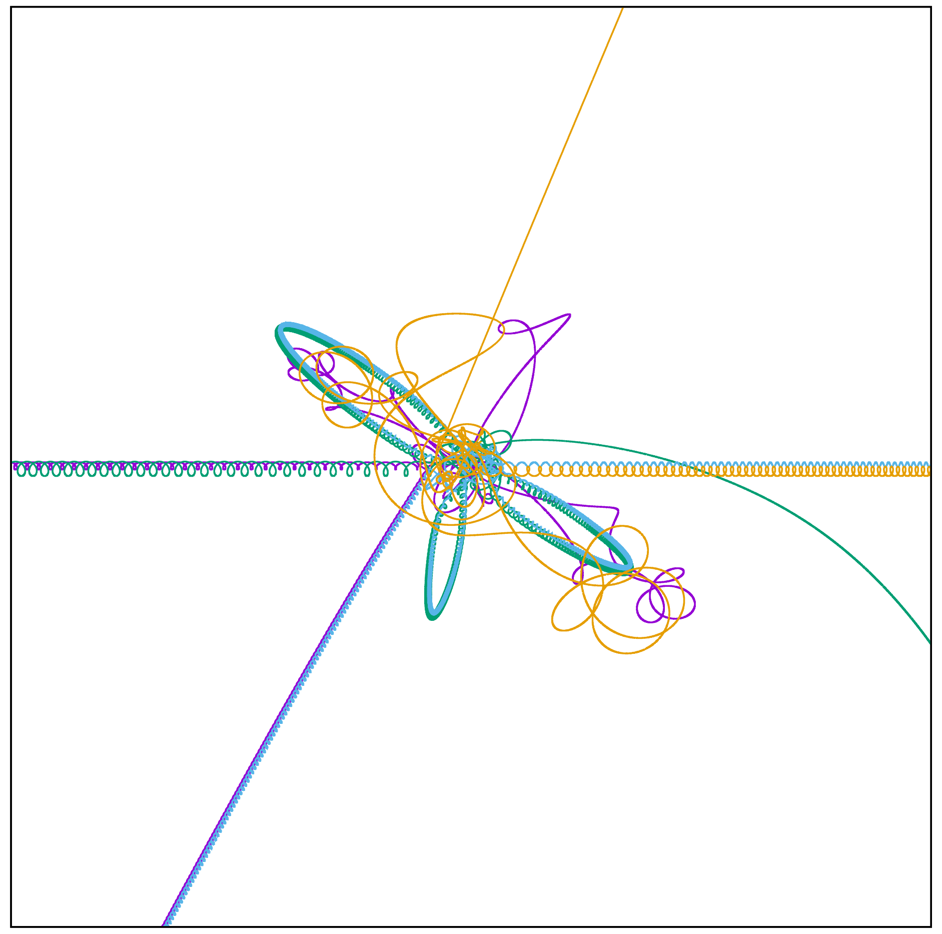
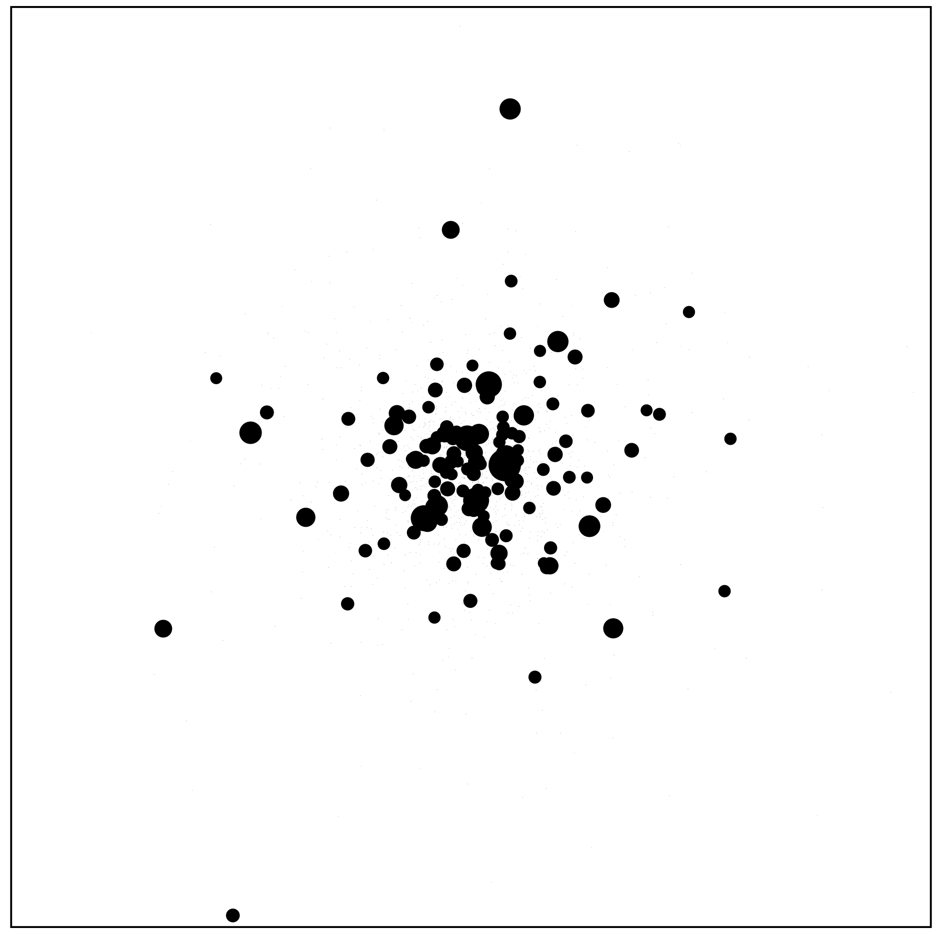


Dynamical evolution of open star clusters in Milgrom-law-dynamics



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From star clusters to field populations, Florence, Villa Galileo, November 2023

Milgromian Dynamics - discretisation

non-conservative field ← conservative field

Milgrom 1983 **Milgrom's law** $$\mu\left(\frac{|\mathbf{a}|}{a_0}\right)\mathbf{a} = \mathbf{g}$$ used here as first step

MoNDian regime | **transition function** | **Newtonian regime**

$$a = \sqrt{a_0 g} \quad \frac{|\mathbf{a}|}{a_0} \ll 1 \quad \longleftarrow \mu(x) \longrightarrow \quad 1 \ll \frac{|\mathbf{a}|}{a_0} \quad a = g$$

$$a_0 \approx 1.2 \times 10^{-8}\,\frac{\mathrm{m}}{\mathrm{s}^2} \approx \frac{cH_0}{2\pi}$$

Bekenstein, Milgrom 1984 **AQUAL** $$\nabla\left(\mu\left(\frac{|\nabla\Phi_{\mathrm{A}}|}{a_0}\right)\nabla\Phi_{\mathrm{A}}\right) = 4\pi G\rho$$

field theories

due to non-linearity very difficult to discretise

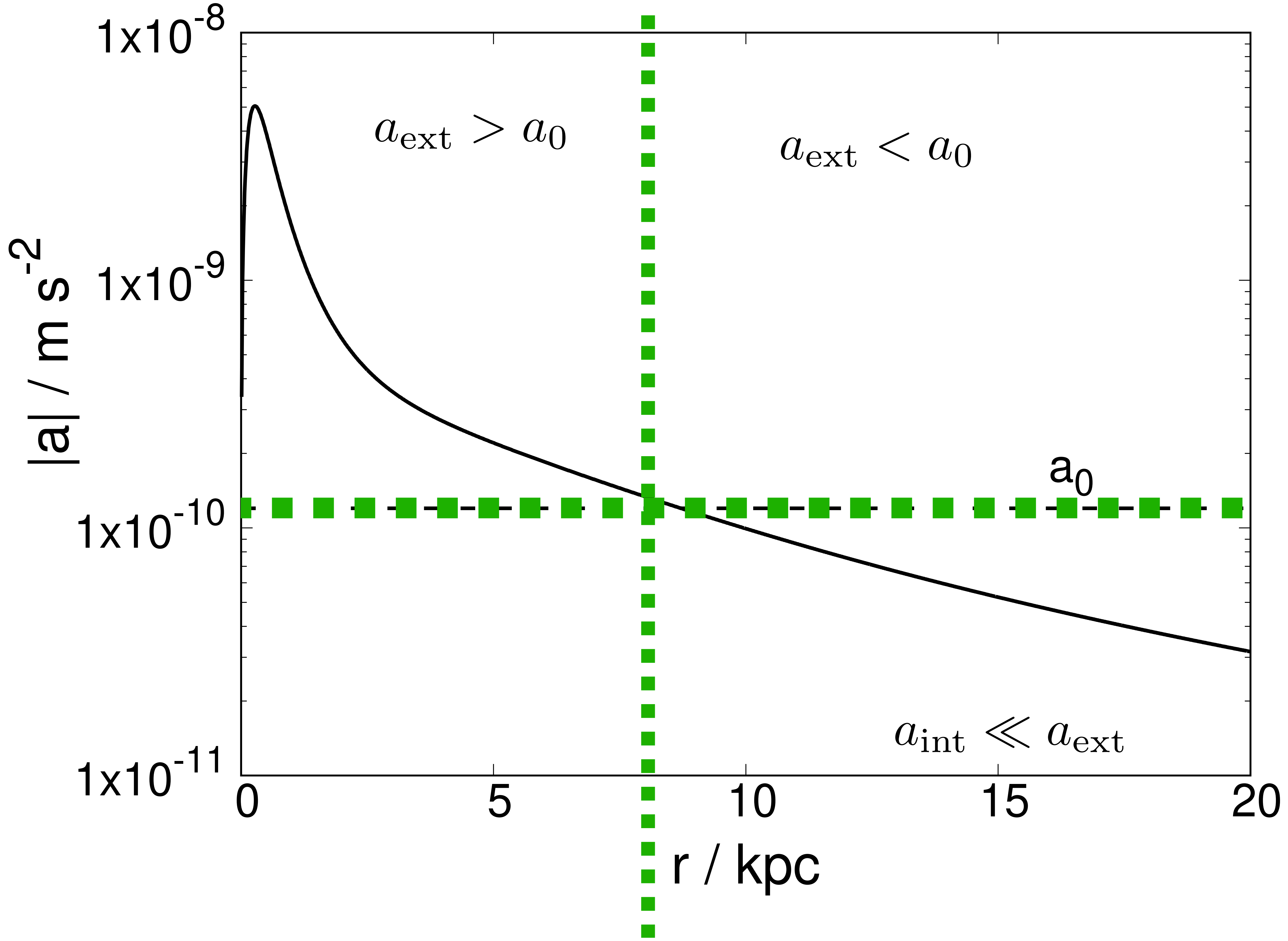
Milgrom 2010 **QMOND** $$\Delta\Phi_{\mathrm{Q}} = \nabla\bullet\left(\nu\left(\frac{|\nabla\Phi_{\mathrm{N}}|}{a_0}\right)\nabla\Phi_{\mathrm{N}}\right)$$

