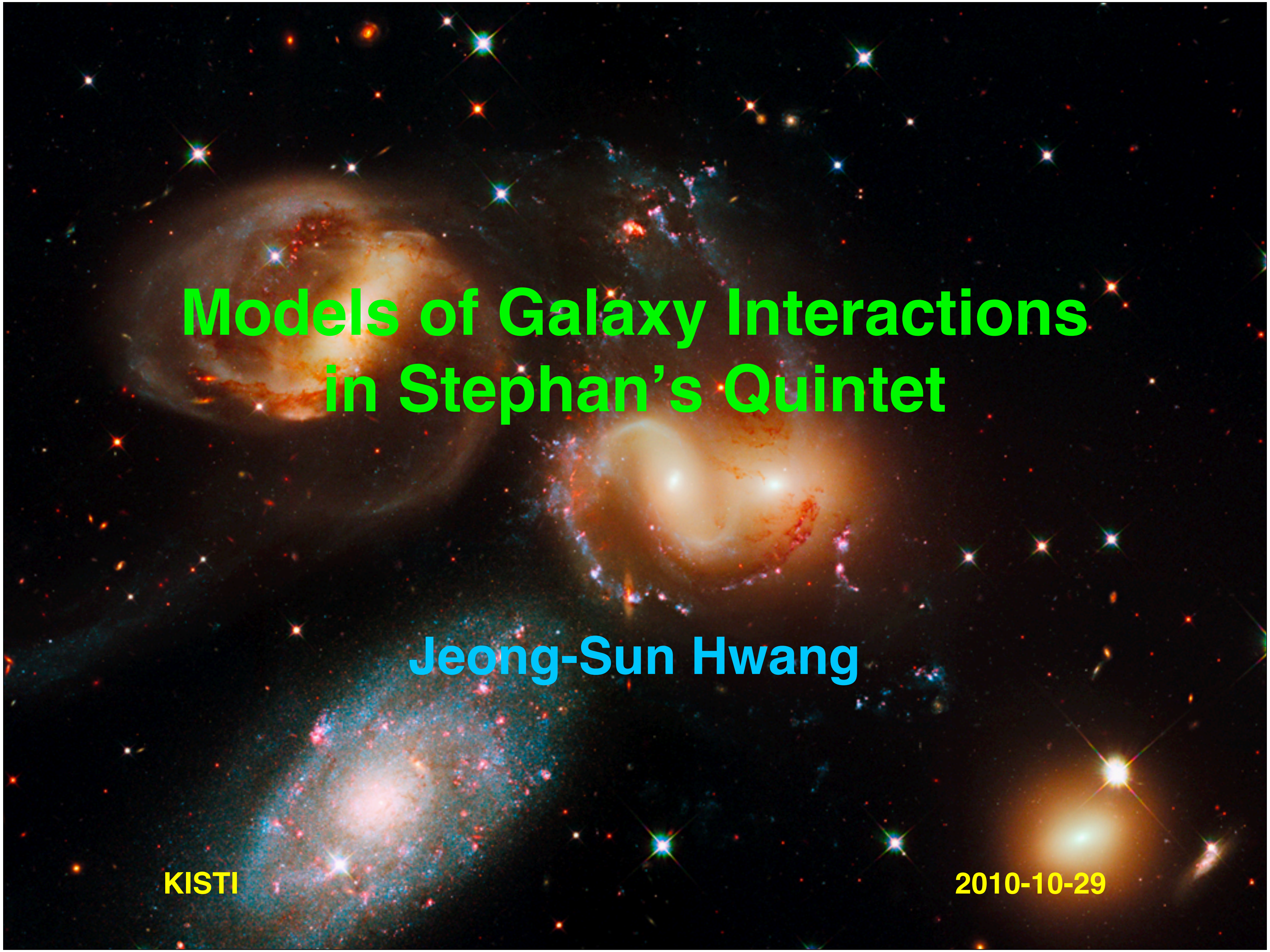

Models of Galaxy Interactions in Stephan’s Quintet

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KISTI

2010-10-29

Contents

Intro: Galaxy Interactions & Evolution

Galaxies are not “Island of Universes”, rather they
interact with neighboring galaxies and matters, and
are affected by environment.

Galaxy interactions (collisions) are common:
The extent of galaxy halos is comparable to the separation between them.
Most galaxies have interaction histories.

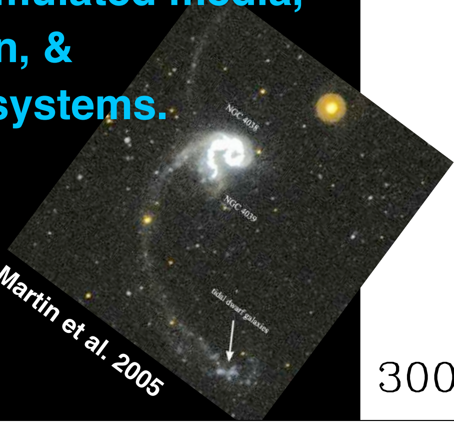
Galaxy interactions are one of the primary drivers of galaxy evolution
by rearranging the structure of the galaxies &
by triggering lots of the cosmic star formation, etc.

Intro: The key to understanding various phenomena driven by interactions

--> Careful comparison of
multi-wavebands observations of nearby galaxies
with dynamical models

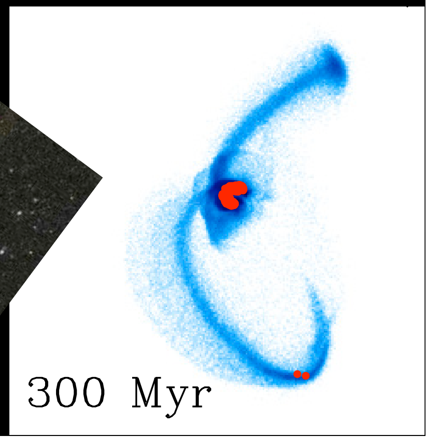
Observations in multi-wavebands reveal
important physical quantities, &
information about various physical processes in the systems.

Well-constrained numerical models provide:
direct laboratory experiments & analyses via simulated media,
predictions of the distributions of star formation, &
additional constrains or information about the systems.

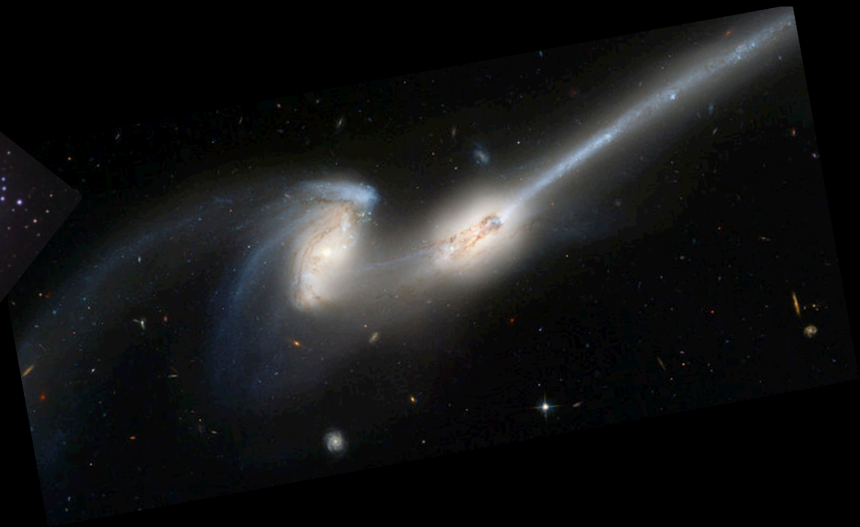


Martin et al. 2005

Renaud, Boily, Naab, &
Theis 2009



Intro: Early Views on Peculiar Galaxies



Until the early 1970's,
there was still much debate on the tidal deformation of interacting galaxies,
particularly for the very extended filamentary features observed:

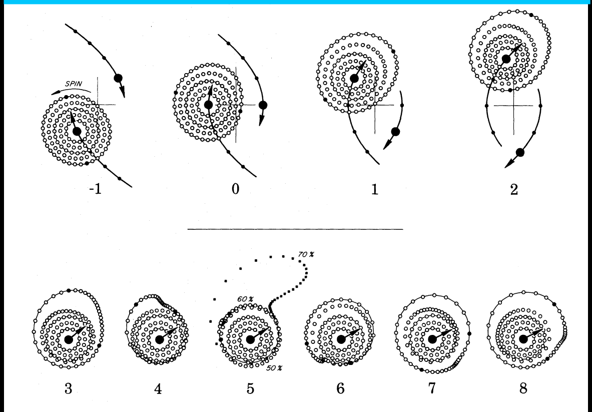
- tidal origins?
- magnetic fields or bizarre explosions involved?

Intro: ‘Galactic Bridges & Tails’

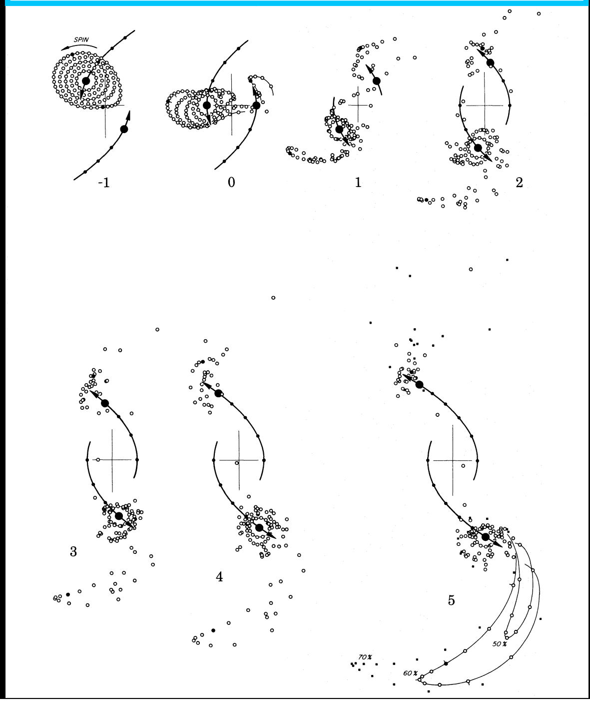
- A seminal work in the field of galaxy interactions & numerical models of encounters
- By Toomre & Toomre (1972)
- Used a simplistic stellar dynamics code

Development of tidal bridges & tails
by a close planner encounter of a companion of equal mass:

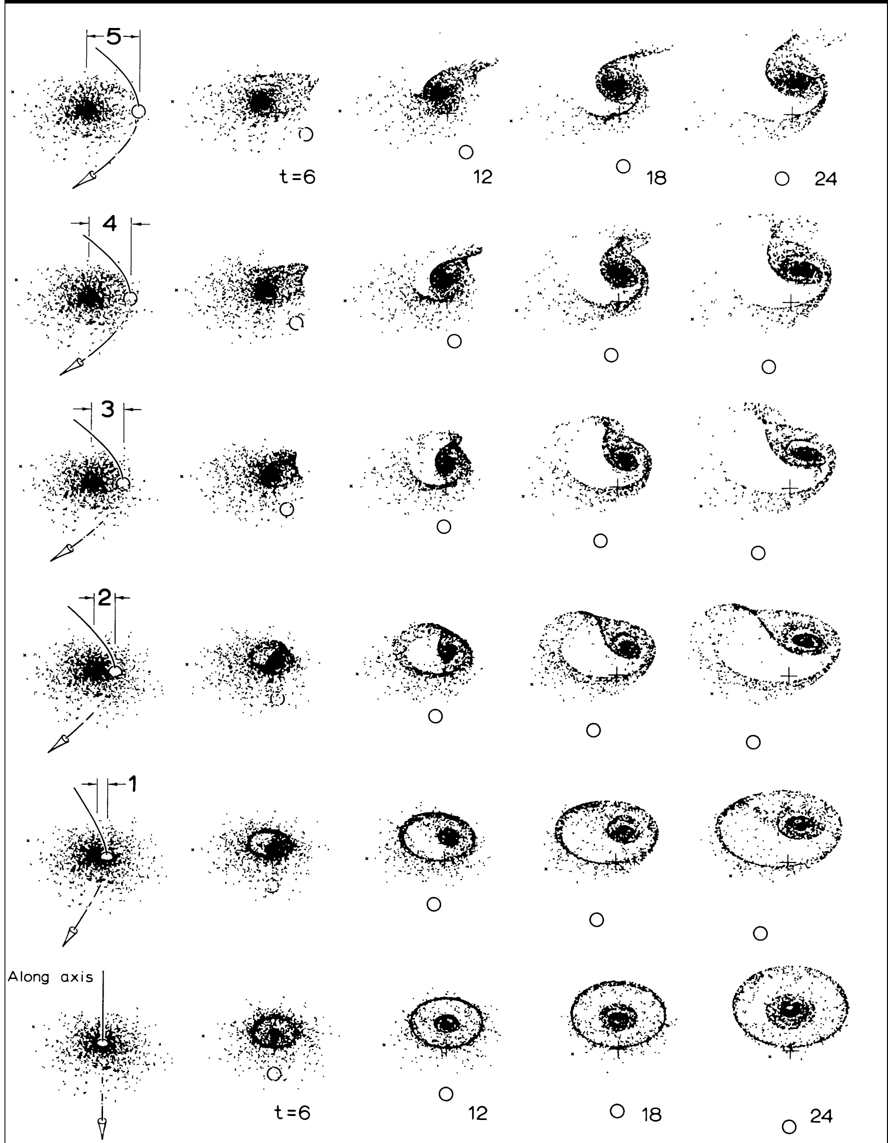
A retrograde passage



A prograde passage



Intro: Collisional Rings



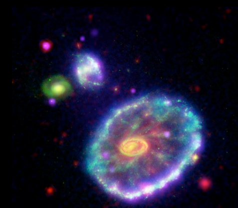
Toomre (1978):

Collisions between a smaller companion with a spiral victim

Smooth transitions from rings to spirals

Completeness & symmetry of rings
- offset of collision
- vertical component of velocity

Star Formation at the center & outer edge



http://www.galex.caltech.edu/

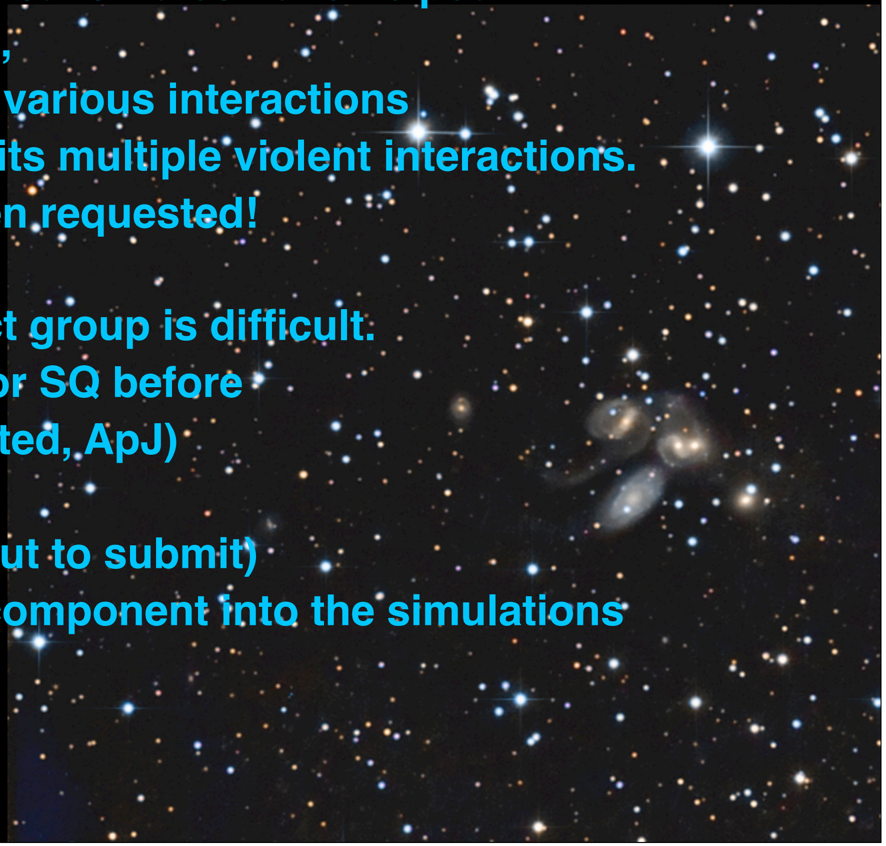
The End of Intro.

Stephan's Quintet

SQ is a relatively close (~94 Mpc), bright, and isolated system,
showing many interesting features of interactions.
---> It has been a popular object of study.

Although numerous observational & theoretical studies have helped
to understand many features in the group,
its evolutionary history and the effects of various interactions
have remained poorly understood due to its multiple violent interactions.
---> Dedicated simulations for SQ has been requested!

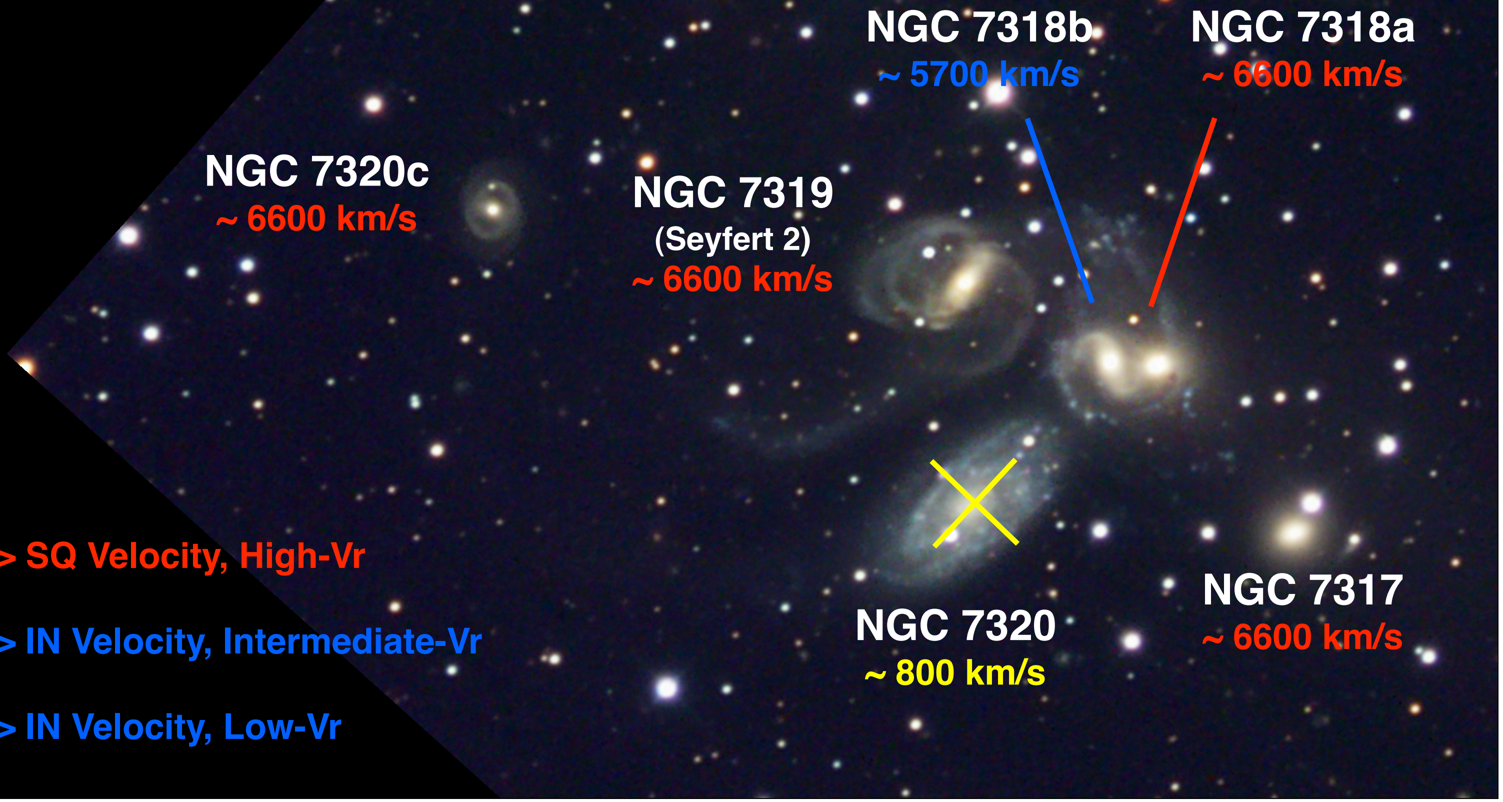
However, constraining models for a compact group is difficult.
No specific modeling has been performed for SQ before
- Renaud, Appleton, & Xu 2010 (just accepted, ApJ)
  ---> N-body stellar dynamics models
- Hwang, Struck, Renaud, & Appleton (about to submit)
  ---> SPH models, including gaseous component into the simulations



Membership of SQ

Stephan's Quintet ('SQ', HCG 92, Arp 319, VV 288):

