The consequences of the MOND external field effect for cluster galaxies

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Dwarf Galaxies on the Shoulders of Giants
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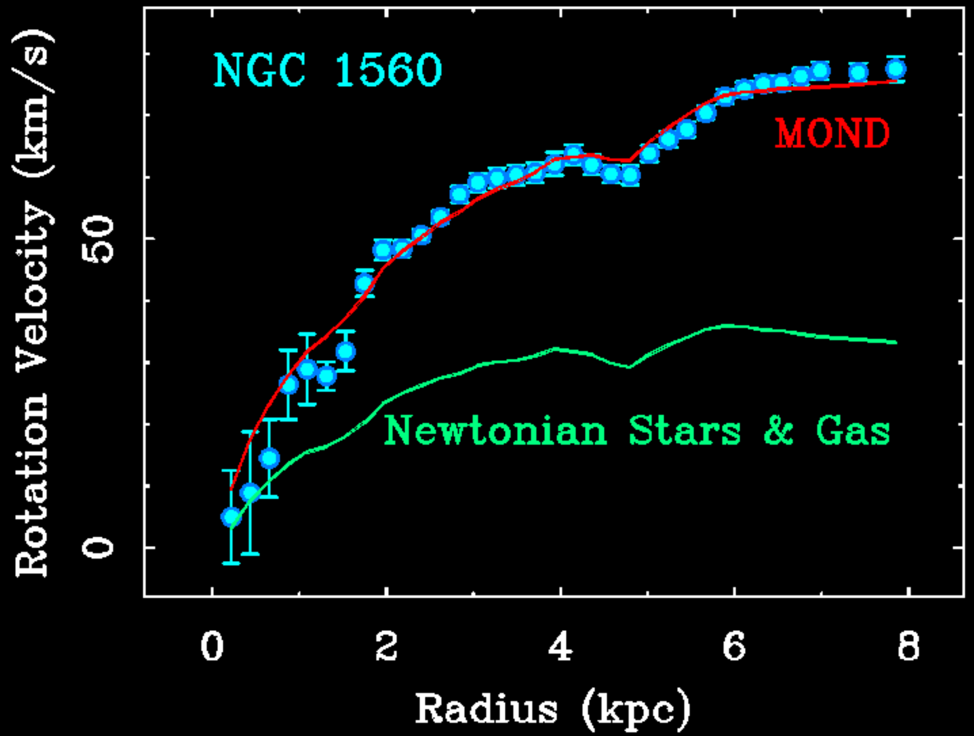
The MOND paradigm

- Weak field limit modification of gravity
- Dark matter in galaxies → modified gravity
  - for review see Famaey & McGaugh 2012



The MOND paradigm

- MOdified Newtonian Dynamics (MOND, Milgrom 1983)
  - Tensor-Vector-Scalar (Bekenstein & Milgrom 1984)
  - Generalized Einstein-Aether (Zlosnik, Ferreira & Starkman 2007)
  - Bimetric MOND (Milgrom 2009)
- Emergent gravity (Verlinde 2016)
  - holographic principle
  - but see Pardo, arXiv:1706.00785
- Non-local gravity (Deffayet, Esposito-Farese & Woodard 2007)
- Spacetime scale invariance at low accelerations?

Non-relativistic MOND formulations

- Aquadratic Lagrangian (AQUAL) formulation of Bekenstein & Milgrom (1984):

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

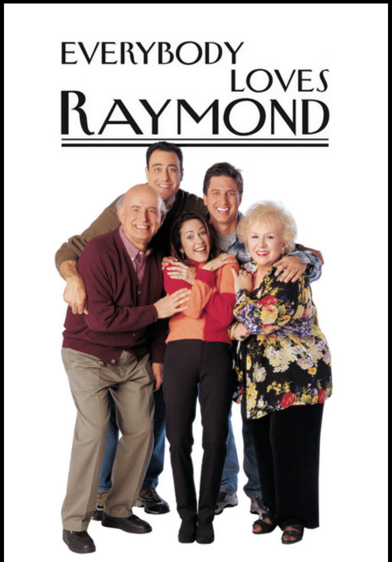
Non-relativistic MOND formulations

- Quasi-linear (QUMOND) formulation of Milgrom (2010):

$$\nabla^2 \phi^N = 4\pi G \rho \qquad \nabla^2 \phi = \nabla \cdot \left[\nu \left(\frac{|\nabla \phi^N|}{a_0} \right) \nabla \phi^N \right]$$

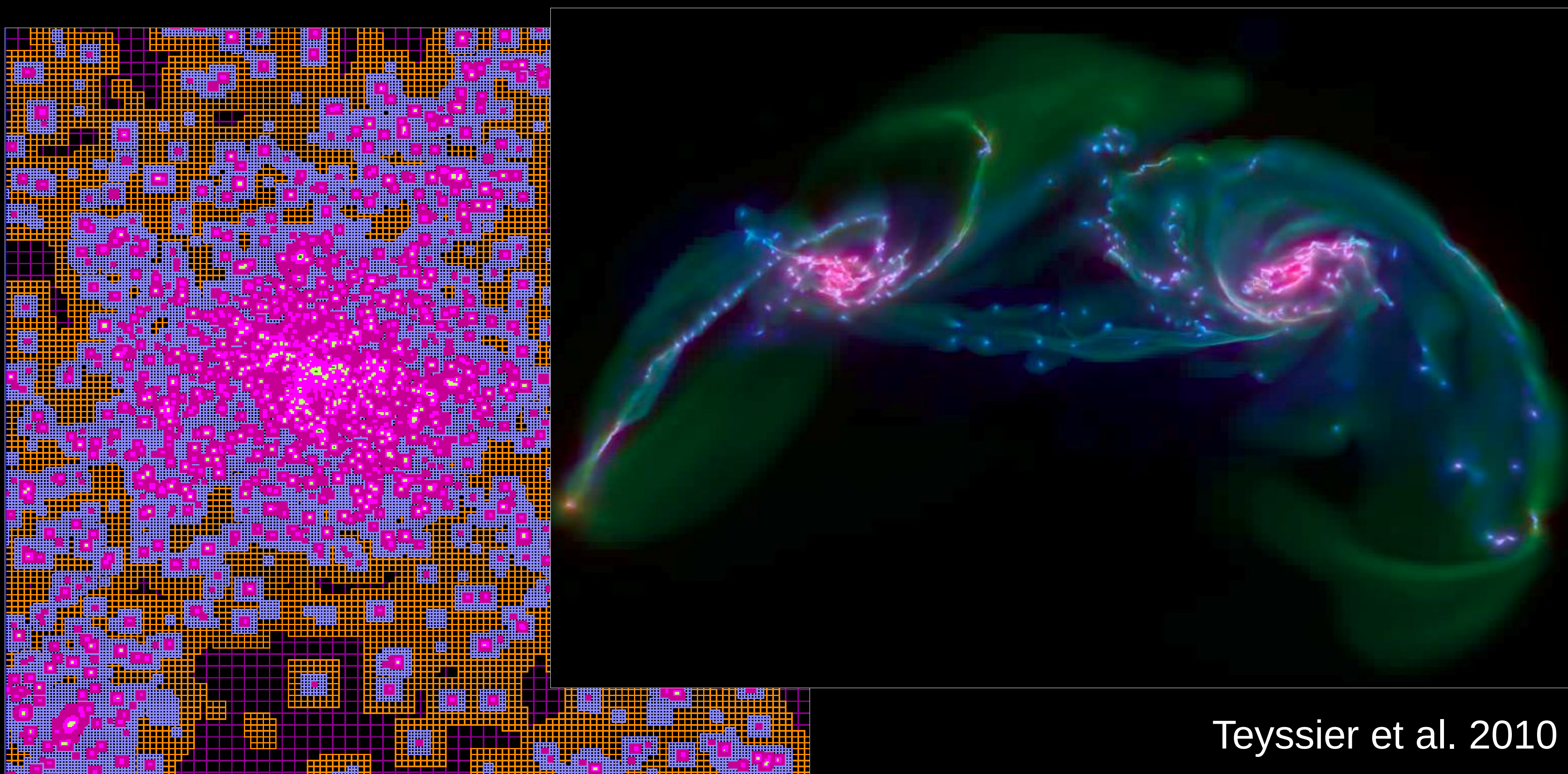
MOND cosmological and galaxy-scale simulations

