The Antennae Galaxies: Archetype for Colliding Galaxies

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National Radio Astronomy Observatory

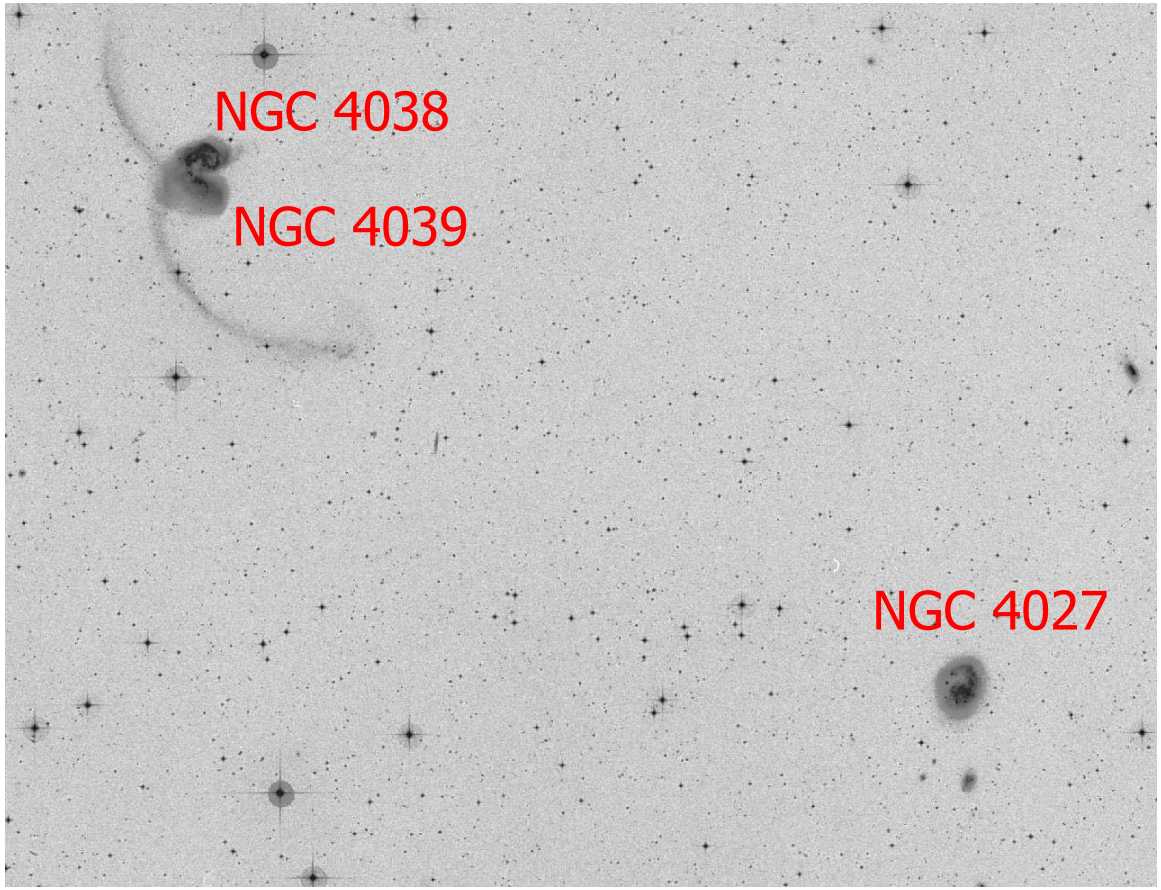
Talk Outline:

- Historical Background
- The Antennae as merger archetype
- Previous modeling efforts
- New dynamical model
  - Constructed with Josh Barnes, IfA

Historical Background: NGC 4038/39

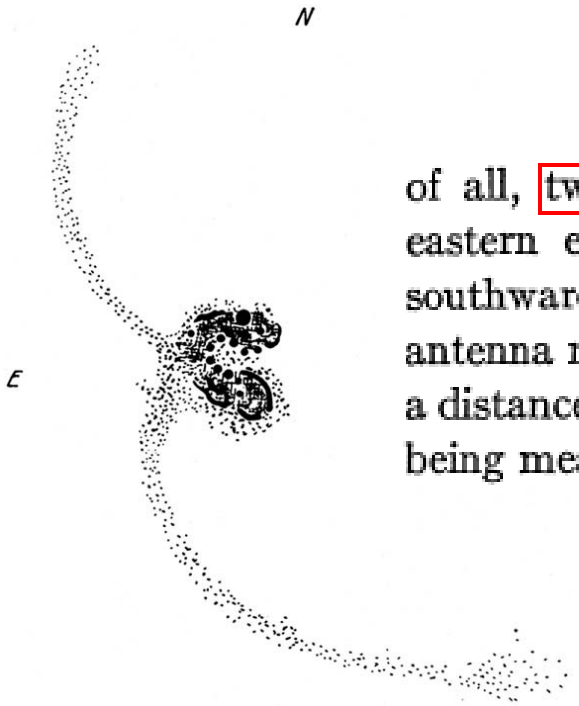
- 1830's: cataloged by Herschels (NGC; Dreyer 1888)
- 1921-1922: 3 brief descriptions
  - 1921, Bulletin of Helwan Obs., No. 21
  - 1921, Ann. Report, Mt. Wilson Obs.
  - Perrine, 1922, MNRAS, 82, 486, `Notes on Four Interesting Nebulae', 75cm Cordoba Telescope: "Hook extending out from a Ring"

All note unique form; draw attention to proximety to one-armed spiral NGC 4027 (42' to the SW)



First description in terms of "Antennae"

- 1923, Duncan, ApJ, 57, 137, 100" Hooker Telescope at Mt. Wilson

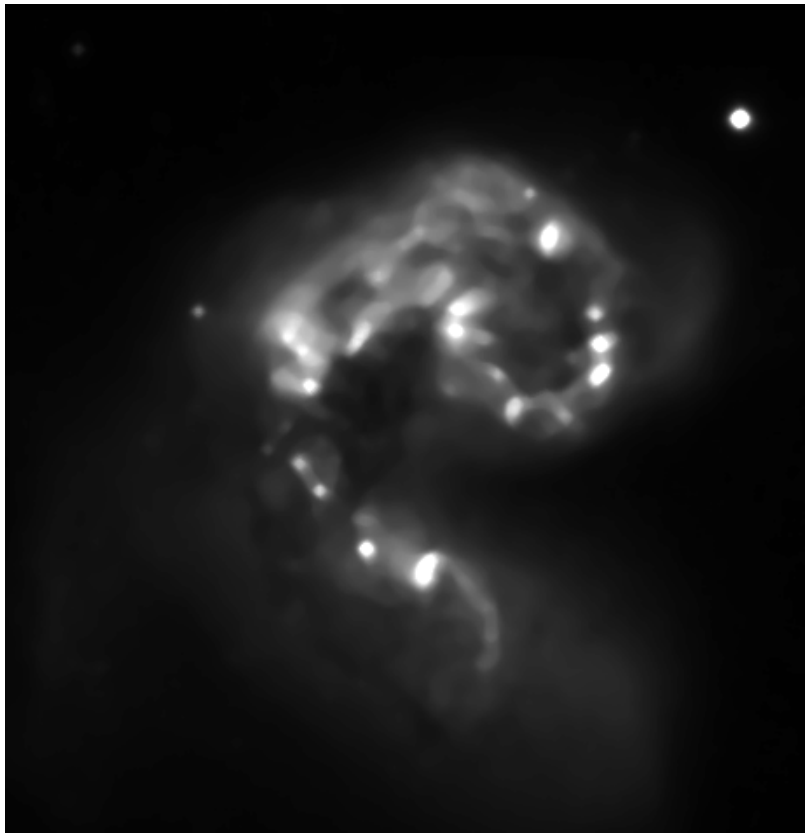


Most remarkable of all, two faint extensions, like antennae, seem to cross at the eastern end of the bag, one reaching northward and the other southward, and both concave toward the west. The northern antenna may be traced to a distance of 6′, and the southern one to a distance of 12′ from the point where they intersect. these distances being measured along chords of the curves.[2]

Sketch from Zwicky, 1954, *Ergebnisse der exakten Naturwissenschaften*, 29, 344

Historical Background: NGC 4038/39

- 1940, Shapley & Paraskevopoulos, Proc. N.A.S., 26, 35
  - Description in terms of "Ring-Tail" structure
- 1940, Struve & Linke, PASP, 52, 139
  - $V_{abs,em}$=1700 km/s



First description in terms of Tidal Interaction

1940ApJ....92..200H

ON THE CLUSTERING TENDENCIES AMONG THE NEBULAE*

ERIK HOLMBERG

ABSTRACT

Part I gives an investigation of double and multiple nebulae contained in the *General Catalogue*. An analysis of the distribution of angular distances between nebulae results in a statistical separation of physical and optical companions (Fig. 2); double and multiple systems are revealed as they actually exist in the sky. The average distances between physically connected nebulae (Tables 1 and 2) appear to be considerably larger than those previously assumed.

In Parts II–IV possible interpretations of the clustering tendencies are discussed. Double and multiple systems, as well as clusters, may be explained as a result of captures between nebulae, effected by tidal forces at close encounters. A summary of the main conclusions is given in Part V.

I. DOUBLE AND MULTIPLE SYSTEMS AS DERIVED FROM A STUDY OF THE SMALL-SCALE DISTRIBUTION OF EXTRA-GALACTIC NEBULAE

... However, photographs of several double nebulae exhibit peculiar features which suggest strong disturbances effected by tidal forces. One of the most interesting cases is that of NGC 4038, 4039.[9] Although catalogued as a double nebula, the components cannot be distinguished on the photographs. Nevertheless, the internal structure appears to be highly disrupted, and two faint extensions suggest that luminous material has been thrown far out into the surrounding space. ...

Historical Background, cont'd

- 1958, Mills, Slee, & Hill, Aus.J.Phys, 11, 360
  - One of the first extragalactic systems identified as radio source
  - Used to support collisional origin of radio galaxies (Baade & Minkowski 1954, ApJ, 119, 206)
- 1962-1975+, numerous radio studies.
  - 1973: Burke & Miley, A&A, 28, 379: radio source centered between galaxies
- 1966, Burbidge & Burbidge; 1970 Rubin, Ford & D'Odorico
  - Detailed optical study; velocity field not indicative of a single object; supports collisional hypthesis

Birth of A Name

- 1968, MCG notes
  - "Re:MCG -03-31-014 A pair (with MCG -03-31-015) of very perturbed interacting galaxies with long `antennas' [sic]. Dimensions and extent of the antenna 18 arcmin!"
- 1972, Toomre & Toomre, ApJ, 178, 623
  - First referred to as "The Antennae"
  - First dynamical model (also Toomre 1974)

1974IAUS...58..347T

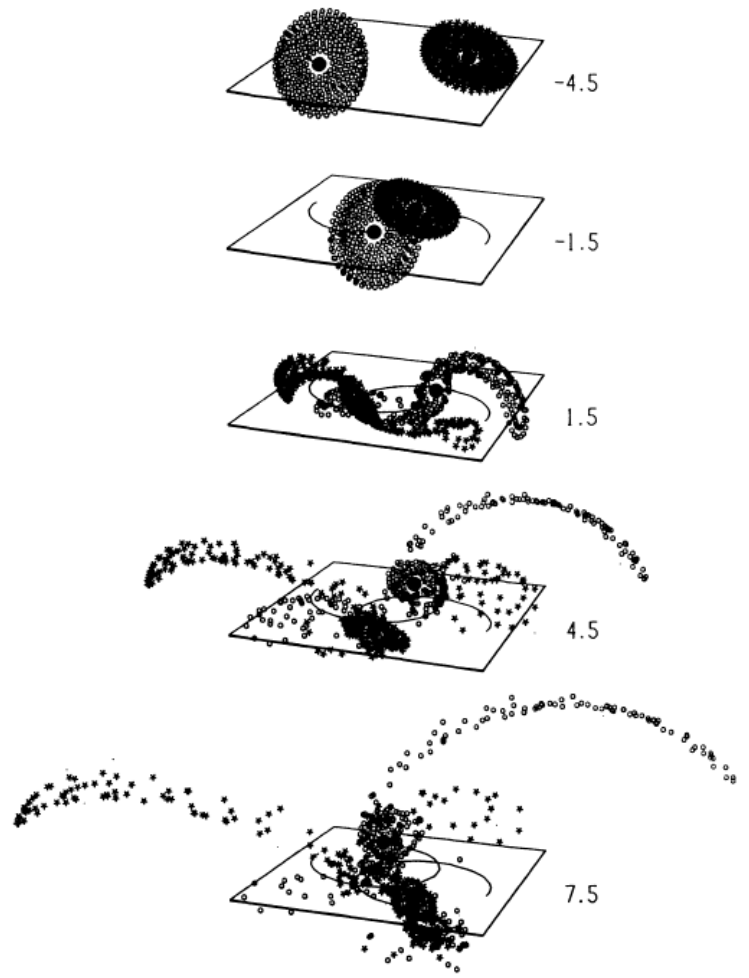


Fig. 9. Five views of the symmetric close encounter of two 60°-inclined disks of test particles presumed by TT (§VI.d) to caricature the recent history of NGC 4038/9. These views are equally spaced in time, with the instant 0 (not shown) meant to represent pericentre. The stereographic projection used here assumes a vantage point at a distance equal to 16 times that of the closest approach of the two central masses, or four times the edge length of the square that denotes their common orbit plane.