$$\Delta\Phi_{\mathrm{N}} = 4\pi G\rho$$

\

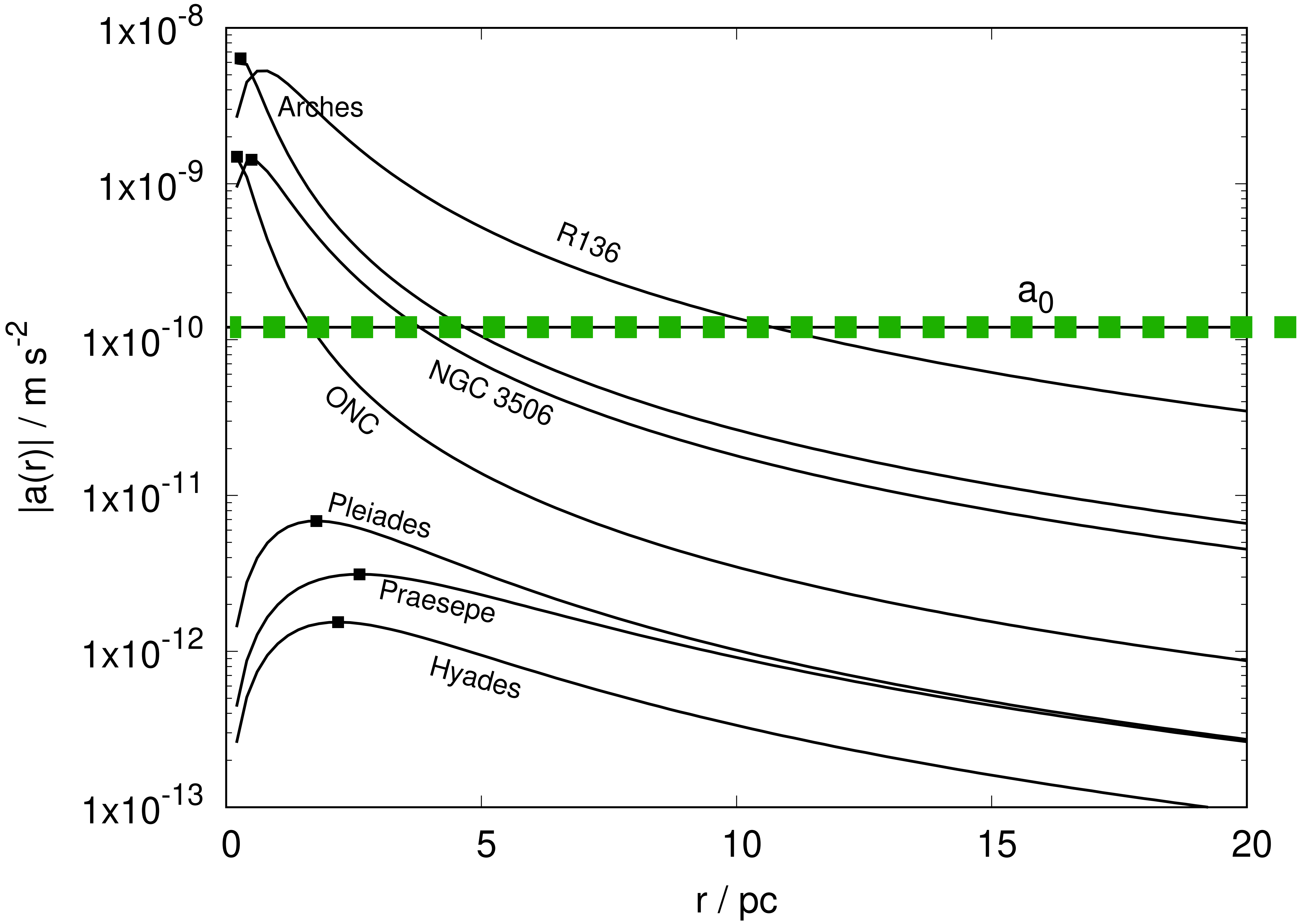
Milky Way acceleration regime

Milky Way: radial acceleration in the mid plane



we are here

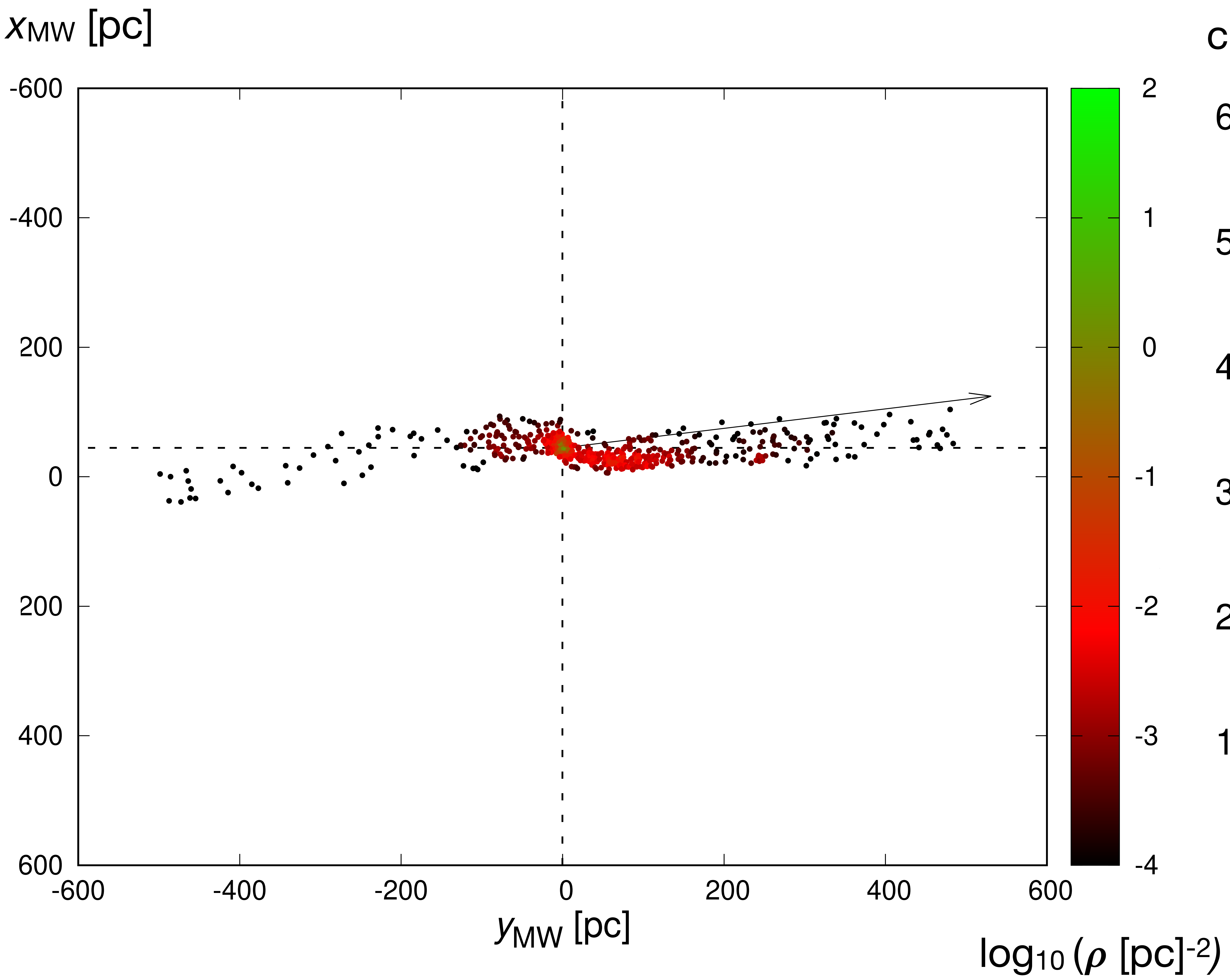
radial internal Newtonian acceleration

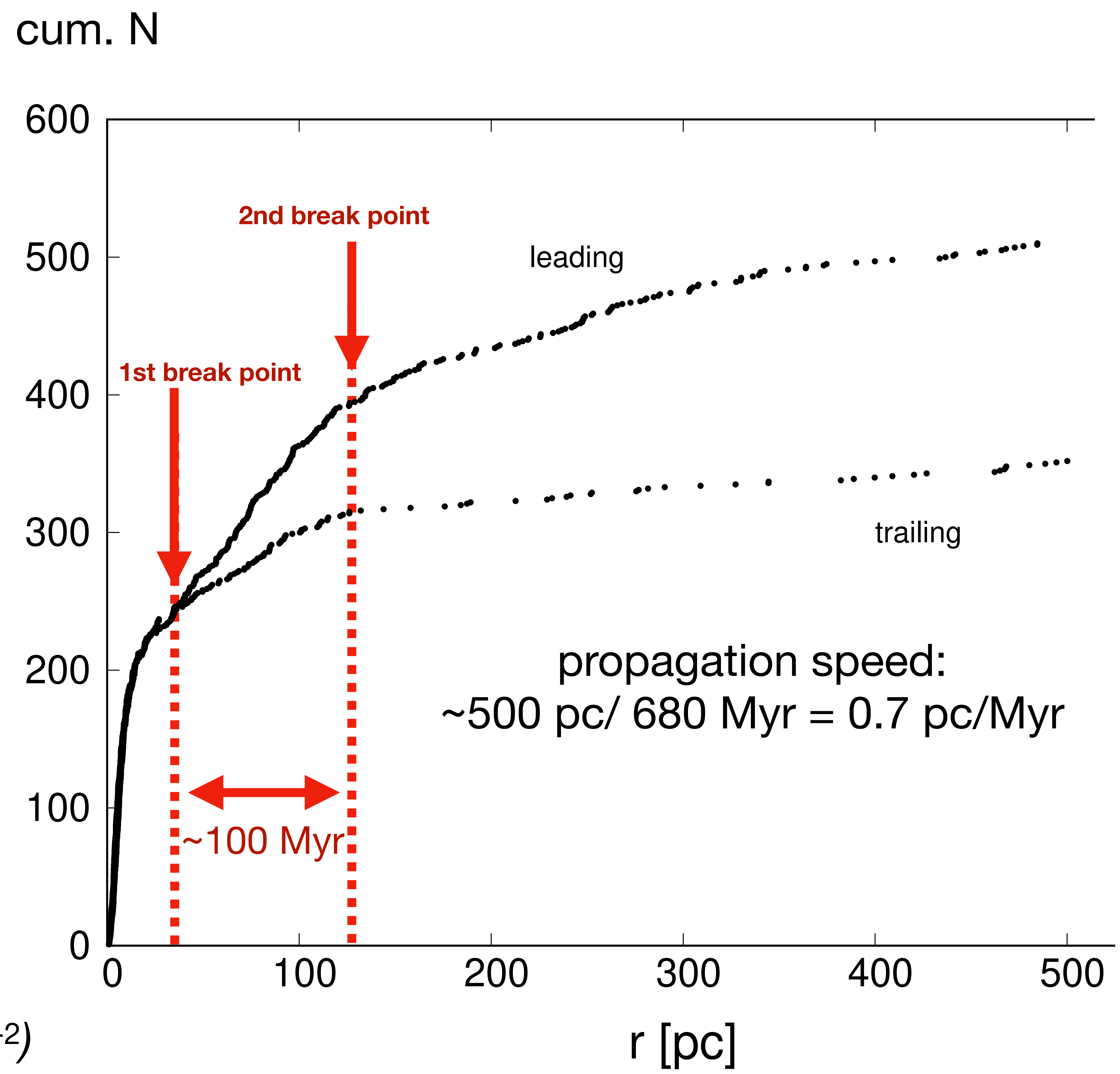


open star cluster are internally MoNDian
but are dominated by the external field -> EFE