- MOND Numerical codes:
  - AQUAL:
    - Amiga MOND (Llinares, Knebe & Zhao, 2008)
    - N-MODY (Londrillo & Nipoti, 2009)
  - QUMOND:
    - PoR (Lüghausen, Famaey, Kroupa, 2015)
  - Both:
    - RAyMOND (Candlish, Smith, Fellhauer, 2015)
    - Based on RAMSES (Teyssier 2002)



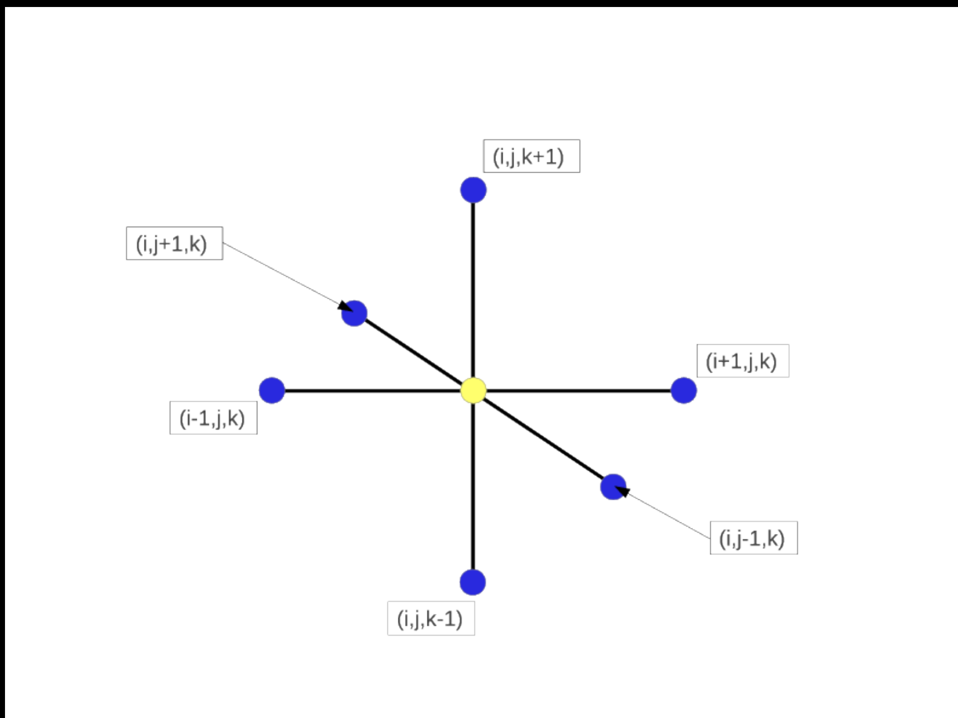
RAMSES

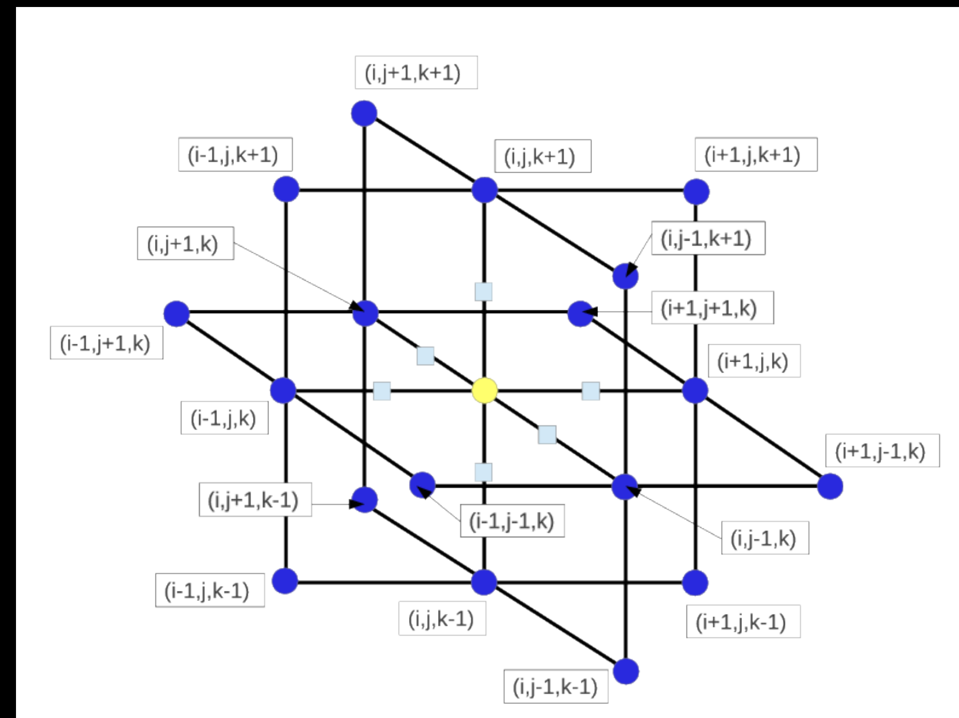
- Multigrid particle-mesh N-body/hydrodynamics solver (Teyssier 2002)



