Star clusters in complex tidal fields

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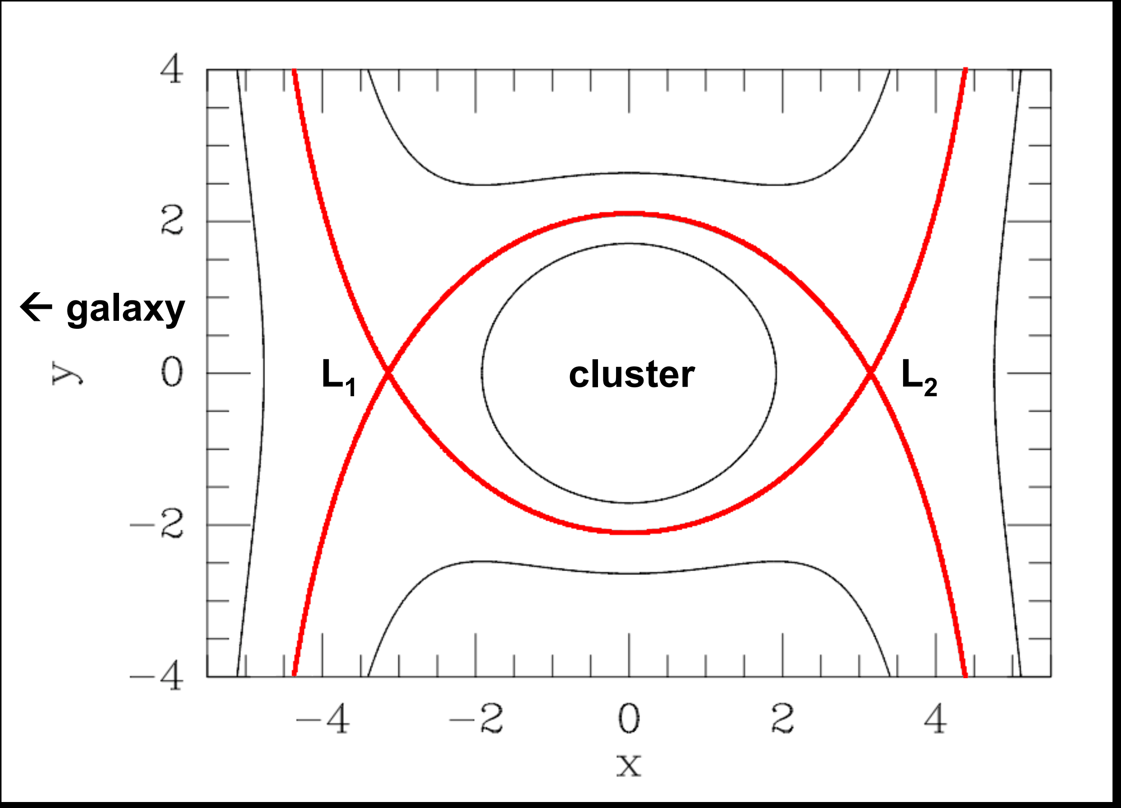
Dissolution of clusters

