# Low Acceleration Gravitational Anomalies in Local Wide Binaries


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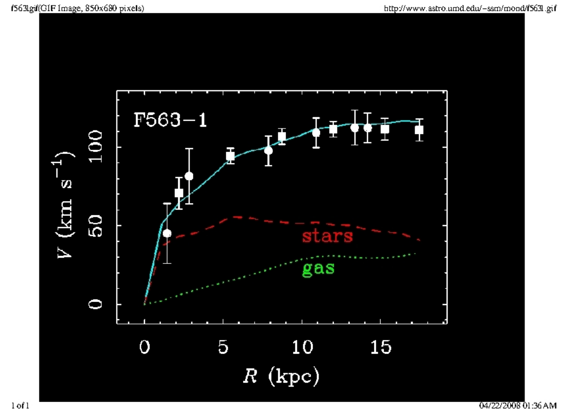
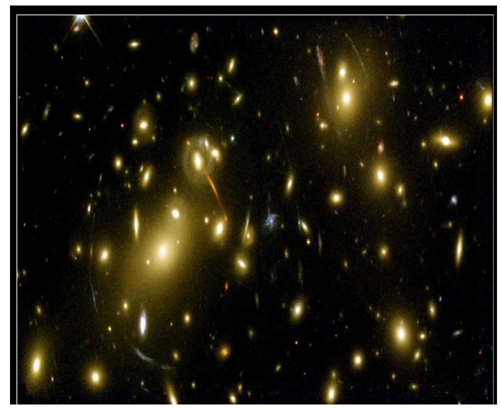
Indirect evidence for Dark Matter?

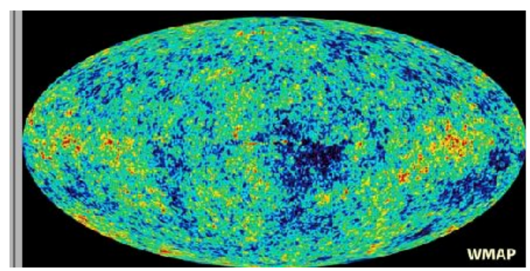
Rotation Curves of Large Spirals
(1-10 kpc)




Dynamics and Lensing of Galaxy Clusters
(1-5 Mpc)



Cosmological Matter Determinations
($>$ 50 Mpc)

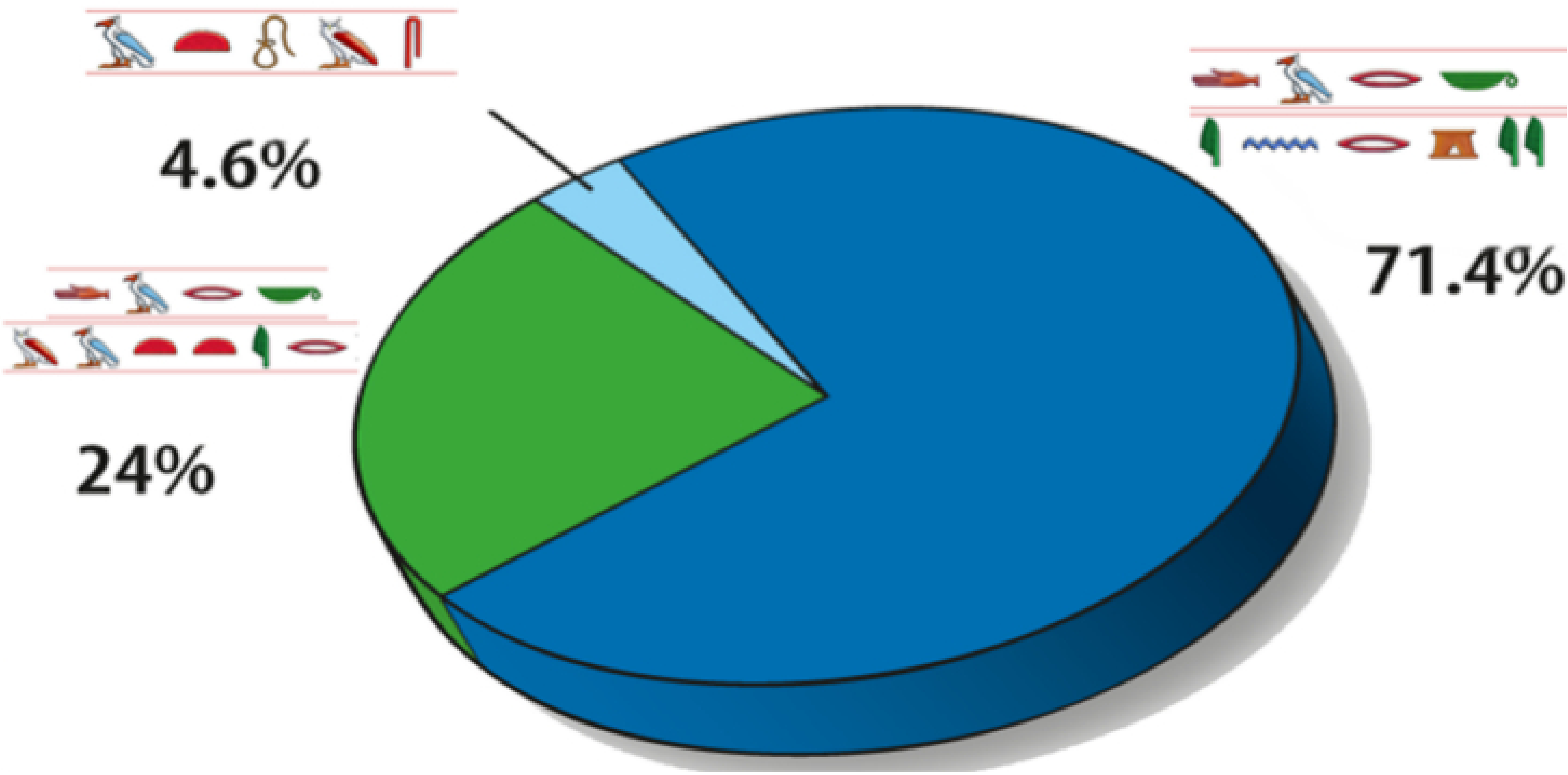



...or direct evidence for the failure of standard Gravity at large scales?

-Direct proof of the law of Gravity exists only for $R < 0.001 pc$

-Direct proof of the existence of Dark Matter is still missing

What is the universe made up of?



## Wide binaries as a critical experiment for gravity

A test particle orbiting a $1M_\odot$ star in a circular orbit of radius $s$, will have an acceleration that falls below $a_0 = 1.2 \times 10^{-10} m/s$ for:

$s > 7000AU = 3.4 \times 10^{-2} pc$.

Therefore, relative velocities of binaries wider than $7000AU$ are predicted to be qualitatively and quantitatively very different under Newtonian Gravity and generically under modified gravity theories.

Which scaling will wide binaries show?

$$\Delta V_N = 2\left(\frac{GM}{s}\right)^{1/2} \quad or \quad \Delta V_{MG} = 2(Ga_0 M)^{1/4} \ ?$$

A large survey of relative proper motions and separations for wide binaries should yield a conclusive answer.

X. Hernandez, M. A. Jimenez & C. Allen (2012) EPJC, 72, 1884

# Newtonian prediction for wide binary samples

- At a fixed $s$, orbital projections effects will lead to a distribution of $\Delta V_N$ values ranging below the circular orbit value.

- Orbits will present a distribution of ellipticities, leading, at fixed $s$ and projection, to a spread of values in $\Delta V_N$ ranging below $\sqrt{2}$ times the circular orbit values.

- Evolution in the Galactic environment, mostly perturbations of field stars and tidal disruption by the Galactic tides, will affect the observed distributions.

