Galaxy merging in Modified Newtonian Dynamics (MOND)

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OUTLINE

- A brief intro to MOND
- Stellar dynamics in MOND
- Galaxy merging in MOND
- Conclusions

In collaboration with P. Londrillo and L. Ciotti (Bologna)

A brief intro to MOND

MOND as empirical law

Milgrom (1983):

Flat rotation curves of disk galaxies can be explained without Dark Matter modifying Newtonian gravity.

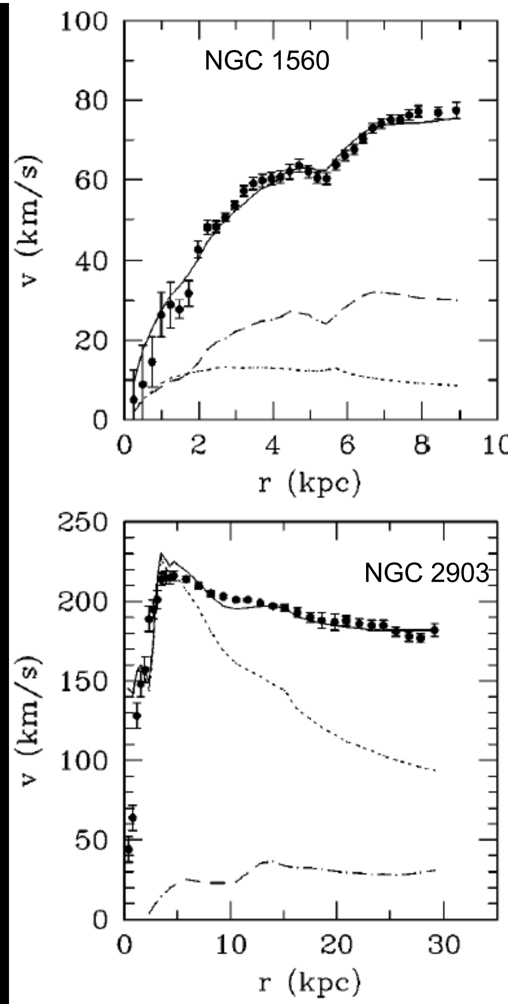
$$a_0 = 1.2 \times 10^{-10} m/s^2$$

characteristic acceleration

$$\mathbf{g}_M \mu(\|\mathbf{g}_M\|/a_0) = \mathbf{g}_N$$

$$\mathrm{g}_M \sim \mathrm{g}_N \qquad if\ \mathrm{g} \gg a_0$$

$$\mathrm{g}_M \sim \sqrt{a_0 \mathrm{g}_N}\ if\ \mathrm{g} \ll a_0$$



Begeman 1987; Sanders & McGaugh 2002

$$\mu(y) = \frac{y}{\sqrt{1+y^2}}$$

interpolating function

MOND as field theory

Classical field theory (modified Poisson equation)

Bekenstein & Milgrom (1984)

$$\nabla \cdot \left[\mu \left(\frac{\|\nabla \phi\|}{a_0} \right) \nabla \phi \right] = 4\pi G \rho$$

$$\mathbf{g}_M = -\nabla \phi$$

NON-linear!!!

$$\mathbf{g}_M \mu(\|\mathbf{g}_M\|/a_0) = \mathbf{g}_N + \nabla \times \mathbf{H}$$

Relativistic field theory (modified Einstein equations)

Bekenstein (2004) Sanders (2005)

TeVeS / BSTV

MOND behaviour on galactic scale

Why study MOND?

1. MOND+TeVeS/BSTV gravity is a serious alternative to Newton-Einstein gravity (cosmology, lensing…)
2. Many observational data are consistent with MOND
3. MOND has some problems (e.g. clusters), but MOND has NOT been disproven!
4. Also CDM has some problems… (e.g. DM cusps)

Stellar dynamics in MOND

Little is known on dynamical processes in MOND

because of

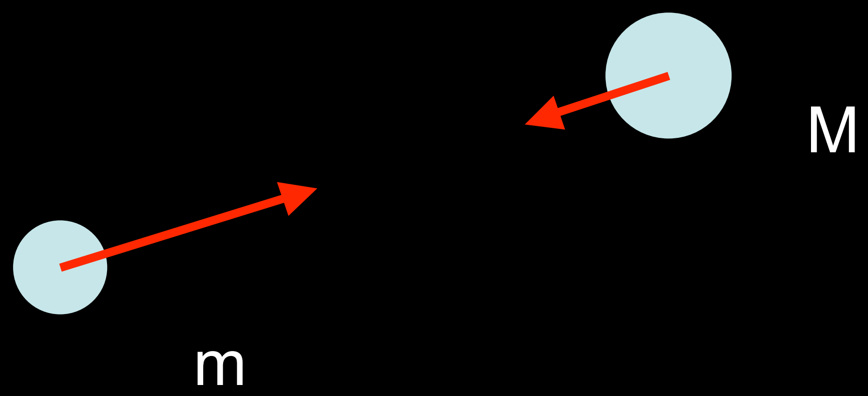
1. NON-linearity
2. Lack of N-body simulations

Two-body problem in MOND

HARD!

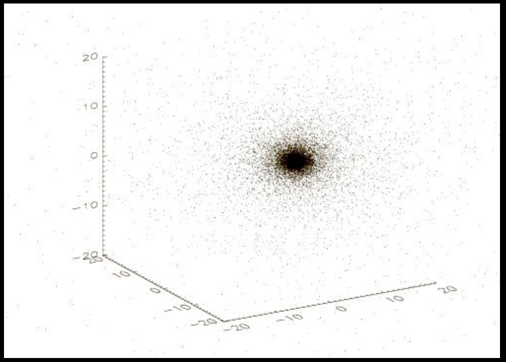
No analytical expression for the force between two particles!

