Interaction Driven Galaxy Evolution

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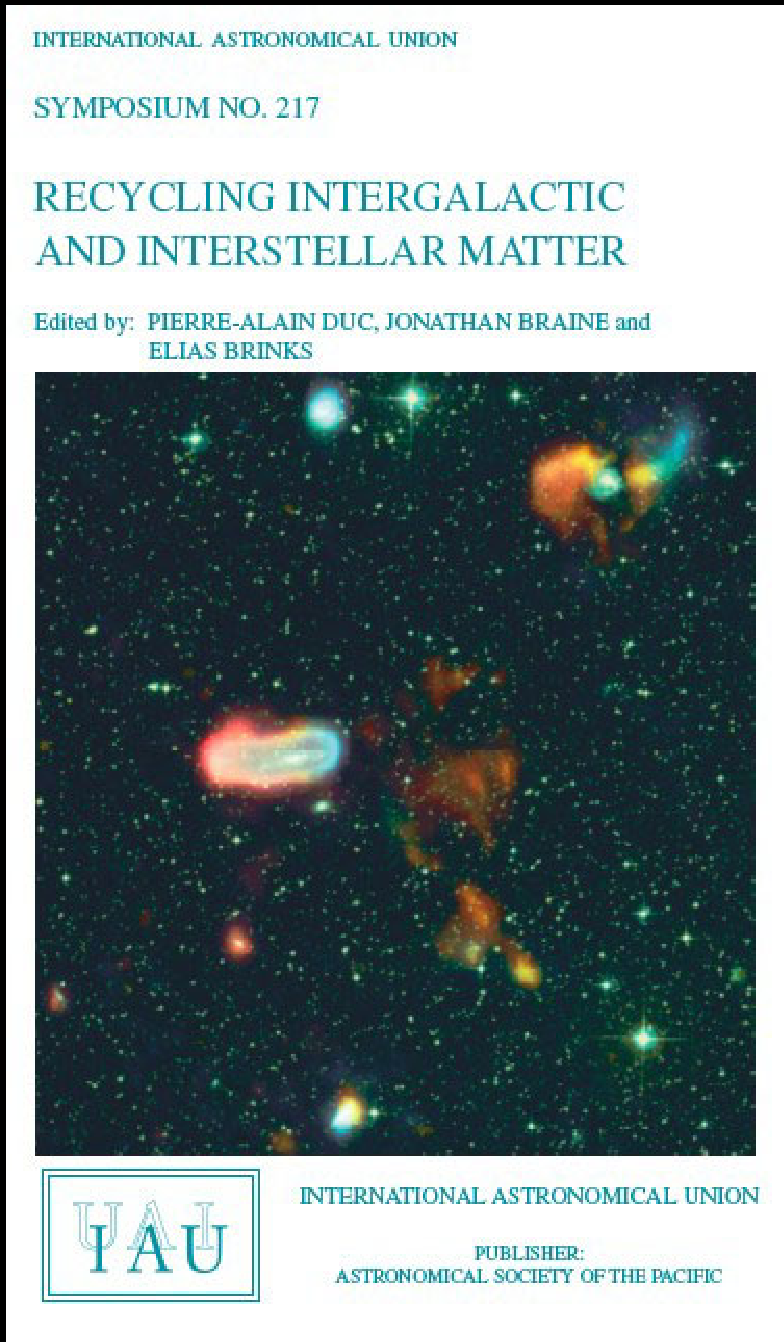
NRAO-CV

Interactions drive both large scale outflows and inflows

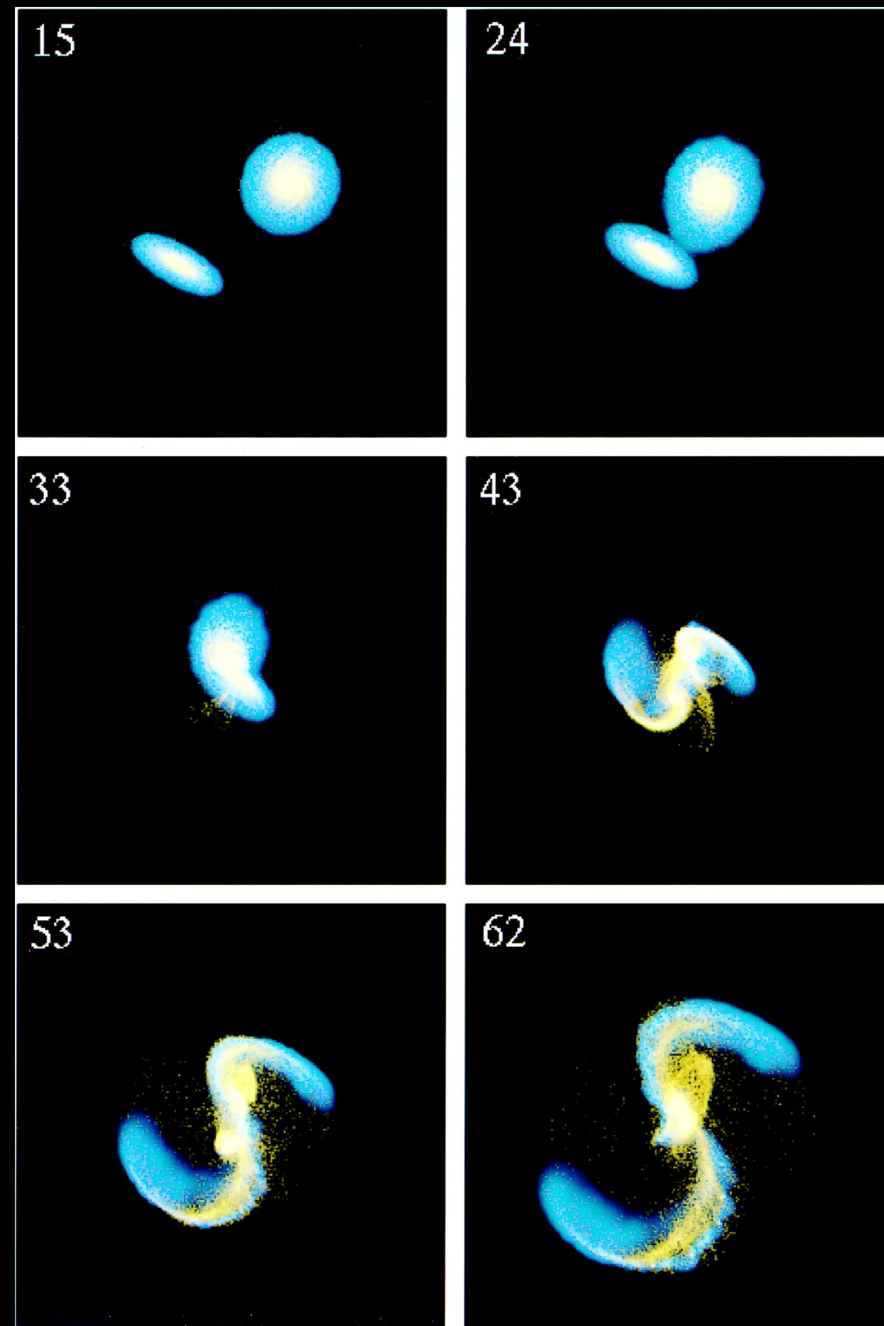
- Tidal Ejection in Isolation
- Tidal Ejection in Denser Evironments
- Tidal Infall
  - Starbursts/AGN => outflows
- Evolution of Remnants
  - Into disks?
  - Into Ellipticals?



Most topics (and many more) covered in great detail in IAU Syposium 217 (2003, Sydney)

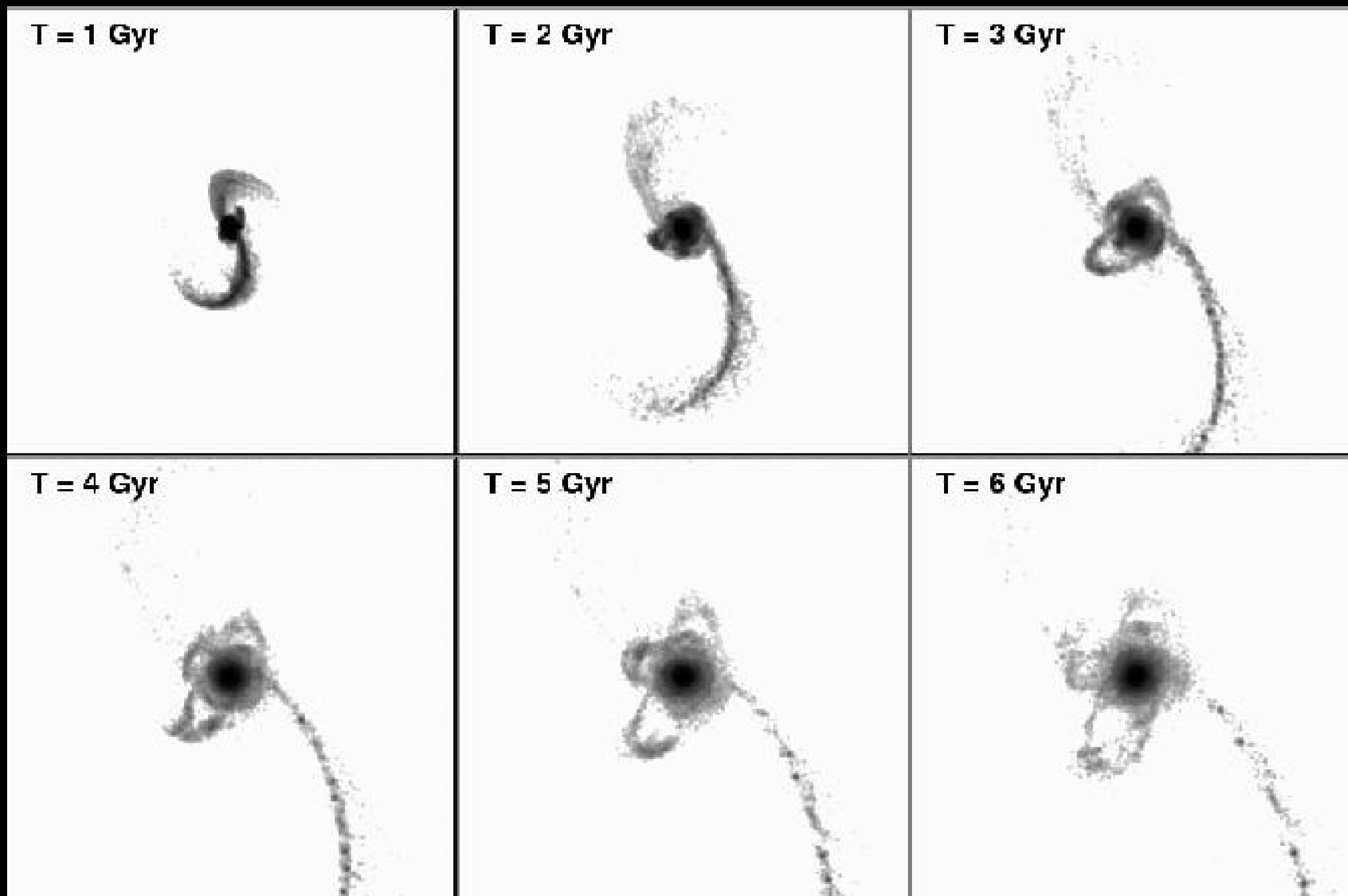
Tidal Ejection (in isolation)

- Tails develop shortly after closest approach
- On the pericentric side, material is drawn into companion system
- On the anti-tidal side, long, often gas-rich tails expand into intergalactic space
- Tails evolve slowly, material at the base constantly raining back in onto remnant