Ever Since TT72, The Antennae has been a key system for validating the once controversial idea that galaxies can and do merge

Challenges to Collisional Interpretation

- 1962, IAU 15, 194, Vorontsov-Velyaminov
  - Tails too long and thin to be tidal
- Refuted: 1978, Schweizer
  - Tails not as thin as you think

GALAXIES WITH LONG TAILS

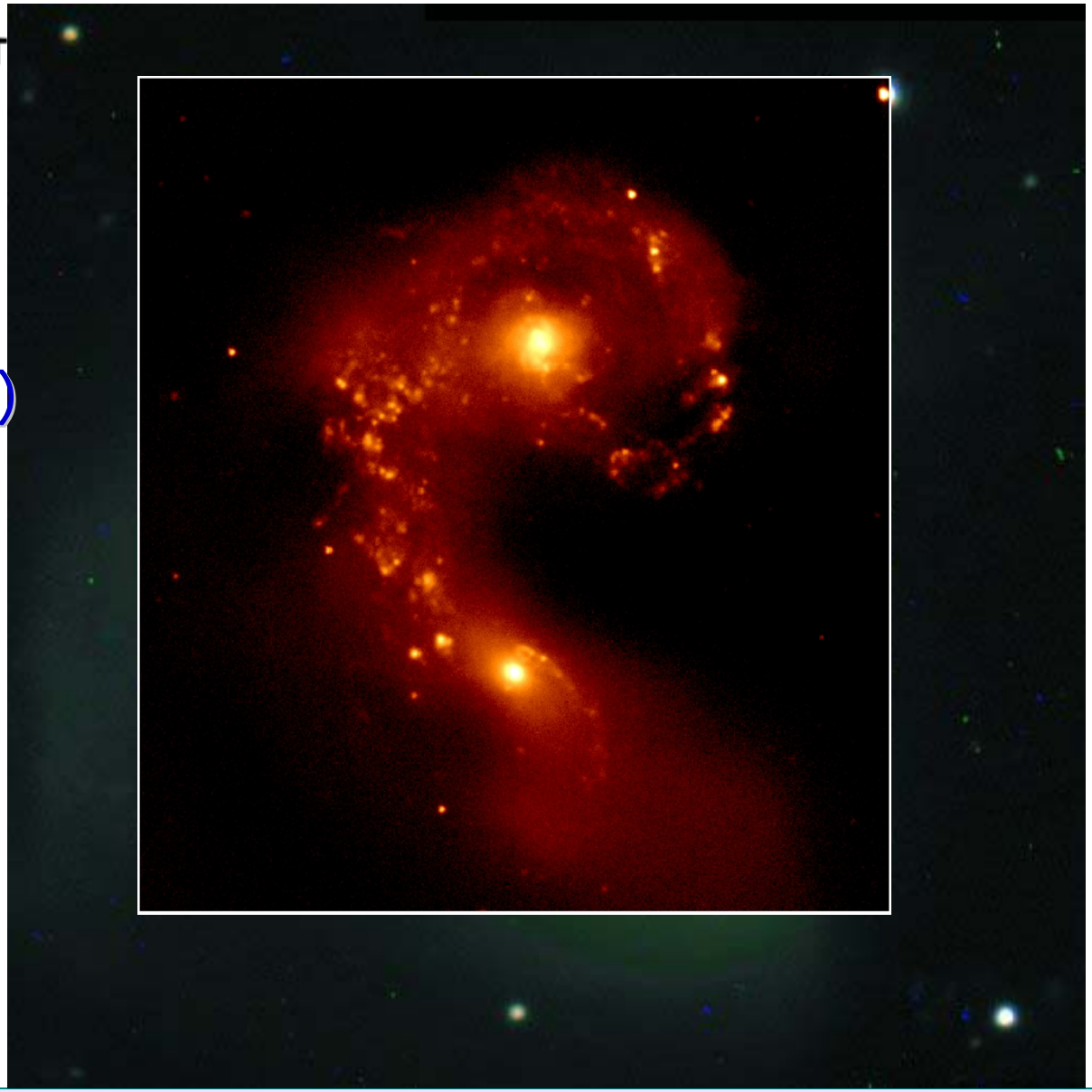
François Schweizer
Cerro Tololo Inter-American Observatory*

E. M. Berkhuijsen and R. Wielebinski (eds.), Structure and Properties of Nearby Galaxies, 279–286. *All Rights Reserved. Copyright © 1978 by the IAU.*

Figure 1. NGC 4038/9 on IIIa-J plates obtained with the CTIO 4-m telescope. North is at the top and east is at the left. (a) (left) Exposure of 50 minutes. (b) (right) Superposition print of two plates totalling 3.5 hours of exposure time. Note the dwarf stellar system near the tip of the southern tail.

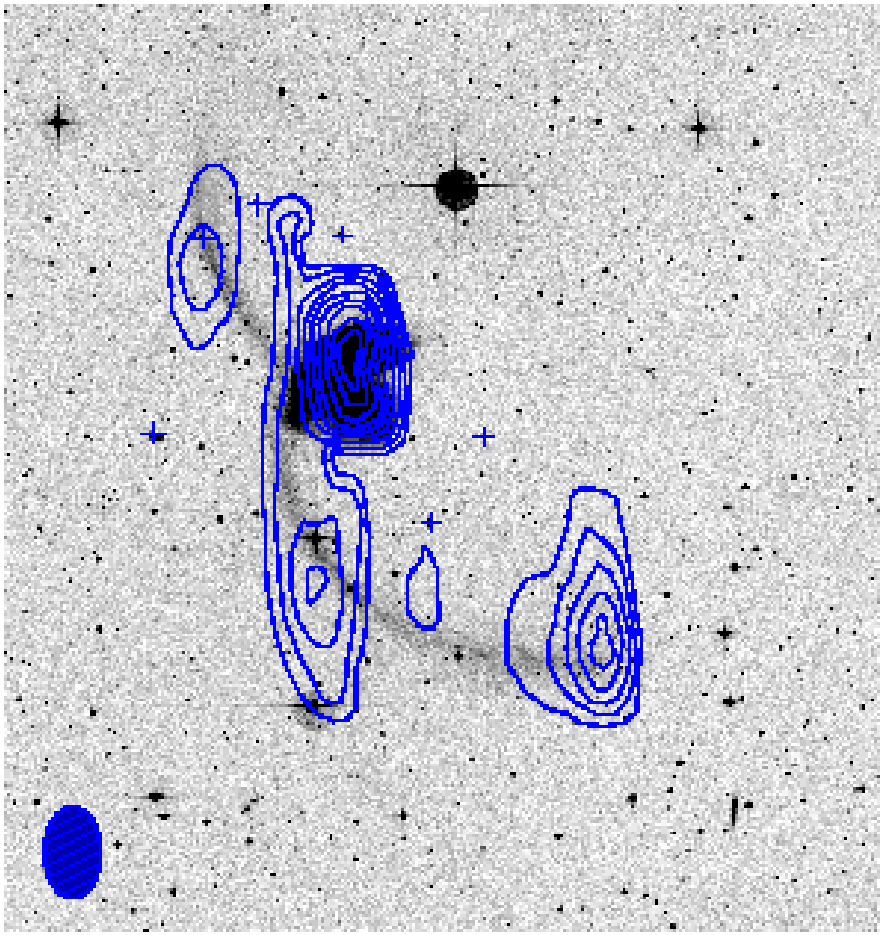
Challenges to Collisional Interpretation

- 1976, 1977 Vorontsov-Velyaminov
  - Not two (obvious) progenitors



B. Brandt & WIRC team
(Cornell; APOD 2002-Apr-11)

Interaction Picture reaffirmed



HI contours on DSS:
van der Hulst, 1977, PhD. Thesis

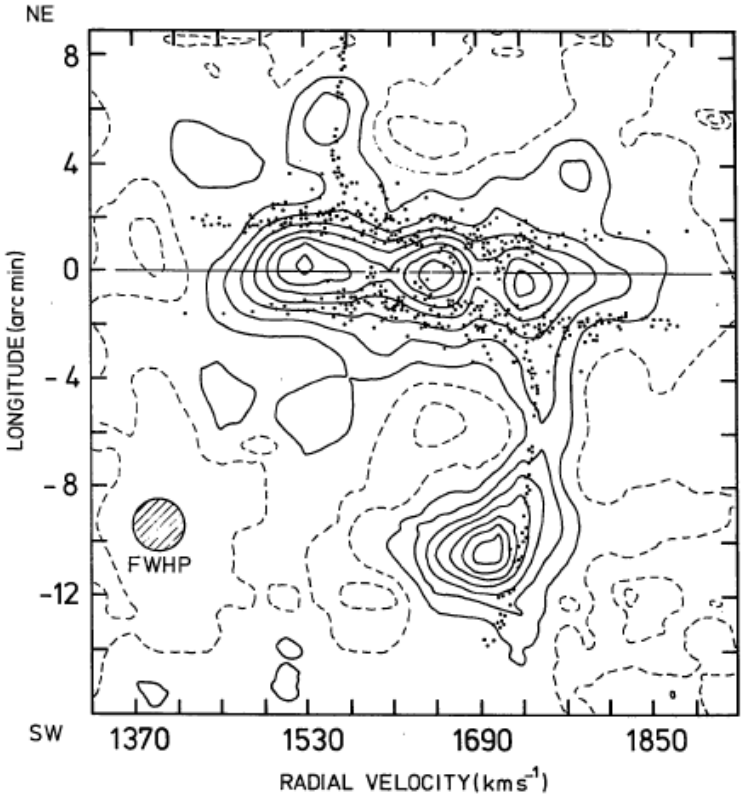
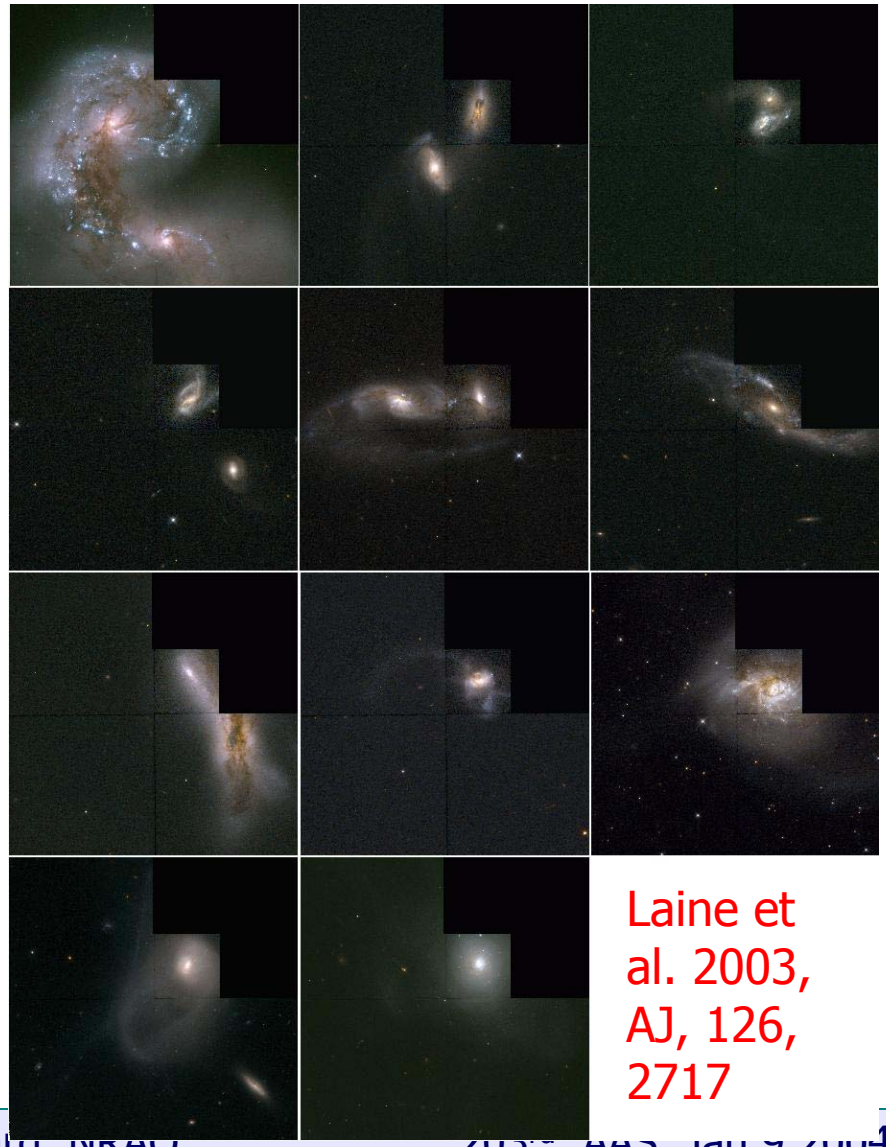


Fig. 11. Contour diagram of an average of four longitude-velocity maps along the four lines (p.a.$=40°$) of Fig. 10. The contour interval is 0.1 K brightness temperature. The zero and negative contour are dashed. The zero point in longitude corresponds to $\alpha = 11^h59^m21^s$, $\delta = -18°36'$. The black dots represent a scaled (see text) version of the model of Toomre and Toomre (cf. Fig. 9). The ellipse in the lower left corner represents the halfpower "longitude-velocity" beam

Increased importance as first member of "Toomre Sequence" of merging galaxies

Toomre, 1977, *"Evolution of Galaxies & Stellar Populations"*, p.401

- Suggestive sequence of peculiar galaxies representing the concept that two spiral galaxies can merge and evolve into an elliptical galaxies (The Toomre "Merger Hypothesis")
- NGC 4038/39 is the earliest and most nearby member of this sequence.



Laine et al. 2003, AJ, 126, 2717

The Antennae is one of the best studied interacting galaxies

coolcosmosipac.caltech.edu/cosmic_classroom/multiwavelength_astronomy/multiwavelength_museum/ant.html

Modeling History: Toomre & Toomre 1972

THE ASTROPHYSICAL JOURNAL, 178:623–666, 1972 December 15
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GALACTIC BRIDGES AND TAILS