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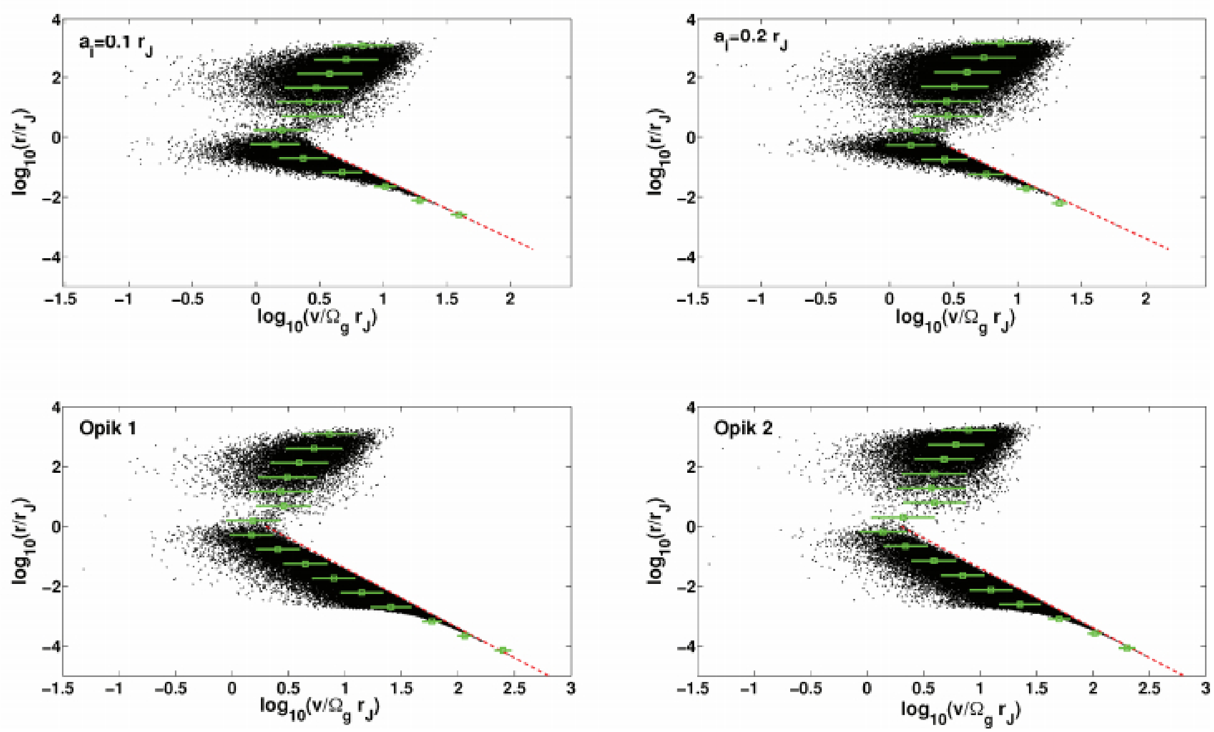
Luckily, All of the above have recently been thoroughly taken into account by Jiang & Tremaine (2010).

They calculate the evolution in the Galactic environment at the Solar radius, of large (50,000) populations of binaries having a distribution of initial ellipticities, and give present day expected ($\Delta V_N$ vs. $s$) distributions, after 10 Gyr of evolution, and after projecting on the plane of the sky.

## Newtonian prediction for wide binary samples

Expected distributions of ($s$ vs. $\Delta V$):




- Below $s = r_J = 1.7pc$, upper velocity envelope closely follows Kepler's law.

- Mostly, disruption occurs for $s > r_J$, the tidal radius of the problem.
$\Rightarrow$ a definitive feature expected at $s = r_J = 1.7pc$

- Unbound stars continue to drift along very similar orbits and will show up in observational samples.

# Newtonian prediction for wide binary samples

Predicted projected RMS 1D $\Delta V$ vs. $s$ relation.

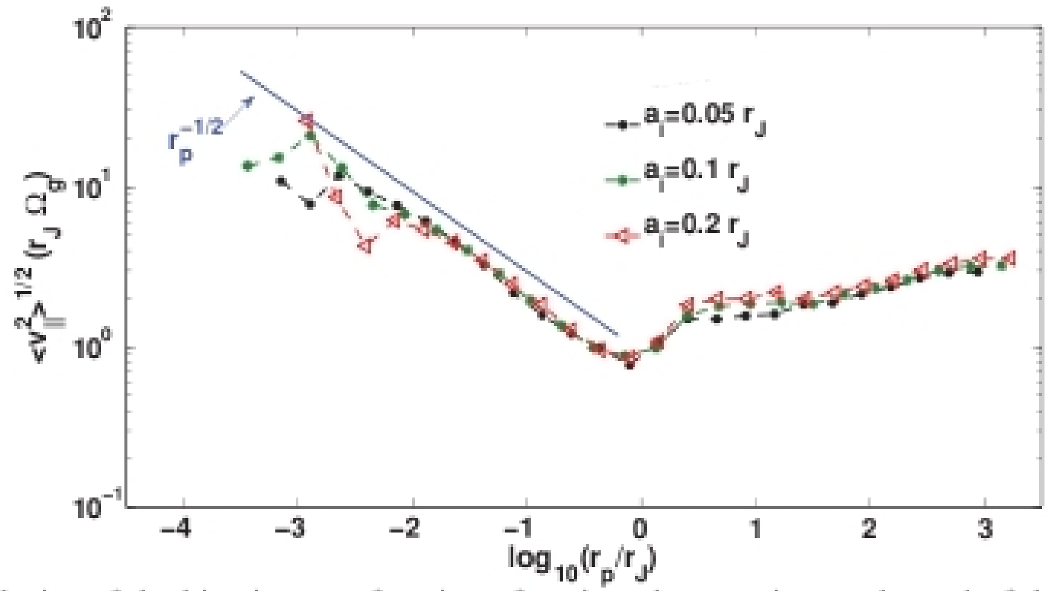



**Figure 7.** RMS line-of-sight relative velocity of the binaries as a function of projected separation, at the end of the simulations. The horizonta projected separation normal to a randomly chosen line of sight, while the vertical axis is the rms line-of-sight relative velocity in each separ Keplerian motion we expect $\langle v_{||}^2 \rangle^{1/2} \propto r_p^{-1/2}$, shown by the straight line. The relation between the line-of-sight relative velocity and the projecte deviates from the Keplerian relation for $r_p \gtrsim r_J$.

- Below $s = r_J = 1.7pc$, curve closely follows Kepler's law.

- Mostly, disruption occurs for $s > r_J$, the tidal radius of the problem.

$\Rightarrow$ a definitive feature expected at $s = r_J = 1.7pc$

- Unbound stars continue to drift along very similar orbits and will show up in observational samples.

Y. Jiang & S. Tremaine (2010), MNRAS 401, 977

## modified gravity prediction for wide binary samples

- At a fixed $s$, orbital projections effects will lead to a distribution of $\Delta V_{MG}$ values ranging below the circular orbit value.

- Orbits will present a distribution of effective ellipticities, leading, at fixed $s$ and projection, to a spread of values in $\Delta V_{MG}$ ranging below $X$ times the circular orbit values.

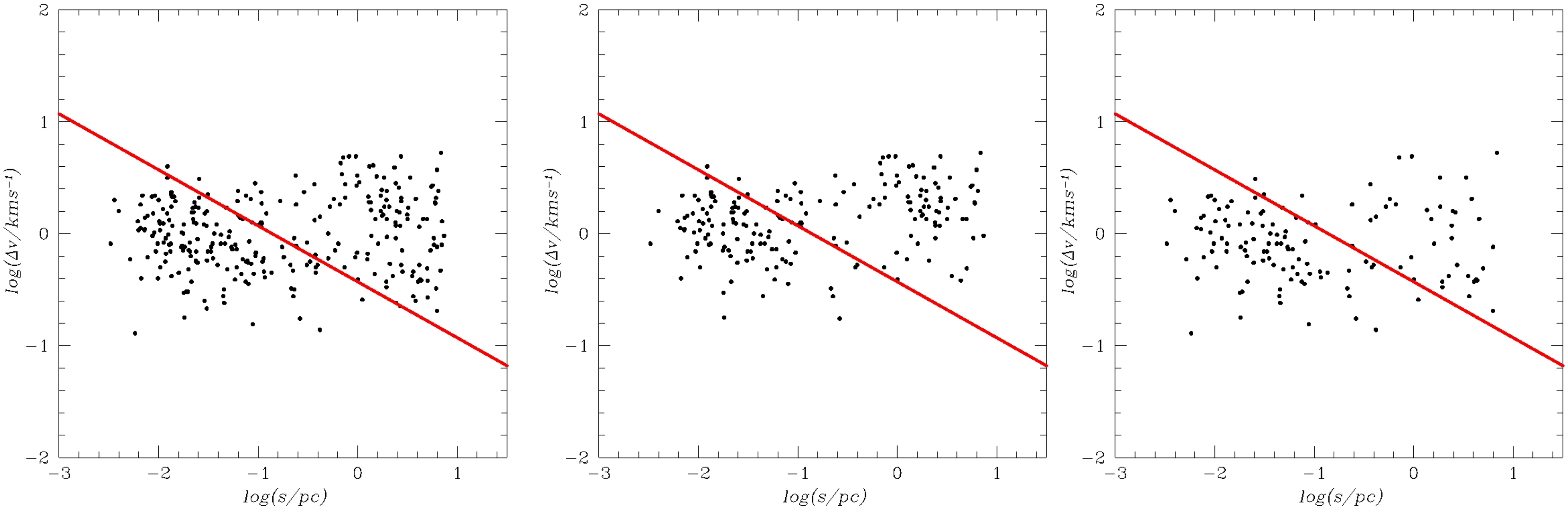
- Evolution in the Galactic environment, mostly perturbations of field stars and tidal disruption by the Galactic tides, will affect the observed distributions.