Pflamm-Altenburg, in prep

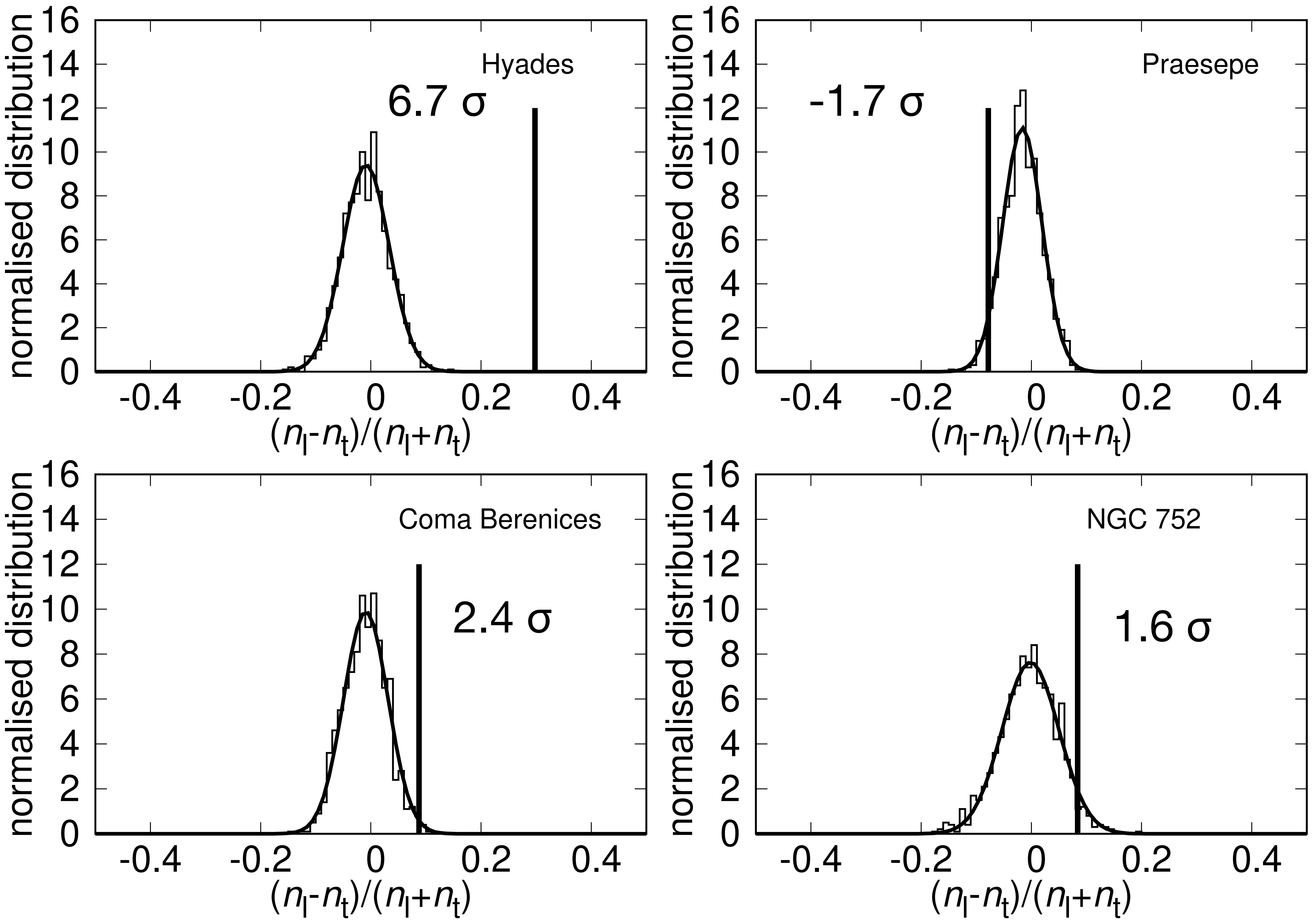
Observed tidal tails of the Hyades





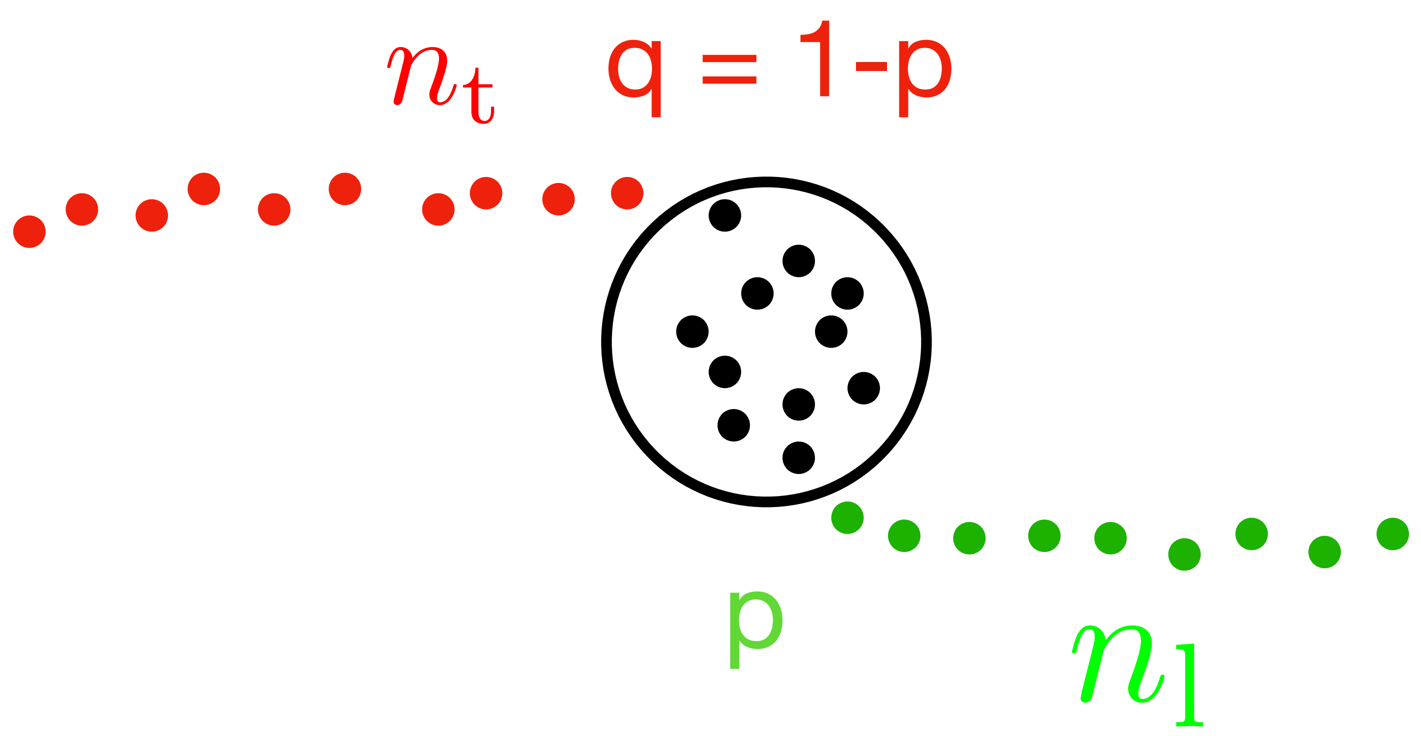
Pflamm-Altenburg, Kroupa, Thies, Jerabkova, Beccari, Prusti, Boffin, 2023

Tidal tails - stochastic Newtonian evaporation



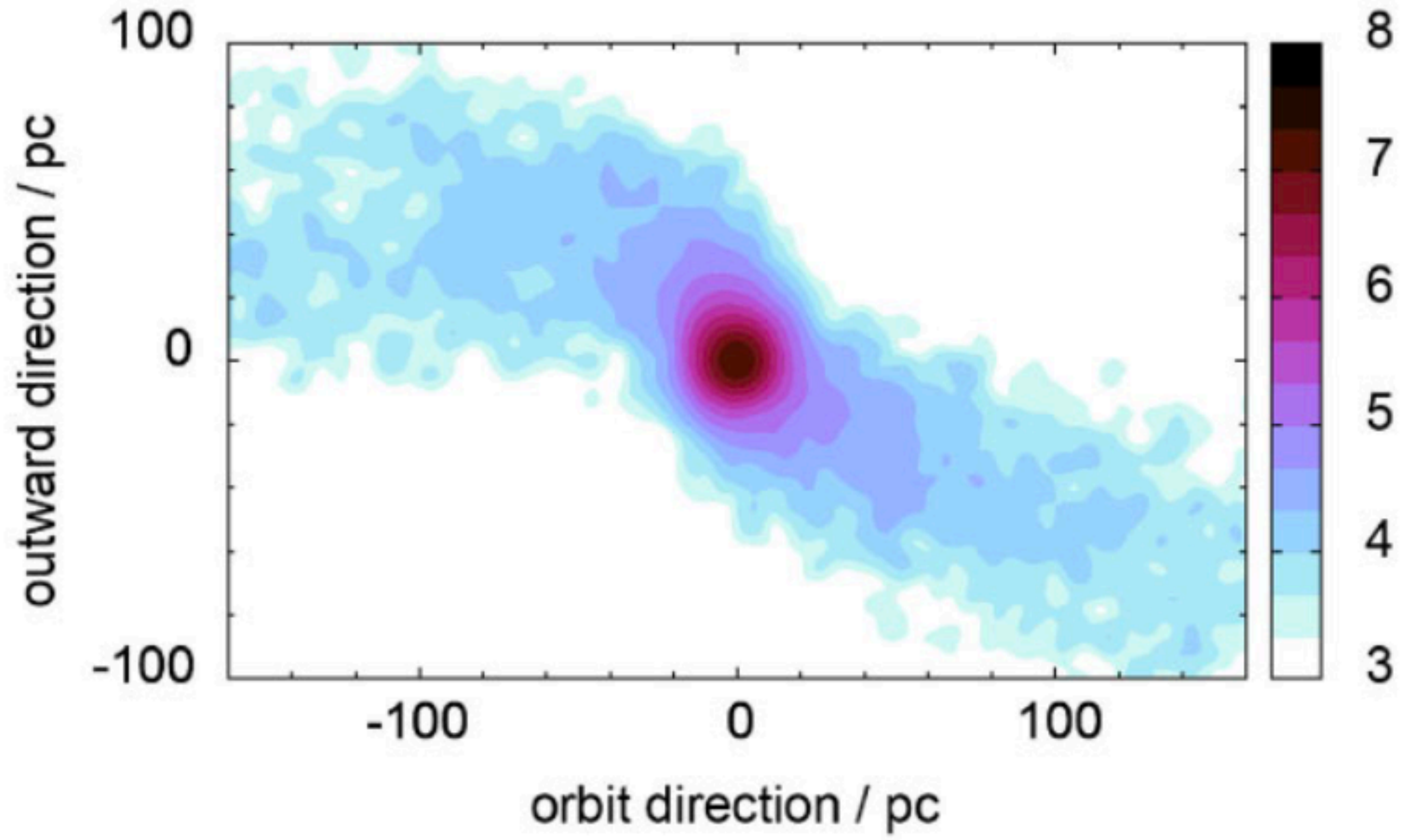
histogramm:
Newtonian monte carlo simulations

