Gaia and the dark matter vs. modified gravity controversy

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Introduction

- Fragile dynamical structures in the Galaxy can be used to test whether they follow Newtonian gravity or whether they are better described by modified gravity theories

- Examples of such structures are:

  - -The outer parts of globular clusters
    - 1. Radial velocity dispersion profiles
    - 2. Density profiles
    - 3. Extratidal features

  - -Wide disk binaries (believed to be the result of dissolved clusters)
  - -Wide halo binaries (remains of moving clusters or accreted structures)

Generic modified gravity predictions

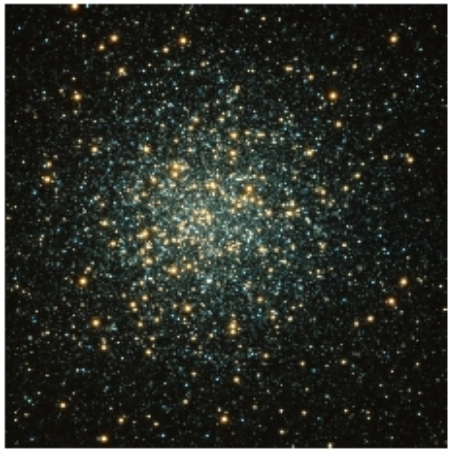
1) All $a > a_0$ systems in the low velocity regime should appear as purely Newtonian, without requiring any dark matter.
-Indeed, no counterexamples to this prediction exist.

2) All $a < a_0$ systems in the low velocity regime should appear as purely "MONDian", requiring substantial dark matter if interpreted under Newtonian Gravity.
-All known "dark matter" presenting systems neatly fall into this category.
-A definitive prediction appears for the outskirts of globular clusters and wide binaries

3) In the $a < a_0$ regime, equilibrium velocities become flat, with systems exhibiting a "Tully-Fisher" relation for $V_{MG}^2 \propto (MGa_0)^{1/2}$

X. Hernandez (2012), Entropy, 14, 484

Surprising New GC Results:



Total masses $\sim 10^5 - 10^6 M_\odot$
Half mass radii $\sim 20pc$

Up to now, with stellar velocity dispersion profiles measured towards the core regions, well modelled as purely Newtonian equilibrium strictures, without any Dark Matter.

Astronomy & Astrophysics manuscript no. ms revised2
August 23, 2010

Testing Newtonian gravity with distant globular clusters: NGC1851 and NGC1904*

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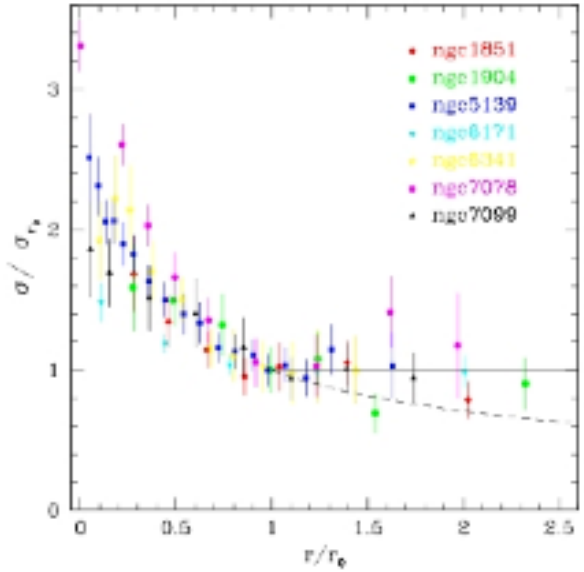
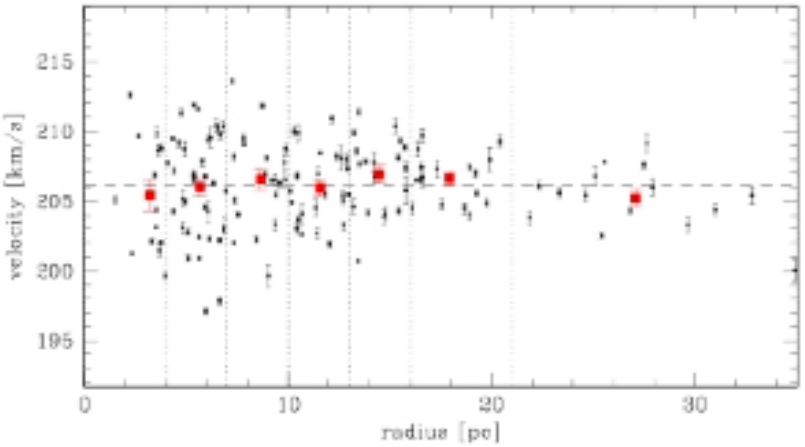
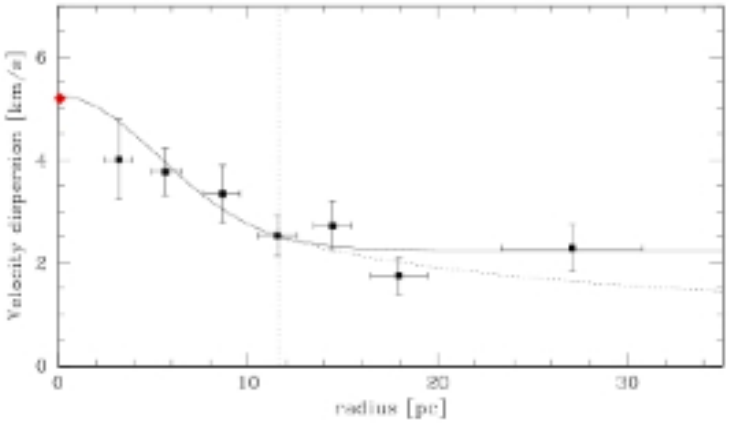
August 23, 2010





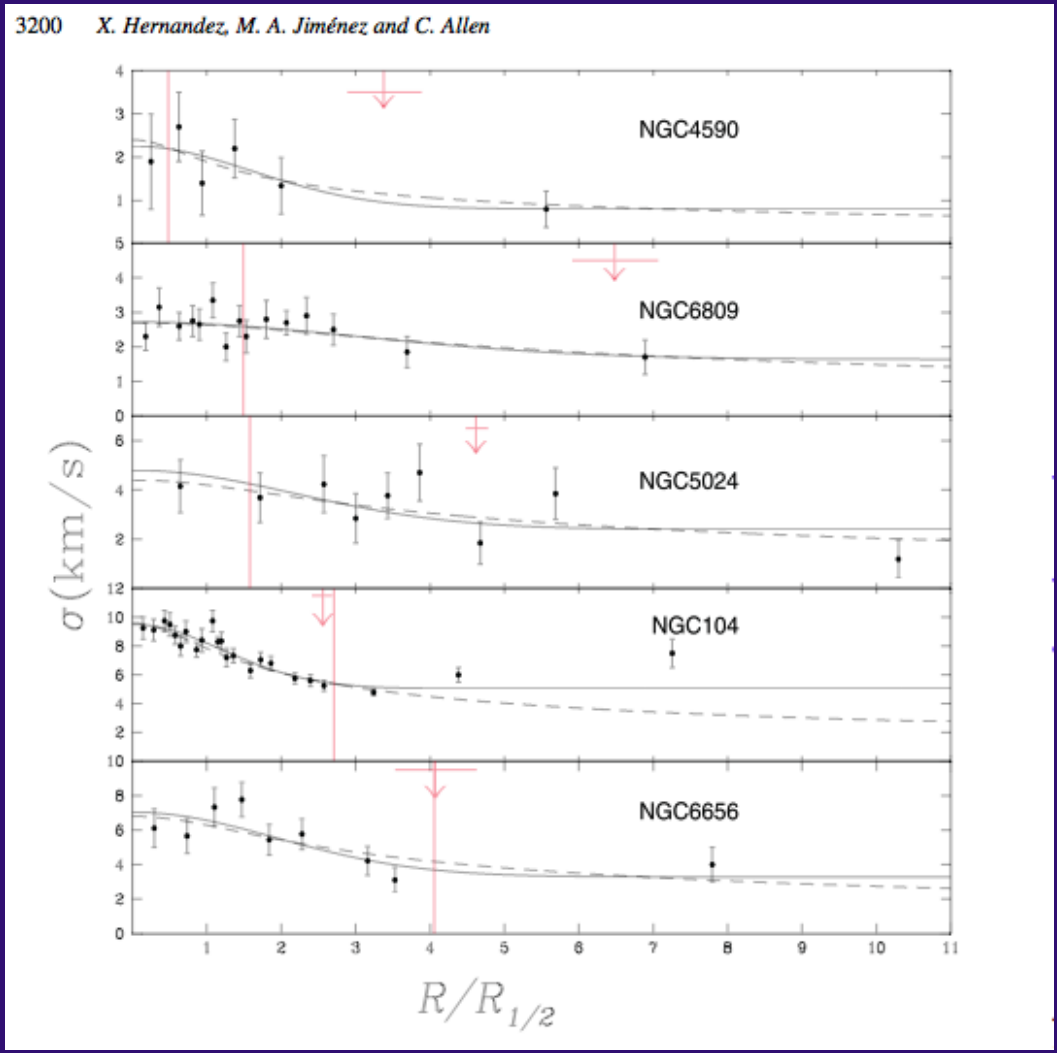


- Hernandez, X. & Jimenez, M.A. (2012 ApJ 750, 9) modeled the structure of GC fully in the MONDian regime

- Hernandez, Jimenez & Allen (MNRAS 428, 3196) studied 16 GC, (Scarpa + Lane) modeling radial velocity dispersion profiles empirically.