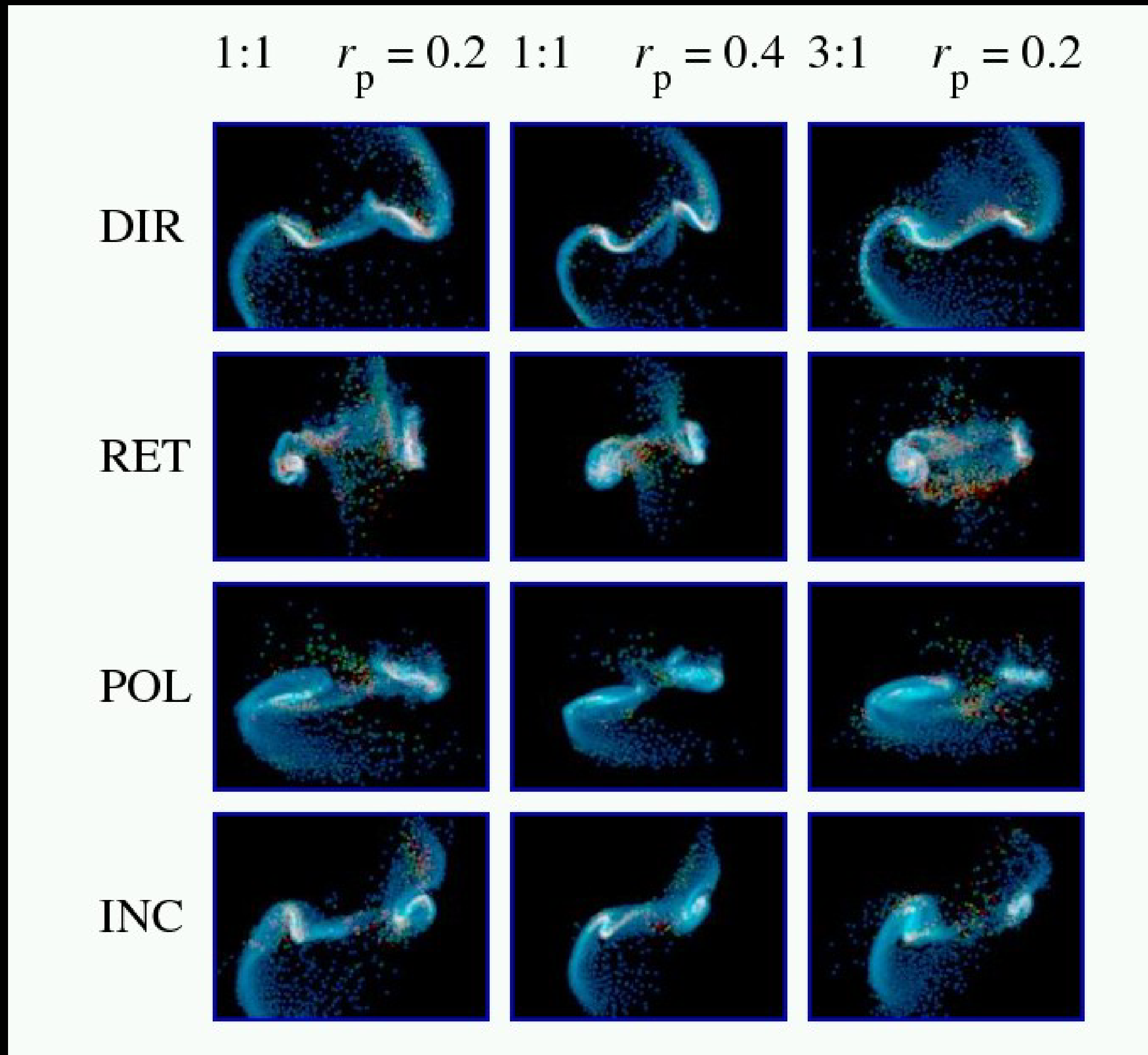


Mihos, 2001, ApJ, 550, 94

Tidal Evolution in Low Density Environment

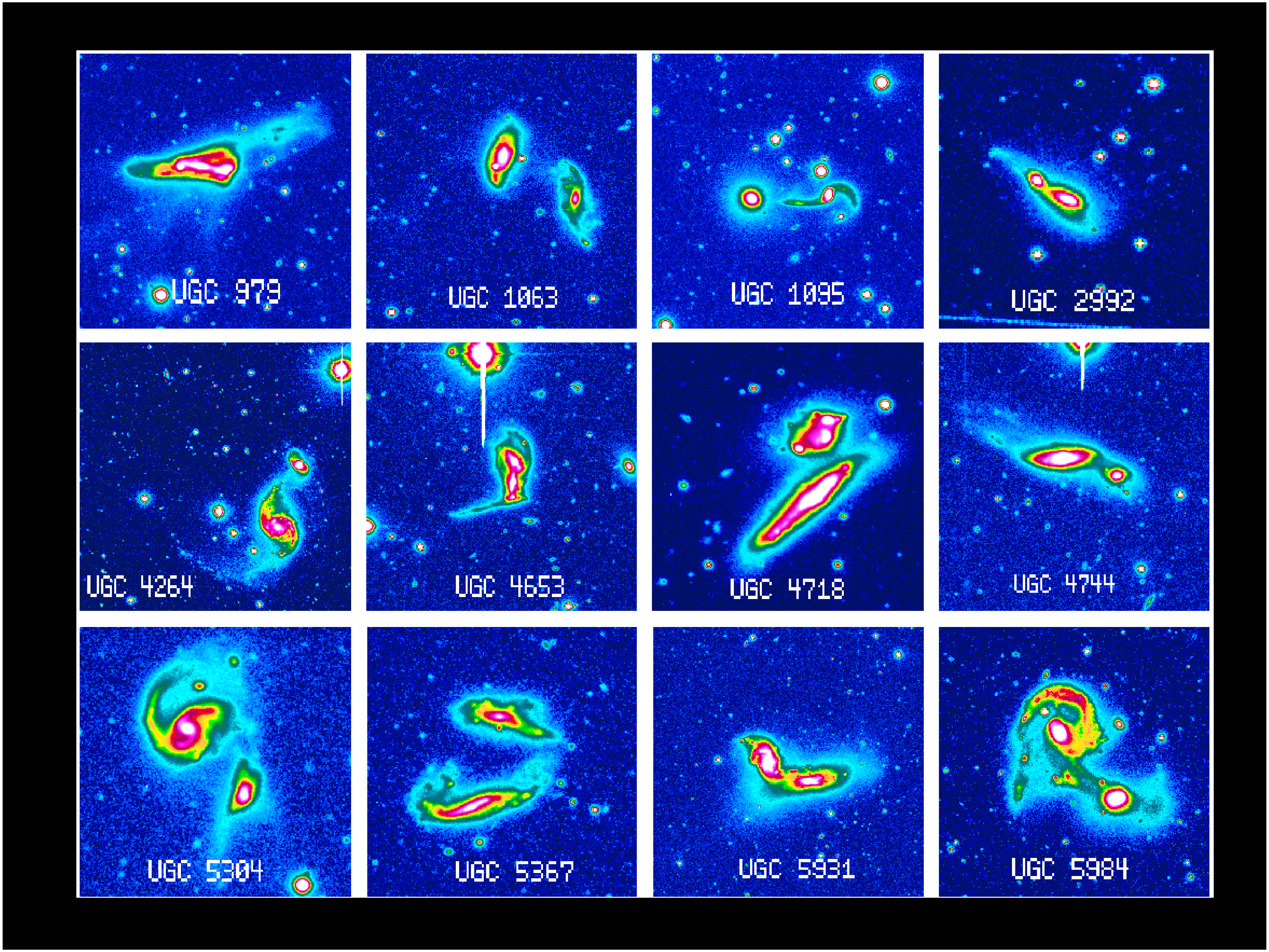


Mihos, 2004, IAU Symp.217, p.390

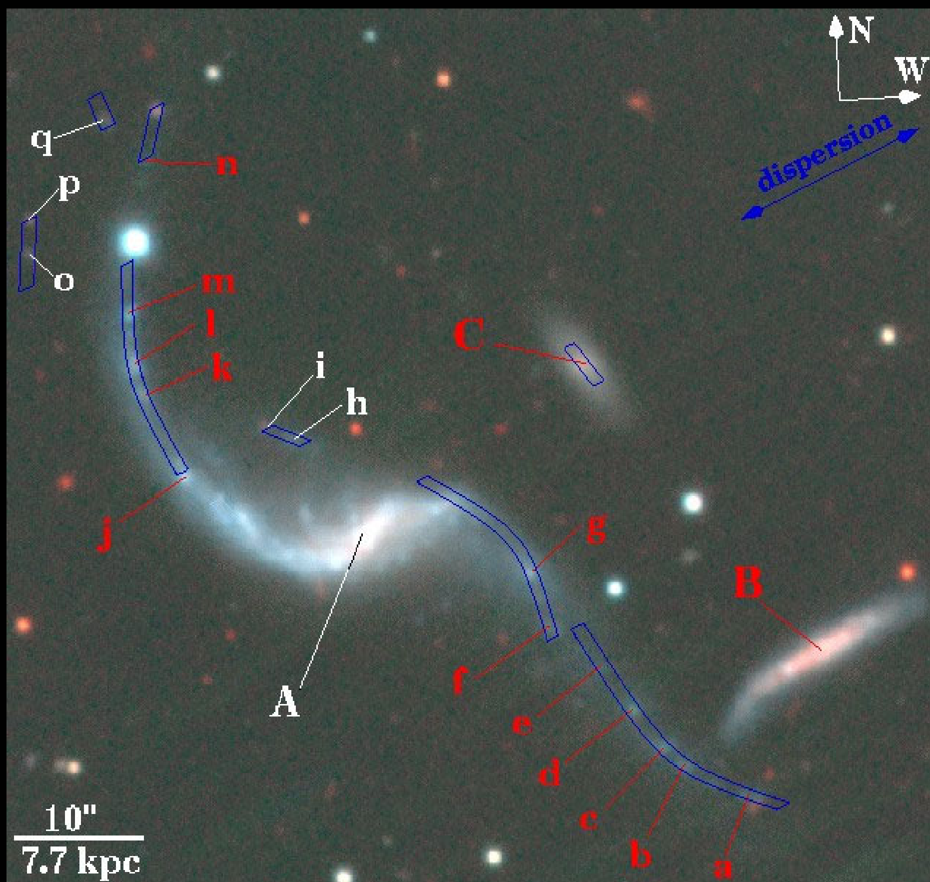


http://www.ifa.hawaii.edu/~barnes/research/gassy_mergers/

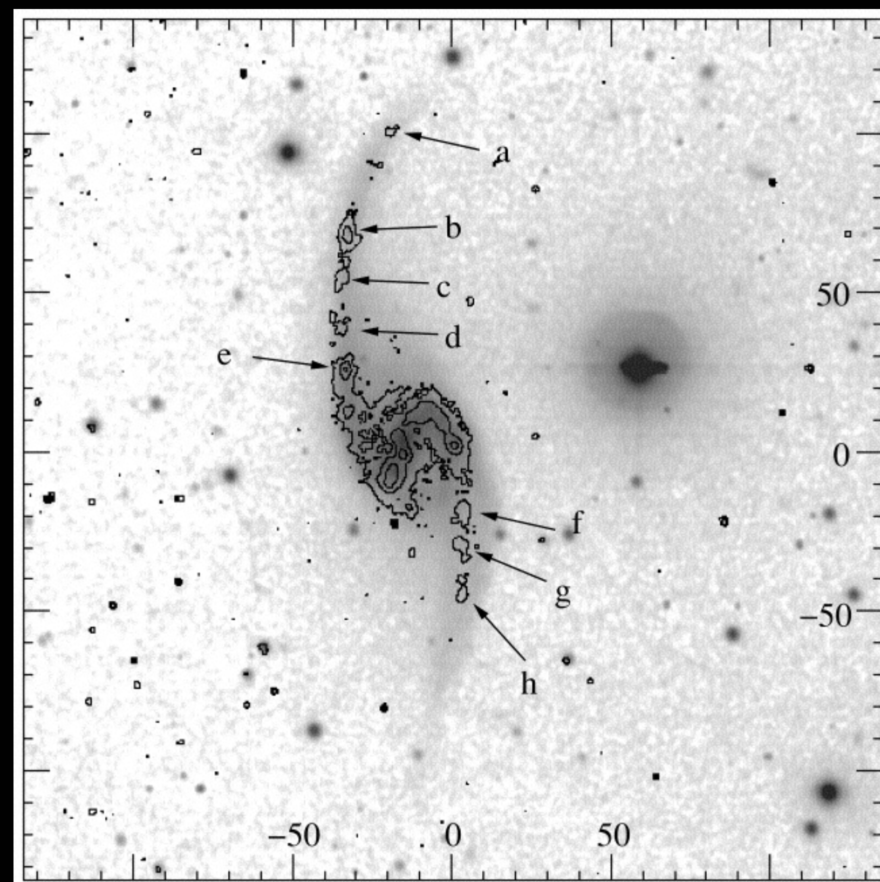
See also Barnes 2002, MNRAS, 333, 481


UGC 979
UGC 1063
UGC 1095
UGC 2992
UGC 4264
UGC 4653
UGC 4718
UGC 4744
UGC 5304
UGC 5367
UGC 5931
UGC 5984

Tidal Ejection in Isolation: extra-disk star formation



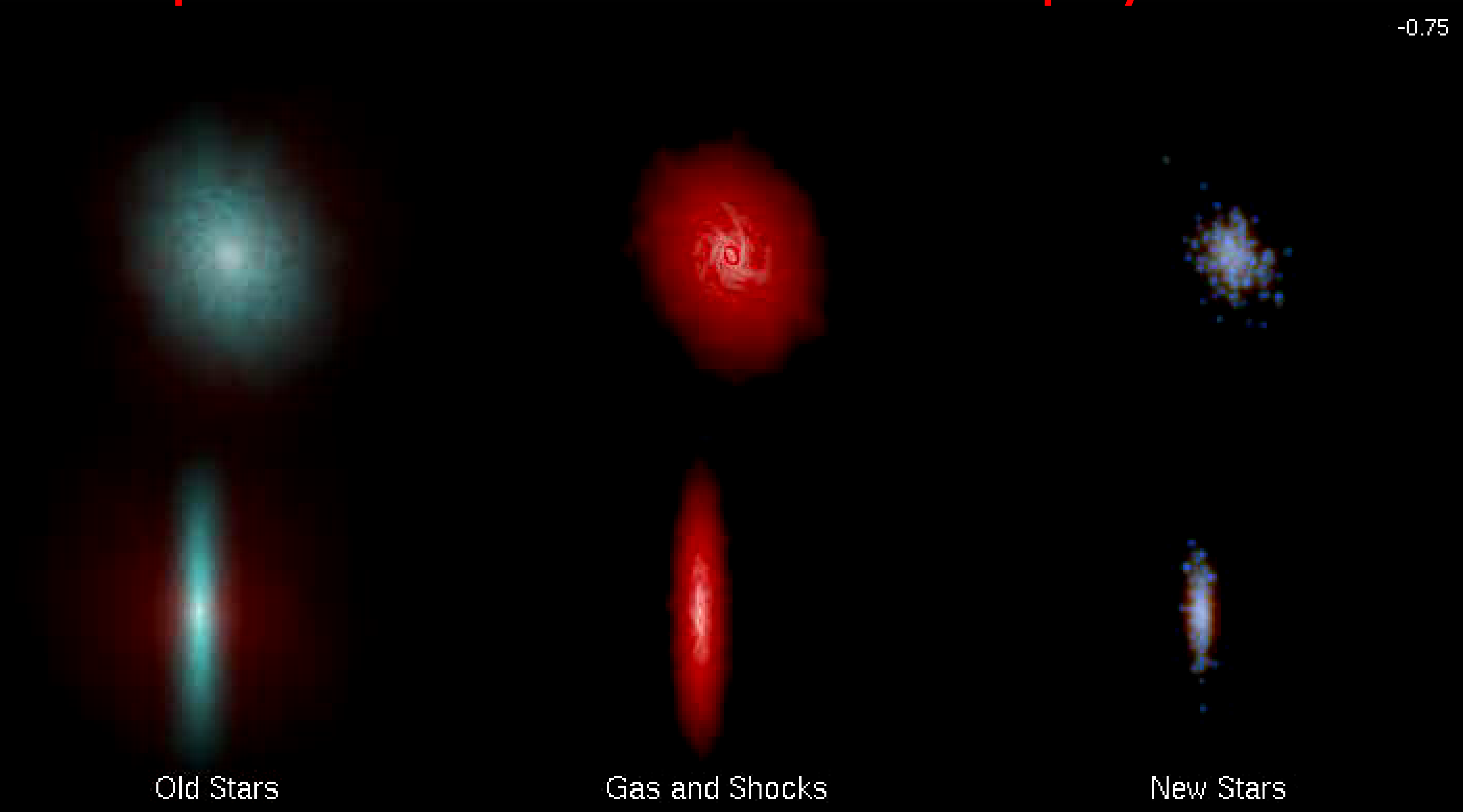
Weilbacher et al. 2000



Iglesias-Paramo & Vilchez 2001

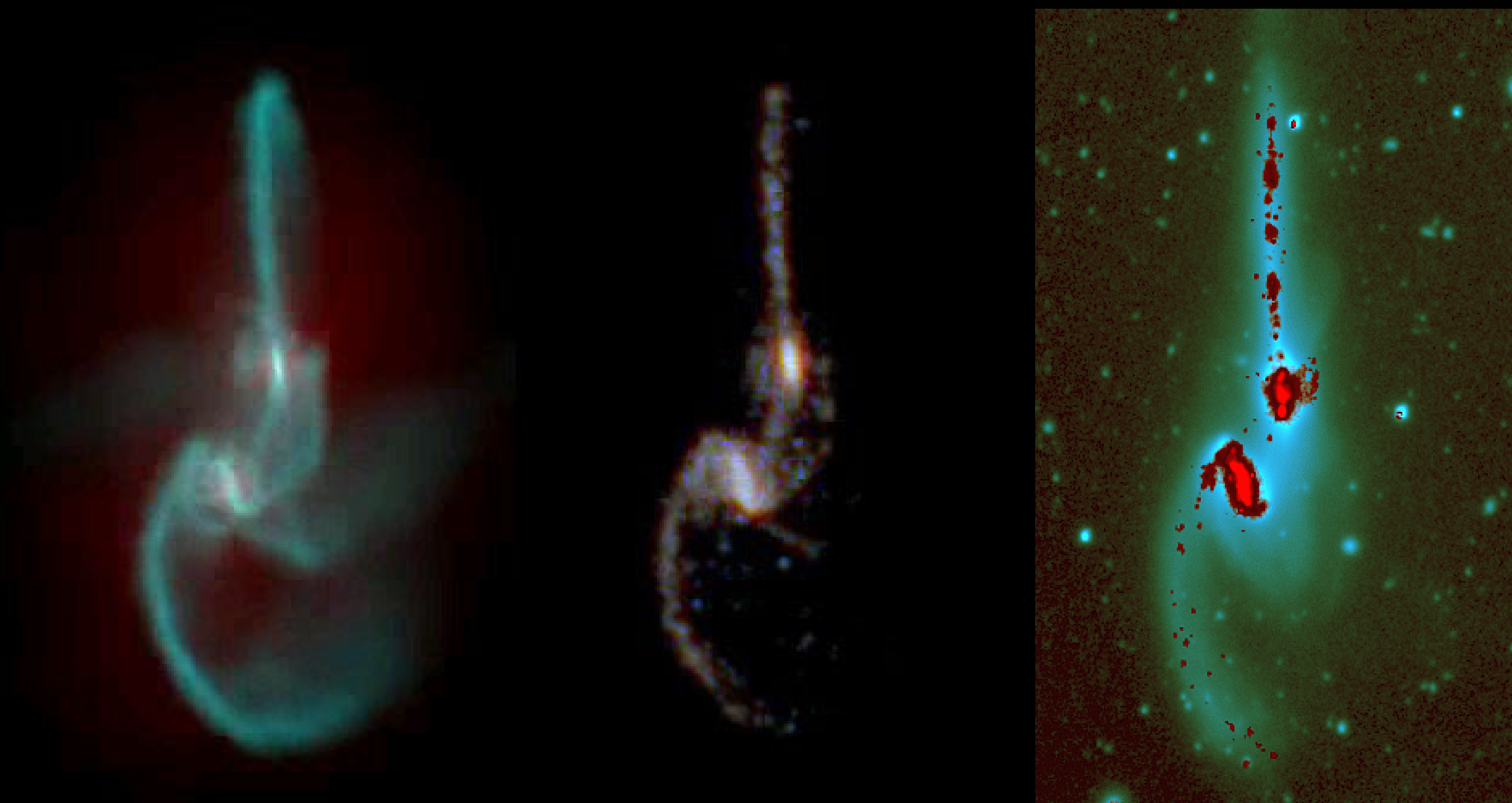
(Stick around for talk by Schiminovich)

Modern models are larger, more sophisticated & include more "physics"



N-body SPH model with star formation and shock heating; Barnes 2004 MNRAS, 350, 798

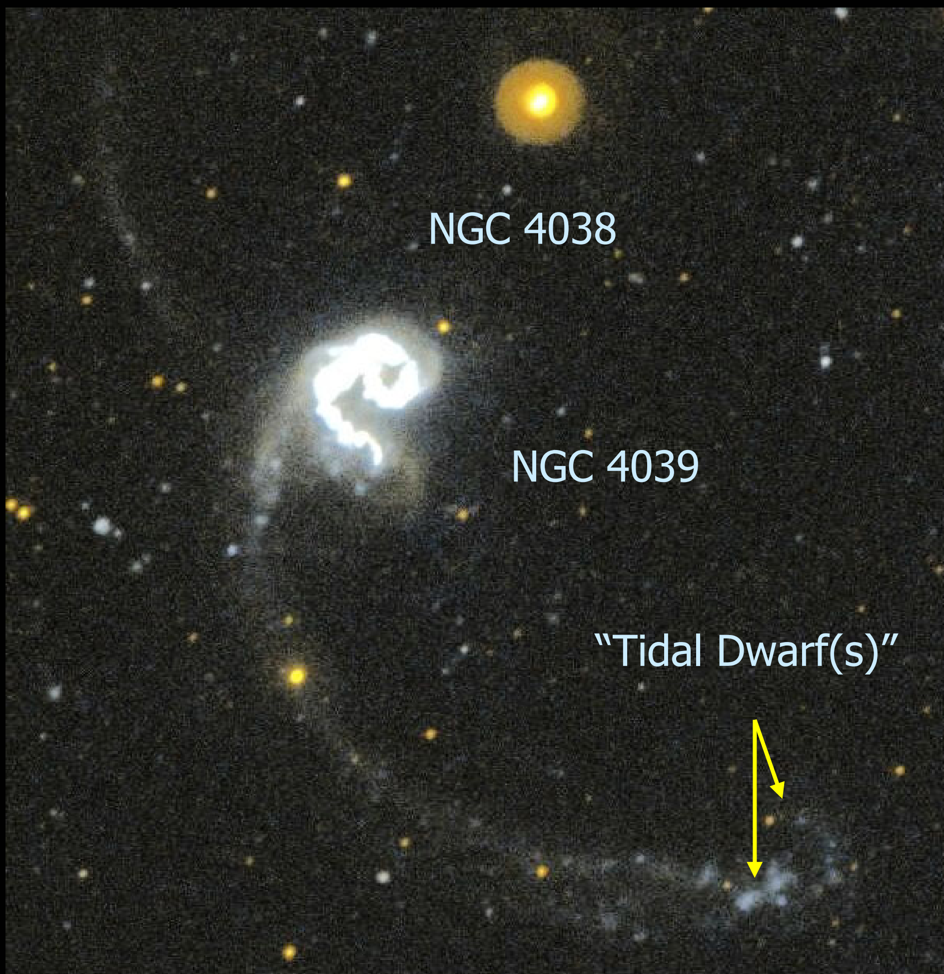
Comparison with observations provides check on model prescriptions

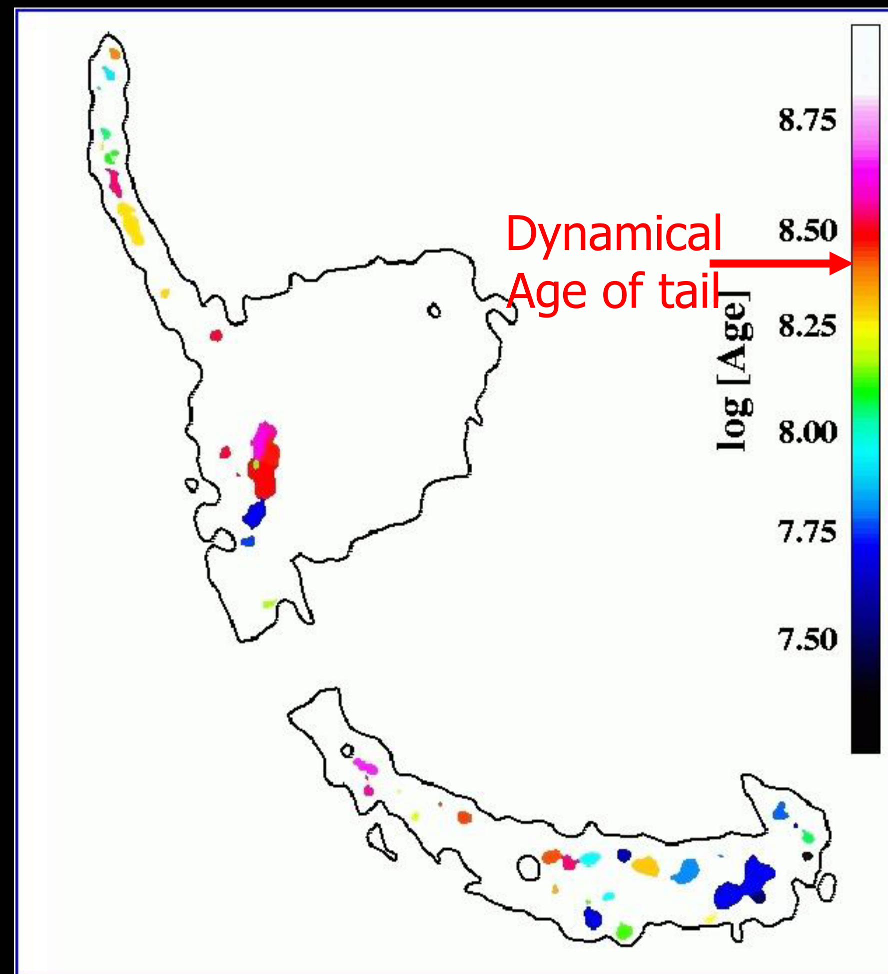


N-body simulation of NGC 4676 “The Mice”

Barnes 2004 MNRAS; Hibbard & Barnes, in preparation

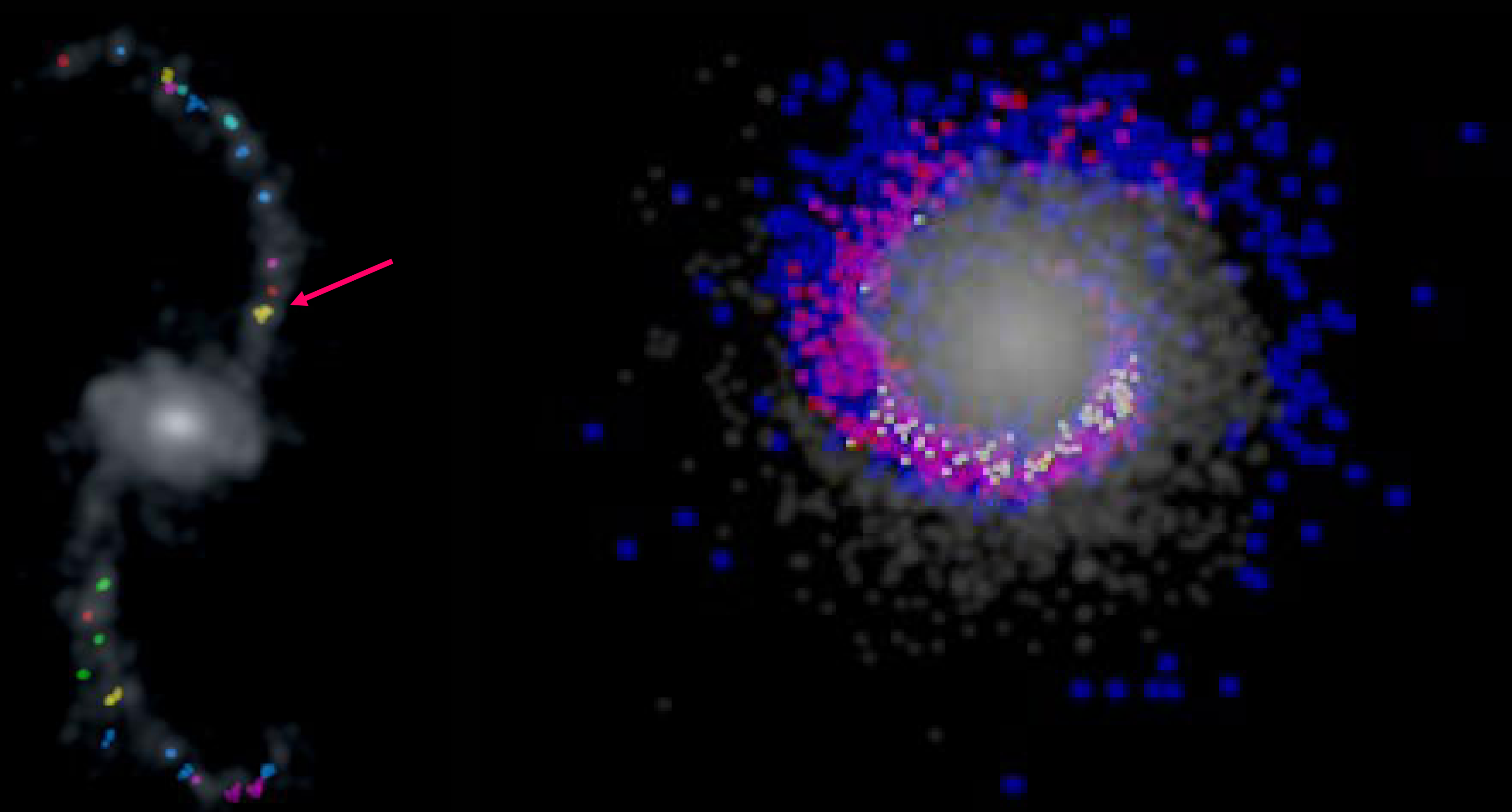
UV-optical colors allow us to uncover sites of past star formation