One must solve the field equation $$\nabla \cdot \left[\mu \left(\frac{\|\nabla \phi\|}{a_0} \right) \nabla \phi \right] = 4\pi G \rho$$



N-body simulations in MOND

NOT TRIVIAL:
you cannot just modify the force law in a Newtonian code!



NON-linear => NO DIRECT SUMMATION CODES!

NO TREECODE!

Need to solve the non-linear field equation $\nabla \cdot \left[\mu \left(\frac{\|\nabla \phi\|}{a_0} \right) \nabla \phi \right] = 4\pi G \rho$

A NEW 3D PARTICLE-MESH CODE WITH MOND POTENTIAL SOLVER IN SPHERICAL COORDINATES

(Ciotti, Londrillo & Nipoti 2006, ApJ; Nipoti, Londrillo & Ciotti 2007, ApJ)

Only another MOND code: Brada & Milgrom (1999) + Tiret & Combes (2007)

Galaxy merging in MOND

Reasons to expect that galaxy merging is less effective in MOND:

1. Galaxies are expected to collide at high speed and there is no friction by DM haloes (e.g. Binney 2004; Sellwood 2004)

$$\mathrm{Newton}: \phi \propto -\frac{M_* + M_{DM}}{d_{rel}}$$

$$\mathrm{MOND}: \phi \propto \sqrt{M_*} \ln d_{rel} \quad (\text{for large } d_{rel})$$

2. Phase mixing and violent relaxation are slower in MOND (Nipoti, Londrillo & Ciotti 2007 ApJ; Ciotti, Nipoti & Londrillo 2007 astro-ph/0701826)

N-body simulations of galaxy merging in MOND

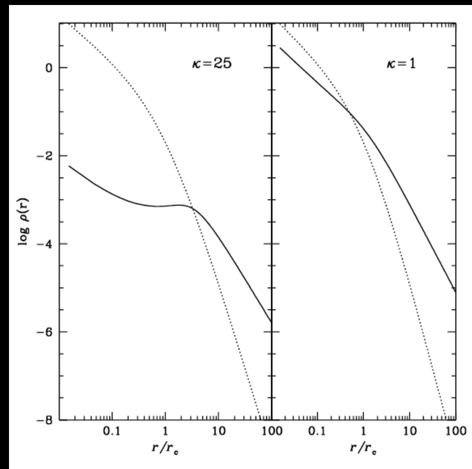
(Nipoti, Londrillo & Ciotti, submitted to MNRAS, arXiv:0705.4633v1)

Dissipationless, equal-mass merging between spherical Hernquist models:

- *MOND systems (only baryons)*

- *Newtonian EQUIVALENT systems (baryons+DM)*

$$\rho_{DM} = \frac{\nabla^2 \phi_{MOND}}{4\pi G} - \rho_*$$



CODES: <

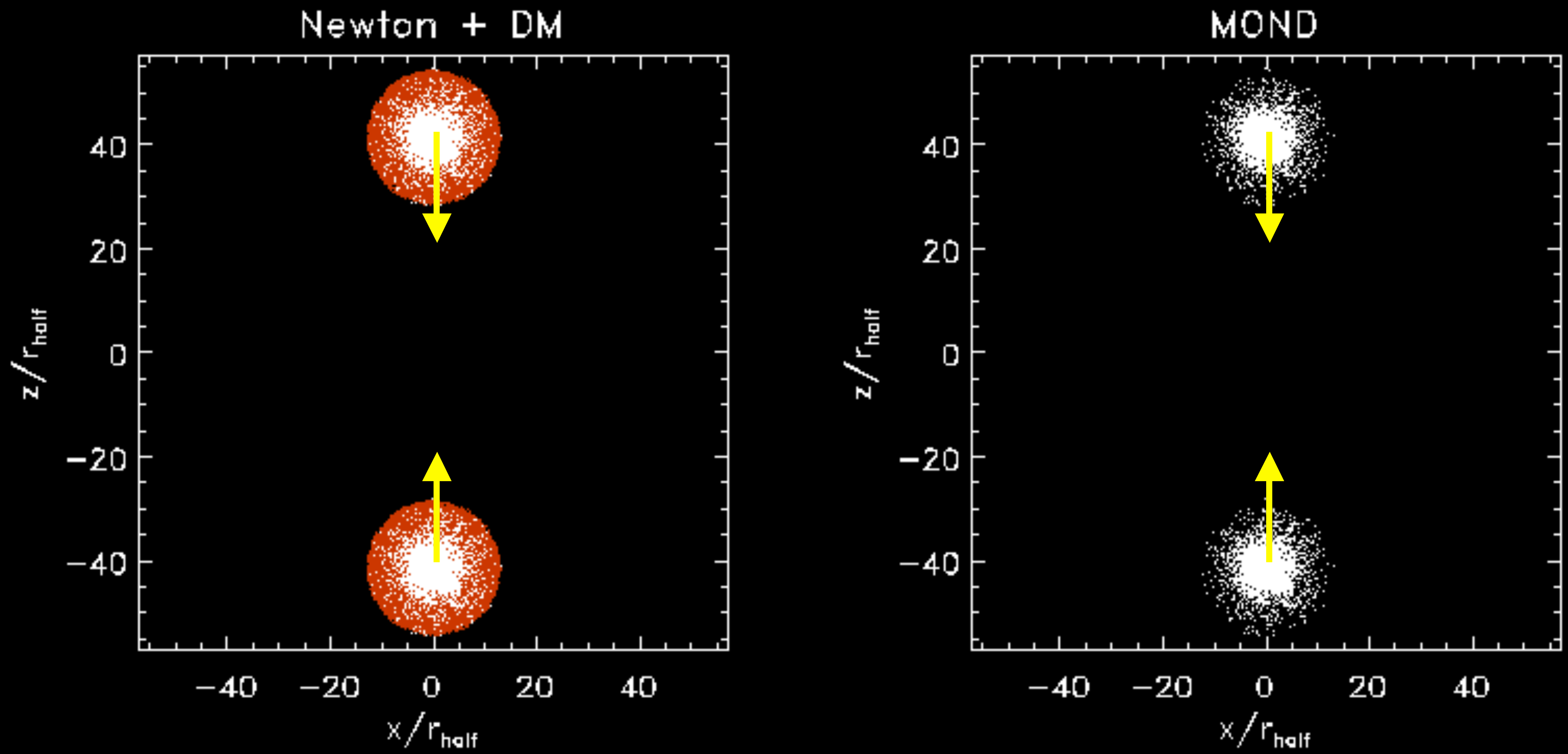
MOND PM CODE (Nipoti, Londrillo & Ciotti 2007)