Star clusters and (tidal) dwarf galaxies are harrased by tidal forces

Wealth of analytical, semi-analytical, numerical studies

$$t_{\rm esc} \propto \left(\frac{E_{\rm crit}}{E - E_{\rm crit}} \right)^2$$

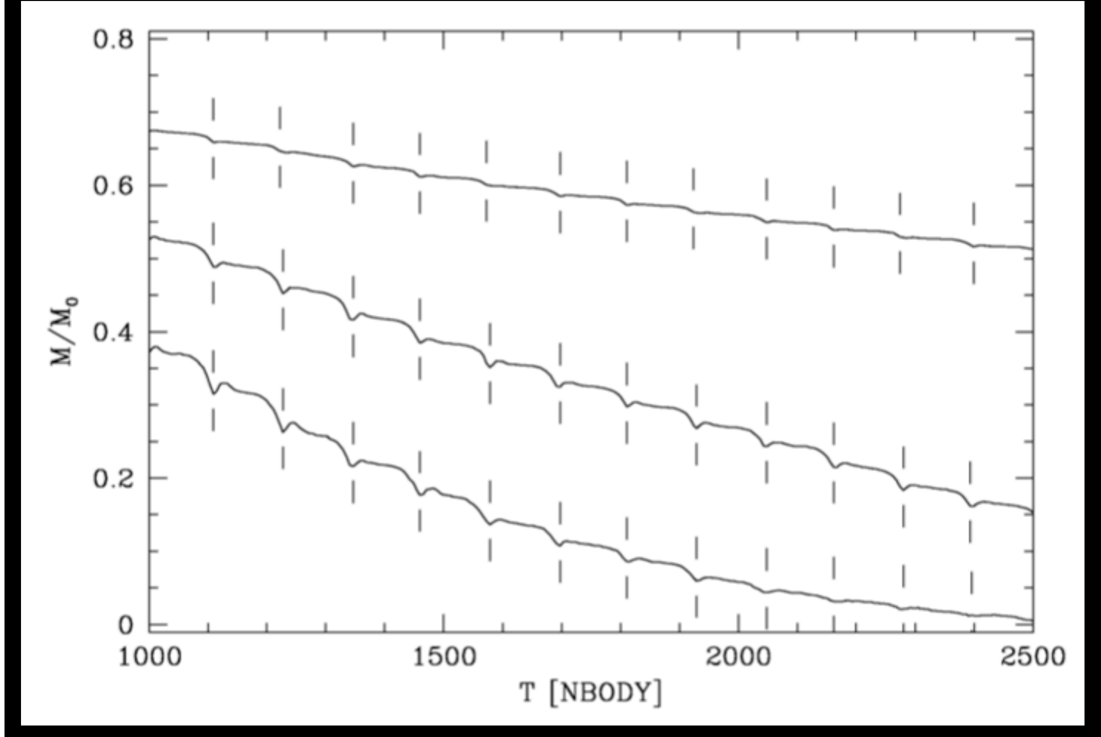
Fukushige & Heggie 2000



$$t_{\rm diss} \propto t_{\rm rh}^{3/4} t_{esc}^{1/4} (E = 2E_{\rm crit})$$

Baumgardt 2001

• Dissolution of clusters

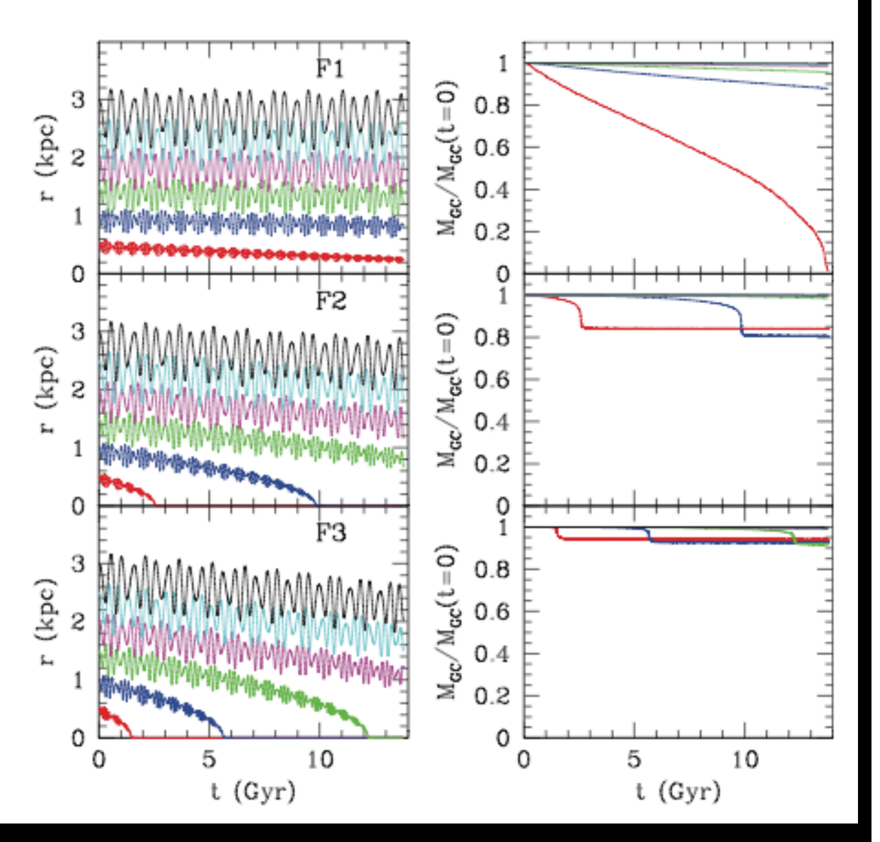


elliptical orbit

Baumgardt & Makino 2003

orbital decay
in a triaxial NFW halo

Peñarrubia, Walker & Gilmore 2009



Tidal radius

$$r_{\rm t} = \left(\frac{GM_{\rm c}}{3\Omega^2}\right)^{1/3}$$

King 1962
Fukushige & Heggie 2000
Binney & Tremaine 2008
Tanikawa & Fukushige 2010
...

$$r_{\rm t} = r_{\rm G}\left(\frac{GM_{\rm c}}{3M_{\rm G}}\right)^{1/3}$$

$$r_{\rm t} = \left(\frac{GM_{\rm c}}{4\Omega^2 - \kappa^2}\right)^{1/3}$$

Tidal tensor

Tidal tensor = 3D representation of the tides

$$T^{ij} = \partial^i F^j$$

3 eigenvalues (intensity)
3 eigenvectors (orientation)

$$\begin{pmatrix} \lambda_1 & 0 & 0 \\ 0 & \lambda_2 & 0 \\ 0 & 0 & \lambda_3 \end{pmatrix}$$

