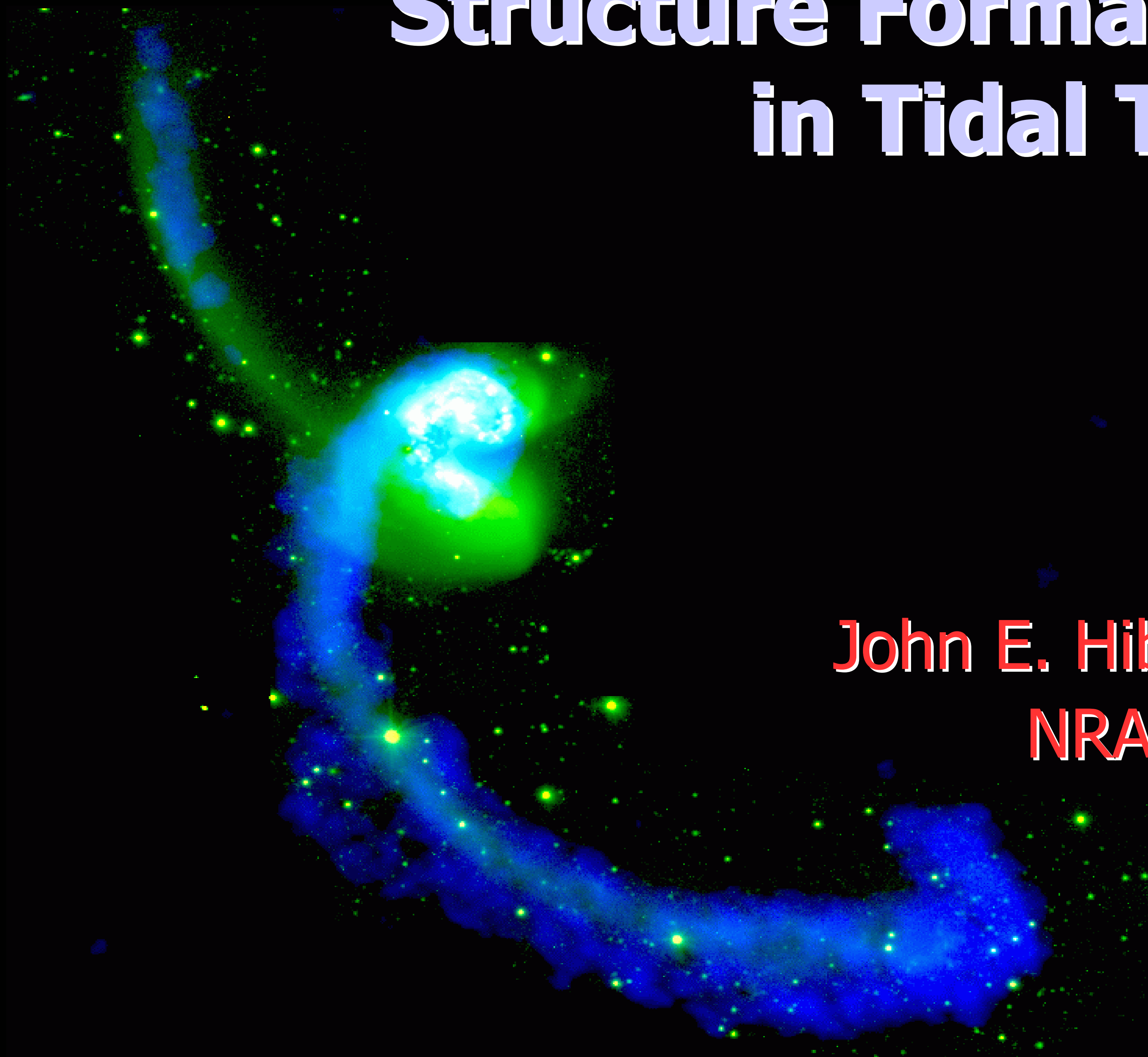
Structure Formation in Tidal Tails



John E. Hibbard
NRAO-CV

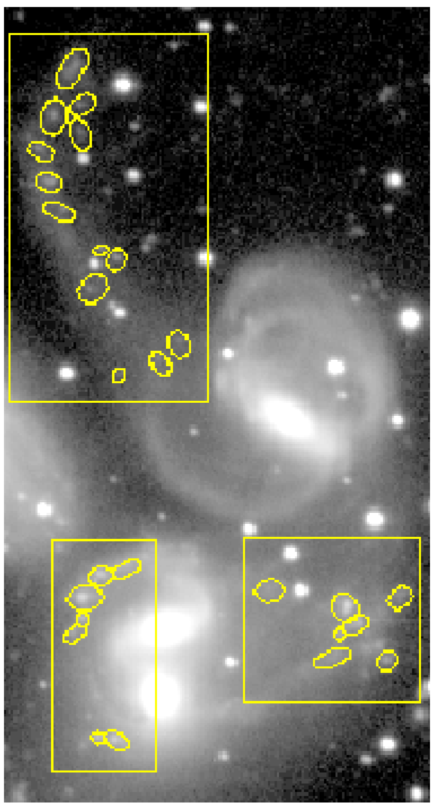
A Range of Substructures are found in Tidal Tails

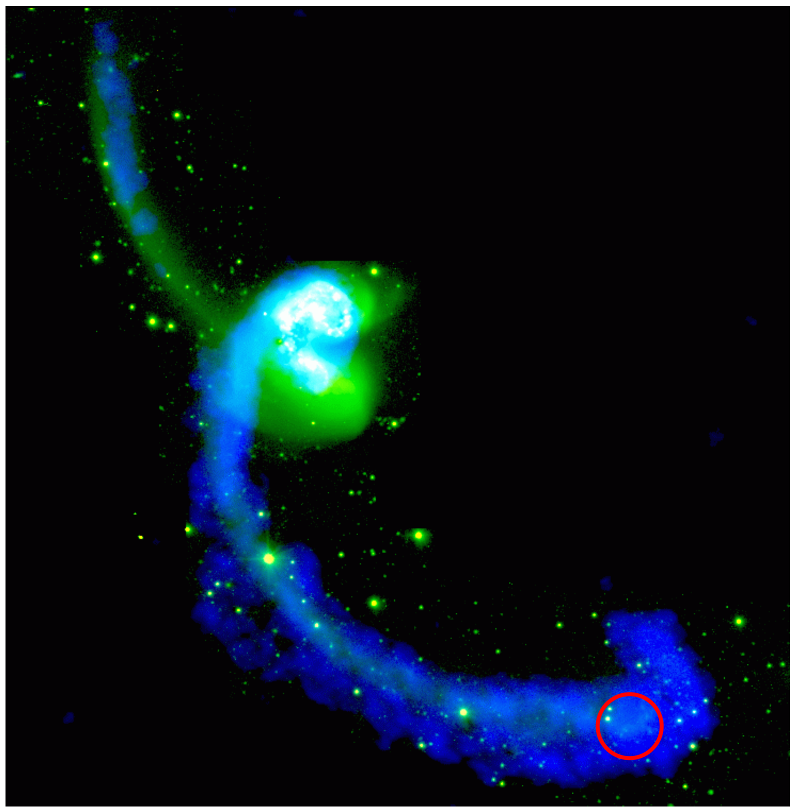
Outstanding Questions:

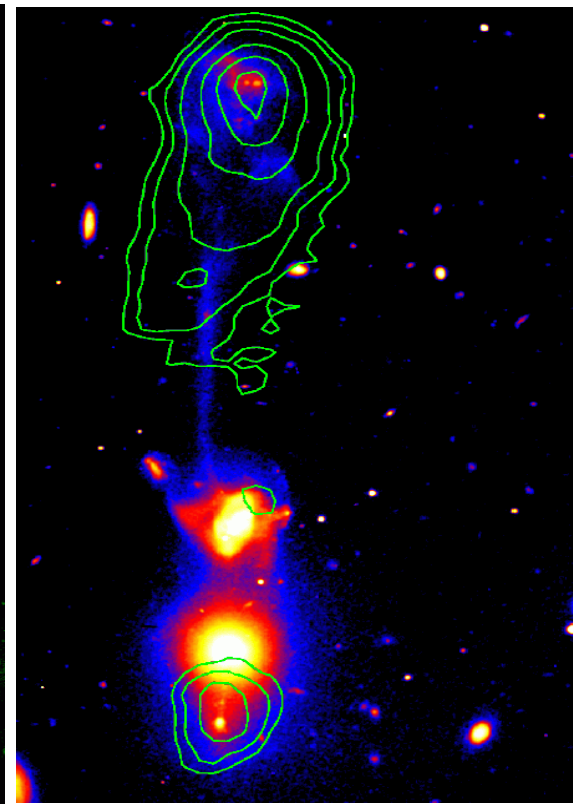
On what scales (if any) are these structures bound?

Is this an evolutionary sequence?

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







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

GALAXIES WITH LONG TAILS

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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 (Hα, [N II], [S II], and [O II] λ3727 lines on my spectrograms). The Hα fluxes are of the order of 100 times the Hα 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).

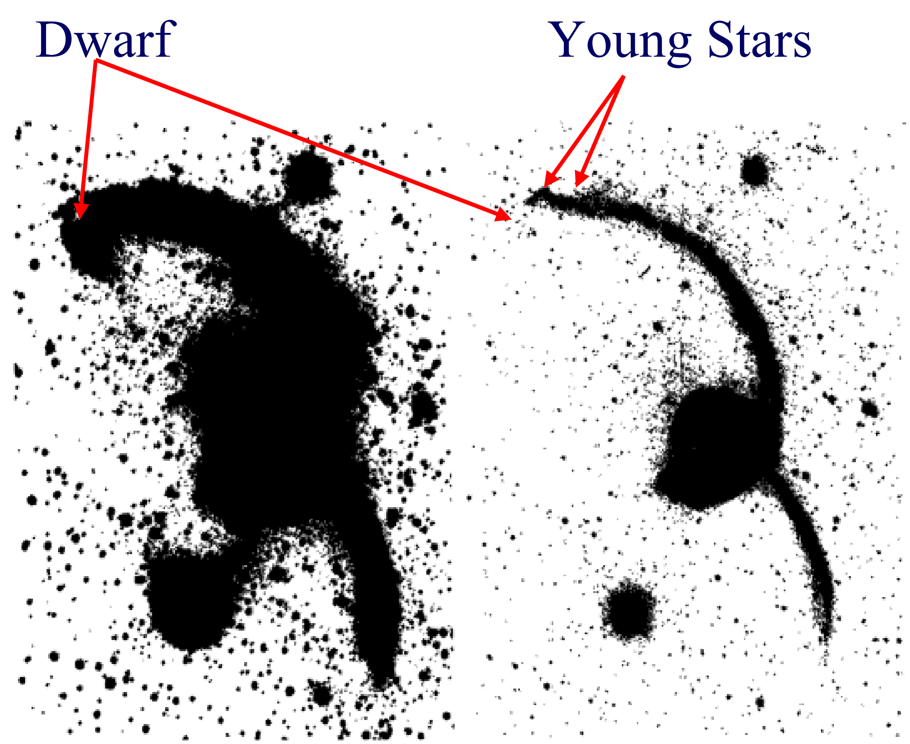

Figure 1. NGC 4038/9 on IIIa-J plates obtained with the CTIO 4-m telescope. North is at the top and east is at the left. (a) (left) Exposure of 50 minutes. (b) (right) Superposition print of two plates totalling 3.5 hours of exposure time. Note the dwarf stellar system near the tip of the southern tail.

Re-discovered in the early 1900's

Astron. Astrophys. 256, L19–L22 (1992)

ASTRONOMY AND ASTROPHYSICS

Letter to the Editor

Genesis of a dwarf galaxy from the debris of the Antennae

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Received December 5, 1991; accepted January 17, 1992

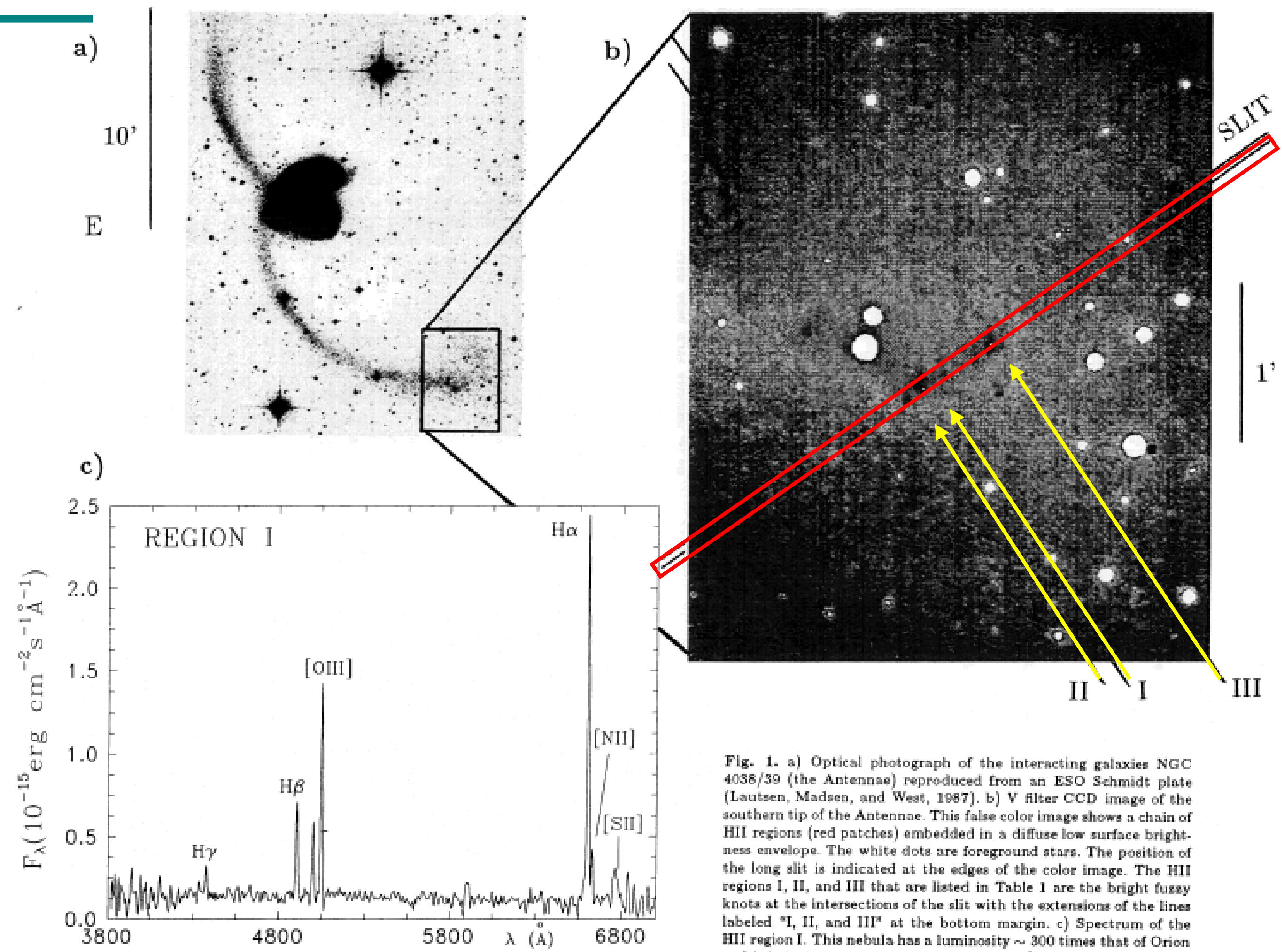


Fig. 1. a) Optical photograph of the interacting galaxies NGC 4038/39 (the Antennae) reproduced from an ESO Schmidt plate (Lautsen, Madsen, and West, 1987). b) V filter CCD image of the southern tip of the Antennae. This false color image shows a chain of HII regions (red patches) embedded in a diffuse 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

TDG "Rogues Gallery"

Arp 245: Duc et al. 2000
AM 1353-272: Weilbacher et al. 2000
Iglesias-Paramo & Vilchez 2001
NGC3860: Sakai et al. 2002
"Tadpole": Tran et al. 2002

See also the following posters:
Lopez-Sanchez et al., #275
Osterloo et al., #284
Temporin et al., #315
Van Driel et al., #324

UGC 10214 Star Clusters

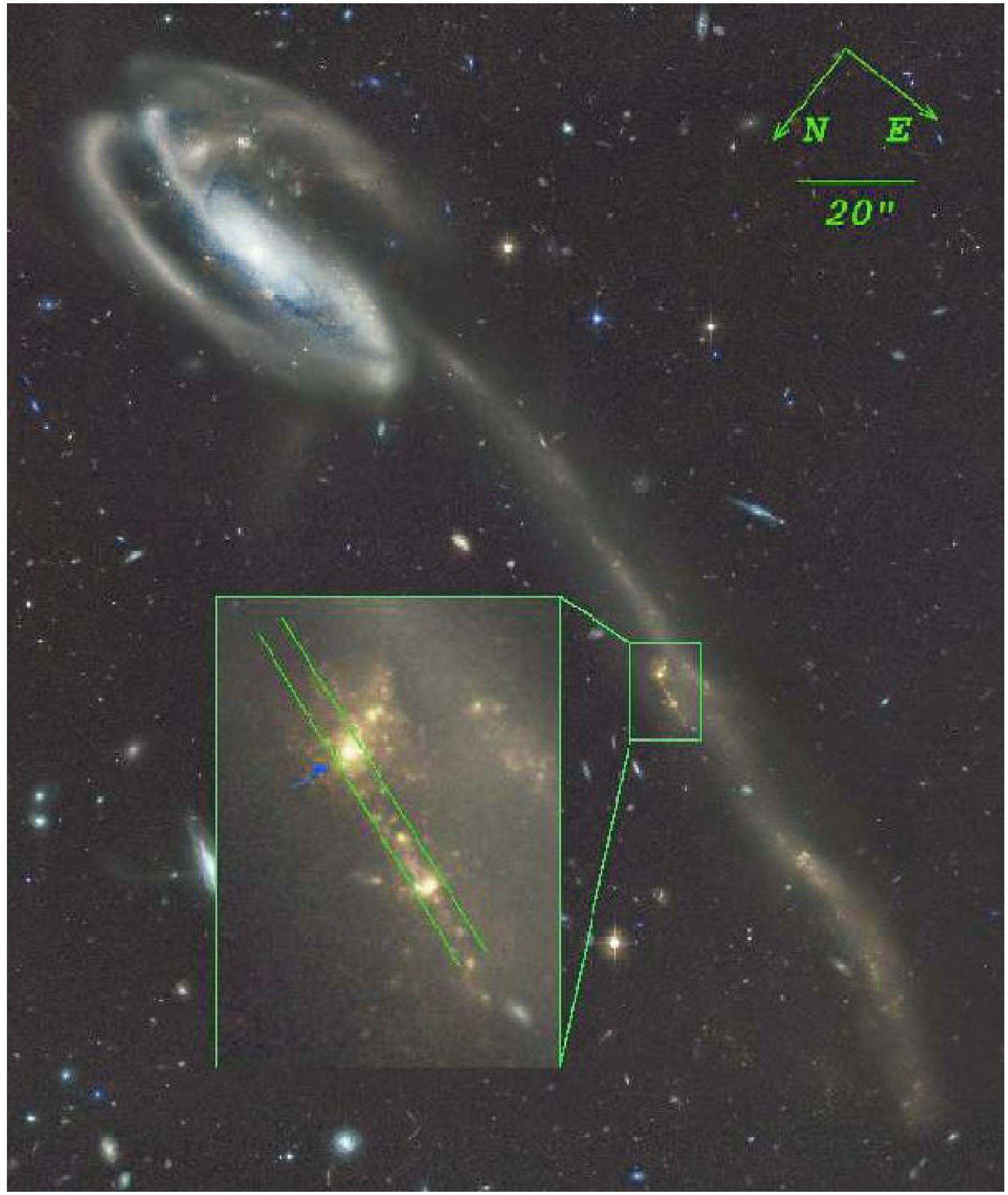
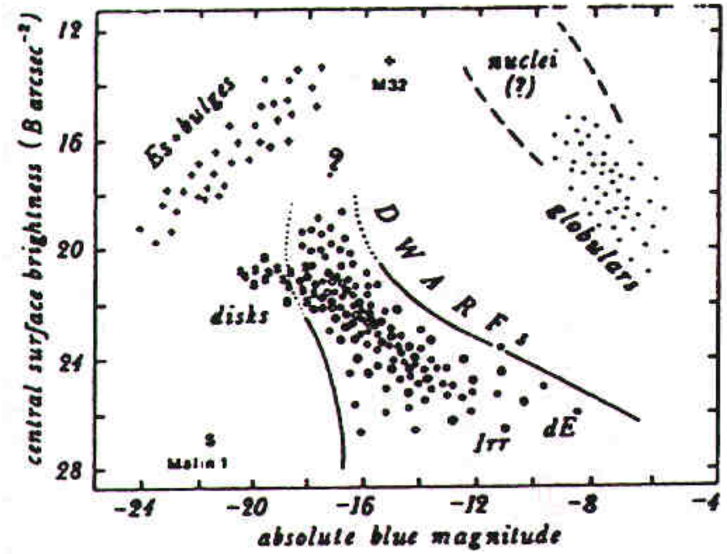


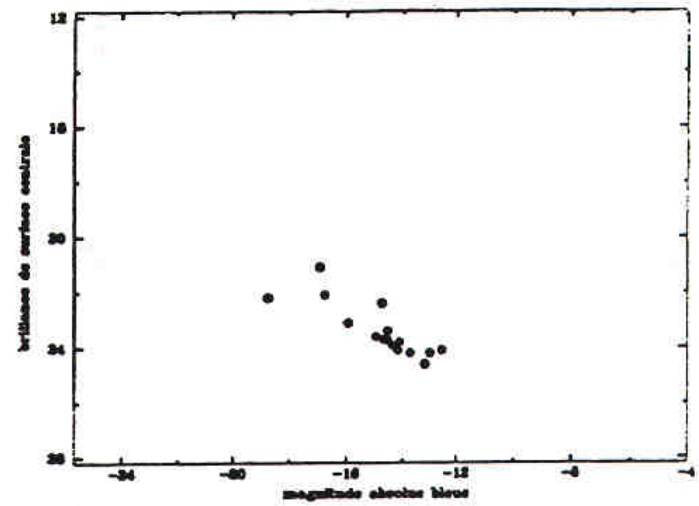
FIG. 1.— Composite g, V, and I color image of UGC 10214, with a close-up of the bright blue clump in the tail. The brightest stellar knot marked by the red arrow is a probable super star cluster (SSC). Parallel lines indicate the slit width and orientation used in the Keck spectroscopy.

