Gravitation astrometric tests in the Solar System with JWST

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ABSTRACT

JWST will deliver unprecedented capabilities for high precision narrow angle astrometry, photon limited to the *μas* level even for comparably faint sources. It is therefore the candidate of choice for Fundamental Physics tests in the Solar system, able to set stringent constraints on the competing theories of gravitation, including General Relativity, and for the first time on effects induced by Quantum Field Theory.

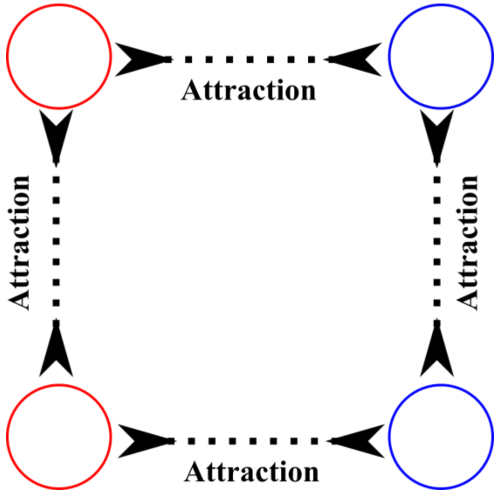
The expected level of gravitational effects of Quantum Vacuum on the trans-neptunian binary system UX25 results in precession amplitude ~0.23″/ orbit. The build-up of precession over 5– 10 years can therefore be clearly detectable by microarcsecond astrometry used to monitor the binary orbit against reference field stars.

JWST has the appropriate combination of sensitivity and precision for detecting it.

We propose a long term observing campaign for monitoring the orbit of UX25 and other trans-neptunian candidates, to detect possible deviations from strict Newtonian dynamics by measuring the effective gravitational field in the external regions of the Solar system.

Precision astrometry of trans-neptunians and other convenient probes provides stringent constraints on the ephemerides of the whole Solar system, i.e. on gravitation in weak field. This constrains the allowed constant values, i.e. γ and β in Parametrised Post-Newtonian formulation, testing e.g. *f(R)* theories, and the acceleration constant a_0 in MOND.

Quantum Vacuum behaviour vs. Gravitation



"Standard model":

matter and anti-matter **attract** each other

Cosmological constant catastrophe! **[Adler et al., 1995]**

Vacuum energy not consistent with Solar System dynamics (e.g. Mercury's precession)?

Alternative theories:

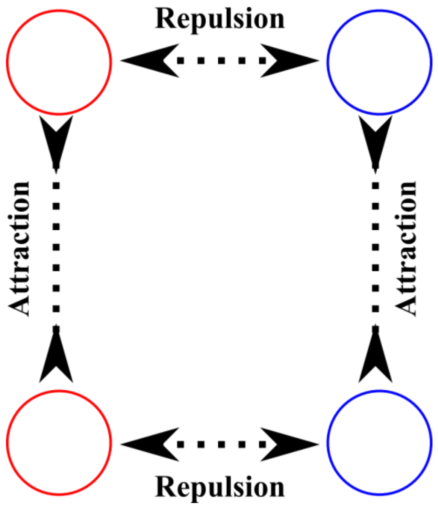
matter and anti-matter **repulse** each other

[matter attracts matter, A-M attracts A-M]