• Tidal radius

$$r_t = \left(\frac{GM_c}{3\Omega^2}\right)^{1/3}$$

King 1962
Fukushige & Heggie 2000
Binney & Tremaine 2008
Tanikawa & Fukushige 2010
...

$$r_t = r_G \left(\frac{GM_c}{3M_G}\right)^{1/3}$$

$$r_t = \left(\frac{GM_c}{4\Omega^2 - \kappa^2}\right)^{1/3}$$

$$r_t = \left(\frac{GM_c}{\lambda_1}\right)^{1/3}$$

Renaud, Gieles & Boily (RGB), in prep

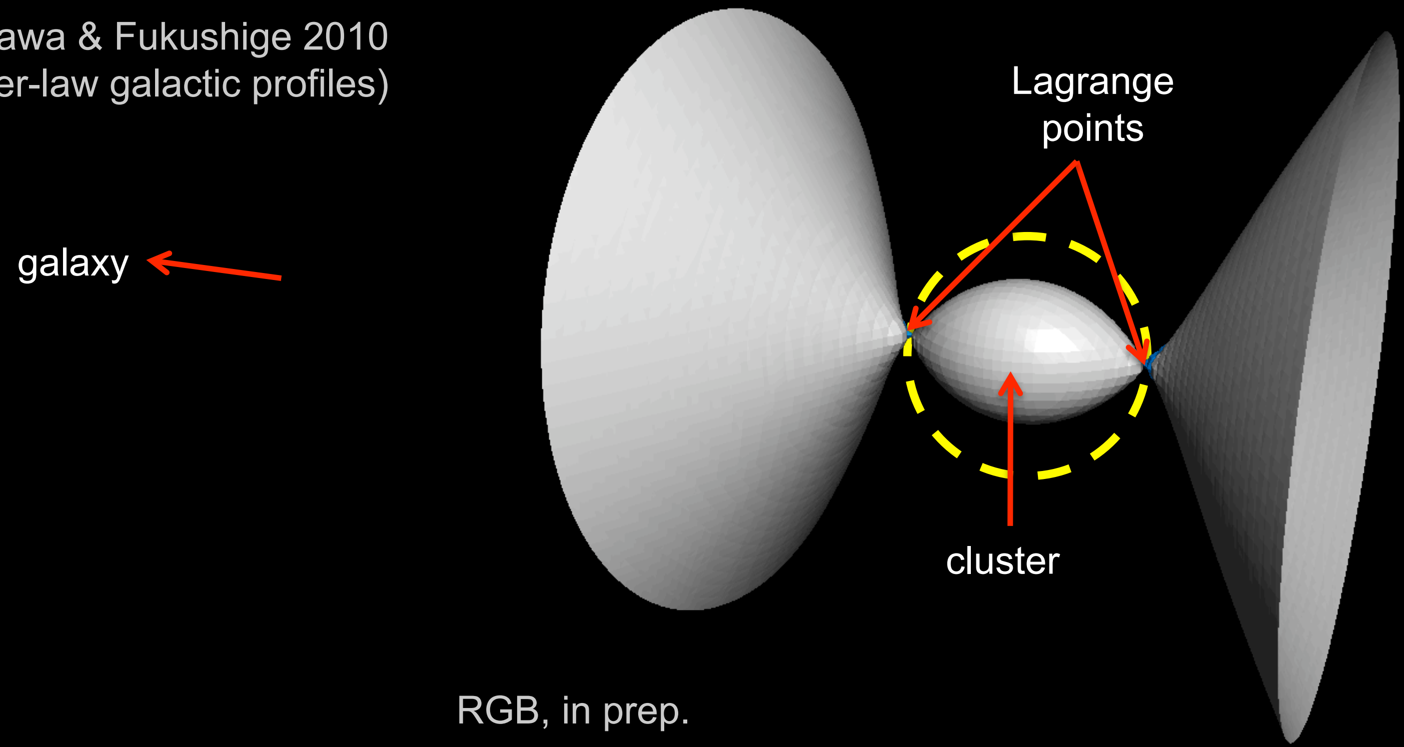
3D Jacobi surface

$$0 = 2r_t^3 + \sqrt{x^2+y^2+z^2}\left(x^2 + \frac{\lambda_2}{\lambda_1}y^2 + \frac{\lambda_3}{\lambda_1}z^2 - 3r_t^2\right)$$

3D shape of the tidal field

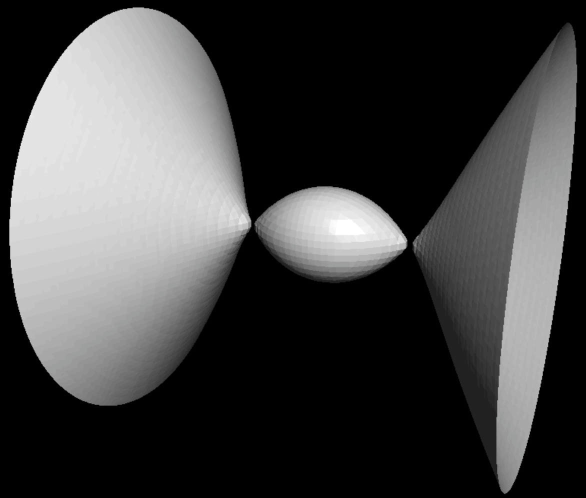
2nd order effect on mass-loss

Tanikawa & Fukushige 2010
(power-law galactic profiles)



RGB, in prep.