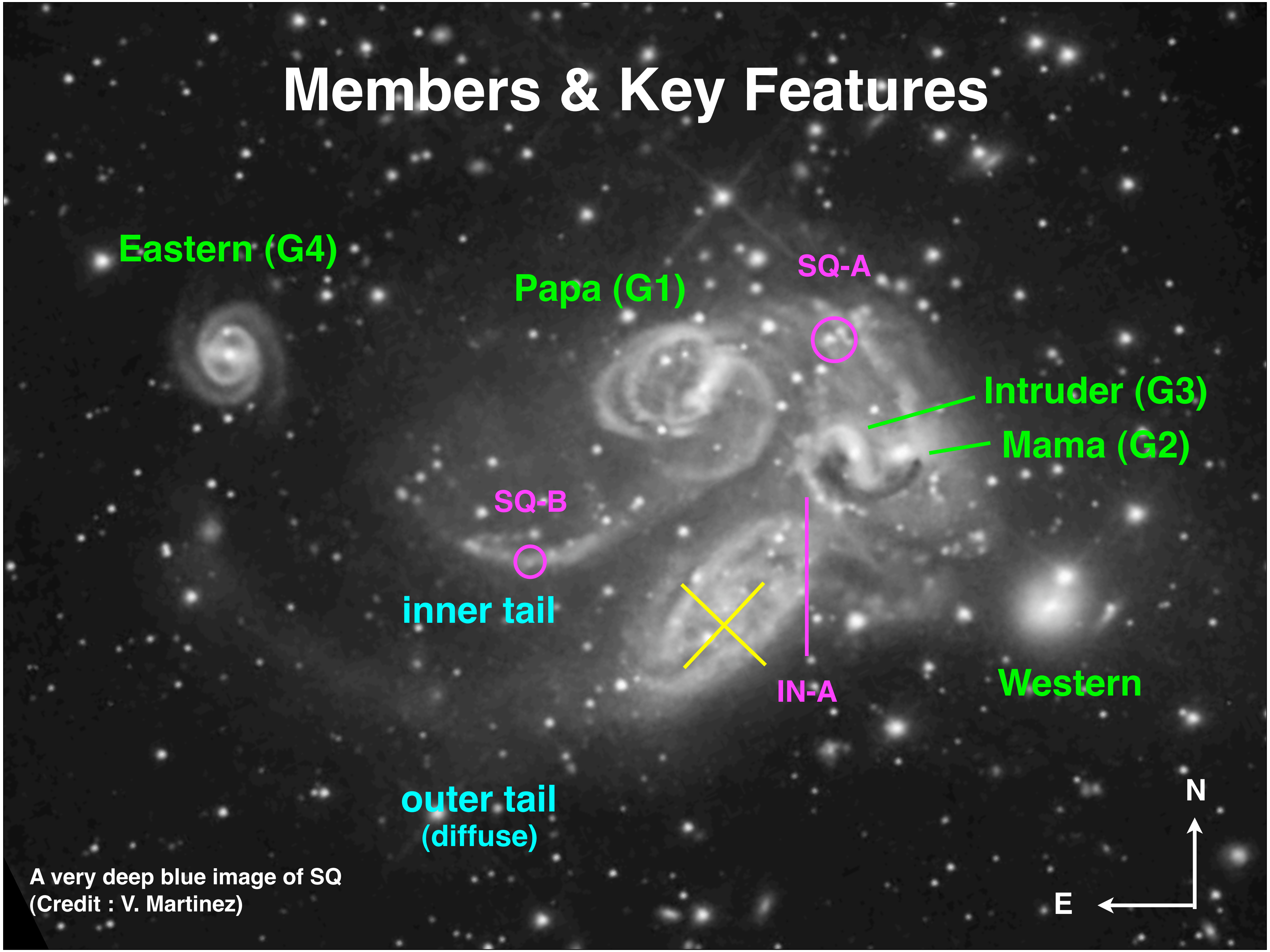
- discovered by Edouard Stephan in 1877
- one of the first compact groups identified (Hickson 1982)
- a visual grouping of five galaxies (NGC 7317, 7318a/b, 7319, & 7320)
- NGC 7320 is a foreground galaxy
- instead, NGC 7320c is related to the group
- NGC 7320c is coming toward us with the large relative velocity, having collided with the IGM, triggering the group-wide shock.



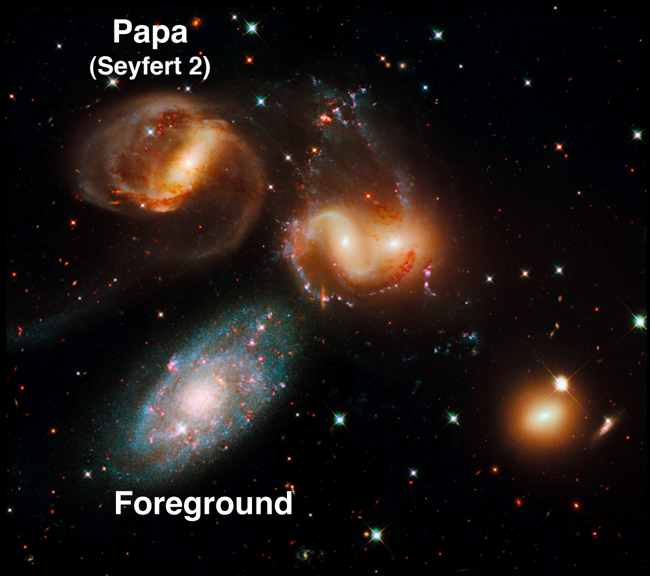
6600 km/s ---> SQ Velocity, High-Vr

6000 km/s ---> IN Velocity, Intermediate-Vr

5700 km/s ---> IN Velocity, Low-Vr

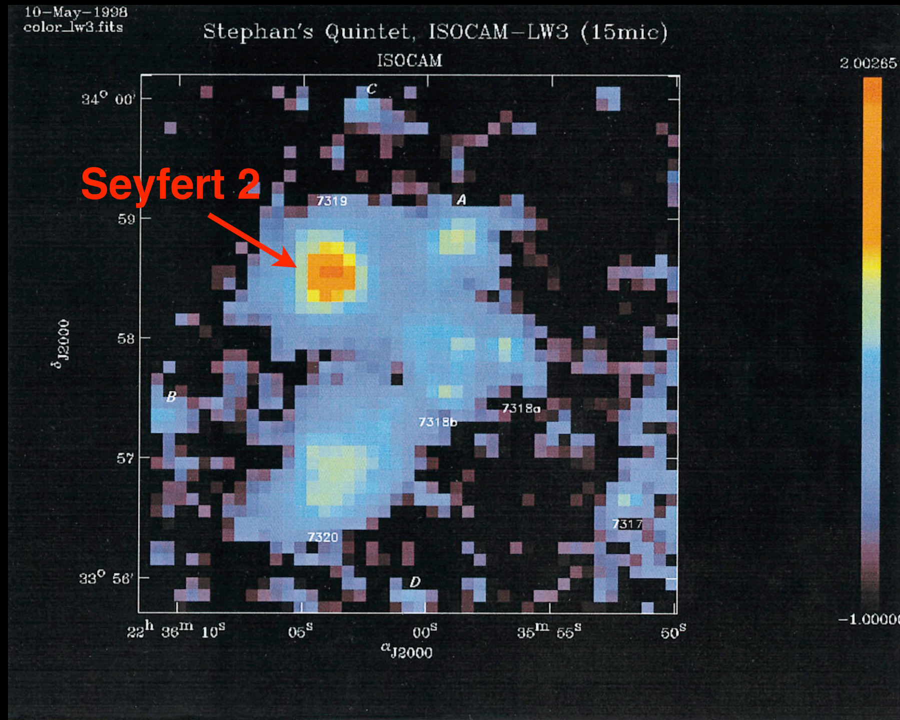

Members & Key Features
Eastern (G4)
Papa (G1)
SQ-A
Intruder (G3)
Mama (G2)
SQ-B
inner tail
IN-A
Western
outer tail
(diffuse)
A very deep blue image of SQ
(Credit : V. Martinez)
N
E

SQ seen in multi-wavebands



WFC3 Hubble Space Telescope

(Credit: NASA, ESA, and the Hubble SM4 ERO Team)

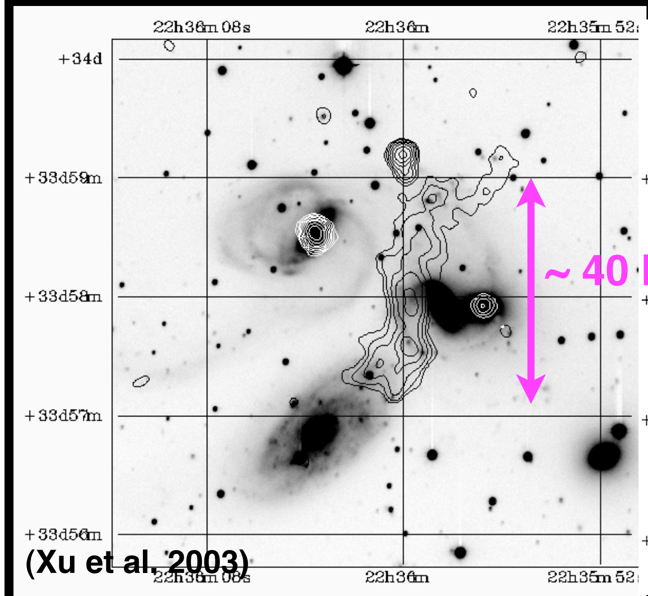


ISOCAM 15 micron image

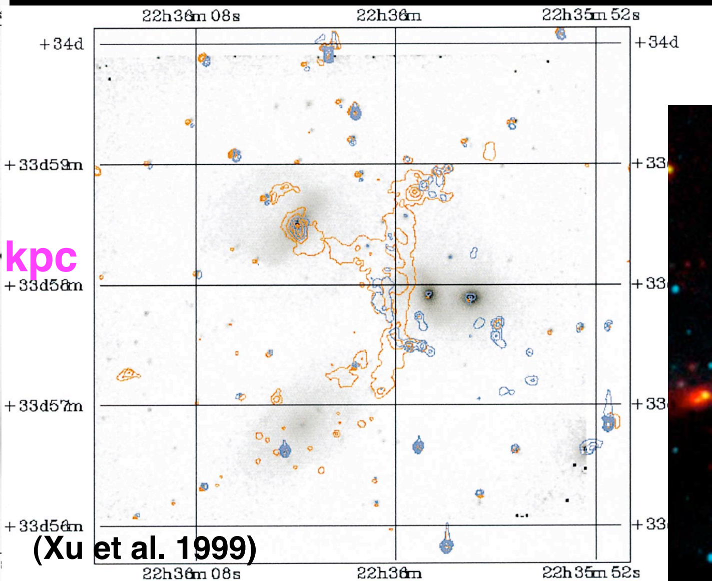
Sources A & B: Star formation regions associated with the group
Source C: A foreground star
Source D: A background galaxy (Xu et al. 1999)

SQ seen in multi-wavebands

Contours: Radio continuum at 1.4 GHz
(VLA B configuration)
Image: R-band



Contours : Hα + [N II]
(~6600 km/s & ~5700 km/s)
Image : K' (2.1 micron)



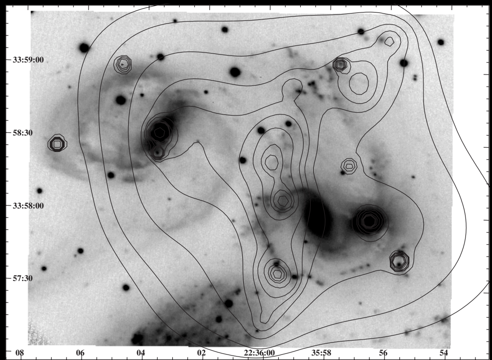
Bleu : R-band
Green : Hα
Red : 8-micron

Credit : NASA/ JPL-Caltech/ Max-Planck Institute/ P. Appleton (SSC/ Caltech)