Teyssier et al. 2010

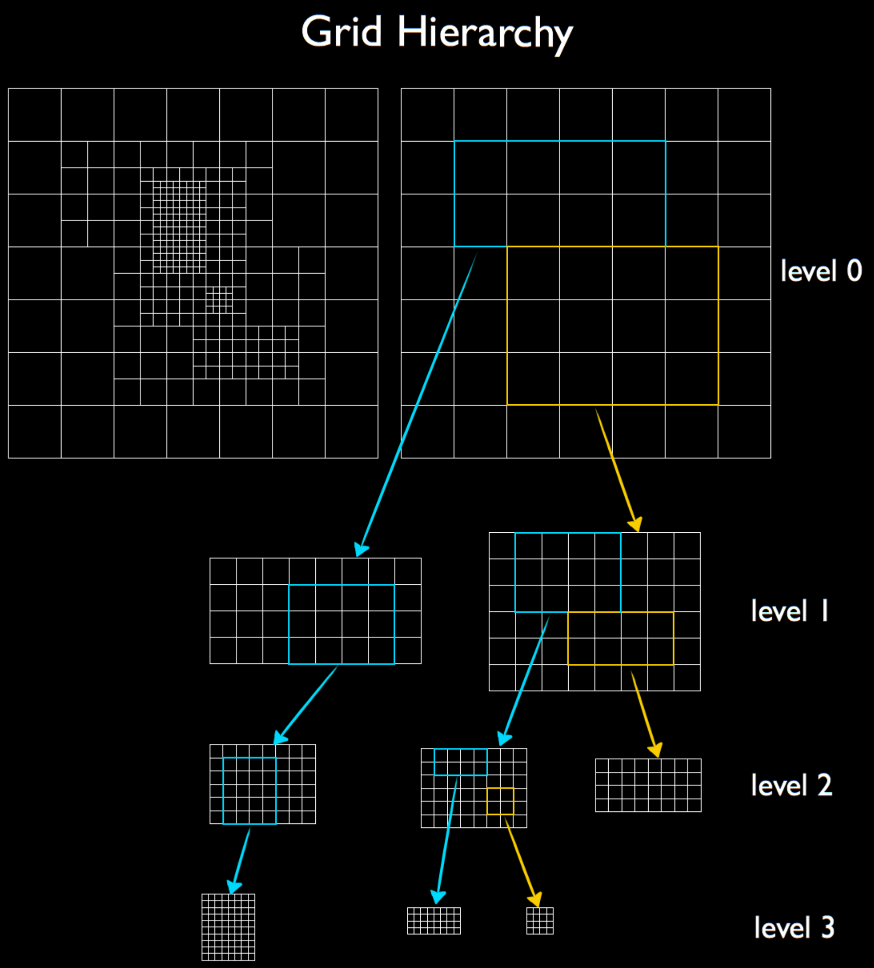
Extended stencil

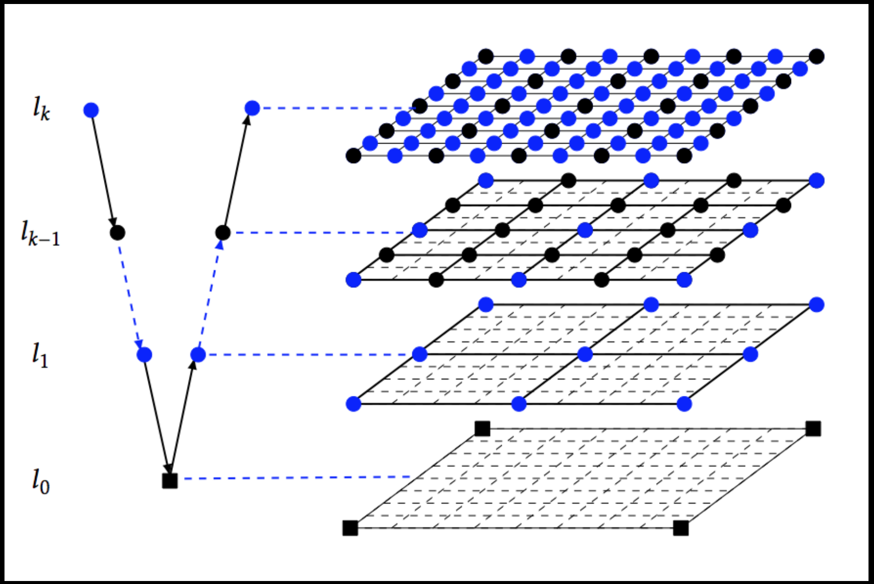




- 6-point stencil in standard RAMSES
- Extended to 18-point stencil for MOND equation

Non-linear multigrid and adaptive mesh refinement





Challenges of MOND simulations

- AQUAL → non-linear solver, longer convergence time
- QUMOND → second solution of the Poisson equation
- Boundary conditions
  - asymptotically logarithmic MOND potential
- Generation of initial conditions

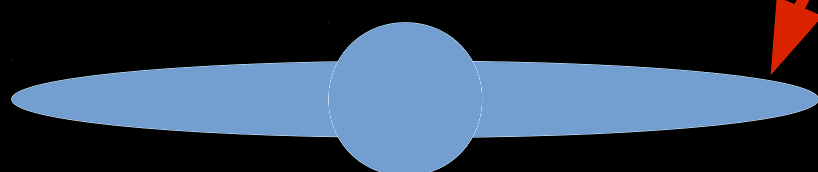
External field effect

- Whether system is in MOND regime depends on the *total* acceleration

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

Isolated galaxy:

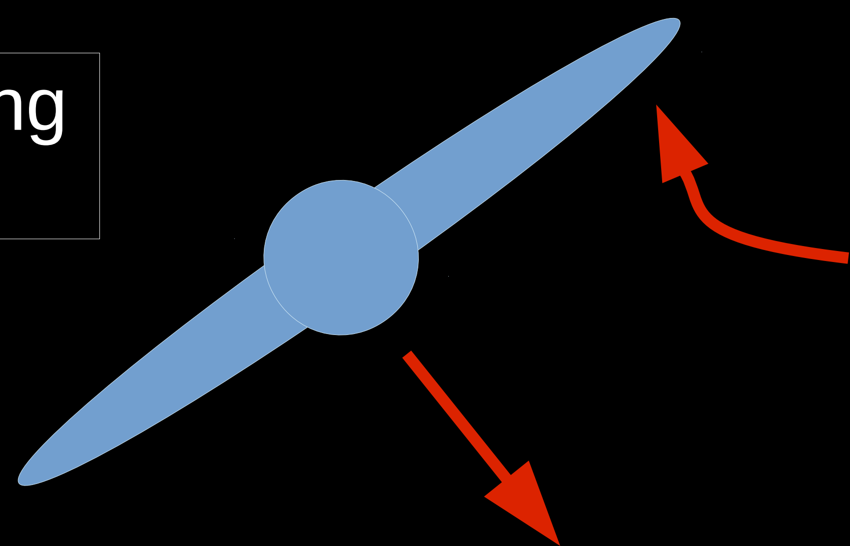
$a << a_0$



External field effect

- Whether system is in MOND regime depends on the *total* acceleration

Galaxy falling into cluster:



Total $a > a_0$

The external field effect

- Background potential modifies internal dynamics
- Violation of the strong equivalence principle
- Non-trivial effects:
  - stellar systems in background fields
  - star clusters, satellite galaxies, etc.

Idealised tests for galaxies in a cluster

- Initial conditions:
  - generated by DICE code (V. Perret)
  - aim for equilibrium *isolated* models
- Evolved in isolation for ~10 Gyr to check stability
- MOND models initially as Newtonian, minus the DM halo

Candlish et al., in prep

Idealised tests for galaxies in a cluster

- Cluster modelled as analytic *density* (not potential) in RAyMOND
  - included in solver, EFE present
- Background static potential
  - Hernquist model
  - r_s = 200 kpc, M = 7.8e14 Msol
- MOND models
  - density modified to match Newtonian potential
- Orbits of ~5 Gyr within cluster

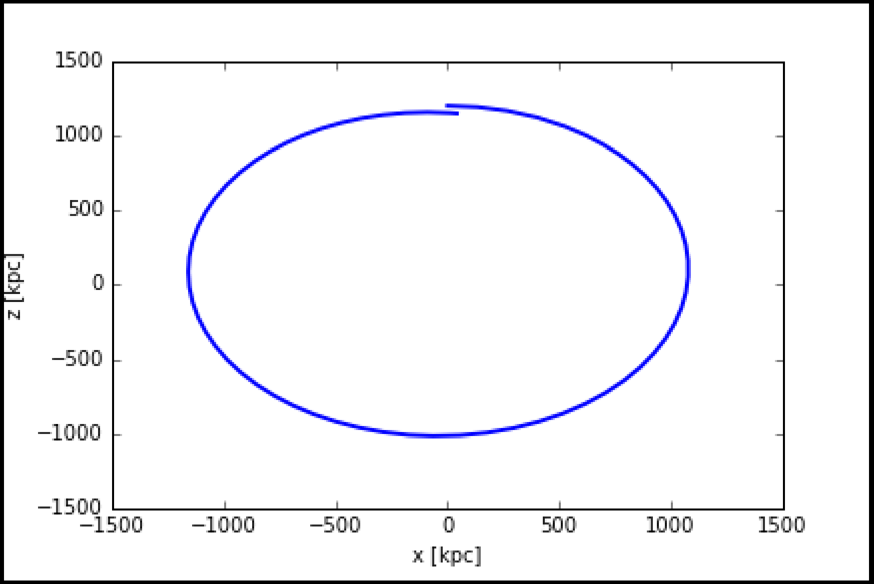
Idealised tests for galaxies in a cluster