solid curve:
Bernoulli experiment ->
Gaussian fit p=0.5

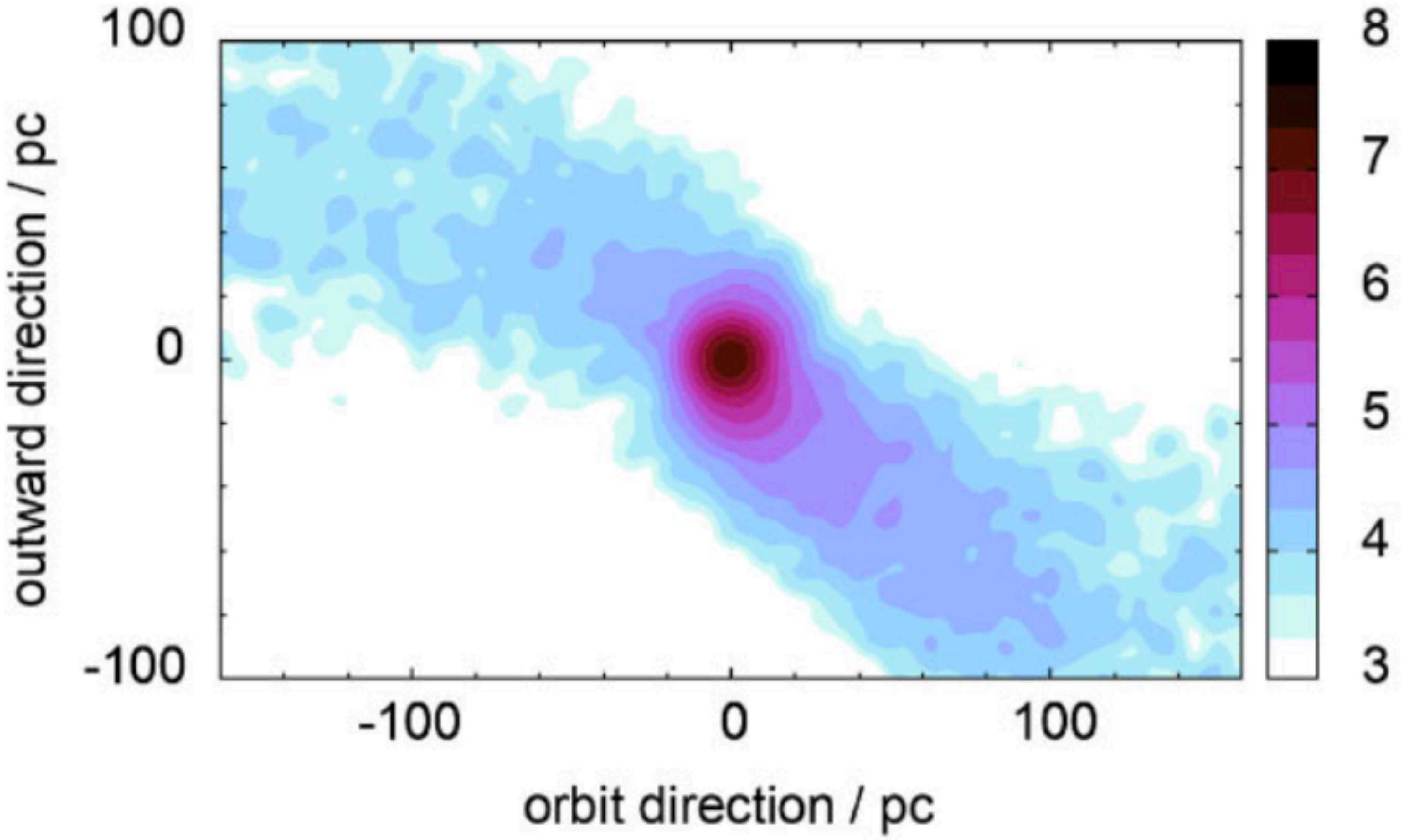


Pflamm-Altenburg, Kroupa, Thies, Jerabkova, Beccari, Prusti, Boffin, 2023

Tidal tails in QUMOND



Newton



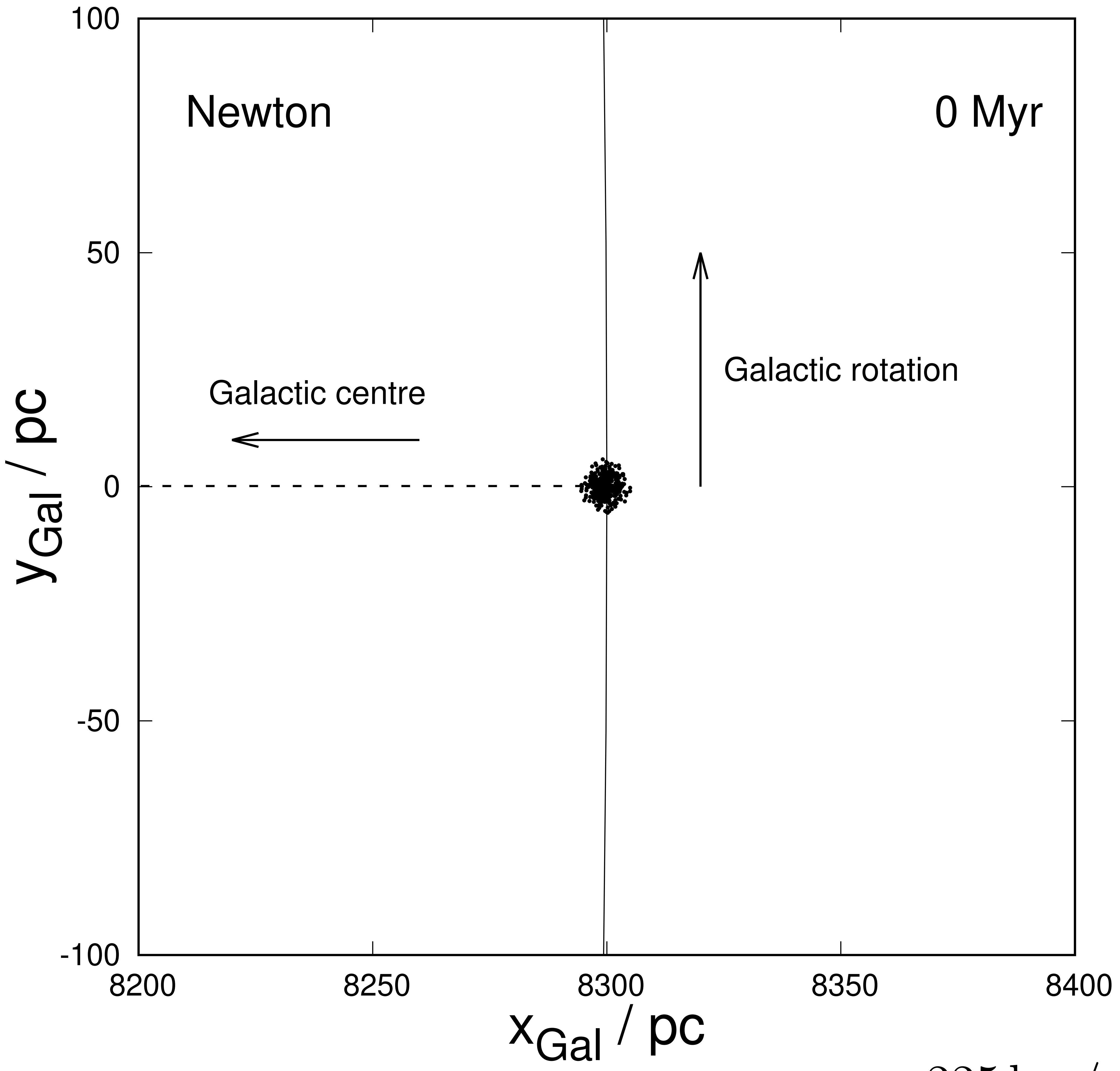
MoND

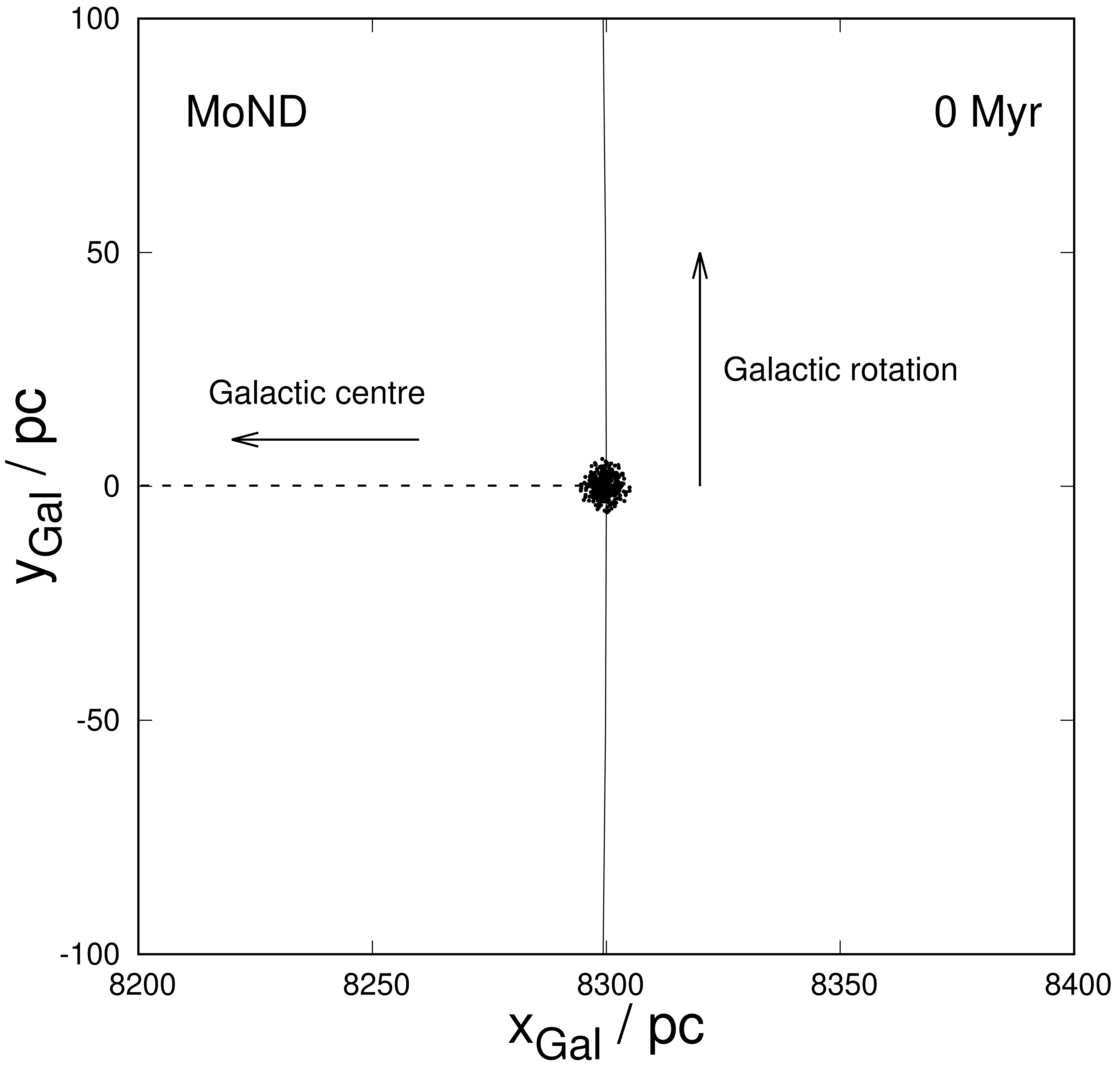
$M = 5000\,M_\odot\ ,\ b = 4.5\,\mathrm{pc}\ ,\ \mathrm{t} = 600\,\mathrm{Myr}$

fewer particle system not feasible in QUMOND due to resolution limits

Kroupa, Jerabkova, Thies, Pflamm-Altenburg, Famaey, Boffin, Dabringhausen, Beccari, Prusti, Boily, Haghi, Wu, Haas, Zonoozi, Thomas, Šubr, Aarseth, 2022, Fig. 8

Star cluster evolution in discrete Milgrom law dynamics





$N = 400\ ;\ M = 200\,M_\odot$

$v_{\rm rot} = 225\,{\rm km/s}$

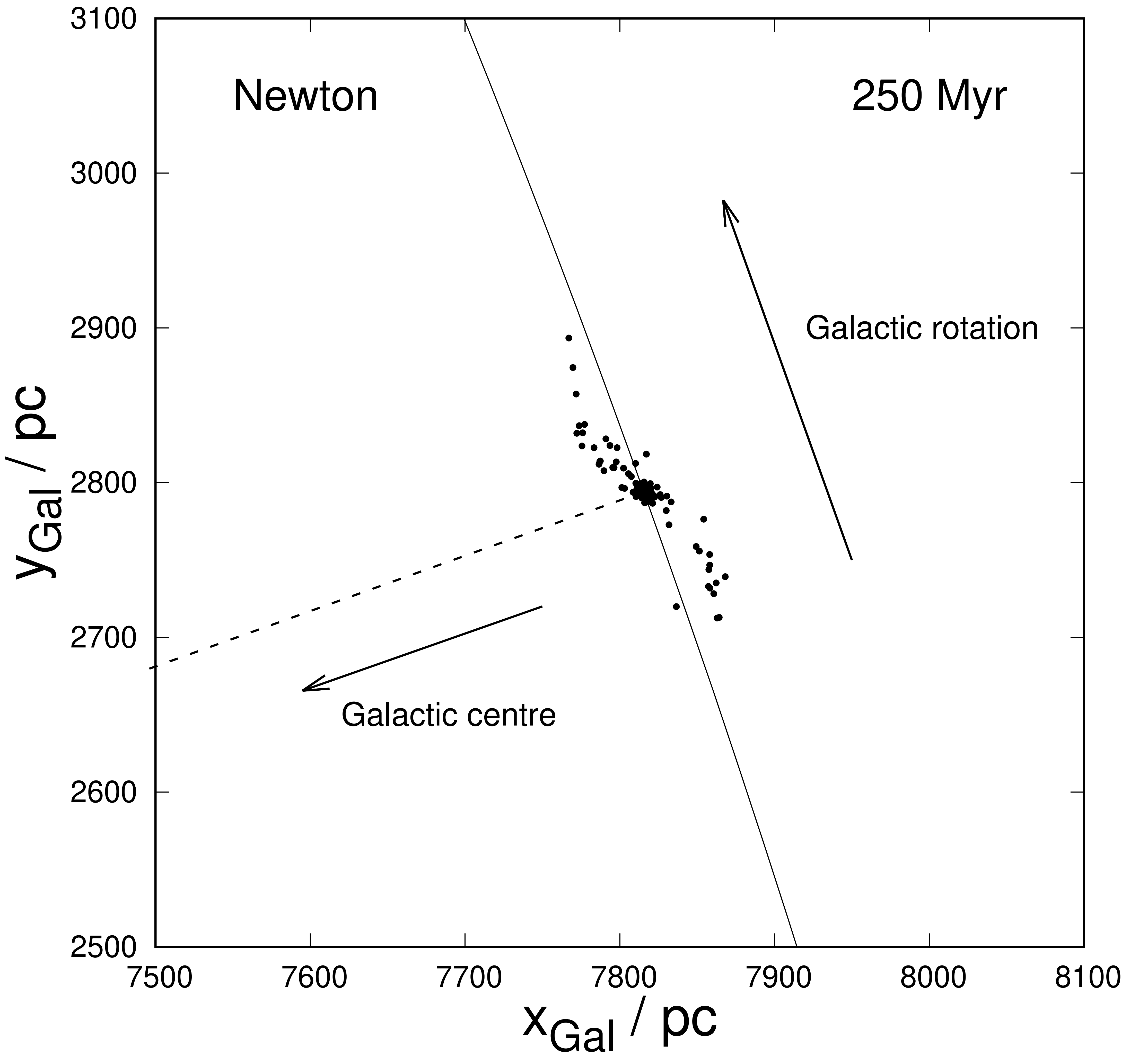
$b = 3.1\,{\rm pc} \quad R_0 = 8300\,{\rm pc}$

