Tidal Tales of Minor Mergers: Star Formation in the Tidal Debris of Minor Mergers

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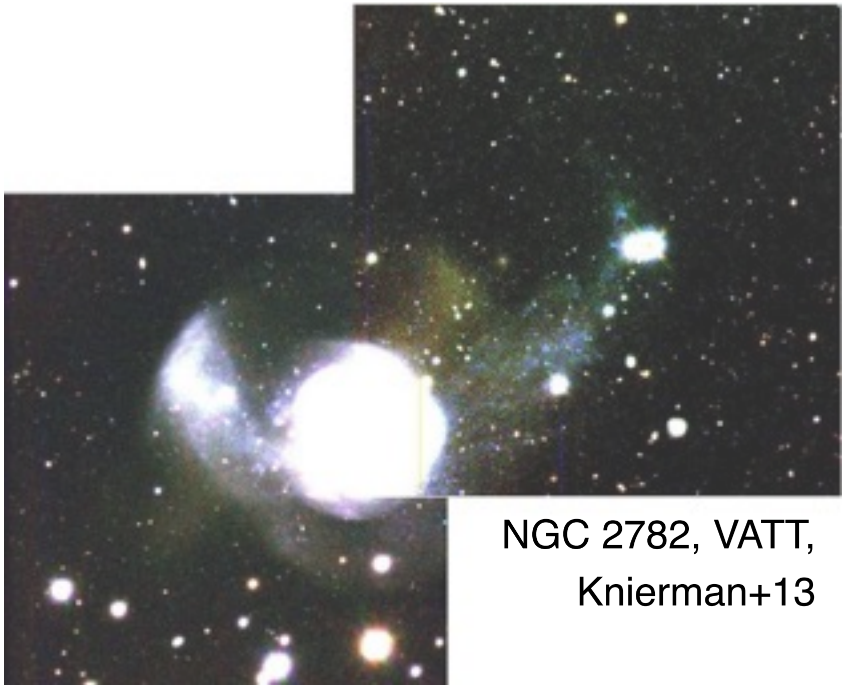
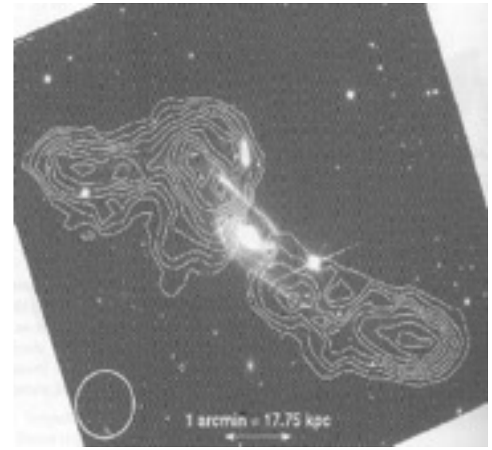
Minor Galaxy Mergers



NGC 2782, VATT,
Knierman+13



NGC 6872
Horellou &
Koribalski (2003)

Minor Merger

Merger between dwarf and spiral galaxies with mass ratio of <0.3 which preserves the disk of the spiral galaxy.

UGC 10214
“Tadpole”
ACS ERO

Importance of Minor Mergers

Minor mergers more common than major mergers

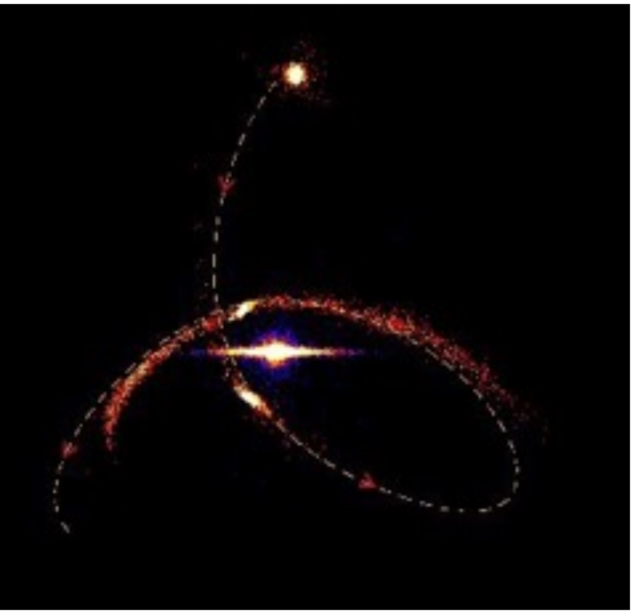
(Based on studies of merger rates out to z~2, a typical massive galaxy has had about 6 minor mergers and only 1 major merger in that time (9.3 Gyr) - Lotz+2011)

Galaxy-sized CDM halos are predicted to gain most of their mass in ~10:1 merger events (Zentner & Bullock 2003)

Minor mergers were more common in the early universe (up to 55% of star formation may be from minor mergers at z~2 Kaviraj+2013)

Tidal debris from interactions may be important in building galaxy halos (e.g., Searle & Zinn 1978; Bullock & Johnston 2005)

Importance of Tidal Debris



Minor Merger Simulation (Johnston+02)

Models with Star Formation:

20-50% of total star formation in merger is in tidal debris using Hopkins+12 models of major mergers

[vs. ~10% from early models of Barnes 2004]

Tidal debris can possibly:

- Fall onto parent galaxy creating streams in the halo, contribute to structures (e.g., thick disk), or add to the star cluster population
- Escape galaxy and enrich IGM and Lyman Alpha Forest
- Form new dwarf galaxies as Tidal Dwarf Galaxies

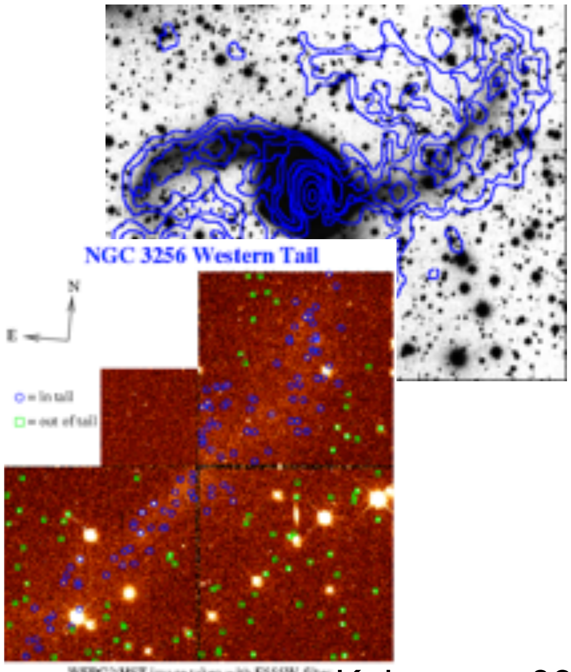
Structures Forming in Tidal Debris

Major Mergers

($M_2/M_1 \sim 1$)

Minor Mergers

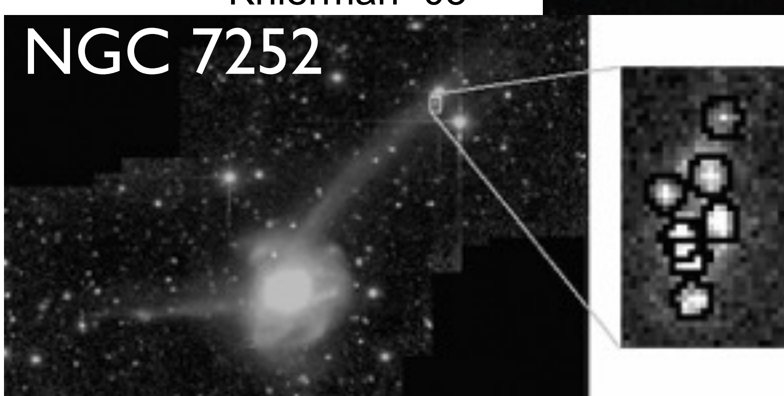
($M_2/M_1 < 0.3$)



Knierman+03

Star Clusters

(Gallagher+01; Knierman+03, 13; Bastian+05; Mullan+11; Rodruck+16)



Tidal Dwarf Galaxies

(Hunsberger et al. 1996; Duc et al. 2000; Weilbacher et al. 2000)

TALES Minor Merger Sample

Merger	Velocity	Mass Ratio	Interaction Stage	$M_{B,1}$	$M_{B,2}$	Projected Separation
	kms^{-1}			mag	mag	kpc
Arp 269	565	0.1	early	-20.39	-18.02	15
NGC 3310	993	< 0.3	merged	-20.25	~ -18	0
Arp 279	1708	~ 0.1	early	-20.22	-18.50	25
UGC 00260	2131	0.1	early	-19.78	-17.43	23
NGC 5666	2221	< 0.3	merged	-19.53	~ -17	0
NGC 7479	2381	0.1	merged	-21.64	~ -19	0
NGC 2782	2562	0.25	late	-20.98	-19	10
NGC 7303	3697	?	merged	-20.34	?	0
NGC 1614	4778	< 0.3	merged	-21.34	~ -19	0
UGC 06665	5560	?	merged	-20.16	?	0
UGC 06503	6143	< 0.3	late	-20.02	~ -18	25
UGC 10214	9401	0.15	late	-21.84	~ -19	5
Arp 219	10521	< 0.3	late	-21.56	~ -19	130
AM 0318-230	10699	< 0.3	merged	-20.91	~ -19	0
UGC 10084	13880	?	merged	-21.74	?	0

Early → **Late** → **Merged**

Tidal Tails of Minor Mergers: Star Formation in the Tidal Tails of NGC 2782

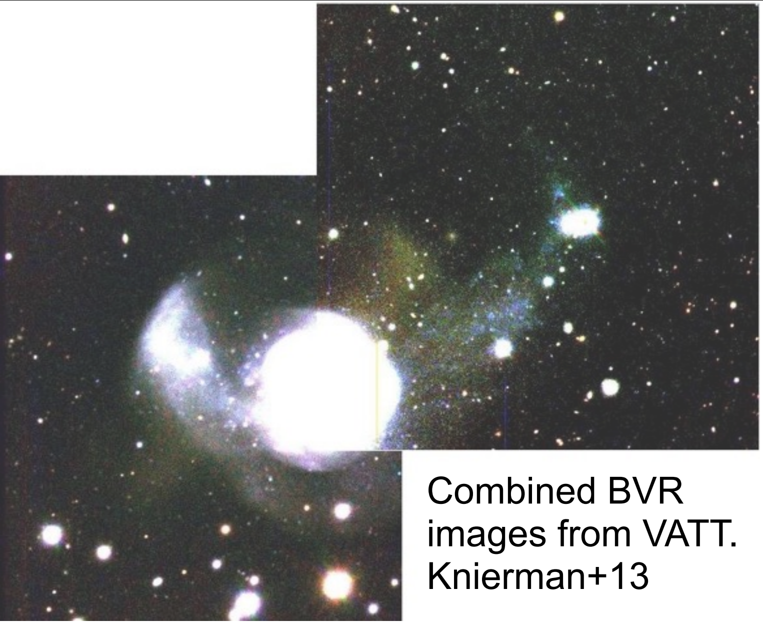
Karen Knierman (ASU), Patricia Knezek (WIYN),
Paul Scowen, Rolf Jansen (ASU) & Elizabeth Wehner (Haverford)

Astrophysical Journal Letters, 2012, 749, L1

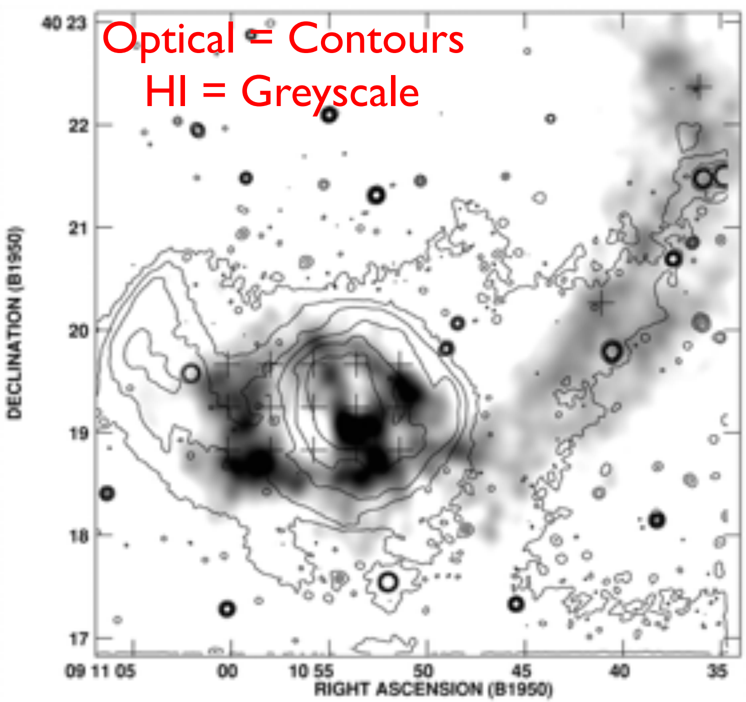
Karen Knierman, Paul Scowen, Todd Veach, Chris Groppi (ASU), Brendan Mullan (PSU), Patricia Knezek (WIYN), I. Konstantopoulos, J. Charlton (PSU)

Astrophysical Journal, 2013, 774, 125

NGC 2782



Combined BVR images from VATT. Knierman+13



From Smith et al. 1999

Peculiar Spiral that had a Minor Merger (M_2/M_1~0.25) ~200 Myr ago (Smith 1994; Smith et al. 1999)

Two Tails:

East: Optically bright, HI, CO

may be shocked "splash" region from spiral

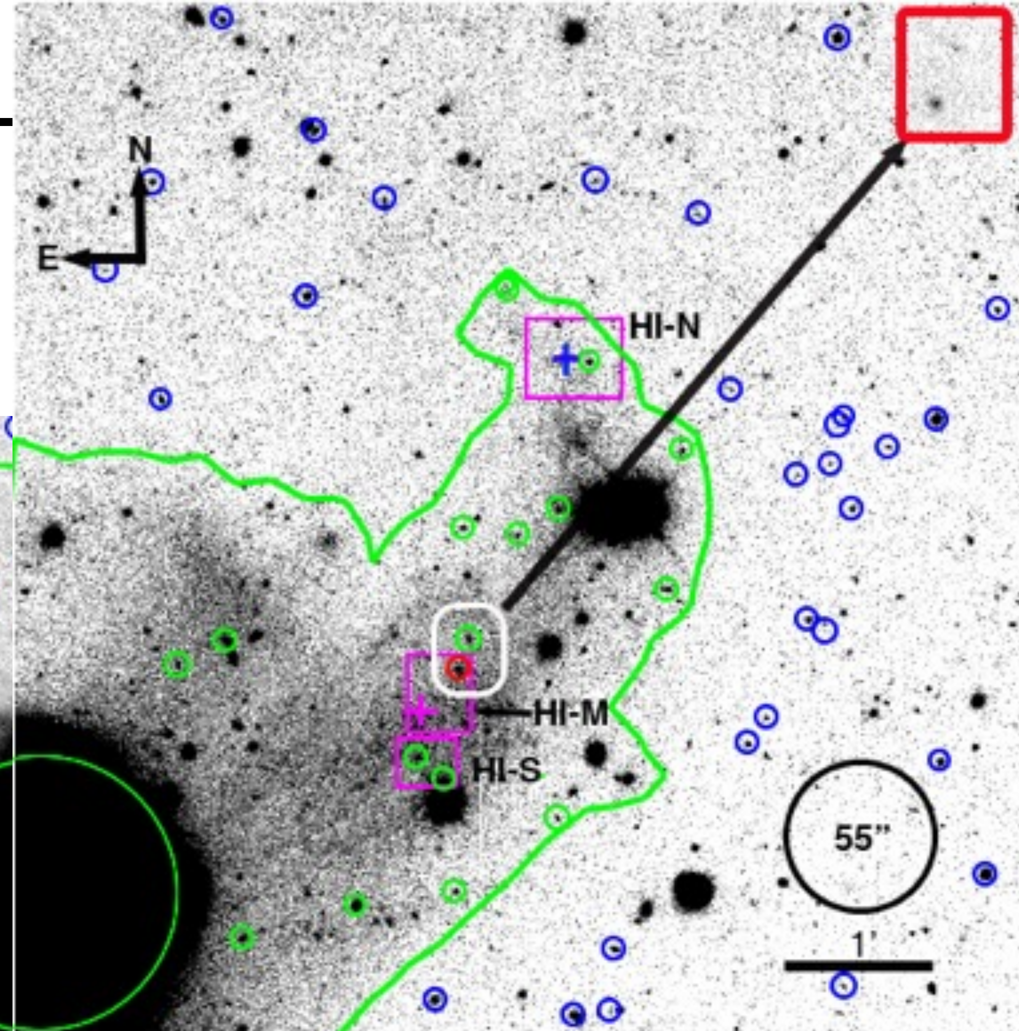
West: Optically faint, HI, no CO

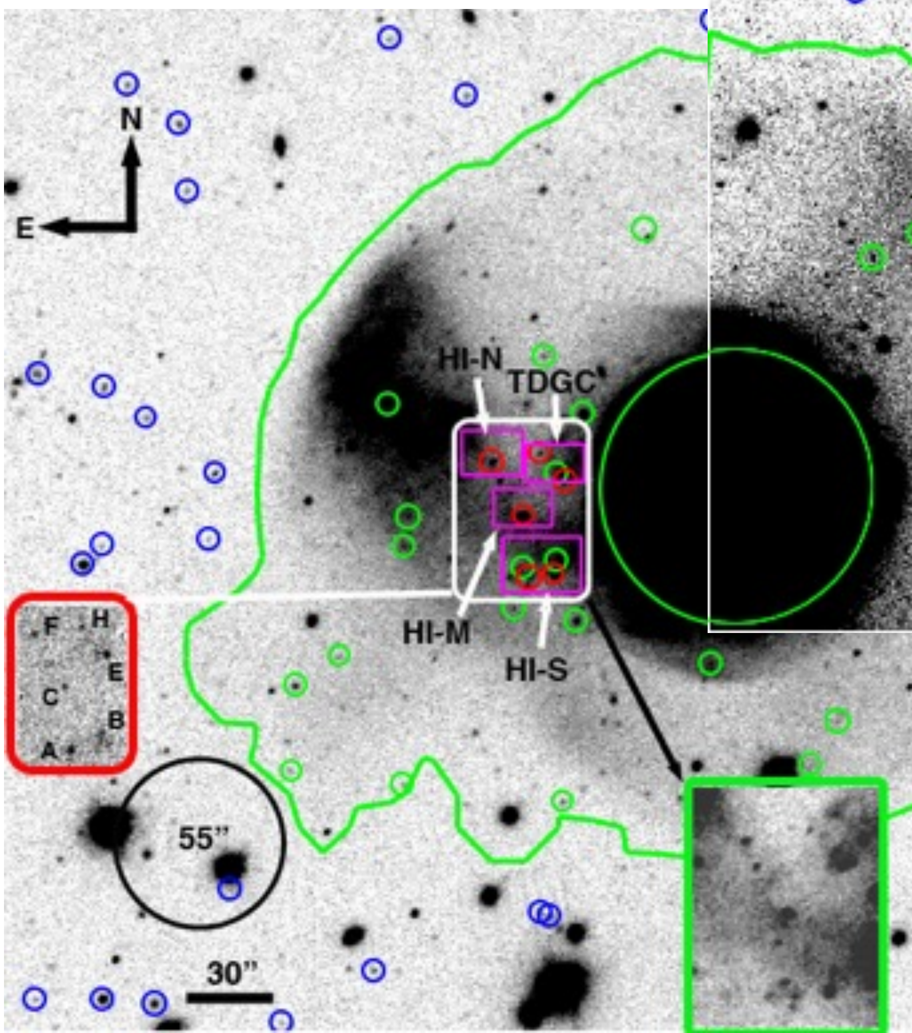
formed tidally

Western Tail HI is not gravitationally bound and has "not had time to condense into H_2 and for star formation to begin." (Braine et al. 2001)

Optical & Hα

Star cluster candidates selected, both in and out of tail.

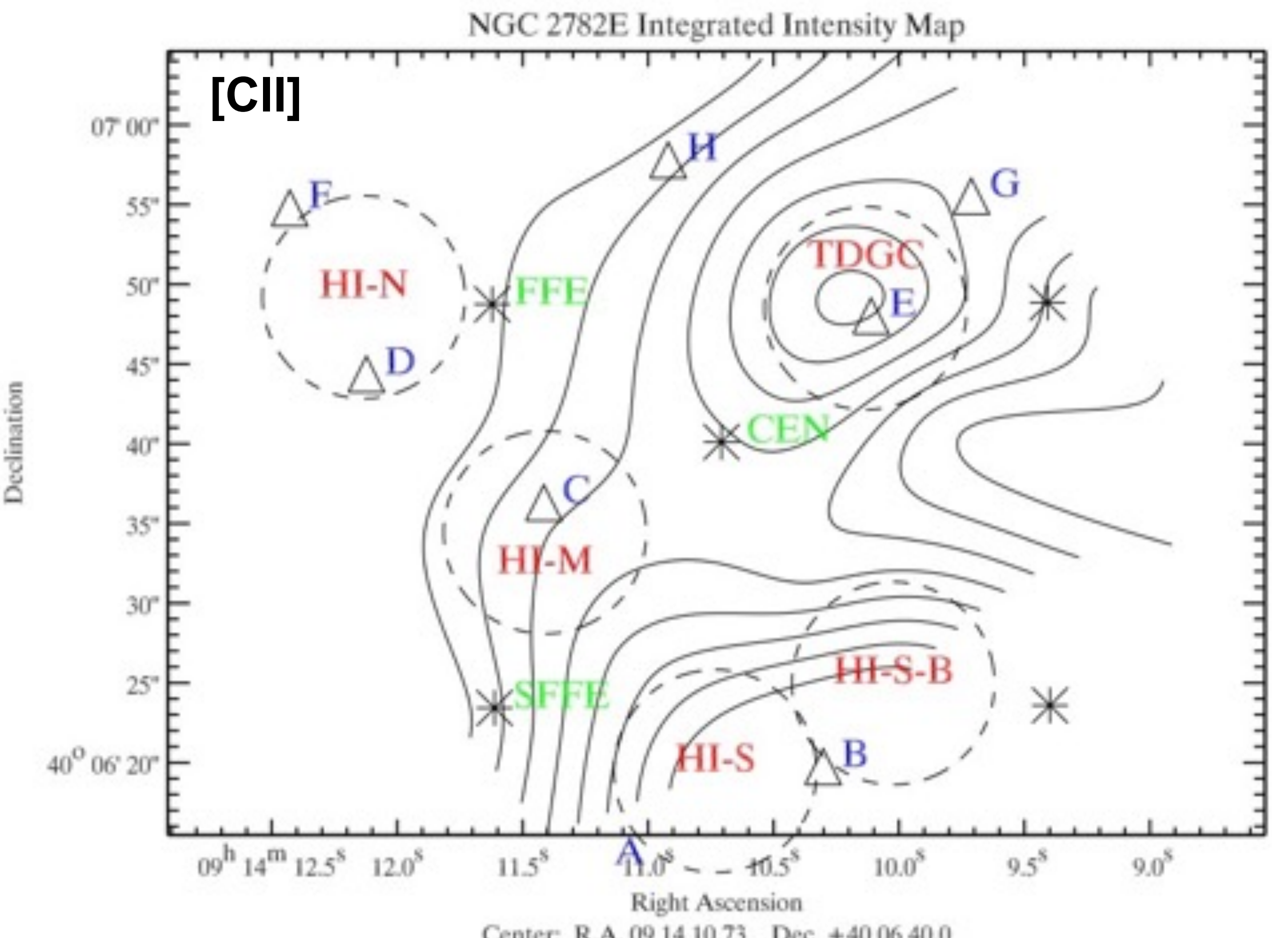


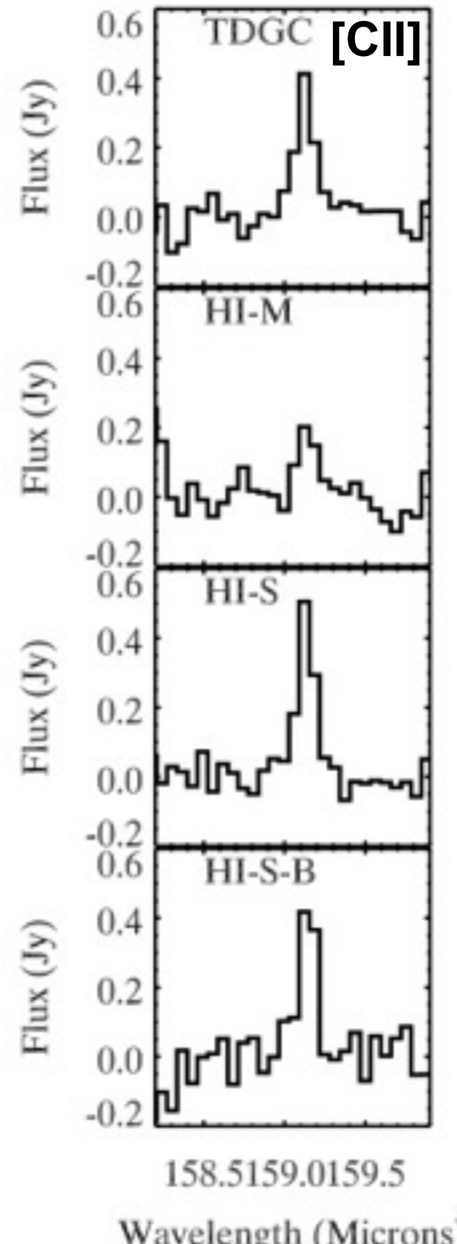


E: 28 SC Candidates
W: 19 SC Candidates
Hα sources:
6 in E (9 in Smith et al. 1999)
1 in W (brighter than E)
(Knierman+13)

Is There Dark Molecular Gas in Western Tail?

