026 / 2033 → (a), (b), (c)

← GRAVITY et al. (2020) limit

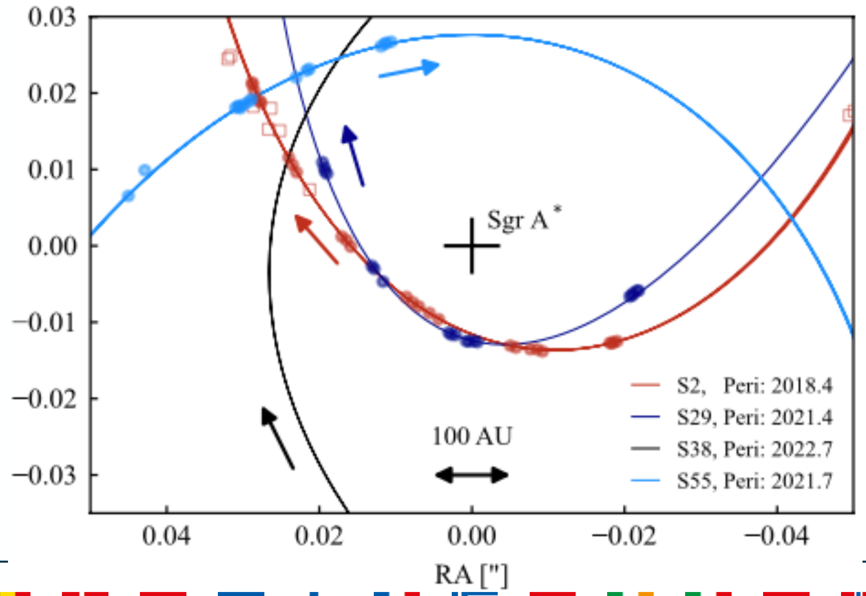
Heißel et al. 2022

Results come with * of **assumed** ρ_0 profile.

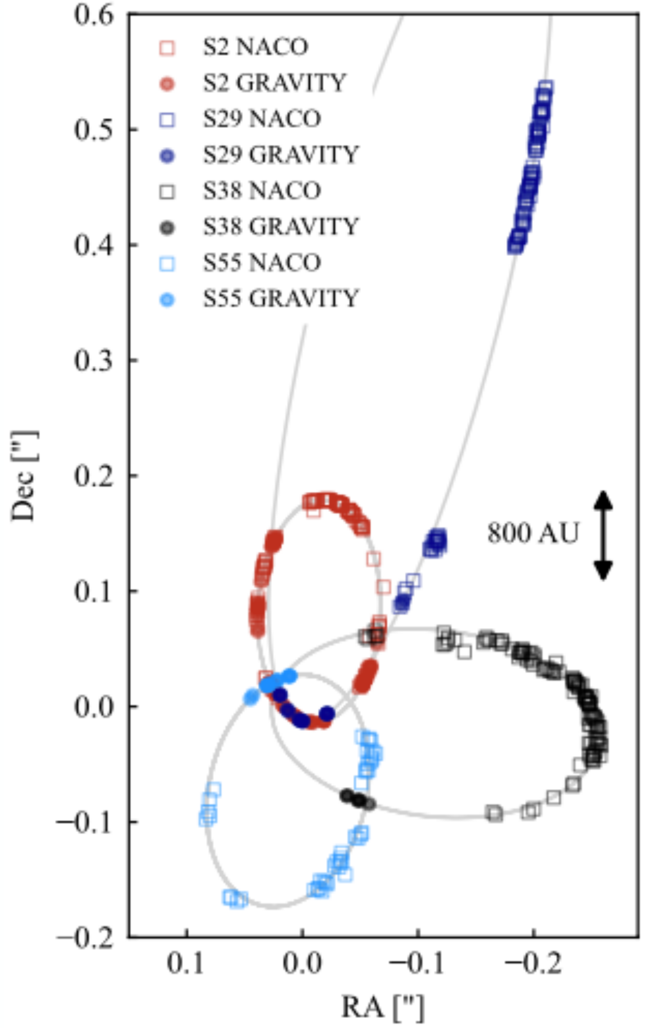
Mass distribution in the Galactic Centre...