- Detailed predictions under modified gravity are not yet available, the potential is not static, orbits are not circular, we are far from the symmetries which apply at galactic rotation curves, the relevance and details of the EFE e.g. potential dependences on relative masses, scales and frequencies remain unknown.

- We shall therefore not attempt to test any particular modified gravity theory, merely to critically explore the validity of Newtonian predictions in the $a < a_0$ regimes.

## Wide binary results *Hipparcos*

From a catalogue of ∼ 280 carefully selected wide binaries we obtain relative velocities on the plane of the sky and projected separations, average S/N=2.0.




- The upper envelope clearly defines a horizontal line, showing the "flat rotation curve" of modified gravity, and not the Kepplerian decline of Newtonian gravity.

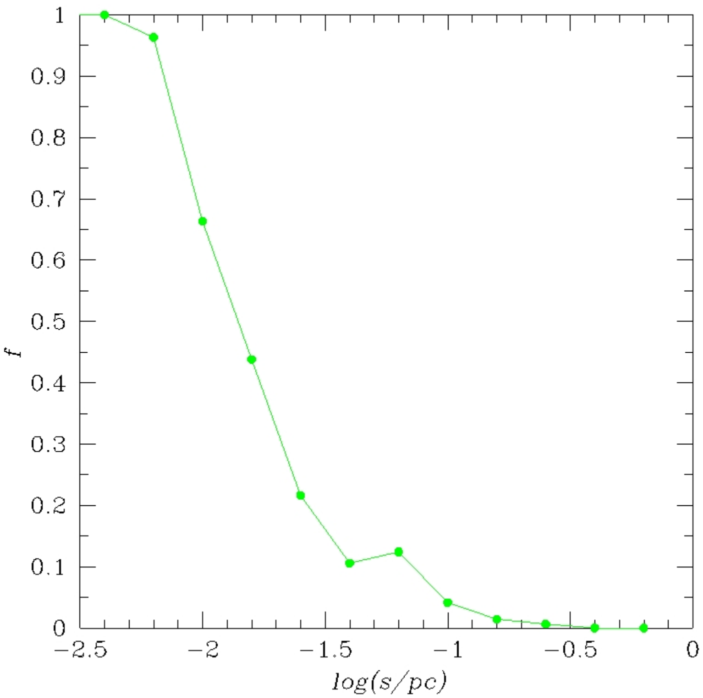
- It can be shown that results are not driven by errors or catalogue selection cuts.

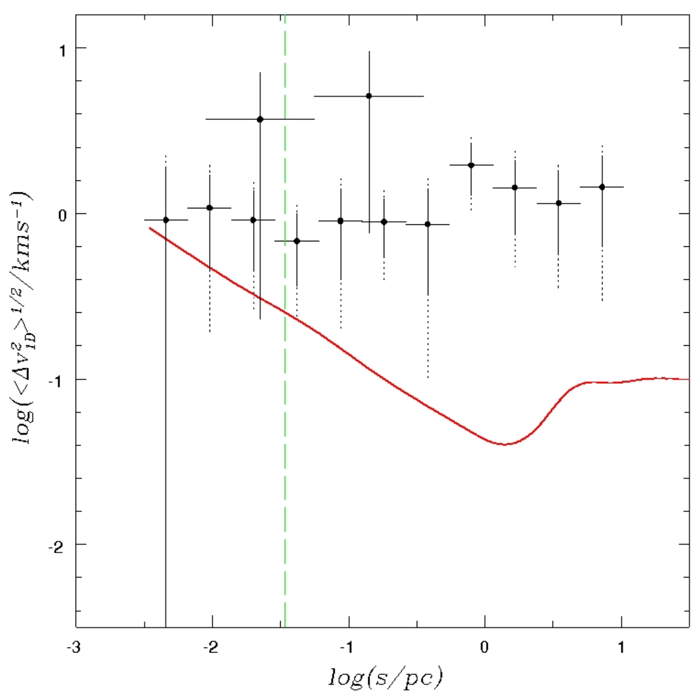
-The data show no feature of any kind on crossing the Newtonian tidal radius at 1.7pc.

E. J. Shaya & R. P. Olling (2011), ApJS, 192, 2

# Wide binary results *Hipparcos*

Quantitative comparison with full Newtonian prediction:




A full Bayesian framework comparing the local 5D phase-space density at the position of each binary to that of a full atlas of the Solar Neighbourhood selects only systems with $P_{ch} < 10\%$.

The trends shown by the data are clearly defining the modified gravity phenomenology, Newtonian Gravity becomes inconsistent with data for accelerations below $a_0$.

X. Hernandez, M. A. Jimenez & C. Allen (2012) EPJC, 72, 1884

# Wide binary results, Gaia Astrometry

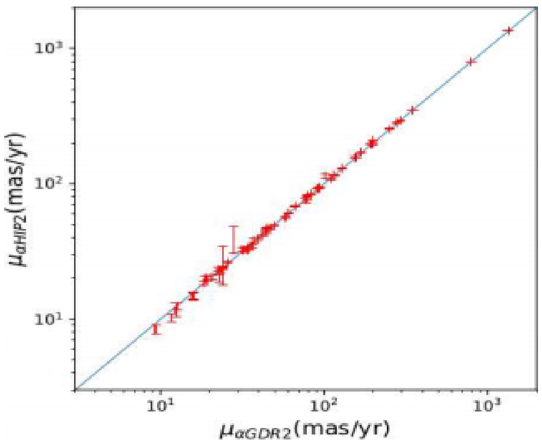



**Figure 1.** Comparison of SO11 *Hipparcos* and Gaia DR2 proper motion data in right ascension for each of the two components of the binaries studied. The agreement with the identity line in the majority of cases shows the stars in question have been successfully identified from the first catalogue to the Gaia DR2 sample.

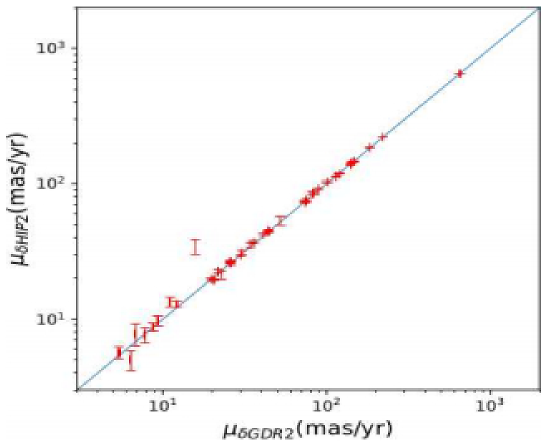



**Figure 2.** Comparison of SO11 *Hipparcos* and Gaia DR2 proper motion data in declination for each of the two components of the binaries studied. The agreement with the identity line in the majority of cases shows the stars in question have been successfully identified from the first catalogue to the Gaia DR2 sample.