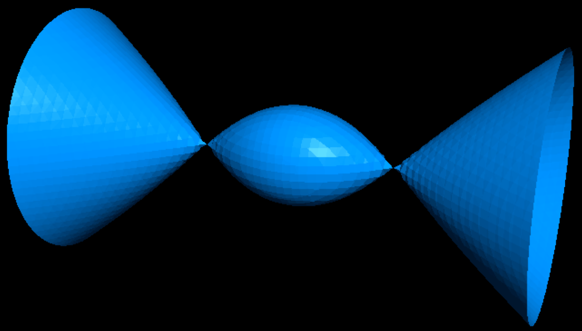
Escape time



for a given tidal radius:

steep profile = short escape time

Tanikawa & Fukushige 2010



$$t_{\rm esc} \propto \left(\frac{E_{\rm crit}}{E - E_{\rm crit}} \right)^2 \sqrt{\left(1 - \frac{\lambda_2}{\lambda_1}\right)\left(1 - \frac{\lambda_3}{\lambda_1}\right)}$$

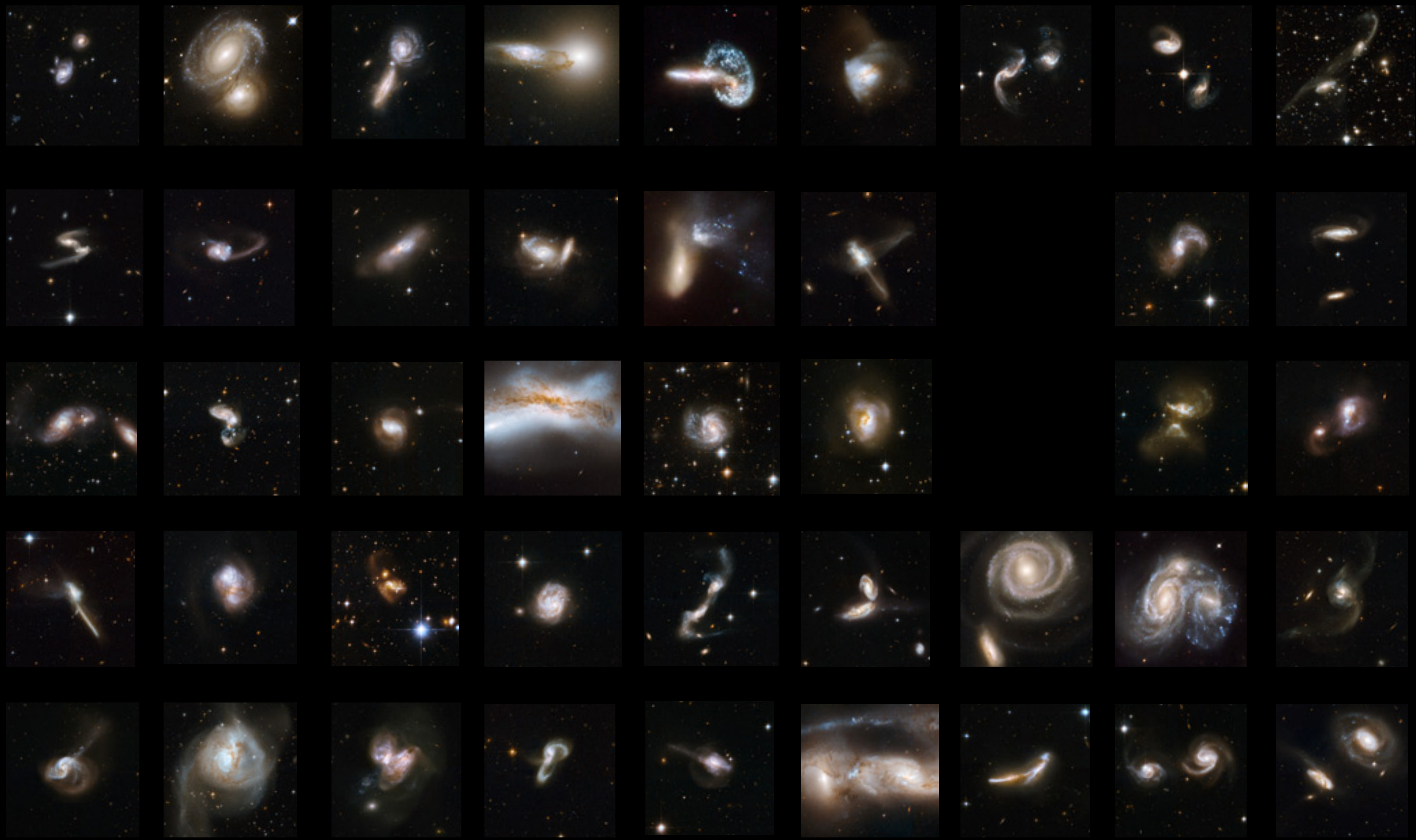
Fukushige & Heggie 2000

RGB, in prep.

in a steady tidal field ...