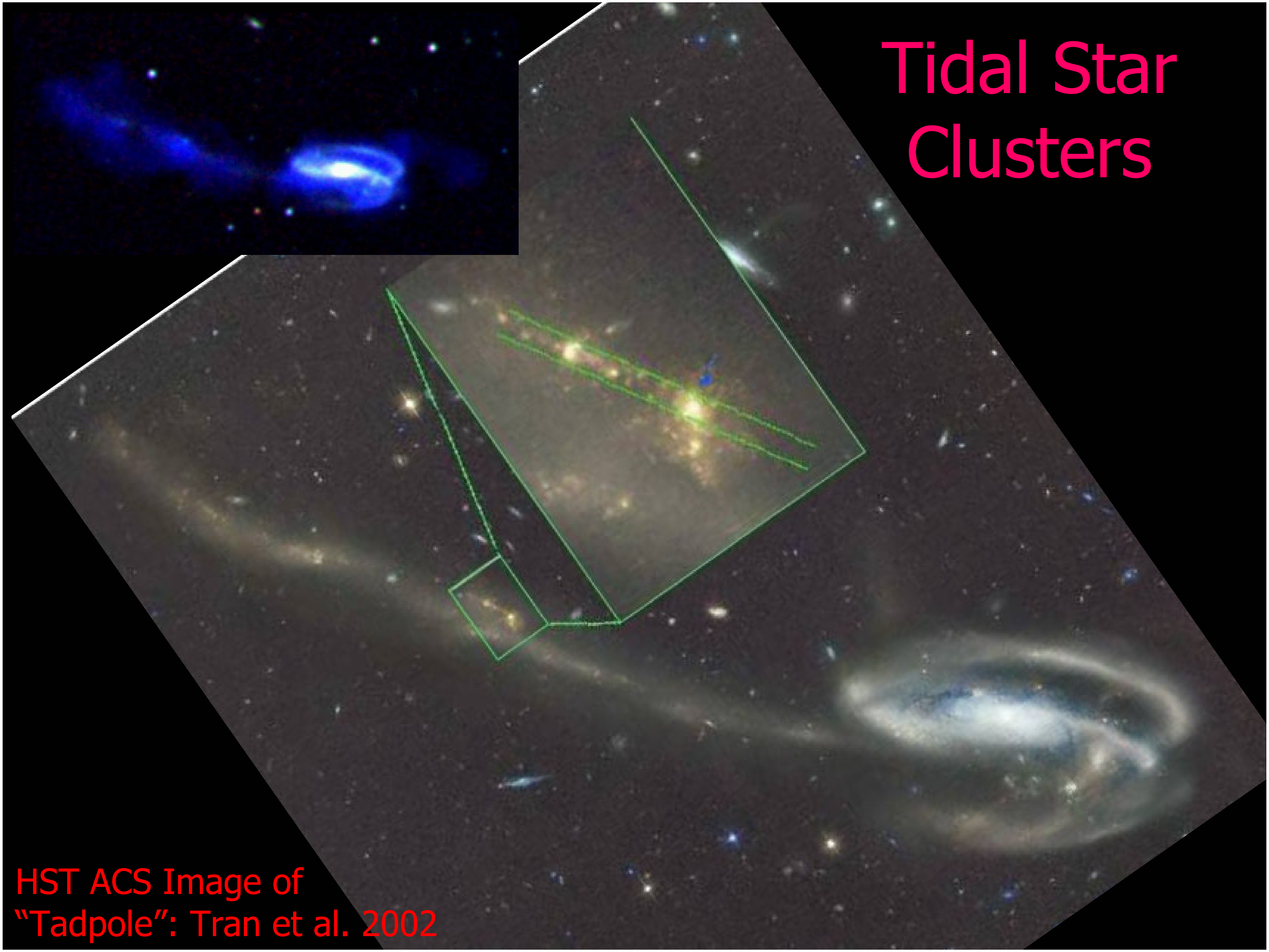
GALEX Observations: Hibbard, Bianchi, Thilker et al. 2005, ApJL, 619, L87

Some regions of tail are Self-gravitating; will give rise to long-lived structures (“Tidal Dwarfs”; “Halo Spaghetti”)



From Barnes, 2005 in preparation

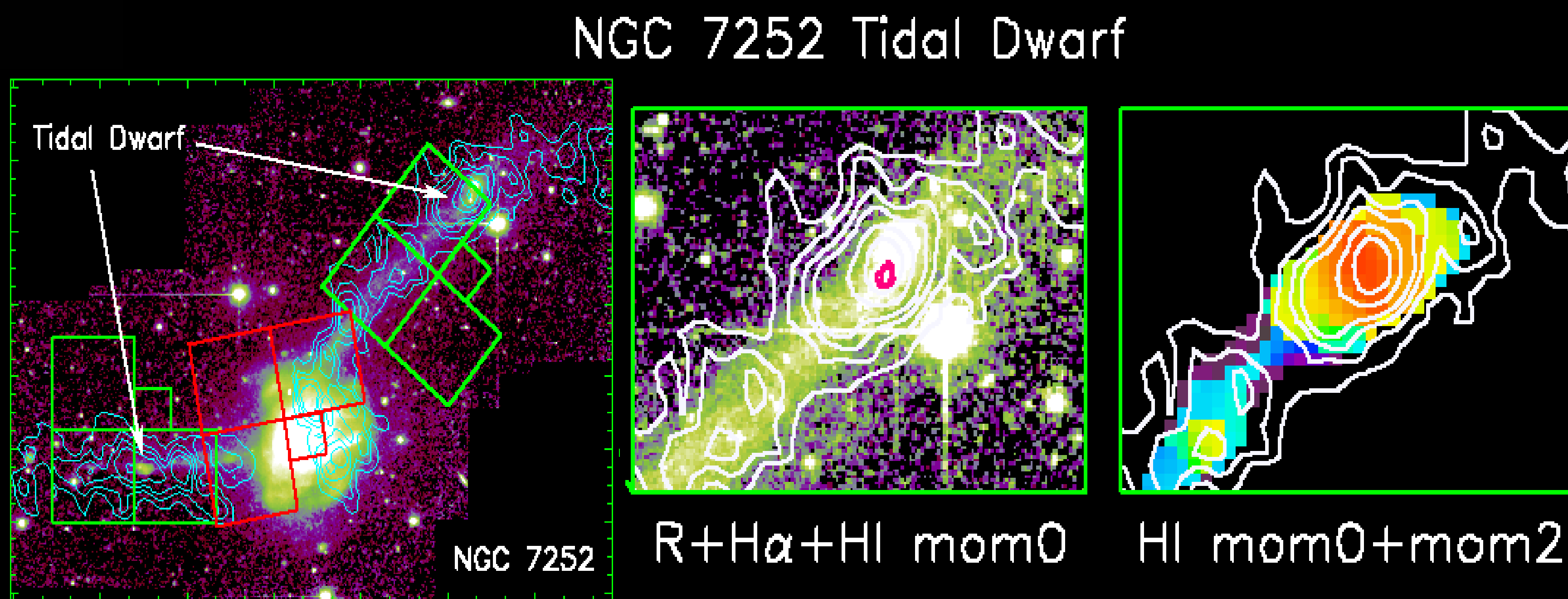
Tidal Star Clusters



HST ACS Image of
“Tadpole”: Tran et al. 2002

Tidal Dwarf Galaxies

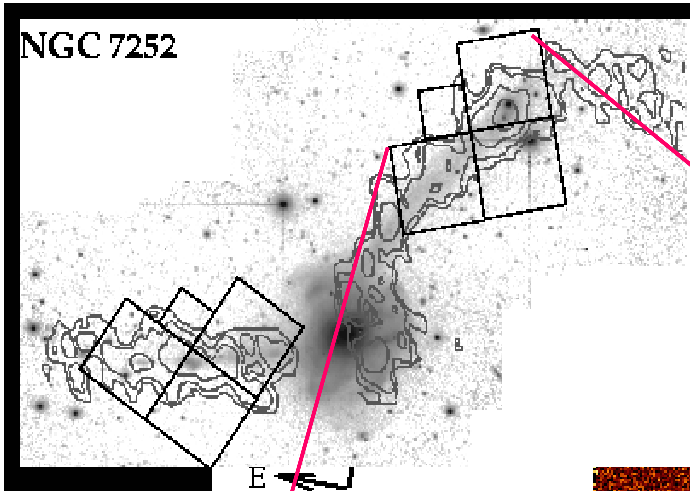
NGC 7252 NW TDG Candidate: Identified by HII regions (Schweizer, 1978)

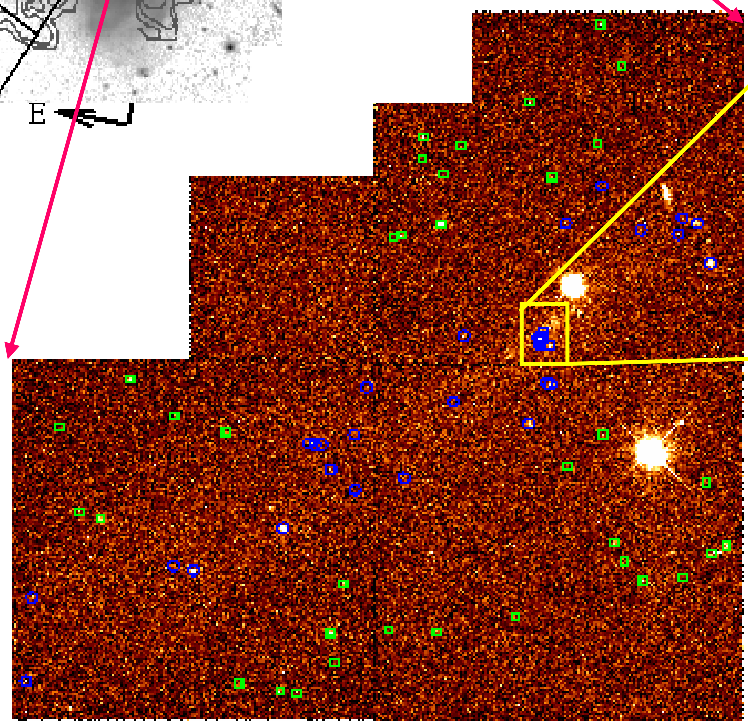


Found to correspond to peak in local HI column density and HI velocity dispersion (Hibbard et al. 1994; Hibbard & van Gorkom 1996)

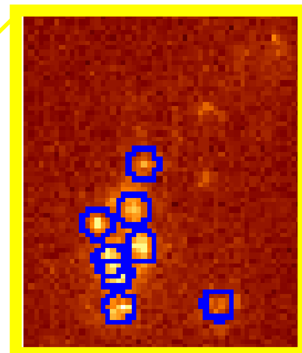
8 Star Cluster Candidates in NGC 7252 NW TDG

Knierman et al. 2003 ApJ, 126, 1227

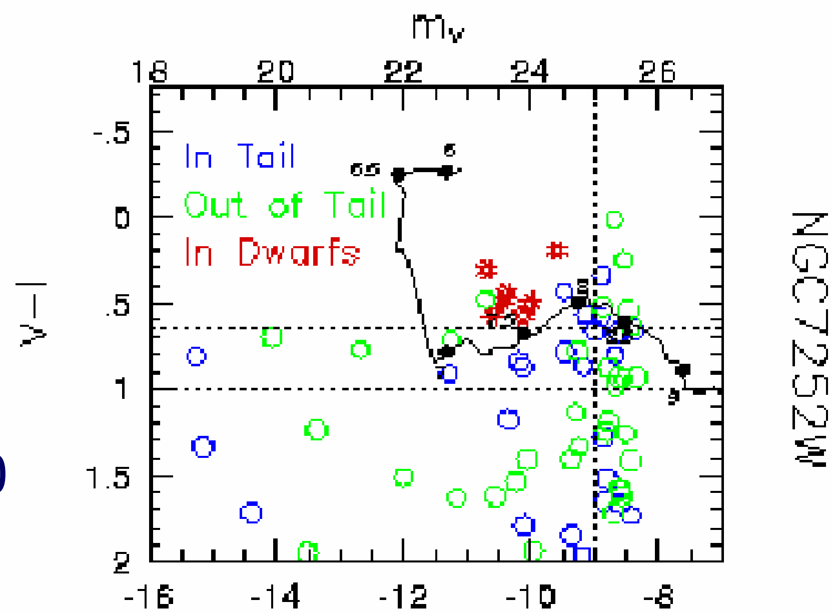




WFPC2/HST image in F555W filter



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



M_V~-10, (V-I)~0.5 => Age ~ 30 Myr (BC93 SSP, no reddening)

Tidal Evolution in High Density Environment

- Stripping or “Threshing”
- “Harassment”
- “Pre-processing”

Not covered:

Ram Pressure Stripping (stick around for Jeff Kenneys talk): removal of cold diffuse gas by ICM

“Strangulation” (e.g. Larson, Tinsley & Caldwell 1980): galaxies lose contact with cold gaseous reservoirs when they enter clusters

Tidal Stripping or "Threshing": Tidal disruption of galaxies as they orbit in Cluster potential

Most effective for diffuse systems on orbits which pass through cluster core

e.g. Byrd & Valtonen 1990; Bekki et al. 2001
(above image from Mayer 2000 *http://pcblu.mib.infn.it/~lucio*)

"Harassment": repeated long-ranged encounters between dwarf spirals and massive cluster galaxies

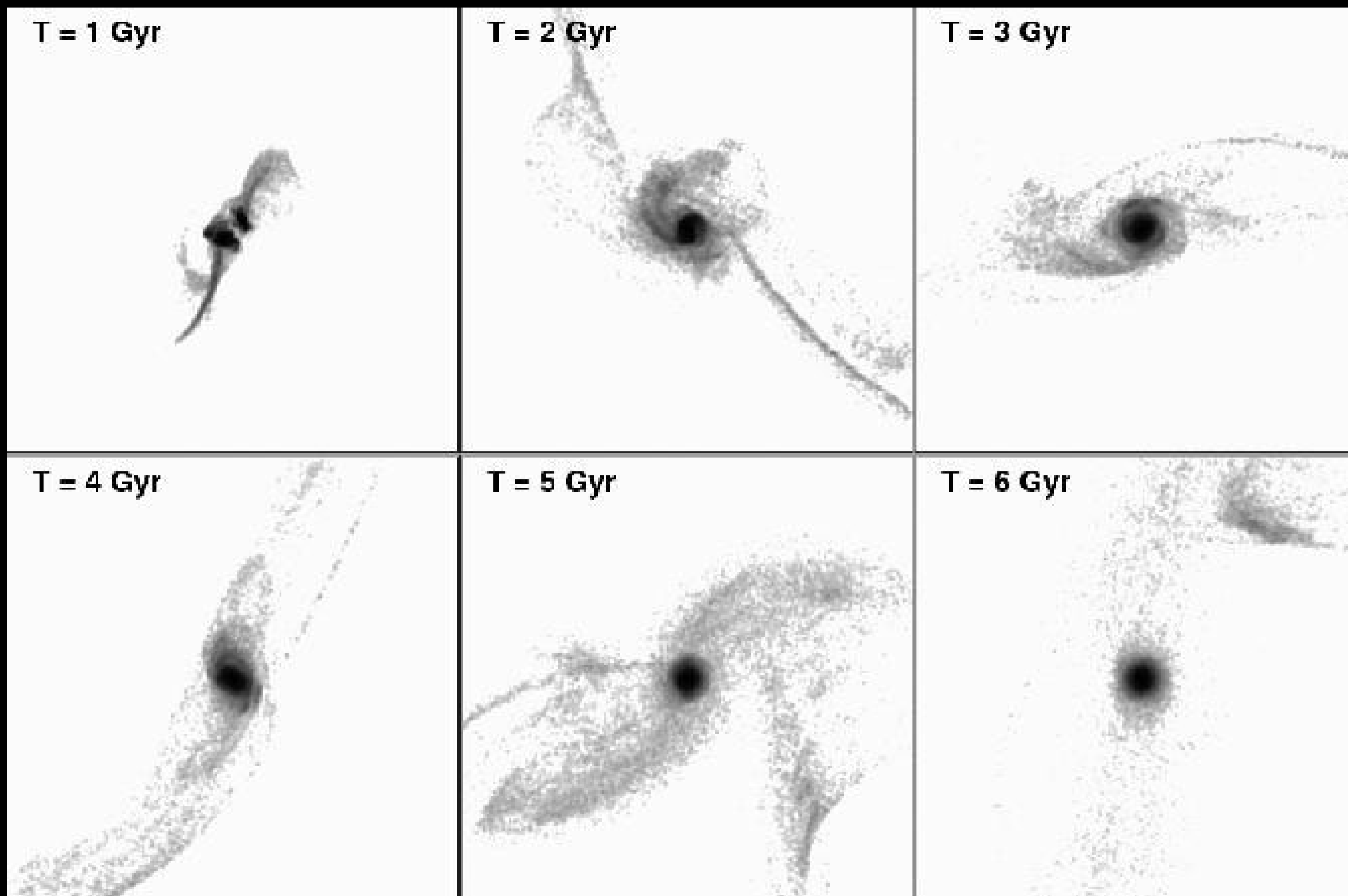
Most effective for diffuse systems on orbits which pass through cluster core

Moore et al. 1996, Nature, 379, 613

"Pre-processing": Accelerated evolution of interacting systems falling into clusters

Mihos et al. 2004 (*http://burro.astr.cwru.edu/*)