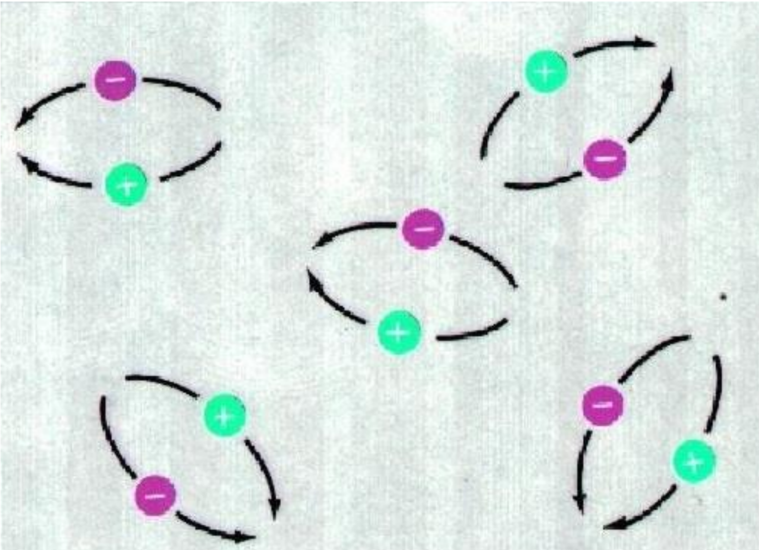
Suggested e.g. from CPT symmetry

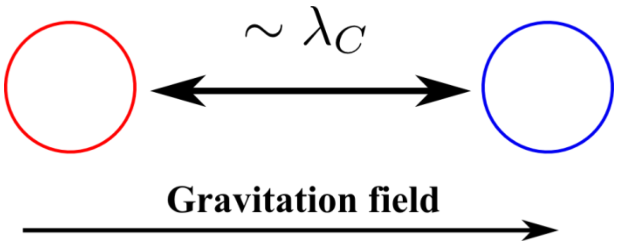
Effects may be tested by astrometry

[Villata, 2011; Kaplan et al., 2014; Villata, 2015]



Polarisation of virtual pairs in Quantum Vacuum



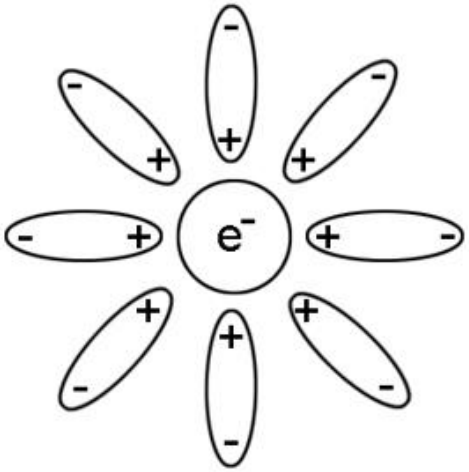


External gravitation field attracts particle and repulses anti-particle

Separation: ~ Compton wavelength

Result: polarisation of virtual pairs

Effect similar to electromagnetic case of charge in dielectric medium



Modified effective gravitation field

Acceleration: $a_0 \simeq 10^{-11}\ m/s^2$

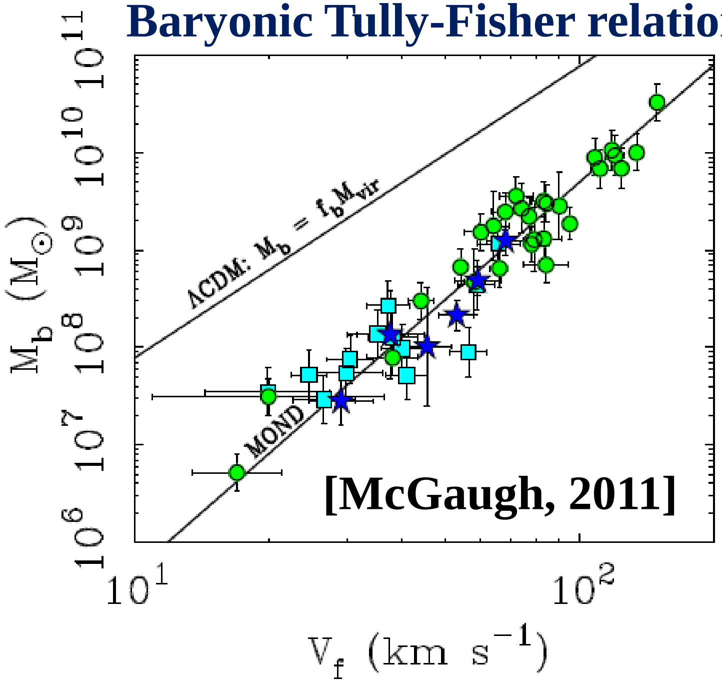
[Hajdukovic, 2014]

MOdified Newtonian Dynamics [MOND]

