Simulations of a disk galaxy falling into a cluster

Jeong-Sun Hwang (Sejong Univ.)

in collaboration with

Changbom Park (KIAS)
Arunima Banerjee (IUCAA)

KNAG 8th meeting at KASI

2016-09-23 F

Research Purpose

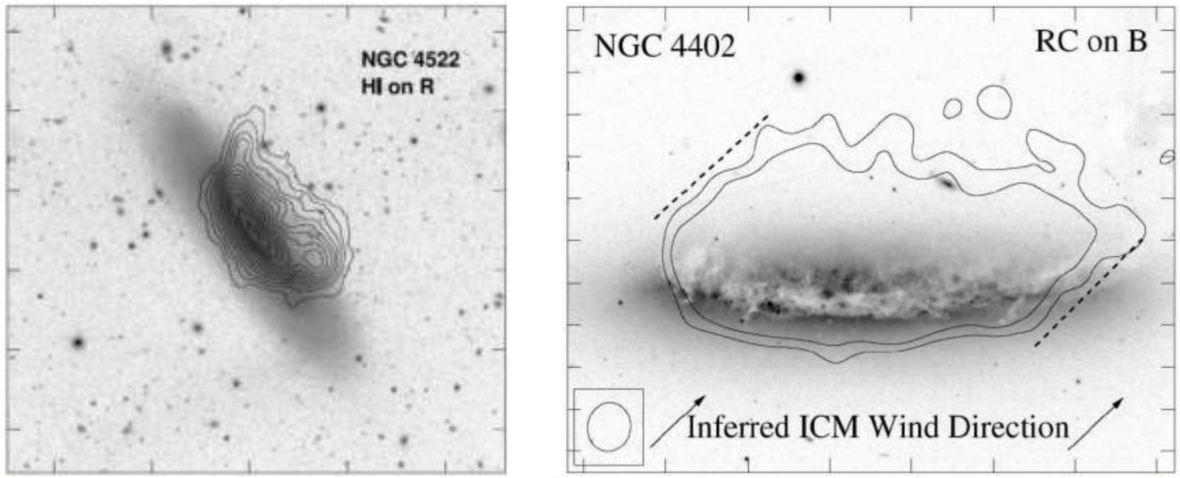


Fig. 1 Two examples of galaxies affected by ram-pressure stripping in the Virgo cluster. Top: H I gas (contours) and stellar light (grey scale, R-band) of NGC 4522. While the stellar distribution looks undisturbed the gas is bent back due to ram-pressure stripping (1.4 GHz radio continuum contours on B-band, from Kenney et al. 2004). Bottom: Similar features in NGC 4402 (from Crowl et al. 2005).

[Schindler & Diaferio 2008, SSRv]

- To understand the mechanisms that drive the evolution of galaxies in clusters
  - cold gas depletion,
  - star formation quenching, &
  - morphology transformation of the disk galaxies

- Hot Cluster Gas vs. Hot Halo Gas of the elliptical galaxies

Research Background

Motivated by Park & Hwang 2009 "Interactions of Galaxies in the Cluster Environment"

→ using the SDSS galaxies associated with the Abell clusters

→ the galaxy–galaxy encounters are very important in a cluster environment

Central region of clusters is dominated by elliptical galaxies

Galaxy morphology changes with clustercentric radius or local density

→ morphology–radius relation (MRR) or morphology–density relation (MDR)

Physical mechanisms to explain the MRR or MDR:

- Galaxy–galaxy tidal interaction
- Galaxy–cluster potential interaction
- Harassment
- Ram pressure stripping due to ICM
- Galaxy–galaxy hydrodynamic interaction
- Viscous stripping, thermal evaporation,…etc

Numerical Codes

ZENO software package

- To generate initial galaxy models (ICs)
- Allows one to build multiple components in mutual equilibrium with user-specified density profiles in collisionless or gaseous form.
- Developed by Joshua Barnes

Gagdet3 simulation code

- To evolve the galaxy models
- *N*-body/SPH (Smoothed Particle Hydrodynamics) code
- Implemented physics:

  Radiative cooling, Star formation, SN feedback,

  Sub-resolution model of multiphase ISM (Springel & Hernquist 2003)
- Provided by Volker Springel

Gadget Code

Radiative cooling:

- Compute cooling function for a gas of primordial composition (H, He)
  (Katz et al. 1996; Springel & Hernquist 2003)
- The abundances of the various ionization states of H and He,
  assuming ionization equilibrium in the presence of an external UV background field
  (Haardt & Madau 1996)

Star formation:

- Conditions: $\nabla \cdot v < 0$

  $\rho_{gas} > \rho_{th}$

  Jeans unstable ($\tau_{sound} = h/c_s > \tau_{dyn} = 1/\sqrt{(4\pi G\rho)}$)

  $T < T_{th}$
- Star formation : $d\rho_{stars}/dt = (1-\beta)\,\rho_{cold} / / t_{star}$

  β = mass fraction of the massive stars ; m=mass of an SPH particle
- t_{star} is chosen to match observation (Kennicutt 1998)

Supernova feedback:

- Massive stars (> 8 $M_\odot$, β=0.1) die instantly, releasing 10^{51} erg/SN to the embient gas
- The energy heats the ISM and evaporates cold clouds ⟶ "self-regulated cycle" for SF

Initial Models

- Disk galaxy model: D $(M = 126 \times 10^{10} M_\odot$, Rvir = 250 kpc)
- Elliptical galaxy model: EH $(M = 252 \times 10^{10} M_\odot$, Rvir = 350 kpc)
- Cluster model: C $(M = 10000 \times 10^{10} M_\odot$, Rvir = 1 Mpc)

D : $M_{halo,DM} + M_{bulge*} + M_{disk,*} + M_{disk,gas}$

(120) + (1) + (4.4 + 0.6)

disk gas fraction = 0.12 (12%)