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

- **Observational Updates** since 2020
  - ➡ **more GRAVITY data**, and GRAVITY data for **more stars**
  - ➡ **S29 & S55** went **through pericentre**
  - ➡ New **faint star S300** detected $m_K^{S300} \approx 19, m_K^{S2} \approx 14$
    GRAVITY et al. (2022b) "Deep images of the GC..."



GRAVITY Collab. et al. 2022



GRAVITY Collab. et al. 2022

Sharpened constraints

- Sharpened measurement of **Schwarzschild precession**

  ➡ **S2** orbit fit

  $f_{SP}^{2020} = 1.10 \pm 0.19$ vs.

  $f_{SP}^{2022} = 0.85 \pm 0.16$

  ➡ **4 star** orbit fit

  $f_{SP}^{2022} = 0.997 \pm 0.144$

  $$f_{SP} = \begin{cases} 0 & \text{Newton} \\ 1 & \text{Einstein} \end{cases}$$

  $\Rightarrow$ Improved **rejection of Newton** from 5 to 7σ

- Sharpened constraints on **dark mass**

  ➡ **S2** orbit fit

  $M_{\text{enclosed}}^{2020} = (\sim 0 \pm 4300)\, M_\odot$ vs.

  $M_{\text{enclosed}}^{2022} = (2700 \pm 3500)\, M_\odot$

  ➡ **4 star** orbit fit

  $M_{\text{enclosed}}^{2022} = (-3800 \pm 2400)\, M_\odot$

  $\Rightarrow$ Improved 1σ **upper bound** from 0.1% to 0.06% of $M_\bullet$

within S2's apocentre

	Case	Enclosed mass $[M_\odot]$
2020	(a)	4261 ← GRAVITY et al. (2020) limit
2026	(b)	2828
2033	(c)	969
	(d)	799
	(e)	699
	(f)	194

Heißel et al. 2022

Predictions so far **confirmed** ✔.

Results come with * of **assumed** ρ_0.

DM reconstruction from stellar orbits in the GC

Lechien T, Heißel G, Jai G, Izzo D in preparation

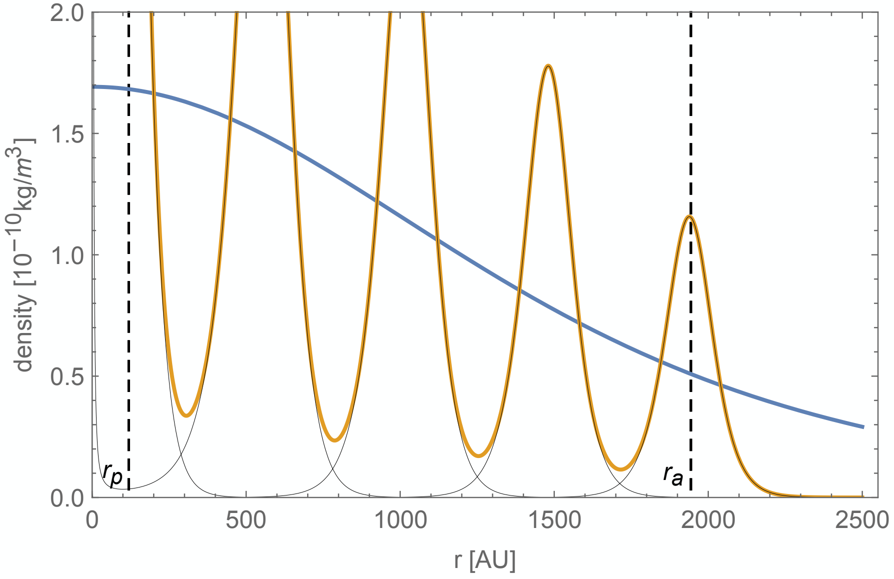
- **Motivation**
  - ➡ get rid of * (assumption of density profile)
  - ➡ give model flexibility to attain different density profiles
  - ➡ fit to data should find true distribution
  - ➡ allow to infer physical nature of DM