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AND
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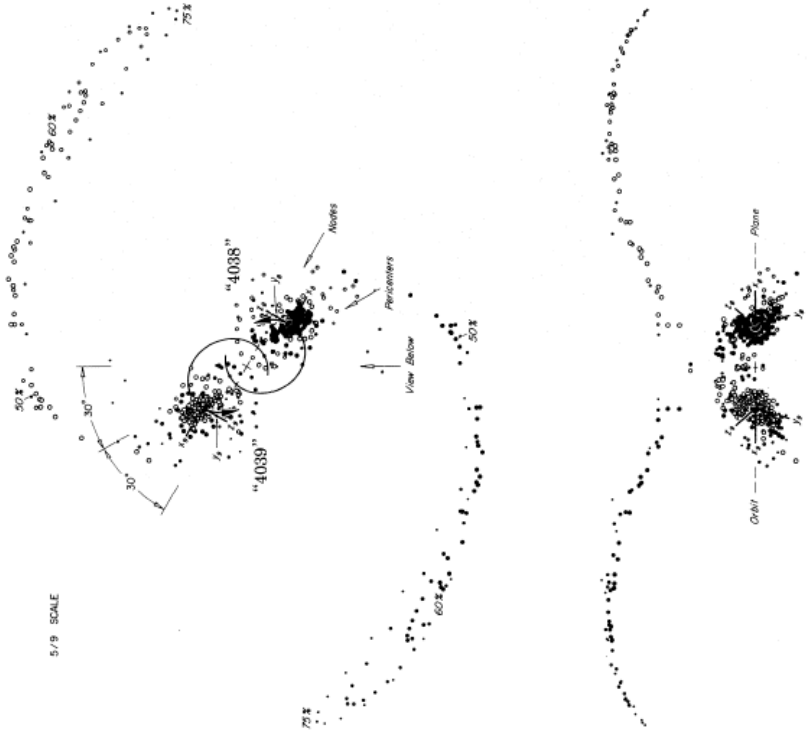
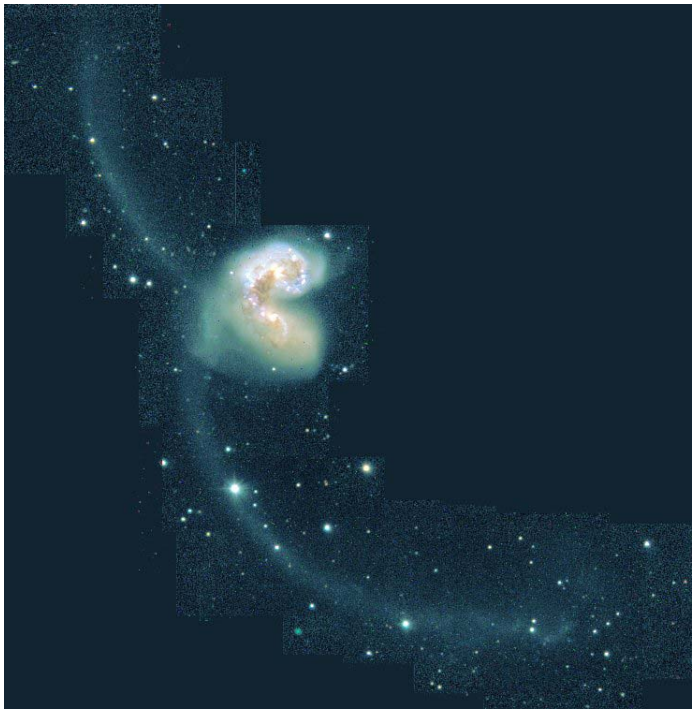
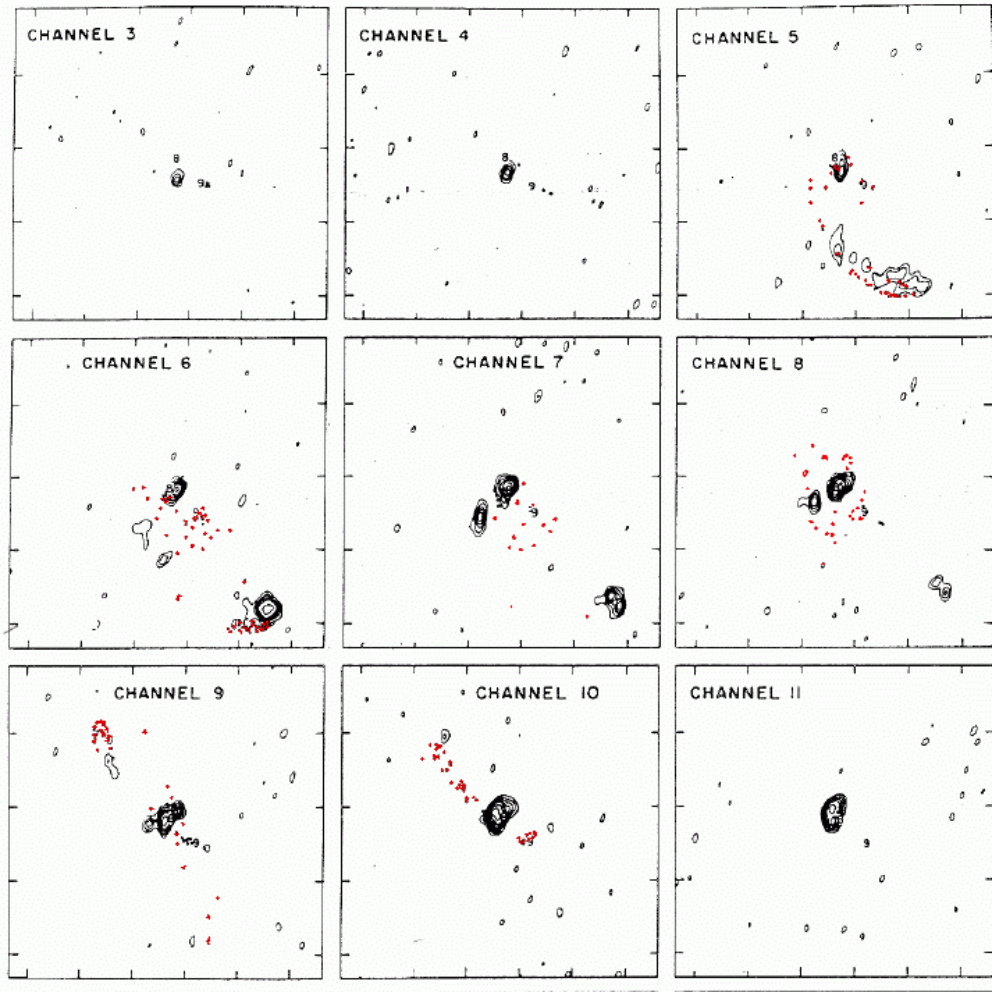
Department of Mathematics, New York University, and
Goddard Institute for Space Studies, New York
Received 1972 May 19

Restricted 3-body
~300 particles per disk
e=0.5, R_{peri}=0.5 encounter





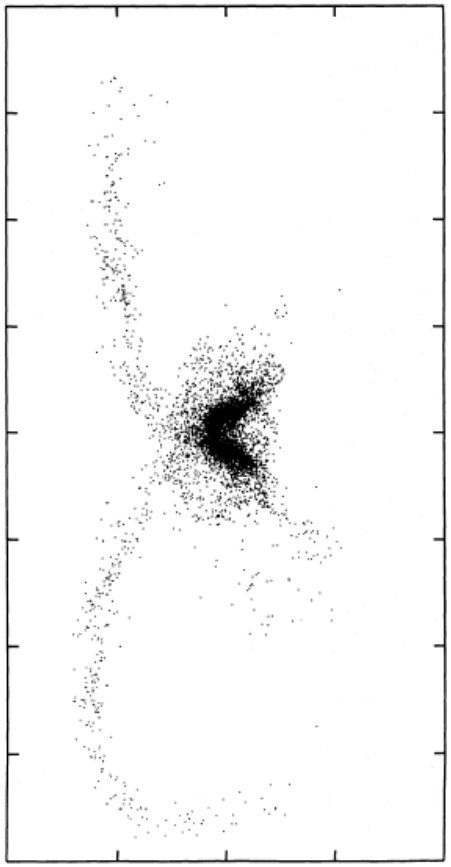
New HI Observation, New model (Mahoney et al. 1984)

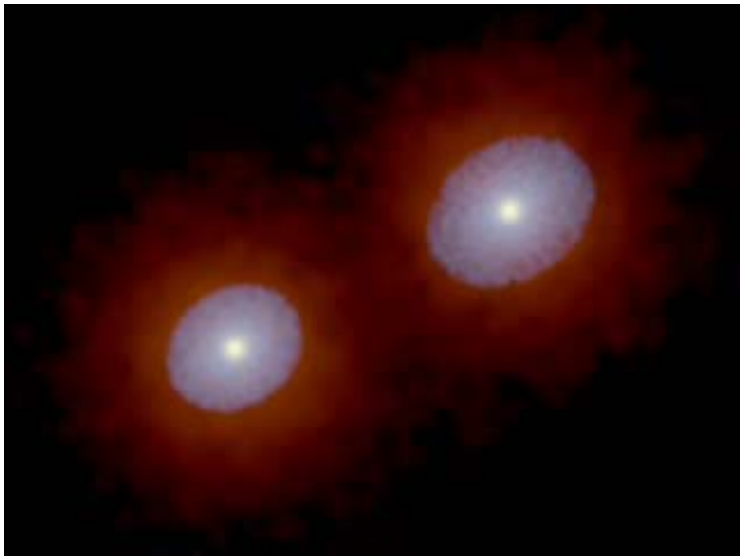


Restricted 3-body with prescription for orbital decay
200 particles per disk
e=0.9, R_{peri}=0.5 encounter

First self-consistent N-body Model: Barnes, 1988

Gravity treated self-consistently
bulge+disk+halo galaxies
N=16,384 per galaxy
e=1, R_{peri}=0.5 encounter





Model with gasdynamics: Mihos, Bothun, & Richstone (1993)

1993ApJ...418...82M

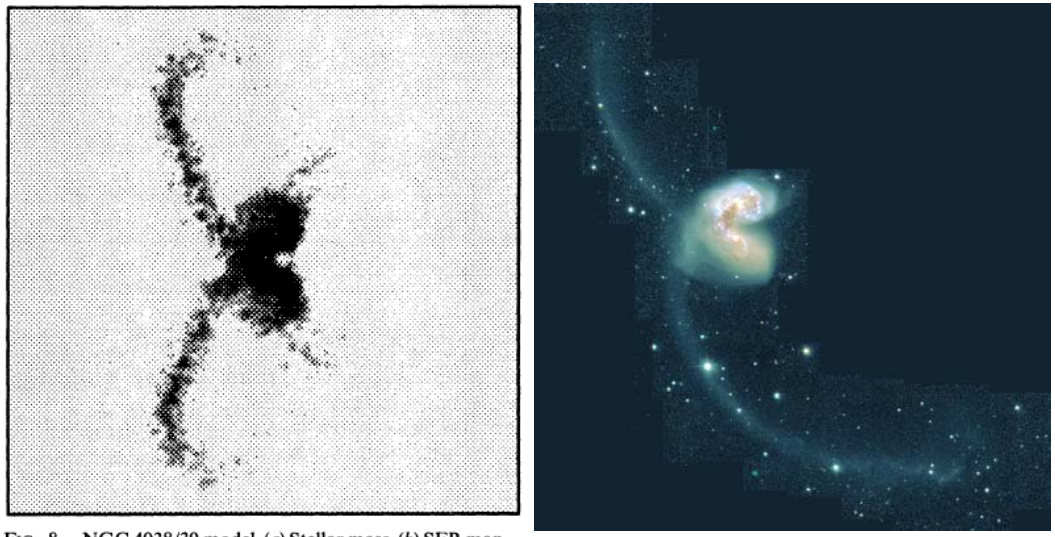


FIG. 8.—NGC 4038/39 model. (*a*) Stellar mass. (*b*) SFR map.

Self-consistent gravity
Sticky particle hydro
Schmidt law SF prescription
Halo+disk+flat ISM galaxies
N=14,000 per galaxy
e=0.5, R_{peri}=0.5

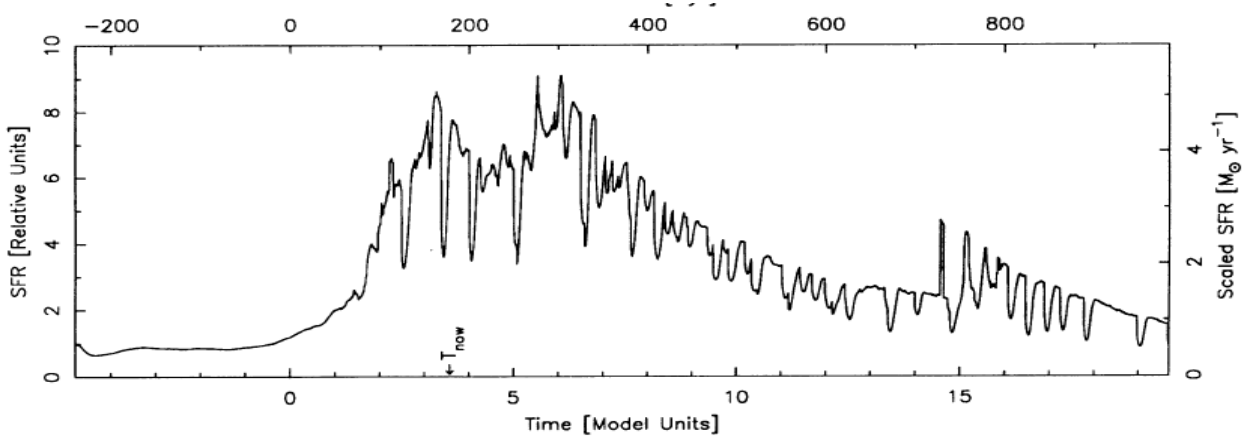
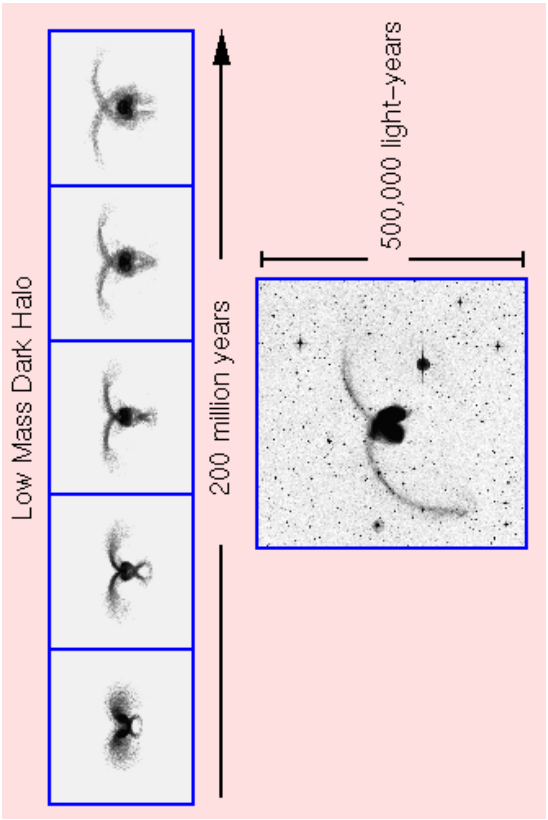
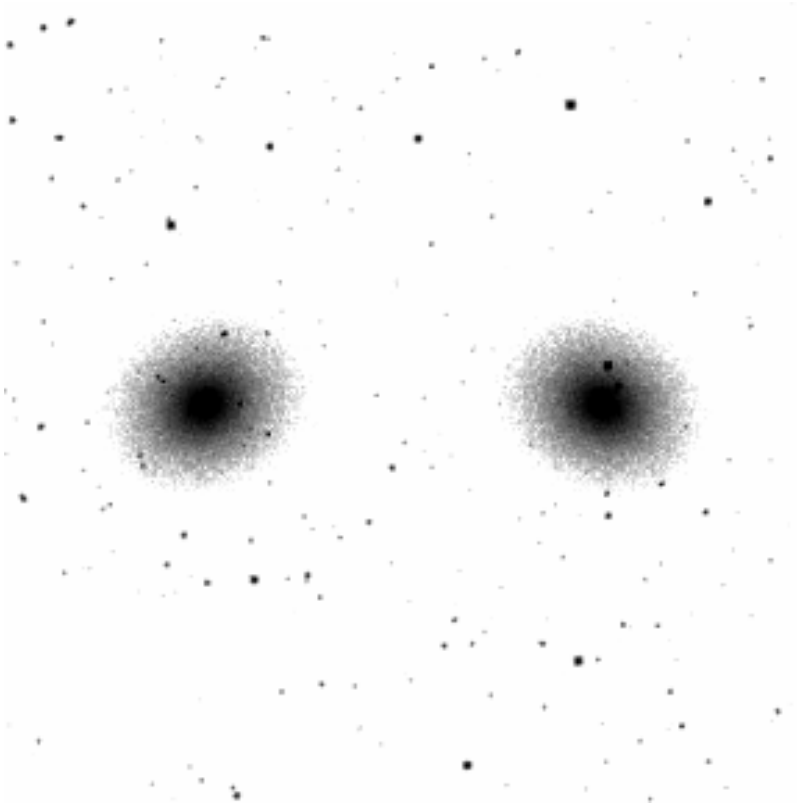


FIG. 13.—NGC 4676 model SFR evolution. Present time is denoted as T_{now}.