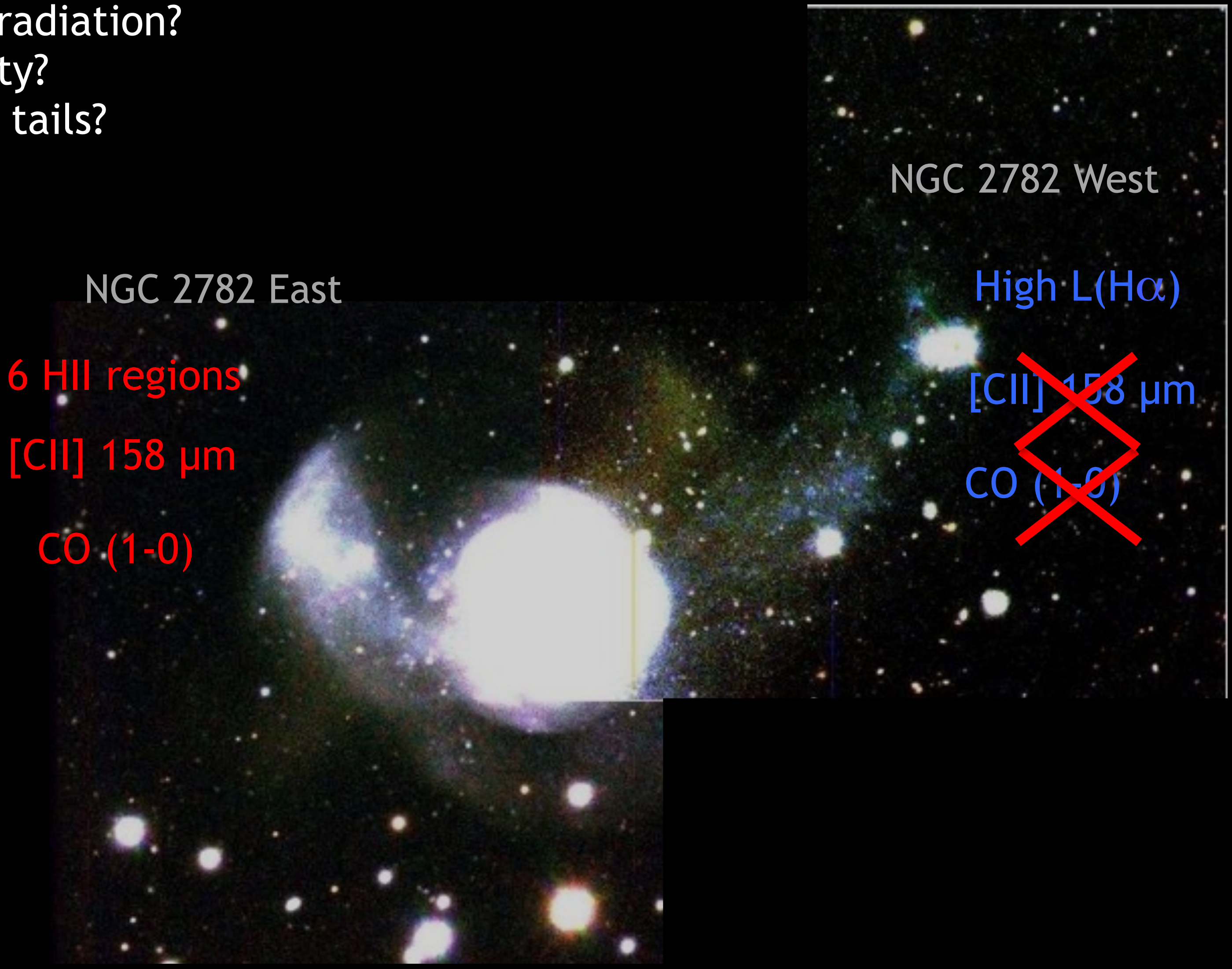
- East
  - ✓CO(1-0): confirm detection from Smith+99
  - ✓[CII]: clumpy structure, near luminous Hα
- West
  - CO(1-0): non-detection with deeper observation
  - [CII]: non-detection





Why are the two tails different?

- High UV radiation?
- Metallicity?
- Origin of tails?



Is There Dark Molecular Gas in Western Tail?

Stars are forming in the Western tail, so there should be molecular gas.

- Hα in W is 3-6 times E tail HII regions, BUT
    - CO in W < 0.05 E, [CII] in W <0.4 times E

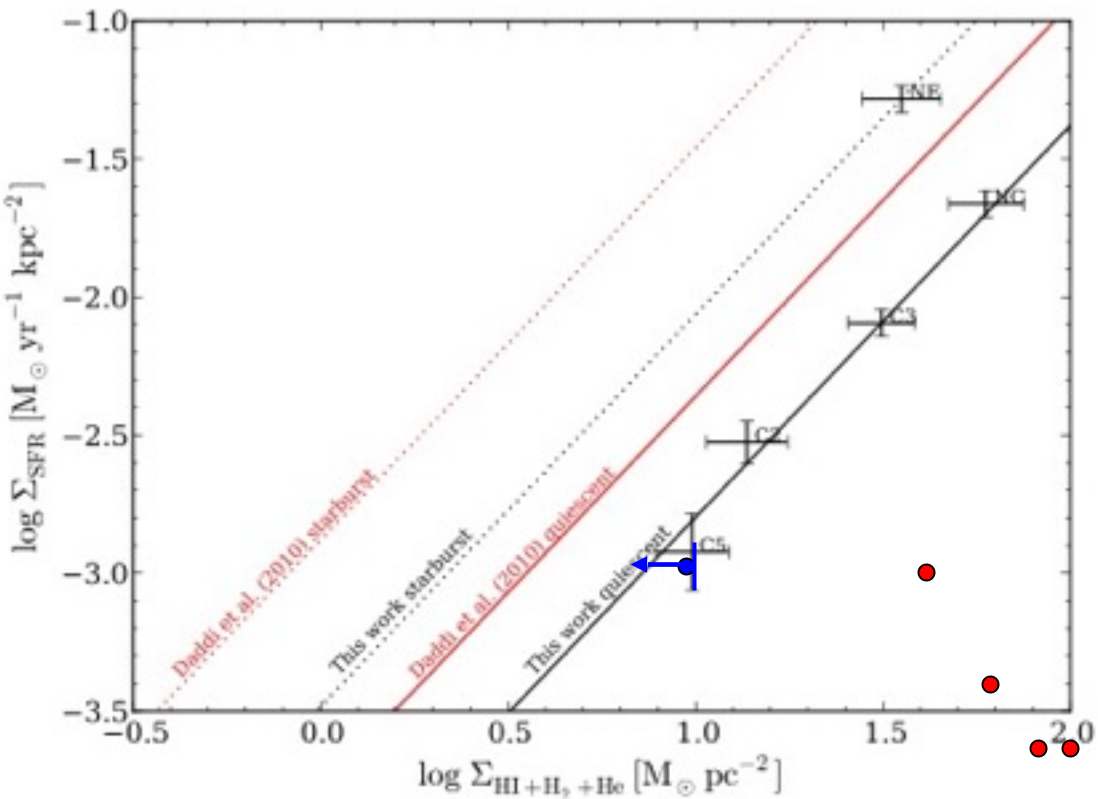
In low pressure and low density environment (A_V<1), expect:

- ✓ H_2
- No CO
    - Harder to form (need A_V>3)
- ✓ C+

Non-detection of [CII] 158μm so dark molecular gas is not C+.
Where is the molecular gas?

- **Dissociated from high UV flux?**
    - But CO easier to dissociate so should still see C+
        - W tail: GALEX: FUV-NUV = -0.14 mag (Torres-Flores+12)
- **Low metallicity?** From O lines: $Z > Z_{sun}$ (Torres-Flores+12)
- **Only H_2 ? (but very difficult to detect)**

Star Formation Efficiency - K-S Law



Total gas vs. SFR(Hα)

Different SFE

E: very low SFE

W: normal SFE

(similar to Arp 158 tidal tail)

Gas depletion time:

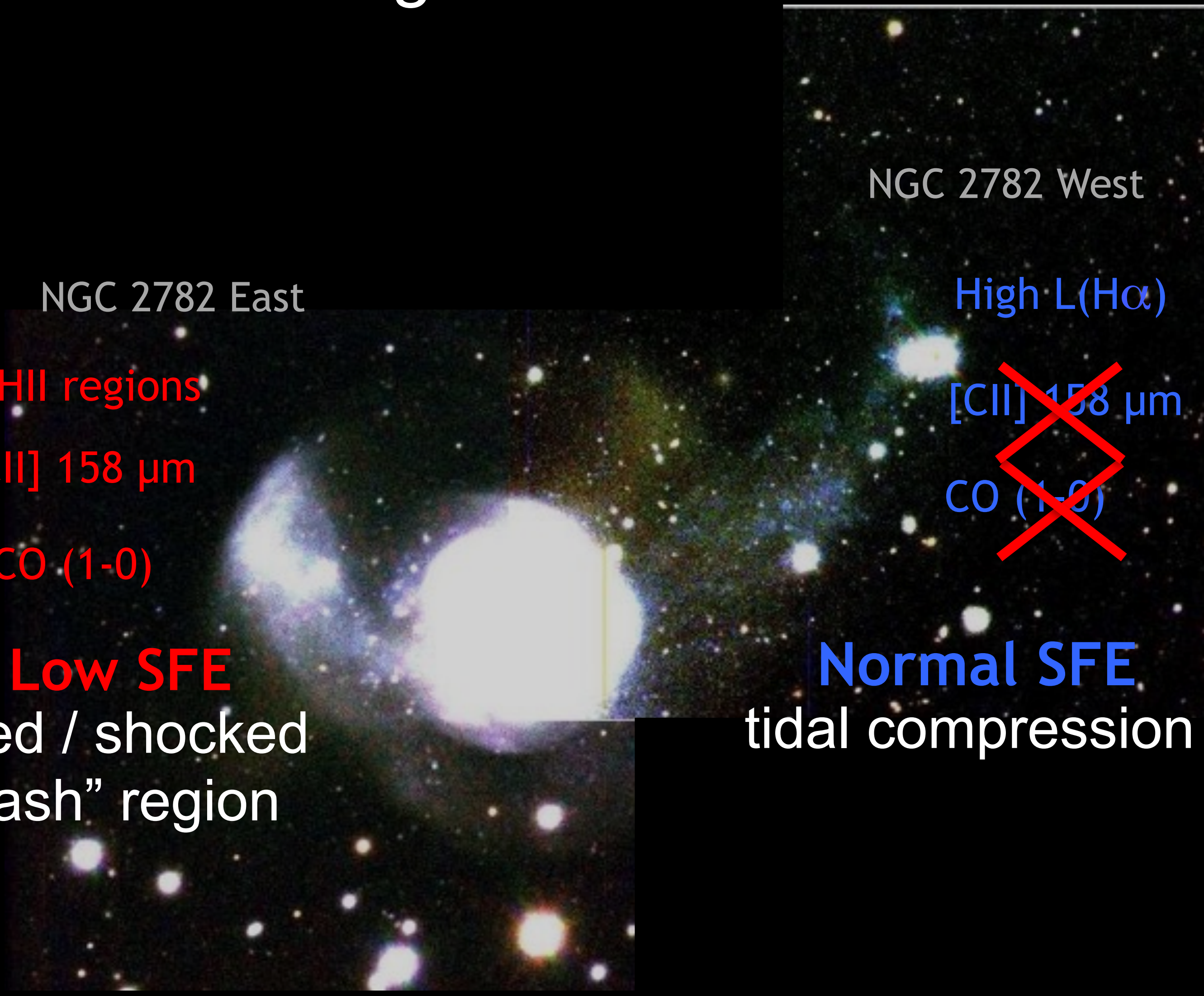
τ_{dep} = M_{mol} / SFR(Hα)

E: τ_{dep} = 33-230 Gyr

W: τ_{dep} < 1.5 Gyr

Fig. 6 from Boquien et al. 2011 with W HII region and E regions. Black points are HII regions in the major merger Arp 158, including tidal debris regions.

Origin of Tails



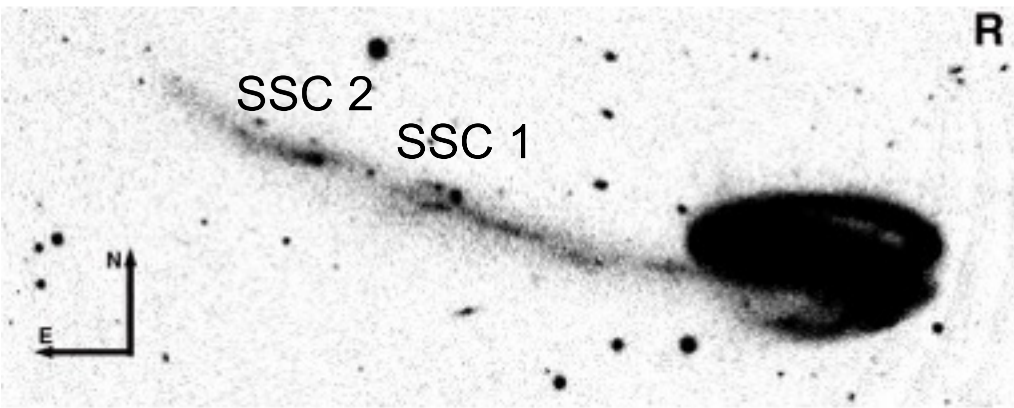
Tidal Tails of Minor Mergers III: Star Formation Efficiency and Origin of Tidal Debris in the Tadpole

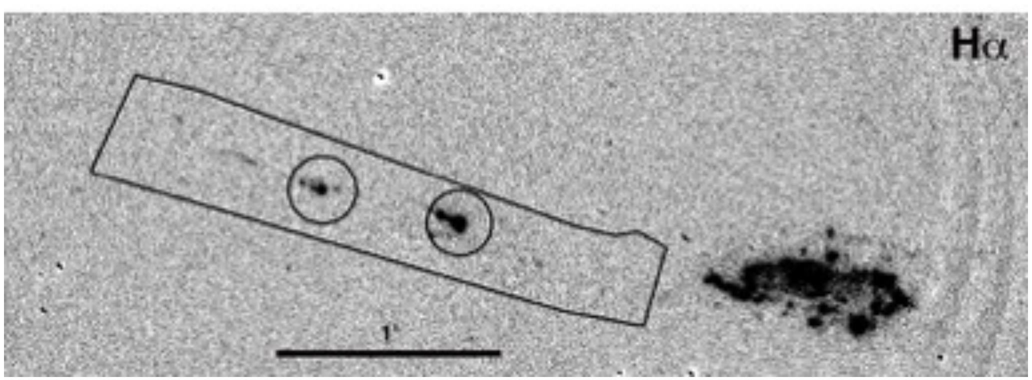
Karen Knierman, Paul Scowen, Chris Groppi (ASU), Ute Lisenfeld (Granada),John Hibbard (NRAO)

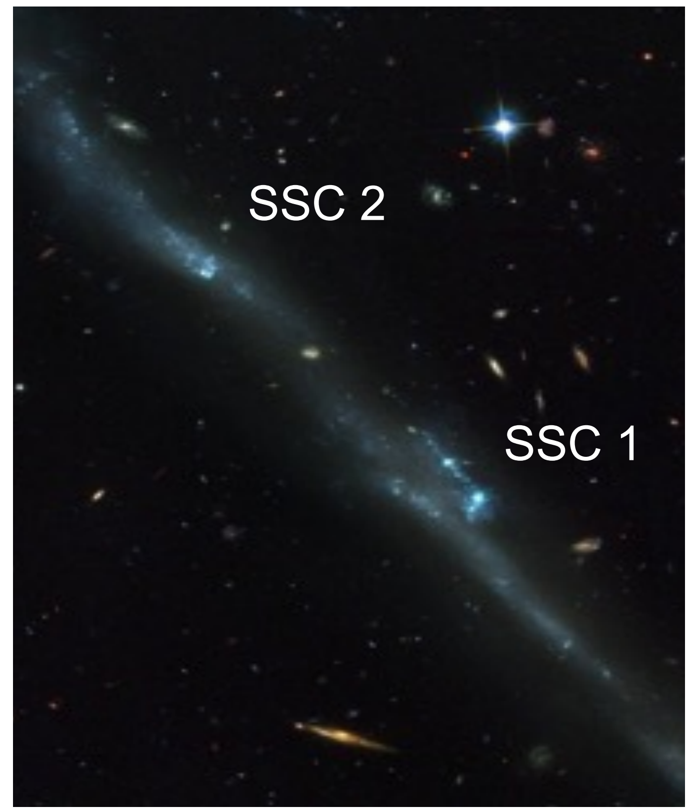
In Preparation

Tadpole Tidal Tail

- SSC 1 - U shaped grouping of star clusters
  - hosts a massive super star cluster (6.6 x 10^6 M_{sun} Jarrett+06)
  - $Z=0.3Z_{sun}$ from optical emission lines (Tran+03, Jarrett+06)
- SSC 2 - Linear grouping of star clusters
- **Entire Tail: SFR = 1.5 M_{sun}/yr which is 30-50% of total SFR in tail** (FIR, 24μm, 70μm Jarrett+06)

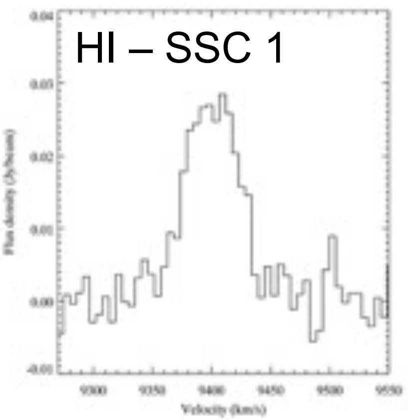






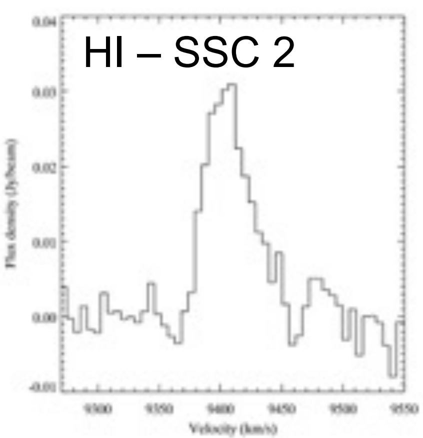
Gas Properties of the Tadpole's Tail

- ✓ Atomic gas: ~ equal in SSC 1 & SSC 2 (similar to NGC 2782 tail clumps)
  - Entire tail: 9×10^9 M_{sun} (5 times larger than NGC 2782 tails)
- Molecular gas: Non-detections of CO(1-0) & CO(2-1) with IRAM 30m



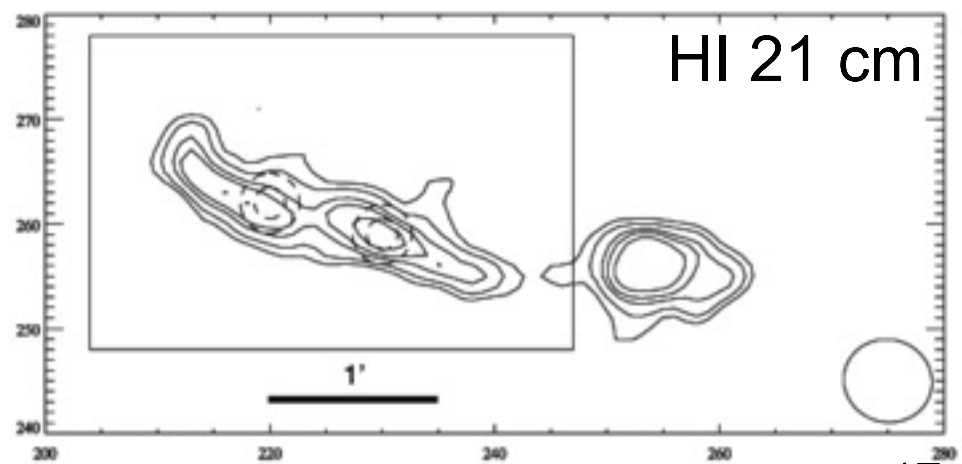
SSC 1:
$M_{mol} < 0.6\text{-}1\times10^8$ M_{sun}

$M_{HI} = 2\text{-}4\times10^8$ M_{sun}

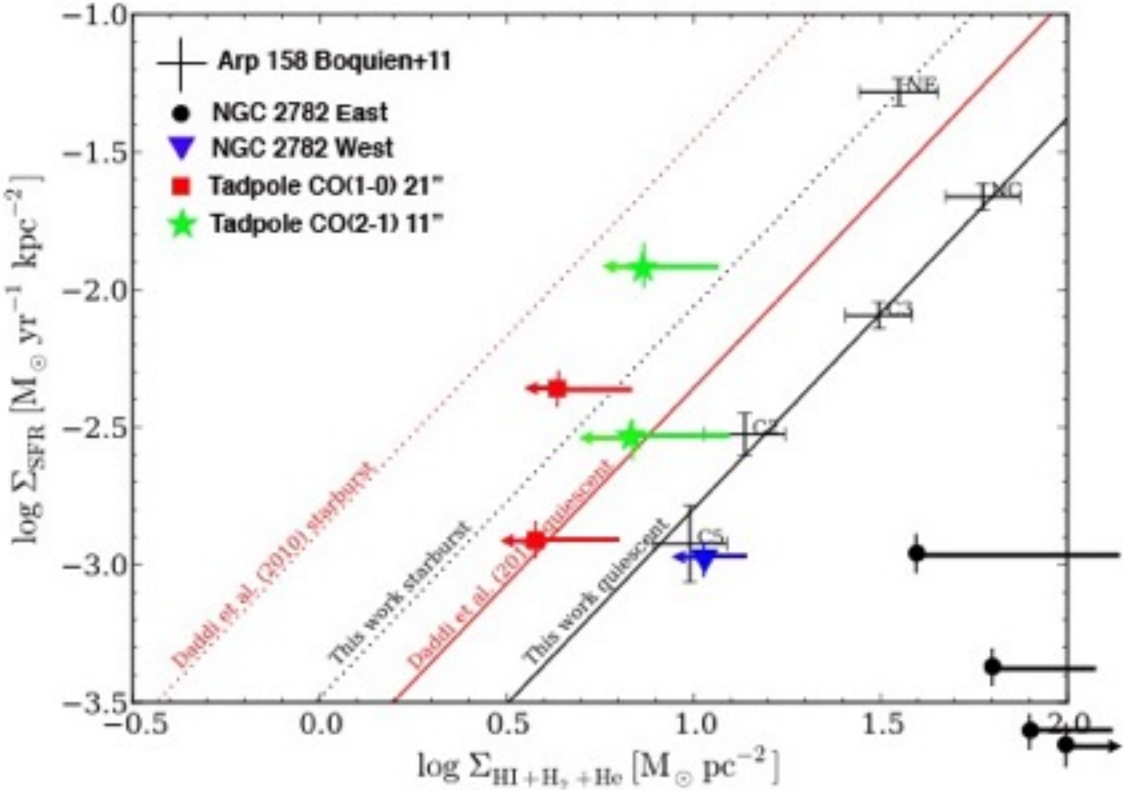


SSC 2:
$M_{mol} < 0.8\text{-}1\times10^8$ M_{sun}

$M_{HI} = 2\text{-}3\times10^8$ M_{sun}



Star Formation Efficiency - K-S Law



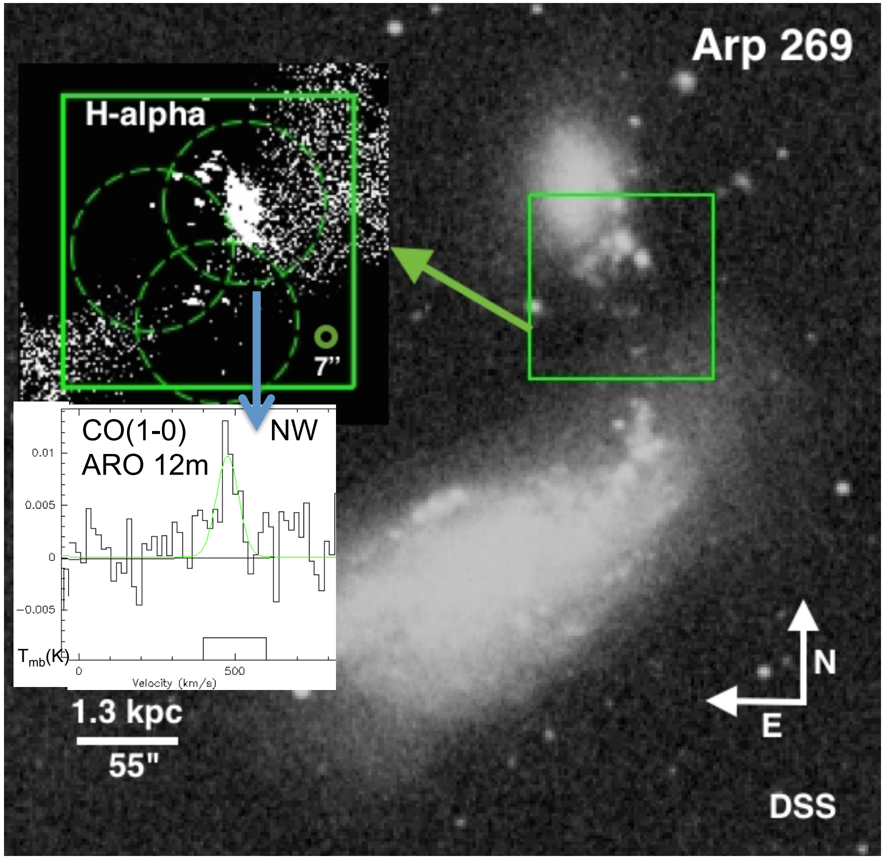
Total gas vs. SFR(Hα)
SSC 1: high SFE
SSC 2: normal SFE

Gas depletion time:
τ_{dep} = M_{mol} / SFR(Hα)
E: τ_{dep} = 33-230 Gyr
W: τ_{dep} < 1.5 Gyr
TSSC1: τ_{dep} = 0.2 Gyr
TSSC2: τ_{dep} = 0.6 Gyr

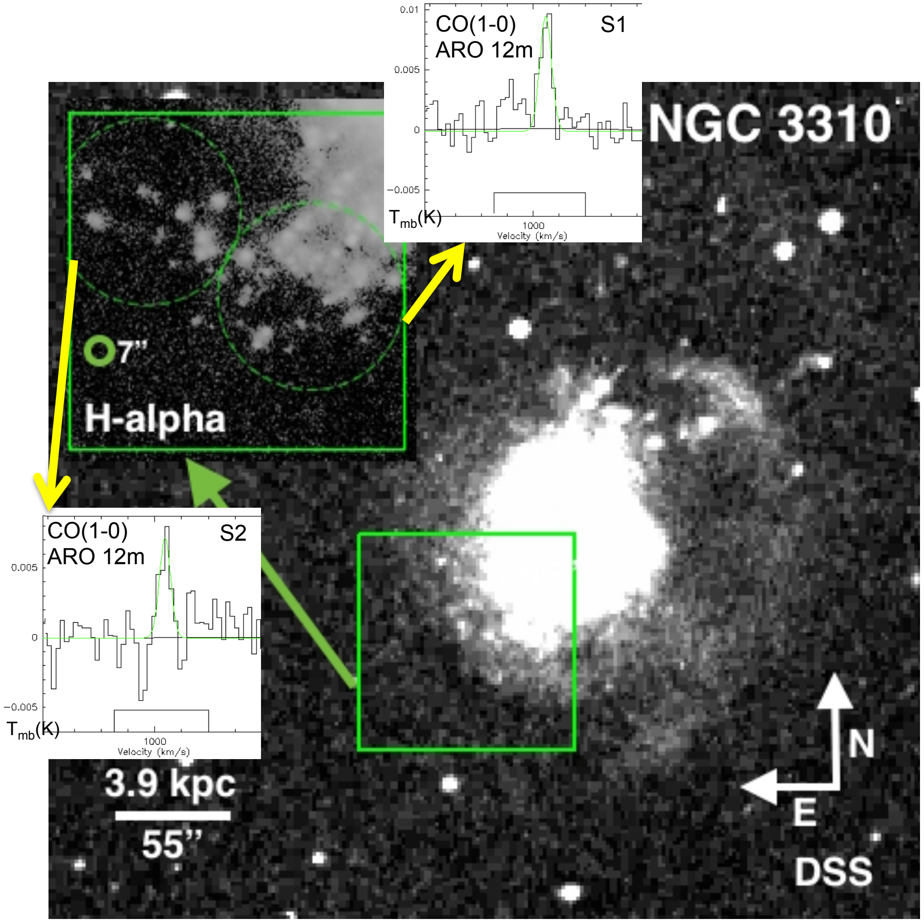
Minor Merger Tidal Debris CO(1-0) survey

