The Combined effects of ram pressure stripping, and tidal influences on Virgo cluster dwarf galaxies, using N-body/ SPH simulation

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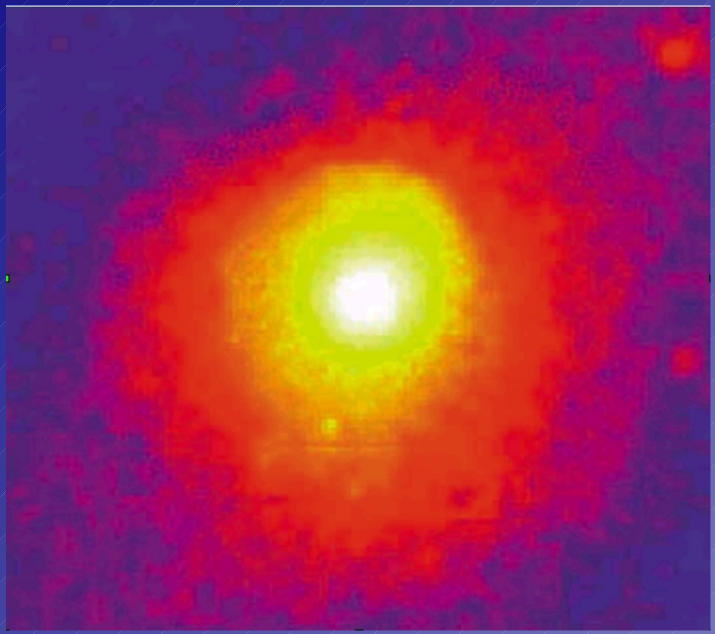
The importance of dwarf galaxies

- Dwarf galaxy – low mass & luminosity (-18<Mabs<-14)
- Building blocks of other galaxies
- Small potential wells – strongly effected by environment.

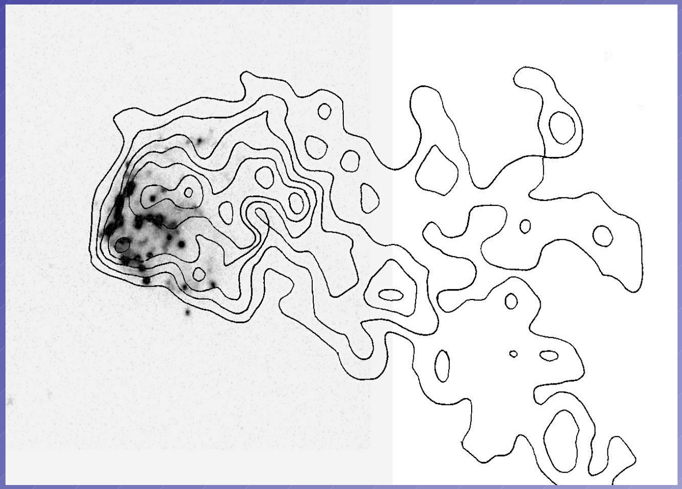
SDSS RGB, VCC009

The Cluster Environment

Ram Pressure stripping:

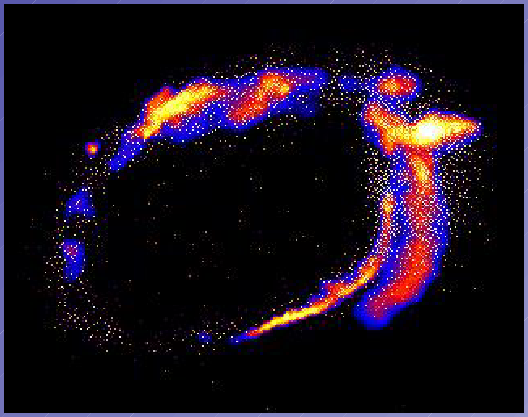


Virgo in X-rays, ROSAT satellite

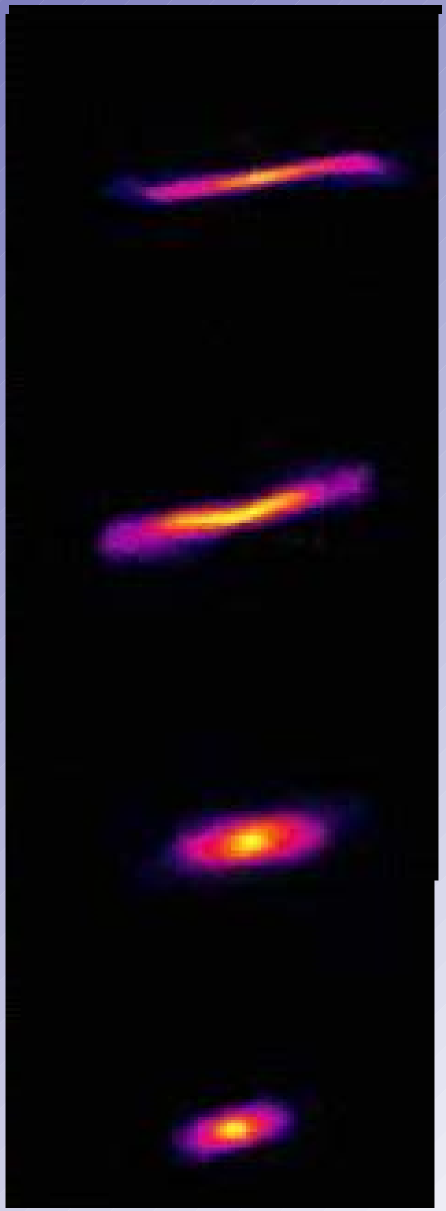


CGCG 97079 – Radio continuum & Halpha, Boselli & Gavazzi 2006

Harassment:



Moore et al,1999



Moore et al,1999

The Morphology-density relation in dwarfs

dwarf irregulars (star-forming, gas-rich, blue) preferentially found in the field,
dwarf ellipticals (old stars, no gas, red and dead) found preferentially in clusters

How did dwarf ellipticals (dEs) form?

Observations of cluster dEs show signatures of recent infall (*e.g. Conselice et al, 2001*)

Possible origins:

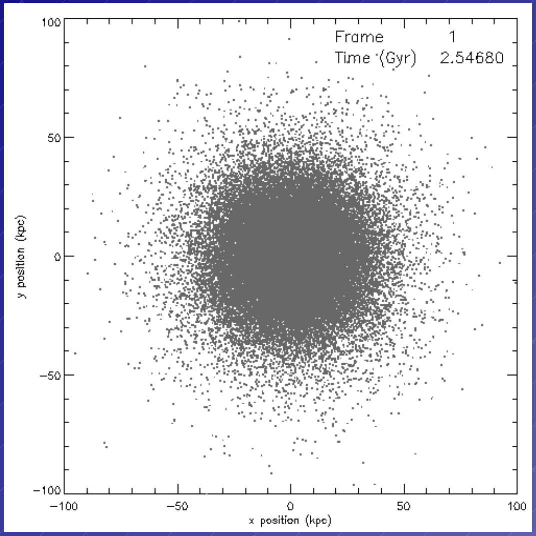
- Harassed medium-mass low surface brightness spirals? (Moore et al, 1999)
- Ram Pressure Stripped in-falling dwarf irregular galaxies? (Boselli et al, 2008)

=> likely both mechanisms occurring simultaneously within cluster, so....

