# Probing Modified Gravity via Wide Binaries

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# Brief Background

## Problem: Weak-Scale Gravity

Environments where Dark Matter (DM) hypothesis is needed

## GR/Newton

- Best description of gravity
- Works very well and tested with high accuracy on Solar System scales
- Can explain weak-field limit, *i.e., flat rotation curves, large scale structures & CMB*, with the inclusion of DM
- **But**, DM hasn't been directly detected..!!

## Modified Gravity theories

- Against the idea of "Exotic" DM to describe weak-scale effects
- They modify GR eqn's with some extra "stuff" (aka Tensors, Vectors, Scalars)
- Use modification of GR to explain weak-scale gravity
- **But**, difficult to test Modified Gravity..!!

# Probe Weak-scale Gravity via **Wide-Binaries**

## Why **Wide-Binaries**..??

- Wide-binaries (WB) are isolated stellar binary systems with a very large separation ($> 7kAu$); but, still gravitationally bound, can survive up to the Jacobi radius $r \sim 1.7pc$.
- The gravitational acceleration within WB pairs is equivalent to that of a stellar body orbiting the galactic center at a distance $> 8kpc$ *(in DM is dominant regions)*.
- $\sim 80\%$ of stars in Milky Way galaxy are stellar binary systems. WBs have been challenging to select in the past, but WBs can be readily selected with GAIA data.
- There is almost certainly **No** DM in WB systems. Also, they may be tidally disrupted, but if so, they un-bind in few Myr.

## Tidal Disruptions (break in Power-Law)

- Number of WB vs WB separation distribution follows a specific Power-law,
  [Yoo et al, 2003 & Quinn et al 2009]

- Halo MACHOs would disrupt WBs above certain separations, lack of a *'break'* in Power-Law can set upper limits on MACHOs.

- Very Wide WB's ($r > 10^5 Au, \sim$ Jacobi radius) more fragile to disruptions by MACHOs $M \sim 10 M_\odot$.

- (Yoo et al, 2003 & Quinn et al 2009) Sample of WB's, expect break in Power-law with MACHOs $M > 50 M_\odot$.

- *Therefore, MACHOs $M > 50 M_\odot$ "Nearly" Ruled out!*

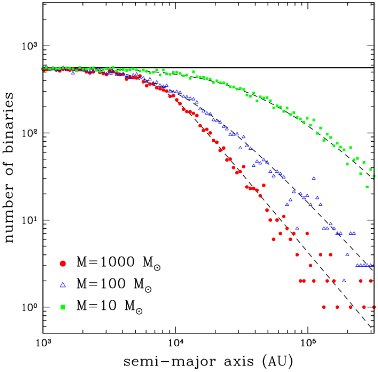



FIG. 2.— Binary distributions as a function of semi-major axis. 100,000 binaries are generated following an arbitrarily chosen flat ($\alpha$=1) distribution represented as a thick solid line. The halo density is set to be $\rho_H$. The squares, triangles and circles represent binary distributions for three different masses of perturber, after $T$ = 10 Gyrs evolution. The fitting curves for each model are shown as dashed lines.

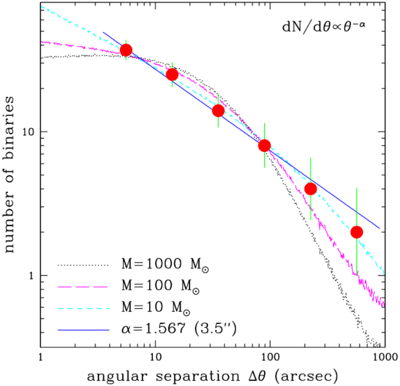



FIG. 5.— The best-fit final binary distributions for various perturber masses, assuming that the initial distribution is a power-law. The halo density is set to be $\rho_H$. The observed halo binary distribution (Fig. 1) is shown for comparison. A model with 1000 $M_\odot$ perturber deviates significantly from the observations while a model with 10 $M_\odot$ is quite consistent with them.