8 newly observed tails have CO(1-0) detections with ARO 12m at > 3 sigma with $M_{mol} \sim 10^6$-10^9 M_{Sun}

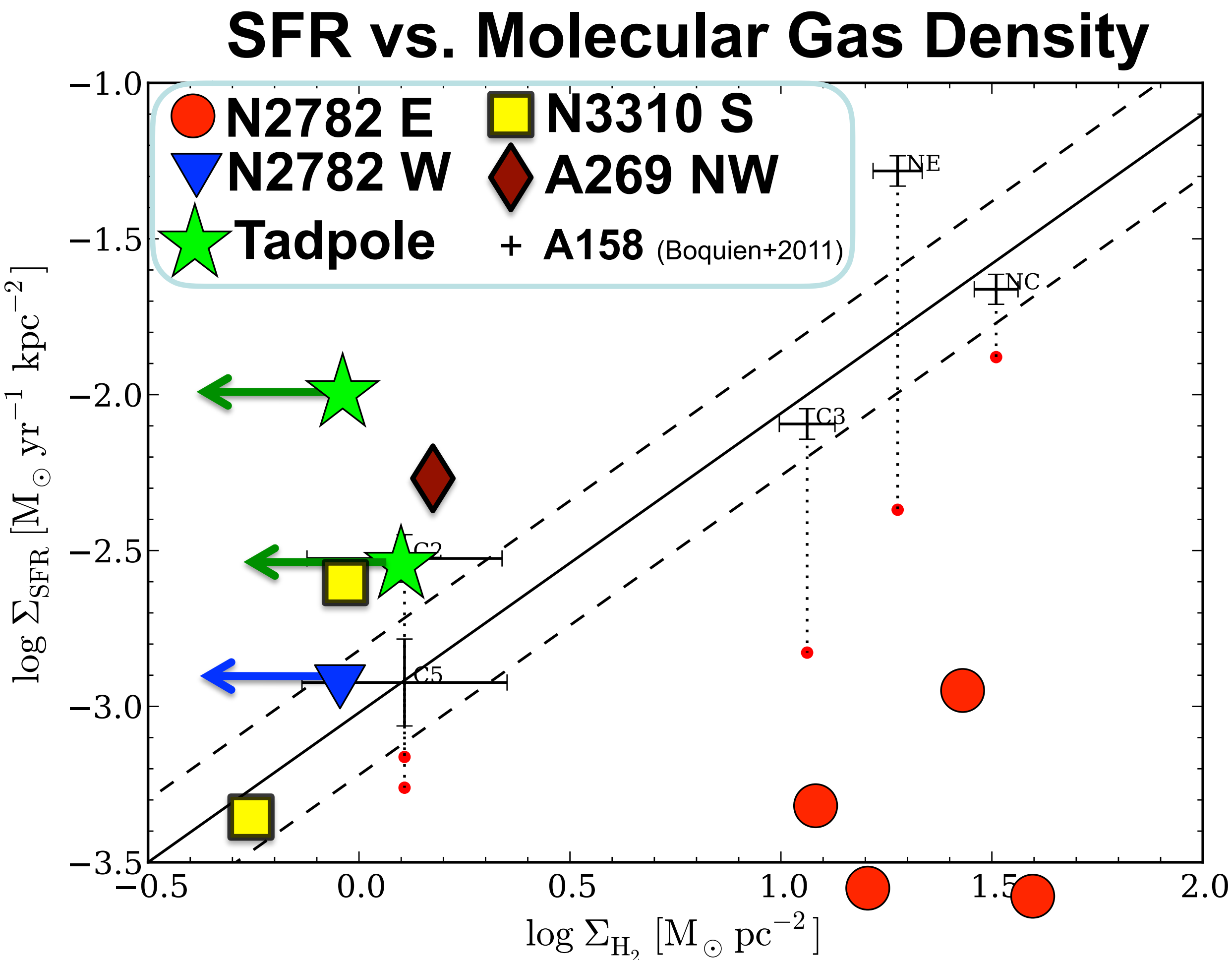
Arp 269



NGC 3310



SFE in Minor Merger Tidal Tails



Gas depletion time:

τ_{dep} = M_{mol} / SFR(Hα)

E: τ_{dep} = 33-230 Gyr

W: τ_{dep} < 1.5 Gyr

Tad1: τ_{dep} = 0.2 Gyr

Tad2: τ_{dep} = 0.6 Gyr

A269Dw: τ_{dep} = 0.3 Gyr

N3310-S1: τ_{dep} = 0.4 Gyr

N3310-S2: τ_{dep} = 1.8 Gyr

In 10 minor merger tidal tail regions presented:

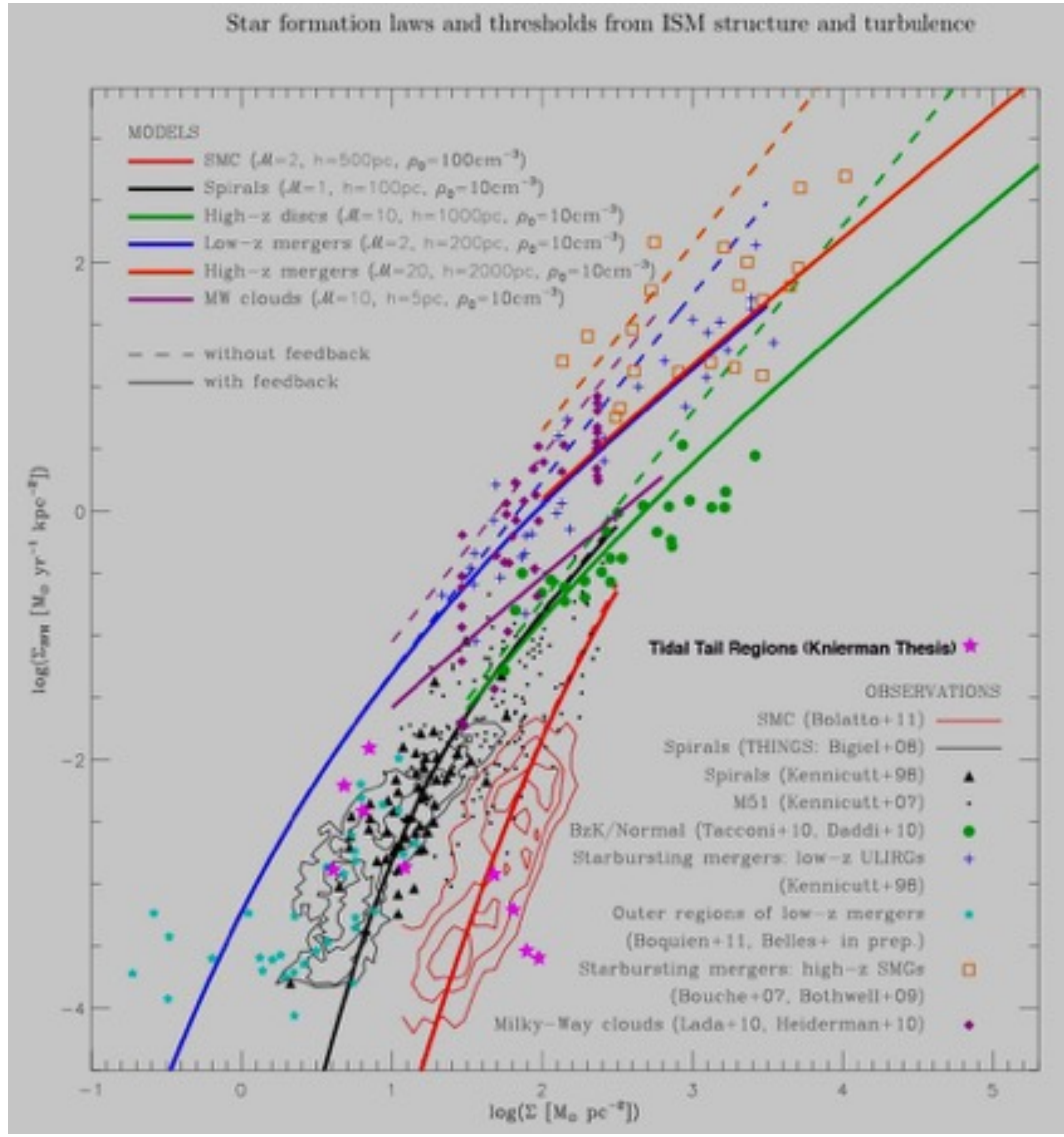
4 have low τ_{dep} = High SFE

2 have normal τ_{dep} = Normal SFE

4 have high τ_{dep} = very low SFE

Star Formation - The Big Picture

- Tadpole & W tail of NGC 2782 consistent with other tidal debris (cyan)
    - Tadpole enhanced SF (gravitational compression in tail)
    - W tail NGC 2782 similar to normal spirals & Milky Way
- E tail of NGC 2782 very low SF for its gas (similar to SMC)
    - SF is suppressed here due to feedback or shocks (“splash” region)

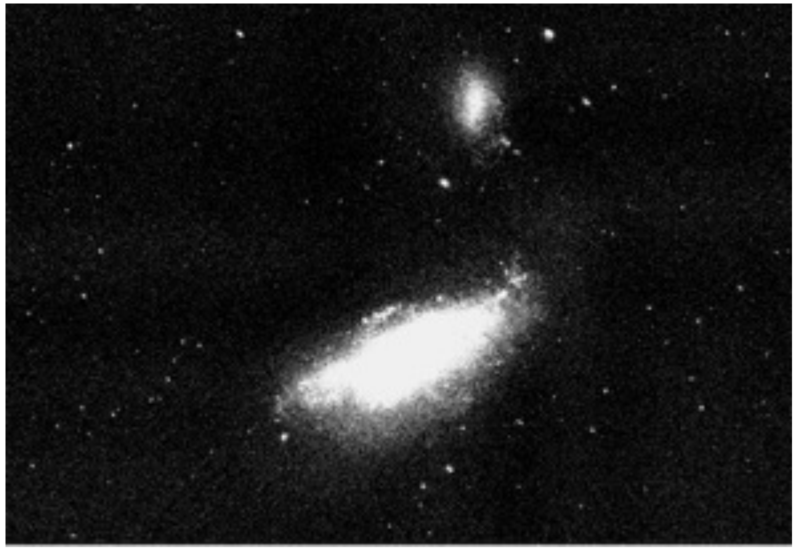


Renaud+12 with ★ from Knierman+13 and in prep.

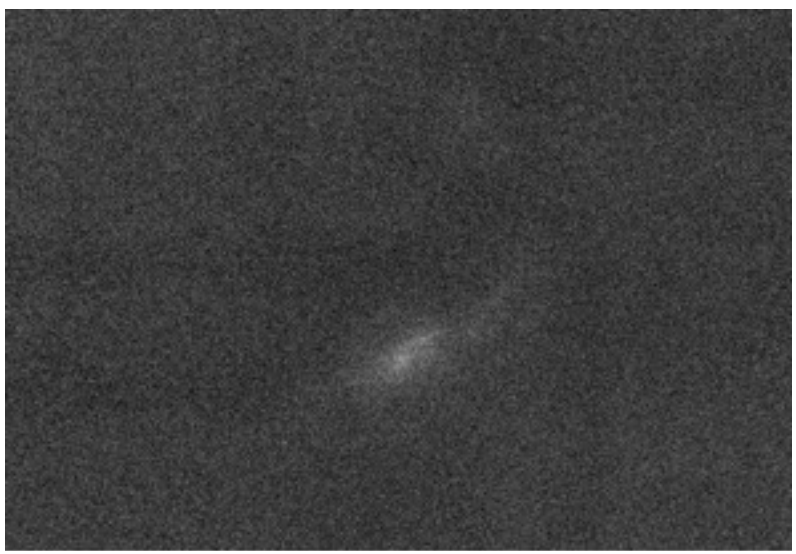
Summary & Future Work

- E tail of NGC 2782
  - Discover [CII] emission
  - Lowest SFE region reported (lower than even SMC)
- Star formation in minor merger tidal tails:
  - Can be as high as half of the total SFR of the entire merger (Tadpole, consistent with merger simulations by Hopkins+12)
  - Hα may not trace all of recent star formation if low mass star clusters are preferred (W tail of NGC 2782)
  - high or low efficiency, depending on formation mechanism (gravitational compression in tidally formed regions increasing SF or shocks in “splash” regions suppressing SF).
- Future work
  - Full Sample: local and global SFR/SFE (HI + CO), origin (Z/Z_{Sun})
  - Is H_2 the dark molecular gas in tidal tails?
    - UKIRT observations of 2.12 micron H_2 line (T~2000K)
  - Estimate the contribution to cosmic SF by tidal debris from major and minor mergers using merger rates

Preliminary Results of the first survey for H_2 in tidal tails using UKIRT WFCAM

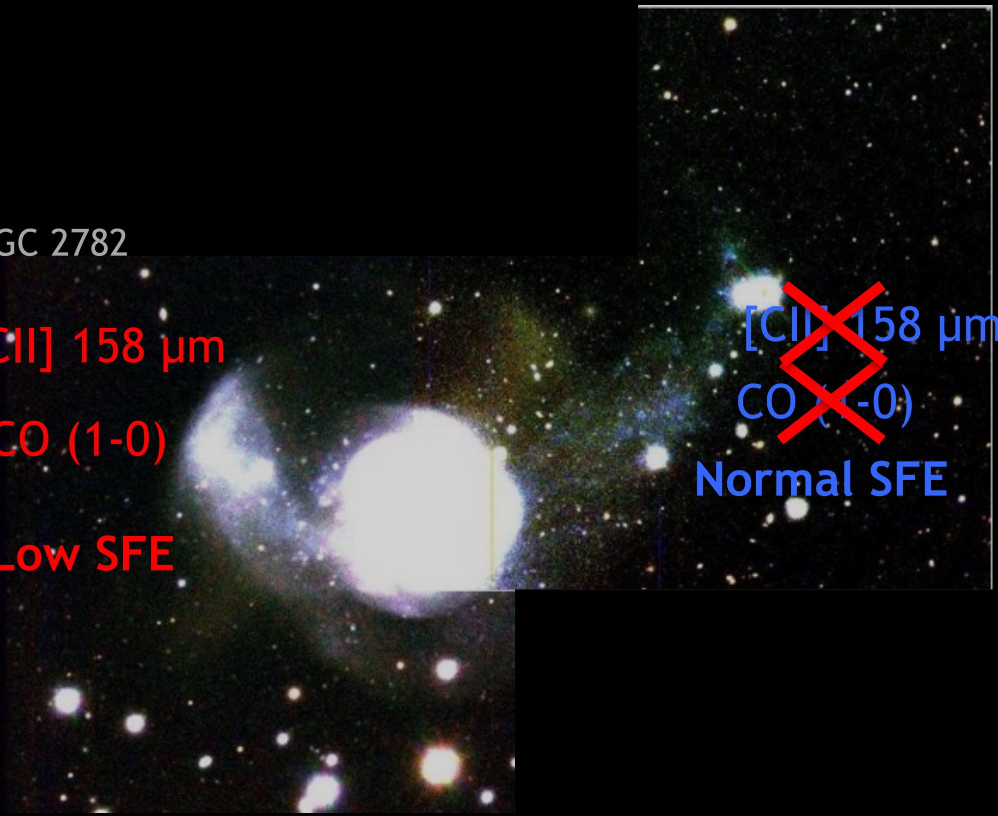


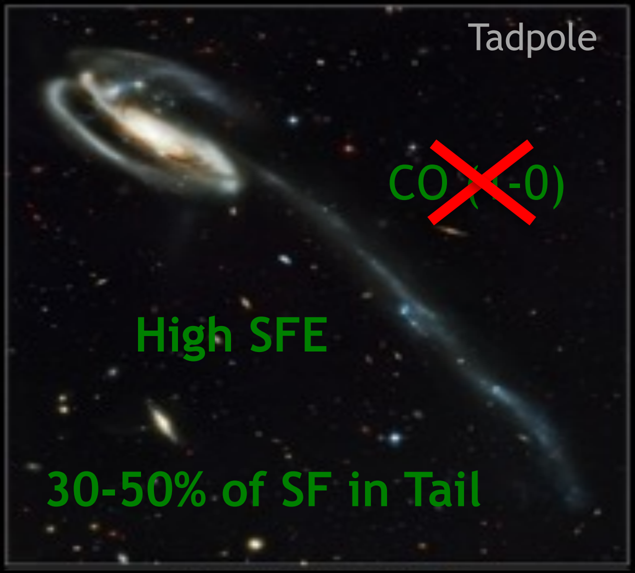
Arp 269
K-band



continuum subtracted
H_2 1-0 S1 2.12μm

Thank you all very much!


NGC 2782
[CII] 158 μm
CO (1-0)
Low SFE
~~[CII] 158 μm~~
~~CO (1-0)~~
Normal SFE


Tadpole
~~CO (1-0)~~
High SFE
30-50% of SF in Tail


Arp 269
CO (1-0)
High SFE


NGC 3310
CO (1-0)
Normal SFE

Gas depletion time:

$\tau_{dep} = M_{mol}$ / SFR(Hα)

E: τ_{dep} = 33-230 Gyr

W: $\tau_{dep} < 1.5$ Gyr

TSSC1: τ_{dep} = 0.2 Gyr

TSSC2: τ_{dep} = 0.6 Gyr

A269Dw: τ_{dep} = 0.3 Gyr

N3310-S1: τ_{dep} = 0.4 Gyr

N3310-S2: τ_{dep} = 1.8 Gyr

Is There Dark Molecular Gas in Western Tail?

Stars are forming in the Western tail, so there should be molecular gas.

- Hα in W is 3-6 times E tail HII regions, BUT
  - CO in W < 0.05 E, [CII] in W <0.4 times E

In low pressure and low density environment (A_V<1), expect:

- ✓ H_2
- No CO
  - Harder to form (need A_V>3)
- ✓ C+

Non-detection of [CII] 158μm so dark molecular gas is not C+.

Where is the molecular gas?

- Dissociated from high UV flux?
  - But CO easier to dissociate so should still see C+
    - W tail: GALEX: FUV-NUV = -0.14 mag (Torres-Flores+12)
- **Low metallicity?**
- **Only H_2 ? (but very difficult to detect)**

Why Lack of [CII] in Western Tail?

Recent star formation with lack of CO & lack of [CII]:

Is the gas just very low metallicity?

Torres-Flores+12 show $Z > Z_{sun}$ using optical emission line spectra of young star clusters in the western tail.
BUT they use the nebular oxygen emission for their abundances.

The Western tail
- may have a different C/O ratio than solar.
because
- it may be undergoing its first generation of stars:
  - O is the most common element produced in core-collapse SN
  - C in the ISM is mostly from AGB stars (Arnett 1996)
  - tail age is 200-300 Myr so it is unlikely to have built up much C
  - have a low C/O ratio
  - origin in dwarf galaxy?

Star Formation Efficiency - τ_{dep}

Gas depletion time: τ_{dep} = Gas mass/SFR = 1/SFE

Normal Spiral: 2 Gyr (Kennicutt98)

Arp 158: 0.5-2 Gyr (Boquien+11); TDGs 0.8-4 Gyr (Braine+01)

M_{mol} / SFR(Hα):

E: low SFE

W: *normal* SFE (similar to Arp 158 tidal tail)

M_{HI} / SFR(Hα):

low SFE

M_{HI} / SFR([CII]):

low SFE

M_{mol} / SFR([CII]):

E: *normal* SFE (PACS field)

W: low SFE

Location	$\tau_{dep,H_2,H\alpha}$ (Gyr)	$\tau_{dep,HI,H\alpha}$ (Gyr)	$\tau_{dep,H_2,[CII]}$ (Gyr)	$\tau_{dep,HI,[CII]}$ (Gyr)
East				
TDGC	33	5	8.2	1.3
HI-N	81	160	>70	>141
HI-M	232	200	21	18
HI-S	38	81	5.6	12
E Tail	16[a]	43	2.7[a]	7
West				
HI-N	<29[a]	>240		
HI-M	<1.5	7.7	<1.4[b]	>7.3
HI-S	<53[b]	>390		
W Tail	< 12	133	< 4[b]	> 45

[a]Using observations from this work.

[b]Both gas mass and SFR are upper limits.

Star Formation Efficiency - τ_{dep}

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Normal Spiral: 2 Gyr (Kennicutt98)

Arp 158: 0.5-2 Gyr (Boquien+11); TDGs 0.8-4 Gyr (Braine+01)

M_{mol} / SFR(Hα):
SSC 1: **high** SFE
SSC 2: normal SFE
(similar to Arp 158 tidal tail)
Total: **high** SFE

M_{HI} / SFR(Hα):
SSC 1: **high** SFE
SSC 2: normal SFE
Total: low SFE

M_{tot} / SFR(Hα):
SSC 1: normal SFE
SSC 2: normal SFE
Total: low SFE

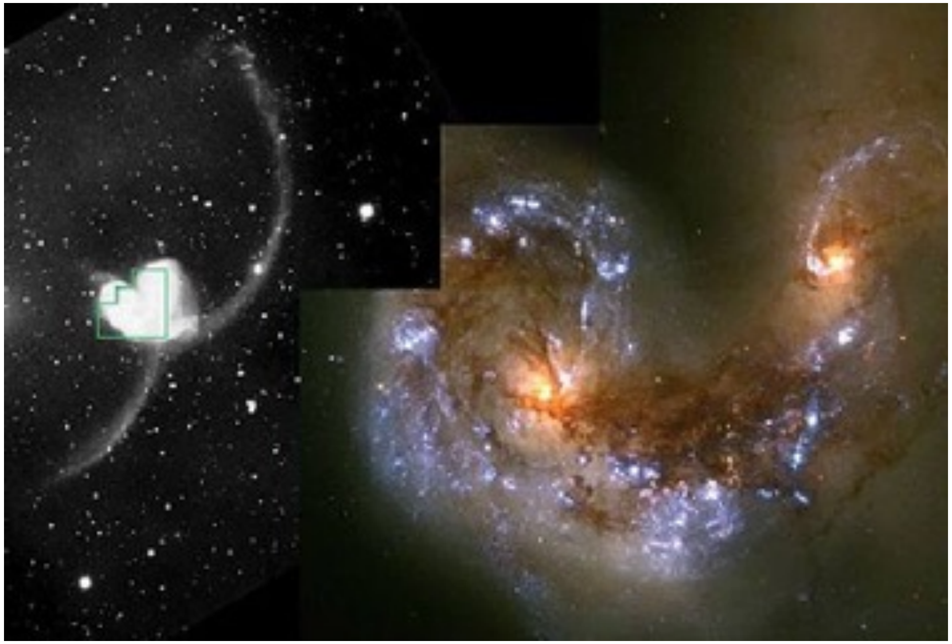
Location	τ_{dep,H_2},Hα (Gyr)	τ_{dep},HI,Hα (Gyr)	$\tau_{dep,tot}$,Hα (Gyr)
CO(1-0) 21″			
SSC 1	< 0.16	0.56	< 0.92
SSC 2	< 0.63	1.9	< 3.2
Total	< 0.17	7.2	< 9.9
CO(2-1) 11″			
SSC 1	< 0.11	0.40	< 0.65
SSC 2	< 0.58	1.3	< 2.3

Major Galaxy Mergers

Major Merger

Mass ratio between galaxies of ~0.5-1.0

NGC 4676 “The Mice” ACS ERO

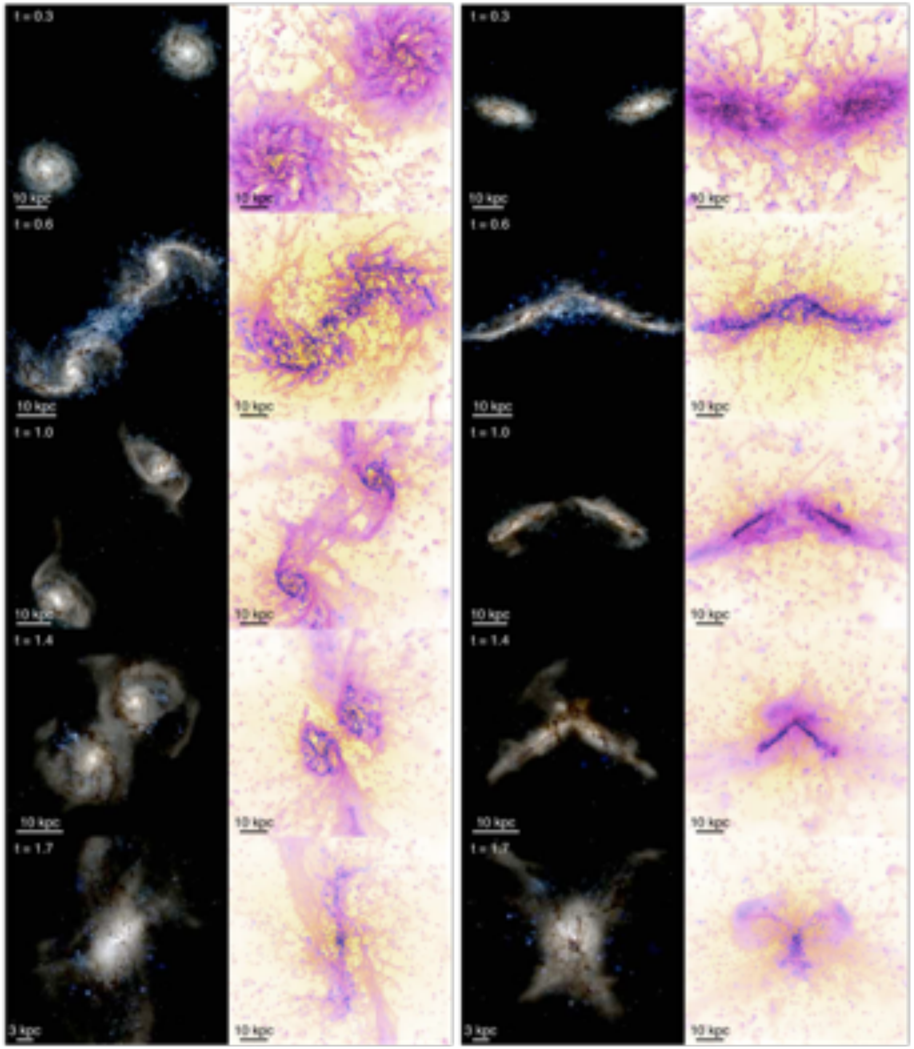


Compact Group “Stephan’s Quintet” WFPC2

NGC 4038/9 “The Antennae” WFPC2

Simulations - Phil Hopkins et al.