Tidal Evolution in High Density Environment

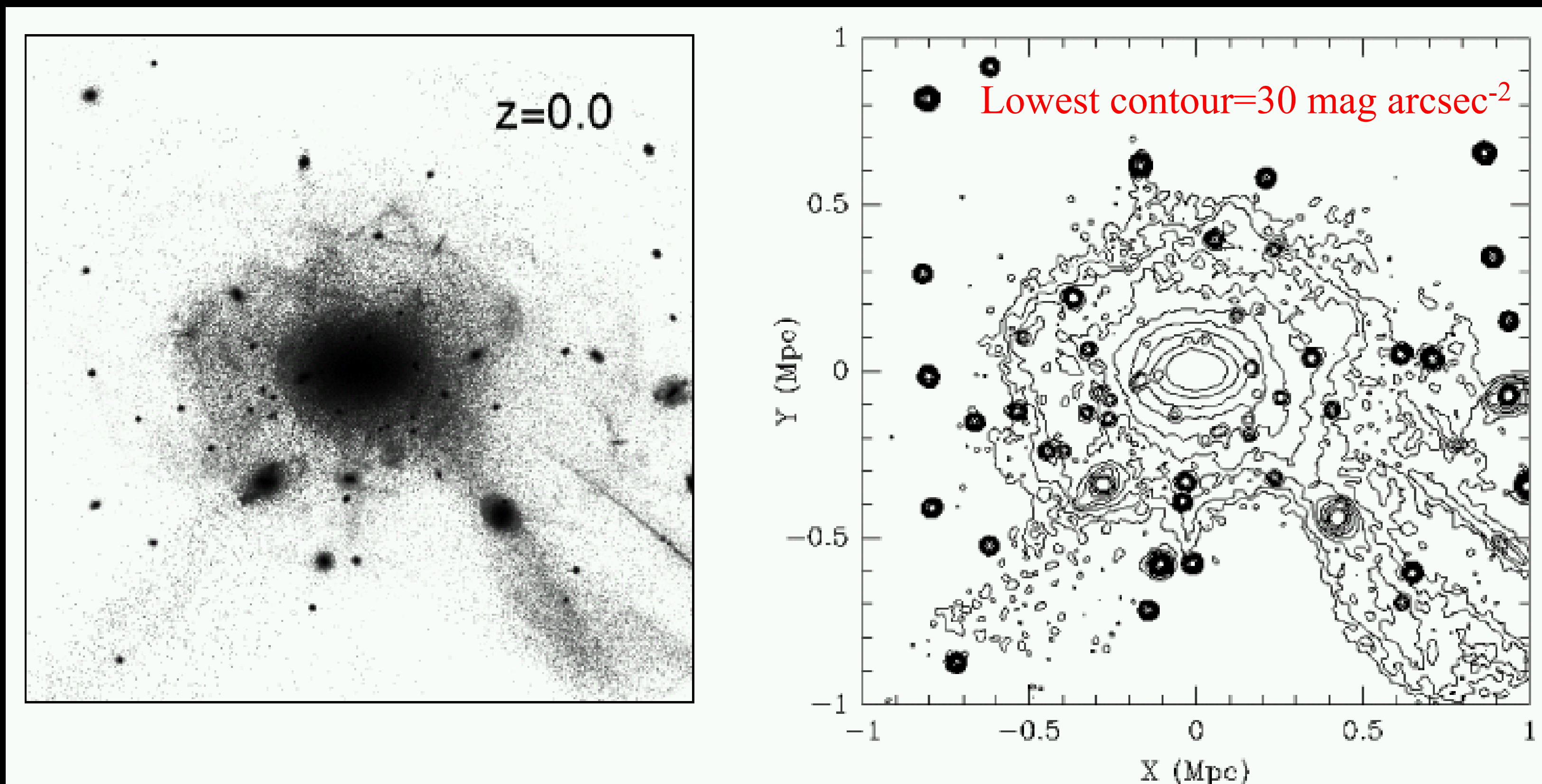


Mihos, 2004, IAU Symp.217, p.390

In Cosmological Simulations, all effects come into play

Simulation of cD Cluster: Dubinski, 1998

Tidal Evolution in High Density Environment



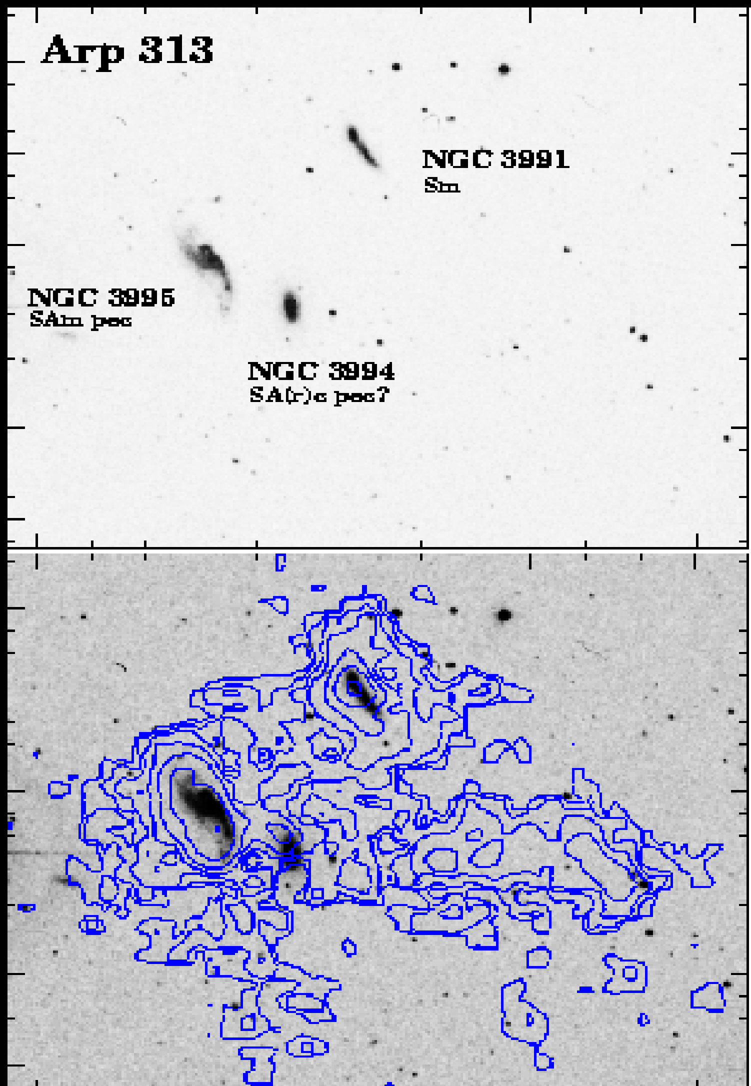
Simulation of cD Cluster: Dubinski, 1998
(see also Feldmeier et al. 2004, ApJ, 609, 617)

All processes will contribute to the emerging intracluster zoo

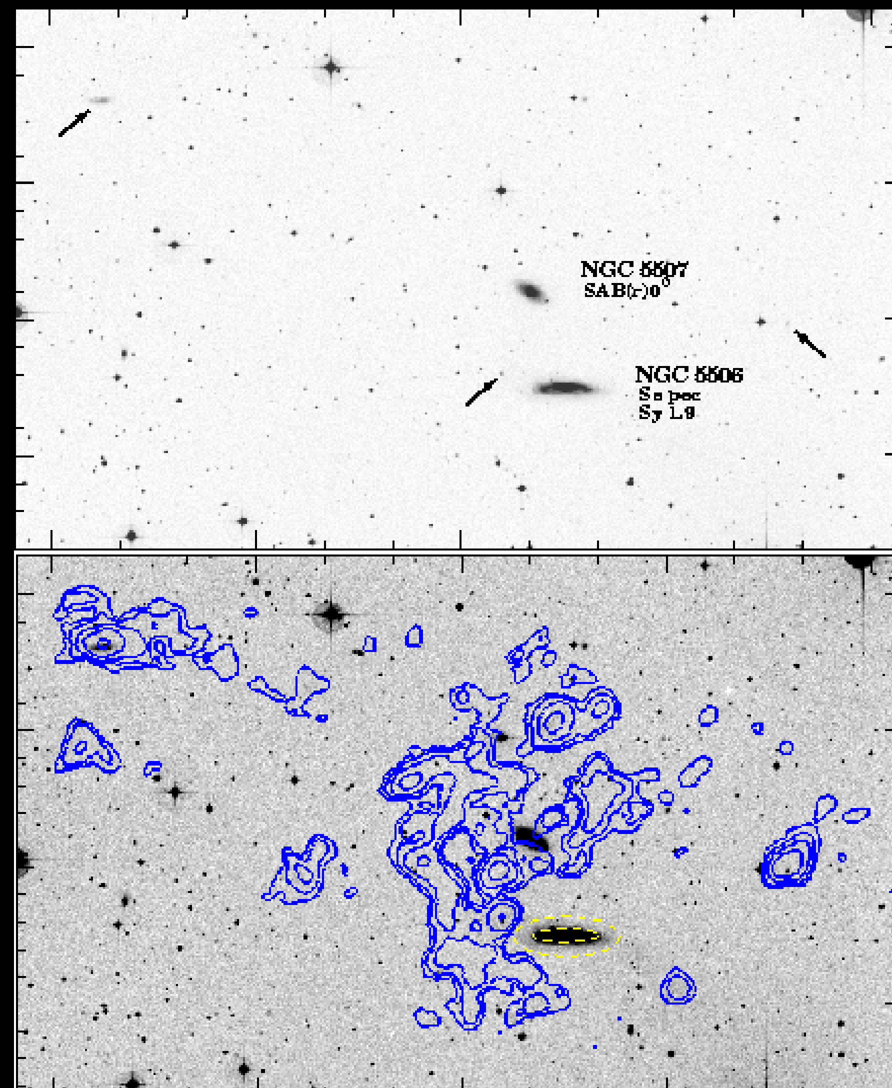
- Genesis of “Ultracompact Dwarfs”?
- Extragalactic HII Regions/ “ELDOTS”
- Intracluster Stars/PNe/GCs etc

Estimates of ICL ~15-50% of total cluster light e.g. Arnaboldi et al. 2002, Feldmeier et al. 2004, Lin & Mohr 2004, Gonzalez et al. 2005, cf. also IAU Symp 217

Tidal Debris in Groups

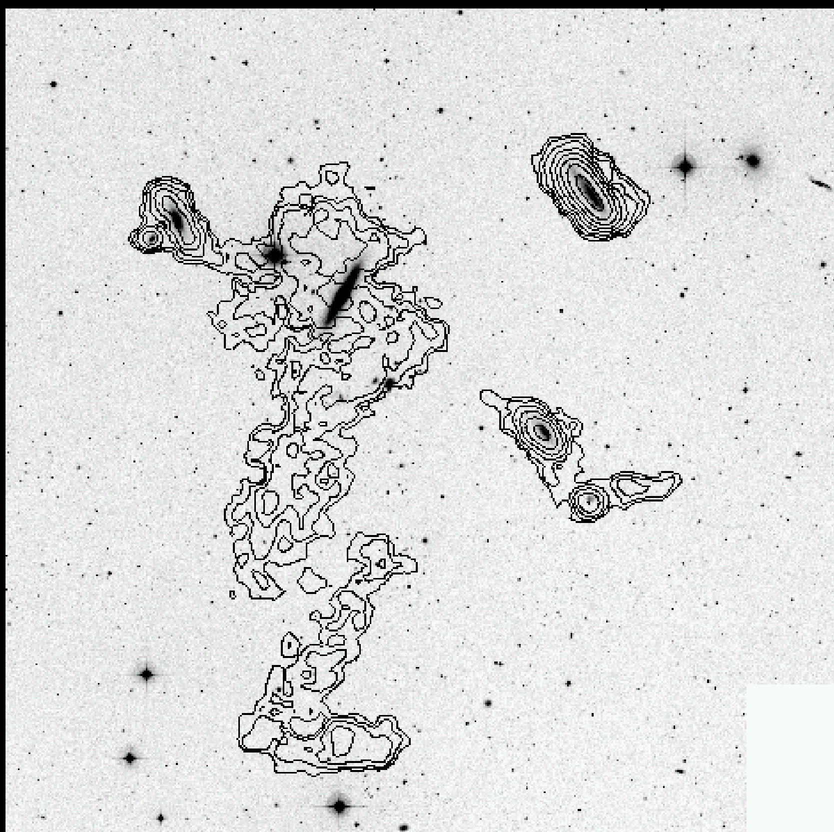


WSRT HI: Swaters et al. 2002

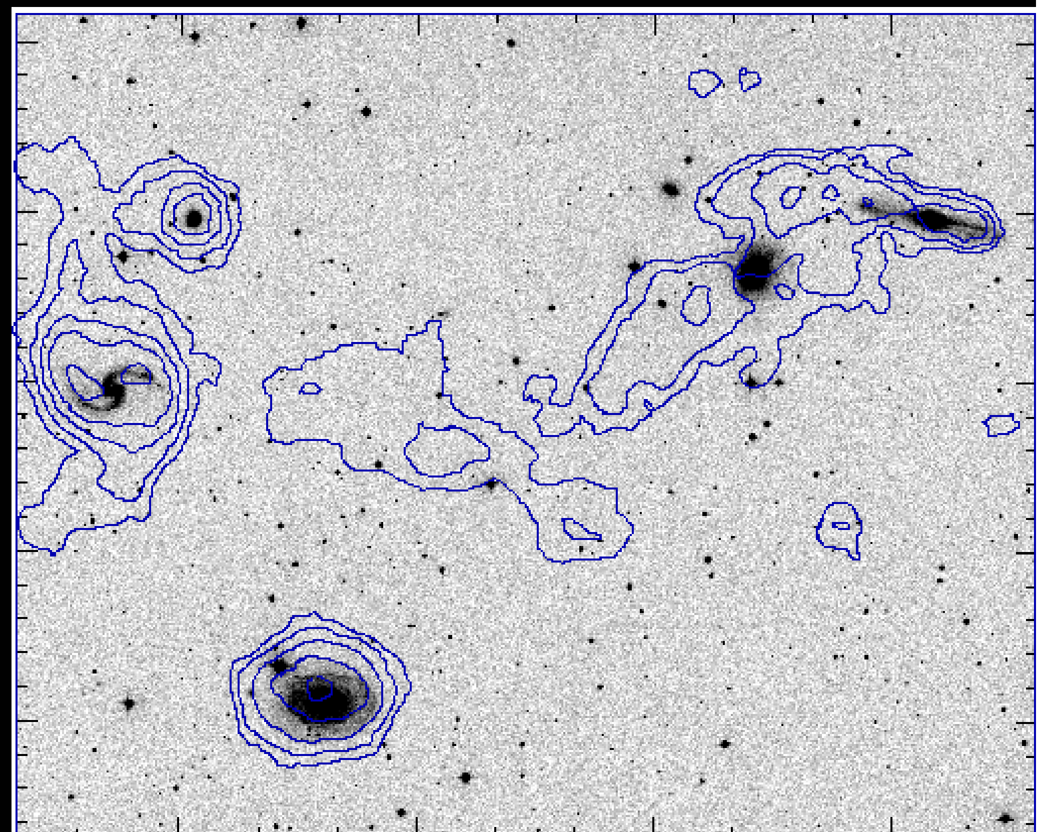


VLA HI: Mundell 2000

Tidal Debris in Group/Cluster Environments

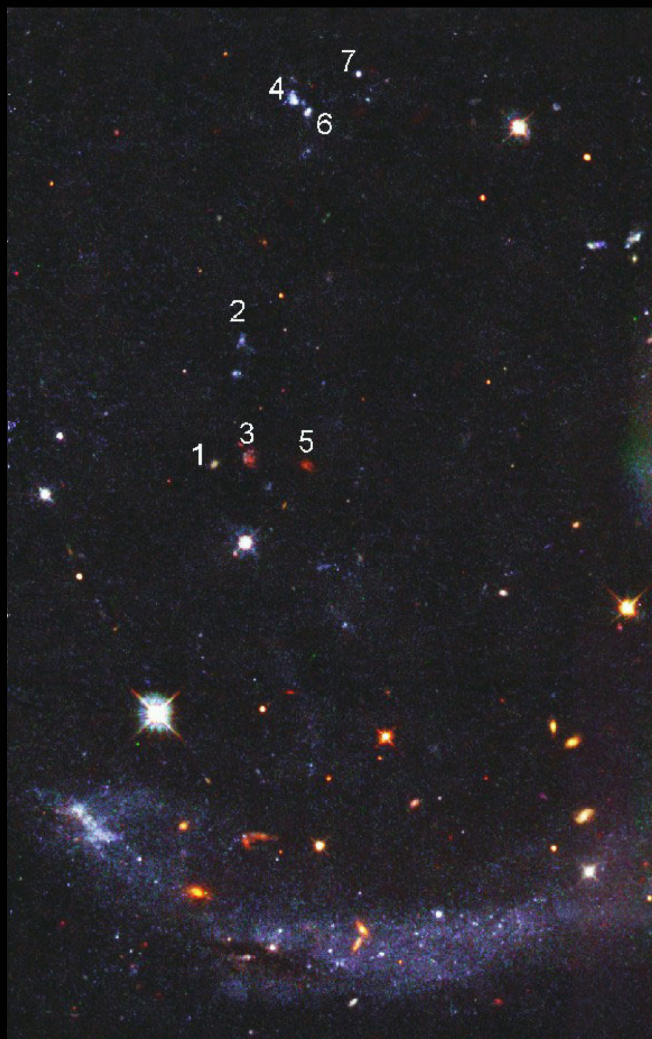


Verheijen & Zwaan 2000
WSRT of NGC 4111 in U.Maj

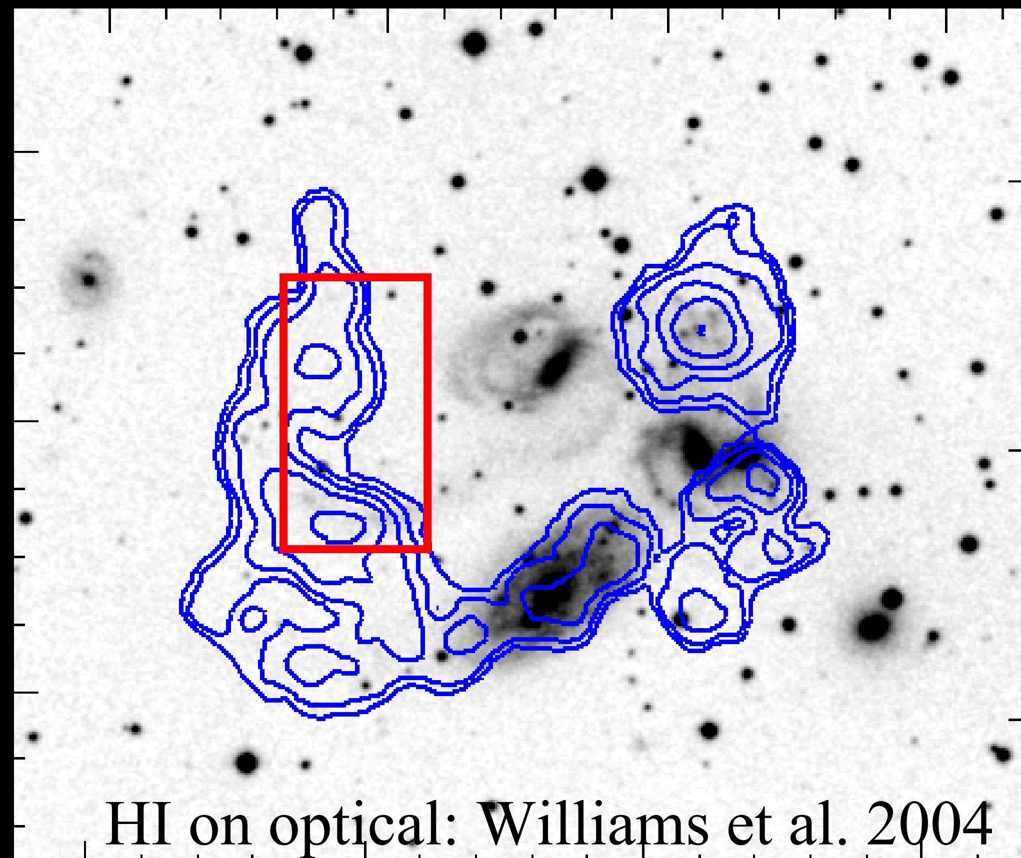


Van Moorsel et al. 1988
VLA of NGC 691 group

"ELdots"

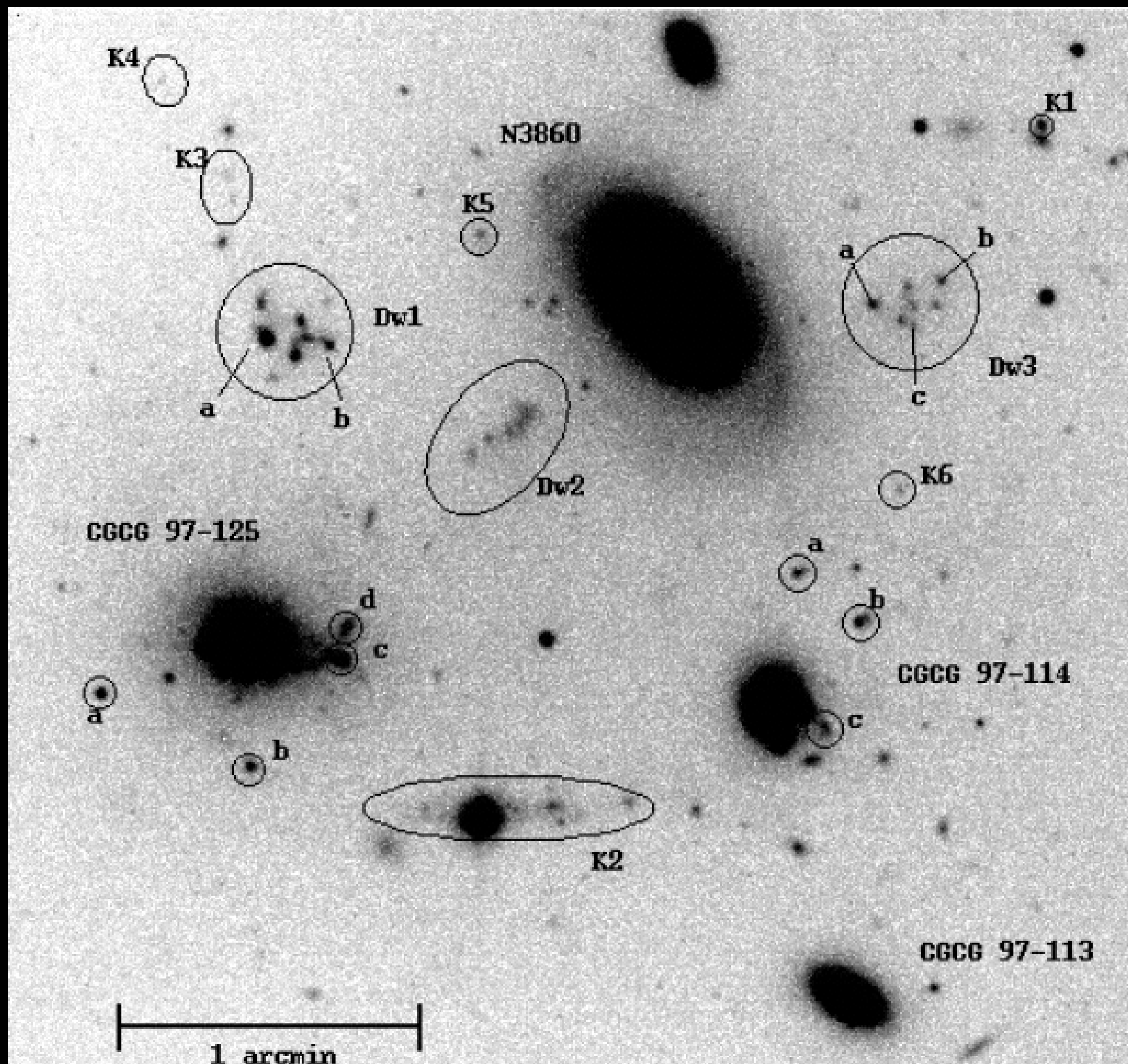


Stephans Quintet (HCG 92)