- Two galaxy models:
  - high mass (10^{11} Msol stellar, 3 x 10^{12} Msol DM)
  - low mass (10^{9} Msol stellar, 10^{11} Msol DM)
- Orbits:
  - weak tides (almost circular, ~1 Mpc clustercentric distance)
  - moderate tides (pericenter ~535 kpc)
  - strong tides (pericenter ~124 kpc)
- Galaxy inclination relative to orbit (disk parallel to x-y plane):
  - perpendicular (orbit in x-z plane)
  - parallel (orbit in x-y plane), retrograde and prograde motion

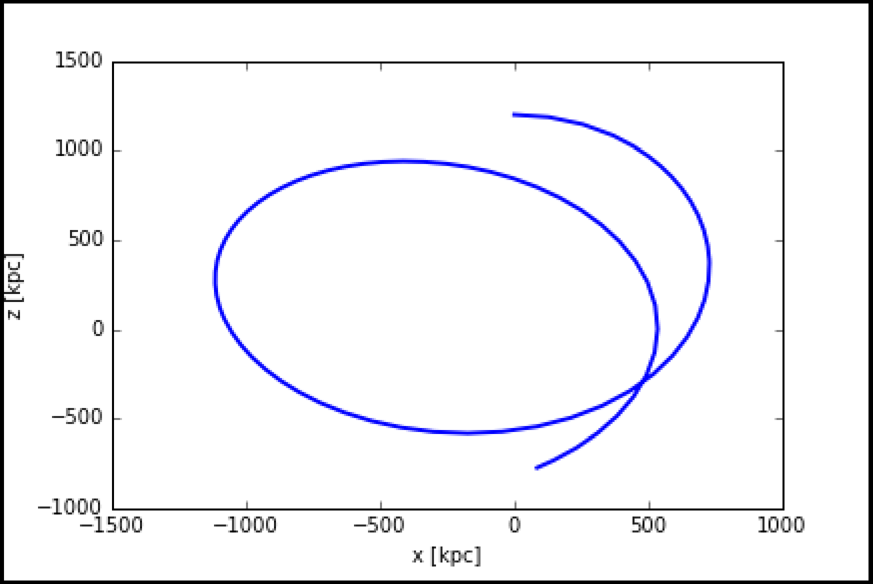
Idealised tests for galaxies in a cluster

- Background *analytic* potential may be added (i.e. specified accelerations for the particles)
- RAyMOND modified:
  - add background analytic accelerations to N-body dynamics of the galaxy
  - Background accelerations NOT included in gravity solver: no EFE (tides maintained)
  - Additional MOND models run without EFE