- 200 million particles, Parsec scales
- Feedback on small scales in GMCs/ SF regions
  - Momentum from:
    - Stellar radiation pressure
    - Radiation pressure from SF regions
    - HII photoionization heating
    - Heating, momentum, mass loss
      - Sne I and II
      - Stellar winds (O & AGB stars)
- Realistic cooling to T < 100 K
- Treatment of molecular/atomic transition in gas and its affect on SF
- Reproduces Star Formation Law with no tuning of parameters
- **20-50% of total star formation in merger in tidal debris (vs. ~10% in early models; Barnes 2004)**



Major Mergers
2 Gas Rich Spiral Galaxies
Hopkins et al. 2012

Sample Selection

For examination of star formation on few kpc scales need:

- Star Formation
  - Deep UBVR optical broadband (VATT 1.8m)
  - High resolution optical images (Hubble)
  - Star Formation Rate (SFR): Hα narrowband (VATT)
- Molecular Gas Mass
  - CO(1-0) (ARO Kitt Peak 12m/IRAM)
  - Dark gas: [CII] 158μm Herschel PACS spectroscopy
- Neutral Gas Mass
  - High resolution 21 cm HI from VLA

NGC 2782 has these data, and then test the techniques for UGC 10214 ("The Tadpole").

Why are there Differences between the Tails?

We find:

-Lack of massive star clusters & complexes in Western tail

-Lack of CO and [CII] in Western tail

-But most luminous HII region in Western tail

Examine:

•Ambient pressure

•**Gas phase**

•Star Formation Rates

•**Amount of gas available for star formation**

•**Star formation efficiency**

Gas Phase

- Molecular to Neutral
  - **W deficient in molecular gas (or CO) compared to HI**
    - M_{mol}/M_{HI}: E: 0.5-6, W=<0.2
- Ionized to Neutral
  - Both tails deficient in [CII] compared to HI
    - Similar or lower [CII] than Standard HI clouds (Stacey+91)
- Ionized to Molecular
  - $I_{[CII]}/I_{CO}$:
    - SF regions = 6300 (Stacey+91)
    - M33 Herschel = 1000-70,000 (Mookerjea+11)
  - **E tail is deficient in [CII] compared to CO**
    - E (HII): $I_{[CII]}/I_{CO}$ = 1800-4900
    - E (tot): >1200 (CO & [CII] spatial scales match)
  - W tail upper limits have higher [CII] compared to CO limit
    - W: $I_{[CII]}/I_{CO}$ >35,000* (similar to LMC 30 Dor: $I_{[CII]}/I_{CO}$ = 40,000)

Gas Reservoir for Star Formation

Inconsistent results:

- Both tails: abundant neutral gas
- E - more molecular & ionized gas
- W - highest local SFR
- E - higher Σ_{gas}
- E - higher SFR([CII])
- BUT Both tails - similar local $\Sigma_{SFR}(H\alpha)$
    - similar SFE?

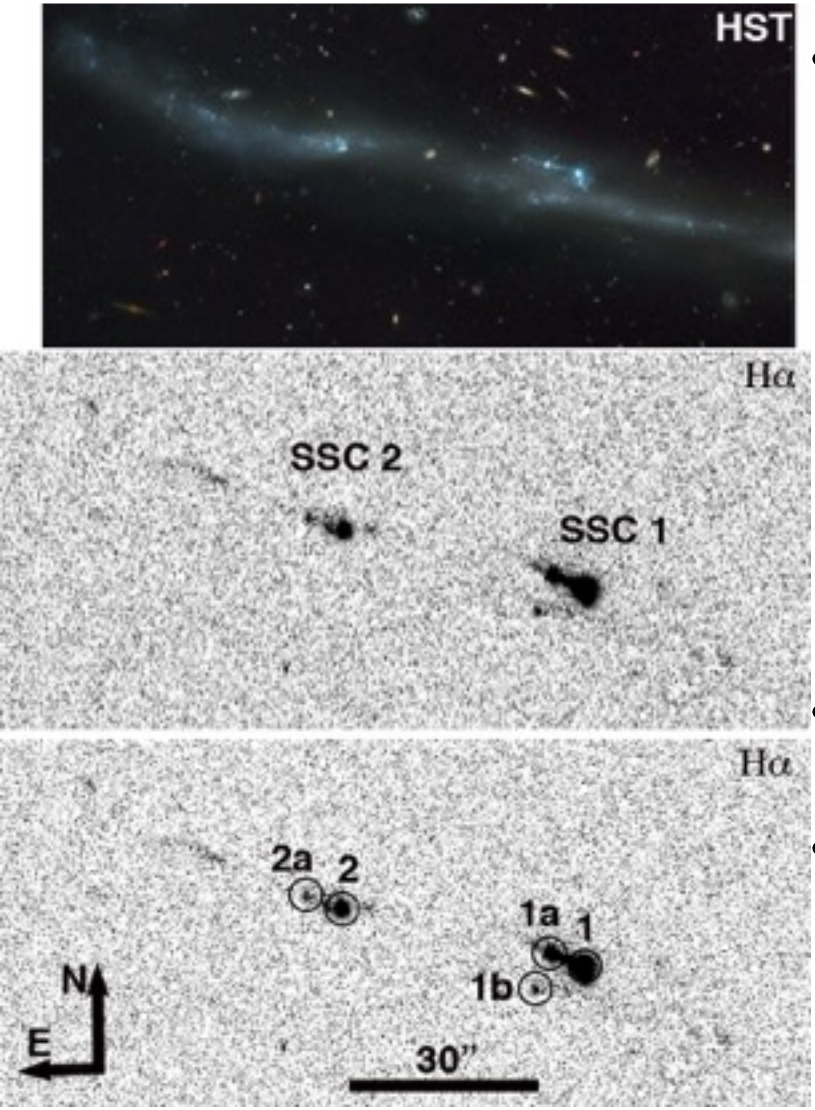
Conclusions – NGC 2782

- Both tails of NGC 2782 host young star clusters or star cluster complexes that formed in situ. But the Western tail lacks massive star clusters & star cluster complexes.
- Discover [CII] emission in the Eastern tail (coincident with Hα) and no detection for Western tail HII region to a significant level.
- Due to lack of CO and [CII] emission, Western tail may have low C/O and be undergoing first generation of stars.
- Western tail has a normal SFE, but Eastern tail has a low SFE. Eastern tail may be shocked "splash" region where gas heating is important, whereas Western tail is a tidally formed region where gravitational compression enhances star formation.

Motivation

- NGC 2782 has different SFE in the tidal debris depending on which indicators (total gas vs. molecular)
  - Is this true for other minor mergers?
- Test methods in 2nd galaxy of same merger stage (late): UGC 10214 (“Tadpole”)
  - Mass ratio ~0.15
  - Tail age ~ 150 Myr (Jarrett+06) or ~400-800 Myr (deGrijs+03)
  - Has similar observations to NGC 2782 plus
    - HST optical images (Tran et al. 2003, de Grijs et al. 2003)
    - Spitzer IRAC & MIPS, near infrared (Jarrett et al. 2006)
    - Optical spectra (Tran et al. 2003, Jarrett et al. 2006)
- Determine
  - SFR from Hα
  - expected SFR from gas surface density
  - SFE

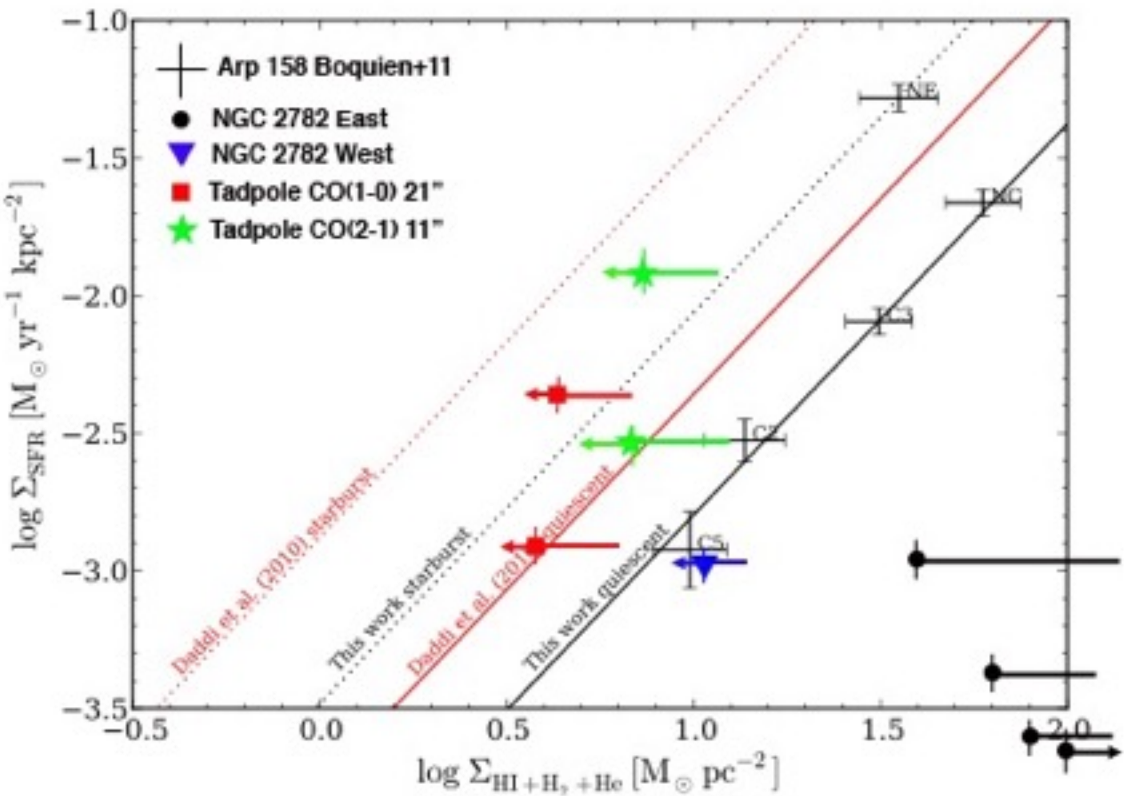
Higher SFR in Tadpole Tail



- Hα has clumpy structure associated with SSC 1 and SSC 2
- 6" scale
  - SSC 1: 3 HII regions
    - Brightest is elongated - multiple SCs
      - SFR 4-24 times higher than 1a and 1b
  - SSC 2: 2 HII regions
    - Brightest is rounder
      - ~5 times higher SFR than 2a
  - **All brighter than NGC 2782 tail HII regions**
- 12" scale CO(2-1) & 21" scale CO(1-0)
  - SSC 1 has SFR 4 times SSC 2
- Entire Tail
  - SFR = 1.5 M_{sun}/yr
  - Similar to SFR of entire Milky Way galaxy
  - **30-50% of total SFR in Tadpole** (using FIR, 24 μm, or 70 μm of Jarrett+06)

Conclusions from Tadpole Tidal Tail

- Confirm methods used for NGC 2782
- Tadpole tail also shows different SFE from different indicators (molecular vs. atomic gas mass)
- Local SFR higher than in NGC 2782 tails
- Global tail SFR is 30-50% of entire SFR for Tadpole
- SFE is higher than in tidal tails of NGC 2782 or Arp 158



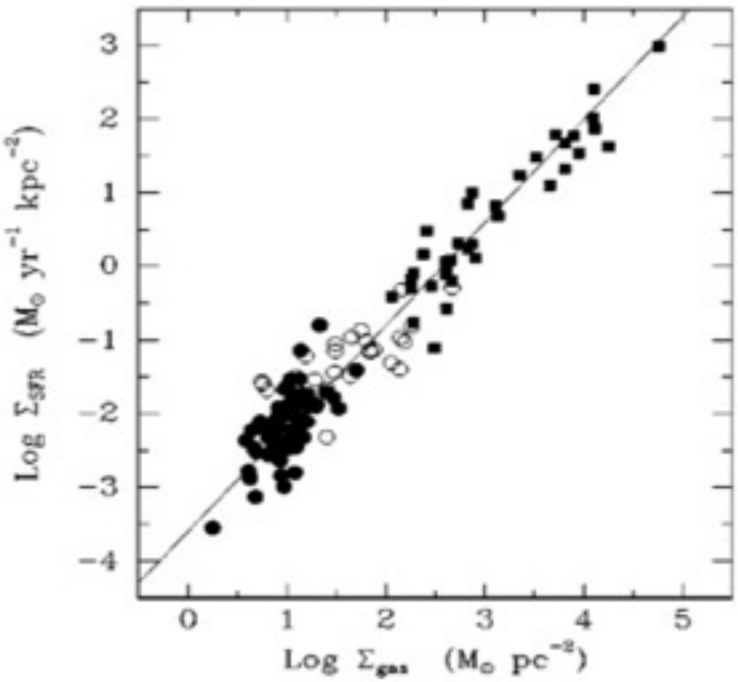
Summary of Observations

- Observed minor mergers with multiwavelength data to examine star formation on local scales in tidal debris
  - Star formation rates
  - Molecular gas mass
  - Atomic gas mass
  - Derived properties:
    - SFR
    - Expected SFR from gas density
    - Gas depletion time
    - SFE
- Found first detection of [CII] in tidal debris (E tail of NGC 2782)
- Different indicators for star formation and how it relates to gas properties can tell different stories in the same object.

Star Formation Laws

- Stars can form when a gas cloud cools and collapses
- Factors that influence SF include
  - Gas density
  - Pressure
  - Temperature
- The surface density of gas is related exponentially to the surface density of star formation via Schmidt Law $\Sigma_{SFR} = A\Sigma^{N}_{gas}$

Kennicutt-Schmidt Law:
(Kennicutt 98):
$\Sigma_{SFR} = 2.4 \times 10^{-4}\ \Sigma^{1.4}_{gas}$
Using normal spirals, Circumnuclear starbursts, and centers of disks

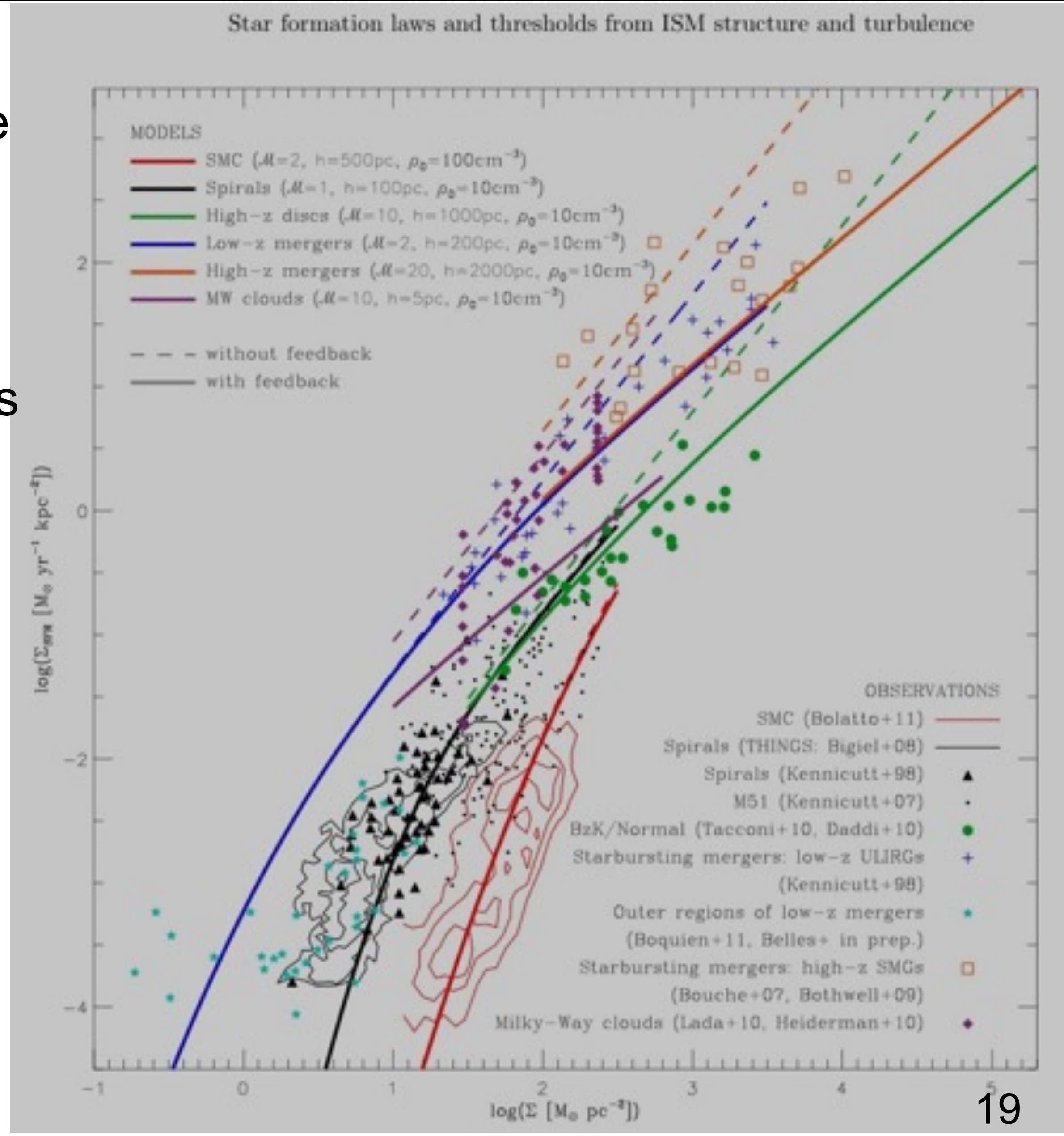


Does Schmidt Law vary in different environment or different spatial scales?

Star Formation Laws

- Recent studies explore the Schmidt Law in different environments & scales
  - High redshift starburst galaxies
  - Regions inside galaxies (~1 kpc)
- The form is similar, but there are variations of ~ 2 dex between environments due to different gas pressures & densities

Renaud+12



Are there differences in star clusters between tails?

Eastern Tail: 28 SC Candidates

Western Tail: 19 SC Candidates

Eastern tail has more luminous SCC than Western tail, indicating possible difference in the mass of star clusters formed.

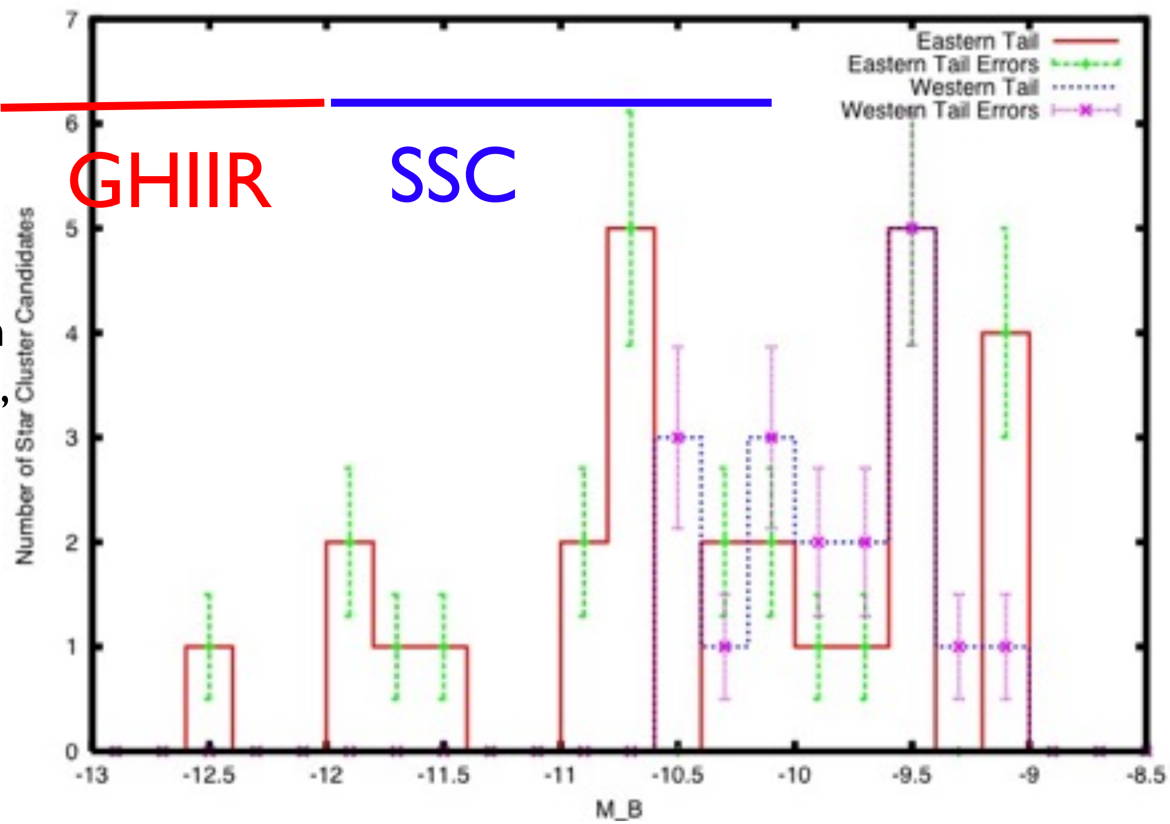
But what are spatial scales of star formation?

TDG

GHIIR

SSC

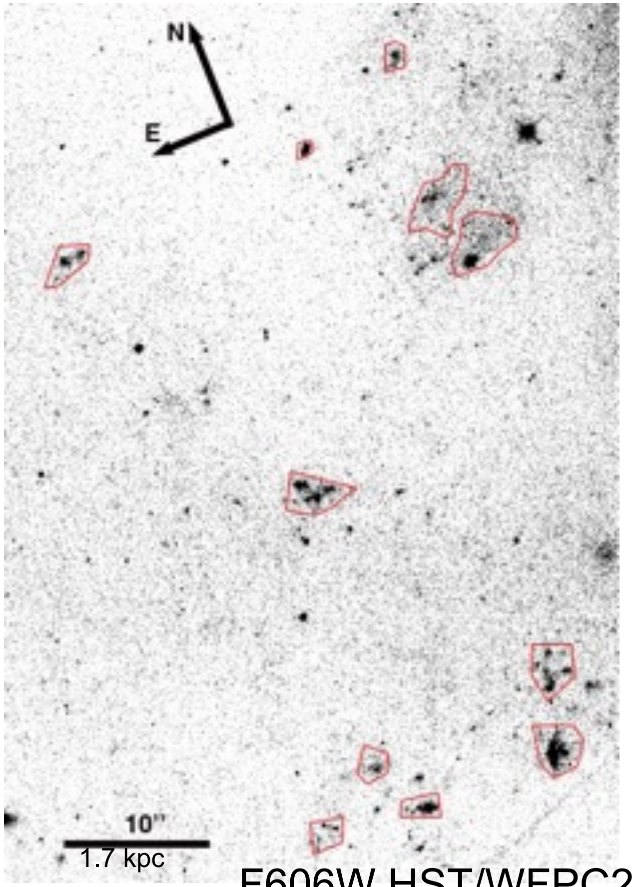
Ranges taken from Ferreiro, Pastoriza, & Rickes 2006



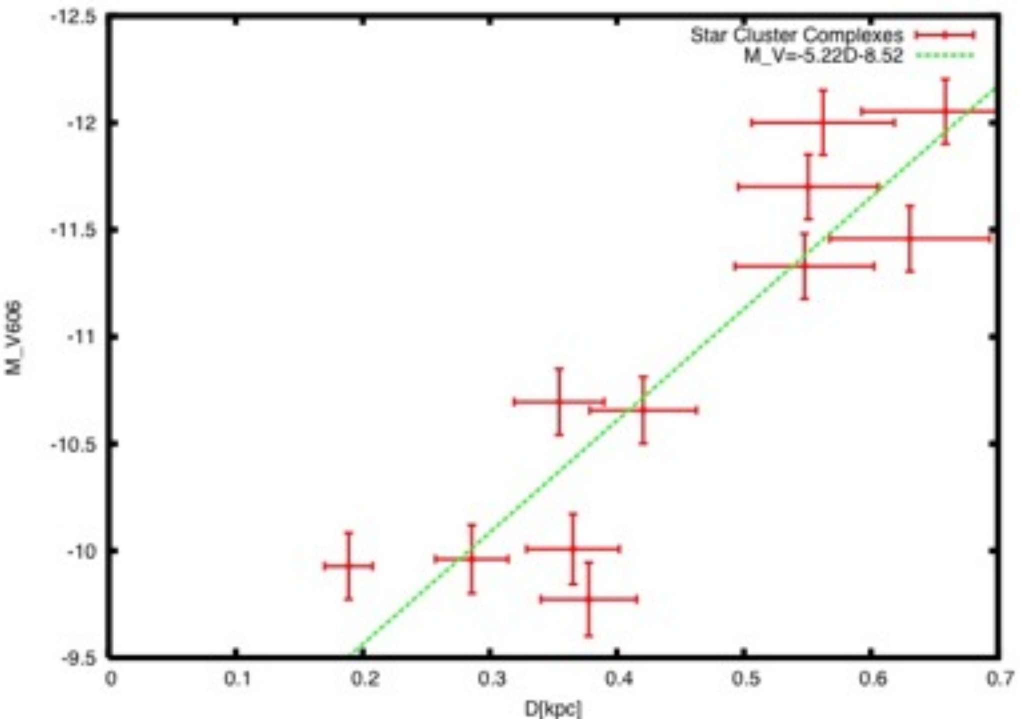
Star Formation Morphology

Using Hubble Space Telescope observations (Mullan et al. 2011)

- E tail has groupings of star clusters called Star Cluster Complexes
  - Has linear Size-Luminosity relation, similar to complexes in nearby spirals (Elmegreen & Salzer 1999) and compact group HCG 59 (Konstanopoulos et al. 2012)
- W tail has isolated star clusters