The shock front
seems to be associated with
the 6600 km/s component

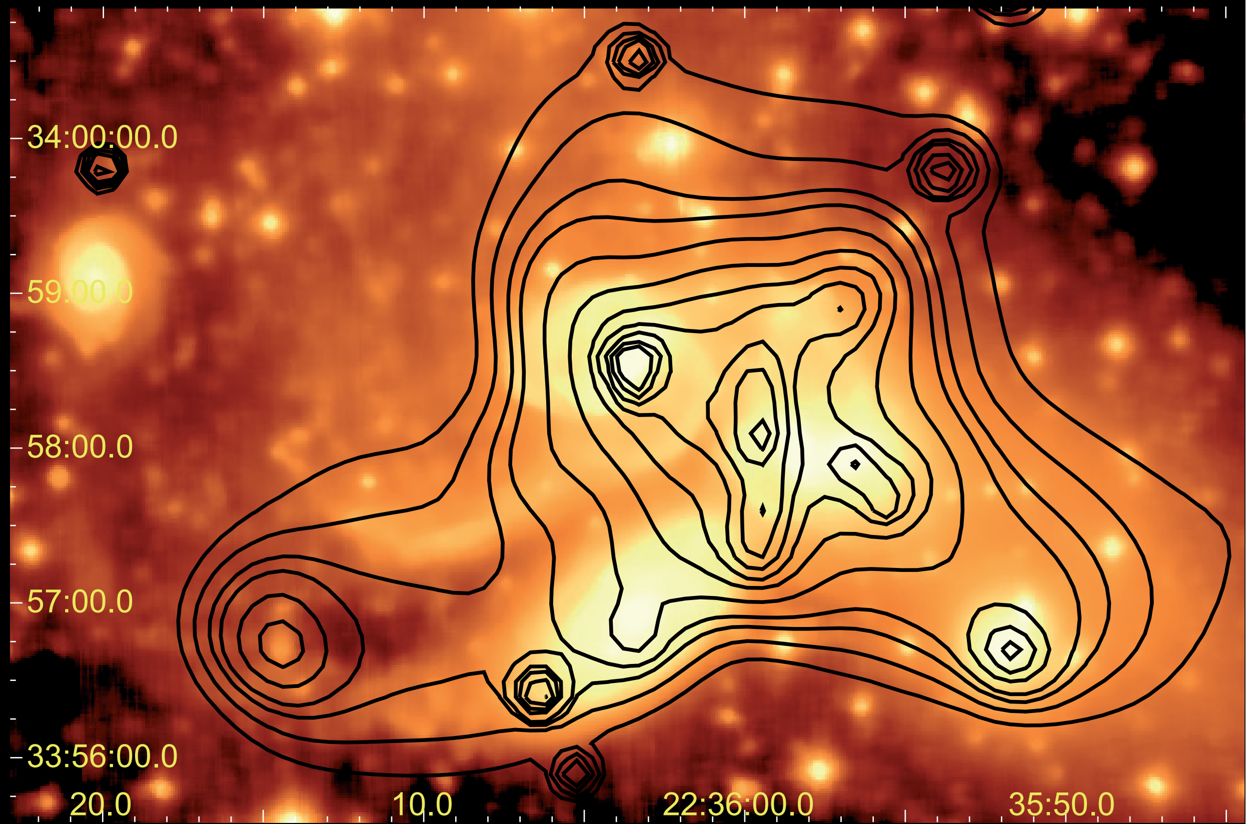
SQ seen in multi-wavebands

Contours : Chandra X-ray (0.5~3 keV)
Image : B-band



(Trinchieri et al. 2003)

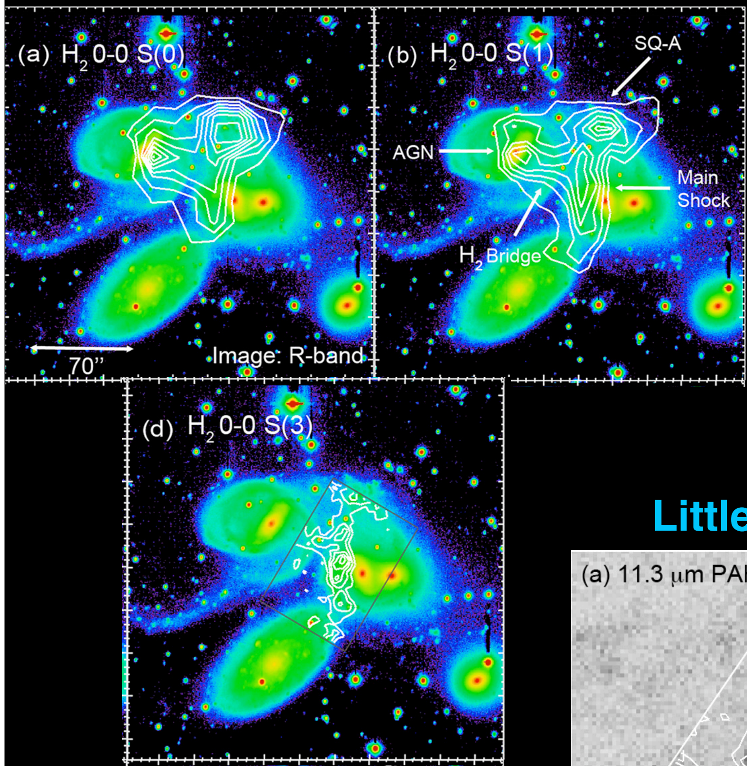
Contours : XMM Newton EPIC-MOS X-ray (0.3~3 keV)
Image : deep B-band



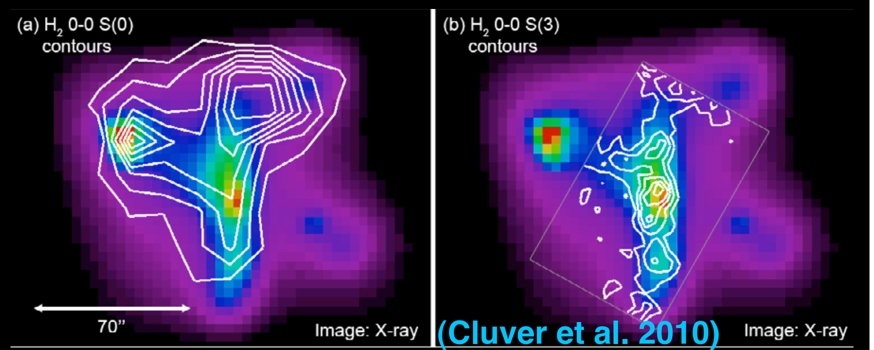
(Trinchieri et al. 2005)

SQ seen in multi-wavebands

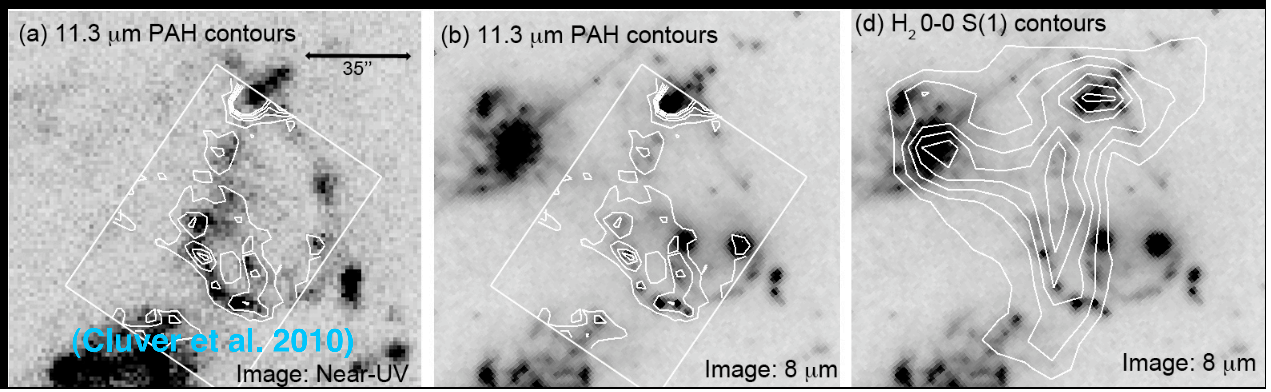
Contours : Spitzer MIR
H_2 rotational line emission
Image : B-band
(Cluver et al. 2010)



Correlation between H_2 and X-ray distributions

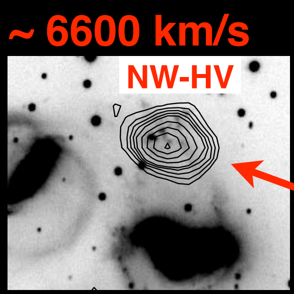


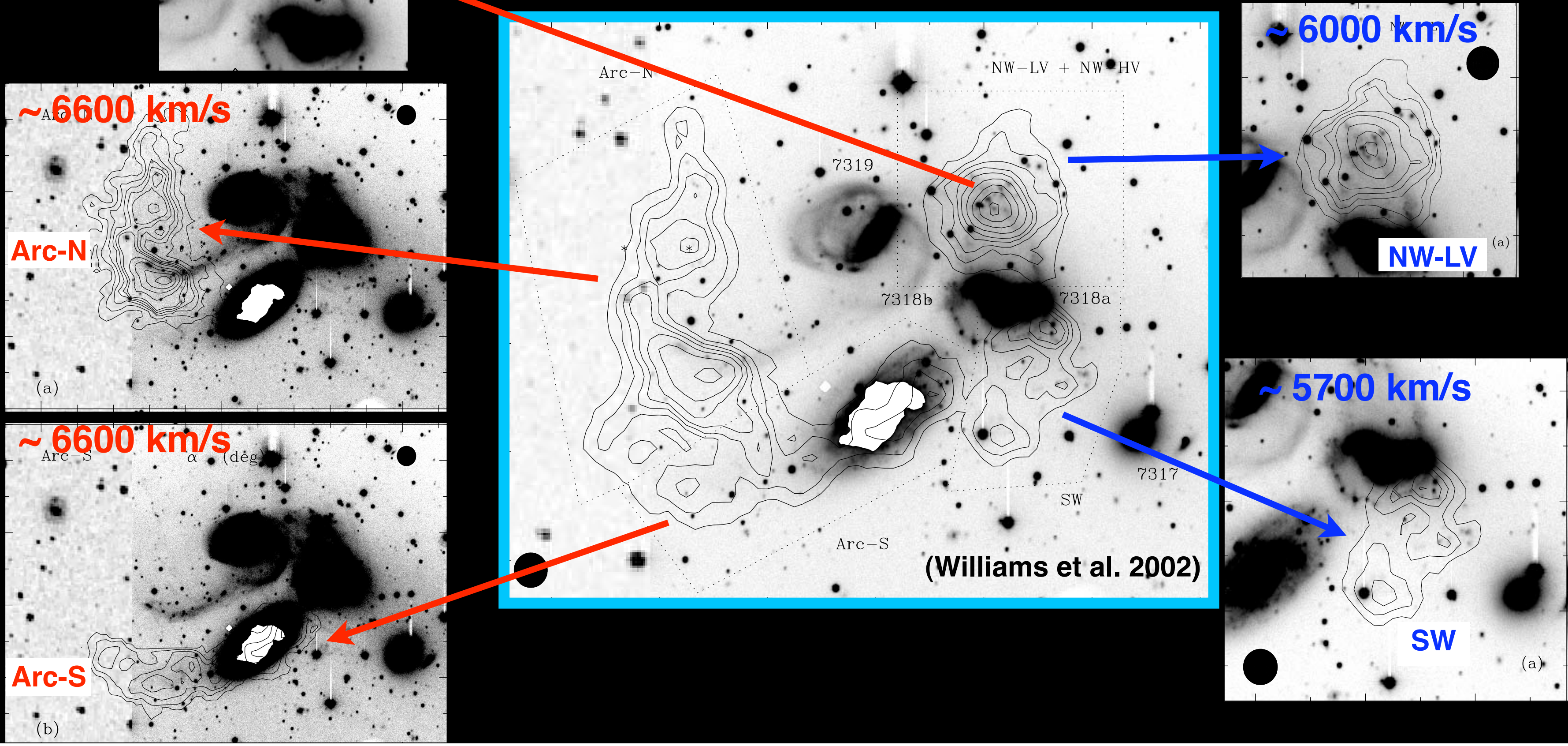
Little correlations between 8 micron and H_2 distributions