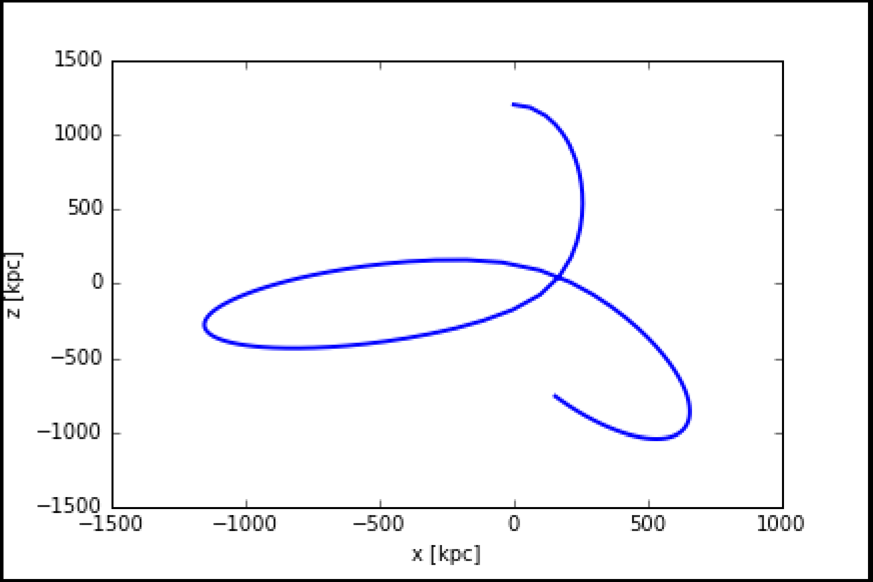
Orbits



Weak tides



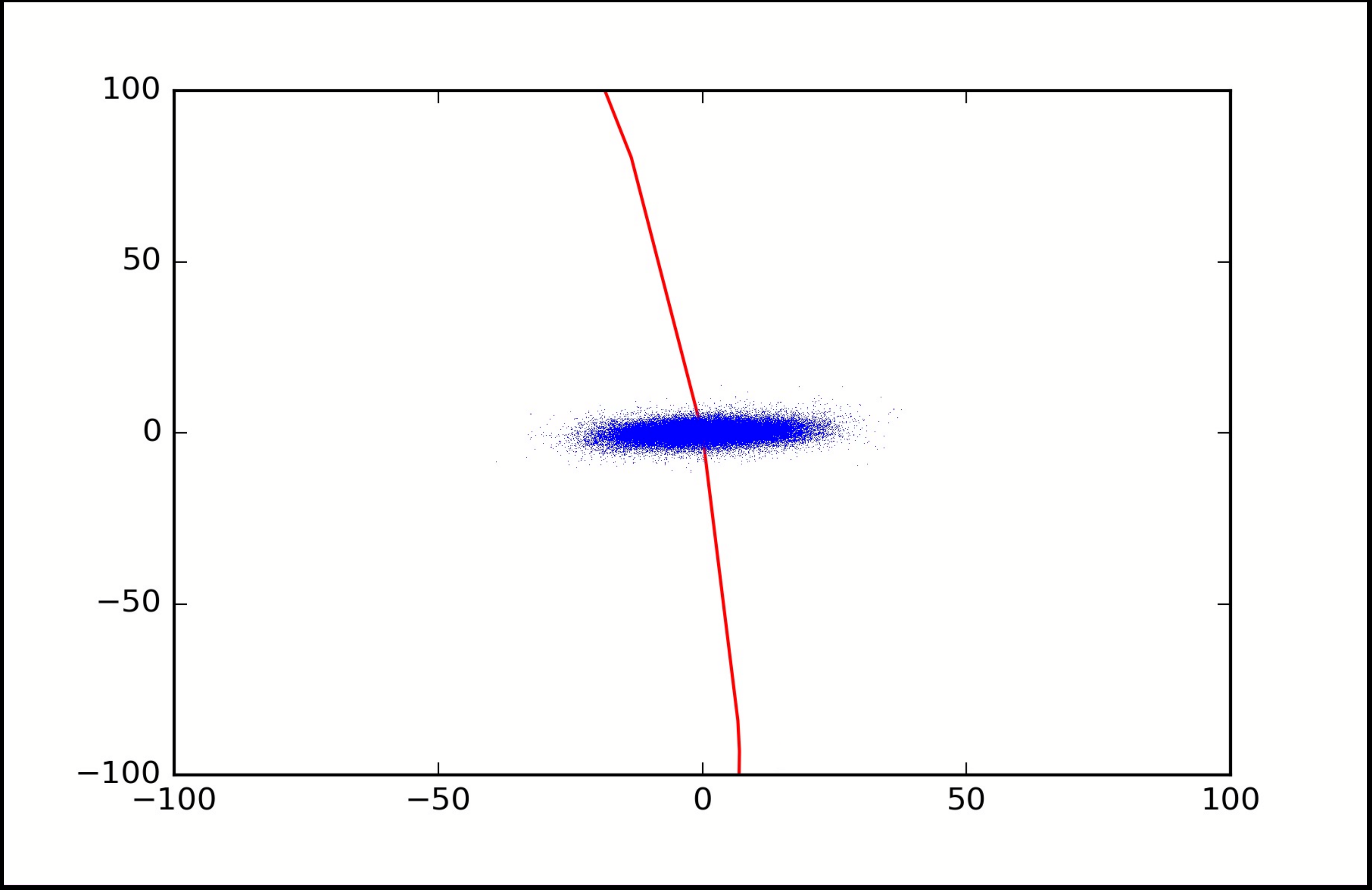
Moderate tides



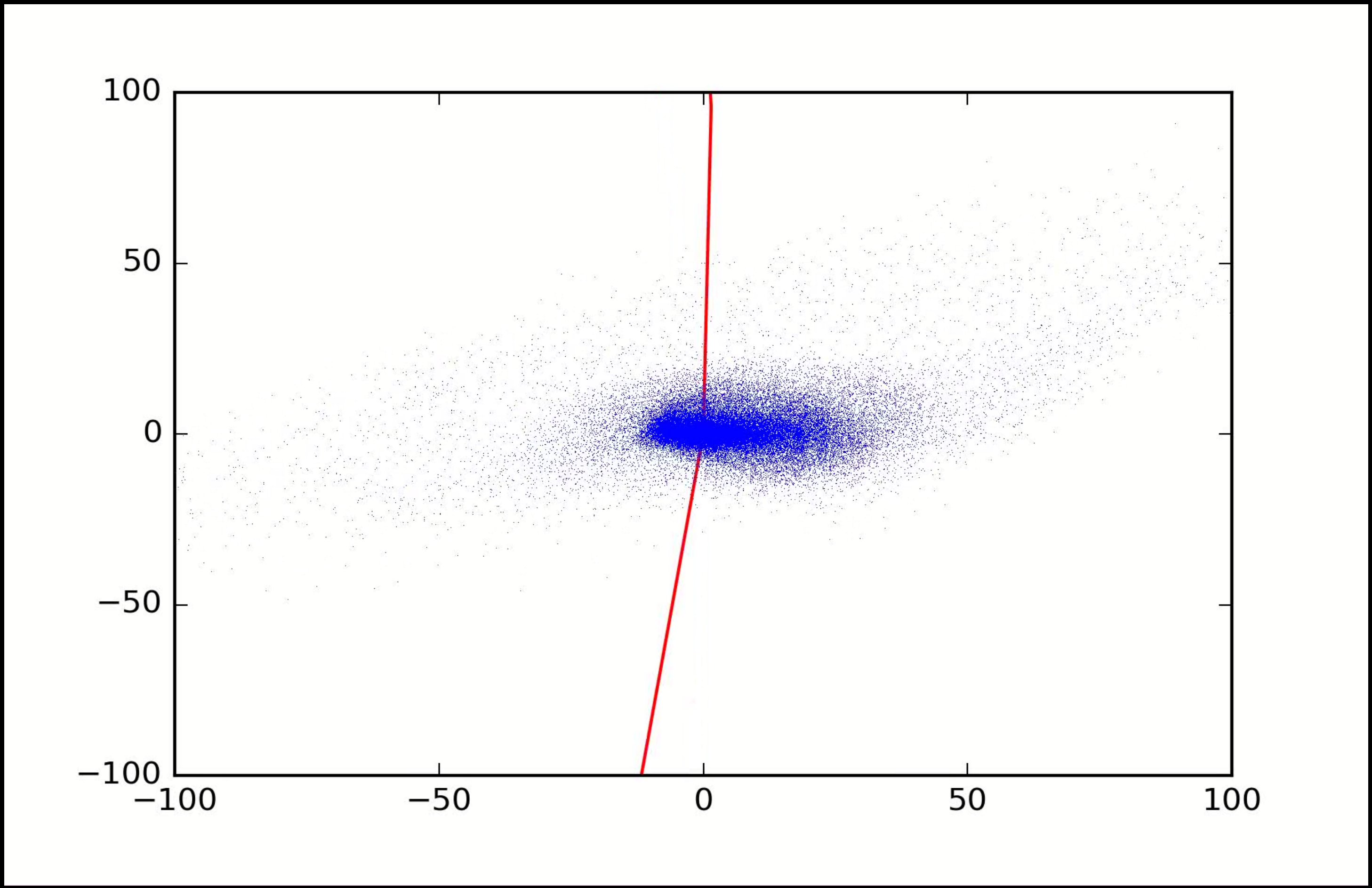
Strong tides

Preliminary results!

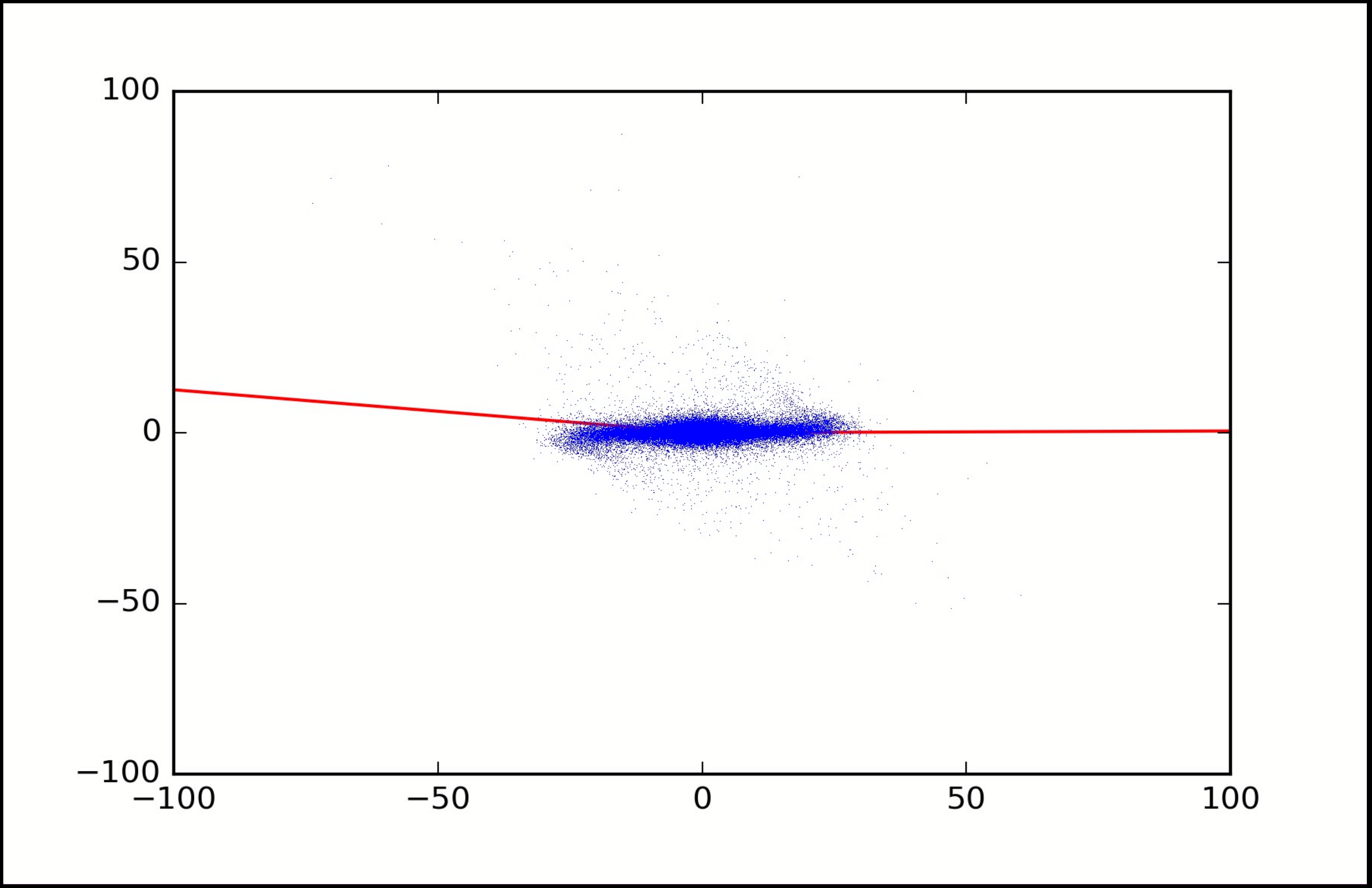
Newtonian, moderate tides, high mass, x-z orbit