FVFPS TREECODE (Londrillo, Nipoti & Ciotti 2003; Dehnen 2000, 2002)

$$N_{part} \sim 2 \times 10^6$$

CASE 1: STANDARD HEAD-ON ENCOUNTER

Two galaxies start at rest with separation ~ 90 r_{half}



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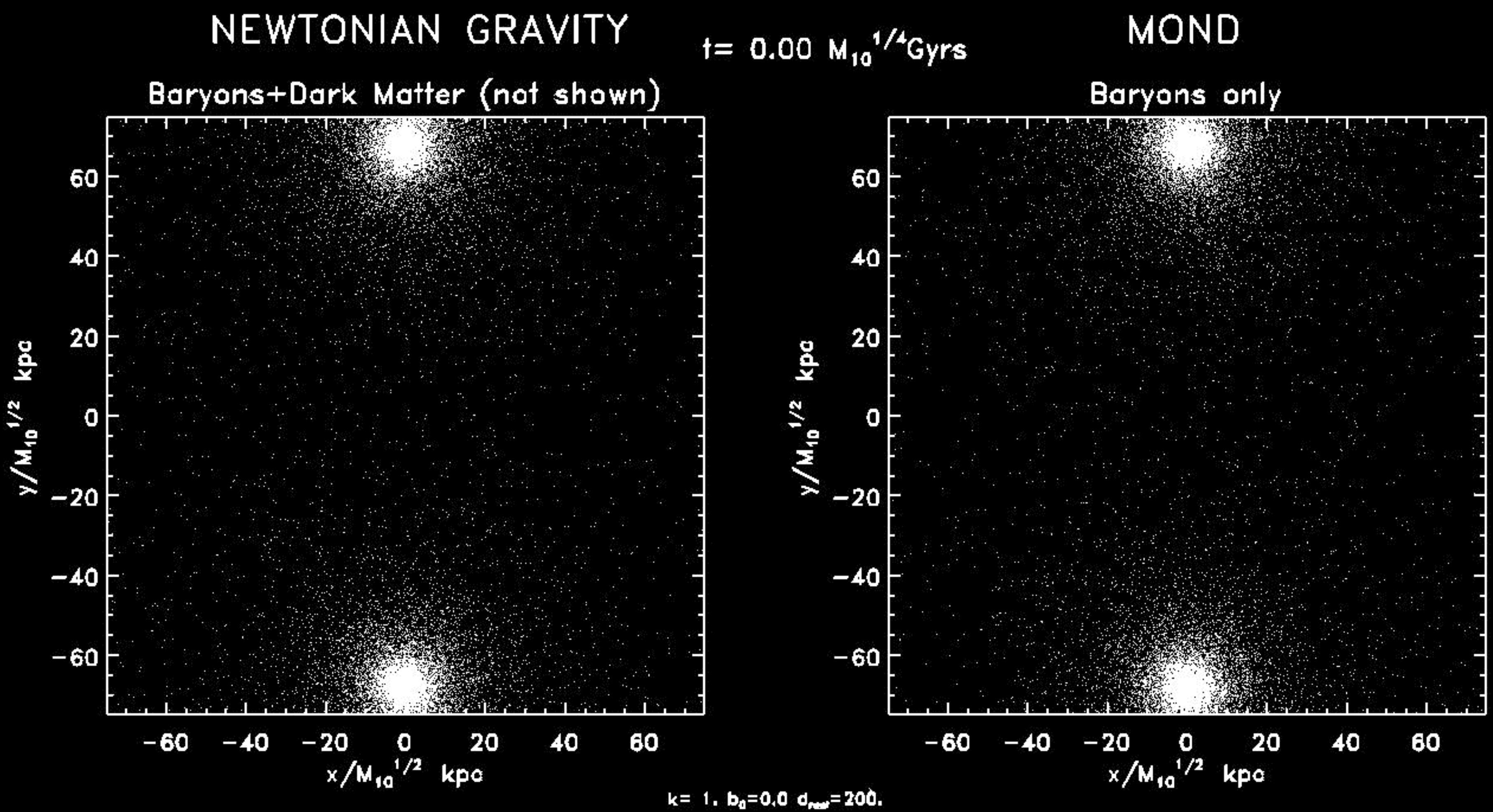
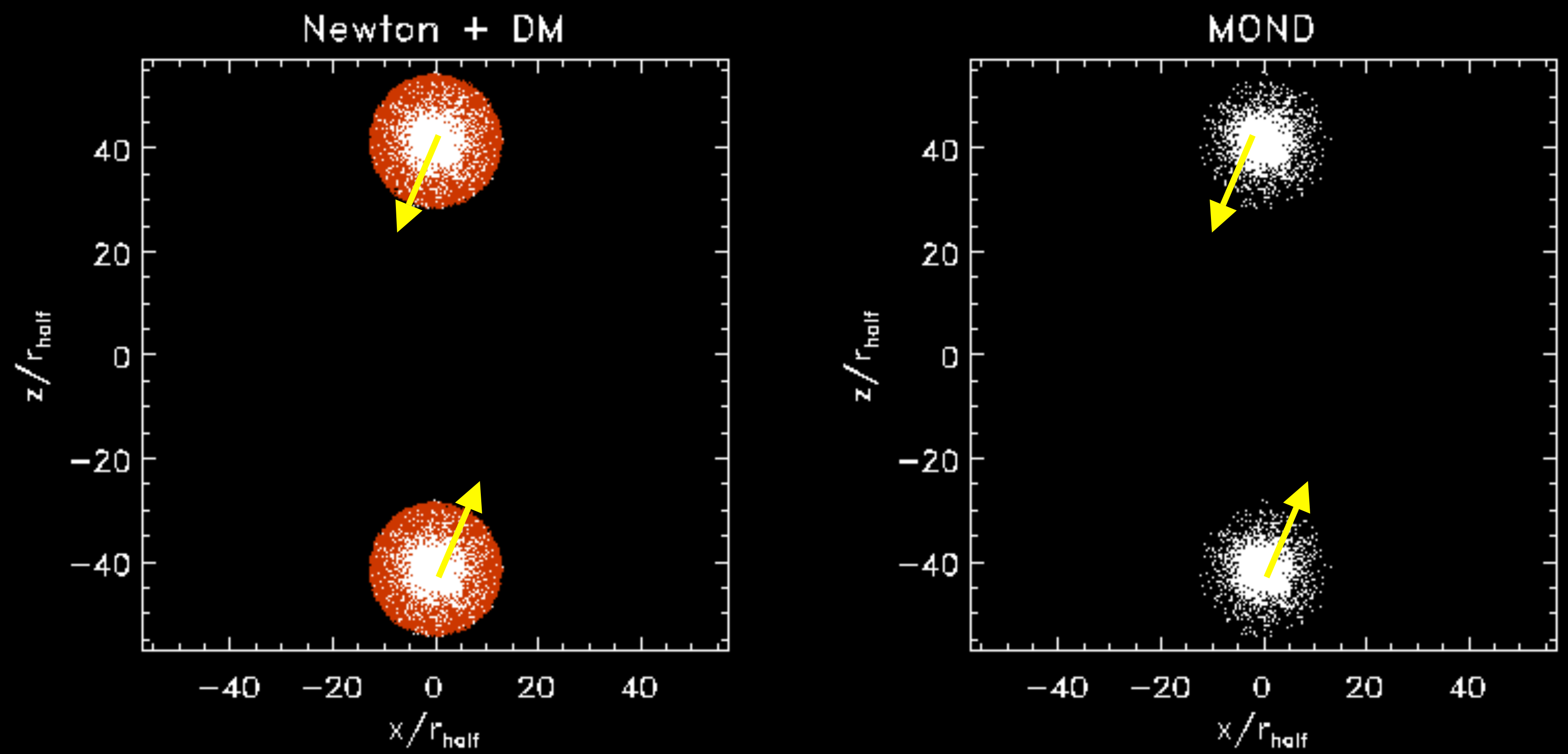