Properties similar to other dwarfs…

- But more metal rich

Duc, 1995, PhD Thesis Univ. Paris





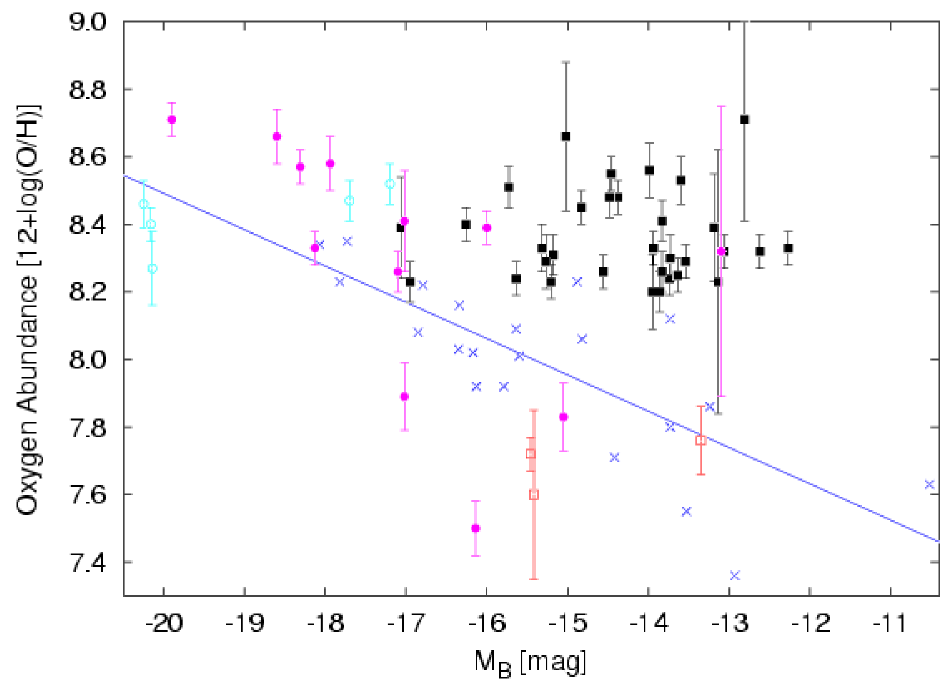
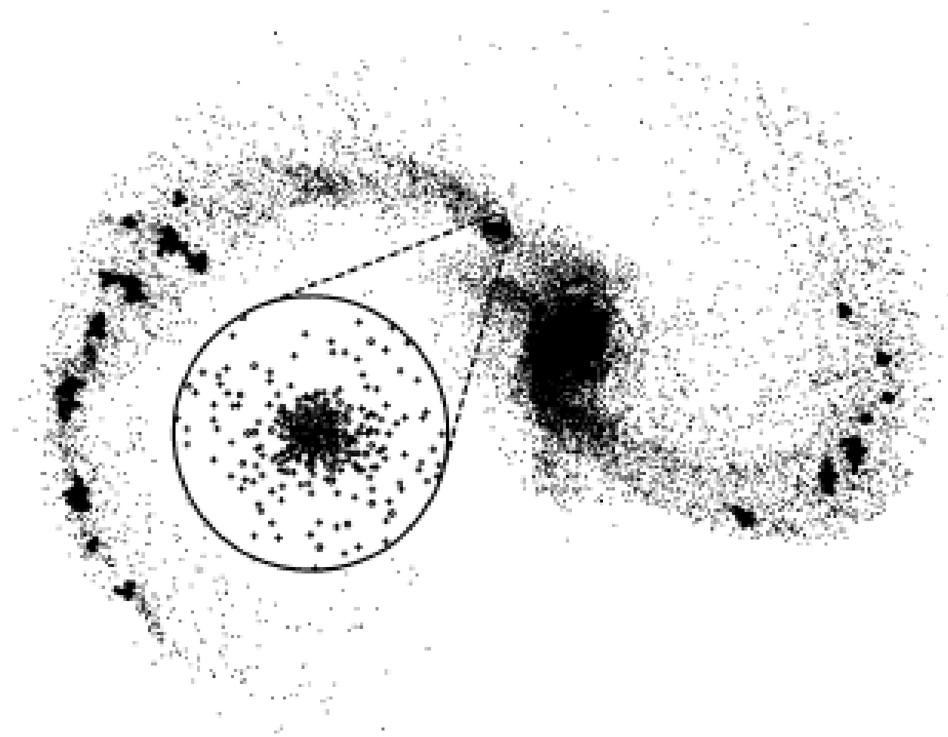


Fig. 3. Metallicity-luminosity relation for different types of objects: local isolated dwarf galaxies (crosses), knots the tidal features (filled/open squares), main group members (filled circles), background objects (open circles).

Weilbacher et al. 2003

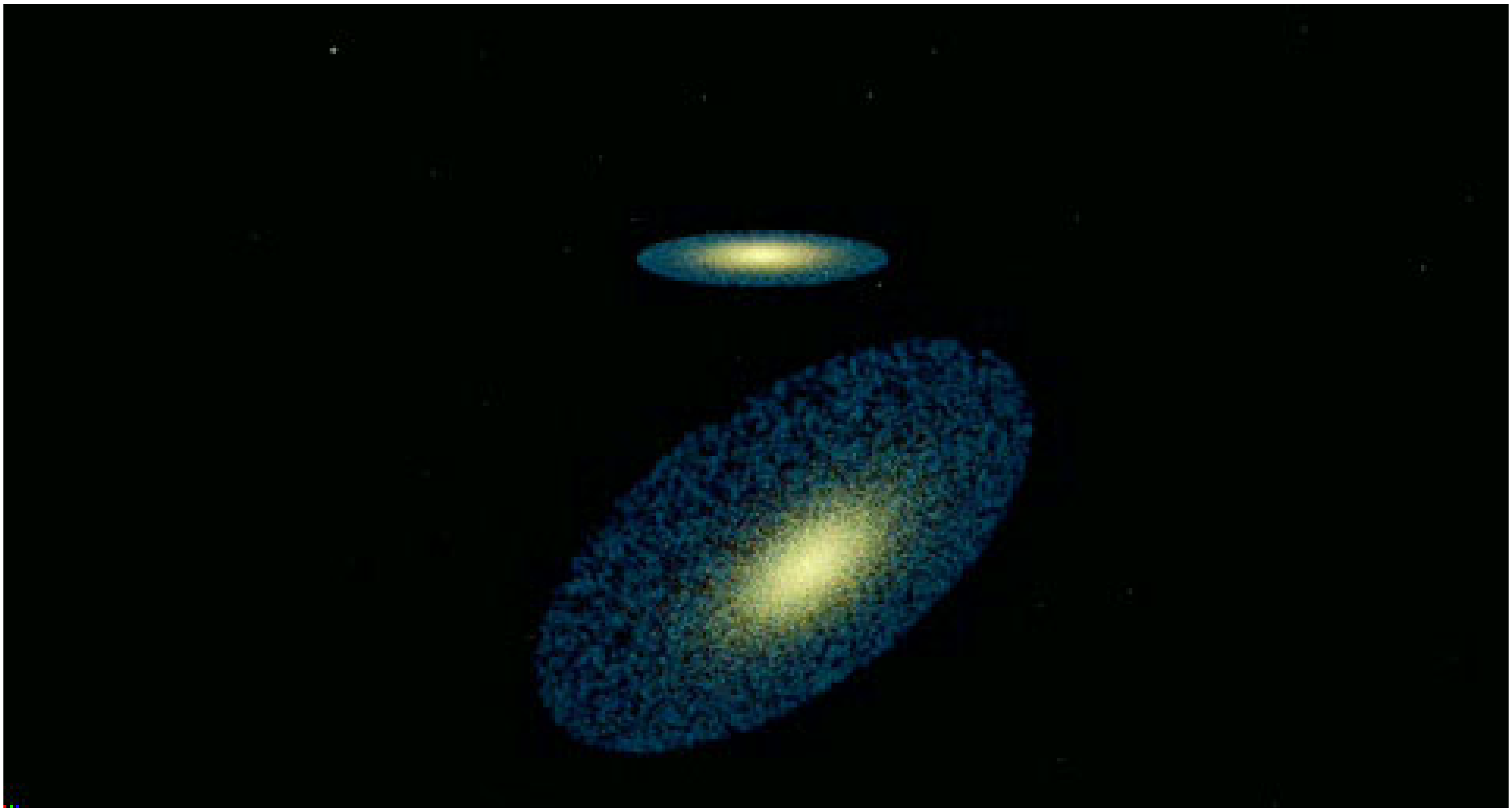
Formation of Self-gravitating Condensations within Tidal Debris supported by Theoretical Work

- Barnes & Hernquist, 1992, Nature: Swing amplification of statistical noise due to N-body nature of simulation
- Postulate that real disks might have similar "noise" (star clusters, GMCs)
- Clumps form primarily from disk material. Very little dark matter
- Largest clumps can be gas rich, but smallest are gas poor (T_{gas}~10^4 K)



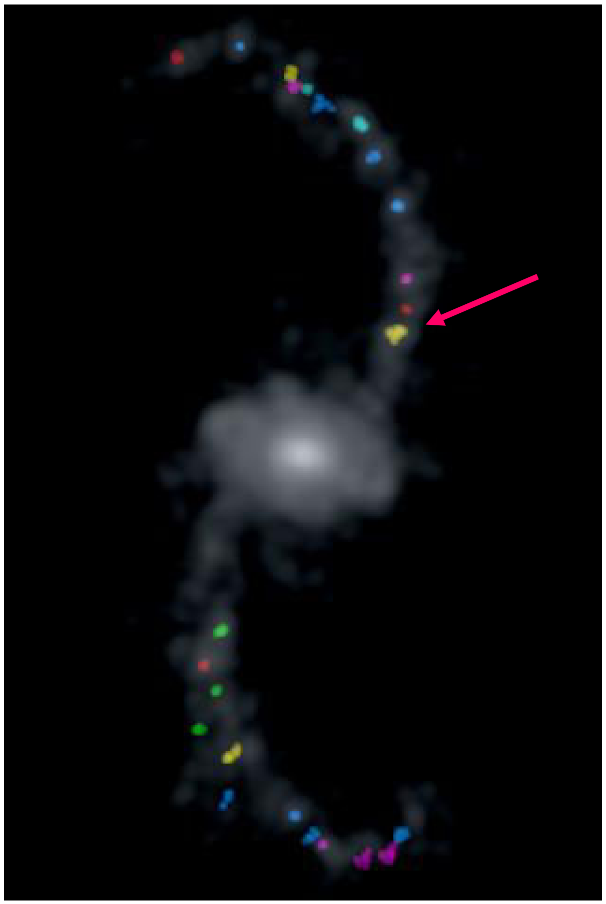
Barnes & Hernquist, 1992, Nature, 360, 715

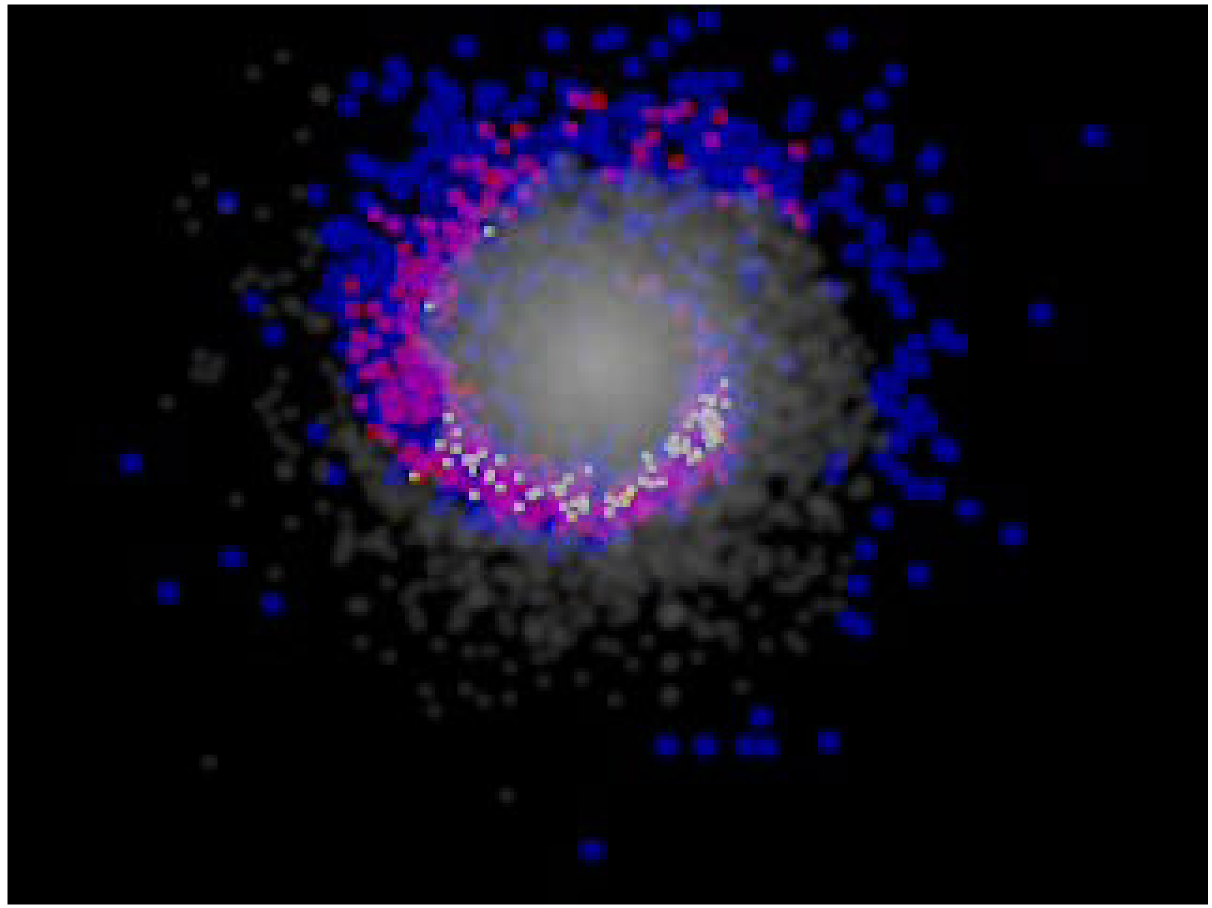
Formation of Self-gravitating Condensations within Tidal Debris supported by Theoretical Work



From Mihos, 2001, ApJ, 550, 94

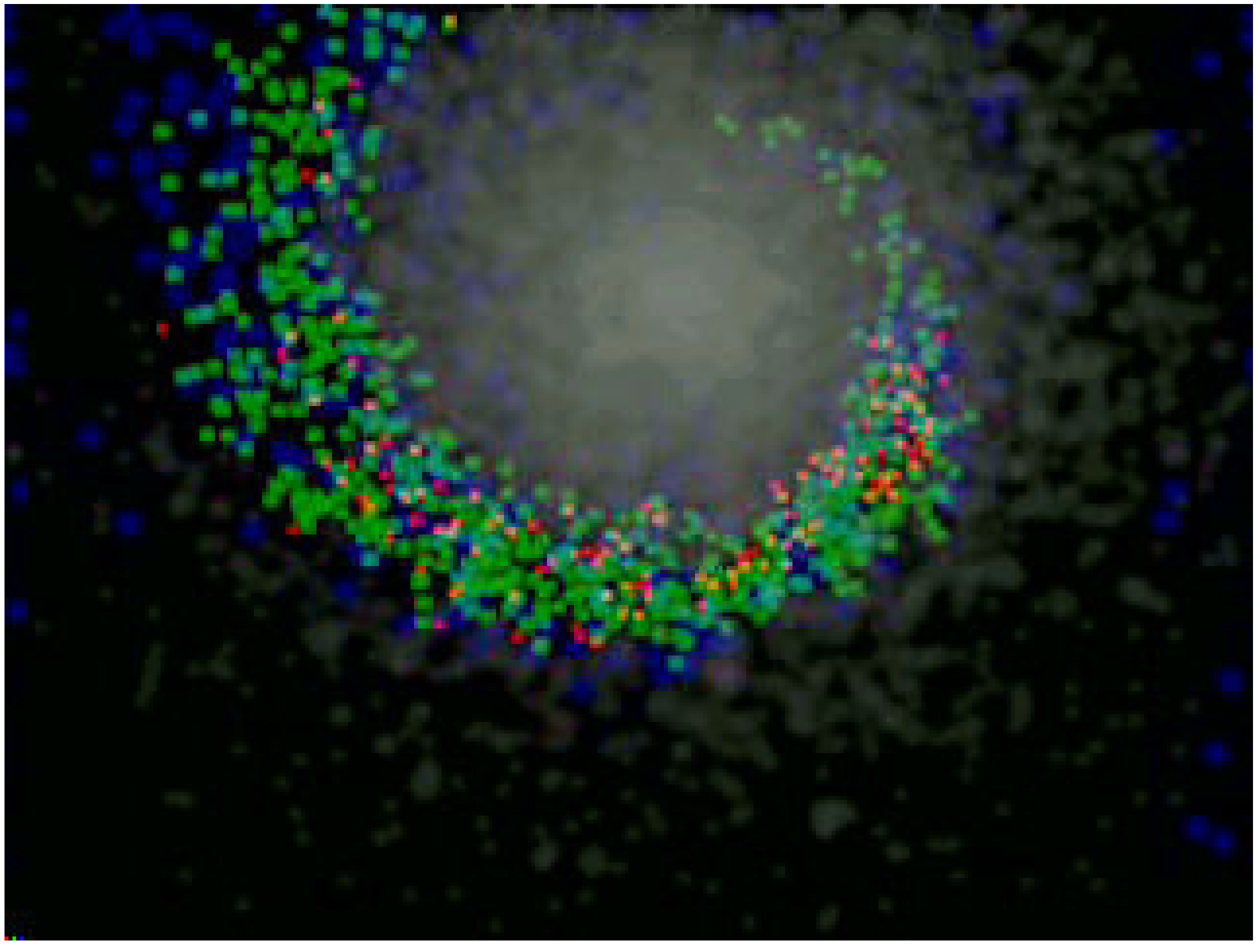
Formation of Self-gravitating Condensations within Tidal Debris supported by Theoretical Work





From Barnes, 2003, in preparation

Formation of Self-gravitating Condensations within Tidal Debris supported by Theoretical Work



From Barnes, 2003, in preparation

Elmegreen, Kaufman & Thomasson, 1993, ApJ:

- Increased Jeans mass in tidally agitated disk
- Dispersion increased, so internal energy is increased, requiring large mass to bind it
- However: Jeans mass is minimum mass that may collapse; doesn't say that there will be mass condensations that large.

THE ASTROPHYSICAL JOURNAL, 412:90–98, 1993 July 20
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AN INTERACTION MODEL FOR THE FORMATION OF DWARF GALAXIES AND $10^8\ M_\odot$ CLOUDS IN SPIRAL DISKS

B. G. ELMEGREEN,[1] M. KAUFMAN,[2] AND M. THOMASSON[3]
Received 1992 June 1; accepted 1993 January 29

In either case, the mass of the primary object that forms is about the local Jeans mass, which, in a disk, is

$$M_J \approx \mu\left(\frac{\lambda}{2}\right)^2 = \frac{\hat{\sigma}^4}{G^2\mu} \quad (1)$$

for a fastest growing wavelength

$$\lambda \approx \frac{2\hat{\sigma}^2}{G\mu} \quad (2)$$

and a fastest growing time scale

$$\tau \approx \frac{\hat{\sigma}}{\pi G\mu}\,. \quad (3)$$

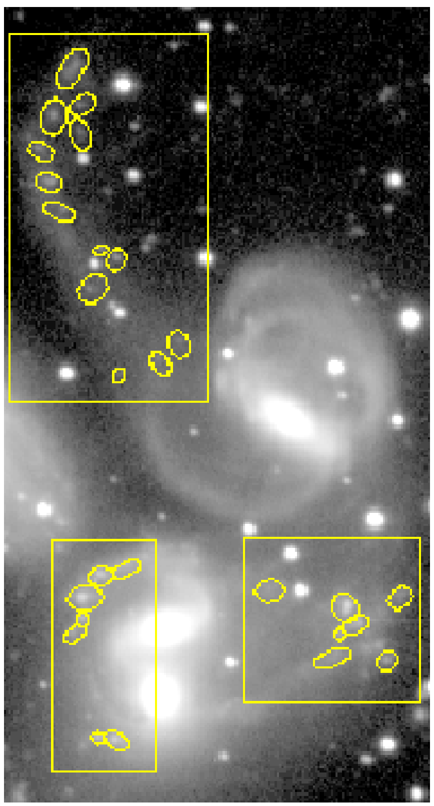
Here μ is the mass column density in the disk, and $\hat{\sigma}$ is the effective velocity dispersion.

