Structure of Merger Remnants:

Lessons from Spectral Line Observations

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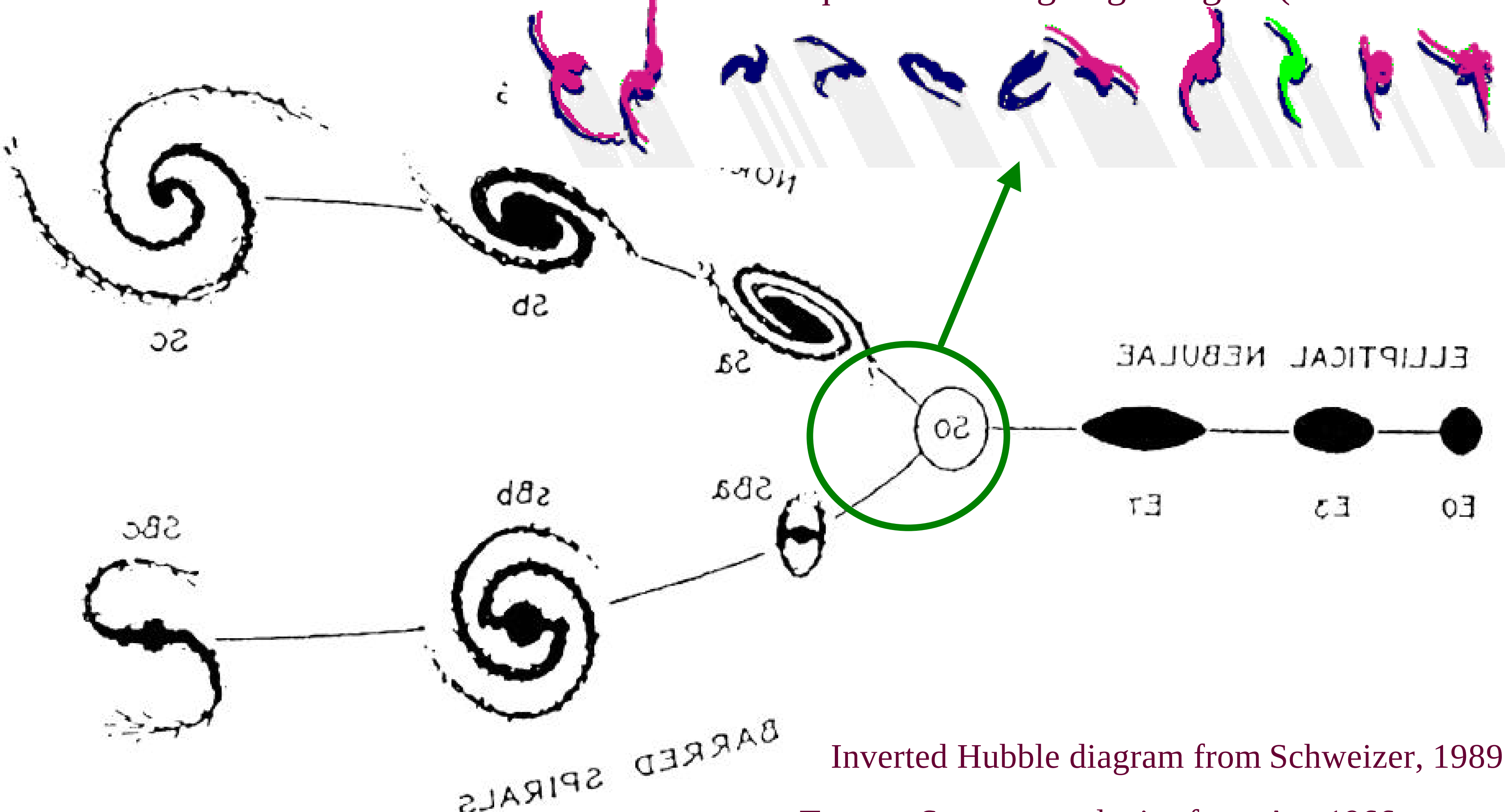
Merger Hypothesis:

Two gas-rich Spirals Merge into One Elliptical

Toomre Sequence of On-going Mergers (Toomre 1977)



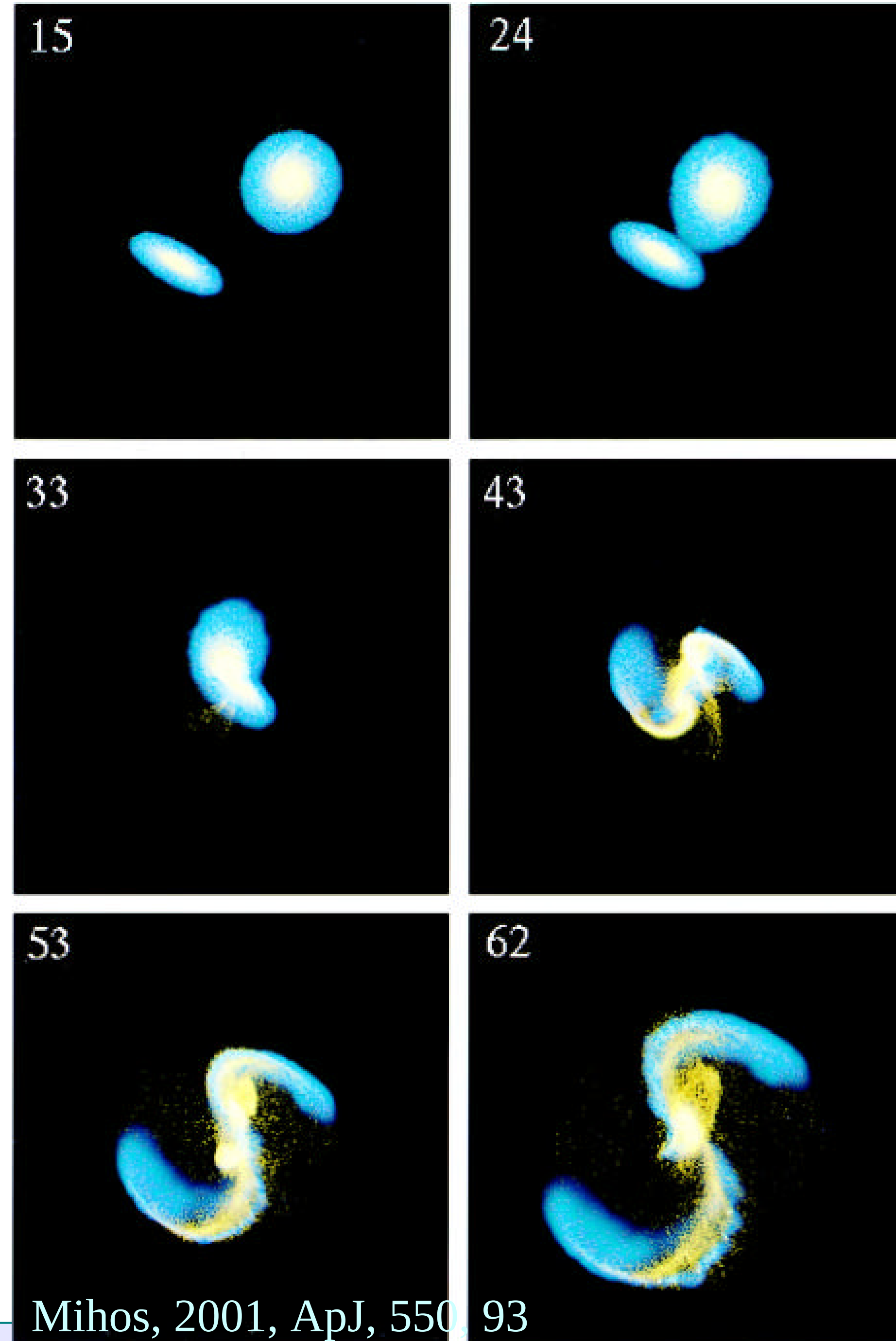
Inverted Hubble diagram from Schweizer, 1989

Toomre Sequence galaxies from Arp 1966

HI Mapping is Well Suited to Explore the Merger Hypothesis

- Progenitors are often gas-rich
- Tails form from outermost regions of progenitor disks and develop kinematically
- Tidal kinematics bear the imprint of the encounter geometry

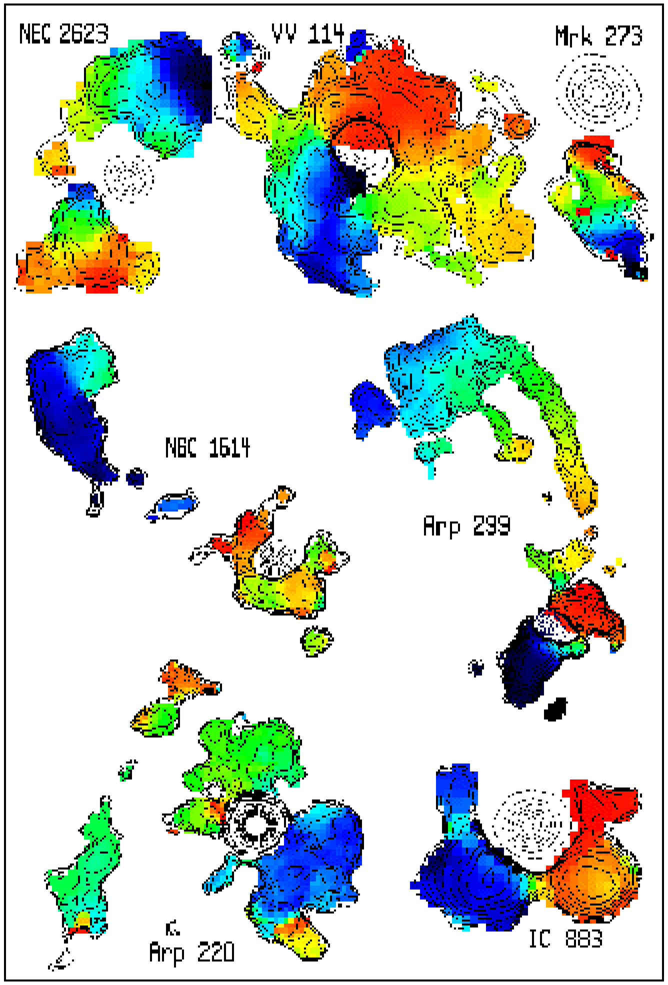
HI provides means to map dynamics of features with no other kinematic tracer



Mihos, 2001, ApJ, 550, 93

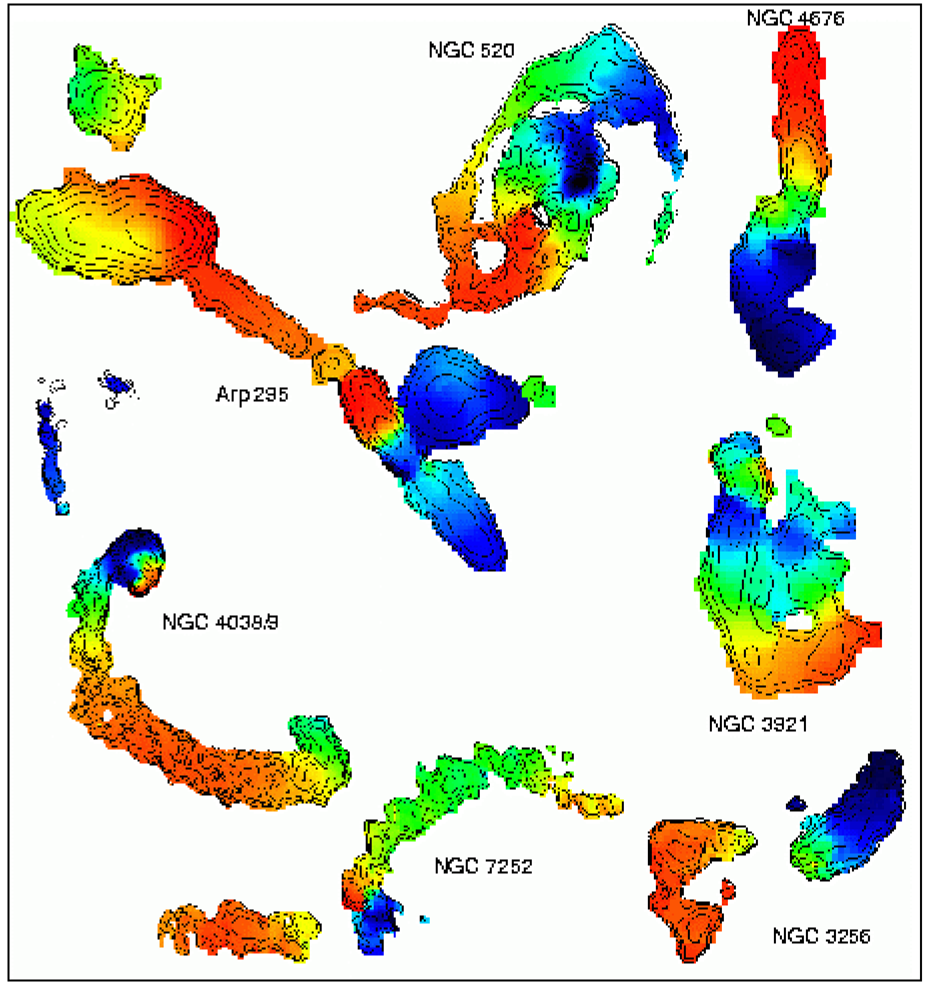
HI emission extends to large radii, simultaneously providing complete kinematical mapping