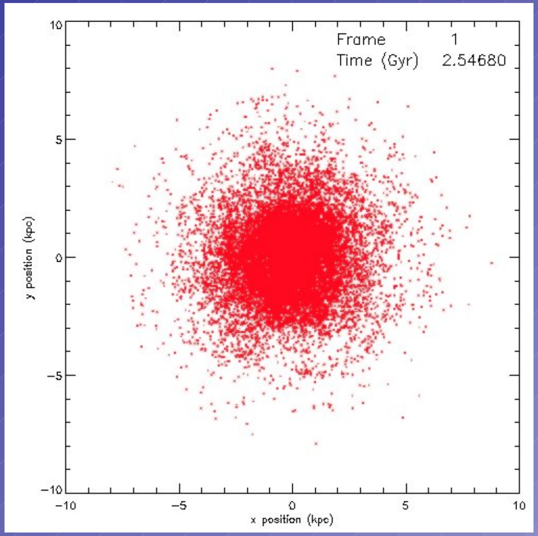
Simulations combining both mechanisms *for the first time,* investigating their separate and *combined* influence on in-falling dwarf galaxies

Model dwarf irregular galaxies:

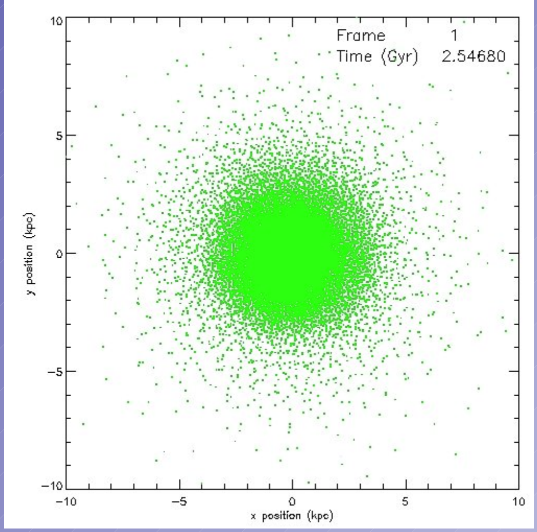
Dark matter halo



Stellar disk

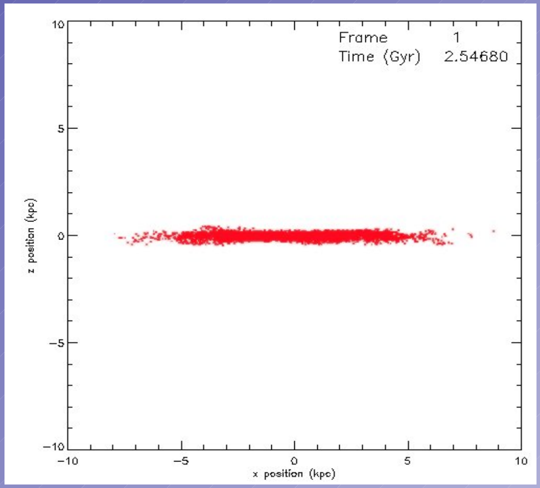


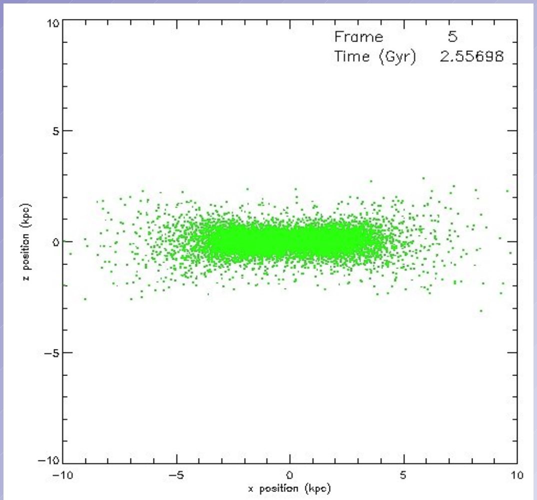
Gas disk



X-Y plot

Spherical halo





X-Z plot

Total Mass: 1 E10 M_sol
f_disk = 0.05
disk mass ratio (gas:star)= 4:1

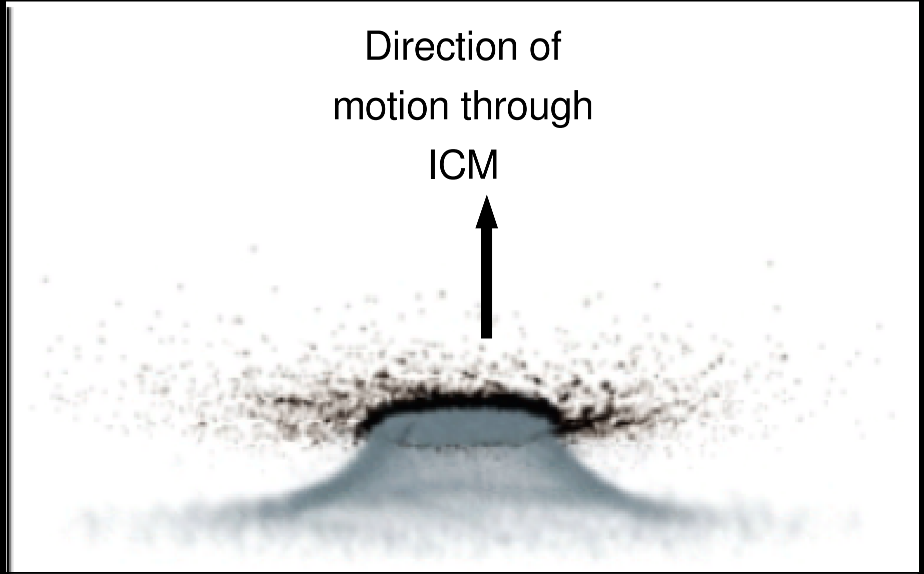
Particles:100,000 dark
20,000 star
20,000 gas

Gas properties:
isothermal (~10^4 K)
sound speed=7.5 km s-1

Ram Pressure Stripping Model

(Similar model to Vollmer et al,2001)

