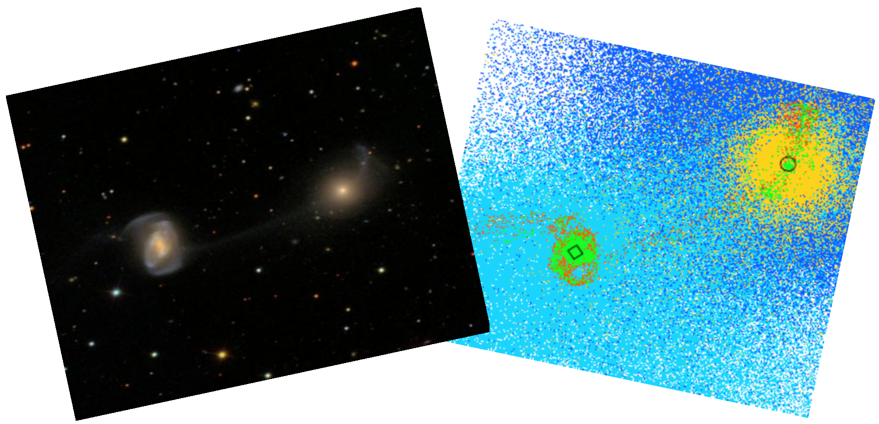
on the star formation & mass transfer

Effects of hot halo gas during distant galaxy-galaxy encounters



Jeong-Sun Hwang (Kyung Hee Univ.)
with
Changbom Park (Korea Inst. for Advanced Study)

The 6th East-Asian Numerical Astrophysics Meeting — Sep. 16, 2014

Motivation

X-ray observations & cosmological hydrodynamical simulations report
not only elliptical galaxies but also some spiral galaxies possess hot gas in their haloes.

So far, almost all hydrodynamic simulations of galaxy interactions
have not included hot gas in the ICs.

- LTG: DM halo + Bulge + Stellar disk + (cold) Gas disk + (hot) halo gas

Moster et al. 2011, 2012

- included (for the first time) a gradually cooling hot diffuse gas halo
- major mergers: halo gas affects the kinematics & internal structure of the merger remnants and the SF activities
- minor mergers: halo gas affects the disk thickness

Galaxy evolution through a whole variety of galaxy interactions:

- Major/Minor mergers → extensively studied
- Flyby or distant encounters → little work done so far

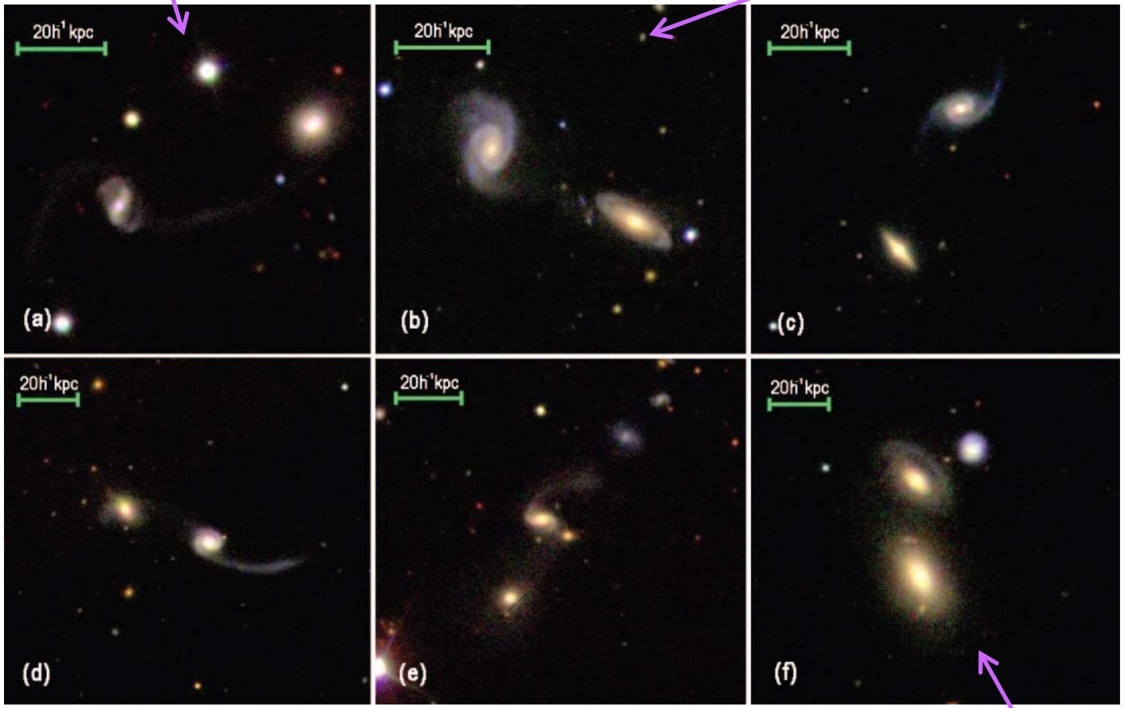
Motivation

- Park, Gott, & Choi, 2008

  "Transformation of Morphology & Luminosity Classes of the SDSS Galaxies"

- A long bridge is connected to the ETG.
- The ETG is very blue & has strong emission lines.
- The LTG is probably feeding its disk materials to the ETG.

