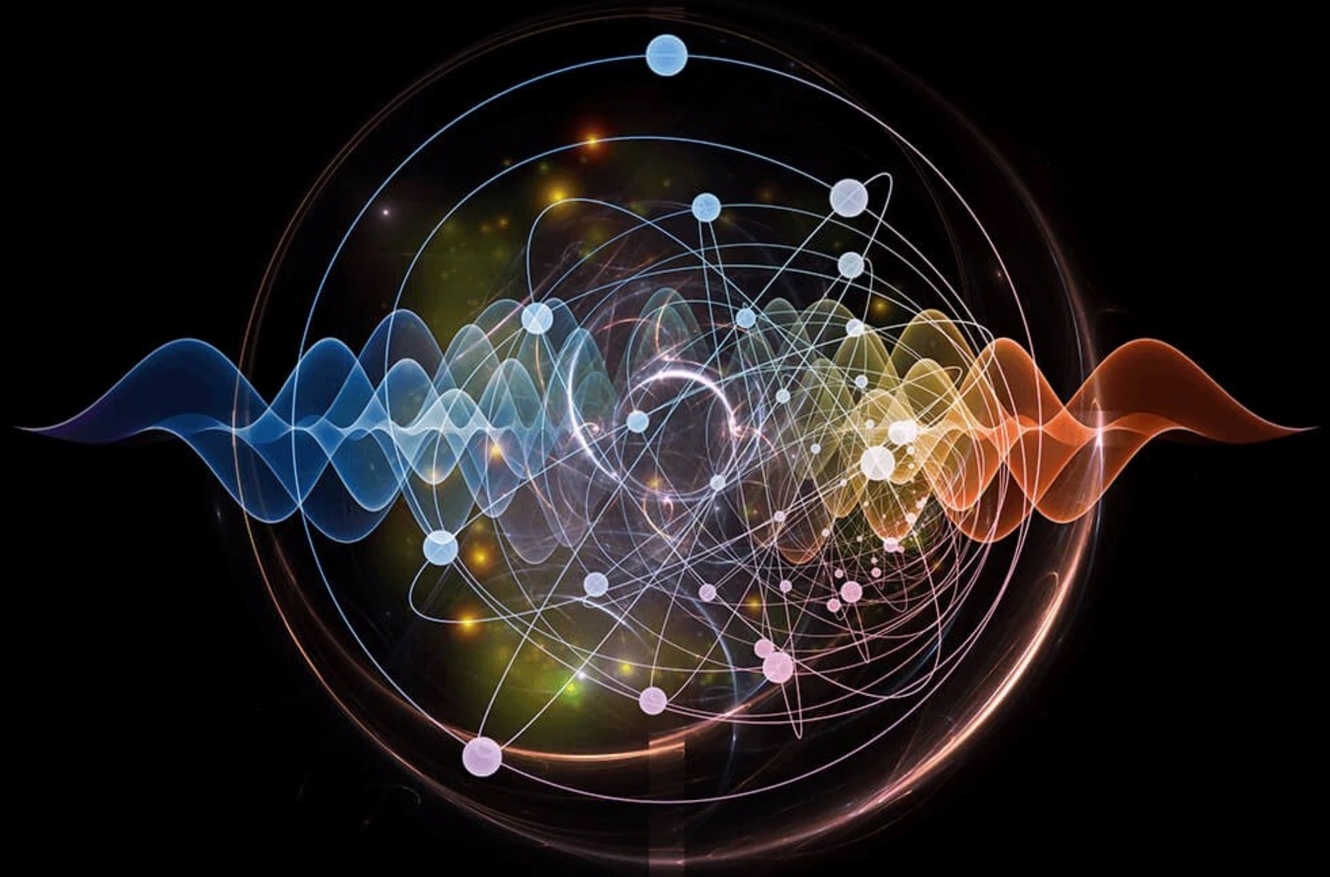
Testing the presence of a fifth force at the Galactic Center

Arianna Foschi - GRAVITY+ workshop - 19 November 2024



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Overview and motivation

IR modification
(cosmological scales)

+

General Relativity

+

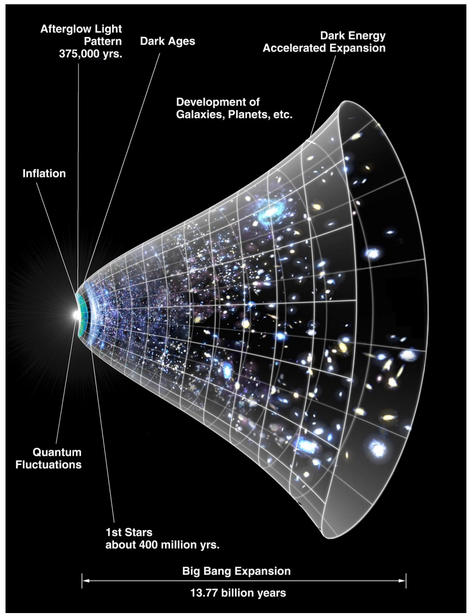
Higher derivatives
(i.e. GR modifications)

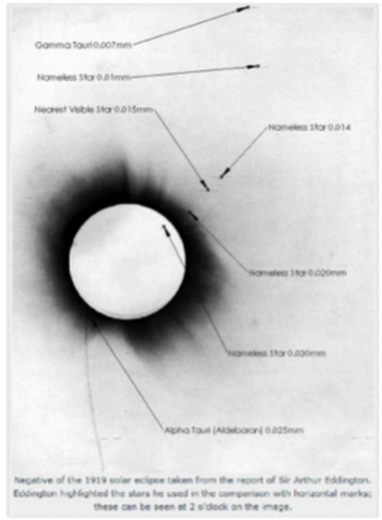
⟶ ⟵

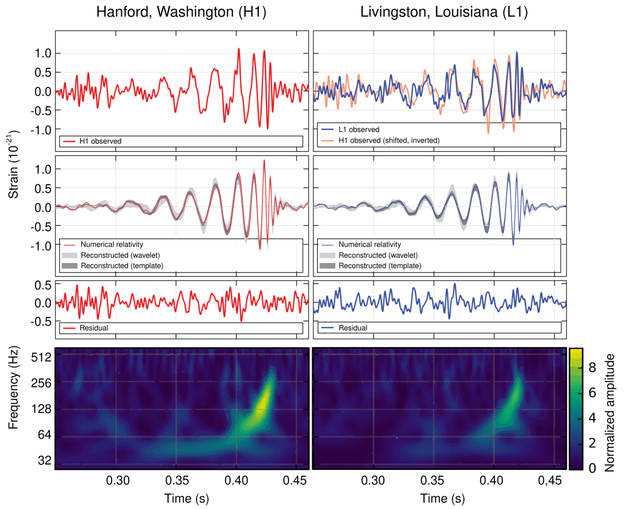
UV completion
(e.g. string theory)