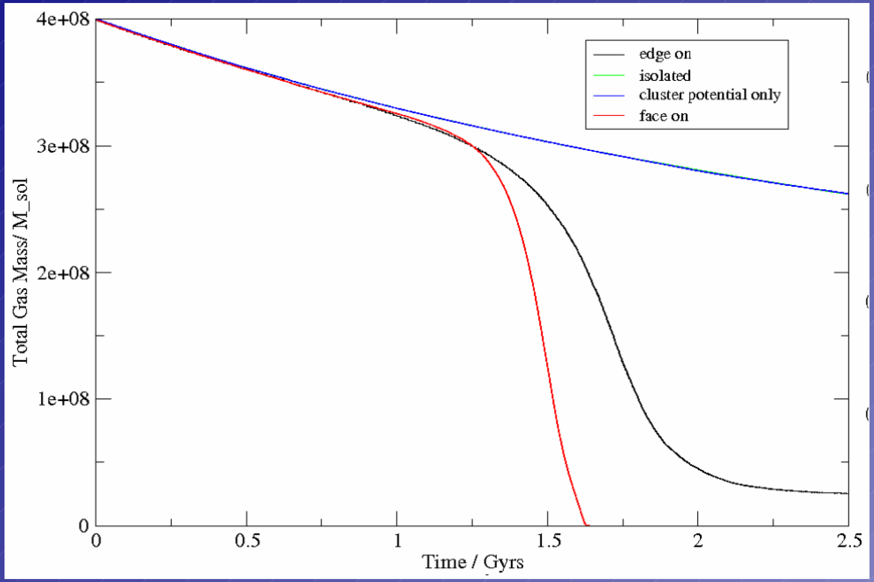
- Drag force felt by gas particle ∝ (velocity through ICM)^2 (density of ICM)
- Analytical solution for density of ICM with cluster radius from x-ray constraints
- NFW potential field (Mass=1.6e14 M_sol, c=4) for cluster potential – to give in-falling dwarf model reasonable velocity and orbit through cluster (peak velocity: ~1600 km s-1, peri-cluster distance: ~200 Kpc)



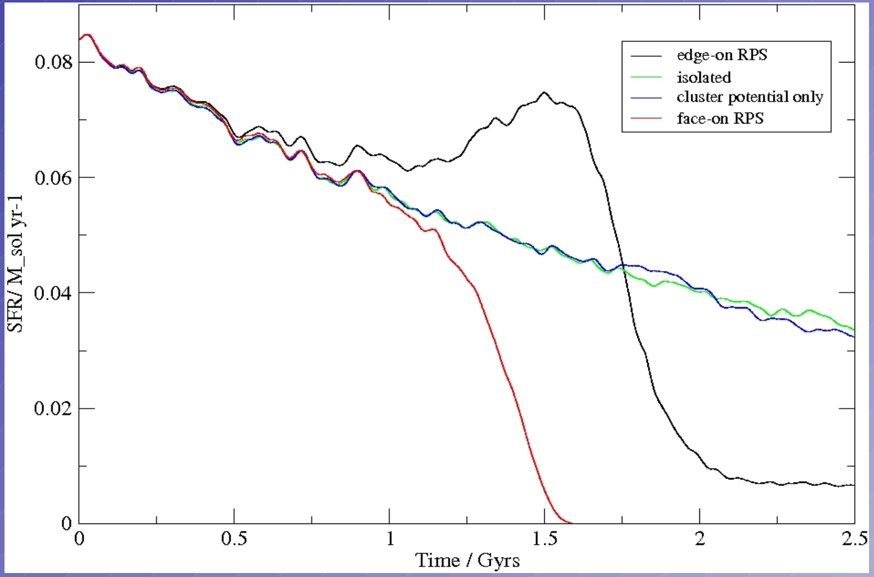
Example of RPS model testing: Stars (black), gas (grey), cone of gas produced behind stellar disk for face-on stripping.

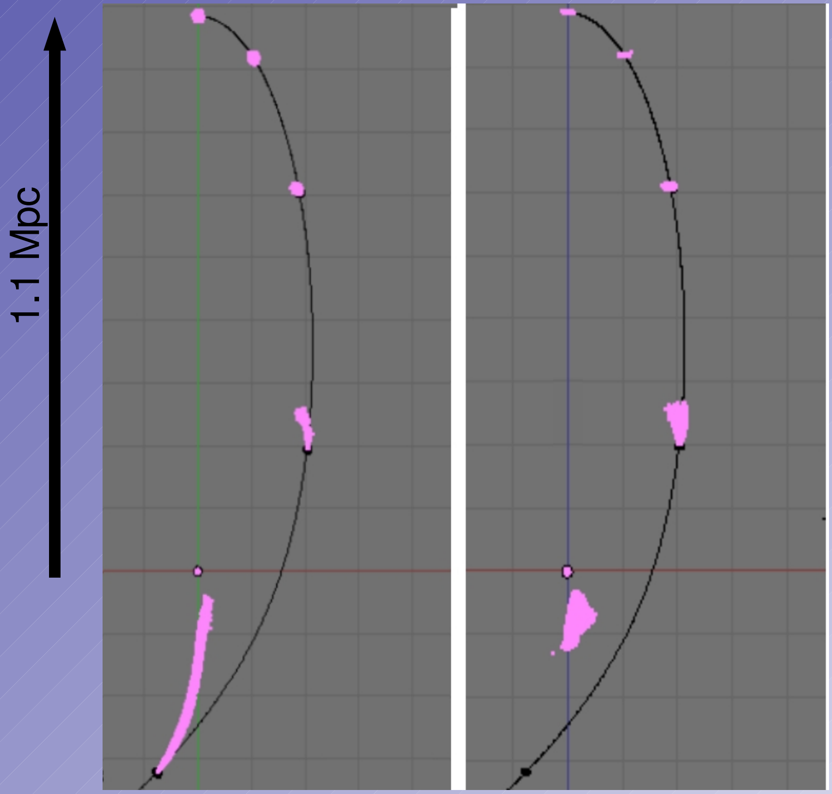
RPS results:

Gas loss:



SFRs:

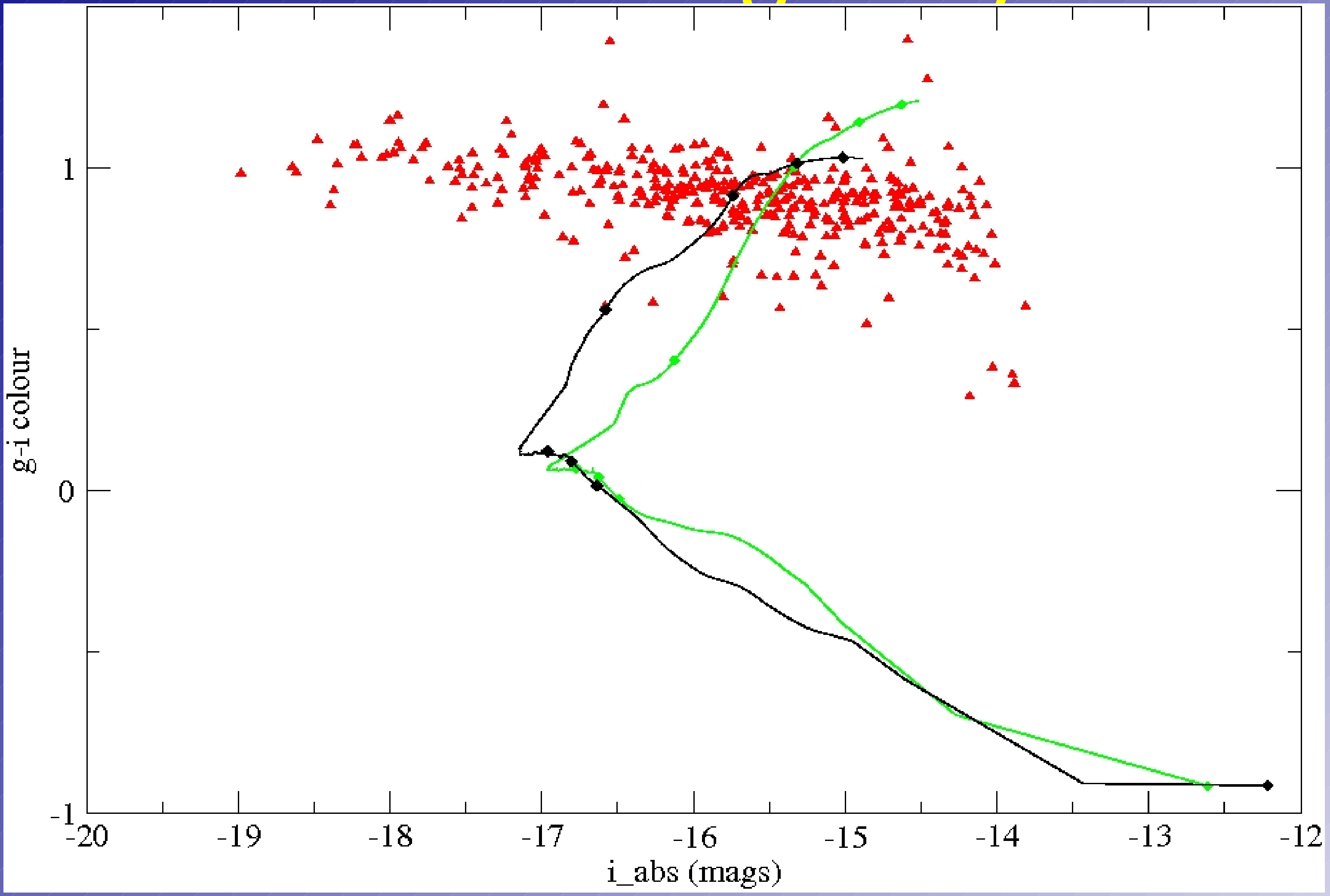




Snapshots of motion of dwarf through ICM each 0.5 Gyrs apart, pink (gas), black (stars). Left is edge-on RPS, right is face-on RPS.

In general, all gas is removed from the dwarf galaxy after one pass of the cluster core, within 0.2-0.5 Gyrs causing a cessation of star-formation.

Effect of RPS on galaxy colour:

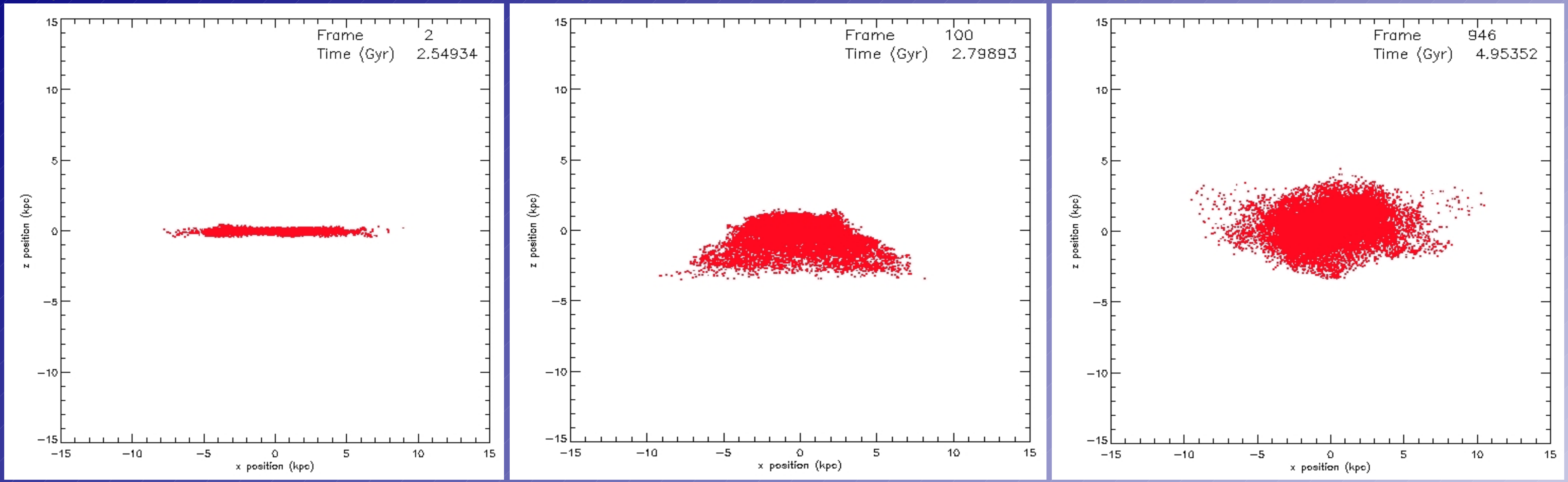


A colour-magnitude plot of Virgo dwarf ellipticals using SDSS data, overlayed with tracks for time evolution of dwarf irregular models (1 Gyr between symbols, 1/5th solar metallicity in black, 1 solar metallicity in green).

Cessation of star formation causes rapid evolution (<2Gyrs) from the blue sequence to colours typical of red sequence dwarf ellipticals.

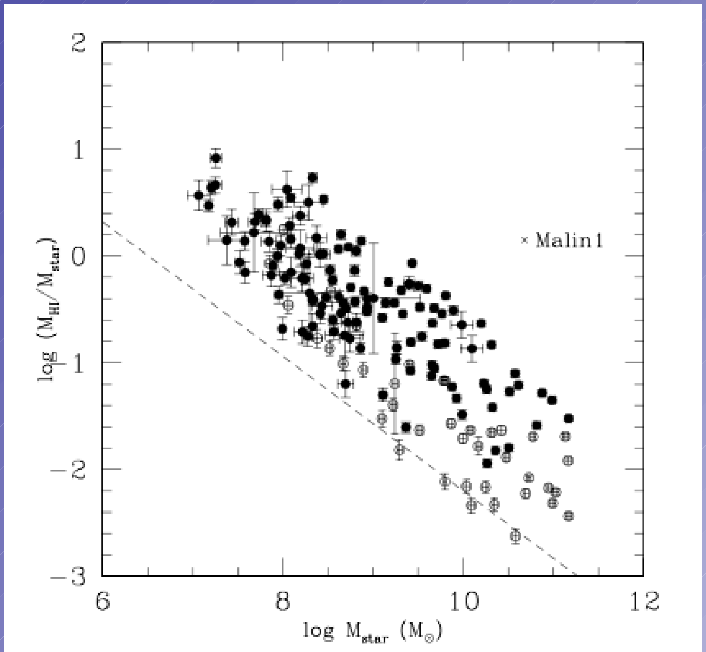
RPS – disk heating/morphological transformation

0 Gyrs   0.2 Gyrs   2.5 Gyrs



(Above) Tidal distortion of stellar disk due to rapid removal of gas mass from disk

(Right) Increasing gas fraction with decreasing stellar mass for star-forming galaxies, taken from Gavazzi et al, 2008



- Produces (v/σ) ~1.4 (in agreement with van Zee et al (2004) hi-res spectroscopic measurements
- Increasing heating effect with decreasing galaxy mass

Rapid removal of gas disk mass causes a tidal force on the stellar disk, causing morphological transformation/ disk heating.