CASE 2: STANDARD OFF-CENTRE ENCOUNTER

Two galaxies start at rest with separation ~ 90 r_{half} + orbital angular momentum



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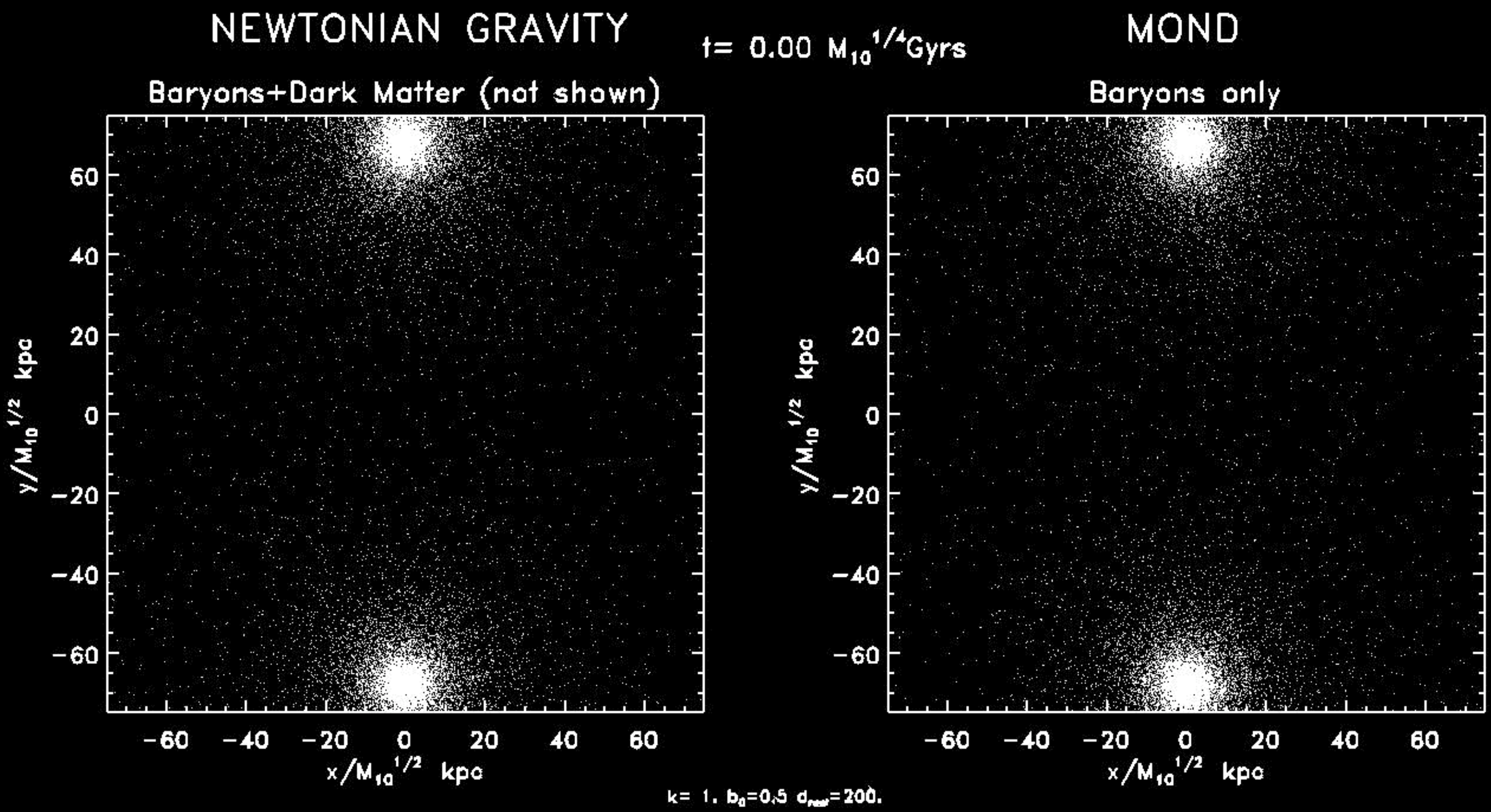