F606W HST/WFPC2

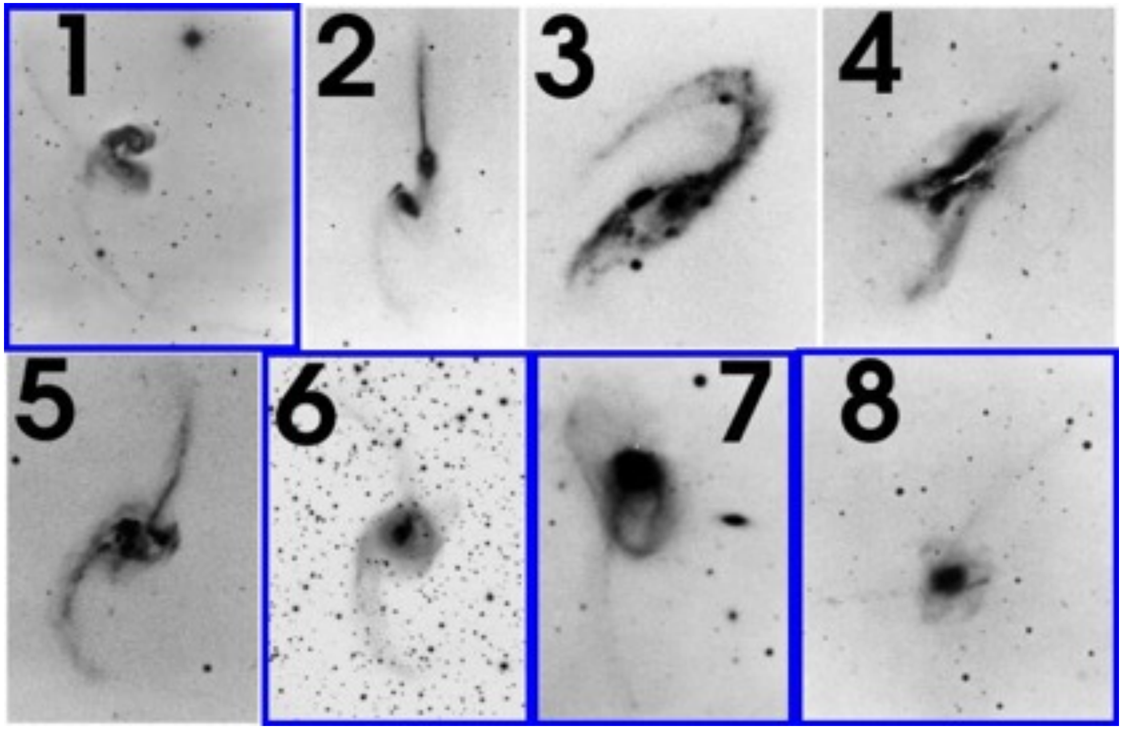


Tidal Tales of Major Mergers

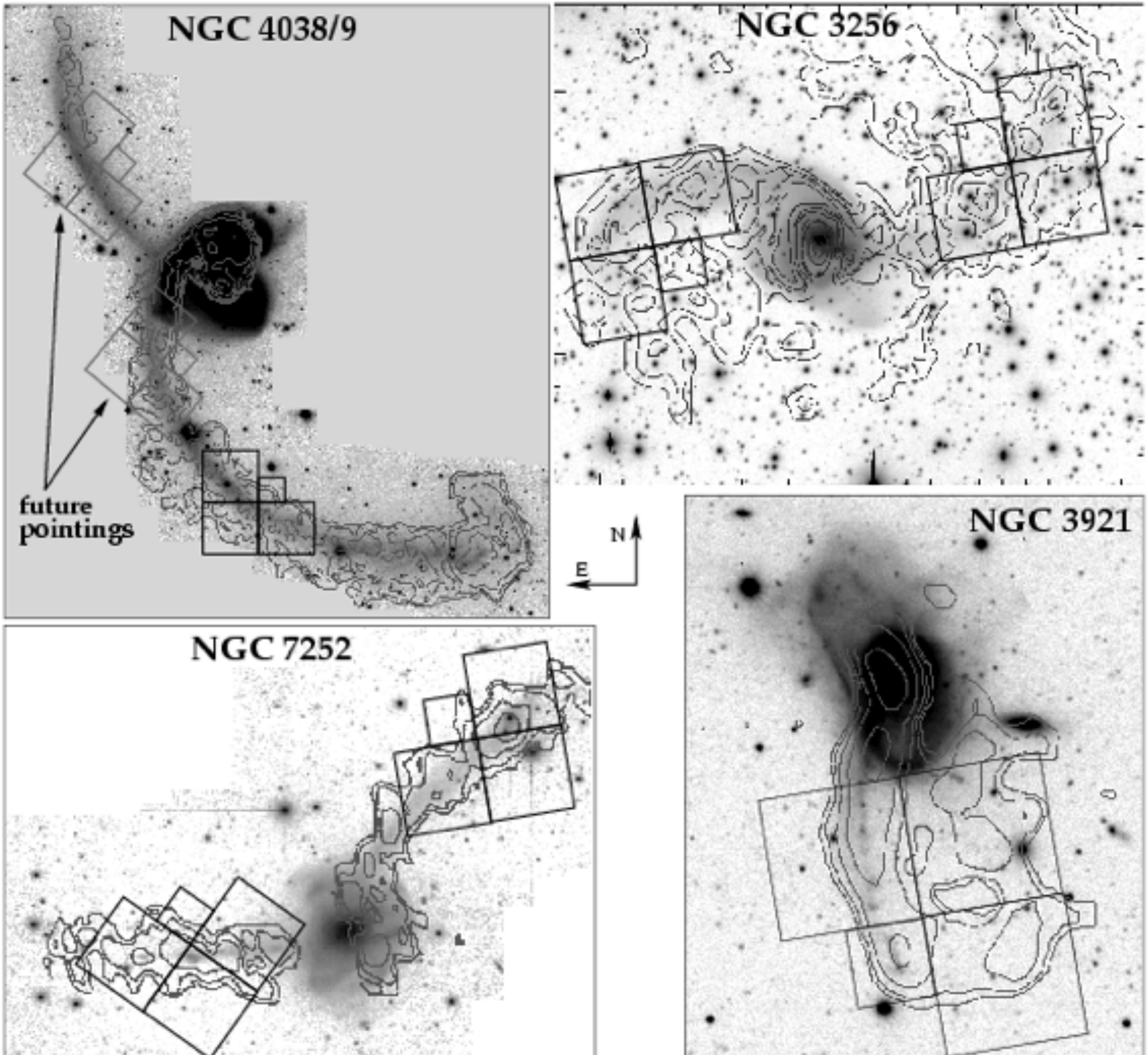
Major Mergers

6 tidal tails in 4 merging galaxy pairs from the Toomre Sequence

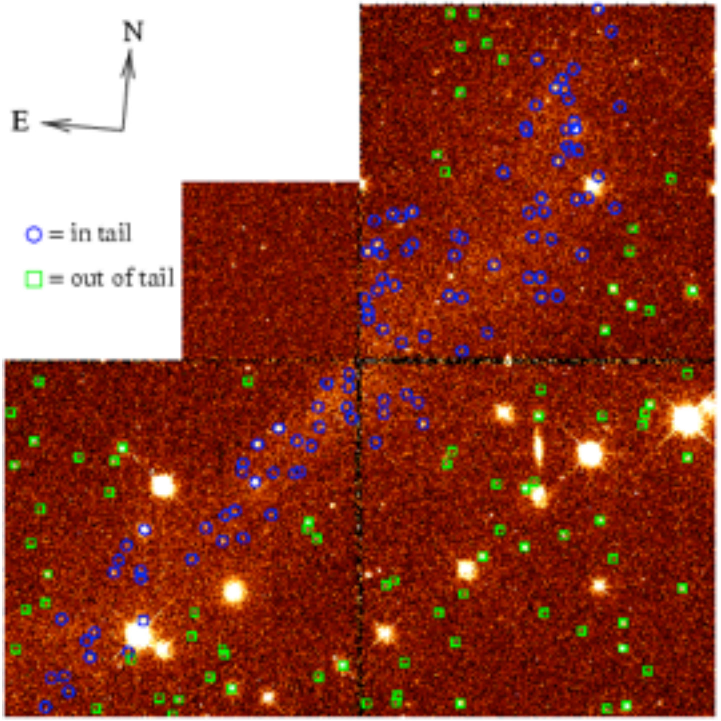
These tails have a range of dynamical state, HI mass, and presence of tidal dwarf galaxy.

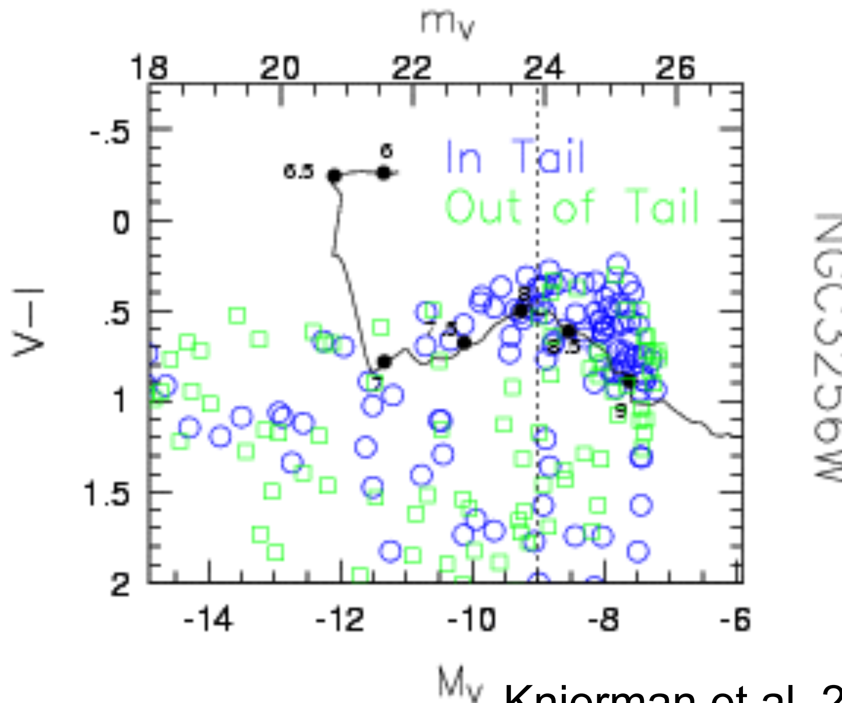


In collaboration with:
Sarah Gallagher (UWO), Jane Charlton, Sally Hunsberger (PSU), Bradley Whitmore (STScI), Arunav Kundu (Eureka), J. E. Hibbard (NRAO), Dennis Zaritsky (Arizona)


NGC 4038/9
future
pointings
NGC 3256
N
E
NGC 3921
NGC 7252

Western Tail of NGC 3256

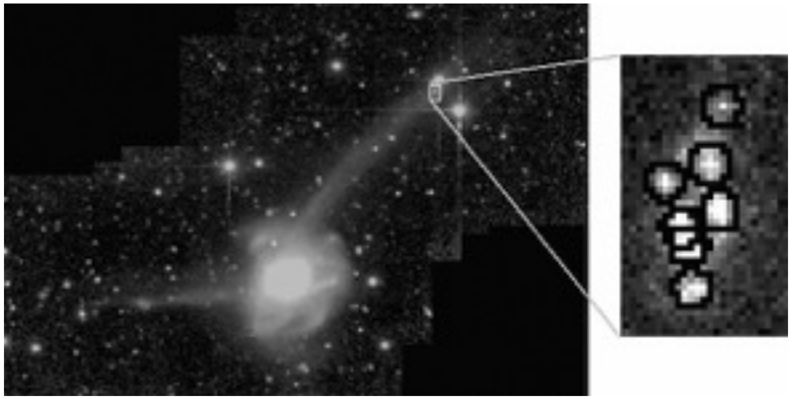




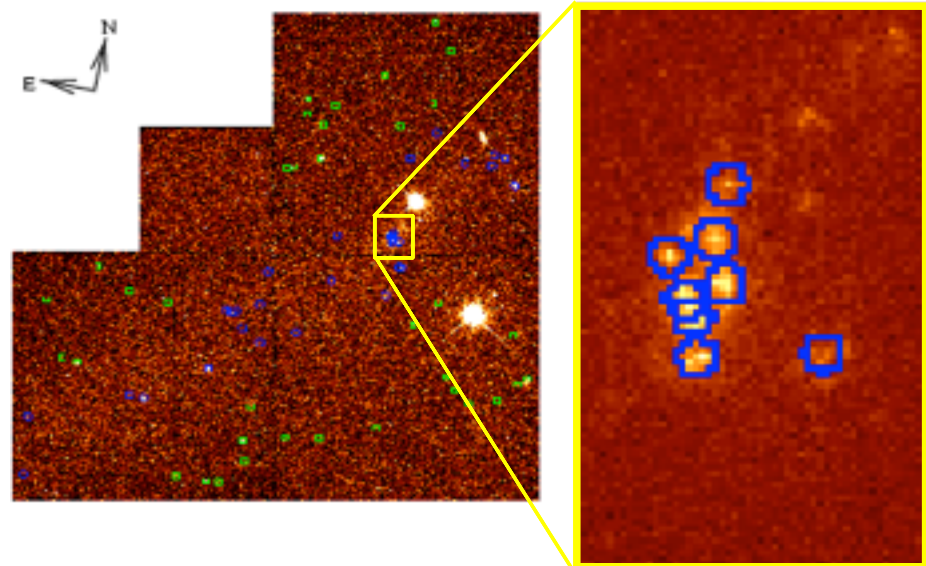
Knierman et al. 2003

- Overdensity of sources within the tail
- Average (V-I) of brighter sources ~0.5
- Sources in and out of the tail are not drawn from the same distribution
- Evolutionary tracks with observed colors imply cluster ages ranging as low as 30 Myr (tail age = 400 Myr) [Bruzual & Charlot tracks with solar metallicity and cluster mass of 10^5 $M_\odot$]

NGC 7252

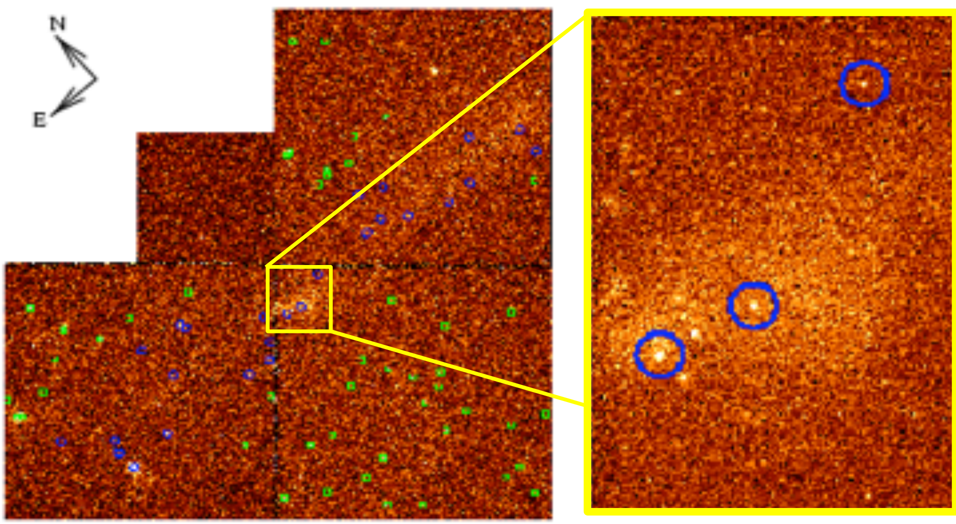


NGC 7252 Western Tail and Tidal Dwarf



Enlargement of tidal dwarf galaxy

NGC 7252 Eastern Tail and Tidal Dwarf



Enlargement of tidal dwarf galaxy

- Tidal dwarf galaxies contain young star clusters 10-100 Myr (tail age = 730 Myr)
- No convincing evidence for clusters along length of tail

Conclusions - Major Mergers

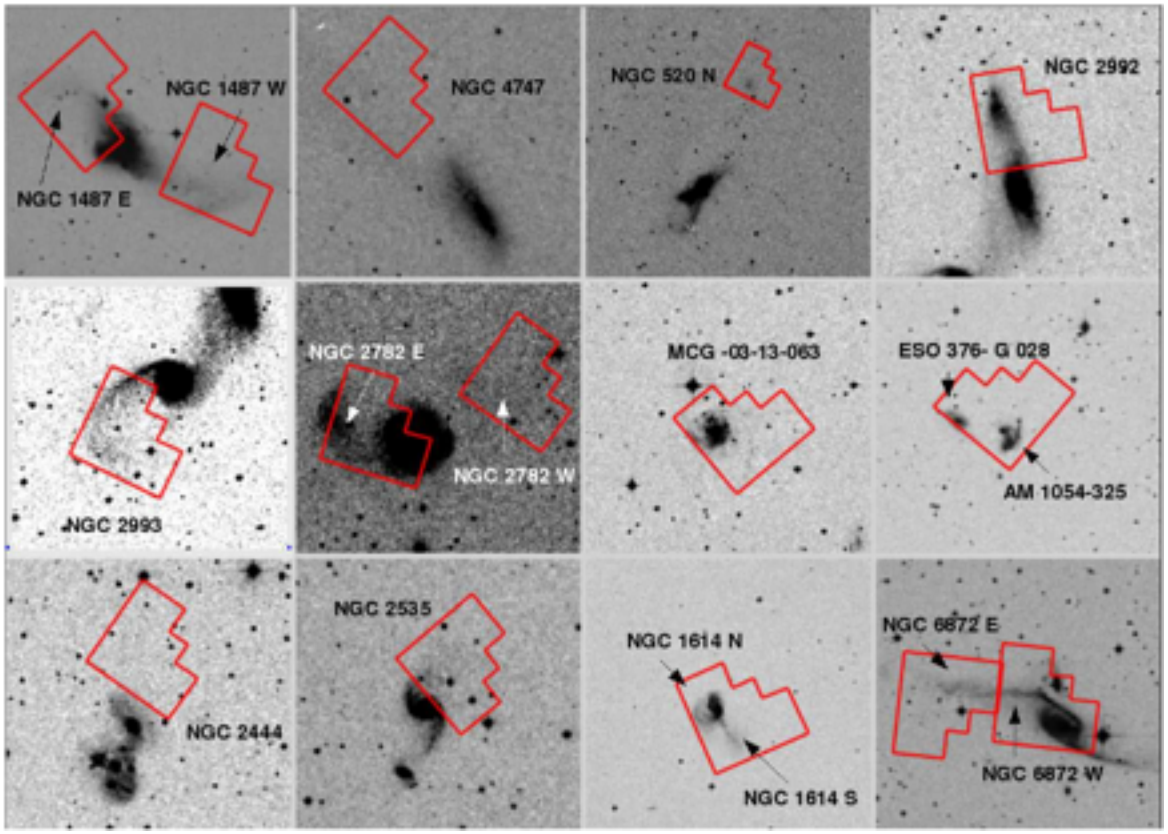
Star clusters form either along tails or in dwarf galaxies, but not both.

- Tails *without* tidal dwarfs have young clusters along tail length (NGC 3256)
- Tails *with* tidal dwarfs have young clusters only in tidal dwarf (NGC 4038/9, NGC 7252)

Increased star formation rate in the central regions is correlated with higher star formation in all regions in merger.

- NGC 3256 has the highest star formation rate and formed many clusters along its tails

WFPC2 Survey: Expanded Sample



- Total of 23 tails
- Variety of properties
  - Mass ratio
  - Ages
  - HI content
  - Optical properties
  - TDG

- Examine
  - Star clusters
  - HI mass & kinematics

Mullan+2011, 2013

NGC 6872

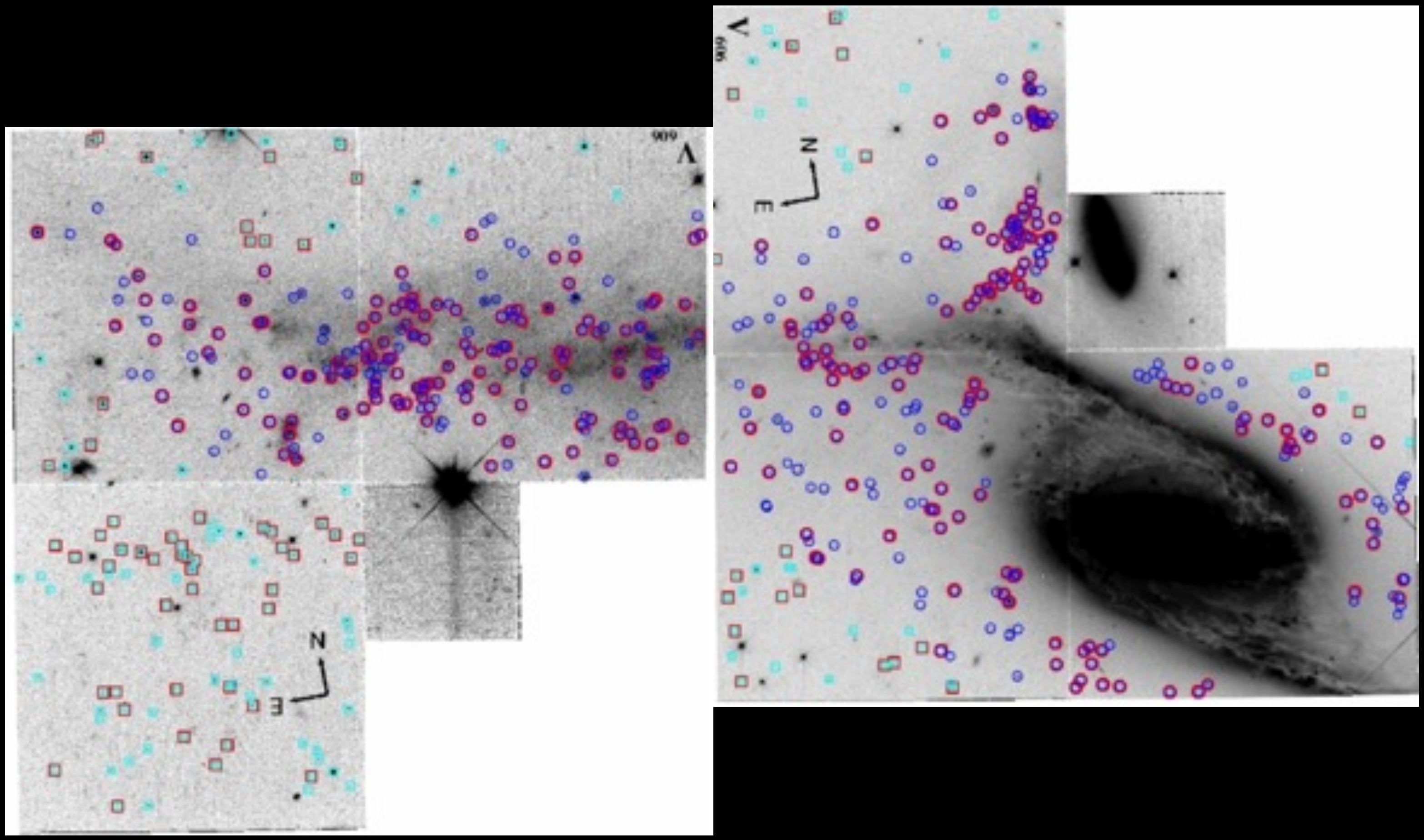
Star Formation in Tidal Tail and Bridge

Color Image by Judy Schmidt @SpaceGeck
Featured as Hubble Image of the Week

NGC 6872:

young, minor merger, high HI density

Over 280 Young Star Clusters



Mullan et al. 2011

Expanded Sample

Star clusters form in variety of environments either along tails or in dwarf galaxies, but not both.

- ✦10/23 have star cluster excesses along tail
  - **3 BOTH along tail and in TDG**
  - 3 “beads on a string”
- ✦13/23 with no star cluster excess along tail
  - Age (>400 Myr), low gas density, or only in TDG

Most star clusters likely form soon after periapse.

- ✦young (<250 Myr) and bright (<24 mag/arcsec^2)

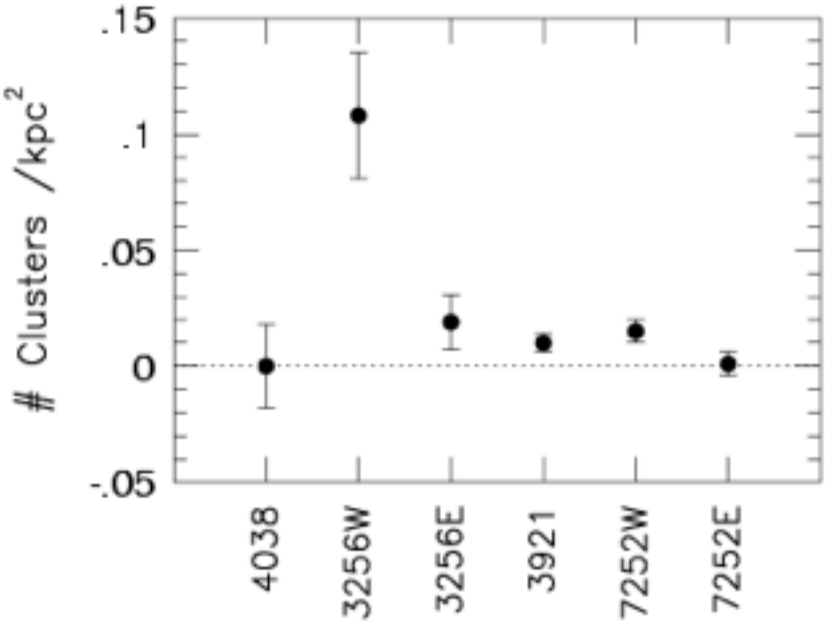
Tails with star clusters= high pressure, young ages.

- ✦log N_{HI}>20.6 cm^{-2}, log Σ_{KE}>46 erg/pc^2, age<250 Myr

Minor merger tails have higher HI column density, major mergers have high velocity dispersion.

- ✦But is this an age vs. mass ratio degeneracy?

Number Density of Star Clusters in the Tails



Number of candidate clusters per kpc^2 in the tails with $M_V < -8.5$ and $(V-I) < 0.7$. Background sources subtracted statistically, using source densities from "out of tail" areas.

NGC 3256W has the highest number density of clusters.

Specific Frequency of Young Clusters:

In a tidal tail:

NGC 3256W: $S_{young} = 2.5$

In the central regions of mergers:

NGC 4038/9 : $S \sim 2$ (Whitmore & Schweizer 1995)

NGC 1316: $S_N = 1.7$ (Goudfrooij et al. 2001)

W Tail Star Cluster Properties

SED fitting of UBVR to determine age, mass, & extinction.