- Individual masses were determined from brightness profiles and stellar population modeling, i.e, non-dynamically

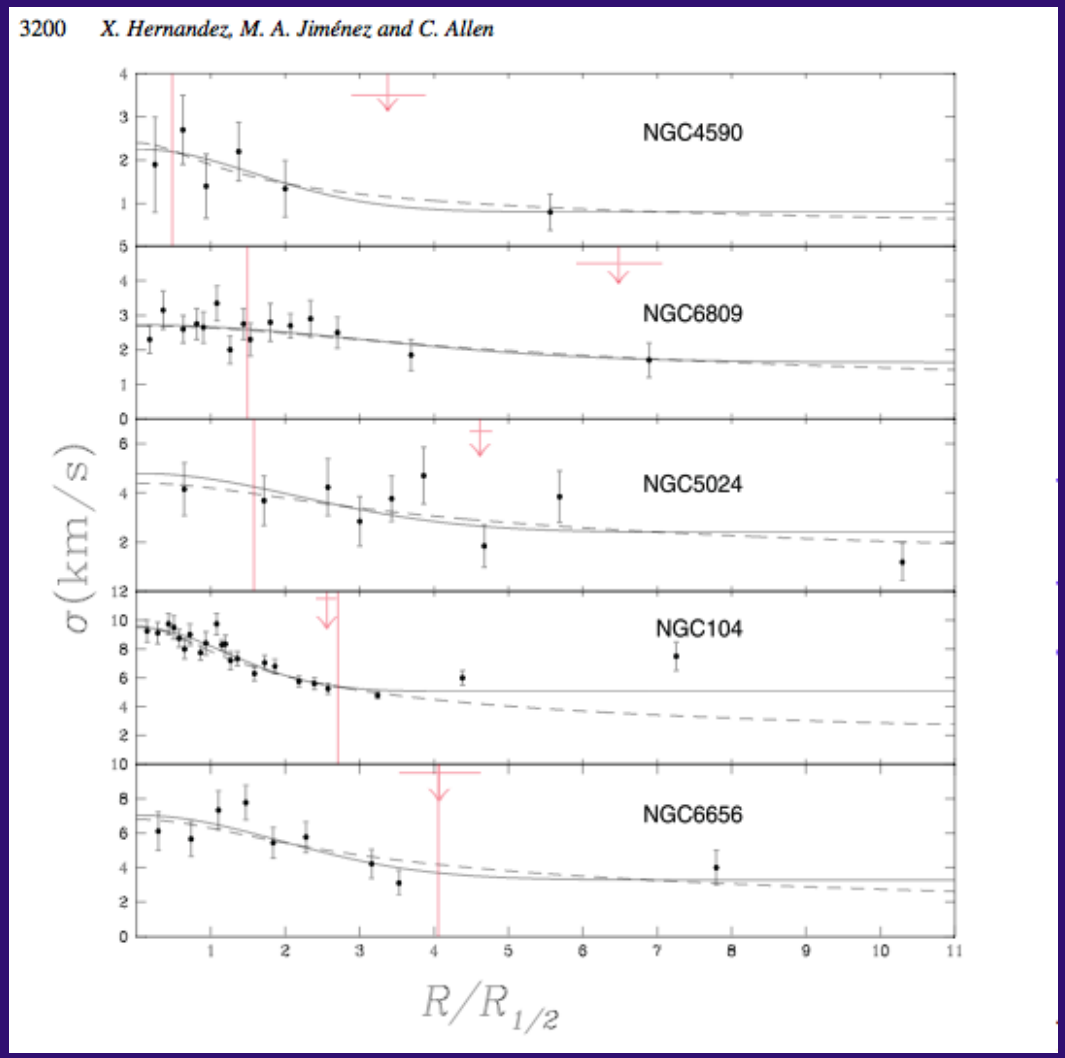
- A good fit to the theoretical MONDian profiles was found
  -notice particularly the flattening outside the critical acceleration a_0



R_a defined trough
$\sigma(R_a)^2/R_a = a_0$ condition

R_f defined trough
$\sigma(R_f) = 0.1\sigma_1 + \sigma_\infty$ condition

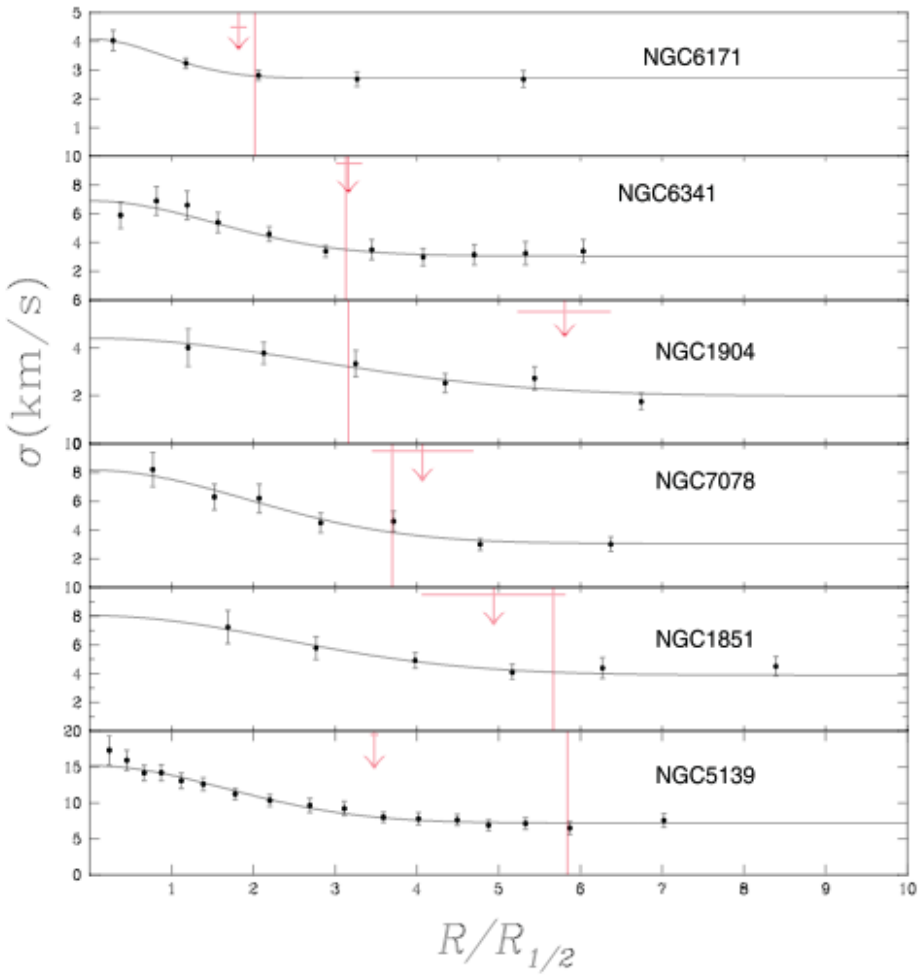
$\sigma(R)$ flattens on crossing a_0,



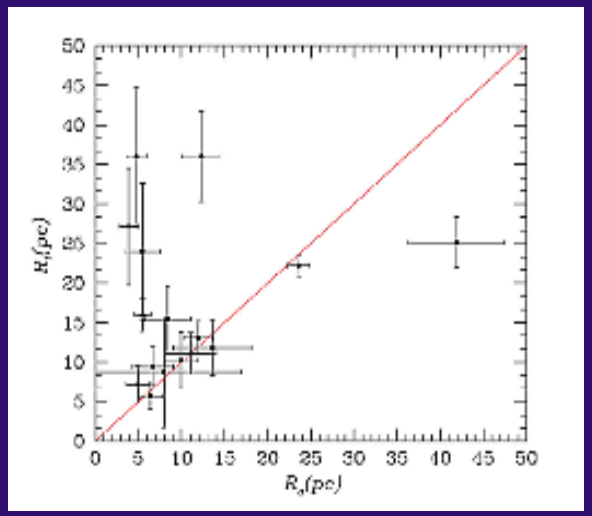
R_a defined through the $\sigma(R_a)^2/R_a = a_0$ condition

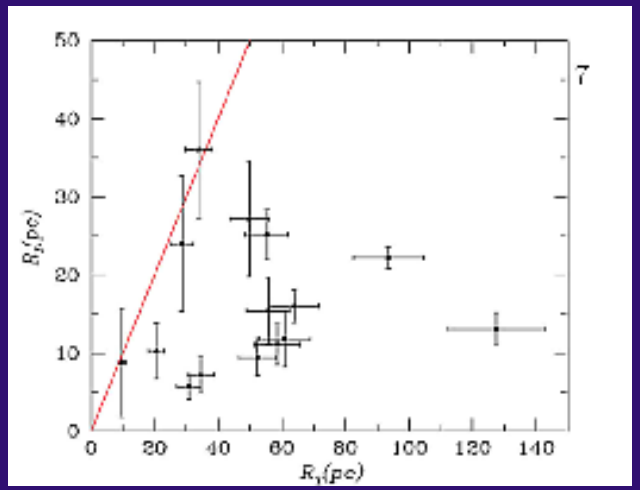
Newtonian R_T carefully calculated using CMD stellar mass estimates and standard Galactic dynamical modelling

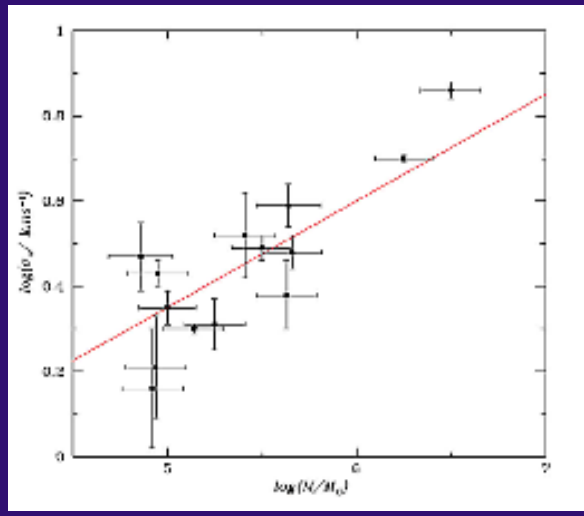
$\sigma(R)$ flattens on crossing R_a, in spite of average $4 < R_T/R_f < 10$


NGC6171
NGC6341
NGC1904
NGC7078
NGC1851
NGC5139
σ(km/s)
R/R1/2

GC conclusions







Flattening of the velocity dispersion profile closely coincides with $a = a_0$ threshold

Using total masses from detailed stellar population modelling tuned to each individual GC, Even at perigalacticon, all the GC in the sample are smaller than their Newtonian tidal radii.