EH : $M_{halo,DM} + M_{halo,gas} + M_{bulge,*}$

(237.6 + 2.4) + (12)

halo gas fraction = 0.01 (1%)

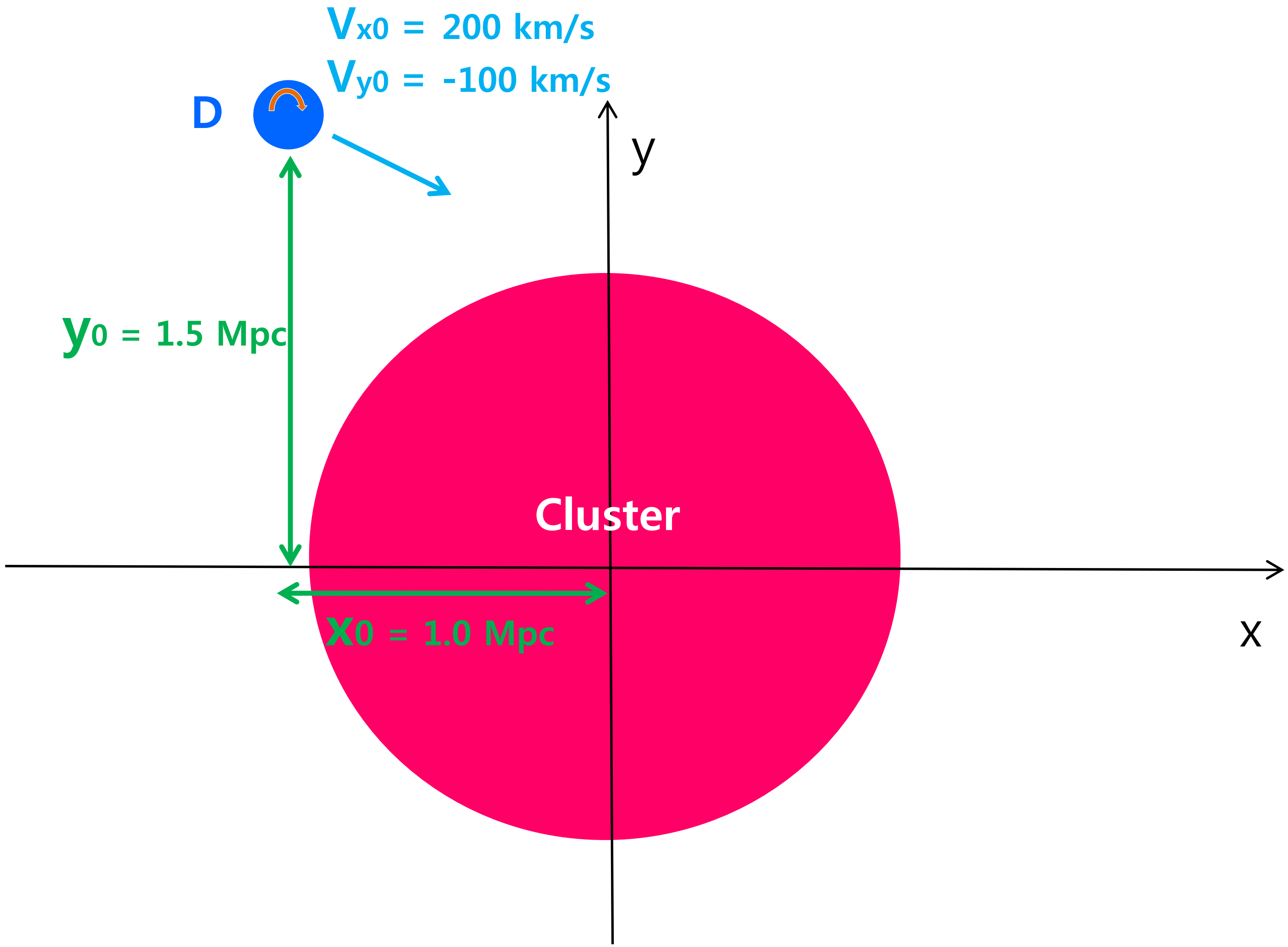
C: $M_{cl,DM} + M_{cl,\ gas}$

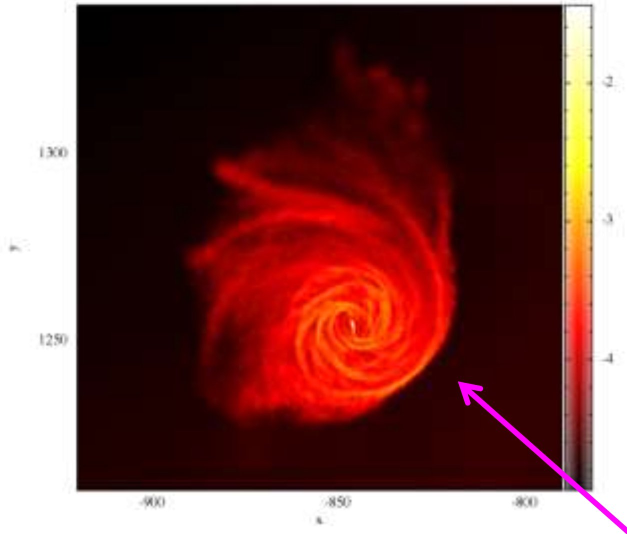
(9000 + 1000)

cluster gas fraction = 0.1 (10%)

- DM Halo: NFW profile
- Gas Halo: Isothermal profile
- Stellar Disk: Exponential profile
  (radial scale length = 3.5 kpc)
- Gas disk: Exponential profile
  (radial scale length = 8.75 kpc)
- Stellar bulge: Hernquist profile