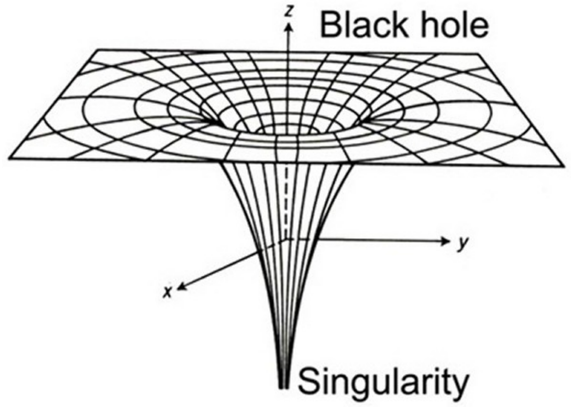
Energy scale →

Ω_Λ $M_\odot$ M $M_{\rm PL}$







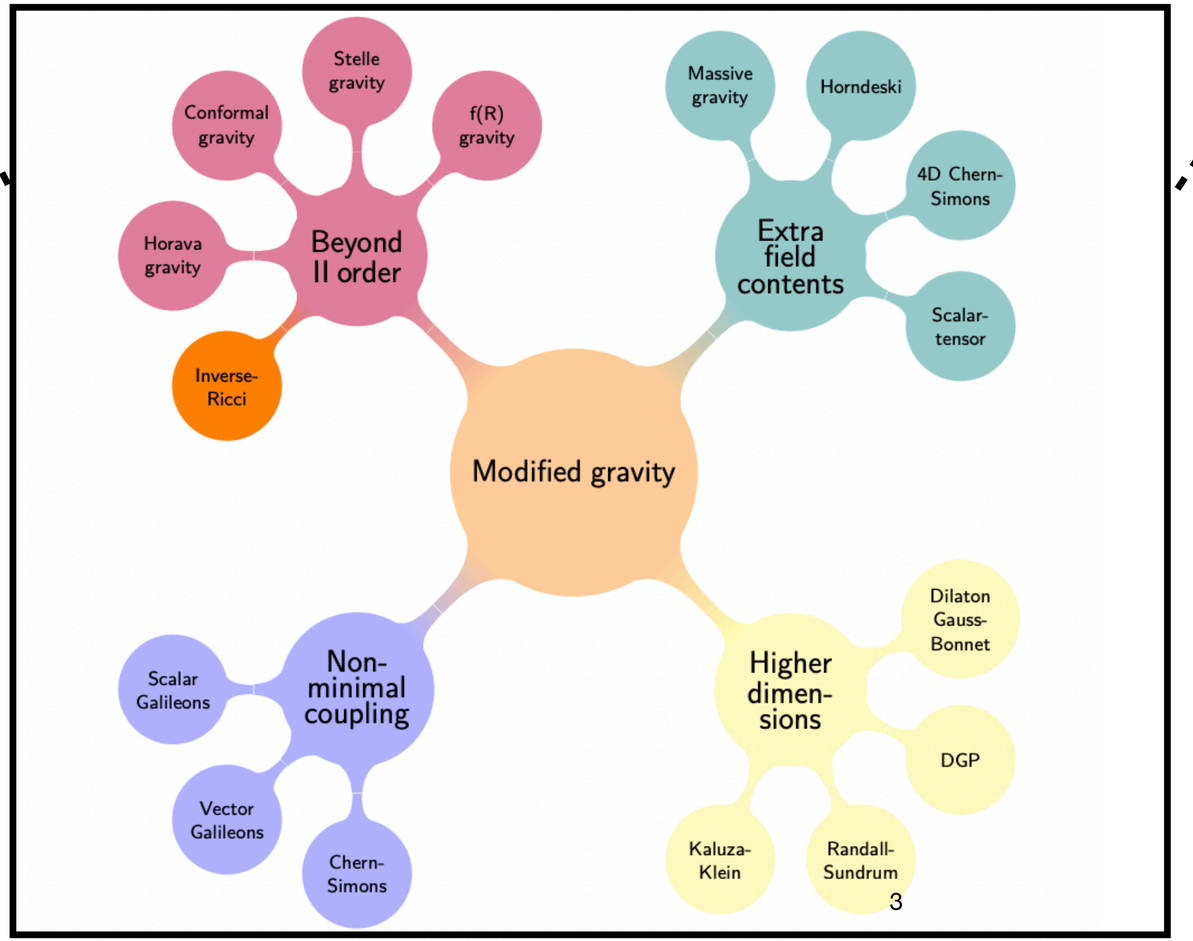


The zoo of Extended Theories of Gravity

IR modification (cosmological scales) + **General Relativity** + Higher derivatives (i.e. GR modifications) ⇄ UV completion (e.g. string theory)

Energy scale

M $M_{\rm PL}$



Lovelock's theorem

GR is the **only theory of gravity** in which:

- EoM are given by second order derivative of the metric;
- The only degrees of freedom are given by $g_{\mu\nu}$;
- Spacetime is in 4 dimensions;
- The theory is covariant.

Figure from Shankaranarayanan et al. (2022) (arXiv: 2204.06533)

Current constraints on $|\alpha|$

$$U = -\frac{GM}{r}\left(1 + |\alpha|\, e^{-r/\lambda}\right)$$

α = Intensity (coupling to gravity)