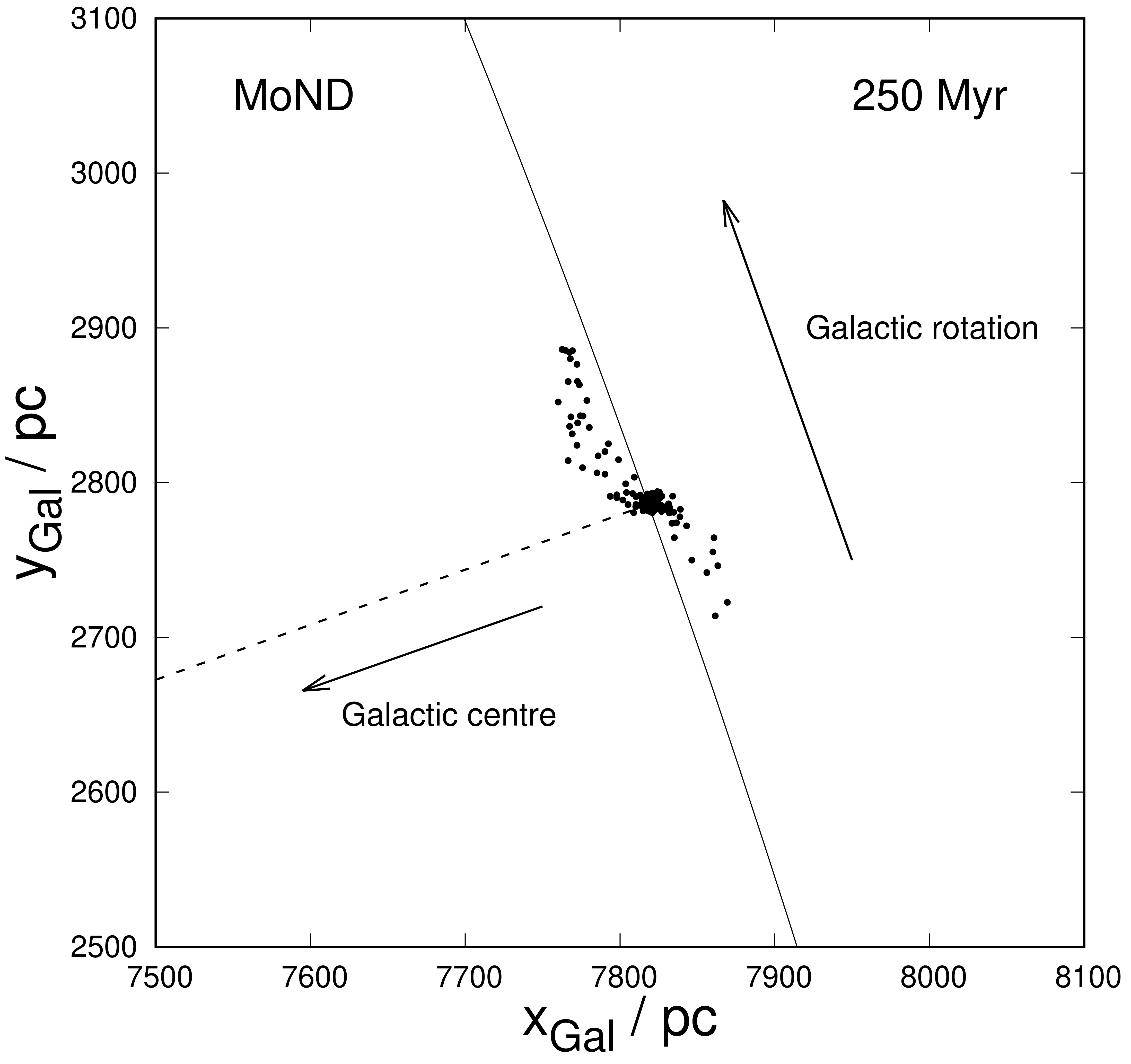
circular orbit

smoothing = 0.001 pc

Pflamm-Altenburg, submitted

Star cluster evolution in discrete Milgrom law dynamics

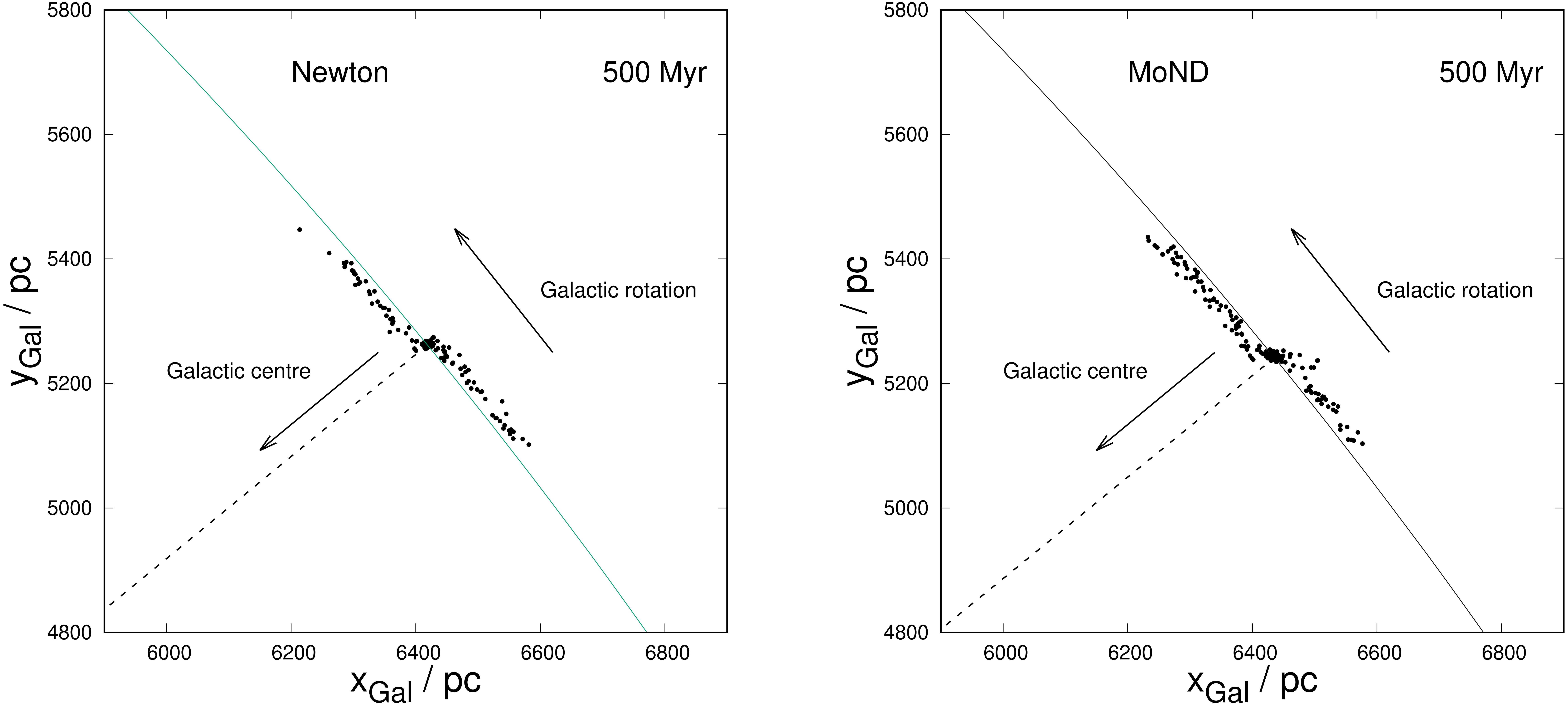




$N = 400\ ;\ M = 200\, M_{\odot}$

Pflamm-Altenburg, submitted

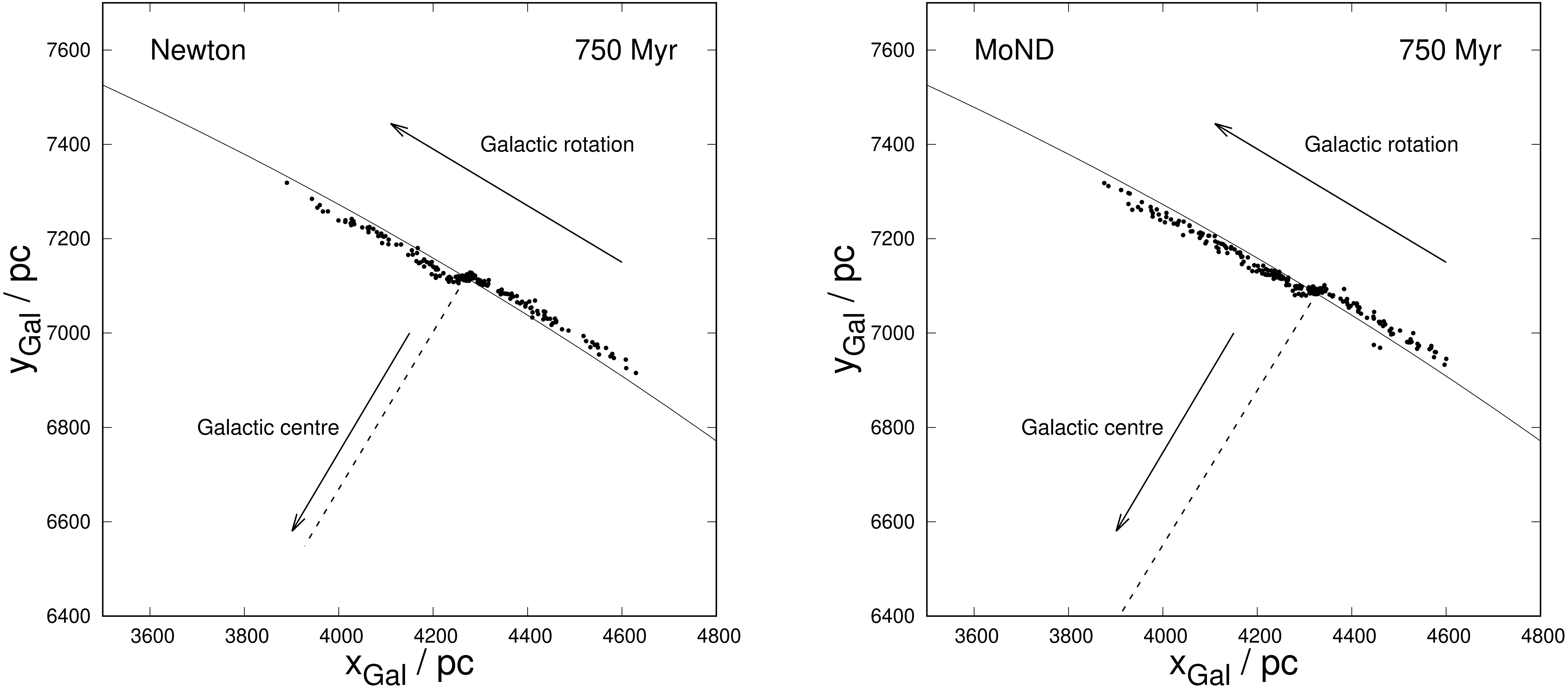
Star cluster evolution in discrete Milgrom law dynamics



$N = 400\ ;\ M = 200\,M_\odot$

Pflamm-Altenburg, submitted

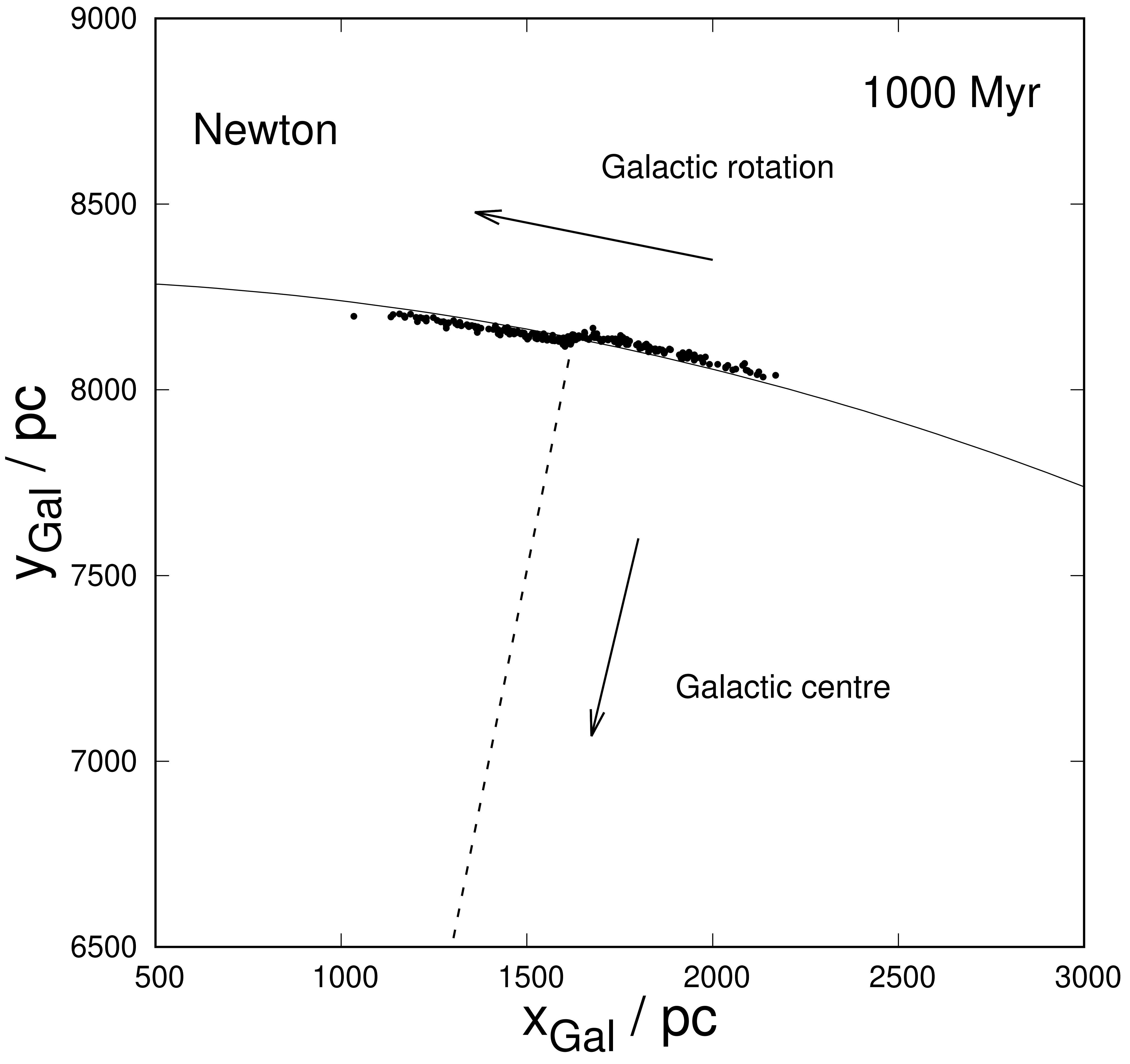
Star cluster evolution in discrete Milgrom law dynamics