Alternative framework to Cosmological Concordance Model Λ-CDM, successfully interpreting e.g. the galactic rotation curves and the empirical Tully-Fisher relation without relying on dark matter halos

[Milgrom, 1983; Blanchet, 2011]

Baryonic Tully-Fisher relation



Characteristic acceleration constant: $a_0 \simeq 1.2 \times 10^{-10}\, m/s^2$

Limit from Solar System ephemerides: $a_0 \leq 2 \times 10^{-10}\, m/s^2$

[Fienga, 2010]

Precision Astrometry in the Outer Solar System

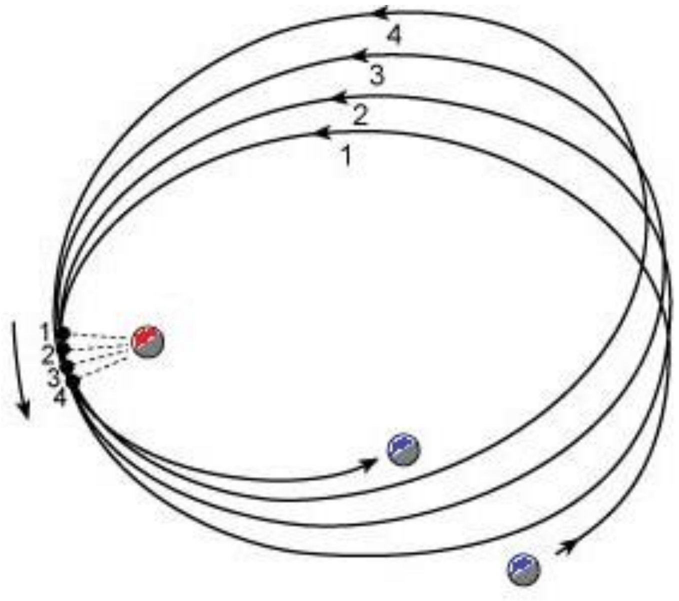
Binary system as test particle:

Newtonian physics => Keplerian closed orbit

Additional interactions => orbit perturbation,

in particular precession

⇒ Precession of binary orbit in external field



Orbit no longer closed

Rotation of ellipse on its plane

Periastron precession

Larger displacement of apastron

Orbit monitoring ⇔ detection of external force

Requirement: Observation against field stars over several orbits

Study case: UX25

UX25 Mass	1.25×10^{20} kg
UX25 Semimajor axis	42.869 AU
UX25 Orbital Period	280.69 years
Satellite Semimajor axis	4770 km
Satellite Orbital Period	8.3094 days
Satellite Eccentricity	0.17

Trans-neptunian binary system

Newtonian precession from the Sun: $\Delta\omega_N = \frac{3\pi}{2}\left(\frac{T_P}{T_{Sun}}\right)^2 \cong 6$ mas/orbit

Estimated precession from vacuum polarisation: $\Delta\omega_{qv} \simeq 0.23$ arcsec/orbit

[Hajdukovic, 2014, hal-00908554]

Cumulative effect on 5 years (~200 orbits): 46 arcsec precession

First experimental goal of the QVADIS
[Quantum Vacuum [effects] Astrometric Detection In the Solar system]
collaboration [Inst. Phys., Astroph., Cosmology (ME); INAF-OATo (I)]

Previous observations… [M. E. Brown, ApJL 2013]

