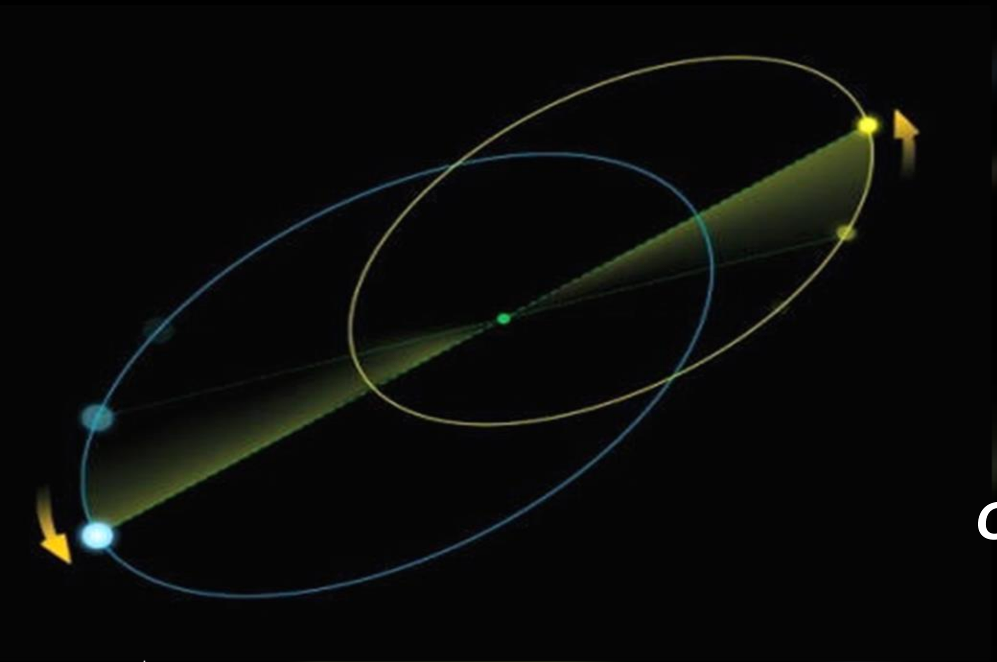
Wide Binaries from Gaia EDR3: Preference for GR over MOND ?



40 years of MOND
a_0
June 2023 St. Andrews

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& Will Sutherland

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outra.

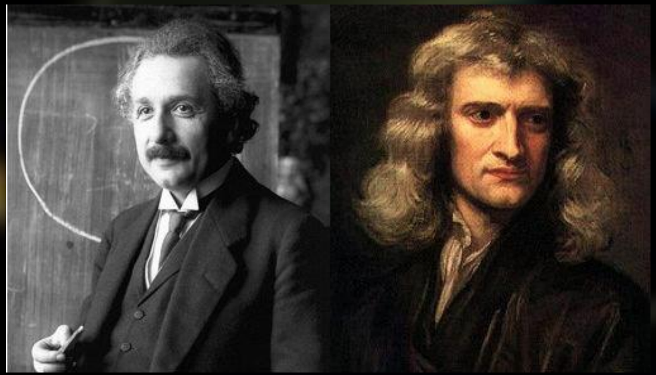
Overview

- INTRODUCTION
    - GR/Newton vs Modified Gravity (MG)
    - Wide Binaries (WB)
    - Gaia Spacecraft
- WIDE BINARY TEST OF GRAVITY
    - Simulations
    - Observables
- WB SEARCH VIA EDR3 & RESULTS (CWB-EDR3 & RESULTS)
    - Sample selection & Cleaning
    - Fitting Distribution of v-tilde with GR and MOND
    - Triple population
    - Modelling of Binaries + Triples + FlyBys
        - Additional cuts
    - Chi^2 comparisons between models
    - Detectability of Faint companions
- CONCLUSION

Intro:
GR/Newton Vs MG at Low Accel Regimes

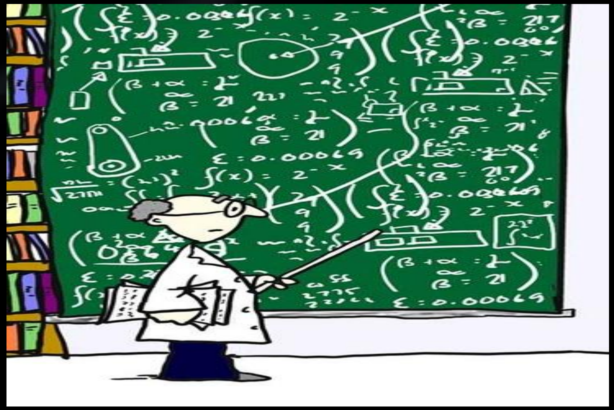
GR/Newton

- Best description of Gravity on all scales.
- Works well and tested with high accuracy on solar systems scales.
- ΛCDM model based on GR including Dark Matter (DM) and Dark Energy (DE) is successful at fitting cosmological observations.
- Can explain the weak-field limit, (*i.e., Flat Rot. curves Galaxies, LSS & CMB)* with the inclusion of DM to match these observations.
- **<u>BUT</u>,** there is no decisive direct detection of DM, leading some to speculate that GR my not be the correct theory for gravity.



MG Theories

- Attempt to explain the weak-field/Low-Accel limit without the inclusion of DM.
- Modifications of GR with extra *dimensions, fields, parameters, forces, modifying dynamics, etc.* to describe the 'Dark Sector' effects.
- So far, no MG-theory (without DM) has been close to successful in fitting the CMB observations, hence ΛCDM remains the standard model.
- **<u>BUT</u>,** there is a large model space for MG-theories, which remains partially explored.



Intro:
WBs (The System)

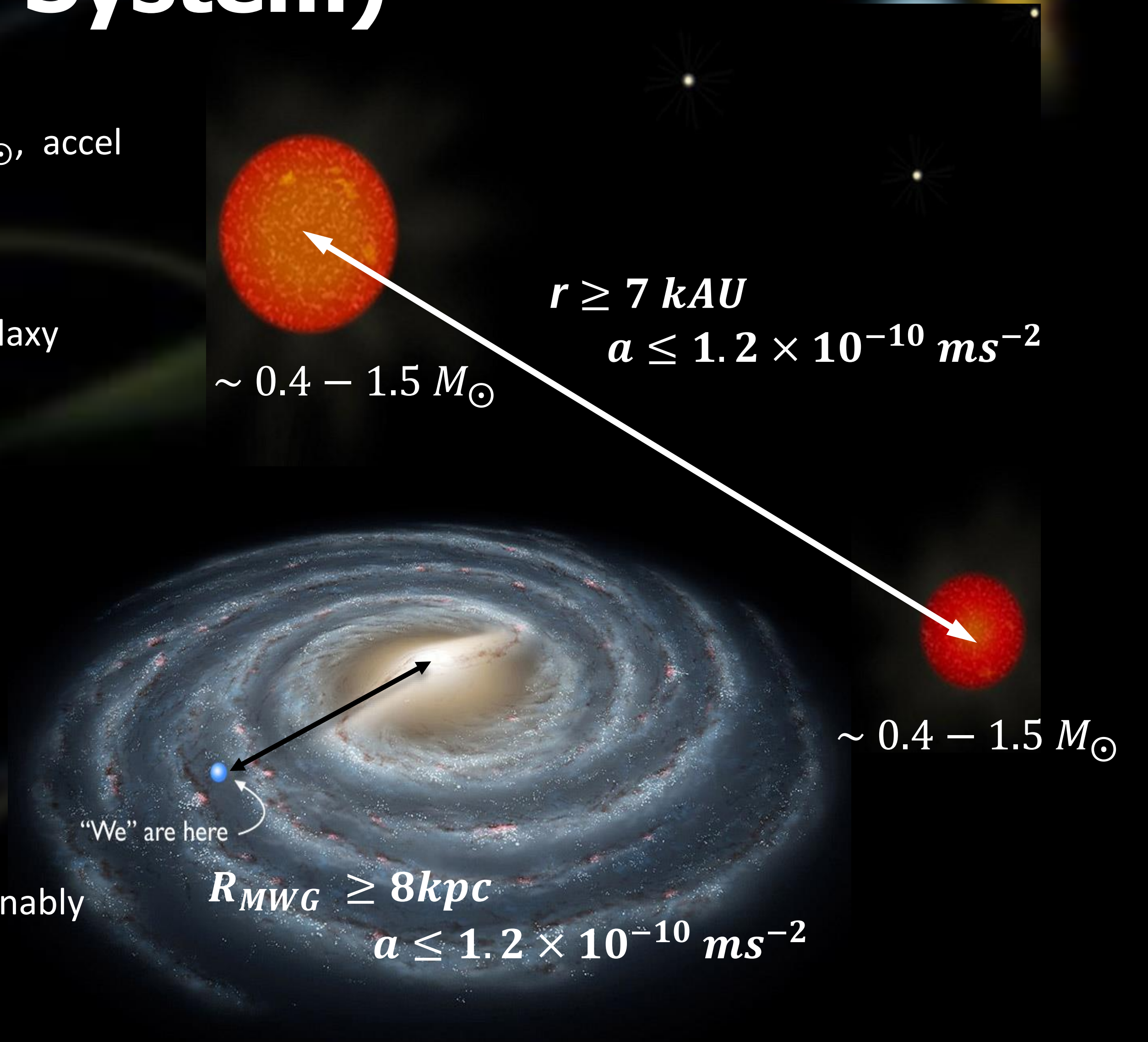
- Consider WBs with radial separations $r \geq 3\ kAU,\ M \sim 0.4 - 1.5\ M_{\odot}$, accel between pair, $a \leq 1.2 \times 10^{-10}\ ms^{-2}$

- Accel comparable to local gravitational accel due to our Milky Way Galaxy (MWG) acting on systems at $R_{MWG} \geq 8kpc$.

- $\sim 80\%$ stars within MWG are stellar binary systems,
  “”sufficient amount of data”....!!

- WBs should **NOT** contain significant amount of DM.

- WBs may be tidally disrupted, but if so, they un-bind on timescales $\sim 10\ Myrs$, much shorter than age of Galaxy; thus should be a reasonably clear distinction between currently-bound and disrupted binaries.



Intro:
WBs (Probes of Gravity)

- **Other Gravitational experiments:**
  - Solar System scale *(i.e., Lensing, Perihelion precession, Shapiro Time-delay, etc.)* ~ Constrain PPN (β, γ)
    - $\beta \sim$ The measure of non-linearity in the superposition law of gravity g_{00}.
    - $\gamma \sim$ The amount of space-curvature g_{ij} produced by a unit rest mass.
  - Gravitational redshift ~ Equivalence Principle (EP).
  - Emission of GWs from Binary pulsars ~ Quadrupole moment
  - GWs from Black Hole Binaries and Neutron Binaries ~ Ratio between light & GW speed, and other parameters
  - SMBH imaging ~ Strong field of gravity.