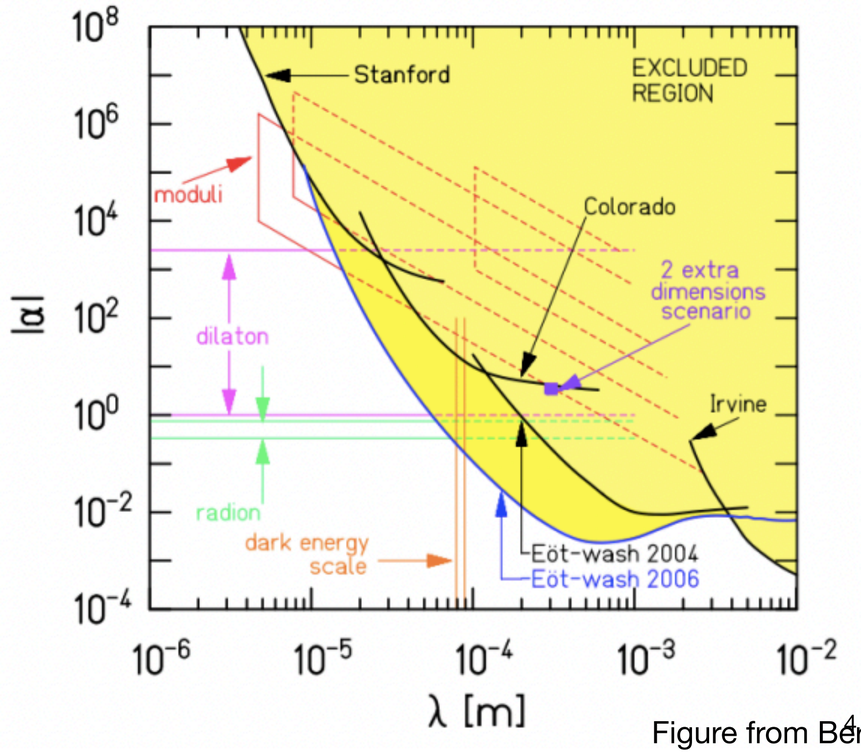
λ = Length scale

$\sim 10^{-6}\,\mathrm{m}$ $\sim 10^{12-13}\,\mathrm{m}$ λ

Tested range

$\ell_{PL} \sim 10^{-35}\,\mathrm{m}$

$\ell_{U} \sim 10^{26}\,\mathrm{m}$



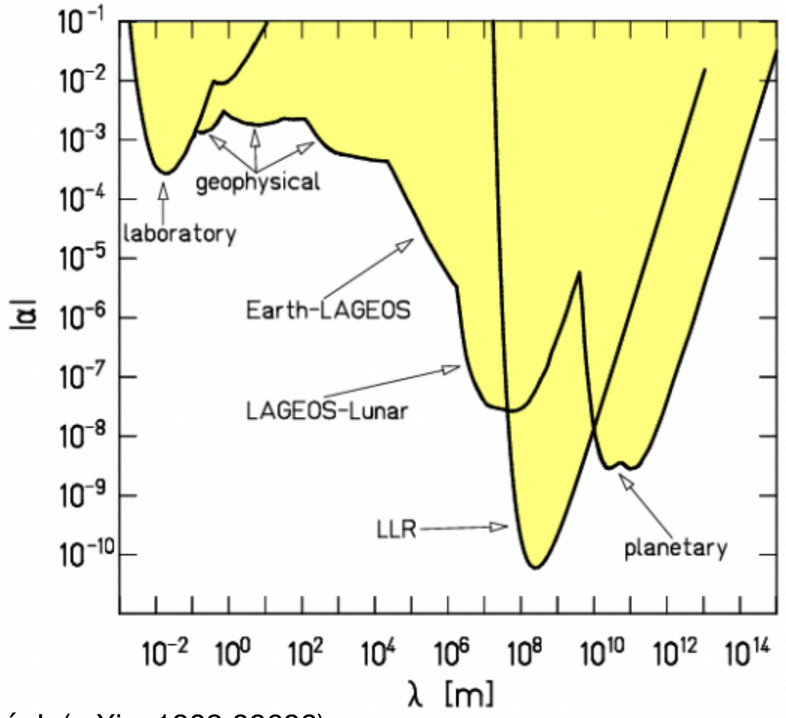


Figure from Bergé J. (arXiv: 1809.00698)