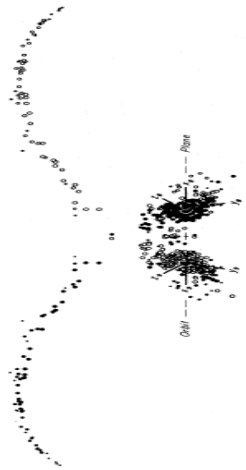
Self-consistent model with e=1: Dubinski 1996



Self-consistent gravity
Bulge+disk+halo galaxies
N=48,000 per galaxy
e=1, R_{peri}=0.35

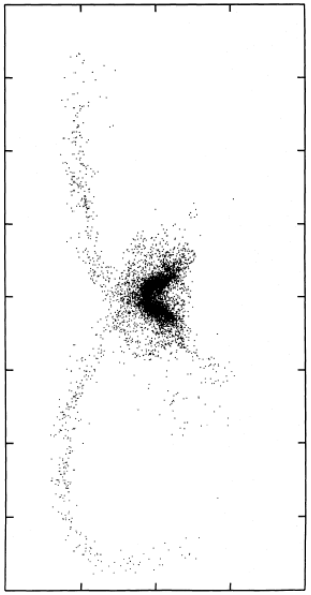


Modeling History: Summary

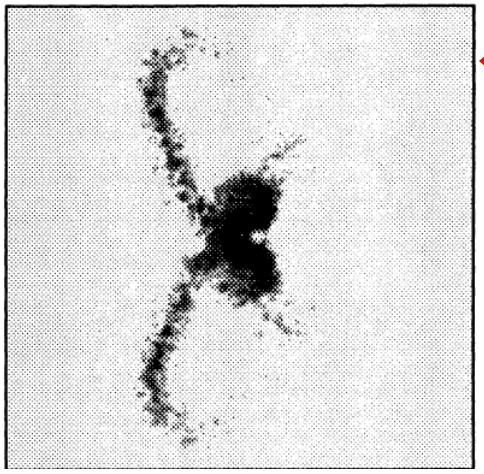


1972, Toomre & Toomre, test particles

Observations

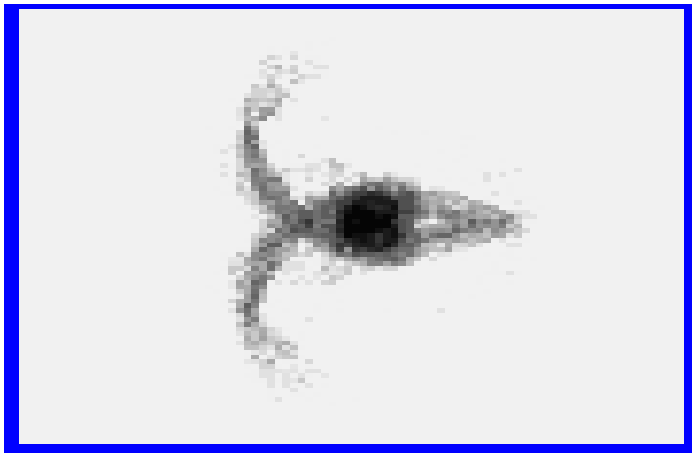


1988, Barnes, self-consistent

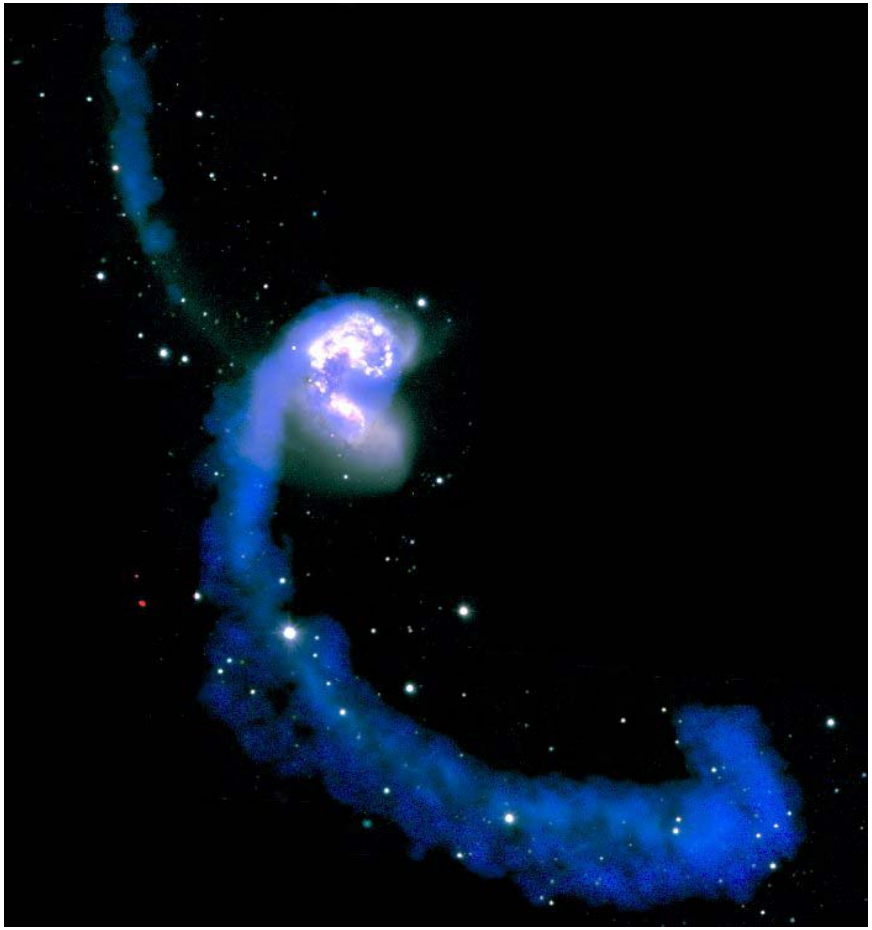


1993, Mihos et al.,
Self-consistent+gas dynamics

1996, Dubinski,
Self-consistent,
parabolic encounter



New HI Observation (Hibbard et al. 2001), New model (Hibbard & Barnes 2004):



Blue=VLA HI Observations

Hibbard, van der Hulst, Barnes & Rich 2001, AJ, 122, 2969

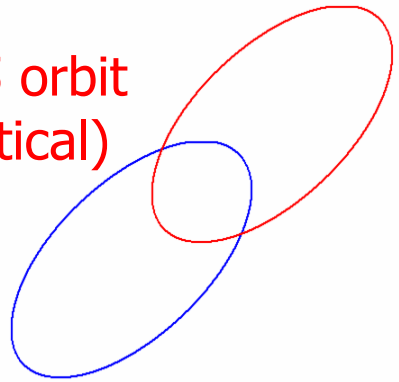
Blue=disk particles

Hibbard & Barnes, Dec 29, 2003

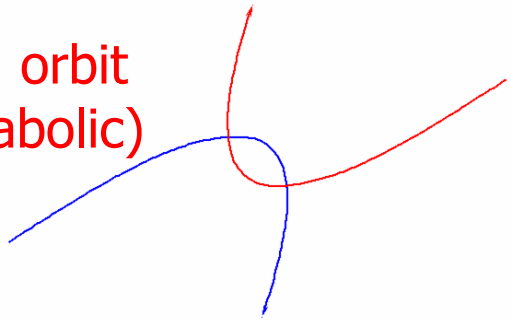
First detailed match to both morphology and kinematics, using realistic galaxy models and starting conditions

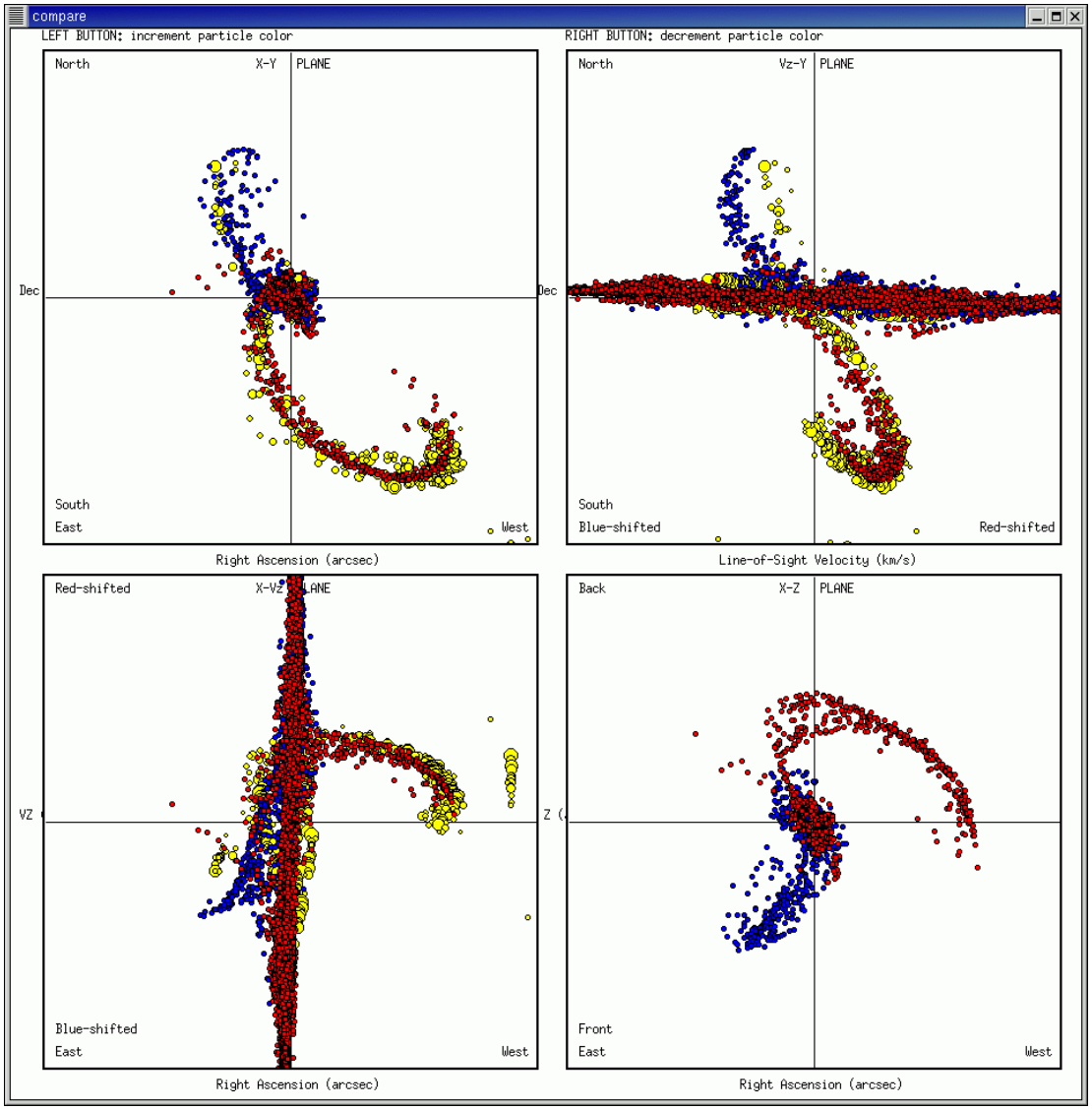
Self-consistent gravity
disk+bulge+halo
galaxies
N=35,000 per galaxy
e=1, R_{peri}=0.5

e=0.5 orbit
(elliptical)



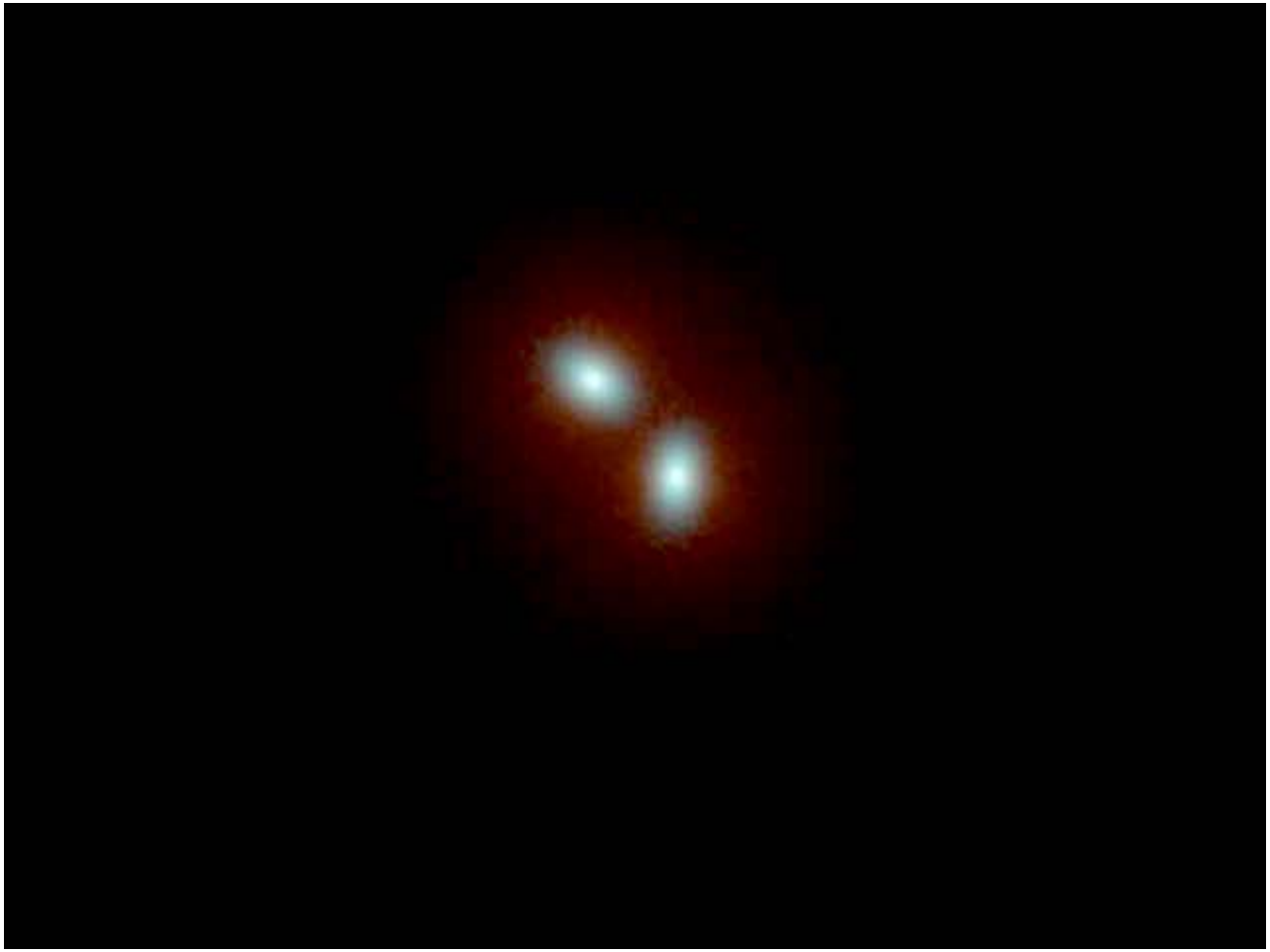
e=1 orbit
(parabolic)