- **WB Test of Gravity**
  - Constrains the Newtonian part of the gravitational field (*time-time* part of the weak-field metric of GR) at low accel regimes.
  - Complementary to other gravity tests on all scales, constraining the PN terms and/or EP.
  - Pure model-independent probe of gravity, with the prospect to discriminate between DM and MG.

Intro:
WBs (The past)

- Little attention in the past due to:
  - Long orbital periods $\sim 10^5 - 10^6\ yrs$
  - Full orbit solutions are impossible, only snapshot of subset six phase-space parameters (3 Rel.Vel, 3 Rel.Pos).
  - Relative velocity are slow ~ 0.3 kms^{-1}, translates to proper motion ~ 0.6 mas yr^{-1} at $d \sim 100pc$, near the limits of 1σ precision in *pre-GAIA* era.
  - Uncertainties in parallax distances, translates to stellar mass uncertainties, blurring any possible constraints.

- WBs selected fairly robustly with *pre-GAIA (Hipparcos and SlowPOKES),* using proper motions; but the Relative Velocities wasn't precise enough to use for dynamical tests.

- *Pre-GAIA* catalogues for WBs have a gap with Mag range, *10<V<14* , potentially containing many thousand WBs, bright enough for follow-up RV with high-res ground-based spectroscopy.

Intro: GAIA Spacecraft

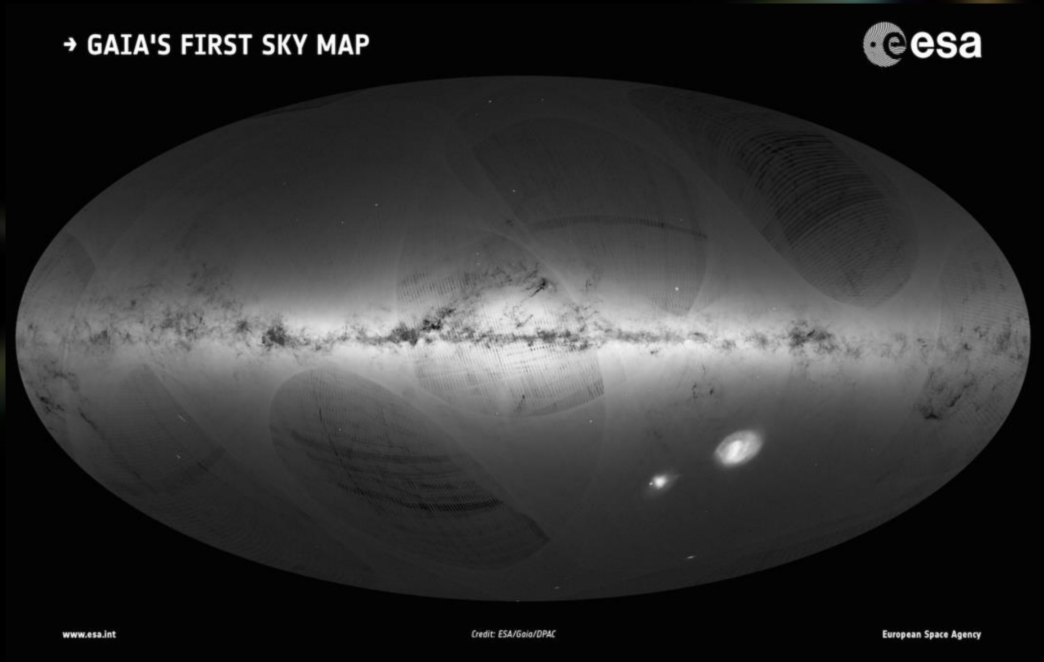
- Proper motions precision **~ 15 $\mu as\ yr^{-1}$** at mag ***G*≈15**, translates to transverse velocity **~ 0.01 kms^{-1}** at $d \sim 100\ pc$.

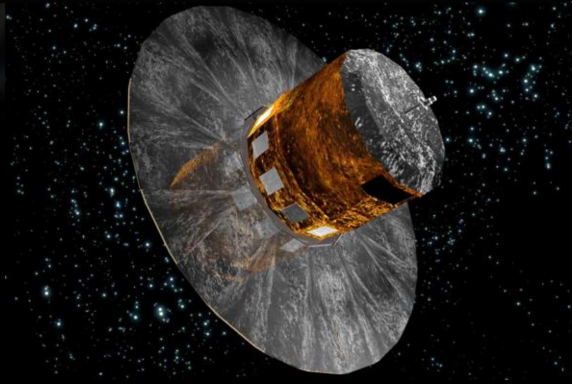
- High precision parallax distances, precise luminosities, can infer masses of WBs using ***Mass-Lum-Metallicity* relation**.

- Distance precision not good enough to resolve *line-of-sight separation* for WBs $r \sim 3 - 20kAU$; though near-by WBs at $d \sim 20pc$ should be possible.

- Radial.Vel (RV), GAIA precision isn't great, but high-accuracy ground-based spectrographs can reach $\sim 0.02\ kms^{-1}$

- GAIA plus high-accurate RV follow-up, we can obtain precise measurements of 5/6 phase-space parameters (3 Rel.Vel, 2 Rel.Pos).
- Enough to potentially perform tests of gravity.



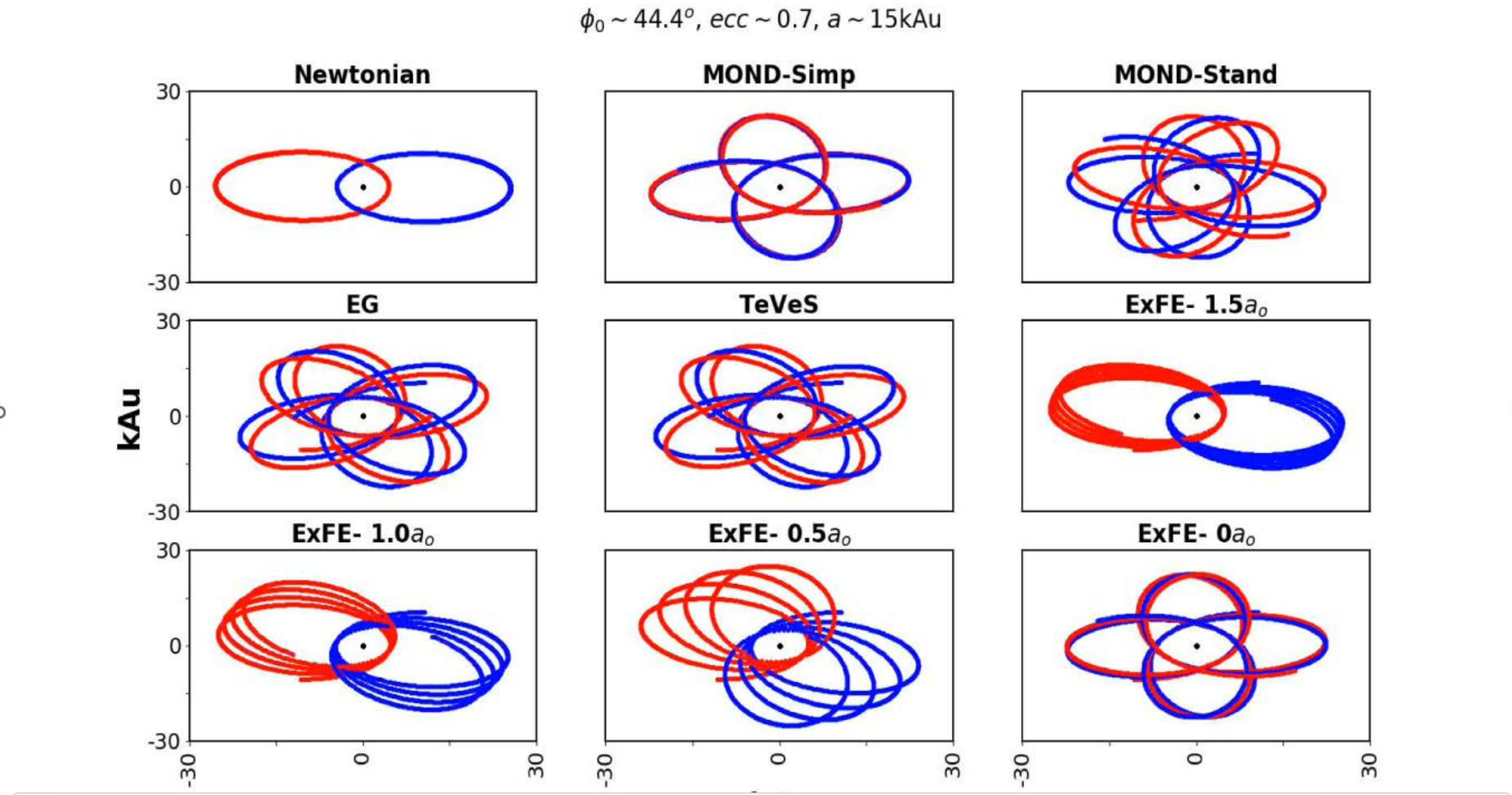


WB Tests of Gravity: Simulations

- **We simulated a large sample of $\sim 5 \times 10^6$ orbits for each gravity theory with random values of :**
    - Semi-major axis, a
    - Eccentricity, e
    - True Anomaly, θ
    - Flight path angle (angle between the Rel.Vel vector $\bar{v}_{3D}$ and tangential direction of orbit), ϕ
    - Orientation, Projections, etc.

- **In the case for MG, orbits are generally not closed ellipses;**
    - Not defined by a, e
    - For MG orbits we define *"effective"* orbit size $\hat{a}$ and *"quasi-eccentricity"* $\hat{e}$
    - $\hat{a}$ Separation at which simulated instantaneous Rel.Vel equals to the velocity for a circular MG orbit at radius r, $v_{3D}(r) = v_{C,MG}(r)$
    - $\hat{e} \equiv sin\phi_{circ}$, where ϕ_{circ} angle between Rel.Vel vector $\bar{v}_{3D}$ and tangential direction when orbital separation crosses $\hat{a}$
    - The above definitions coincide with the usual a, e for standard Newton-gravity.

- **Thus, keeping all the initial conditions consistent across all gravity theories.**


$\phi_0 \sim 44.4^o$, $ecc \sim 0.7$, $a \sim 15$kAu
Newtonian
MOND-Simp
MOND-Stand
EG
TeVeS
ExFE- 1.5a_o
ExFE- 1.0a_o
ExFE- 0.5a_o
ExFE- 0a_o
kAu
30
0
-30
00:39.86

WB Tests of Gravity: Observables

- We can't observe a full WB orbit solution.

