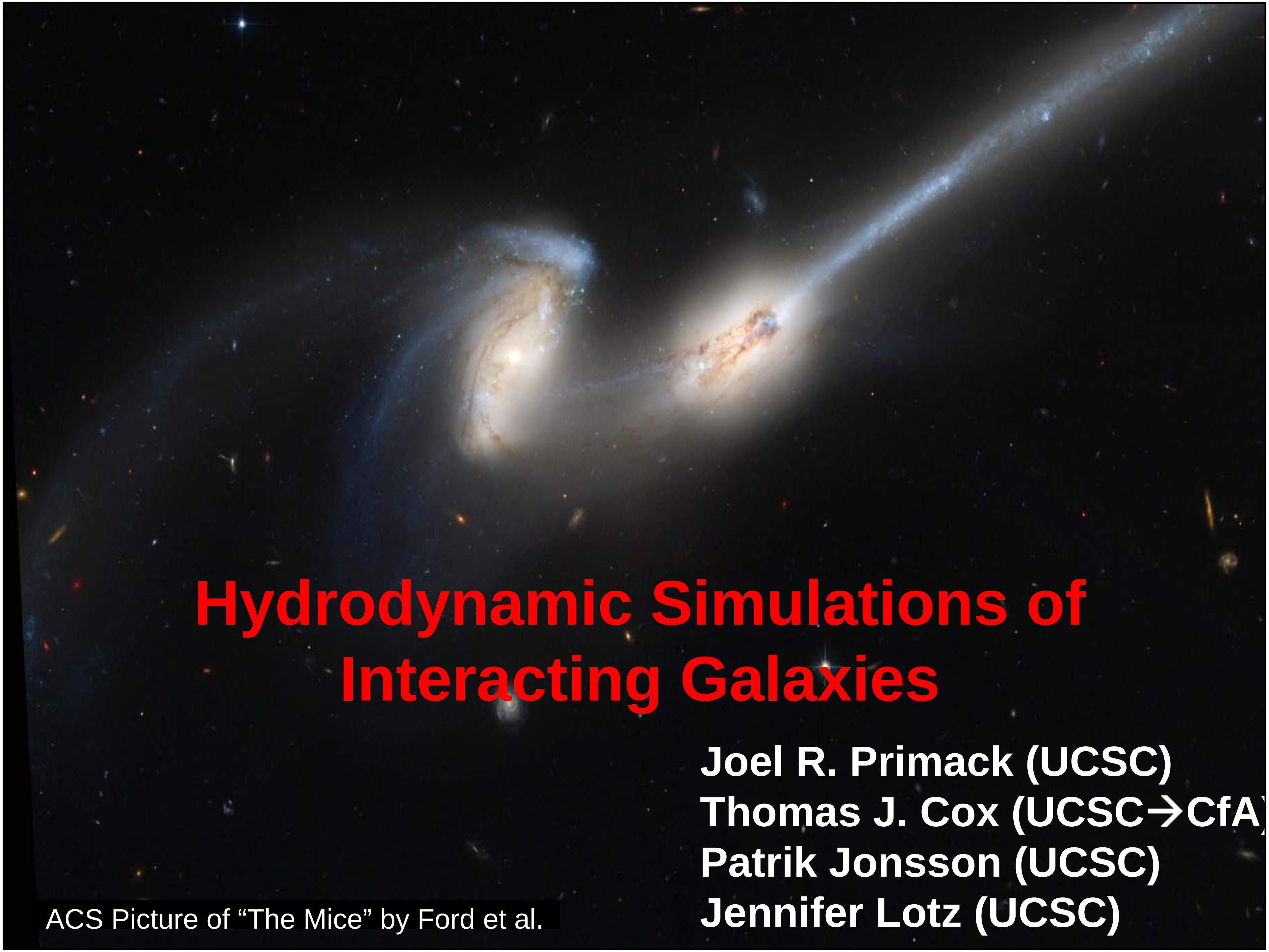


Hydrodynamic Simulations of Interacting Galaxies

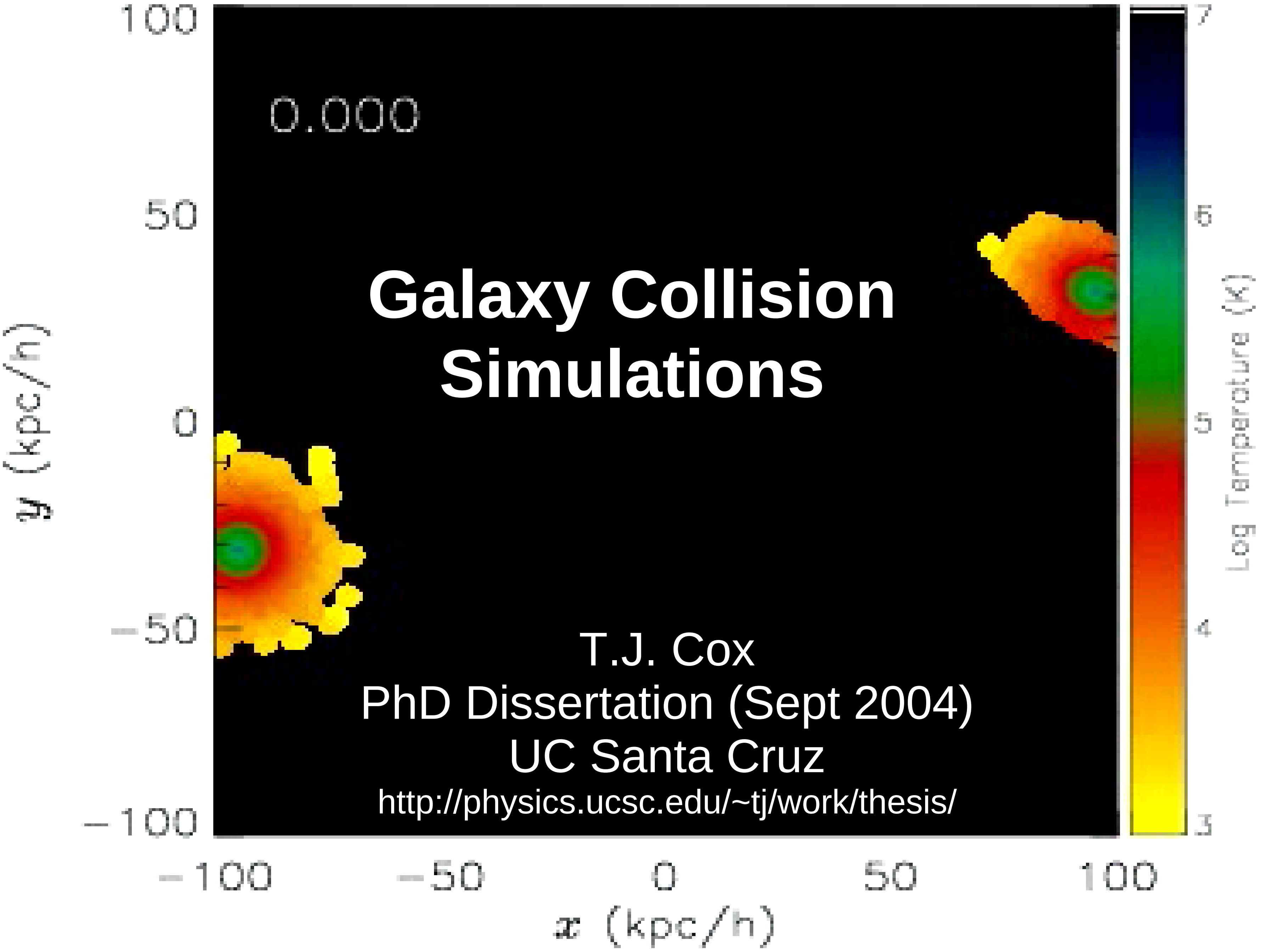
Joel R. Primack (UCSC)
Thomas J. Cox (UCSC→CfA
Patrik Jonsson (UCSC)
Jennifer Lotz (UCSC)

ACS Picture of “The Mice” by Ford et al.

Goals of Galaxy Interaction Simulations

- Understand the amount of star formation due to galaxy mergers TJ Cox PhD thesis Sept 2004
- Study properties of merger remnants TJ Cox
  - → DM/stellar and gas distributions
  - → Angular momenta
- Predict appearance of interacting galaxies throughout merger, including dust scattering, absorption, and reradiation Patrik Jonsson PhD thesis Sept 2004

Statistically compare to observations (ACS, SIRTF, GALEX, DEEP2, GOODS) Jennifer Lotz Piero Madau, and Rachel Somerville



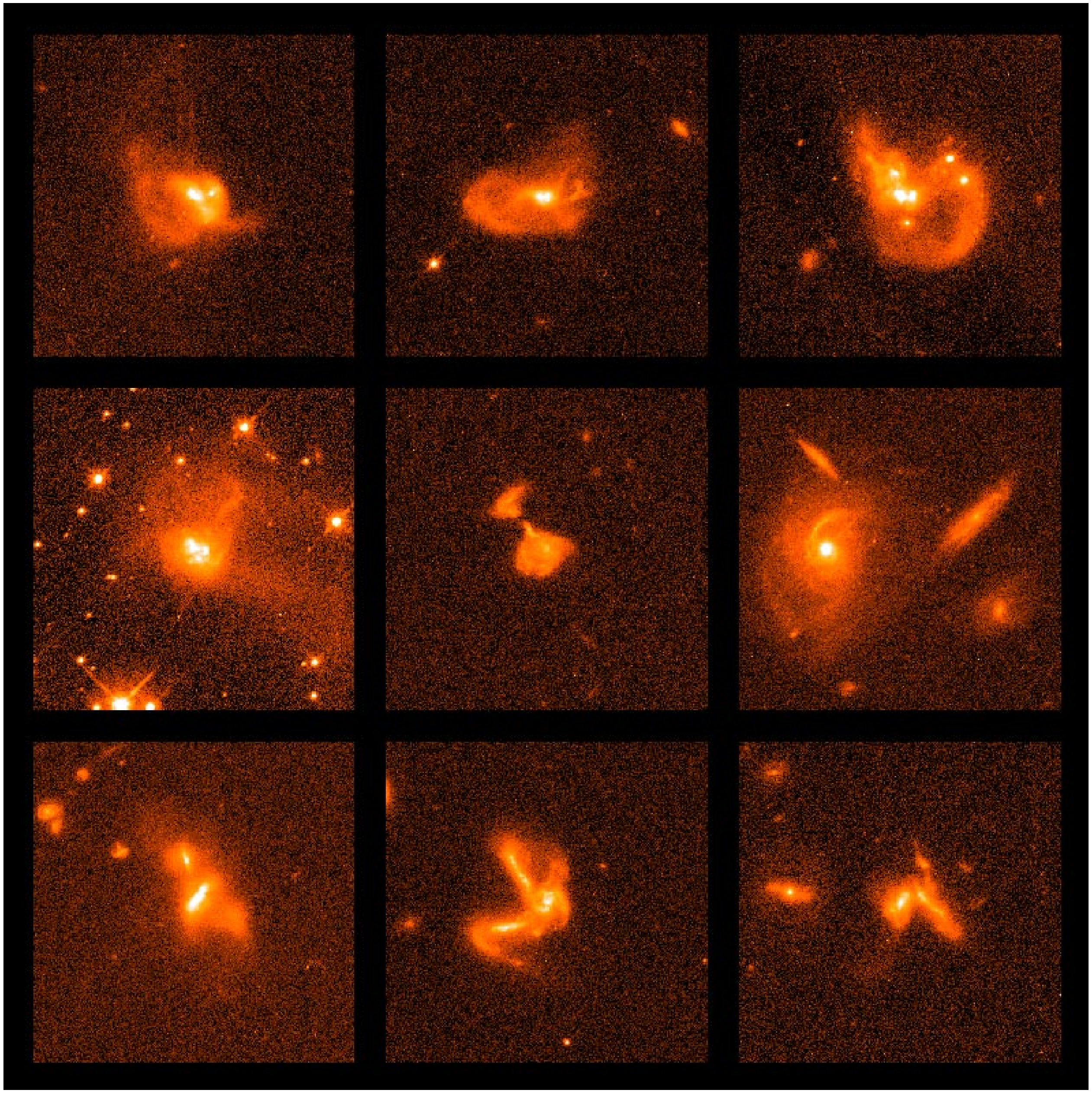
Galaxy Collision Simulations

T.J. Cox

PhD Dissertation (Sept 2004)

UC Santa Cruz

http://physics.ucsc.edu/~tj/work/thesis/



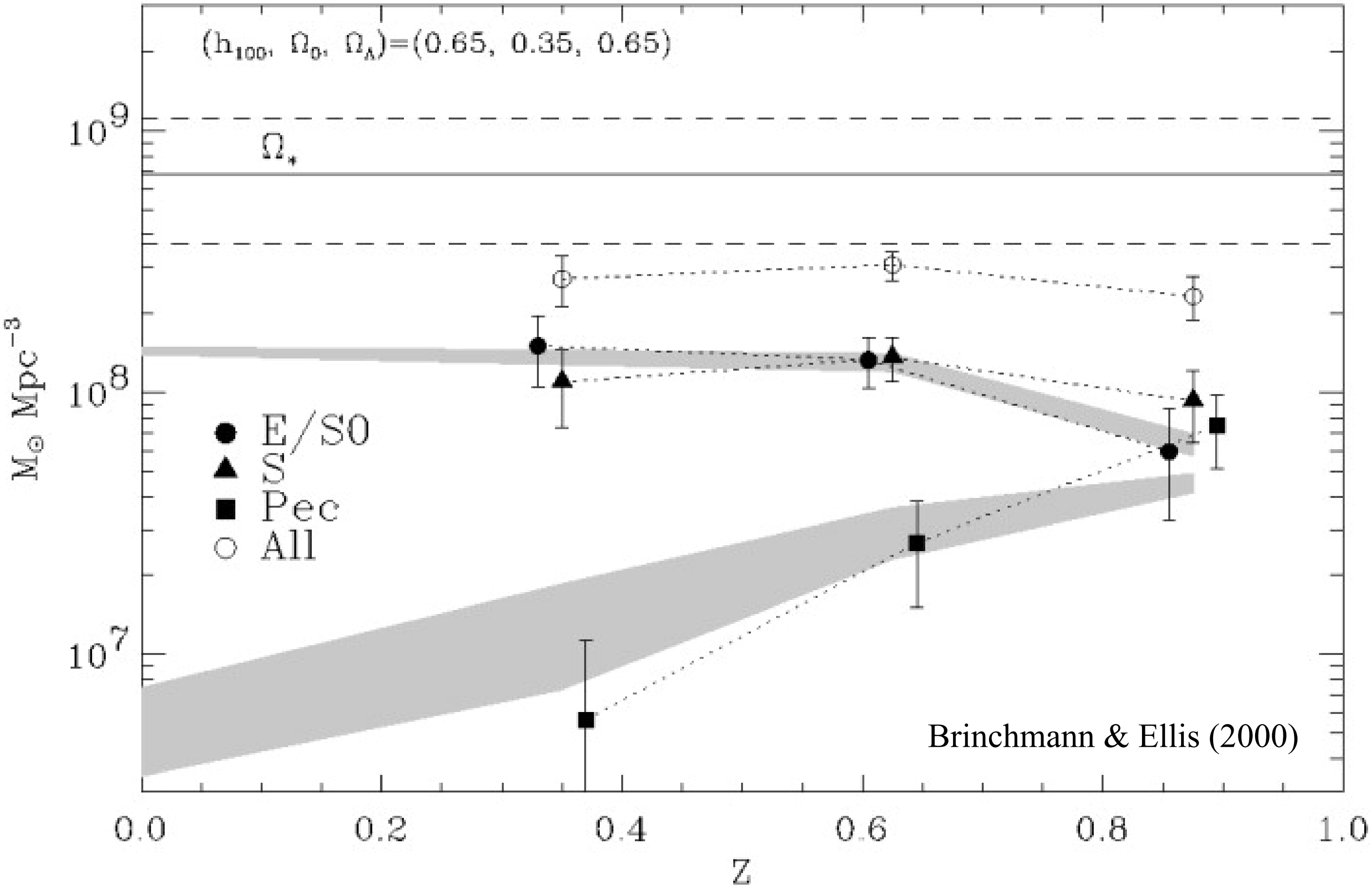
Ultra-Luminous IR Galaxies (ULIRGs) are the most prodigious star forming (>100 $M_\odot$/yr) galaxies in the local universe.

Many (arguably all) show signs of multiple nuclei, tidal features, or are visibly several galaxies involved in a “train wreck”!

Borne et al. (2000)

Cosmological Connections

1) The fraction of merging/peculiar galaxies is found to increase to z~1 (Brinchmann & Ellis 2000, Conselice et al. 2003), consistent with measurements of the galaxy pair fraction (Zepf & Koo 1989, Le Fevre et al. 2000, Patton et al. 2002, Bundy et al. 2004, but see Lin et al. 2004).

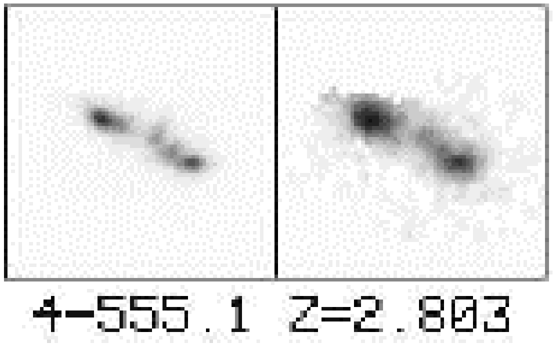


Brinchmann & Ellis (2000)

Cosmological Connections

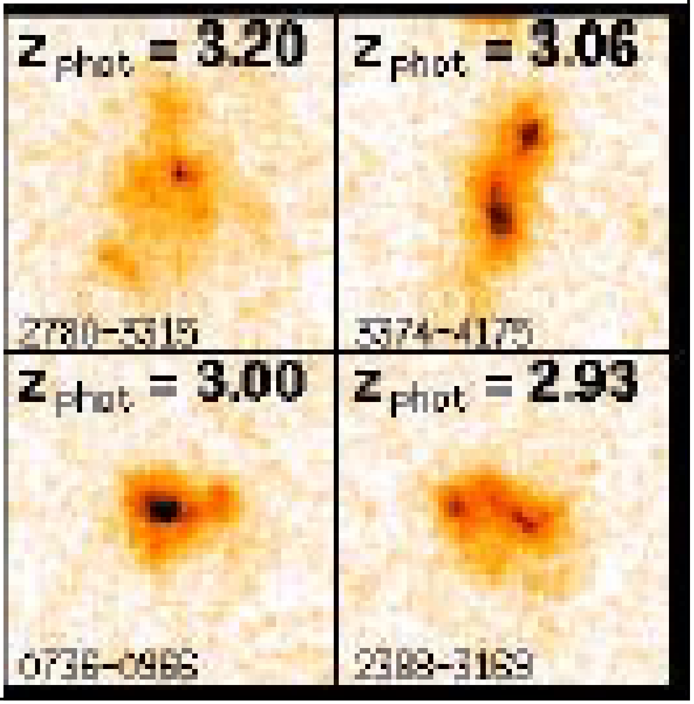
1) The fraction of merging/peculiar galaxies is found to increase to z~1 (Brinchmann & Ellis 2000, Conselice et al. 2003), consistent with measurements of the galaxy pair fraction (Zepf & Koo 1989, Le Fevre et al. 2000, Patton et al. 2002, Bundy et al. 2004, Lin et al. 2004).

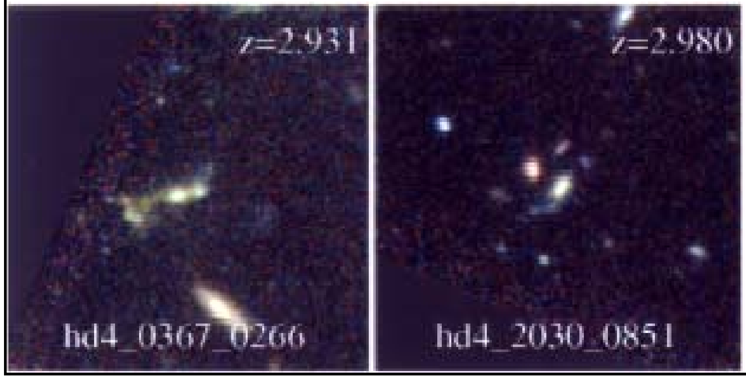
2) There are many high redshift merger candidates (LBGs and SCUBA galaxies) which appear to be actively forming stars.