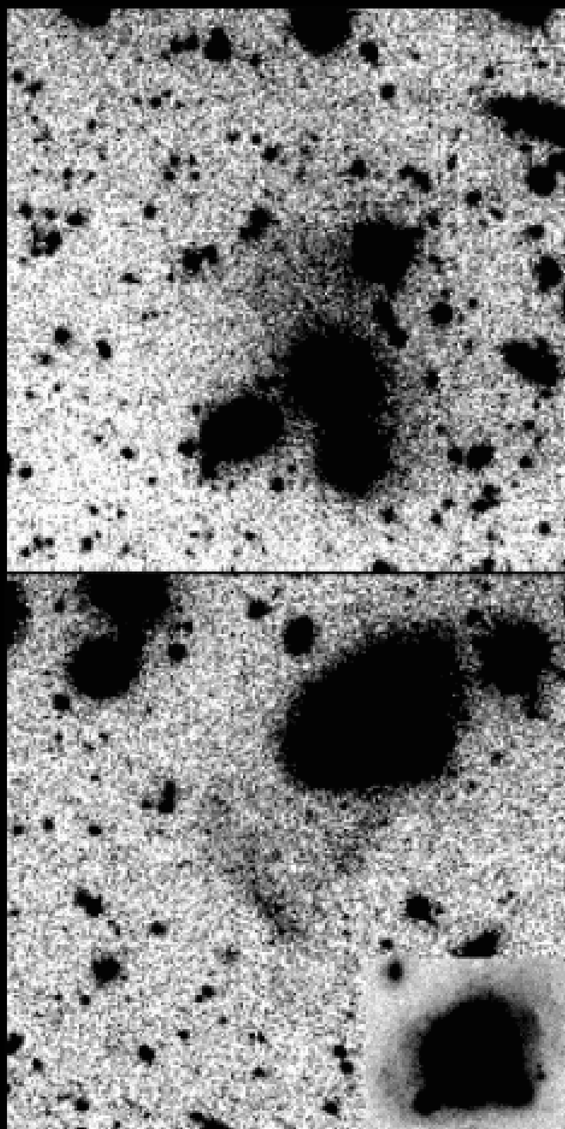
Palma et al. in prep. See also Ryan-Weber et al. 2003, 2004

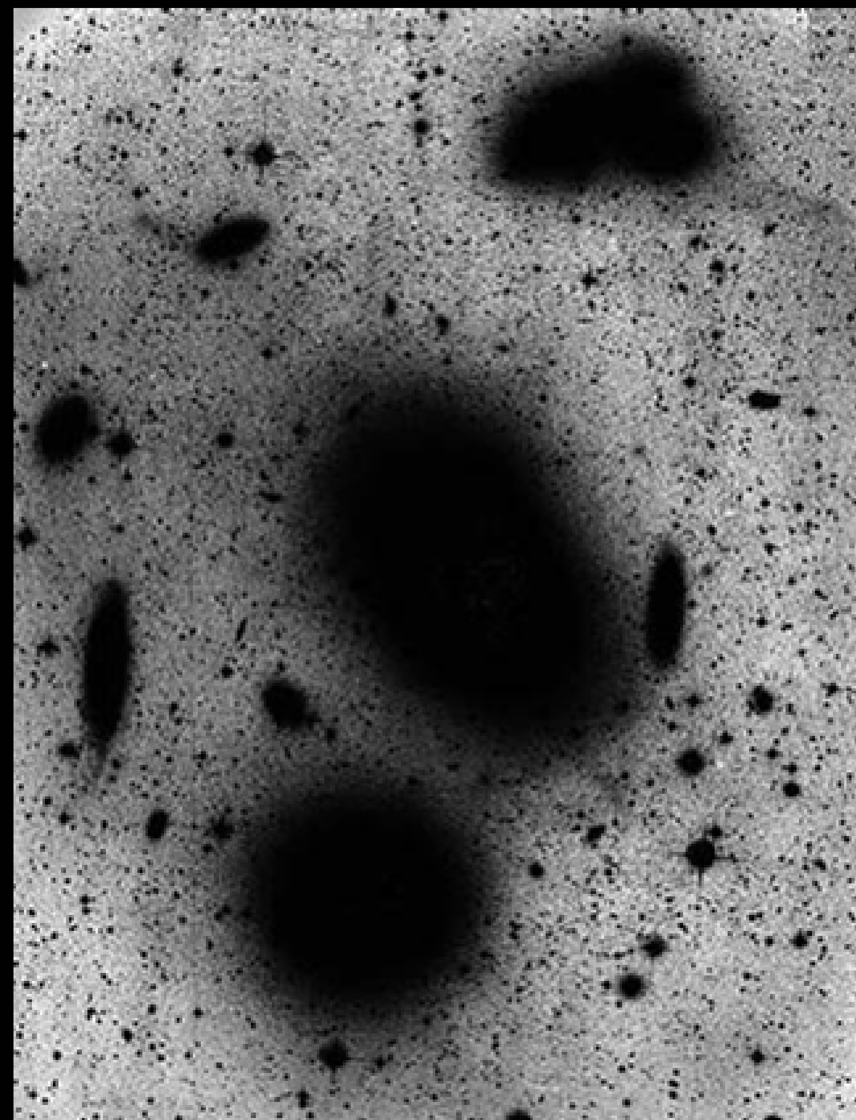
Extragalactic Star Forming Regions



NGC3860: Sakai et al. 2002, ApJ, 578, 842

Intercluster Light & Galactic "Ghosts"





Coma: Gregg & West, 1998, Nature, 396, 549 Virgo: Malin (AAO/ROE c.1985-2002

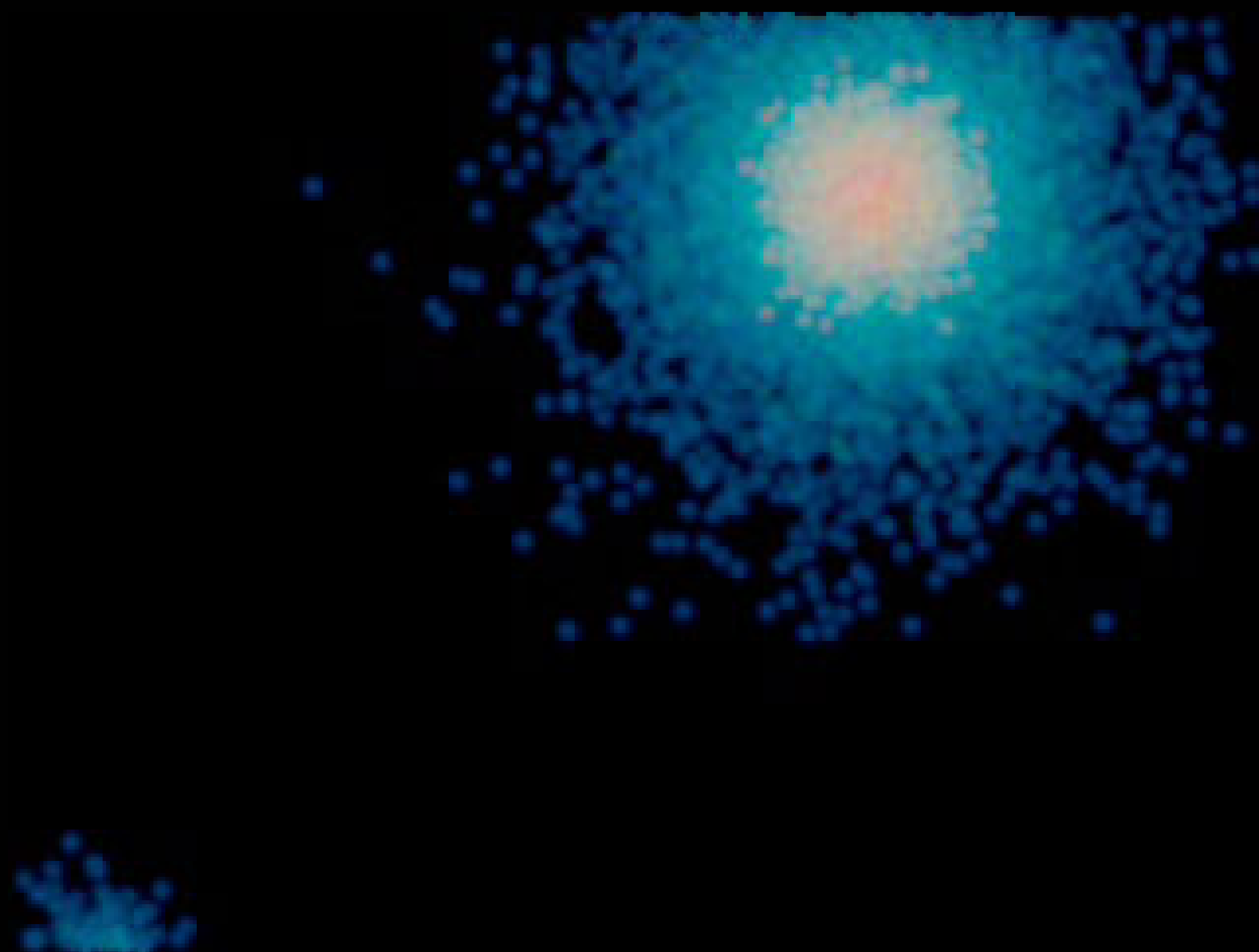
Interaction Induced Inflow

- Drives disk-wide star formation
- Leads to large central concentrations of cold gas
- Gives rise to super starbursts, ULIGs, superwinds, AGN

Ultimately, interaction induced inflows can lead to large scale outflows

Very important for structure of remnant and evolution of gas phase

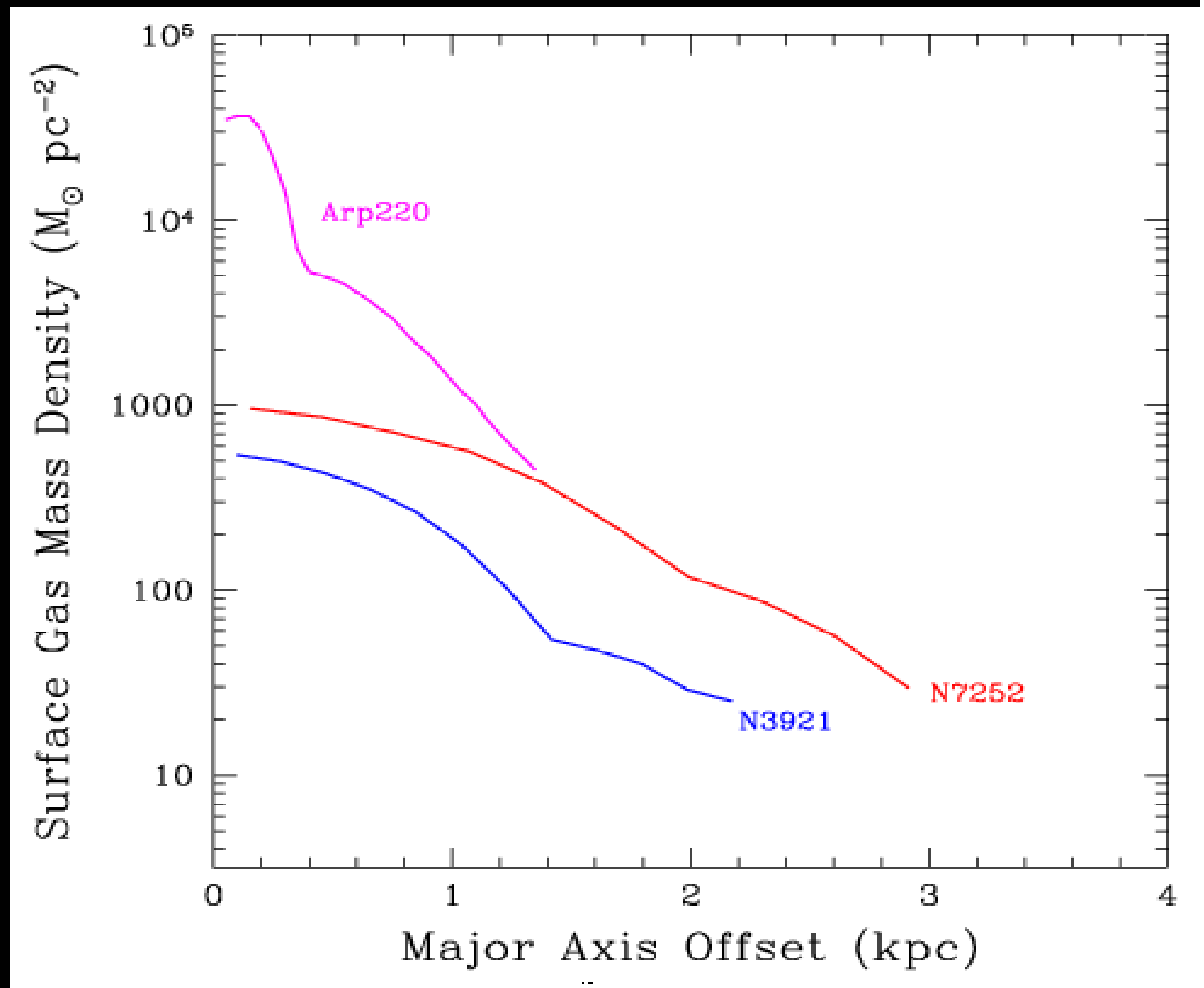
3:1 Mass Ratio;
Retrograde



http://www.ifa.hawaii.edu/~barnes/research/gassy_mergers/.
See also Barnes 2002, MNRAS, 333, 481

Mergers with highest Σ_{gas} give rise to largest starbursts

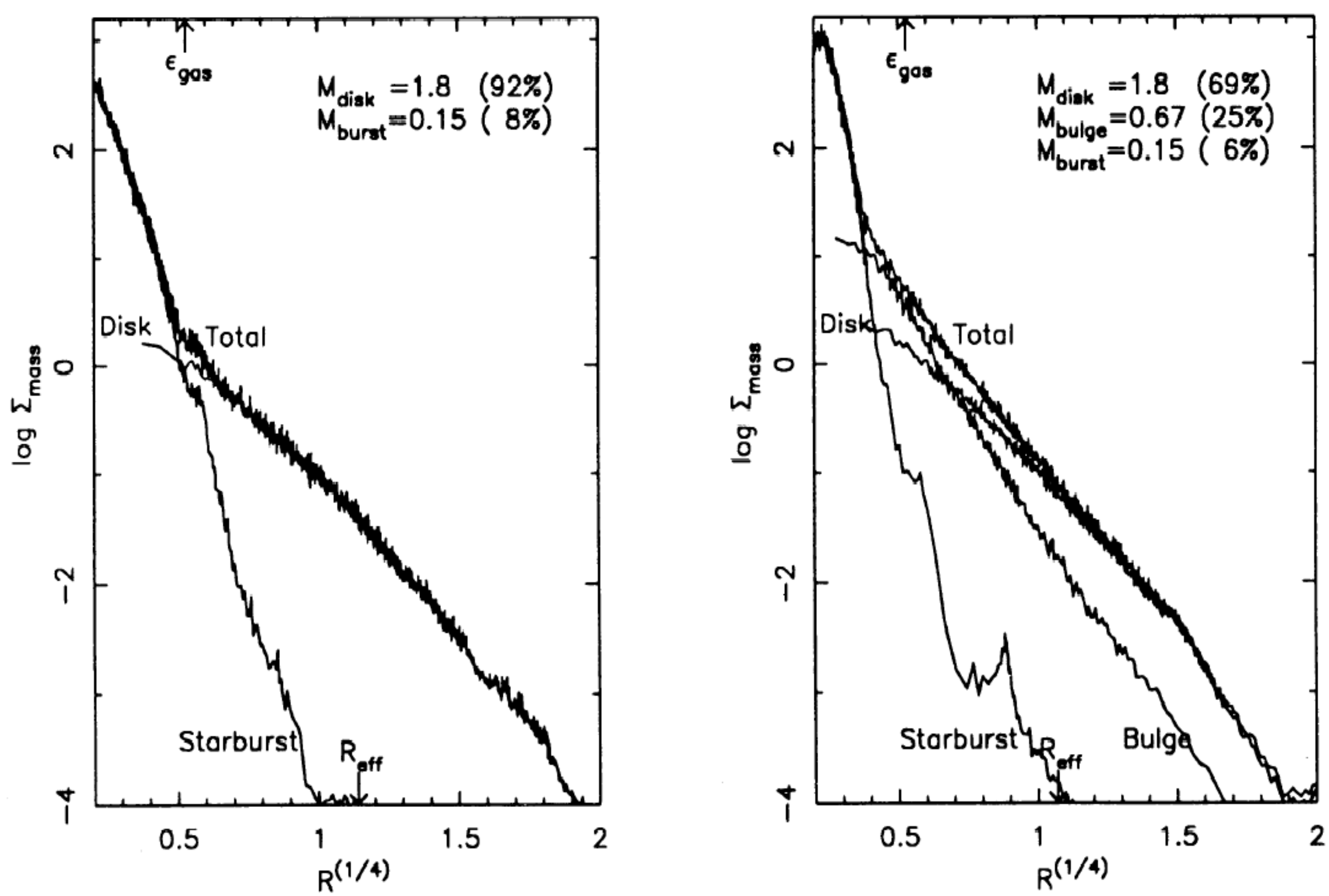
Pre-merger and merger remnants have modest H_2 surface densities. ULIGs have much higher values.