- The red galaxy have two blue spiral arms.



- The hot gas of the ETG seems to remove cold gas from its neighbor.

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

Initial Galaxy Models

2 ETG models: E, EH → total mass = 252 x 10^{10} $M_\odot$
2 LTG models: L, LH → total mass = 126 x 10^{10} $M_\odot$

$M_{ETG} : M_{LTG} = 2:1$

E : $M_{halo,DM} + M_{bulge,*}$
(240) + (12)

EH : $M_{halo,DM} + M_{halo,gas} + M_{bulge,*}$
(237.6 + 2.4) + (12)
$f_{hg} = 0.01$

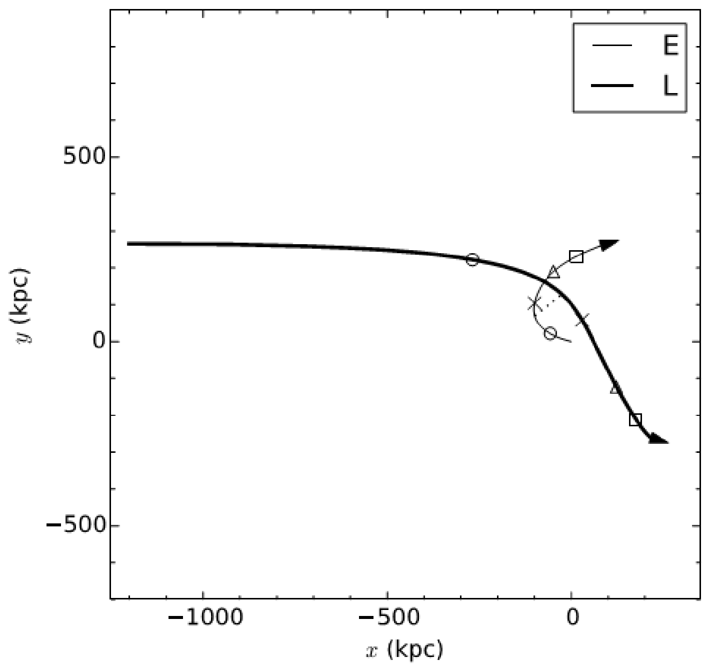
L : $M_{halo,DM} + M_{bulge*} + M_{disk,*} + M_{disk,gas}$
(120) + 1 + (4.4 + 0.6)
$f_{dg} = 0.12$

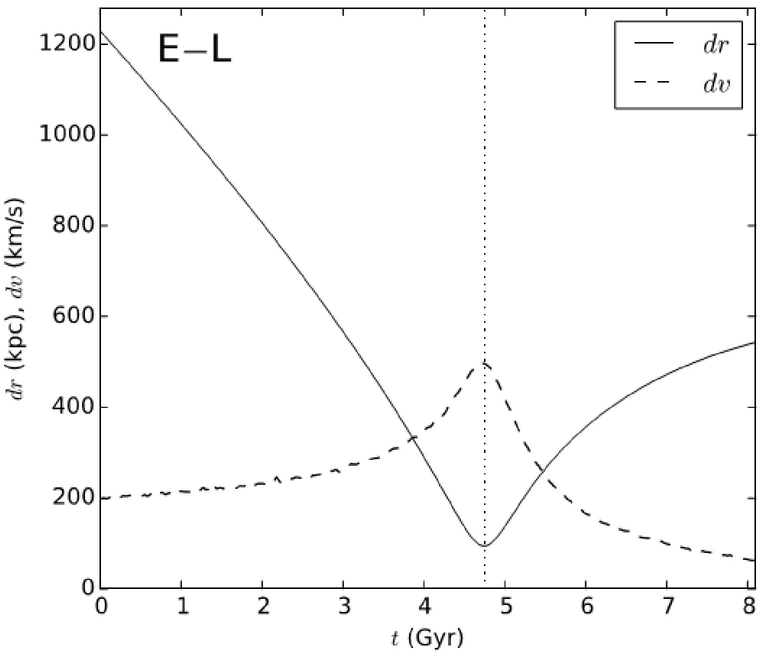
LH: $M_{halo,DM} + M_{halo,gas} + M_{bulge*} + M_{disk,*} + M_{disk,gas}$
(118.8 + 1.2) + 1 + (4.4 + 0.6)
$f_{hg} = 0.01$ $f_{dg} = 0.12$