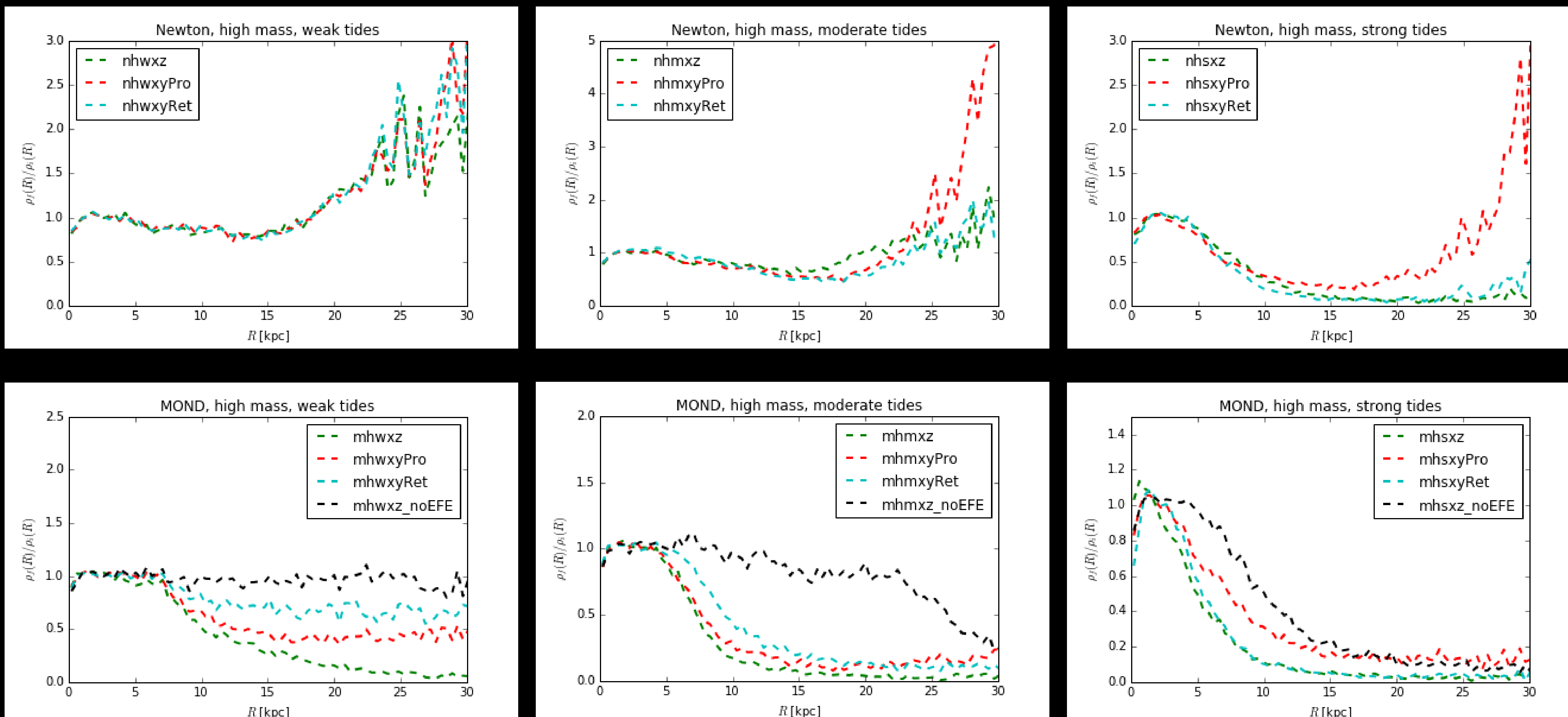
MONDian, moderate tides, high mass, x-z orbit