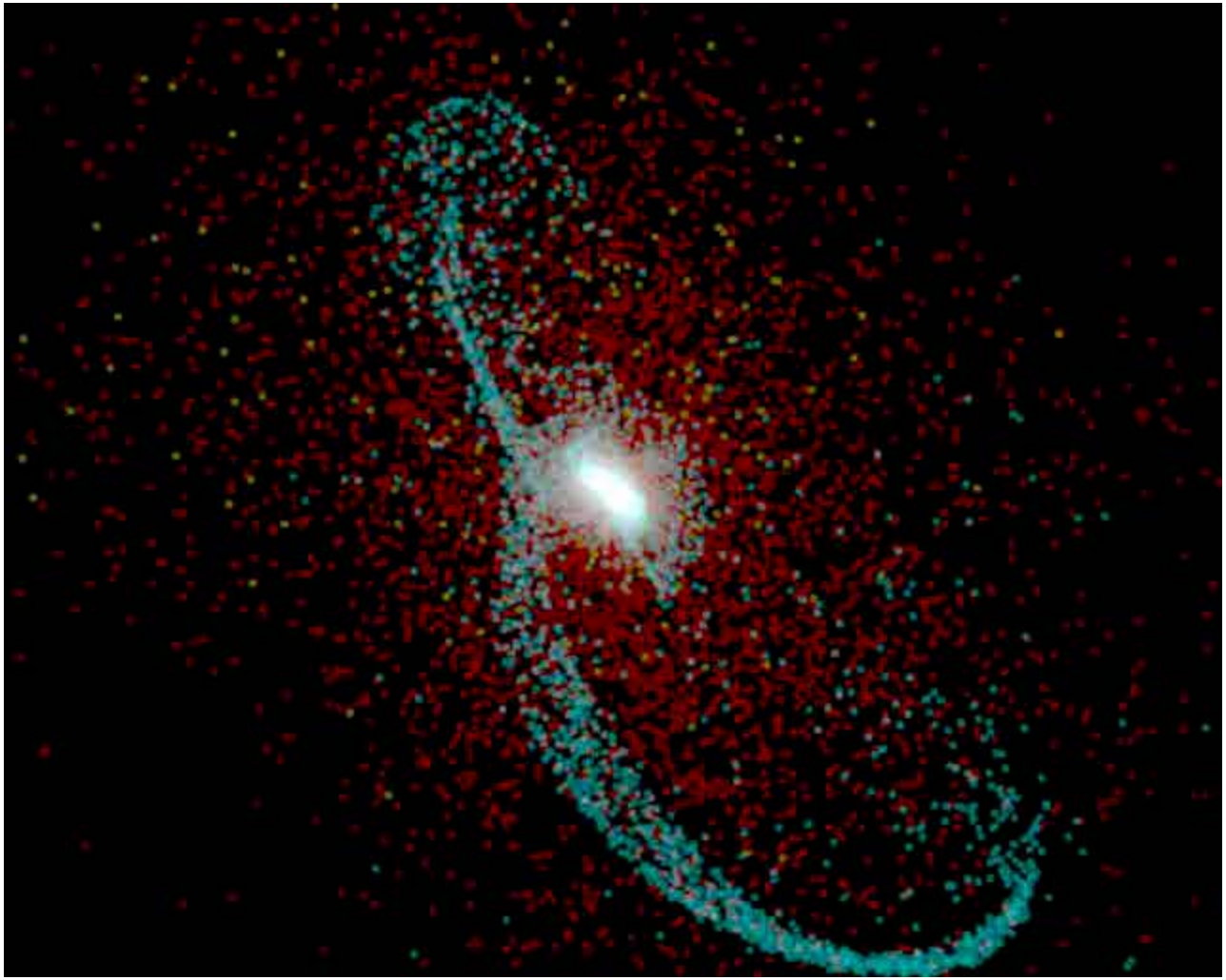
Time Evolution

1 million particle simulation of best fitting parameters

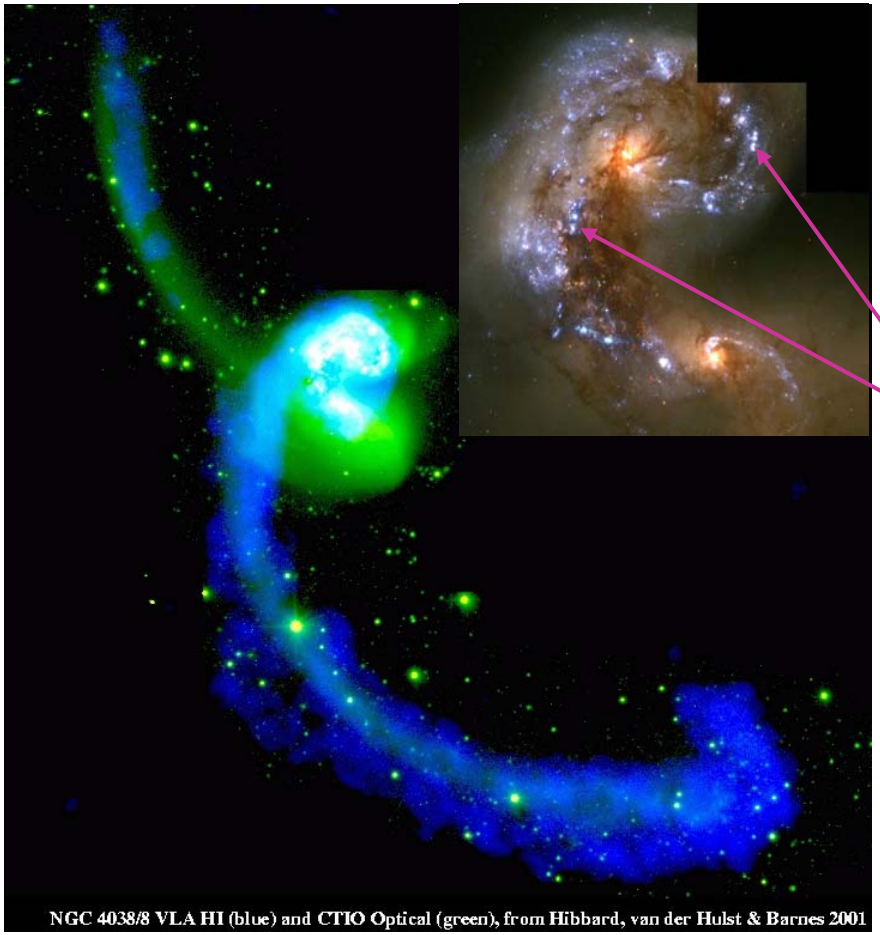


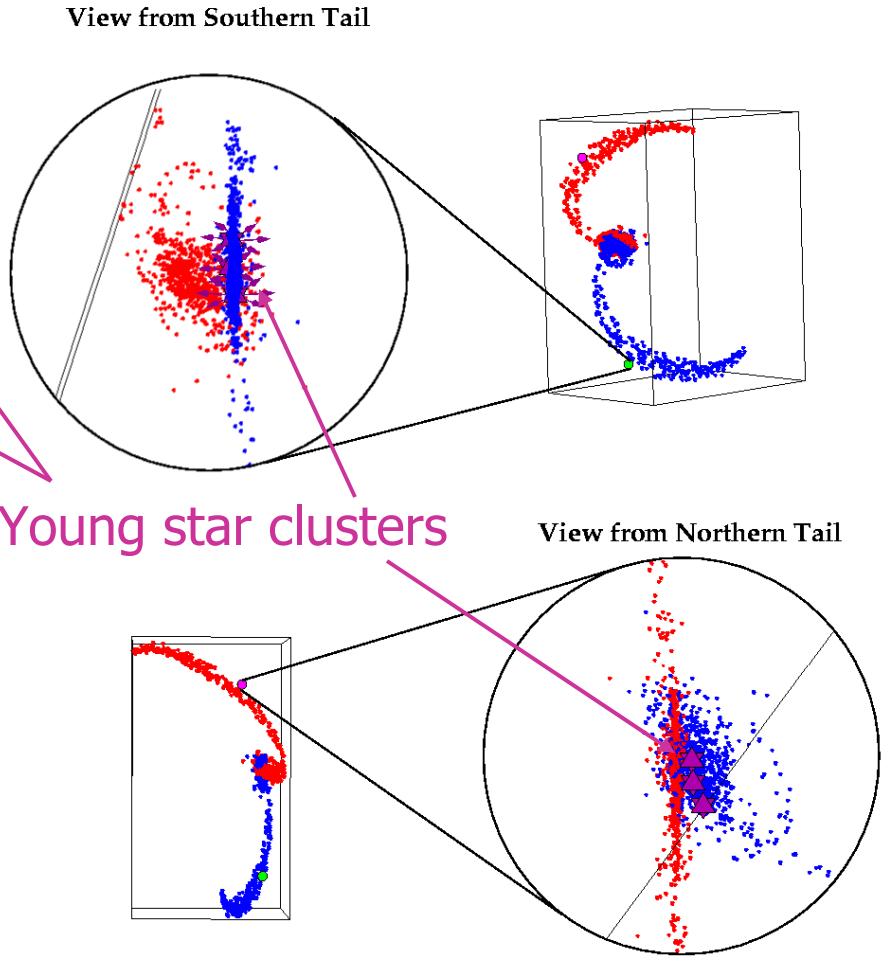
System made first pass ~220 Myr ago; will merge in ~40 Myr

3-dimensional structure of The Antennae



3-dimensional structure of The Antennae may help explain some outstanding puzzles





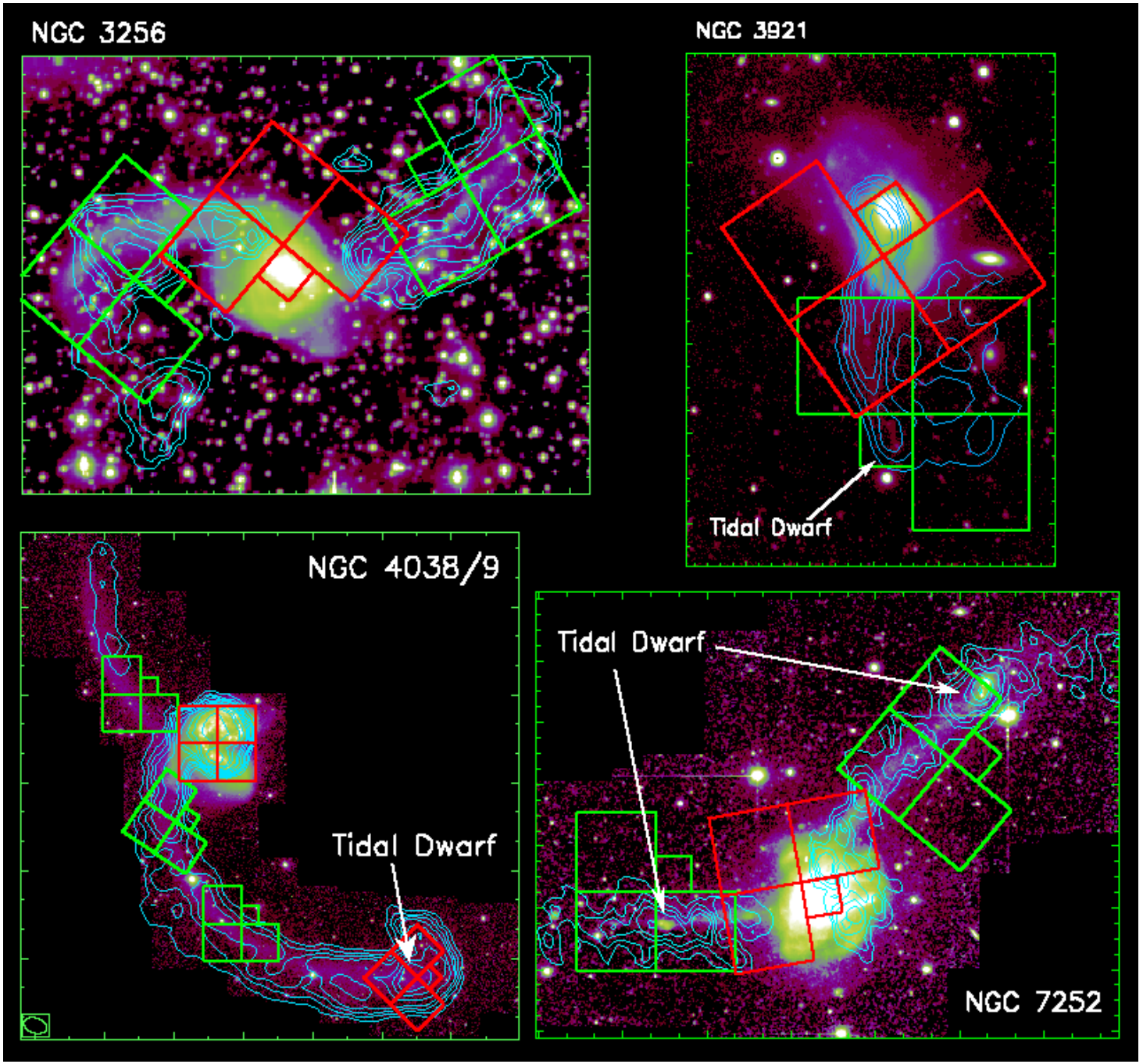
Our new model is an important step for increasing our understanding of this merger archetype