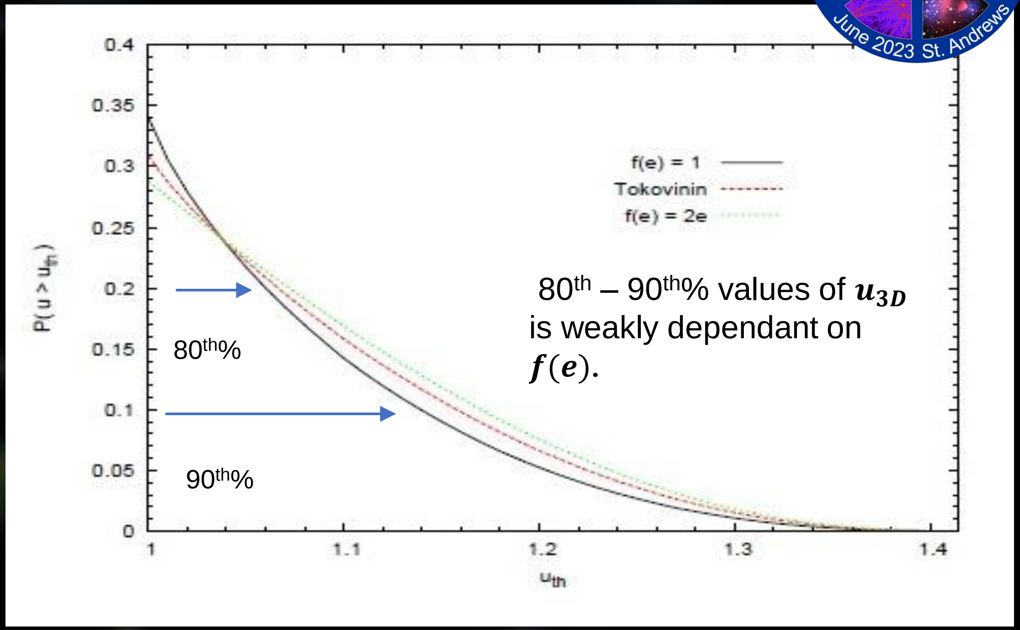
- But we can observe a snapshot of 5/6 phase-space parameters (3 Rel.Vel and 2 Rel.Pos) missing one is line-of-sight separation.
  - We only use 4/6 phase-space, because Gaia Radial Velocities are not good enough.

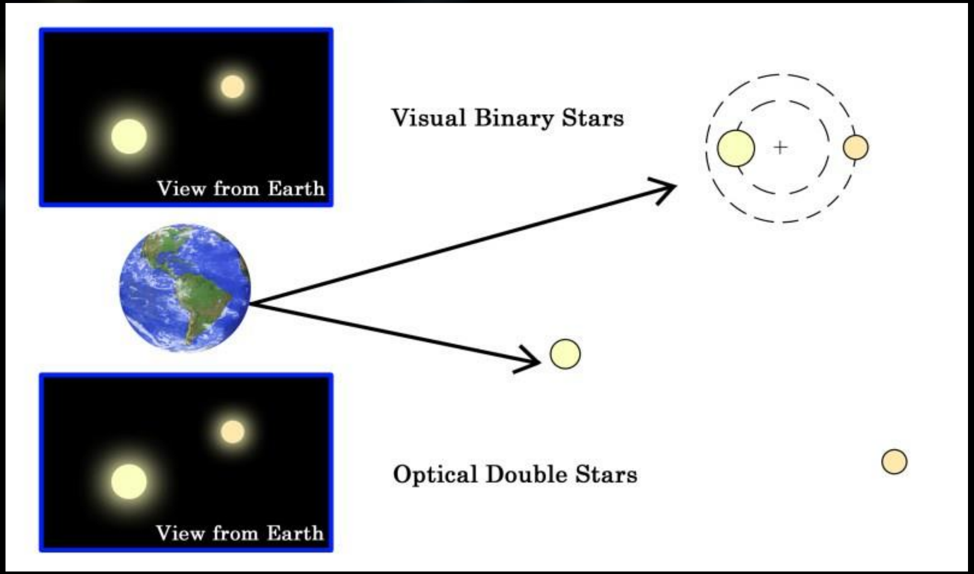
- Study the joint distribution of observables, in particular:
  - Projected separation $\boldsymbol{r_p}$
  - Ratio between the Rel.Vel and the circular Newtonian velocity at the current projected separation, $\widetilde{\boldsymbol{v}} = \boldsymbol{v_{3D}}/\boldsymbol{v_C}(\boldsymbol{r_p})$

- $\widetilde{\boldsymbol{v}}$ is convenient,
  - Since distribution is independent of $\boldsymbol{r_p}$ in case of Newtonian gravity, when ecc-distribution $\boldsymbol{f}(\boldsymbol{e})$ independent of $\boldsymbol{a}$.
  - 80^{th} & 90^{th}% values should be nearly independent of unknown $\boldsymbol{f}(\boldsymbol{e})$.

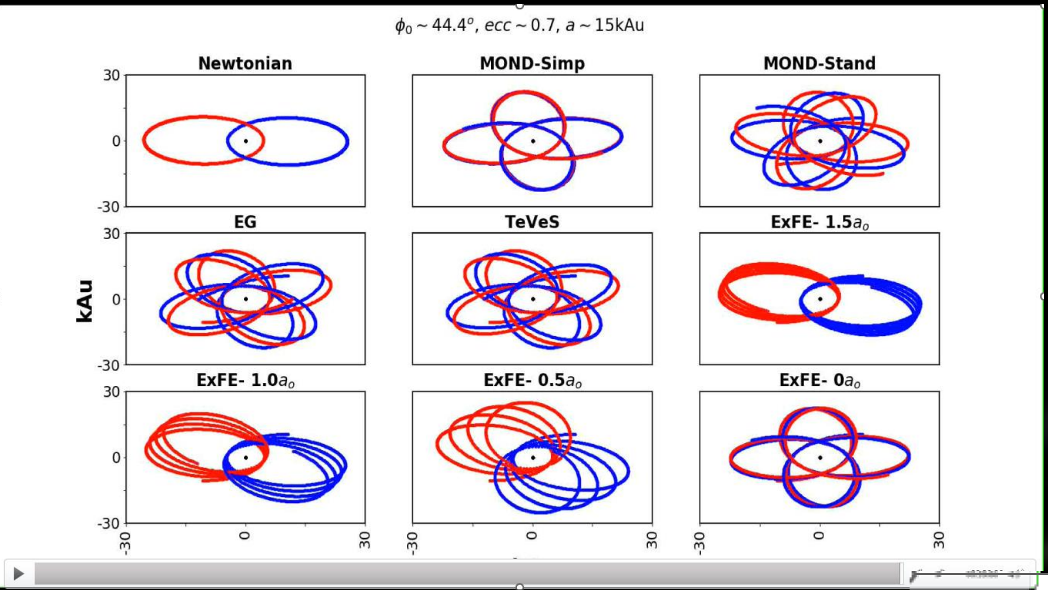
Distribution of $\tilde{v}$ & r_p

- An ideal case where all parameters *(i.e., mass and six phase-space)* well measured
  - $\tilde{v}_{3D} \equiv v_{3D}(r)/v_C(r)$, **where** $v_{3D}(r)$ is the instantaneous 3D.Vel,
  - $\tilde{v}_{3D} = \sqrt{2 - (r/a)}$, terms of a & ecc
  - $\tilde{v}_{3D} < \sqrt{2}$ (well known) for any bound orbit.
- Prob.Dist for $\tilde{v}_{3D}$, for a large sample observed at random times (*i.e. now*), $\tilde{v}_{3D} \geq 1.2$ are quite uncommon;
  - Low-ecc binaries never exceed this value, $\tilde{v}_{3D} \lesssim 1.1$
  - High-ecc do, $\tilde{v}_{3D} \gtrsim 1.1$ but only for small fraction of time around orbit peri-centre.
- In reality, we only have 5/6 components, missing line-of-sight separation
- Make do $\tilde{v}_{3D} \equiv v_{3D}/v_C(r_p)$, where $\tilde{v} = u_{3D}\sqrt{sin\beta}$, shifting the distribution of $\tilde{v}$ to smaller values compared to $\tilde{v}_{3D}$