HI in IR Luminous Mergers



Hibbard & Yun, in preparation

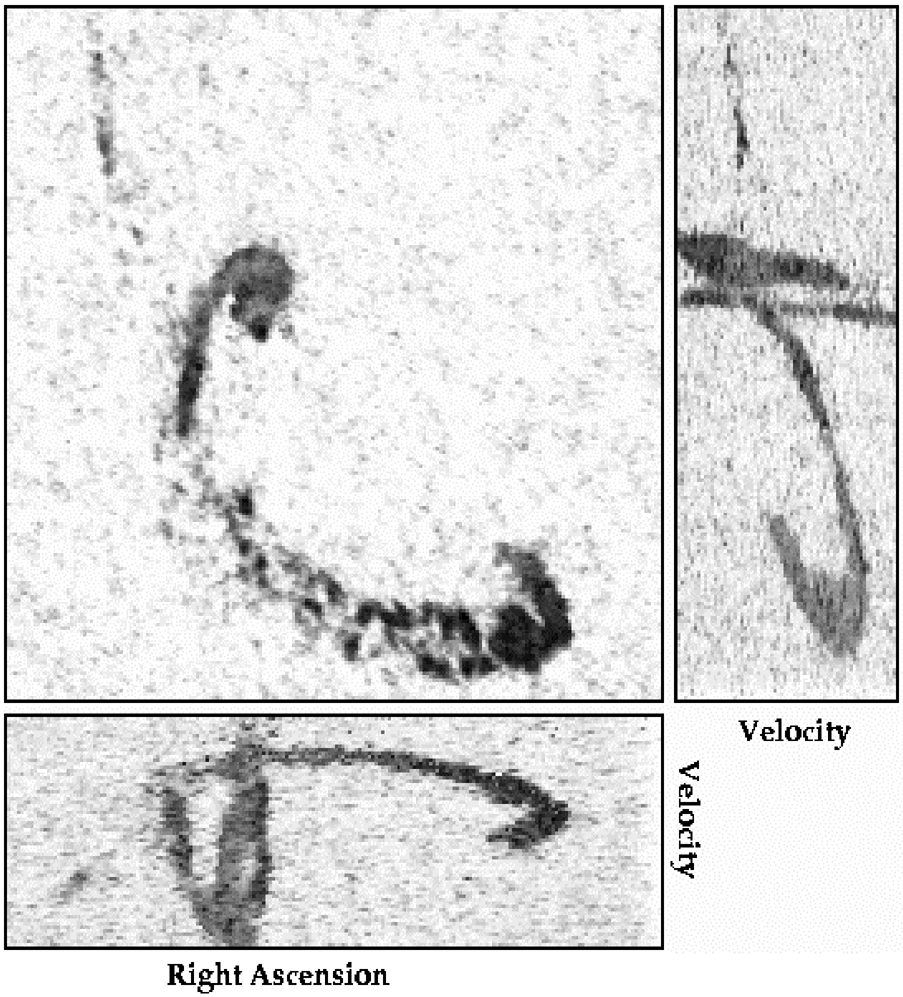
HI in Optically Selected Mergers

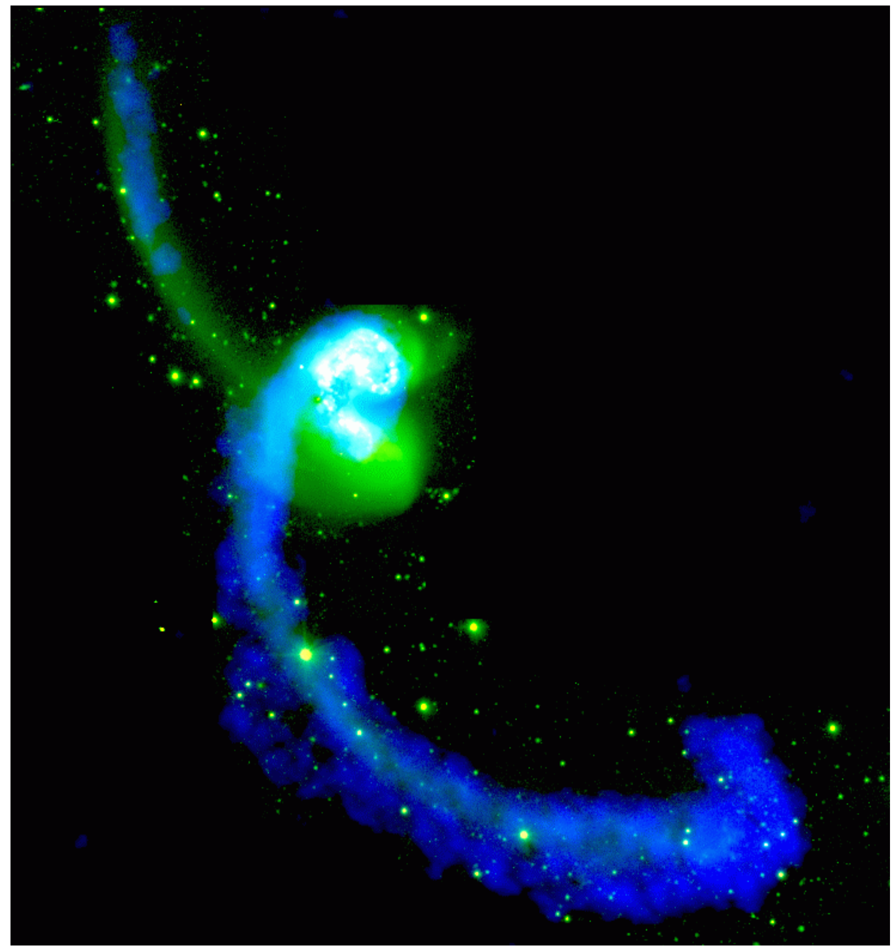


Hibbard & van Gorkom 1996, Hibbard et al. 1999, English et al. 1999

HI contours on HI velocity field

For Gas Rich Progenitors, Tails are Gas Rich, providing near continuous kinematics

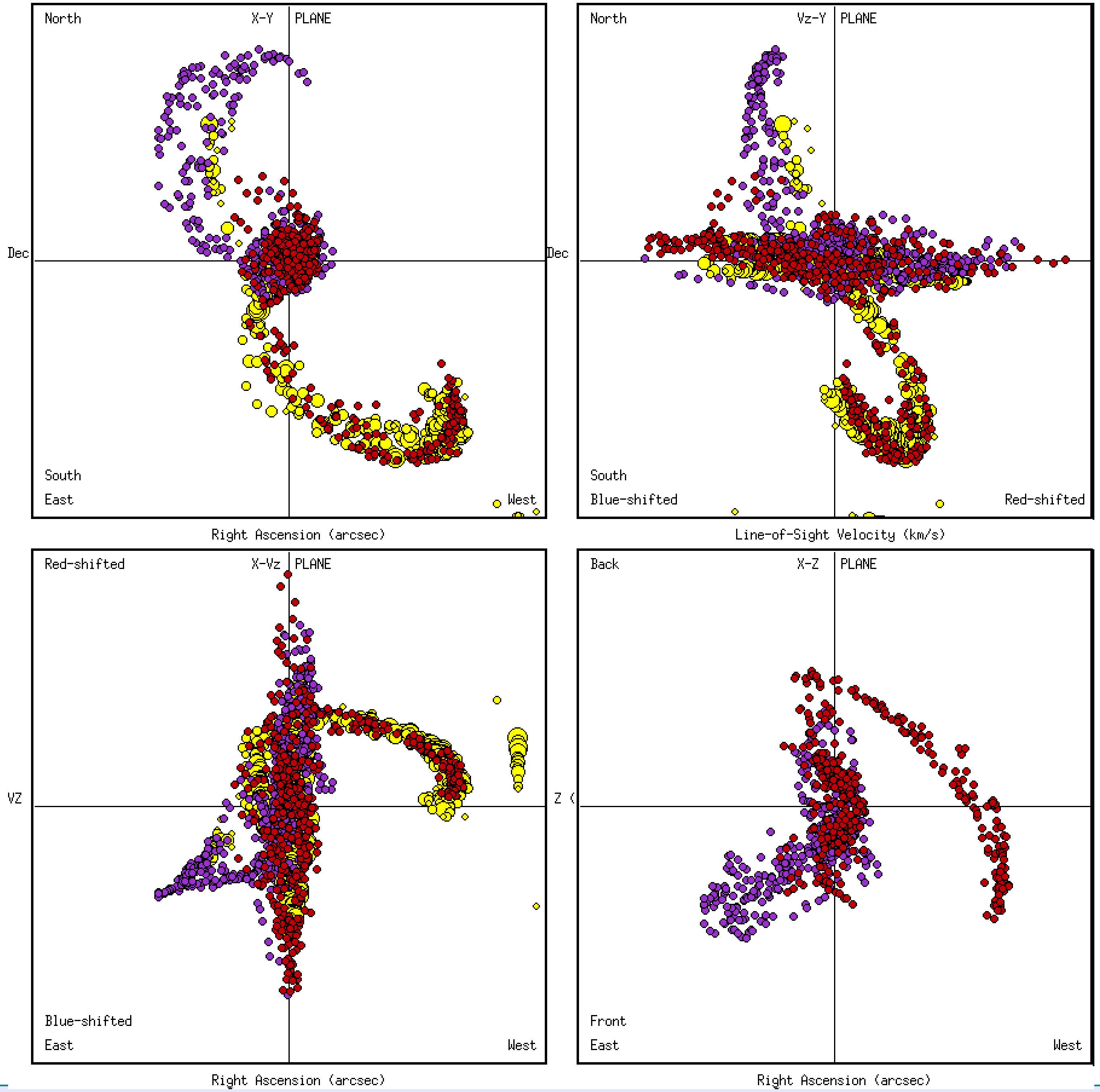




Hibbard, van der Hulst, Barnes & Rich, 2001, AJ, 122, in press

Tidal kinematics bear the imprint of the encounter geometry

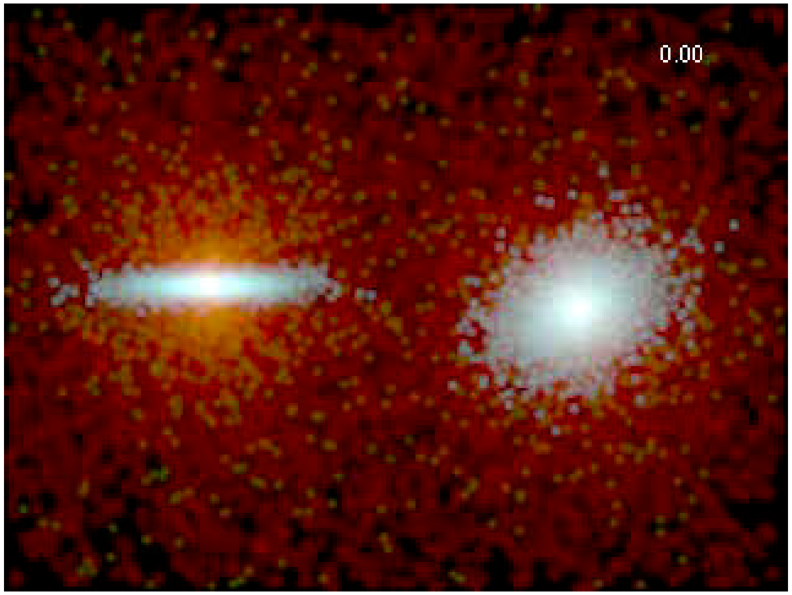
- provide strong constraints on N-body models