- First model which matches both the observed shape and motions of The Antennae tidal features in detail.
- Parabolic orbit much more plausible starting condition
- Time evolution can be compared to data from star clusters/populations
- 3-d structure can help us understand some outstanding puzzles

HST study of Optical Substructure in Tidal Tails

N4038/9, N3256
N3921, N7252
WFC VI
13 orbits
P.I. Charlton
Kniermann et al.
AJ, submitted

N4038 TDG
WFC UBVI
11 orbits
P.I. Hibbard
Saviane et al.
AJ, submitted



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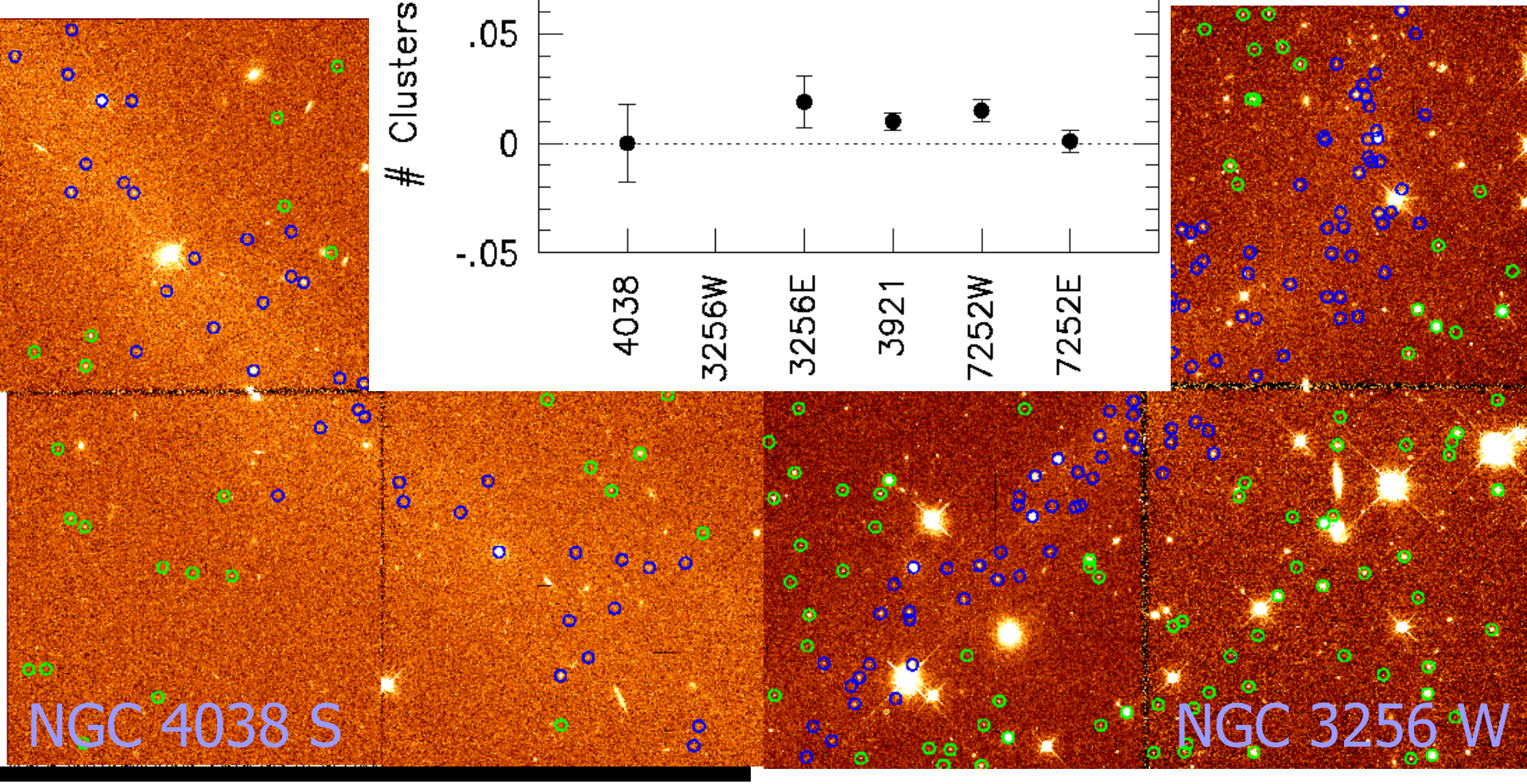
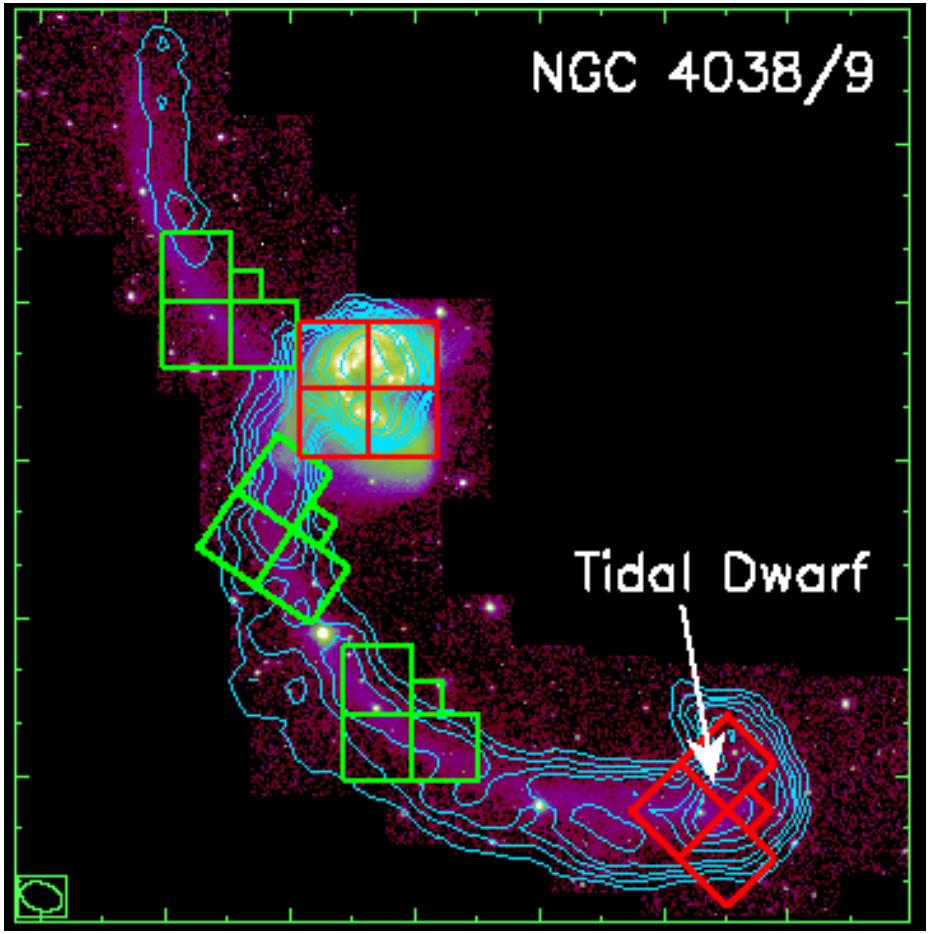
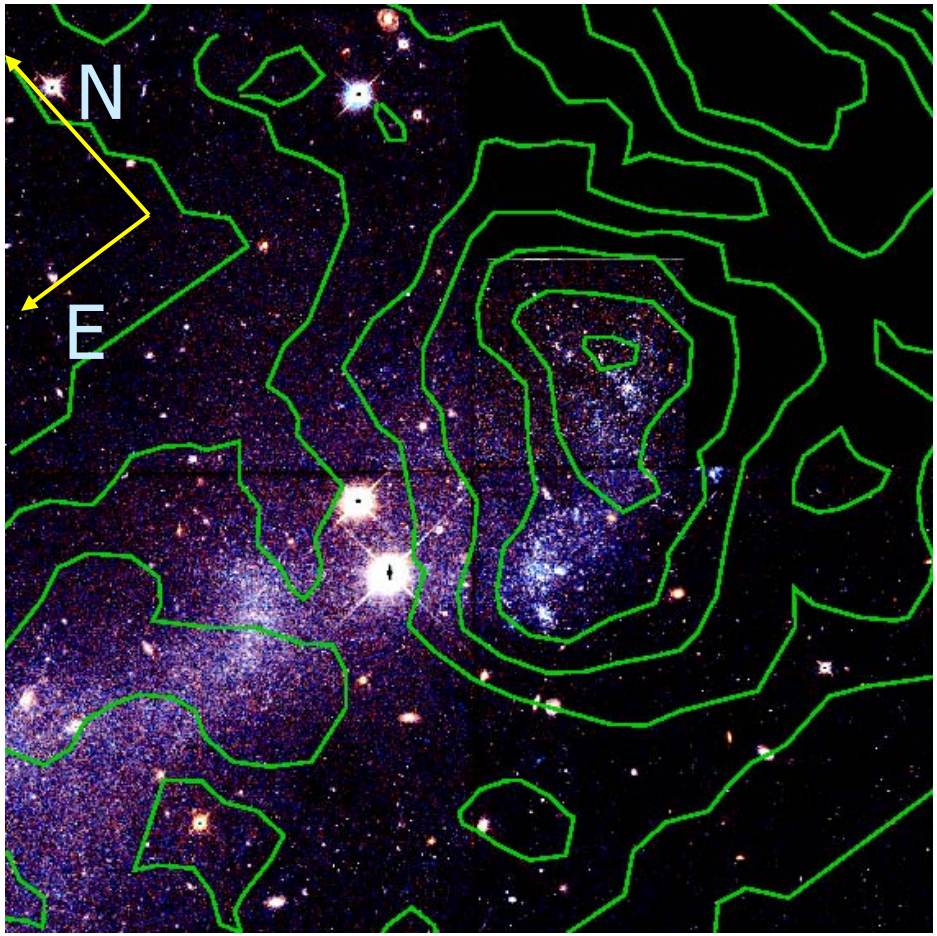


Knierman et al. 2004, AJ, in press

NGC 4038 TDG Candidate.

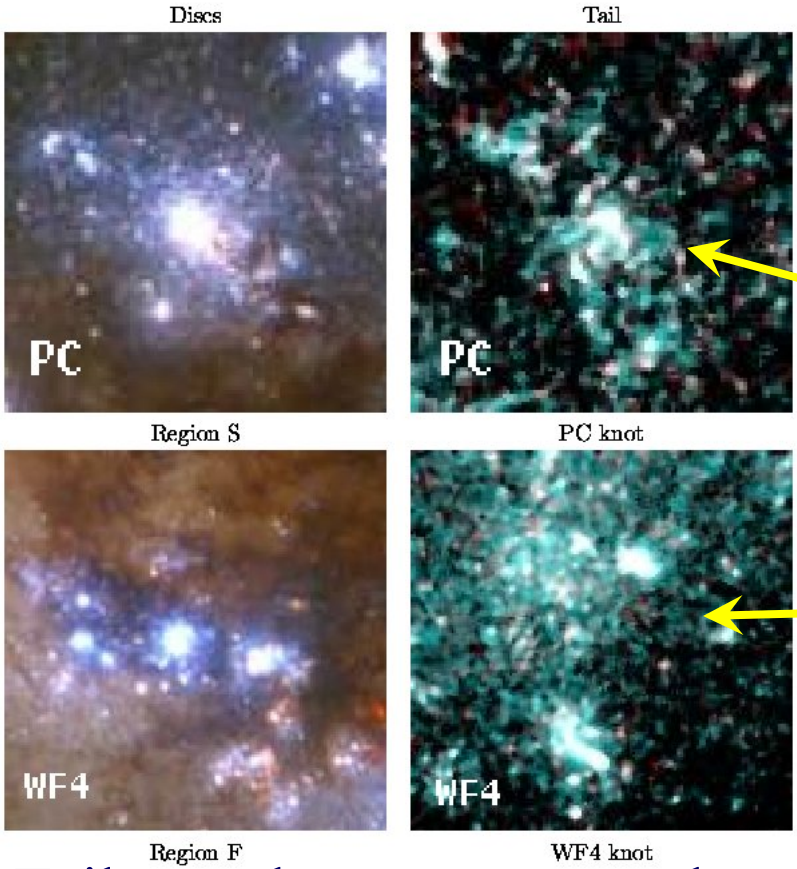




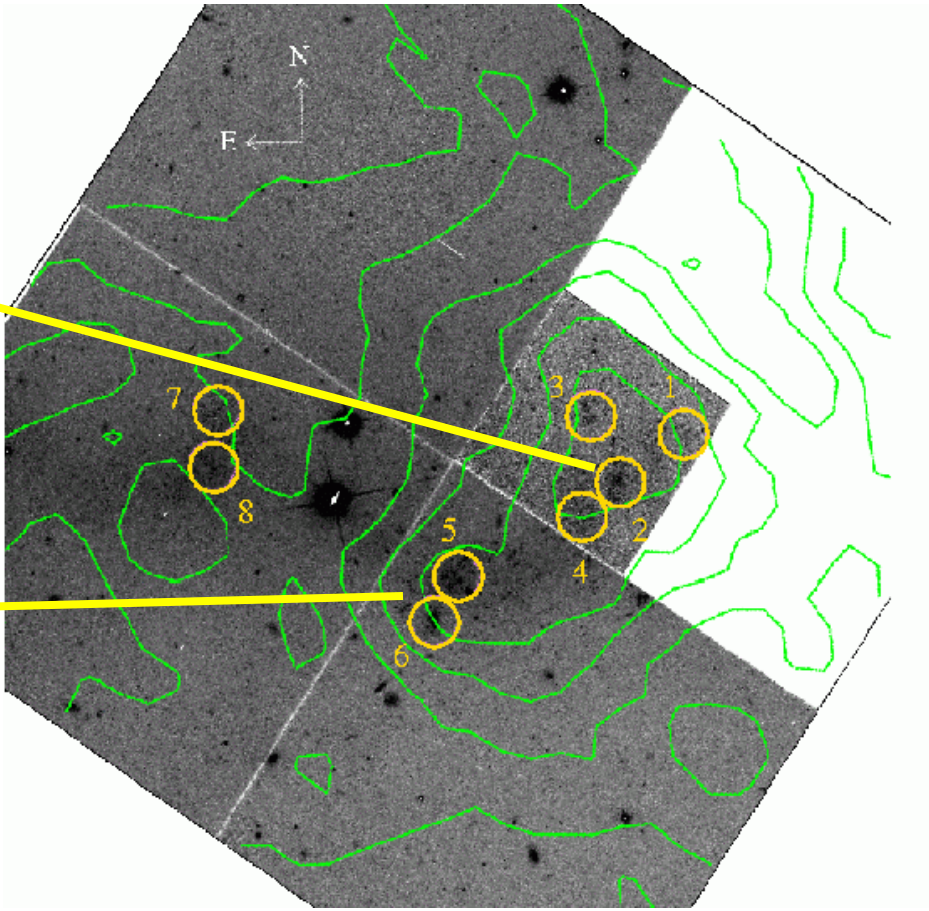
HST: Saviane, Hibbard & Rich, AJ, submitted
HI: Hibbard, van der Hulst, Barnes & Rich, 2001