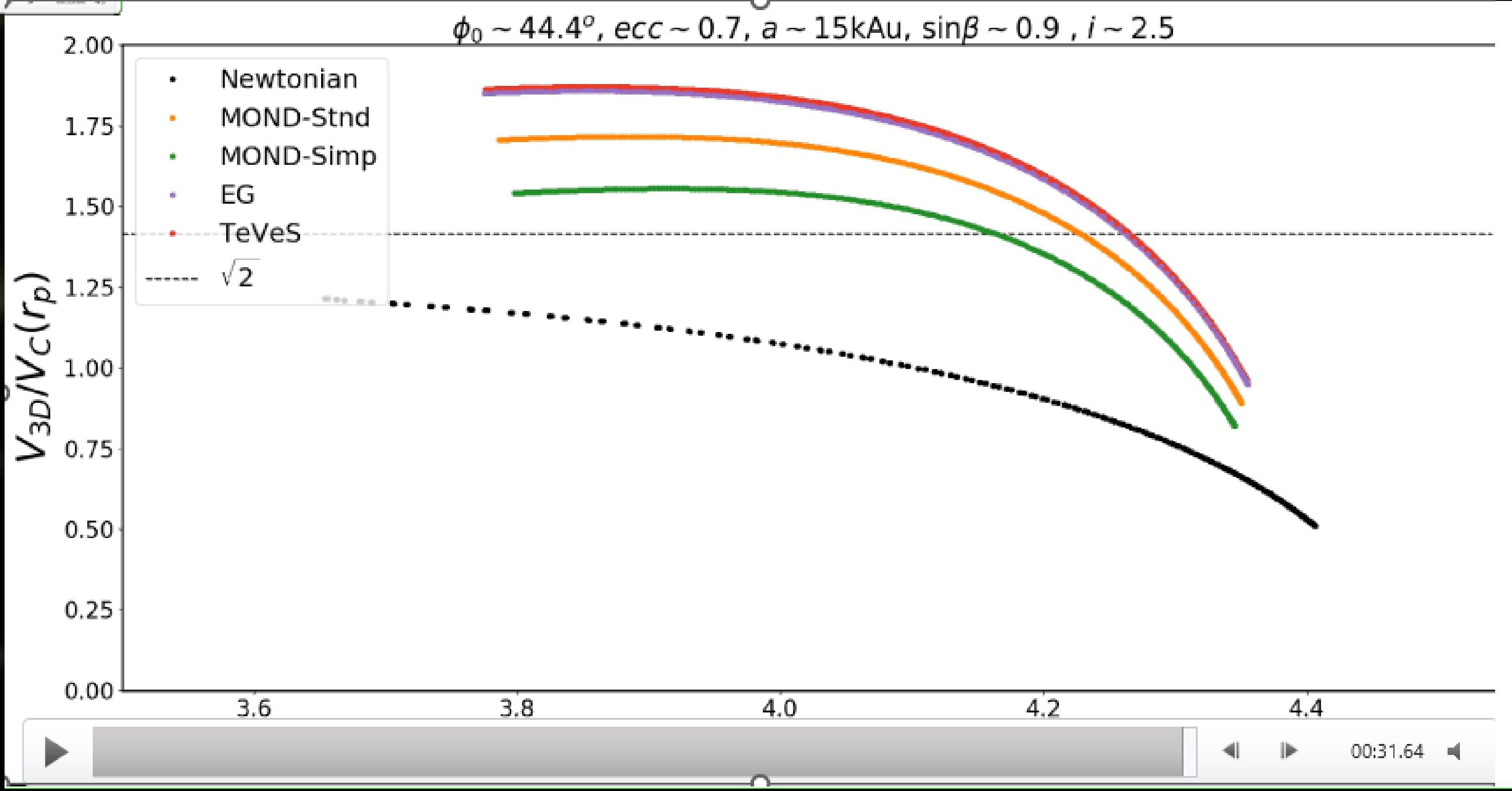


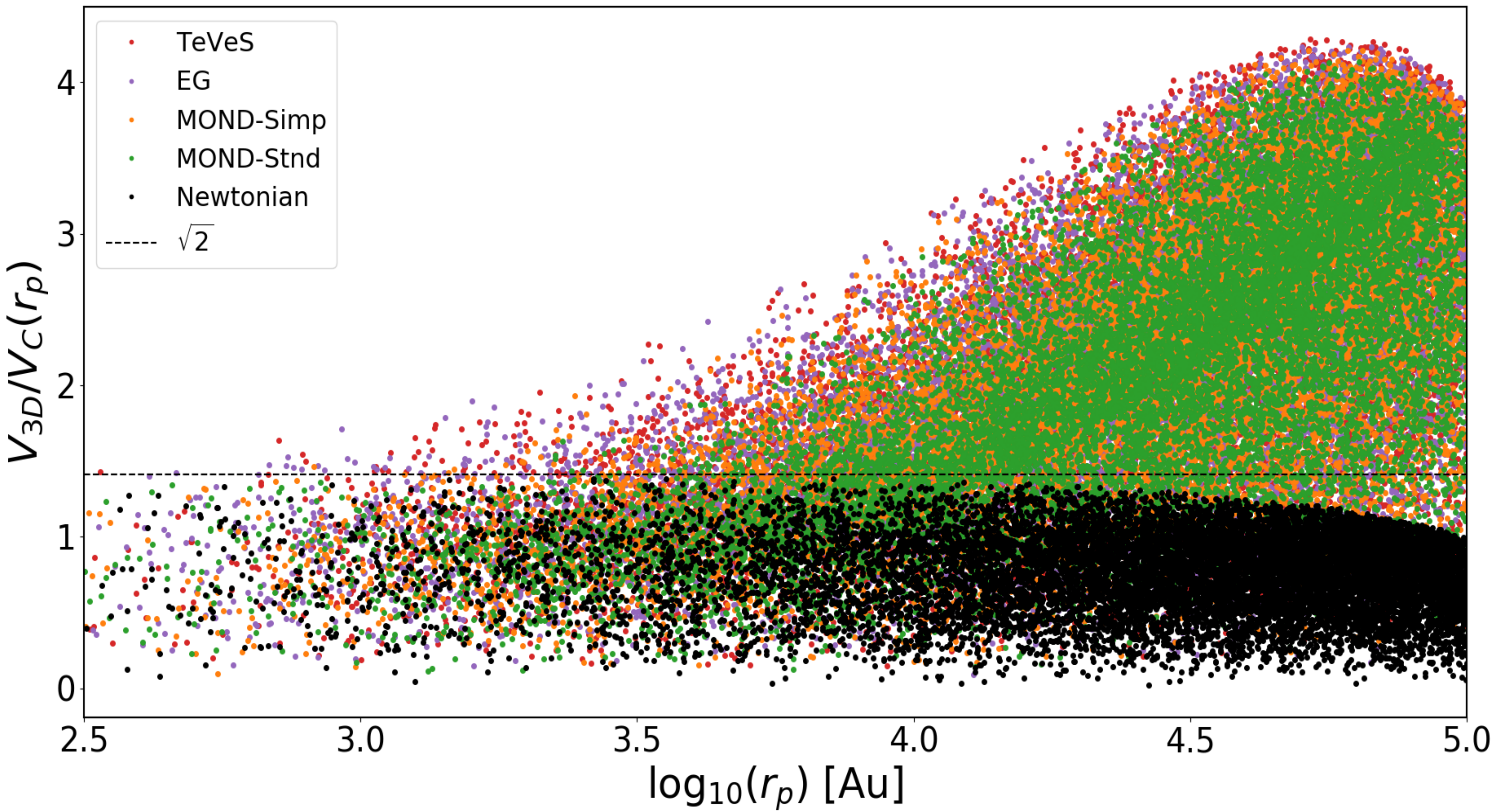


From Orbits to Observables

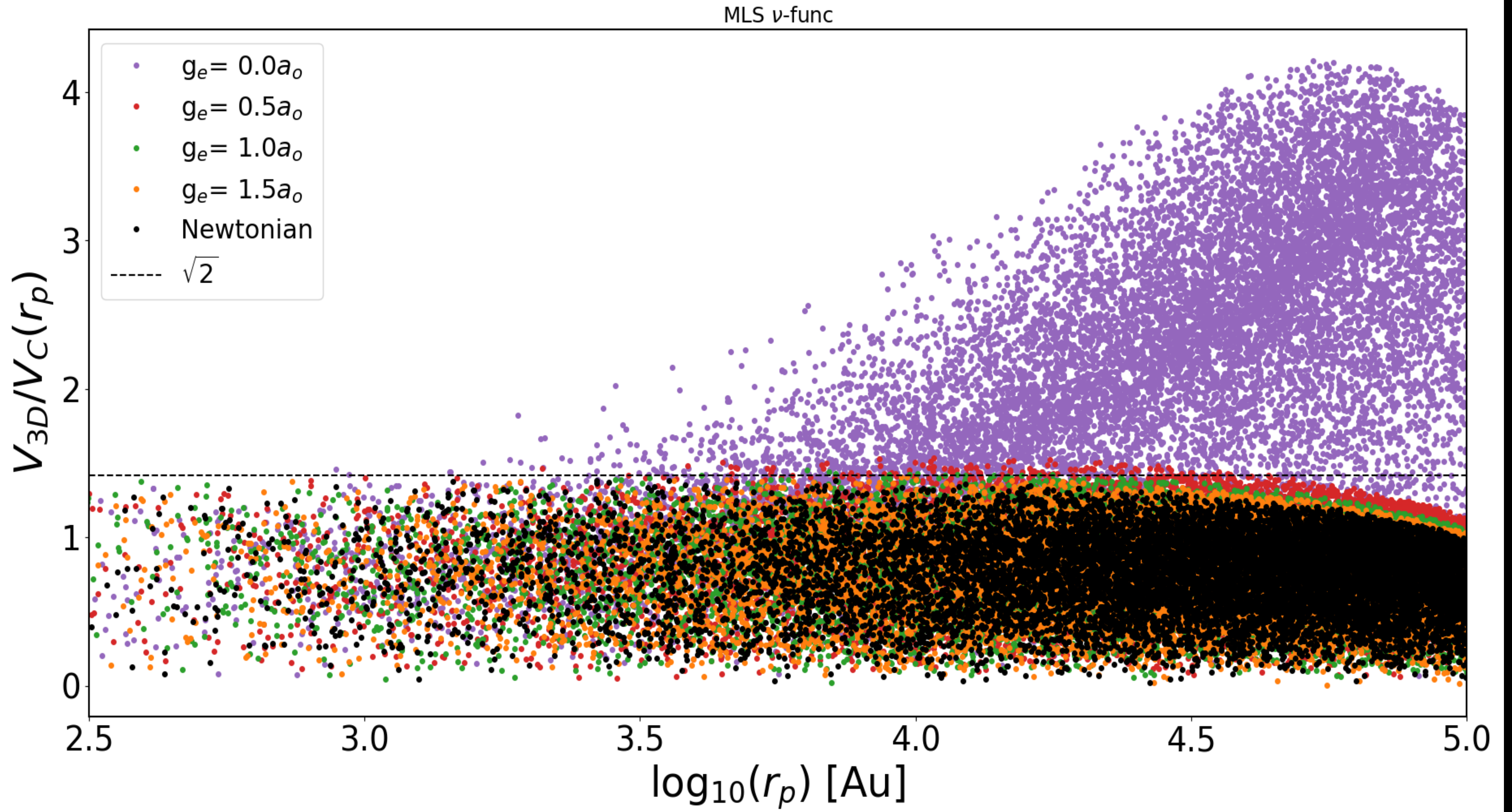


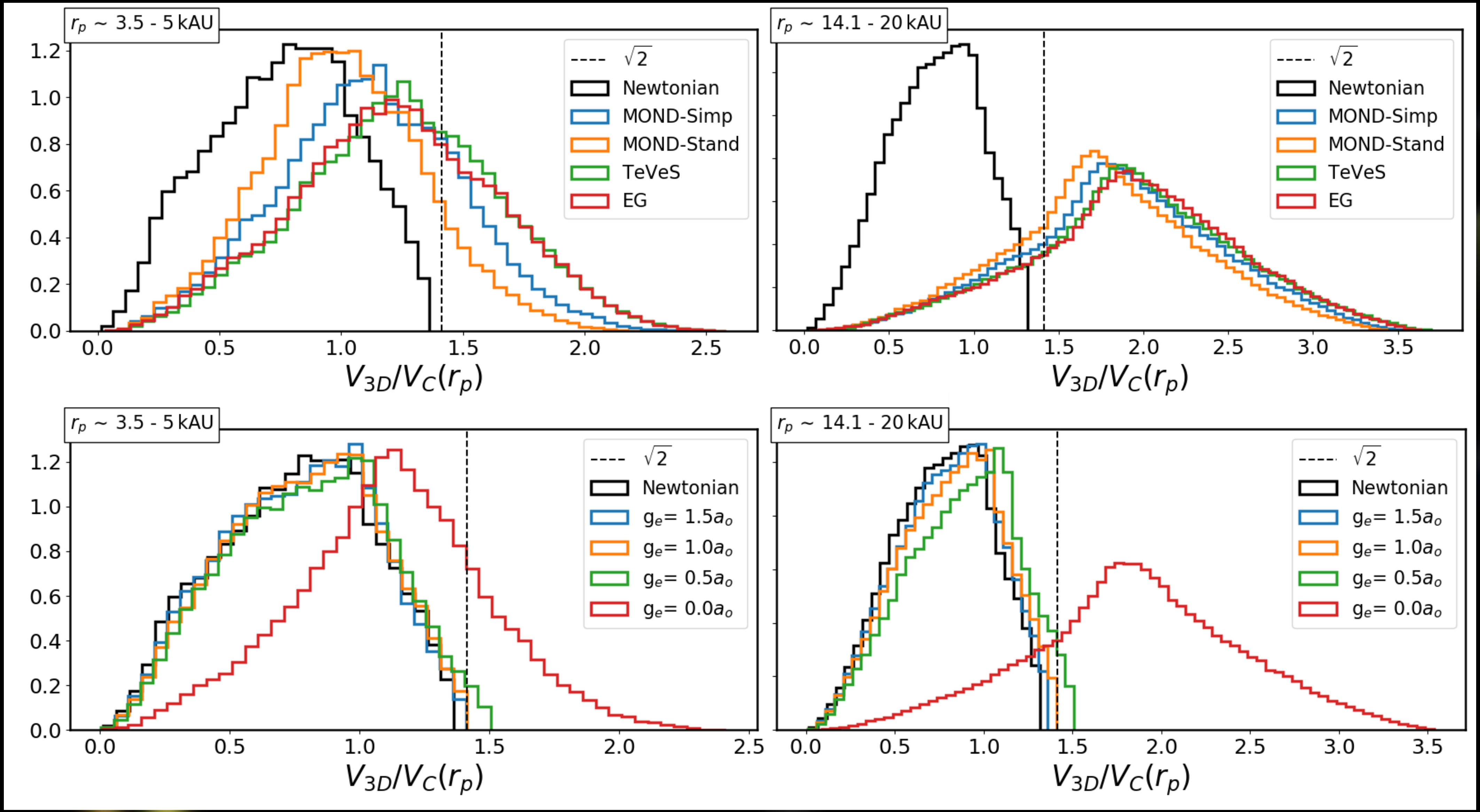
- Projected separation, r_p
- Velocity ratio , $\tilde{v} = v_{3D}/v_C(r_p)$