Current constraints on $|\alpha|$ for $\lambda > 1\,\mathrm{cm}$

$$U = -\frac{GM}{r}\left(1 + |\alpha| e^{-r/\lambda}\right)$$

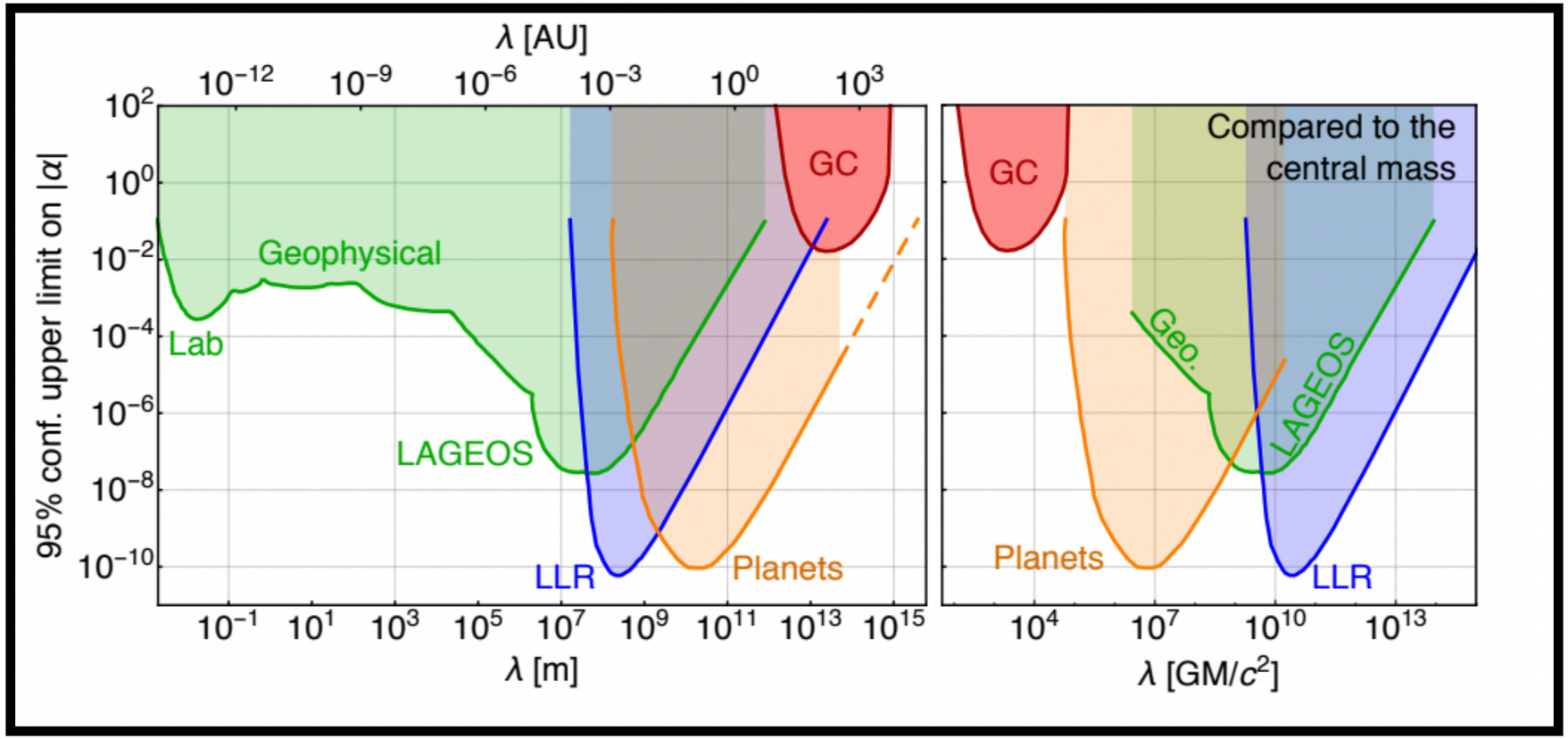
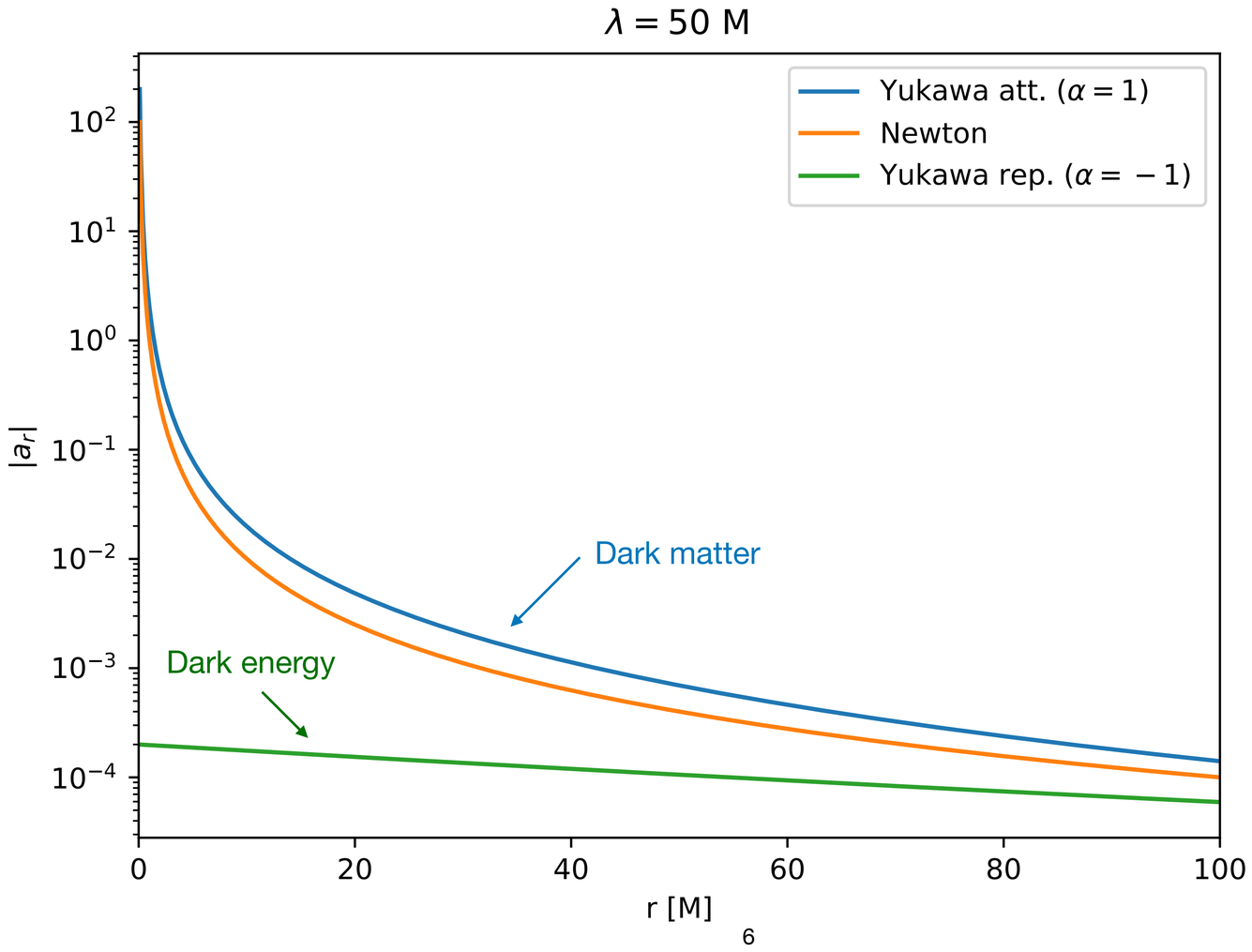


Figure from Hees et al. 2017 (arXiv: 1705.07902)

Yukawa-like correction: behavior of the acceleration

$$U = -\frac{GM}{r}\left(1 + |\alpha| e^{-r/\lambda}\right)$$



$\alpha > 0$: force mediated by massive **scalars**

$\alpha < 0$: force mediated by massive **vectors**

(Moffat 2016)

Dataset

Available Data for S2

- **Astrometry**
  - **NACO & SHARP** from 1992 to 2019 ($\sigma \sim 0.5\,\mathrm{mas}$);
  - **GRAVITY** data from 2016 to 2022 ($\sigma \sim 50\,\mu\mathrm{as}$).
- **Spectroscopy**

  (Radial velocity measurements)
  - **SINFONI** data from 2000 to 2022 ($\sigma \sim 10 - 20\,\mathrm{km/s}$).