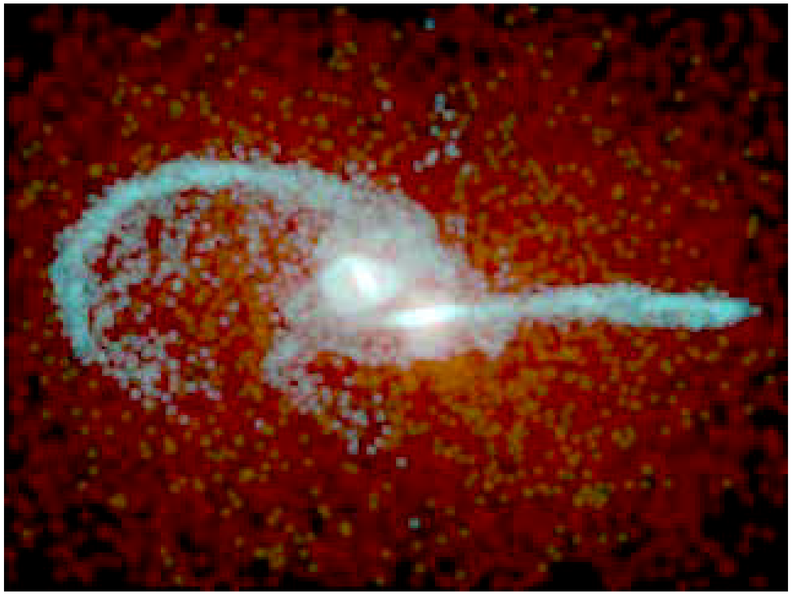


Model matching allows us to explore past and future evolution of tidal material

N-body simulation of NGC 4676 “The Mice”
Hibbard & Barnes, in preparation

N-body simulations provide past/future evolution and 3-D geometry

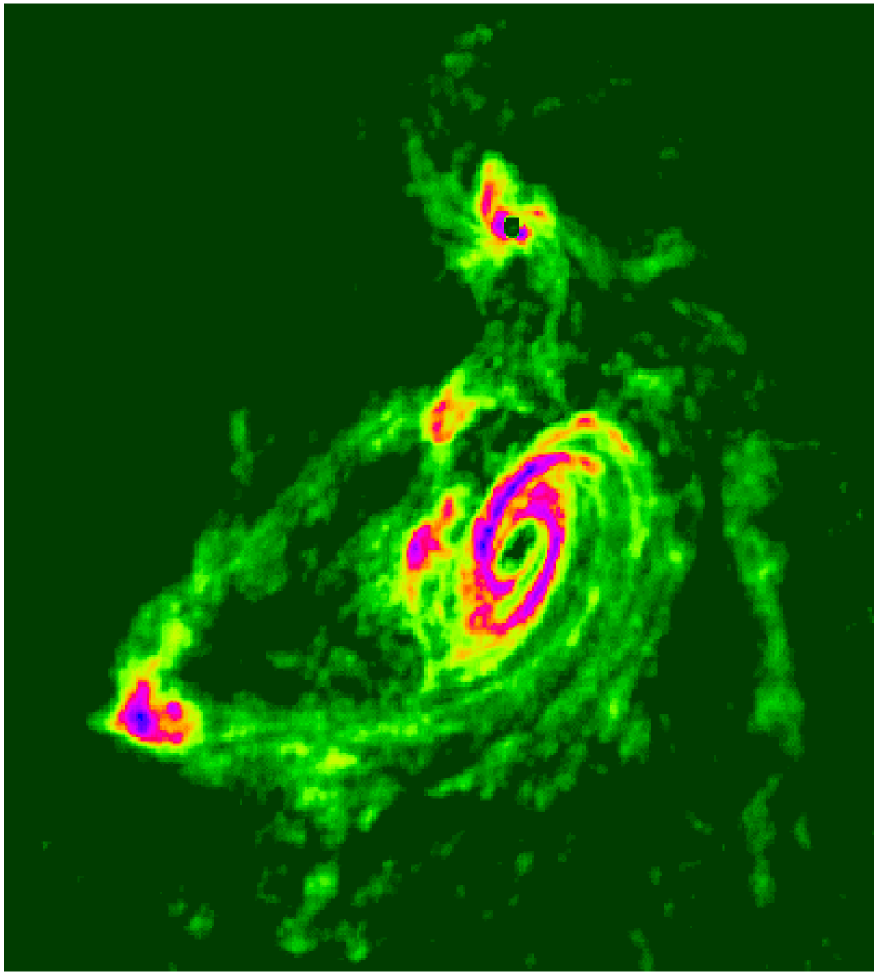


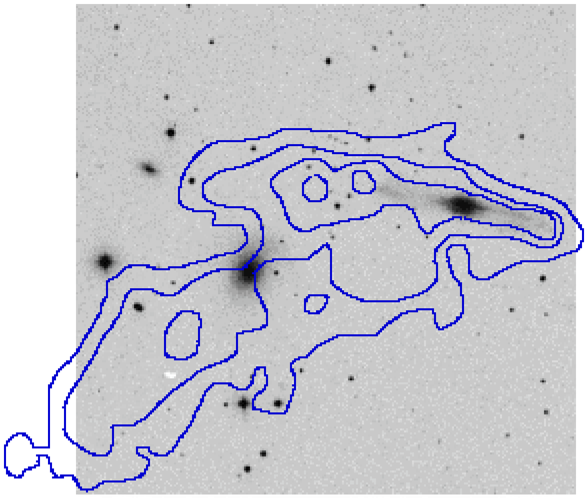


HI Observations often reveal surprising dynamical connections

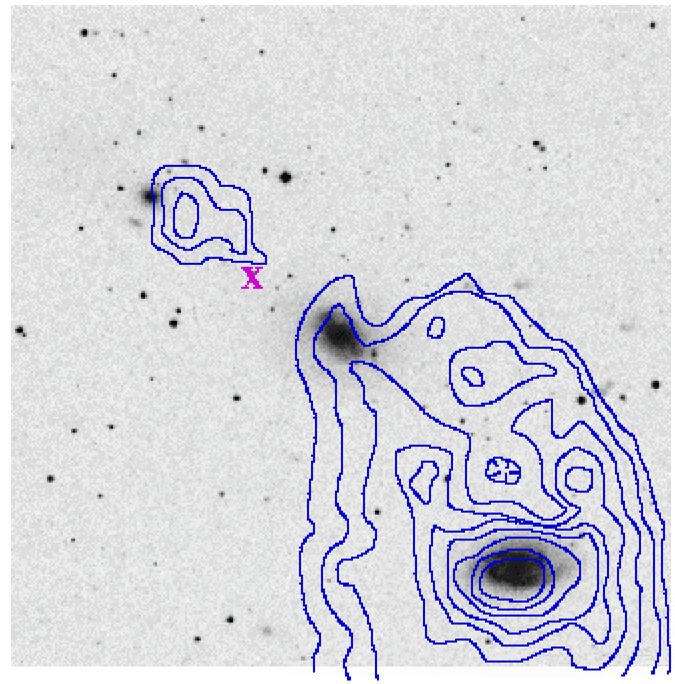
M81/M82/NGC3077

VLA 12-pointing mosaic
Yun et al. 1994

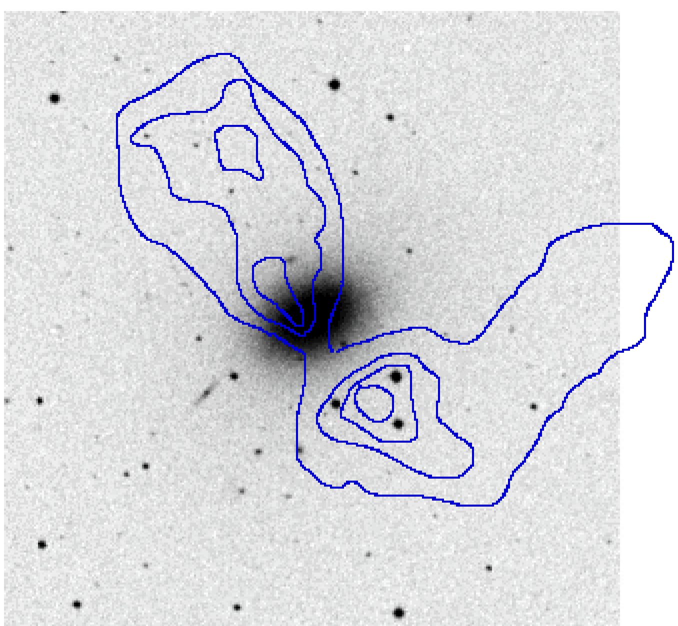




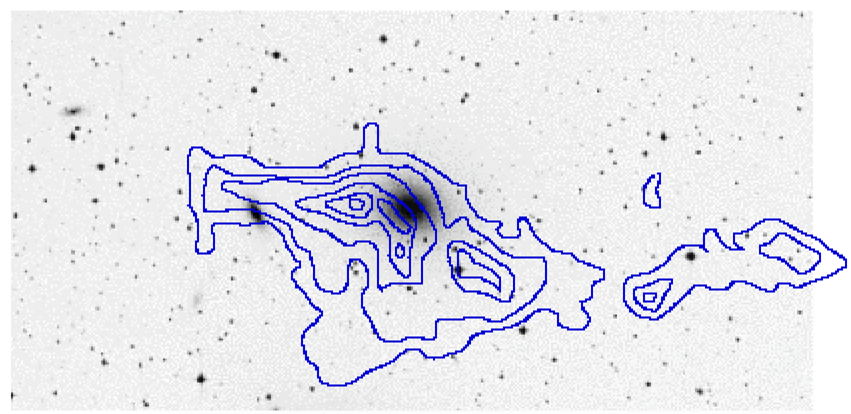
NGC 678+680, Sb+Epec, van Moorsel 1988



NGC 2964+2968+2970, Sb+I0+E1 with extragalactic SNe
van Gorkom & Tyson, in prep



NGC 1052, E4, Sy2, van Gorkom et al. 1986



NGC 5903, E2, Appleton, Pedlar & Wilkinson 1990

…and some not so surprising dynamical connections

Arp 188 = UGC 10214

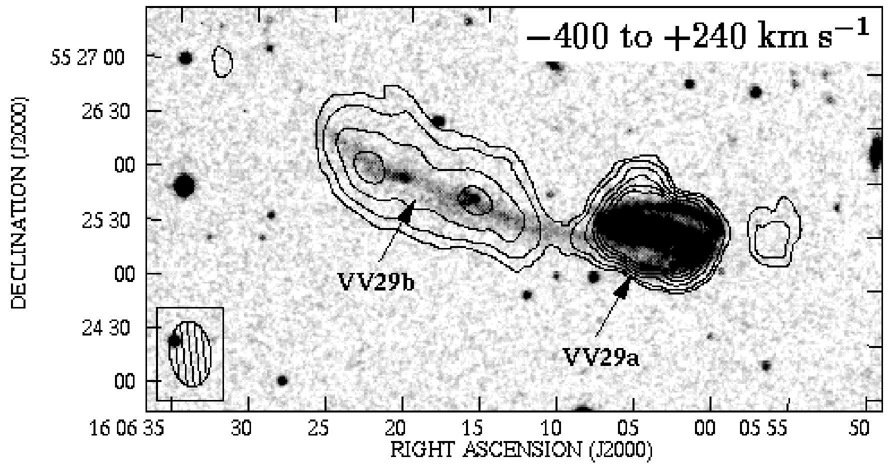
INT g-band image
Trentham, Moller & Ramirez-Ruiz 2001
MNRAS, 322, 658

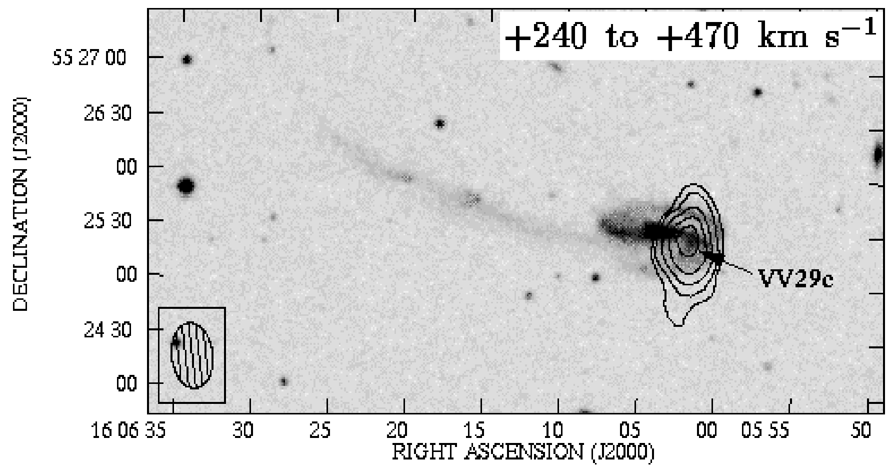
A Dark Galaxy Collision??

…Or Not

WSRT HI Map
Briggs et al. 2001
A&A, in press

HI reveals 2 distinct kinematic components





astro-ph/0110115 Accepted for publication in A&A
F.H. Briggs, O. Moller, J.L. Higdon, N. Trentham, E. Ramirez-Ruiz

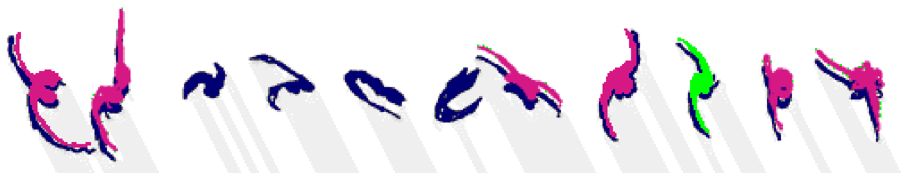
True population of peculiar objects will be greater than derived optically

- This will be even more true in the past, when galaxies were much more gas rich
- Local peculiar fraction ~5-10%
- Increases to 40% by z~0.5

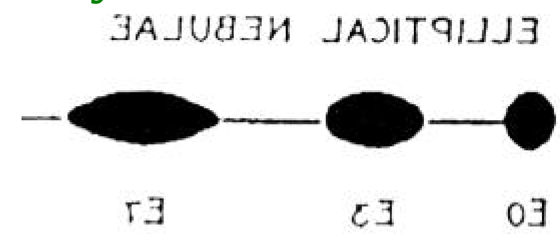
HI Mapping and Simulations provide strong support that the Toomre Sequence is a Merger Sequence

But what comes Next?