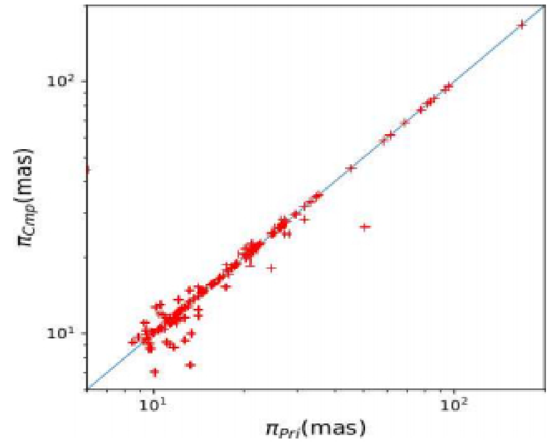


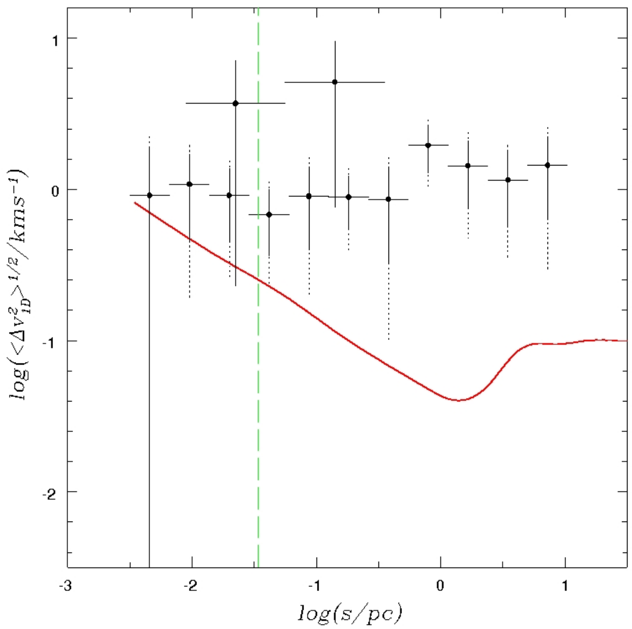

**Figure 3.** Comparison of the Gaia DR2 reported parallax for the two distinct components of each of the binaries studied. The disagreement of only a handful of cases with the identity line allows to exclude such discordant pairs as part of the expected 10% misidentified binaries in the original SO11 catalogue, or as misidentified stars in going from the *Hipparcos* catalogue to the Gaia DR2.

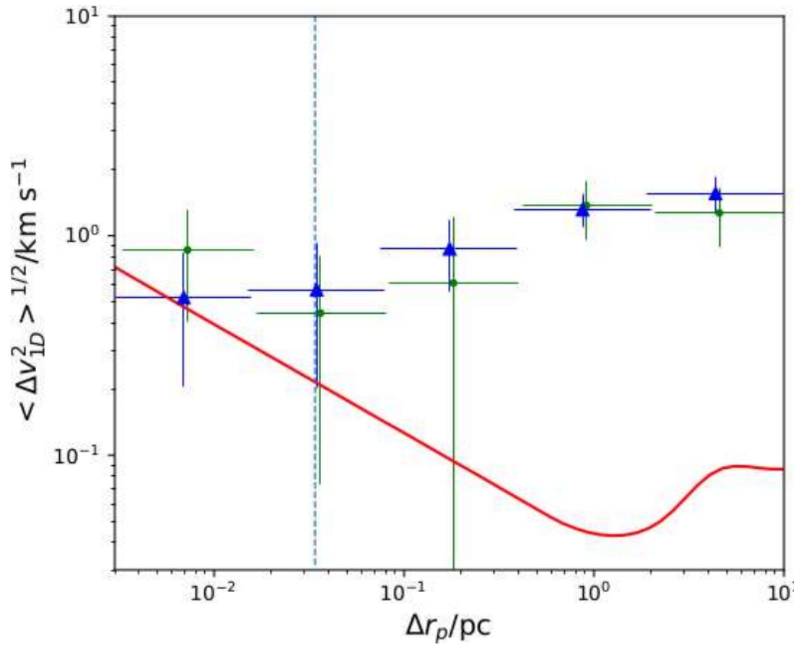
We begin by taking advantage of the *Hipparcos* identification feature in the Gaia DR2 to use the Shaya & Olling (2011) Bayesian wide binary selection function, updating now to Gaia astrometry.

We remove pairs with inconsistent proper motions between *Hipparcos* and Gaia and inconsistent Gaia parallaxes or radial velocities between the two components, $<\Delta V_R>= 28km/s$ to identify a small sample of 81 *bona fide* wide binaries.

X. Hernandez, R. A. M. Cortes, C. Allen & R. Scarpa (2019) IJMPD, 28, 1950101

# Wide binary results, Gaia Astrometry




Gaia DR2 astrometry confirms earlier *Hipparcos* results.

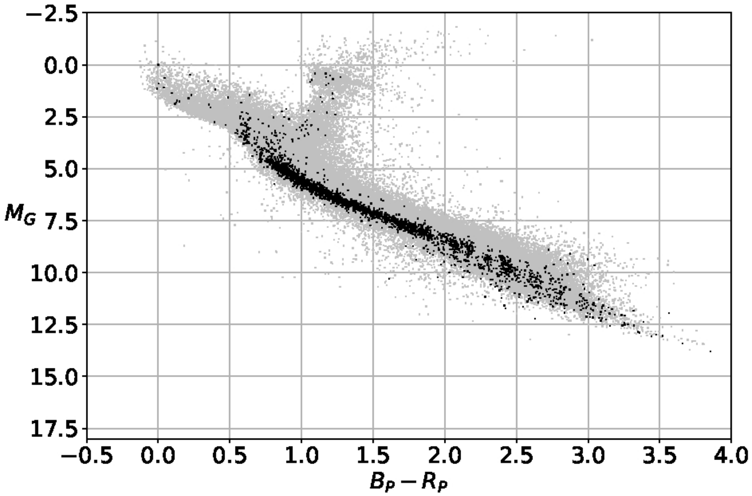
This eliminates unaccounted systematics or the error structure of the *Hipparcos* catalogue as explanations for the observed trend.

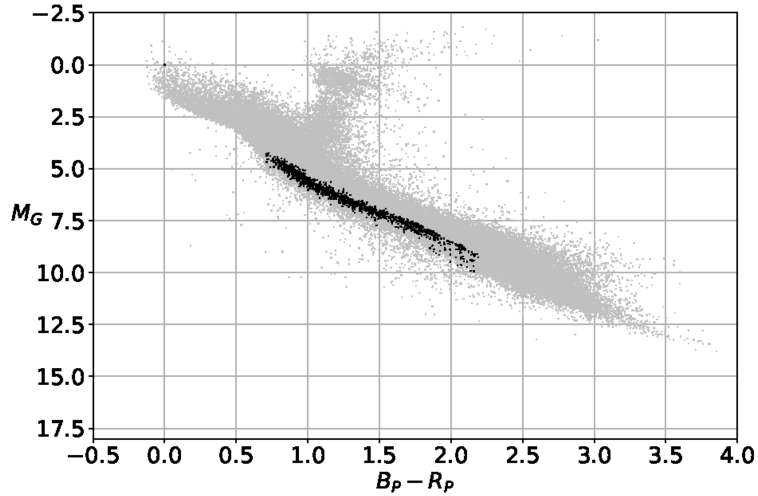
Comparing *Hipparcos* to Gaia DR2 astrometry essentially yields a 10 year base line for the problem, eliminating proper motion contamination from undetected third components.

The trends shown by the data are clearly defining the modified gravity phenomenology, Newtonian Gravity becomes inconsistent with data for accelerations below $a_0$.


X. Hernandez, R. A. M. Cortes, C. Allen & R. Scarpa (2019) IJMPD, 28, 1950101

# Latest Gaia DR3 Results: Sample Selection




-D<200pc, $(S/N)_{\varpi} > 100$, $(S/N)_G > 5$, $\Delta D - 3\sigma_{\Delta D} < 2s$, $\mapsto \sim 7 \times 10^6$ Binary candidates.