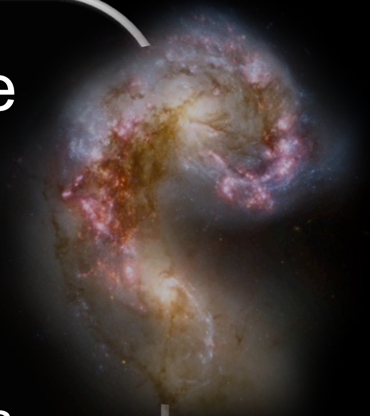
• Cosmological Context

• Non-static potentials



• Two steps

Galactic scale

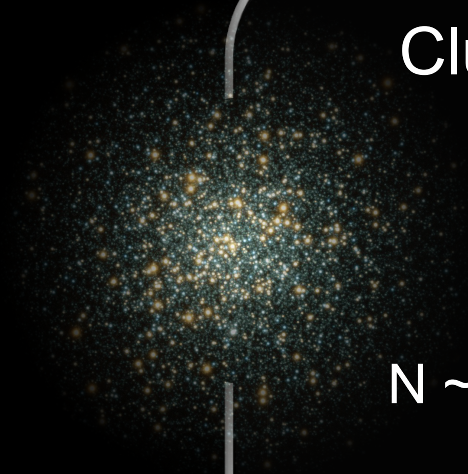


collisionless

N ~ 10^7 particles

1 particle = 1 star cluster
(10^5 $M_\odot$)

2^{nd} coupling
(feedback)



Cluster scale

collisional

N ~ 10^5 particles

1 particle = 1 star
(1 $M_\odot$)

1^{st} coupling
(formation, tidal field)

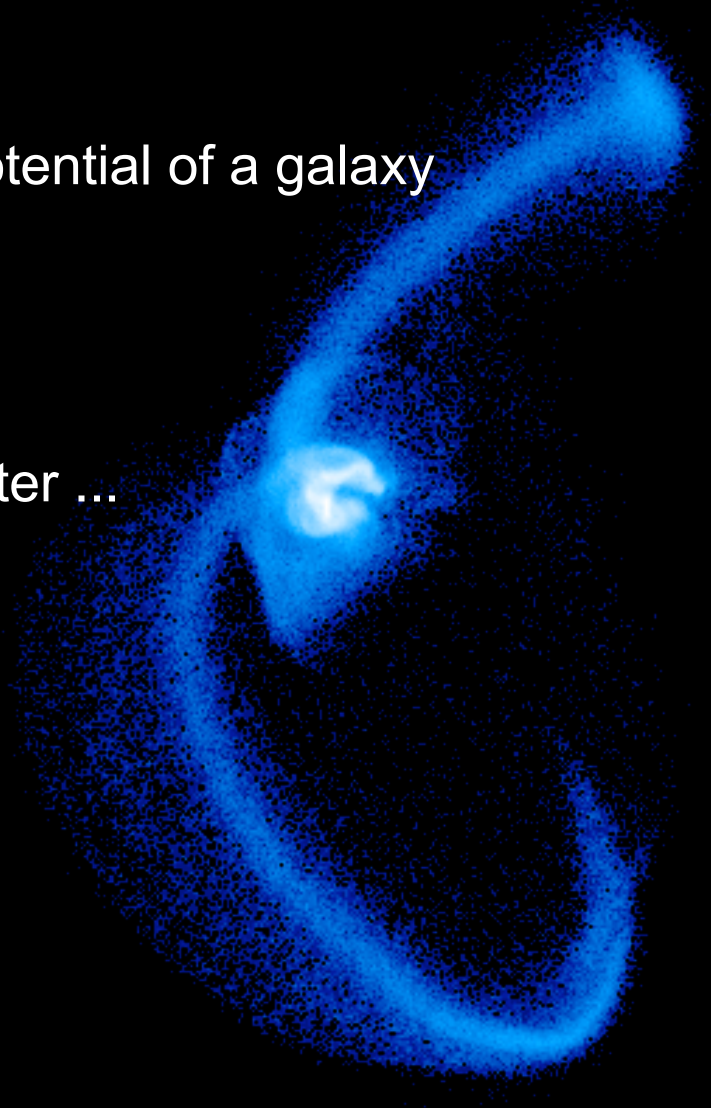
• Galactic Potential

Representation of the gravitational potential of a galaxy

Can be *any* potential:

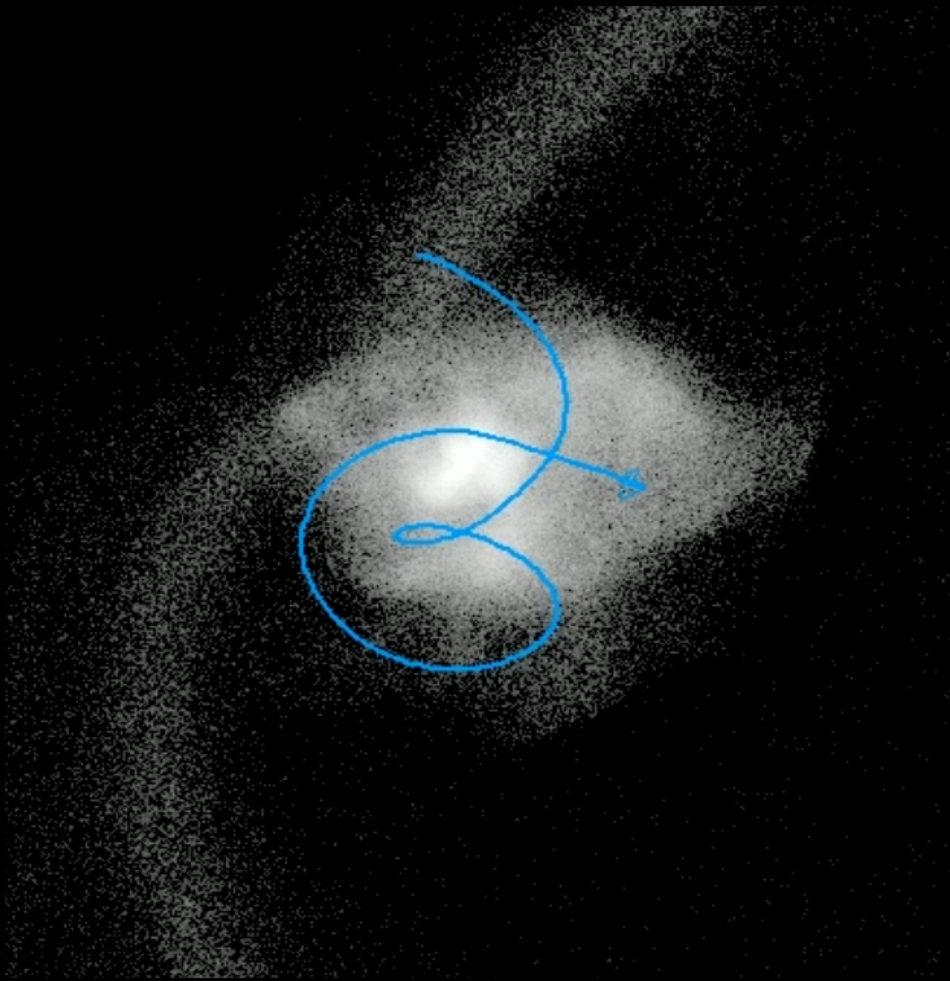
- isolated disk, merger, group, cluster ...
- analytical, N-body, grid-based
  (SPH, AMR, PM, Sticky ...)

e.g. the Antennae (NGC 4038-39)