HST WFPC2 Truecolor (V,V+I,I) with HI contours

Star Cluster concentration in TDG Candidate in the S tail of NGC 4038



Tail star clusters compared to SSCs in inner regions: smaller, more irregular



Location of Tail Star Clusters

Saviane, Hibbard & Rich, AJ, submitted

The Occurrence of Young Stars within Tidal Debris has been Noted for Some Time

GALAXIES WITH LONG TAILS

François Schweizer
Cerro Tololo Inter-American Observatory*

E. M. Berkhuijsen and R. Wielebinski (eds.), Structure and Properties of Nearby Galaxies, 279–286. *All Rights Reserved. Copyright © 1978 by the IAU.*

the tip of the southern tail is resolved into bright stars (clusters?) and fuzzy knots. These knots are clearly H II regions, as shown by their emission-line spectra (H∝, [N II], [S II], and [O II] λ3727 lines on my spectrograms). The H∝ fluxes are of the order of 100 times the H∝ flux of the entire Orion nebula, and the line ratios indicate an excitation similar to that of, e. g., H II regions at intermediate radii in M 101. The remarkable fact which I wish to emphasize here is that *at about 100 kpc projected distance from the main bodies of NGC 4038/9, stars are still actively being formed as a consequence of some tidal interaction which took place* 7×10^8 *yr ago!* Furthermore, the gas out of which these stars are forming is not as metal-poor as one might expect from its remote location, but rather seems of a metallicity found typically at the outskirts of a giant disk galaxy. This, of course, fits in nicely with the tidal-interaction model for the Antennae.

The radial velocities of the four H II regions intersected by the spectrograph slit (1690, 1708, 1710, and 1711 km s^{-1}) agree closely with the 1710 km s^{-1} velocity of the H I gas observed by van der Hulst (this meeting). However, note that the H II regions are clearly located within the tip of the tail, whereas the H I gas seems to be more concentrated in that dwarf stellar system near the tip of the tail. The dwarf is therefore likely to be physically associated with the tail. Although nothing is known as yet about its stability, we should envisage the possibility that *tidal interactions may create dwarf galaxies* and that *these dwarfs may contain more metals than we would expect* if we somehow think of primordial material out there. This possible mechanism for the formation of dwarfs was emphasized already long ago by Zwicky (1956).

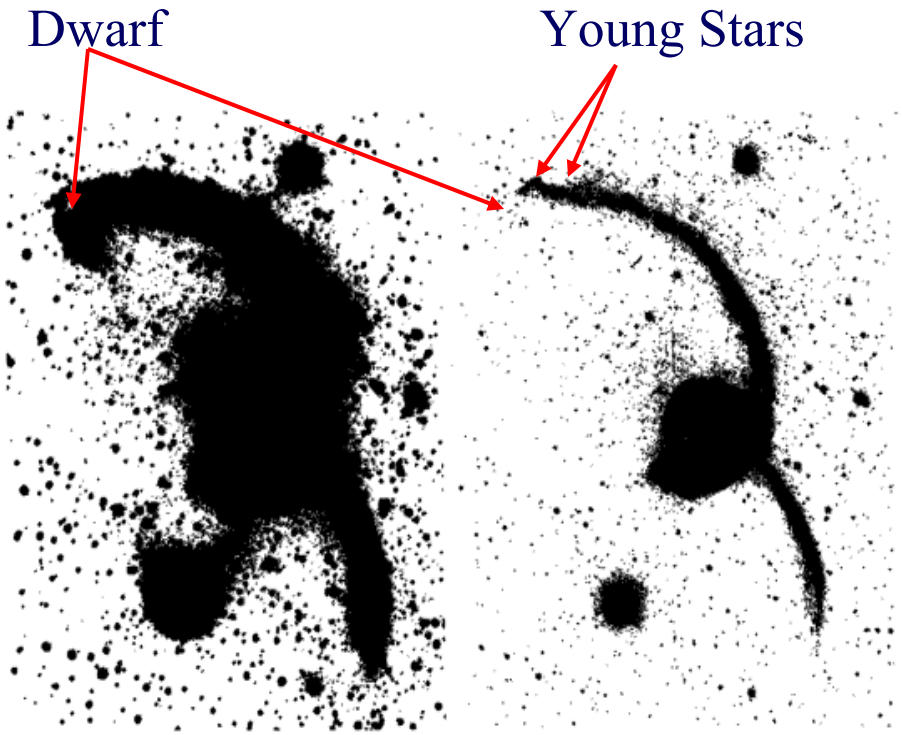


Figure 1. NGC 4038/9 on IIIa-J plates obtained with the CTIO 4-m telescope. North is at the top and east is at the left. (a) (left) Exposure of 50 minutes. (b) (right) Superposition print of two plates totalling 3.5 hours of exposure time. Note the dwarf stellar system near the tip of the southern tail.

Re-discovered in the early 1900's

Termed "Tidal Dwarf Galaxies" (TDGs)

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ASTRONOMY AND ASTROPHYSICS

Letter to the Editor

Genesis of a dwarf galaxy from the debris of the Antennae

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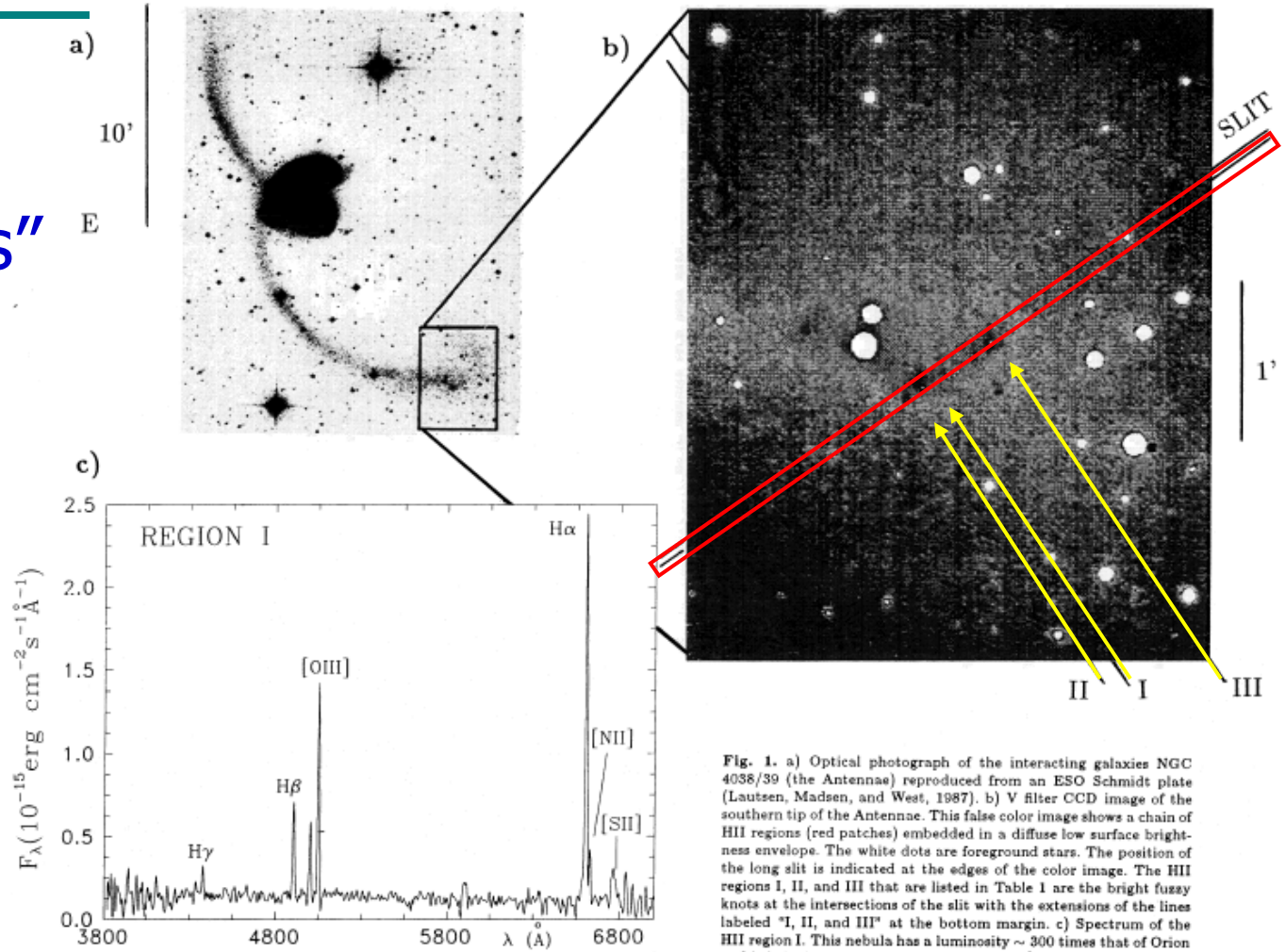


Fig. 1. a) Optical photograph of the interacting galaxies NGC 4038/39 (the Antennae) reproduced from an ESO Schmidt plate (Lautsen, Madsen, and West, 1987). b) V filter CCD image of the southern tip of the Antennae. This false color image shows a chain of HII regions (red patches) embedded in a diffuse low surface brightness envelope. The white dots are foreground stars. The position of the long slit is indicated at the edges of the color image. The HII regions I, II, and III that are listed in Table 1 are the bright fuzzy knots at the intersections of the slit with the extensions of the lines labeled "I, II, and III" at the bottom margin. c) Spectrum of the HII region I. This nebula has a luminosity ~ 300 times that of Orion

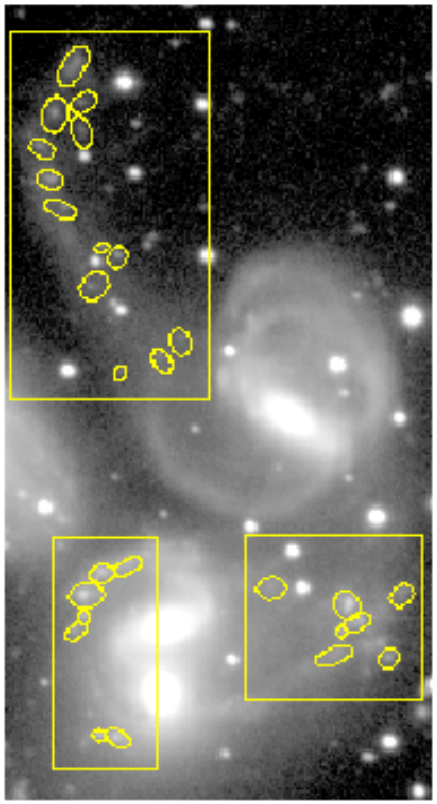
Observed structures span a large range of sizes

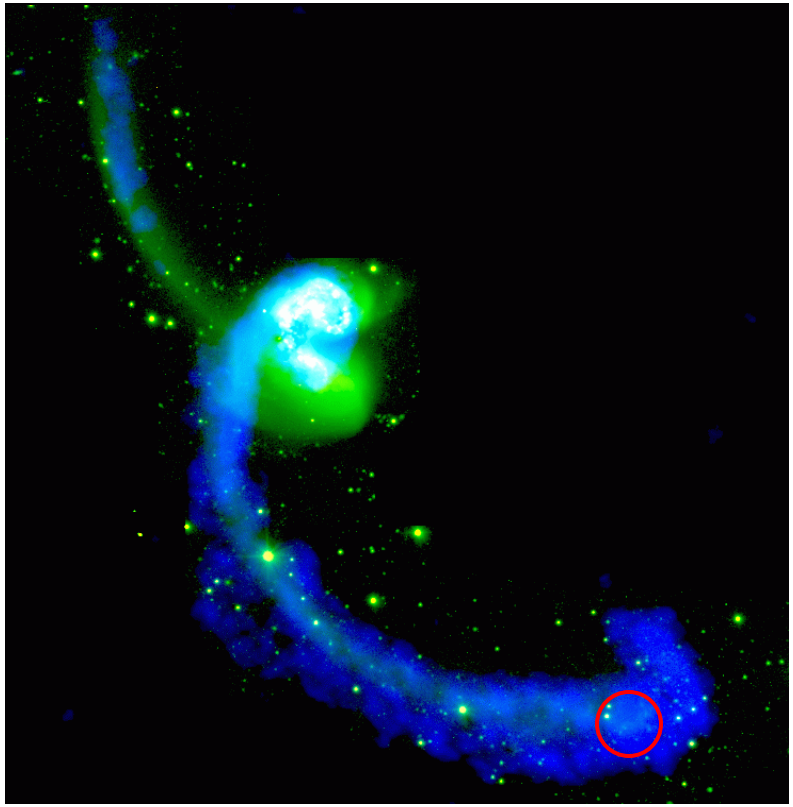
Outstanding Questions:

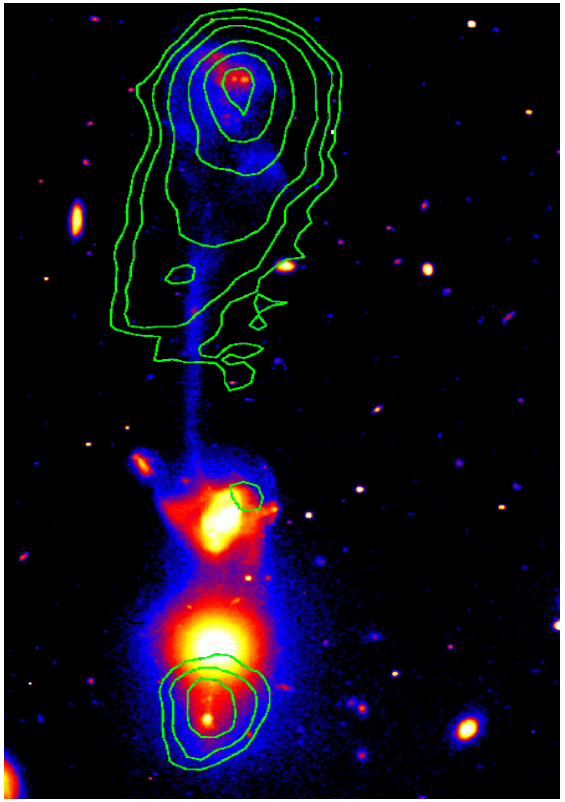
On what scales (if any) are these structures bound?