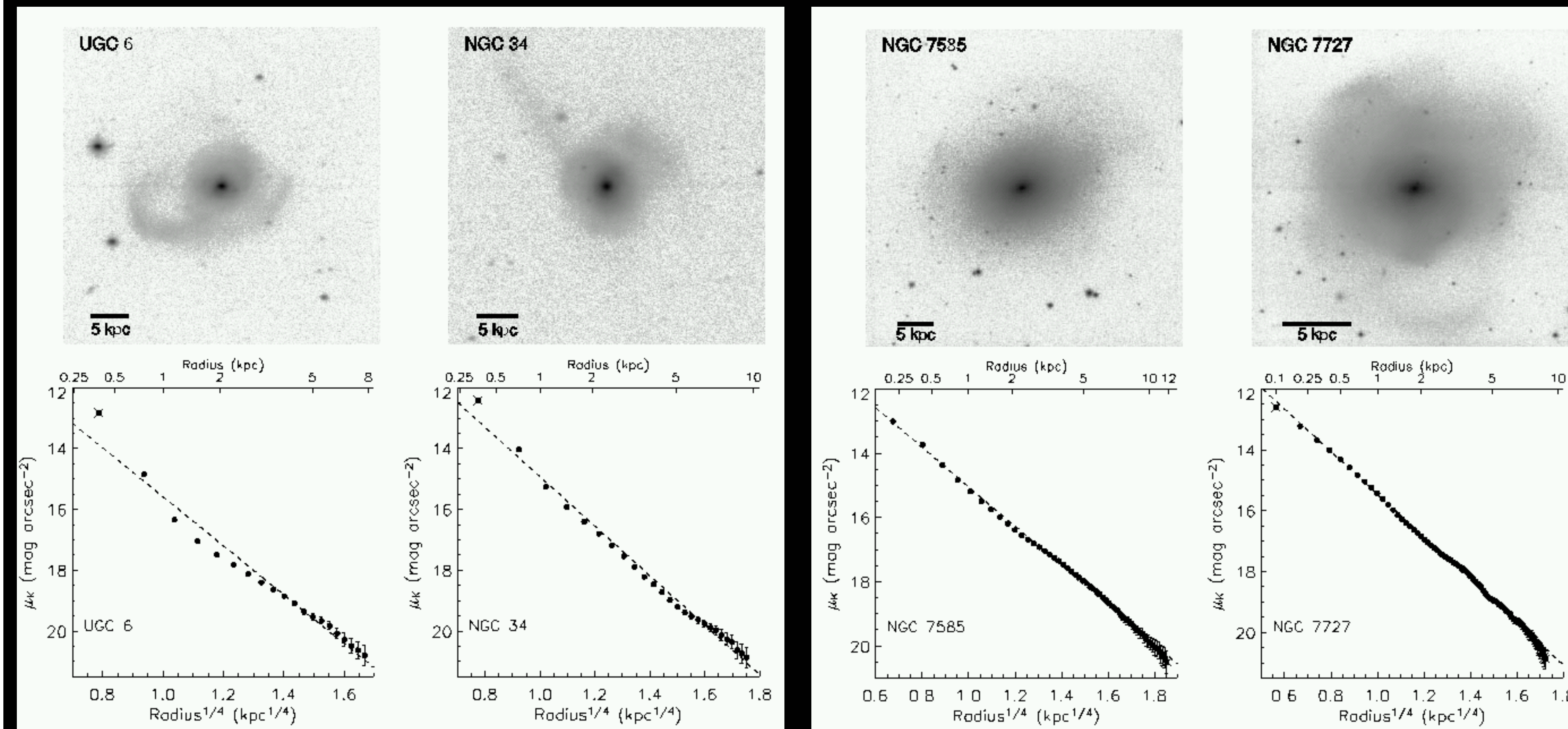
Yun & Hibbard 1999 ApJ

Models (w/o feedback) predict these dense gaseous concentrations will leave sharp spikes in luminosity profiles of remnants

MIHOS & HERNQUIST



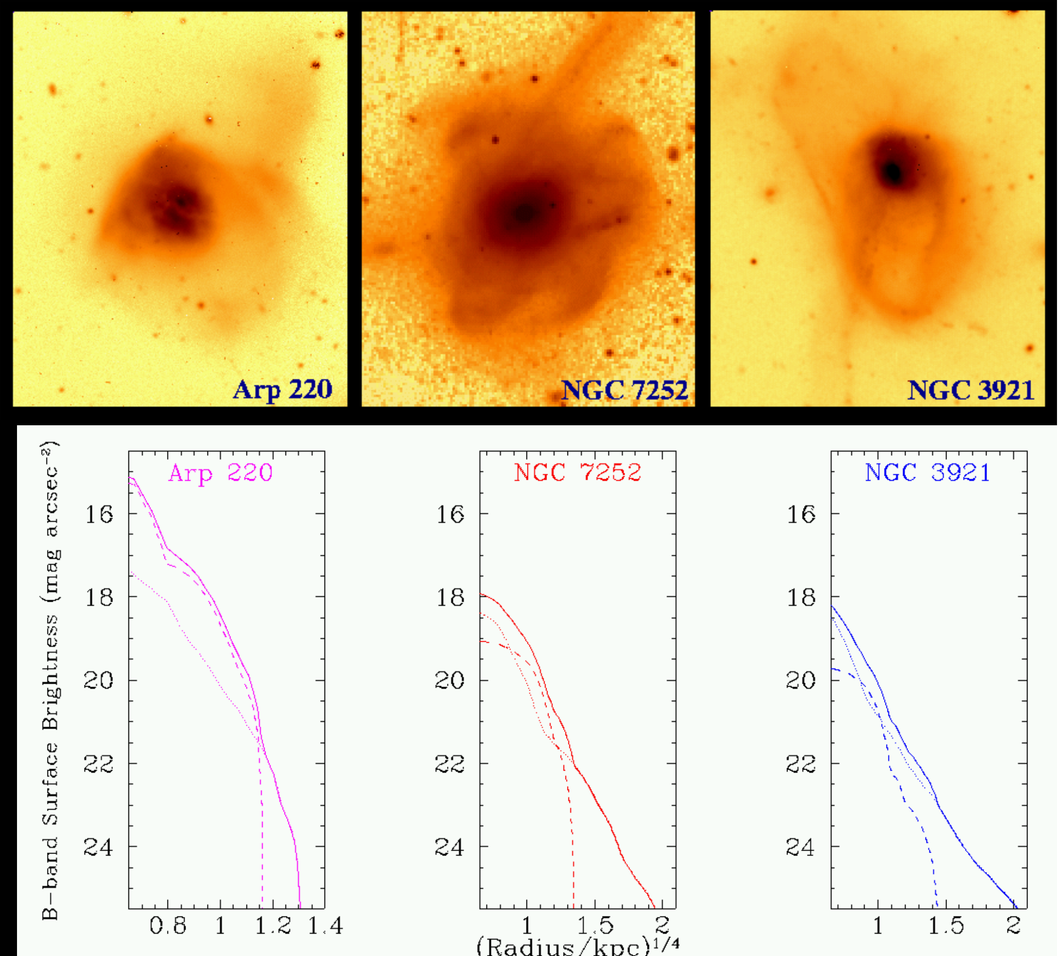
Observed profiles of large number (51) of remnants show modest or no luminosity enhancements



Rothberg & Joseph, 2004 AJ, 128, 2098

Compute expected profiles assuming central molecular gas becomes stars

- In ULIG (Arp 220), burst population will dominate light even after 2 Gyr; irregular central profile
- (But not by 2 orders of magnitude)
- Light profiles of advanced (~0.5-1 Gyr) remnants NGC 7252, NGC 3921 will be typical of early types



Hibbard & Yun 1999, ApJ, 522, L93

Can ULIG evolve normal light profile?

Population Synthesis Modeling of NGC 7252 spectra

- Burst occurred 1.2 Gyr ago
- Peak SFR was 300-540 Mo/year (ULIG)
- Progenitors definitely very gas rich; will evolve into M_B=-21.0 early type
- Yet profile normal!

778 U. Fritze - v. Alvensleben & O.E. Gerhard: The star formation history of NGC 7252

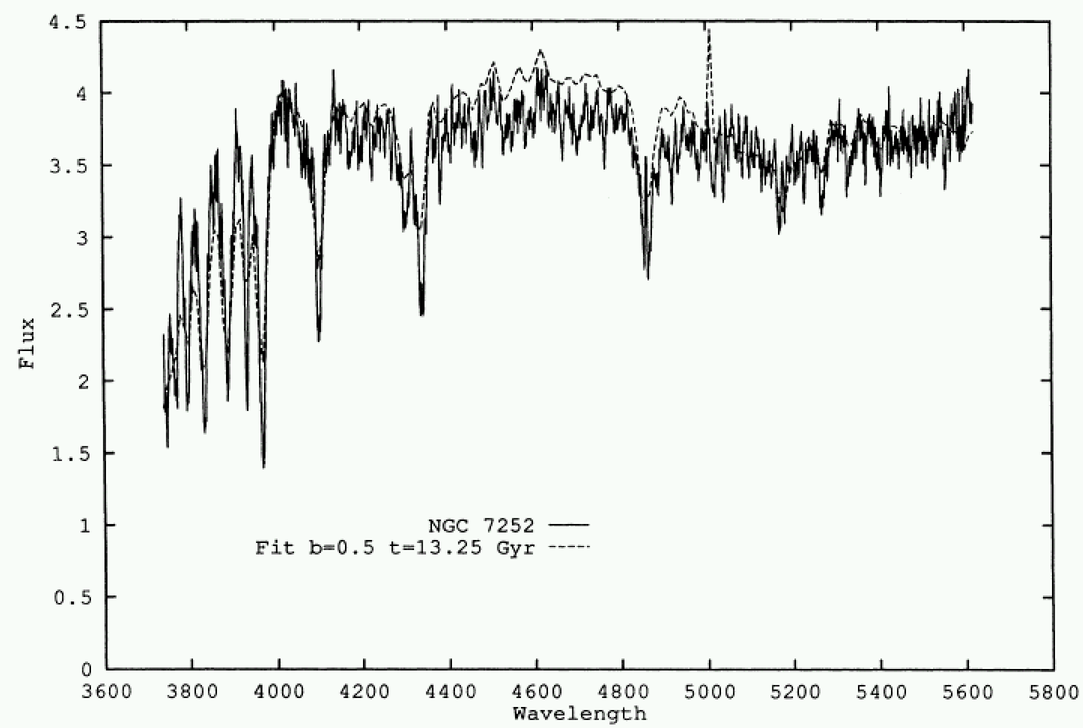


Fig. 1. Best fit to the observed spectrum of NGC 7252 in the central 2"×2" (Schweizer 1990). The model is an $Sc - Sc$ merger at 12 Gyr with a SFR in the burst $\Psi_b \propto e^{-t/t_*}$, $t_* \sim 1 \cdot 10^8$ yr, and burst strength $b = 0.5$. Spectrum at time 13.25 Gyr. Fluxes are in (2.35 10^{-15} erg cm^{-2} s^{-1} Å^{-1}) for a total mass of the system of $2 \cdot 10^{11}$ $M_\odot$, the factor 2.35 resulting from a transformation of Schweizer's $H_0 = 50$ to the $H_0 = 75$ used throughout this paper

Fritz-v.Alvensleben & Gerhard 1994 A&A, 285, 775

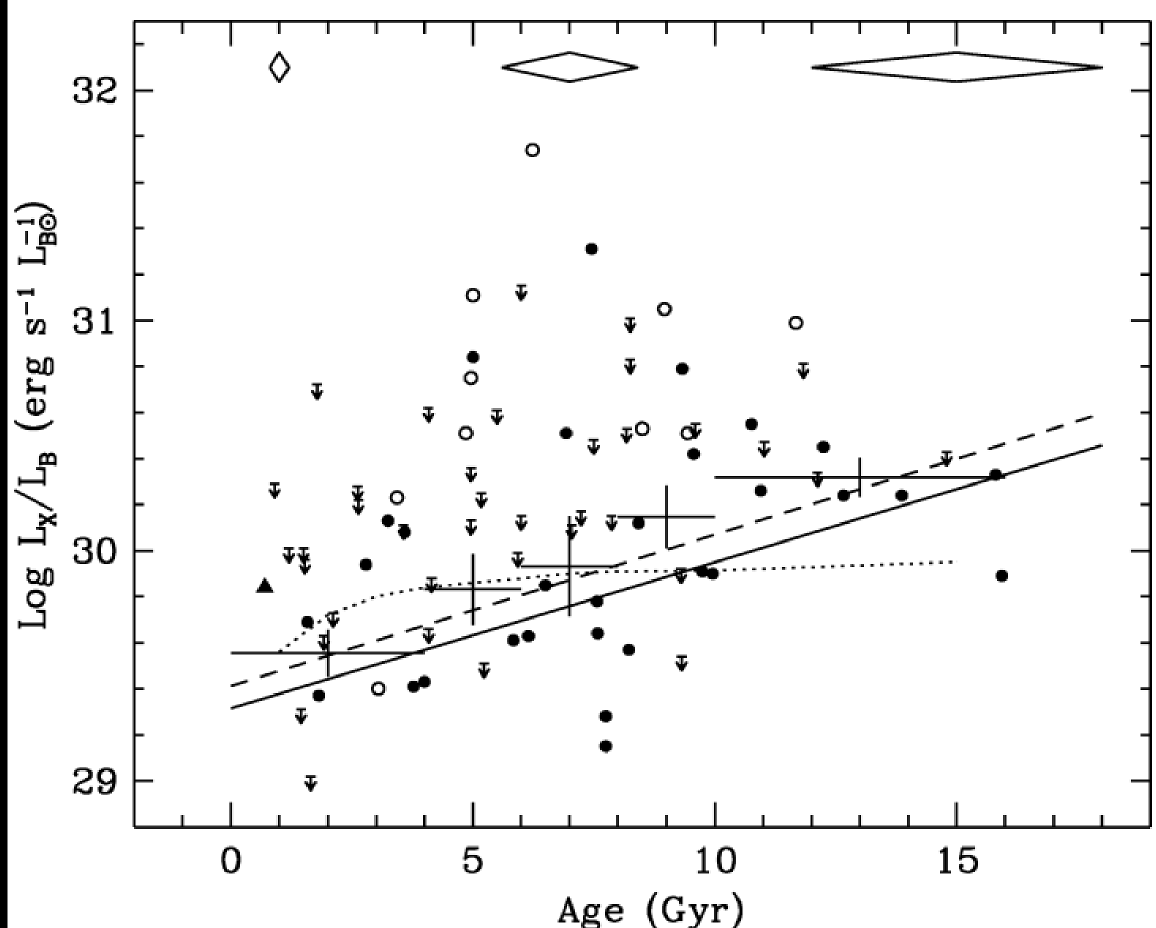
Suggests massive central gas concentrations can be expelled during ULIG phase, probably via mass loaded superwind

- SCUBA & SPITZER observations suggest many more ULIGs in the past; progenitors of todays spheroidals

Other possibilities: Top-Heavy IMF; CO-H2 conversion factor

Evolution of Merger Remnants

- Attempts to place merger in evolutionary sequence have not been very successful
  - Progenitors have high cold gas content, low Lx/Lb
  - Es have high Lx/Lb, low cold gas content
- Expect trends between merger stage, Lx/Lb, and cold gas content
- No clear trends observed



O'Sullivan, Ewan, Forbes, Duncan A. & Ponman, Trevor J. (2001) The X–ray emission in post–merger ellipticals. *Monthly Notices of the Royal Astronomical Society* **324** (2), 420–426.

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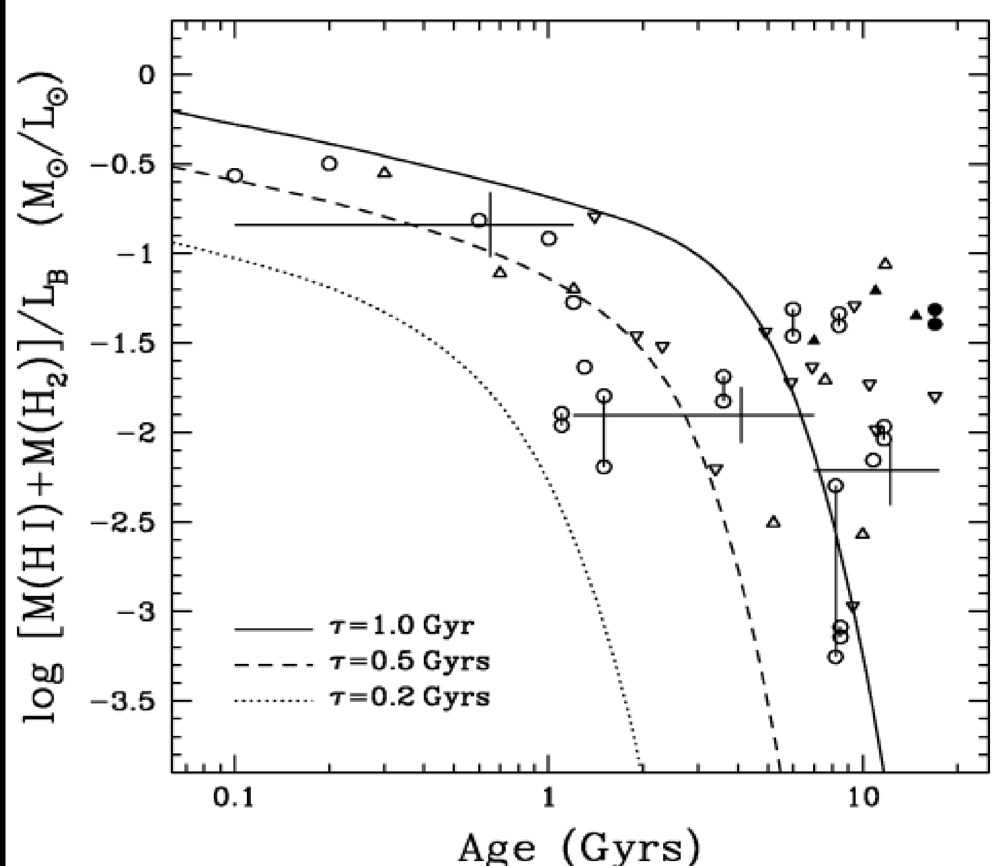
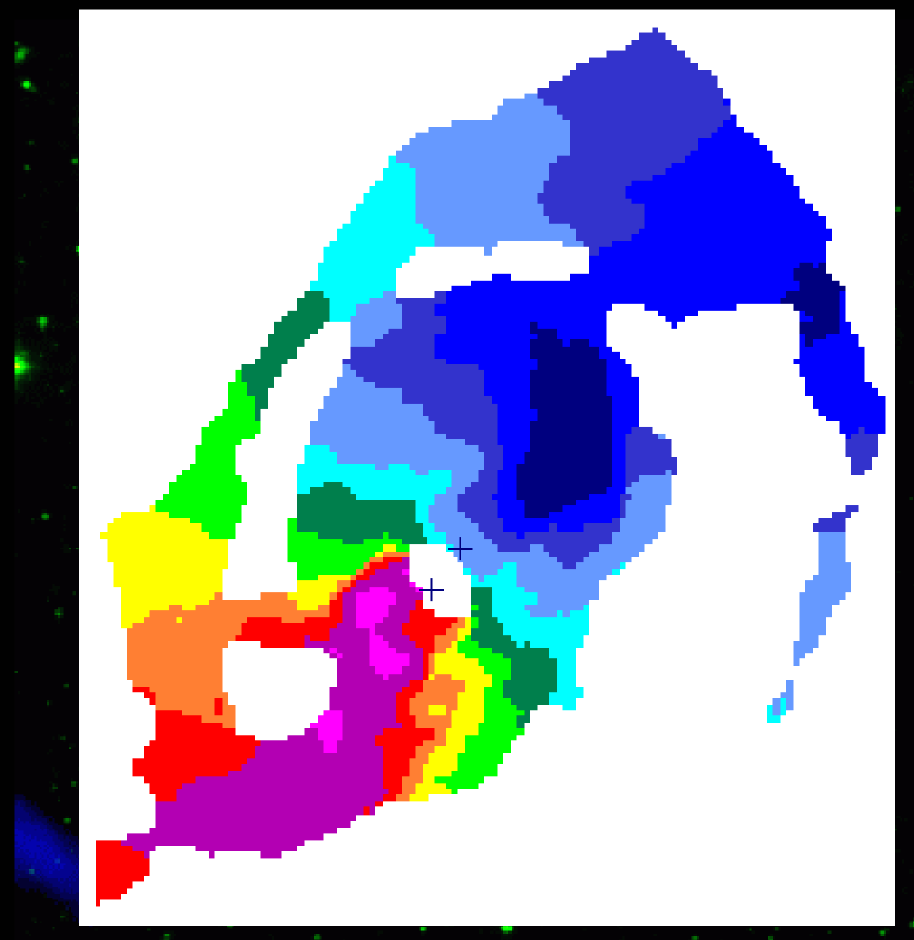


Georgakakis, A., Hopkins, A.M., Caulton, A., Wiklind, T., Terlevich, A.I. & Forbes, Duncan A.
Cold gas in elliptical galaxies.
Monthly Notices of the Royal Astronomical Society **326** (4), 1431–1440.

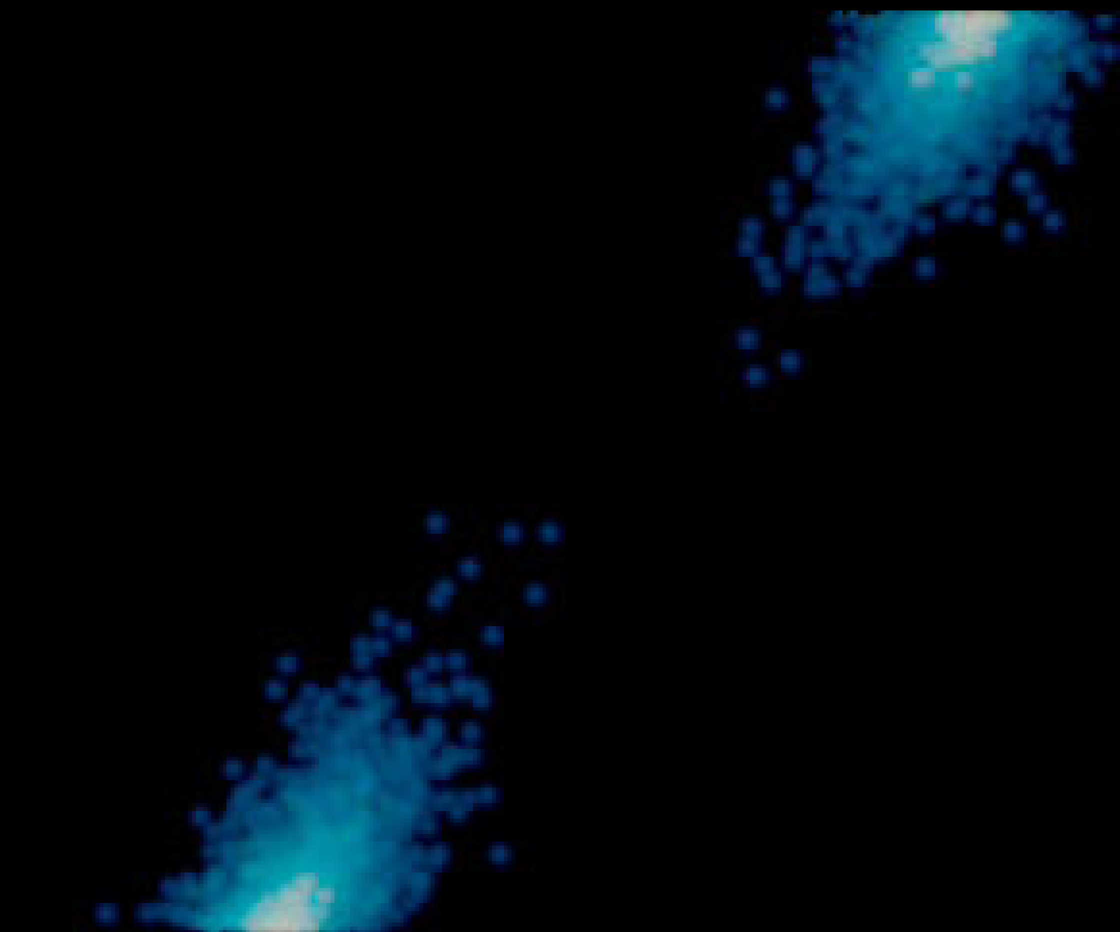
Partial solution: multiple evolutionary paths.