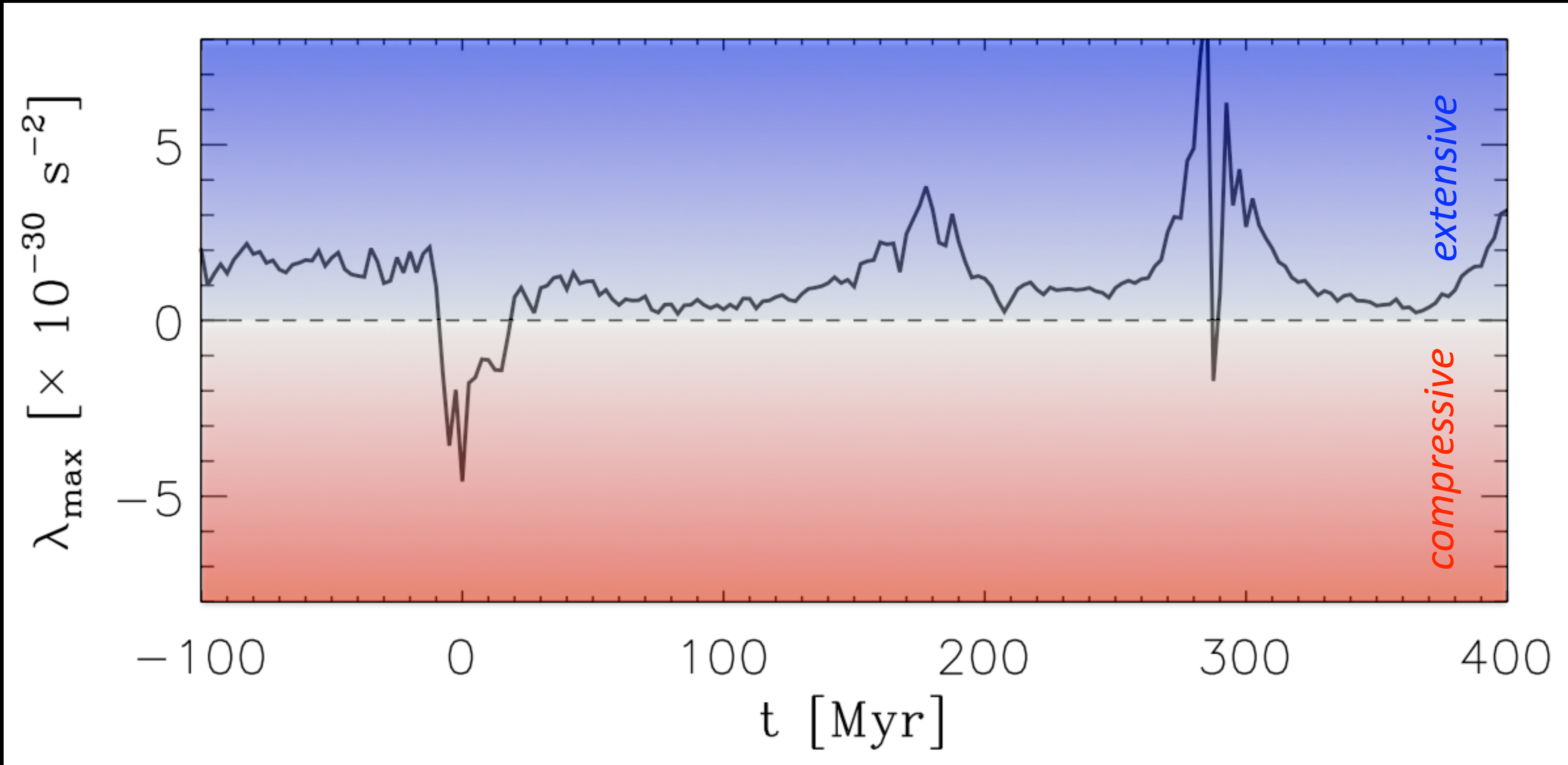
Renaud et al. 2008

• Select an orbit



Renaud et al. 2009

• Compute the tides



Renaud 2010

• First step: Done!

Galactic scale

collisionless

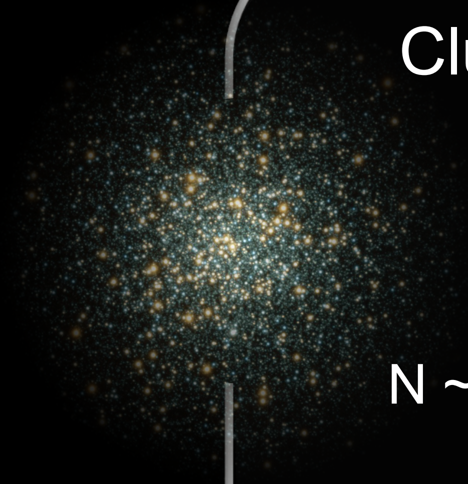
N ~ 10^7 particles

1 particle = 1 star cluster (10^5 $M_\odot$)

Table of tidal tensors

t_0	T^{xx}	T^{xy}	T^{xz}	T^{yy}	T^{yz}	T^{zz}
t_1	T^{xx}	T^{xy}	T^{xz}	T^{yy}	T^{yz}	T^{zz}
...						
t_f	T^{xx}	T^{xy}	T^{xz}	T^{yy}	T^{yz}	T^{zz}

Cluster scale



collisional

N ~ 10^5 particles

1 particle = 1 star (1 $M_\odot$)

• At cluster scale

N-body simulation of the cluster

NBODY6 (on GPUs) Aarseth 2003

"I cannot imagine that somebody would choose anything else"

Anonymous, 2011

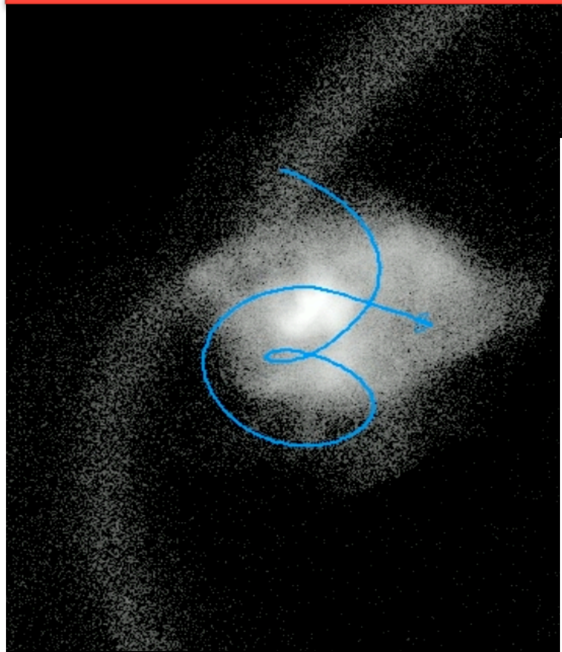
NBODY6tt (on GPUs too!) RGB, in prep.