σ vs. Mass relation compatible with expected "Tully-Fisher" a_0 relation.

Density profiles of trace populations

-Under MONDian dynamics isothermal distribution of trace particles will follow naturally a density profile rho $=k\ r^{-3}$

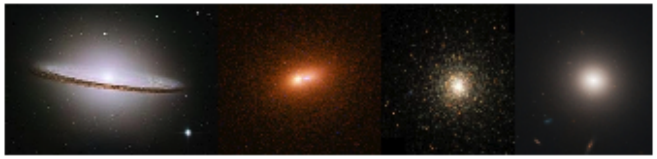
-This implies a surface density profile sigma $= k\ r^{-2}$

-Such profiles are fairly ubiquitous

-Under Newtonian dynamics a particular explanation for each system has to be invoked

(Hernandez, X., Jimenez, M.A, & Allen, C. 2013, ApJ 770, 83

Density profiles of trace populations



$\rho(r) = \rho_0 (r_0/r)^3$, $\Sigma(R) = \frac{\pi \rho_0 r_0^3}{2R^2}$ profiles are relevant because:

For the stellar halo of the Milky Way:
Morrison et al. (2000) find $\rho(r) \propto r^{-3}$, Juric et al. (2008) report $\rho(r) \propto r^{-2.8\pm0.3}$, Bell et al. (2008) $\rho(r) \propto r^{-3}$ for the preferred single power law model and Sesar et al. (2011) a best fit single power law of $\rho(r) \propto r^{-2.9}$.

For the stellar halo of Andromeda:
Ibata et al. (2007) obtain $\Sigma(R) \propto R^{-1.91\pm0.12}$, Tanaka et al. (2010) $\Sigma(R) \propto R^{-2.17\pm0.15}$, and Gilbert et al. (2012) measure $\Sigma(R) \propto R^{-2.2\pm0.2}$ out to 175 kpc, coming to $\Sigma(R) \propto R^{-2.0\pm0.5}$ for $20kpc < R < 90kpc$.
In going to larger samples, Zibetti et al. (2004) showed through the stacking of images from 1047 edge-on spiral galaxies from the SDSS, that these very generally present extended tenuous stellar halos well described by $\rho(r) \propto r^{-3}$.

For the globular cluster systems of the Milky Way and Andromeda:
Bica et al. (2006) find the metal rich population follow $\rho(r) \propto r^{-3.2\pm0.2}$ for large radii, and $\rho(r) \propto r^{-3.2\pm0.9}$ if one conciders oblateness. For the globular cluster system of M31 Racine (1991) determined $\Sigma(R) \propto R^{-2}$.

Disk wide binaries as a critical test of classical 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.

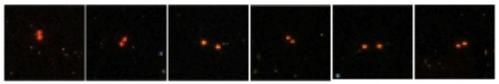
Which scaling will wide binaries show?

$$\Delta V_N = 2\left(\frac{GM}{s}\right)^{1/2} \quad or \quad \Delta V_{MG} = 2(Ga_0M)^{1/4} \ ?$$

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

Hernandez, Jimenez & Allen, Europ. Phys. J. C. 2012, 72, 1884

Newtonian prediction for wide binary samples



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

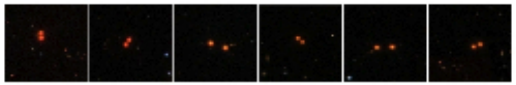
- Orbits will present a distribution of ellipticities, leading, at fixed s and projection, to a spread of values in ΔV_N ranging below $\sqrt{2}$ times the circular orbit values.

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

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 (ΔV_N vs. s) distributions, after 10 Gyr of evolution, and after projecting on the plane of the sky.

Newtonian prediction for wide binary samples



Predicted projected RMS 1D ΔV vs. s relation.

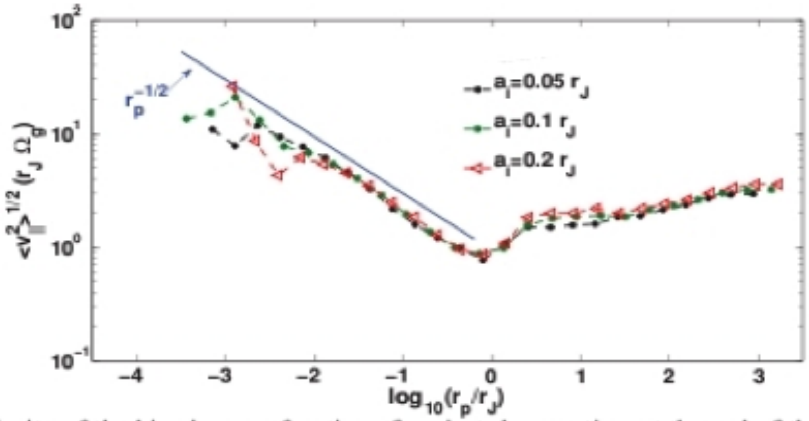


Figure 7. RMS line-of-sight relative velocity of the binaries as a function of projected separation, at the end of the simulations. The horizont projected separation normal to a randomly chosen line of sight, while the vertical axis is the rms line-of-sight relative velocity in each separ Keplerian motion 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.

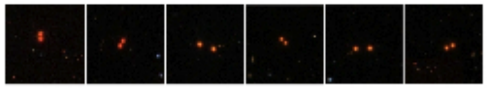
- Mostly, disruption occurs for $s > r_J$, the tidal radius of the problem.

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

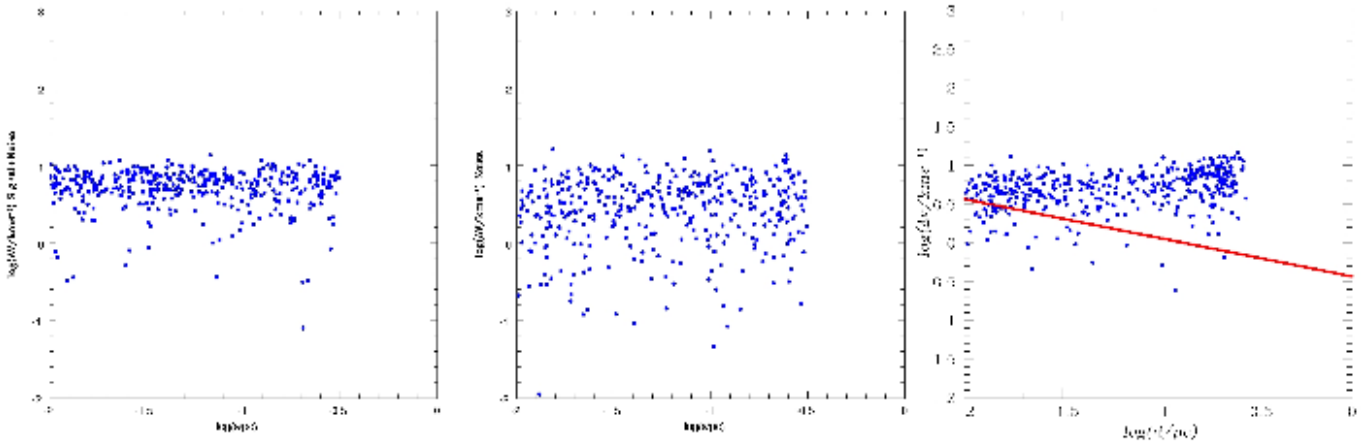
- Unbound stars continue to drift along very similar orbits and will show up in observational samples.

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

Wide binary catalogues -1) SDSS



From a catalogue of 1250 carefully selected wide binaries we obtain relative velocities on the plane of the sky and projected separations, average S/N=0.5.

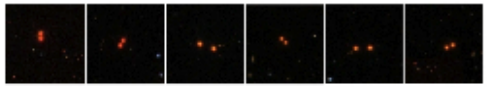


- The upper envelope clearly defines a horizontal line, showing the "flat rotation curve" of modified gravity, and not the Kepplerian decline of Newtonian gravity.