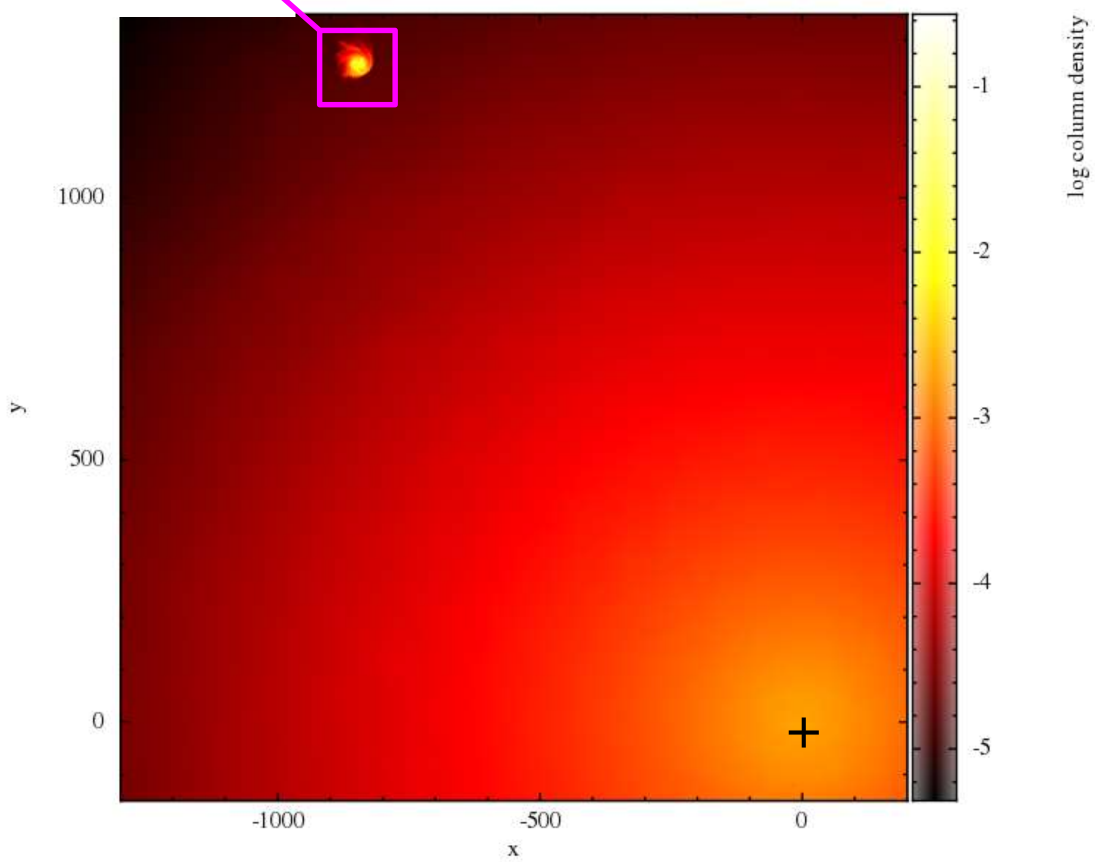
Galaxy–Cluster Simulations



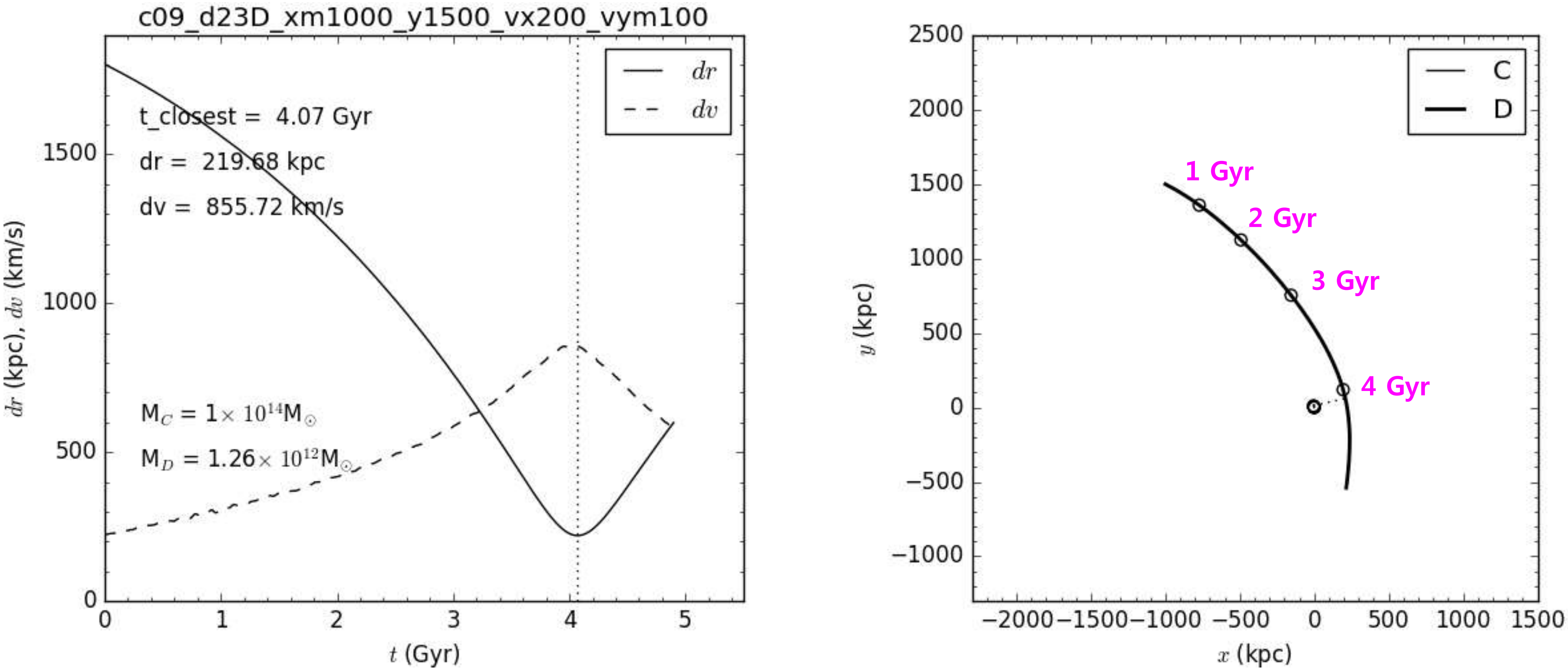