(*End of the MACHO Era*, Yoo et al, 2003)

# Testing Gravity with WB

## How we probe Gravity

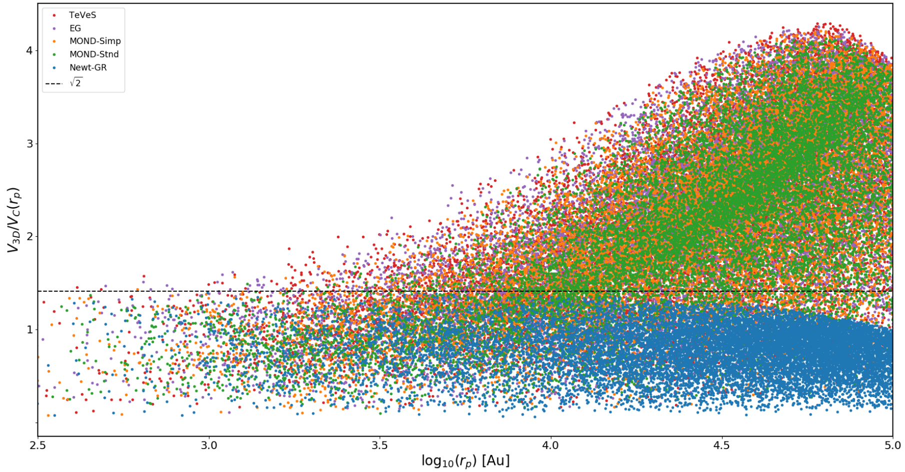
- Compare with weak-field limit between GR/Newton and popular Modified Gravity Theories.,
  (e.g. MOND, TeVeS, Emergent Gravity and MOND + External Field Effect (EFE))
- Produce simulations and integrate WB orbits for each theory
- Compute their observables, *(i.e., Relative Velocity vs Projected Radius )*
- Model the predicted distributions for the on-going GAIA mission and future ESO's 4MOST.

# Observables

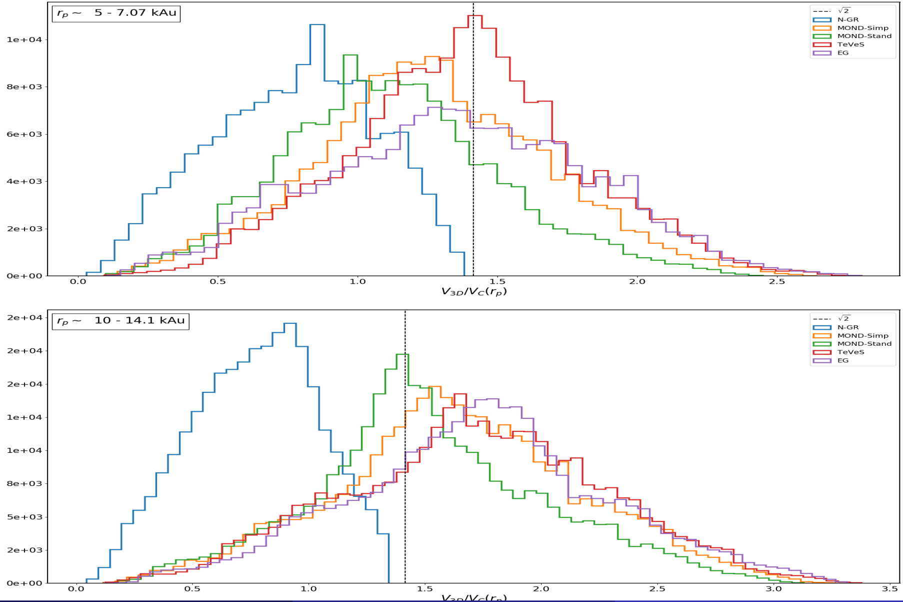
- GAIA gives projected separation and transverse velocity difference.
- Ground-based telescopes give radial velocity difference
- Have 5/6 components (missing one is the line-of-sight separation of the stellar pair)
- Can estimate masses from distance, colour, spectra
- Convenient to 'scale' by circular velocity at $r_p$, $V_C(r_p)$, $V_C(r_p) > V_C(r_{true})$, so $\frac{V_{3D}}{V_C(r_p)} \leq \frac{V_{3D}}{V_C(r_{true})}$
- $\frac{V_{3D}}{V_C(r_p)} \leq \sqrt{2}$ for Keplerian orbits.
- Distribution depends on (unknown) distribution of eccentricities, but not very strongly.
- Model the eccentricity, $(e)$ distribution using (Tokovinin & Kiyaeva 2015), (flat or $f(e) = 1.2e + 0.4$)
- Simulate orbits, (observe) at random phase & alignment.