TeVeS
EG
MOND-Simp
MOND-Stnd
Newtonian
$\sqrt{2}$
$V_{3D}/V_C(r_p)$
$\log_{10}(r_p)$ [Au]
0
1
2
3
4
2.5
3.0
3.5
4.0
4.5
5.0


MLS ν-func
g_e= 0.0a_o
g_e= 0.5a_o
g_e= 1.0a_o
g_e= 1.5a_o
Newtonian
√2
V_3D/V_C(r_p)
log10(r_p) [Au]
0
1
2
3
4
2.5
3.0
3.5
4.0
4.5
5.0



No ExFE

ExFE MLS-Func

- Newtonian gravity predicts the histogram of $\tilde{v}$ for WBs should exhibit a steep decline above values $\tilde{v} \sim 1.1$
- Clear distinction and obvious shifts, thus, conclude that all MG models *without ExFE* can be robustly tested or ruled out by *GAIA* WB samples with ground-based RV follow-up.

Observational Considerations

- *Without ExFE*, ~ we predict large and easily detectable shifts in the distributions.
- *With ExFE*, ~ the shifts due to MG are relatively small so it would be necessary to obtain a large sample of WBs in order to get useful statistics.
- Combining:
  - Luminosity Function (LF) from Chabrier (2003), Binary Separation Distribution (BSD) from Andrews et al (2017)
  - Mass range ~ $0.4 \leq \frac{M}{M_\odot} \leq 1.5$, for FGK and early M stars.
- Estimate No. of WBs :
  - WB separation range $\sim 3 < r < 20\ kAU$
  - WBs at distance and app.magnitude ~ $D < 200\ pc,\ V < 15$
  - No. of WBs ~ over 10,000
  - Roughly 1000-2000 WBs per $\sqrt{2}$ separation bin
- Sample ~ 1000 well measured WBs can give statistically significant detections of an offset ~ 0.04 (4%) relative to Newtonian prediction.
- Enough to robustly detect offset predicted by MG and various ExFE cases, *if* all systematics errors, contamination can be controlled and/or statistically corrected via simulations.

Observational Caveats

- **For binaries in our desired range ($D < 200pc, V < 15$),**
  - *GAIA* statistical proper-motion errors "today"~ $0.09\ kms^{-1}$, (5yr~ $0.02\ kms^{-1}$, 7-9yr $\lesssim 0.02\ kms^{-1}$)
  - Planet-hunting spectrographs *(HARPS & ESPRESSO)* can readily reach RV precision << $0.01 kms^{-1}$ $at\ V{\sim}15$

- However, other sources or error are potentially more serious such as;
  - *velocity absolute accuracy*
  - *contamination by un-bound pairs*
  - *confusion from hierarchical triple/quadruple systems.*

- Our method does rely on a rather good calibration of *Lum-Mass* relation;
  Potentially testable using binaries $r_p \lesssim 1kAu$ where deviations due to MG are negligible.

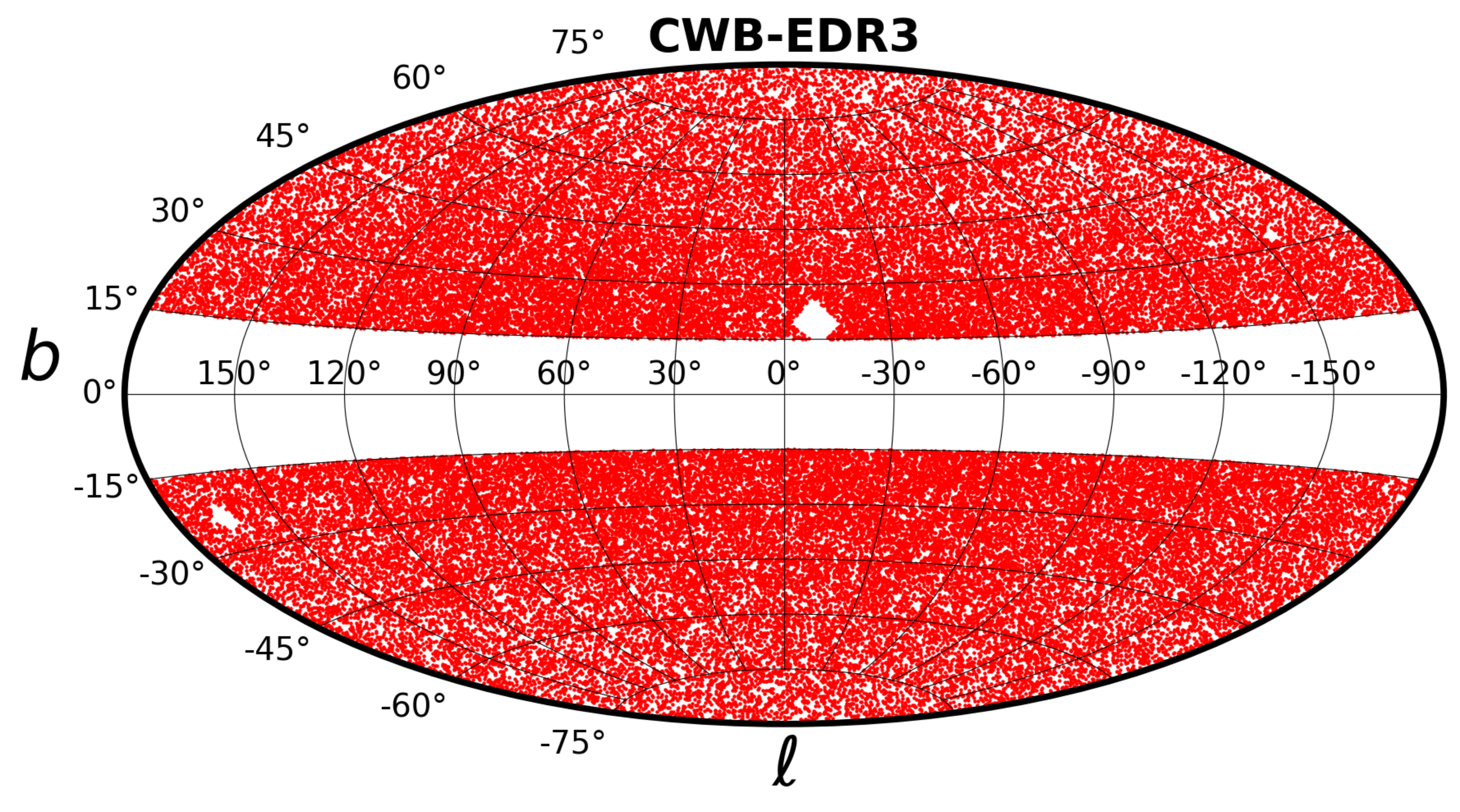
- Also, high-quality spectra (for RV) should provide precise metallicities, allowing this to be included in the calibration.

WB Search Via EDR3 & Results: Sample Selection & Cleaning

- We aim to produce a ‘clean’ unperturbed sample of WBs.
- We search & select WBs via EDR3, (bright enough for follow-up RV from ground-based) with the following conditions:
  - GAIA magnitude limit ~ $G < 17$
  - Parallax $\widehat{\omega} > \frac{10}{3} mas$, (translates to distance $d < 300\ pc$)
  - Max projected separation r_p ~ $50\ kAU$
  - The distances to both pair in WB not differing by no more than ~ $\Delta\mathrm{d} \leq 4\sigma$
  - Projected velocity difference ~ $\Delta\mathrm{v_p} \leq 3\ kms^{-1}$

- In Addition, we cut out:
  - Galactic plane ~ (due to higher density of background sources, lower WB data)
  - Clusters ~ (WBs in clusters a subject to tidal disruptions)
  - Removed hierarchical systems like `faint’ third star companions
  - `Lower-quality’ stars that fail the criteria given by Arenou et al (2018) ~ (stars with low visibility periods)