Dickinson (2000)

Moller et al. (2002)

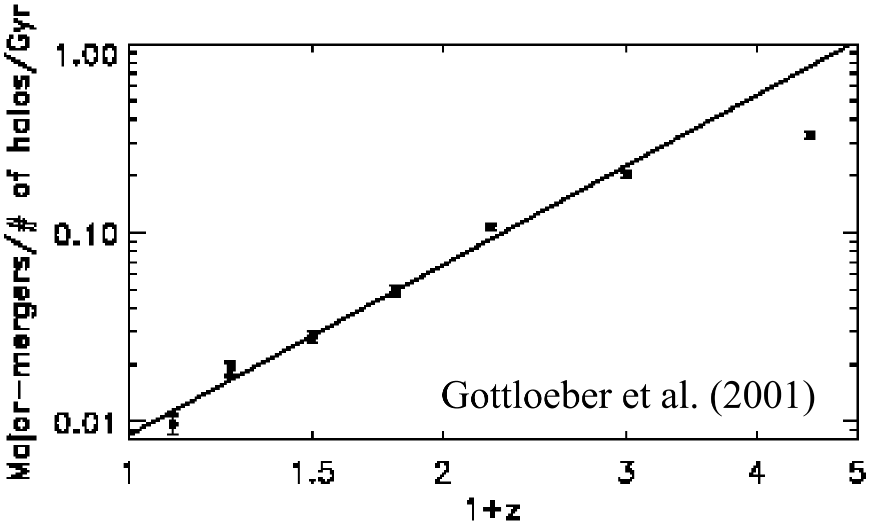




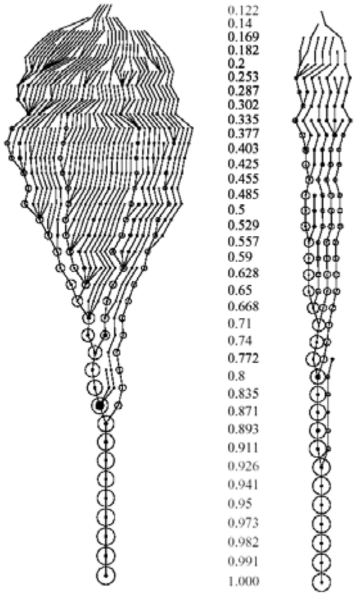
Lowenthal et al. (1997)

Cosmological Connections

1) The fraction of merging/peculiar galaxies is found to increase to z~1 (Brinchmann & Ellis 2000, Conselice et al. 2003), consistent with measurements of the galaxy pair fraction.
2) There are many high-z merger candidates (LBGs, SCUBA galaxies) which appear to be actively forming stars.
3) It is intriguing that item 1 (above) is consistent with the concordant CDM cosmology, where structure forms hierarchically and the dark matter halo merger rate increases with redshift (Kolatt et al. 1999, Khochfar & Burkert 2001, Gottloeber et al. 2001).

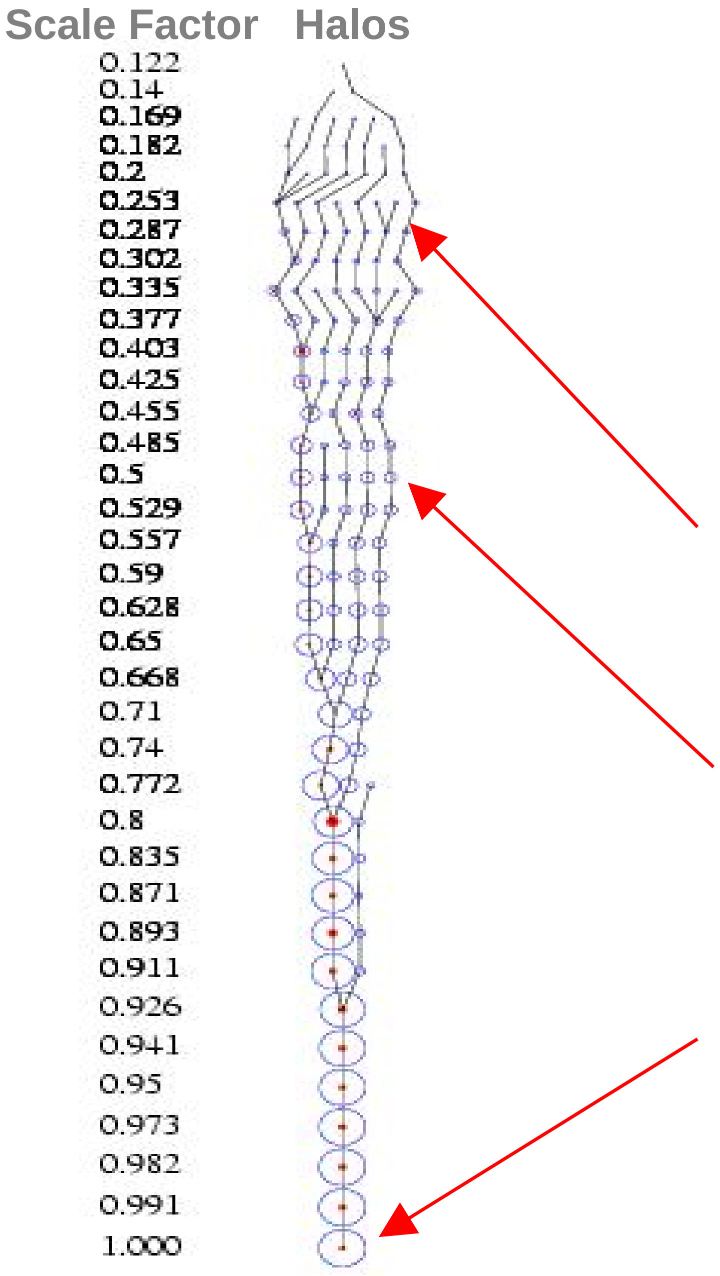


Gottloeber et al. (2001)



Pictorial representation of dark matter accretion history by Wechsler et al. (2002)

ΛCDM merging halos



Within the currently favored cosmology (LCDM), structure forms hierarchically. Dark matter halos (and presumably the galaxies they host) are built by a series of discrete merging events.

- ***Z=3***

  Major progenitor: 3.9 x 10^{11} $M_\odot$

  12 distinct halos (> 2.2 x 10^{10} $M_\odot$)

- ***Z=1***

  Major progenitor: 1.5 x 10^{12} $M_\odot$

  6 distinct halos (> 2.2 x 10^{10} $M_\odot$)

- ***Z=0***

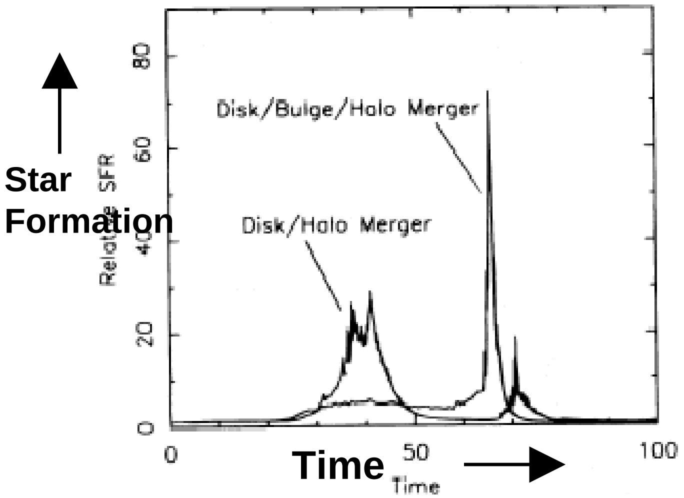
  1 Galaxy size halo, Mass=2.9 x 10^{12} $M_\odot$

Wechsler et al. 2002, based on her UCSC PhD dissertation

Cosmological Connections

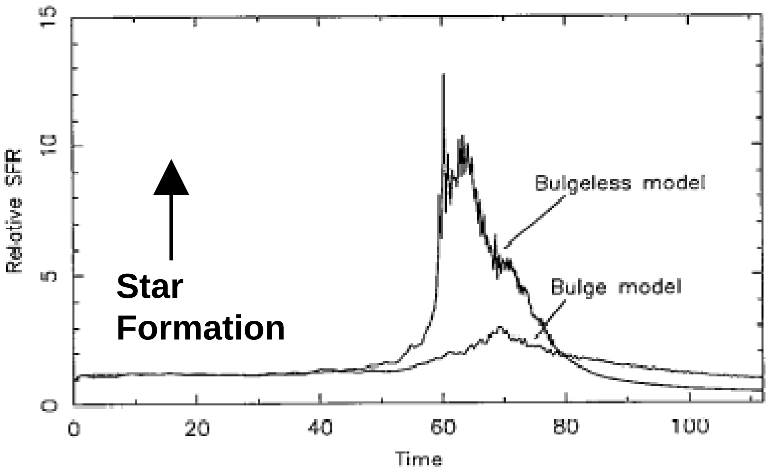
1) The fraction of merging/peculiar galaxies is found to increase to z~1 (Brinchmann & Ellis 2000, Conselice et al. 2003), consistent with measurements of the galaxy pair fraction.
2) There are many high redshift merger candidates (LBG's and SCUBA galaxies) which appear to be actively forming stars.
3) It is intriguing that item 1 (above) is consistent with the concordant CDM cosmology, where structure forms hierarchically and the dark matter halo merger rate increases with redshift (Kolatt et al. 1999, Khochfar & Burkert 2001, Gottloeber et al. 2001).
4) Lastly, mergers are suspected to transform rotationally supported spiral galaxies into spheroids and hence may play a crucial role in shaping (or reshaping) galaxies – in other words, the Hubble sequence may be a merger sequence. (Toomre & Toomre 1972, Toomre 1977, Barnes & Henquist 1991, Hernquist 1992, Mihos & Hernquist 1996, Barnes & Henquist 1996, Bekki & Shioya 1997, Dantas et al. 2003, Naab & Burkert 2003, + many others)

Numerical Simulations of Star Formation in Colliding Disk Galaxies: Earlier Work



- Major mergers (Mihos & Hernquist 1996, Springel 2000) (original disks are identical) generate significant bursts of star formation consuming ~80% of the original gas mass.
- Internal structure of progenitor disk galaxy (bulge or not) dictates when the gas is funneled to the center and turned into stars.

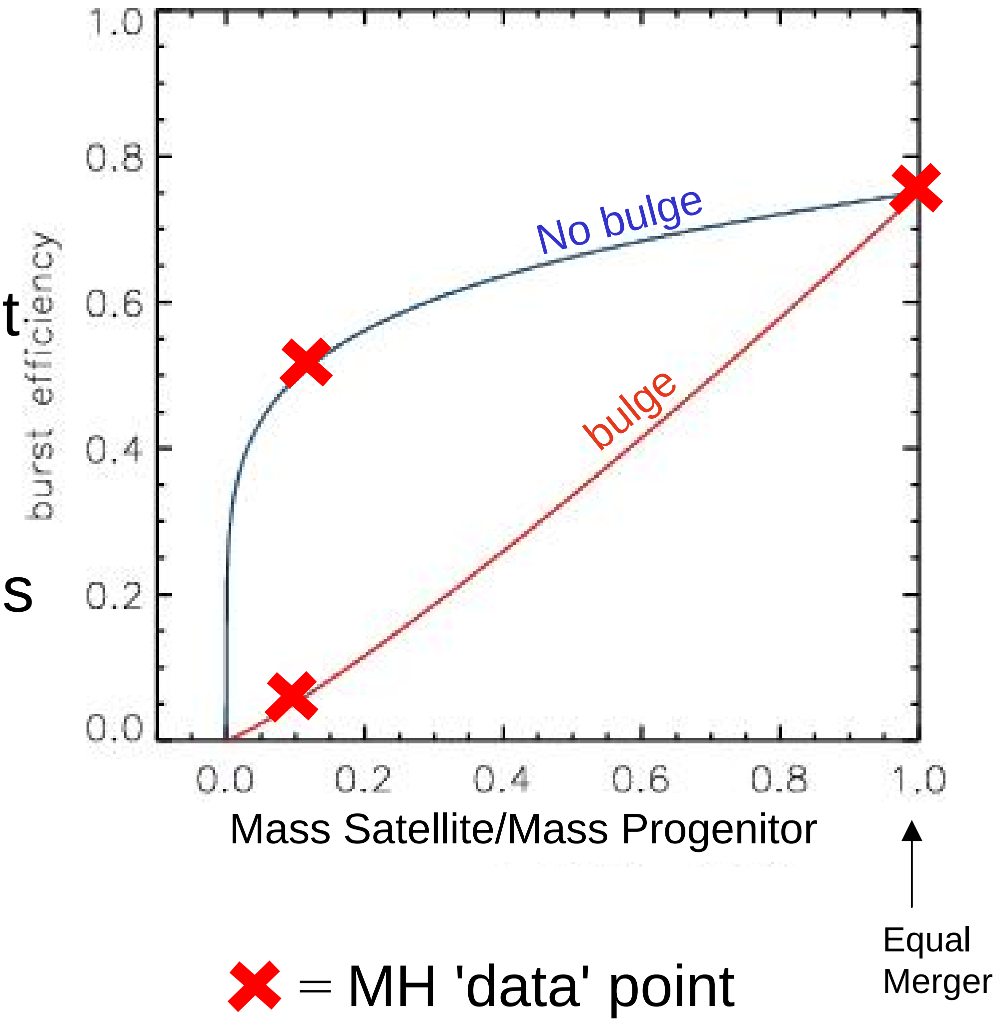
- Minor mergers (Mihos & Hernquist 1994) (satellite galaxy is 10% of the original disk mass) generate significant bursts of star formation only when there is no bulge in progenitor disk galaxy.



NOTE: These simulations used a version of SPH which has been shown not to conserve entropy (Springel & Hernquist 2002).

Parameterizing Starbursts

Based upon the results of Mihos & Hernquist (the 3 ‘data’ points), Somerville, Primack & Faber (2001, SPF01) estimated the burst efficiency (amount of gas converted to stars due to the galaxy merger) as a function of the merger mass ratio. A motivation of the present work is to improve the statistics and understanding of mergers.



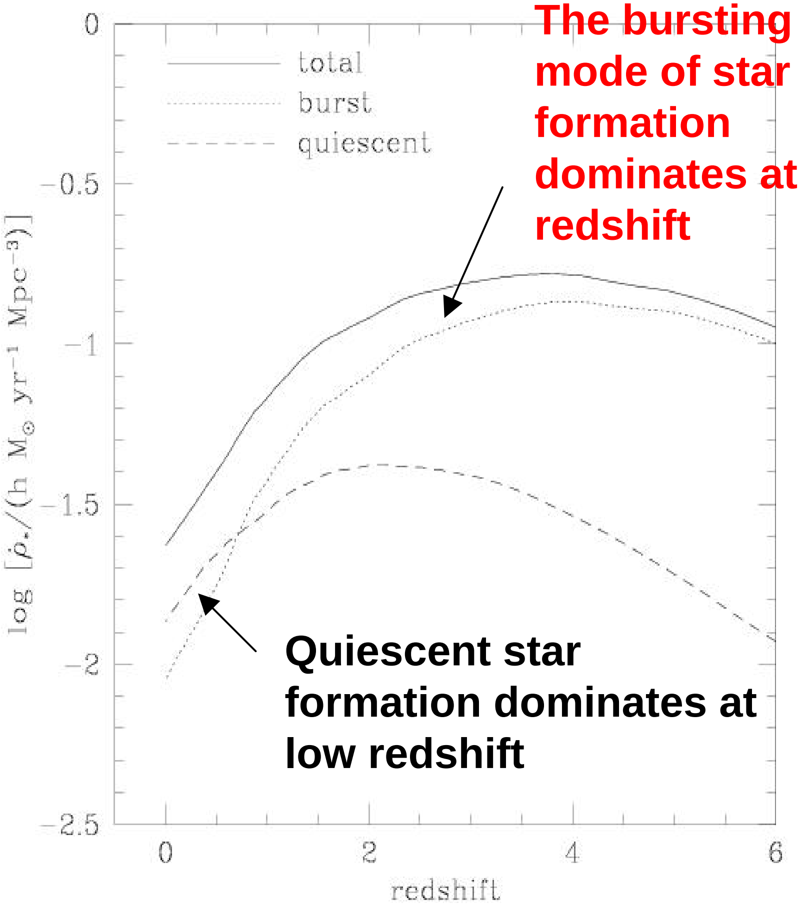
Cosmological Semi-Analytic Models (SAMs)

Feeding the parameterized starbursts into semi-analytic models for galaxy formation, SPF01 found this model (as opposed to models without collisional starbursts) better fit data for:

1) Co-moving number density of galaxies at $z > 2$

2) Luminosity function at $z = 3$ (and more recently the star formation rate to $z = 6$)

The majority of stars were generated by star formation induced by galaxy mergers.

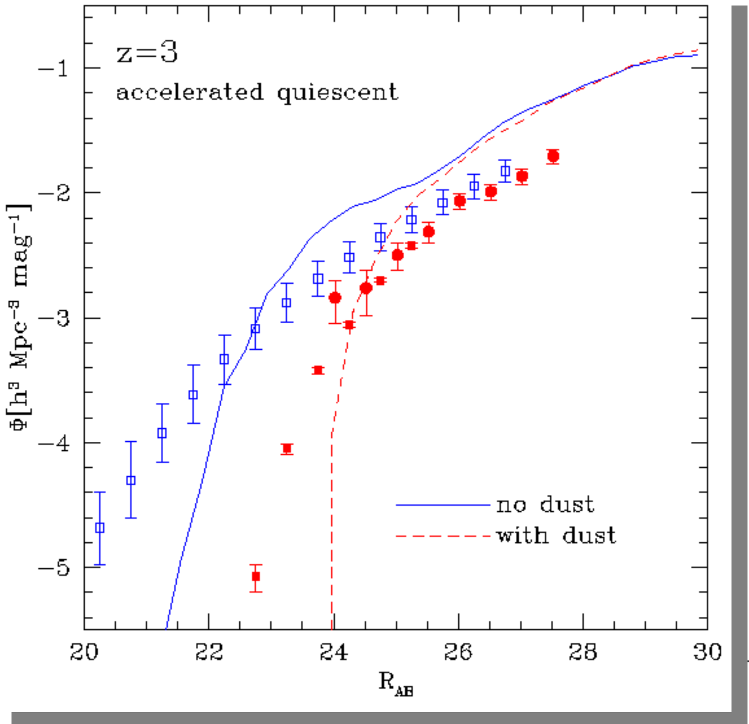


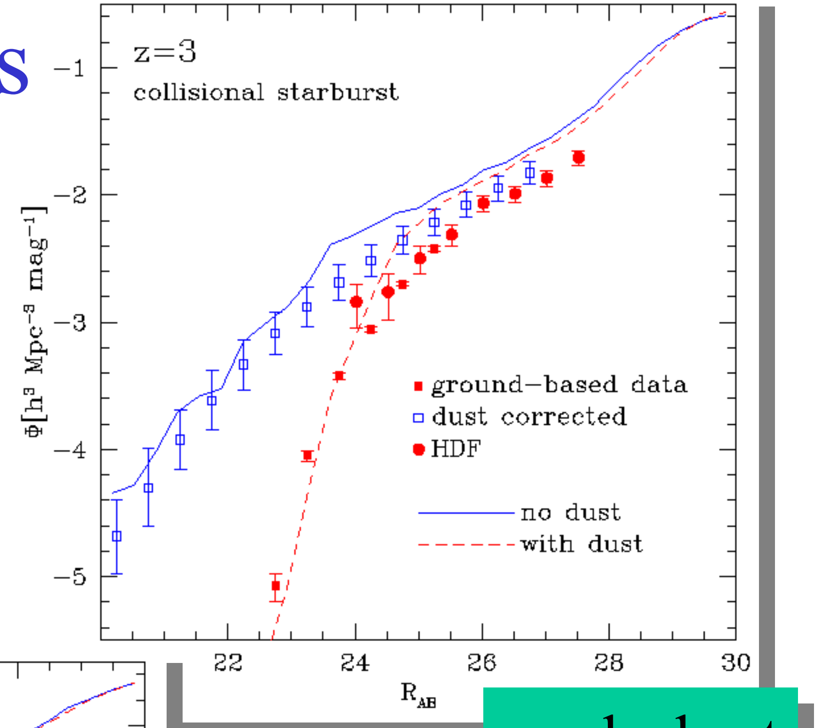
The bursting mode of star formation dominates at high redshift

Quiescent star formation dominates at low redshift

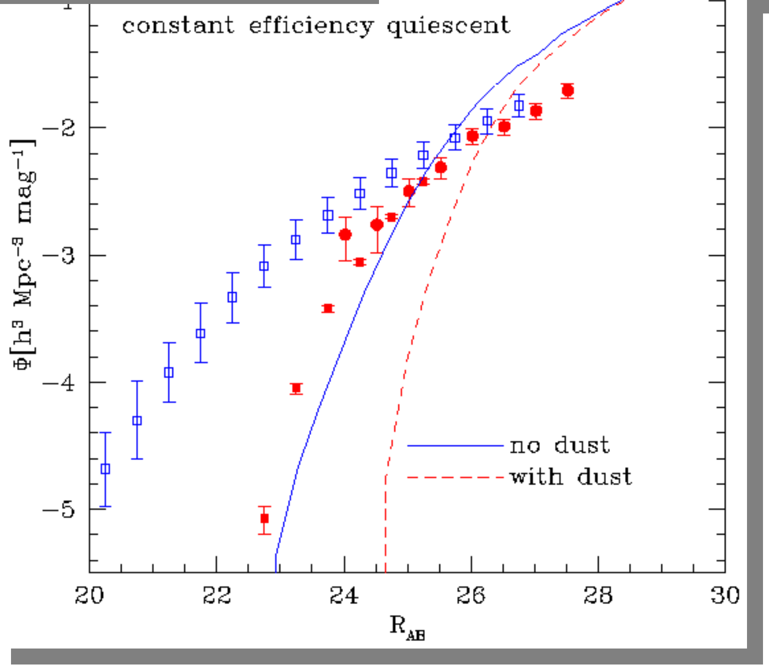
Note: this is redshift, not time!