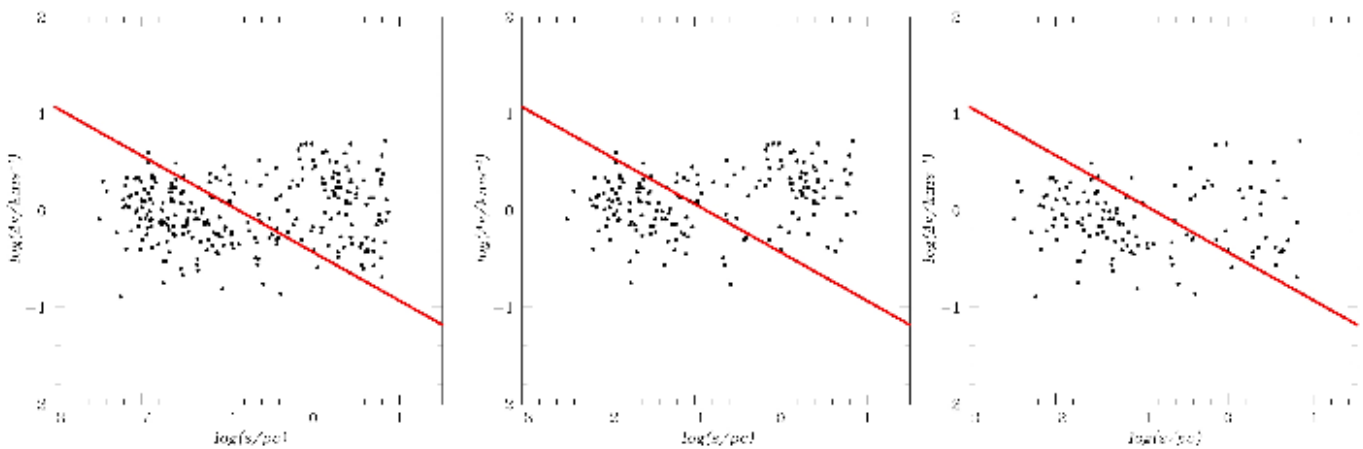
- It can be shown that results are not driven by errors or catalogue selection cuts.

Dhital et al. (2010) AJ, 139, 2566

Wide binary catalogues -2) *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.



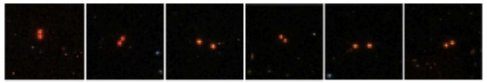
- The upper envelope clearly defines a horizontal line, showing the "flat rotation curve" of modified gravity, and not the Kepplerian decline of Newtonian gravity.

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

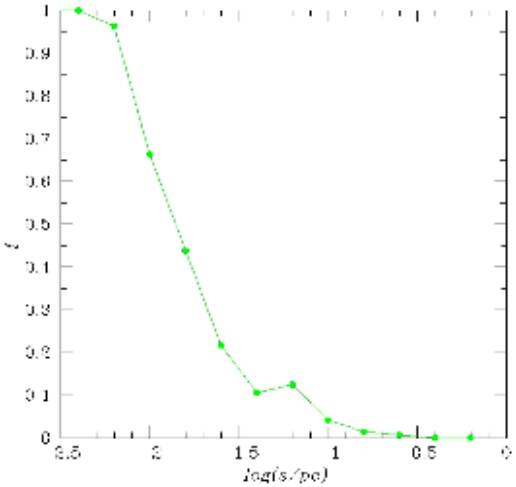
-The data show no feature of any kind on crossing the Newtonian tidal radius at 1.7pc.

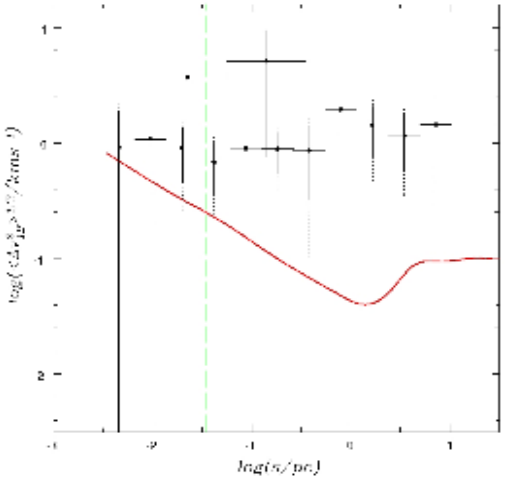
E. J. Shaya & R. P. Olling (2011), ApJS, 192, 2

Wide Binary conclusions



Quantitative comparison with full Newtonian prediction:





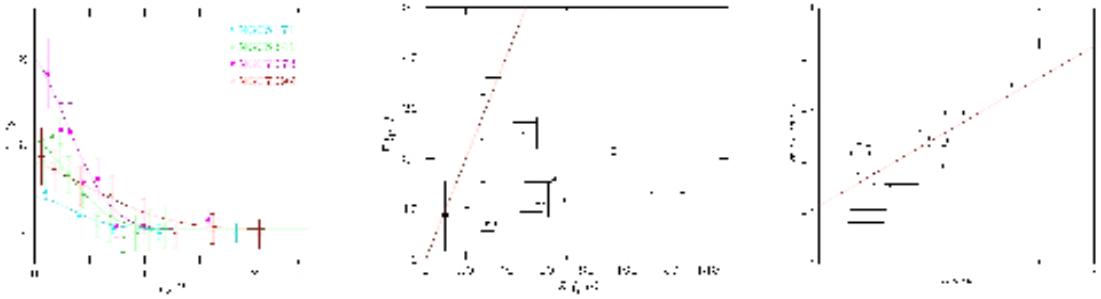
- The trends shown by the data are clearly defining the modified gravity phenomenology, Newtonian Gravity is only consistent with the data with a probability $< 3 \times 10^{-5}$.

- The two completely independent catalogues yield fully consistent results.

- The data rule out the Newtonian model at a 4σ level.

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

Outer velocity dispersions of globular clusters become flat and show the same galactic $\sigma \propto M^{1/4}$ TF scaling



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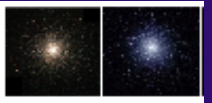
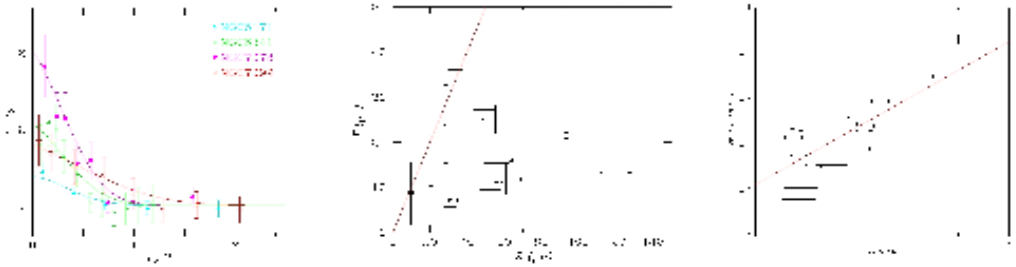
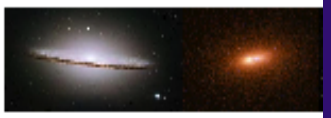
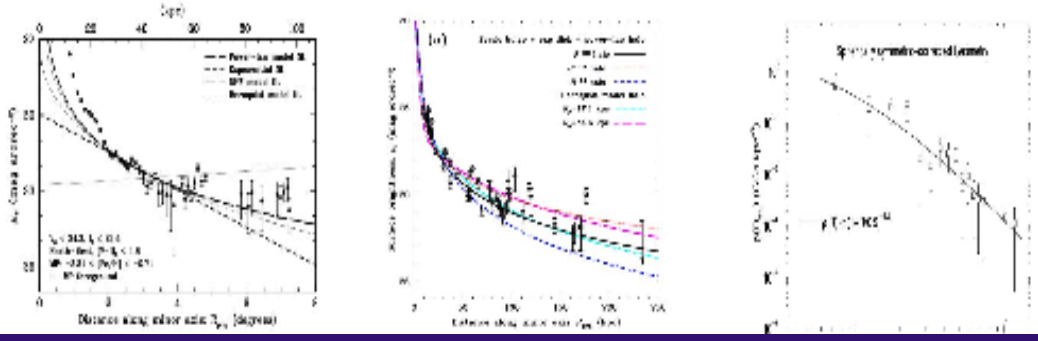




The density profile of tenuous tracer populations matches observed scalings across astrophysical systems





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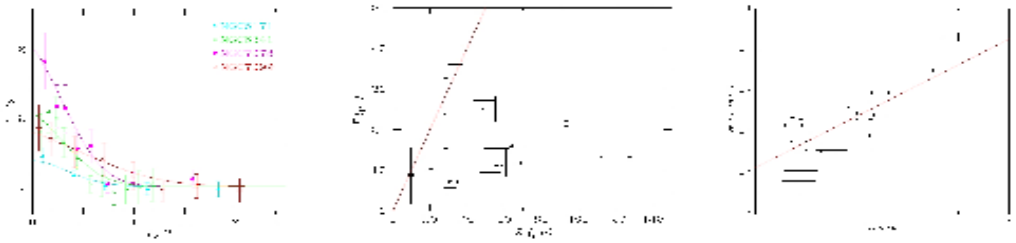

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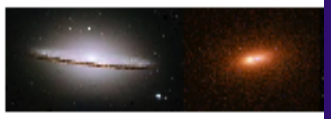
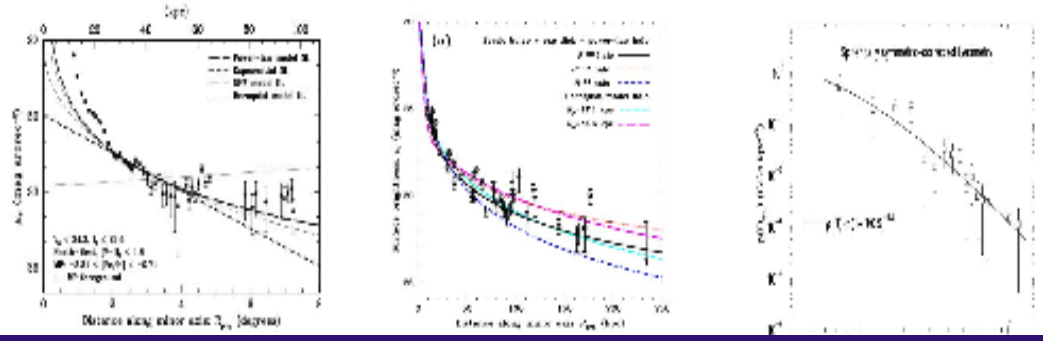
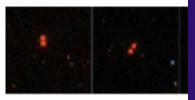
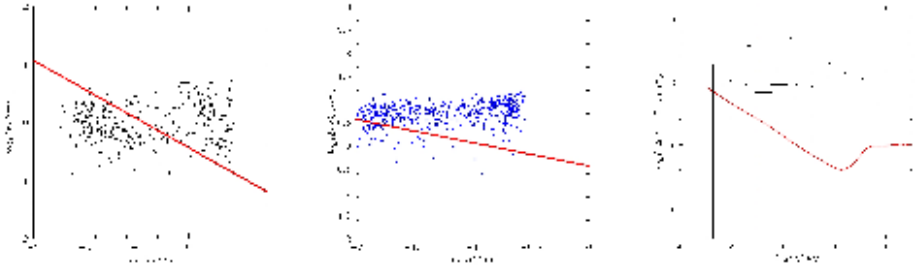