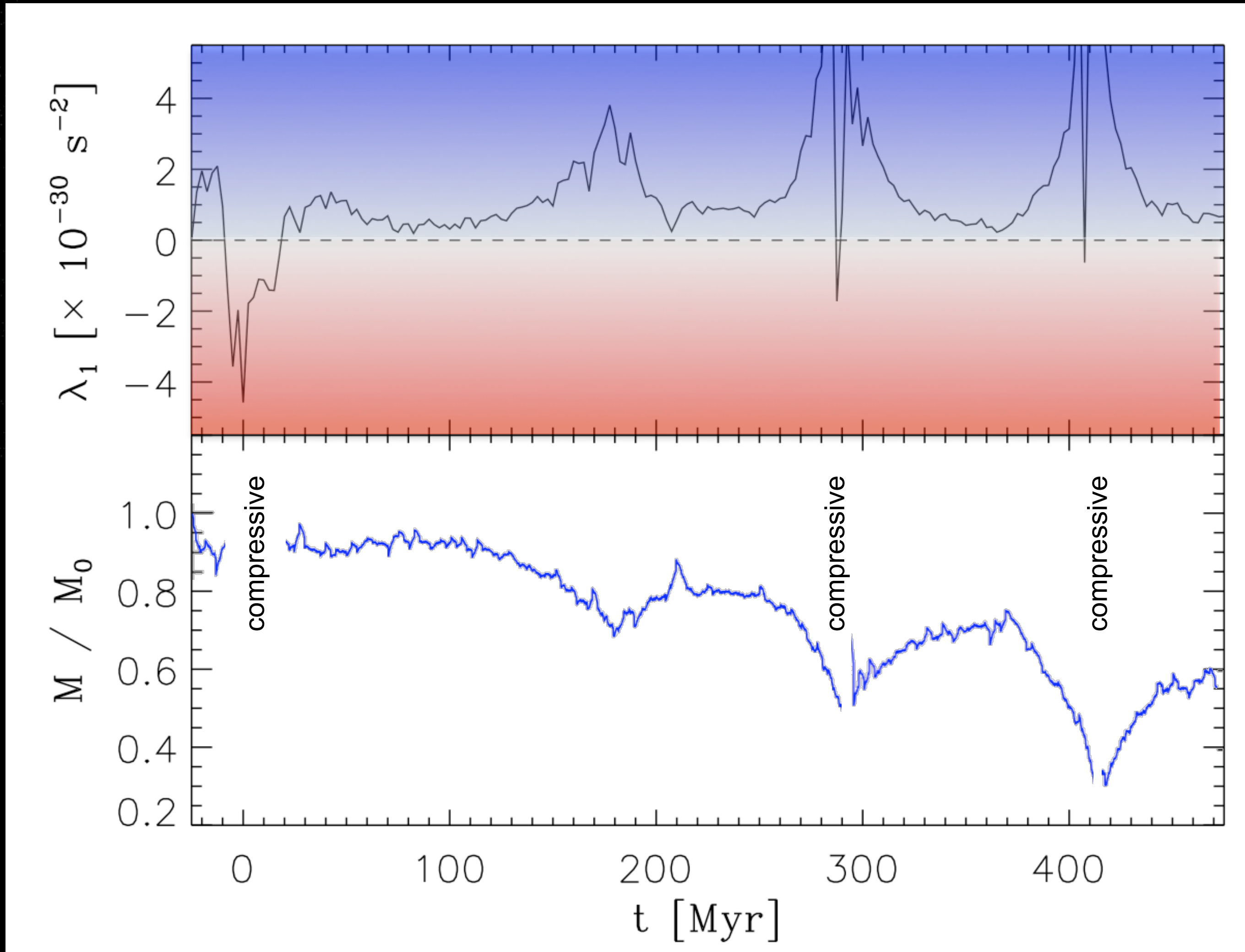
adds the tidal force

All NBODY6 features are ready to use in NBODY6tt

(primordial binaries, IMF, stellar evolution ...)

• A FIRST APPLICATION





Cluster:

N = 8000

equal-mass

Plummer sphere

• Many questions raised

What is the mass-loss in compressive mode?

What happens when switching from compressive to extensive?

preliminary answers in Renaud 2010

How does stellar evolution regulate the effect of the tides?

...

Statistical study at medium resolution (N ~ 10^4 bodies)

In isolated disks, and mergers

Renaud, Gieles & Boily, Papers II, III, in prep.