LBGs





works best



Lyman Break Galaxies are selected by their colors to be at z~3

Somerville, Primack & Faber 2001(SPF01)

Our New Work

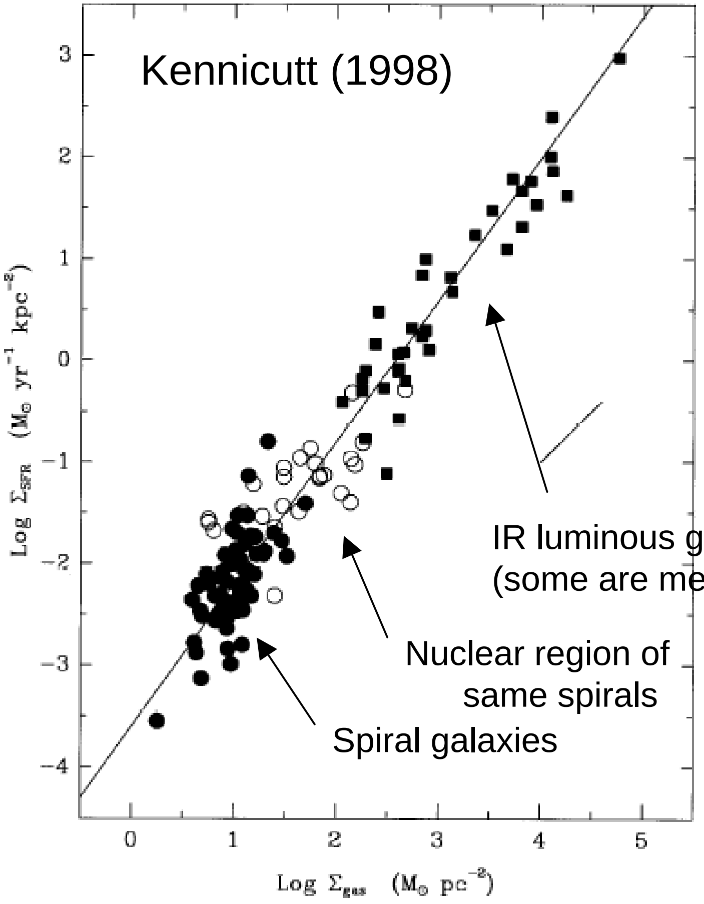
In order to investigate galaxy mergers (and interactions) we build observationally motivated N-body realizations of compound galaxies and simulate their merger using the SPH code GADGET (Springel, Yoshida & White 2000). These simulations include:

- An improved version of smooth particle hydrodynamics (SPH) which explicitly conserves both energy and entropy (Springel & Hernquist 2002).
- The radiative cooling of gas (H and He)
- Star formation: $\rho_{sfr} \sim \rho_{gas}/\tau_{dyn}$ for $(\rho_{gas} > \rho_{threshold})$
- Metal Enrichment
- Stellar Feedback

Our simulations contain > 100,000 particles per galaxy and the resolution is typically ~100 pc

Selecting Parameters

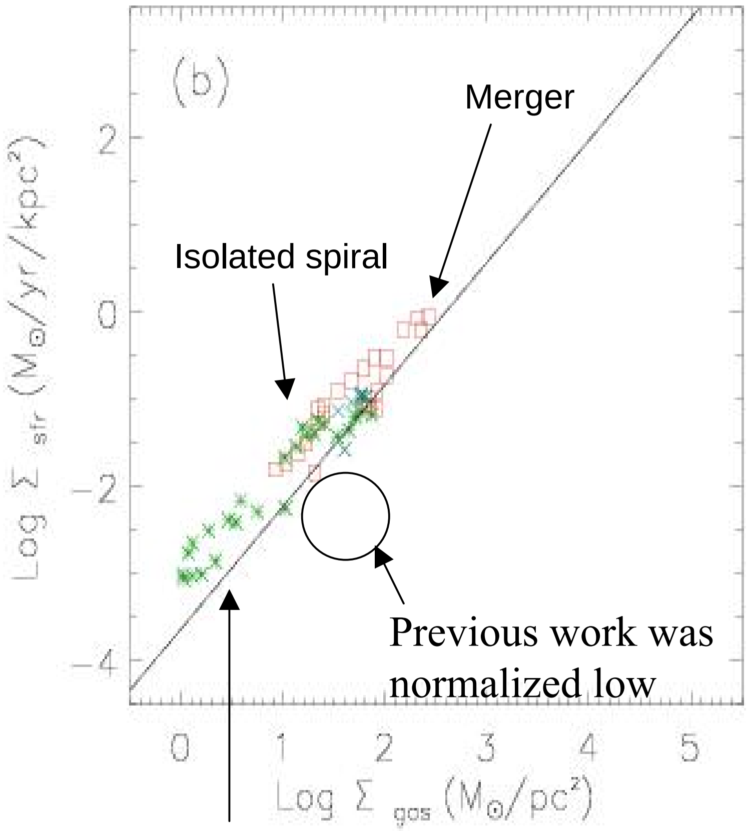
Kennicutt (1998) determined that the surface density of star formation was very tightly correlated with the surface density of gas over a remarkable wide range of gas densities and in a wide variety of galactic states. We use this ‘law’ to calibrate our star formation ($c_\star$) and feedback (β) parameters by requiring an isolated disk to follow the Kennicutt law.



IR luminous galaxies (some are mergers)

Nuclear region of same spirals

Spiral galaxies



Merger

Isolated spiral

Previous work was normalized low

Galaxies tend to fall off the law once gas is depleted.

Initial Conditions

The orbits and initial conditions for our galaxy merger simulations are motivated by cosmological simulations.

Galaxies

- NFW Dark Matter Halo (M_{vir}, c, l)
- Exponential disk (m_d, gas fraction f, R_d)
- Bulge (m_b, r_b)

Orbits

- Galaxies are placed on an orbit defined by the initial separation R_{start}, their impact parameter b, the eccentricity e, and disks may be inclined with respect to the orbital plane

Feedback

- Supernova feedback (pressurizes star forming regions) similar to Springel (2000)

Disk Galaxy Models

- **The Milky Way** + Mass Excursions (40+ Major Mergers)

  A large, *low gas fraction* galaxy has been the starting point for the majority of all previous merger simulations (MH94-96, Springel 2000, and our early work).

  The mass excursions have a higher gas fraction (50%).

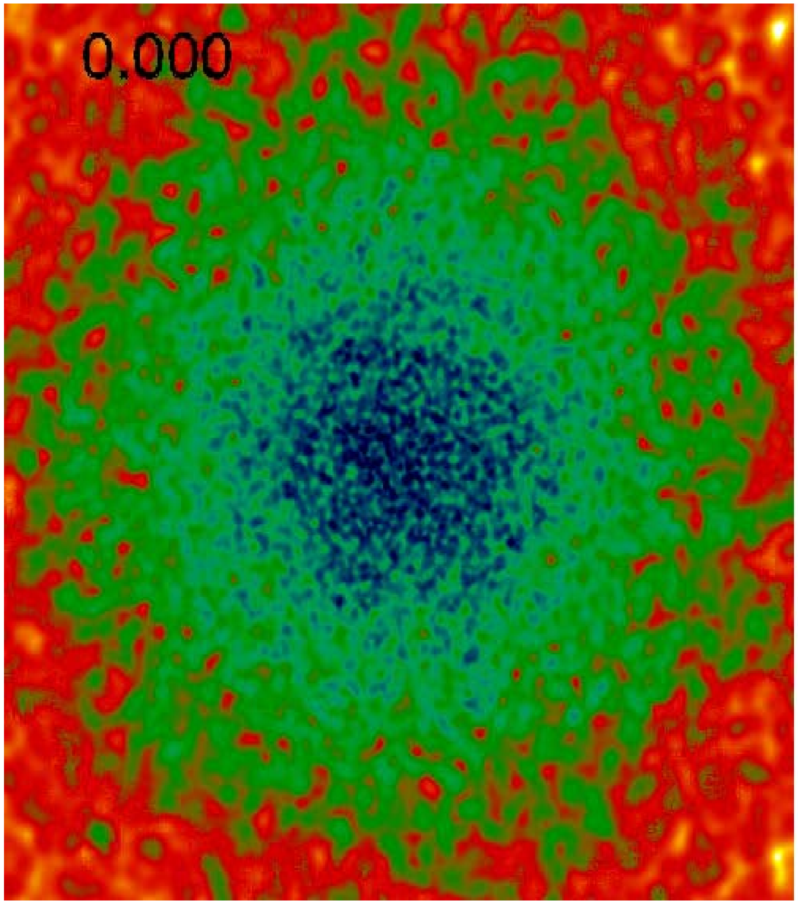
- **Sbc/Sc models** (50+ Major Mergers)

  Built to model the observed properties (Roberts & Haynes 1994) of local Sbc/Sc galaxies. While (roughly) the same size as the Milky way these models have a large amount of extended gas. Sc has a no bulge and Sbc has a small bulge.

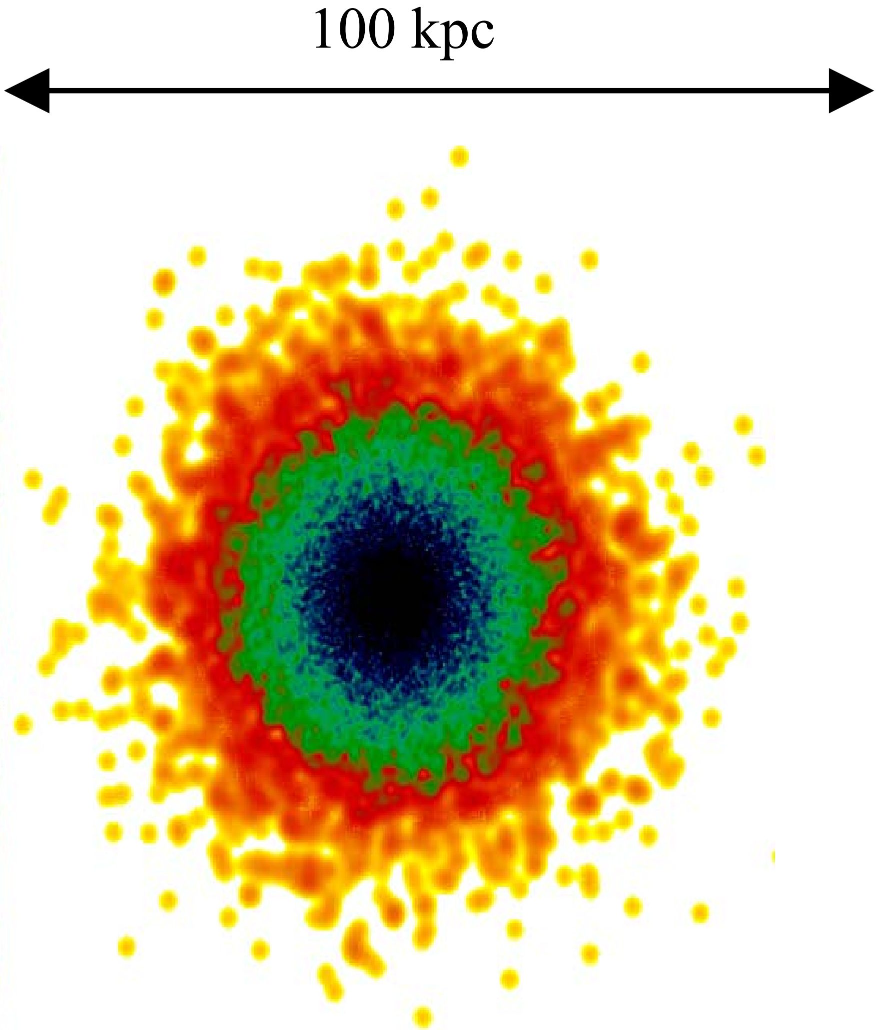
- **G models** (13 Major Mergers, 18 Minor Mergers)

  There are 4 G galaxies (G3,G2,G1,G0, ordered by mass) which are statistically average galaxies whose properties are extracted from SDSS plus other local late-type galaxy surveys. The dark mass and concentration are constrained to match the baryonic TF relation.

Stable Disk

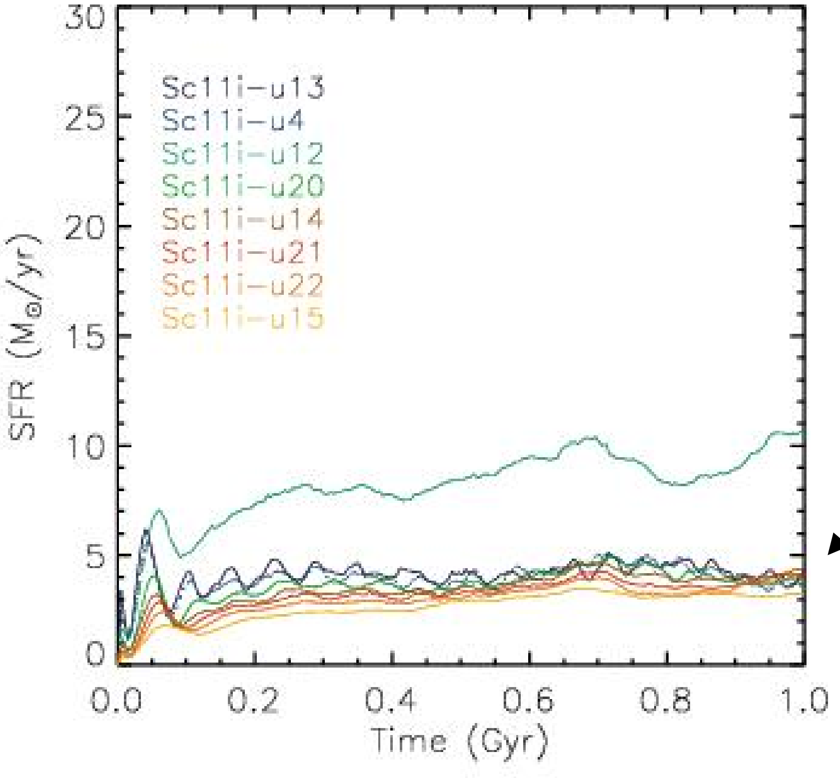


Gas



Stars

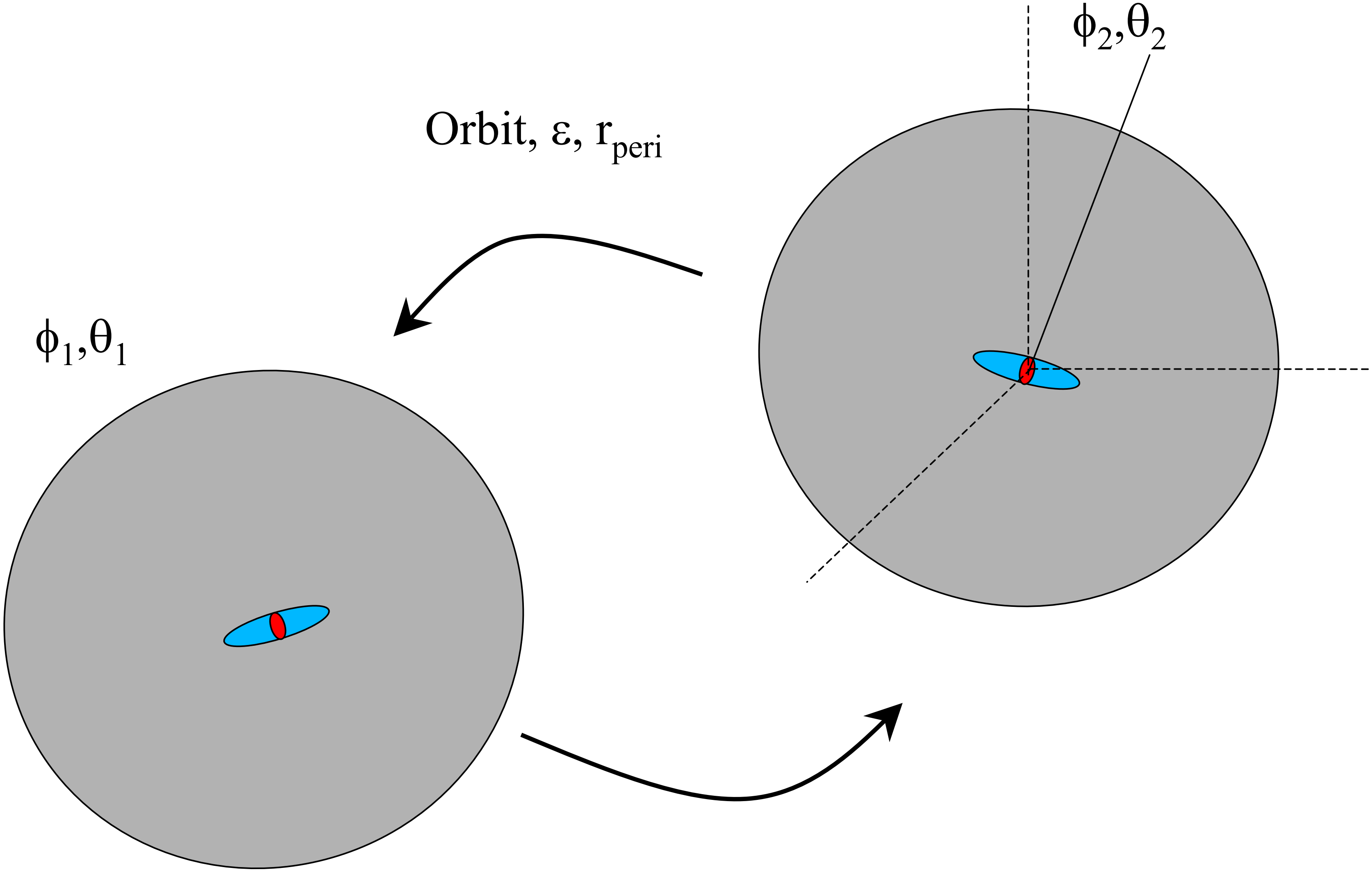
The Star Formation Rate (SFR)



The SFR is roughly constant, as is observed in most "normal" spiral galaxies – GOOD!

➔ We can produce and simulate stable disk galaxies.

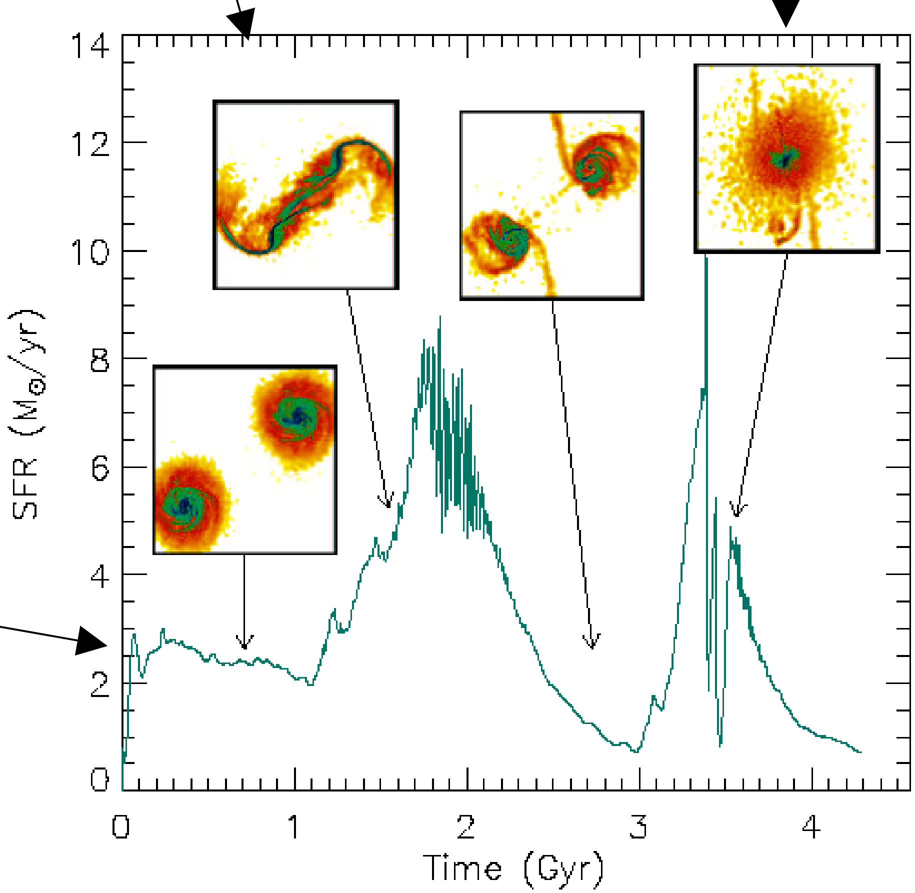
Now Let’s Merge Two Disks



Major Merger Morphology and Resulting Star Formation

1st encounter

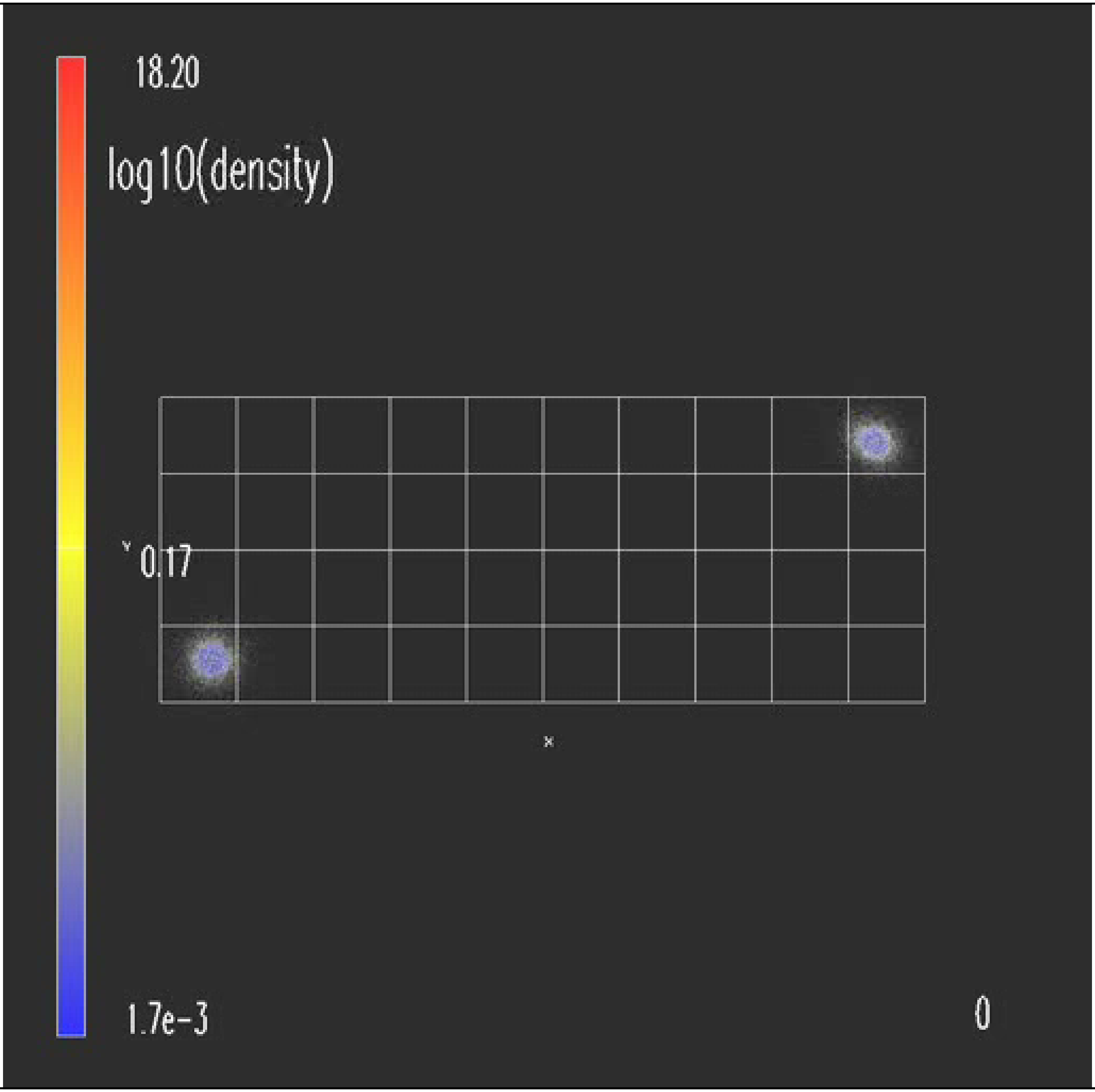
Final merger



Initially,
SFR ~ 2x(disk's
quiescent rate)