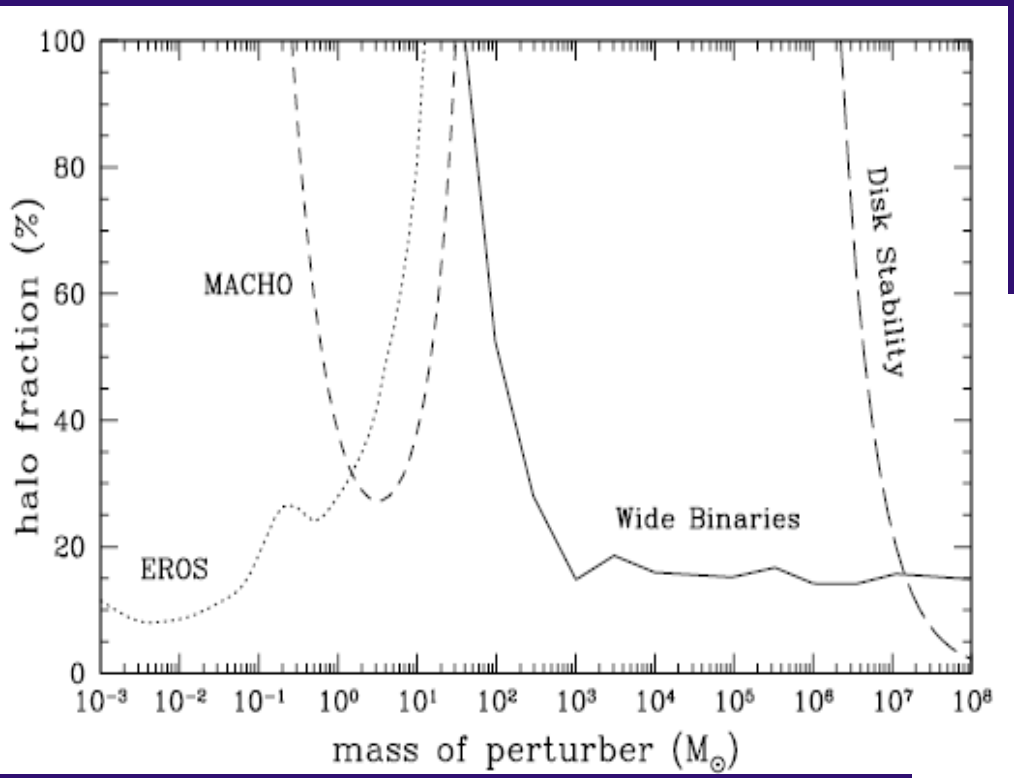


The relative velocities of observed Wide binaries are inconsistent with Newtonian Gravity and GR

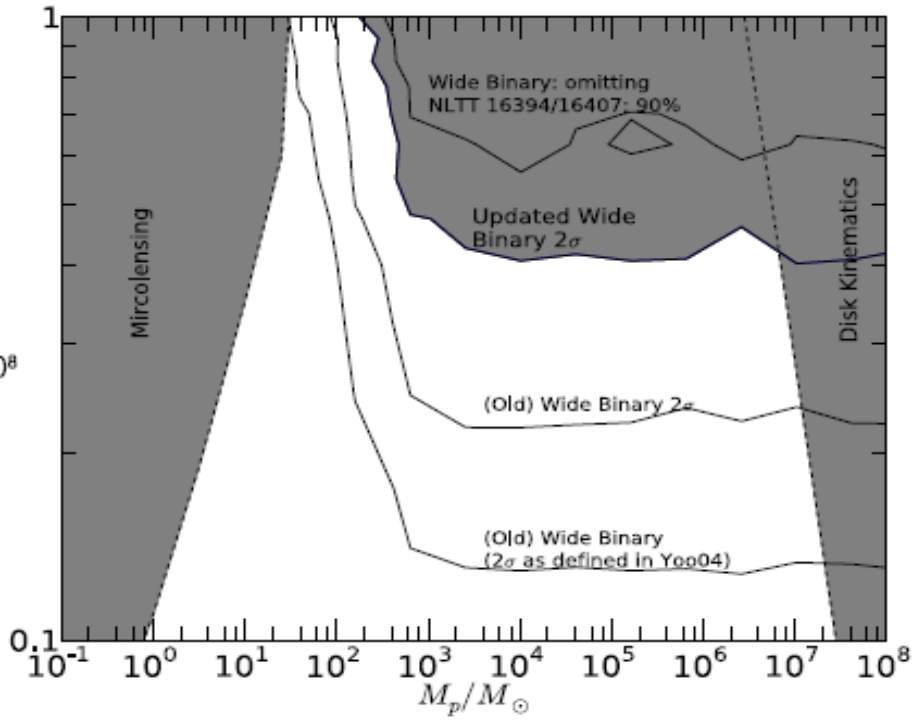




Halo wide binaries
– The end of the MACHO era?



Previous results:
Yoo et al. (M = 43 Mo)



Quinn et al. (M=300-500 Mo)

The widest halo binaries

-Are they physical? Radial velocities are needed

-Quinn et al. 2009 obtained radial velocities for 4 of the widest binaries in ChG04, confirming physical nature for 3 of them

-Excluding the optical pair, but assuming a power law distribution for the separations, they find limits for MACHO masses

$$30\ M_\odot < m < 500\ M_\odot$$

-Clearly, results are very sensitive to the largest separations

Main results from the new catalog

- We have compiled a list of 252 candidate halo wide binaries

- The distribution of separations and major semi-axes for all the subgroups appears to be Oepik´s, i.e. alpha = -1 up to different limiting semiaxes

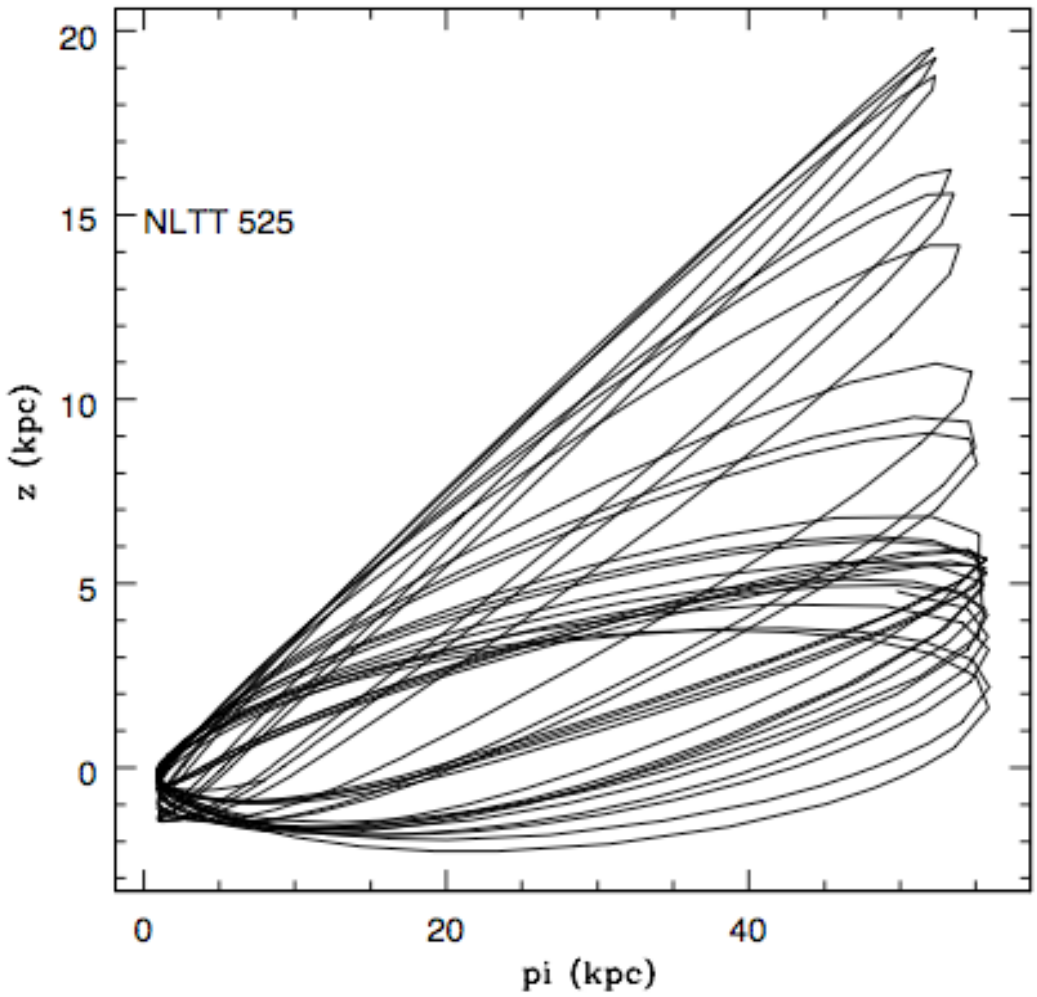
- We have obtained galactic orbits for 150 binaries and computed times spent within galactic disk