Harassment Model:

2 components: (i) Background cluster potential (NFW, Virial radius: 1.1 Mpc, static)
(ii) Individual harasser galaxies potential (NFW, varying mass,dynamical)

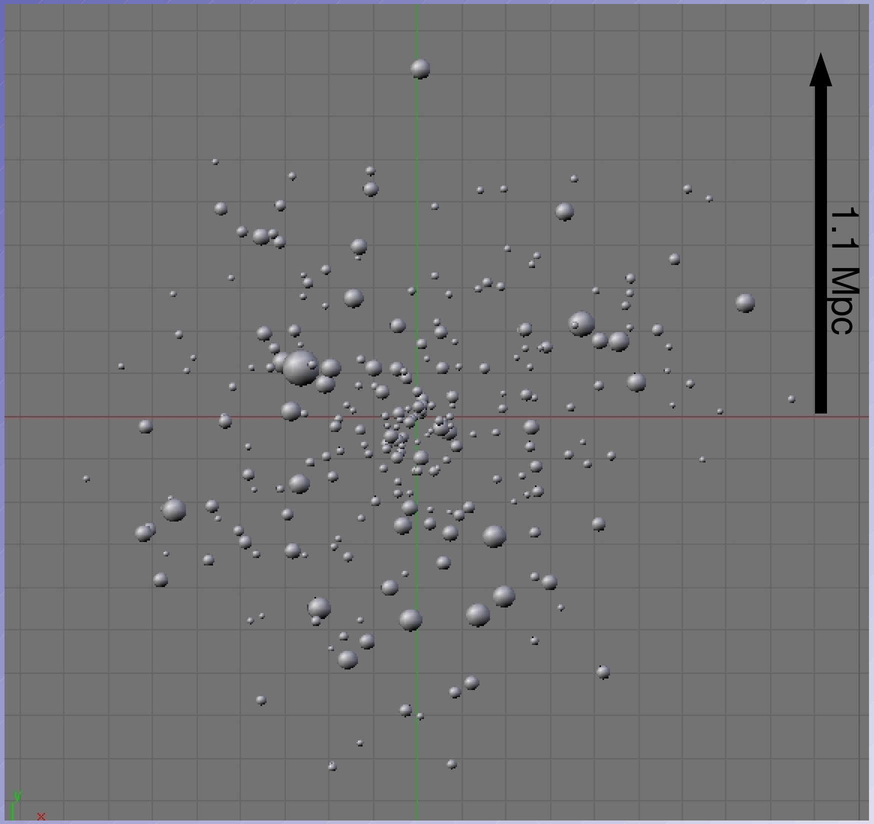
- Masses of galaxy from Sandage Schector function:

M/L=20 assumed for all galaxies

$$\Phi(L)\,dL = \Phi_*(L/L_*)^{\alpha} e^{-L/L_*}$$

$$\alpha = -1.5 \quad L_* = 2.25\,E\,10\,L_{sol}$$

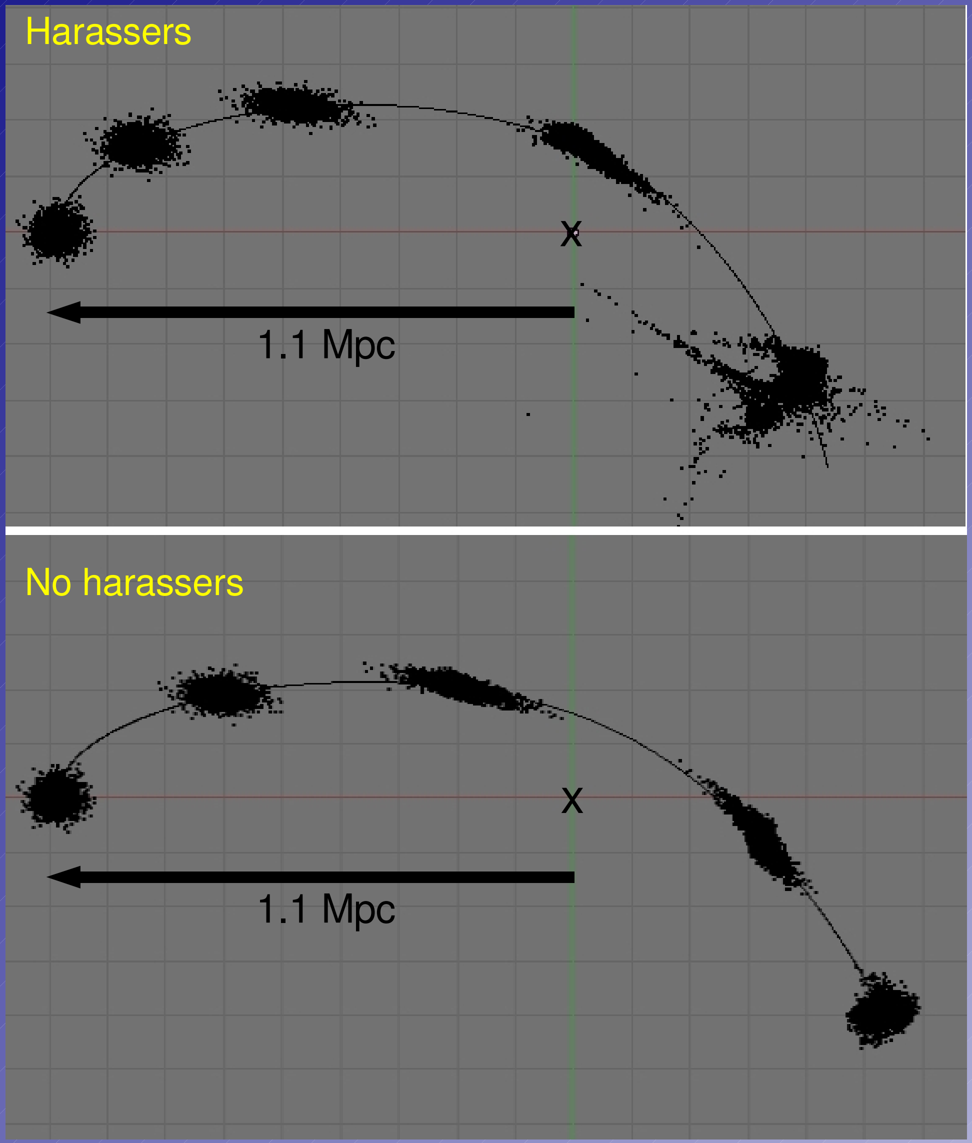
- Produces 250 galaxies with mass > dwarf galaxy model
- Total cluster mass:1.6 e14 M_sol



The distribution of harasser galaxy halos within the cluster potential (halos shown at 1/5th Virial radius)

Harassment results:

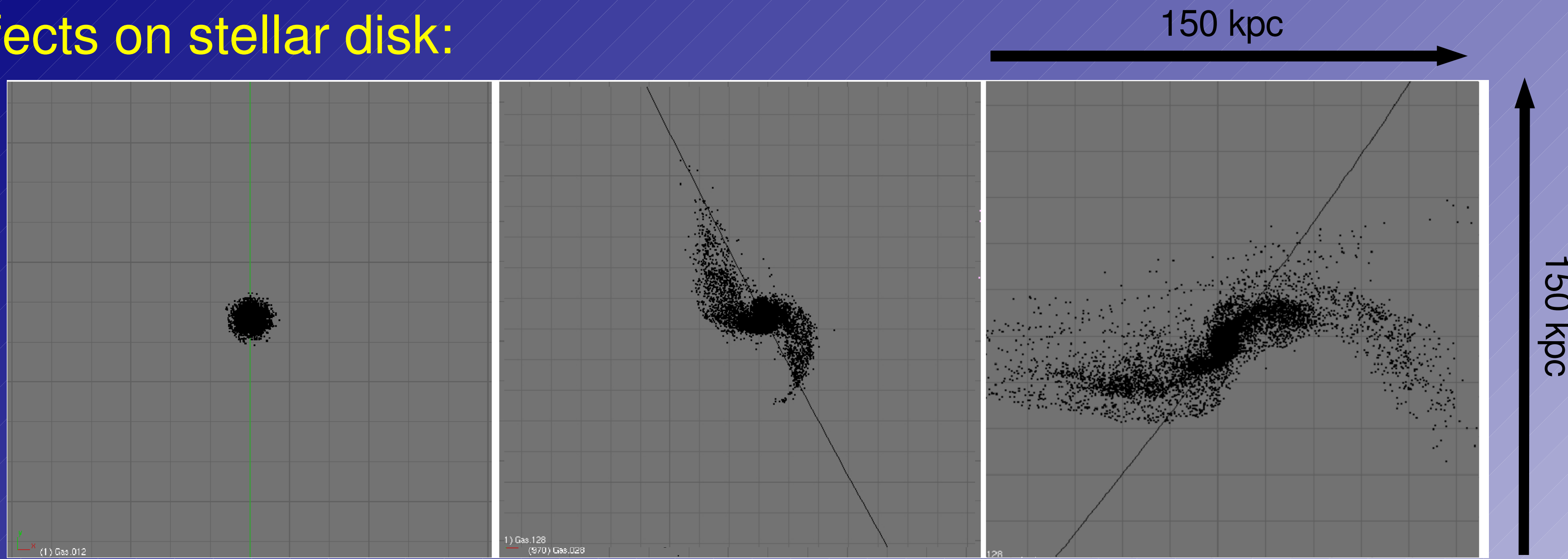
Effects on dark matter halo:



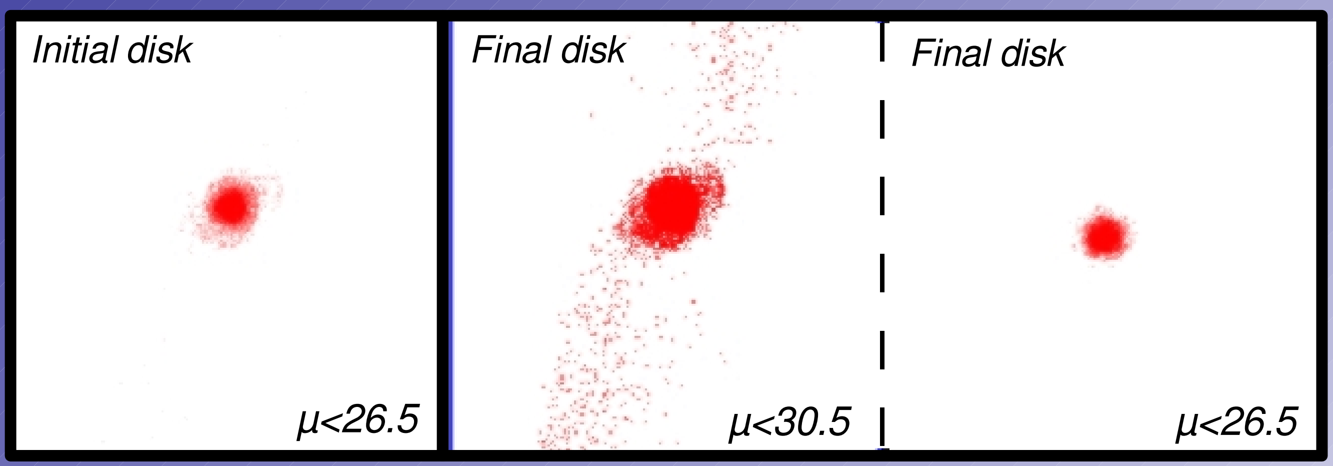
Snap shots of halo, each separated by 0.5 Gyrs: (Top) Effects of 2.5 Gyrs harassment on final dark matter distribution, (bottom) static cluster potential only (i.e. No harassers)

A few close encounters with harassing galaxies as the dwarf galaxy passes the cluster centre produces tidal tails of dark matter, and tidal heating of the halo.

Effects on stellar disk:

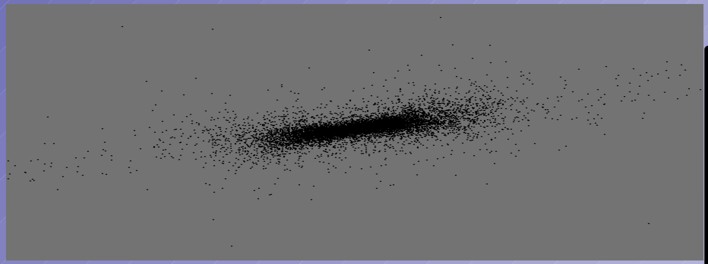


(Left) Stellar disk before harassment, (centre & right) after 2.5 Gyrs evolution for two models



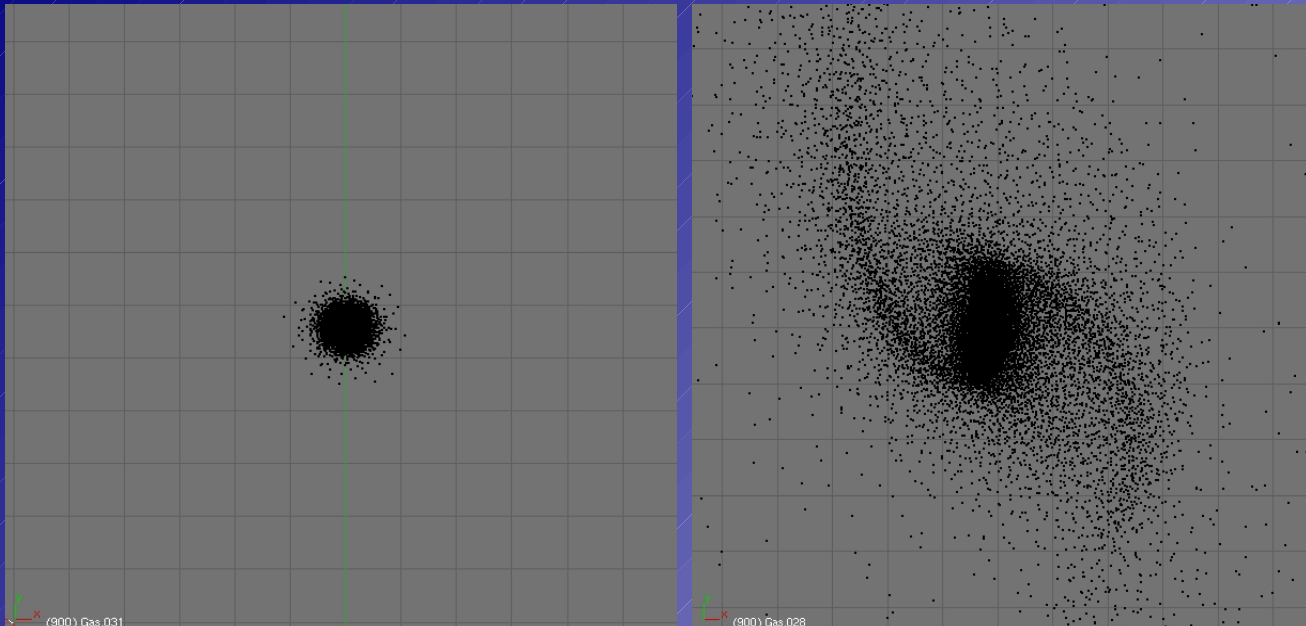
(Left) Initial stellar disk, and after 2.5 Gyrs harassment (centre & right) - the same disk seen at two different surface brightness limits. Surface brightnesses quoted in units of mag arcsec^2