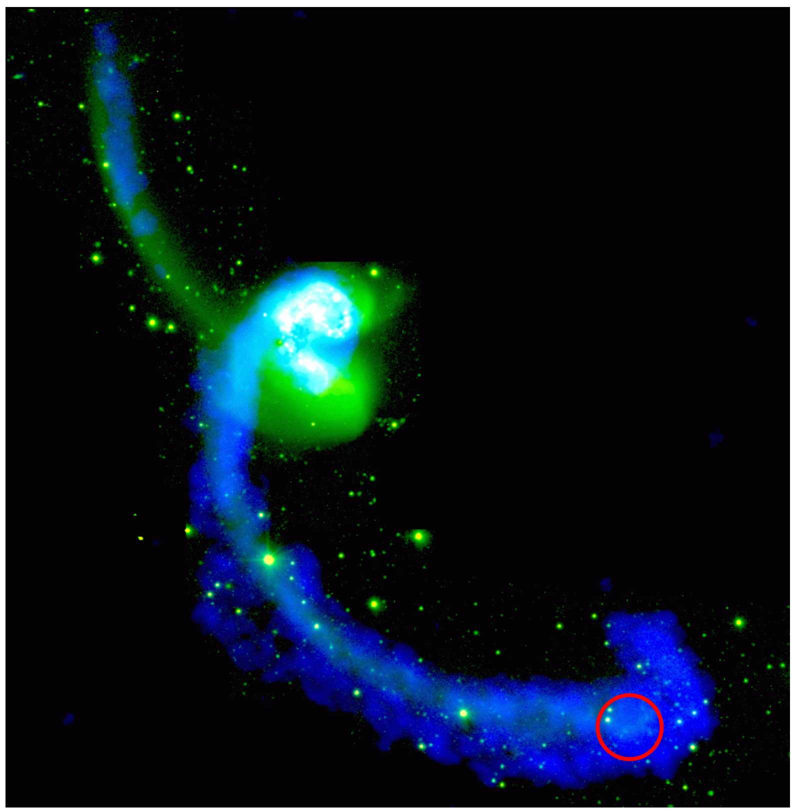
The velocity dispersion used here is $\hat{\sigma} \approx (\gamma_{eff}\sigma^2 + v_A^2)^{1/2}$ for an effective ratio of specific heats $\gamma_{eff} \approx 0.3$ (Cowie 1981; Elmegreen 1991) and for an Alfvén speed v_A of the uniform magnetic field component that is transverse to the collapse. In our Galaxy the Alfvén speed for the uniform component of the magnetic field is comparable to or slightly less than the velocity dispersion, but it could be much less in perturbed galaxies if the turbulent velocity dispersion increased because of the collision while the uniform component of the magnetic field has to wait for a dynamo to operate. The important point here is that a small increase in the velocity dispersion changes the Jeans mass by a large factor; for example, from a typical value of $\sim 10^7\ M_\odot$ for $\hat{\sigma} \approx 10$ km s^{-1} and $\mu = 30\ M_\odot$ pc^{-2} to 10^8 or $10^9\ M_\odot$ for $\hat{\sigma} = 15$ km s^{-1} or 30 km s^{-1}, respectively.

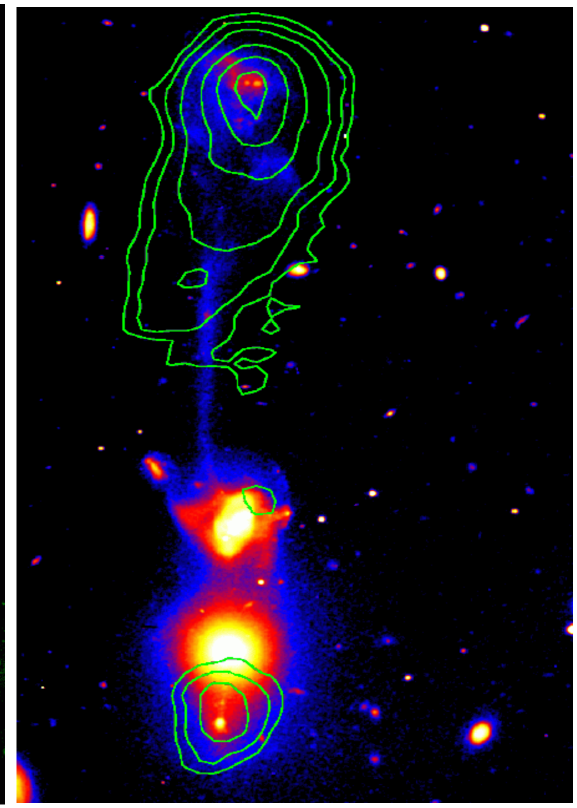
It is common to call any enhancement a TDG or TDG candidate.

The presumption is that this represents an evolutionary sequence

Form... ⇨ Grow... ⇨ Ejected...







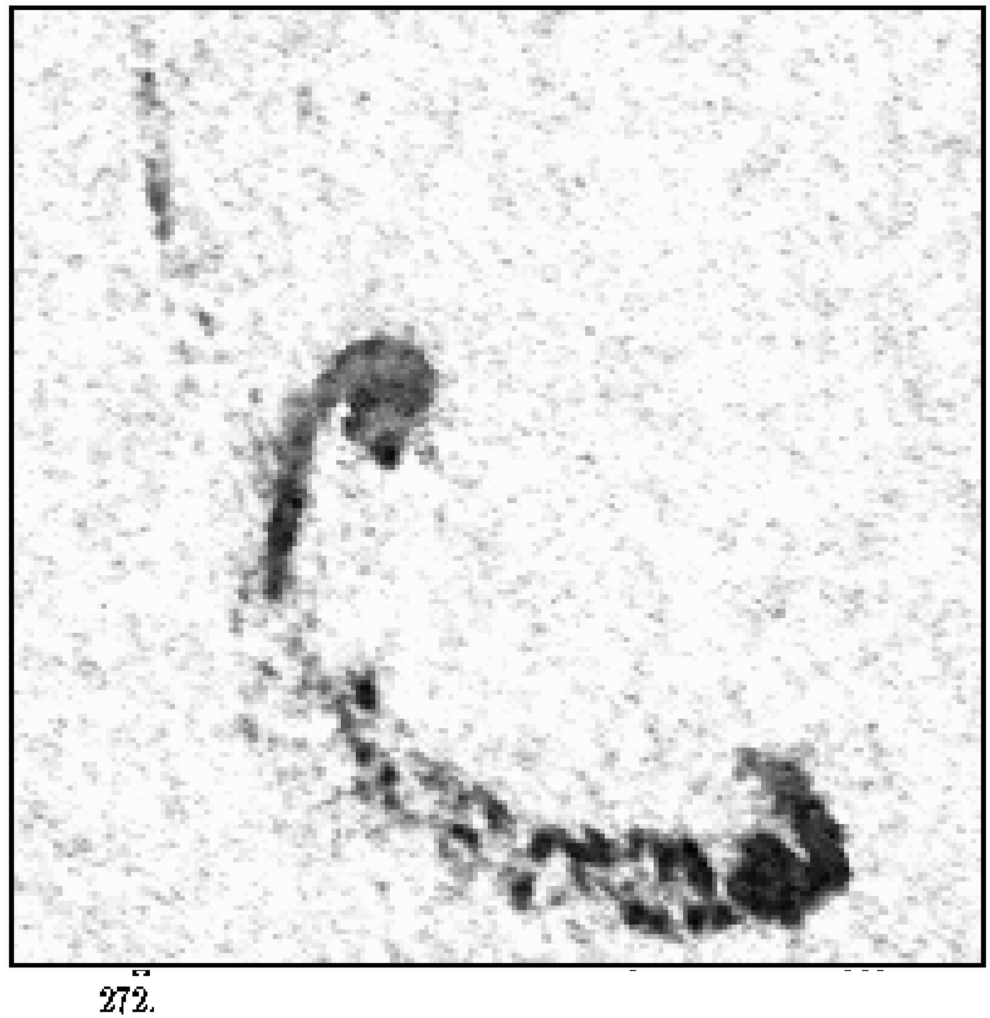
Questions to be addressed:

- Are there bound gaseous precursors to optical condensations?
- Are TDGs bound by baryons alone?
- Can the physical properties of tidal substructures be accurately derived?
- Do Super Star Clusters (SSC) occur within tidal tails?

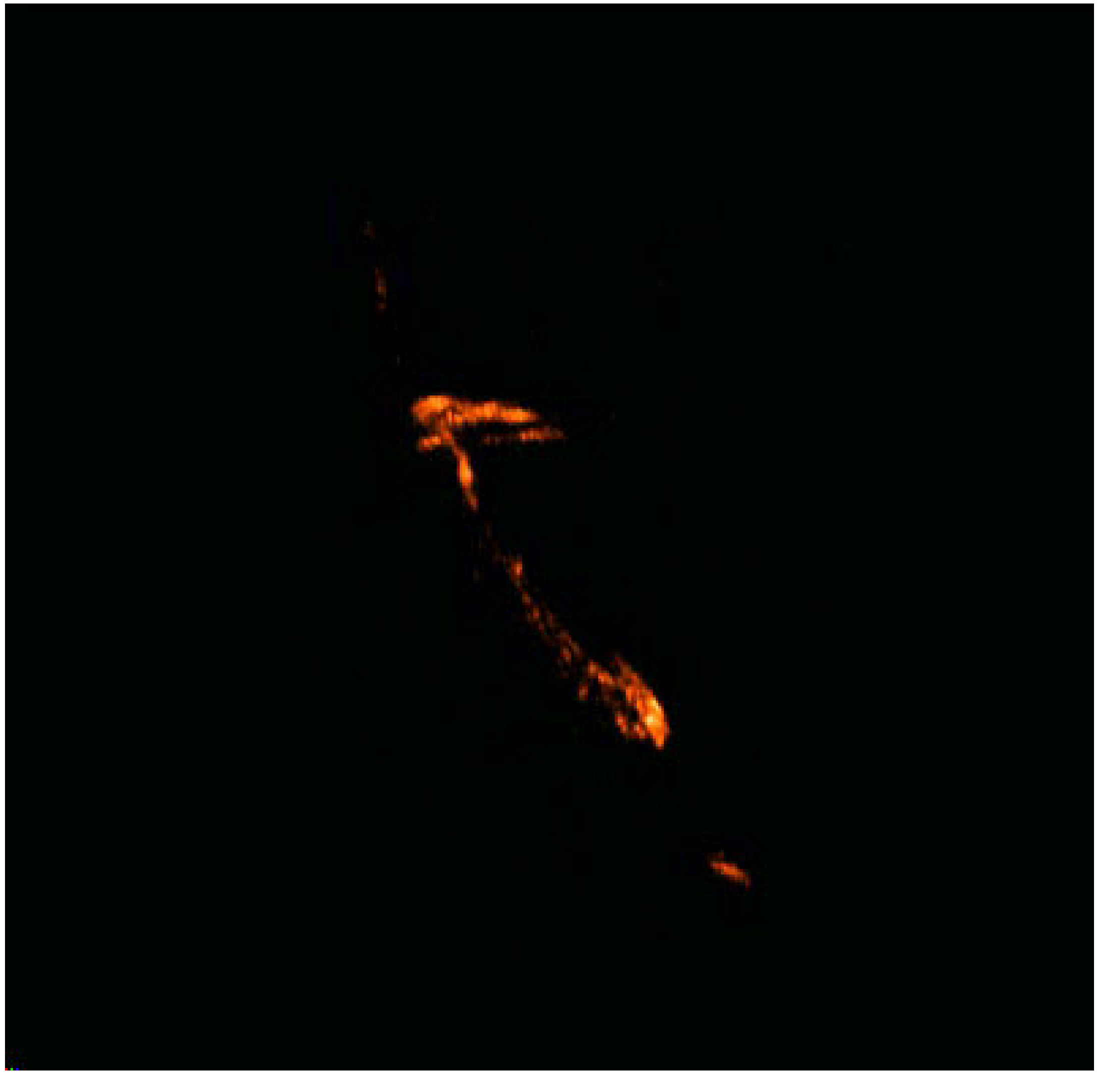
Under many TDG evolutionary scenarios, optical TDGs should have gaseous precursors

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

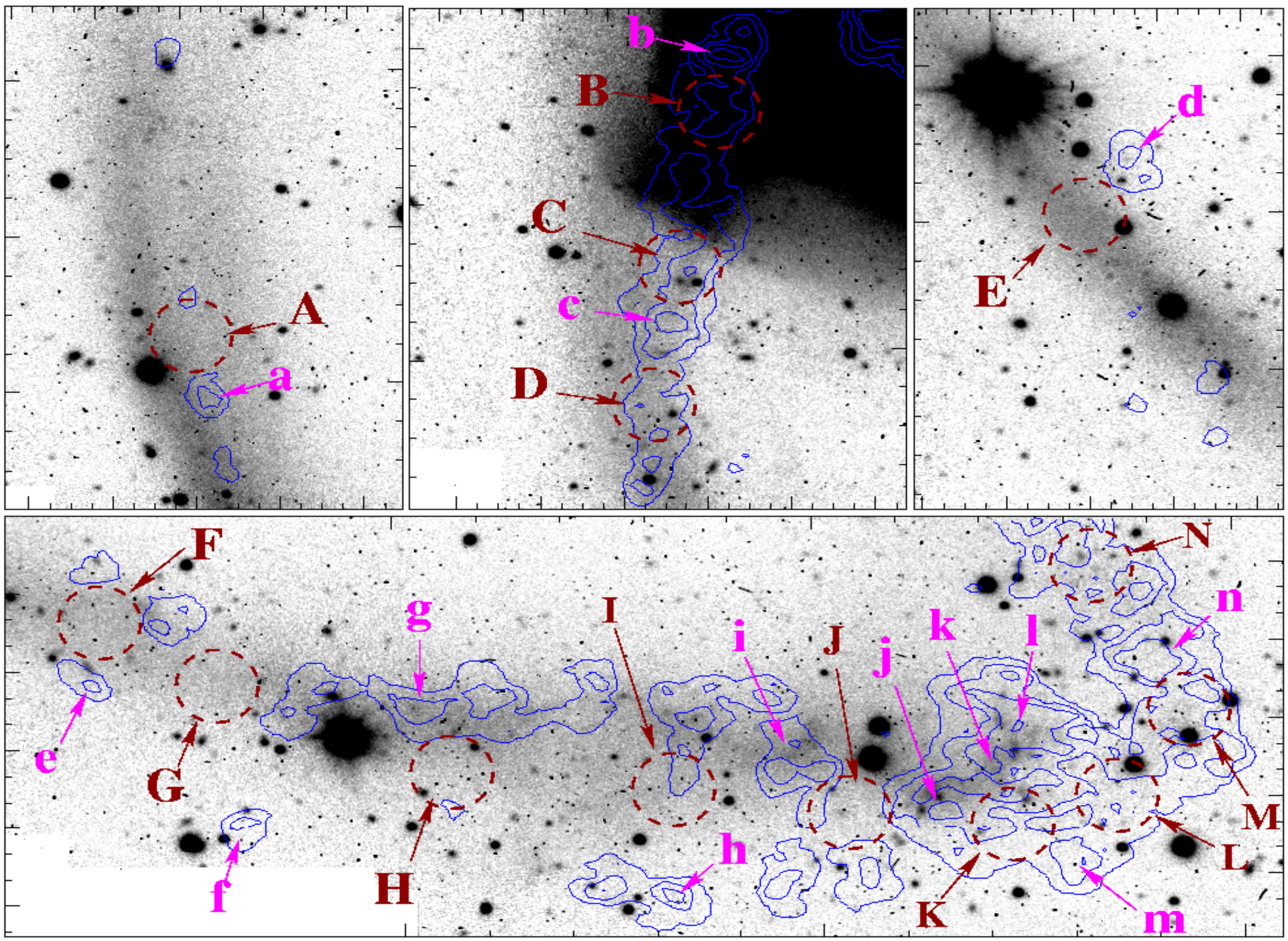
VLA observations of NGC 4038/9: Hibbard, Barnes, van der Hulst & Rich, 2001



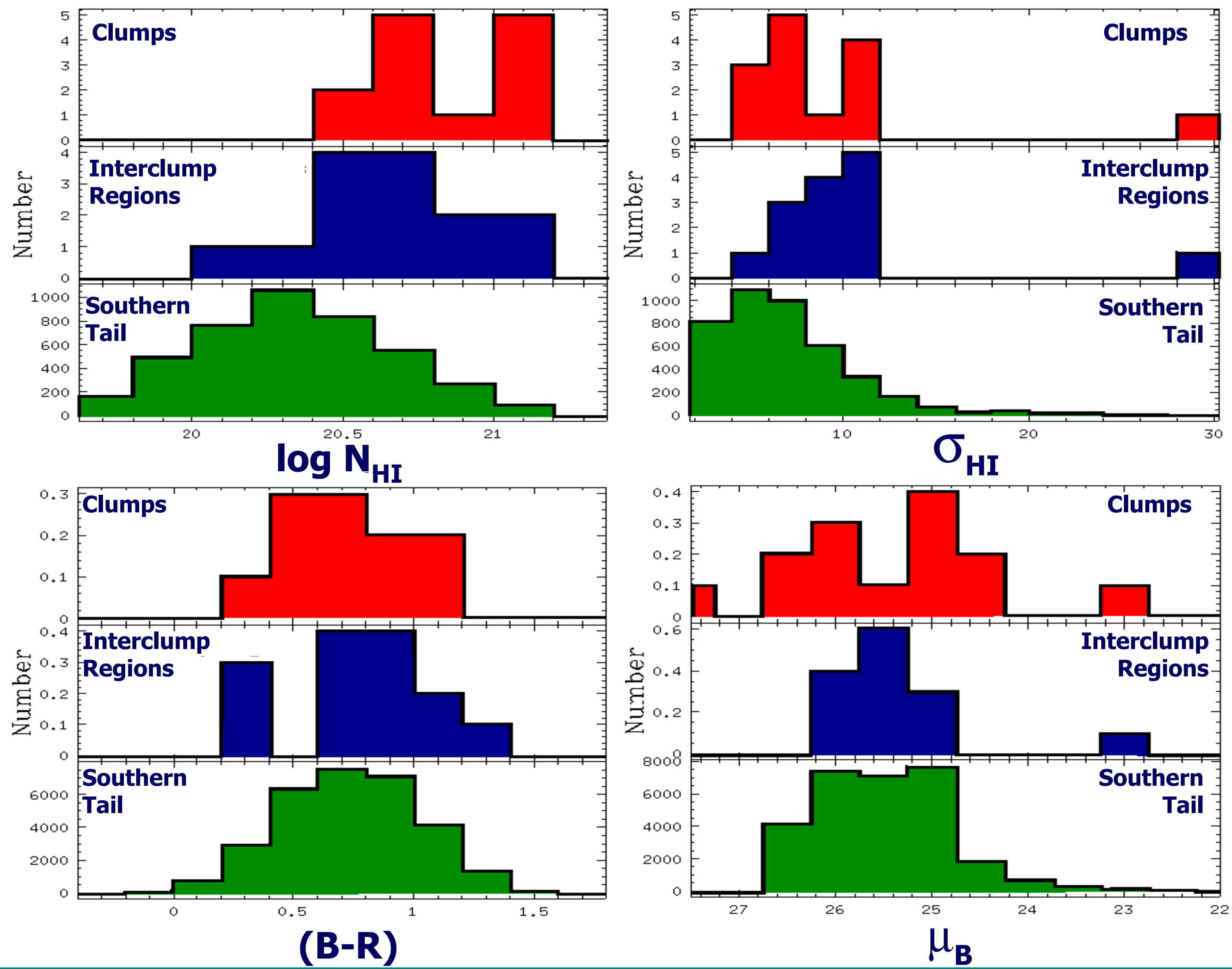
HI observations reveal a wealth of structure within the tails. (resolution ~10"-20", Δv=5.2 km/s)



Identified clumps in tails with contrast of 2 from surrounding material, and with S/N>6 Also Identified an equal number of "interclump" regions



Clumps do not distinguish themselves from interclump region in terms of optical or HI properties



Dynamical Analysis: Is there enough mass in gas and stars to make clumps bound?