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

Distant Encounters

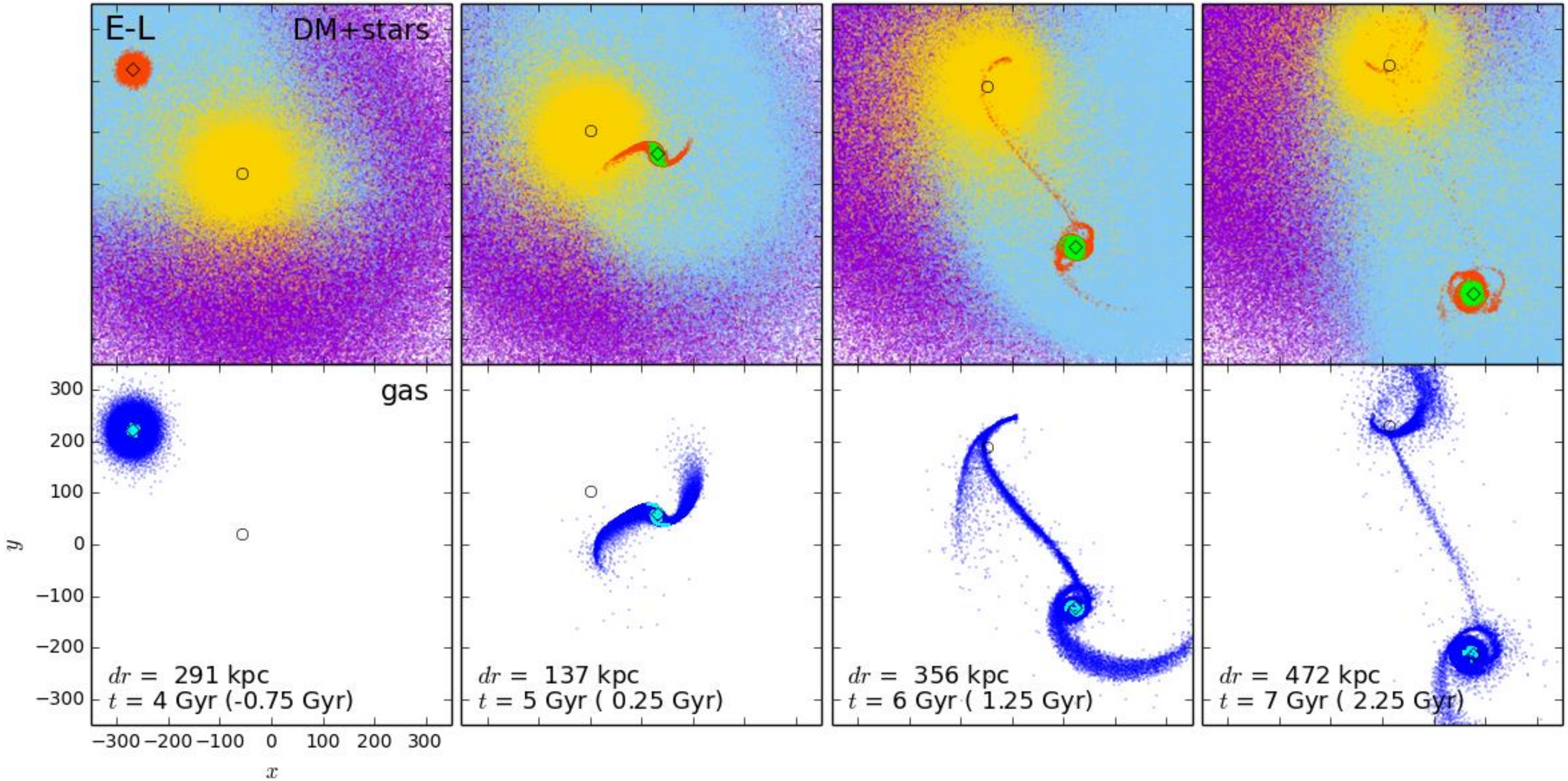
ETG-LTG	ETG		LTG		1st closest approach		
	x_0, y_0, z_0 (kpc)	v_{x0}, v_{y0}, v_{z0} (km s^{-1})	x_0, y_0, z_0 (kpc)	v_{x0}, v_{y0}, v_{z0} (km s^{-1})	dr (kpc)	dv (km s^{-1})	t (Gyr)
E-L	0, 0, 0	0, 0, 0	−1200, 265, 0	200, 0, 0	94.3	495.6	4.75
EH-L	0, 0, 0	0, 0, 0	−1200, 265, 0	200, 0, 0	94.4	494.8	4.75
EH-LH	0, 0, 0	0, 0, 0	−1200, 265, 0	200, 0, 0	94.8	495.5	4.75