Prograde
parabolic
orbit, initial
separation
250 kpc,
pericentric
distance 7
kpc

Gas
Particles
color-
coded by
density



Simulations

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1 Run = 1,500 Processor Hours (low-resolution)
12,000 Processor Hours (high-resolution)

(Note: 1 Year = 8760 Hours)

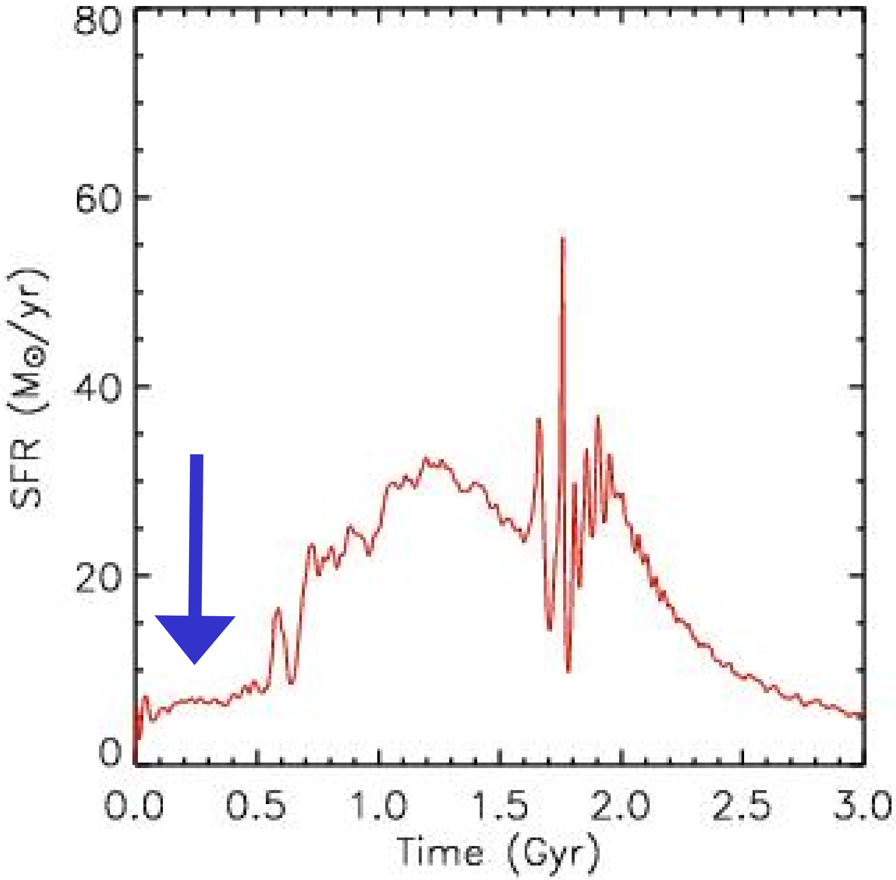
Massively Parallel Computers (Supercomputers) make this possible:

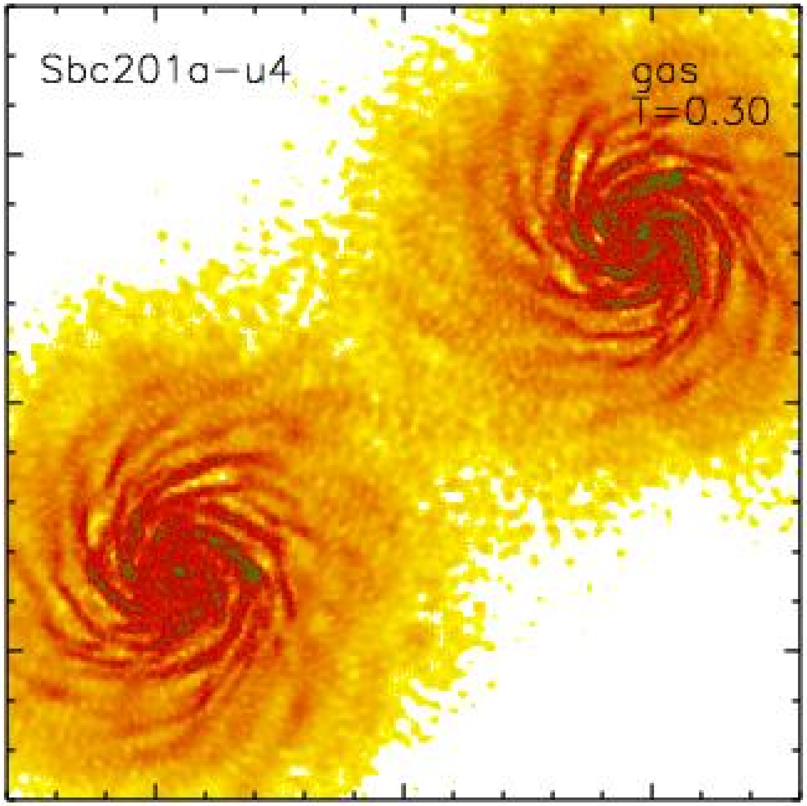
Our simulations have used the following resources:
* National Energy Research Scientific Computing Center (NERSC) computer Seaborg at LBL which has a 6,656 IBM SP3 processors, and 1-4 Gb RAM/processor
* The beowulf UpsAnd at UCSC which has 264 1.4 GHz Athlon processors, 0.5 Gb RAM/processor, and Gbyte interconnections

Simulations so far …

113 Isolated Galaxy Simulations (low resolution)
120 Major Merger Simulations (low)
23 Minor Merger Simulations (low)
4 Isolated Galaxy Simulations (high)
4 Major Merger Simulations (high)

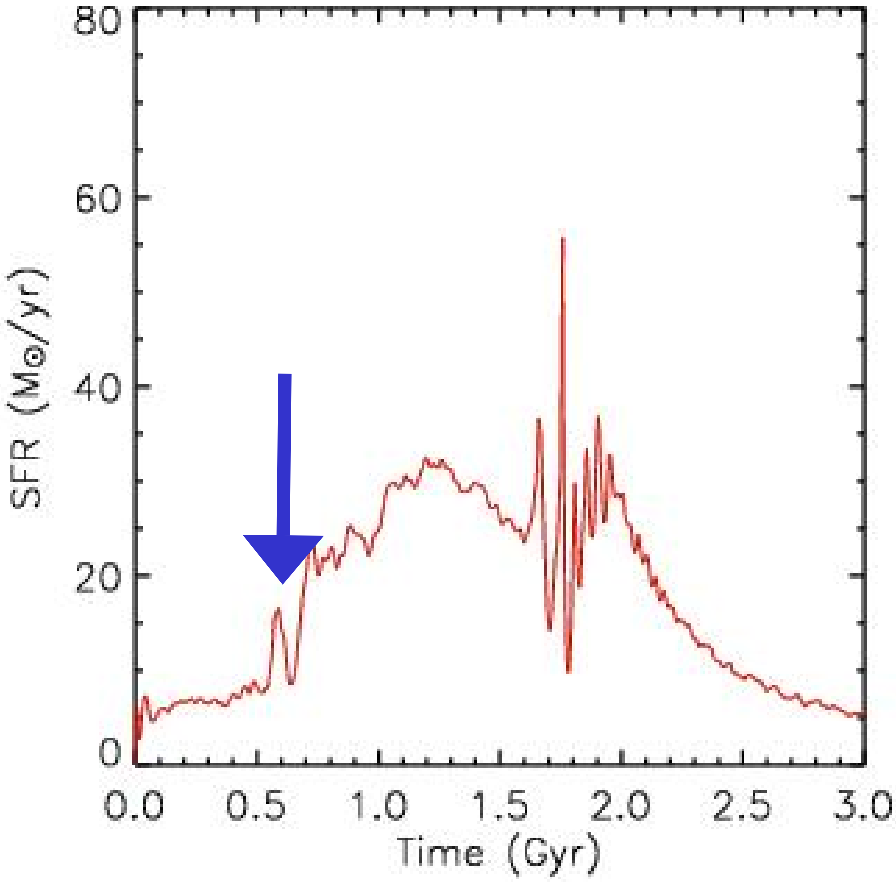
Star Formation History: pre-first passage

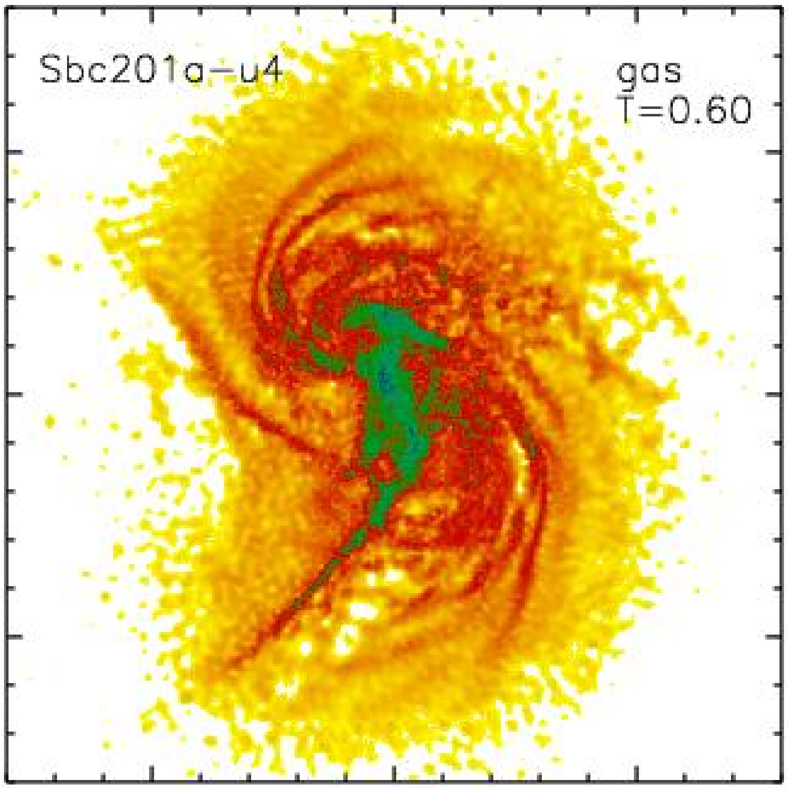




Projected gas density ~green (or darker) is star forming gas

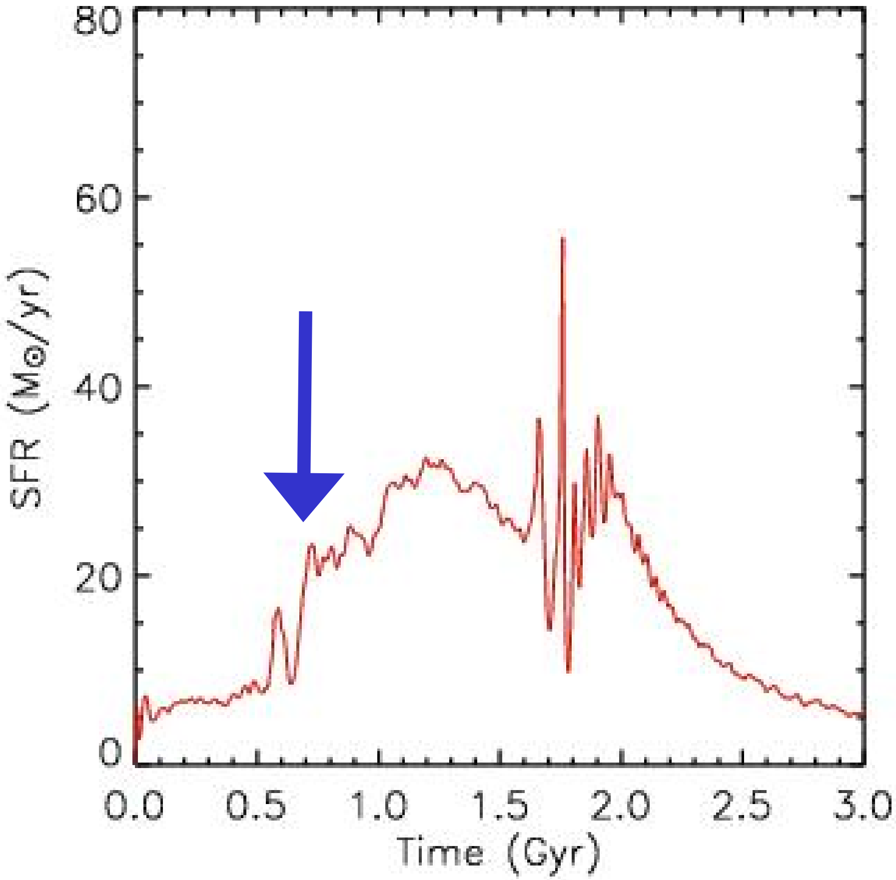
Star Formation History: first passage

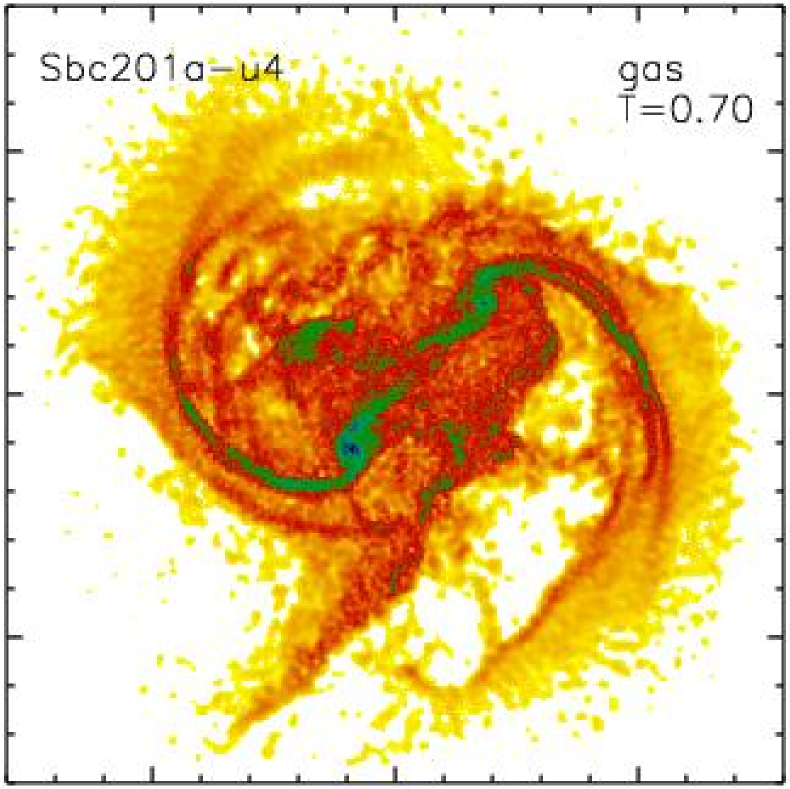




Projected gas density ~green (or darker) is star forming gas

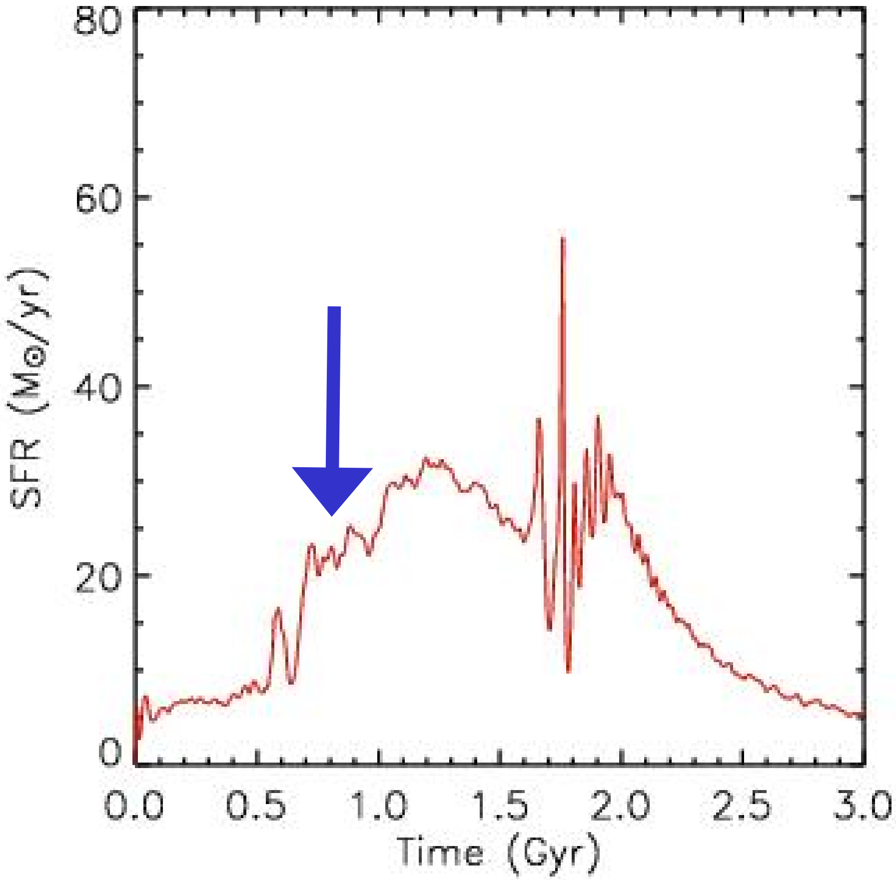
Star Formation History: first passage (2)

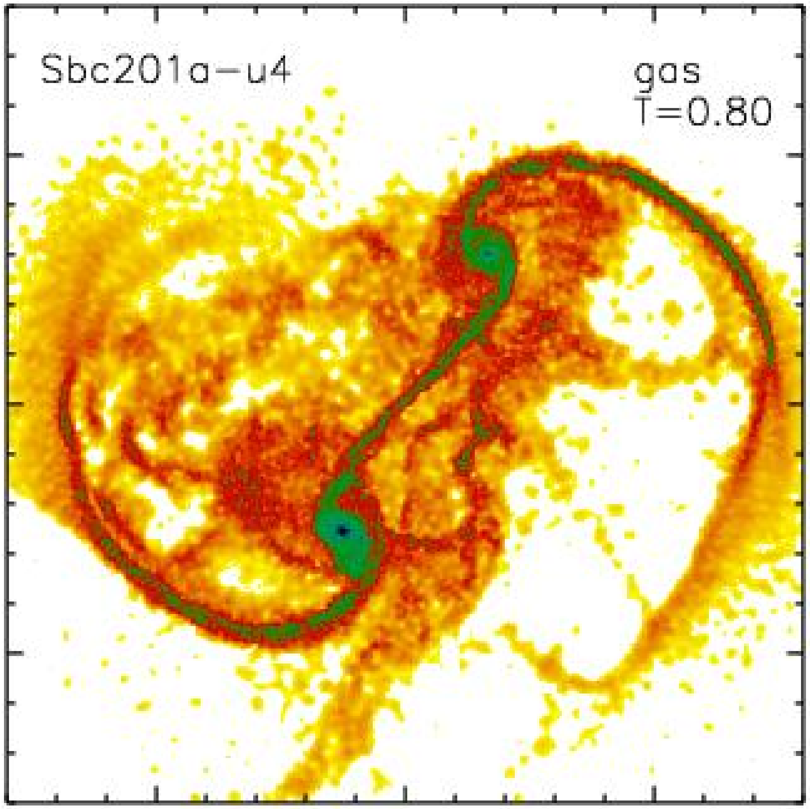




Projected gas density ~green (or darker) is star forming gas

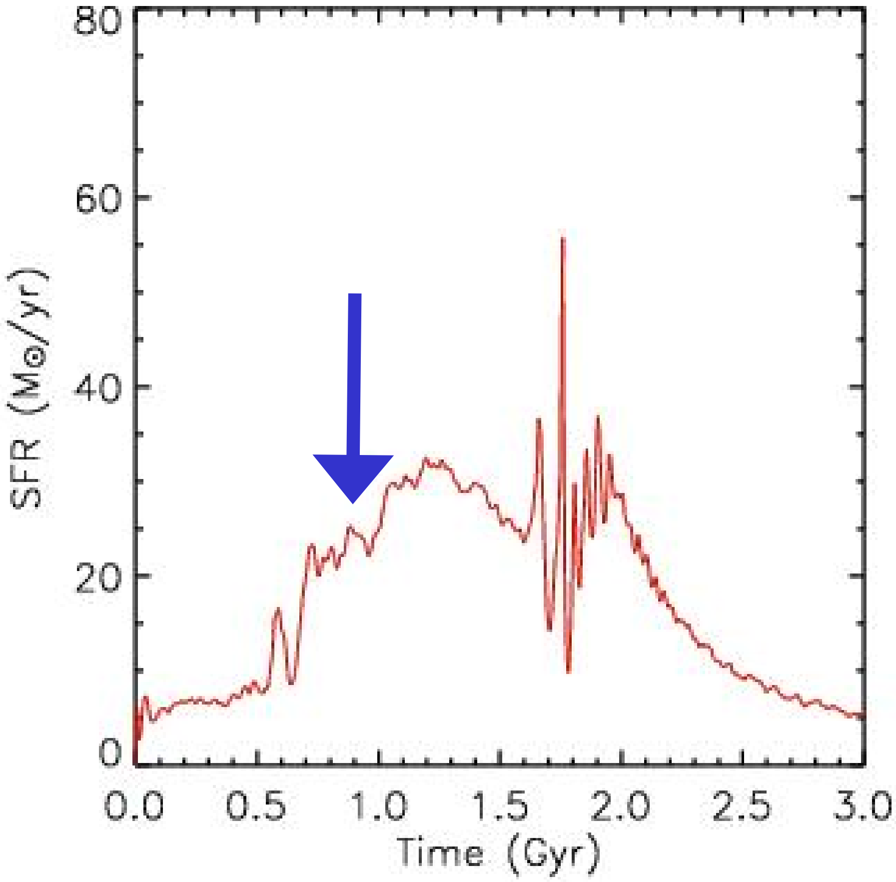
Star Formation History: post-first passage