0.3 Gyr 1 Gyr ? 5 Gyr?



Toomre Sequence of On-going Mergers (Toomre 1979)

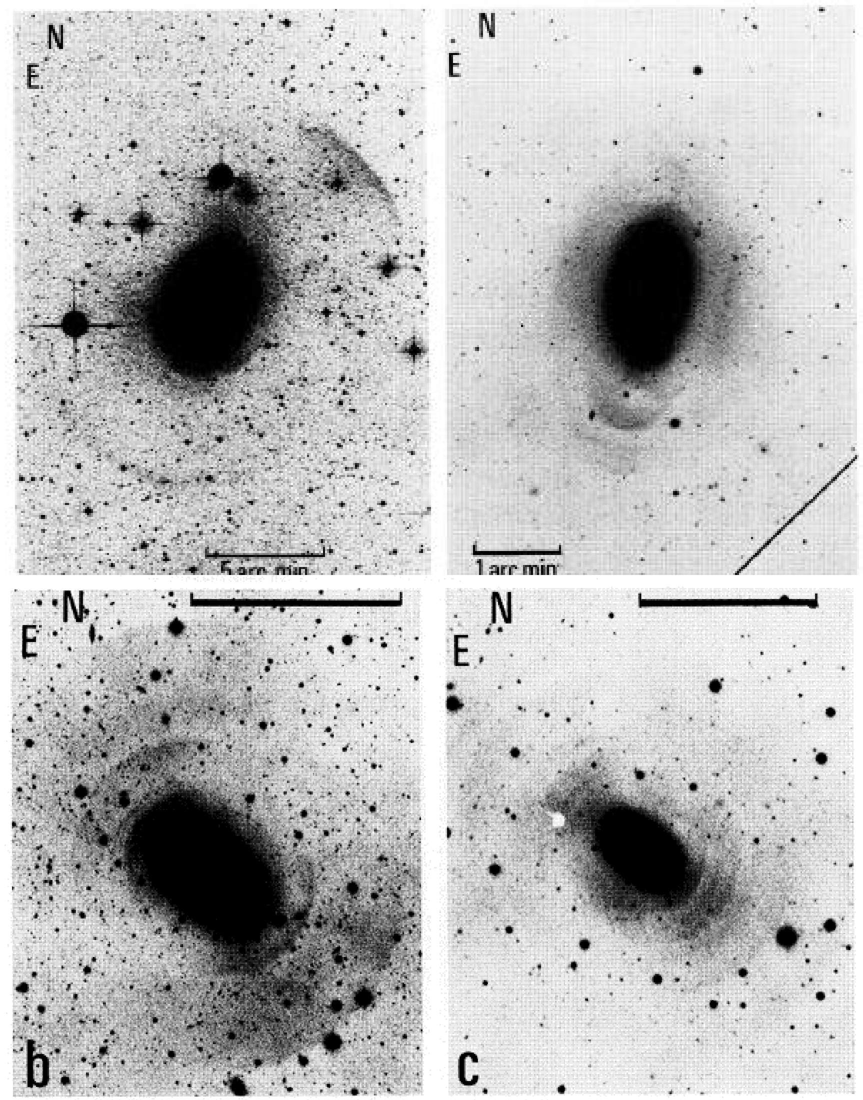


This is the "King Gap"
(Ivan King, quoted in Toomre, 1977)

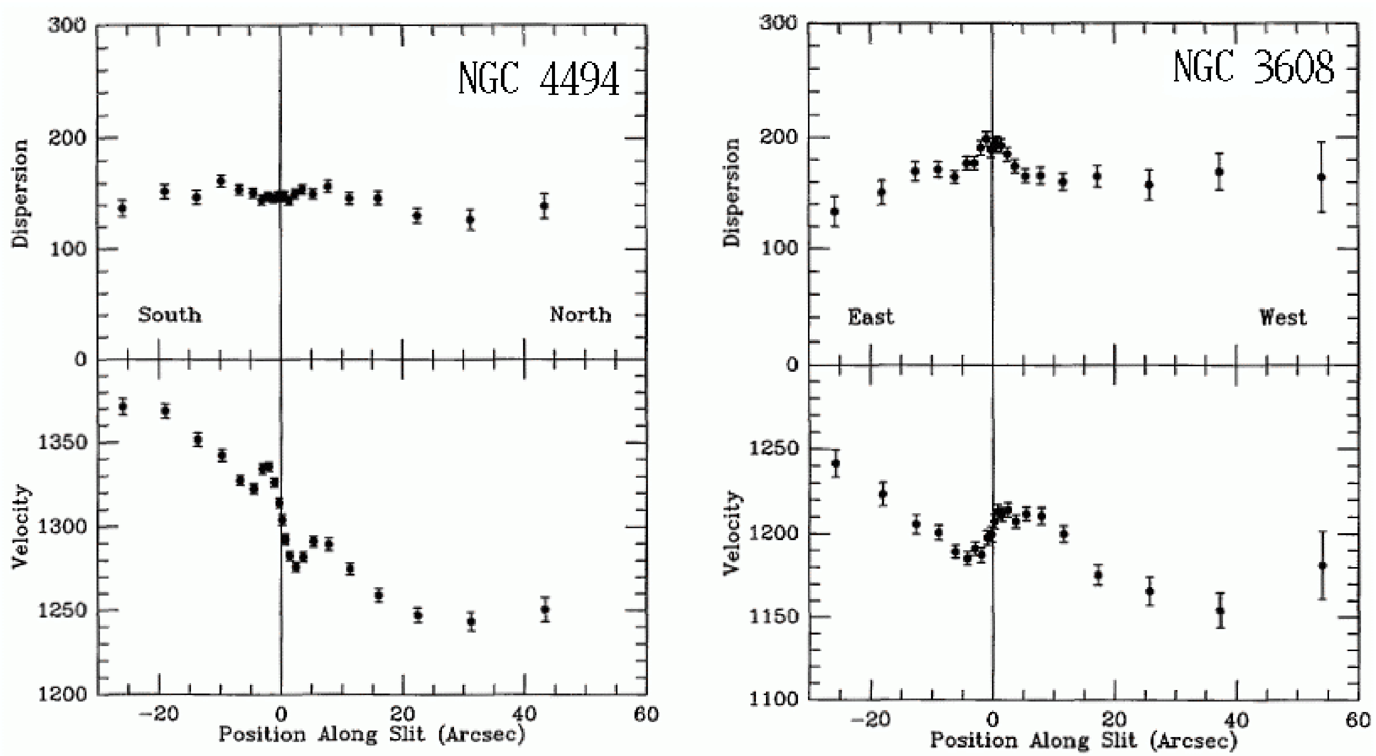
King-Gap Candidates:

- Shell Galaxies (e.g. Malin & Carter 1983+), or Early Types with "Fine Structure", Σ (e.g. Schweizer & Seitzer 1992)

Σ = S + log (1+n) + J + B + X



King-Gap Candidates:

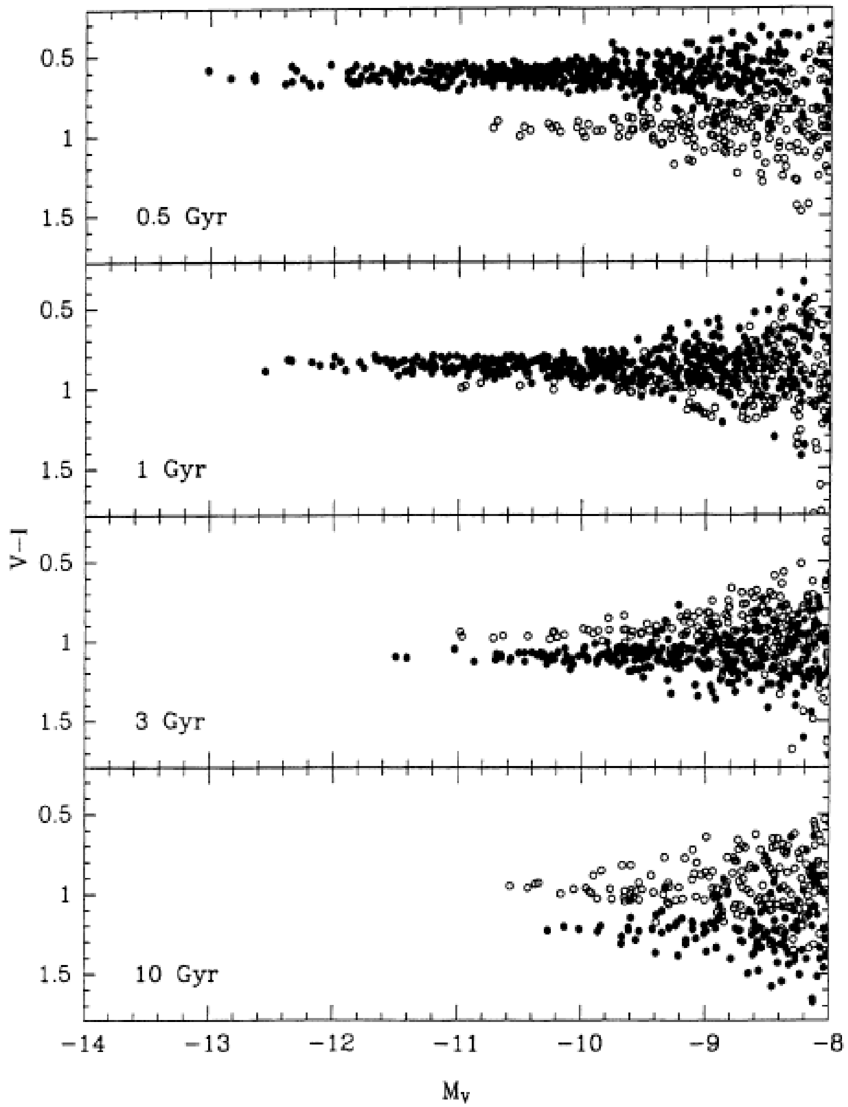


Jedrzejewski & Schechter 1988, ApJ, 330, L87

- Ellipticals with Kinematically Distinct Cores (KDCs, e.g., Efstathiou et al. 1982, Franx et al. 1989)

King-Gap Candidates:

- Ellipticals with Bimodal Globular Cluster systems (e.g. Zepf & Ashman 1993, Elston & Santiago 1996, Miller & Fall 1997, Goudfrooij et al. 2000)



Whitmore, Miller, Schweizer & Fall 1997

Other King-Gap Candidates:

- Early types with Boxy isophotes
- Early types with Disky isophotes
- Ellipticals with cold gas
- E+A Galaxies

Problems for Merger Hypothesis?

- Simulations predict that light profiles of merger remnants will not resemble those of ellipticals
- King Gap candidates fail to show expected color gradients
- King Gap candidates fail to show expected correlations between gas phases and age indicators

Problems for Merger Hypothesis?

- Numerical simulations predict merger-driven gas inflow will lead to dense nuclear stellar population that will not join smoothly with mass profile of pre-existing population
- Conclude that mergers of gas-rich disks may not have contributed greatly to present day population of ellipticals

Problems for Merger Hypothesis?

MIHOS & HERNQUIST

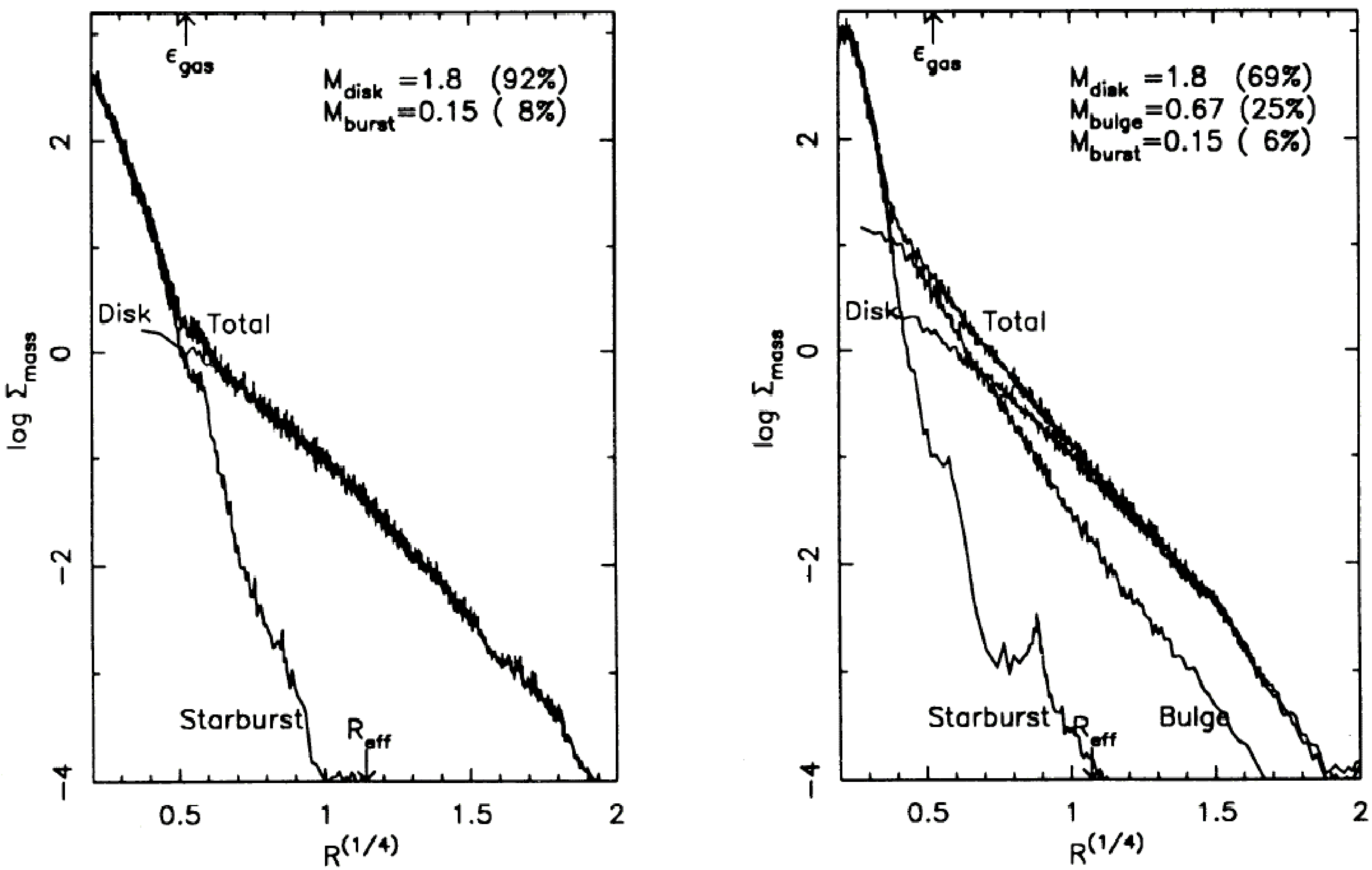


FIG. 1*a* FIG. 1*b*

Do Early Types really have seamless luminosity profiles?