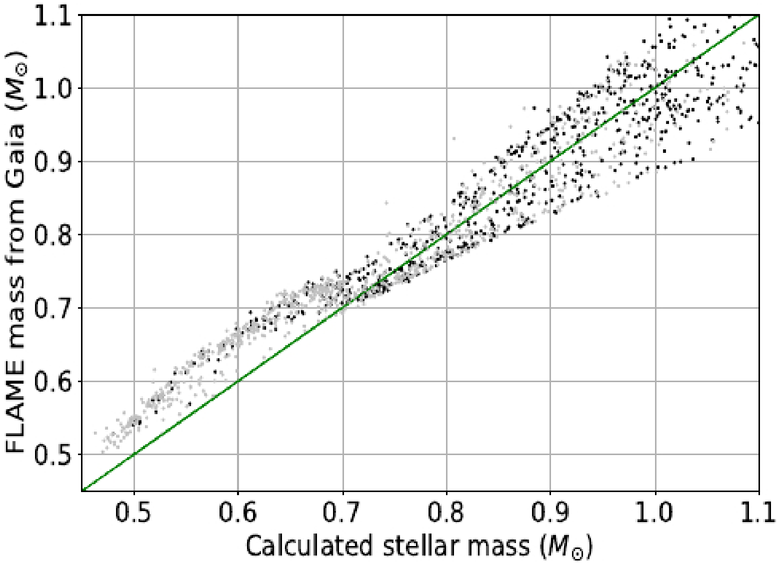
-Aggressive de-grouping, all candidate binaries including any star which is a member of more then 1 binary candidate are removed, $\mapsto$ 97,251 binary candidates.

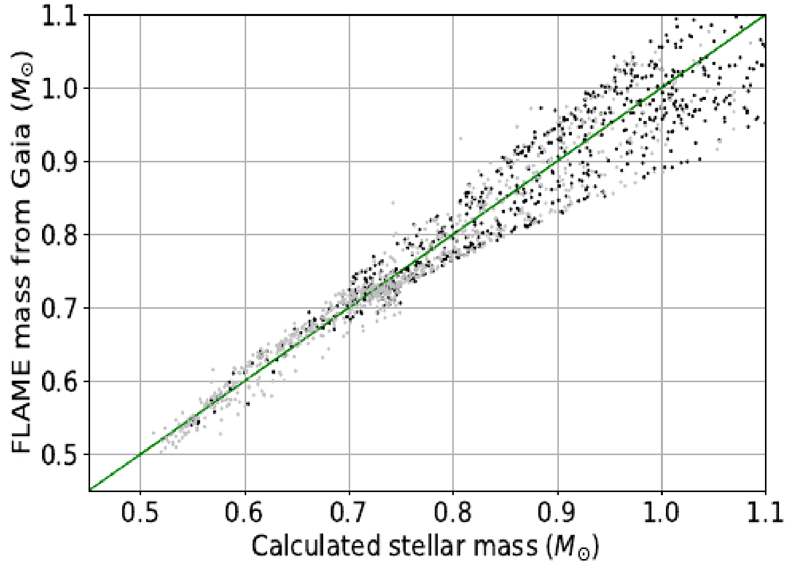
-Keep only bound systems, only binaries with $V_R$ for both stars and $\Delta V_R < 4km/s$ and good quality single star GAIA fits for both stars, RUWE<1.2, $B_p < 0.2$, $(S/N)_{RGB} > 20 \mapsto 1352$ binary candidates.

-Keep only binary candidates where both stars appear in the HR region which maximises exclusion of hidden tertiaries e.g. Belokurov et al. (2020) MNRAS, 496, 1922. $\mapsto$ 688 isolated, bound and well measured binaries.

X. Hernandez, S. Cookson, R.A.M. Cortes, (2022) MNRAS, 509, 2304
X. Hernandez (2023), arXiv:2304.07322

# Latest Gaia DR3 Results: Mass calibration




Generally a magnitude-mass scaling assumed e.g. Pittordis & Sutherland (2019) MNRAS 488, 4740:

$$M = 10^{0.0725(4.76-M_G)} \tag{1}$$

-Left: Comparison of new GAIA DR3 FLAME masses to luminosity scaling, an important systematic appears for small masses.

-Right: Comparison of new GAIA DR3 FLAME masses to luminosity scaling, after an offset is applied to small masses, no important systematic remains.

-I shall use GAIA DR3 FLAME masses whenever available, supplemented by the corrected mass luminosity scaling shown above otherwise.

X. Hernandez, S. Cookson, R.A.M. Cortes, (2022) MNRAS, 509, 2304
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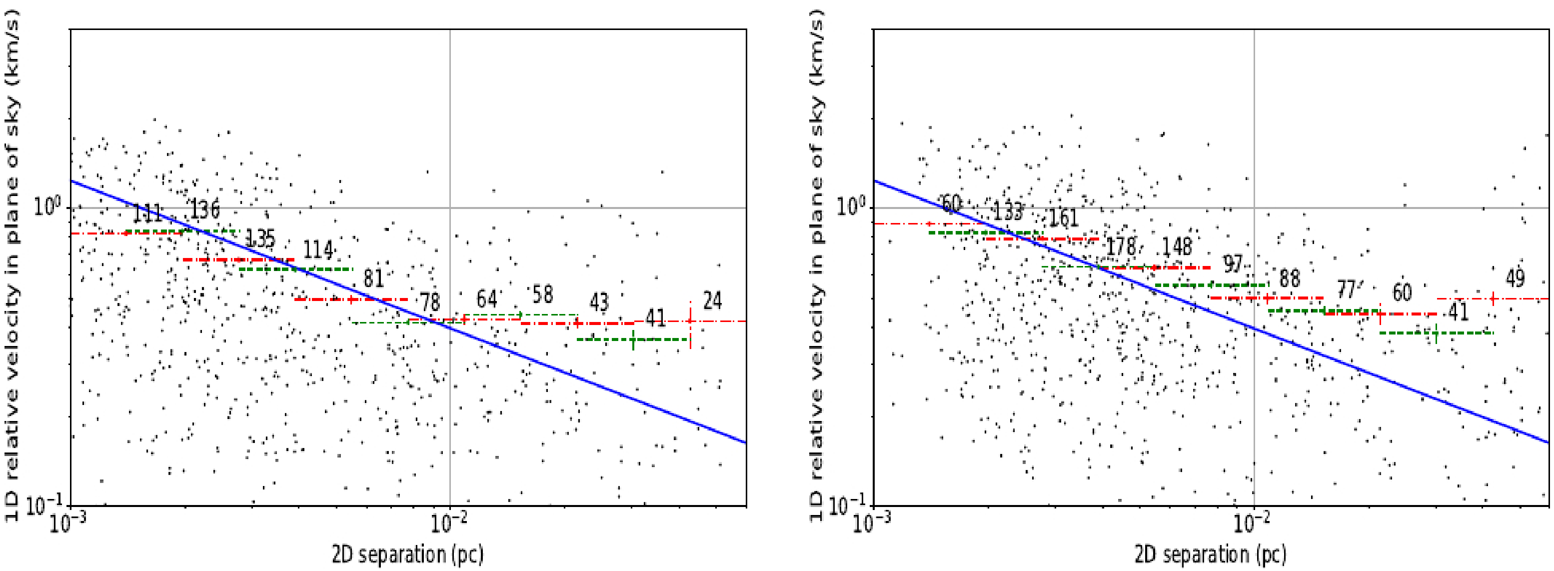
# Latest Gaia DR3 Results: Kinematic Scalings



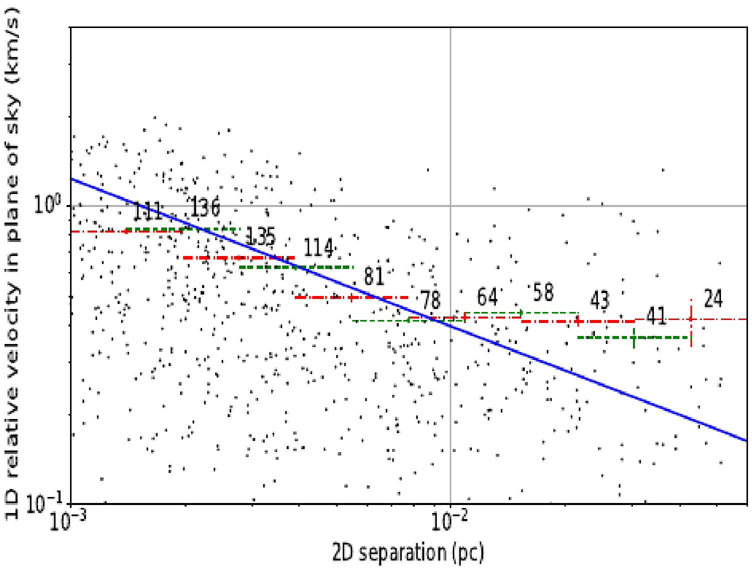

- LEFT: D<125 clean sample $< S/N >_{pm}= 3442$, $< S/N >_{\varpi}= 855.4$, $< S/N >_{\Delta V}= 15.7$, $< RUWE >= 1.01$, $< B_p >= 0.07 \mapsto$ 450 systems, $< M_{tot} >= 1.56$, GAIA FLAME masses=63%. Fastest 3% systems per bin have been removed.