With fairly standard initial conditions

quick merging

in Newtonian gravity

high-speed encounters

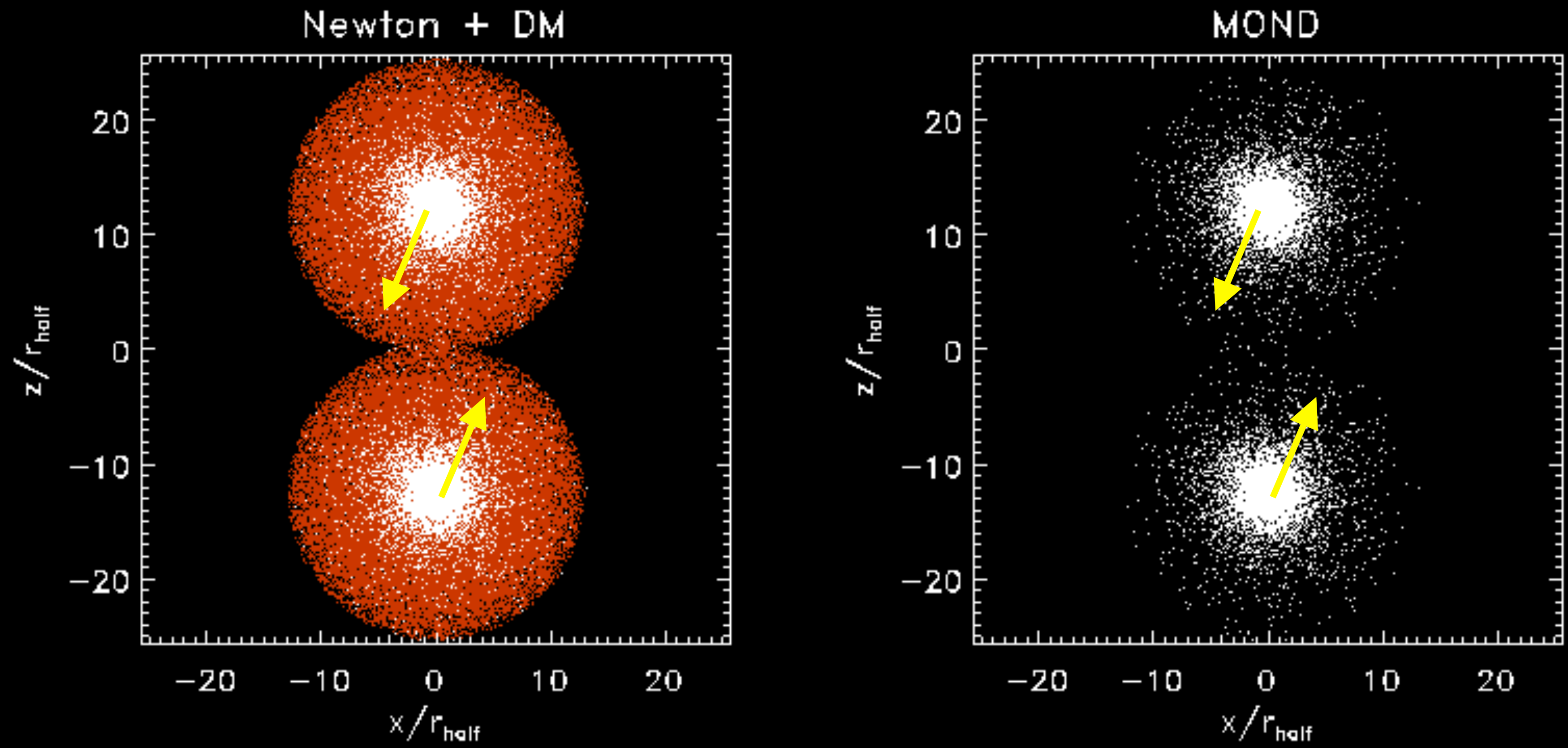
in MOND

MERGING IS PROBLEMATIC FOR MOND!

Let’s try initial conditions more favourable to merging…..