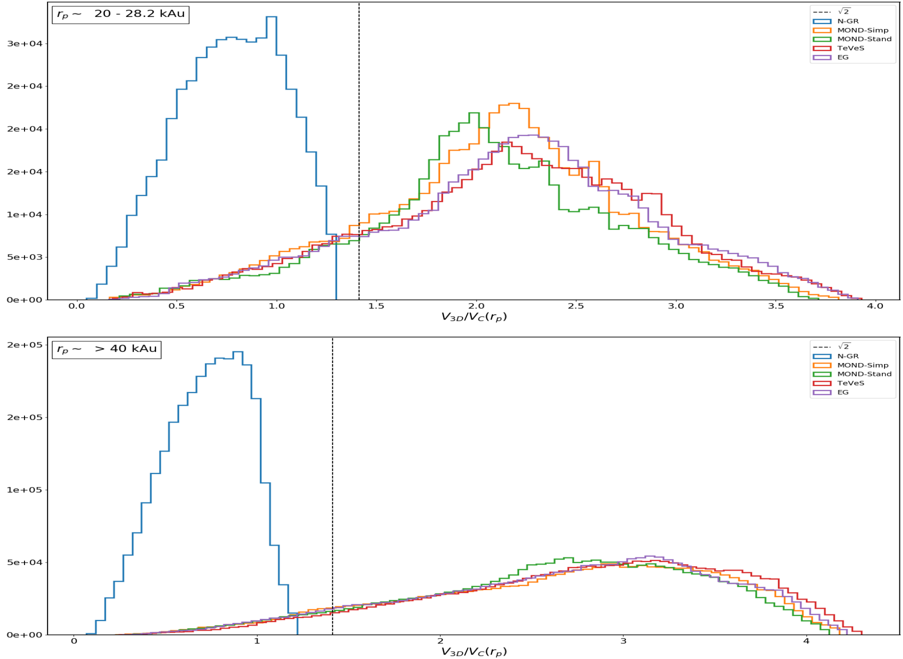
# Relative Velocity, $(\frac{V_{3D}}{V_C(r_p)})$ vs Projected Radius $r_p$

*GR, TeVeS, MOND and EG*



# Histograms at various $r_p$, *GR, TeVeS, MOND, EG*

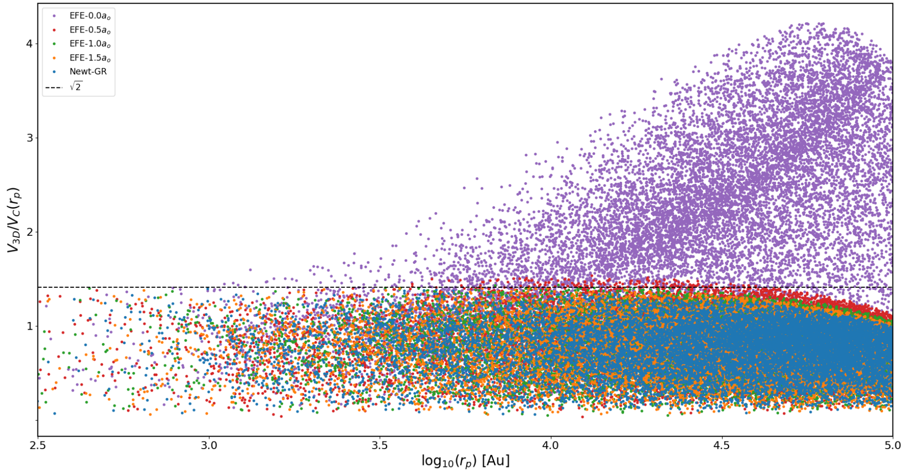




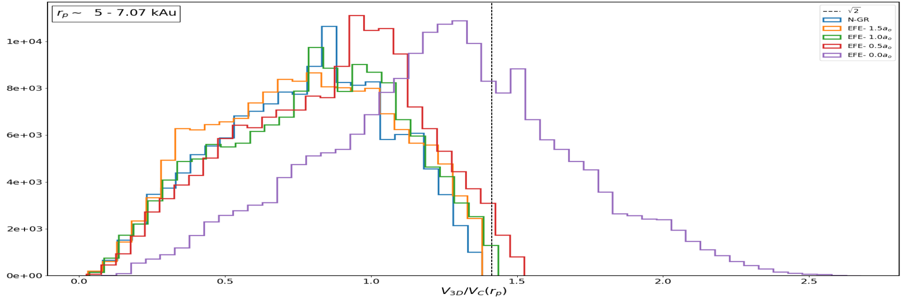
$r_p \sim$ 20 - 28.2 kAu
$\sqrt{2}$
N-GR
MOND-Simp
MOND-Stand
TeVeS
EG
0e+00
5e+03
1e+04
2e+04
2e+04
2e+04
3e+04
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
$V_{3D}/V_C(r_p)$
$r_p \sim$ > 40 kAu
$\sqrt{2}$
N-GR
MOND-Simp
MOND-Stand
TeVeS
EG
0e+00
5e+04
1e+05
2e+05
2e+05
0
1
2
3
4
$V_{3D}/V_C(r_p)$