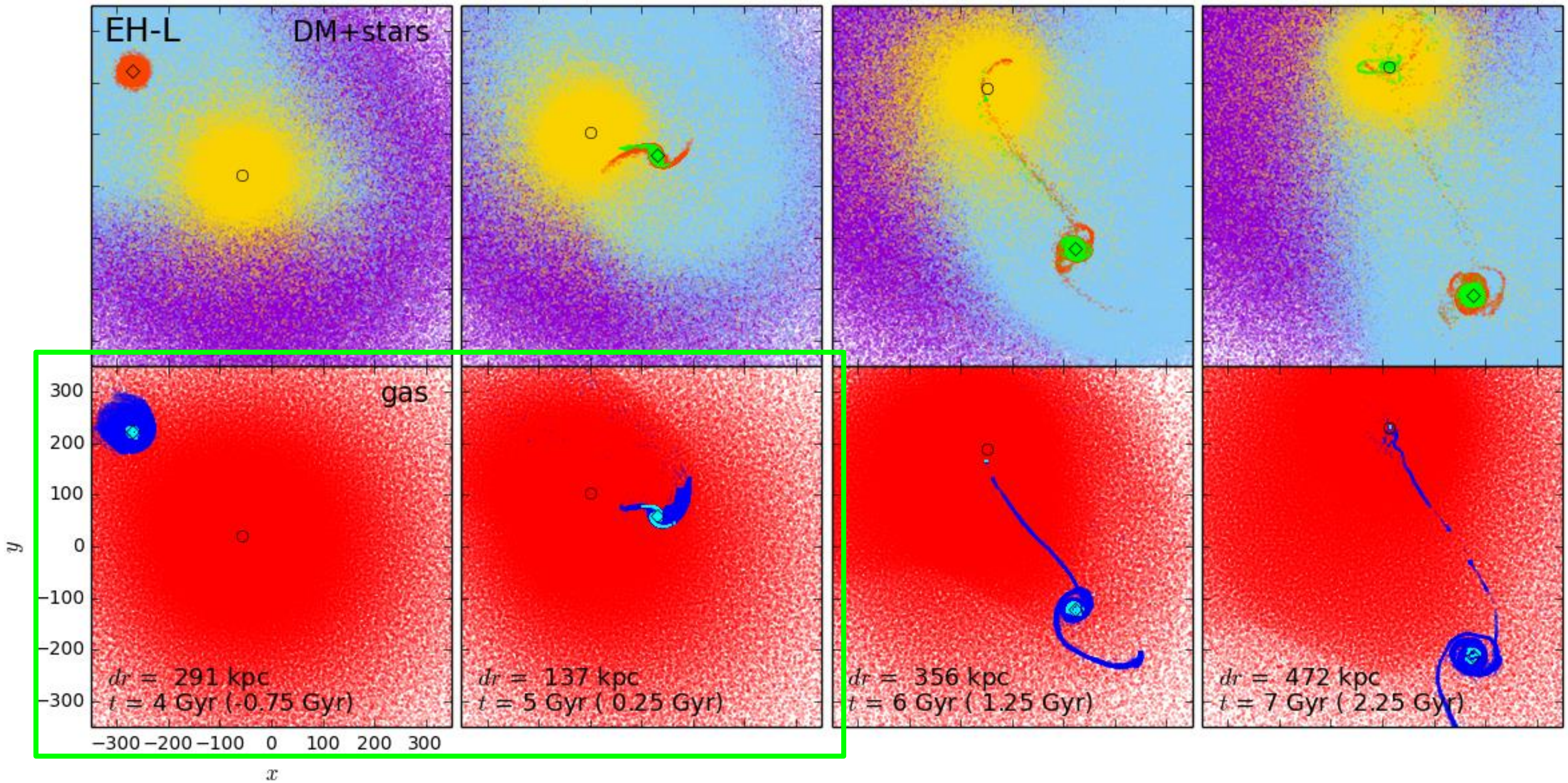
o at 4Gyr; x at 5Gyr; △ at 6Gyr; □ at 7Gyr

Evolution of E-L



- Four snapshots taken at t = 4, 5, 6, & 7 Gyr, projected onto the x-y plane (-350 < x,y < 350, all z)
- Top panels: dist. of the collisionless particles, bottom panels: dist. of the gas particles
- ◊=CM of LTG, ○=CM of ETG, Color shows the origin of the particles, Green='young' stars, Orange='old' stars, Cyan=SFing gas
  time in ( ) = time measured from the 1st closest approach, dr = separation in 3D
- 5 Gyr: the disks develop the inner and outer tidal tails.
- 6 Gyr: 'old' disk stars & non-SFing disk gas are transferred from L to E, but no young stars nor the SFing gas are transferred.
- 7 Gyr: the accreted cold gas and the old stars appear to orbit around the center of E.