Is this an evolutionary sequence?

Are these "Tidal Dwarf Galaxies" (TDGs) robust entities?

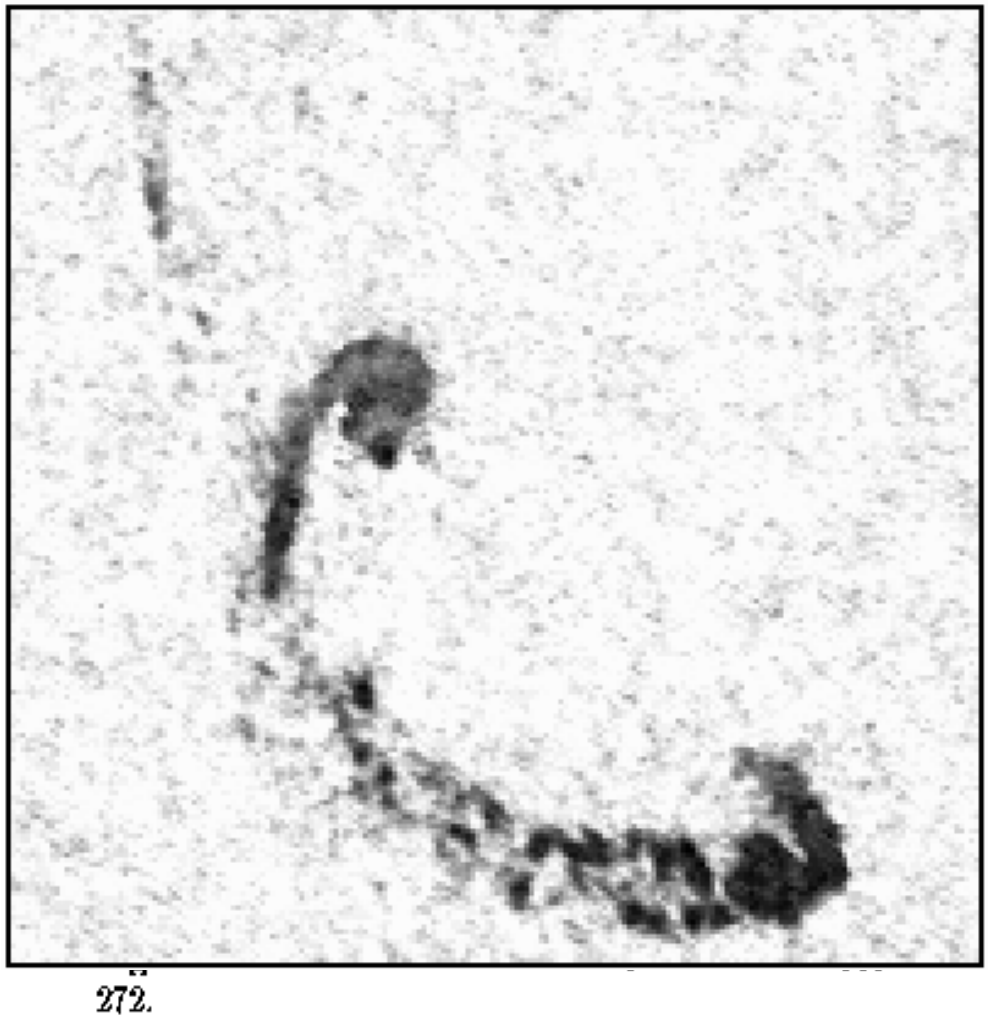






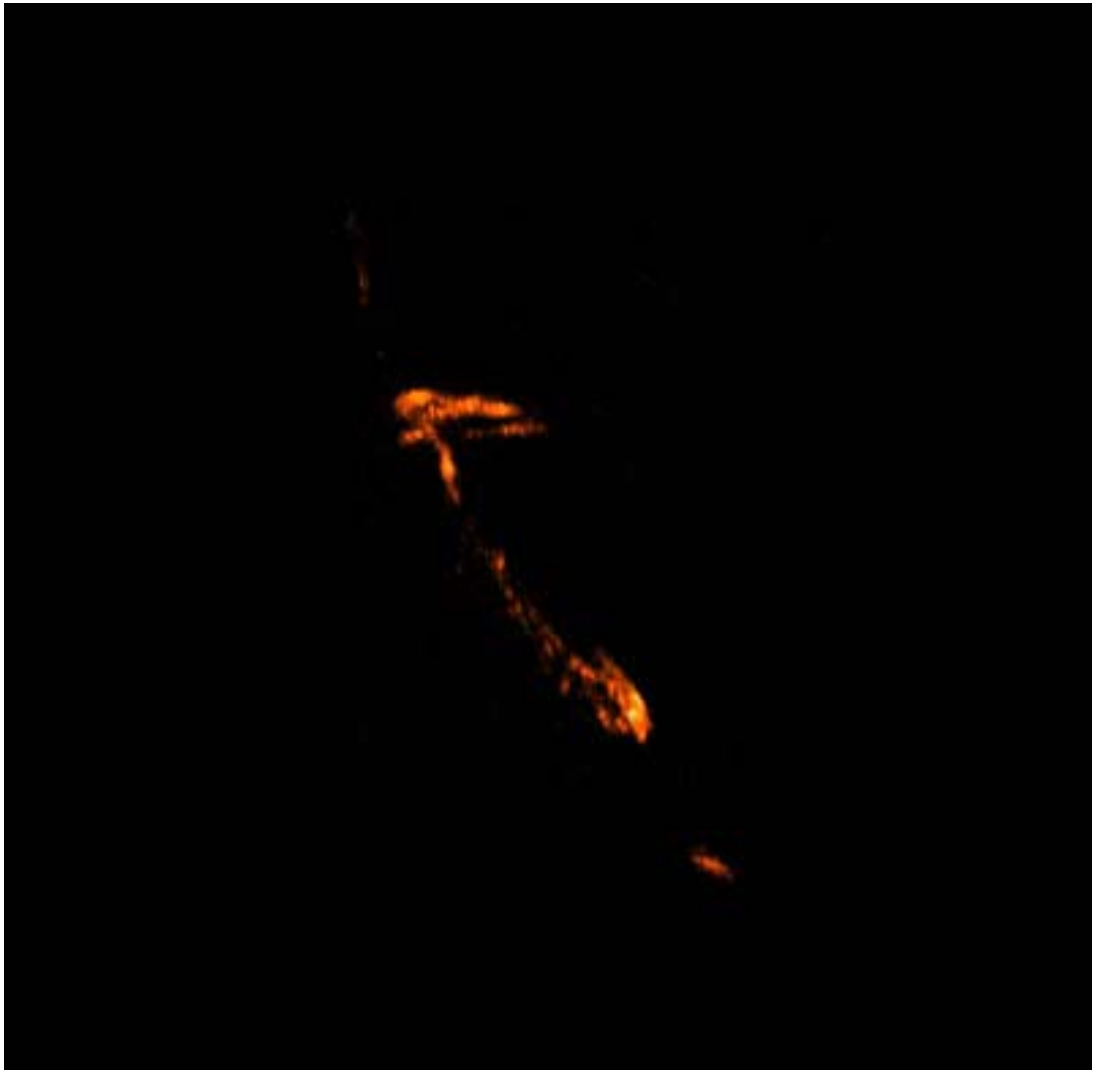
Under many TDG evolutionary scenarios, optical TDGs should have gaseous precursors

- Use distribution and kinematics of moderate resolution HI observations to estimate dynamical nature of gaseous substructure

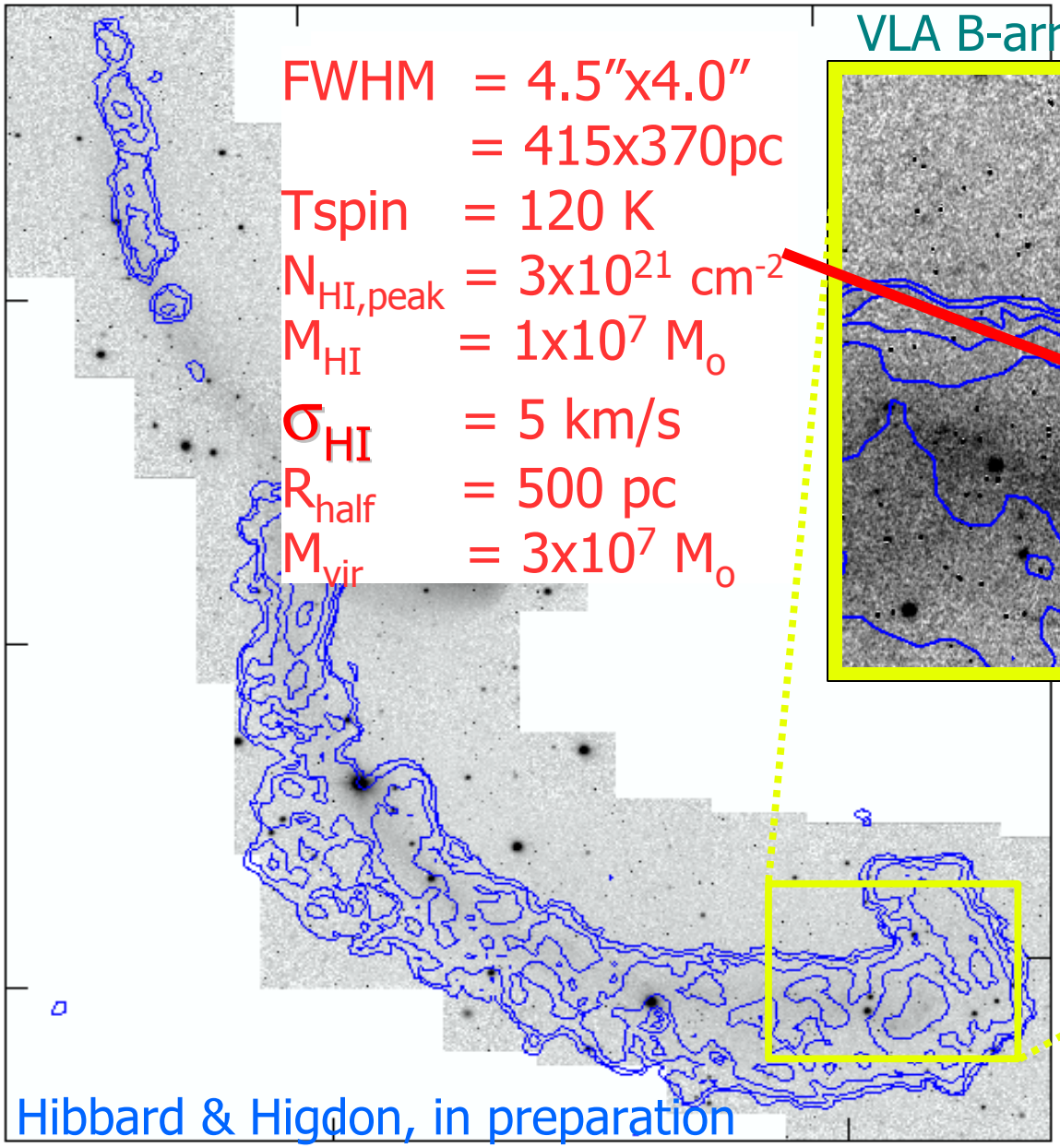


VLA observations of NGC 4038/9: Hibbard, Barnes, van der Hulst & Rich, 2001

HI observations reveal a wealth of structure within the tails. (resolution ~10"-20", Δv=5.2 km/s)

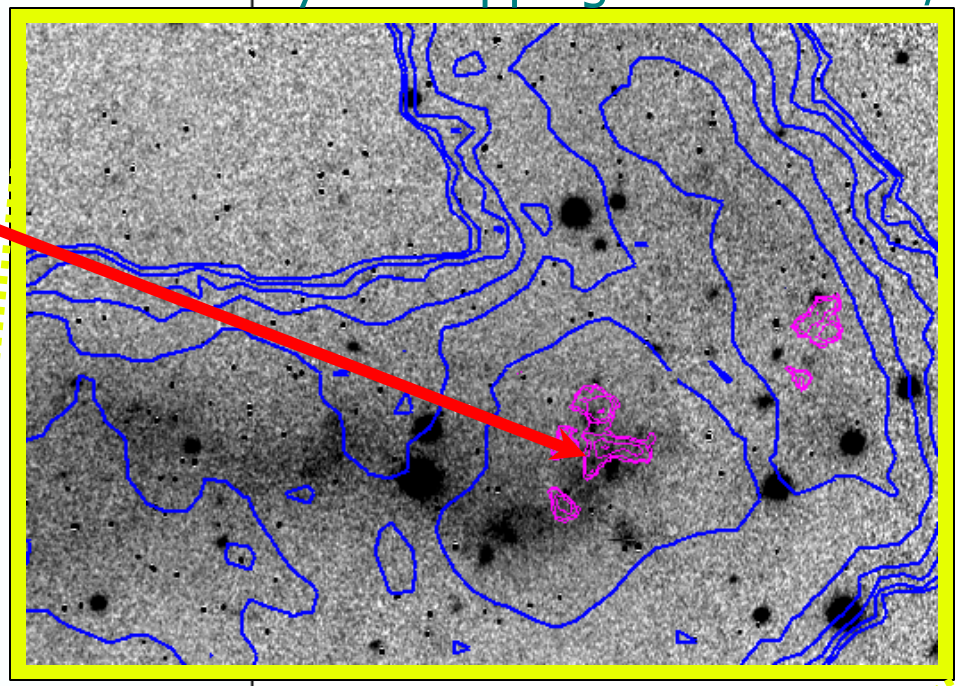


Some regions may be bound, but on smaller scales



FWHM = 4.5″x4.0″
= 415x370pc
Tspin = 120 K
$N_{HI,peak}$ = $3x10^{21}$ cm^{-2}
M_{HI} = $1x10^{7}$ M_o
σ_{HI} = 5 km/s
R_{half} = 500 pc
M_{vir} = $3x10^{7}$ M_o

VLA B-array HI Mapping of NGC 4038/9



Compare C+D Array:
Tspin = 40 K
$N_{HI,peak}$ = $1.4x10^{21}$ cm^{-2}
M_{HI} = $2.4x10^{8}$ M_o
σ_{HI} = 13 km/s
R_{half} = 3.2 kpc
M_{vir} = $1x10^{9}$ M_o

Hibbard & Higdon, in preparation