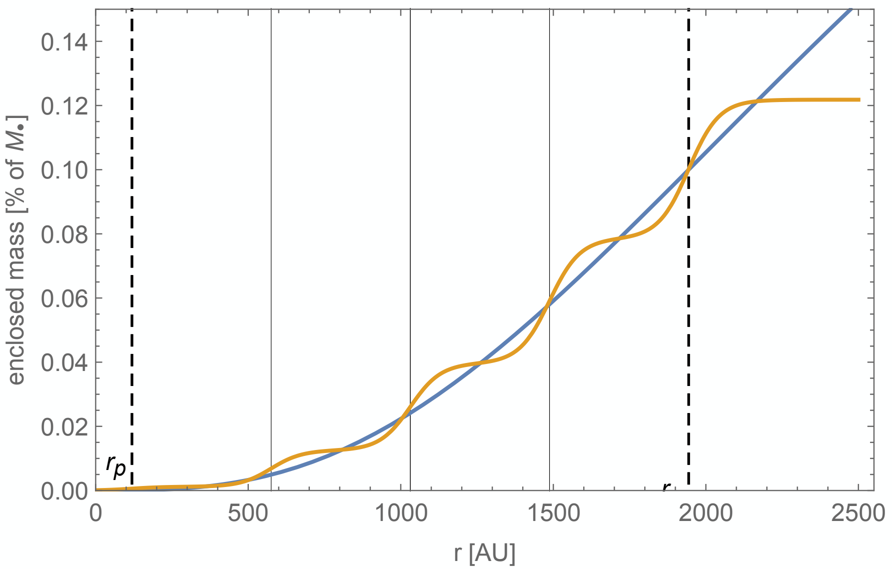
$$\rho(r) = \begin{cases} \rho_0 \left(1 + \frac{r^2}{r_0^2}\right)^{-5/2} & \text{Plummer} \\ \rho_0 \left(\frac{r}{r_0}\right)^{-7/4} & \text{Bahcall-Wolf cusp} \\ \rho_0 \left(\frac{r}{r_0}\right)^{-\gamma \in (0.5, 2.5)} & \text{particle dark matter} \\ \text{etc.} \\ \text{mix of the above} \end{cases}$$

Not necessarily spherically symmetric!