MONDian, moderate tides, high mass, x-z orbit, no EFE

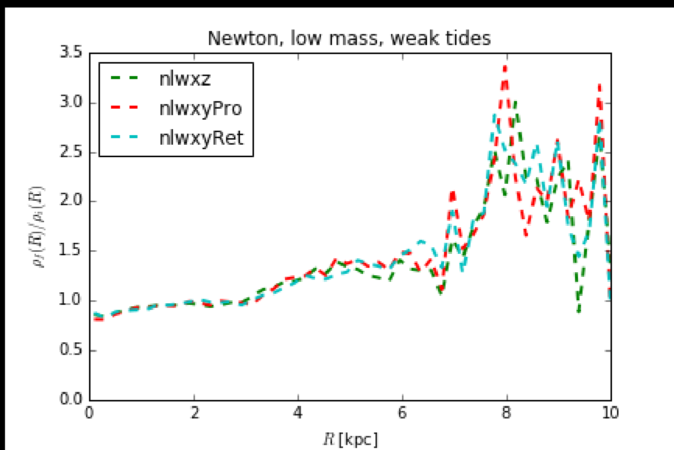


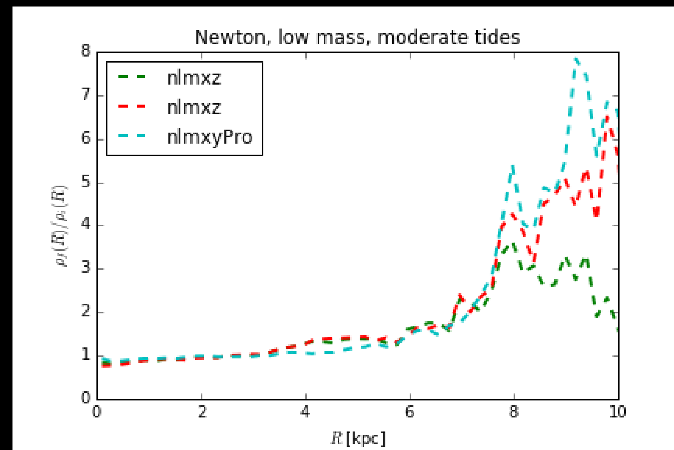
Radial density evolution: high mass

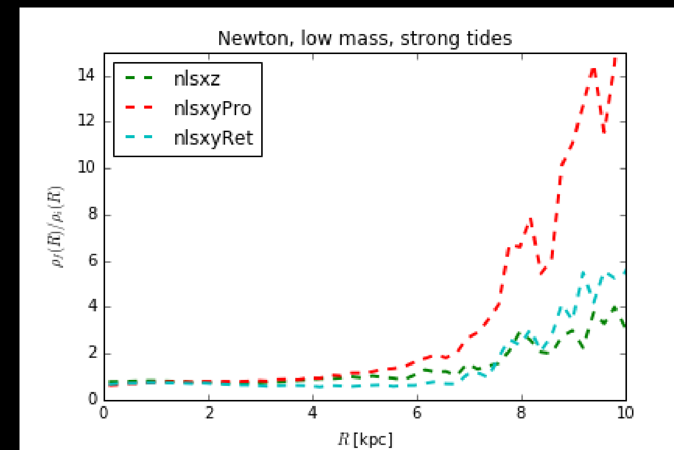


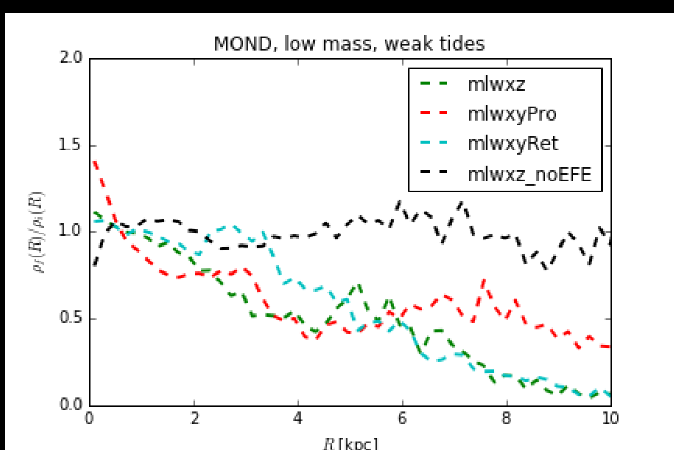
Preliminary results!