Nuker Sample:

Lauer et al. 1995,
Byun et al. 1996:

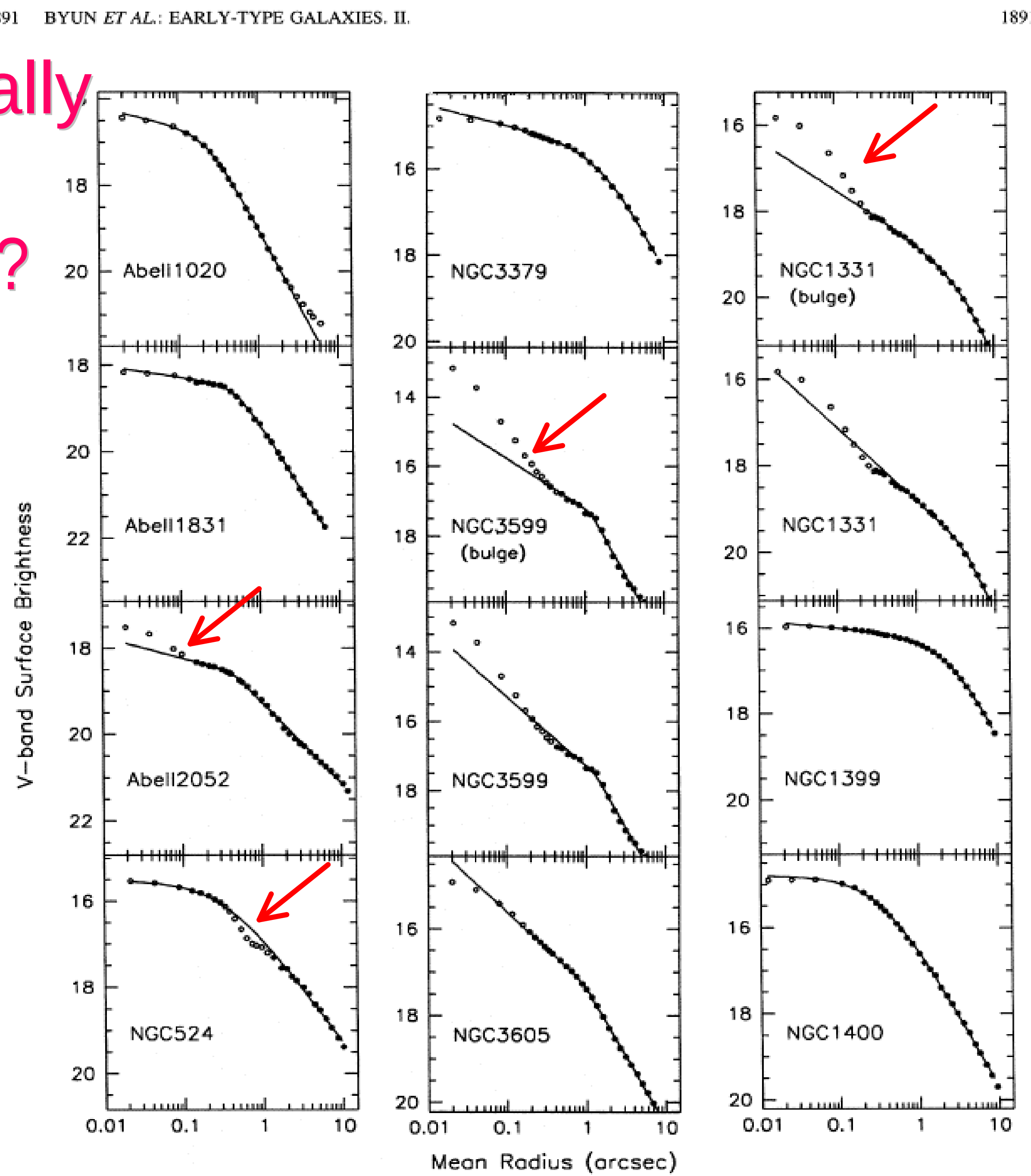
WFPC F555W

N=45 (37 E, 6 S0, 2 Sp)

Non-smooth profiles:

35% E

50% S0



Do Early Types really have seamless luminosity profiles?

LEDA Sample:

Rest et al. 2001:

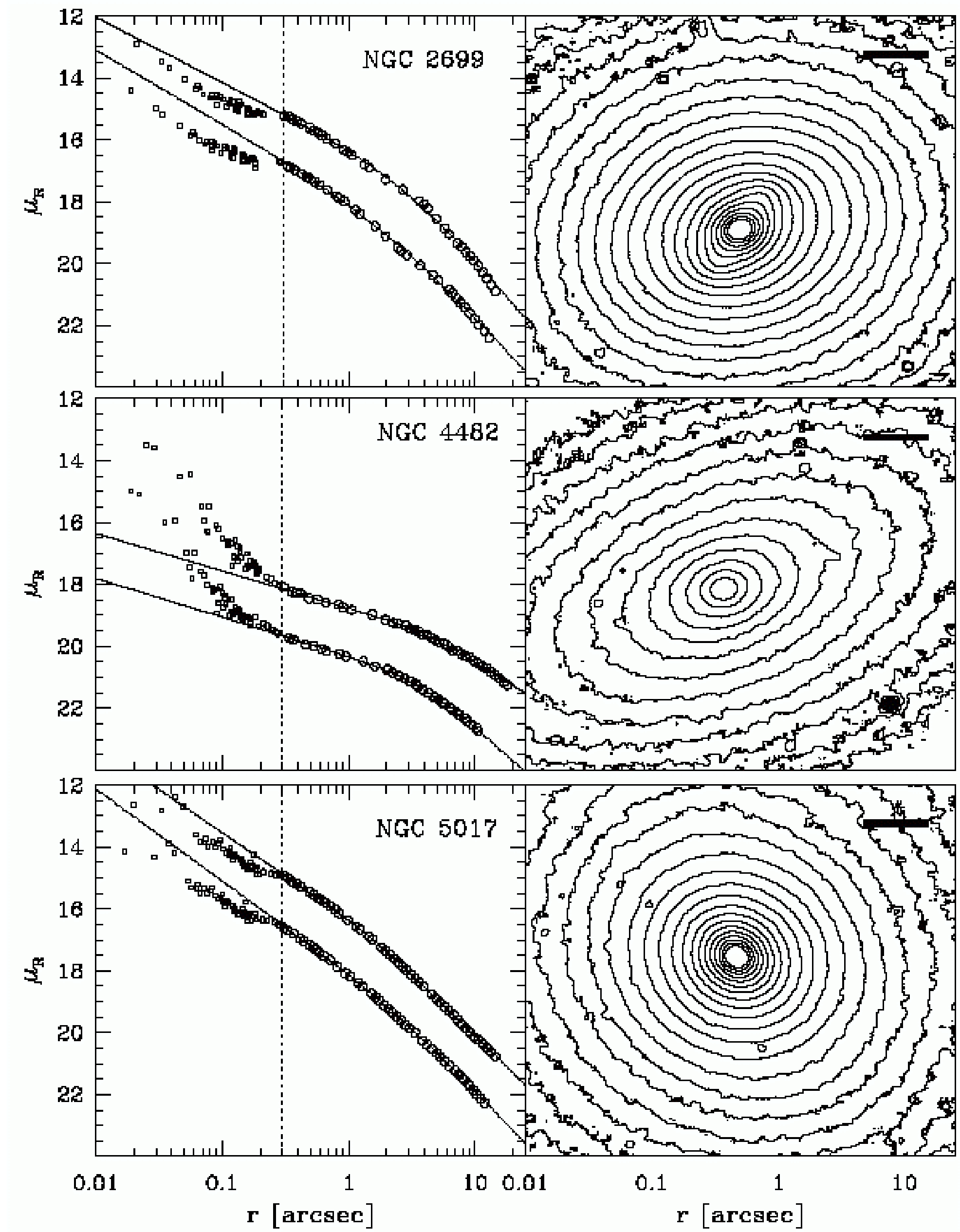
WFPC2 F702W

N=67 (36 E, 6 E/S0, 25 S0)

Non-smooth profiles:

40% E

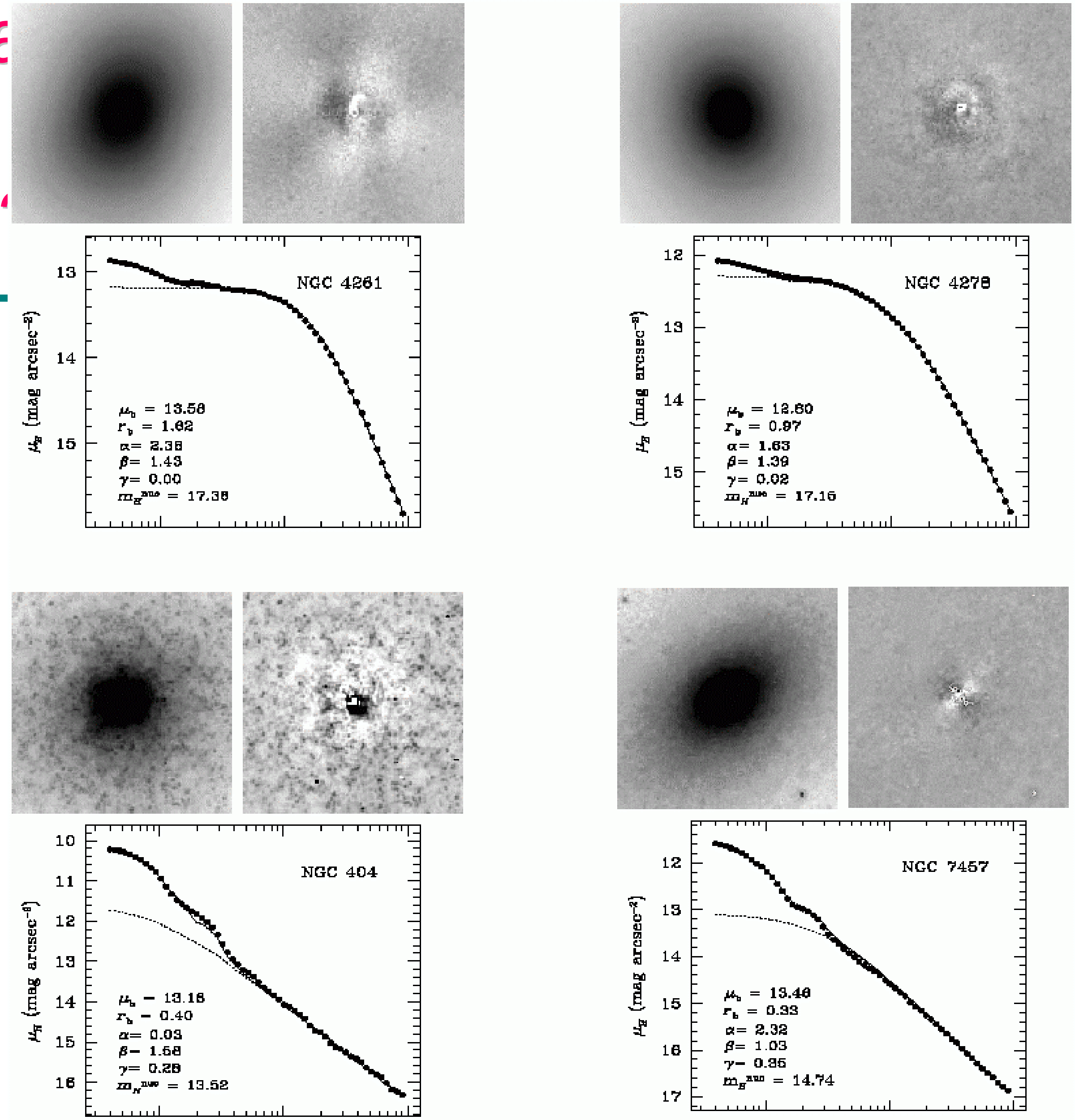
30% E/S0,S0



Rest et al. 2001, AJ, 121, 2431 HST WFPC2 F702W

Do Early Types rea
have seamless luminosity profiles

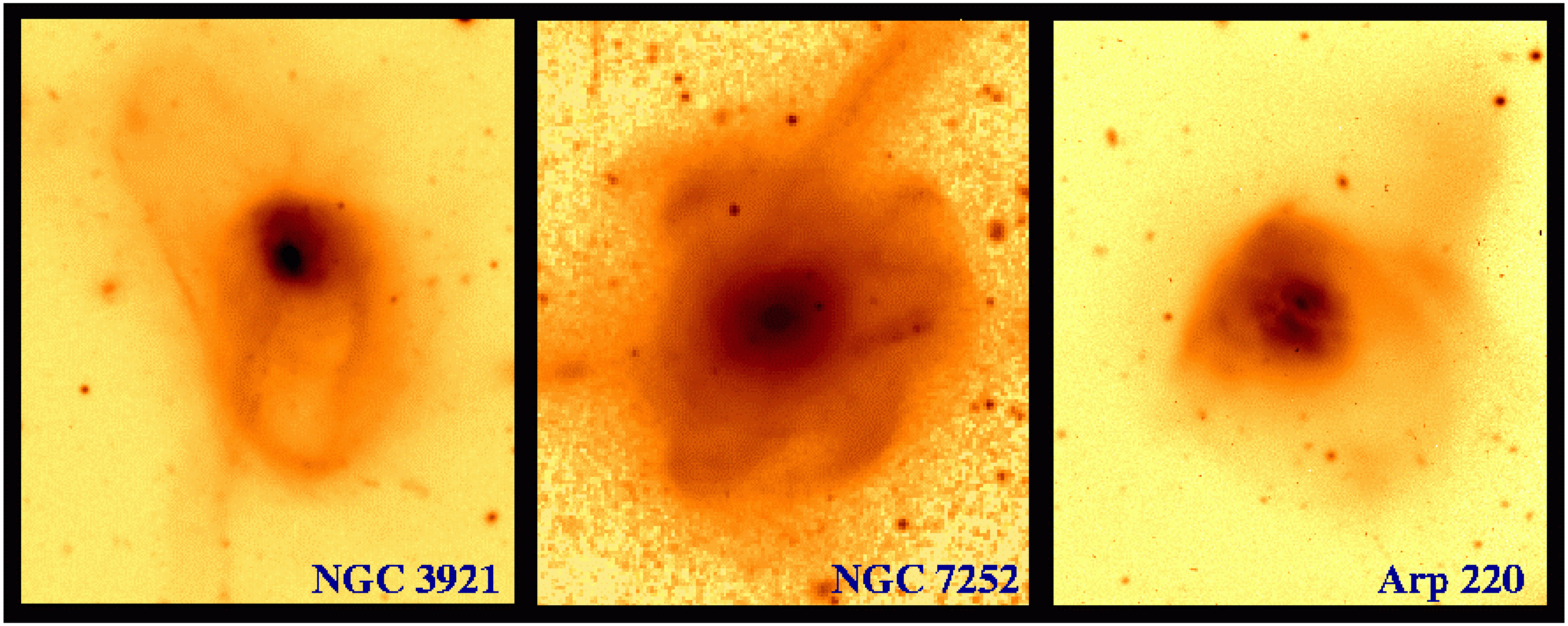
- **HST NICMOS archive sample:**
- **Ravindranath et al. 2001:**
- **NIC3 F160W**
- **N=33 (14 E, 16 S0, 3 S0/a)**
- **Non-smooth profiles:**
- **30% E**
- **50% S0, S0/a**



Ravindranath et al. 2001, ApJ, 122, 653 HST NIC3 F160W

Luminosity Profiles of Merger Remnants

Will well established Merger Remnants evolve to have non-characteristic light profiles?