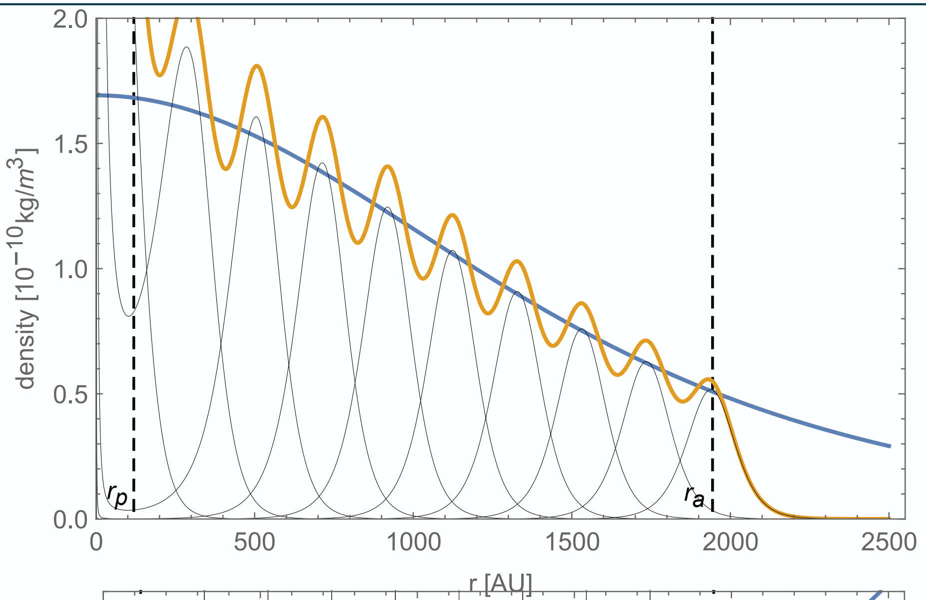
Mass shell model

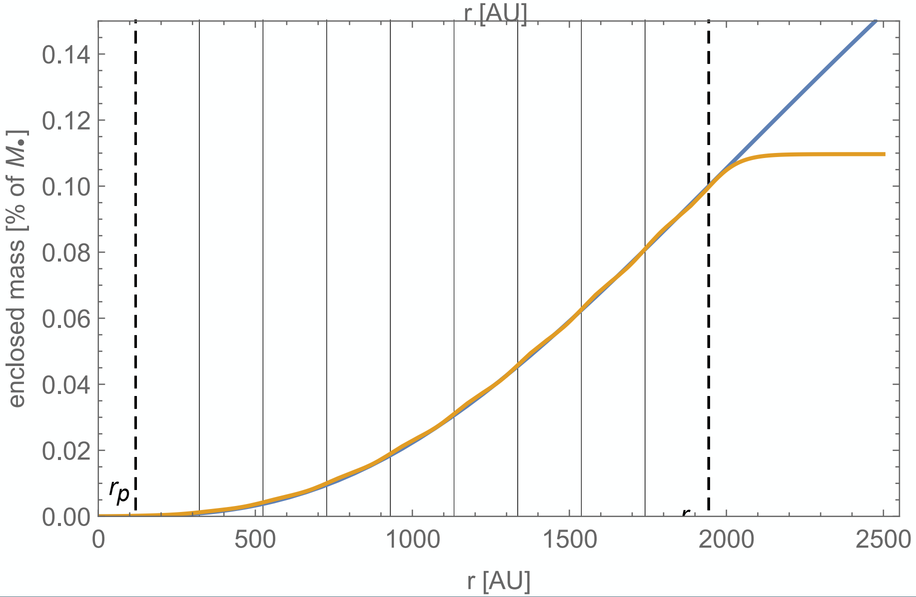
5 shells





10 shells





Mass shell model

- **Advantage**
  - ➡ flexibility of model
  - ➡ can find true distribution from fitting to data
- **Disadvantage**
  - ➡ higher number of model parameters
  - ➡ more data needed to constrain model

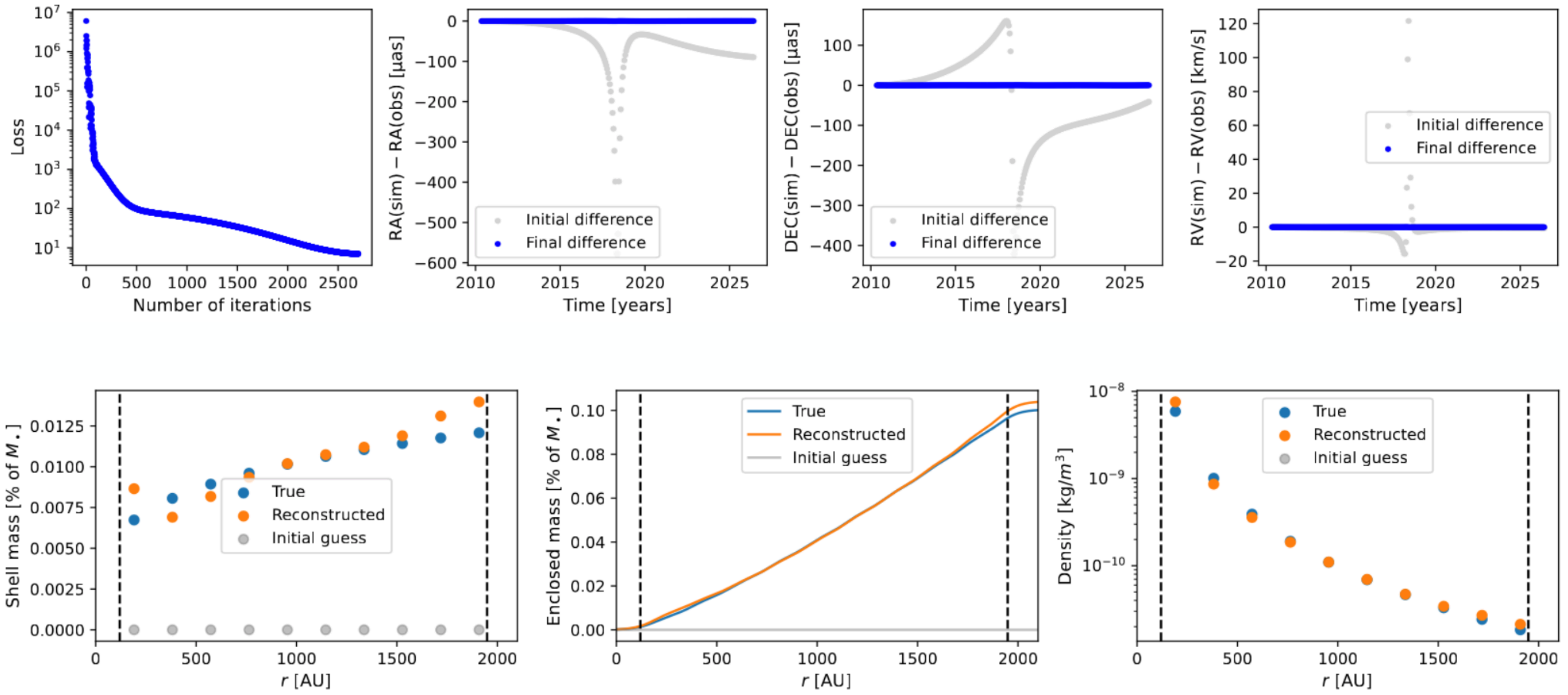
$$\rho(r) = \rho_0 \left(1 + \frac{r^2}{r_0^2}\right)^{-5/2}$$