Cluster Simulations

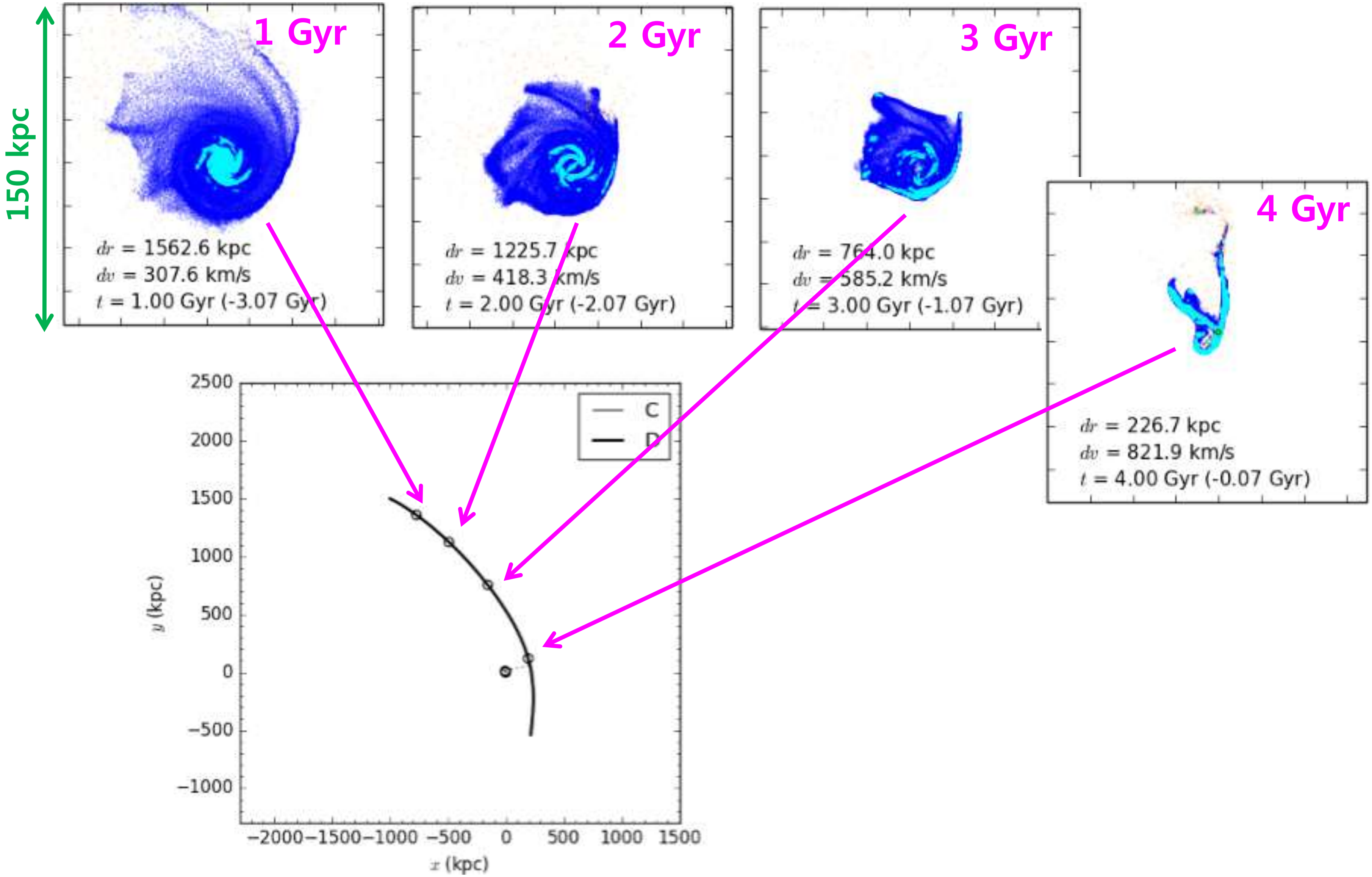
Color-bar: Log column density of gas
(disk gas + cluster gas)