Mergers do not necessarily destroy disks



NGC 520 VLA HI
Hibbard & van Gorkom 1996

…And disks can reform from returning tidal material



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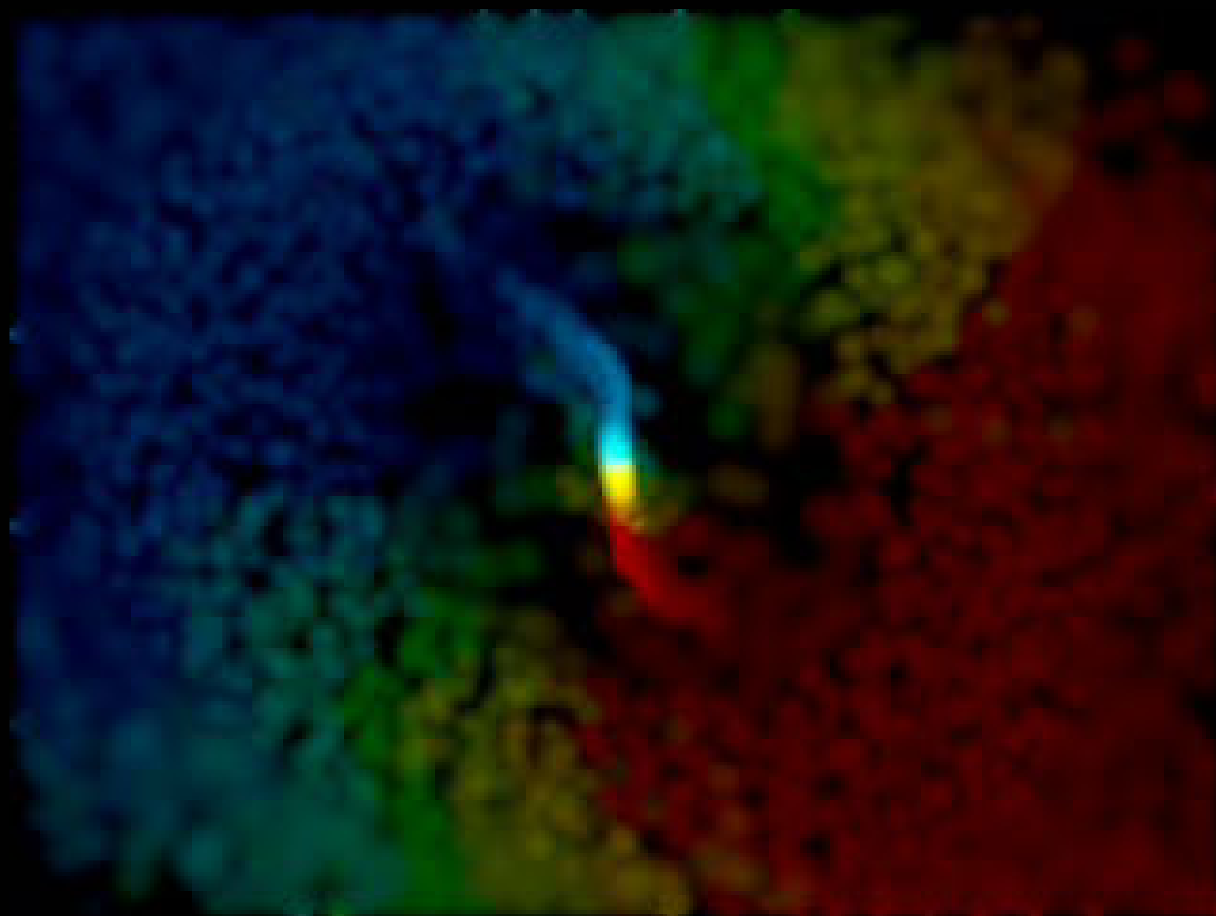
See also Barnes 2002, MNRAS, 333, 481

1:1 Mass Ratio;
Inclined Prograde



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HI Rogues Gallery

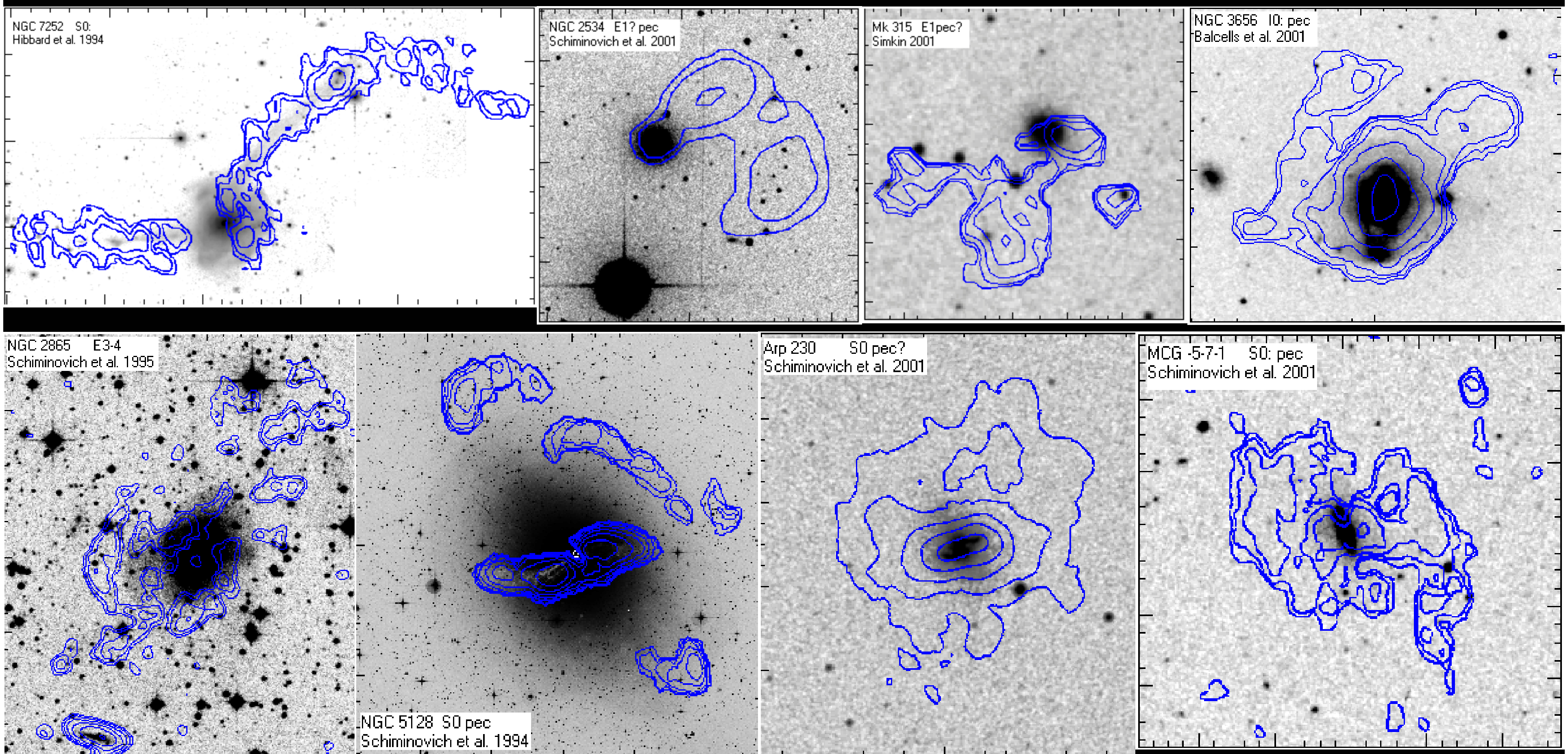
Hibbard, van Gorkom, Schiminovich & Rupen, in "Gas & Galaxy Evolution", ASP Conference Series, Vol 240

www.nrao.edu/astrores/HIrogues

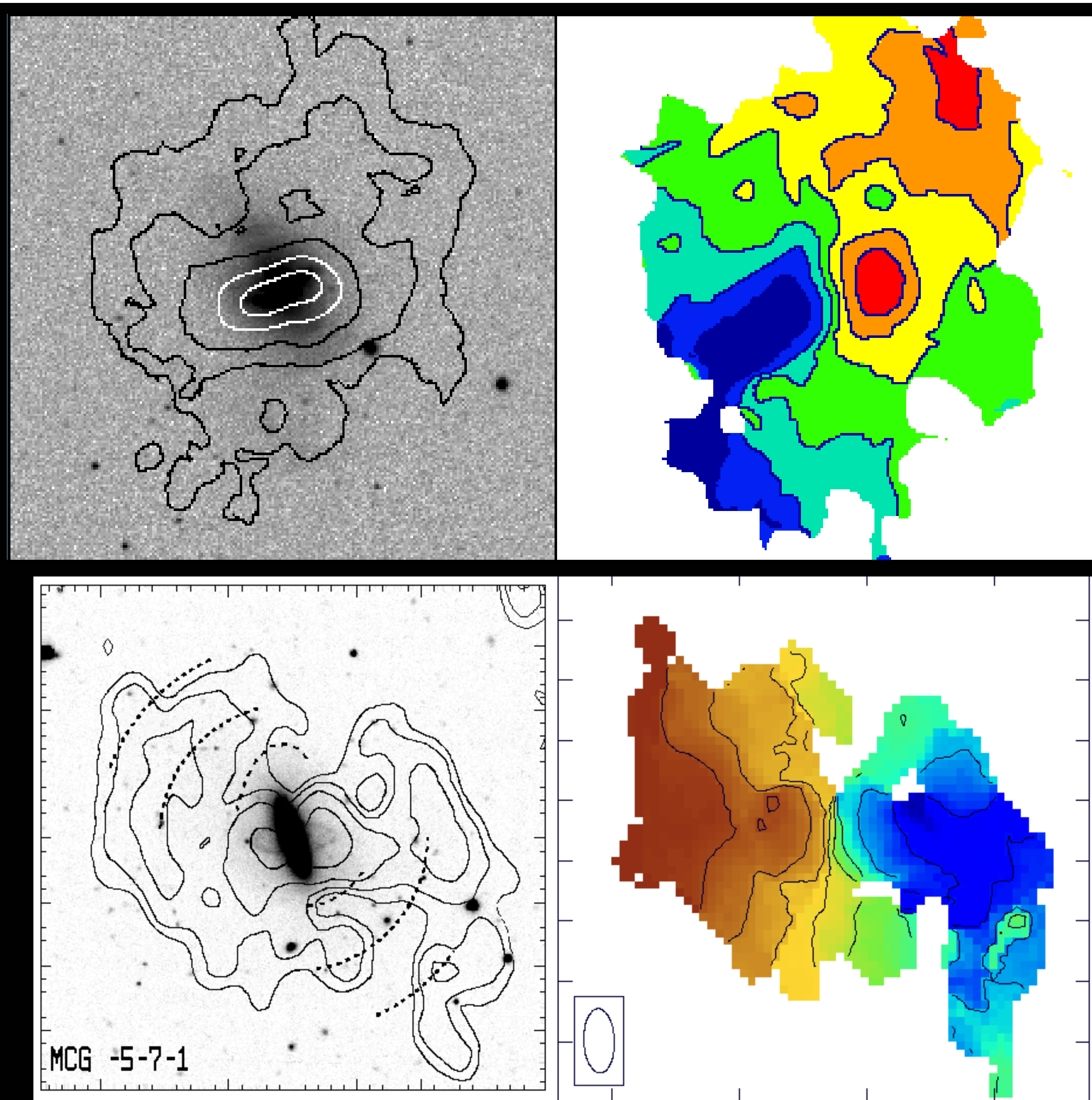
- With J. van Gorkom & D. Schiminovich, tried to arrange post-merger systems in plausible evolutionary sequence (after Toomre 1977)
- Ended up creating two sequences: one to disks, the other to spheroids
  - Sp+Sp=>S0=>Sp
  - Sp+Sp=>S0=>E

Peculiar Early Types with HI within Optical Body

Arranged from Irregular to Regular morphology & kinematics



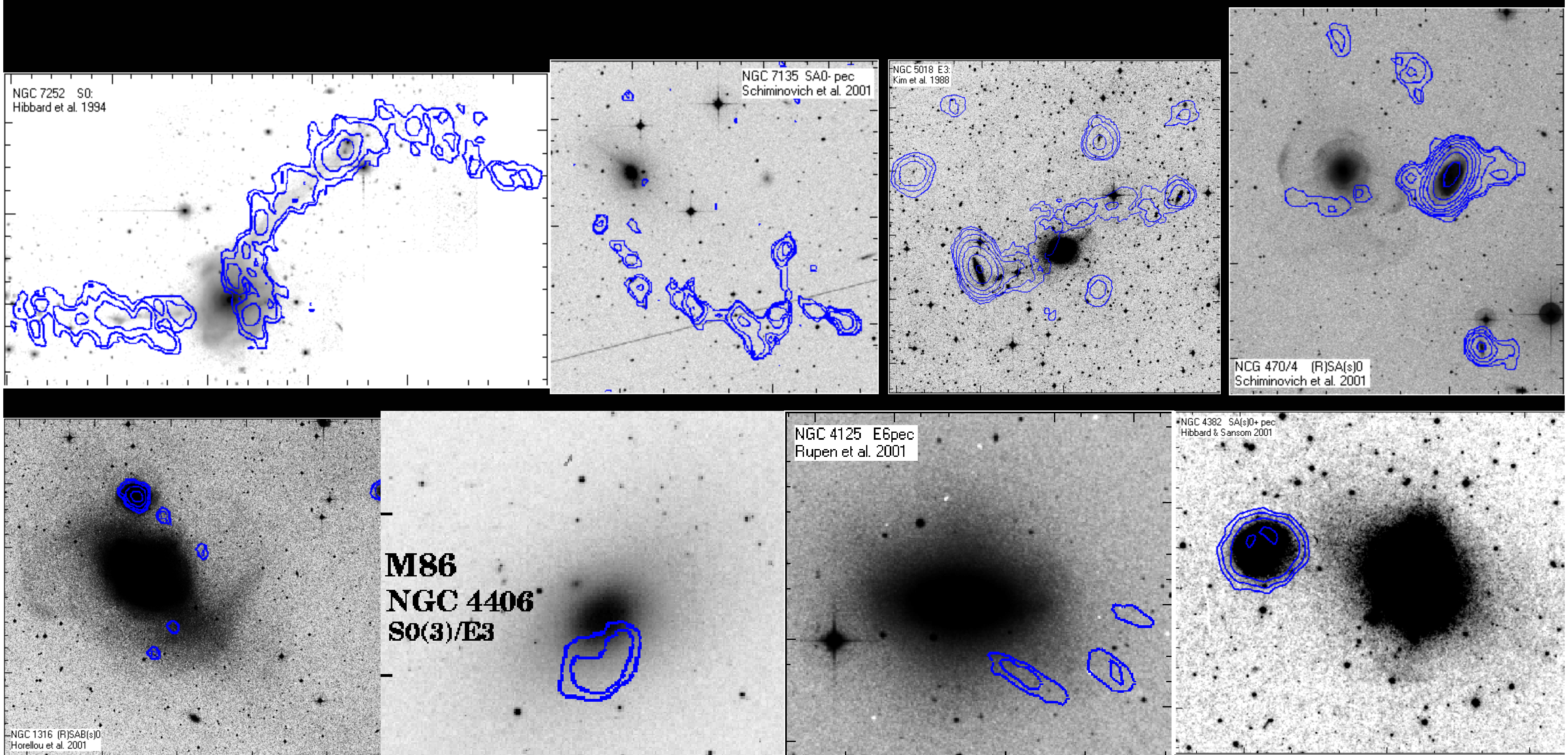
www.nrao.edu/astrores/HIrogues



VLA HI Schminovich, van Gorkom & van der Hulst 2001

Peculiar Early Types with HI outside Optical Body

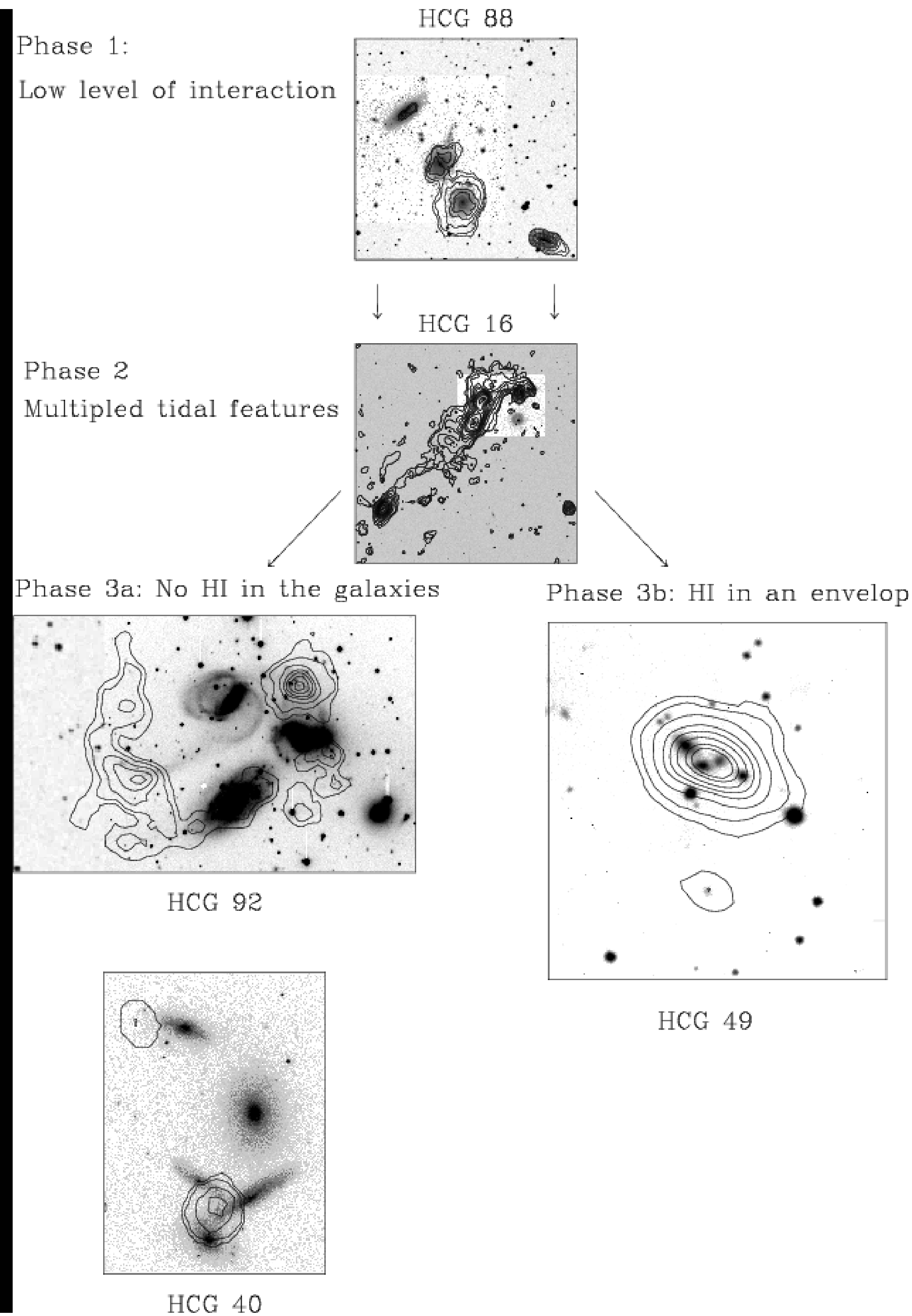
Arranged by decreasing HI content



www.nrao.edu/astrores/HIrogues

Similar split evolutionary sequence suggested for Compact Group evolution

Verdes-Montenegro et al. 2001, A&A, 377, 812



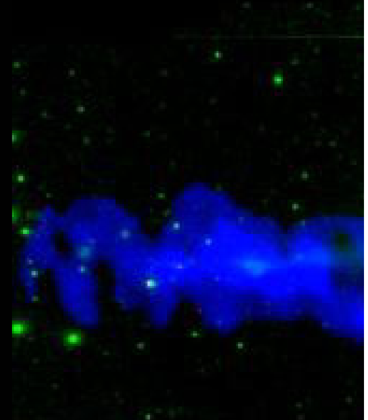
Main questions :