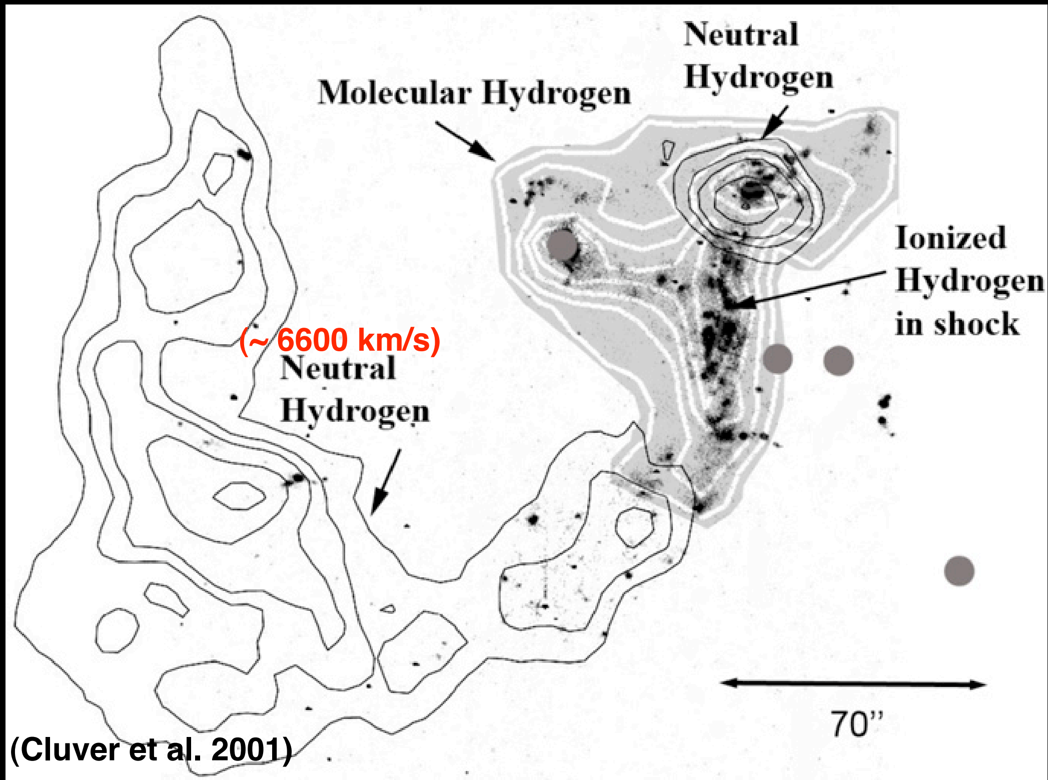
HI distribution

Most of the HI gas are found outside the members
in 5 physically distinct components,
("Arc-N", "Arc-S", "NW-HV", "NW-LV", & "SW"),
in 3 discrete velocity bands
(high, intermediate, & low Vr ranges).





SQ seen in multi-wavebands



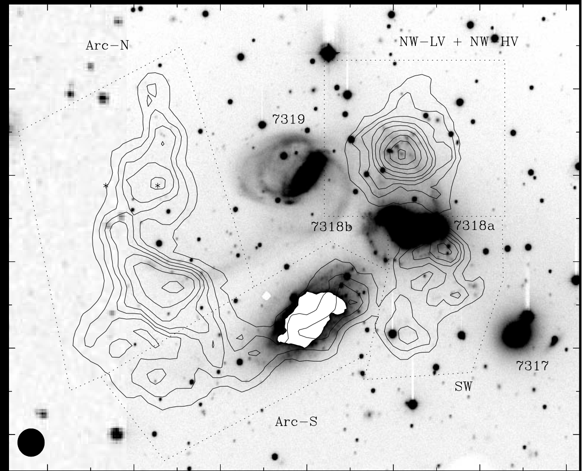
HI seemed to be converted into
both a hot X-ray component and a warm H2 component

Dynamical History & Model Constrains

Past dynamical history:

- two long parallel tidal tails
- stripping of most of the HI from Papa (and other involving members)

---> 3 scenarios



Current dynamical state:

- Intruder is colliding though the IGM at a high speed (~900 km/s), triggering the large-scale shock.

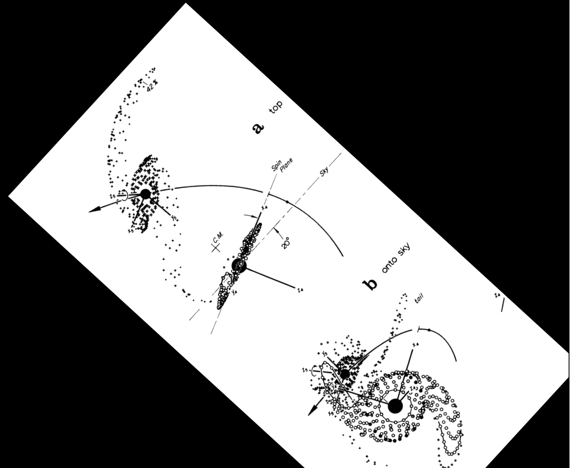
Relatively close past ~ current:

- Intruder looks still intact
  ==> entering the group for the first time?

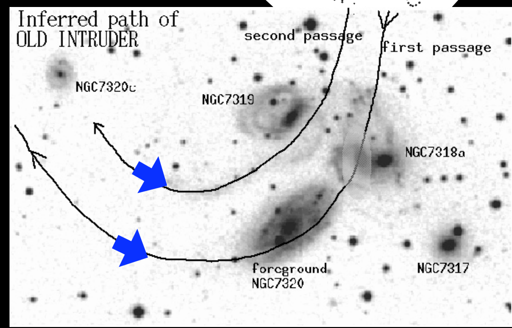
- *however*, seems to have experienced tidal disruption
  ==> might interacted (with Mama) before!

3 Scenarios for the Parallel Tails

Involving Papa, Eastern, and/or Mama:

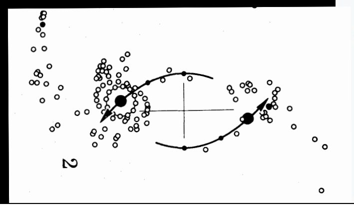


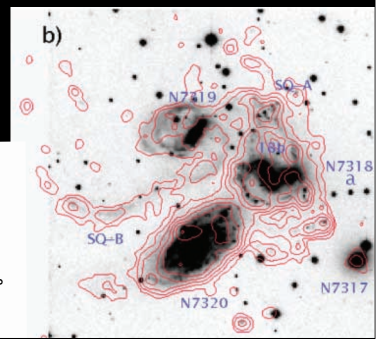
(A) Both tails produced simultaneously
by an encounter of Eastern with Papa (Moles et al. 1997):
- the same formation age for the parallel tail
- parallel tails are not seen frequently



(B) The outer and inner tails produced one after one
by two (or more) encounters of Eastern with Papa
(Moles et al. 1997; Sulentic et al. 2001):
- 1st: at least 500 Myr ago
- 2nd: as recently as 200 Myr ago

(c) The outer tail produced by an encounter of Eastern with Papa, and then
the inner tail by an encounter of Mama with Papa (Xu et al. 2005)
- but, slow passage of Eastern require more time
- UV inner tail ==> Mama / Papa





Modeling Goals & Strategy

Our modeling work is extension of the earlier work of
Renaud et al. (2010) which used an N-body stellar dynamics code
adding thermohydrodynamic effects to the N-body models.

The primary goal is
to figure out the dynamical interaction history
in hopes that SQ is a prototypical
and that teaches us about other systems too.

Several interactions seem to occur sequentially:
a sequence of two-at-a-time collisions
(which makes modeling of this complex system more feasible).

Three major stages:
(1) to reproduce the inner and outer tails in a good configuration,
stripping much of gas off the involving members, ==> based on the 3 scenarios
(2) to test the occurrence of any intermediate interaction before the present,
(3) to make a high-speed collision between Intruder & the IGM.

The Simulation Code

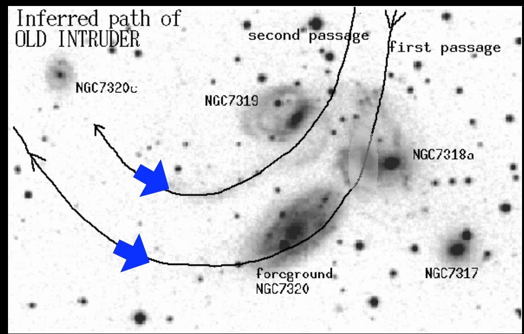
The SPH code of Struck (1997, ApJS, 113, 269):

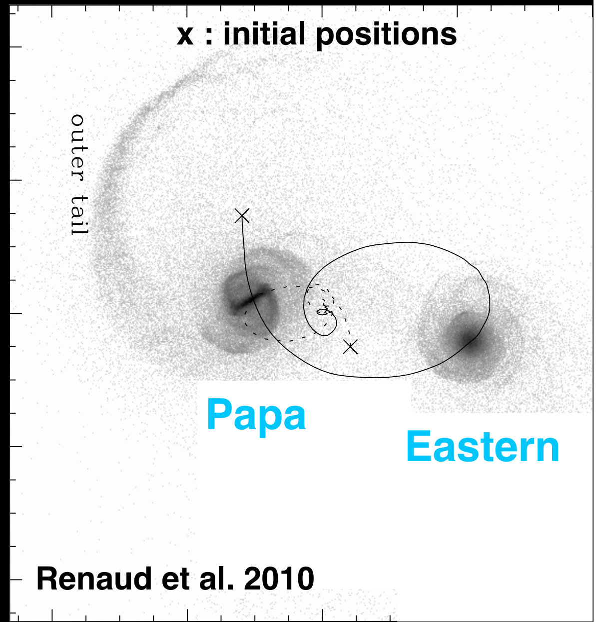
- Hydrodynamical forces are computed with a spline kernel on a grid.
- Local self-gravity is calculated between gas particles in adjacent cells.
- Each model galaxy consists of two disks with gas & collisionless star particles, & a rigid dark matter halo.
- Simple treatment of heating & cooling for gas particles are included.
- Star-forming gas particles are identified by using density & temp. thresholds.
- A restricted 3-body approximation for the halos is used to simulate the large-scale dynamics.
- The effects of dynamical friction are included, in some cases.
- The non-inertial reference frame of a “primary” galaxy is used.
- The code variables are dimensionless & are converted to the physical units after simulations.

Models of Type A, B, & C

Models A: Both tails --> by Eastern (a single encounter)

Models B: The outer tail --> by Eastern (earlier encounter)
The inner tail --> by Eastern (recent encounter)





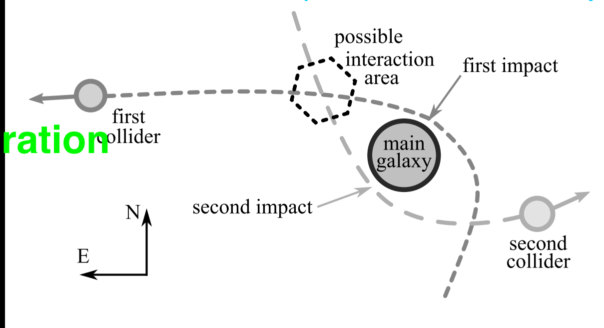
Models C: The outer tail --> by Eastern
The inner tail --> by Mama