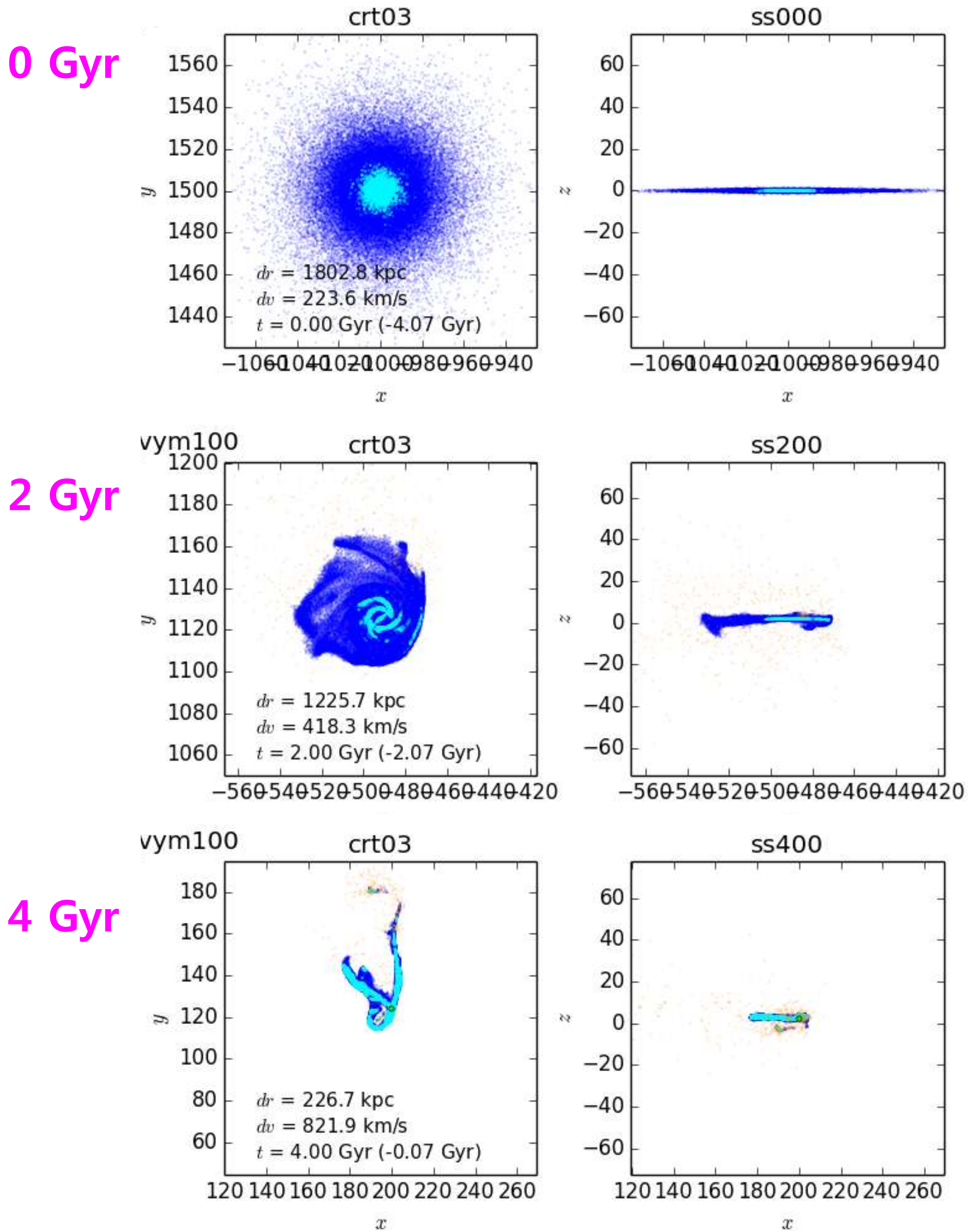


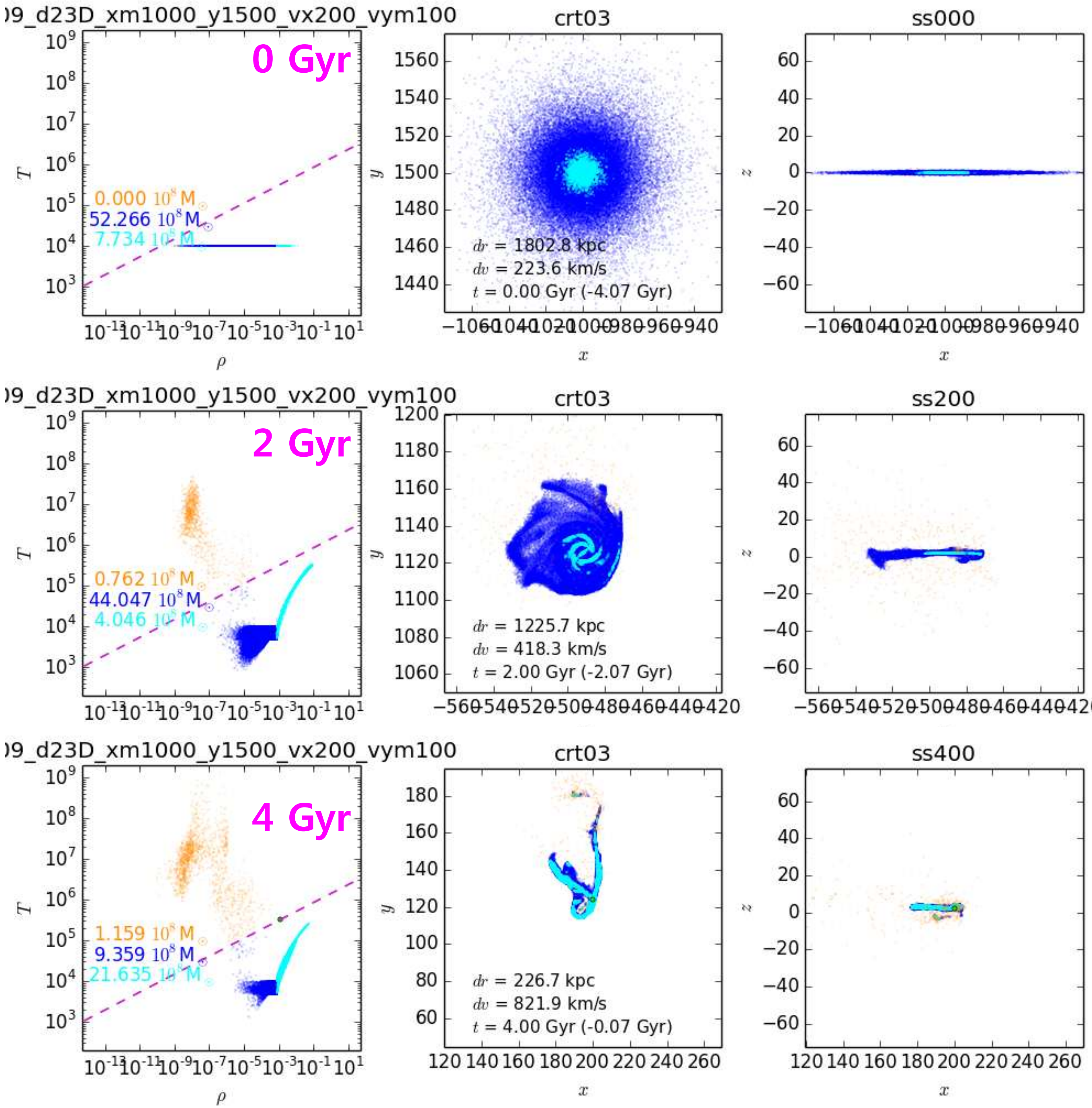
Galaxy-Cluster Simulations



Galaxy-Cluster Simulations




0 Gyr
2 Gyr
4 Gyr
crt03
ss000
ss200
ss400
vym100
dr = 1802.8 kpc
dv = 223.6 km/s
t = 0.00 Gyr (-4.07 Gyr)
dr = 1225.7 kpc
dv = 418.3 km/s
t = 2.00 Gyr (-2.07 Gyr)
dr = 226.7 kpc
dv = 821.9 km/s
t = 4.00 Gyr (-0.07 Gyr)
x
y
z