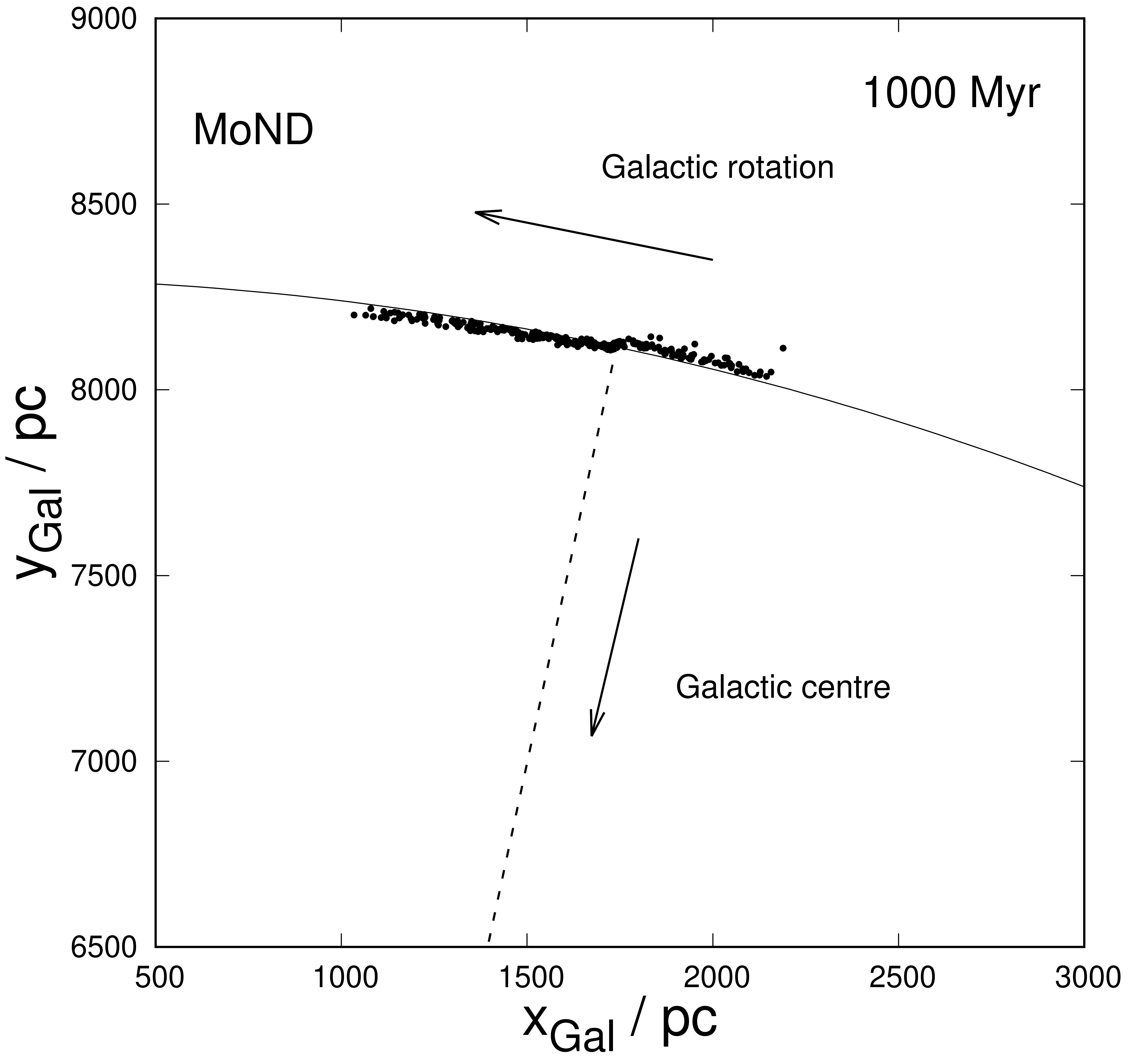


$N = 400\ ;\ M = 200\, M_{\odot}$

Pflamm-Altenburg, submitted

Star cluster evolution in discrete Milgrom law dynamics

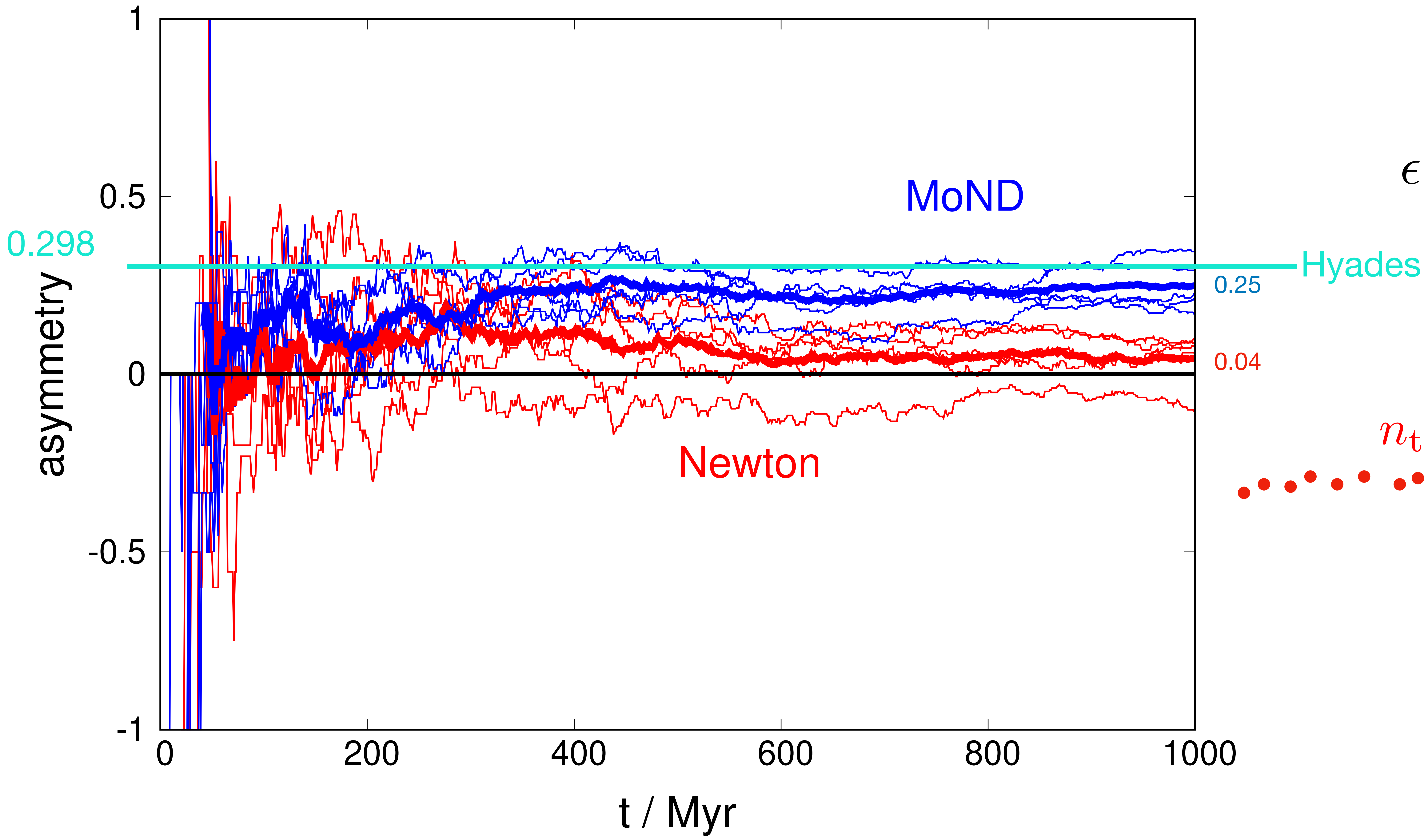




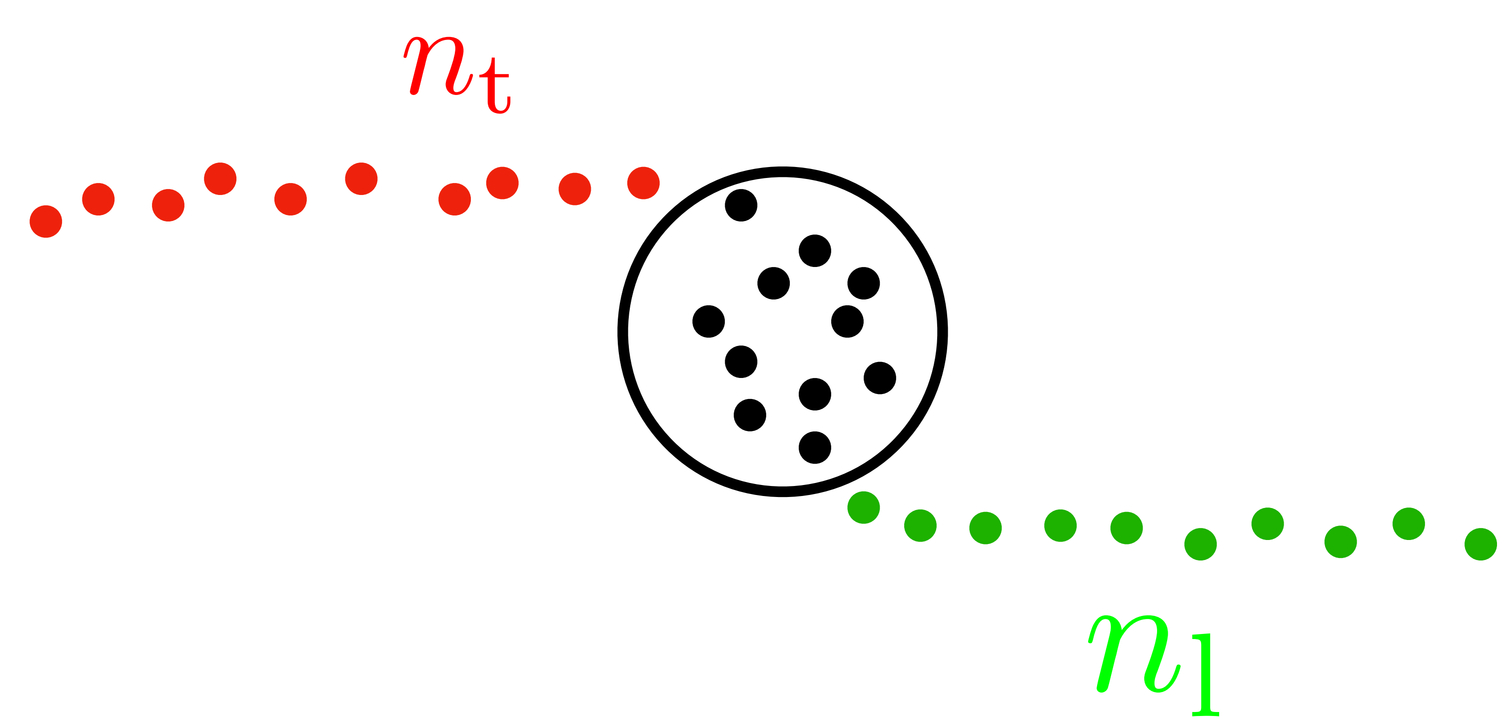
$N = 400\ ;\ M = 200\, M_\odot$

Pflamm-Altenburg, submitted

Asymmetry evolution of tidal tails in Milgrom law dynamics



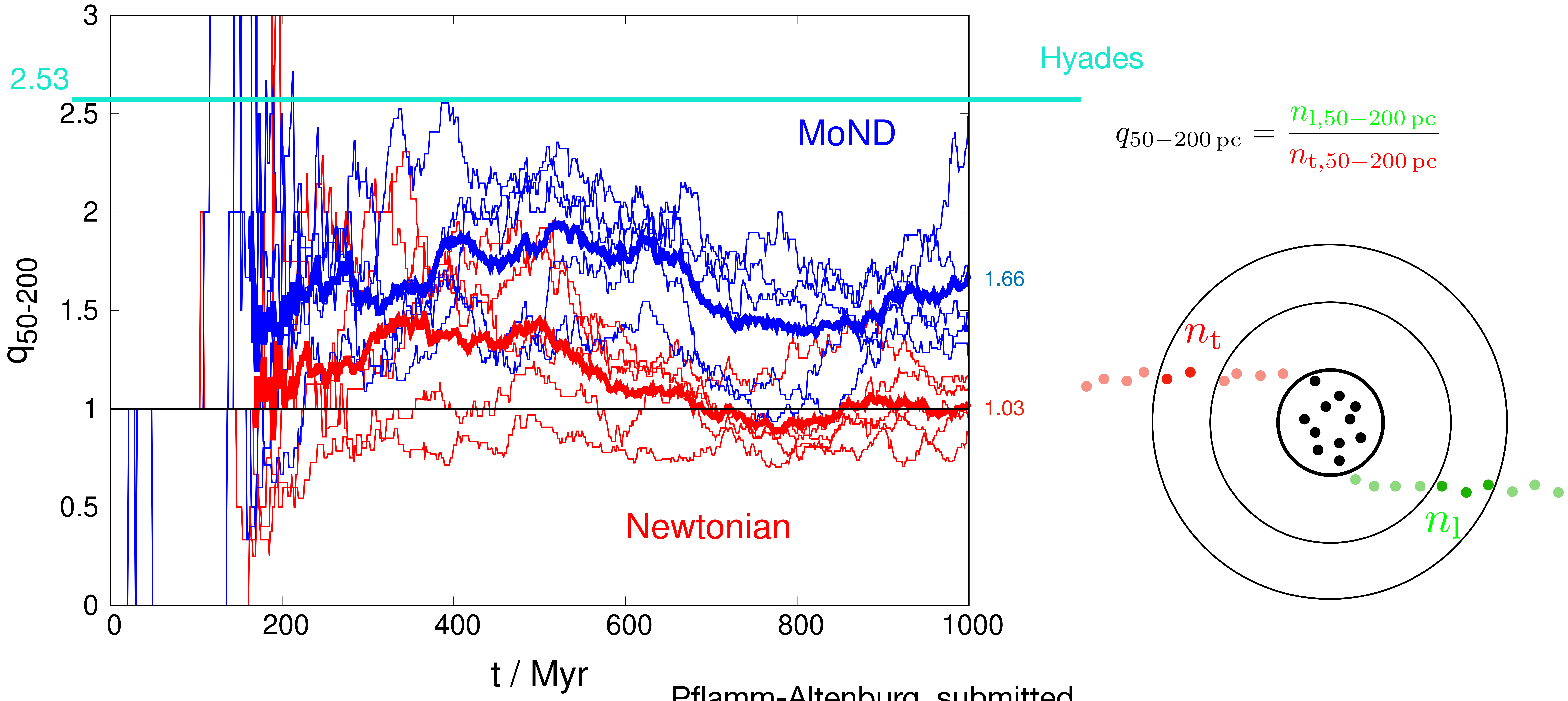
$$\epsilon = \frac{n_\mathrm{l} - n_\mathrm{t}}{n_\mathrm{l} + n_\mathrm{t}}$$