- $2T = -U$

  $3\sigma_{HI}^2 = G M_{vir}/(aR_{1/2})$

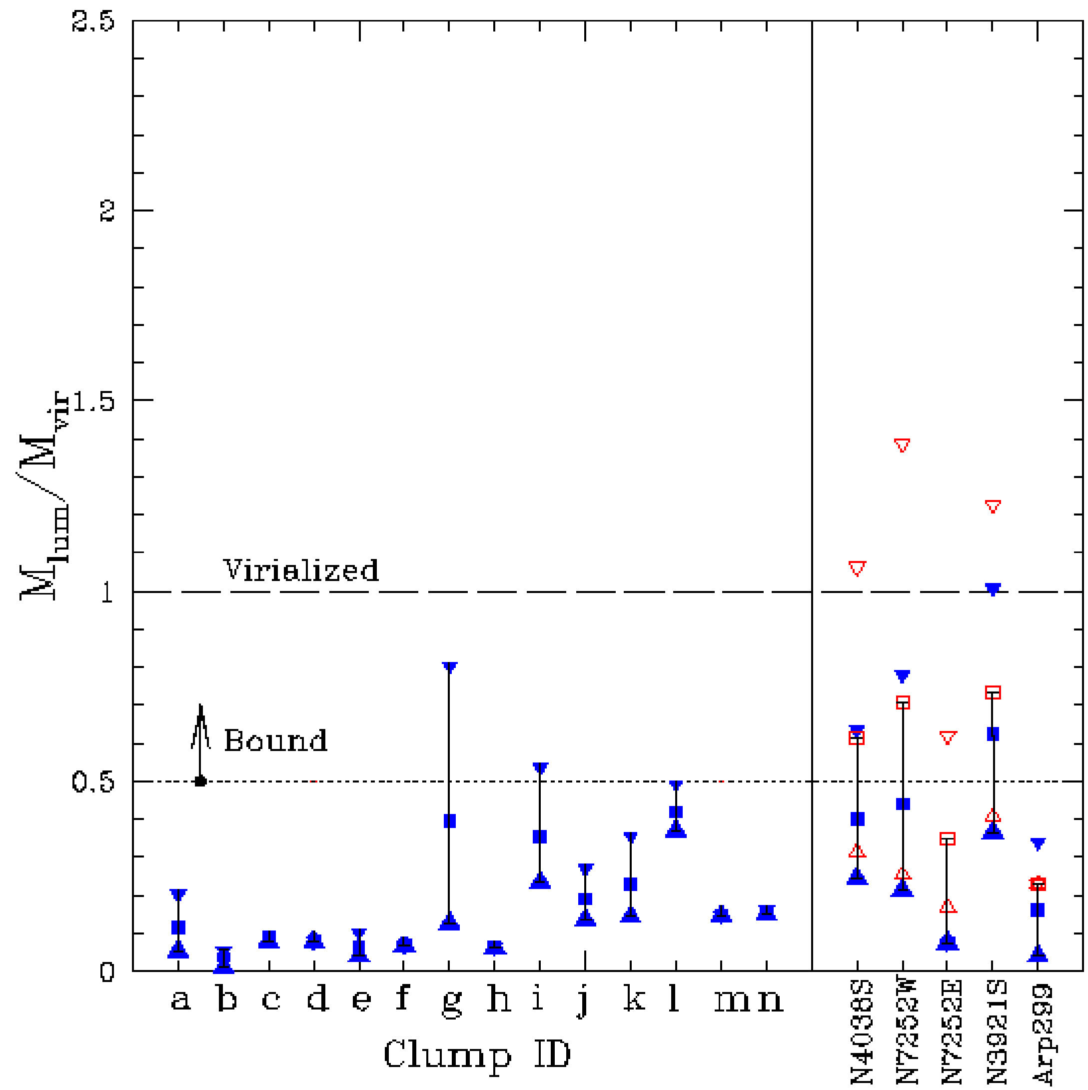
  $M_{vir} = 1.91\times10^6\ \sigma_{HI}^2 R_{1/2}$
- $M_{gas}=1.36M_{HI}$
- $M_{stars}=(M_*/L_B) * L_B$

▲ $M_*/L_B=0$

■ $M_*/L_B=2$ const SFH, 10 Gyr

▼ $M_*/L_B=5$ exp SFH, 10 Gyr

- filled symbols = foreground & background subtraction



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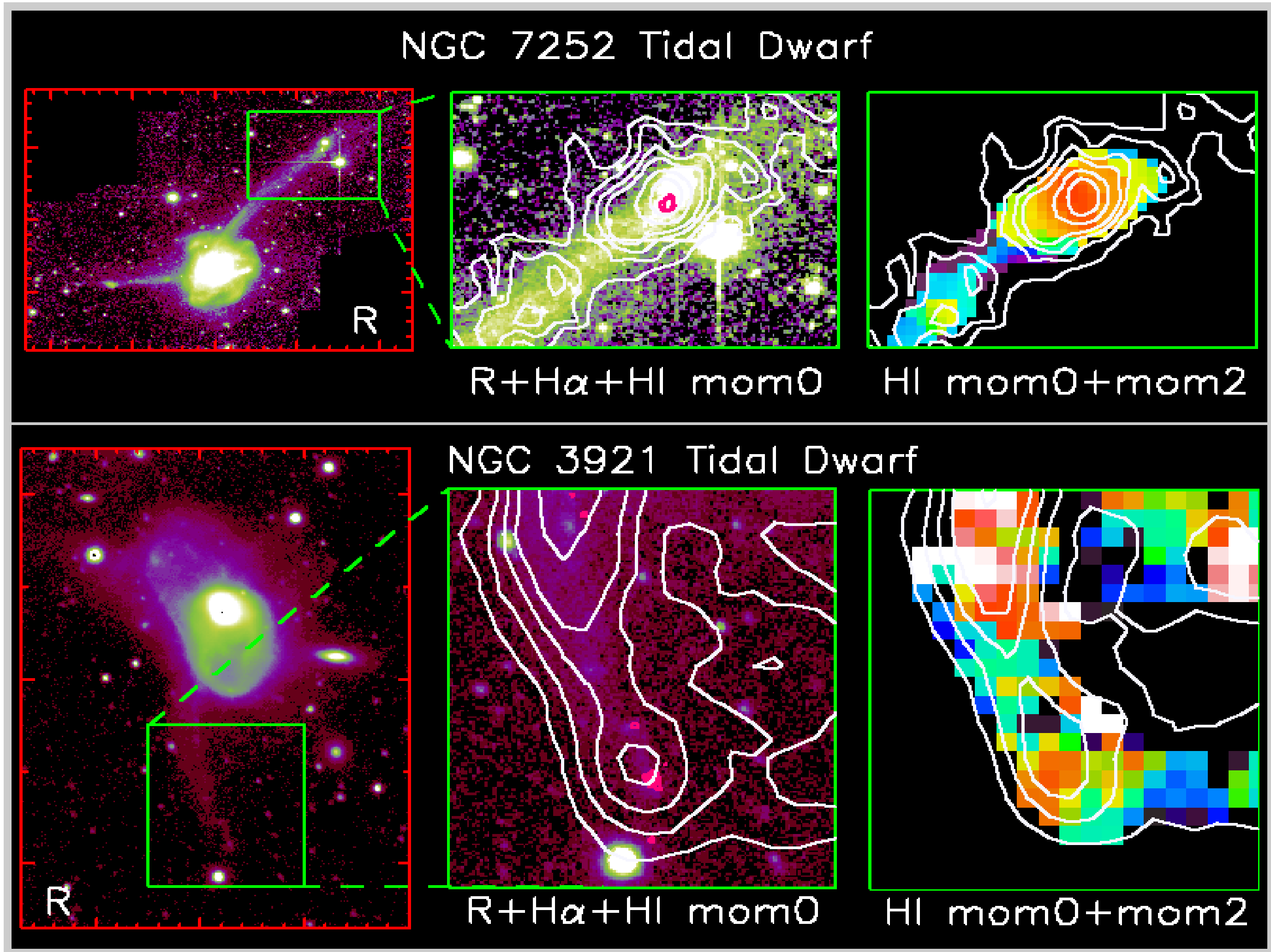
NGC 7252, NGC 3921: Concentration of gas, young stars, HII regions coincide with increased HI velocity width.

If bound, then $M/L \sim 4\text{-}6$; $M_{vir}/M_{baryons} \sim 2$

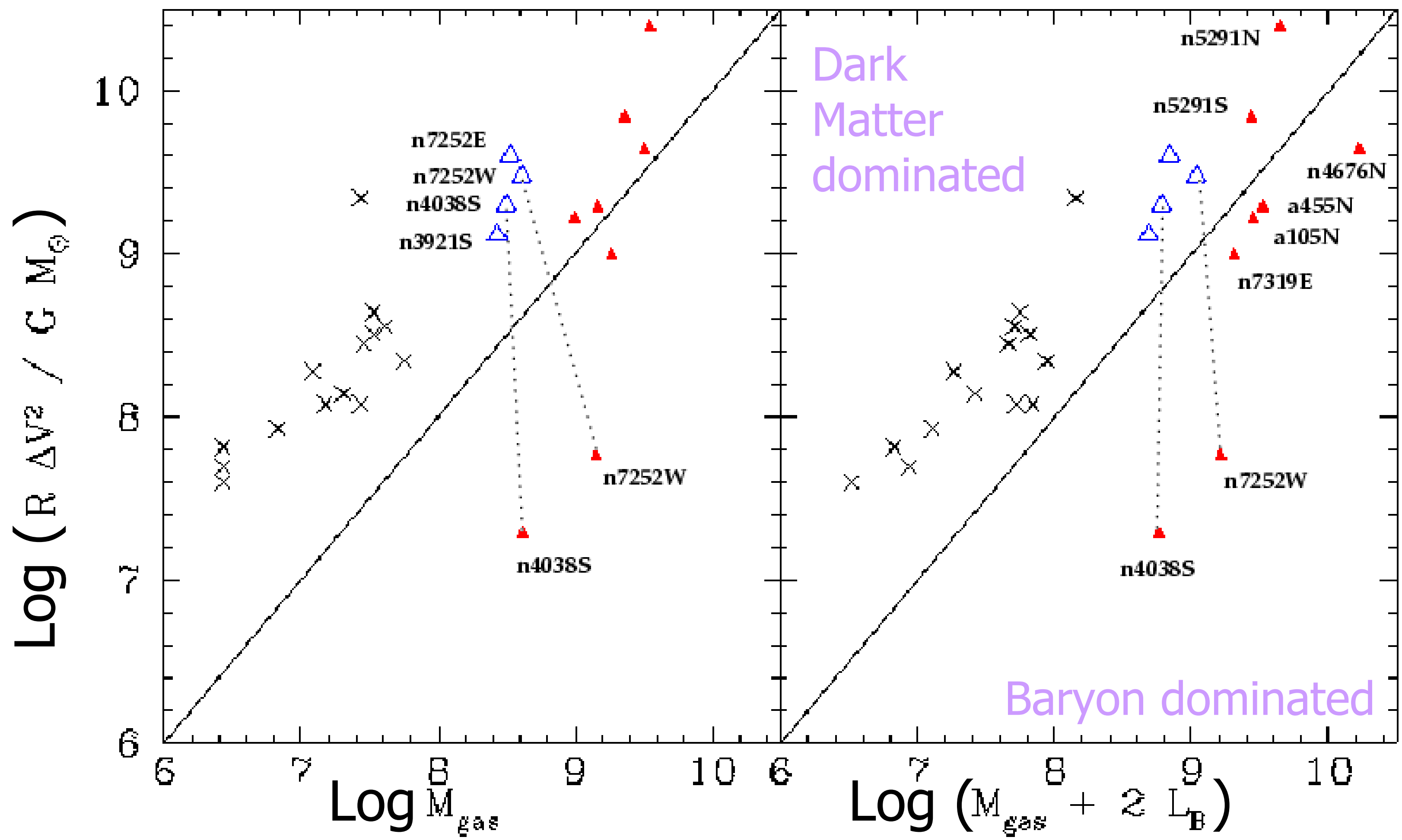
See also: Temporin et al. 2003 (poster #315) Mendes de Oliveira et al. 2001 ($M/L \sim 5\text{-}17$)

Expect $M/L<2$ for disk (especially in light of observed HII regions)



Hibbard et al. 1994, Hibbard & van Gorkom 1996

For reasonable M_*/L, clumps and TDG candidates require significant dark matter to be self-gravitating



X's = clumps in S. tail of NGC 4038

Blue points from Hibbard et al., in preparation

Red points from Braine et al. 2001, A&A, 378, 51

Elmegreen, Kaufman & Thomasson, 1993, ApJ:

- The condensations they point to are very dark matter dominated

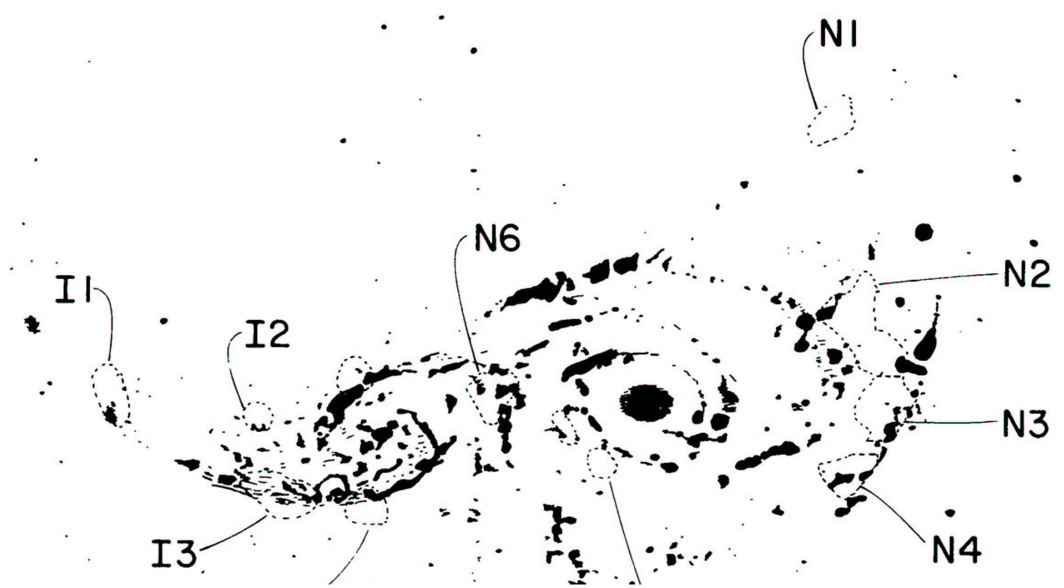


TABLE 1

GIANT H I CLOUDS IN IC 2163 AND NGC 2207

Galaxy	Cloud	Cloud Mass ($\times 10^8\ M_\odot$)	Box Area (square arcsec)	$\langle N(\text{H I})\rangle$ ($M_\odot$ pc^{-2})	$\langle\sigma\rangle$ (km s^{-1})	M_{jeans} (M_o)	M_{jeans}/M_{HI}
NGC 2207	1	7.7	1290	21	56	2.8E10	36
	2	10	1190	29	49	1.2E10	12
	3	5.5	648	29	41	6E09	11
	4	3.9	504	27	40	6E09	15
	5	3.8	504	26	40	6E09	16
	6	4.6	576	28	46	5E09	11
IC 2163	1	1.8	315	20	19	4E08	2
	2	1.4	270	18	55	3E10	21
	3	2.6	486	19	50	2E10	8
	4	1.0	180	19	34	4E09	40

Recent Observations show drastic kinematical gradients across candidates

- Optical emission lines (Hα, Hβ, [OIII])
- Gradients of 100's km/s across 1-2 kpc
- Not all appear to be a locations where tail is bending back along line-of-sight
- Inferred dynamical masses up to 10^{10} M_o
- Implies $M/L_B \sim$ 100-200 M_o/L_o

See also: Temporin et al, Poster #315; Lopez-Sanchez et al. Poster #275

Weilbacher, Duc, Fritze-v.Alvensleben 2003, A&A

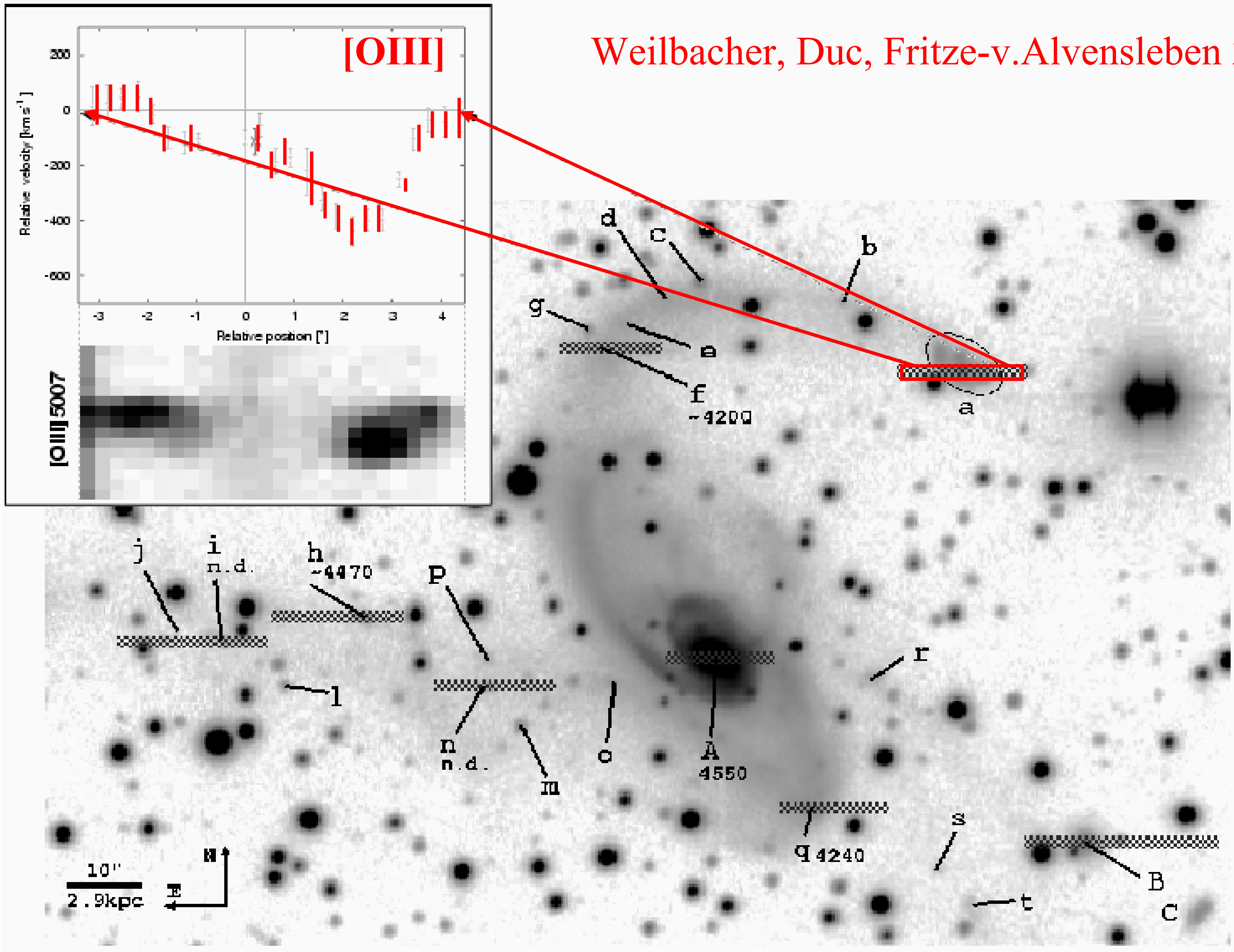
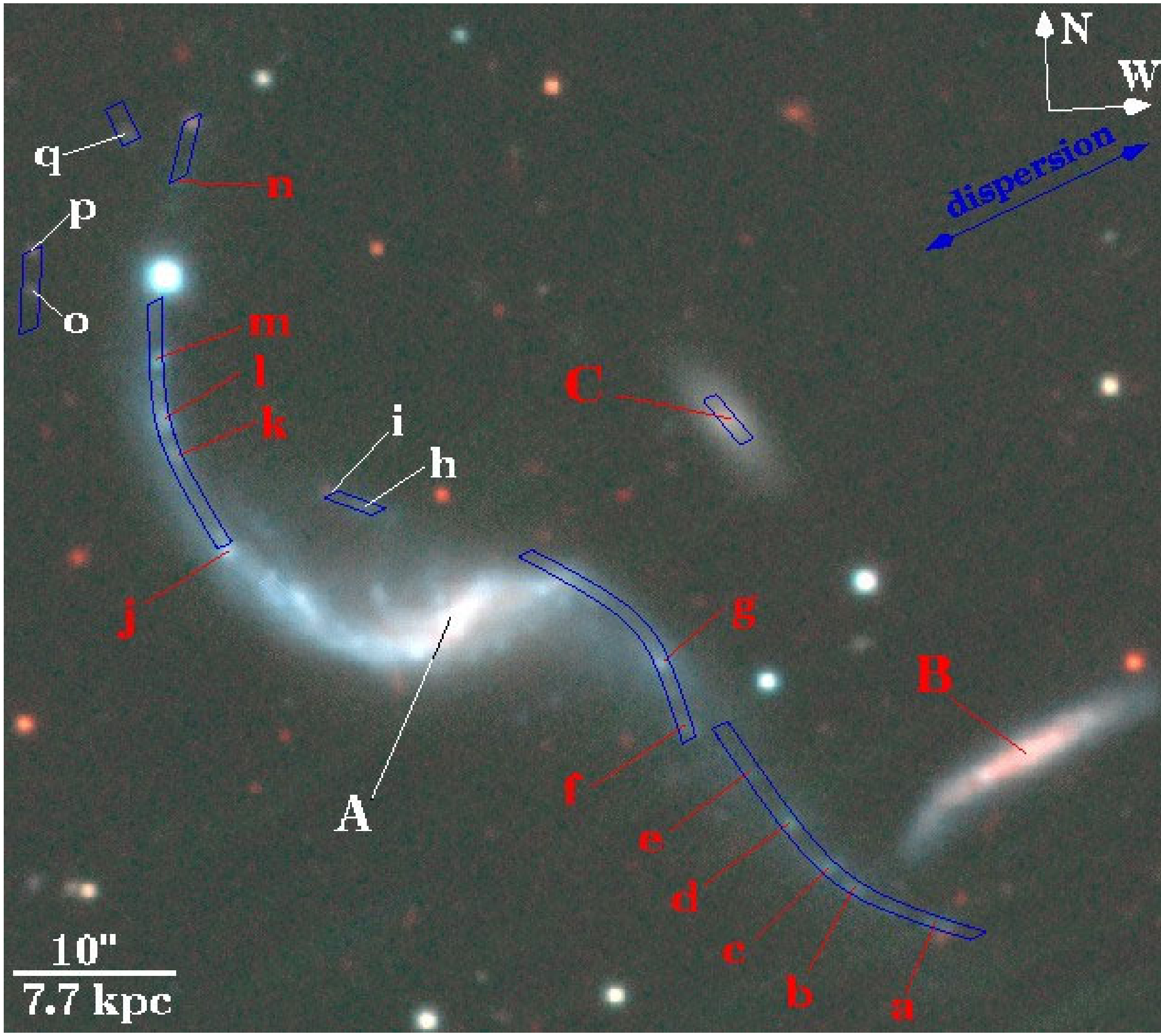
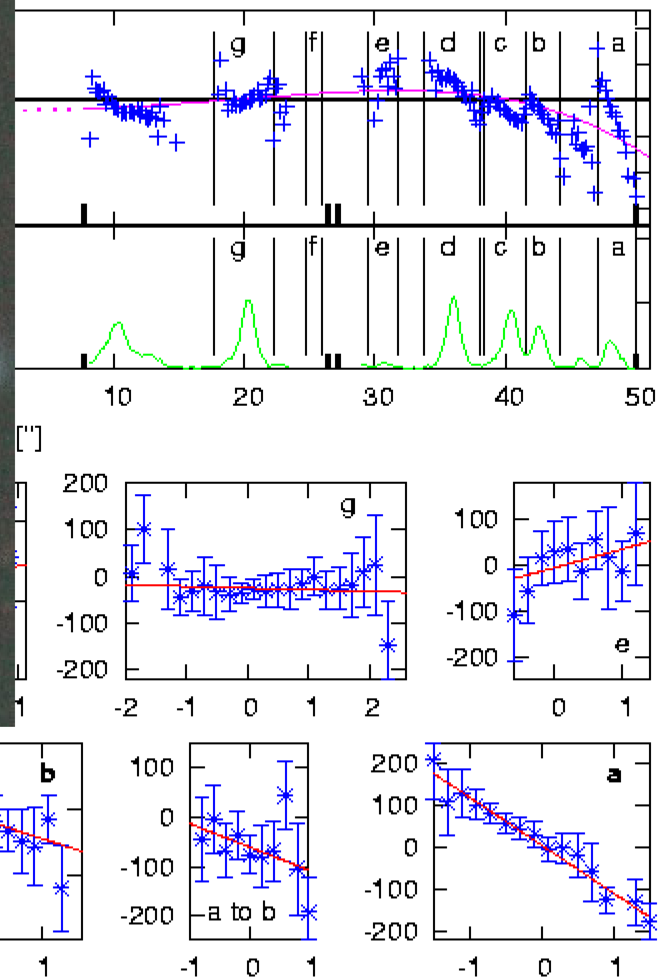