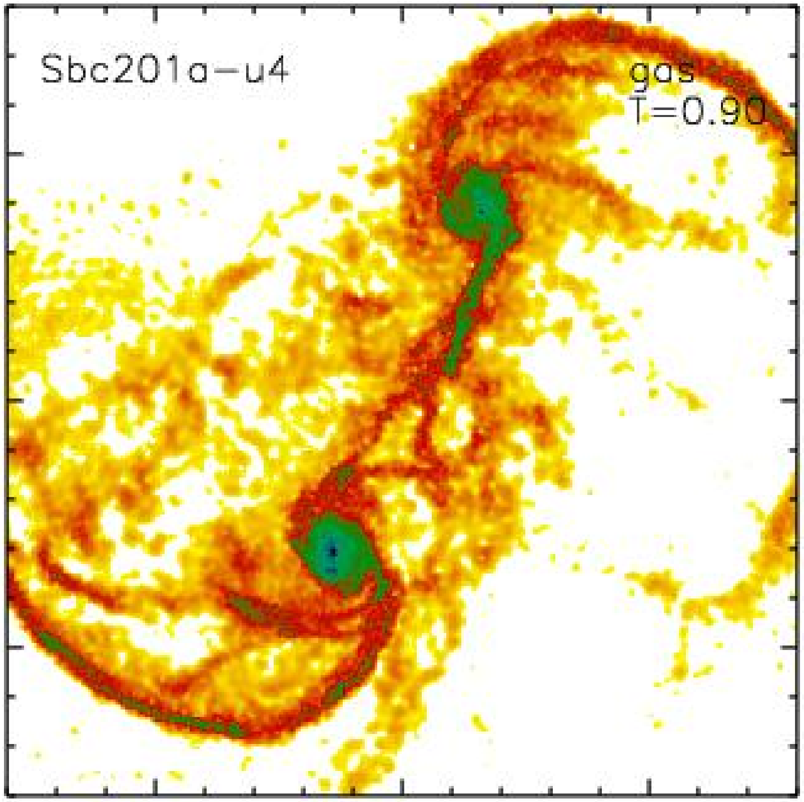




Projected gas density ~green (or darker) is star forming gas

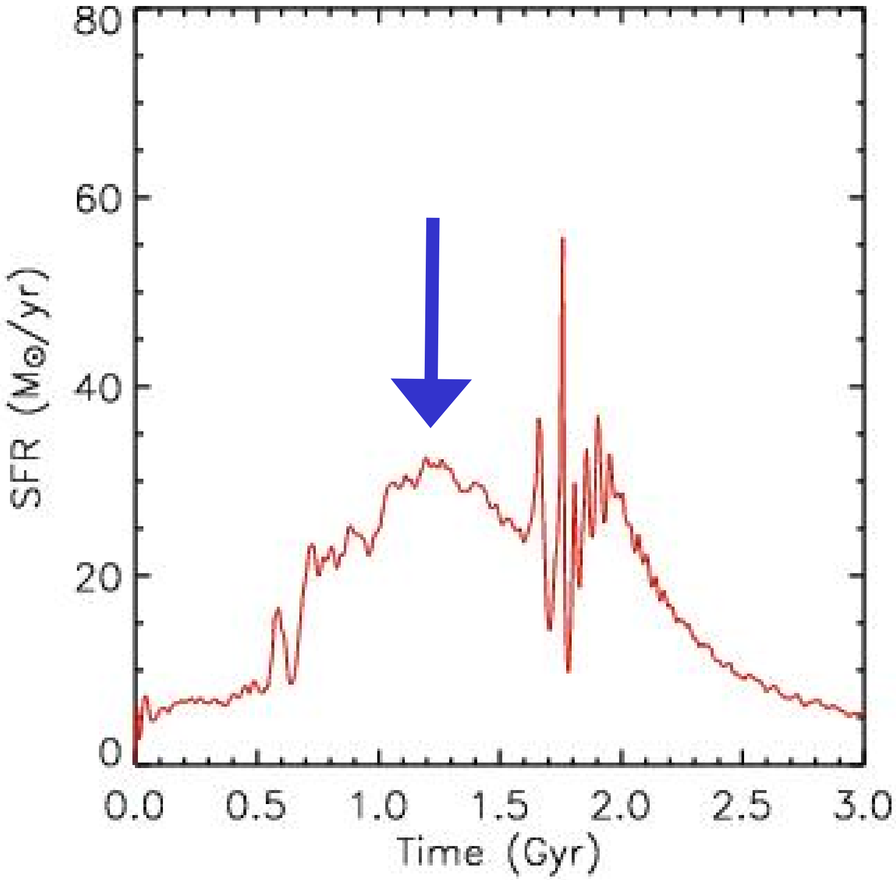
Star Formation History: post-first passage (2)

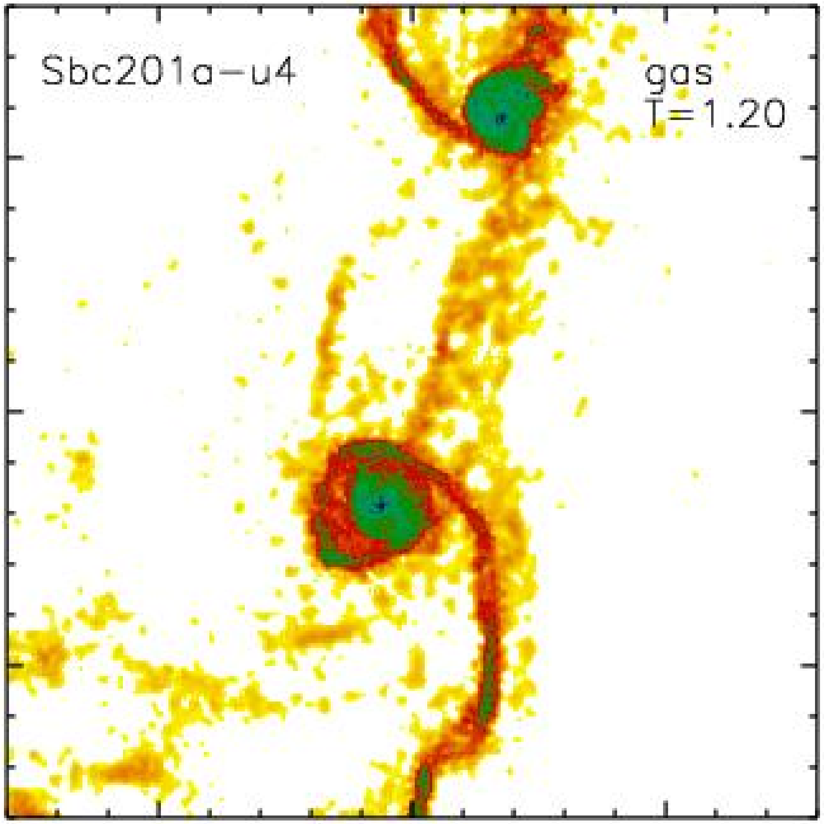




Projected gas density ~green (or darker) is star forming gas

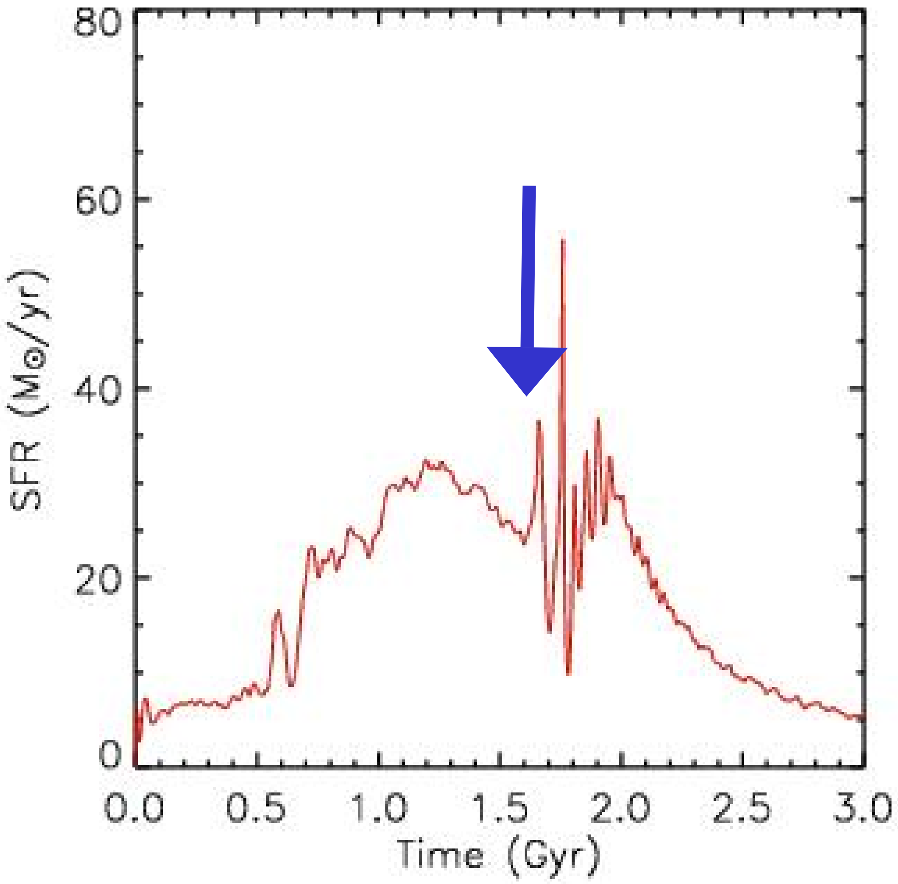
Star Formation History: apocenter

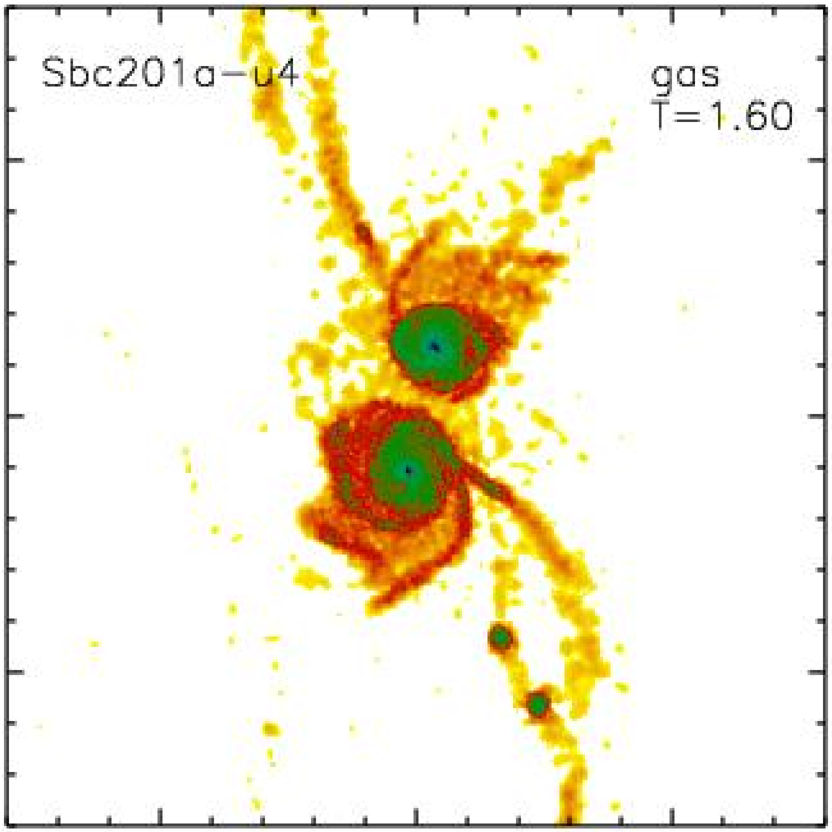




Projected gas density ~green (or darker) is star forming gas

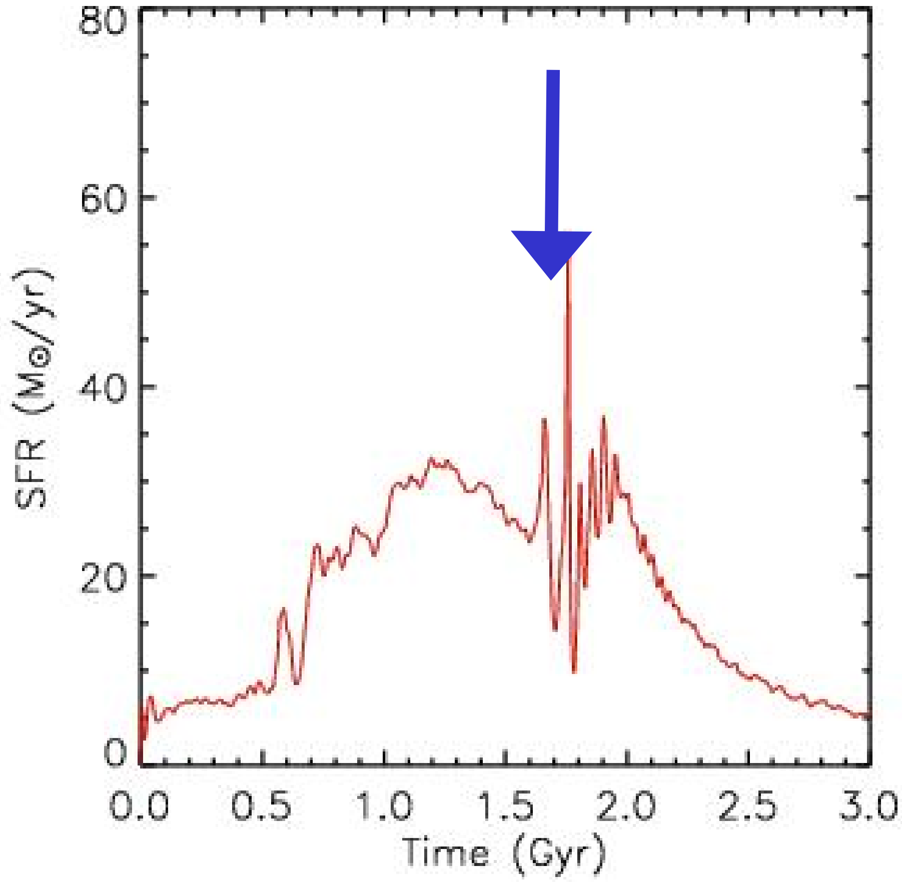
Star Formation History: pre-final merger

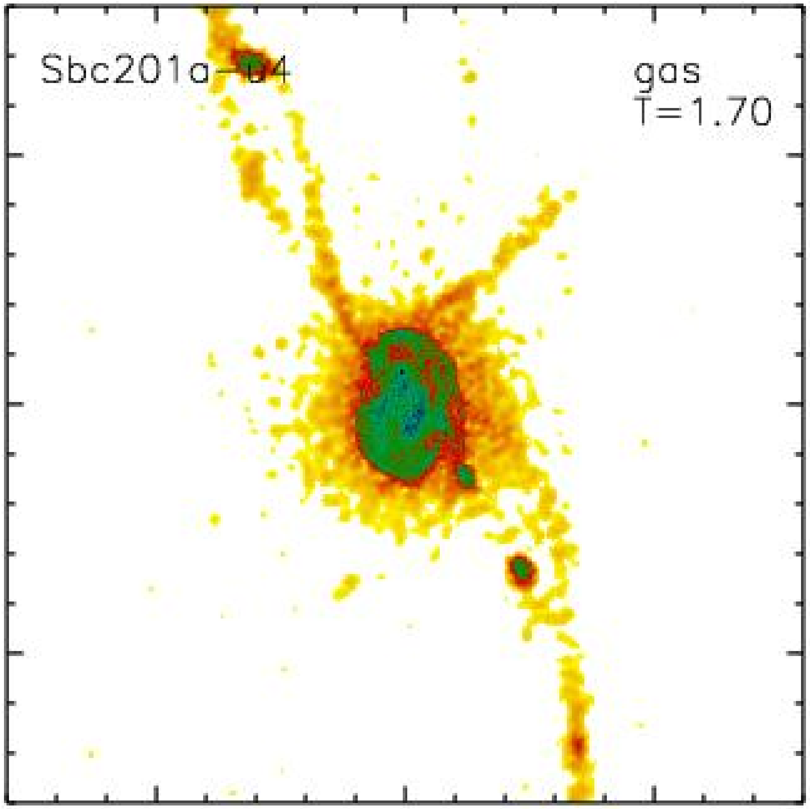




Projected gas density ~green (or darker) is star forming gas

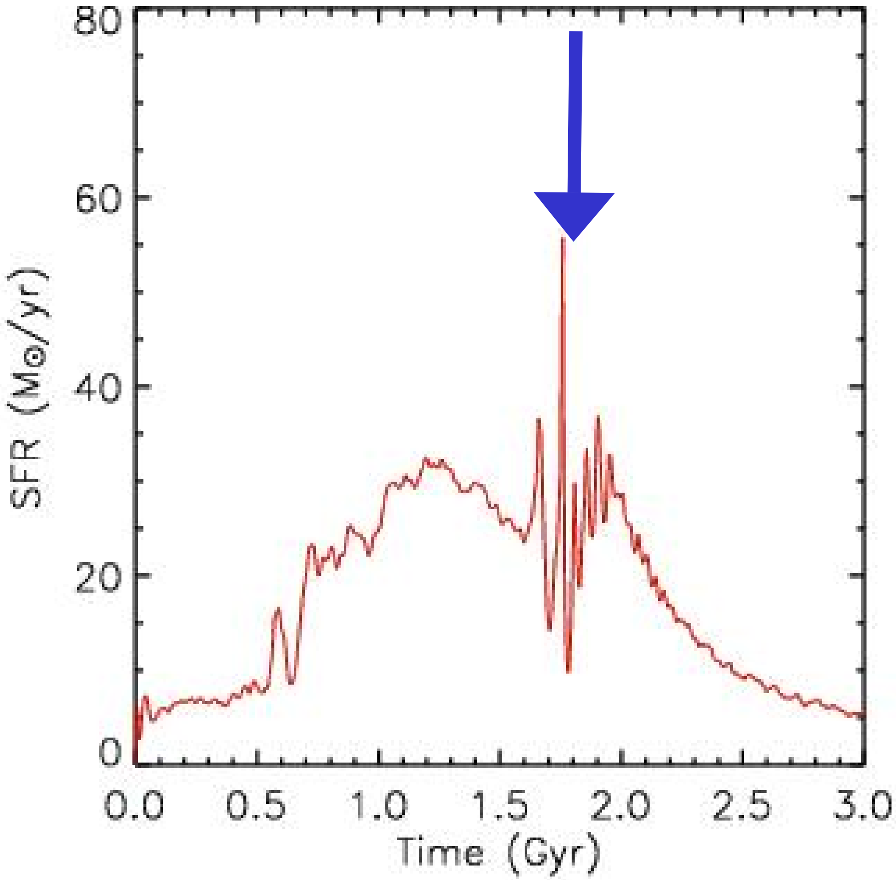
Star Formation History: first passage of final merger