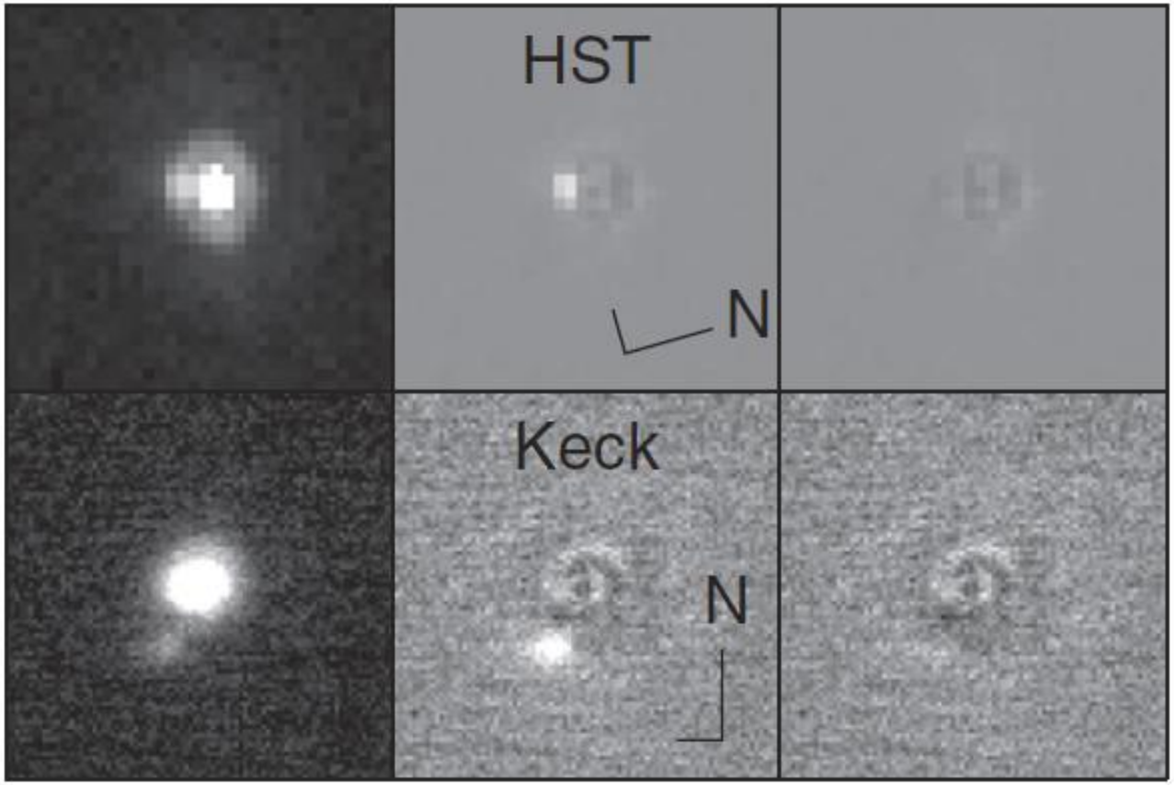
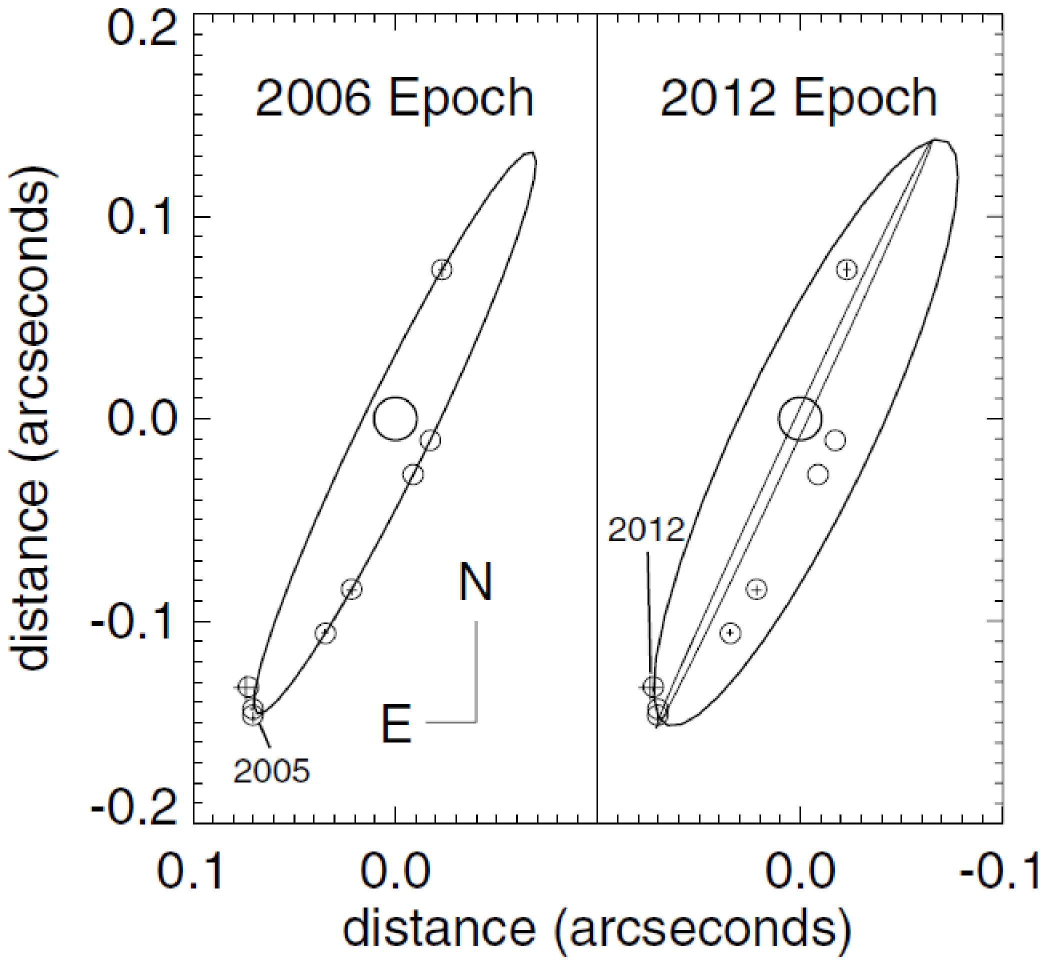