Fig. 2. Velocity curves along the tidal tails of the interacting system AM 1159-530. The large velocity gradient at the tip of the western tail probably indicates the presence of a forming Tidal Dwarf Galaxy. (Weilbacher et al. 2002)

"Dentist Chair" Galaxy



Weilbacher et al. 2002, ApJ



Velocities from Hβ

Questions to be addressed:

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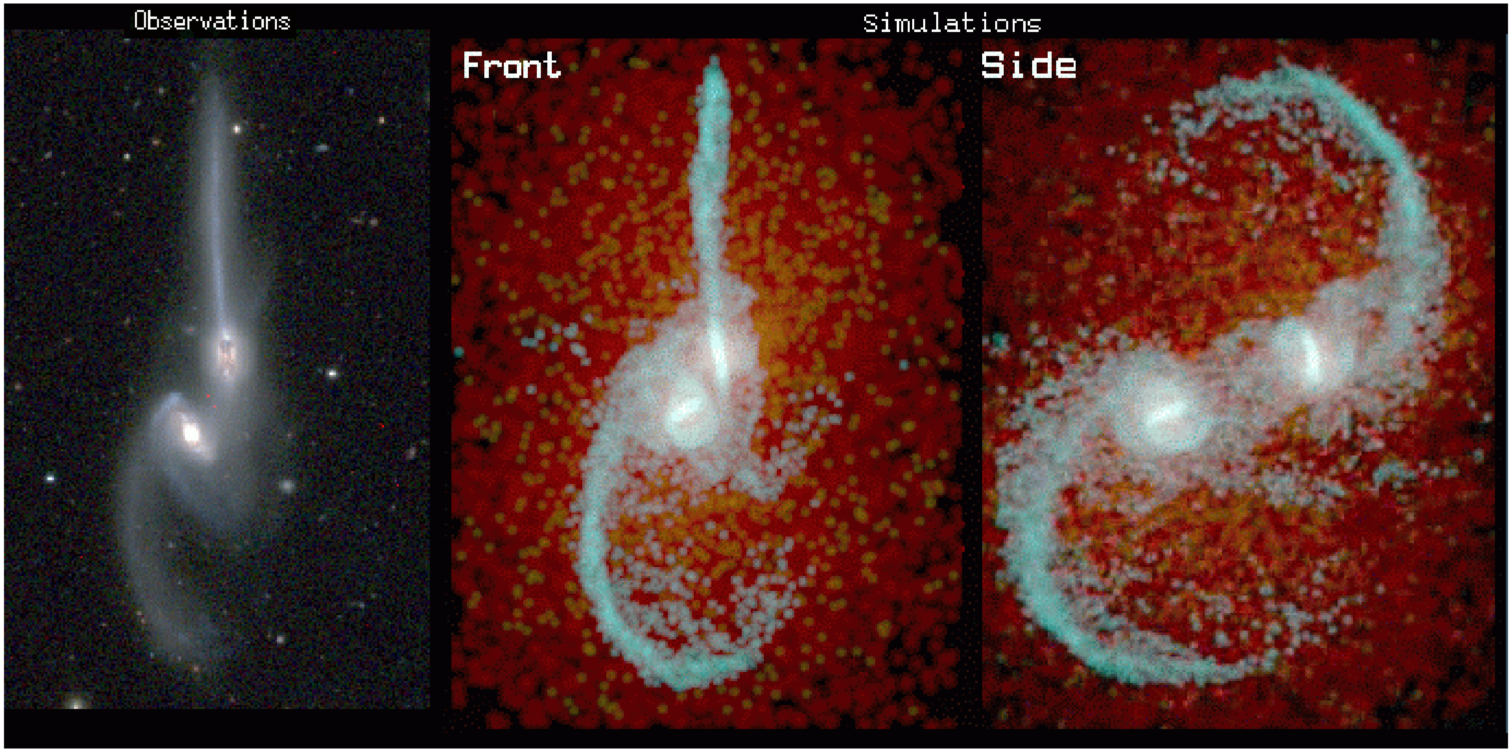
High resolution N-body model of "The Mice"

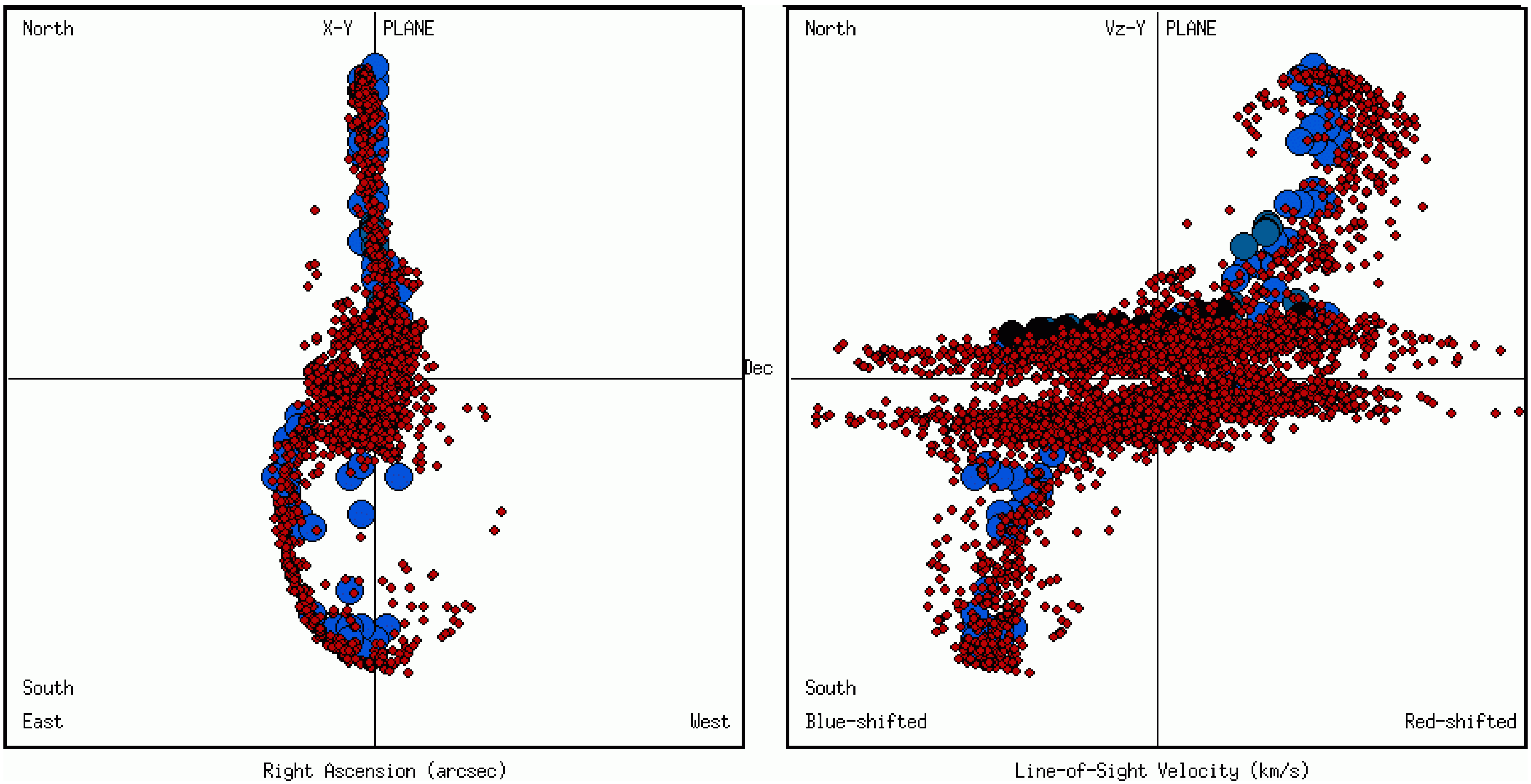


- Bulge-disk-Halo progenitors (Barnes (1988, 1996)
- $M_{dark}/M_{lum}=4$

- 1E6 particles
  - 64k per bulge
  - 200k per disk
  - 300k per halo

Barnes & Hibbard, in preparation

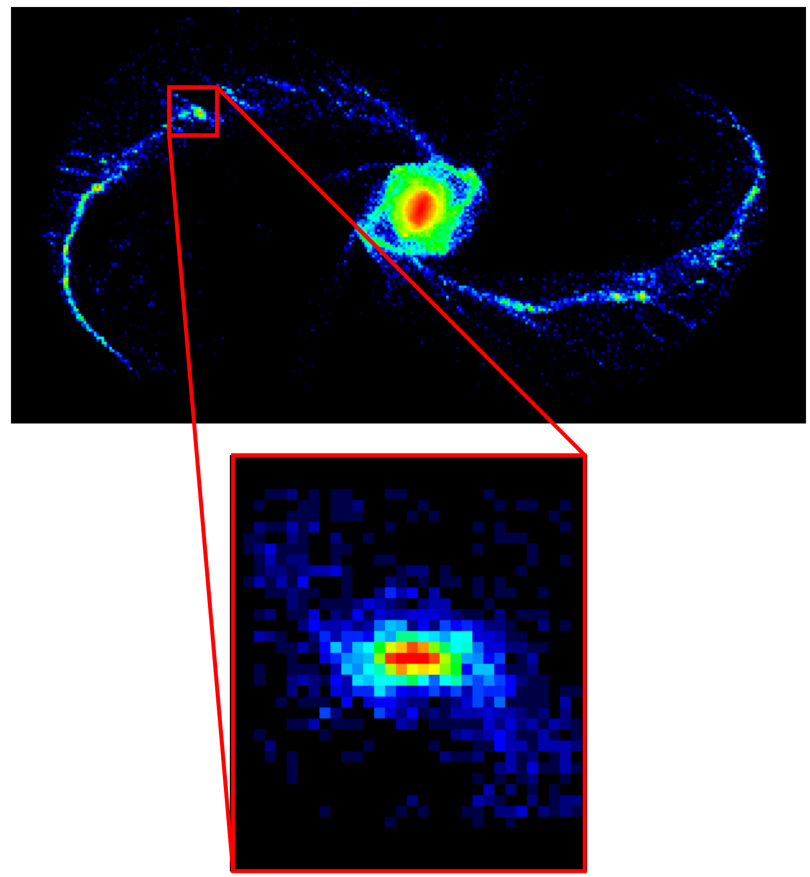
Fit HI, CO, Halpha morphology and kinematics



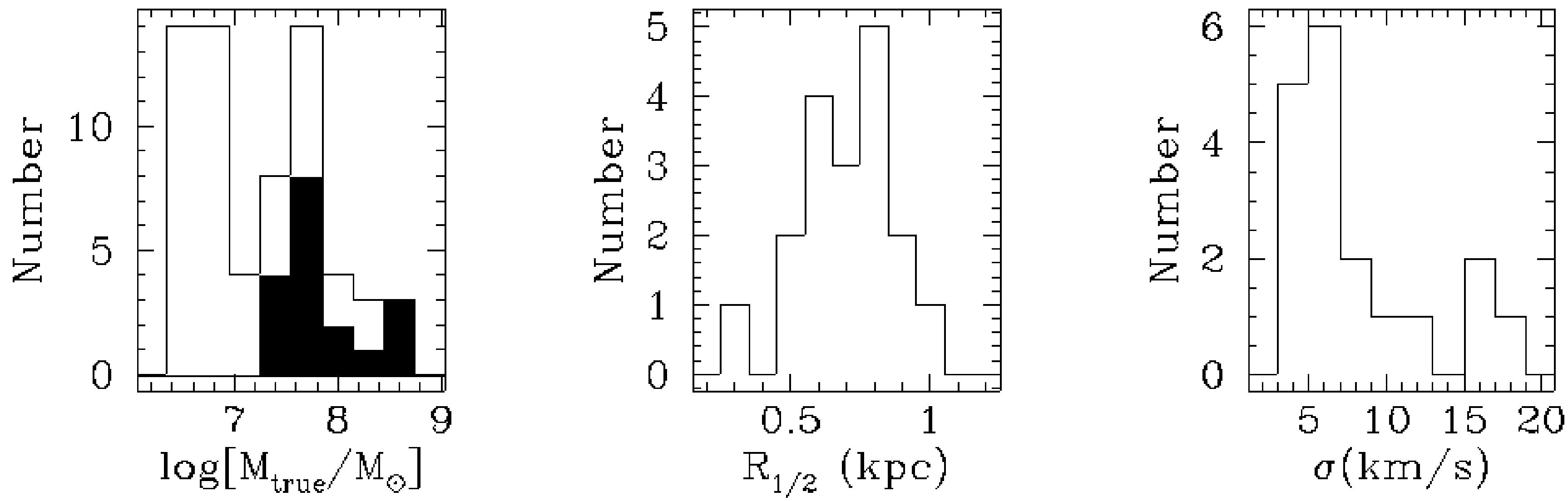
HI: Hibbard & van Gorkom 1996; CO: Yun & Hibbard 2001; Halpha: Mihos et al. 1993

High resolution allows significant number of particles per TDG

- $N_{max} \sim 1100$
- Allows accurate determination of physical properties (half-light radius, velocity dispersion, virial mass)



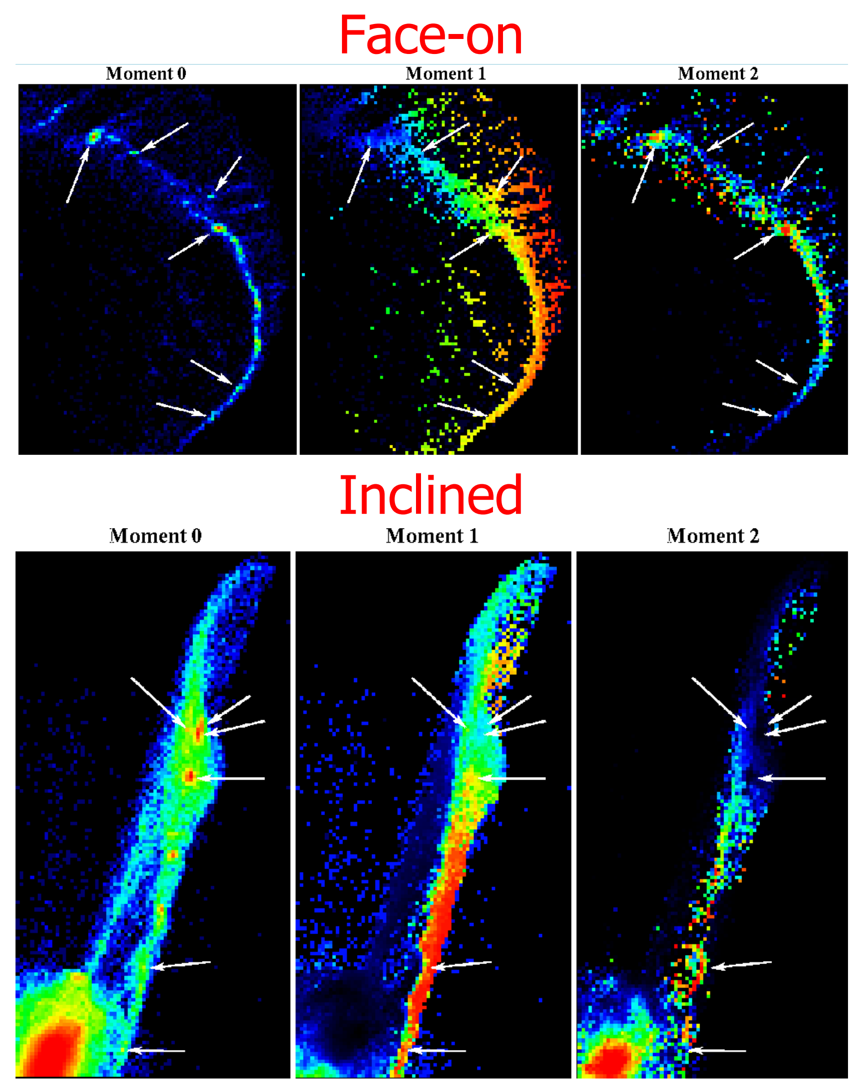
Identify 64 clumps at late times (~300 Myr from today) with E/m<0, T/U<-0.5



- Restrict this to 18 with N>50, well defined peak
- Particles extracted from tail & measure half-light radius and velocity dispersion
- Physical scales set by match to observations

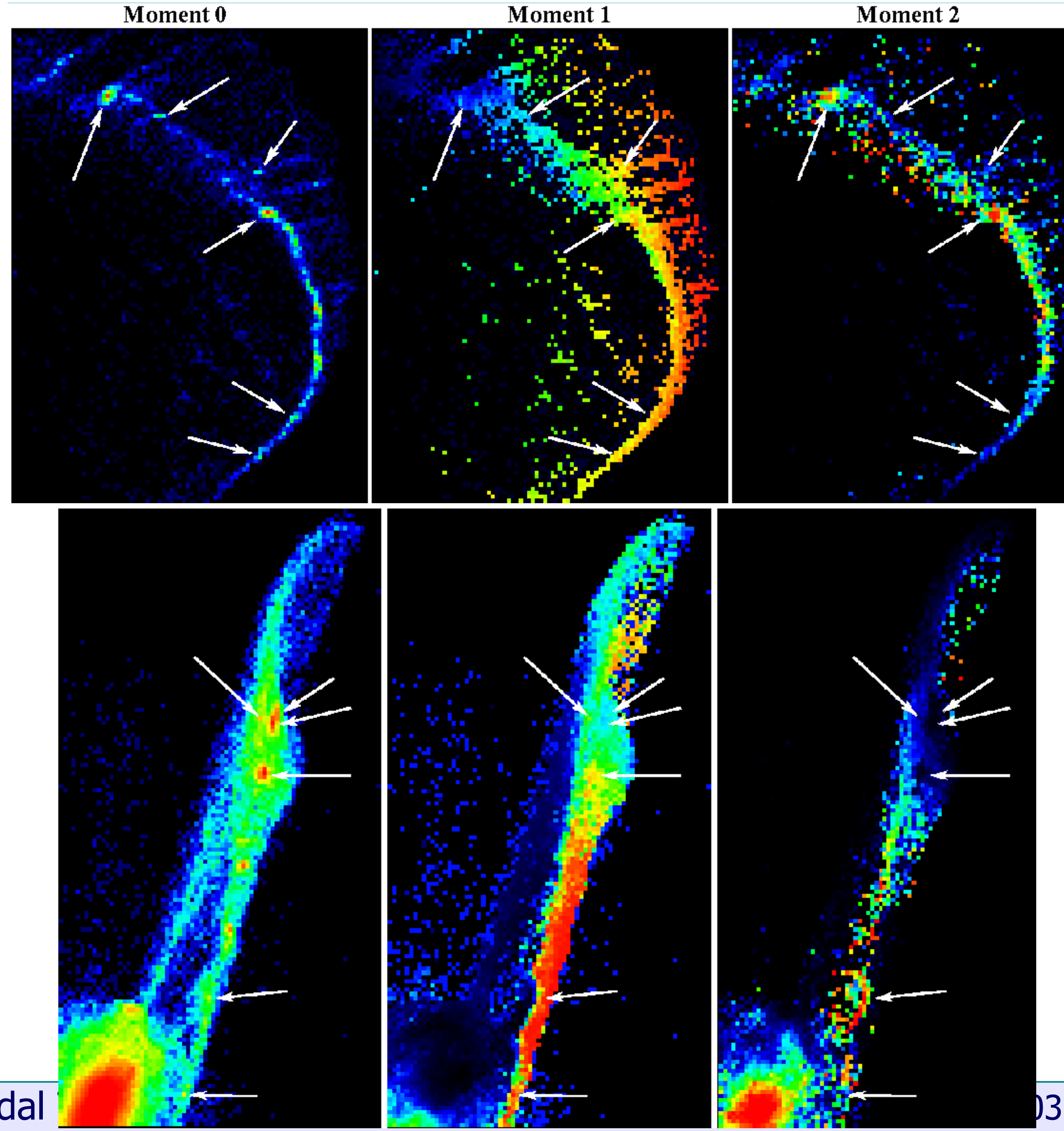
Do bound regions show distinct observational signatures?