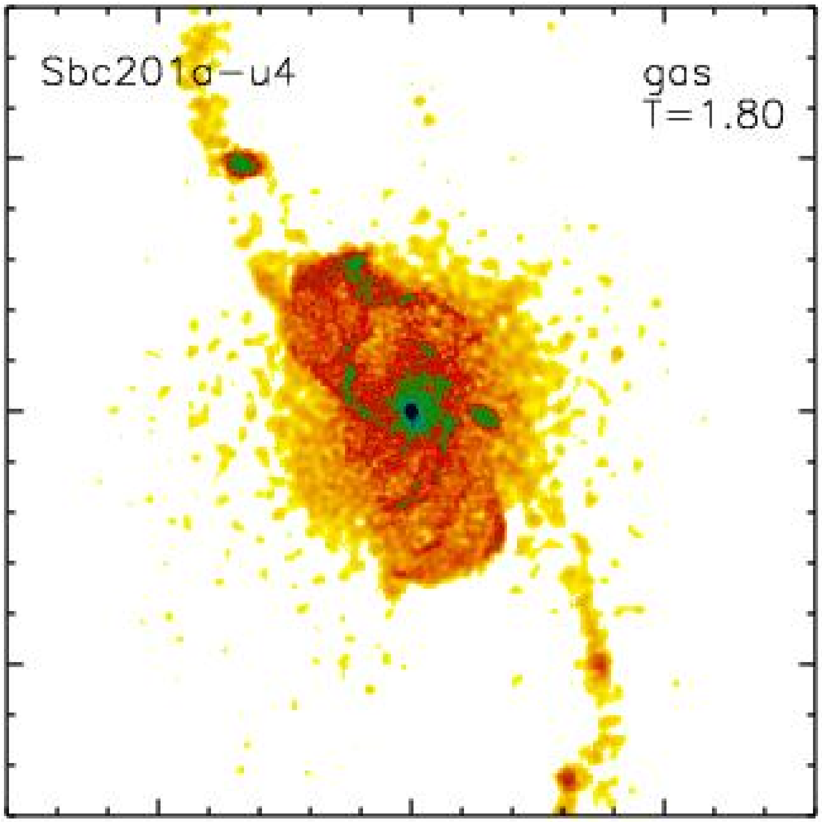




Projected gas density ~green (or darker) is star forming gas

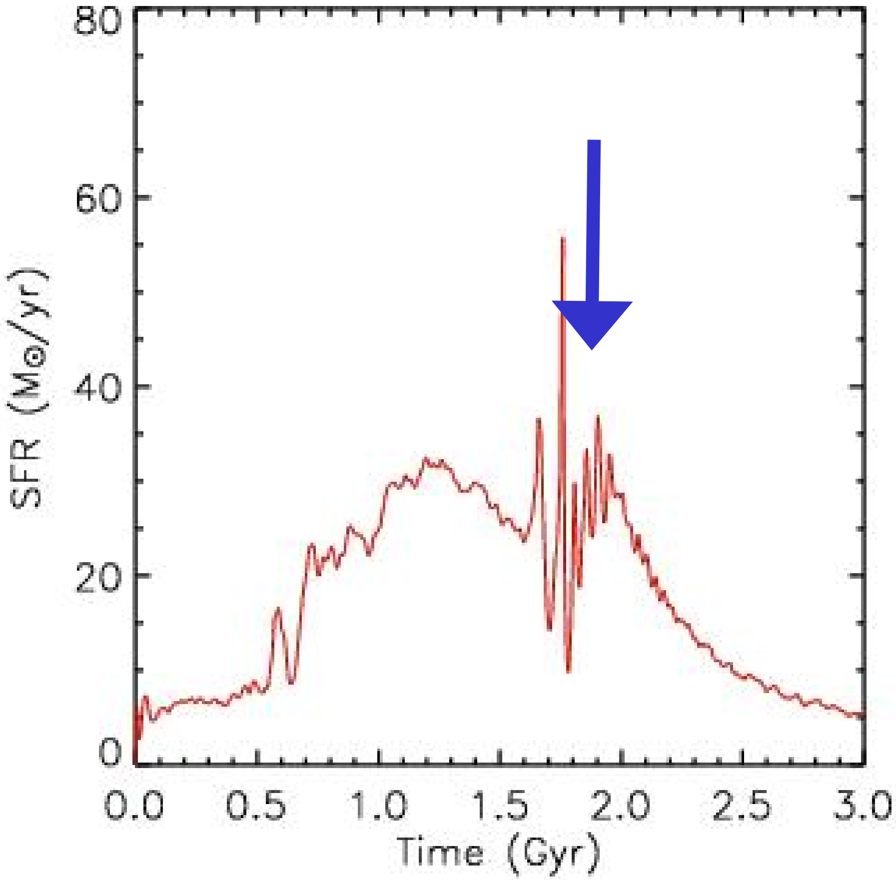
Star Formation History: final merger

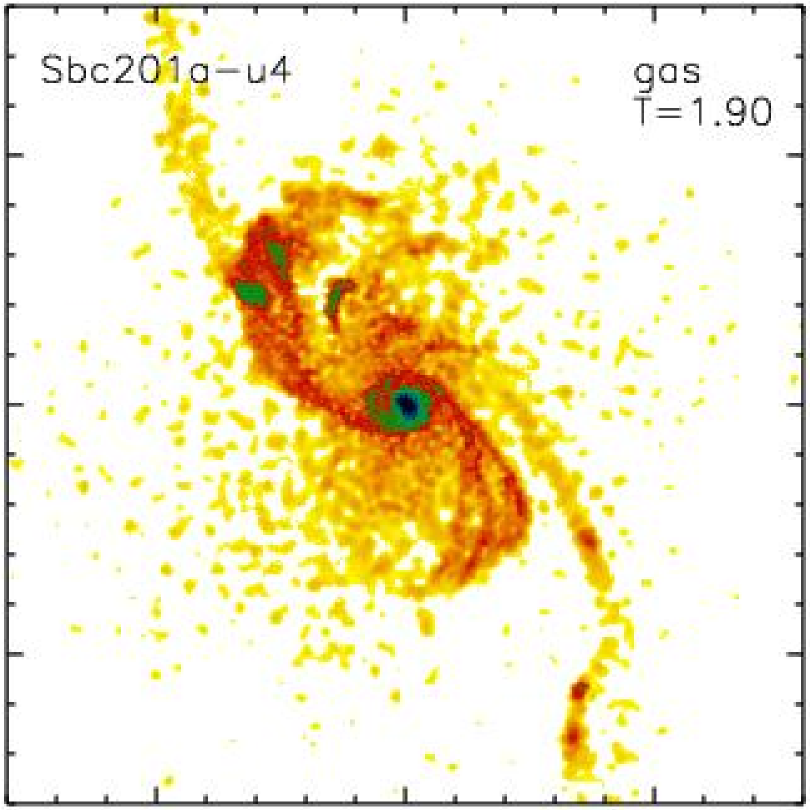




Projected gas density ~green (or darker) is star forming gas

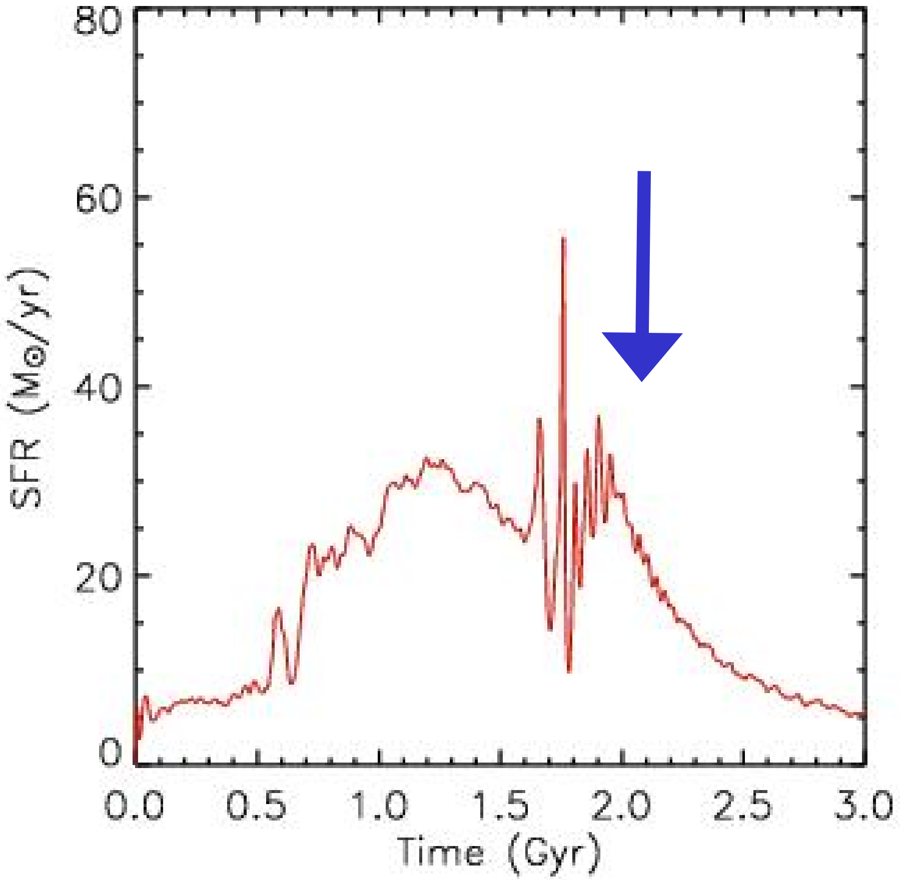
Star Formation History: 100 Myr after final merger

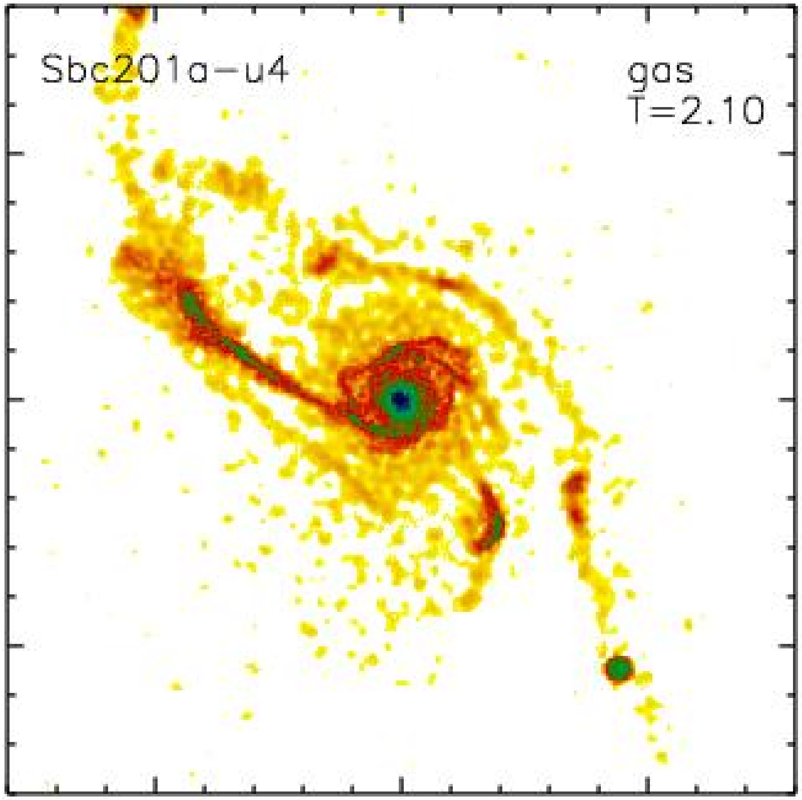




Projected gas density ~green (or darker) is star forming gas

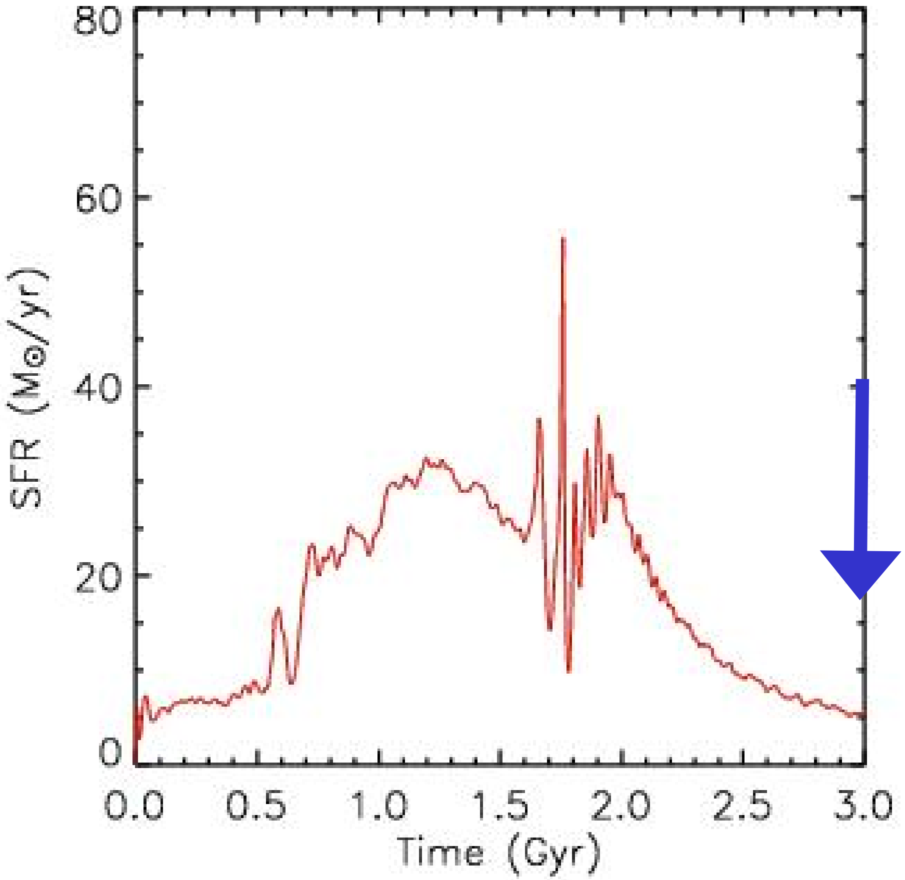
Star Formation History: 300 Myr after final merger

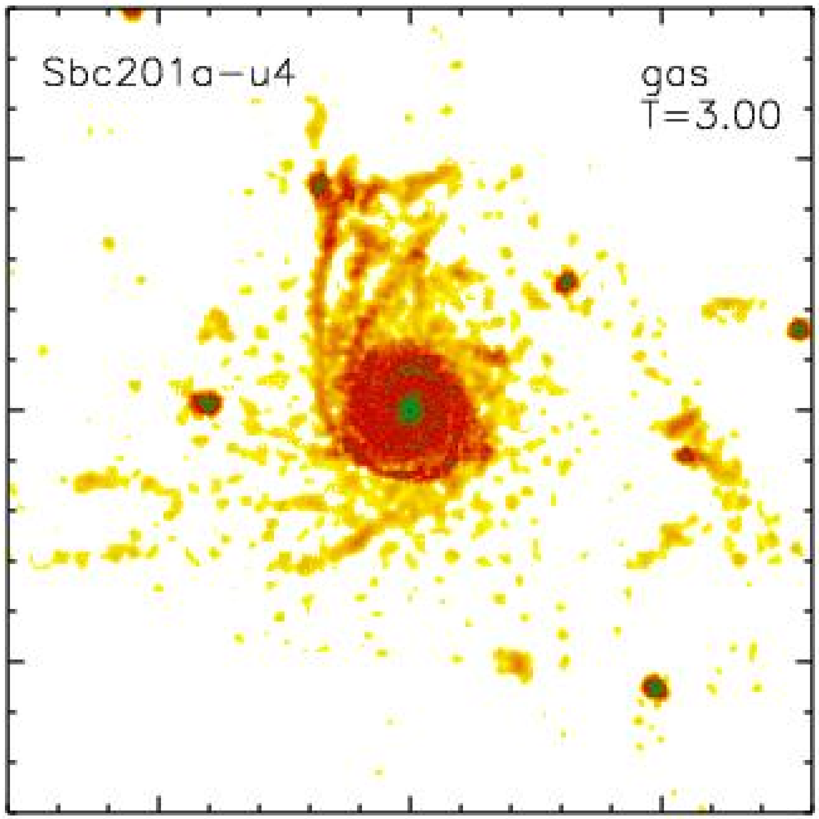




Projected gas density ~green (or darker) is star forming gas

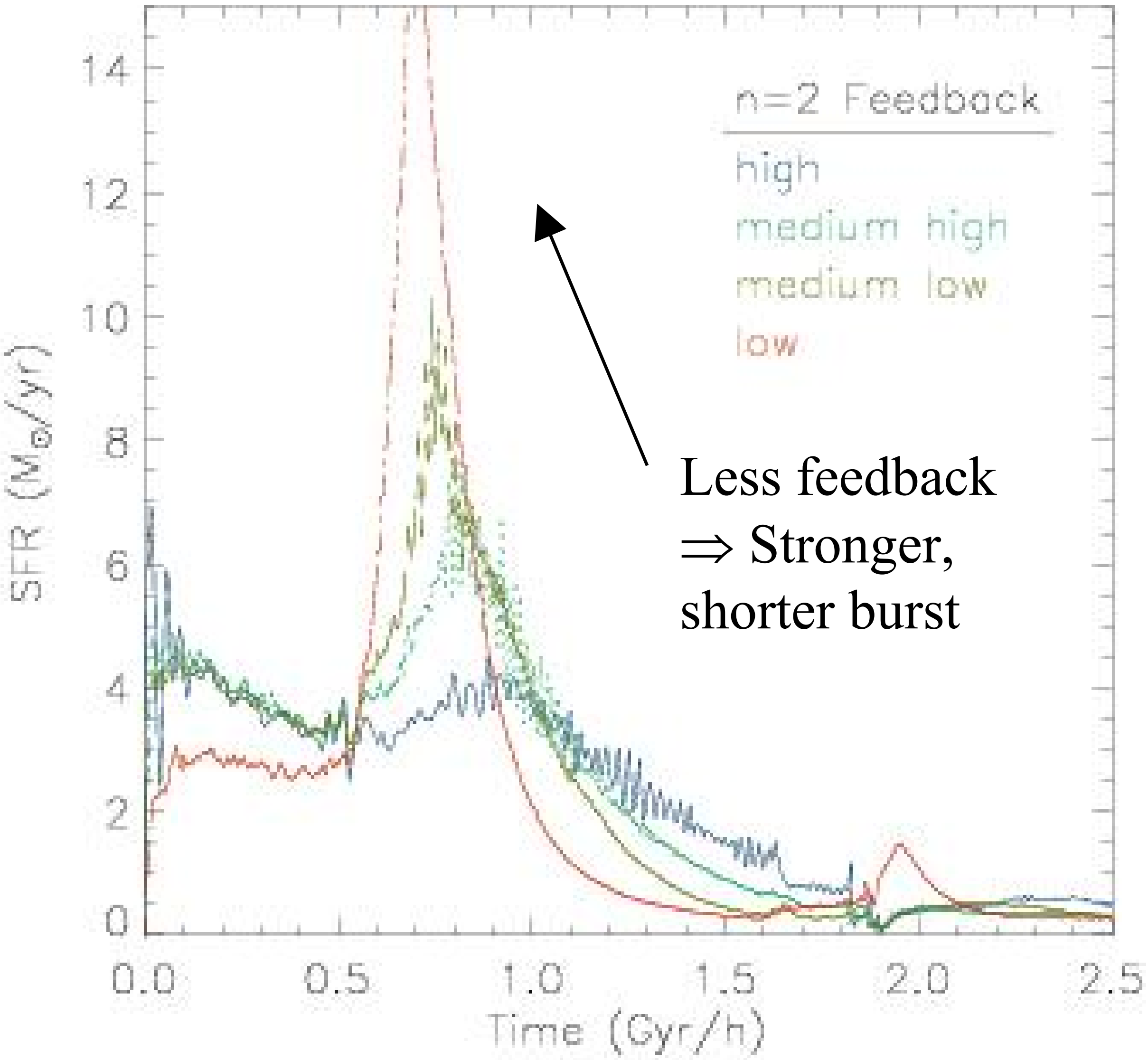
Star Formation History: 1.2 Gyr after final merger





Projected gas density ~green (or darker) is star forming gas

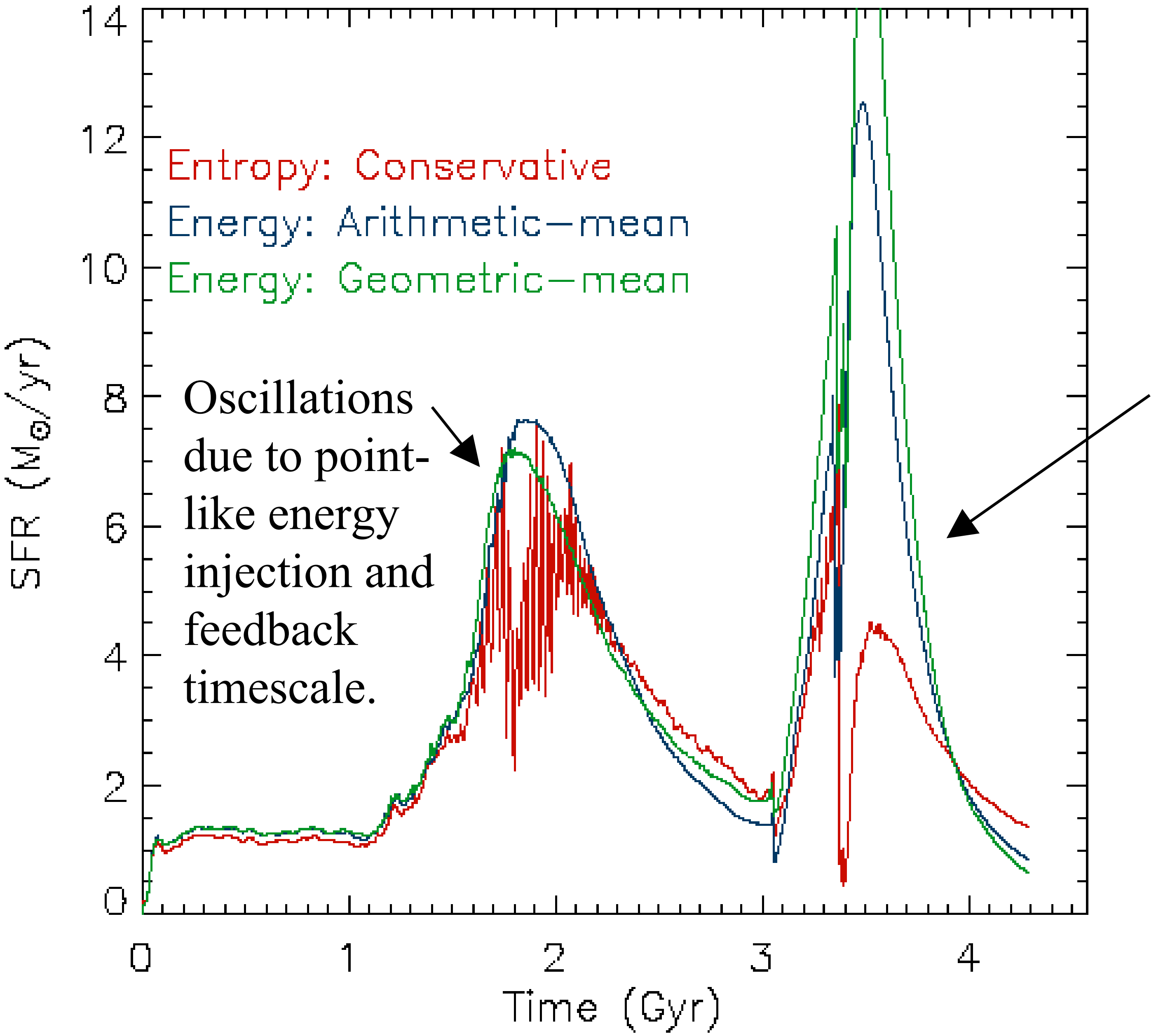
SFR vs. Free Parameters



Less feedback
⇒ Stronger,
shorter burst

While SF/Fb parameters are fixed to make star formation fall on Kennicutt (1998), we can still get a range of burst strengths and durations.