Figure 1. Observations of the 2002 UX25 system with *HST*/HRC and Keck LGS-AO/NIRC2. The northward orientation arrow is 0.25 arcsec long, for scale. In the first column, we show the image of both 2002 UX25 and its satellite. From this image we simultaneously fit a PSF to both the primary and satellite. In the second column we show the image with the primary part of the fit subtracted. In the final column we show both components subtracted. The *HST* observation is from JD 2453939.98322 and is the most blended of the detections.

…and reconstructed orbit

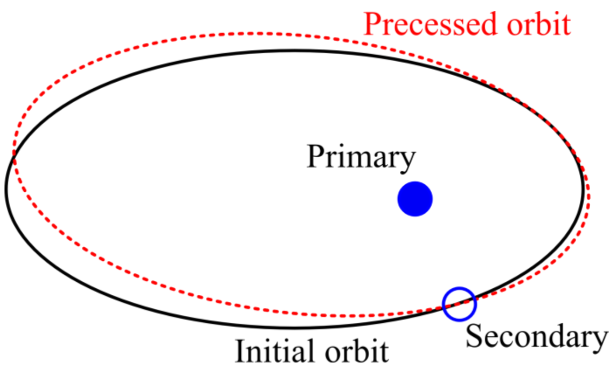


Semi-major axis angular amplitude: ~150 mas

System unresolved by conventional telescopes

Faint visible magnitude:

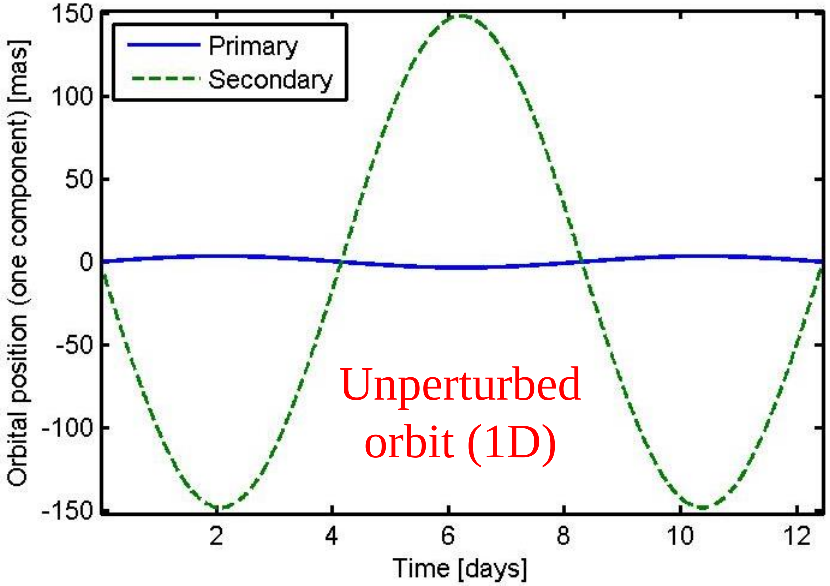
- 20 mag primary
- 22 mag secondary

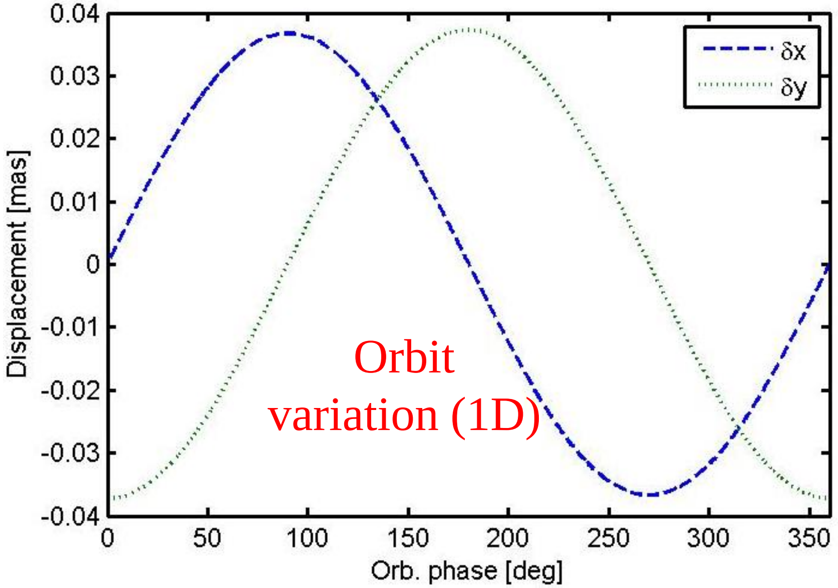


Observing problem

Orbit variation over 5 years

[Gai & Vecchiato, 2014]





Challenge: reliable μas astrometry on faint objects, narrow field

Requirement: few μas final precision

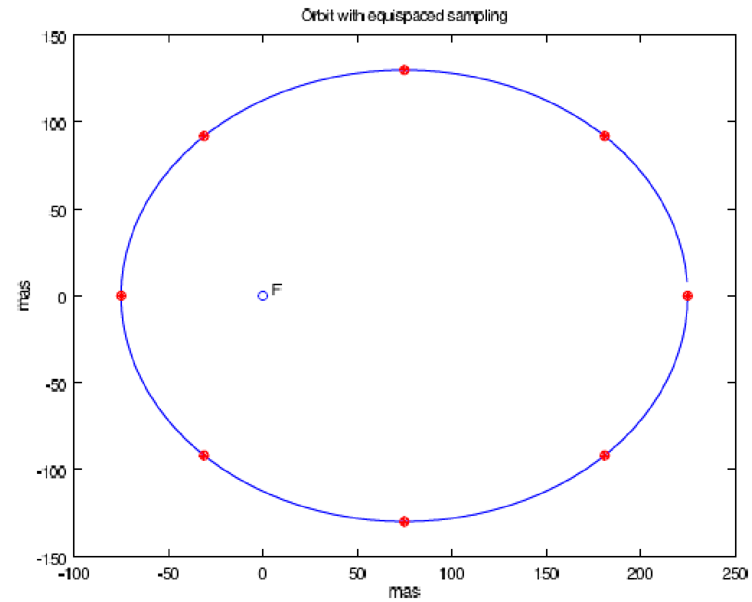
Small field (~10-20 arcmin) to have several reference stars (e.g. from Gaia)