(left) Stellar disk after 2.5 Gyrs seen edge on.

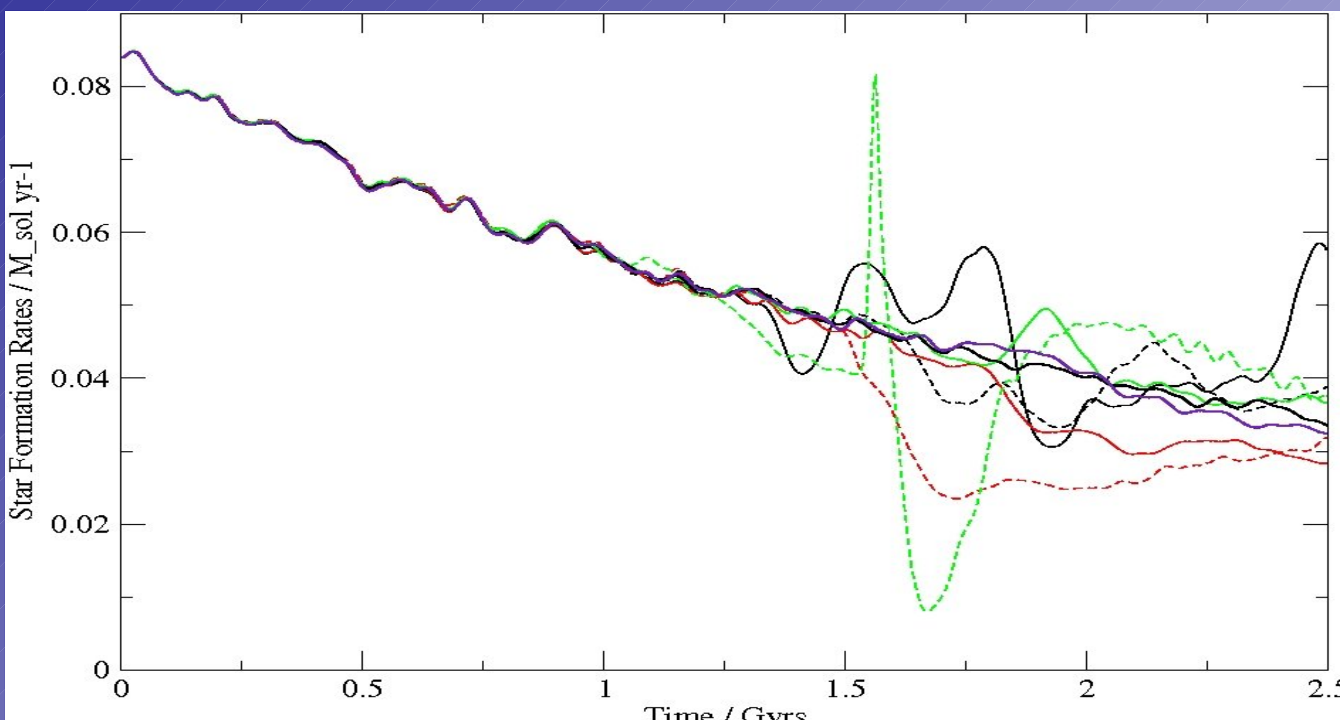


Harassment generally produces VLSB features, and does not cause significant morphological transformation in dwarf models

Effects on gas disk:



(left) Individual strong encounters can cause barring/spiral structure formation in the gas disk



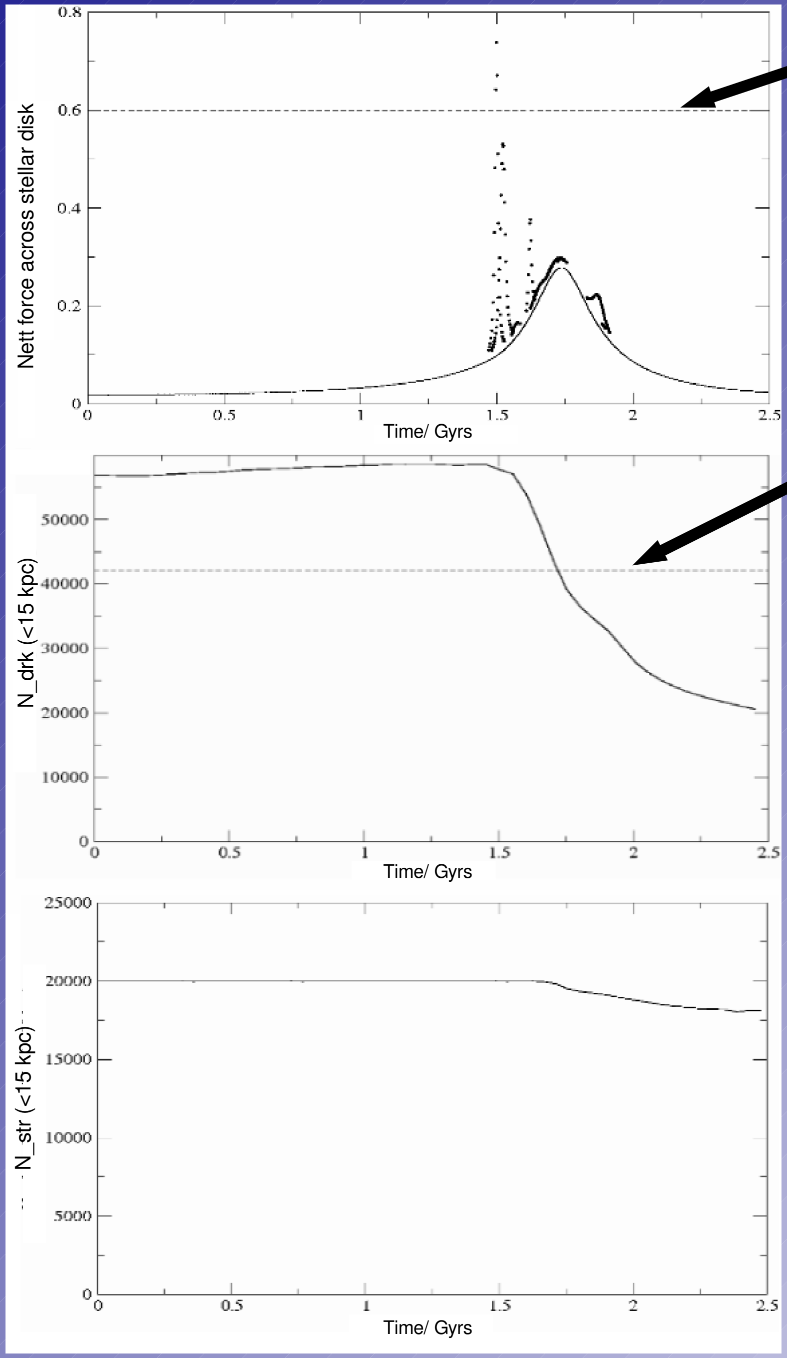
(left) Alone, harassment can induce short-lived star formation burst