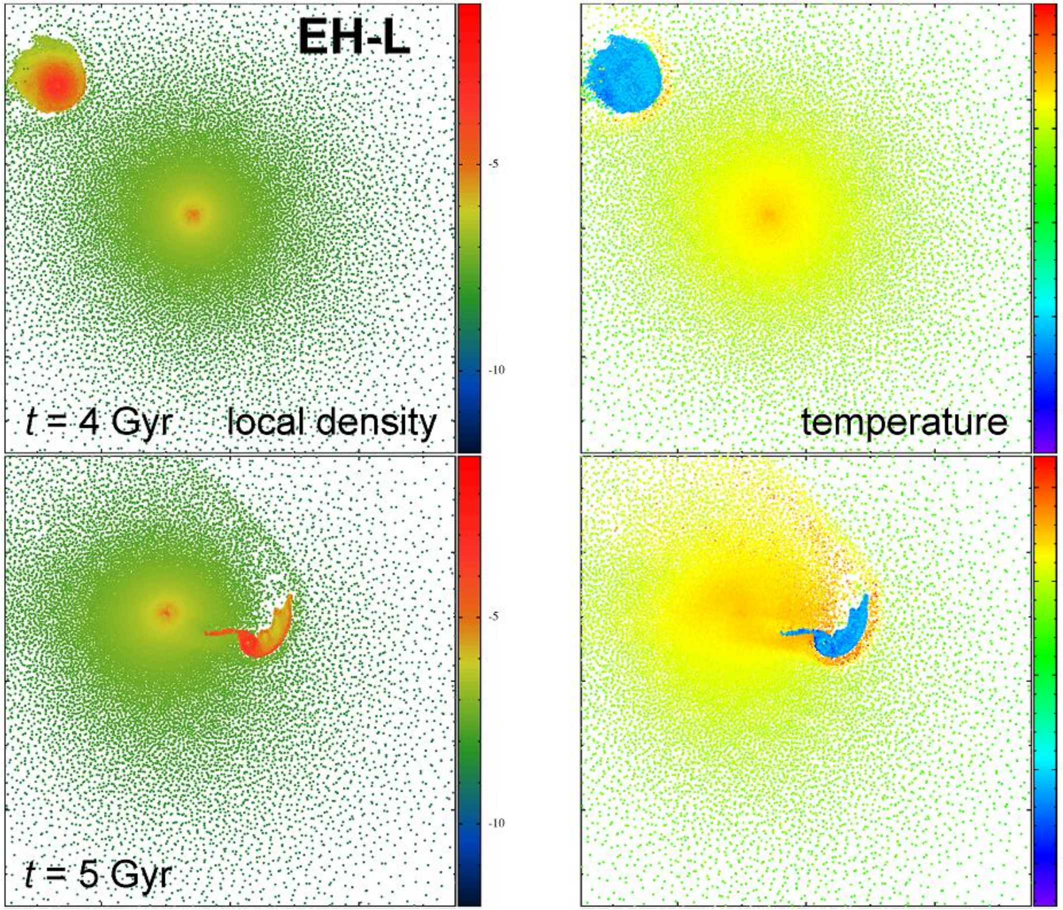
Evolution of EH-L



- The same snapshots as before • red points: halo gas of the ETG
- The distribution of the old disk stars is overall similar to the previous run, but that of young stars and disk gas are different.
- 4 Gyr: The gas disk forms the **bow-like front**
- 5 Gyr: The **gas bridge** develops nearly **straightly**; **A burst of SF** in the shock-compressed gas along the gas bridge; the offset
- 6 Gyr: The **gas bridge** including some of **SFing gas** continues to extend almost **radially** to the center of EH.
- 7 Gyr: The **accreted old and young stars orbit around EH** with different orbits.

  Some **young stars** and **cold gas** accumulate **at the center of EH**.