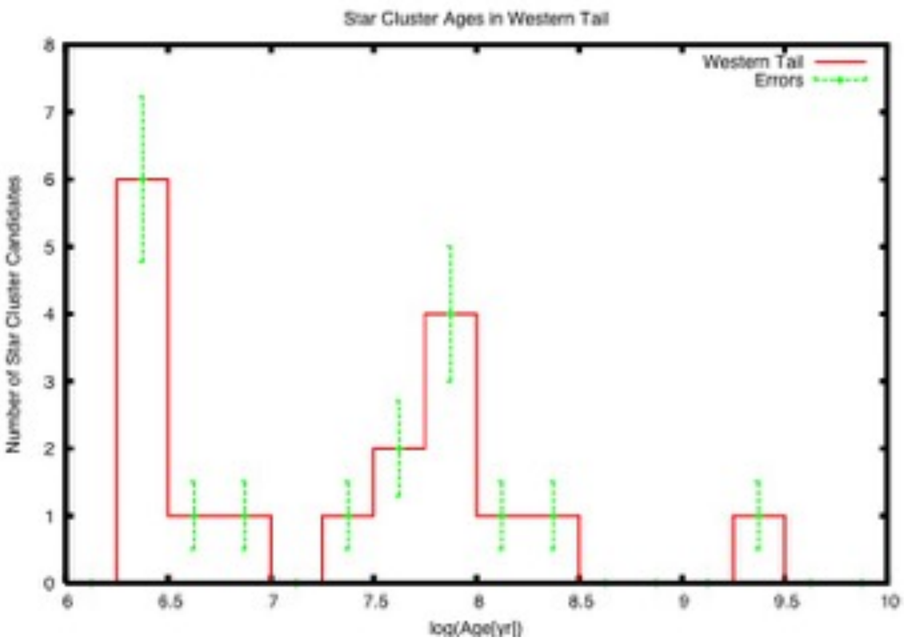
- 3DEF method (Bik et al. 2003) with Bruzual & Charlot 2003 models

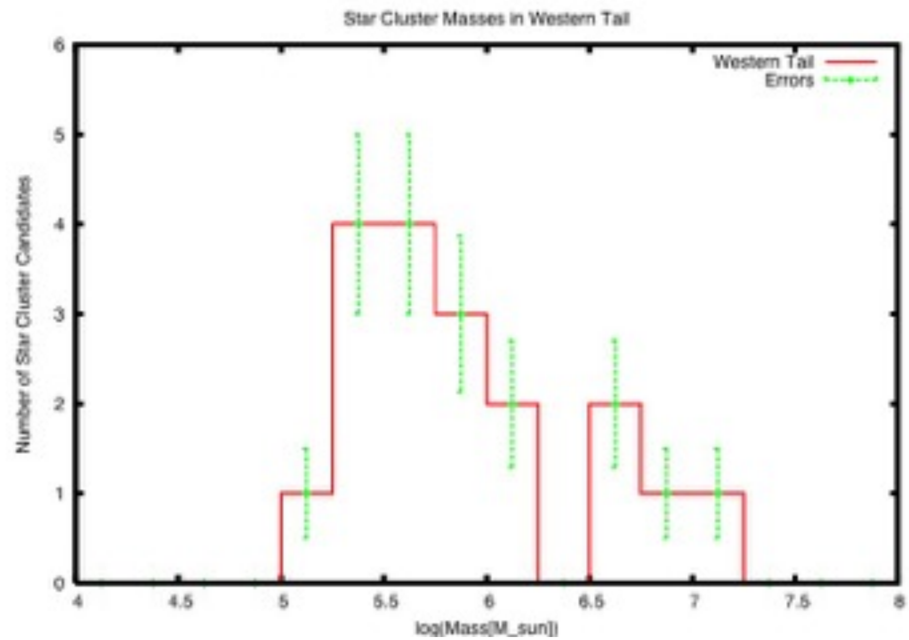
Star cluster candidates:

W: median age = 150 Myr

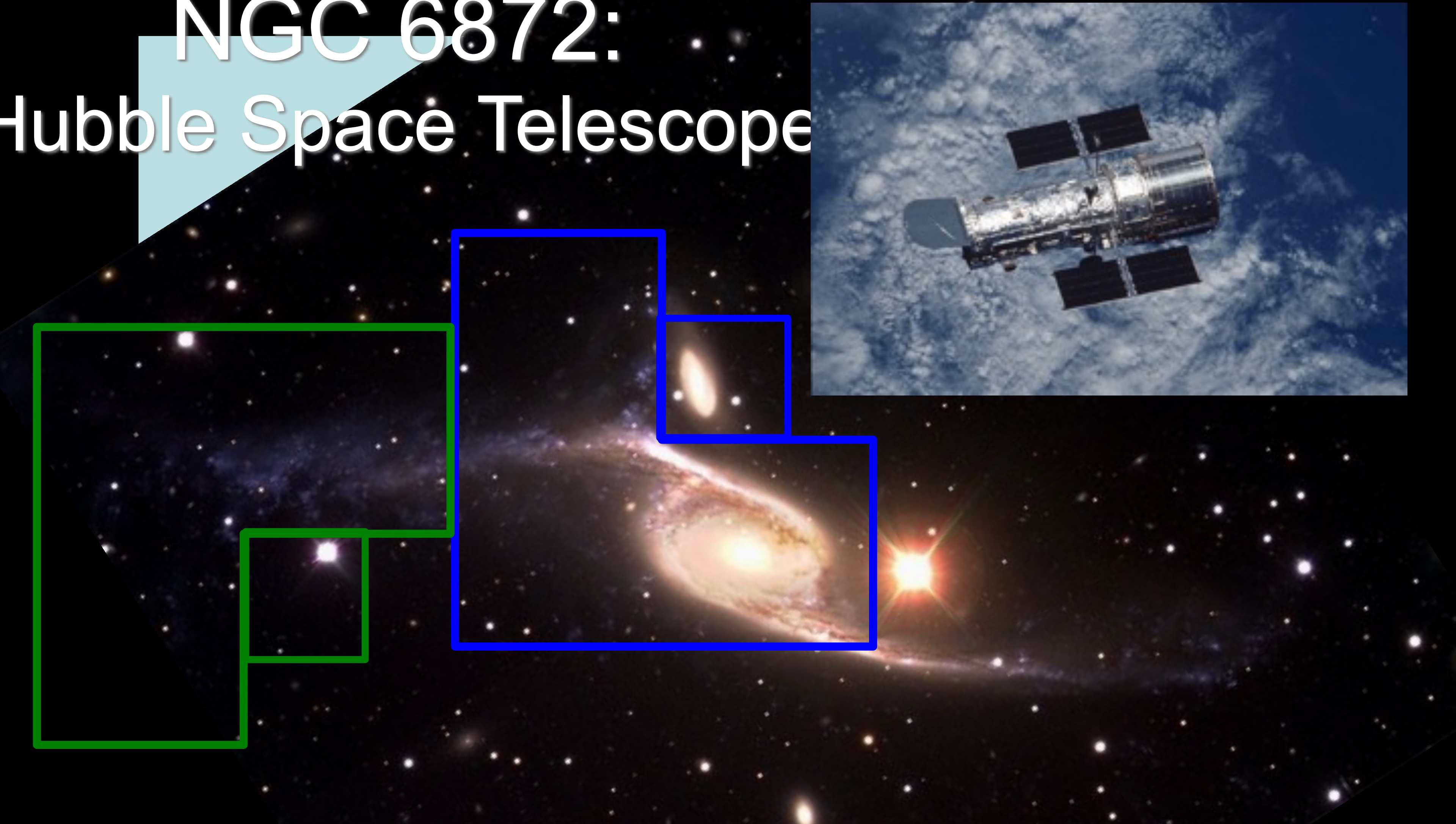
90% have age < 200 Myr (16)

W: median mass = 5×10^{5} M_{sun}





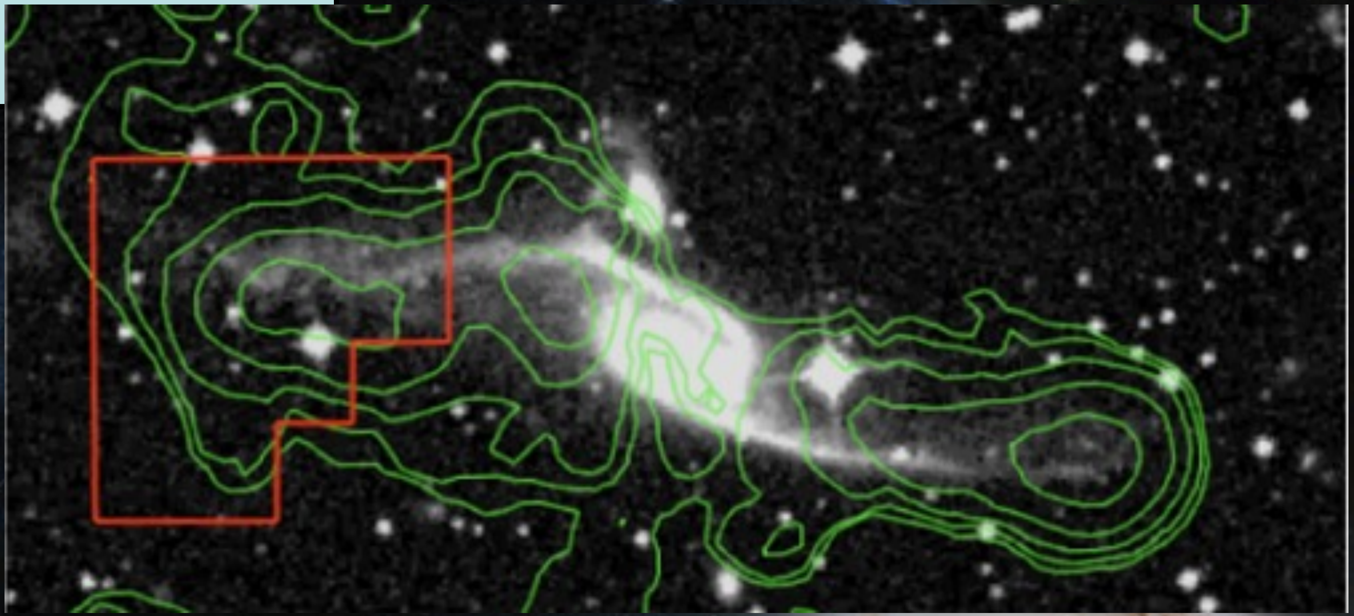
NGC 6872: Hubble Space Telescope



In collaboration with: Brendan Mullan (Pittsburgh Planetarium), Iraklis Konstantopoulos (Australia Nat. Obs), Jane Charlton, Caryl Gronwall, Sally Hunsberger, Chris Palma (Penn State), Rupali Chandar (University of Toledo), Sarah Gallagher (Western Ontario), Pat Durrell (Youngstown State), Nate Bastian (Munich), J. E. Hibbard (NRAO), Kelsey Johnson (Virginia), Debbie Elmegreen (Vassar), Aparna Maybhate (STScI), Jayanne English (Manitoba)

NGC 6872: Gas + Dust = Stars

Hydrogen Gas imaged in Radio from Australian Telescope Compact Array



Why so much Star Formation in Tidal Tail and Bridge???

For dust need CO from ALMA in Atacama Desert of Chile

Gas Phase

Molecular to Neutral

M_{mol}/M_{HI}: E: 0.5-6, W=<0.2

W deficient in molecular gas (or CO)

Ionized to Neutral

Deficient in [CII]

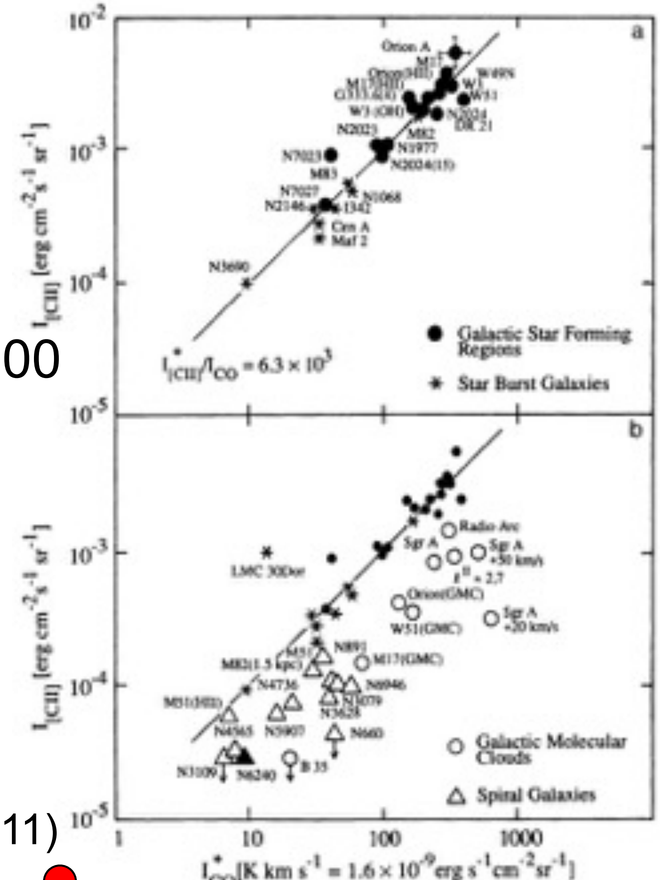
Ionized to Molecular

$I_{[CII]}/I_{CO}$:

E (HII): 1800-4900

E (tot): >1200

W>35,000*



SF: 6300

(Stacey et al. 1991)

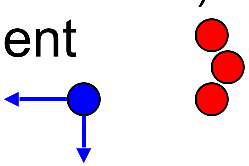
M33 Herschel:

1000-70,000

(Mookerjea et al. 2011)

E is deficient

in [CII]



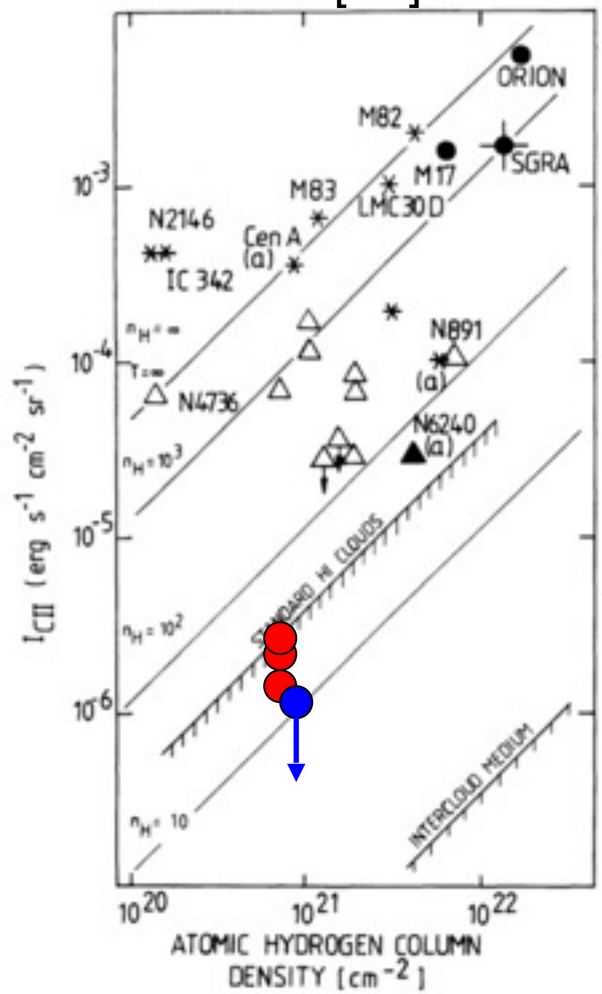
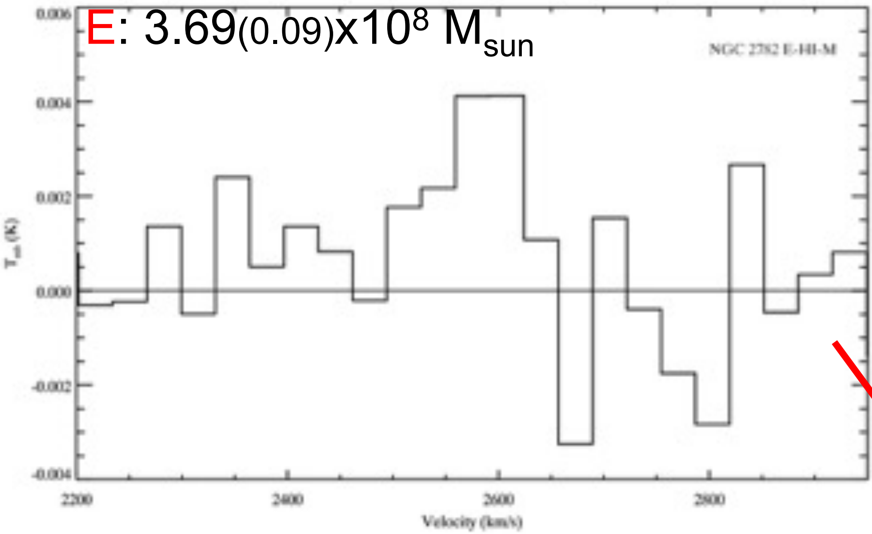
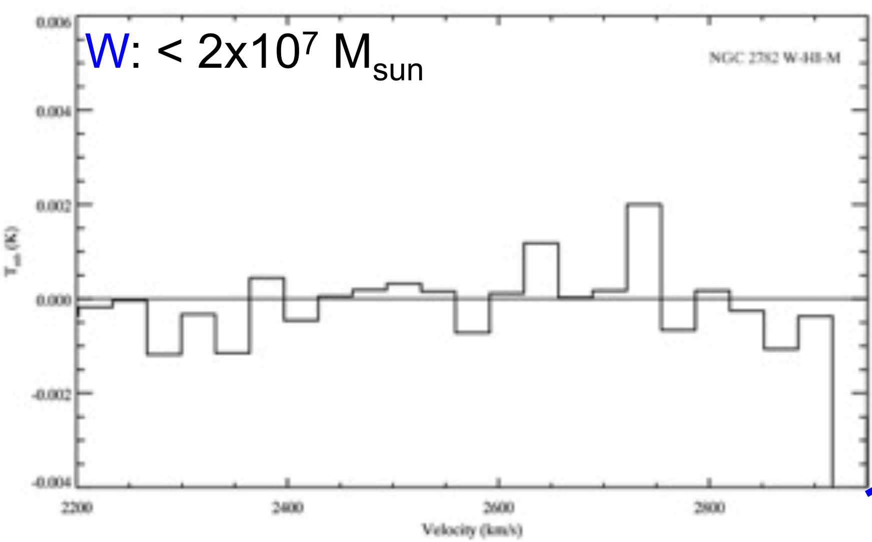


FIG. 16.—Integrated [C II] line intensity as a function of atomic hydrogen column density derived from 21 cm H I measurements. Lines of 45° slope represent calculated [C II] line intensities for the indicated volume densities in the infinite temperature ($T \gg 91$ K) limit. The locations of "standard" H I clouds ($n_H \sim 30$ cm^{-3}, $T_{kin} \sim 100$ K) and of the H I intercloud medium ($n_H \sim 0.1$ cm^{-3}, $T_{kin} \sim 1000$ K) are also indicated.

CO(1-0) from ARO 12m



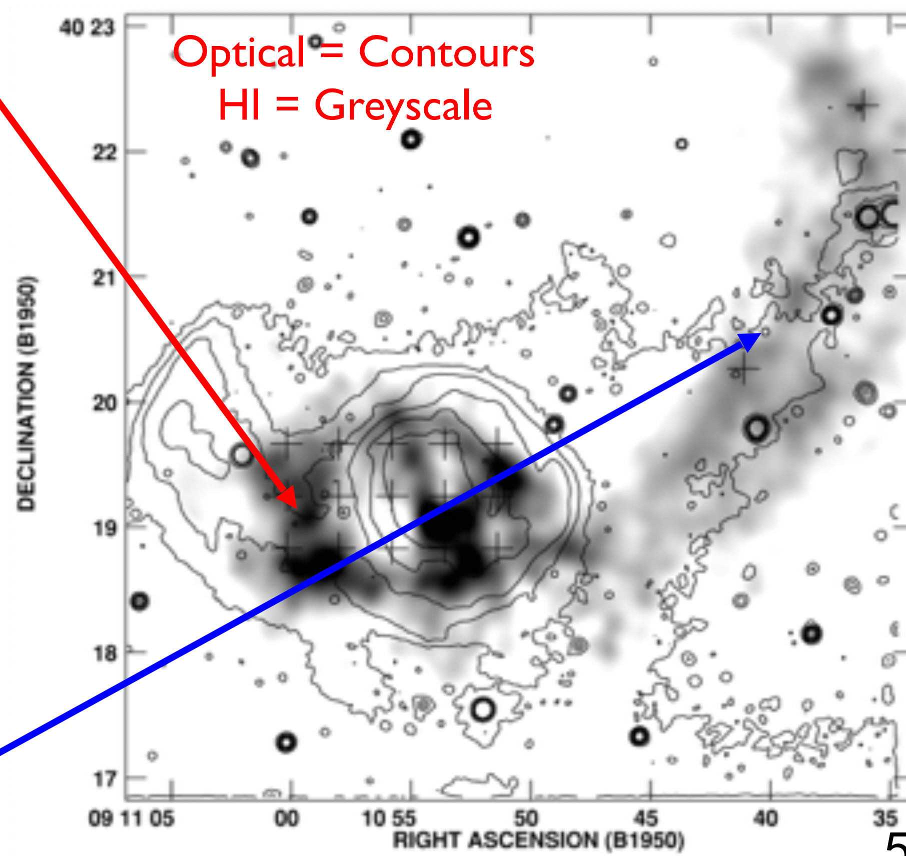


E: 3 pts. 2.6-3.8x10^8 M_{sun}

total M_{mol}~8.6x10^8 M_{sun}

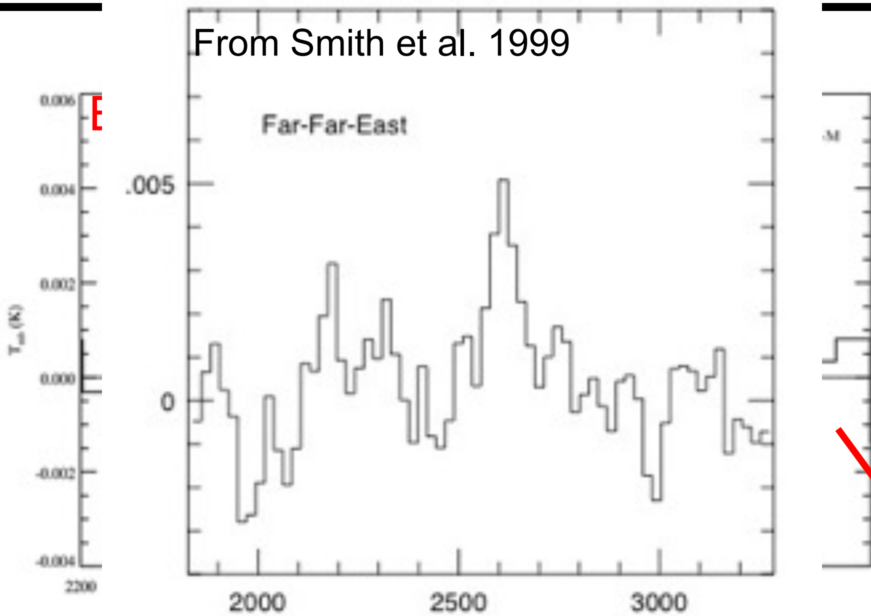
using also Smith et al. 1999

W: < 2x10^7 M_{sun}

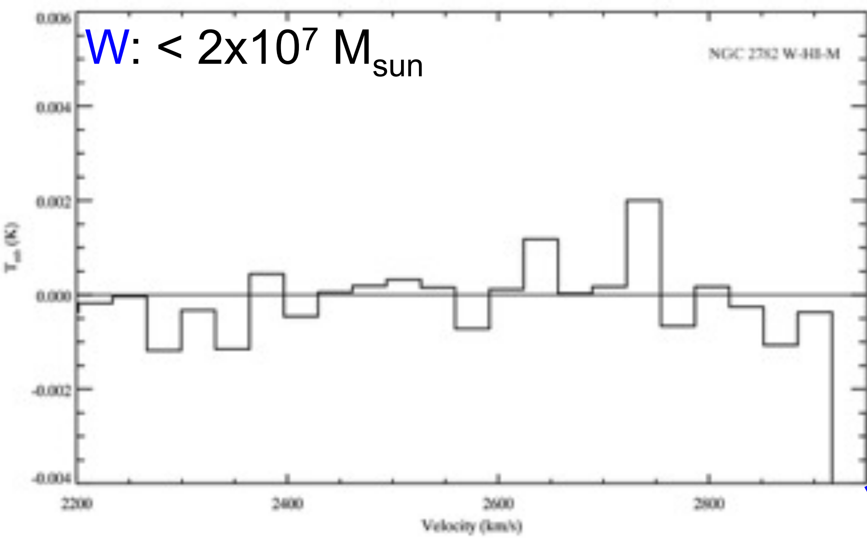


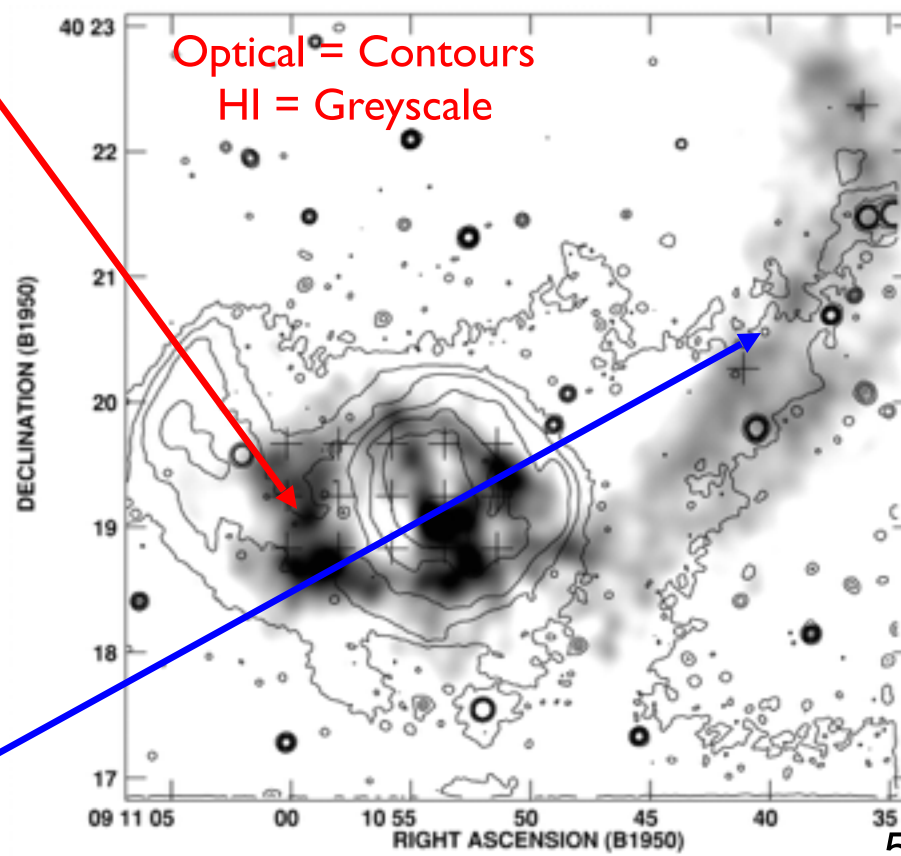
From Smith et al. 1999

CO(1-0) from ARO 12m



E: 3 pts. 2.6-3.8x10^8 M_{sun}
total M_{mol}~8.6x10^8 M_{sun}
using also Smith et al. 1999
W: < 2x10^7 M_{sun}





From Smith et al. 1999

Overdensity of Star Clusters

To statistically remove foreground and background contaminating sources, we use the technique of Knierman et al. (2003):

Calculate the number of young (<300 Myr) star cluster candidates per unit area in the tail and subtract the number of SCCs per unit area out of the tail.

Both tails have a positive overdensity 0.005-0.006 SCCs/kpc^2 or ~14 (E) and ~10 (W) star clusters.

Table 6. Overdensity of star clusters in tails

Tail	Pixel size pc	N_{in}	Area$_{in}$ pix^2	Area$_{in}$ kpc^2	N_{in}/kpc^2	N_{out}	Area$_{out}$ pix^2	Area$_{out}$ kpc^2	N_{out}/kpc^2	Surplus
E	80.69	20	345877	2252.0	0.009(0.002)	9	475199	3094.0	0.003(0.001)	0.006(0.002)
W	80.69	17	257238	1674.9	0.010(0.002)	19	584730	3807.2	0.005(0.001)	0.005(0.003)

Ambient Pressure

Location & mass of GMCs likely regulated by structure of HI, particularly where dominated by atomic gas (Blitz & Rosolowsky 2006).

From Elmegreen, Kaufman, & Thomasson (1993):
$M_{char} = \pi\, l_{min}\, c_g\, (\mu/2G)$ = mass of "super cloud" which then fragments
c_g = 3D velocity dispersion
$\mu = M/l_{max}$
l_{min} = minor axis of cloud
l_{max} = major axis of cloud

Similar M_{char}, not large ambient pressure difference. Lack of Molecular gas (or CO?) in W.