)9_d23D_xm1000_y1500_vx200_vym100
crt03
ss000
0 Gyr
0.000 10^8 M☉
52.266 10^8 M☉
7.734 10^8 M☉
dr = 1802.8 kpc
dv = 223.6 km/s
t = 0.00 Gyr (-4.07 Gyr)
)9_d23D_xm1000_y1500_vx200_vym100
crt03
ss200
2 Gyr
0.762 10^8 M☉
44.047 10^8 M☉
4.046 10^8 M☉
dr = 1225.7 kpc
dv = 418.3 km/s
t = 2.00 Gyr (-2.07 Gyr)
)9_d23D_xm1000_y1500_vx200_vym100
crt03
ss400
4 Gyr
1.159 10^8 M☉
9.359 10^8 M☉
21.635 10^8 M☉
dr = 226.7 kpc
dv = 821.9 km/s
t = 4.00 Gyr (-0.07 Gyr)
T
ρ
x
y
z

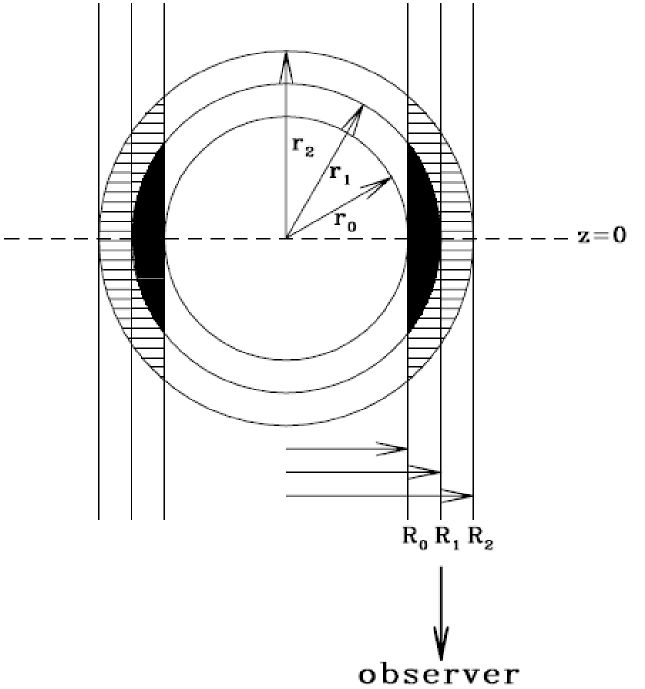
Coma Cluster Catalog

To estimate the number of interactions between D and other galaxies in the cluster

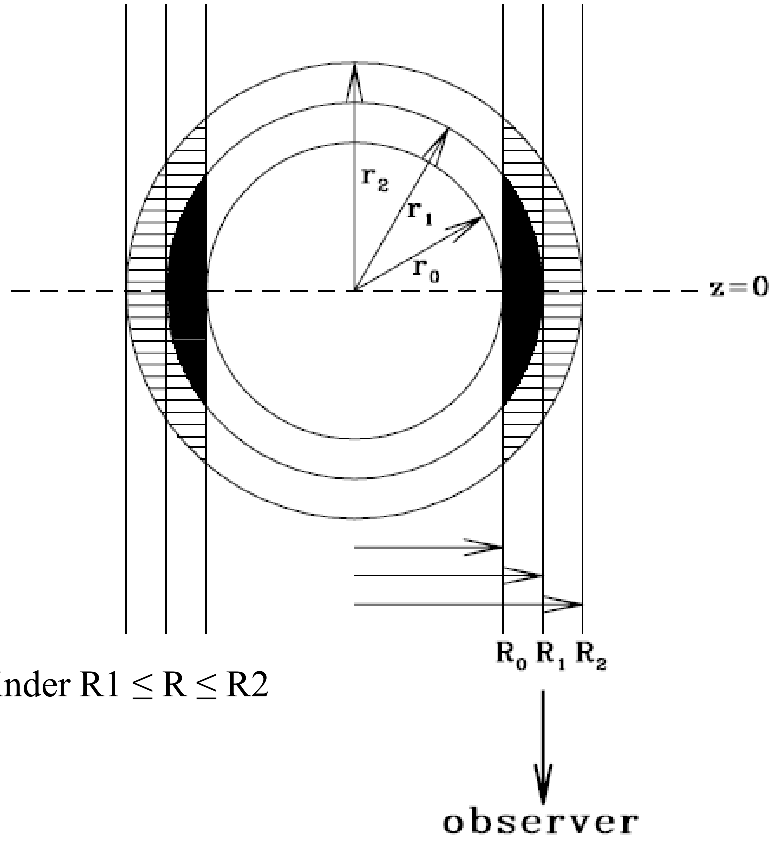
Coma Cluster catalog (provided by Ho Seong Hwang)

- 1088 member galaxies with 1.9 Mpc/h
- 2D projected positions ----> 3D positions,
  using a geometrical deprojection algorithm [McLaughlin 1999]