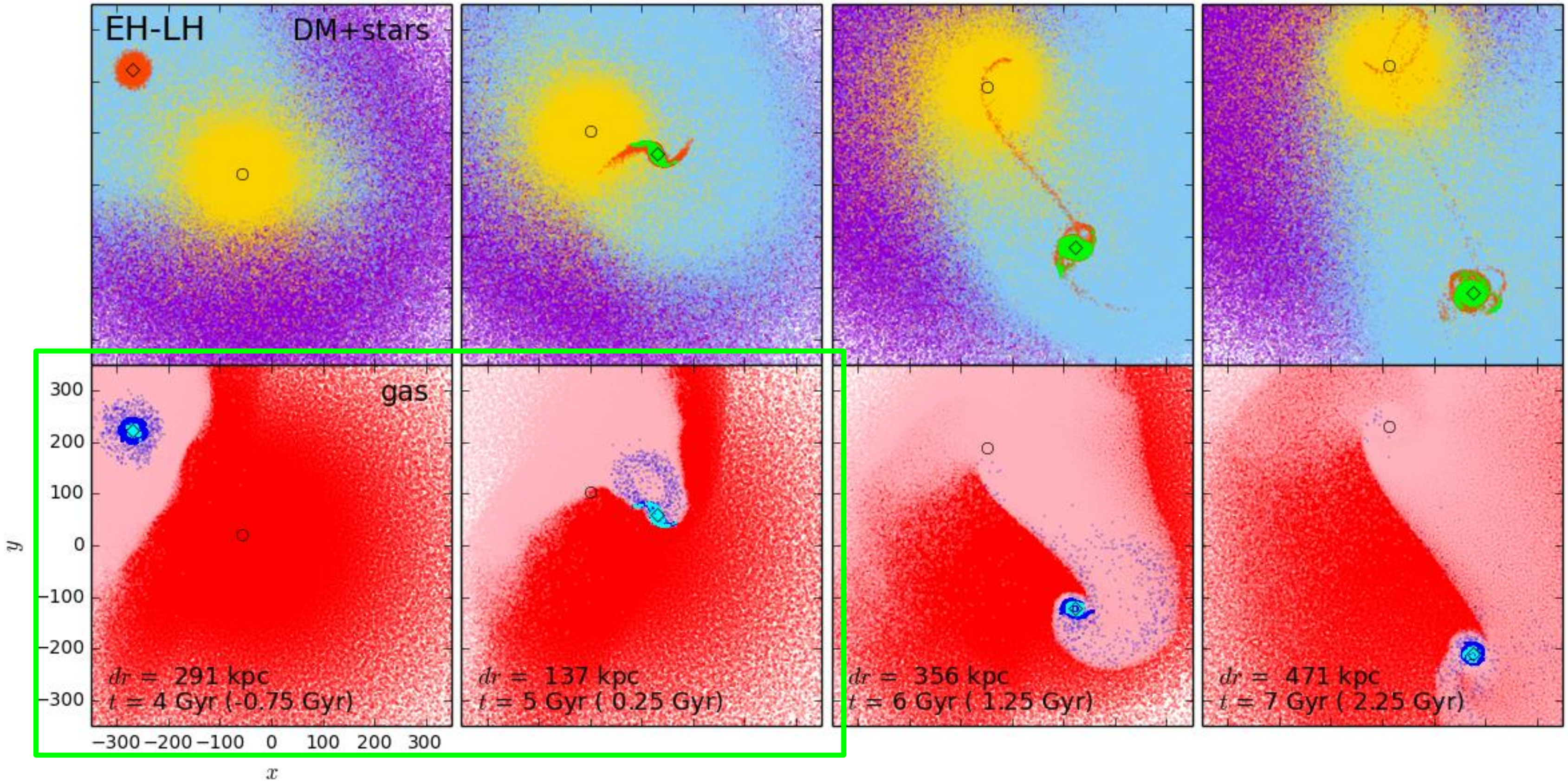
Evolution of EH-L



- Local Density (left) & Temperature (right) of the gas particles within |z| < 15 kpc.
- 4Gyr: Gas density at the leading side of the disk rises; Some halo gas piles up along the bow-like front.
- 5Gyr: **A channel** for the cold gas **toward the center of E** is created.

  The cold gas can **flow though this channel** and is not blocked by shocks.