Table 10. Characteristic Sizes of HI Clumps in the Tidal Tails of NGC 2782

Location	σ_v[a] (km/s)	l_{min} (kpc)	l_{max} (kpc)	M_{HI}[a] ($10^8 M_\odot$)	M_{char} ($10^8 M_\odot$)	Observed M_{mol} ($10^8 M_\odot$)
E-HI-N	30	2.96	2.96	3.85	15.3	2.6(0.5)[b]
E-HI-M	40	1.78	2.96	2.31	9.50	3.69(0.09)
E-HI-S	40	2.96	5.92	6.02	18.1	3.8(0.5)[b]
W-HI-N	49	2.10	3.05	0.54	6.56	< 0.086[c]
W-HI-M	35	5.67	7.56	1.00	10.9	< 0.22
W-HI-S	30	3.78	3.78	0.86	8.19	< 1.5[b]
N7252 TDG	31	5.00	5.00	10	33.2	0.2

Star Formation Rate

Global Scales: SFR(Hα) & SFR ([CII]) << expected SFR(gas)
Low SFE in both tails?

Local Scales (few kpc):
W: highest SFR(Hα) but upper limit on SFR([CII])
([CII] emission is suppressed)
SFR(Hα) & SFR ([CII]) << expected SFR(gas)
Low SFE in both tails on local scales, too?
Per area:
Σ_{SFR}(Hα) similar in both tails

Expected Σ_{SFR}(gas): E > W (14-40 times)

Star Formation Rates

Comparing SFR per kpc^2 from Hα with the expected SFR from gas density (Kennicutt 1998)

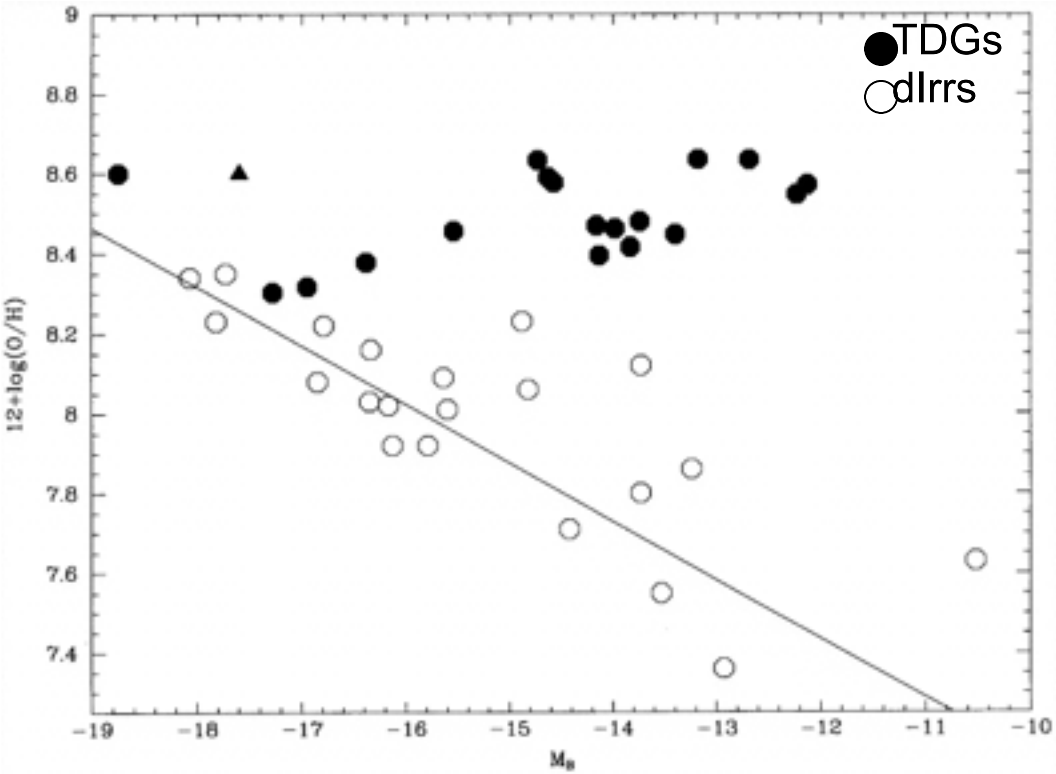
Table 1
Comparison of Star Formation Rates in the western Tail of NGC 2782

Location	Area (kpc^2)	Hα SFR ($M_\odot$ yr^{-1})	Σ_{SFR}(Hα) ($M_\odot$ yr^{-1} kpc^{-2})	M_{HI}[a] (10^8 $M_\odot$)	M_{mol}[b] (10^8 $M_\odot$)	Σ_{gas}[c] ($M_\odot$ pc^{-2})	Σ_{SFR}(gas)[d] ($M_\odot$ yr^{-1} kpc^{-2})
H I-N	8.6	<0.0003	<0.00003	0.73	<0.086[e]	<12.9	<0.006
H I-mid	14.7	0.015(.002)	0.001(0.0002)	1.15	<0.16[f]	<12.2	<0.005
H I-S	19.3	<0.0003	<0.00002	1.16	<0.16[f]	<9.4	<0.004
W Tail	2300	0.015	0.000009	20	<0.4[e,f]	<11.7	<0.005

There is slightly less current star formation per kpc^2 than expected from the gas density (but gas density is an upper limit).

Origin of Tidal Debris - Motivation

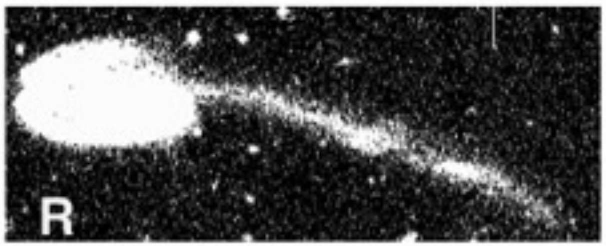
- Tidal dwarf galaxies have metallicities of ~1/3 Zsun, (= outer regions of spiral galaxies), so they likely originate from material pulled from the outer part of the merging spiral (Duc et al. 2000).

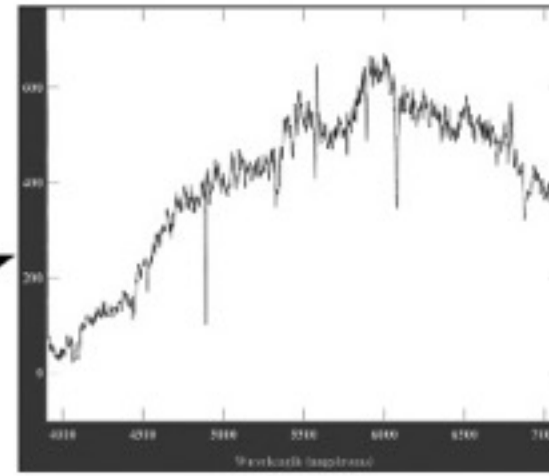


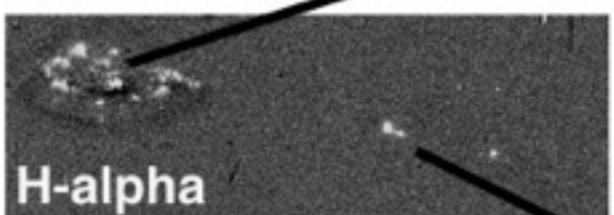
Duc et al. 2000

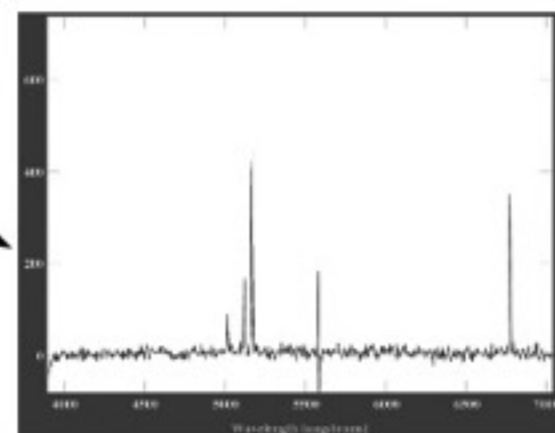
Origin of Tidal Debris - Methods

- Optical spectra from Bok 90-inch with the B&C
  - 2 HII regions in tidal tail
  - Central region (absorption line)
  - HII regions in spiral arms
  - Dwarf galaxy (fainter emission lines)









- R_{23} -> Metallicity
- Compare metallicity of tidal tail to spiral and dwarf regions

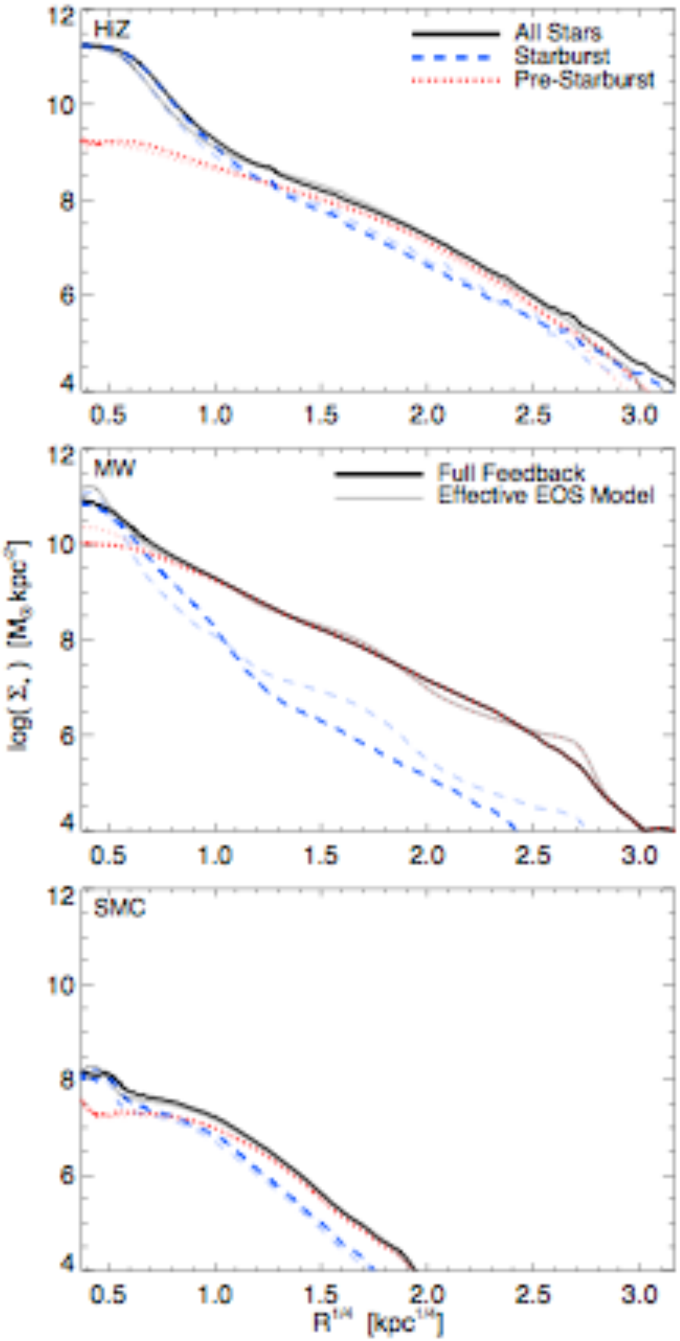
Hopkins' New Models

- Quasi-steady ISM with GMCs forming and dispersing
- ISM with different phases which agree with observations
- Able to predict winds from the stellar feedback

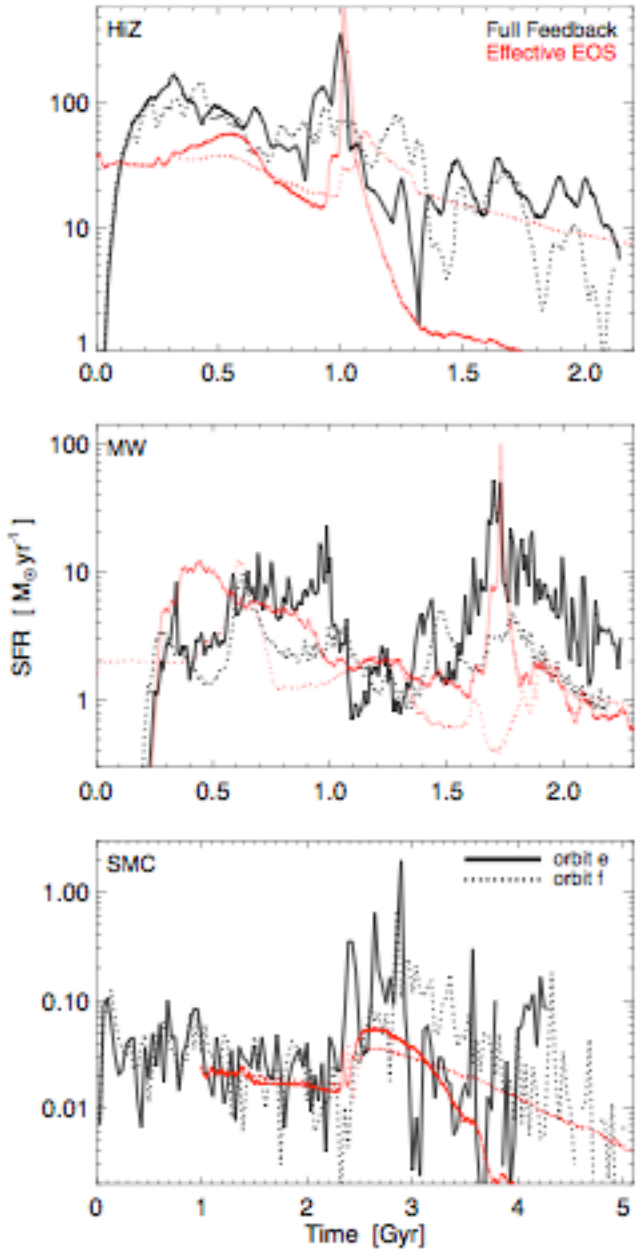
Hopkins Models

- Major mergers
  - Idealized mergers
  - Mass ratios of 1:1
  - 4 sets of disk models
    - MW
    - Sbc
    - Hi-Z
    - SMC
  - Base much of their physics on Starburst99 models

Hopkins Global Properties



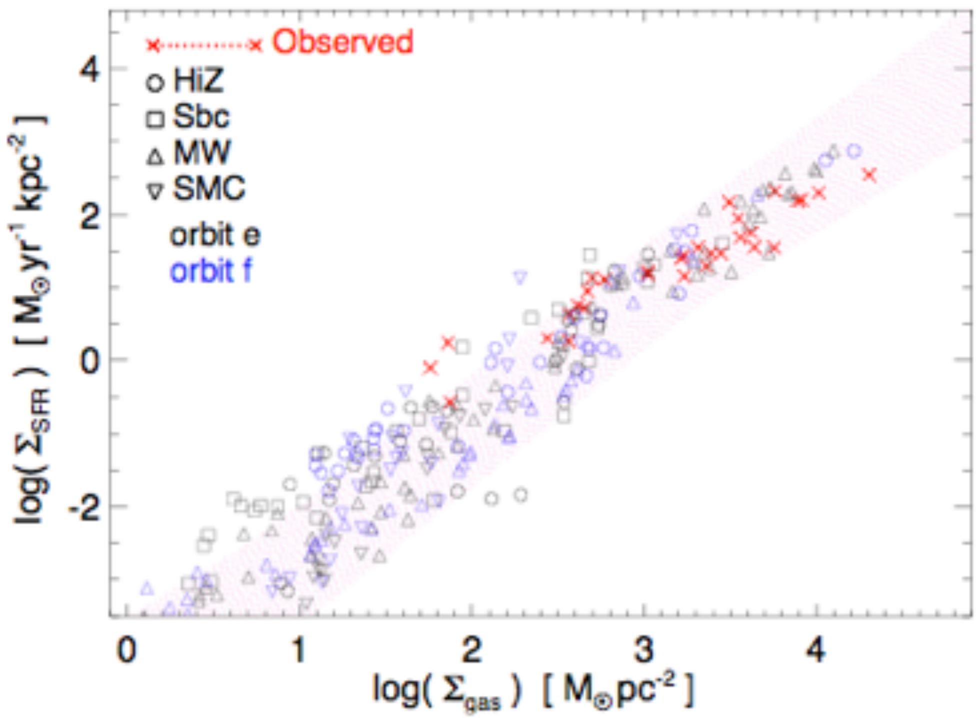
- Merger morphology (movies)
- Remnant: similar
  - More massive core
    - Dissipation > efficient
  - More SF at ~10 kpc
- Disk survival
  - Similar to EOS



Hopkins SFH

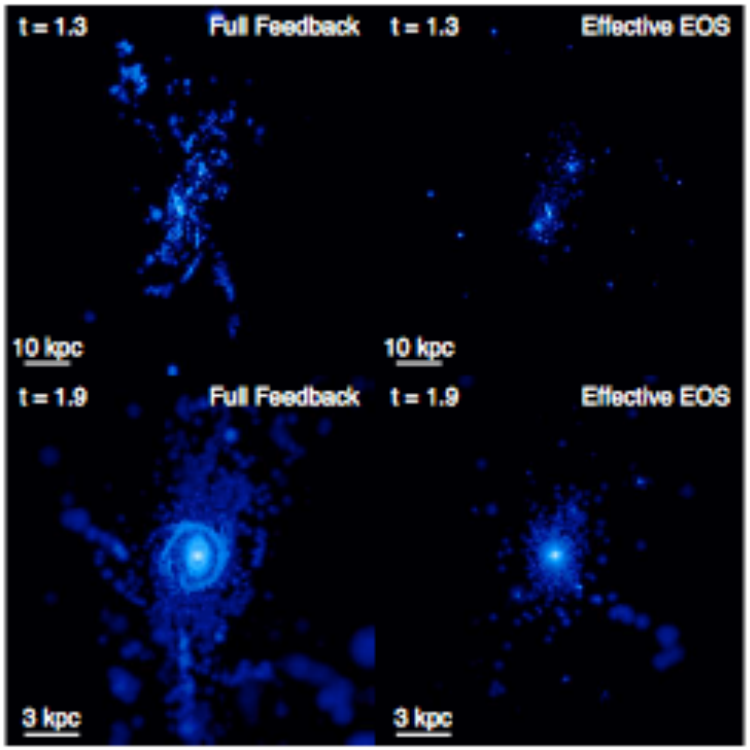
- More bursty
  - ISM less homogenous
- SMC has stronger bursts
- Tail of SFH enhanced
  - Winds help recycle gas
  - *SB winds make quenching less efficient*

Hopkins K-S Relation



- EOS models were constructed to lie on line
- No feedback: above line by factor of 20-100
- These fall on relation with no fiddling, even for SB
- No bimodality, but might push upper envelope at high SFR

Where is SF?

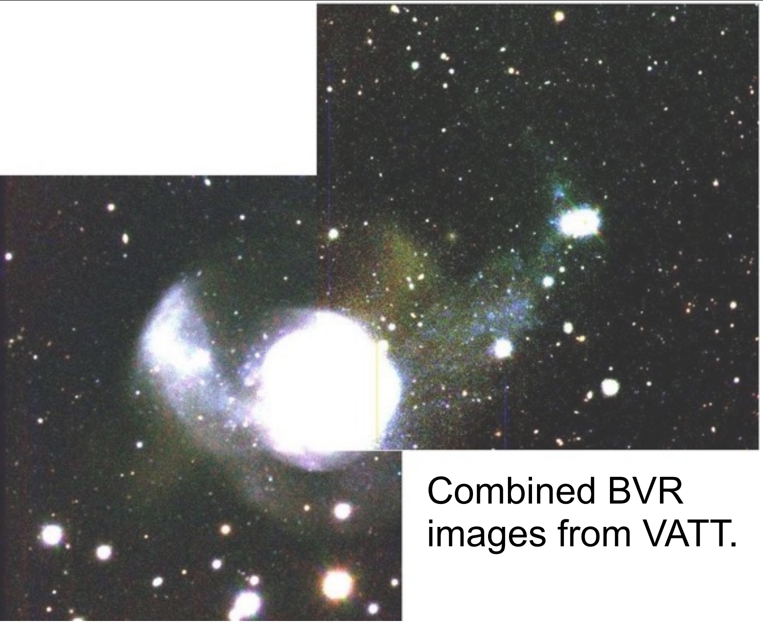


- SF in center is consistent
- But SF greater at large radii
  - 20-50% of total SFR in tidal and bridge regions (vs. only 10% in previous models)
  - Shocks better treated with higher resolution and more compressible gas

Hopkins Result Summary

- Compare their models with previous ones (EOS models)
  - Match on global properties
  - Differ on sub-galactic scale and SFR
    - Higher SFR in tails/bridges (shocks)
    - Resolve Super Star Clusters
    - SF more time variable

NGC 2782



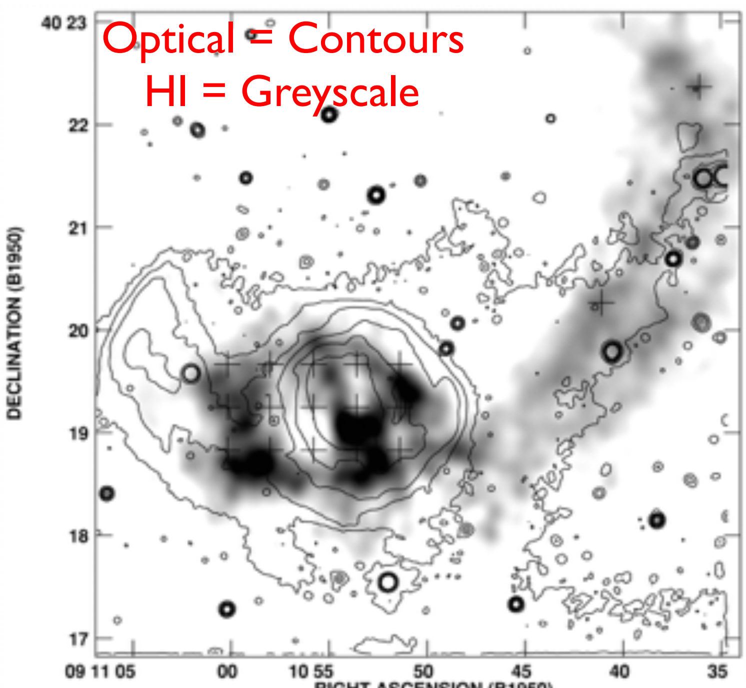
Combined BVR images from VATT.

Peculiar Spiral that had a Minor Merger ($M_2/M_1 \sim 0.25$) ~200 Myr ago (Smith 1994; Smith et al. 1999)

Two Tails:

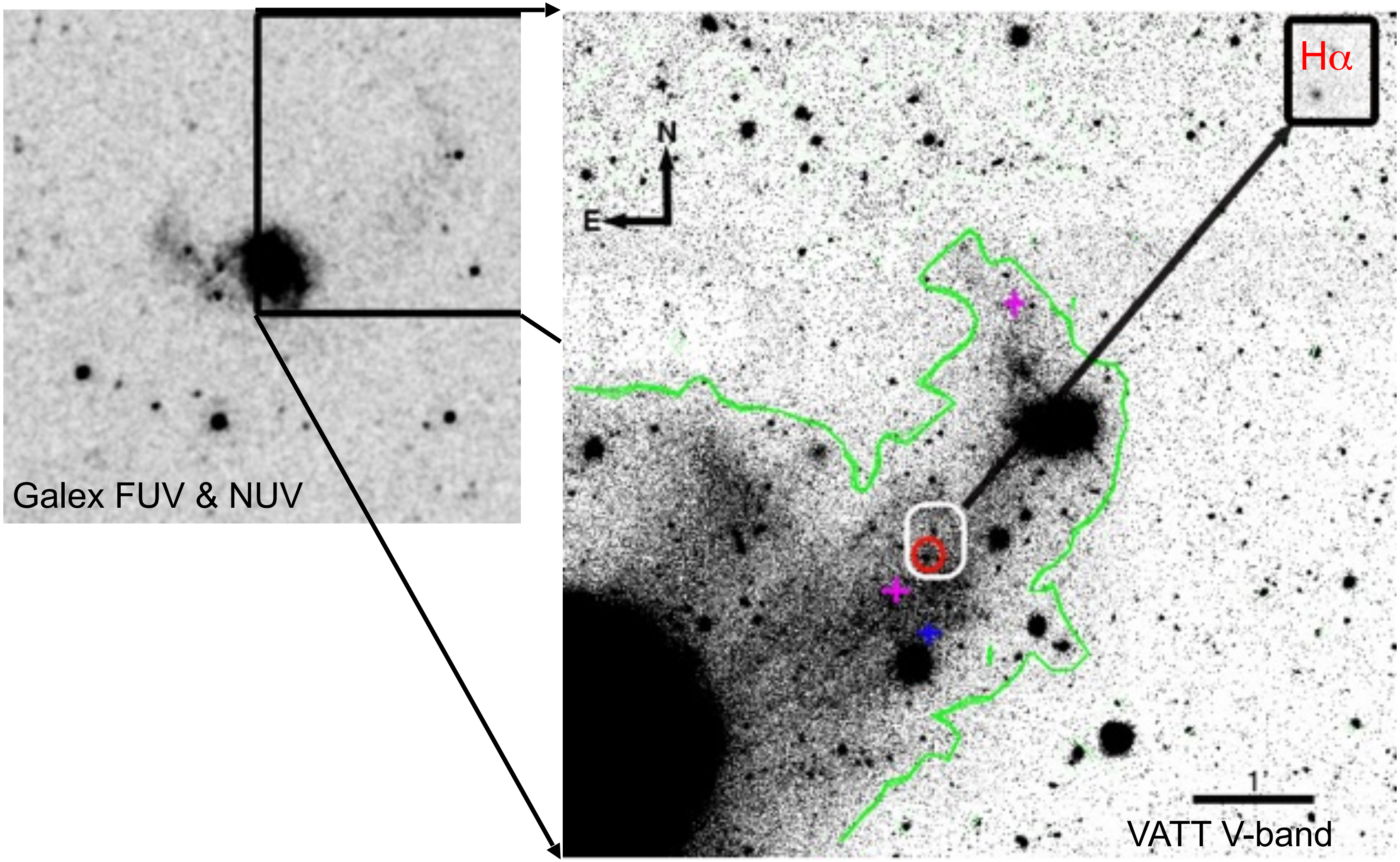
East: Optically bright, HI, CO

West: Optically faint, HI, no CO



From Smith et al. 1999

Western Tail HI is not gravitationally bound and has "not had time to condense into H_2 and for star formation to begin." (Braine et al. 2001)



Right: V-band image of Western tail of NGC 2782 from VATT. White box indicates region shown by inset which shows continuum subtracted narrowband Hα image. Red circle indicates HII region Magenta crosses indicate locations of massive HI clouds with non-detections of CO (both: Smith 1994; North: Braine et al. 2001). Blue cross indicates massive HI cloud (Smith 1994). Left: Galex FUV & NUV composite image with box indicating region shown in right image.

Local Star Formation Rate in Western Tail

Comparing SFR per kpc^2 from Hα with the expected SFR from gas density (Kennicutt 1998)

Position	Σ_{SFR}(Hα) [M_{sun} yr^{-1} kpc^{-2}]	M_{mol} [10^8 M_{sun}]	Σ_{gas} [M_{sun} pc^{-2}]	Σ_{SFR}(gas) [M_{sun} yr^{-1} kpc^{-2}]
HII Region	0.0010(0.0002)	<0.16	<12.2	<0.005

There is slightly less current star formation per kpc^2 than expected from the gas density (but gas density is an upper limit).