- Assumption: spherical symmetry
- Projected radius: Ro, R1, R2, …
- Bands R1 ≤ R ≤ R2, R0 ≤ R ≤ R1
  axial cross sections of cylinders
- 3D radius: ro, r1, r2, …
- Shells are chosen such that
  r0 = R0, r1 = R1, r2 = R2, …



- If r2=R2 is the outer edge of the cluster,
  all galaxies seen in the outermost cylinder
  come from the outer shell
  (i.e., hatched regions between R1 & R2)



- Average volume number density of the outer shell:

$$n_{\rm cl}(r_1, r_2) = \frac{\mathcal{N}_{\rm cl}(R_1, R_2)}{V_{\rm int}(r_1, r_2; R_1, R_2)}$$

← given

↑ volume of the shell r1 ≤ r ≤ r2 which is intersected by the cylinder R1 ≤ R ≤ R2

- Average volume number density of the inner shell:

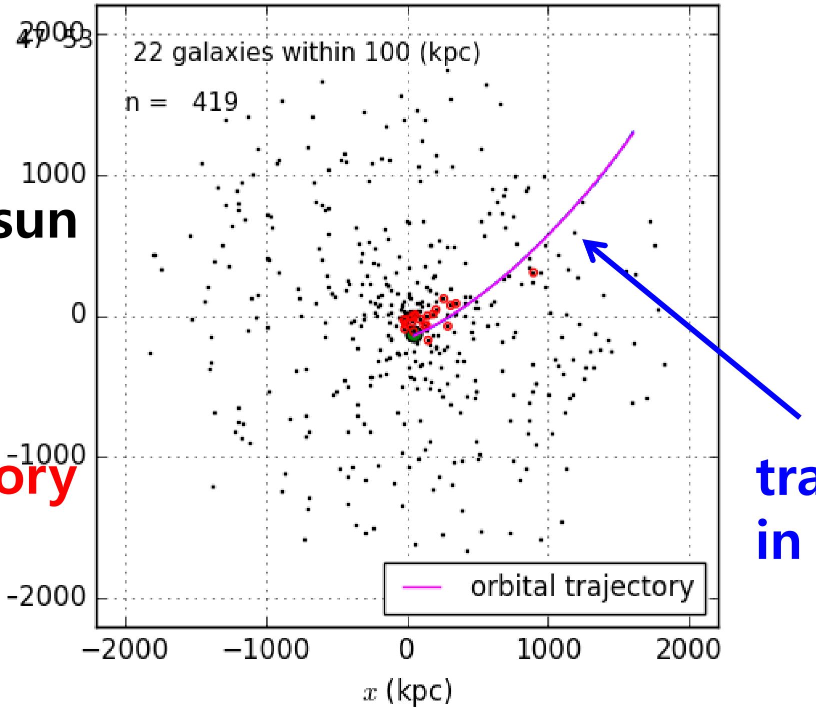
$$n_{\rm cl}(r_0, r_1) = \frac{\mathcal{N}_{\rm cl}(R_0, R_1) - n_{\rm cl}(r_1, r_2)V_{\rm int}(r_1, r_2; R_0, R_1)}{V_{\rm int}(r_0, r_1; R_0, R_1)}$$

$$n'_{\rm cl}(R_{i-1}, R_i) = \frac{\mathcal{N}_{\rm cl}(R_{i-1}, R_i) - \sum_{j=i+1}^{m}[n_{\rm cl}(R_{j-1}, R_j)V_{\rm int}(R_{j-1}, R_j; R_{i-1}, R_i)]}{V_{\rm int}(R_{i-1}, R_i; R_{i-1}, R_i)}$$