Evolution of EH-LH

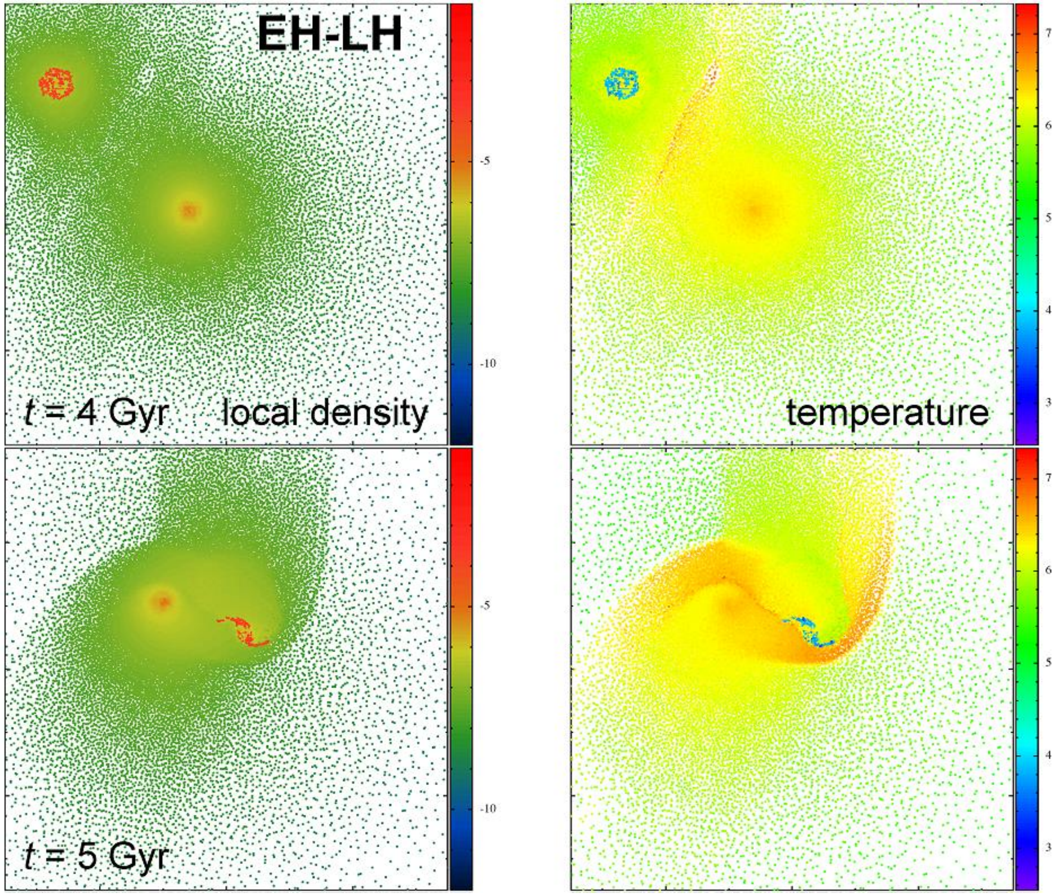


- The same snapshots as before
- pink points: halo gas of the LTG;
- The old disk stars evolve in the same way as in the two previous runs at all times, but the cold gas evolves in a unique way.
- 4 Gyr: A large-scale shock is formed between the two hot gas halos.

  The cold disk has lost particles at the outskirt partly by the ionization;

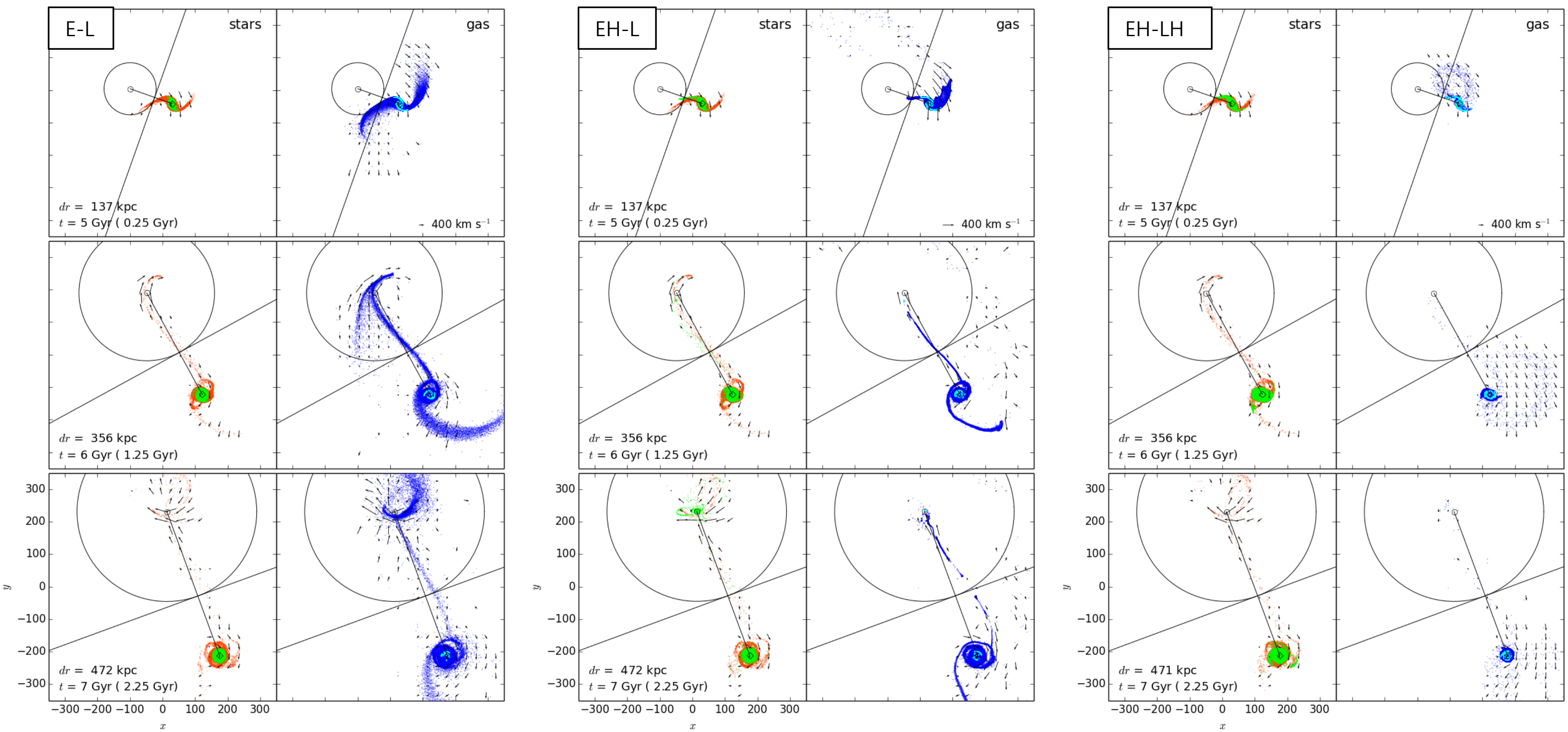
  The **gas disk** has **dissipated** more quickly than the other & produced **more stars** due to the compression exerted by its halo
- 5 Gyr: The gas disk **does not develop** a strong and almost **no cold gas is delivered to EH**.