- Sometimes…
  - Most clumps correspond to density enhancements
  - Larger clumps visible have enhanced velocity dispersion
- But…
  - Not all clumps are obvious enhancements
  - Not all enhancements are bound clumps
  - Most clumps have dispersion ~ interclump material, so are not distinct
  - Projection effects can wipe out signatures

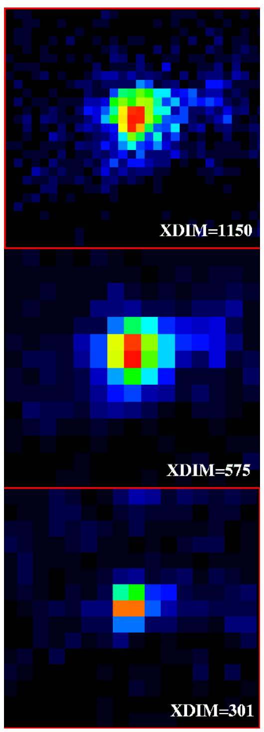


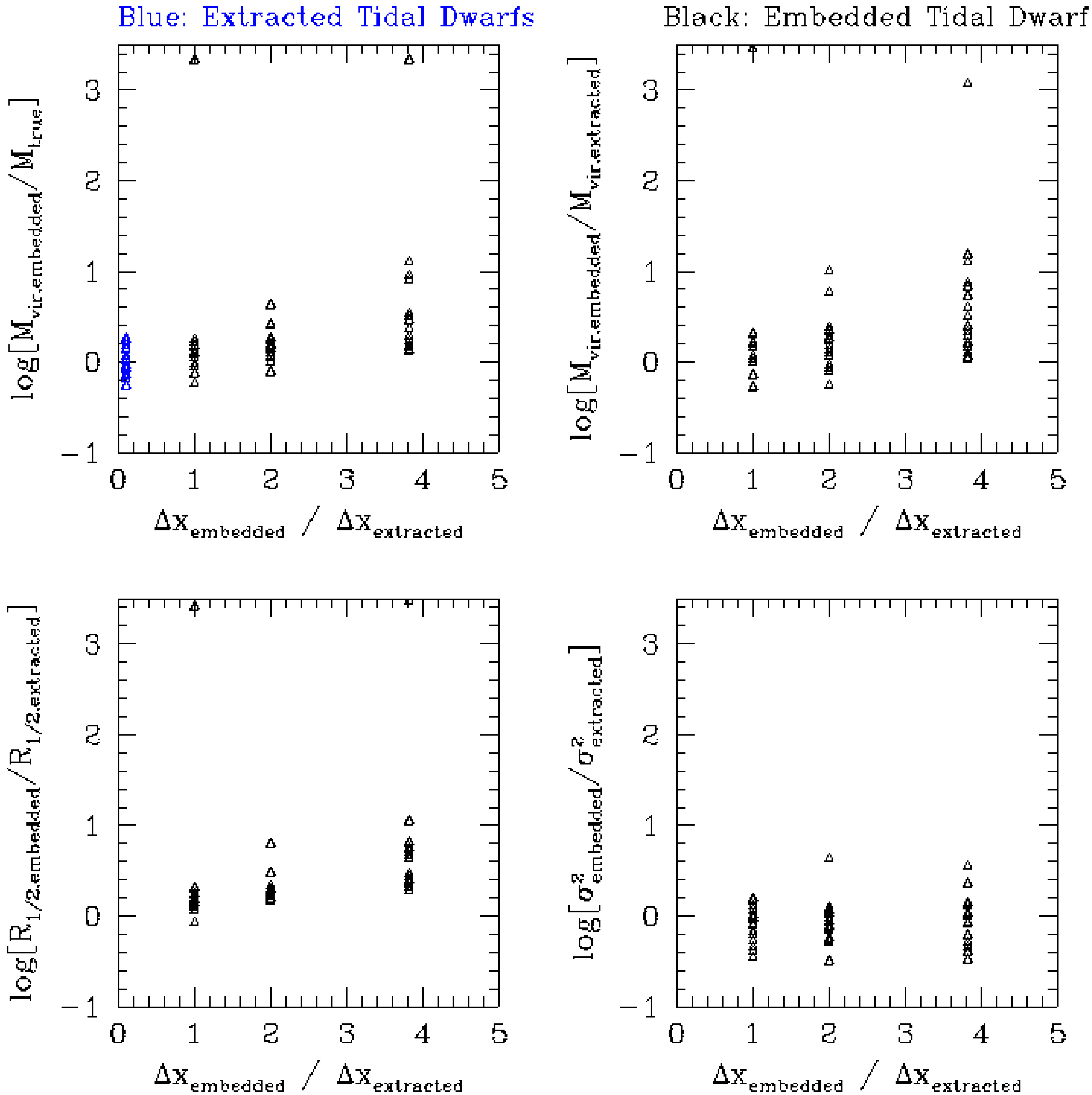
Face-on

Inclined

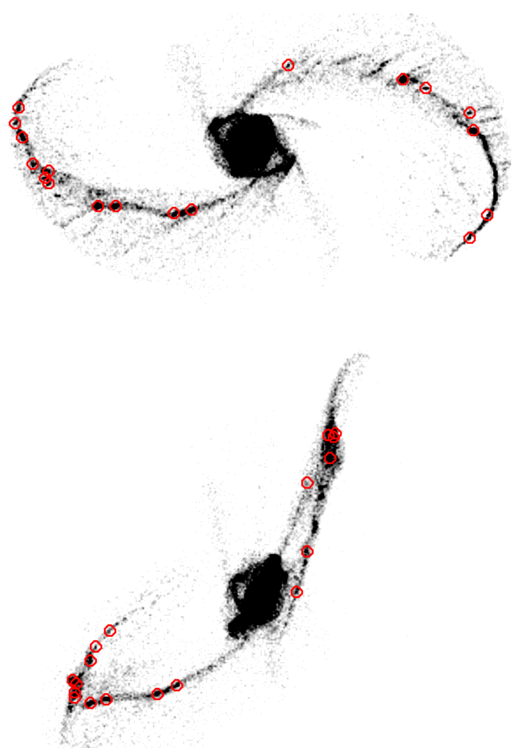


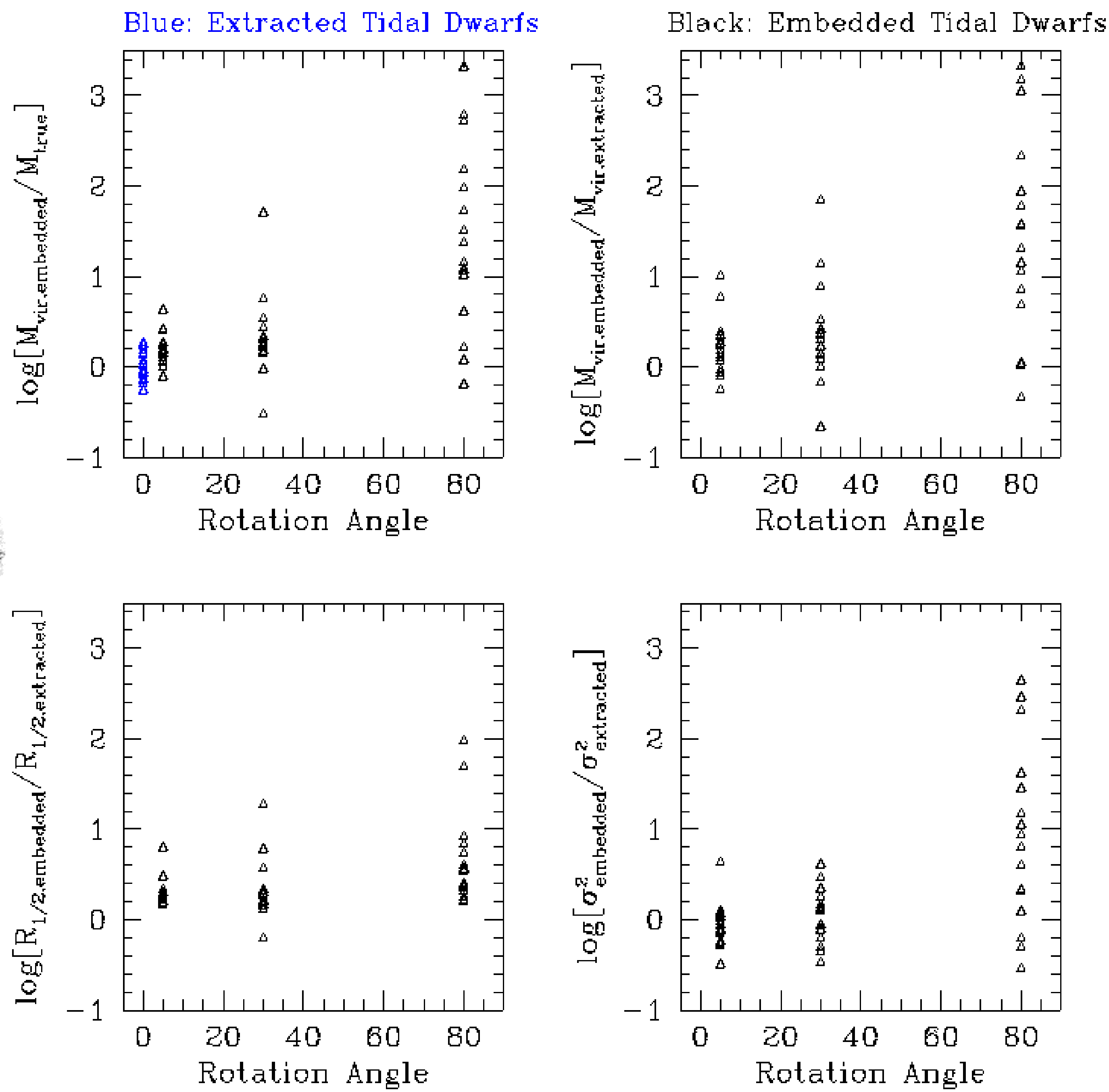
Ability to recover true physical parameters depends on resolution…





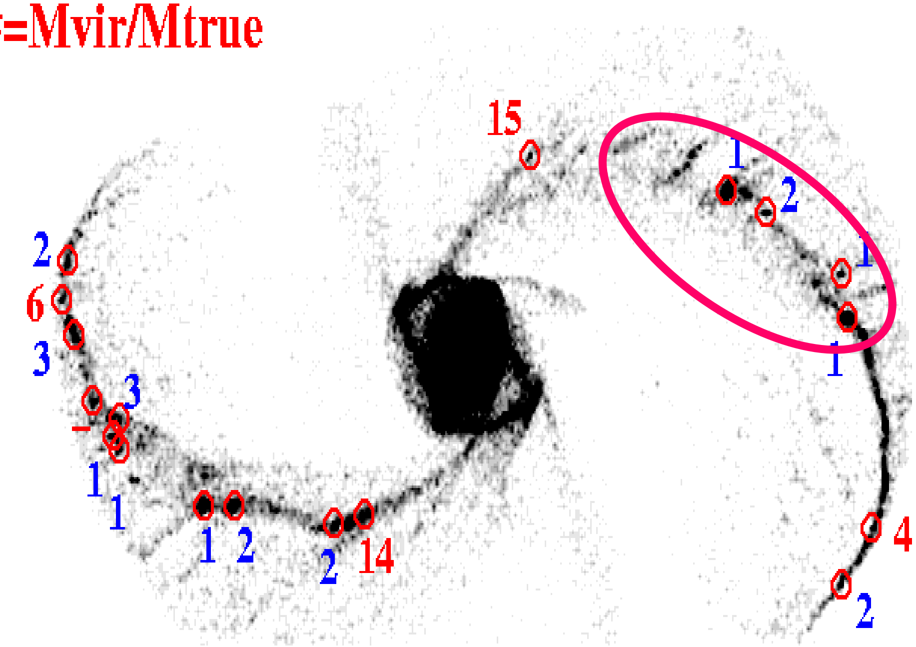
…and, most importantly, on viewing angle



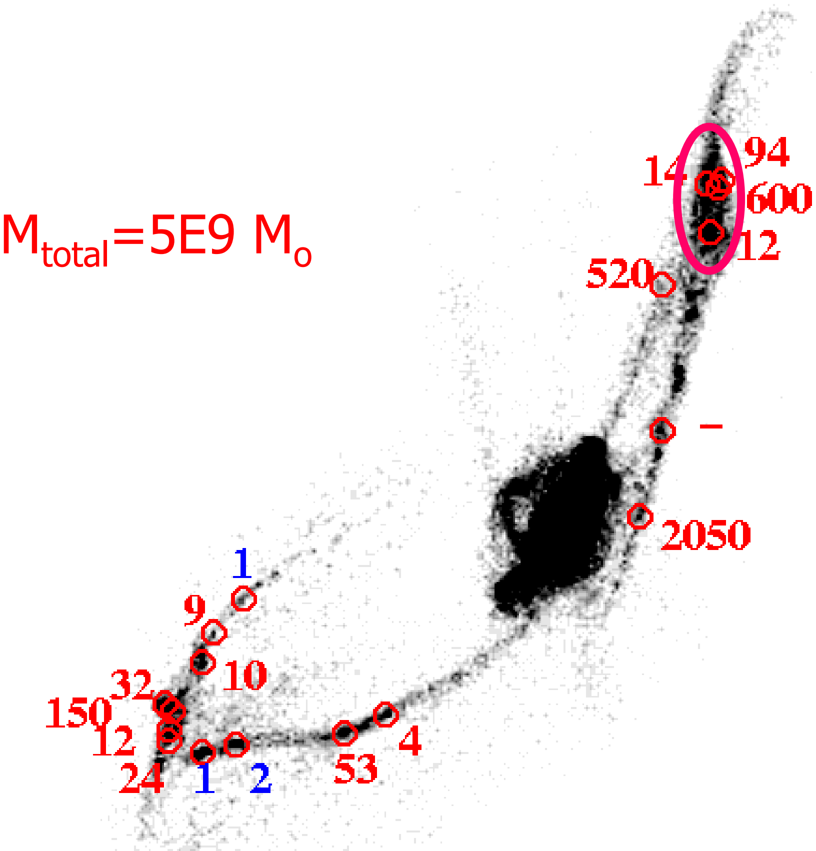


Ability to derive true properties depends critically on viewing angle

#=Mvir/Mtrue



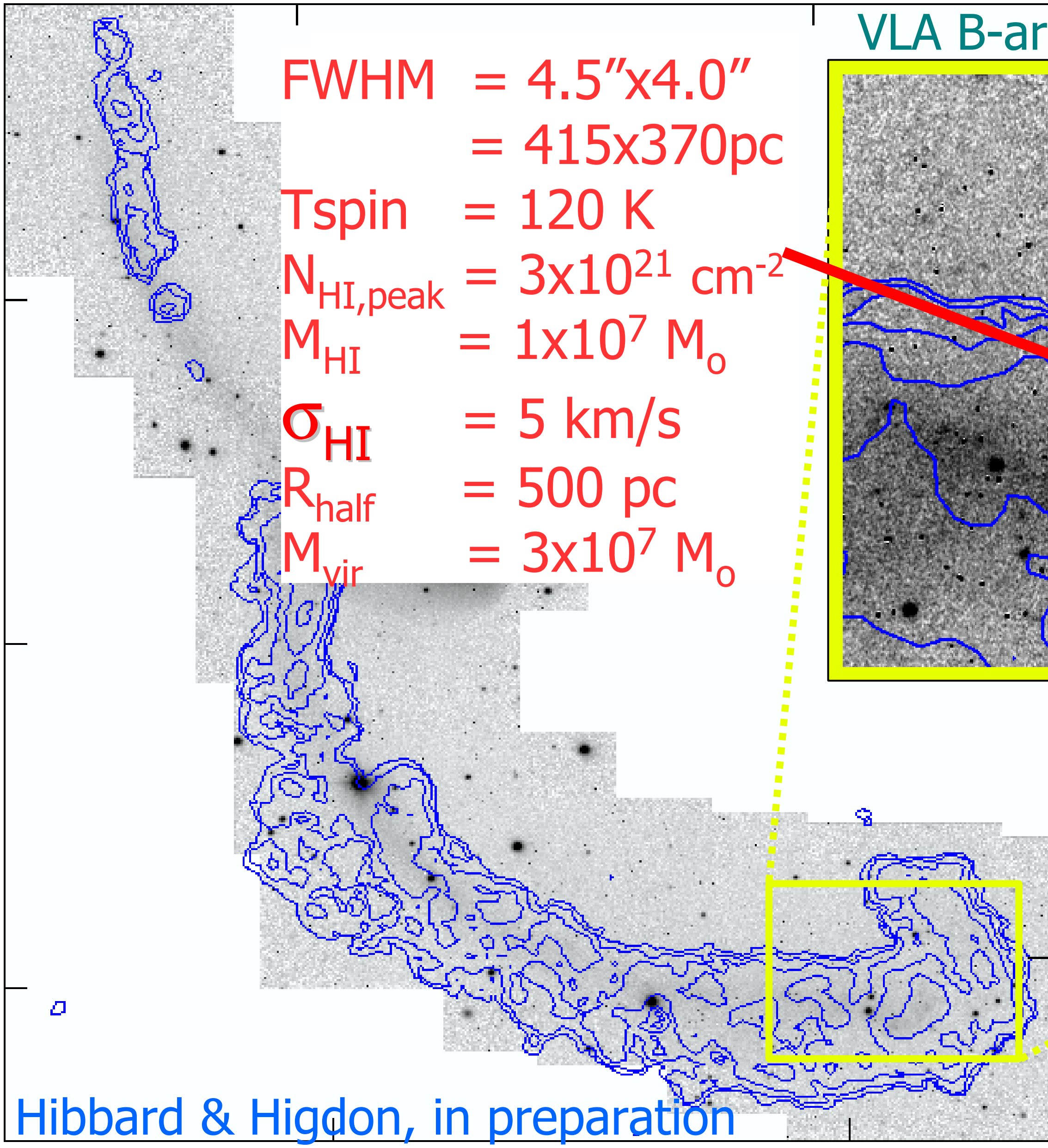
M_{total}=5E9 M_o



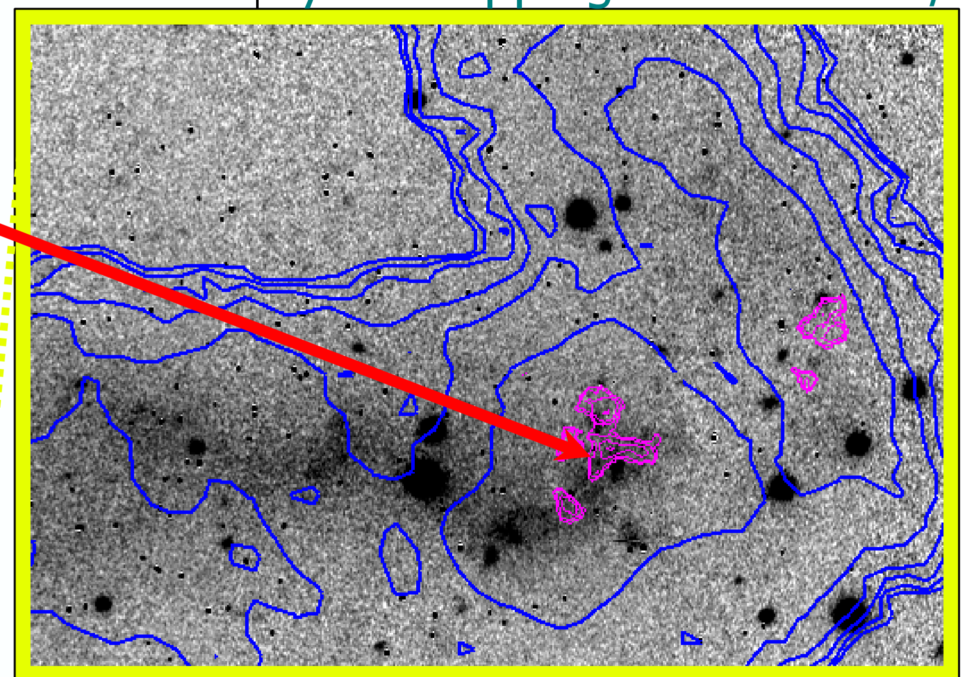
Face-on

Inclined

Some regions may be bound, but on smaller scales



VLA B-array HI Mapping of NGC 4038/9



FWHM = 4.5″x4.0″ = 415x370pc

Tspin = 120 K

$N_{HI,peak}$ = 3×10^{21} cm^{-2}

M_{HI} = 1×10^{7} M_o

σ_{HI} = 5 km/s

R_{half} = 500 pc

M_{vir} = 3×10^{7} M_o

Compare C+D Array:

Tspin = 40 K

$N_{HI,peak}$ = 1.4×10^{21} cm^{-2}

M_{HI} = 2.4×10^{8} M_o

σ_{HI} = 13 km/s

R_{half} = 3.2 kpc

M_{vir} = 1×10^{9} M_o

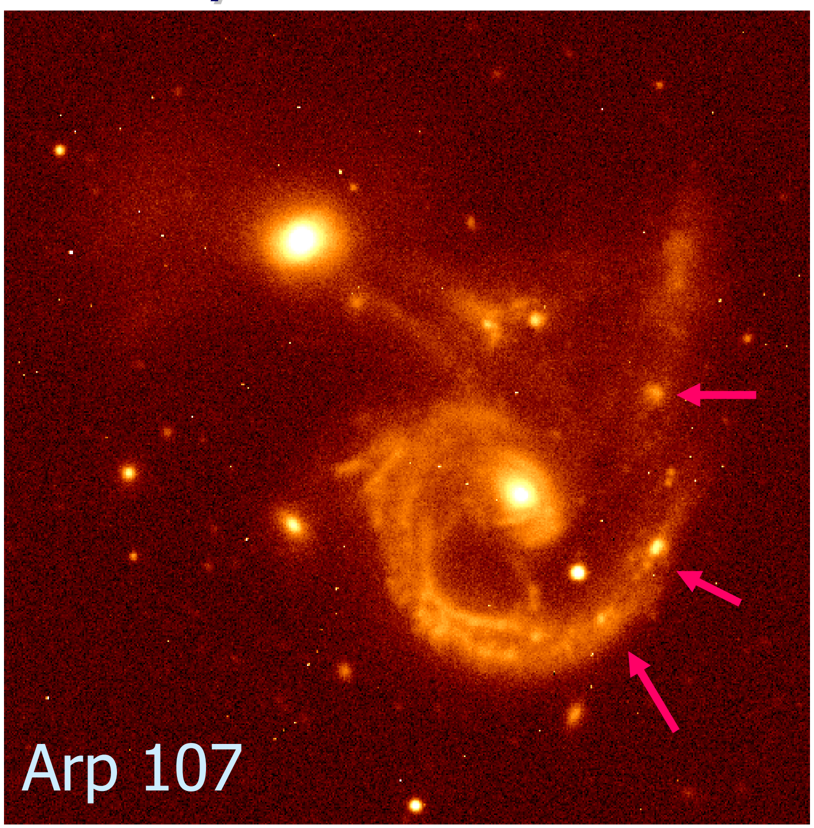
Hibbard & Higdon, in preparation

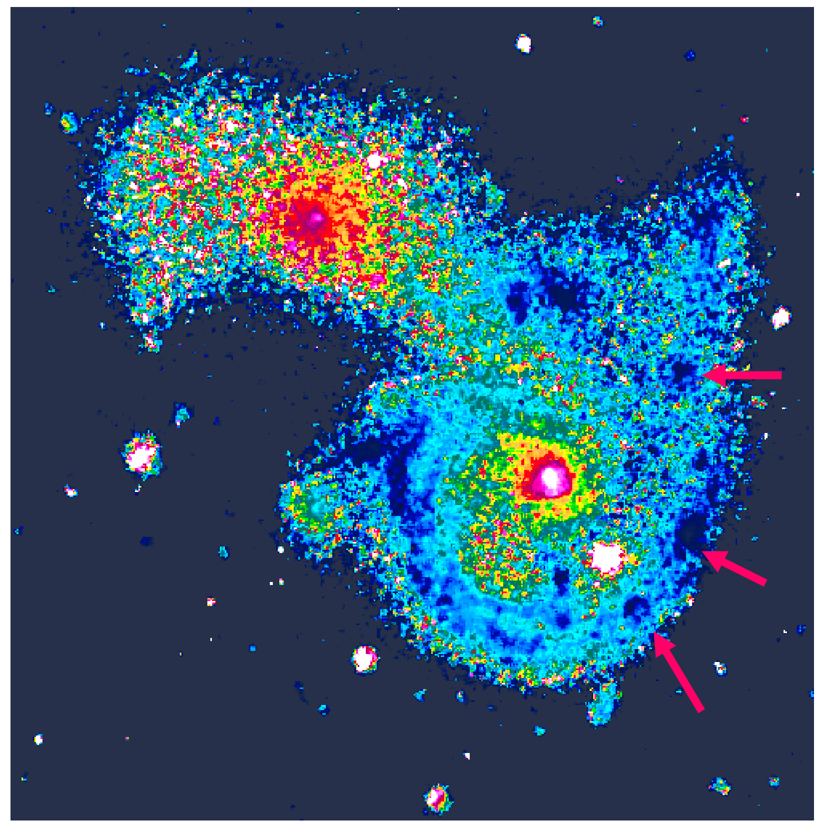
Tidal Substructure Conclusions:

- Most condensations do not have enough luminous matter to be self-gravitating.
- If they ARE self-gravitating, they must be dark matter dominated
- Recent kinematical signatures very intriguing – require large amounts of dark matter
- Derivation of dynamical properties confused by adjacent tidal material, resolution, and especially projection effects
- Many TDG candidates may be collection of smaller bound units. In this case, mass scale may be more appropriate to dSph than to dIrr

Tidal Substructure Conclusions:

- Would be very reassuring to find evidence of kinematically distinct TDG candidate in face-on system





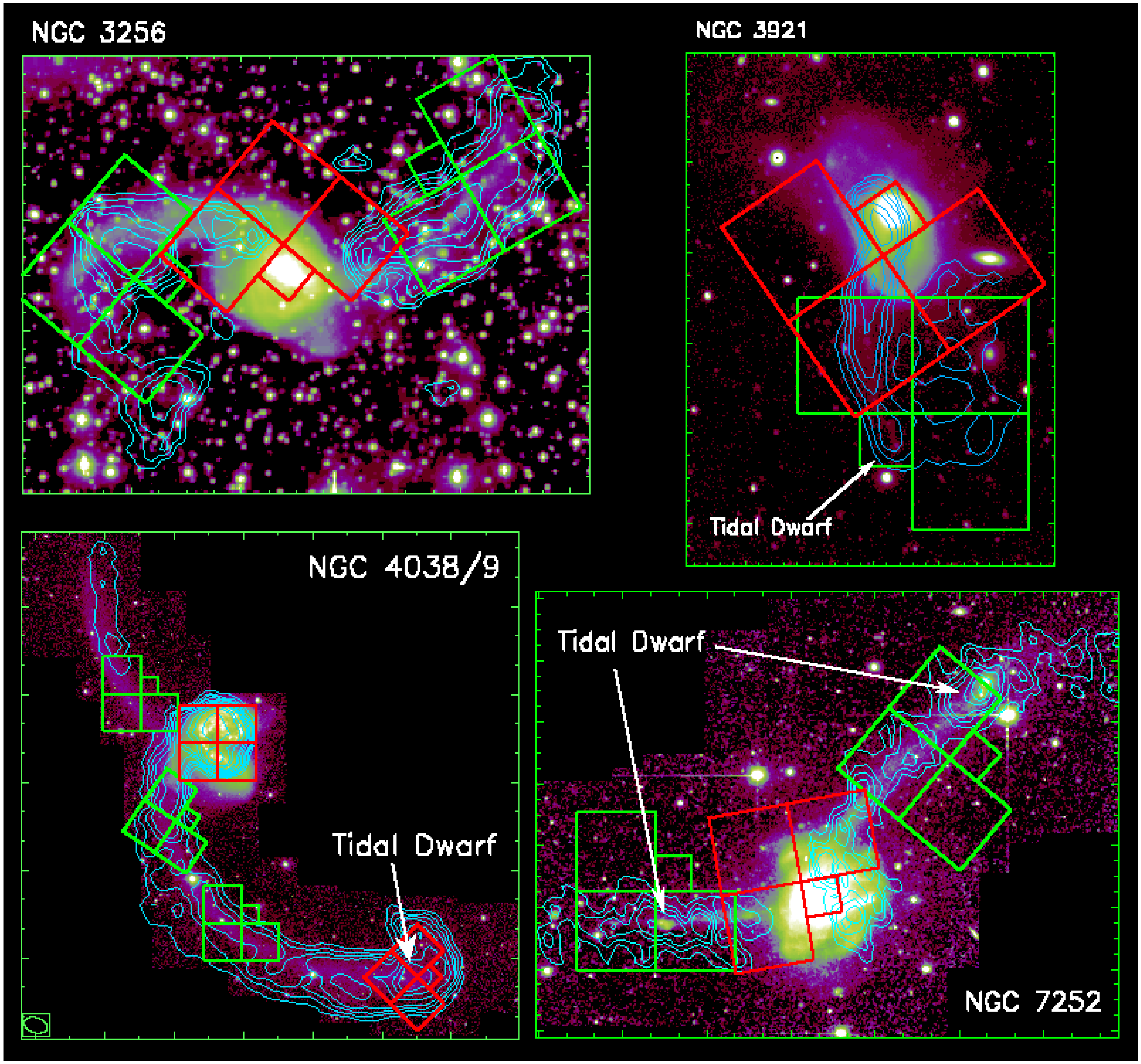
Questions to be addressed:

- Are there bound gaseous precursors to optical condensations?
- Are TDGs bound by baryons alone?
- Can the physical properties of tidal substructures be accurately derived?
- Do Super Star Clusters (SSC) occur within tidal tails?

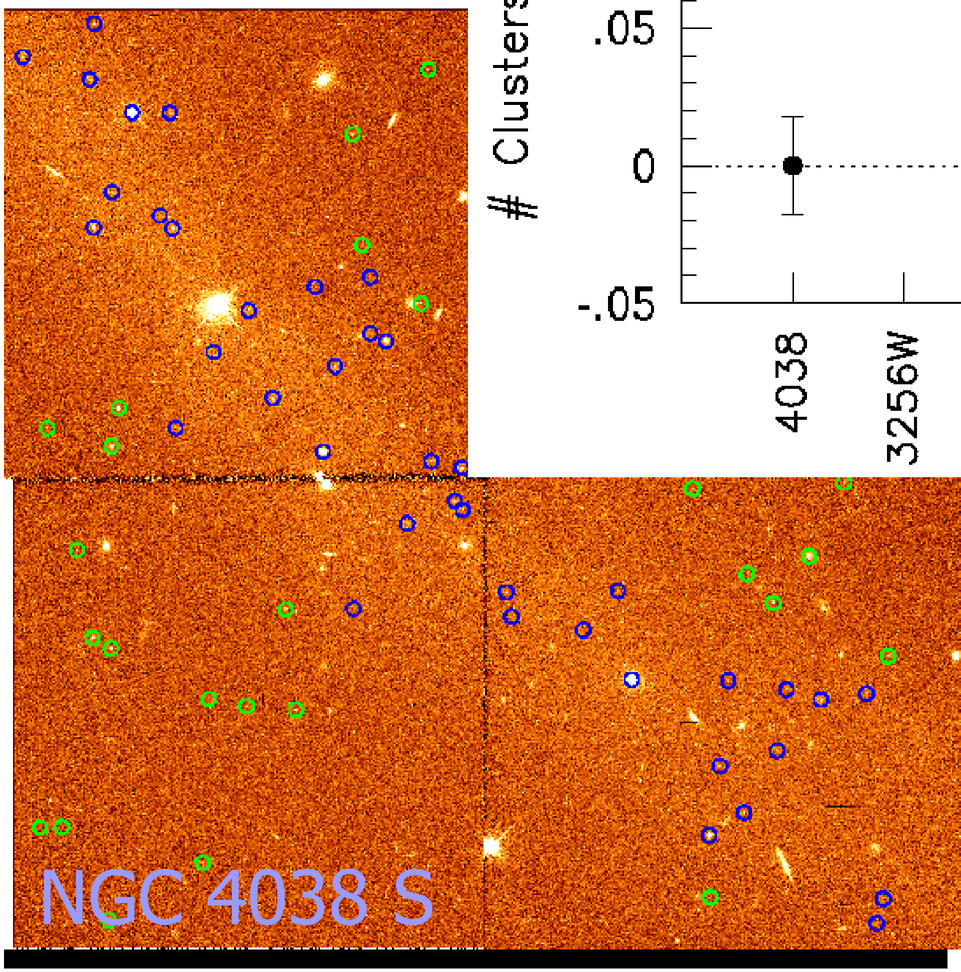
HST study of Optical Substructure in Tidal Tails

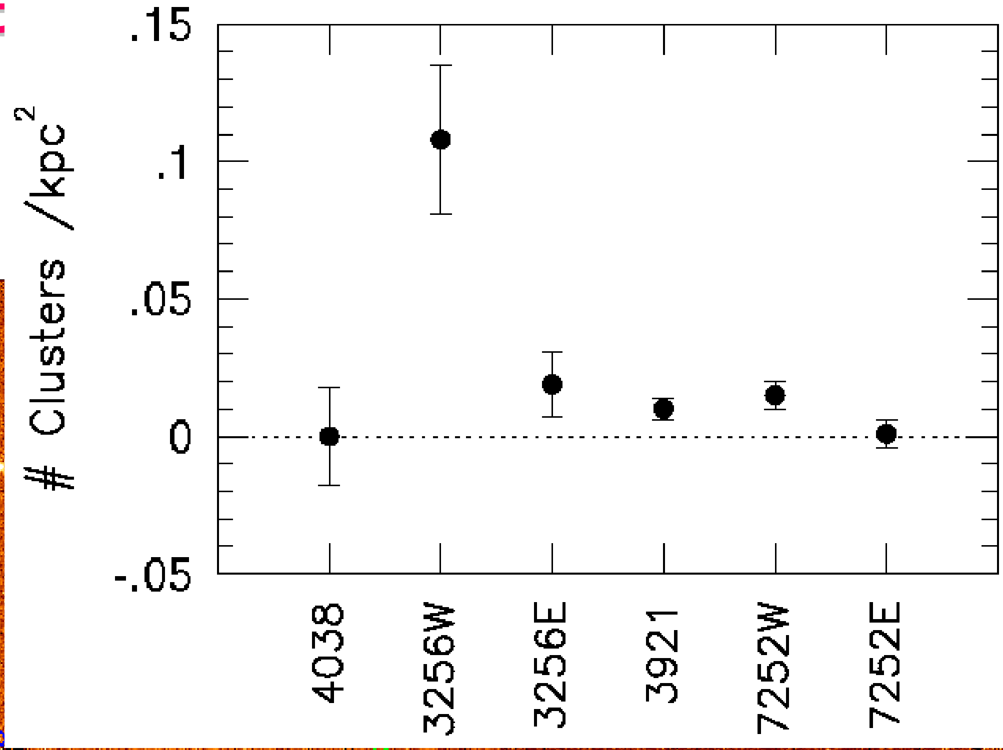
N4038/9, N3256
N3921, N7252
WFC VI
13 orbits
P.I. Charlton
Kniermann et al.
AJ, submitted

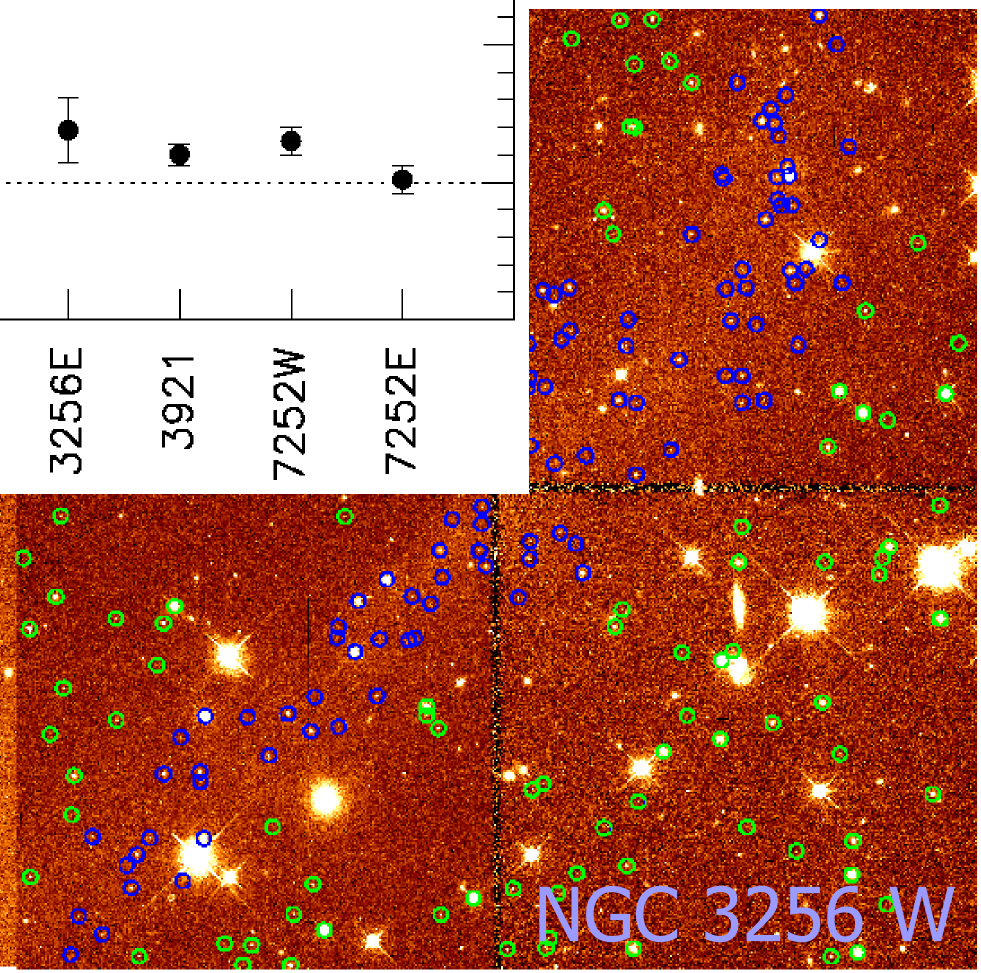
N4038 TDG
WFC UBVI
11 orbits
P.I. Hibbard
Saviane et al.
AJ, submitted



After corre… …amination, only one … …lation of

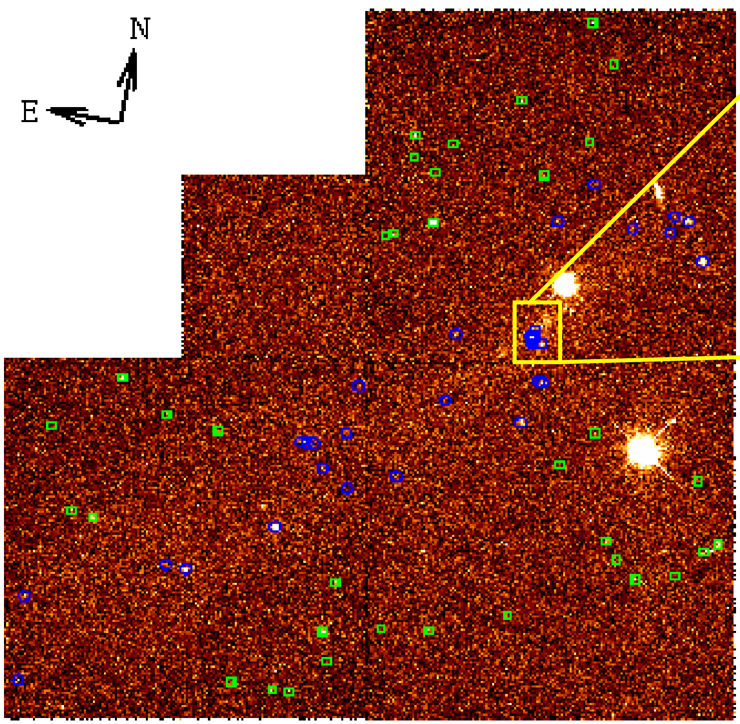




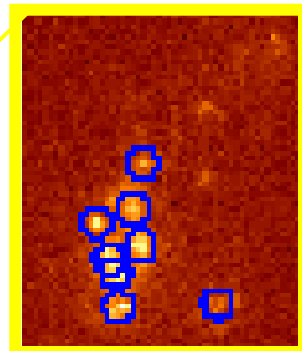


Knierman et al., AJ, submitted

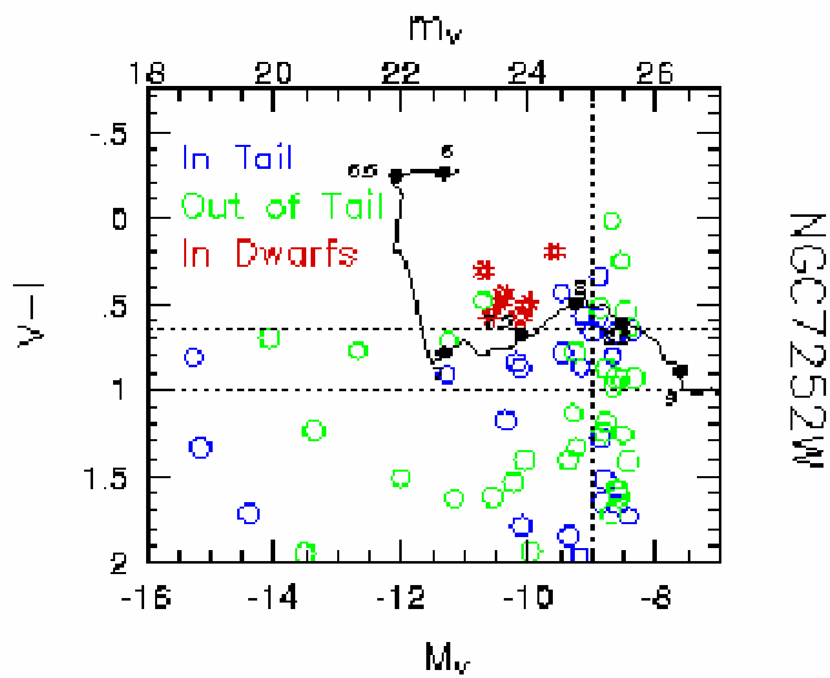
Despite the lack of a significant tidal population of star clusters, there are concentrations of star clusters associated with the TDG candidates in both NGC 7252 and NGC 4038