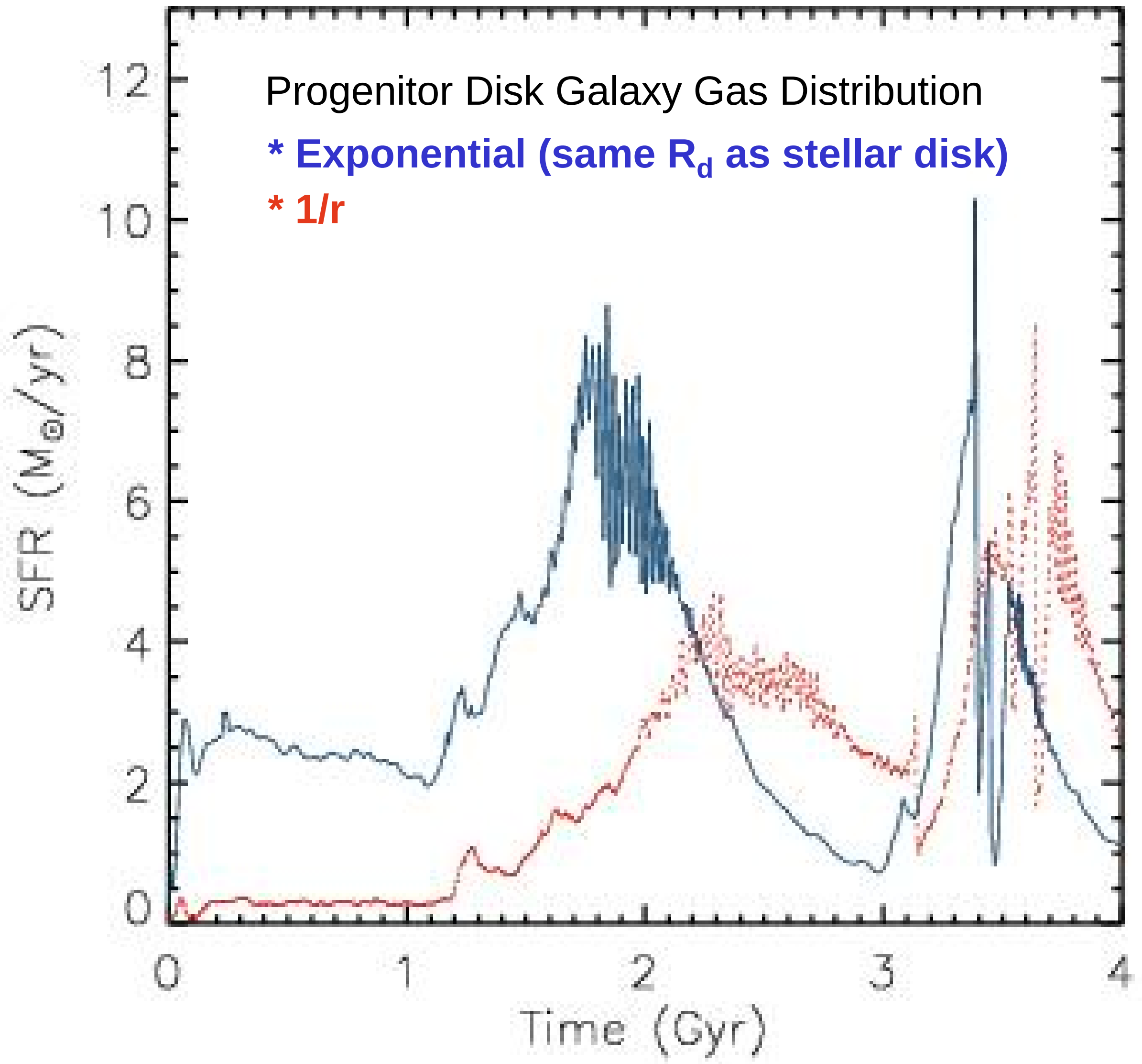
SPH & Star Formation



Oscillations due to point-like energy injection and feedback timescale.

Half as much star formation during final merger with entropy-conserving SPH.

Star Formation and the Initial Gas Distribution



Progenitor Disk Galaxy Gas Distribution

*** Exponential (same R_d as stellar disk)**

*** 1/r**

Total Gas Consumption:

76%

55%

Peak SFR / Quiescent SFR

~5

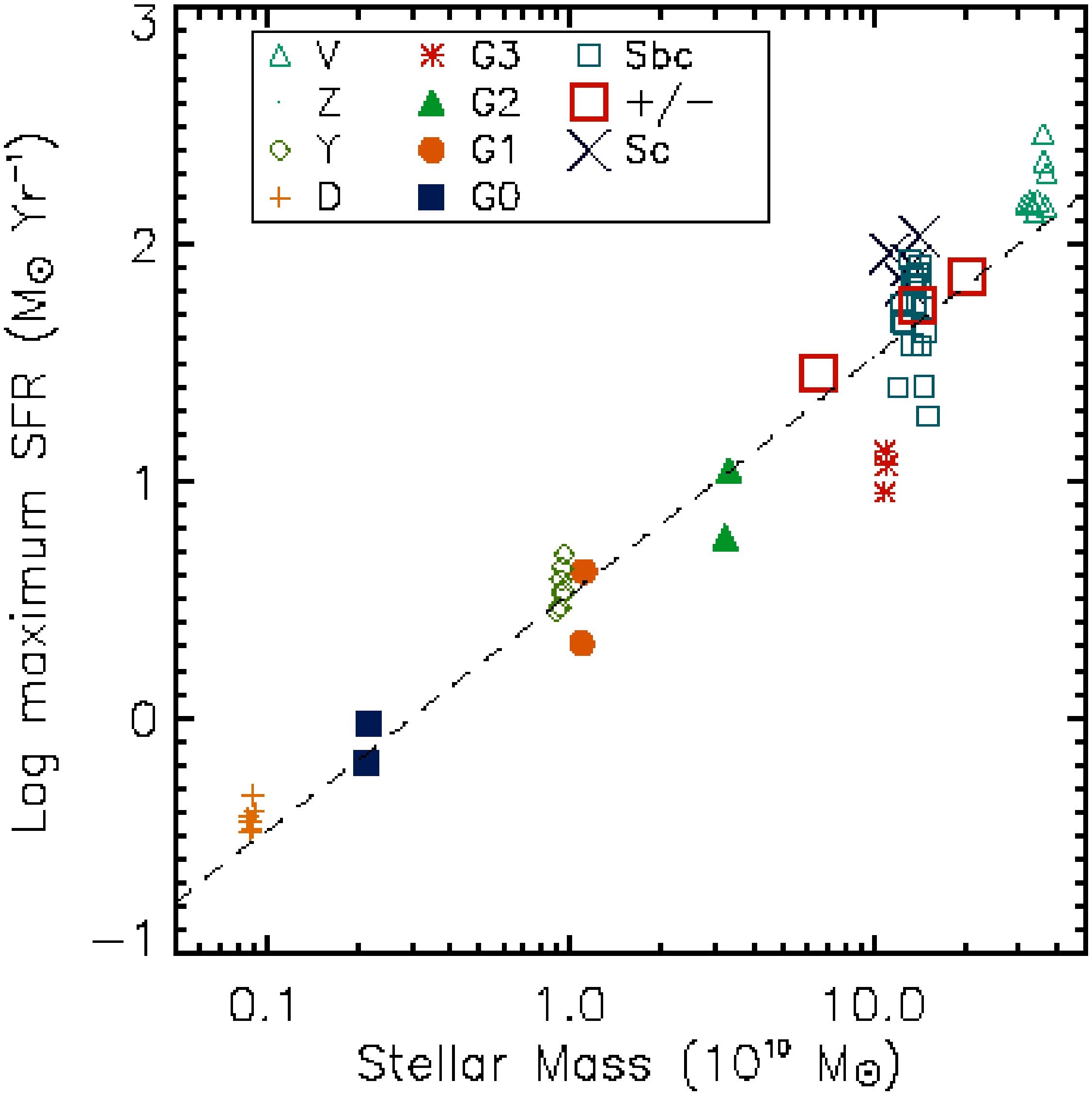
~30

The initial gas distribution makes a large difference in the burst efficiency!

Maximum Star Formation Rate: peak of star formation during merger event

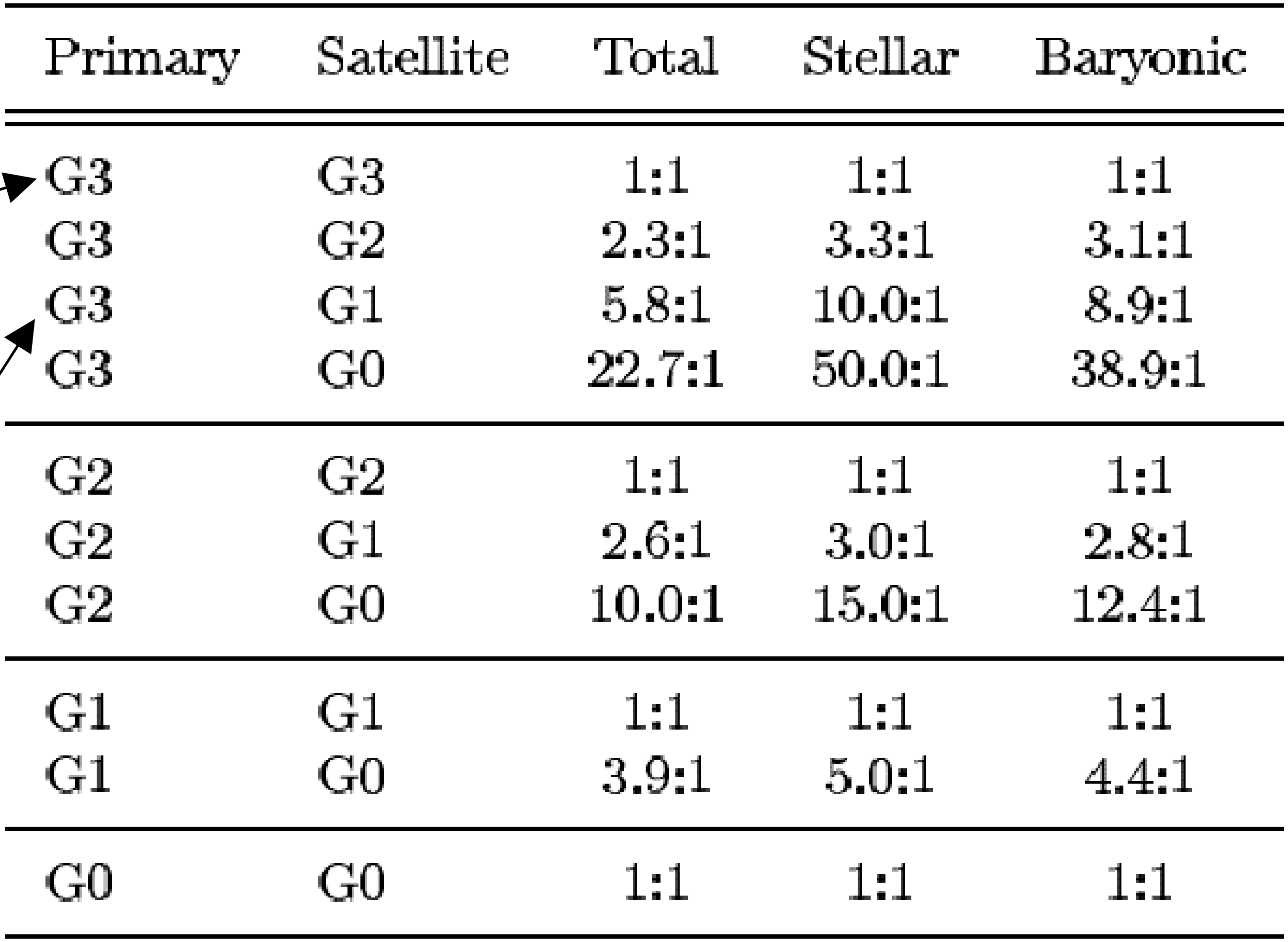
Strong correlation between the maximum star formation rate and the stellar mass.

- Galaxies with larger supplies of cold gas tend to be higher than relation.



Merger Mass Ratios

Now some minor mergers.



Primary	Satellite	Total	Stellar	Baryonic
G3	G3	1:1	1:1	1:1
G3	G2	2.3:1	3.3:1	3.1:1
G3	G1	5.8:1	10.0:1	8.9:1
G3	G0	22.7:1	50.0:1	38.9:1
G2	G2	1:1	1:1	1:1
G2	G1	2.6:1	3.0:1	2.8:1
G2	G0	10.0:1	15.0:1	12.4:1
G1	G1	1:1	1:1	1:1
G1	G0	3.9:1	5.0:1	4.4:1
G0	G0	1:1	1:1	1:1

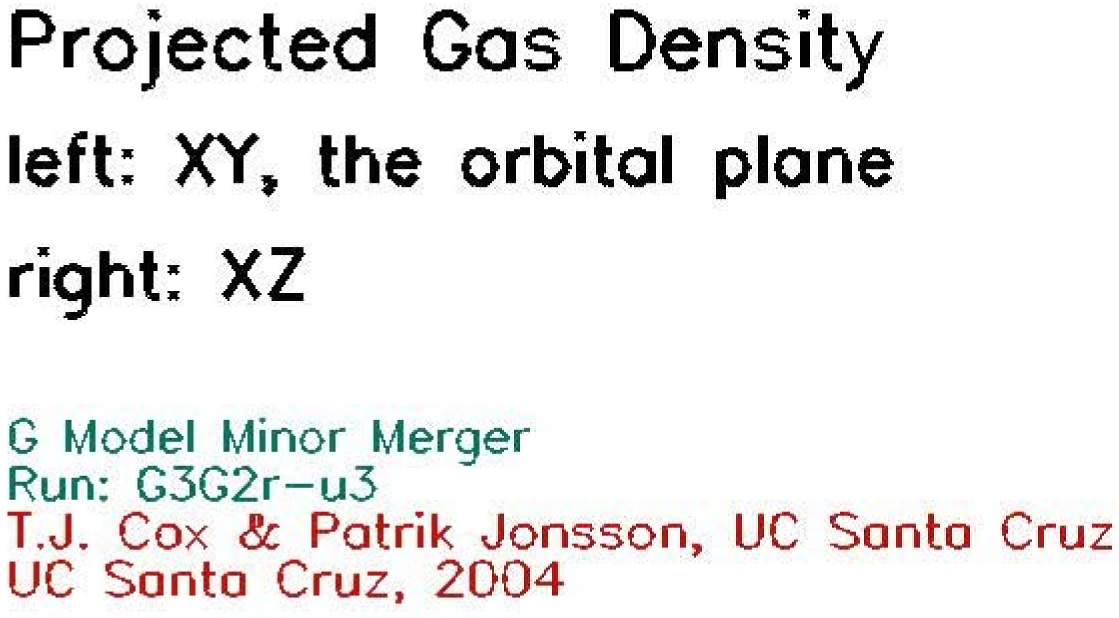
G3G3: Major merger between two G3's

G3G1: Minor merger between G3 and smaller G1

Movie: Minor (1:3) Merger

Projected Gas Density
in the orbital plane

Projected Stellar Density
in the orbital plane



Projected Gas Density

left: XY, the orbital plane

right: XZ

G Model Minor Merger
Run: G3G2r-u3
T.J. Cox & Patrik Jonsson, UC Santa Cruz
UC Santa Cruz, 2004

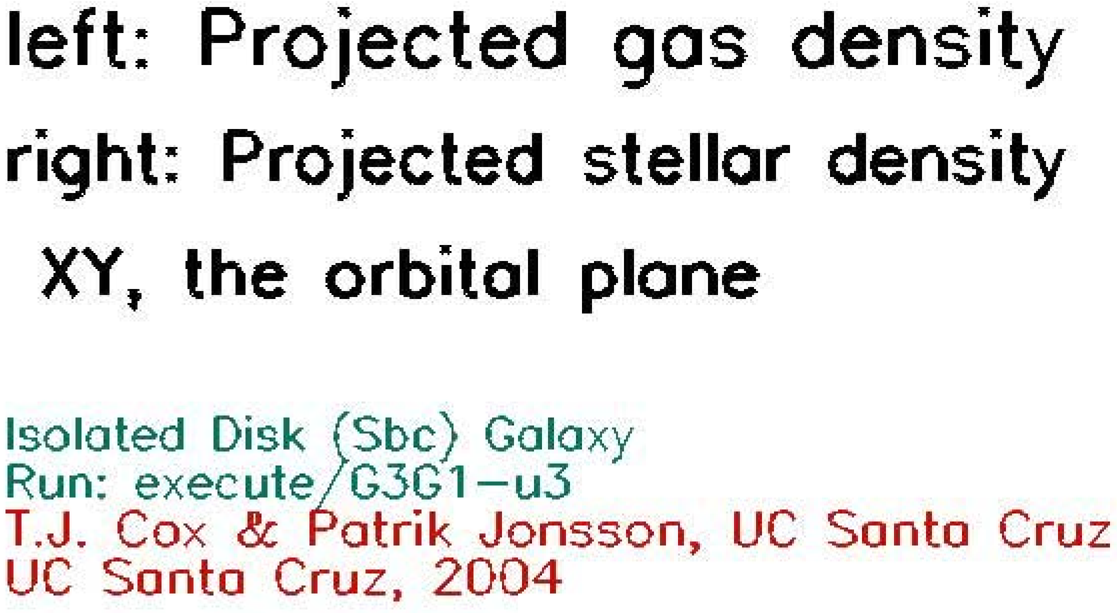
G3G2r: 1:3 retrograde merger

Movie at:
http://physics.ucsc.edu/~tj/work/movies/

Movie: Minor (1:6) Merger

Projected gas density

Projected stellar density



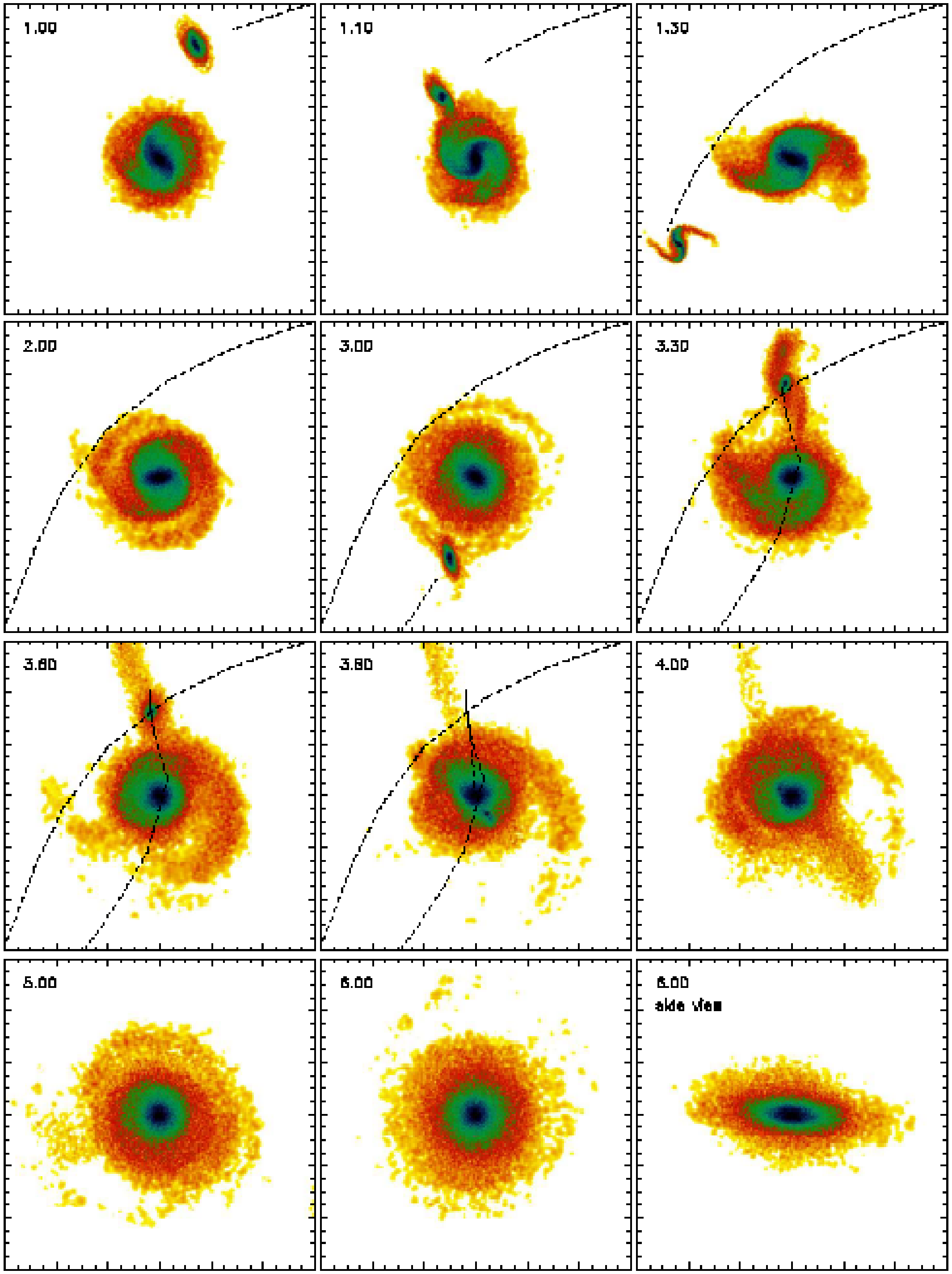
left: Projected gas density
right: Projected stellar density
XY, the orbital plane