Star Formation Law & Efficiency

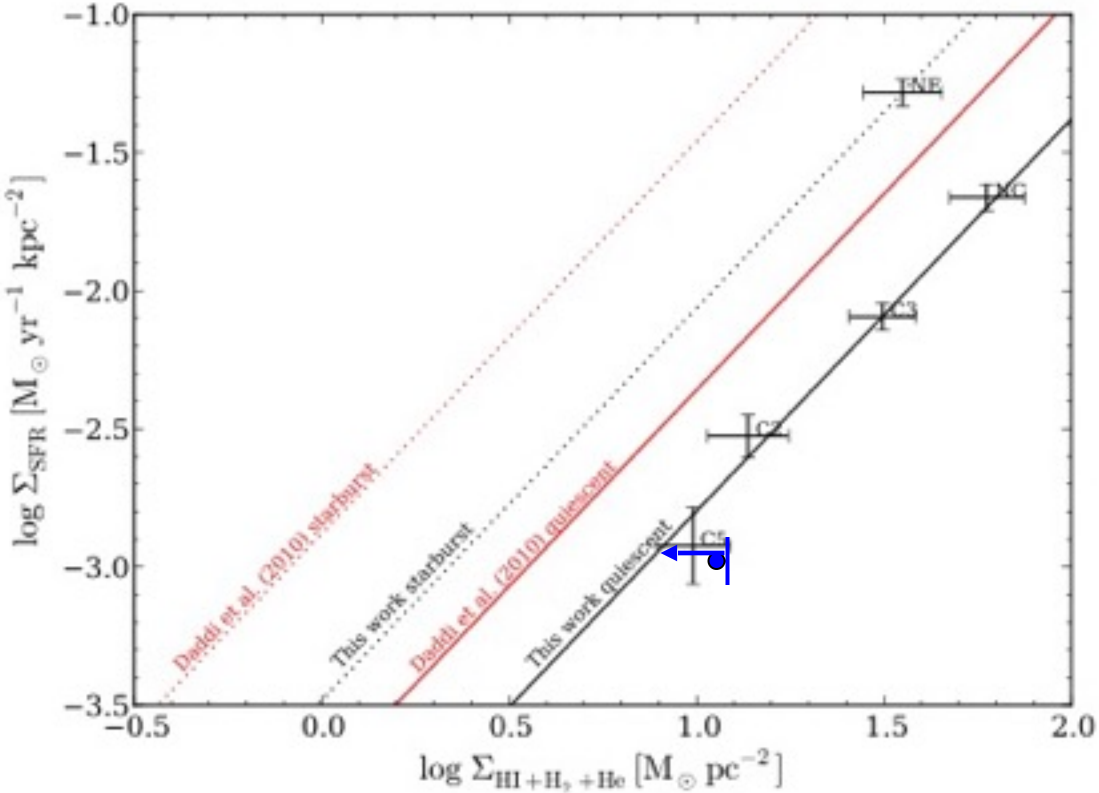


Fig. 6 from Boquien et al. 2011 with HII region in blue. Black points are HII regions in the major merger Arp 158, including tidal debris regions.

- Low SFE from total gas density: Star formation in Western tail of NGC 2782 is proceeding similar to major merger Arp 158 tidal debris but less than normal and starburst galaxies.

- BUT normal SFE from Molecular gas τ_{dep} < 1 Gyr. (Arp 158 -Boquien et al. 2011: 0.5-2 Gyr; TDGs from Braine et al. 2001: 0.8-4 Gyr)

Western tail of NGC 2782 is either a locally dense region, or a low metallicity or low pressure region.

Why don't we see CO if stars are forming?

- Molecular gas might be in smaller clouds and not visible since observed with large beam sizes

- Molecular clouds could have been disrupted by UV radiation of young massive stars (possibly see in C^+)

- Lower metallicity gives less C,O but still have H_2

- Ambient pressure might be lower in Western tail (Blitz & Rosolowsky 2006)

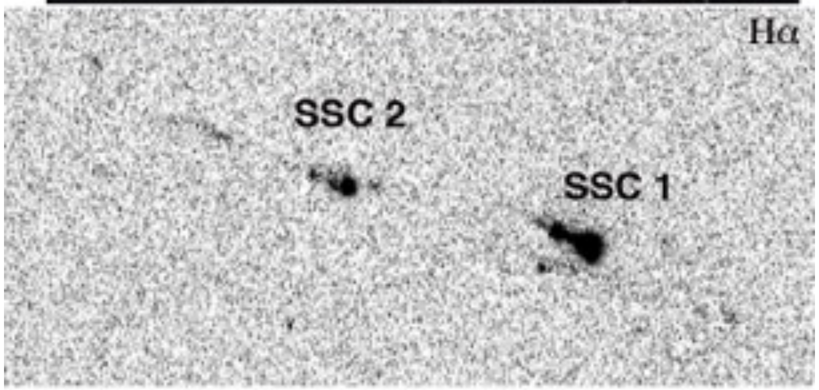
Conclusions

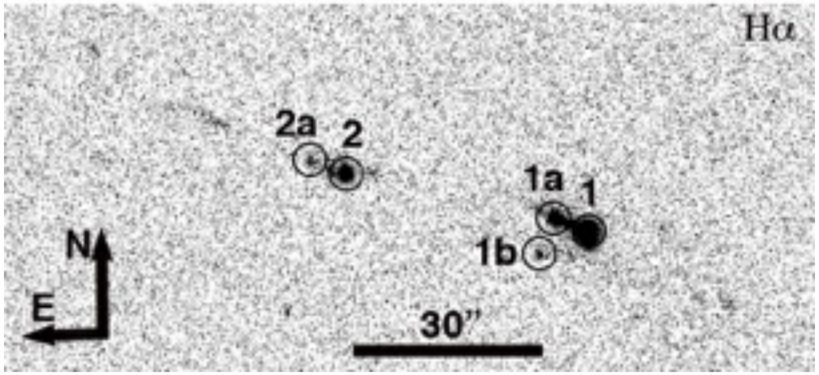
- Western tail of NGC 2782 hosts star formation despite undetected molecular gas.
- From total gas density and star formation rate density, the tail is hosting SF at a lower rate than expected from normal or starburst galaxies.
- Low SFE from total gas density, but normal SFE from molecular gas limit.
- Star formation may occur differently in tidal tails, which are seen to have lower pressure and density.

Minor Merger Sample

Merger	Velocity	Mass Ratio	Interaction Stage	$M_{B,1}$	$M_{B,2}$	Projected Separation
	kms^{-1}			mag	mag	kpc
Arp 269	565	0.1	early	-20.39	-18.02	15
NGC 3310	993	< 0.3	merged	-20.25	~ -18	0
Arp 279	1708	~ 0.1	early	-20.22	-18.50	25
UGC 00260	2131	0.1	early	-19.78	-17.43	23
NGC 5666	2221	< 0.3	merged	-19.53	~ -17	0
NGC 7479	2381	0.1	merged	-21.64	~ -19	0
NGC 2782	2562	0.25	late	-20.98	-19	10
NGC 7303	3697	?	merged	-20.34	?	0
NGC 1614	4778	< 0.3	merged	-21.34	~ -19	0
UGC 06665	5560	?	merged	-20.16	?	0
UGC 06503	6143	< 0.3	late	-20.02	~ -18	25
[redacted]						
Arp 219	10521	< 0.3	late	-21.56	~ -19	130
AM 0318-230	10699	< 0.3	merged	-20.91	~ -19	0
UGC 10084	13880	?	merged	-21.74	?	0

Star Formation in Tidal Tail





- Narrowband image shows Hα has clumpy structure (6" scale)
  - SSC 1: 3 HII regions, brightest is elongated
    - SFR = 0.017-0.41 M_{sun}/yr
  - SSC 2: 2 HII regions
    - SFR = 0.02-0.1 M_{sun}/yr
- On 12" scale (CO(2-1) & Jarrett+06)
  - SSC 1: SFR(Hα) = 0.53 M_{sun}/yr
    - SFR(Hα+24um) = 0.4 M_{sun}/yr (Calzetti+07)
  - SSC 2: SFR = 0.14 M_{sun}/yr
    - SFR(Hα+24um) = 0.1 M_{sun}/yr (Calzetti+07)
- On 21" scale of CO(1-0)
  - SSC 1: SFR = 0.65 M_{sun}/yr
  - SSC 2: SFR = 0.17 M_{sun}/yr
- Entire Tail
  - SFR = 1.5 M_{sun}/yr
  - Similar to SFR of entire Milky Way galaxy

Star Formation in Tidal Tail

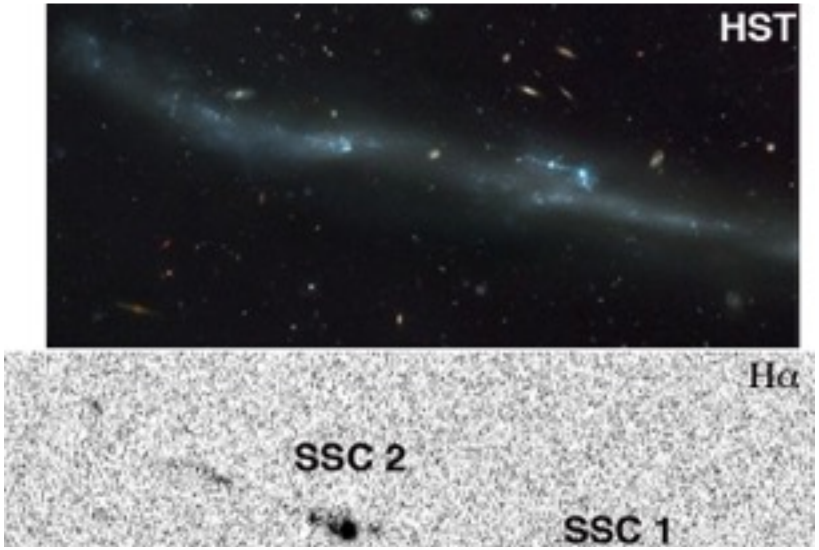


Table 4.1: Properties of $H\alpha$ sources in Tidal Tail of Tadpole

Location	Area kpc^2	$L_{H\alpha}$ 10^{39}erg s^{-1}	SFR(Hα) $M_\odot$ yr^{-1}	$\Sigma_{SFR}(H\alpha)$ $10^{-3} M_\odot yr^{-1} kpc^{-2}$
1	11.97	53(7)	0.41(0.06)	35(4)
1a	11.97	14(2)	0.11(0.02)	9(1)
1b	11.97	2.1(0.4)	0.017(0.003)	1.4(0.3)
2	11.97	13(2)	0.10(0.01)	8(1)
2a	11.97	2.9(0.5)	0.022(0.004)	1.9(0.3)
1	47.87	67(9)	0.53(0.07)	11(2)
2	47.87	18(3)	0.14(0.02)	2.9(0.4)
1	146.6	82(1)	0.65(0.09)	4.4(0.6)
2	146.6	22(4)	0.17(0.03)	1.1(0.1)
Tail	2318	160(20)	1.3(0.2)	0.54(0.08)

- Hα has clumpy structure associated with SSC 1 and SSC 2

  6" scale
  - SSC 1: 3 HII regions
    - Brightest is elongated
      - SFR 4-24 times higher than 1a and 1b
  - SSC 2: 2 HII regions
    - Brightest is rounder
      - ~5 times higher SFR than 2b

  12" scale (CO(2-1) & in Jarrett+06) & 21" scale Hα (CO(1-0))

  C 1 has SFR 4 times SSC 2

  ail

  R = 1.5 M_{sun}/yr

  nilar to SFR of entire Milky Way galaxy

  -50% of SFR from entire Tadpole (using FIR, um, or 70 um of Jarrett+06)

Gas Properties of the Tadpole's Tail

- Molecular gas: Non-detections of CO(1-0) ($<1\mathrm{x}10^8$ M_{sun}) & CO(2-1) ($<0.6\text{-}0.8\mathrm{x}10^8$ M_{sun})
- Atomic gas: SSC 1 & 2: $\sim 2\mathrm{x}10^8$ M_{sun} (12"), $3.2\text{-}3.6\mathrm{x}10^8$ M_{sun} (21") M_{sun}

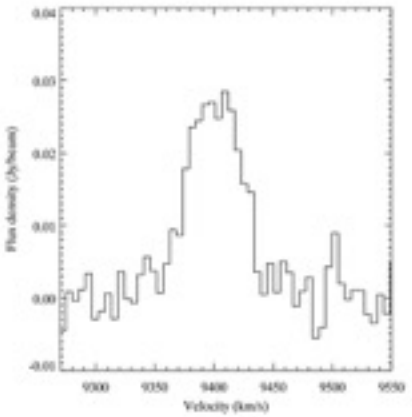
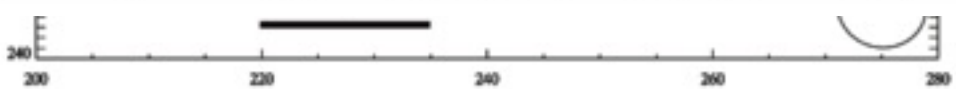


Table 4.2: Molecular and HI Gas in Tadpole Tidal Tail Locations

Location	I_{CO} K km s^{-1}	M_{mol} 10^8 $M_\odot$	FWHM km s^{-1}	Δv km s^{-1}	$\langle N_{\rm HI}\rangle$ 10^{21}cm^{-2}	$N_{\rm HI}$ 10^{21}cm^{-2}	$M_{\rm HI}$ $10^8 M_\odot$	M_{gas} $10^8 M_\odot$
CO(1-0) 21"								
SSC1	<0.115	<1.06	60	82.2	0.73(0.01)	6.56(0.01)	3.6(0.3)	<6.00
SSC2	<0.118	<1.09	50	60.3	0.65(0.01)	5.85(0.01)	3.2(0.2)	<5.44
CO(2-1) 12"								
SSC1	<0.178	<0.60	60	82.2	0.76(0.02)	3.78(0.02)	2.1(0.2)	<3.45
SSC2	<0.240	<0.81	50	60.3	0.66(0.02)	3.31(0.02)	1.8(0.1)	<3.26
Tail		<2.15	60	109.6	0.120(0.001)	164.0(0.1)	90(6)	<125



Star Formation in Tadpole Tidal Debris

- SSC 1:
  - $\Sigma_{SFR}(H\alpha)$ > 2.4 times SFR expected from Σ_{gas}: very efficient
  - $\tau_{dep,mol} < 0.16$ Gyr, $\tau_{dep,HI} = 0.56$ Gyr, $\tau_{dep,tot} < 0.92$ Gyr
- SSC 2:
  - $\Sigma_{SFR}(H\alpha)$ > 0.8 times SFR expected from Σ_{gas}: low-normal efficiency
  - $\tau_{dep,mol} < 0.16$ Gyr, $\tau_{dep,HI} = 0.56$ Gyr, $\tau_{dep,tot} < 0.92$ Gyr

- Entire Tail
  - $\Sigma_{SFR}(H\alpha)$ > 0.2 times SFR expected from Σ_{gas}: low efficiency

Location	$\tau_{dep,H_2},\mathrm{H}\alpha$ (Gyr)	$\tau_{dep,\mathrm{HI},\mathrm{H}\alpha}$ (Gyr)	$\tau_{dep,tot},\mathrm{H}\alpha$ (Gyr)
CO(1-0) 21″			
SSC 1	< 0.16	0.56	< 0.92
SSC 2	< 0.63	1.9	< 3.2
Total	< 0.17	7.2	< 9.9
CO(2-1) 11″			
SSC 1	< 0.11	0.40	< 0.65
SSC 2	< 0.58	1.3	< 2.3

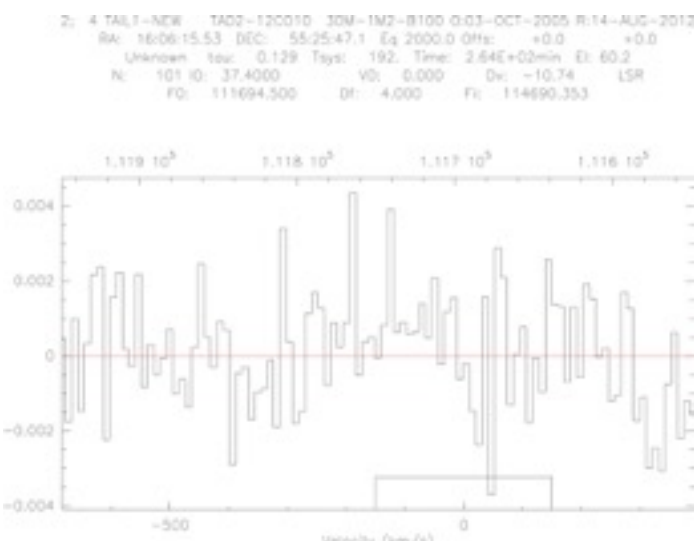
Star Formation in Tadpole Tidal Debris

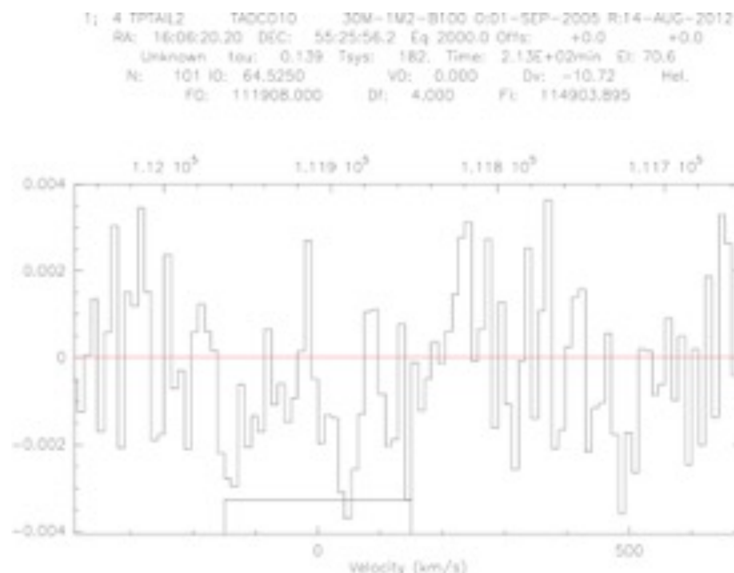
Table 4.3: Comparison of Local & Global Star Formation Rates in the Tadpole Tidal Tail

Location	Area kpc^2	$\Sigma_{SFR}(H\alpha)$ $10^{-3} M_{\odot} yr^{-1} kpc^{-2}$	Σ_{gas} $M_{\odot} pc^{-2}$	$\Sigma_{SFR}(\mathrm{gas})$ $10^{-3} M_{\odot} yr^{-1} kpc^{-2}$
CO (1-0)				
1	146.6	4.4(0.6)	< 4.06	< 1.8
2	146.6	1.2(0.2)	< 3.71	< 1.6
Tail	2318	0.54(0.08)	< 5.37	< 2.6
CO (2-1)				
1	47.9	11(2)	< 7.2	< 4.0
2	47.9	2.9(0.4)	< 6.8	< 3.7

Star Formation in Tidal Tail - Methods

- Data:
  - IRAM CO(1-0) and (2-1) observations - 2 locations in tail
    - Taken in 2005 by Ute Lisenfeld
    - Data reduced by them
    - Table of upper limits (rms ~ 1.5mK) in tidal debris emailed to me.





$M_{mol} < 1.1 \times 10^8\ M_{sun}$

Hα from Jarrett et al. 2006 optical spectra indicate SFR = 0.23 M_{sun}/yr

SFR ~200 times larger than Western tail HII region in NGC 2782

τ_{dep} ~0.4 Gyr (More efficient!)

Early Merger Simulations

- Can begin to see formation of large scale structures (tidal tails, bridges, loops) from tidal forces.
- Prograde encounter produces better “tails”

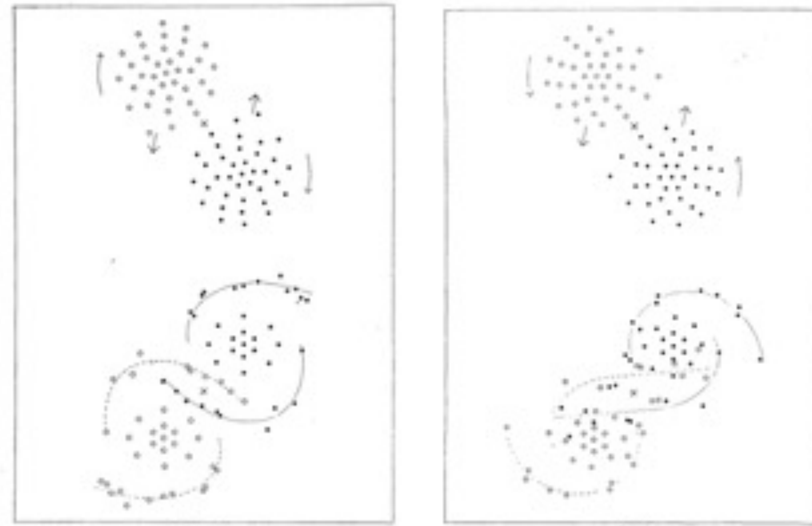


Fig. 4a Fig. 4b

Fig. 4a.—Tidal deformations corresponding to parabolic motions, clockwise rotations, and a distance of closest approach equal to the diameters of the nebulae. The spiral arms point in the direction of the rotation.

Fig. 4b.—Same as above, with the exception of counterclockwise rotations. The spiral arms point in the direction opposite to the rotation.

First Simulation
By Holmberg 1941
Used light bulbs as
Test particles.

Early Minor Merger Simulations

- Early comparison of minor and major merger simulations
- Minor mergers have shorter tidal tails than in major mergers
- But Minor mergers have longer lasting tidal tails
  - Not accreted back onto parents as quickly
- Minor merger tidal debris can be lost from the system to the IGM

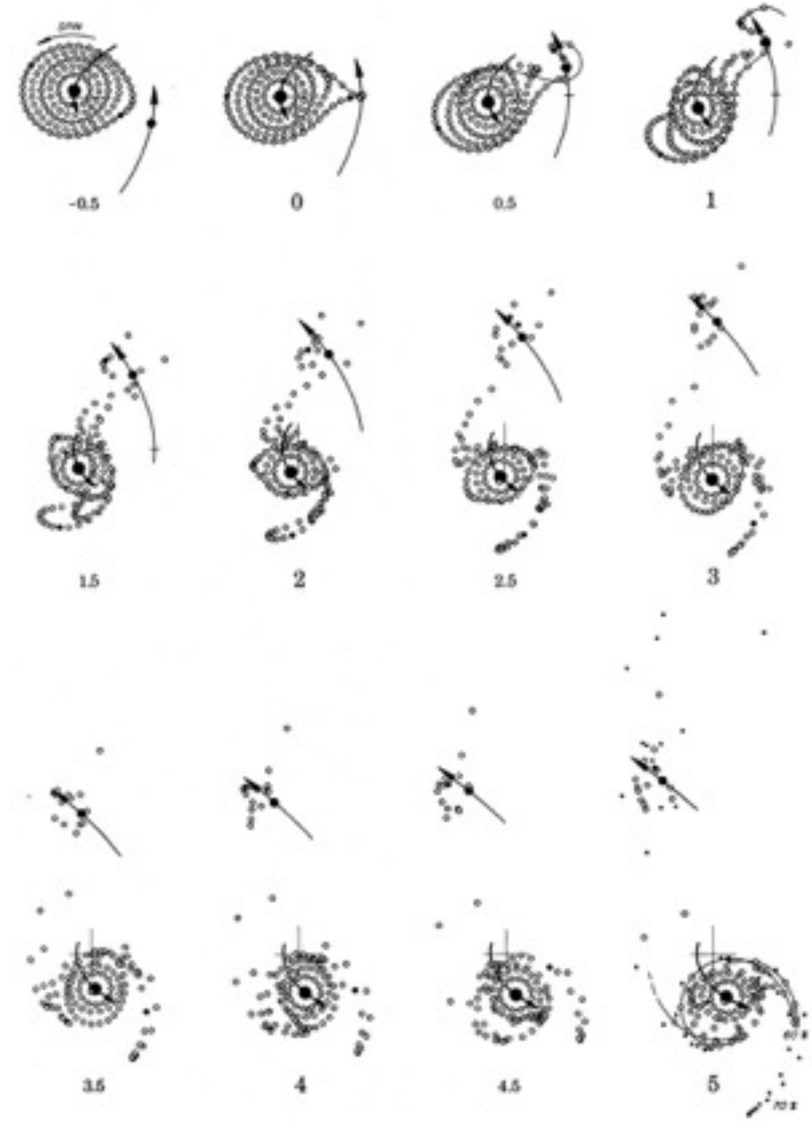
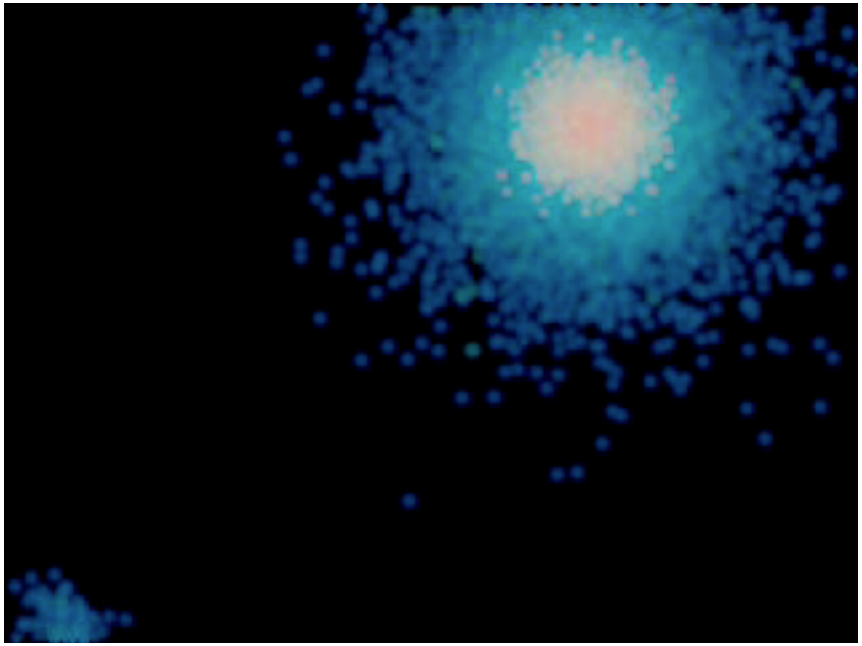


FIG. 4.—A flat direct ($i = 0°$) parabolic passage of a quarter-mass companion

Minor Merger, Mass ratio = 1:4
Toomre & Toomre 1972

Early Minor Merger Simulations

- Can see formation of large scale structures (tidal tails, bridges, loops)
- But
  - Low resolution
  - Average SF properties
    - Stellar feedback added by hand
  - Physics of ISM not included or only limited prescriptions
- ~10% of total star formation of merger is in tidal tails and bridges (e.g., Barnes 2004)



Minor Merger, Mass ratio = 1:3
Barnes 2001