CASE 3: "SLOW" OFF-CENTRE ENCOUNTER

Two galaxies start at rest with separation ~ 25 r_{half} + orbital angular momentum



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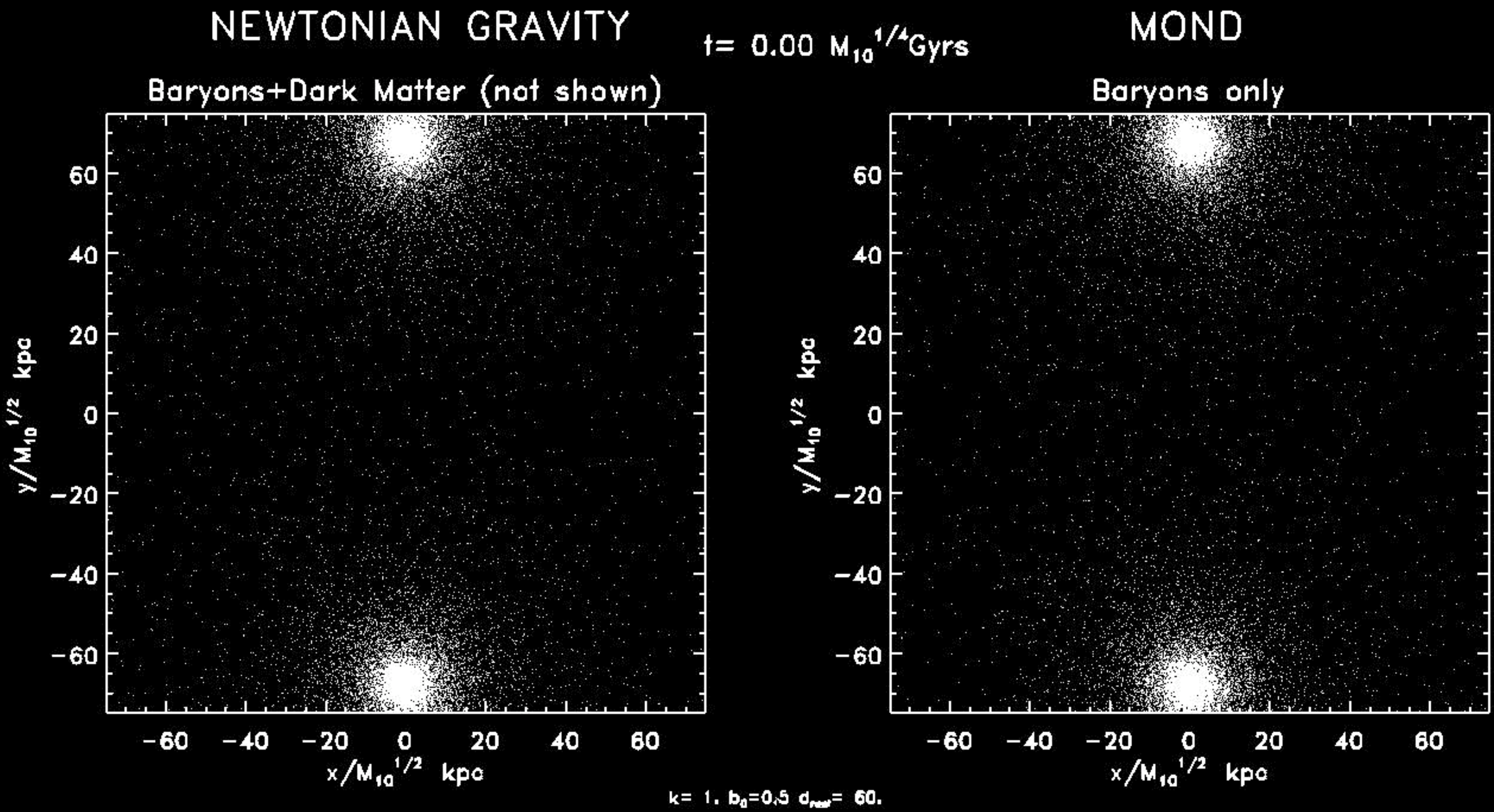
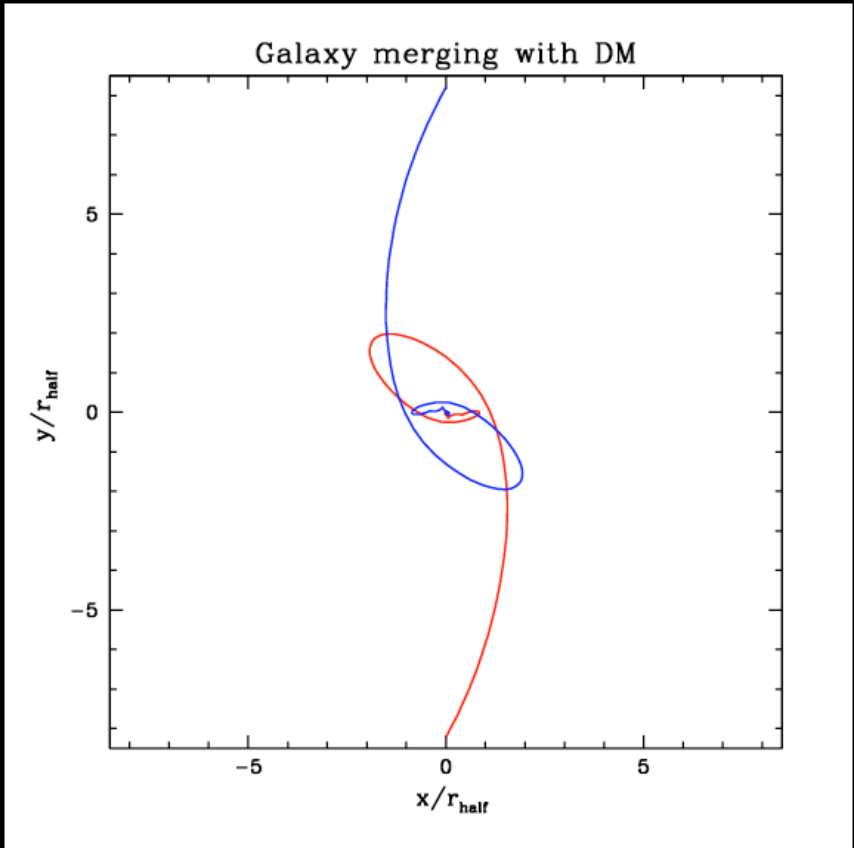
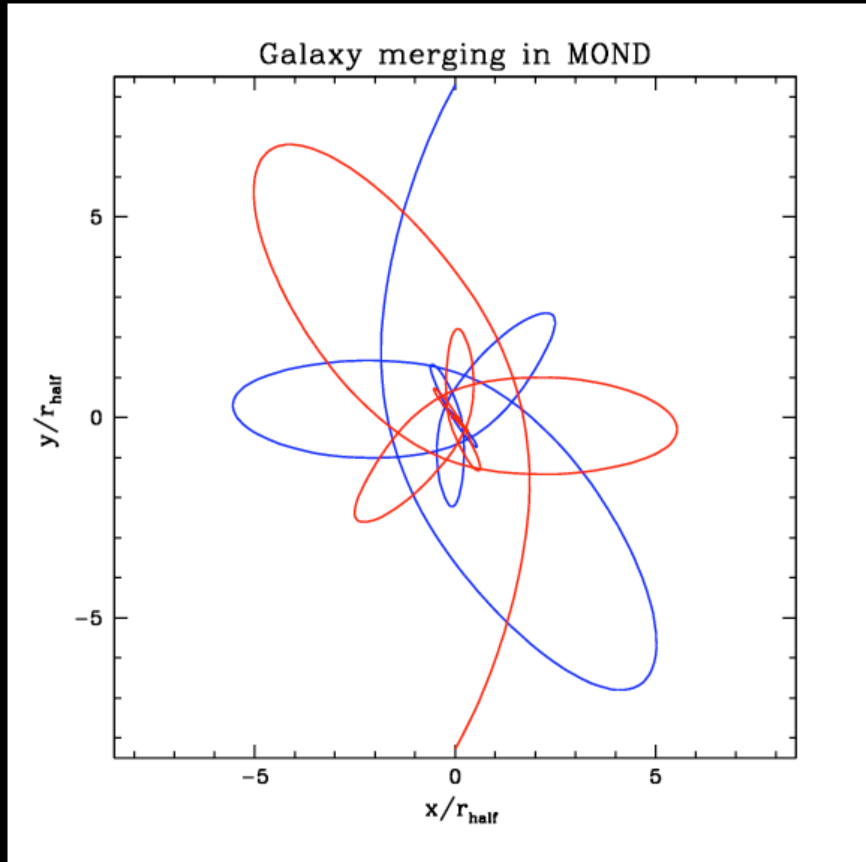