- Separating the binaries into three groups: most disk-like, intermediate, and most halo-like, we obtain Oepik´s distribution up to semiaxes:

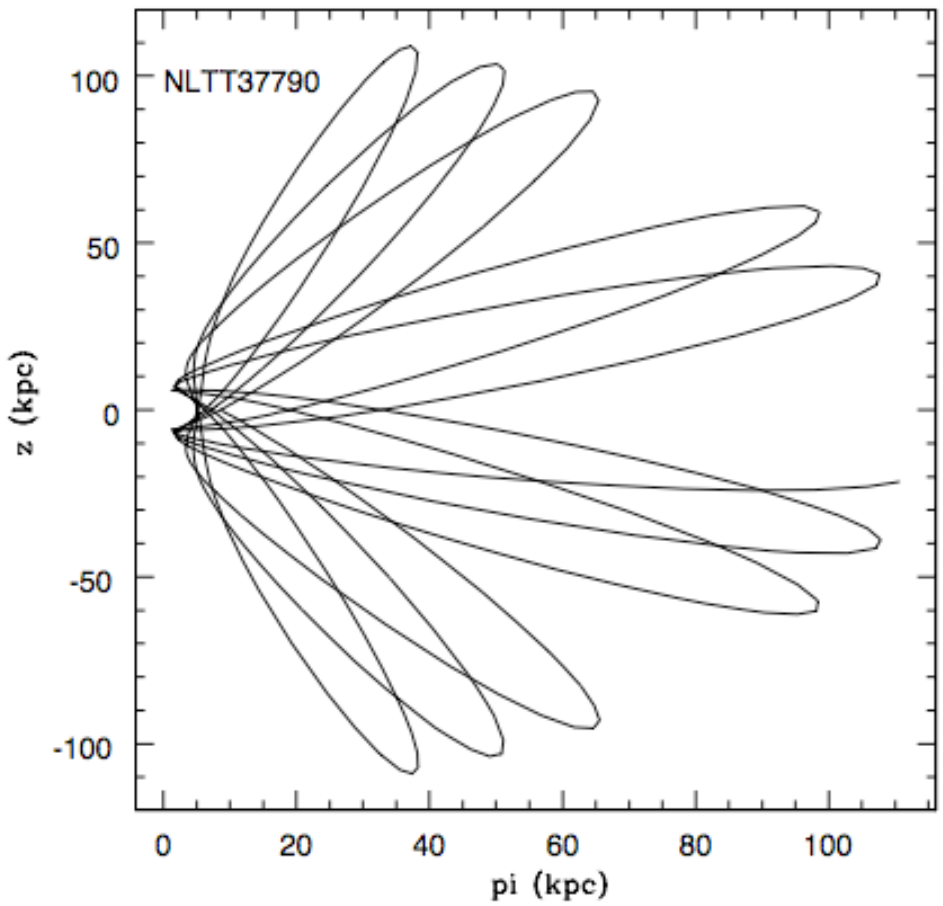
- <a> = 10,000 AU for the group of 50 most disk-like binaries (<Td/T >= 1)
- <a> = 63,000 AU for the 50 most halo-like binaries (<Td/T> = 0.18)

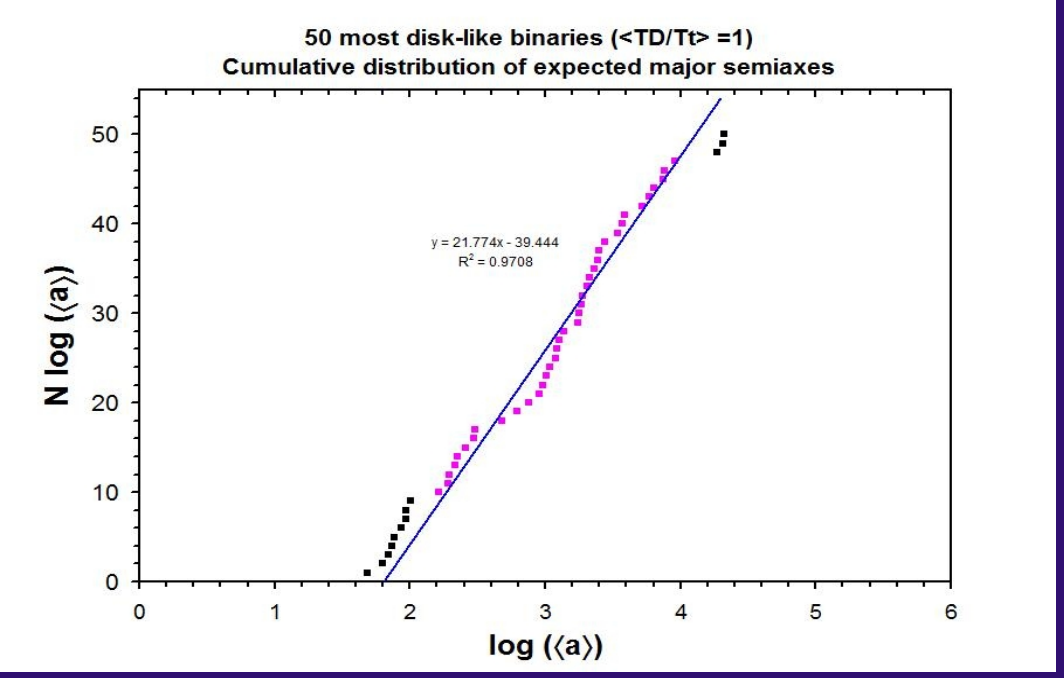
Allen & Monroy-Rodríguez, 2013 ApJ (in press)

Meridional galactic orbit of NLTT 525
T**d**/T**t** = 0.157



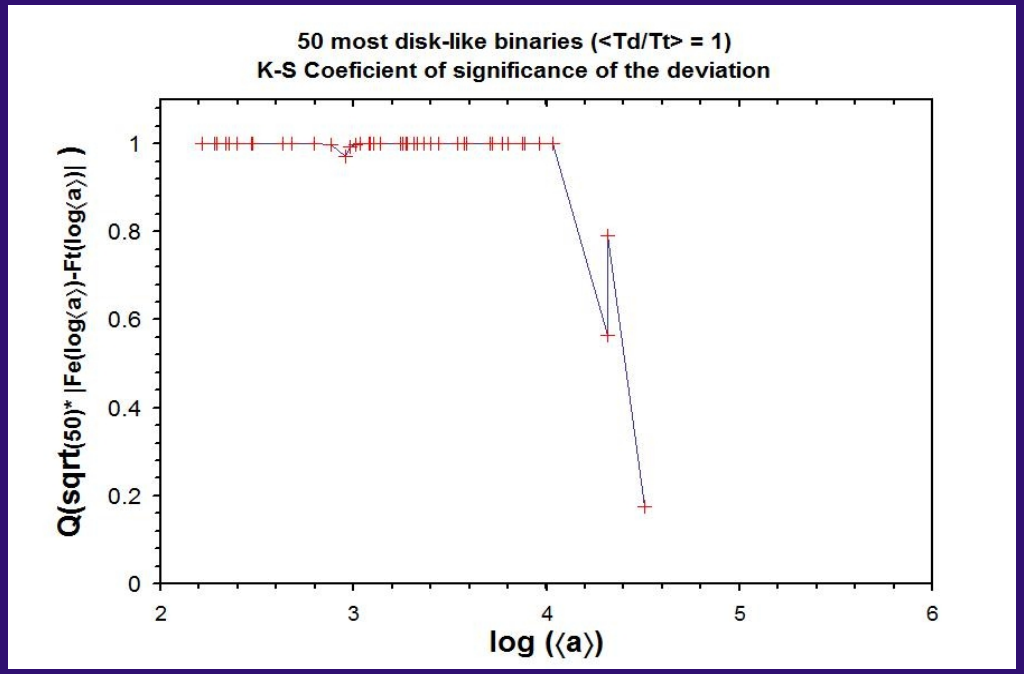
Meridional galactic orbit of NLTT 37790
Td/Tt = 0.003