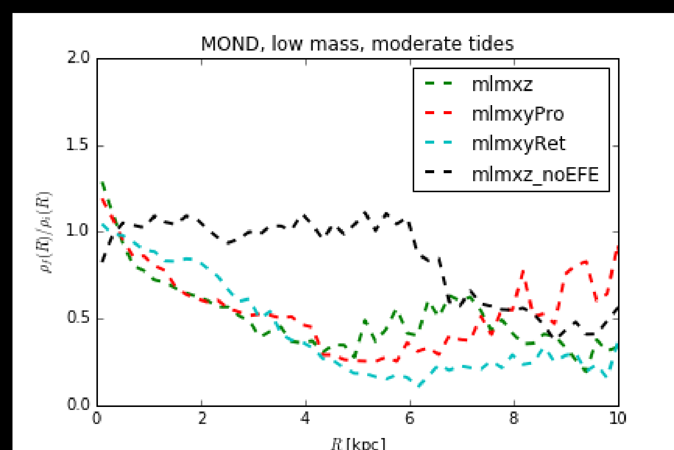
Radial density evolution: low mass

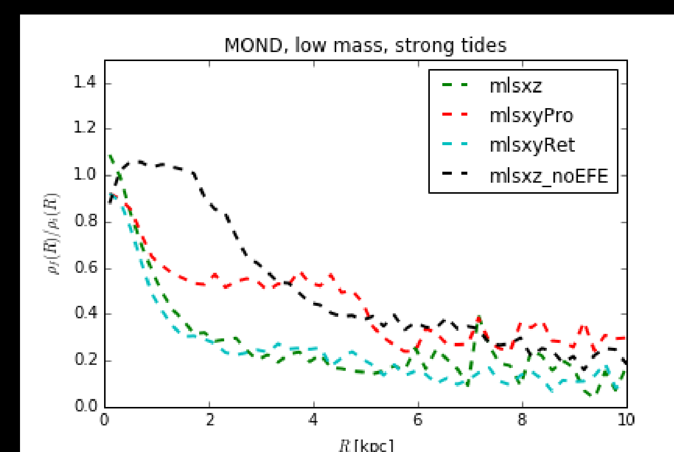






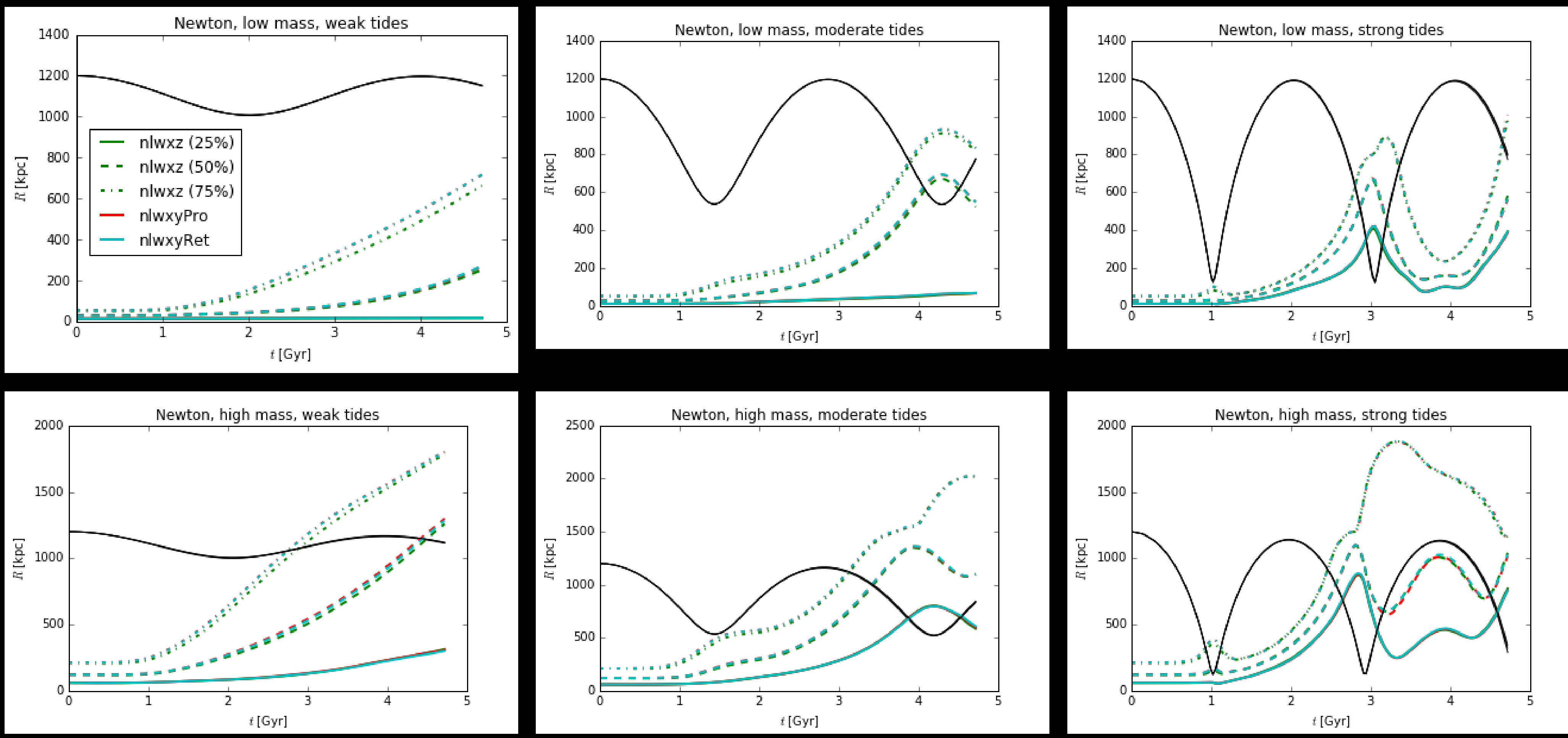






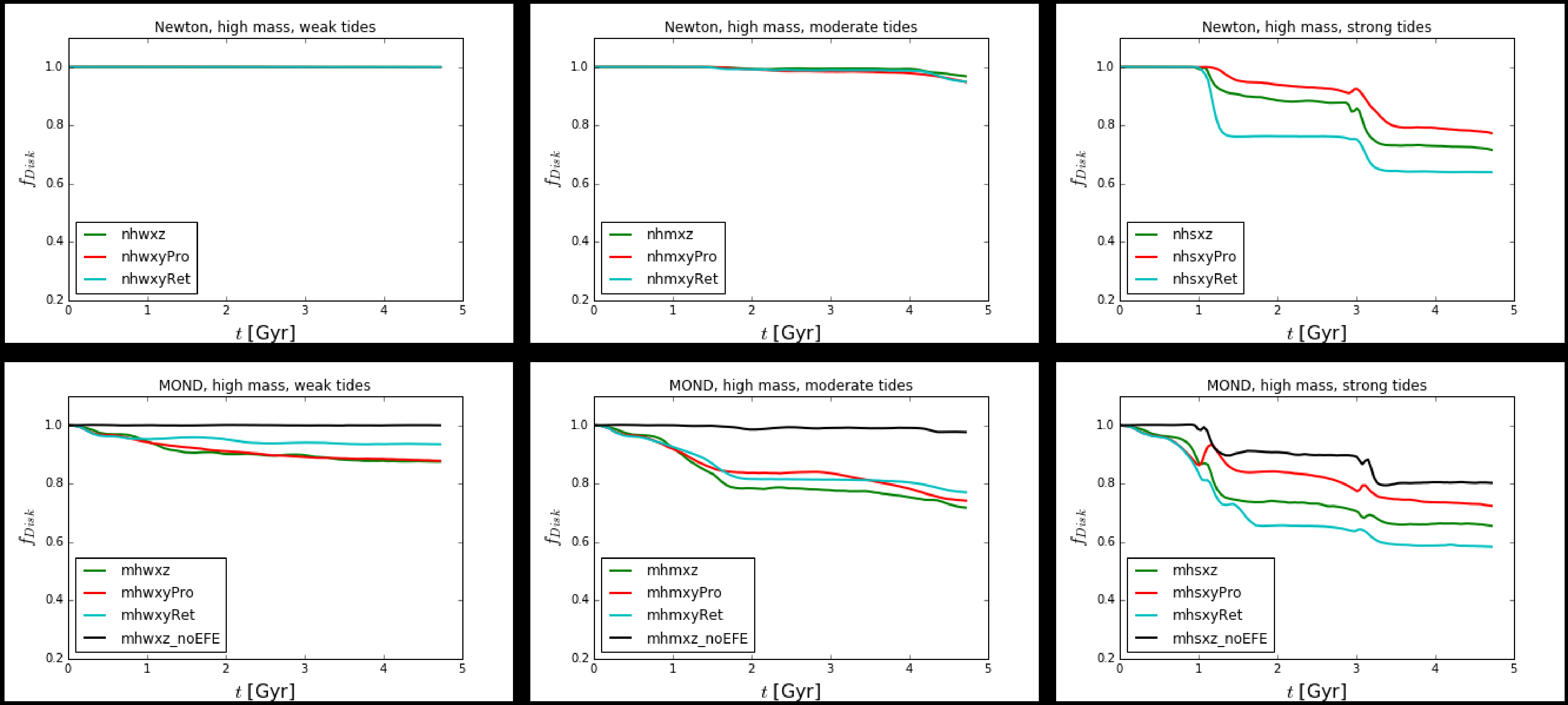
Preliminary results!

Evolution of halo mass loss



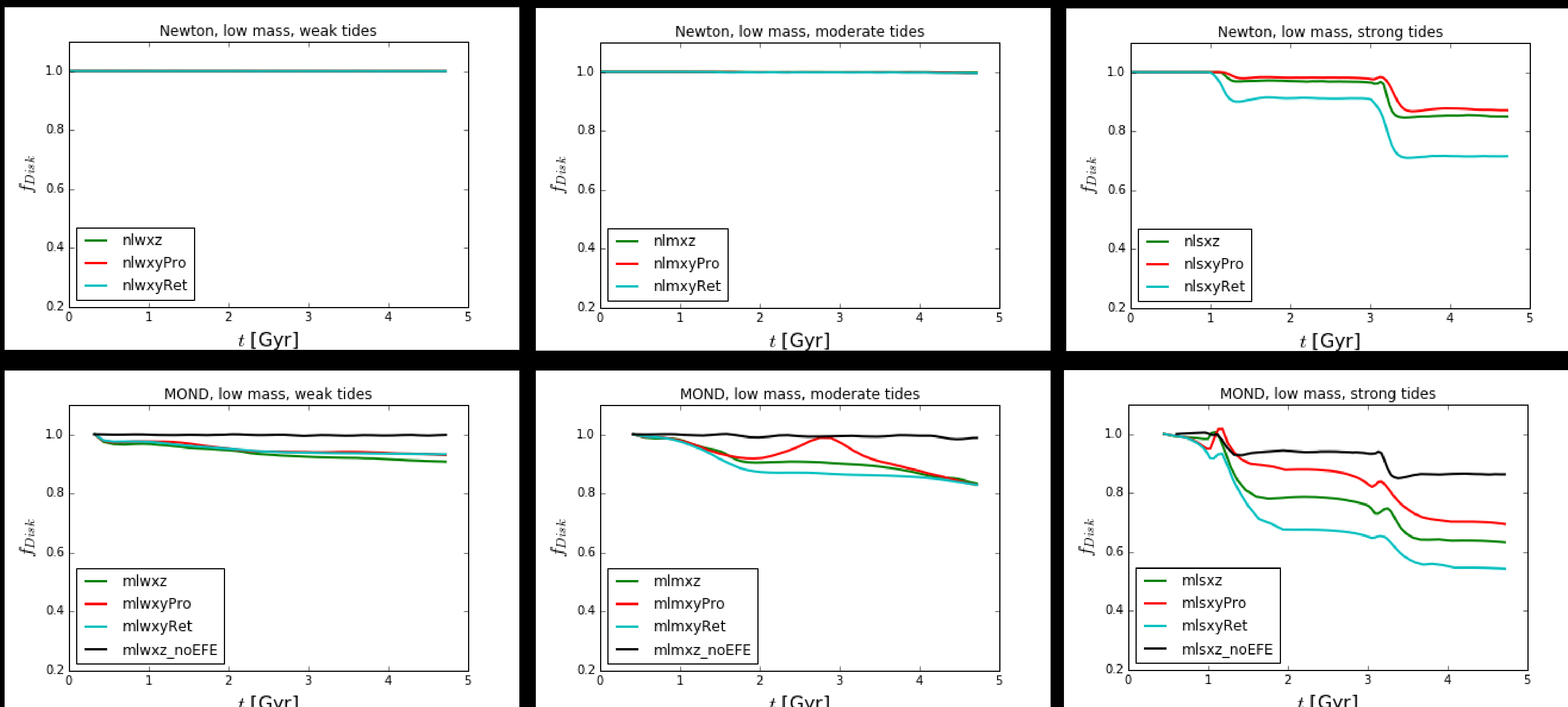
Preliminary results!

Evolution of disk mass loss



Preliminary results!

Evolution of disk mass loss



Preliminary results!

Summary

- The non-linear nature of MOND gravity strongly motivates the use of numerical simulations
- The external field effect may offer a means to find tests of MOND
  - galaxy evolution in MOND is still a largely unexplored area
- MOND galaxies within clusters may generally be more tidally disrupted than their LCDM counterparts

Questions and future prospects

- A full MOND cosmology?
- MOND cosmological simulations, velocity field
  - Candlish 2016, see also Katz et al. 2015
  - Angus et al. 2011, 2013; Llinares et al. 2008, 2009; Knebe & Gibson 2004
- EMOND: remove the remaining mass discrepancy in galaxy clusters?
- Relativistic theories: further MOND effects on non-stationary phenomena?

Questions and future prospects

What about Λ?!