CENTRE OF MASS ORBITS



NEWTON + DM



MOND

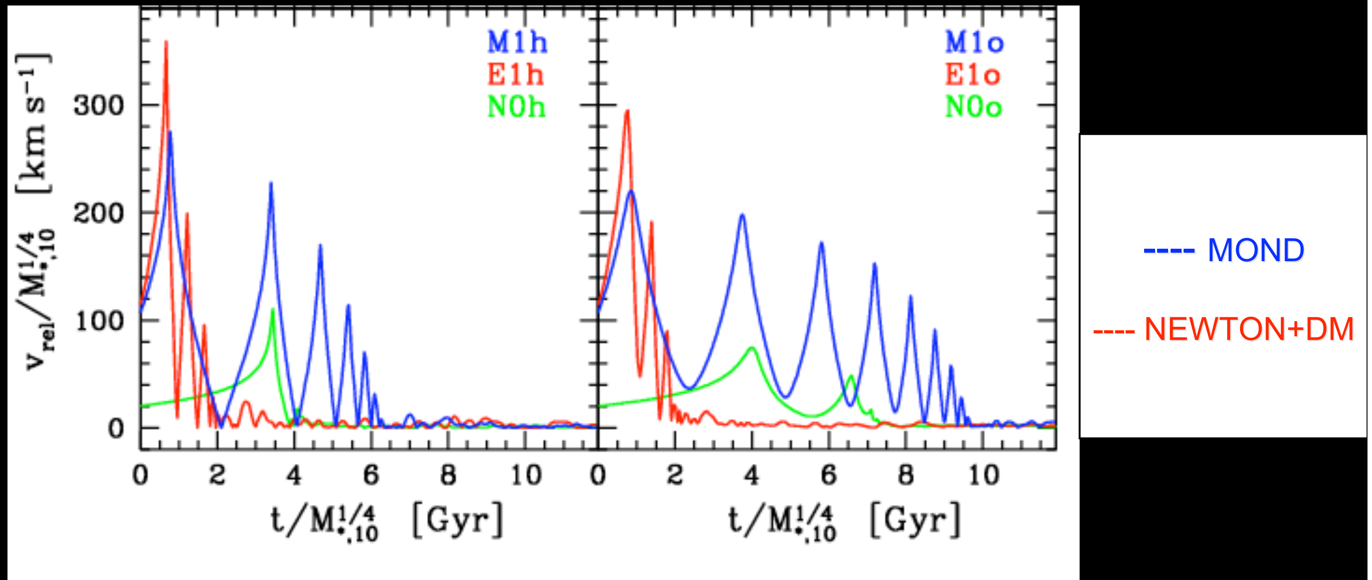
MERGING TIMESCALES (k=1): $a_{int} \ll a_0$

$$\kappa \equiv \frac{GM_*}{a_0 r_*^2} = 1$$

$$M_{DM} = 30 M_*$$

HEAD-ON | OFF-CENTRE

RELATIVE SPEED



TIME

"Slow" encounters!