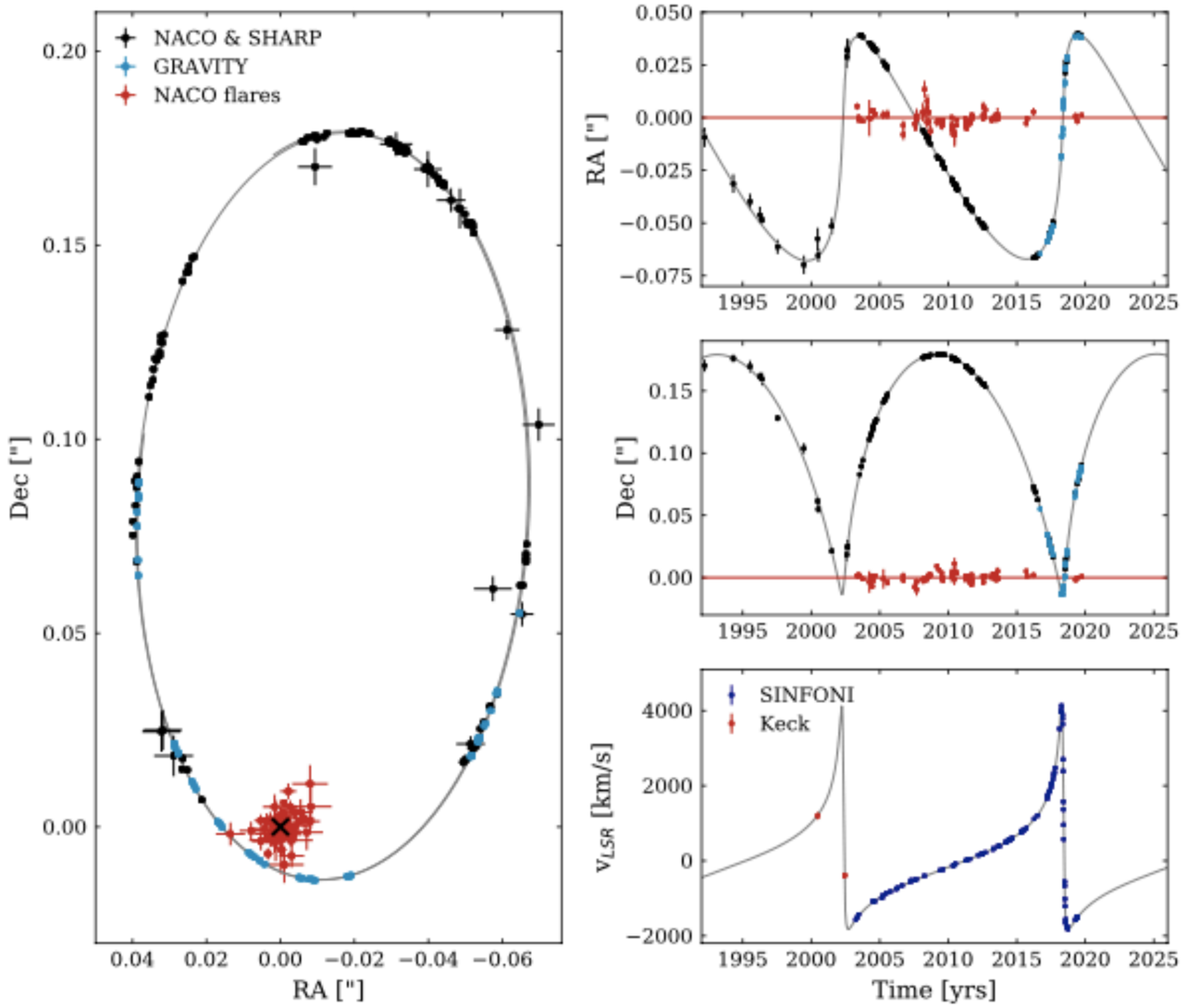


Figure from GRAVITY Coll. *et al.* 2020

Corrections to the Keplerian model in the fit

(GRAVITY Coll. 2018, Alexander 2005)

- **Newtonian effect**: the Roemer delay due to finite value of c.

- **1st Post Newtonian (PN) correction**

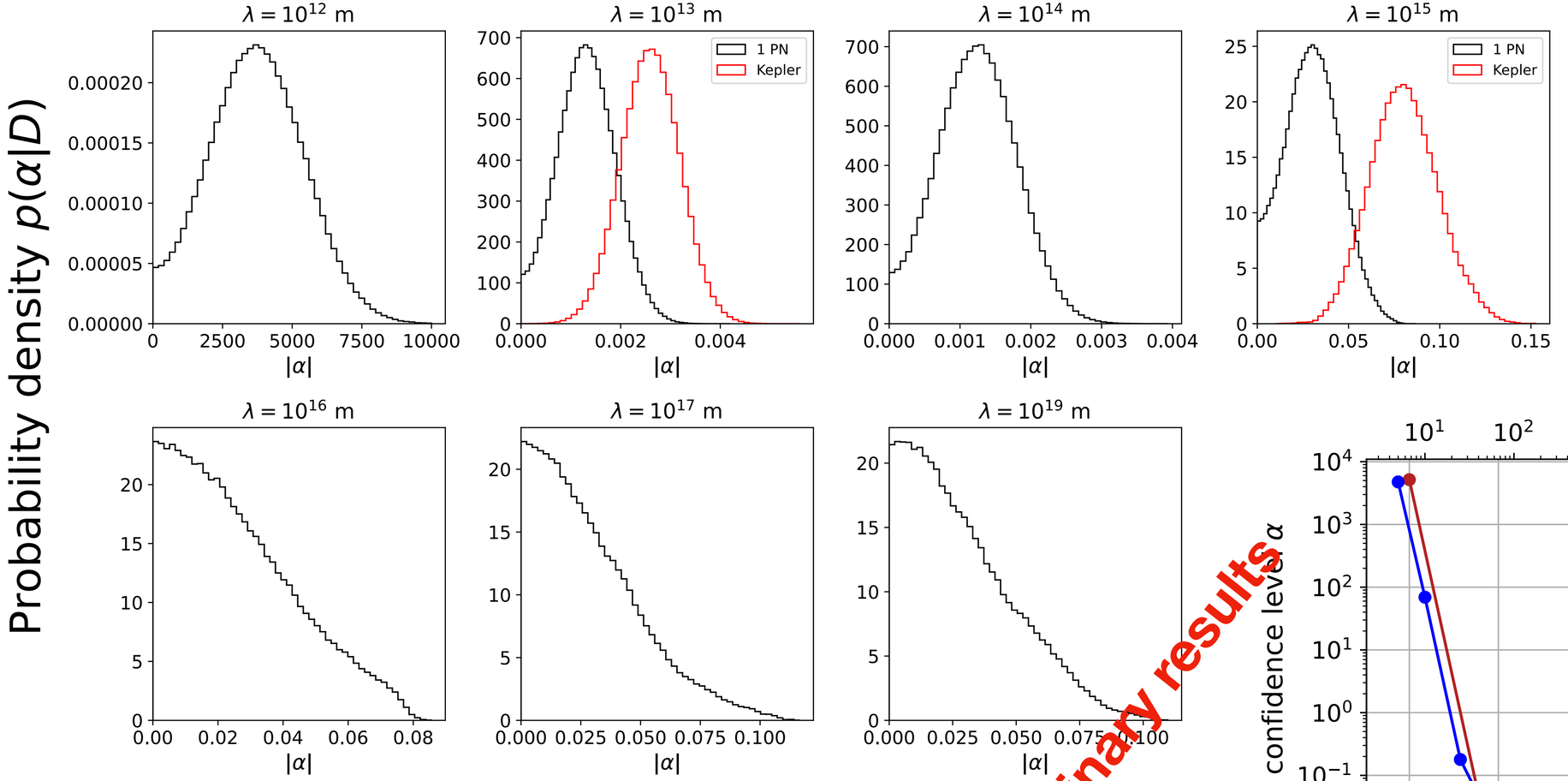
  Schwarzschild precession has been detected on S2 motion at 10σ confidence level
  (GRAVITY Coll. 2024)