Models C

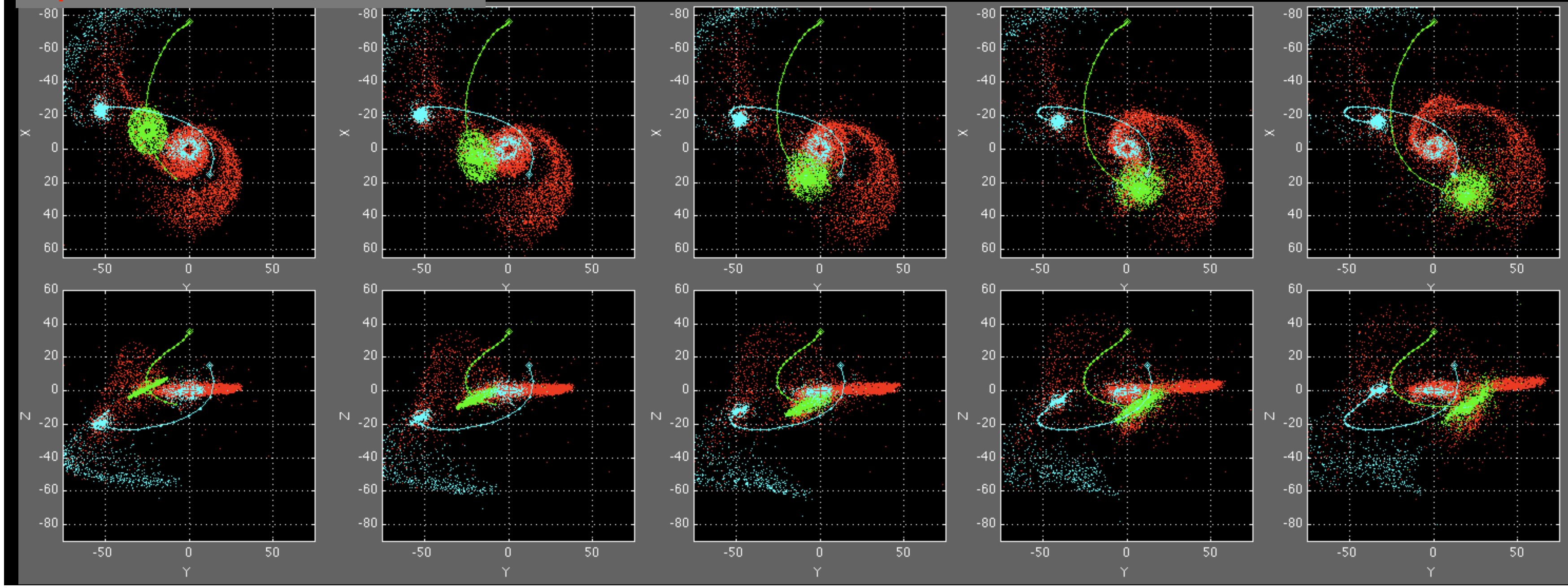
Models C (based on Scenario C):
to produce the outer tail from an encounter of Eastern/Papa,
and then the inner tail from a different encounter of Mama/Papa.

Our models show that
reconstructing the parallel tails one after one in a good configuration
out of a disk of Papa by two different close encounters
is very difficult and unlikely.

(Renaud et al. 2010)

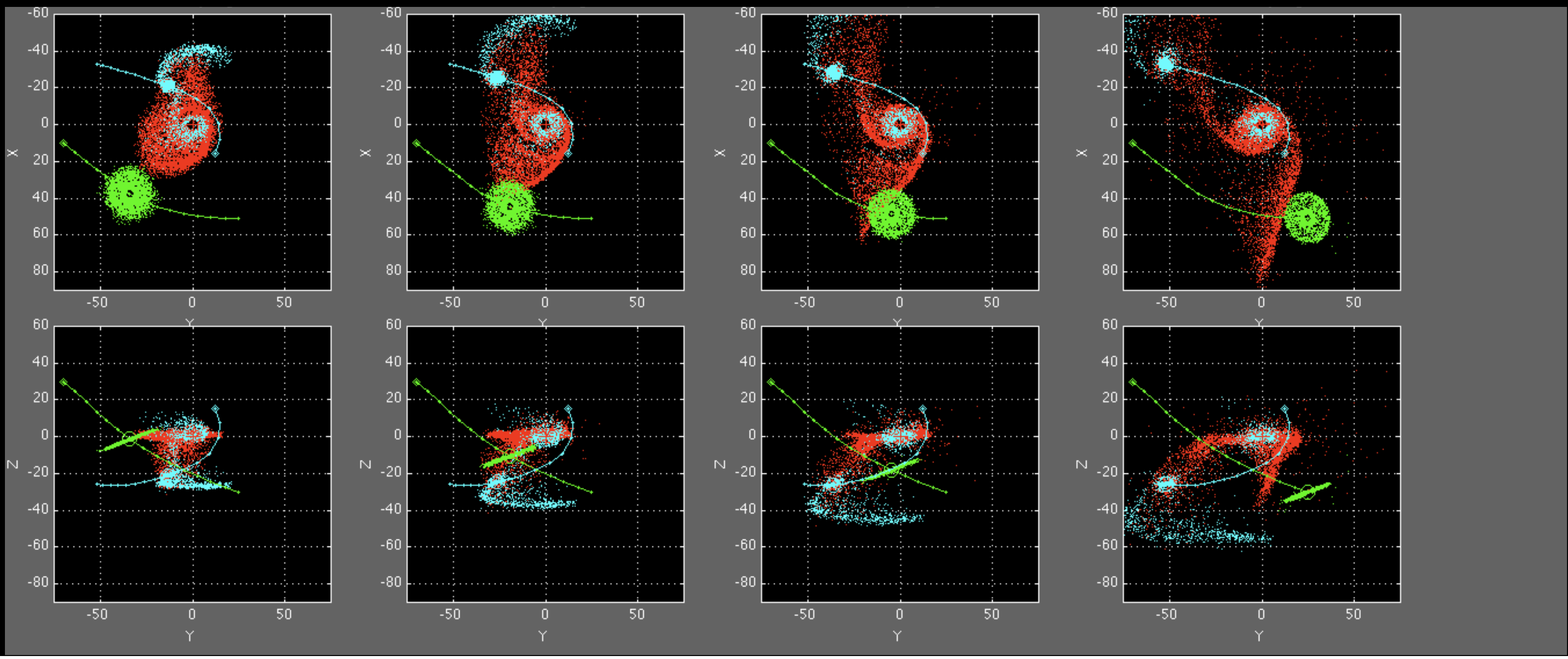


Papa, Mama, Intruder, & Eastern



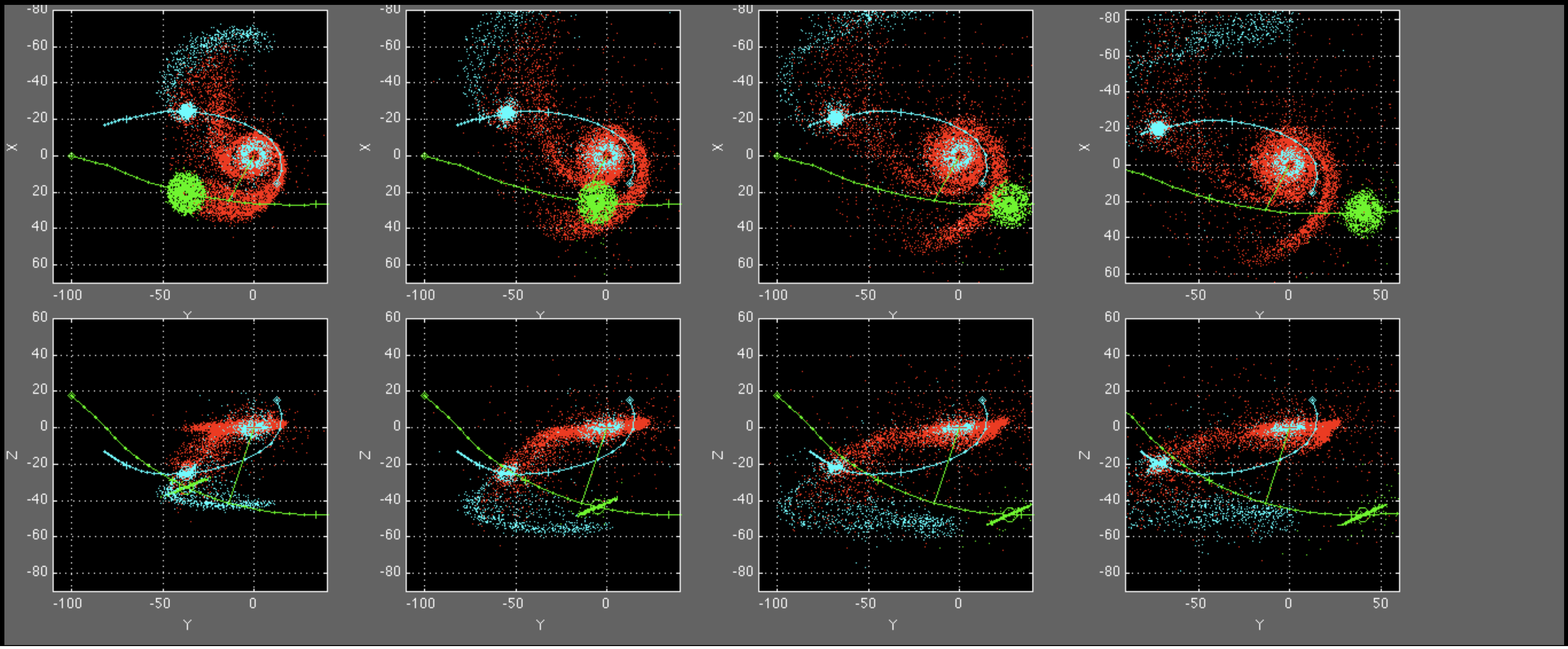
Models C

In models C,
when Mama passes the vicinity of Papa,
Mama destroys/disturbs the early generated nearby delicate tidal features.



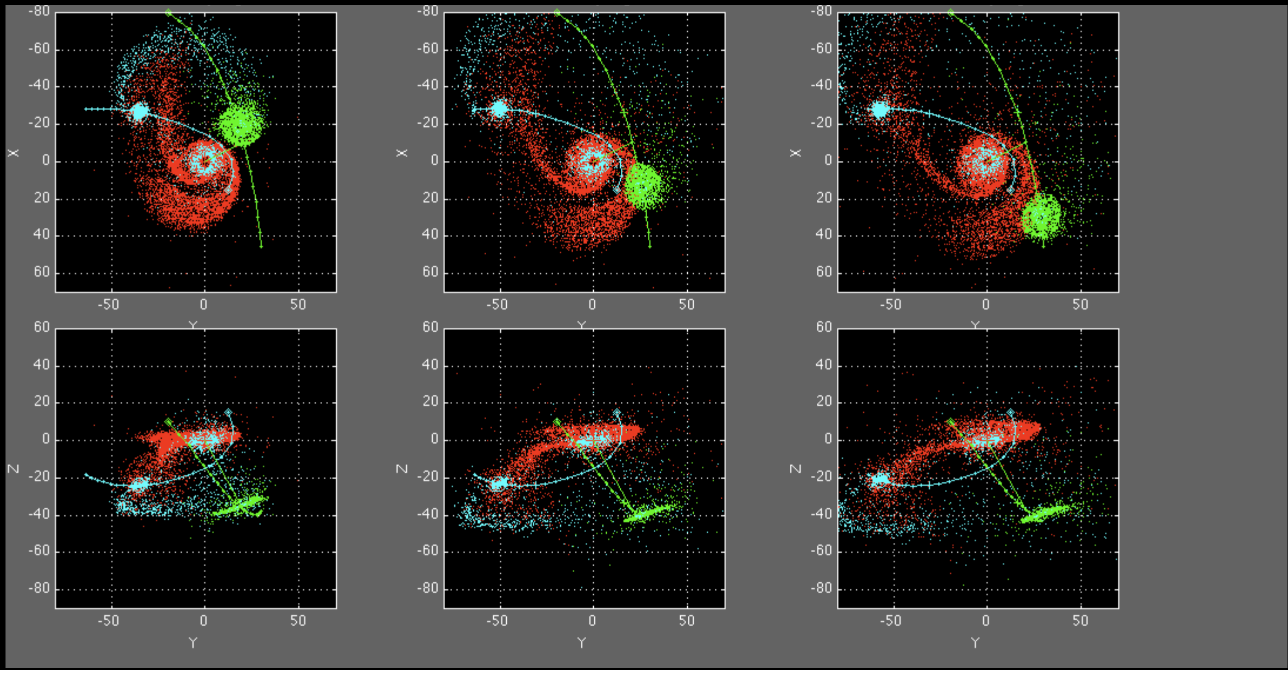
Models A

In models A,
Mama do not contribute in generating any of the parallel tail.
Mama needs to stay far from the parallel tails so that they can grow in a good configuration.