WFPC2/HST image in F555W filter

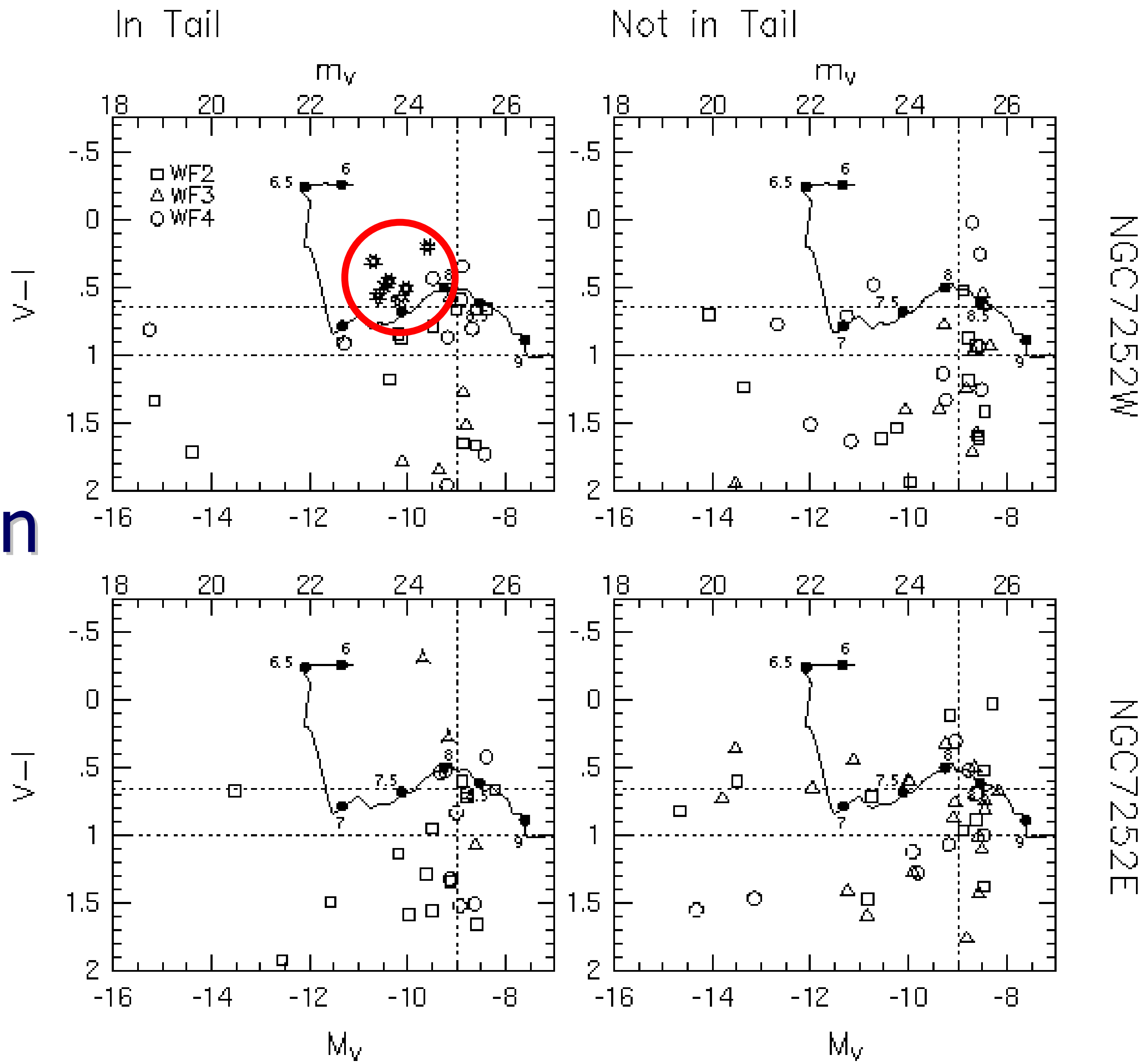


Tidal dwarf galaxy at the tip of the western tail of NGC 7252

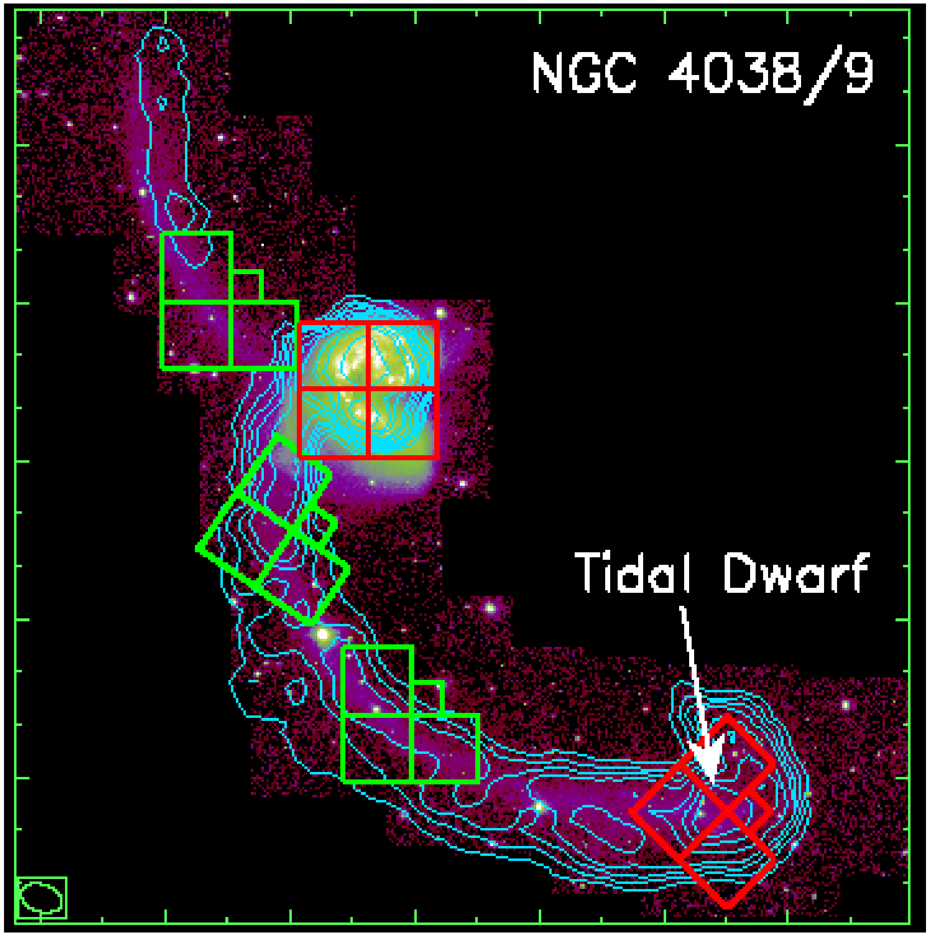


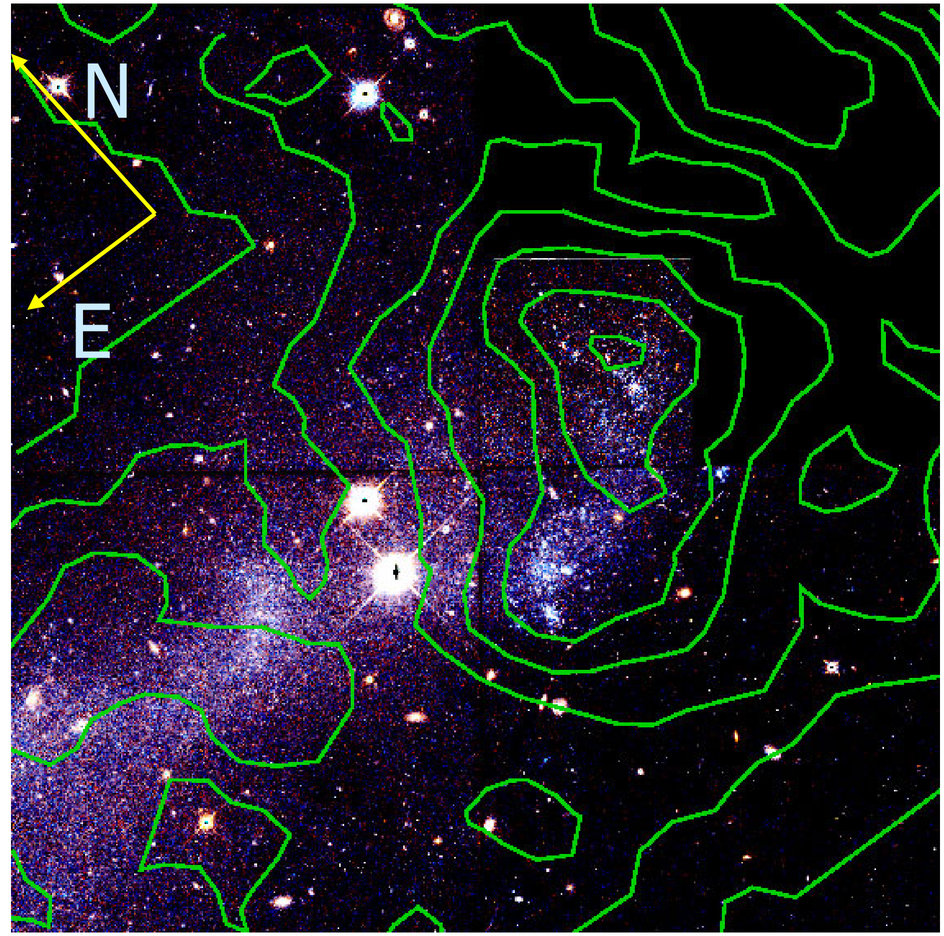
Knierman. et al. 2001. submitted to AJ

No similar population in CMD either on or off the tail



NGC 4038 TDG Candidate.

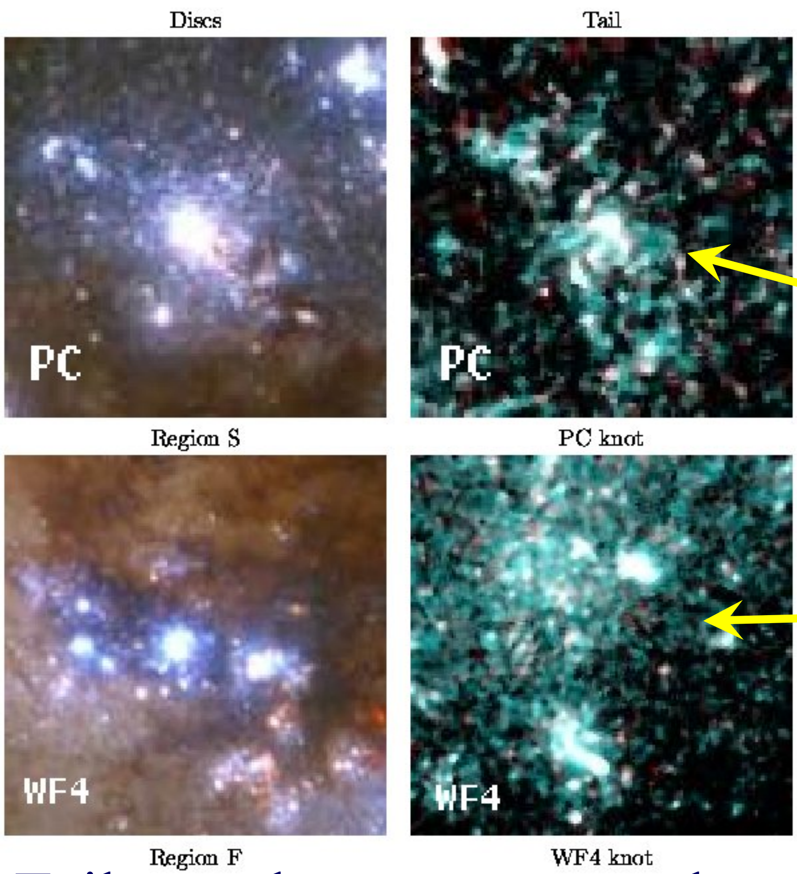




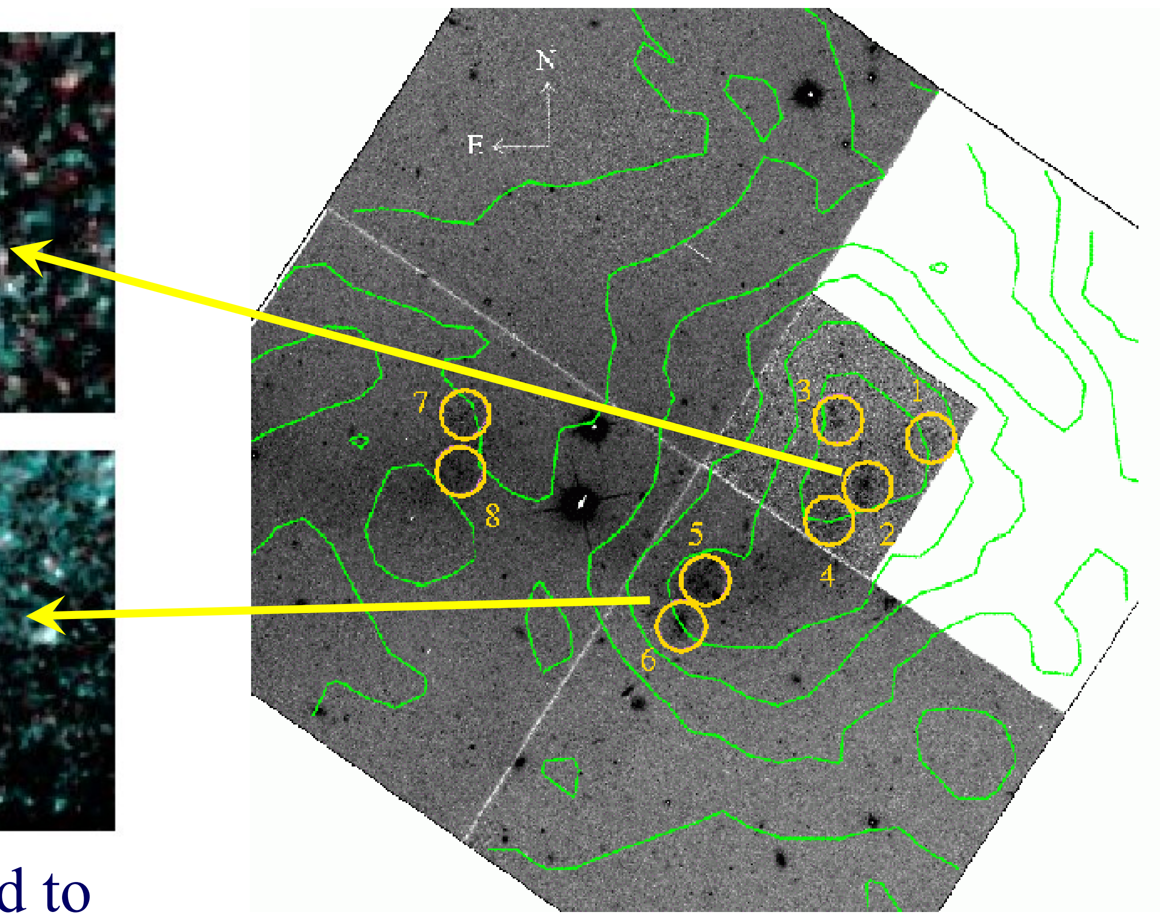
HST: Saviane, Hibbard & Rich, AJ, submitted
HI: Hibbard, van der Hulst, Barnes & Rich, 2001

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

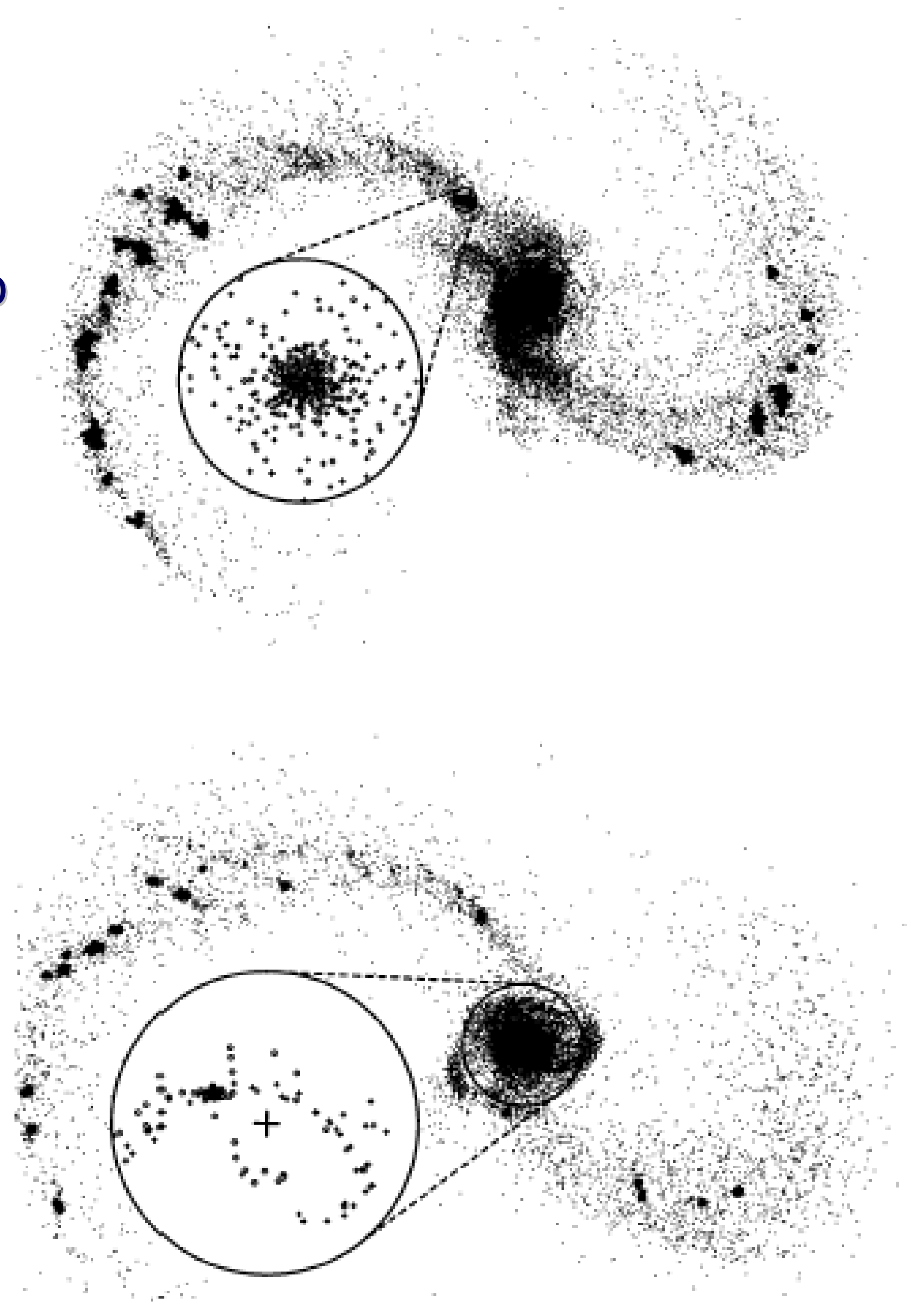
Saviane, Hibbard & Rich, AJ, submitted

Tidal Substructure Conclusions:

- Bright star clusters sometimes, but not always, found in tails
- Star clusters “often” concentrated in vicinity of TDG candidates

Fate of clumps?

- Most tidal material remains bound to remnant, streams back in on scales of Gyr
- Bound units will be tidally heated and stripped down to a few % of original mass
- In cluster environment, outer regions will be stripped
- Fate of more energetic ends of tails depends on dark matter content



Barnes & Hernquist, 1992, Nature, 360, 715