e.g. Plummer: 2 parameters

Mas shell: 10+ parameters

Results (preliminary)

perfect mock data (no noise), 300 obs, 1 orbit

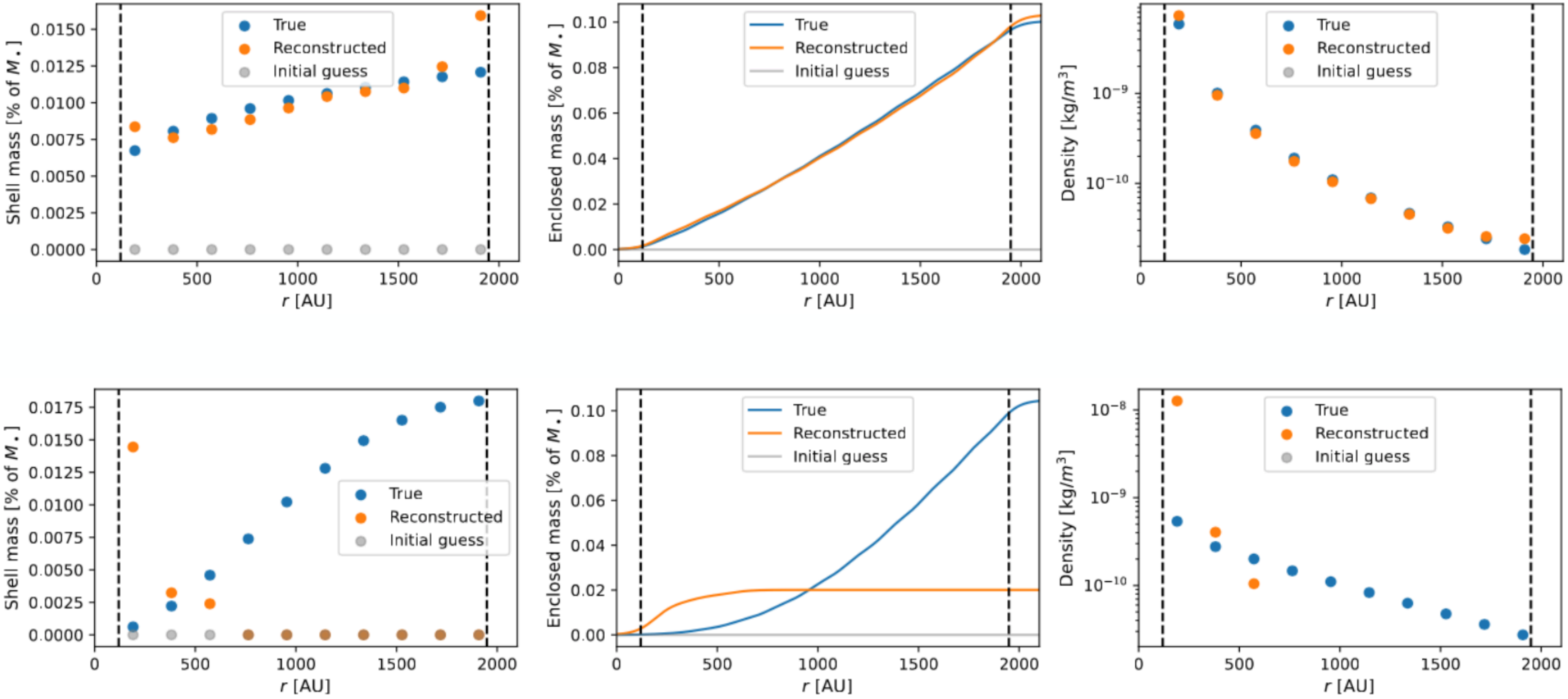


Results (preliminary)