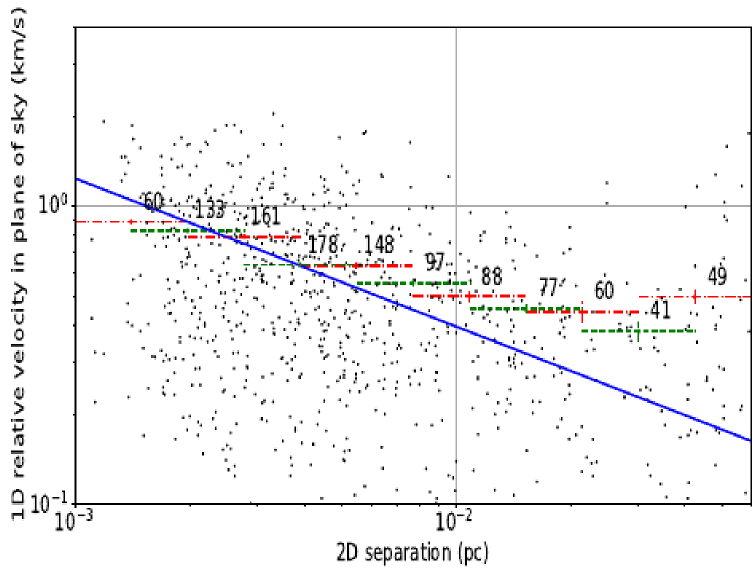
For high accelerations, $s < 10^{-2}$ pc, results very accurately trace the Jiang & Tremaine (2010) prediction. Implies the sample is clean.

For low acceleration, $s > 10^{-2}$ pc, results show a "flat rotation curve region", at an amplitude of $0.4 km/s$. $0.35 \times 1.56^{0.25} = 0.39 km/s$, BTF galactic scaling, McGaugh et el. (2000).

The trends shown by the data are clearly defining a modified gravity phenomenology, Newtonian Gravity becomes inconsistent with data for $s > 0.01$pc.

# Latest Gaia DR3 Results: Kinematic Scalings



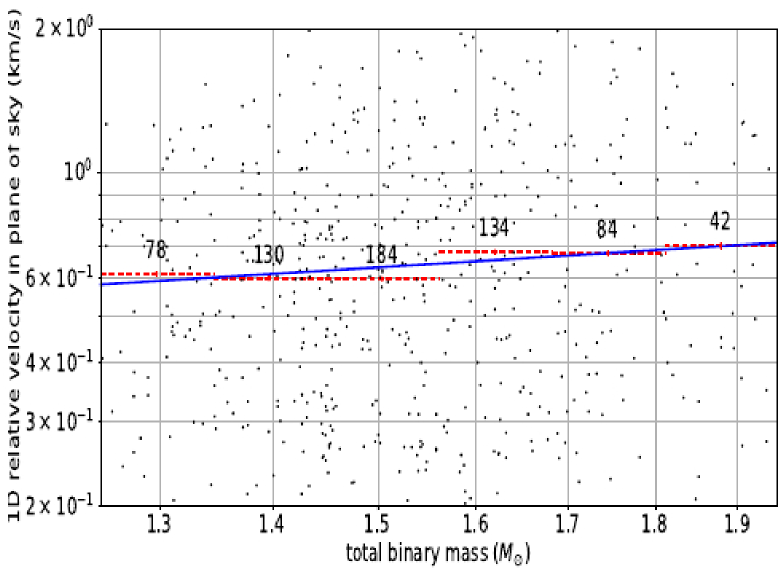

- LEFT: D<125 clean sample- $< S/N >_{pm} = 3442$, $< S/N >_{\varpi} = 855.4$, $< S/N >_{\Delta V} = 15.7$, $< RUWE >= 1.01$, $< B_p >= 0.07 \mapsto 450$ systems, $< M_{tot} >= 1.56$, GAIA FLAME masses=63%. Fastest 3% systems per bin have been removed.

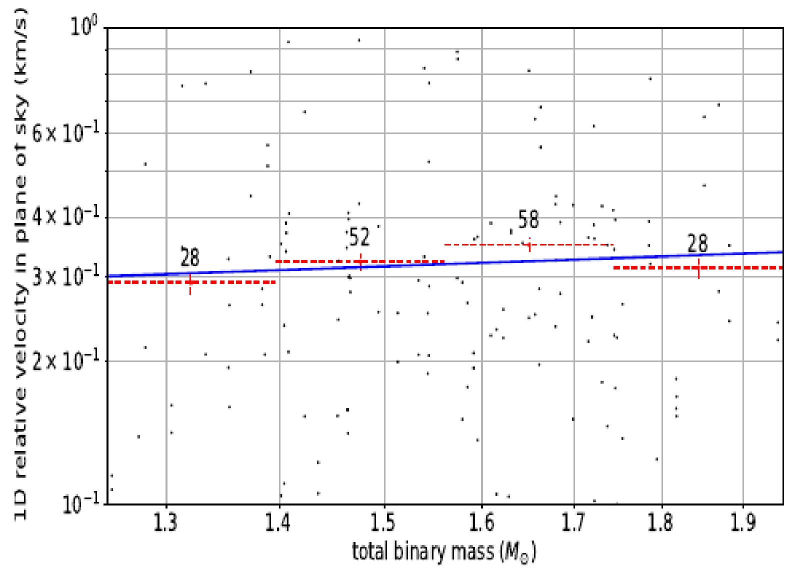
- RIGHT: 125<D<200 sample- $< S/N >_{pm} = 1798$, $< S/N >_{\varpi} = 474.4$, $< S/N >_{\Delta V} = 7.5$, $< RUWE >= 1.01$, $< B_p >= 0.06 \mapsto 450$ systems, $< M_{tot} >= 1.59$, GAIA FLAME masses=65%. Fastest 3% systems per bin have been removed.

For high accelerations, $s < 10^{-2}$ pc, results approximately trace the Jiang & Tremaine (2010) prediction, with an error offset. Implies the sample is not clean.

For low acceleration, $s > 10^{-2}$ pc, results show a noisy "flat rotation curve region", at an amplitude of $0.6 km/s$.

# Latest Gaia DR3 Results: Mass Scalings D<125pc



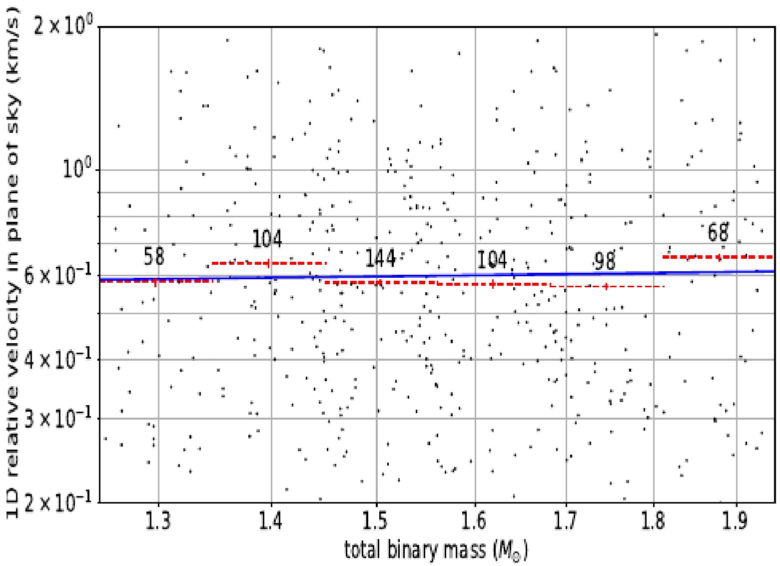

-Left panel $D < 125$pc clean sample $s < 0.01$pc. Mass-Velocity scaling with a slope of $\alpha = 0.46 \pm 0.13$, consistent with Newtonian expectations, showing the sample to be clean. $r = 0.87$.