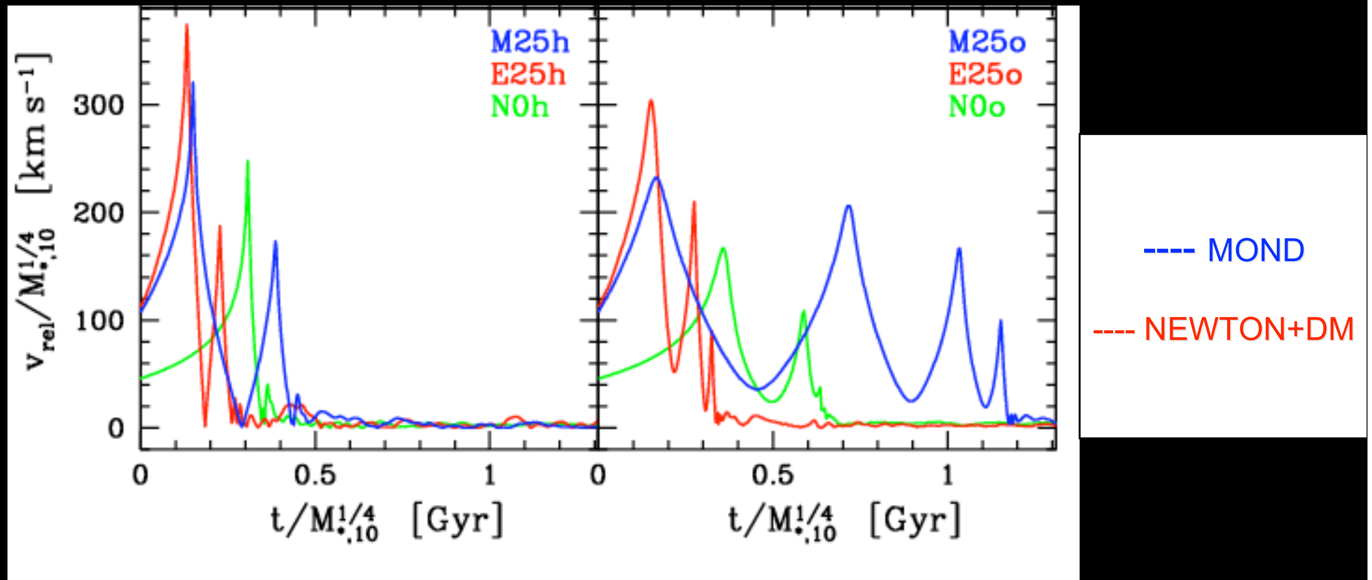
MERGING TIMESCALES (k=25): $a_{int} \gtrsim a_0$

$$\kappa \equiv \frac{GM_*}{a_0 r_*^2} = 25$$

$$M_{DM} = 5M_*$$

HEAD-ON OFF-CENTRE

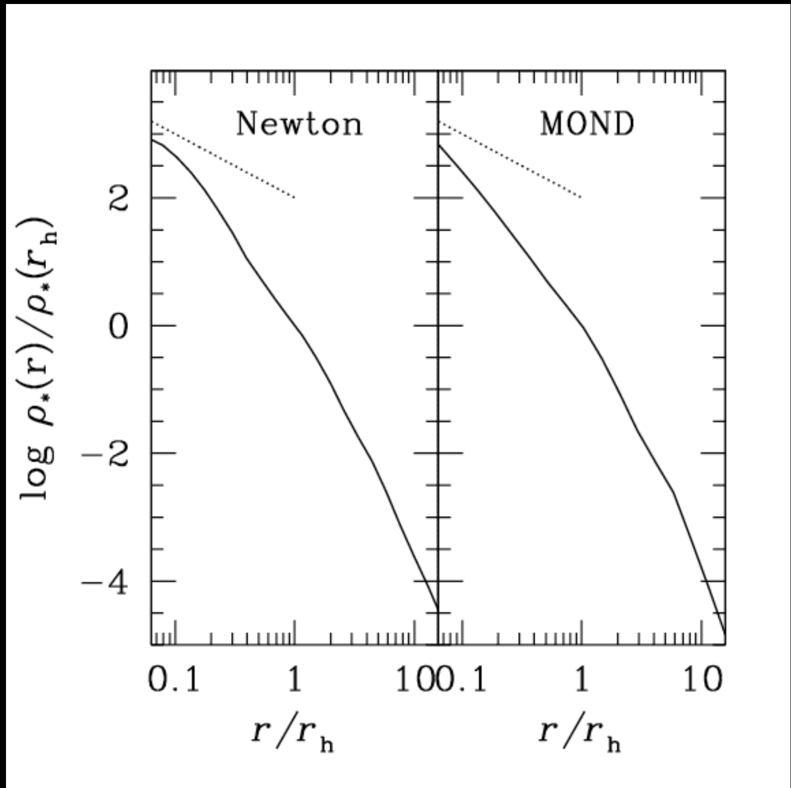
RELATIVE SPEED



TIME

"Slow" encounters!

MERGING END-PRODUCTS



When two galaxies eventually merge in MOND the end-product is hardly distinguishable from an equivalent Newtonian merger

Conclusions

Conclusions

1. Merging less effective in MOND than in Newtonian gravity with DM
2. Specific orbital properties to have mergers in $t<t_{Hubble}$ in MOND
3. Repeated high-speed encounters are a common feature in MOND
4. MOND and Newtonian merging end-products are similar

Observational evidence of merging appears difficult to explain in MOND!

Thanks!