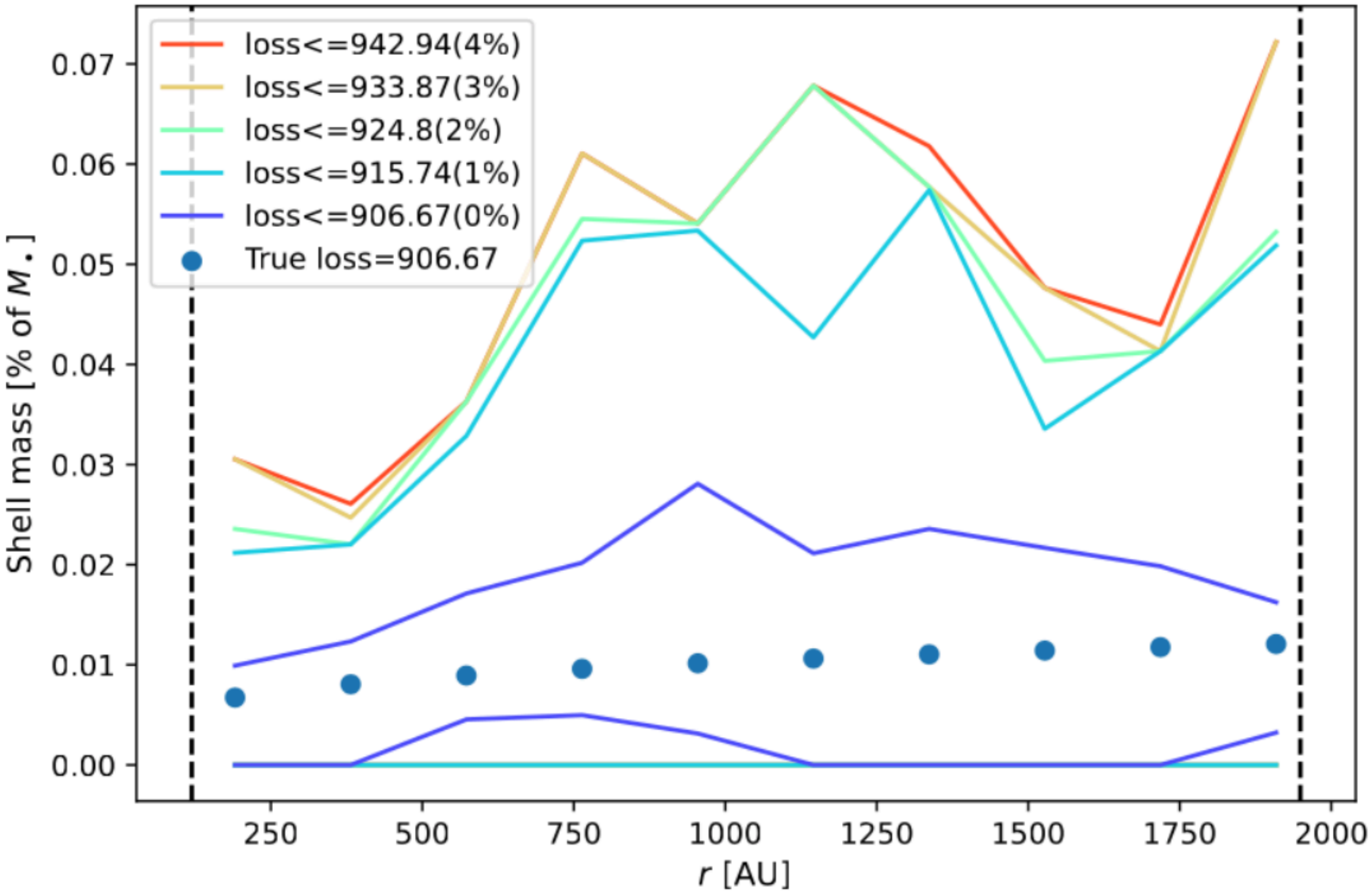
mock data with noise, 300 obs, 1 orbit

noise = $\sigma/10$

noise = σ



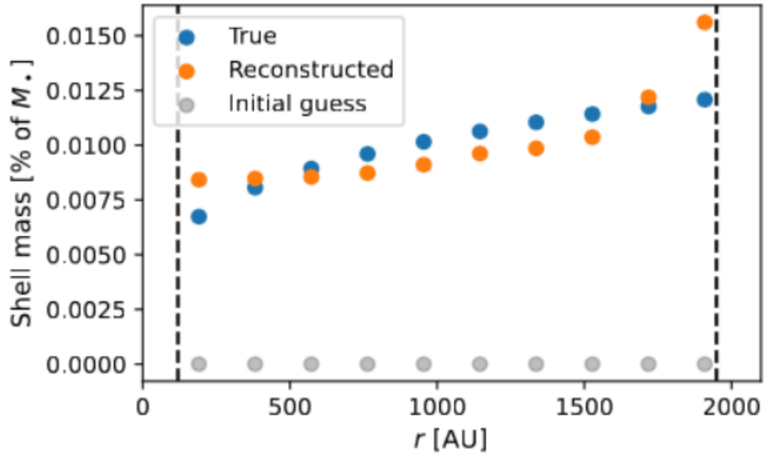
Results (preliminary)