$$a_{\mathrm{1PN}} = f_{\mathrm{SP}} \frac{GM_\bullet}{c^2 r^2} \left[\left(\frac{4GM_\bullet}{r} - v^2 \right) \frac{\boldsymbol{r}}{r} + 4\dot{r}\boldsymbol{v} \right] \qquad \text{with } f_{\mathrm{SP}} = 1$$

$$\left(\beta = \gamma = 1\right)$$

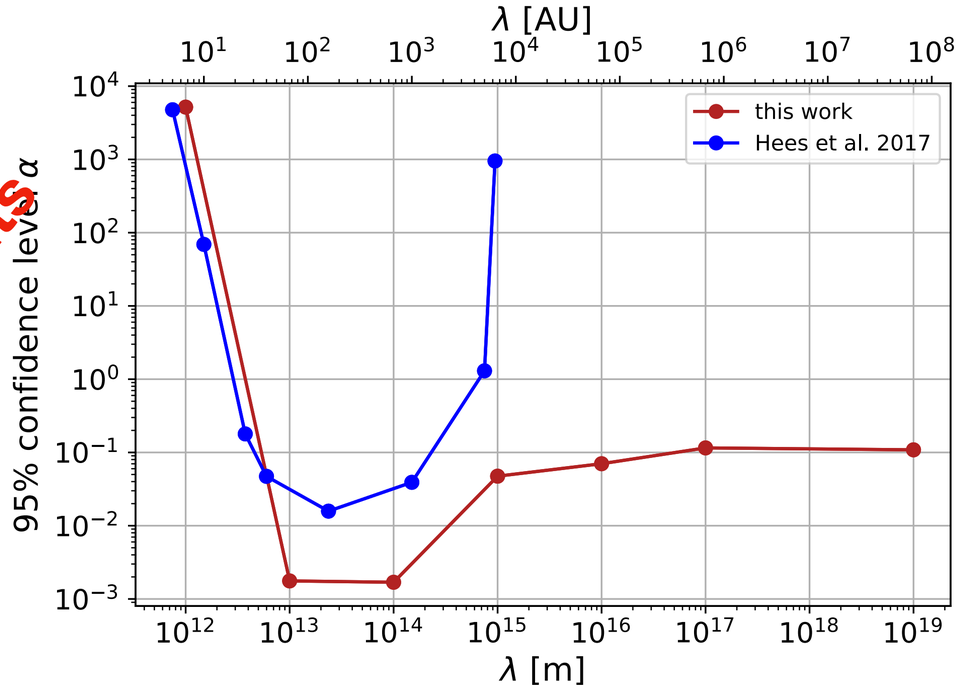
Results: χ^2 minimization and MCMC analysis

Posterior distributions of $|\alpha|$ for fixed λ



Red curves: only Kepler model

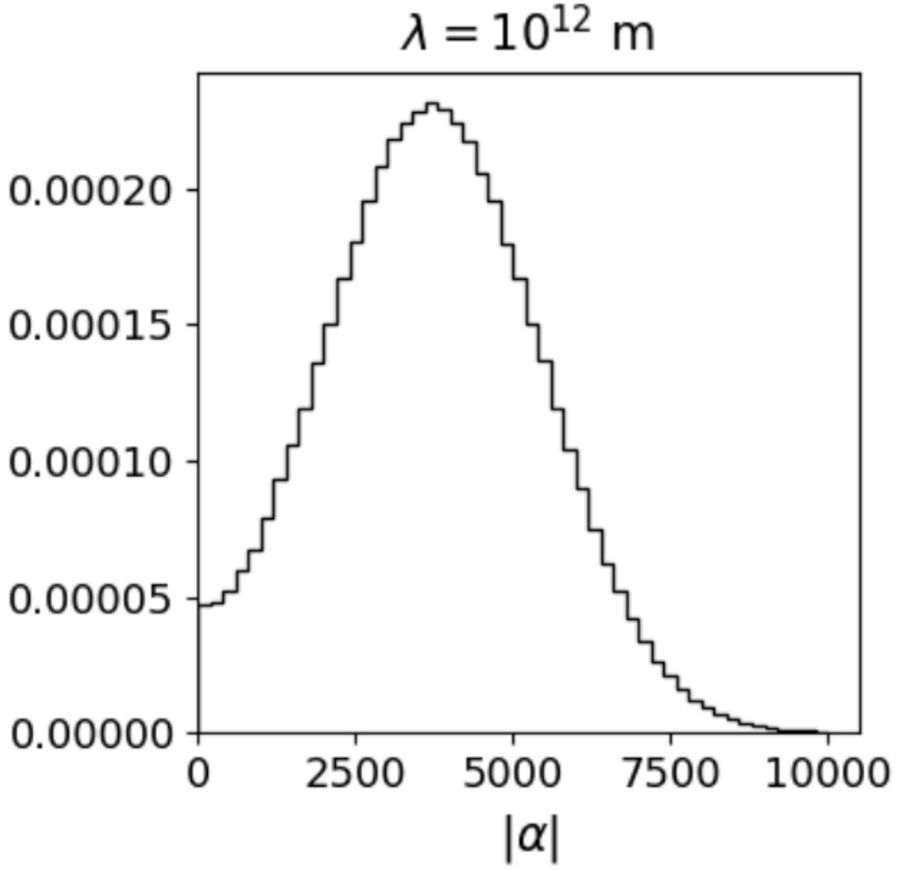
Black curves: 1PN term included (assuming $\gamma = \beta = 1$)