Coma Cluster Catalog & D-C Simulation

Black dots (419):
galaxies in the catalog
with M* > 1.0 X 10^10 Msun

Red dots (22):
galaxies within 100 kpc
from the magenta trajectory

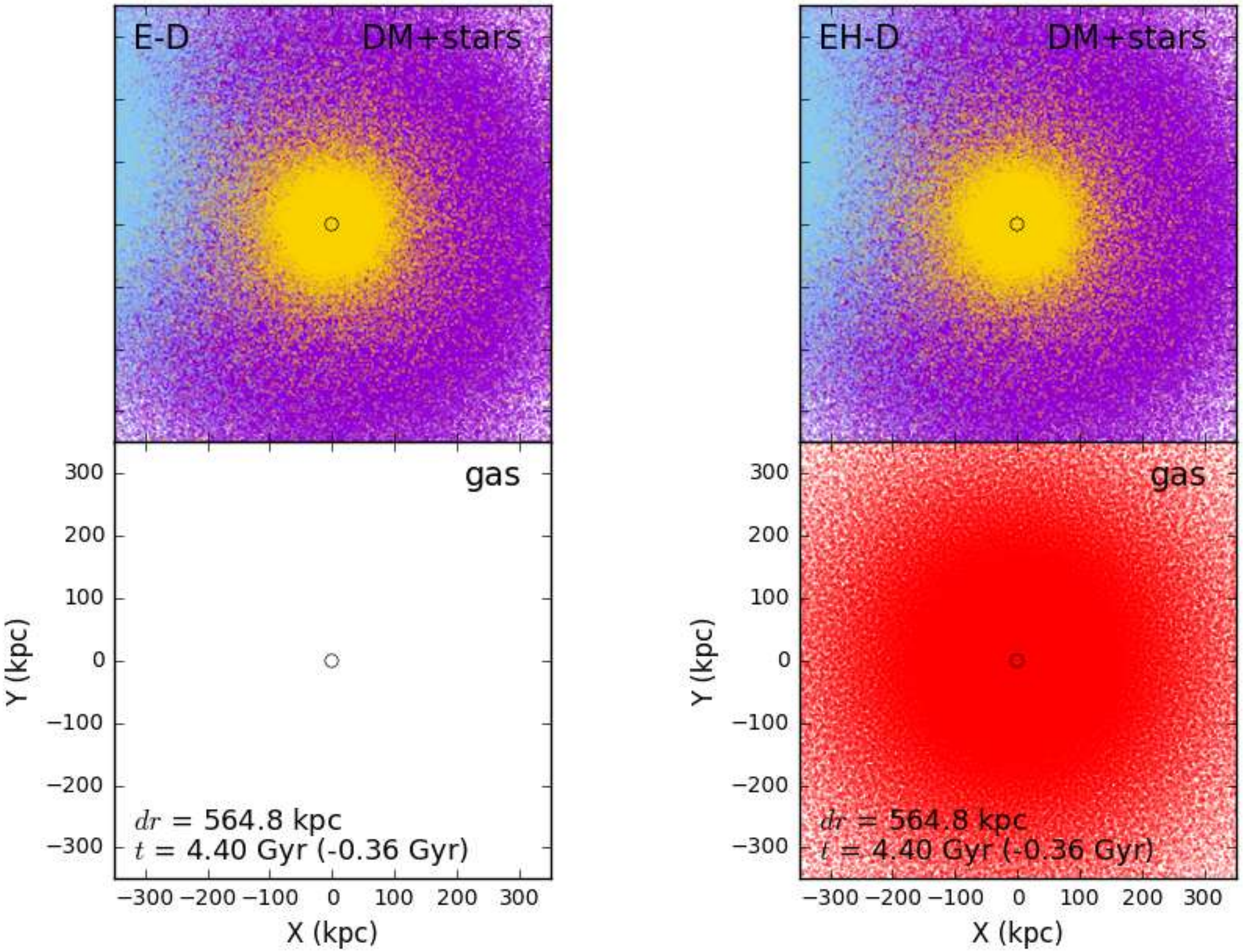


trajectory of D
in C (simulation)

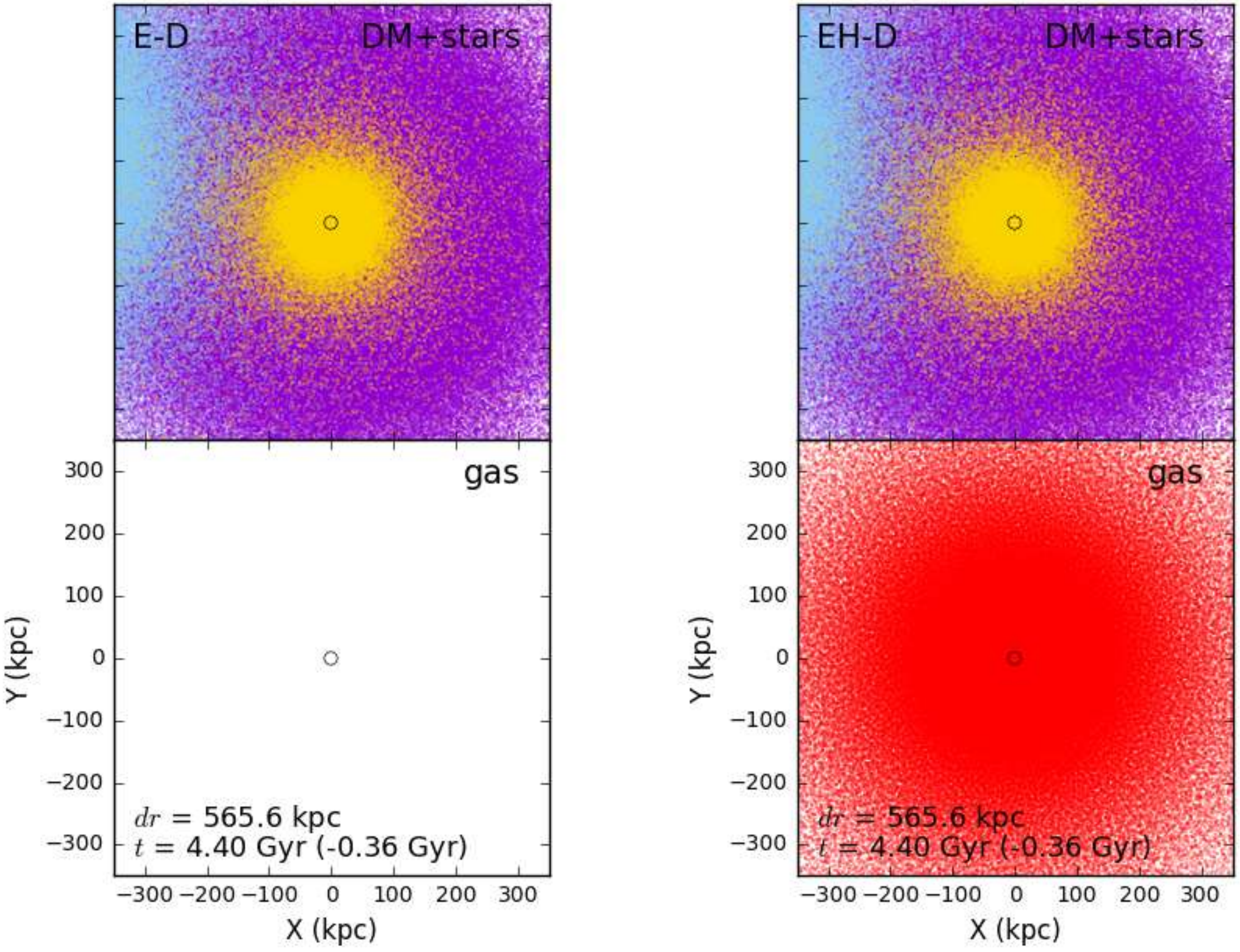
22 closest approach distances:

30.0, 39.6, 40.6, 50.2, 63.5,
68.2, 72.4, 73.3, 74.1, 74.3,
77.0, 85.5, 87.2, 88.3, 89.8,
91.0, 92.2, 92.3, 94.0, 95.1,
95.2, 96.2

Galaxy-Galaxy fast flyby (face on)



Galaxy-Galaxy fast flyby (edge on)



Thank you! :-)