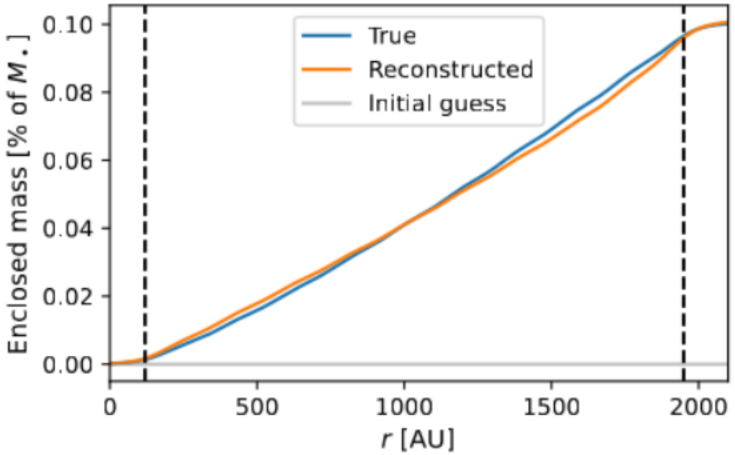


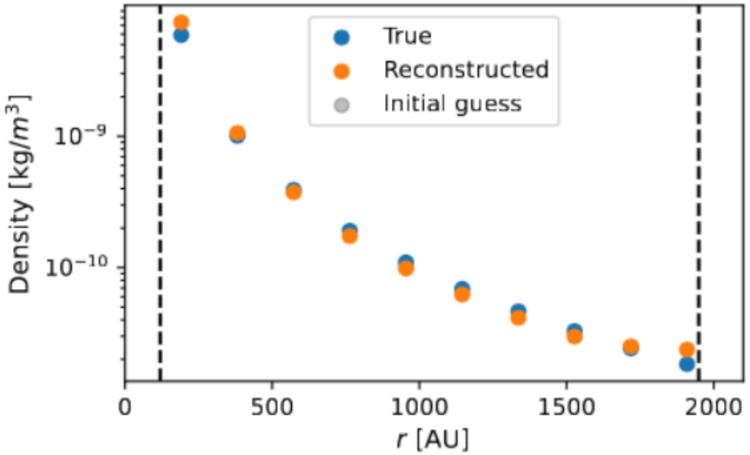
- **What is (likely) going on?**
  - ➡ Neighbouring shell masses correlate
  - ➡ too many parameters → end up fitting the noise