Predicting luminosity profiles of merger remnants after 2 Gyr:

- Fade present profile by 2 Gyr
- Turn CO to gas using galactic X_{co} factor, and accounting for He
- Add expected burst population under most favorable conditions (no gas lost to winds, SNe; Salpeter IMF; single burst $dt<10^8$ yrs)

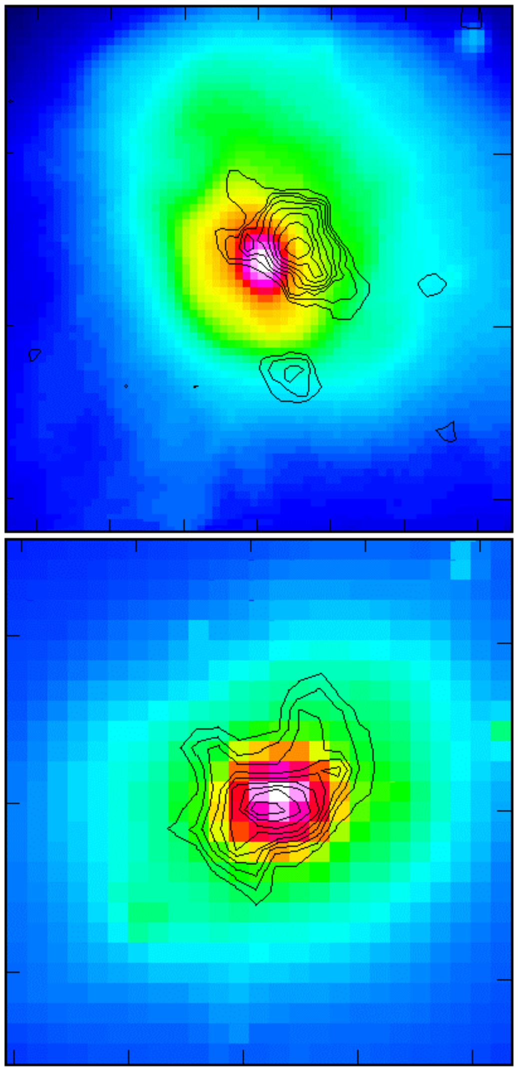
- Using well studied merger remnants NGC 3921, NGC 7252
- Use Bruzual & Charlot 1993 evolutionary models
- $\Delta\mu_{B,fade} \sim 1$ mag arcsec $^{-2}$
- $(M_*/L_B)_{burst+2Gyr}=0.9\ M_o\ L_o^{-1}$

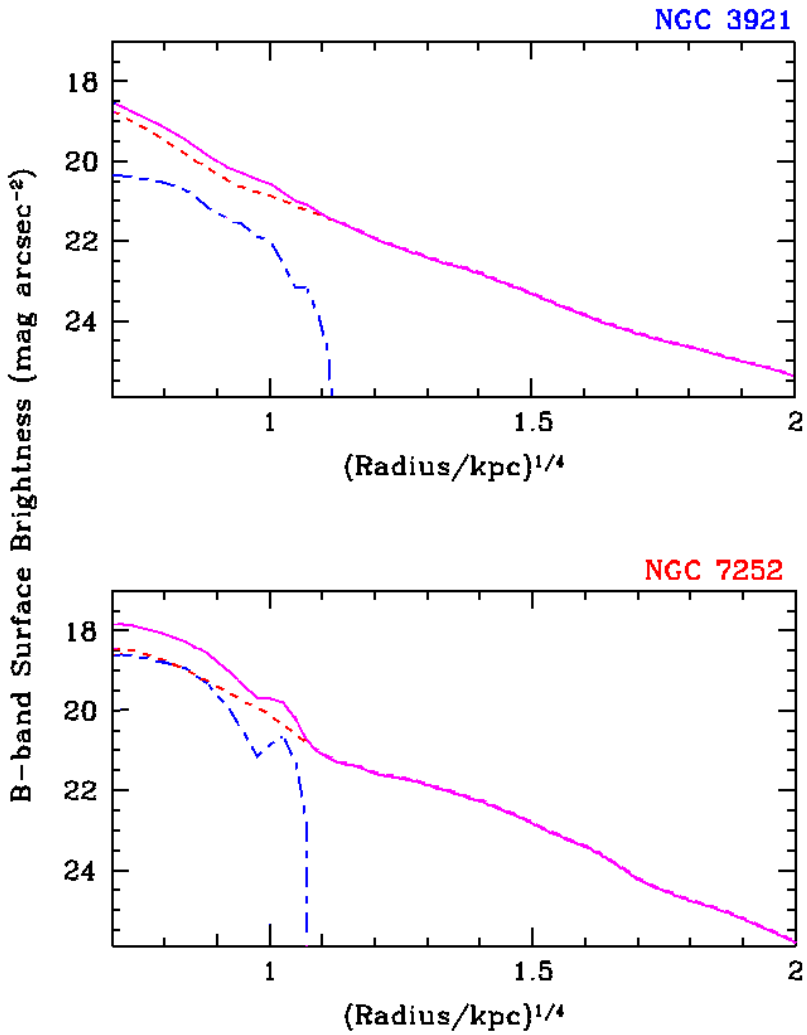
➡ $\Delta\mu_B < 0.7$ mag arcsec^{-2}

Factor of < 2

⟶ basically seamless

Predicting luminosity profiles of merger remnants after 2 Gyr (all gas goes to stars; fade present population):





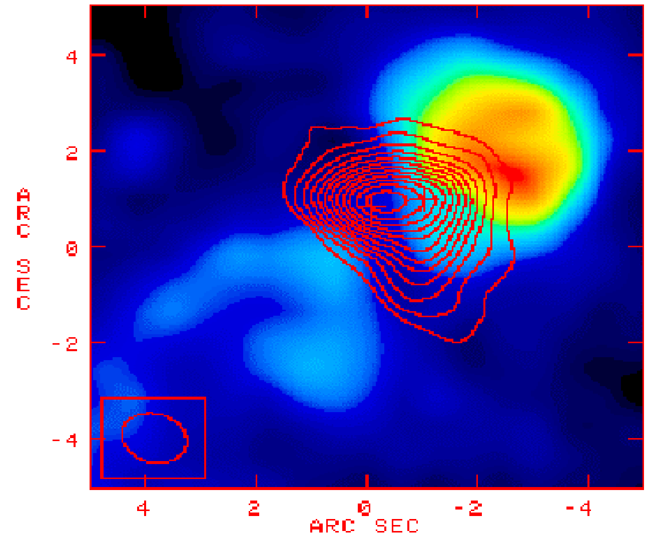
Hibbard & Yun 1999, ApJ, 522, L93

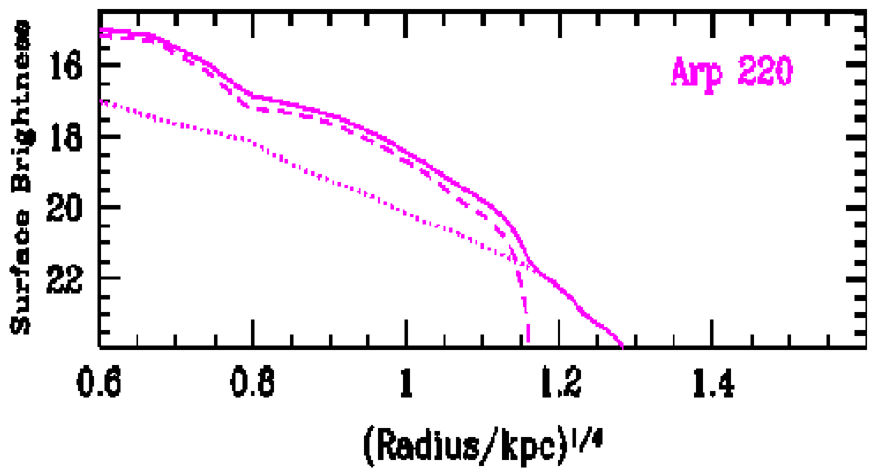
Factor of < 2

→ Basically seamless

What about mergers with highest Σ_{gas}?

- Remnants have modest H_2 surface densities. ULIGs have much higher values.
- Repeat exercise for ULIRG Arp 220





Factor of ~ 7

→ may not be seamless

So do ULIGs evolve into peculiar Ellipticals?

- Either they do, in which case fraction of E's with "spikey" luminosity profiles can constrain fraction of past ULIGs
- Or they don't, in which case all cold gas must be expelled or converted into other phases
- Can constrain by observations of:
  - E's with anomalous luminosity profiles, looking for evidence of merger origin
  - 1-3 Gyr old merger remnants, looking for evidence of dense aging burst population
  - Compare space density of ULIGs at z~1 with space density of Es with "spikey" luminosity profiles today

Luminosity Profiles of Merger Remnants: Conclusions

- Non-ULIR mergers will not evolve anomalous luminosity profiles
- ULIGs either evolve into that fraction of E's observed with such profiles, or they expel most of their cold nuclear gas
- However, fraction of mergers that experience ULIG phase is at present unknown, as is the fraction of Early Types with anomalous profiles.

Problems for Merger Hypothesis?

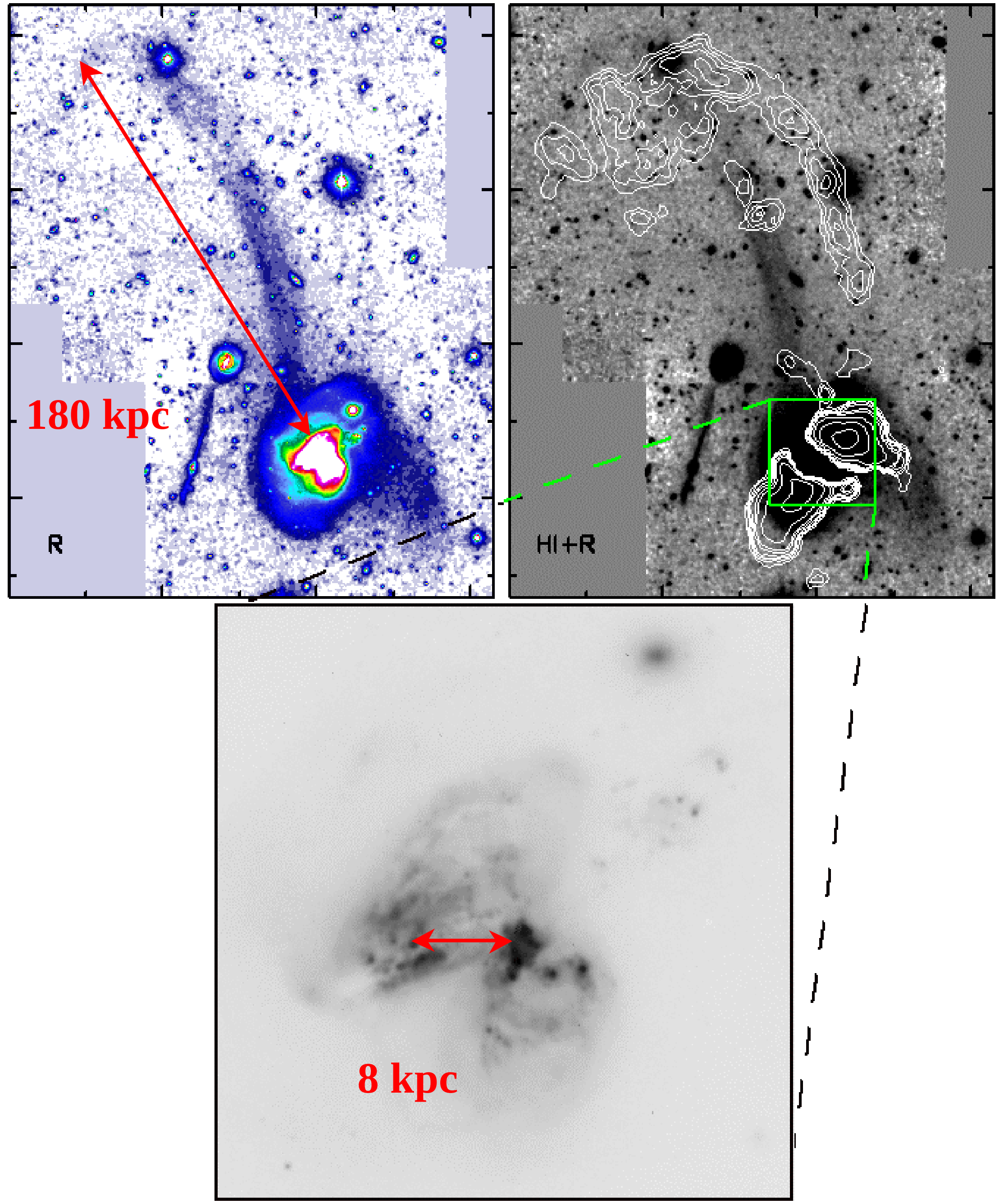
- Early Type Galaxies with Shells, Fine structure, KDC fail to show expected central color gradients
  - KDCs: Forbes et al. 1995, Corollo et al. 1997,
  - NIR of Σ: Silva & Bothun 1998a,b
  - Optical-NIR of z~0.8 Early Types: Hinkley & Im 2001
  - Any color differences can be attributed to metallicity, rather than age differences

Why don't King Gap candidates show expected color differences?