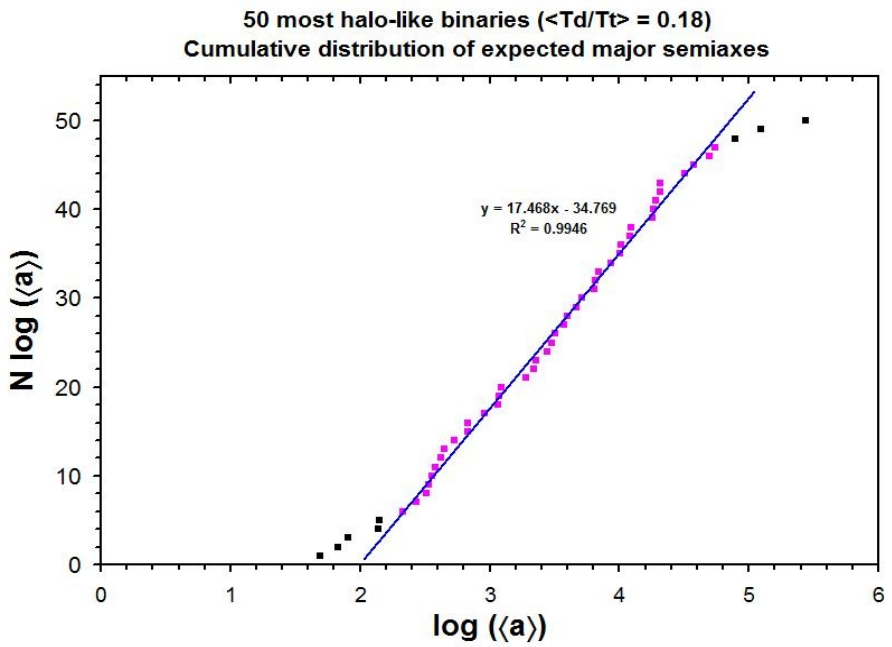




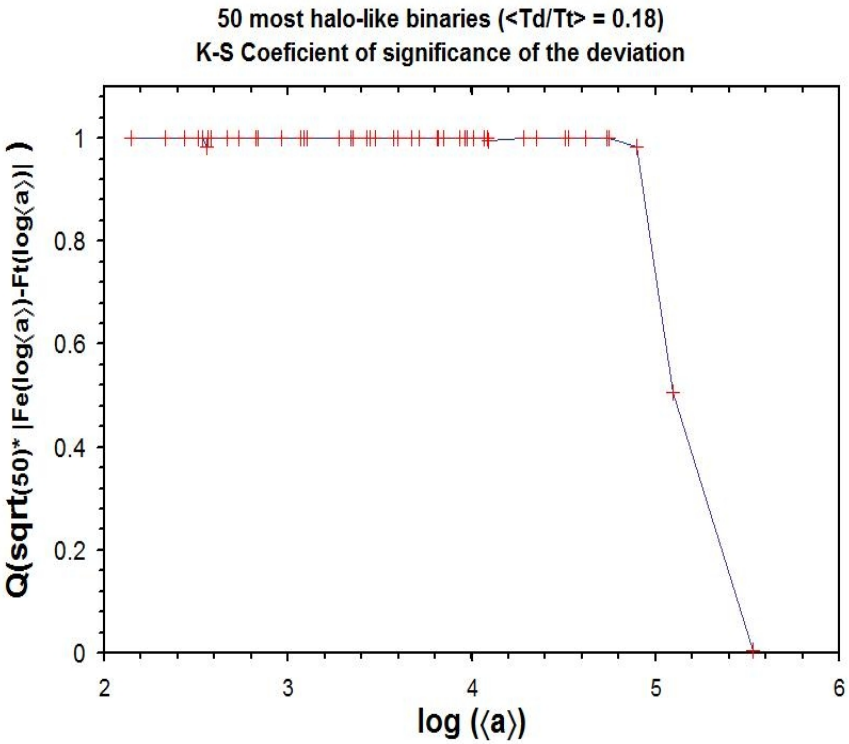
50 most disk-like binaries

<a> = 10,000 AU





50 most halo-like binaries



<a> = 63,000 AU
<Td/T> = 0.18

Dynamical model

- We follow closely the Monte Carlo procedure of Yoo et al (2004)

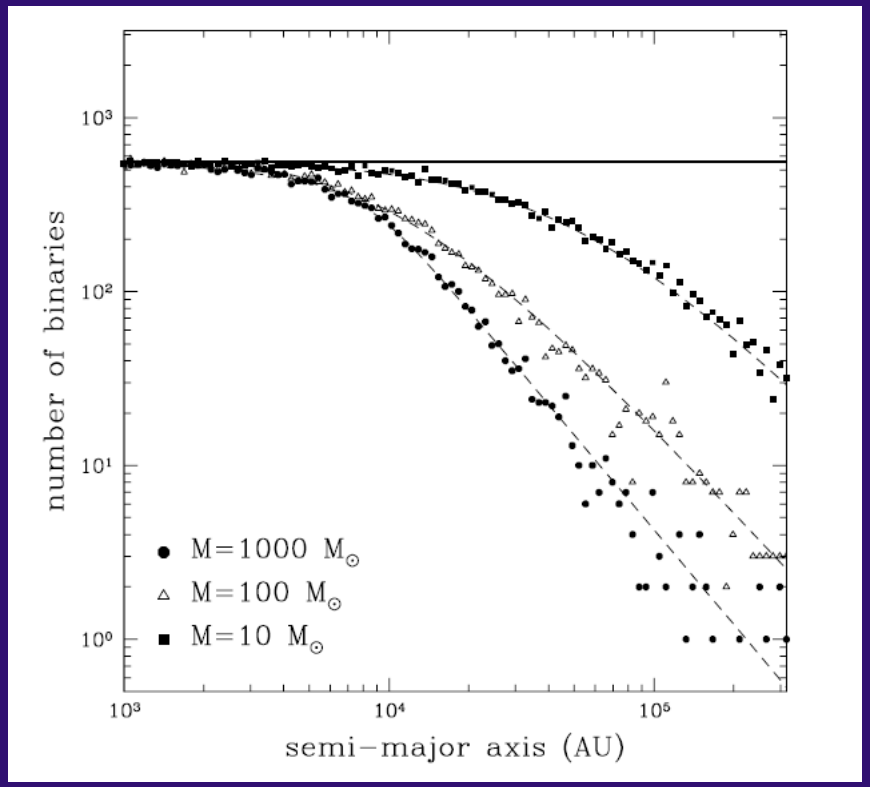
- Consider extreme regimes: tidal (perturbations dominated by single close encounters, and Coulomb (continued weak encounters). Evaluate transition separation.

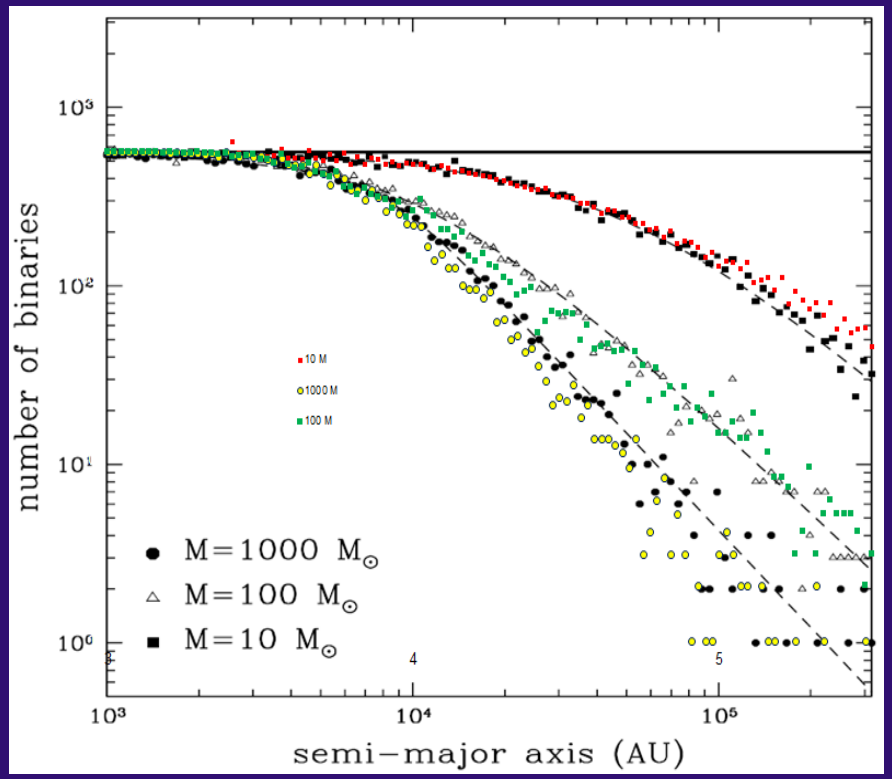
- Use impulse approximation. Neglect large-scale tides and molecular clouds (OK for halo binaries). Neglect dissolved binaries.

- Assume (for now) constant halo density. Attribute to MACHOs the total local density, ie, 0.007 Mo/pc^3

- Fit directly to semiaxes

Dynamical models: Montecarlo simulations



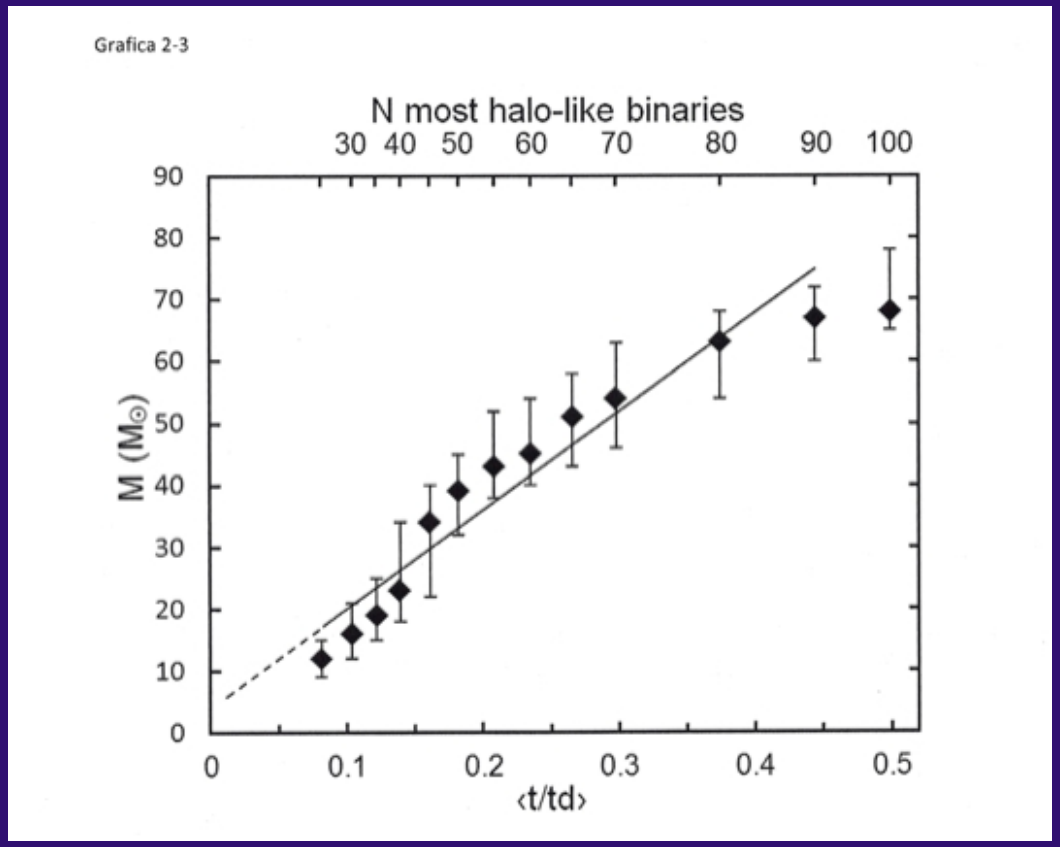


Evolution of distribution of major semiaxes for 100 thousand binaries subject to random perturbations over 10 Gyr with perturbers of different masses. Left: (Yoo et al 2004) initial distribution is Oepik. Right: our model (Monroy-Rodríguez & Allen, ApJ submitted)