Preliminary results

Results: χ^2 minimization and MCMC analysis

Posterior distributions of $|\alpha|$ for fixed λ



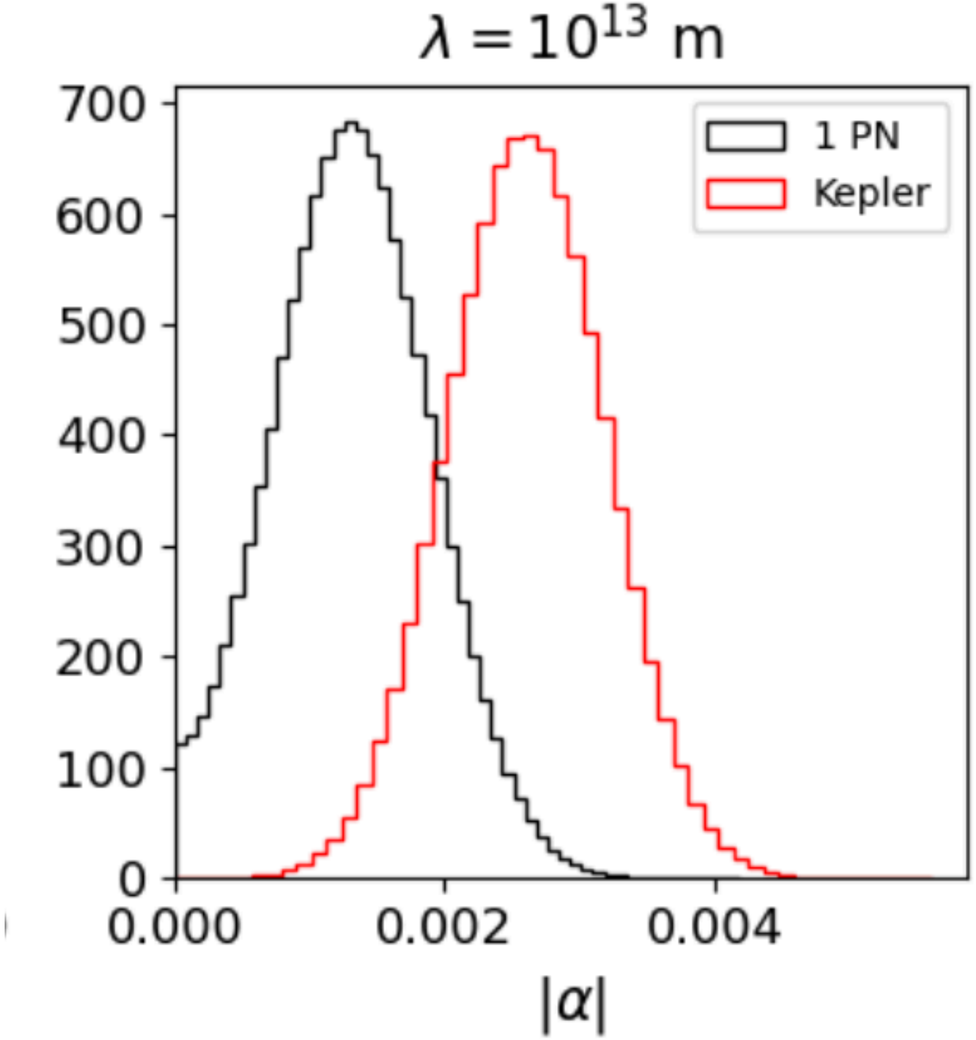
$\lambda < r_{s2}$ $\quad r_{s2} \sim \left(10^{13} - 10^{14}\right)$ m

$$U = -\frac{GM}{r}\left(1 + |\alpha| e^{-r/\lambda}\right)$$

$$\approx -\frac{GM}{r}$$

Results: χ^2 minimization and MCMC analysis

Posterior distributions of $|\alpha|$ for fixed λ



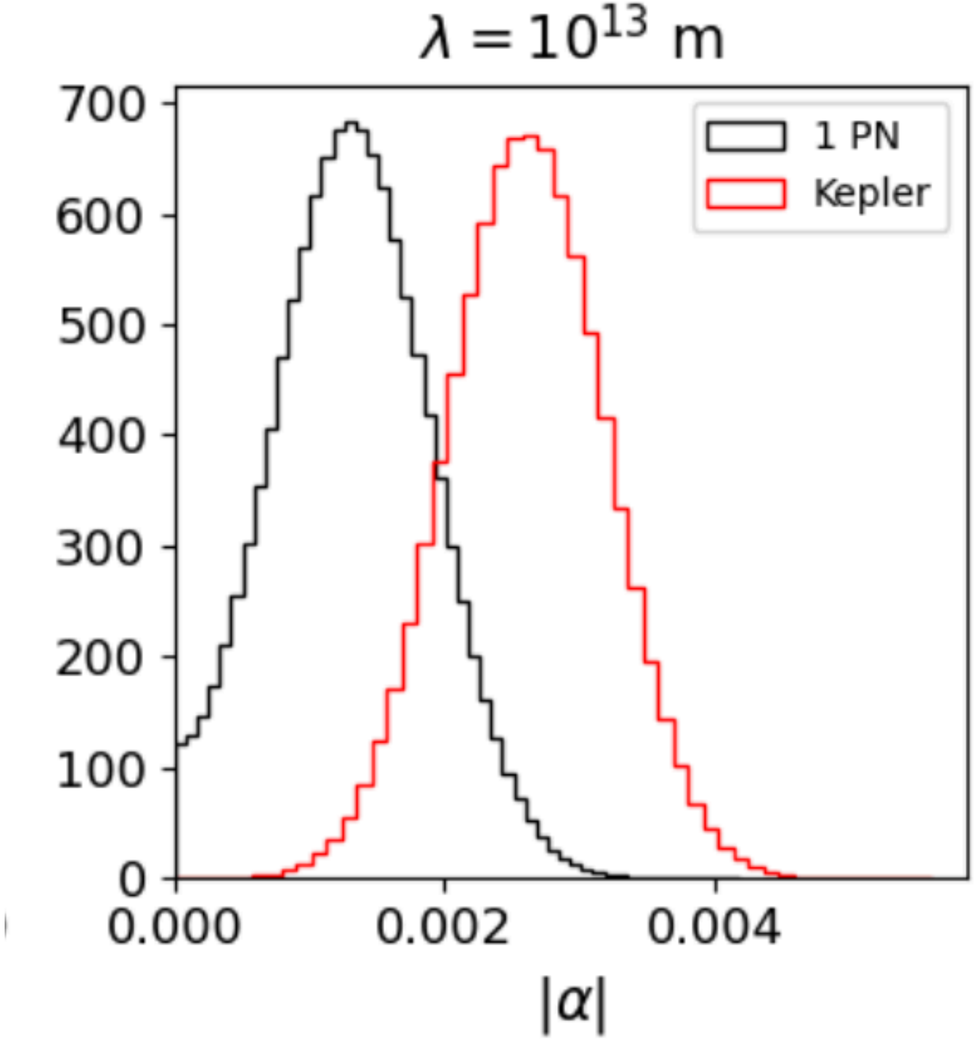
$\lambda \sim r_{s2}$ **Kepler + Yukawa**