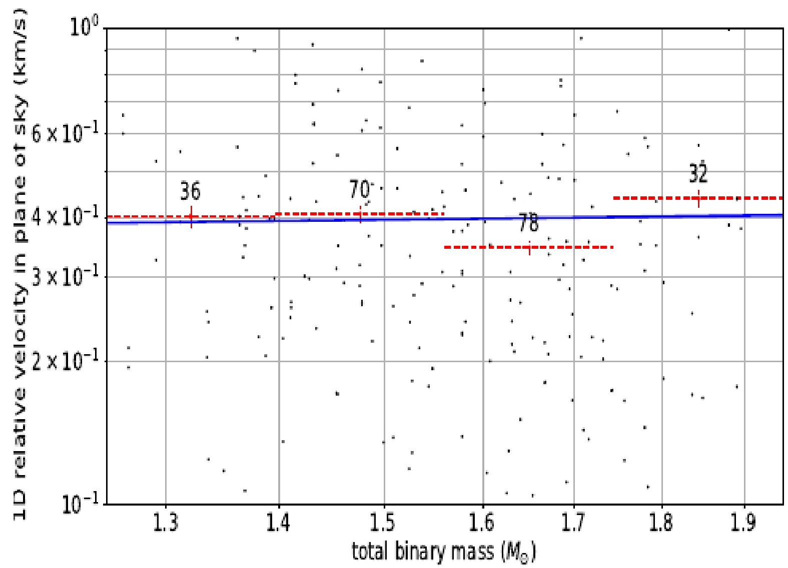
-Right panel $D < 125$pc clean sample $s > 0.01$pc. Mass-Velocity scaling with a slope of $\alpha = 0.263 \pm 0.32$, consistent with simplest MOND scalings. $r = 0.50$.


X. Hernandez, S. Cookson, R.A.M. Cortes, (2022) MNRAS, 509, 2304

X. Hernandez (2023), arXiv:2304.07322

# Latest Gaia DR3 Results: Mass Scalings 125pc<D<125pc



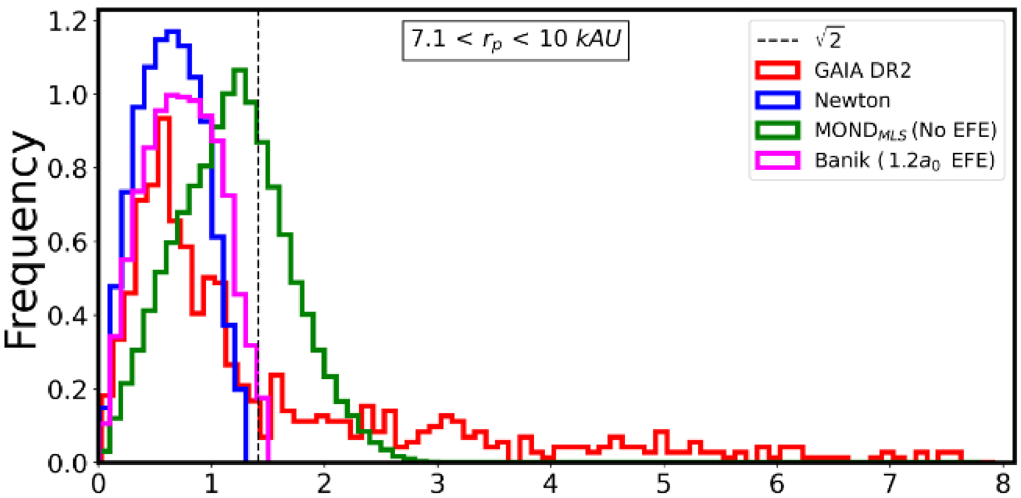

-Left panel $125 < (D/pc) < 200$ sample $s < 0.01$pc. Mass-Velocity scaling with a slope of $\alpha = 0.089 \pm 0.21$, not consistent with Newtonian expectations, showing the sample to be compromised through noise and kinematic contaminants. $r = 0.21$.

-Right panel $125 < (D/pc) < 200$ sample $s > 0.01$pc. Mass-Velocity scaling with a slope of $\alpha = 0.86 \pm 0.49$. Consistent with no mass-velocity dependence. $r = 0.21$.


X. Hernandez, S. Cookson, R.A.M. Cortes, (2022) MNRAS, 509, 2304

X. Hernandez (2023), arXiv:2304.07322

## Latest Gaia DR3 Results: $\tilde{v}$ Scalings

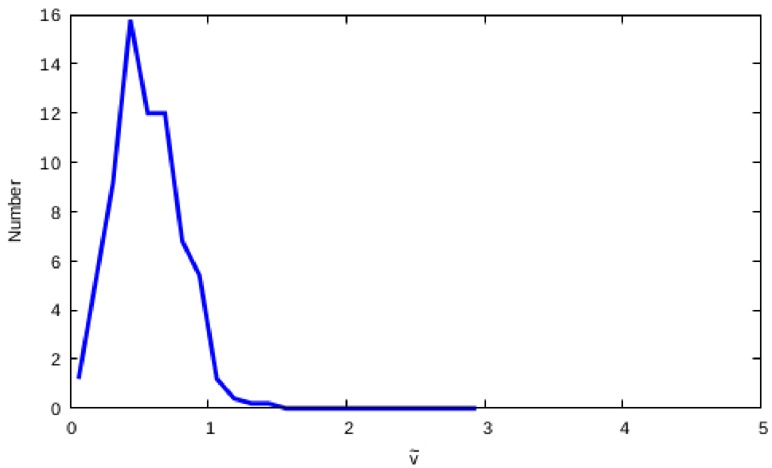


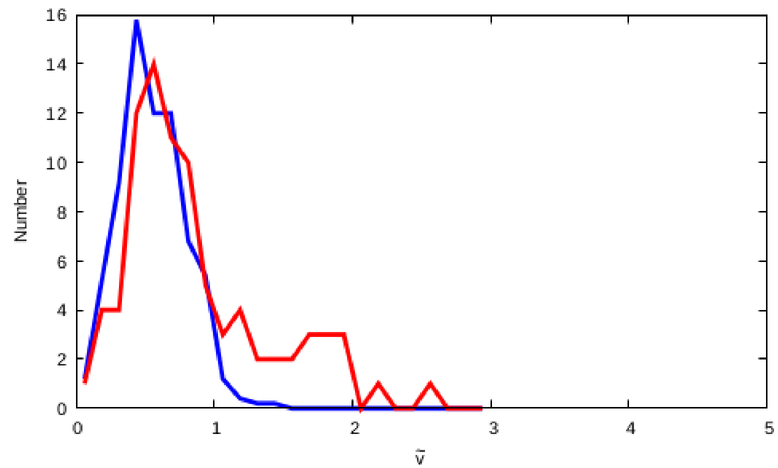

An alternative presentation of Wide Binary kinematics is through the use of $\tilde{v}$ distributions, where:

$$\tilde{v} = \frac{\Delta V_{2D}}{\sqrt{GM_{tot}/s}} \tag{2}$$

Banik & Zhao (2022) Symm, 14, 1331.
Pittordis & Sutherland (2019) MNRAS 488, 4740.

# Latest Gaia DR3 Results: $\tilde{v}$ Scalings




-High acceleration region of $D < 125$pc sample in good agreement with Newtonian calculations of distributions of this parameter, dependent on ellipticity distribution.

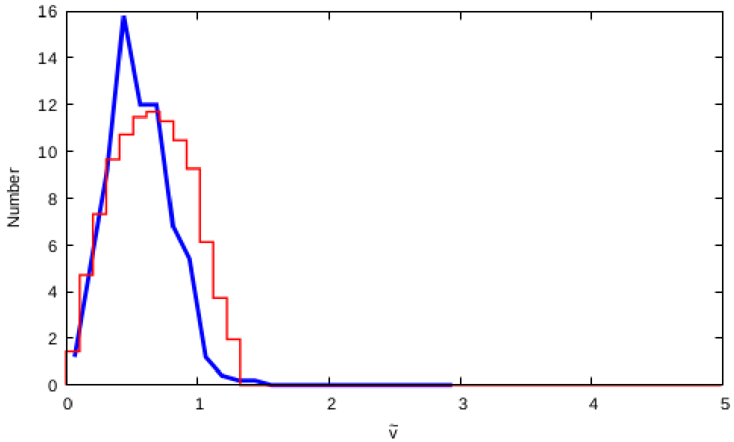
-No noise beyond $\tilde{v} = 1.5$, showing again the sample to be clean.