Samples of binaries used to establish limits and evaluate effects of disk and non-uniform halo density

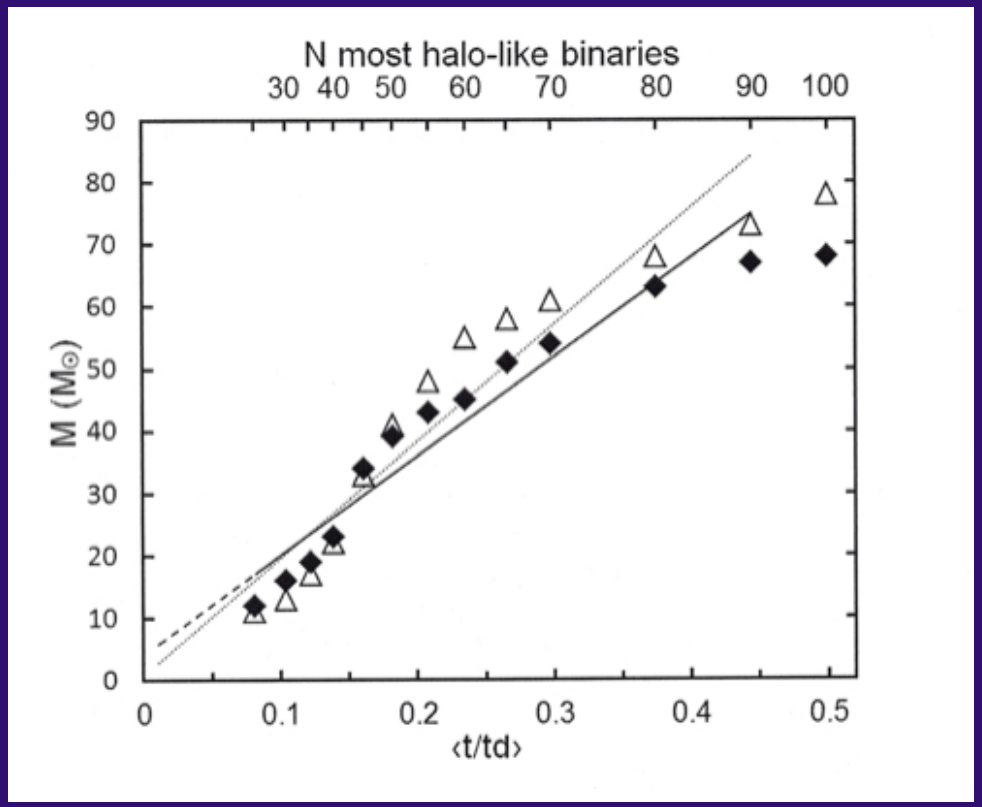
# estrellas	<rho>	<Td/Tt>
25	1.24	0.08
30	1.39	0.1
35	1.62	0.12
40	1.75	0.14
45	1.76	0.16
50	1.72	0.18
55	1.73	0.21
60	1.77	0.24
65	1.77	0.27
70	1.80	0.3
80	1.85	0.37
90	1.94	0.44
100	1.95	0.5
110	1.95	0.55

Macho mass limits



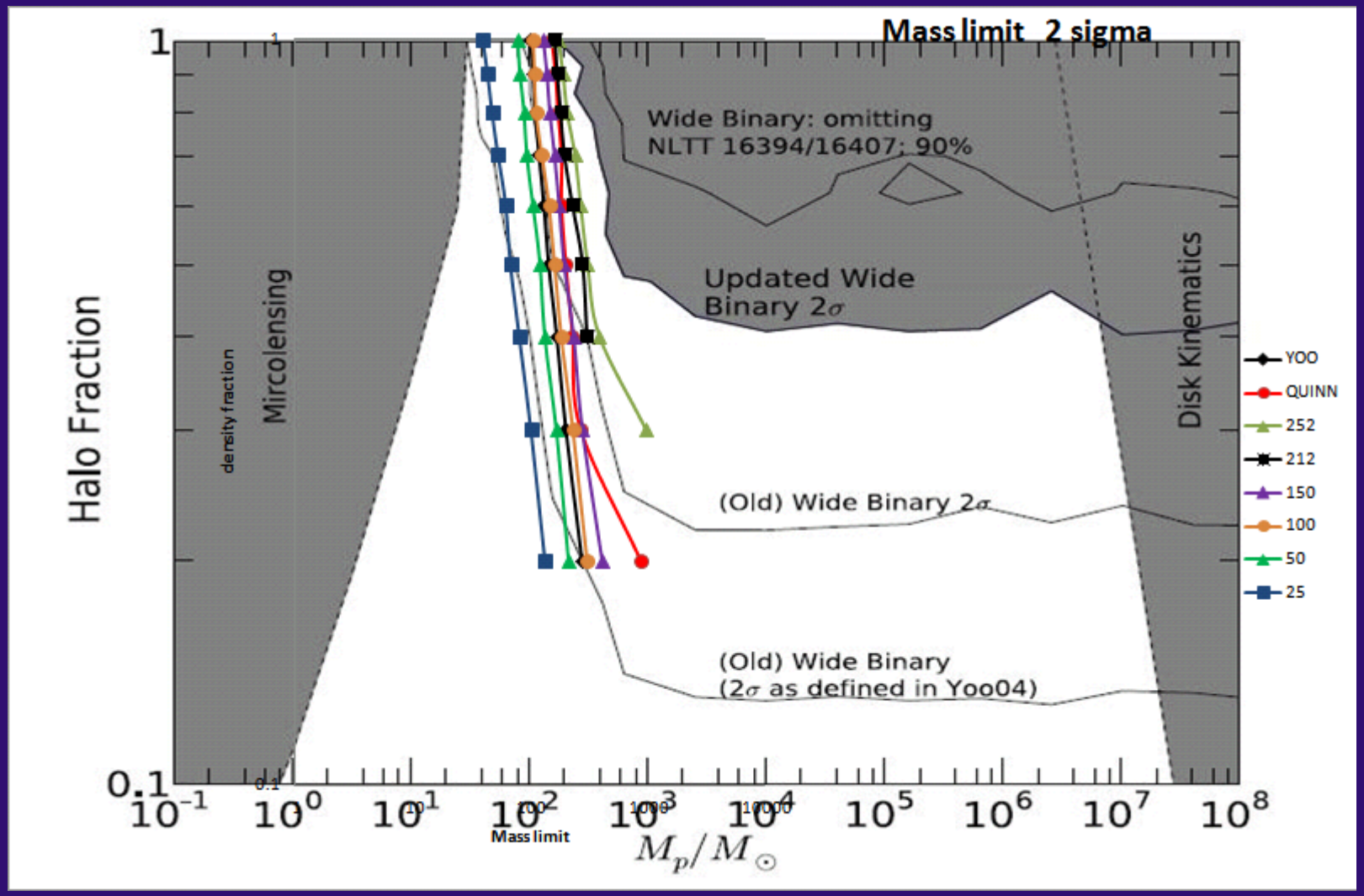
-Constant halo density, 20% uncertainty in distances

MACHO mass limits



Triangles: non-uniform halo density

Exclusion contours using 2-sigma fits for various subgroups of binaries



Halo wide binary summary

-We have compiled a catalog with 251 high-velocity low-metallicity binaries. There are 212 halo candidates among them.

-We found that Oepik distribution holds for all subsamples, up to different limiting separations.

-Galactic orbits were computed for 150 binaries. Time spent within disk was evaluated.

-A dynamical model for the evolution of wide halo binaries subject to perturbations by MACHOs was developed and validated.

Halo wide binary summary (cont.)

-Applying the model to different subsamples from the catalog we obtain as upper limits for the masses of MACHOs:

From 211 candidate halo binaries: 112 Mo
From 150 halo binaries with galactic orbits: 85 Mo
From 100 binaries with smallest times spent in disk: 68 Mo
Same, but taking into account non-uniform halo density: 78 Mo
From 25 most halo-like binaries (<Td/T> = 0.08): 8-12 Mo

So, once again, we have all but excluded MACHOs -at least in the galactic halo!
No dark matter => Limit of validity of Newtonian dynamics....

Our conclusions:

The limit of the validity regime for Newtonian gravity has been observed in a variety of low acceleration astrophysical structures:

-velocity dispersion distribution in globular clusters -flat
-density distribution in globulars, galaxies, etc. (r^{-3})
-wide disk binaries => non-Newtonian distribution of delta v
-wide halo binaries => no MACHOs in galactic halo

But:

-All these results depend on subtle observational data, still controversial

-With Gaia it will be possible to:

-study outskirts of globular clusters, determine membership
-map in detail density and 3d-velocity dispersion distributions
-determine cluster proper motions, hence accurate galactic orbits
-do better census of disk wide binaries (CPM, CRV, CD)
-idem for halo wide binaries => Better galactic orbits
-etc....

So, here too, Gaia will play a decisive role!

Thank you

Muchas gracias