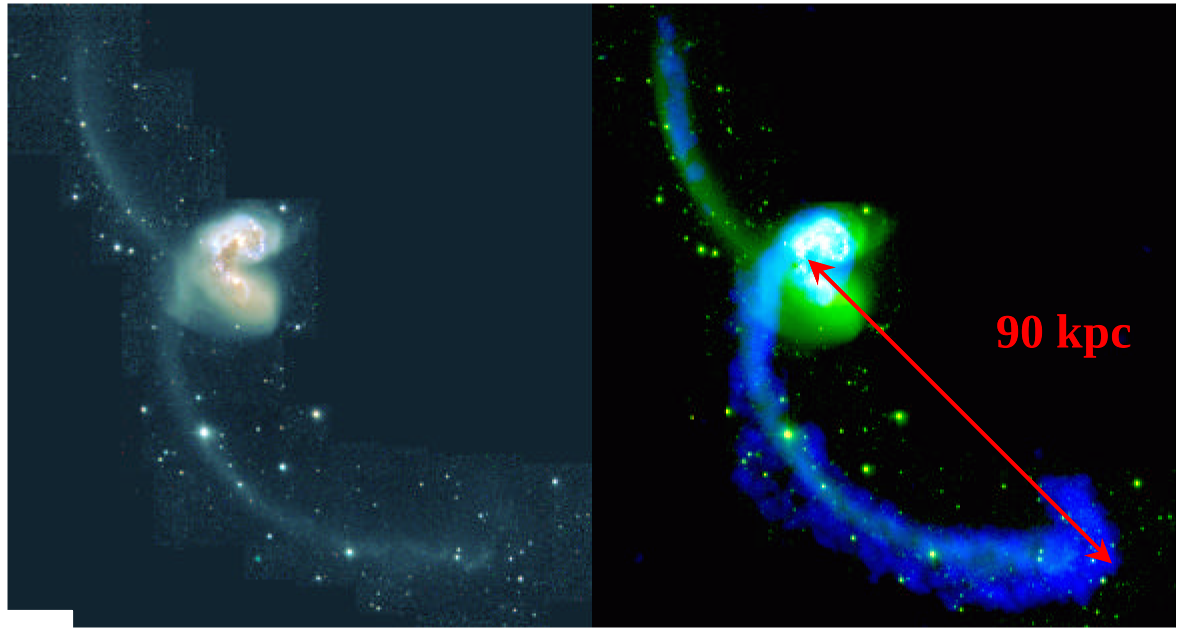
- Conclusion is based on assumption that merger is accompanied by strong starburst that is localized in time and in space
  - Under these conditions, merger induced burst population will exist as distinct population, and will not join seamlessly to pre-existing stellar population either in light profile or color
- Color differences sensitive to age differences < 4 Gyr
  - Fine Structure Ellipitcals have "Heuristic Merger Ages" > 3-7 Gyr (Schweizer et al. 1992)

Timescales for star formation are much larger than timescale of present bursts

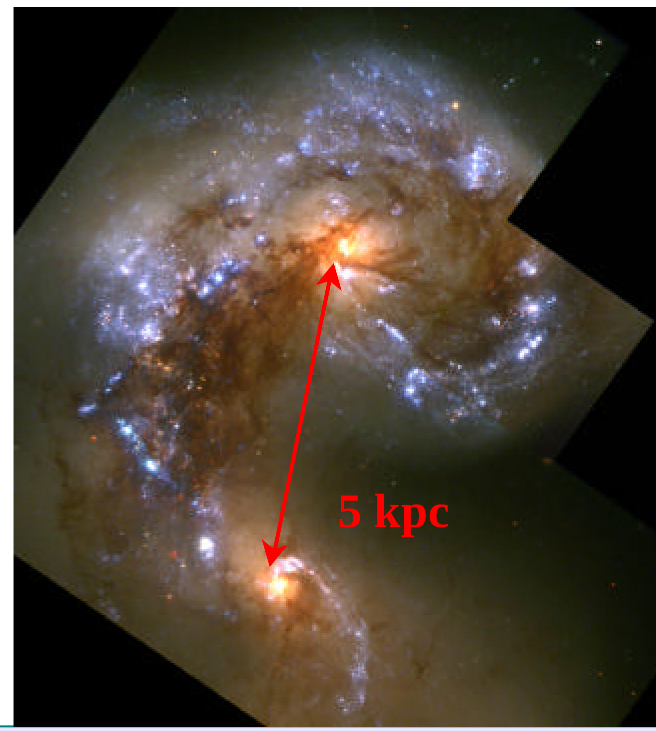
- Arp 299: tail length and rotational velocities suggest tail formation began ~750 Myr ago.
- $L_{IR} \sim 6 \times 10^{11} L_{o}$. Current SFR ~ 60 M_{o}/yr
- Dynamical considerations suggest merger will be complete in < 60 Myr



Timescales for star formation are much larger than timescale of present bursts



- Resulting burst population will be spread over a broad range of radii, color, and metallicity
- Resulting signatures in evolved remnants will be much less severe than often assumed, especially after a few Gyr



Extended burst populations supported by recent observations

- E+A: Norton et al. 2001, ApJ, 557, 150
- High-z spheroidals: Menanteau, Abraham & Ellis, 2001, MNRAS, 322, 1

  Young stellar populations are more centrally concentrated than the older populations, but they are not confined to the galaxy core

6 *F. Menanteau, R. G. Abraham and R. S. Ellis*

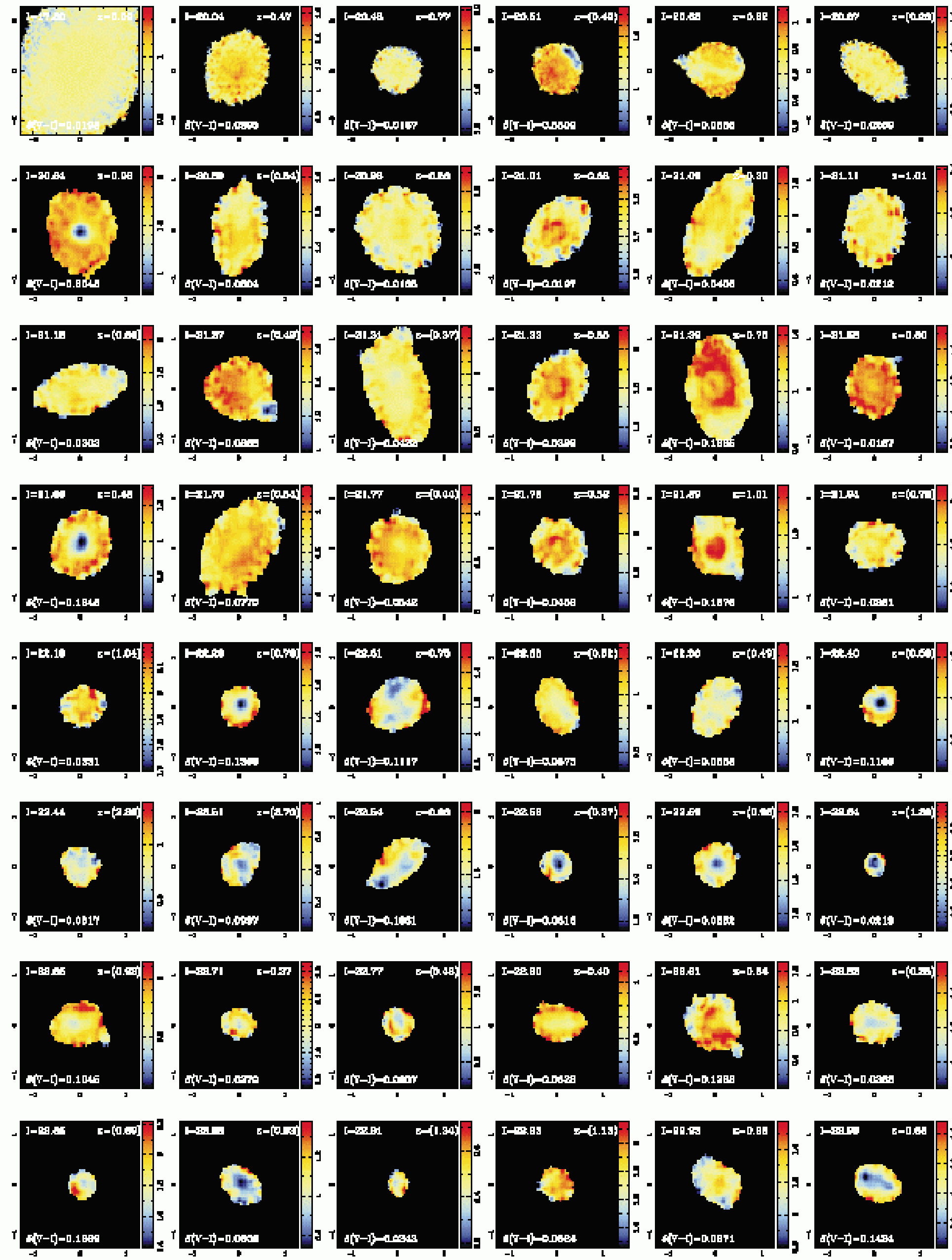
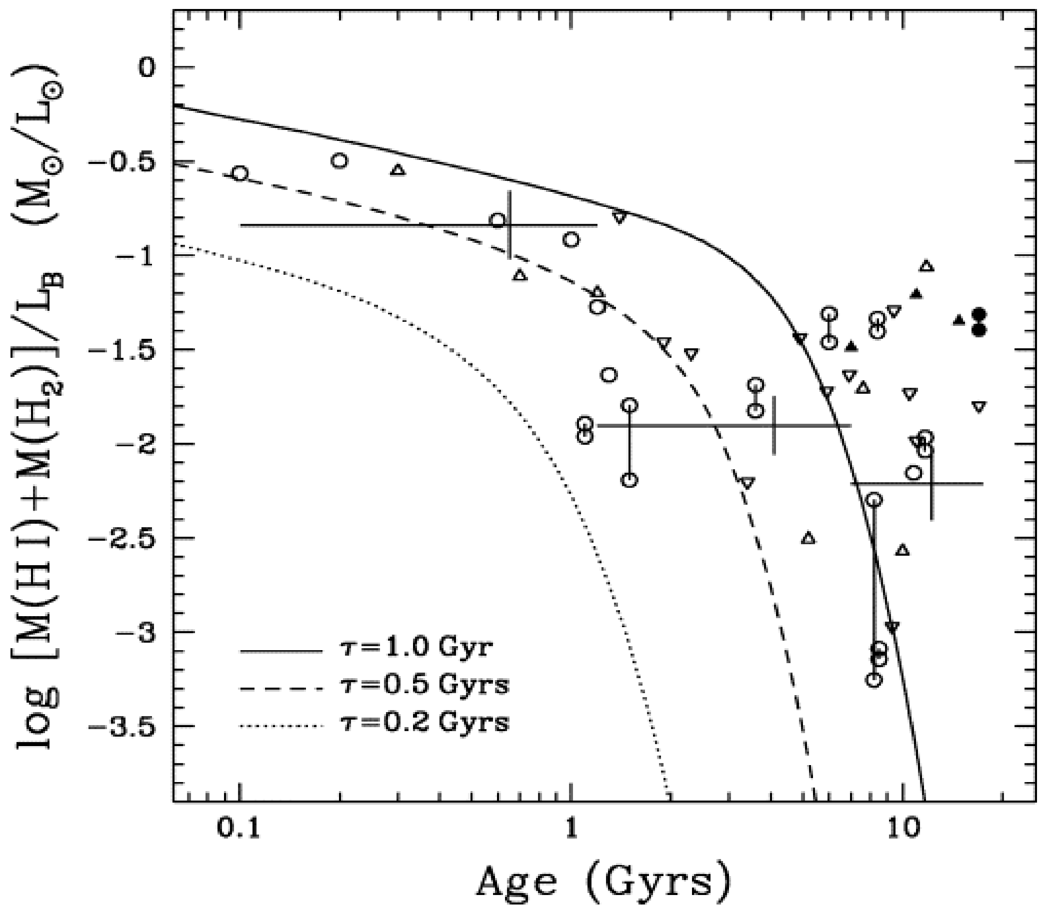


Figure 4. Colour images of 79 HDF field spheroidals keyed to their $V_{606} - I_{814}$ colours. The integrated I_{814} mag for each galaxy is shown in each subpanel together with the redshift and $\delta(V-I)$. Redshifts in parenthesis indicate photometric estimates. Axes labels correspond to arcsec.

Problems for Merger Hypothesis?