$N = 400\ ;\ M = 200\, M_\odot$

Pflamm-Altenburg, submitted

q-parameter evolution of tidal tails in Milgrom law dynamics

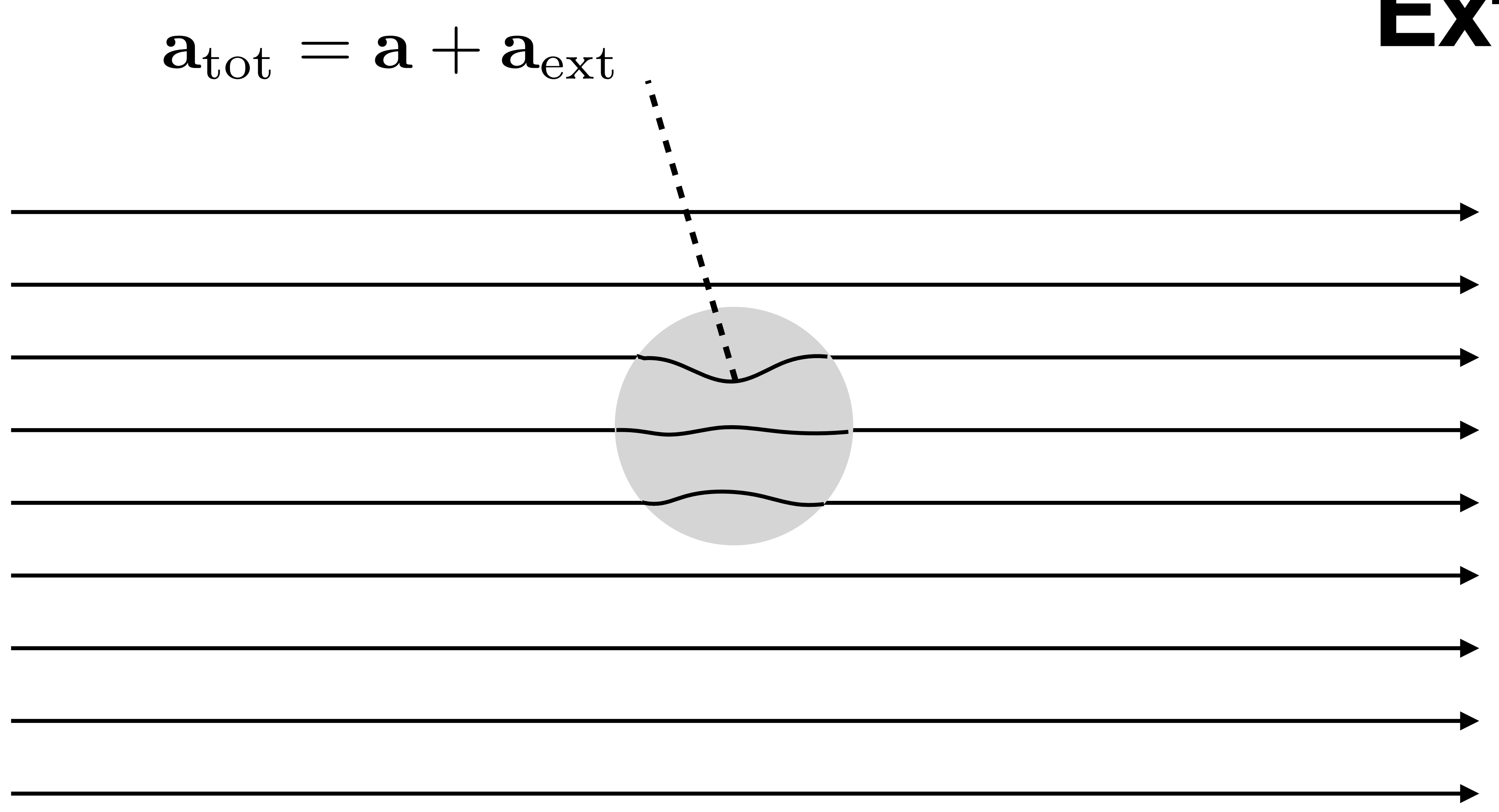


$$q_{50-200\,\mathrm{pc}} = \frac{n_{\mathrm{l},50-200\,\mathrm{pc}}}{n_{\mathrm{t},50-200\,\mathrm{pc}}}$$

$N = 400\ ;\ M = 200\,M_\odot$

Pflamm-Altenburg, submitted

External field effect



boundary conditions

$$-\nabla\Phi_{\text{G}} = \mathbf{a}_{\text{ext}} \approx const.$$

internal acceleration:

$$\mathbf{a} := \mathbf{a}_{\text{tot}} - \mathbf{a}_{\text{ext}}$$

considered as perturbation of the (constant external field)

$$|\mathbf{a}| \ll |\mathbf{a}_{\mathbf{ext}}|$$

small perturbation, **on the whole domain!**

fulfilled by open star clusters in the Galactic field

AQUAL: $\nabla\left(\mu(|\mathbf{a}_{\mathbf{tot}}|/a_0)\mathbf{a}_{\mathbf{tot}}\right) = 4\pi G\rho$ → effective Poisson equation: $\Delta'\Phi = 4\pi G'\rho'$

1) stretching along external field: $G' = \dfrac{G}{\mu_{\text{ext}}}$ $\qquad G' = \dfrac{G}{\mu_{\text{ext}}} > G$ **stronger internal dynamics**

2) stretching along external field: $z' = \dfrac{1}{\sqrt{1+L_0}}z$ $\qquad L_0 := \dfrac{\mu'_{\text{ext}}}{\mu_{\text{ext}}}\dfrac{a_{\text{ext}}}{a_0} > 0$ **asymmetry**

$$\sqrt{1+L_0} > 1 \longrightarrow z' = \frac{1}{\sqrt{1+L_0}}z < z$$

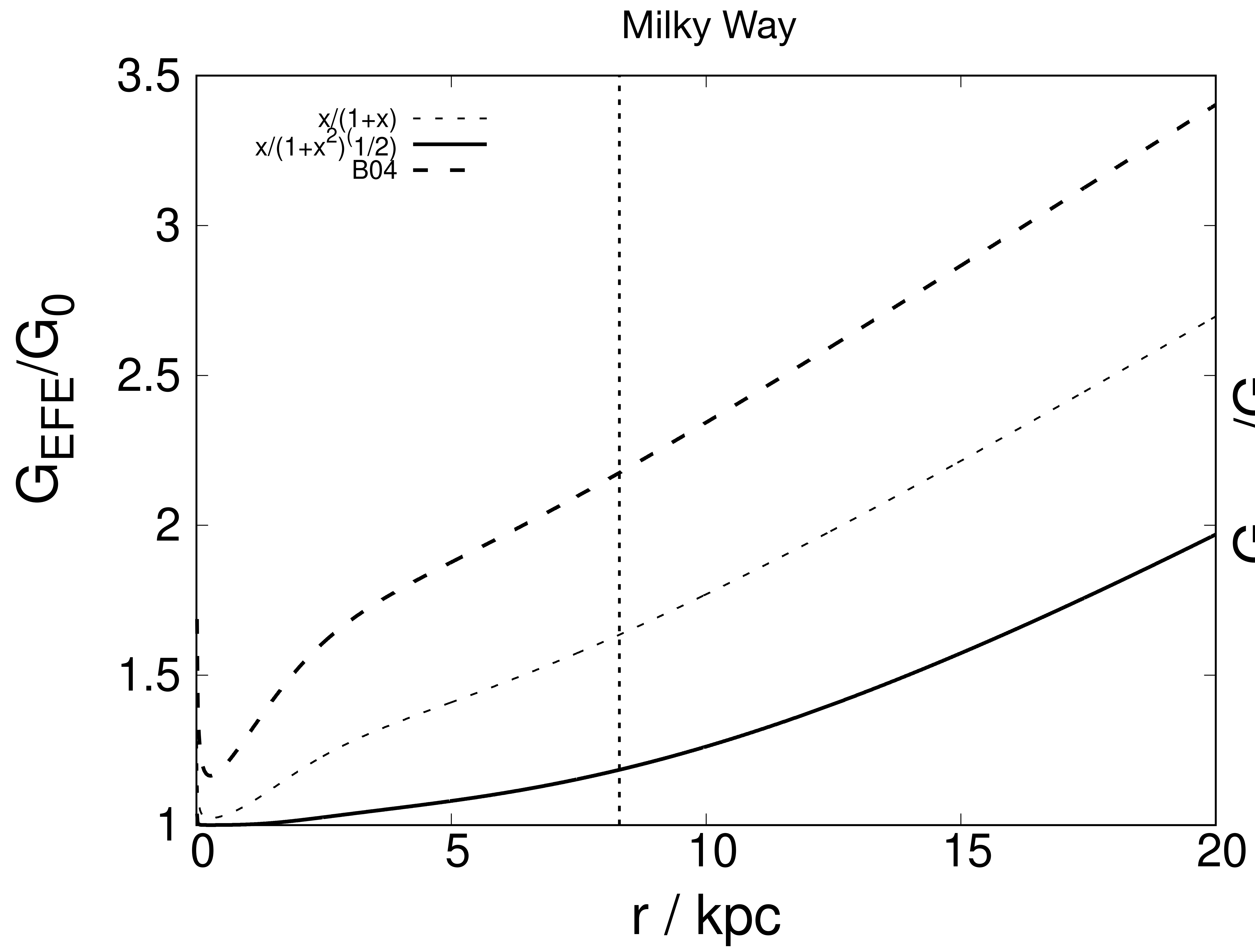
e.g. Bekenstein & Milgrom (1984), Milgrom (1986), Banik & Zhao (2015)

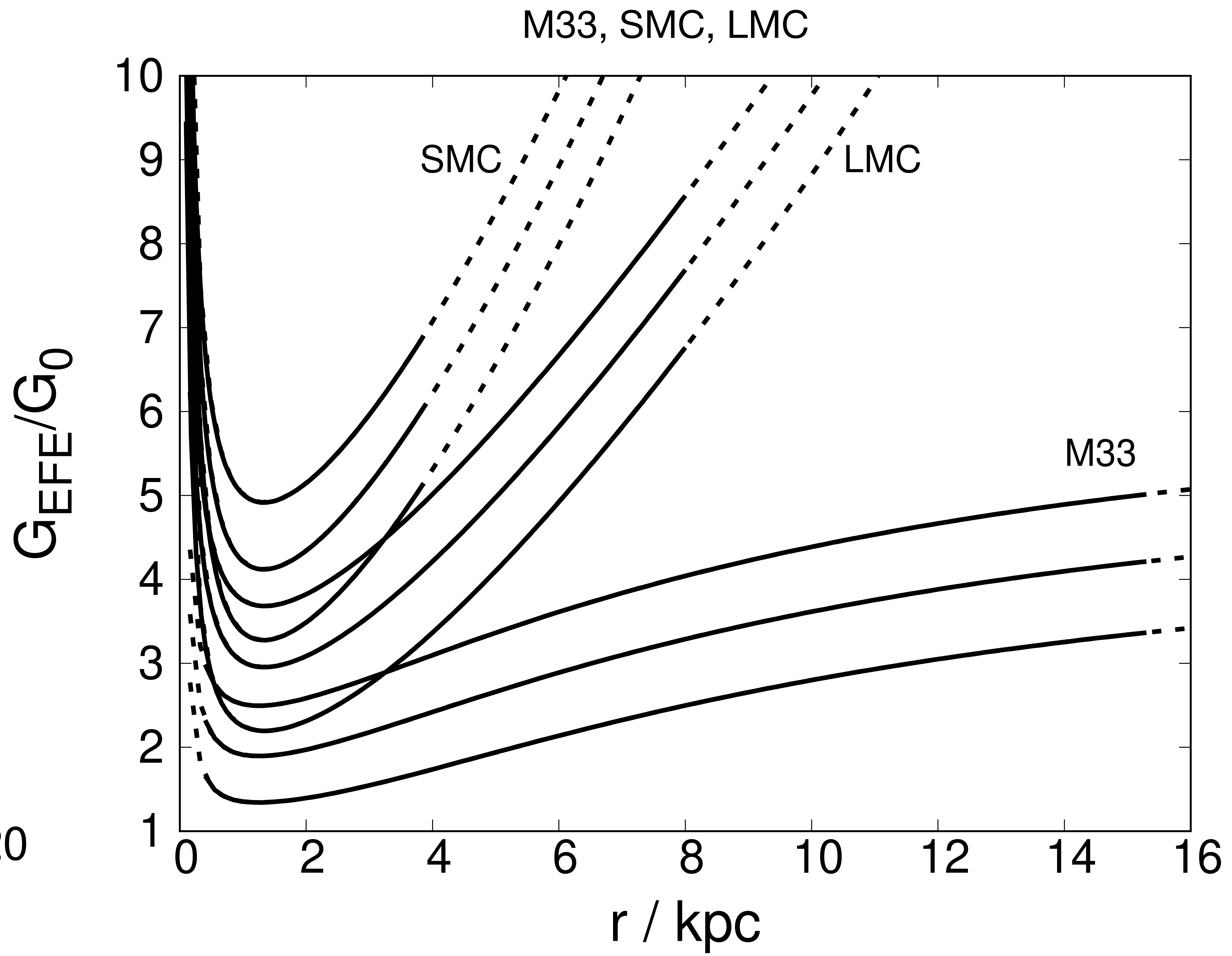
Dynamical masses of the Pleiades

Newton:	$\sigma^2 \approx \frac{G}{2}\frac{M}{r_\mathrm{h}}$	$M \approx \frac{2\sigma^2 r_\mathrm{h}}{G}$	$M \approx 1200\ \mathrm{M}_\odot$	too high?
observed:	r_h = 3.2 pc	$\sigma_\mathrm{l.o.s}$ = 0.48 km/s σ = 0.83 km/s	$M_\star \approx 800\ \mathrm{M}_\odot$	
isolated MoND:		$M = \frac{81}{4}\frac{\sigma^4_\mathrm{l.o.s}}{a_0 G}$	$M \approx 63\ \mathrm{M}_\odot$	too low!

Pflamm-Altenburg, in prep

Local Group galaxies: radial effective Gravitational constant





hot but virialised star clusters

Pflamm-Altenburg (in prep.)