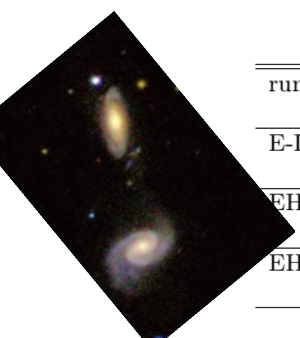
Evolution of EH-LH



- Local Density (left) & Temperature (right) of the gas particles within |z| < 15 kpc.
- 4Gyr: A large-scale shock is formed due to the collision of the two gas halos.
- 5Gyr: The inner trailing **shock propagates toward the center of EH** before the cold gas tidal bridge starts to extend toward EH.

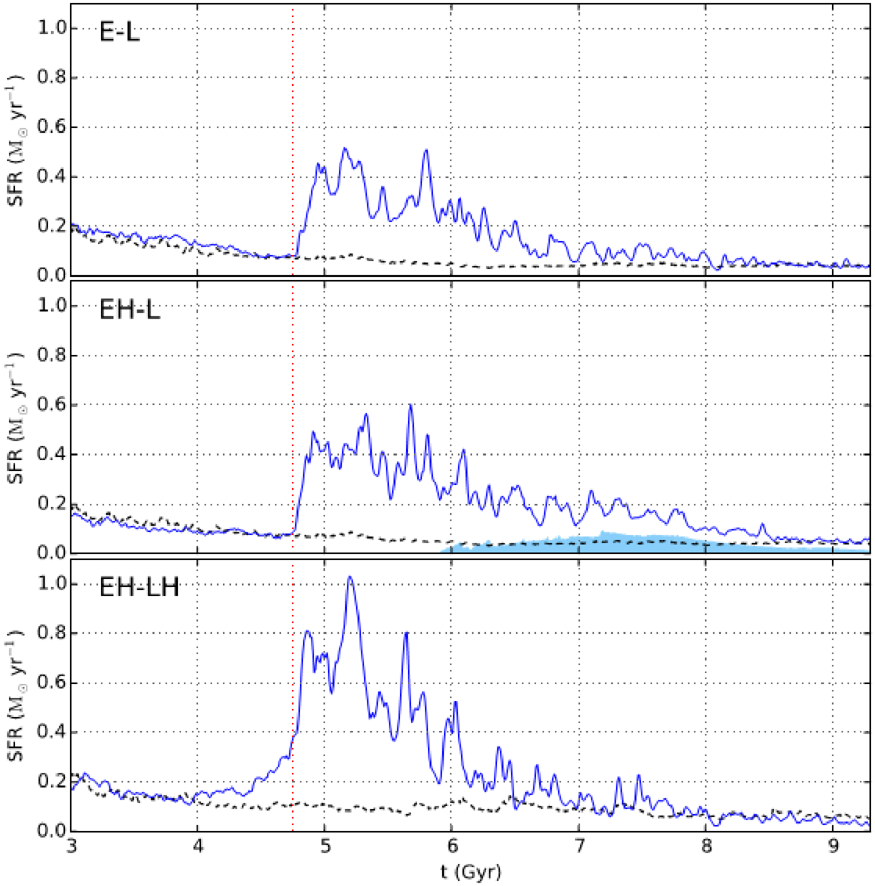
Mass transfer from LTG to ETG





run	t (Gyr)	old disk stars (10^8 M$_\odot$)	new disk stars (10^8 M$_\odot$)	non-star forming disk gas (10^8 M$_\odot$)	star forming disk gas (10^8 M$_\odot$)	sum[a] (10^8 M$_\odot$)
E-L	6	0.449	0	3.303	0	3.752
	7	0.464	0	3.396	0	3.860
EH-L	6	0.452	0.057	1.506	0.319	2.334
	7	0.469	0.515	0.818	0.595	2.398
EH-LH	6	0.463	0	0.021	0	0.484
	7	0.478	0	0.018	0	0.496

Star Formation Rates



SFR increases rapidly right after the closest approach
The excess (over black) diminishes after ~7Gyr

SFR increases rapidly right after the closest approach.
The maximum amplitude is higher.
The excess (over black) diminishes after ~8.5 Gyr.

SFR increases before the closest approach.
The maximum amplitude is the highest.
The excess (over black) diminishes after ~7 Gyr

Summary

We find that the dynamics of the cold disk gas in the tidal bridge and the amount of the newly formed stars depend strongly on the existence of a gas halo.

E-L case:

- The gas and stars accreted into the ETG do not include 'new' stars.

EH-L case:

- A shock forms along the cold disk gas tidal bridge and induces star formation near the closest approach.
- The shock front is parallel to a channel along which the cold gas flows toward the center of the ETG.
- The ETG can accrete star-forming cold gas and newly born stars at and near its center.

EH-LH case:

- A shock is formed between the two gas halos somewhat before the closest approach.
- The shock-compressed halo gas of the LTG consequently compresses the disk gas and gives rise to enhanced star formation before the closest approach.
- The shock hinders the growth of the cold gas bridge to the center of the ETG and also ionizes it.
- Only some of the disk stars transfer through the stellar bridge.