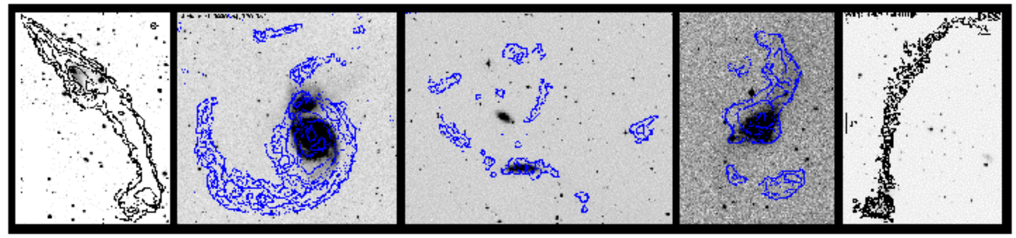
- On-going mergers have high cold gas content, low Lx/Lb. Es have high Lx/Lb, low cold gas content.
- Expect trends between merger stage, Lx/Lb, and cold gas content
- However, Early Type Galaxies with Shells, Fine structure fail to show expected correlations between gas phases and age indicators



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.

Does HI Mapping provide clues?

- "An HI Rogues Gallery"
  - 181 images of HI in peculiar galaxies, or peculiar HI in normal galaxies
- Available on-line at:
  www.nrao.edu/astrores/HIrogues
- Published in "Gas & Galaxy Evolution", ASP Conference Series, Vol 240, Editors Hibbard, Rupen & van Gorkom



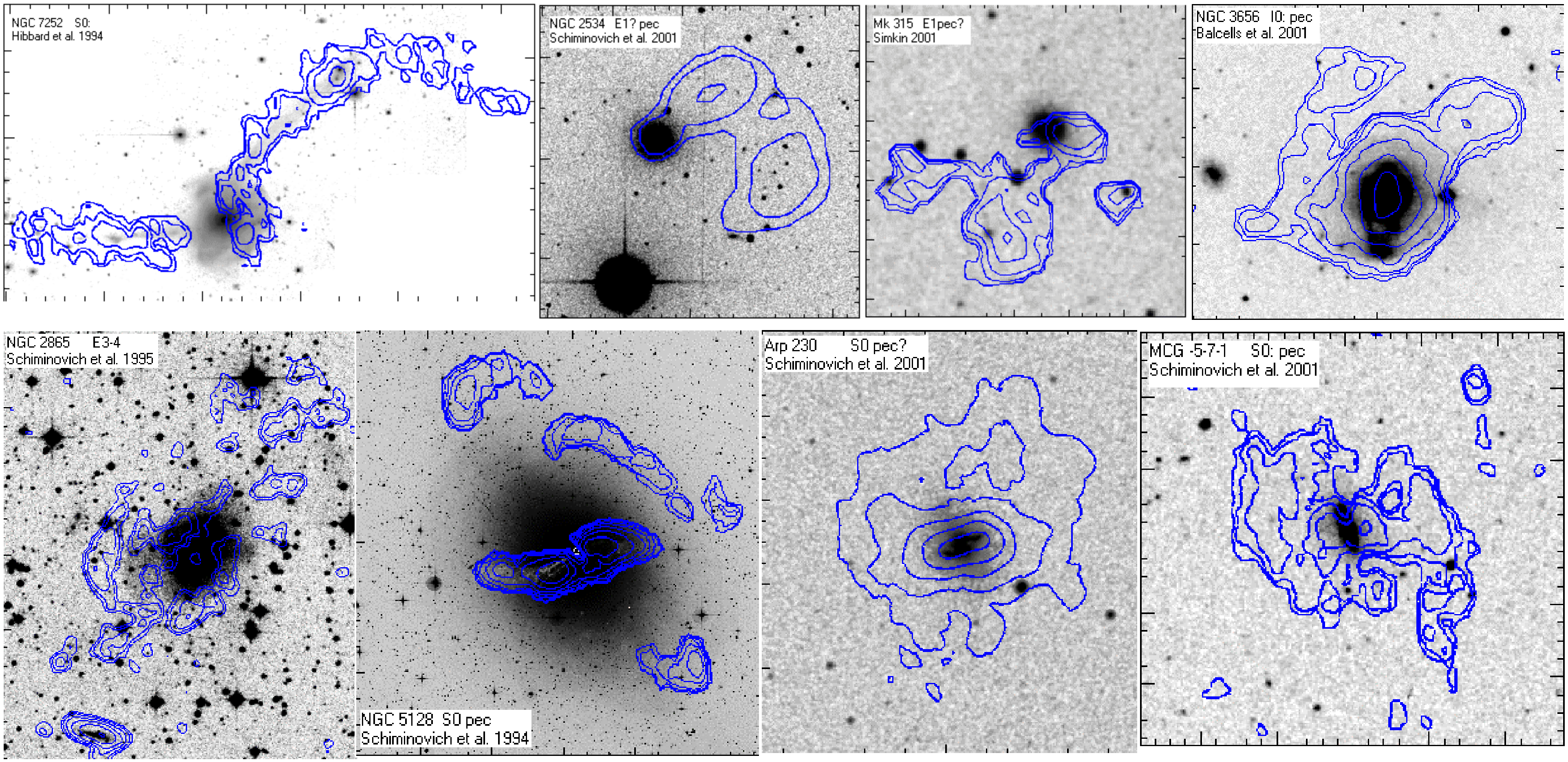
The Gallery

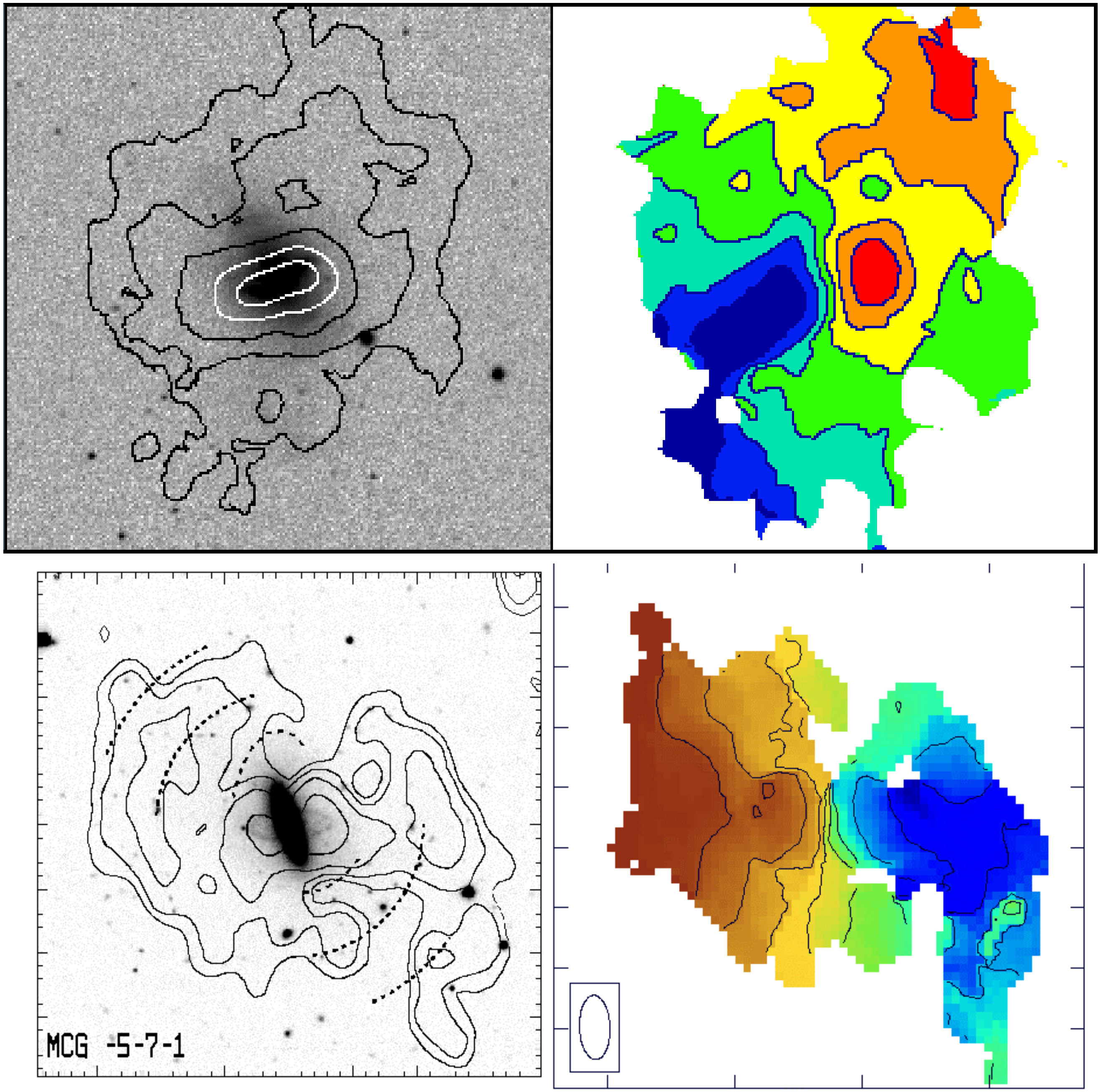
Next Up Previous
Next: Extended HI Envelopes **Up:** An HI Rogues Gallery **Previous:** Acknowledgments

John Hibbard
Tue Sep 18 17:11:04 EDT 2001

Peculiar Early Types with HI within Optical Body

Arranged from Irregular to Regular morphology & kinematics

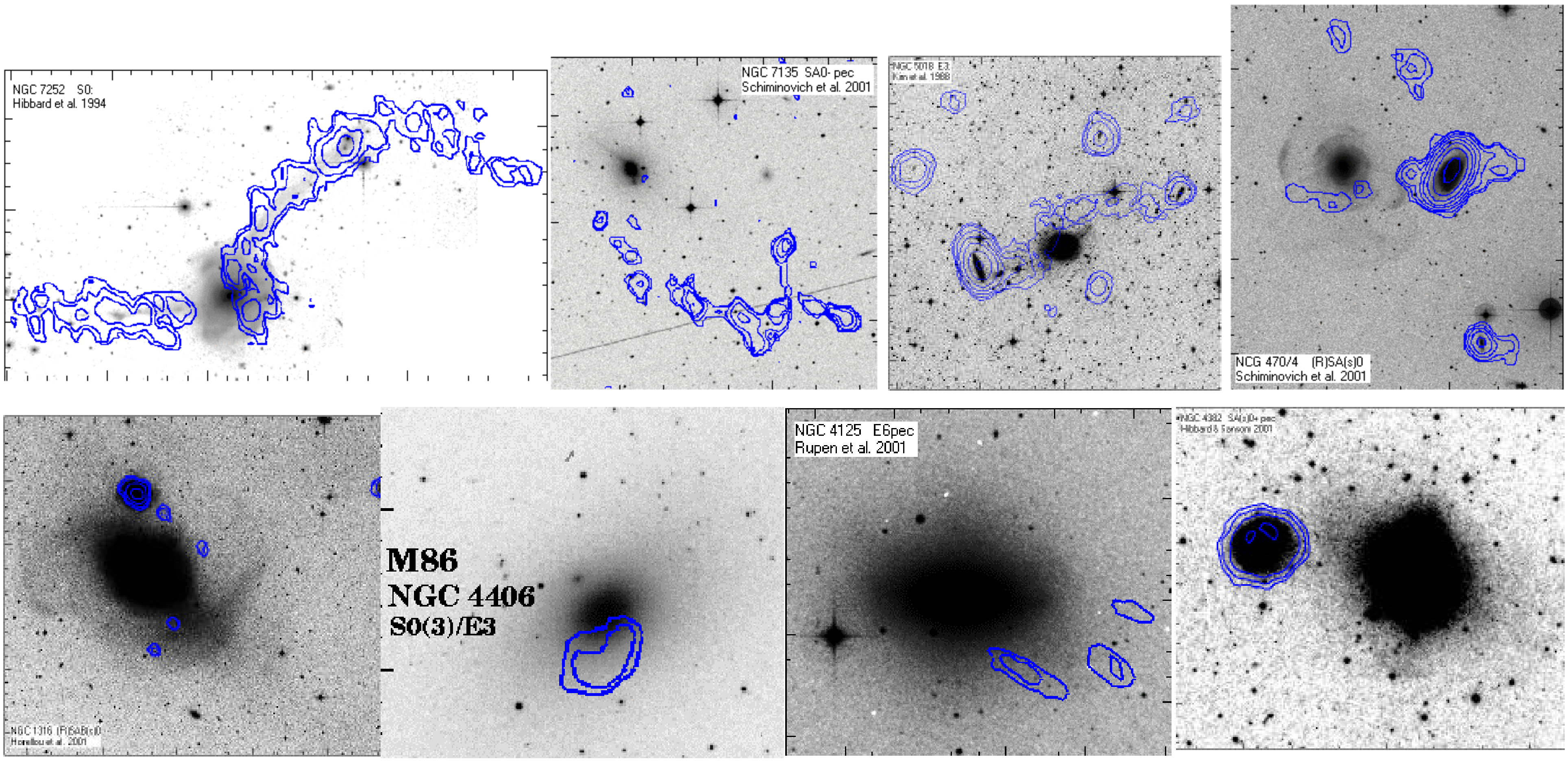




VLA HI Schminovich, van Gorkom & van der Hulst 2001

Peculiar Early Types with HI outside Optical Body

Arranged by decreasing HI content



Evolution of Gas Phases in Merger Remnants: Inconclusive

- Cold and Hot Gas indicators span >2 orders of magnitude in likely progenitors and products
- Trends of Gas Phase for Merger Remnants may depend on other factors
  - Progenitor Types
  - Merger Geometry
  - Environment

Lessons learned from Spectral Line imaging of Galactic Mergers:

- Fraction of Peculiars larger than inferred optically
- Provides dynamical information not otherwise available
- Evolution of merger remnants:
  - Some mergers will evolve into normal E's
  - Unclear whether ULIGs will evolve into peculiar E's
- Still unclear how gas phases and burst populations evolve as remnants age
  - Need to properly identify King Gap objects and empirically measure properties