$\alpha_{BF} \approx 0.0026 \longrightarrow \Delta\varphi \sim 0.13°$

$(\Delta\varphi_{SP} \sim 0.20°)$

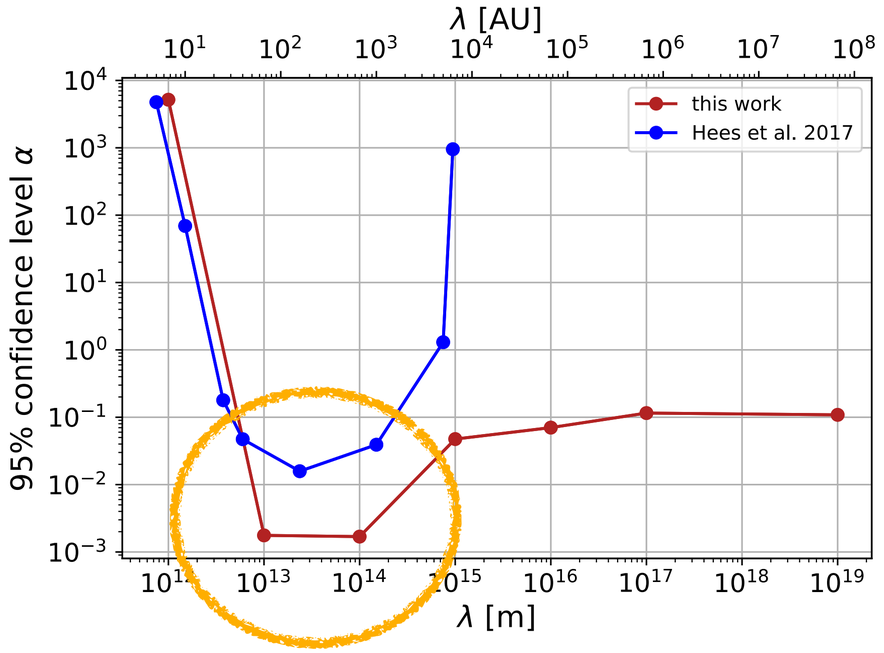
Results: χ^2 minimization and MCMC analysis

Posterior distributions of $|\alpha|$ for fixed λ



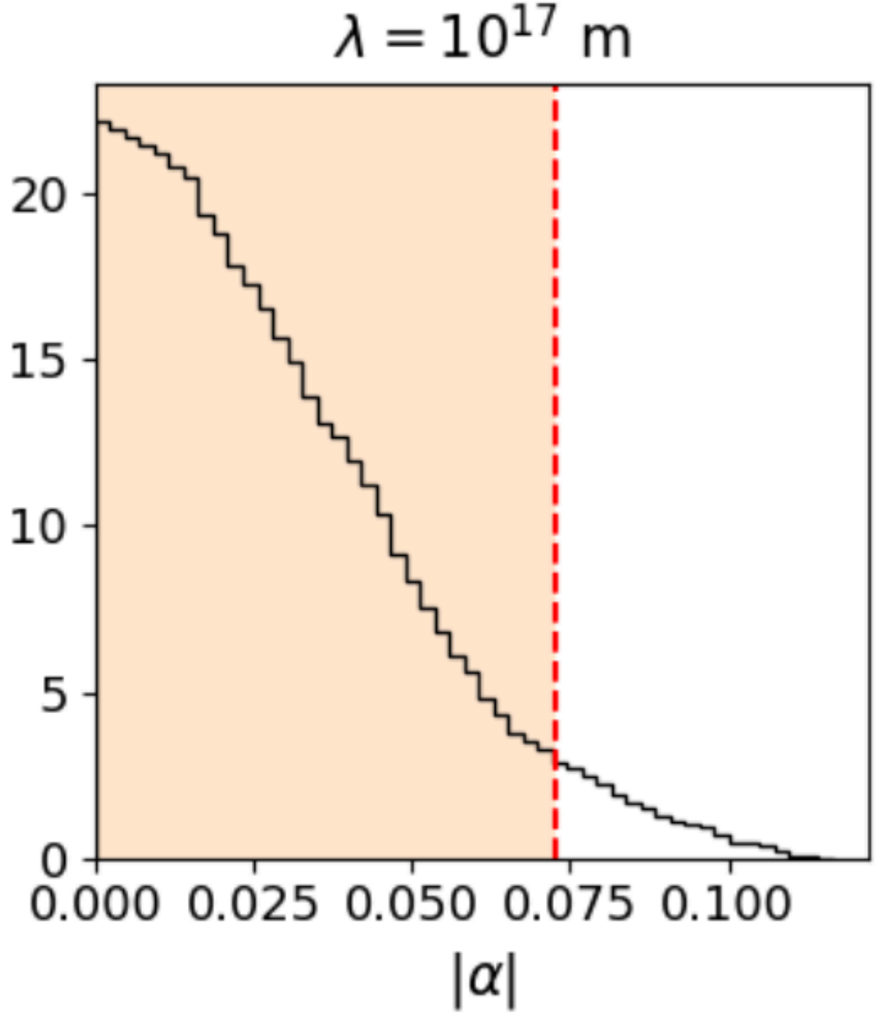
$\lambda \sim r_{s2}$ **Kepler + Yukawa + 1PN**

$|\alpha| \lesssim 10^{-3}$ at 95 % confidence level



Results: χ^2 minimization and MCMC analysis

Posterior distributions of $|\alpha|$ for fixed λ



$\lambda \gg r_{s2}$ **Kepler + Yukawa + 1PN**

$$U = -\frac{GM}{r}\left(1 + |\alpha| \underbrace{e^{-r/\lambda}}_{\approx 1}\right) \qquad (\lambda \gtrsim 10^{15}\,\mathrm{m})$$

$$\approx -\frac{GM(1+\alpha)}{r}$$

$|\alpha| \lesssim 0.075$ at 95 % confidence level

$$M_\bullet = (4.29 \pm 0.01) \cdot 10^6\, M_\odot$$

Conclusions

- Investigated the presence of a fifth force at the GC via the introduction of a Yukawa-like potential in S2 equations of motion;
- For the first time we used GRAVITY data and included the 1st PN correction;
- Found **no constraints** on $|\alpha|$ for $\lambda < 10^{13}\,\mathrm{m}$;
- Much stringent constraints for $10^{13} \leq \lambda \leq 10^{14}\,\mathrm{m}$, $|\alpha| \lesssim 10^{-3}$ at 95% confidence level;
- Good constraints for $\lambda \geq 10^{15}\,\mathrm{m}$, $|\alpha| \lesssim 10^{-1}$ at 95% confidence level (still to fully understand why).

Thank you for your attention!