Aitoff.Proj, WB sample with Selection criteria and cuts = 73,087



WB Search Via EDR3 & Results: Computing $V_C(r_p)$

- Since we have r_p , and the magnitudes from GDR2, we can then determine

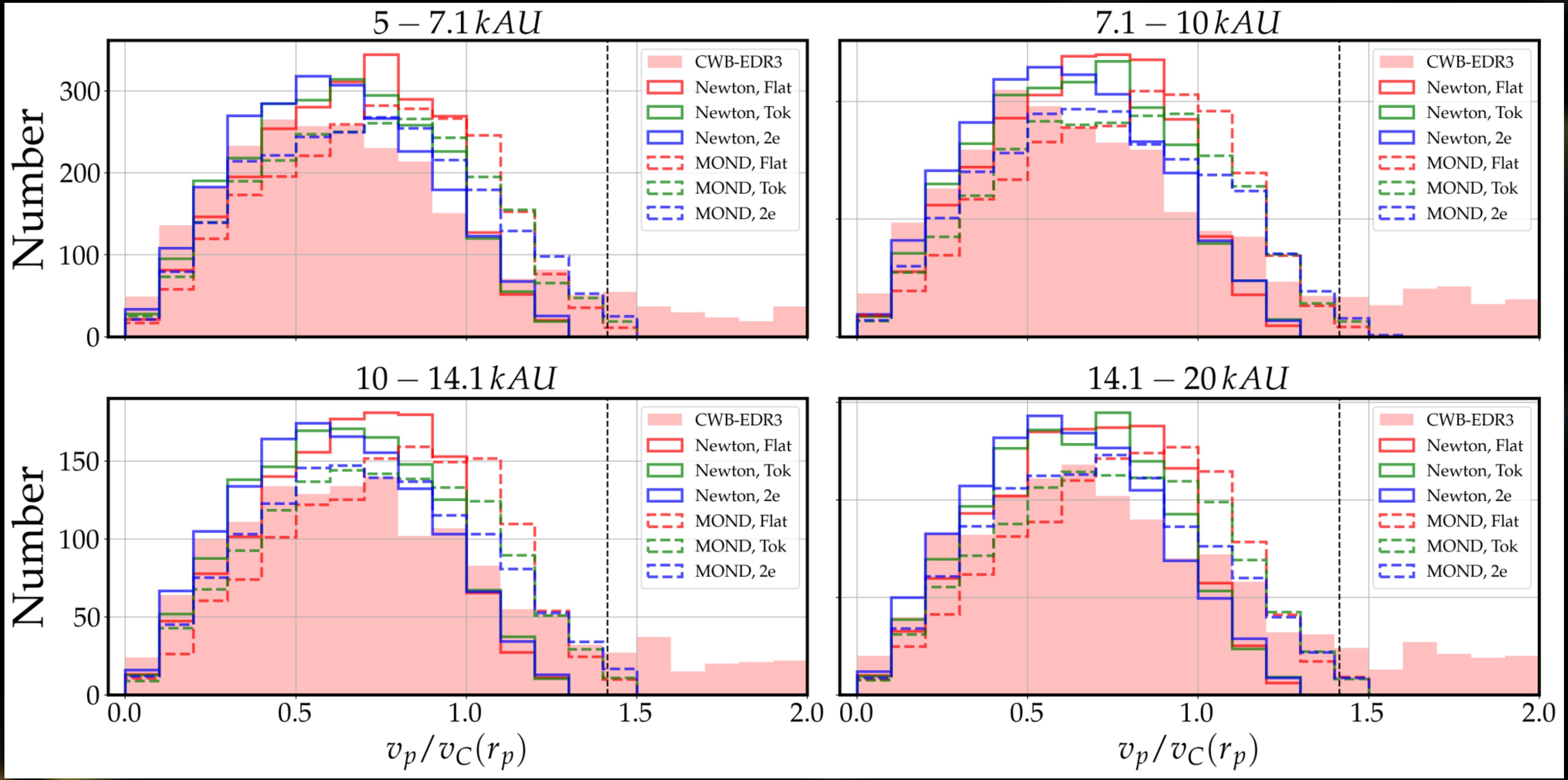
$$v_C(r_p) = \sqrt{G(M_1 + M_2) \,/\, r_p}$$

- The masses are estimated using the Mass-Magnitude relation
- We use the stellar parameter data from Pecaut & Mamajek (2013):
  - For mass range $0.4 < M/M_\odot < 1.5$
  - Spectral type ~ FGK and early M stars (stars bright enough for follow-up RVs and do not suffer from observational caveats)

- Convert GAIA G-mag. to V-mag using Johnson-Cousins relation:

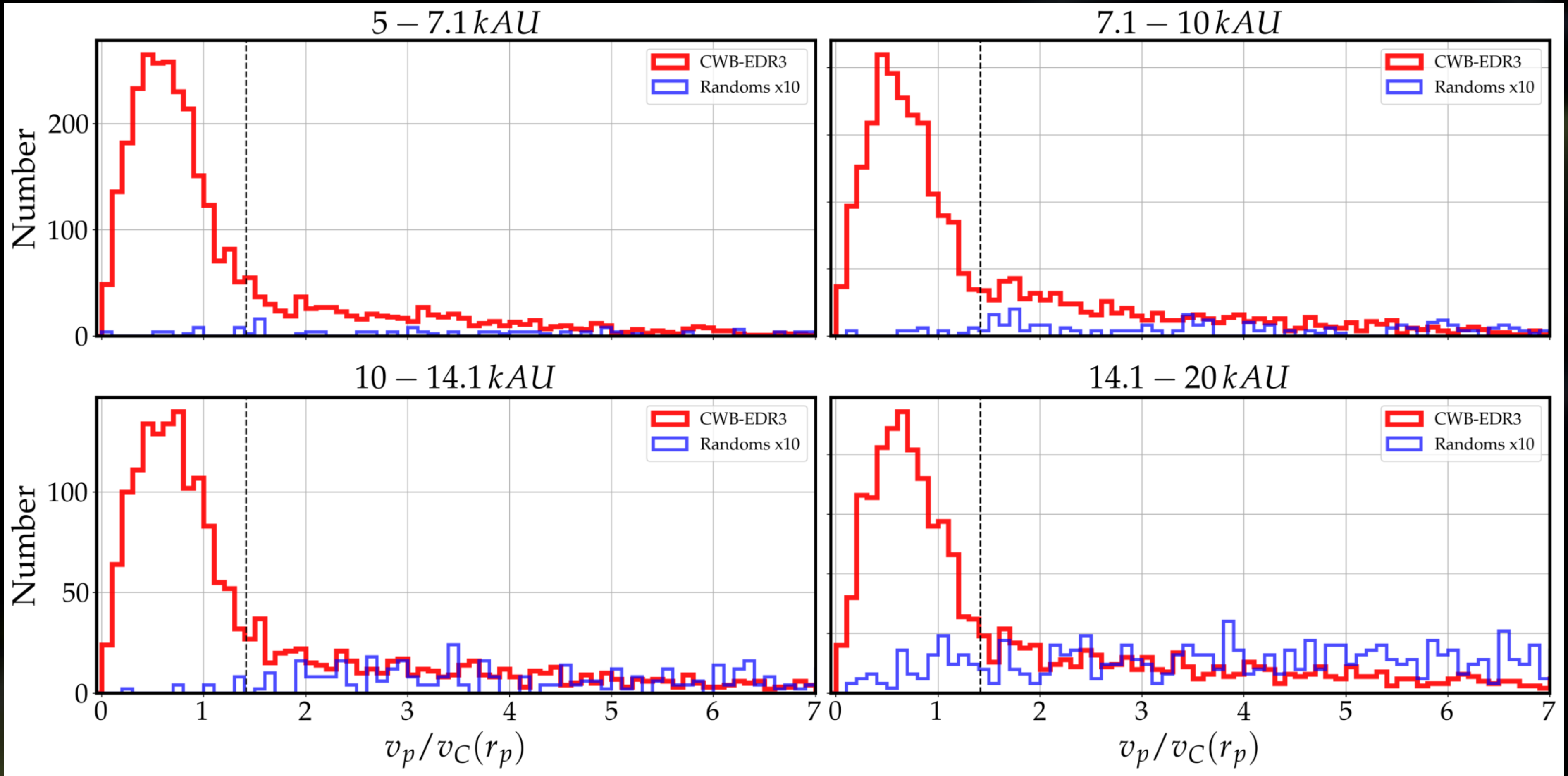
$$G \simeq V - 0.01597 + 0.02809(V - I) - 0.2483(V - I)^2$$
$$+ 0.03656(V - I)^3 - 0.002939(V - I)^4$$

CWB-EDR3 & Results: Fitting dist. $\tilde{v}$ GR & MG



- The EDR3 WB sample peaks at $\tilde{v}\sim \mathbf{0.6}$
- MG ***without ExFE*** peaks at $\tilde{v} > \sqrt{2}$ for $\boldsymbol{r_p > 7\ kAU}$, hence ruled these MG theories out.
- However, the EDR3 WB sample has ‘tail’ at values $\tilde{v} > \sqrt{2}$

CWB-EDR3 & Results: Randoms/Chance Projs.



- Random samples, containing fewer "cand. WB" than the EDR3.
- As expected, no peaks at low vel.ratios, with a gradual rise at large vel.ratios.
- The EDR3 "tail" is much more populous than the randoms.
- So clearly not due to chance projected stars.
- This high velocity "tail" is under investigation…!!

CWB-EDR3 & Results: Modelling Triples+WB+FlyBys

Triples (3 star WB Systems)

- WBs where one of the candidates is a 'inner' binary system.
  - Star 1 : outer single star (orbits barycentre of Star 2 & 3)
  - Star 2 & 3 : 'inner' binary
- Masses
  - Choose random masses for Stars 1,2,3, flat dist. $m < 0.7\ M_\odot$, decline $m^{-2.35} > 0.7\ M_\odot$
  - Constrains, Stars 1,2 $m > 0.5\ M_\odot$, Star 3 $m > 0.01\ M_\odot$
- Orbit sizes,
  - $\hat{a}_{out}\ flat\ dist.in\ \log_{10}(\hat{a}_{out}/1kAU)$
  - $0.1AU < \hat{a}_{inn} < 0.3\hat{a}_{out}\ flat\ dist.in\ \log_{10}(\hat{a}_{inn})$
  - $f(ecc) = [flat, tok, 2ecc(i.e., thermal)]$ both *outer & inner* orbits
- Observables
  - $\bar{v}_{3D} = \bar{v}_{out} - f_{pb}\boldsymbol{R}\bar{v}_{inn}$
    - $\boldsymbol{R} = Rotation\ Matrix$
    - $f_{pb} = PhotoBarycentre = \begin{cases} \frac{M_3}{M_3+M_2} - \frac{L_3}{L_3+L_2}\ (\theta < 1\ arsec) \\ \frac{M_3}{M_3+M_2}\ (\theta > 1\ arsec) \end{cases}$

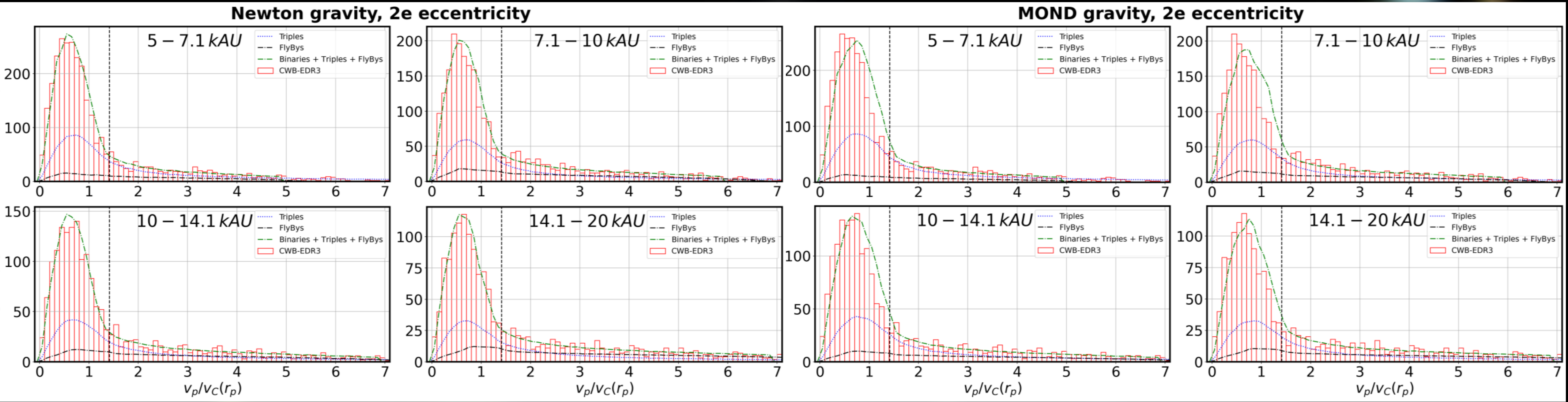
FlyBys (co-natal stars born in same open cluster)

- Co-natal stars born from the same open cluster, therefore having similar velocities currently undergoing chance FlyBys (on unbound hyperbolic FlyBy trajectories)
- Extrapolate downwards from the high.vel "tail".
- FlyBy model:
  - Simul. Newton + flat V_∞ dist.
  - Kept shape of both populations fixed.
  - Fitting to the EDR3 sample.
  - Assuming Poisson errors for maximum likelihood.