Mass loss due to harassment:

Tidal history:

Dark matter:

Stars:



Dwarf galaxy Roche limit

Losses due to static cluster potential alone

Dark matter:
=> ~ 60 % losses
(<25% from static cluster potential)

Stars:
=> ~ 10 % losses
(0% from static cluster potential)

Harassment can lower the dynamical mass-to-light ratio by a factor ~2

A Monte Carlo harassment simulation:

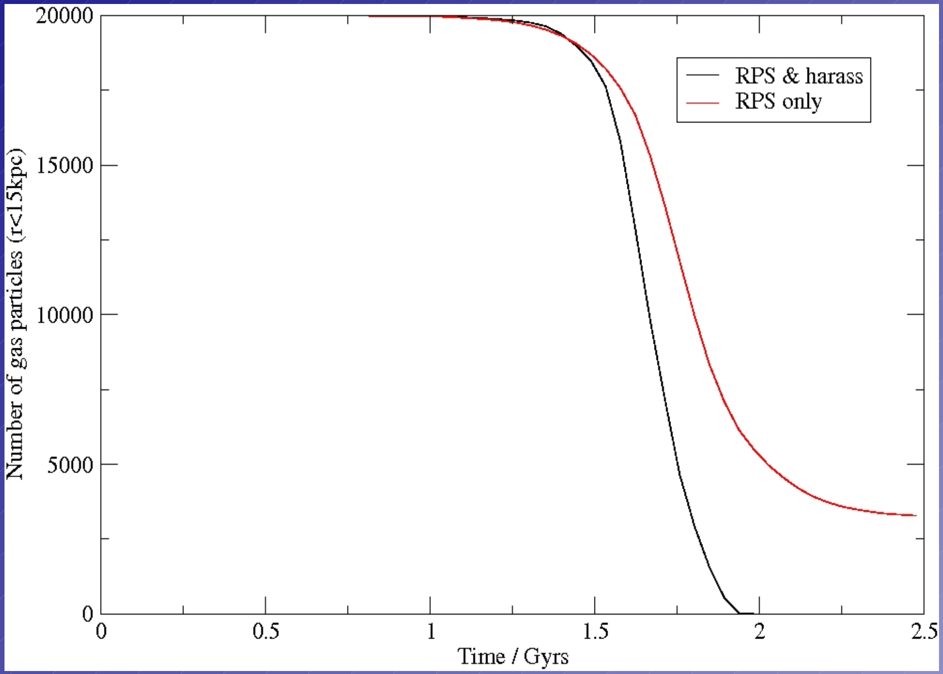
Statistics of harassment:

- Average close encounters : 3.96 ± 2.48 (within virial radius of halo - <40 kpc)
- Average encounter velocity: 2000 ± 647 km s-1 (<1% at < 500 km s-1)
- Average encounter radius within cluster: 219 ± 171 kpc
- ~50 % of in-falls experience a peak tidal force less than dwarf galaxy's Roche limit. Strong encounters are rare (<20% of infalls)

Summary: On *average* there are no easily/clearly observable influences of harassment on in-falling dwarf galaxies.

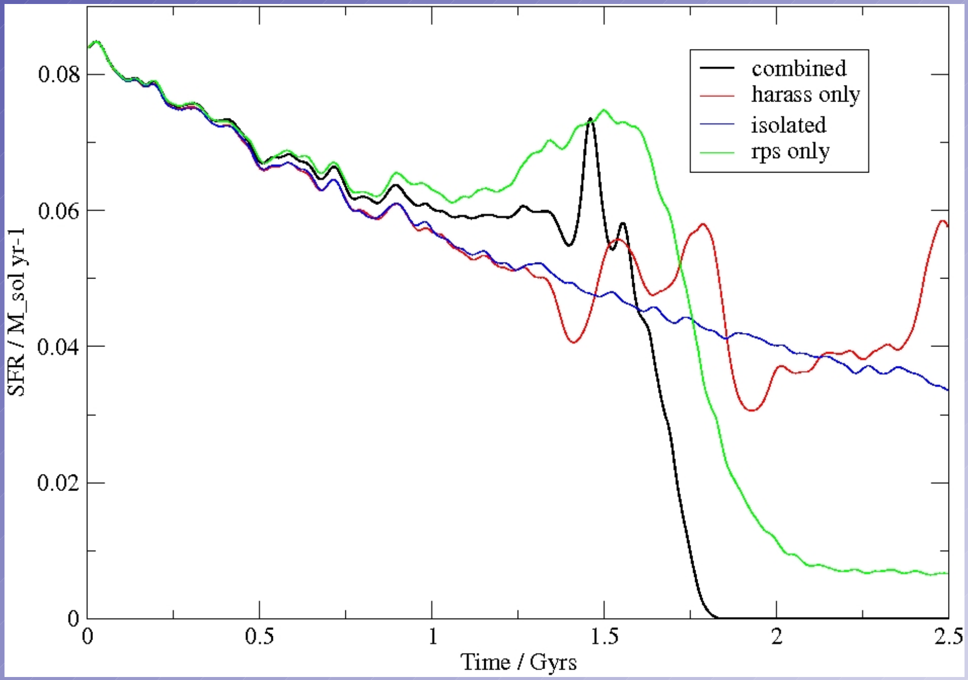
Combined effects of ram pressure stripping and harassment:

- Harassment enhances ram pressure stripping:



(Above) Dark matter stripping during harassment allows for more efficient gas removal, by reducing the potential well of the dwarf galaxy

- RPS dominates star formation influences:



The bursty star-formation history found in harassment simulations (red) is halted by rapid gas removal when ram pressure stripping is included (black).

In general, ram pressure stripping dominates the environmental influences on dwarf galaxies, with small modifications due to the influences of harassment

Conclusions:

- Ram Pressure stripping dominates the environmental influences on in-falling cluster dwarf galaxies, halting their star formation and causing rapid evolution to the red sequence

- A surprising degree of tidal heating can occur during a ram pressure stripping incident causing morphological transformation

- Generally the effects of harassment on in-falling dwarfs (reduced mass-to-light ratios, low surface brightness features) are unlikely to be observable with current data sets.

Ram Pressure Stripping appears capable of producing a significant fraction of the cluster dwarf galaxies in the Virgo cluster, both in colour and morphology.