Models A

In models A,
The initial orbit of Mama is not strongly constrained.



The Fiducial Model

The fiducial model (a representative of models A) designed:

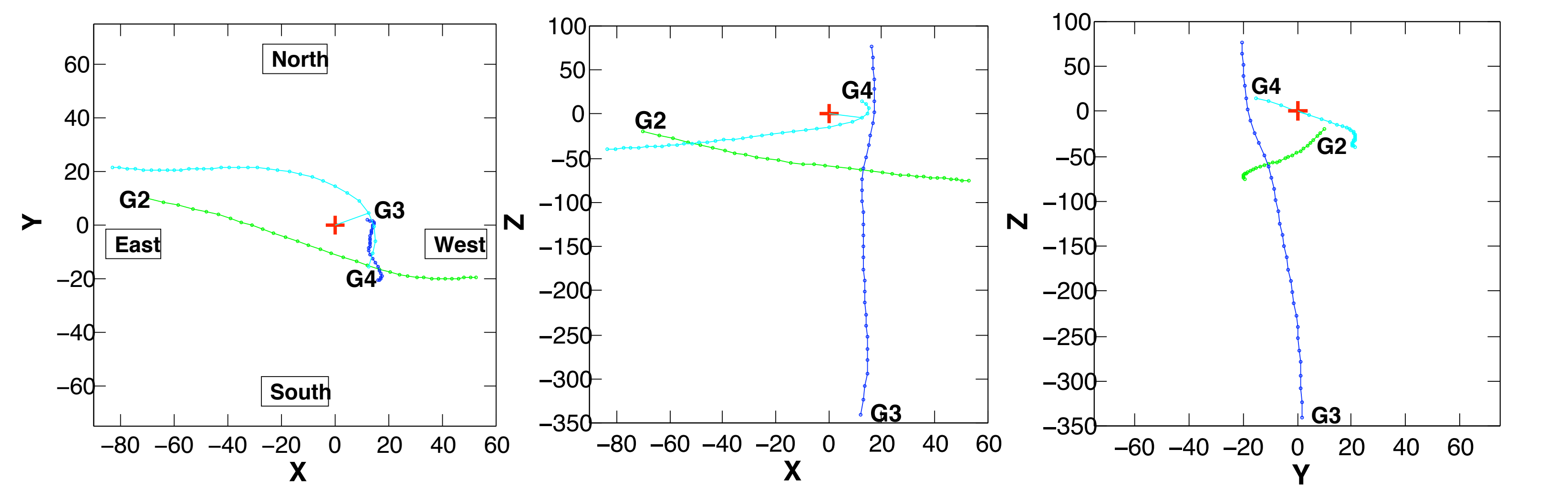
(1) to generate the inner & outer tails simultaneously
by a close encounter of Eastern (G4) with Papa (G1),

(2) to have a collision between Mama (G2) & Intruder (G3)
far below the plane of Papa,

(3) to make a high-speed collision
between Intruder (G3) & the IGM.

The initial parameters of the fiducial model

	G1	G2	G3	G4
Halo masses[a] ($\times 10^{10} M_\odot$)[b]	12.6	8.2	7.1	2.4
Halo cutoff radii[c](kpc)	135.0	55.0	80.0	45.0
Gas disk radii (kpc)	27.0	8.0	16.0	9.0
Stellar disk radii (kpc)	18.0	11.0	11.0	7.0
Gas particle numbers	68,680	6,000	24,000	7,480
Star particle numbers	32,000	11,760	11,760	4,960
Disk orientations[d]		180° about x-axis	180° about x-axis	
Initial center positions[e] (x,y,z) (kpc)	at origin	(−70.0, 10.0, −20.0)	(12.0, 2.0, −340.0)	(12.5, −15.3, 15.3)
Initial center velocities [f] (v_x,v_y,v_z) (km s^{-1})	(0.0, 0.0, 0.0)	(110.0, −27.0, −72.5)	(20.0, −7.5, 300.0)	(35.9, 79.5, −77.5)

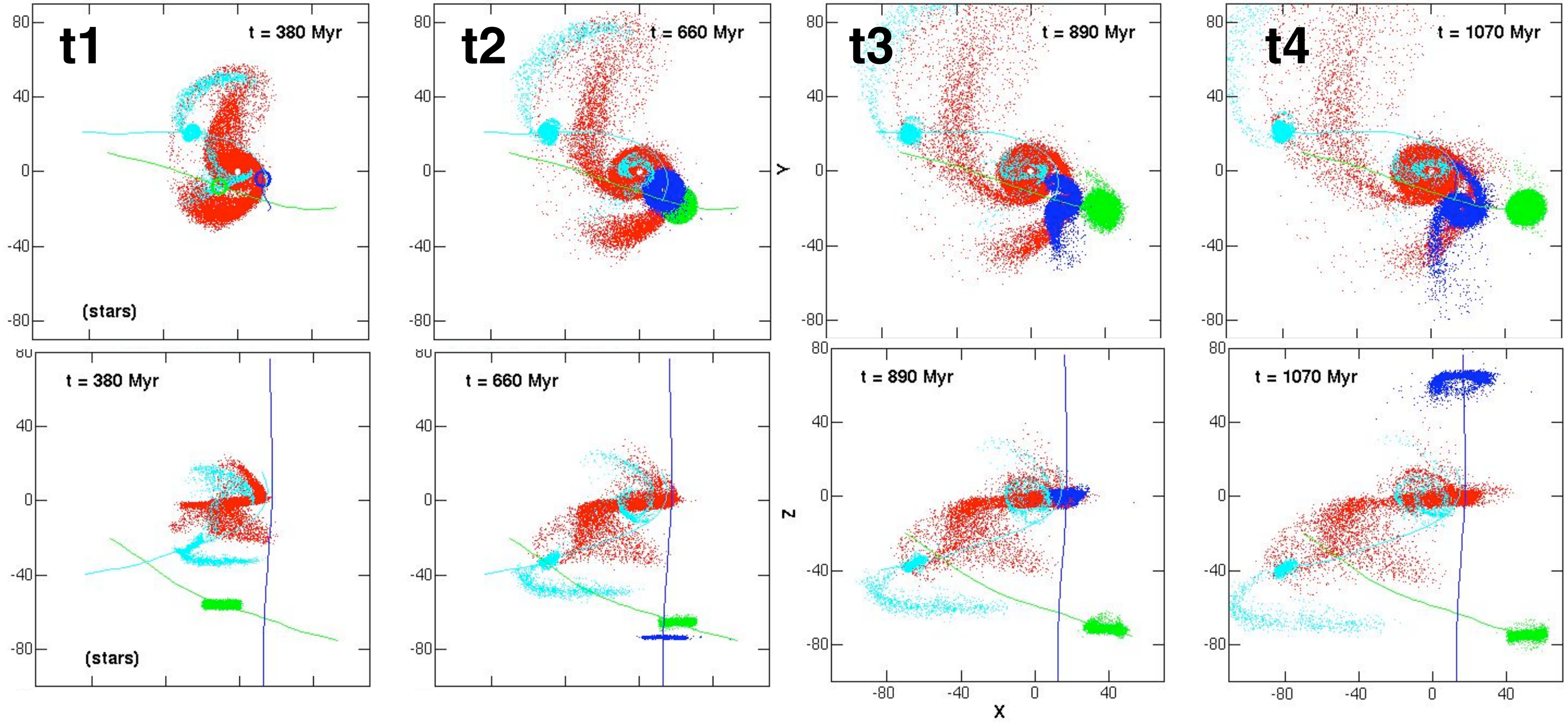


Model Results

Evolution of star particles at 4 times:

1. Early development of the parallel tails.
2. The onset of the collision between Mama / Intruder.
3. During the high-speed collision between Intruder / IGM.
4. Shortly after the high-speed collision.

Papa, Mama, Intruder, & Eastern

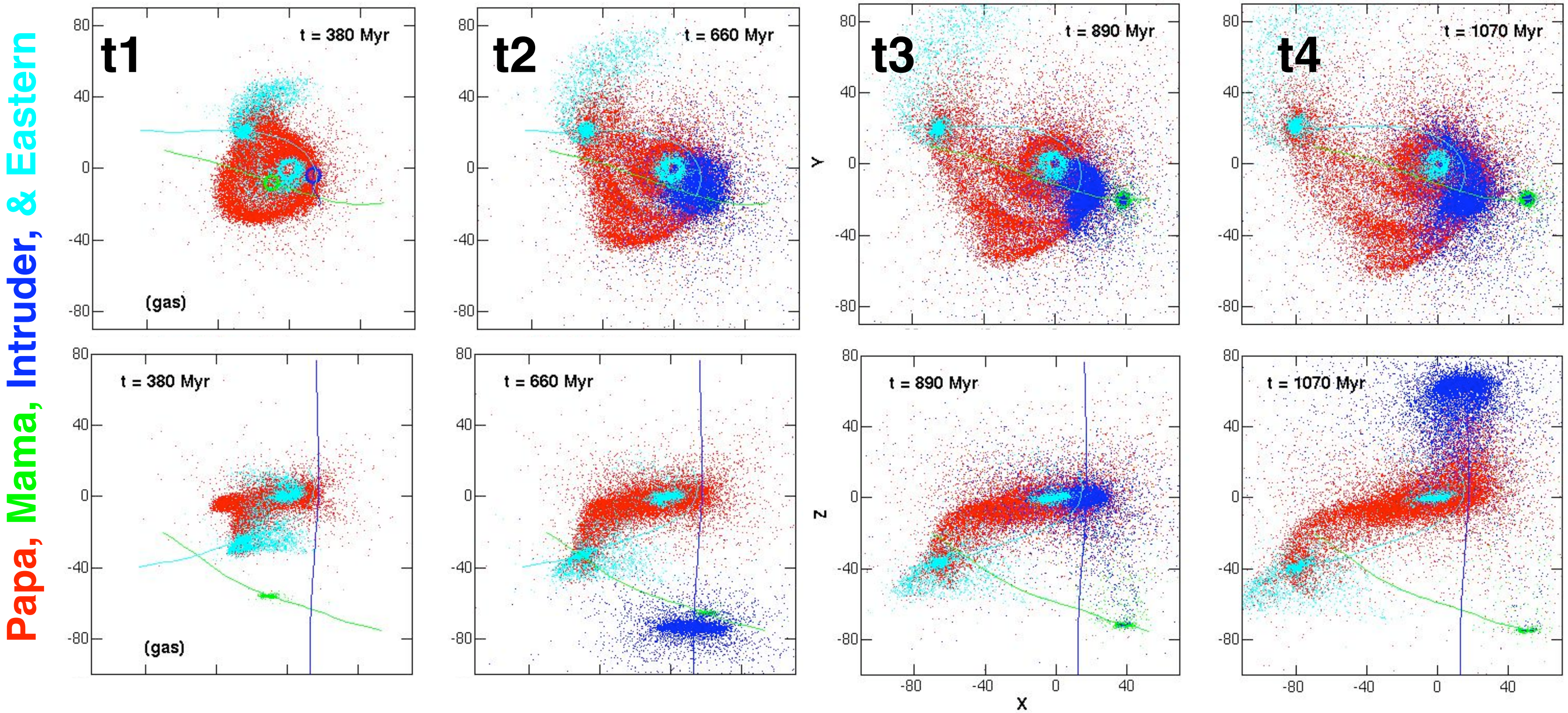


Model Results

Evolution of gas particles at 4 times:

1. Early development of the parallel tails.
2. The onset of the collision between Mama / Intruder.
3. During the high-speed collision between Intruder / IGM.
4. Shortly after the high-speed collision.