Model: Combining Triples+WB+FlyBys populations

- Combining a mixture of Wide Binaries , Triples and FlyBys populations, and fitting $\tilde{\boldsymbol{v}}$ distribution to Gaia CWB-EDR3 sample.
- Produced best fits for eccentricity dist. $f(ecc) = 2ecc$ both *outer & inner* orbits for both GR/Newton and MG

CWB-EDR3 & Results: Modelling Triples+WB+FlyBys



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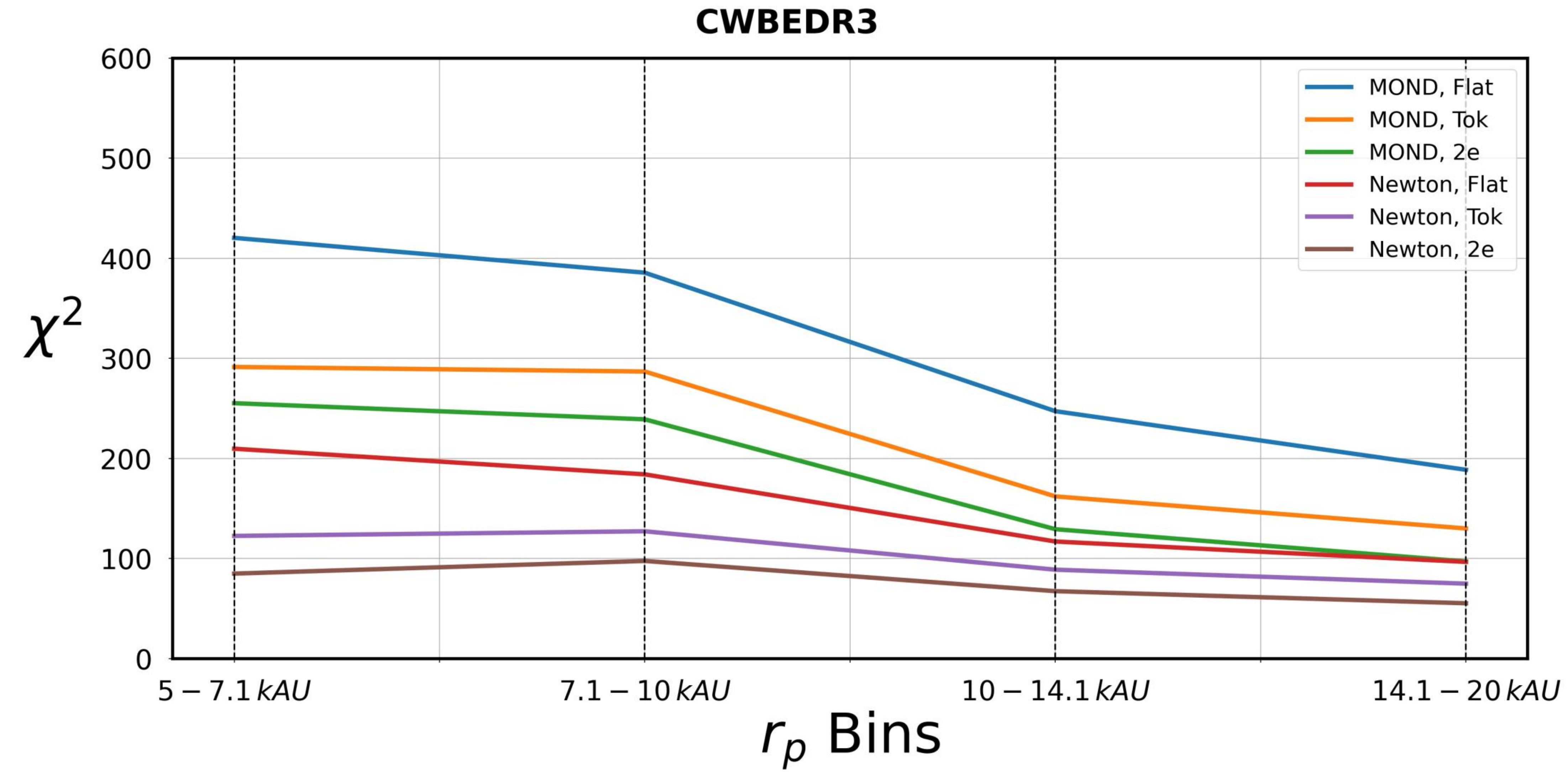
CWB-EDR3 & Results: χ^2 comparison between models



CWB-EDR3 & Results: Additional cuts

- Work by (A Hartman, Zachary D.; Lépine, Sébastien; Medan, Ilija, 2022) *Vetting the ``Lobster'' Diagram: Searching for Unseen Companions in Wide Binaries Using NASA Space Exoplanet Missions*
- By cross-matching & examining Gaia, SUPERWIDE, TESS, K2 and Kepler archives, produced a technique to distinguish between 'true' WBs and higher-order multiples via identifying the Overluminous candidates in WB systems.
  - Dense region = 'True' WBs , which have the same metallicity & age (scatter diagonal line)
  - Everywhere else = Overluminous, higher-order multiple systems

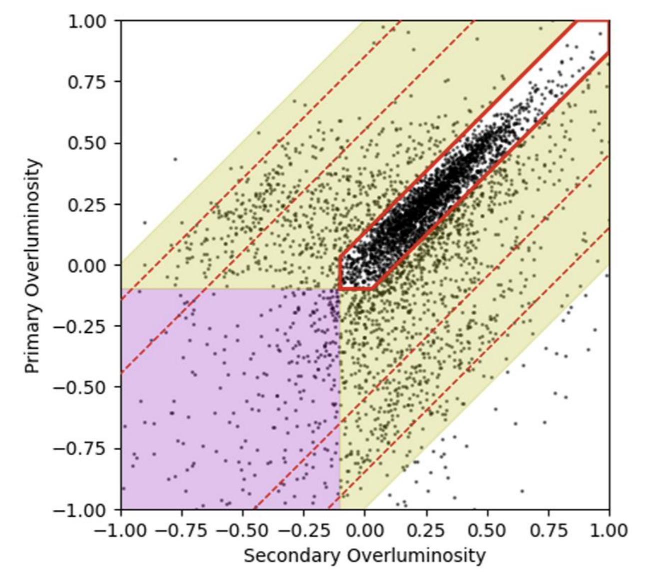
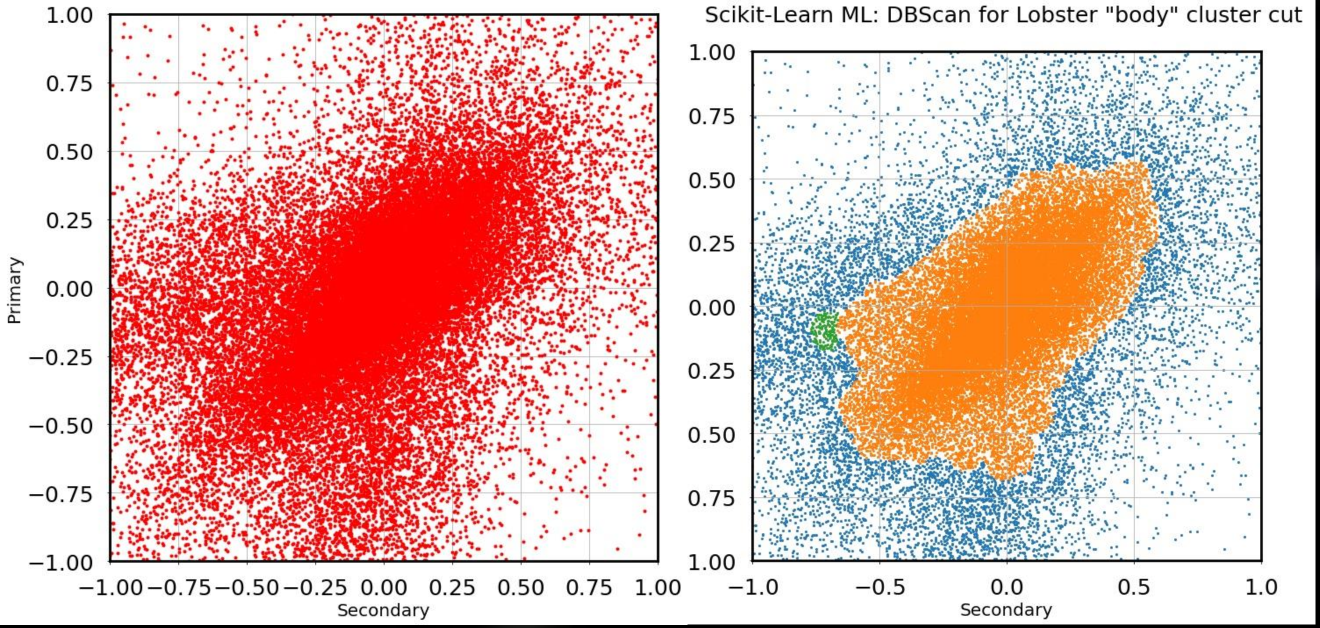


Figure 7. The "Lobster diagram" plotting the overluminosity factor F_{OL} of the primary star as a function of the F_{OL} of the secondary star for the most of the 4647 K+K wide systems in the assembled sample. Two key features stand out in this plot. The dense locus along the 1:1 line represents "true" wide binaries where both components are single in the eyes of *Gaia*. Points lying outside of this locus represent systems where unresolved components make either the primary or secondary components suspiciously overluminous. If a point falls in the purple region, it may represent a possible quadruple system or a young system, where both components are unusually overluminous.