Star cluster dissolution rate expected from the EFE

dissolution time scale of star clusters

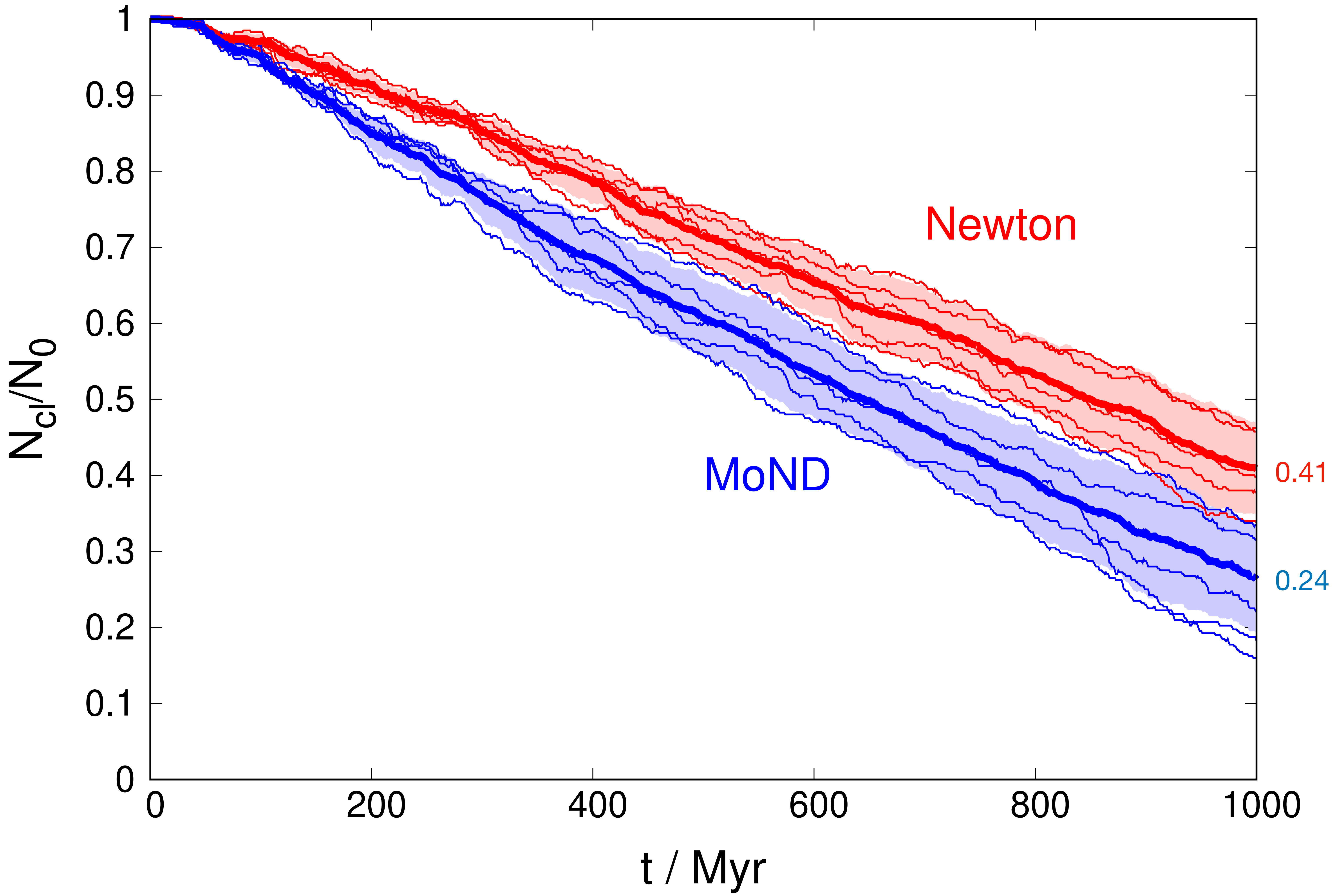
$$T_{\rm diss} = k' \left[\frac{N^{1/2}\, r_{\rm h}^{3/2}}{G^{1/2}\, m^{1/2}\ \ln(\gamma N)} \right]^{x} \left[\frac{r_{\rm h}^{3/2}}{G^{1/2}\, N^{1/2}\, m^{1/2}} \right]^{1-x}$$

Baumgardt, Makino 2003

$$T_{\rm diss} \propto \frac{1}{\sqrt{G}} \qquad G\uparrow \longrightarrow T_{\rm diss}\downarrow \qquad G_{\rm EFE} \approx 1.2 \ldots 1.5\, G$$

$$\frac{T_{\rm diss,EFE}}{T_{\rm diss}} = \sqrt{\frac{G}{G_{\rm EFE}}} = 0.81 \ldots 0.91$$

star cluster dissolution in Milgrom law dynamics



$$\frac{T_{\rm diss,EFE}}{T_{\rm diss}} = \frac{\dot{N}_{\rm N}}{\dot{N}_{\rm M}} = 0.80$$

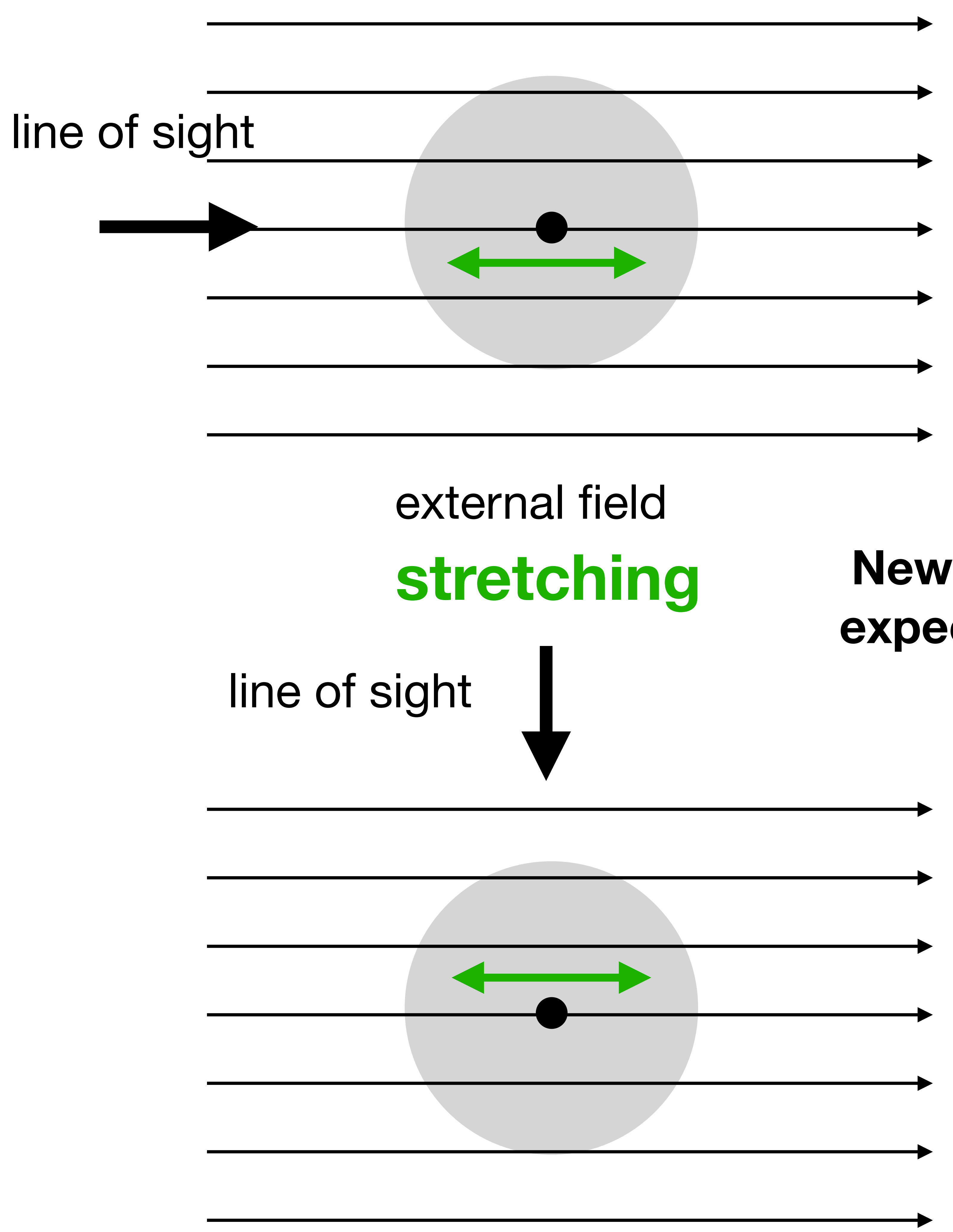
$$\dot{N}_{\rm N} = \frac{0.236\,\rm stars}{\rm Myr} = \frac{1\,\rm star}{4.2\,\rm Myr}$$

$$\dot{N}_{\rm M} = \frac{0.296\,\rm stars}{\rm Myr} = \frac{1\,\rm star}{3.4\,\rm Myr}$$

$N = 400\ ;\ M = 200\,M_\odot$ Pflamm-Altenburg, submitted

evaporation ~25% faster in MOND

Asymmetric velocity dispersion tensor
A prediction!



$$\frac{<\sigma_r>^2}{<\sigma_t>^2} = \frac{1+L_0}{2}$$

$$\approx 0.63 \ldots 0.68$$

Newtonian expectation

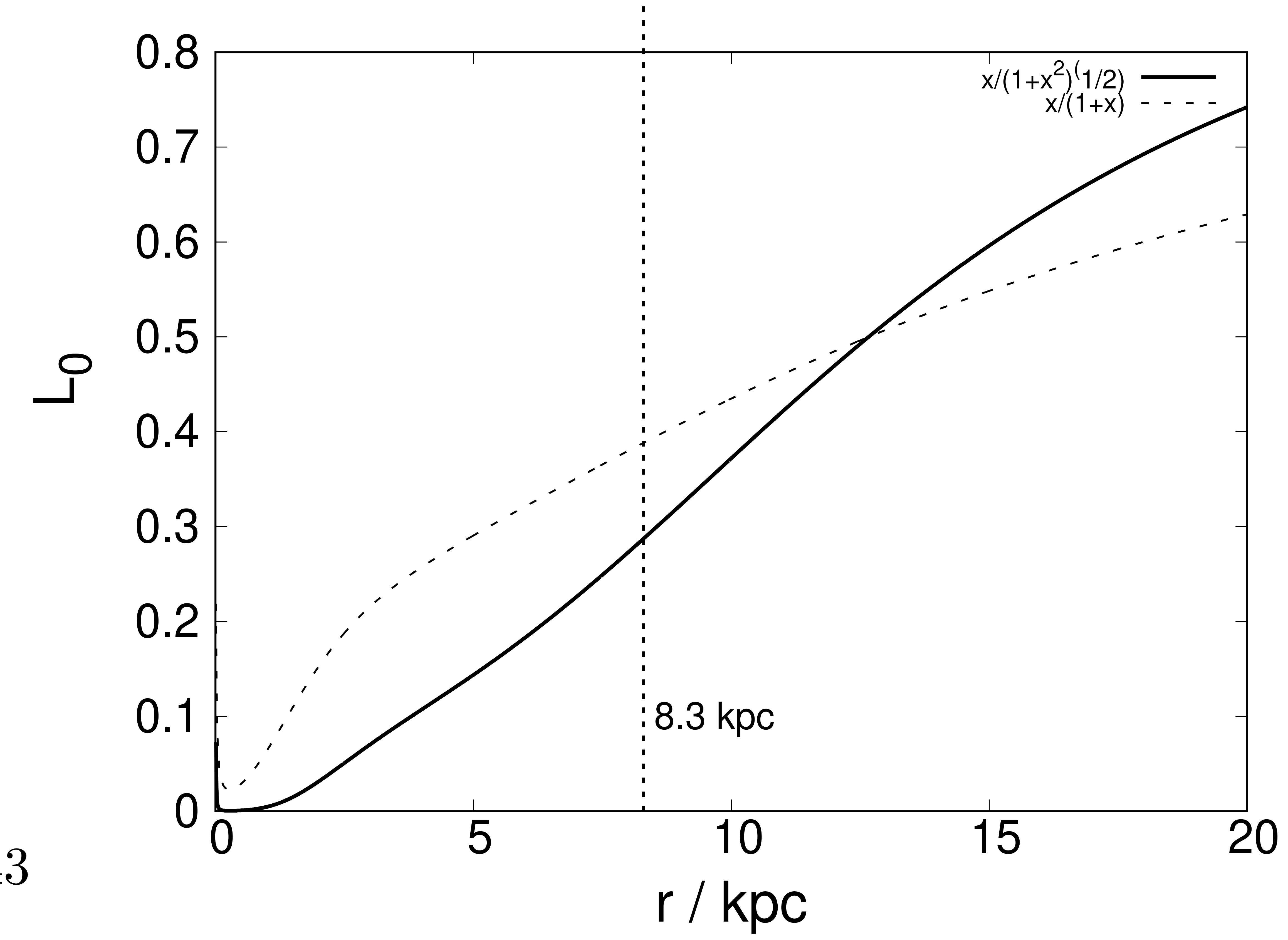
$$\frac{<\sigma_r>^2}{<\sigma_t>^2} = \frac{1}{2}$$

$$\frac{<\sigma_r>^2}{<\sigma_t>^2} = \frac{1}{2+L_0}$$

$$\approx 0.45 \ldots 0.43$$

L_0 in the Milky Way

$$0.25 \gtrsim L_0 \lesssim 0.35$$



superimposed by tidal effect

Conclusion

		MoND (MLD)	Newton
tidal arms	total length	identical	
	length	leading > trailing	leading = trailing
	(a)symmetry	asymmetric leading arm more members than trailing arm	symmetric
	evaporation/ dissolution	faster	slower
velocity dispersion	viral state	slightly supervirial compared to Newton but no expansion	
	tensor	asymmetric	symmetric

except for tidal field