Results (preliminary)

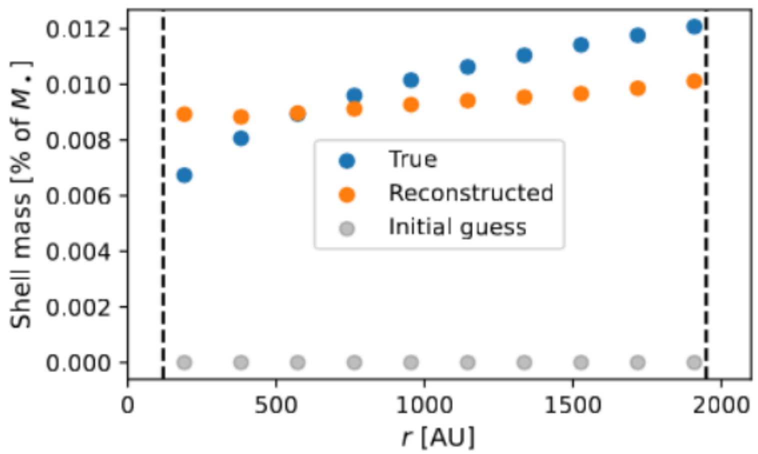
10 x nr. of obs.

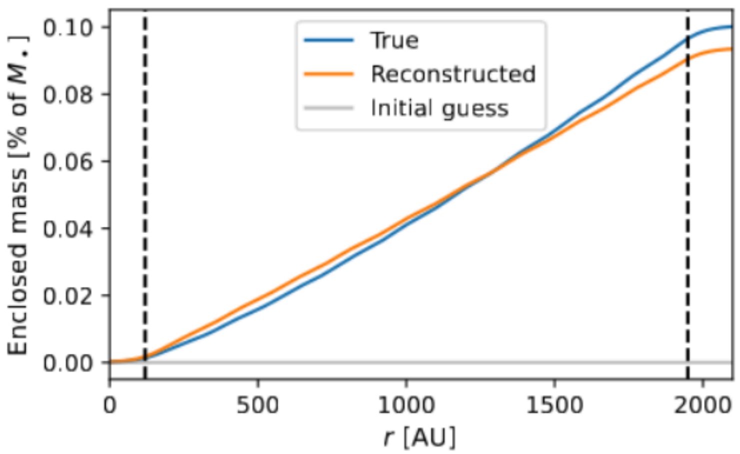


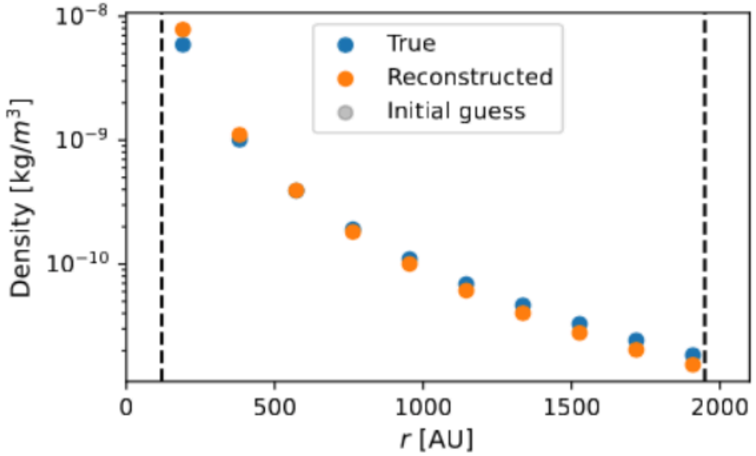




10 orbits, same obs/orbit







Conclusions

- Mass shell model reliable for noiseless data
- Not robust enough for current number of observations and instrument precision on one star.
- Not yet applicable to the GC, but potentially in the future. (more data, better accuracy, good data for more stars)