Gas tends to be affected more by encounters than stars.

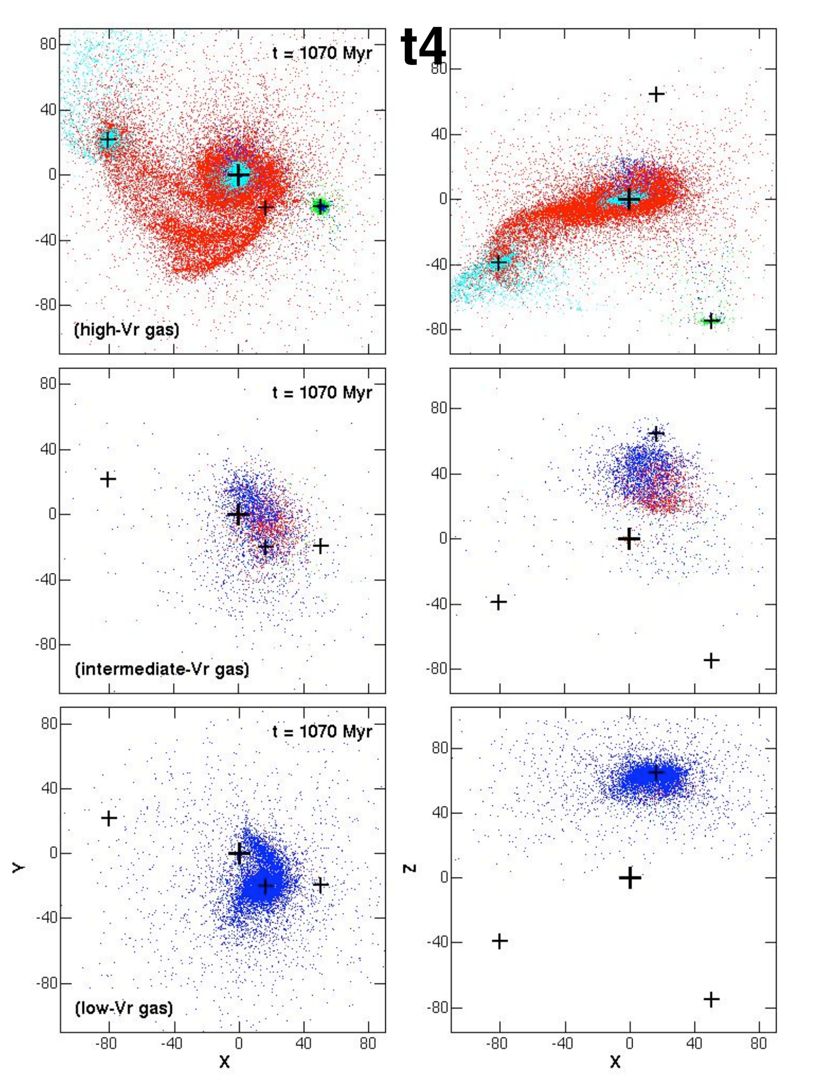


Model Results

High-Vr gas:
- mostly from Papa, Mama, & Eastern
- bulk of gas along the parallel tails
- some gas at N of Intruder (W of Papa) forming a compact feature

Intermediate-Vr gas:
- mostly from Intruder & Papa
- gas at N of Intruder in a more extended feature

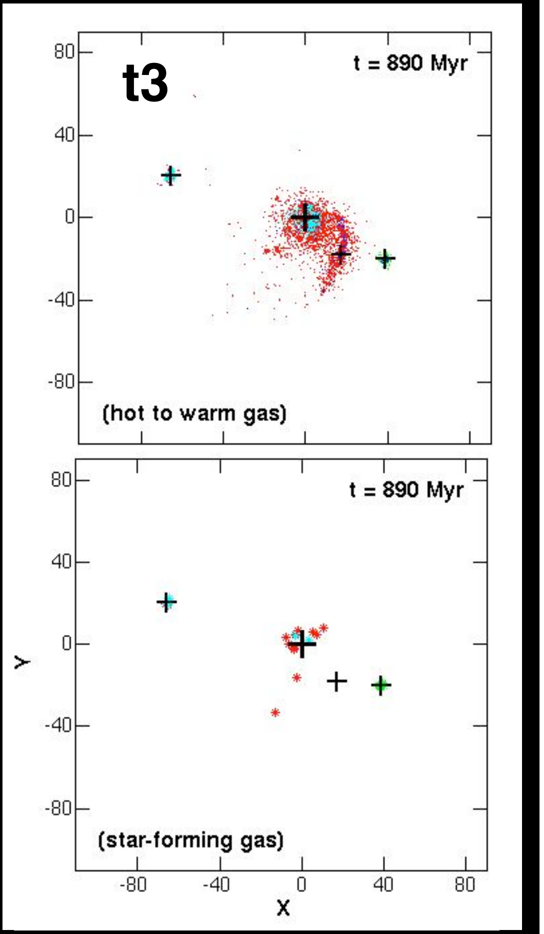
Low-Vr gas:
- mostly from Intruder
- Some diffuse gas at S of Intruder



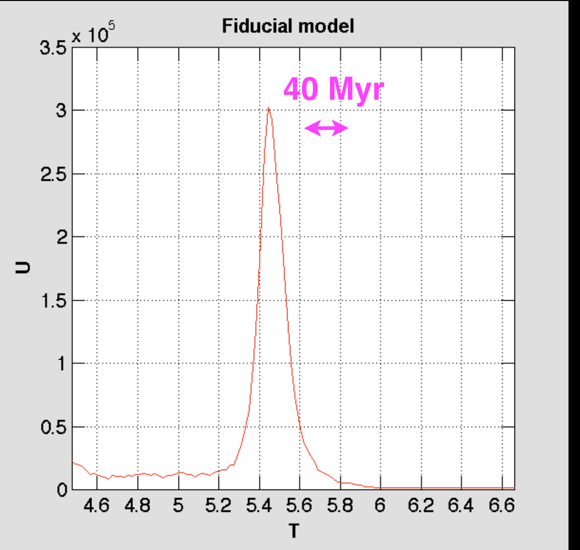
Model Results

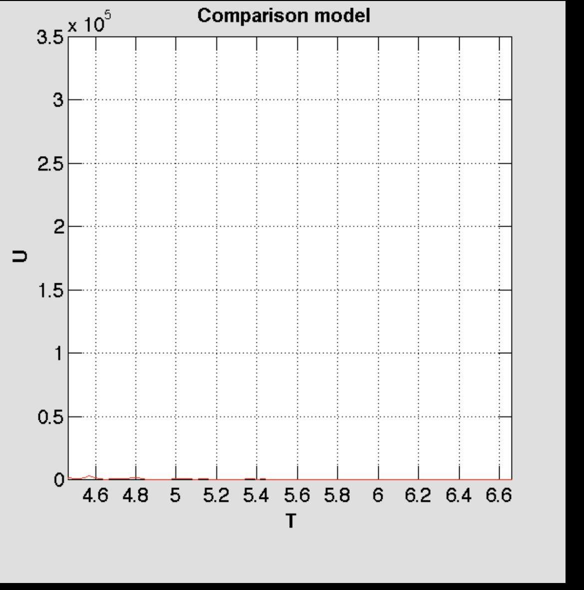
The hot gas in high-Vr range (during the high-speed collision) shows an elongated feature at W of Papa.

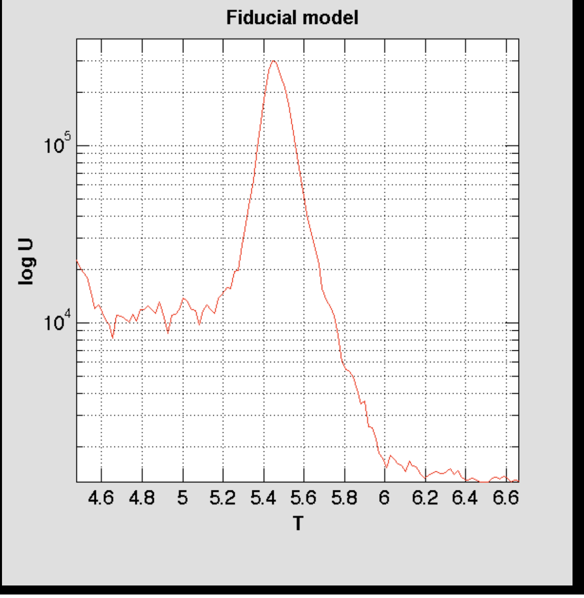
Little star-forming gas is found at the shock region, indicating the elongated feature is heated not by star formation, rather by the high-speed collision.



Model Results







Guillard et al. (2009):
The cooling time is significantly longer than the age of the shock (~ 5 Myr).

Our models:
Gas particles (clouds) continue to interact for some tens of millions of years.

This amounts to decaying turbulence with many small shocks of various strengths in that region and we think it can account for the observed emission without much star formation.

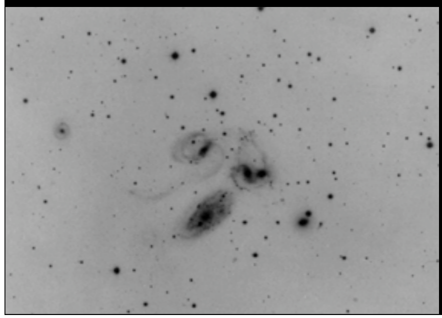
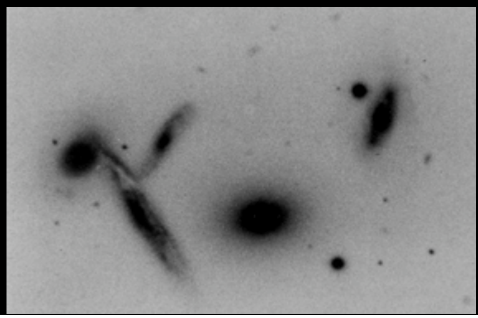
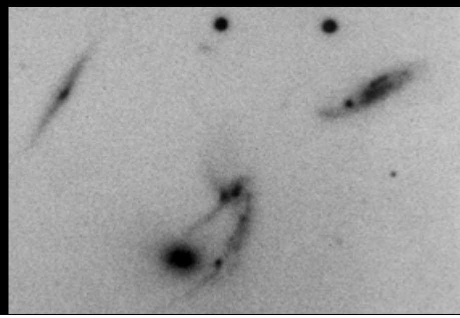
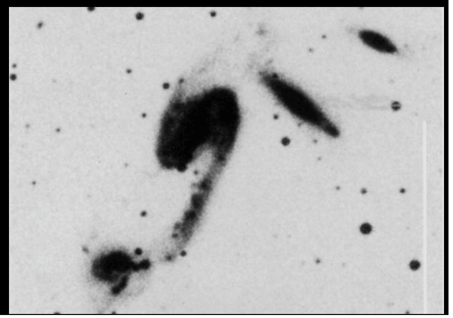
The End of Model Results.

Summary

We found a very interesting result in SQ, with collisions on mostly two-at-a-time.

This result may be general, because flyby or the final merger together time would be short compared to the total orbital time.

So, our major result can be extended to other groups in studying the evolutionary histories or finding initial conditions of collisions.


Thank you!