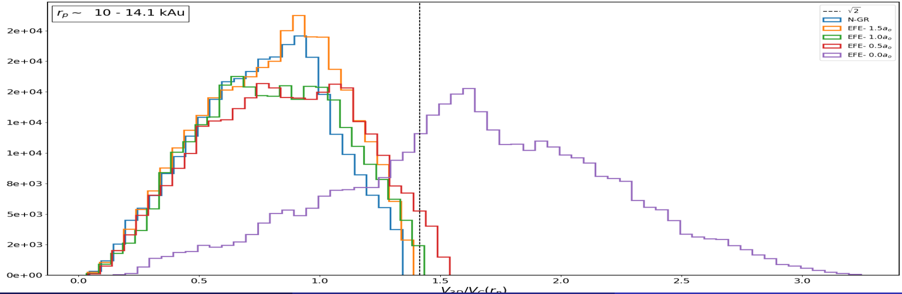
# Relative Velocity, $(\frac{V_{3D}}{V_C(r_p)})$ vs Projected Radius $r_p$

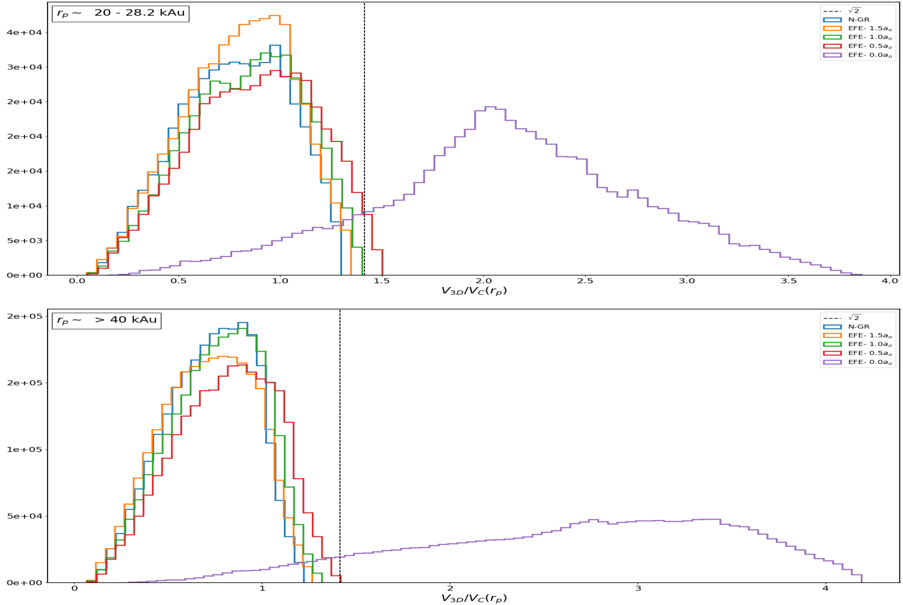
## *GR and EFE*$\sim [0, 0.5, 1, 1.5]a_o$



# Histograms at various $r_p$, $GR$ & $EFE \sim (0, 0.5, 1, 1.5)a_o$






*'Tricky' part, due to the Solar neighbourhood EFE$\sim 1.5a_o$*

# Table of 90% of EFE$\sim (0.5, 1, 1.5)a_o$ & N-GR

90%ile of $\mathbf{V_{3D}}/\mathbf{V_C}(\mathbf{r_p})$ at various slices of $\mathbf{r_p}$.

| **Grav-Model** | $5-7$ **kAu** | $10-14.1$ **kAu** | $20-28.2$ **kAu** | $>40$ **kAu** |
|---|---|---|---|---|
| **N-GR** | 1.1554 | 1.1286 | 1.1256 | 1.008 |
| **EFE-1.5**$a_o$ | 1.1925 | 1.1791 | 1.1372 | 1.0288 |
| **EFE-1.0**$a_o$ | 1.1962 | 1.1979 | 1.1942 | 1.0674 |
| **EFE-0.5**$a_o$ | 1.2537 | 1.2672 | 1.2745 | 1.1422 |

# Conclusion

- WB are good probes for Modified Gravity (especially in the weak-field limit) due to:
  - Not being tidally disrupted by other gravitating sources, even DM.
  - There is No DM present within the WB system, just two stars orbiting.
  - WB have gravitational accelerations ($a \leq a_o = 1.2x10^{-10} ms^{-2}$).

- $EFE << a_o$ results in large differences in observables.
- $EFE \sim 1.5 a_o$ makes differences a lot smaller; but still potentially observable.
- We have made predictions for missions such as GAIA and ESO's 4MOST
  (telescopes that can observe relative motions $\sim 10^{-1} kms^{-1}$).

Thank you for listening