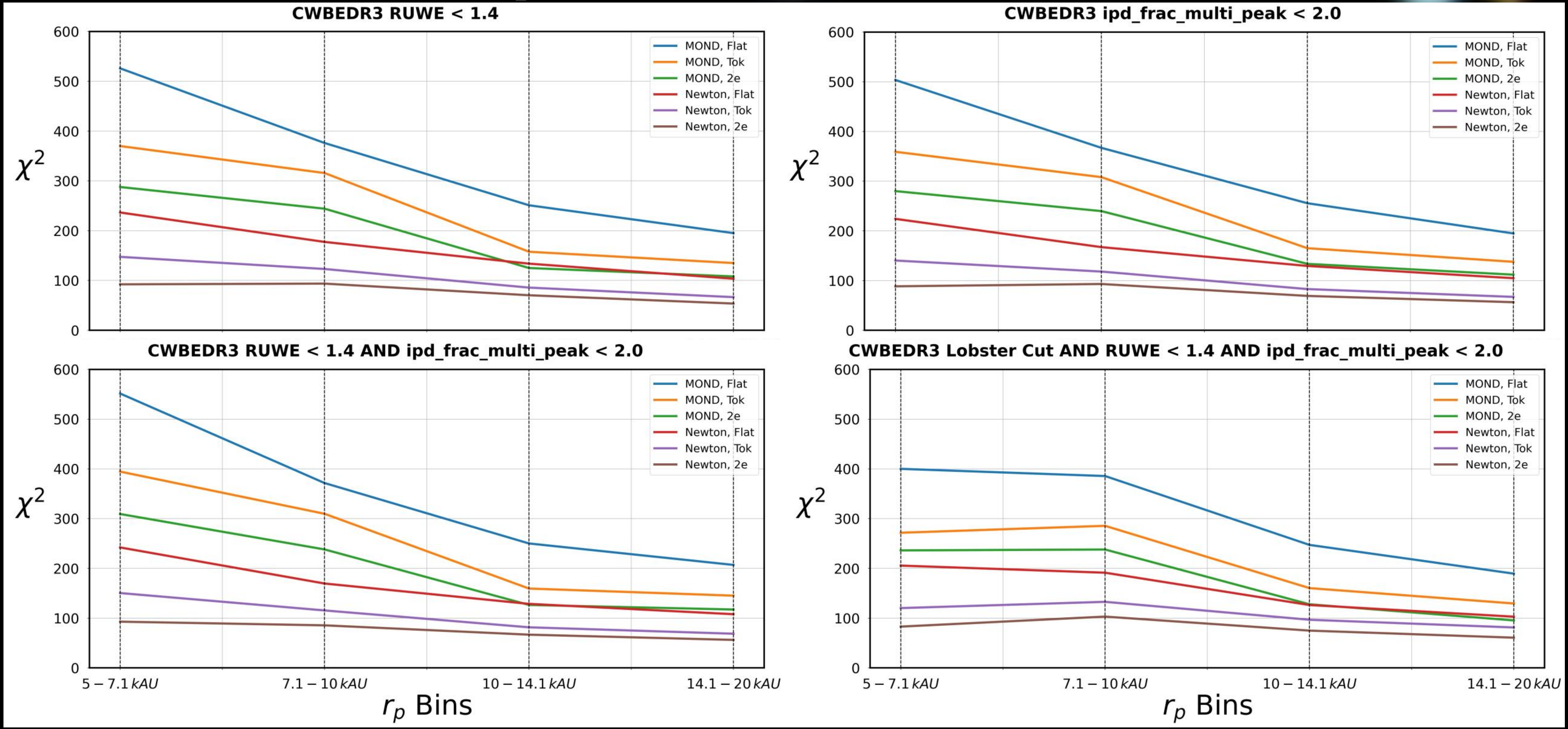
- **RUWE (Renormalised unit weight error) < 1.4**
  - Measure of scatter of individual GAIA observations around the basic 5-parameter fit parallax + uniform propermotion, scaled so the median RUWE is close to 1. Objects with RUWE >1.4 indicative of excess scatter which may indicate a poor fit or marginally resolved close pair.

Ipd_frac_multi_peak < 2.0

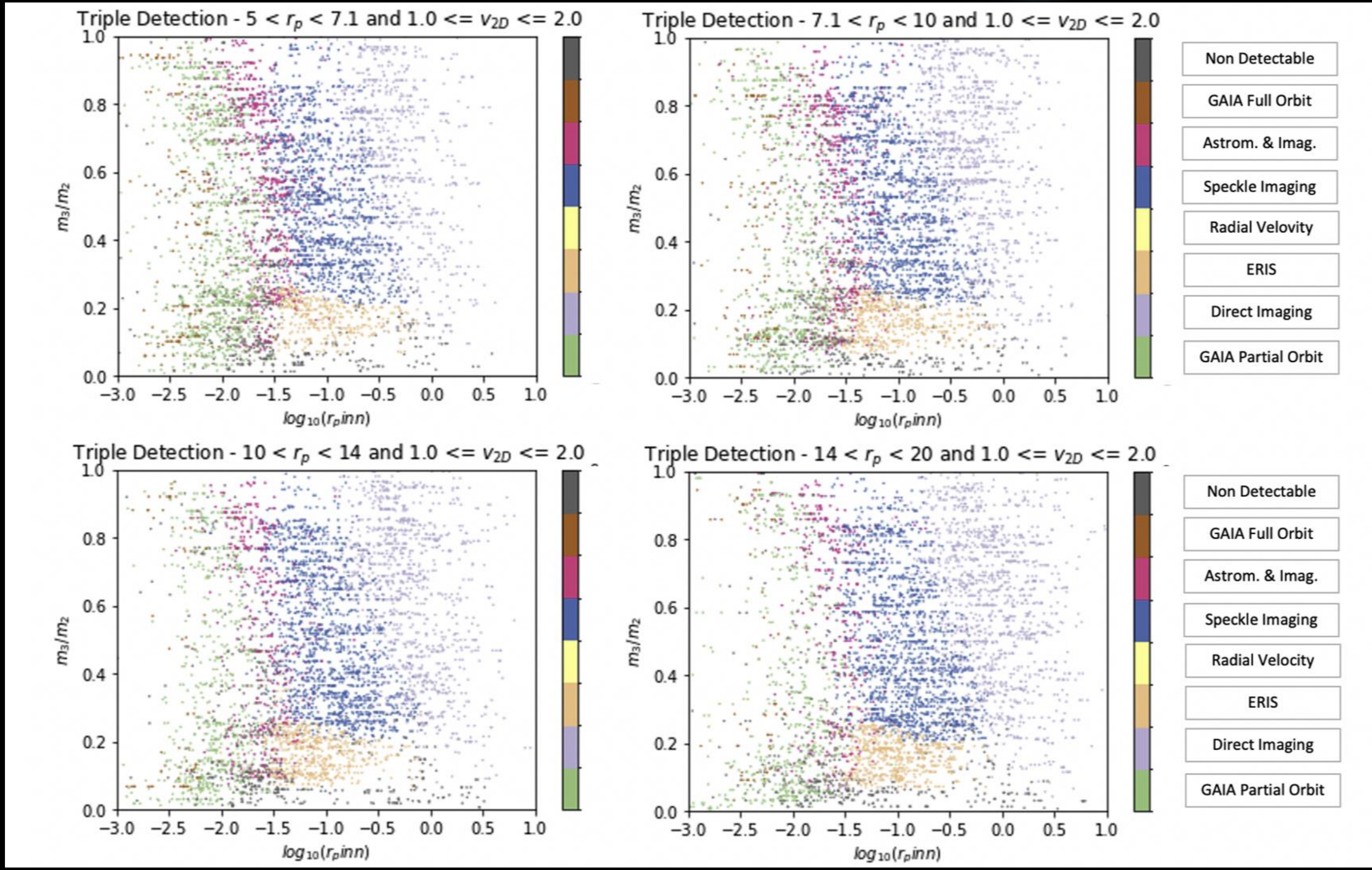
- Percent of successful-IPD windows with more than one peak (byte). This field provides information on the raw windows used for the astrometric processing of this source coming from the Image Parameters Determination (IPD) module in the core processing. It provides the fraction of windows (having a successful IPD result), as percentage (from 0 to 100), for which the IPD algorithm has identified a double peak, meaning that the detection may be a visually resolved double star (either just visual double or real binary). The quantity was computed using all transits where the IPD was successful.

(LEFT) Our Lobster sample with RUWE <1.4 and ipd_frac_multi_peak <2.0 = 27,511 Candidates.

CWB-EDR3 & Results: χ^2 comparison between models



CWB-EDR3 & Results: Detectability of Faint Companions



- Scatter plots of mass ratio M3/M2 (y-axis) vs inner-orbit projected separation (logscale, x-axis) for simulated triple systems, in the slice of observable velocity ratio $0.5<\tilde{v}<2.0$.
- The four panels show four slices in outer-orbit projected separation, as in the legend.
- Points are colour-coded by detectability of the third object, as labelled in the colour-bar:
  - Non-detectable (black)
  - GAIA astrometry
    - brown for period <10yr
    - green for period >10yr
  - Seeing-limited imaging (grey)
  - Speckle imaging (blue)
  - ERIS Coronagraph (orange)
  - Magenta points are detectable by GAIA astrometry and at least one imaging method.

Manchanda,D.,Sutherland,W.,&Pittordis,C.2022,arXiv e-prints,arXiv:2210.07781

Conclusion

- WBs give opportunities for:
  - New test of gravity in extremely low-accel regime, $\boldsymbol{a \leq 1.2 \times 10^{-10}\ ms^{-2}}$
  - Testing Newtonian part of the gravitational field (*i*.e., *time-time* part of the weak-field metric of GR)
  - Complementary to other tests of gravity on all scales.
  - Containing NO significant amount DM.
  - Pure model-independent test of gravity, (Discriminating between DM and MG)
  - Obtain large samples for great statistics
  - $r_p \sim \boldsymbol{5 - 20\ kAU}$ **ideal !** Not prone to too many observational caveats and still obtain a clear MG signal
- Best models contain $f(ecc) = 2ecc$ '*thermal*'' , Preference for Newtonian over MOND
- Future prospects for the WB test of gravity seems very good:
  - Larger samples and more precise measurements from Gaia DR4
  - Improvement for more precise & better understanding of triples (higher-order multiples) and FlyBys populations
    - Chae (arXiv:2305.04613v1) and Hernandez (arXiv:2304.07322) analyse WBs and claim a MOND signal. Main difference is treatment of triples - we need better understanding of triples
  - Observational prospects to detect triples (faint companions) directly via;
    - Deep Sky Surveys
    - Adaptive-Optics
    - Speckle Imaging
  - These will help in understanding higher-order multiple populations, to better clean our WB sample

Thank you all for listening

And get prepared for a more detailed analysis of the WBT straight after this by Indranil Banik ..!!

40 years of MOND

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