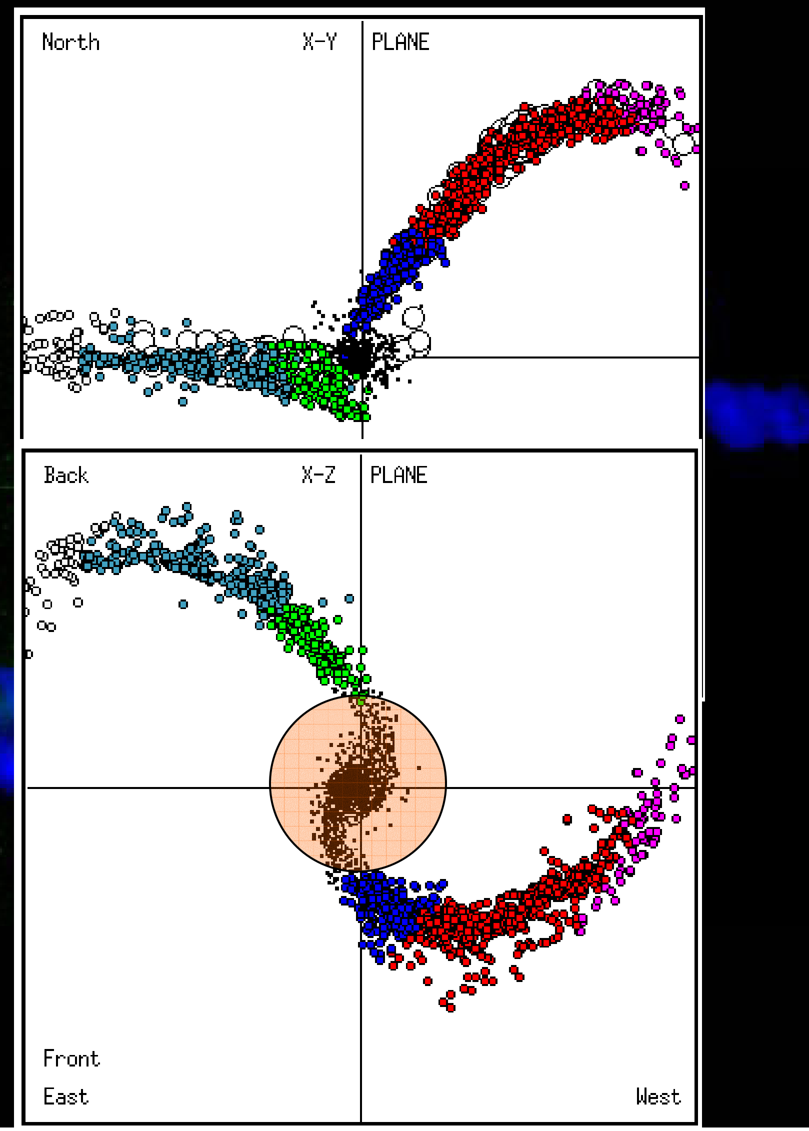
- How is cold gas removed, hot halo built up along second sequence?
  - Not done simultaneously

Recent merger remnant NGC 7252: X-ray underluminous (Nolan et al. 2004), but cold gas being removed now

- Tails must extend back into remnant, but HI abruptly ends
- Gas is currently falling back into remnant at 1-2 Mo/yr
- Yet body remains devoid of HI

How?





Main questions :

- How is cold gas removed, hot halo built up along second sequence?
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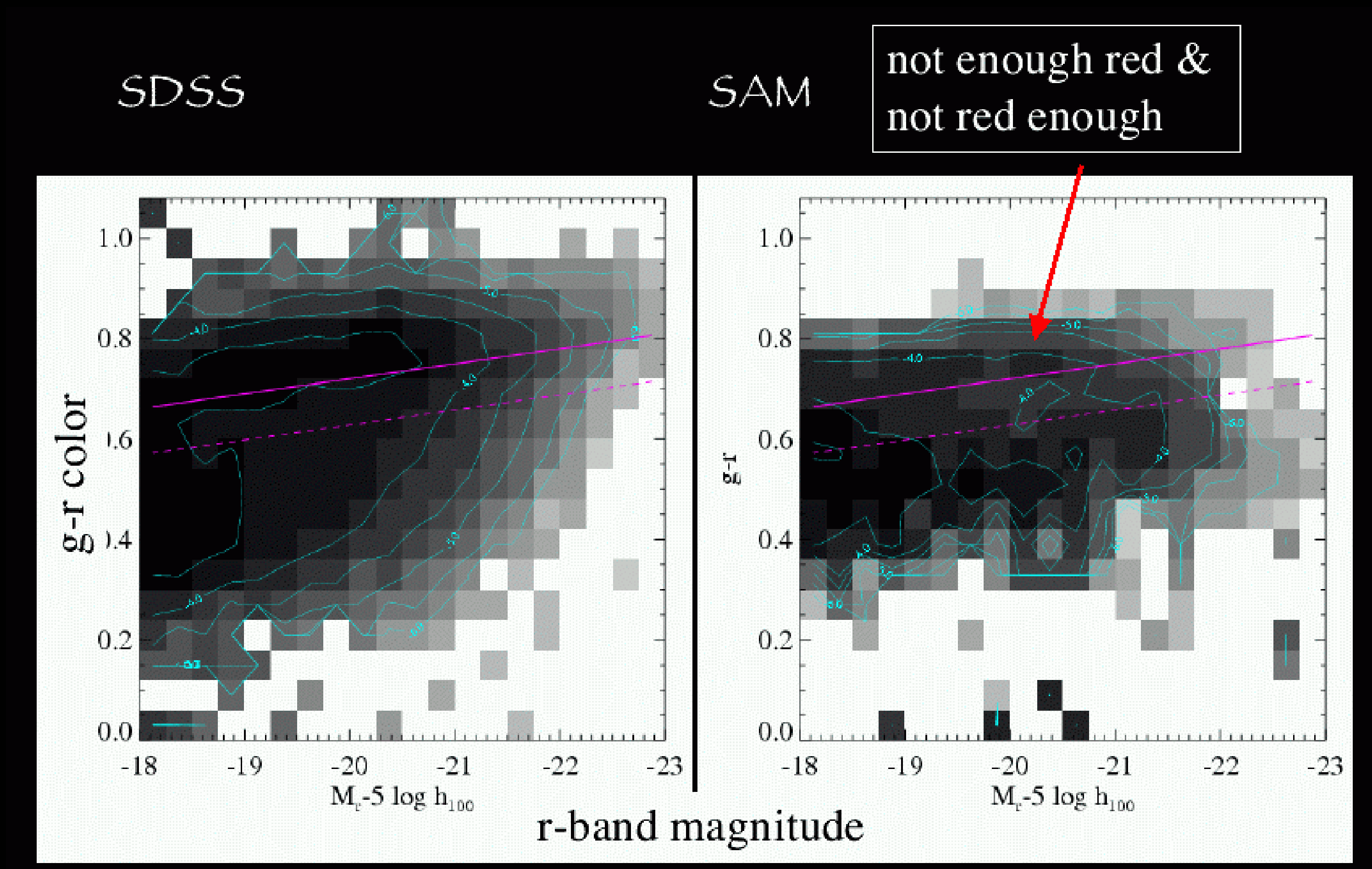
- Will second sequence (Sp+Sp=>S0=>E) evolve in a way that can help explain color bimodality in galaxy CMDs?

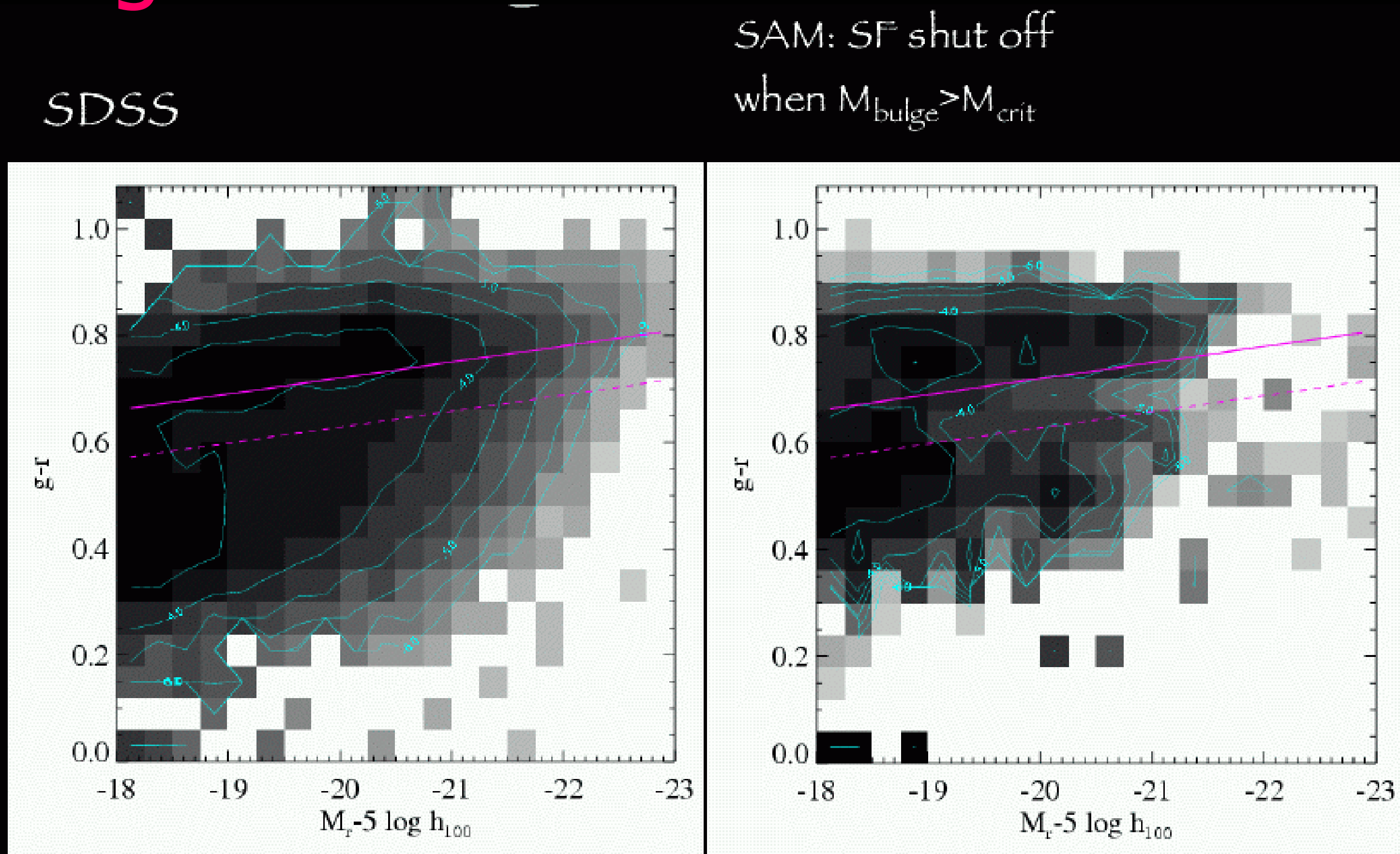
In models, continued infall slows color evolution of remnants



From talk by Rachel Somerville 2004

STScI Workshop, Cosmic Evolution of Massive Galaxies

SAMs can reproduce observed bimodality by truncating SF when bulge gets above some critical value



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  - Not done simultaneously
- Will second sequence (Sp+Sp=>S0=>E) evolve in a way that can help explain color bimodality in galaxy CMDs?
  - Does SFR decline quickly enough? Colors evolve as required?
  - If so, what is the main difference between two sequences? Mass? Environment? Merger geometry?

Conclusions

- Interaction Driven Outflows:
  - Tidal debris can give rise to extra-disk star formation, tidal star clusters, tidal dwarfs
  - Denser environments leads to rapid evolution of debris; allows several other tidal effects to take place
  - Significant contribution to ICL, IC-PNe, ELdots, etc.
- Interaction Driven Inflows:
  - Fuels starburst/AGN=>winds
  - ULIGs drive strong enough winds to drive out dense cetral cold gas concentrations; should evolve fairly normal light profiles
  - Delayed infall can reform disks (Sp+Sp=>S0=>Sp)
  - Also see evolution Sp+Sp=>S0=>Early Type, but not clear how gas kept out
  - Answer to last question may be important for reconciling hierarchical formation models with observations (specifically, bimodal color distribution)

[redacted]

Most galaxies are “Early Type”

2MASS/SDSS sample: Bell et al. 2003, ApJS, 149, 289

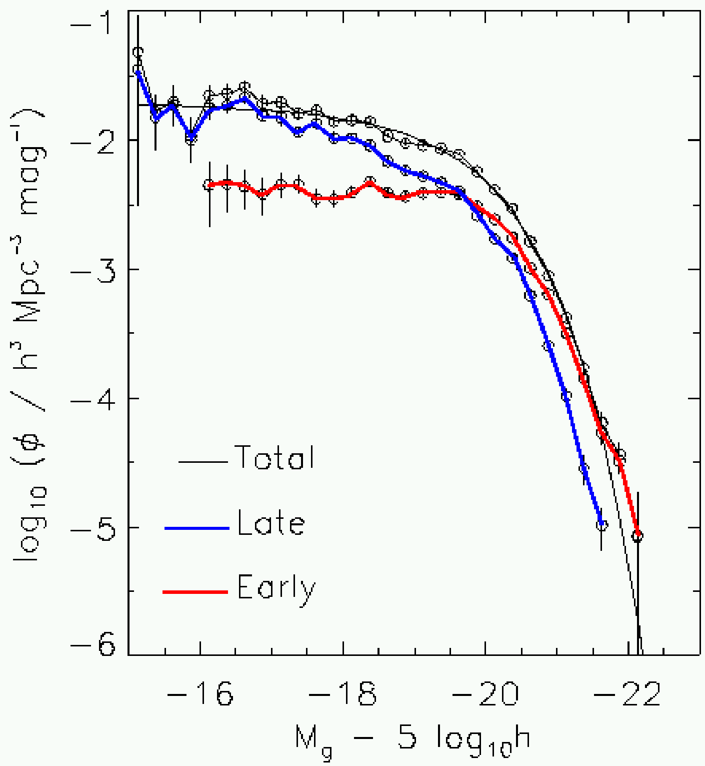


FIG. 12.— *g*-band LF split by morphological type. The solid line represents the total LF. The dotted and dashed lines represent the LF for late and early-type galaxies, separated using $c_r = 2.6$.

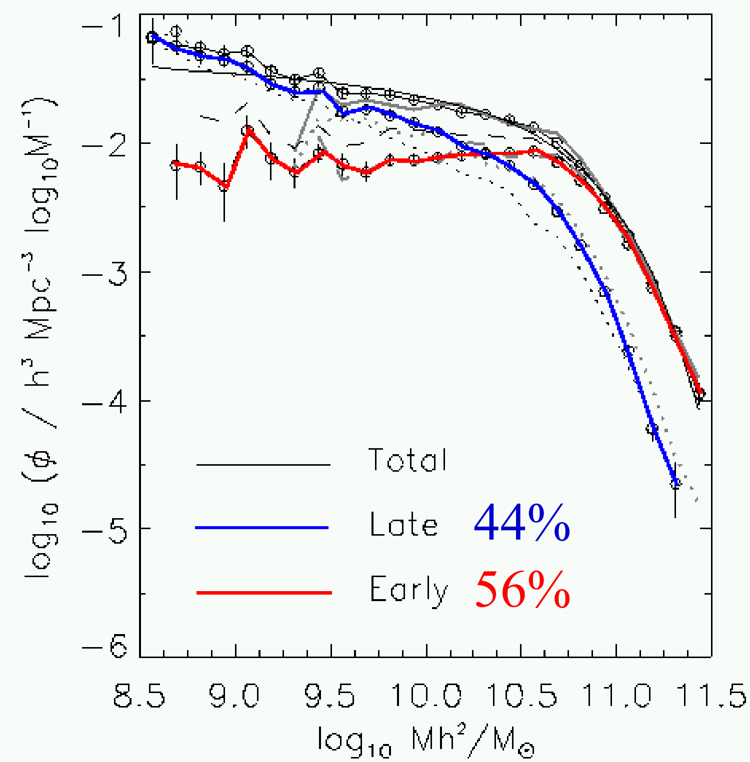
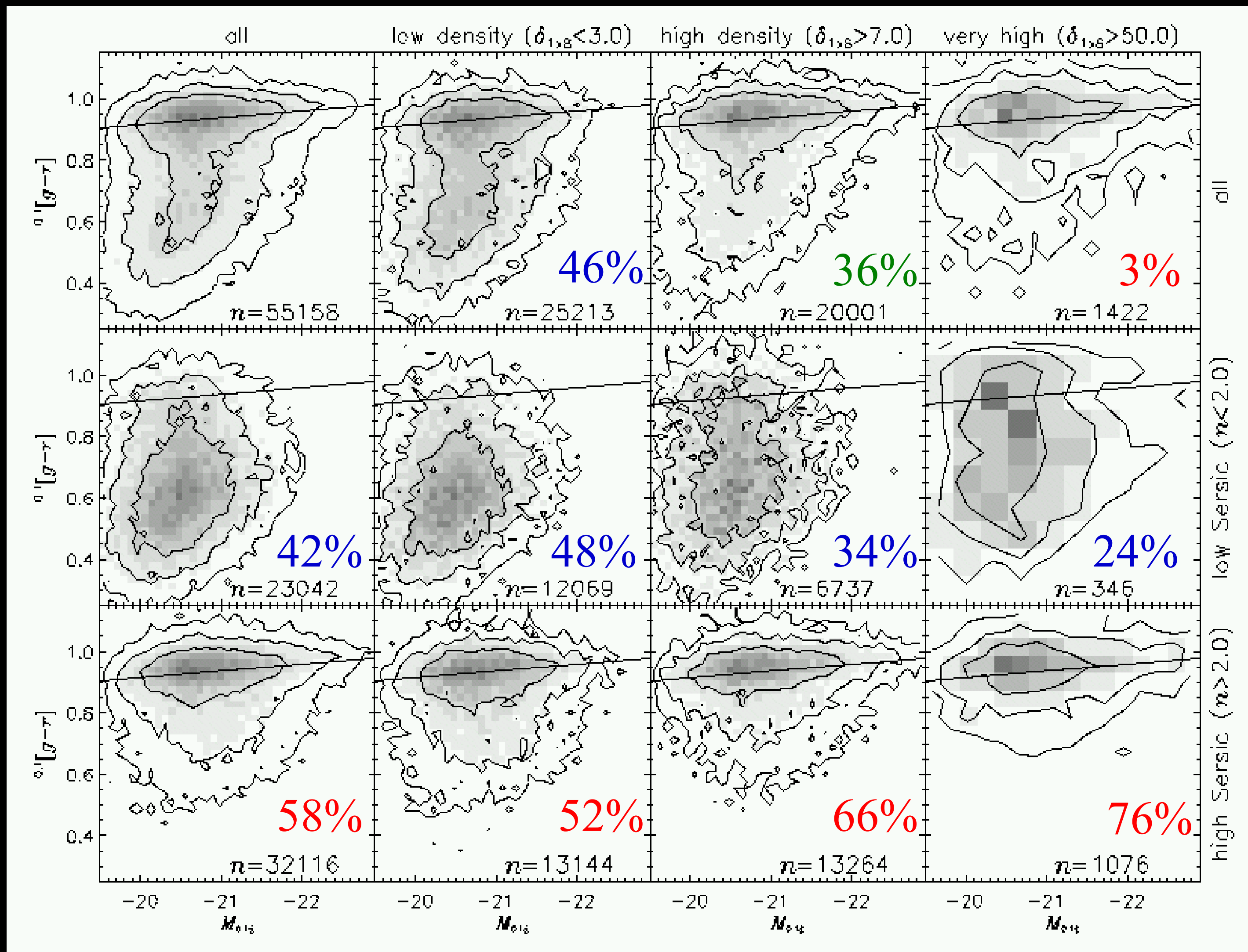


FIG. 17.— *g*-band derived stellar MF. The solid line represents the total MF. The black dotted and dashed lines represent the MF for late and early-type galaxies, separated using the $c_r = 2.6$ criteria.

Note: “Early Type” nowadays usually means concentration index>some value

Most galaxies (including "Early Types") live in low density environments



SDSS color-magnitude diagram: Hogg et al. 2004, ApJL, 601, L29