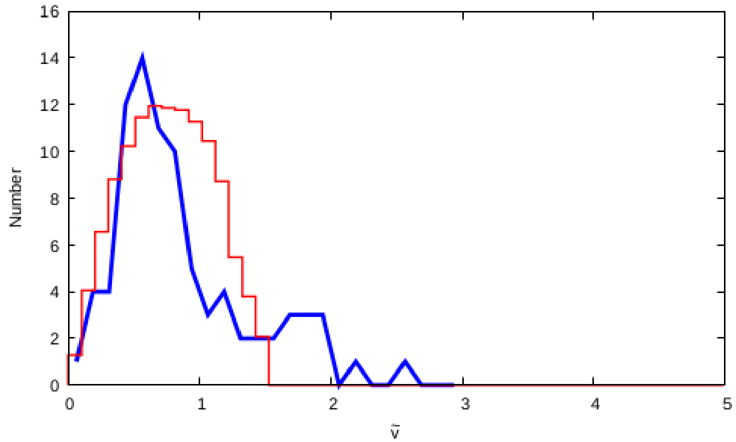
-Low acceleration region of $D < 125$pc sample shows a slight shift to the right with respect to the Newtonian region, together with the appearance of a small but meaningful population with $1 < \tilde{v} < 2$.

-Practically no noise beyond $\tilde{v} = 2.5$, showing again the sample to be clean.

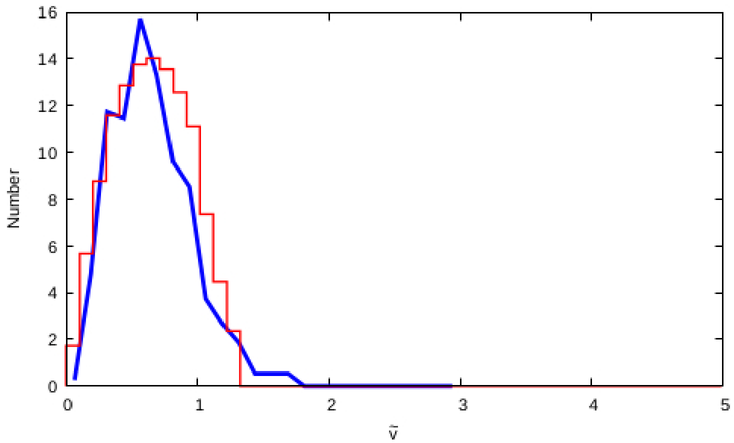
## Latest Gaia DR3 Results: $\tilde{v}$ Scalings

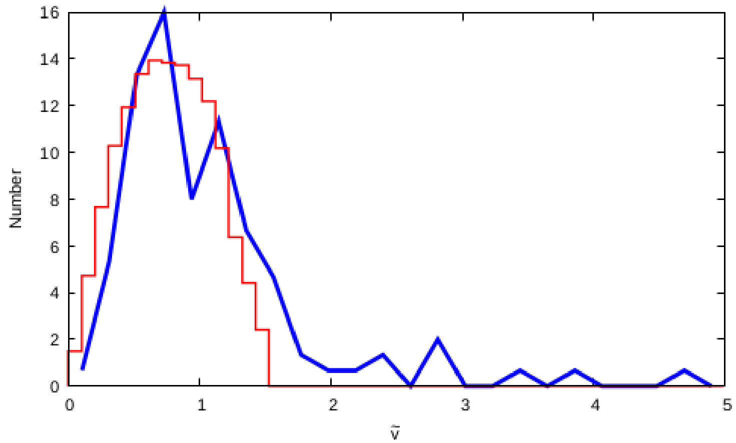
$D < 125pc$ $s < 0.01$pc, $s > 0.01pc$



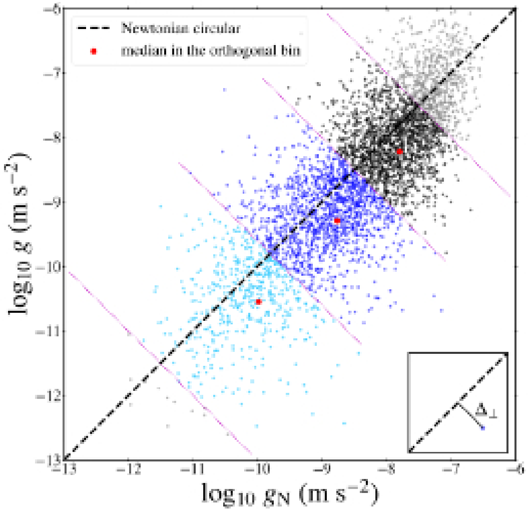

$125 < D < 200pc$ $s < 0.01$pc, $s > 0.01pc$

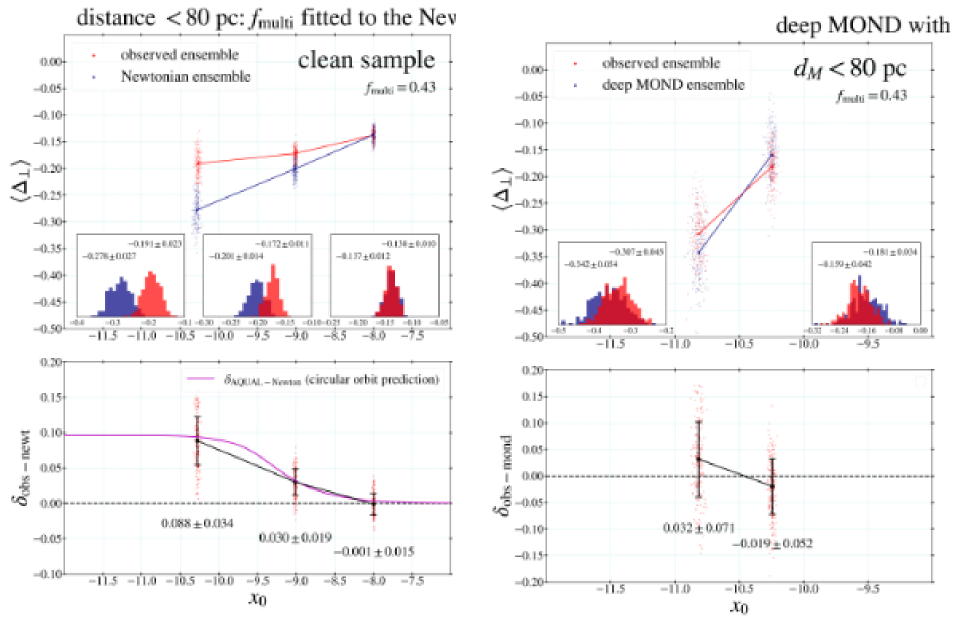


# Independent confirmation of Non-Newtonian behaviour

"Breakdown of the Newton-Einstein Standard Gravity at Low Acceleration in Internal Dynamics of Wide Binary Stars"





A clear inconsistency with Newtonian predictions is reported in the low acceleration regime.

Chae, Kyu-Hyun (2023) arXiv:2305.04613.

## Conclusions

• We present a sample of 450 isolated and bound wide binaries which were very carefully selected against chance associations, projection effects and the presence of hidden tertiaries through a variety of independent data quality and selection cuts.

• We then compare to Newtonian predictions for the relative velocity between the components of each binary and their projected separations, including modeling orientation effects, distributions of ellipticities and the effects of Galactic tides and stellar and stellar remnant perturbers over a 10 Gyr period, by Jiang & Tremaine (2010).

• For separations below 0.01pc, where accelerations are expected to be above the $a_0 = 1.2 \times 10^{-10}$ m s$^{-2}$ of MOND, we find the data to be consistent with the Newtonian predictions, including resulting mass-velocity scalings.

• For projected separations above 0.01pc, however, the data are inconsistent with Newtonian predictions, and suggestive of MOND first order scalings.

• This shows the existence of gravitational anomalies, as recently confirmed by Chae (2023) arXiv:2305.04613, of the type generally attributed to the presence of a hypothetical and dominant dark matter component, this time down to the relatively tiny sub-parsec stellar scales.