Observation setup

Multiple samples of orbital period

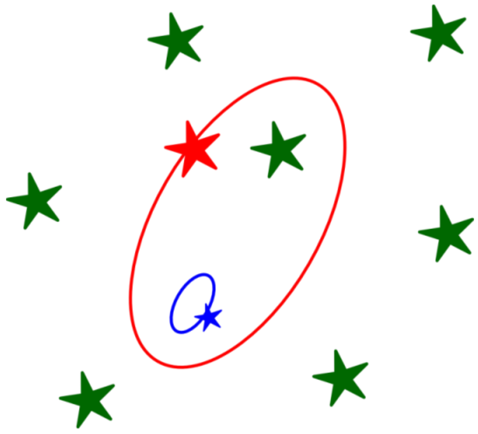
Determination of positions and velocity against field stars

Orbital fit: parameter estimate

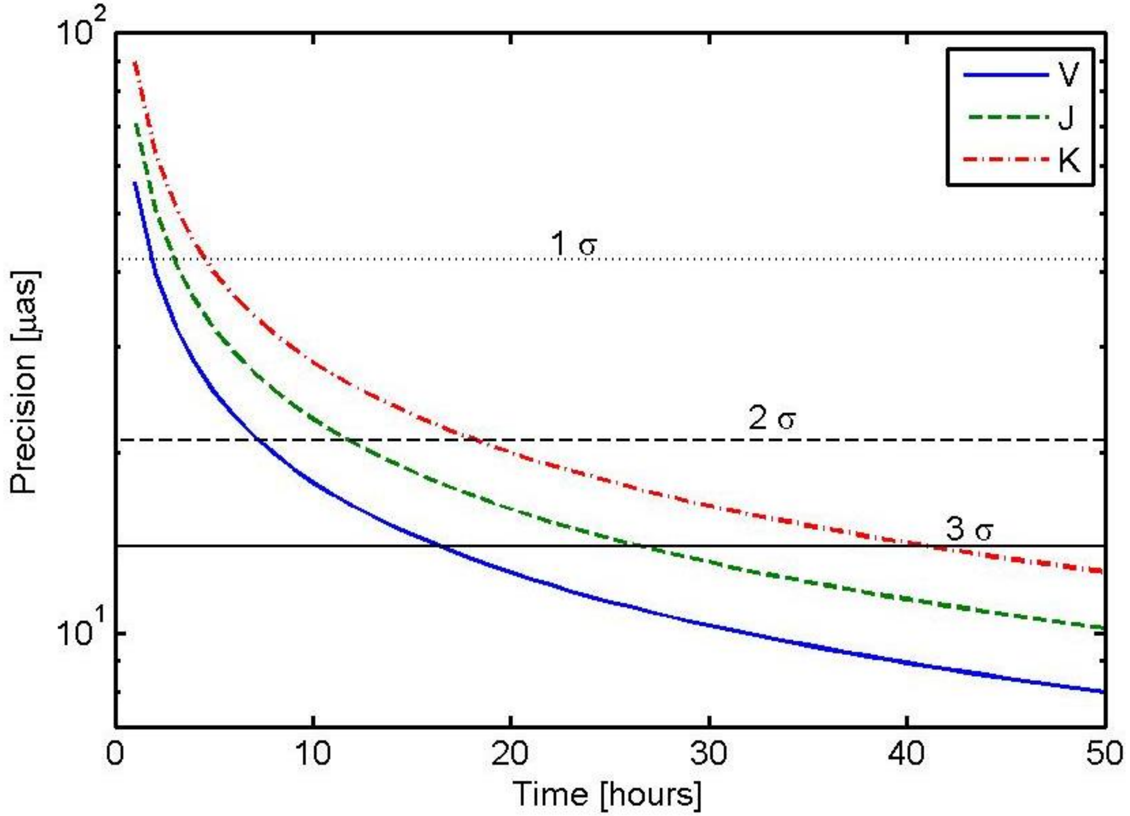


Long term monitoring with significant cadence sampling required:

- measure time sequence of positions AND velocity
- measure shape / brightness distribution
- measure albedo / surface composition
- deduce mass distribution
- cross-check actual dynamics with high fidelity model predictions



Performance estimate on JWST



Observation from visible to near infrared bands

Photon noise, near diffraction limited imaging

Exploit best instrument performance

Feasible with limited observing time requirements: 20 – 40 hours/year

Key achievements: First detection of Quantum Vacuum polarisation effects

Crucial constraints on MOND and General Relativity