Isolated Disk (Sbc) Galaxy
Run: execute/G3G1-u3
T.J. Cox & Patrik Jonsson, UC Santa Cruz
UC Santa Cruz, 2004

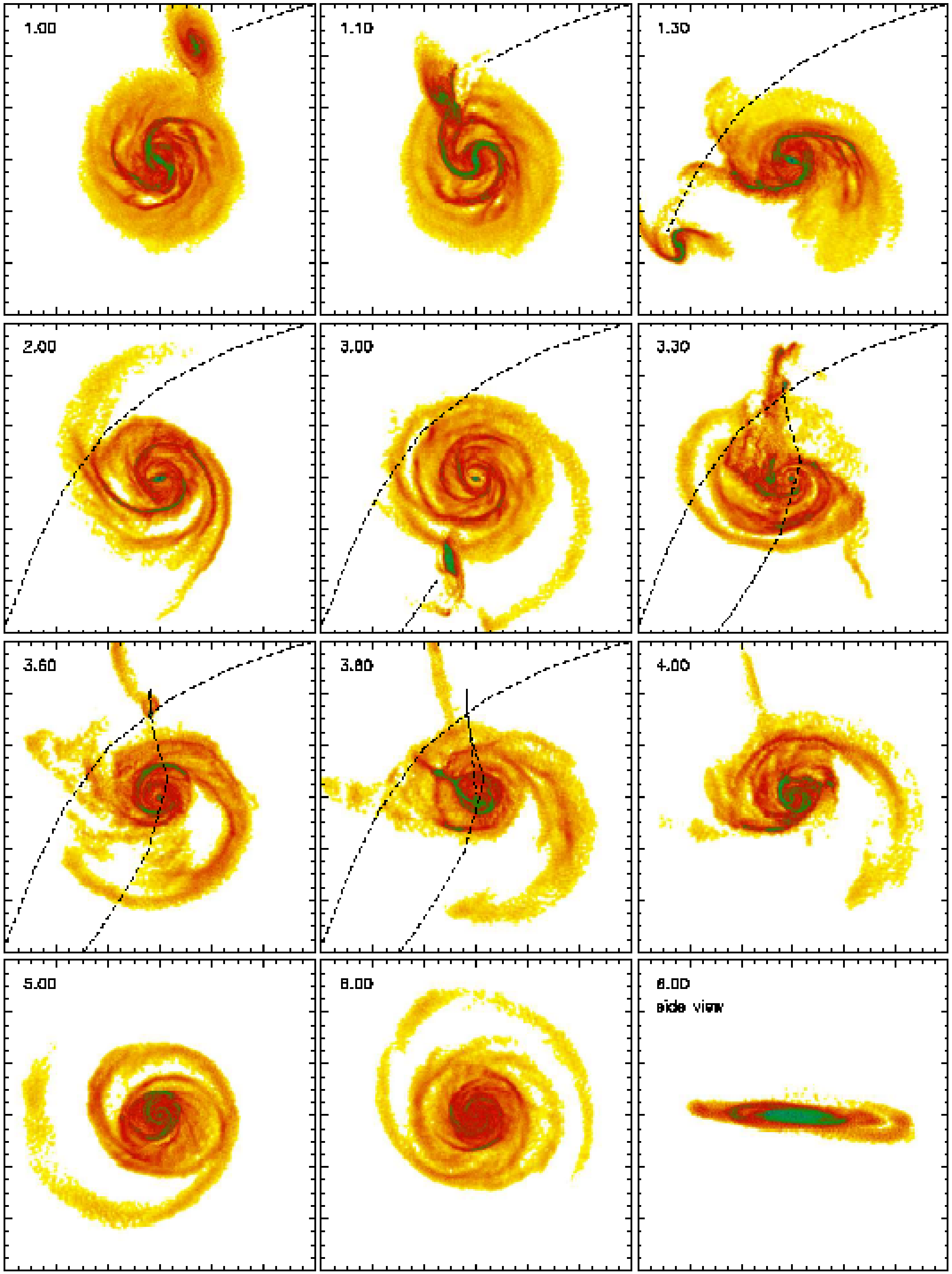
G3G1: prograde minor merger

Movie at:
http://physics.ucsc.edu/~tj/work/movies/

Stellar Density

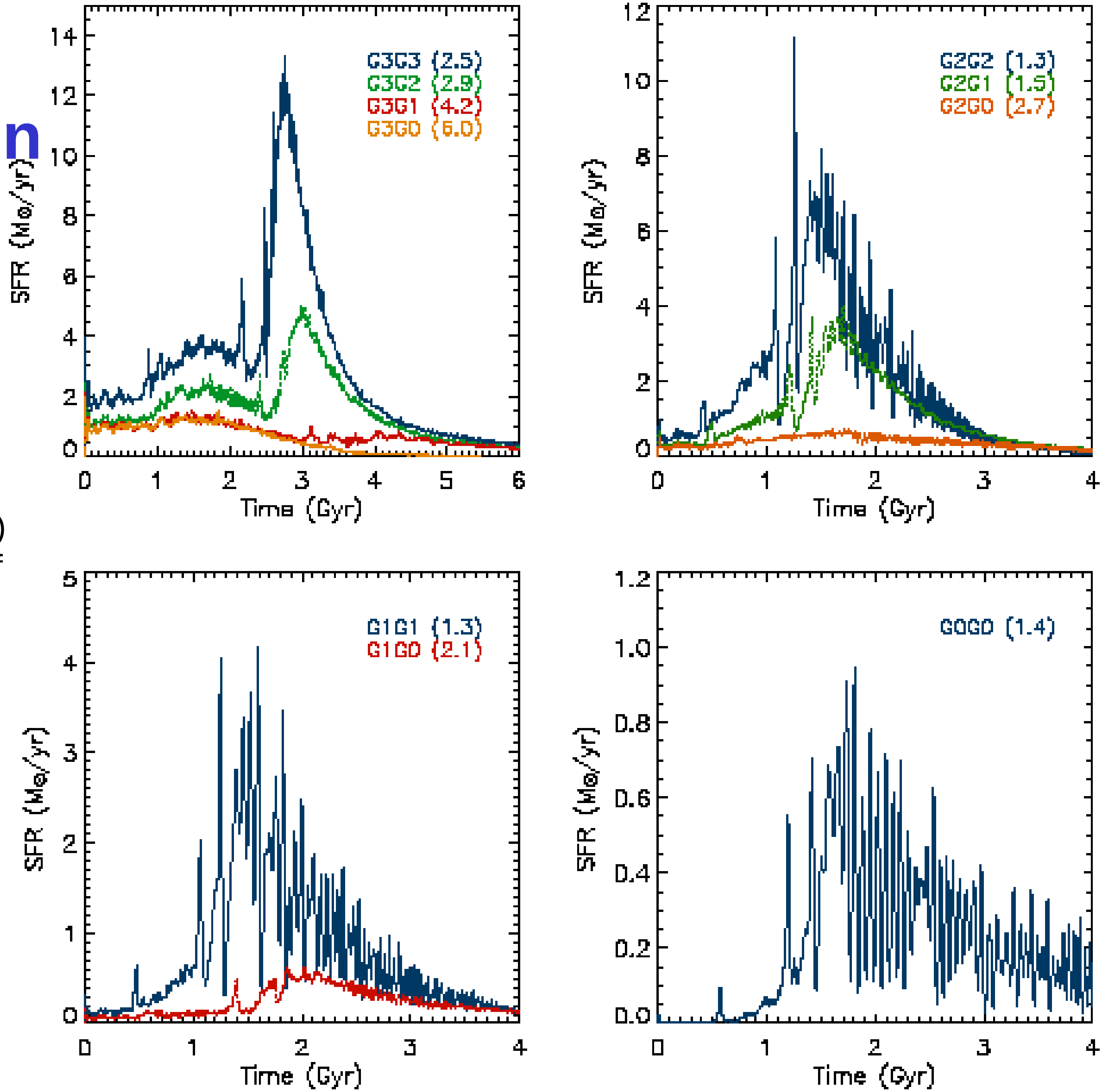


Gas Density



Star Formation in G Mergers

- Due to the small bulge in G3 there is a small increase in star formation during the first encounter (between t=1-2 Gyr).
- Large (in some models) burst (>10x quiescent) of star formation follows final merger.
- Max SFR decreases with mass
- The burst strength increases with merger mass ratio, with rough dividing line at 1:5 for generating a burst at all.
- Large mass ratios are tricky!

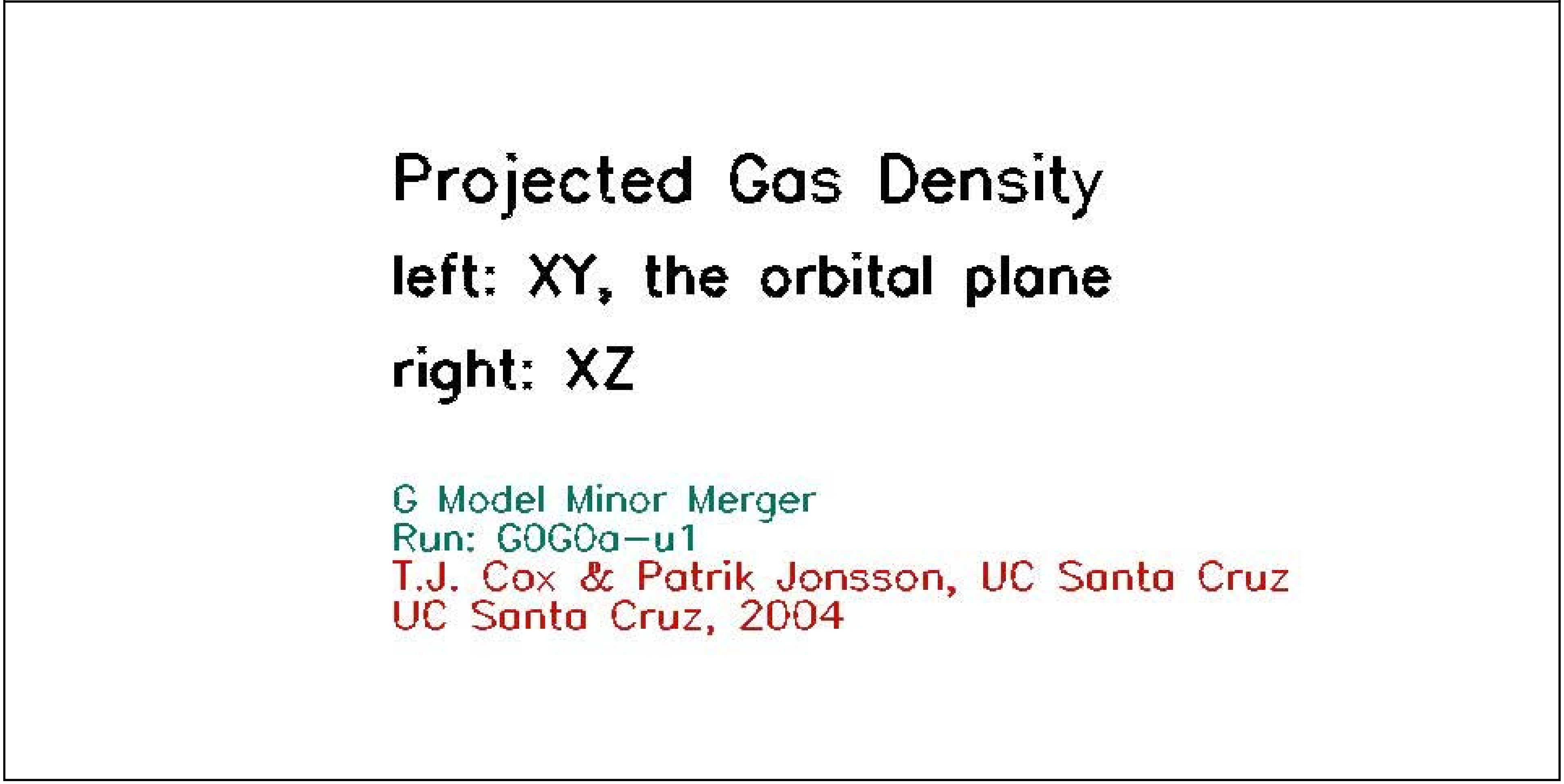


The smallest major merger

Projected gas density for the G0 major merger.

Orbital plane

Perpendicular view



Projected Gas Density

left: XY, the orbital plane

right: XZ

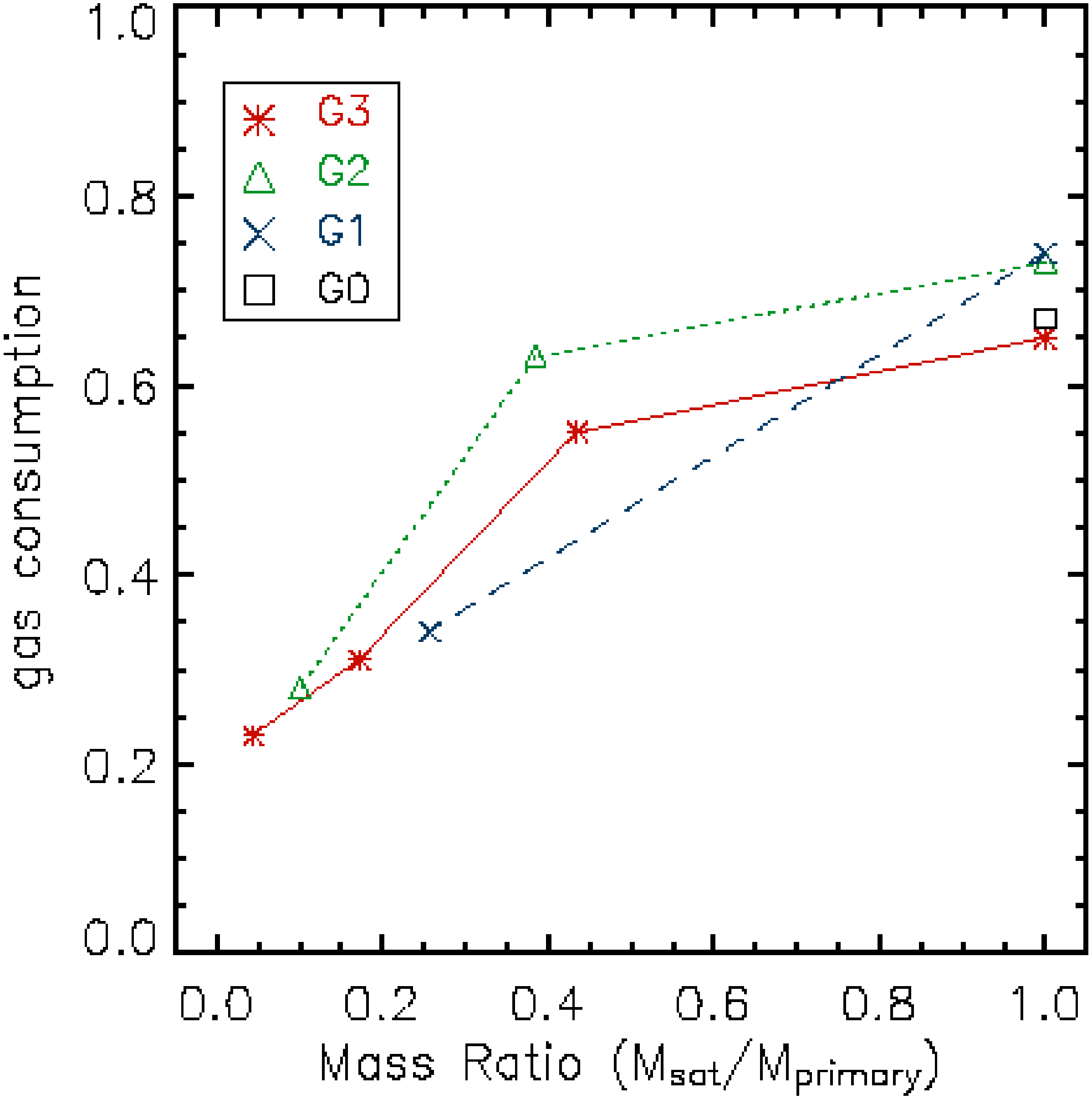
G Model Minor Merger
Run: G0G0a-u1
T.J. Cox & Patrik Jonsson, UC Santa Cruz
UC Santa Cruz, 2004

Star Formation Efficiency

- Fraction of original gas consumed during the simulation.

- Major mergers consume more gas than minor mergers.

- Looks very similar to the SPF01 burst efficiency (for the bulgeless case).



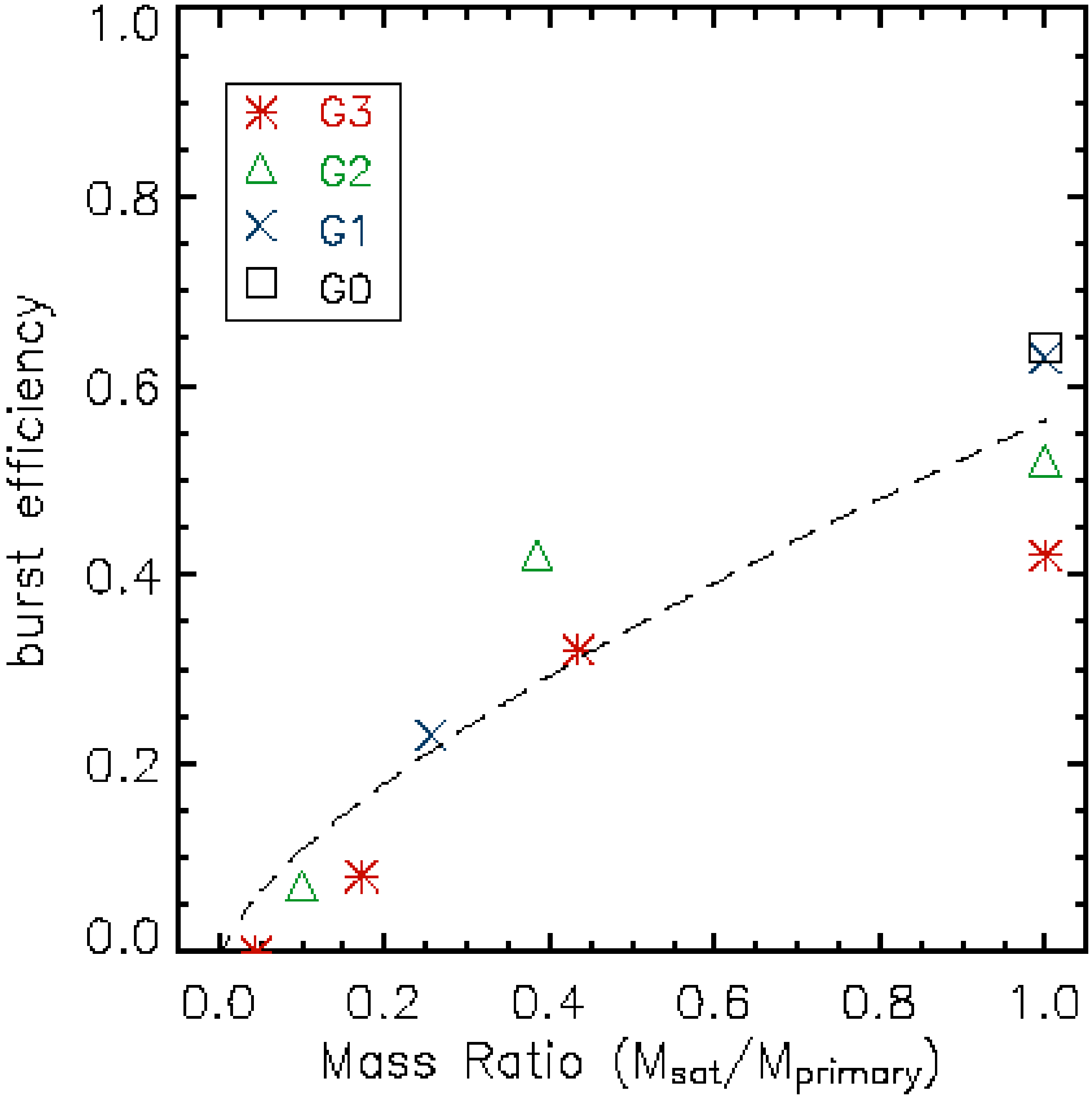
Burst Efficiency

The quiescent star formation has been subtracted.

$$e = e_{1:1} \left(\frac{\mathrm{M_{sat}}}{\mathrm{M_{primary}}} \right)^{\gamma}$$

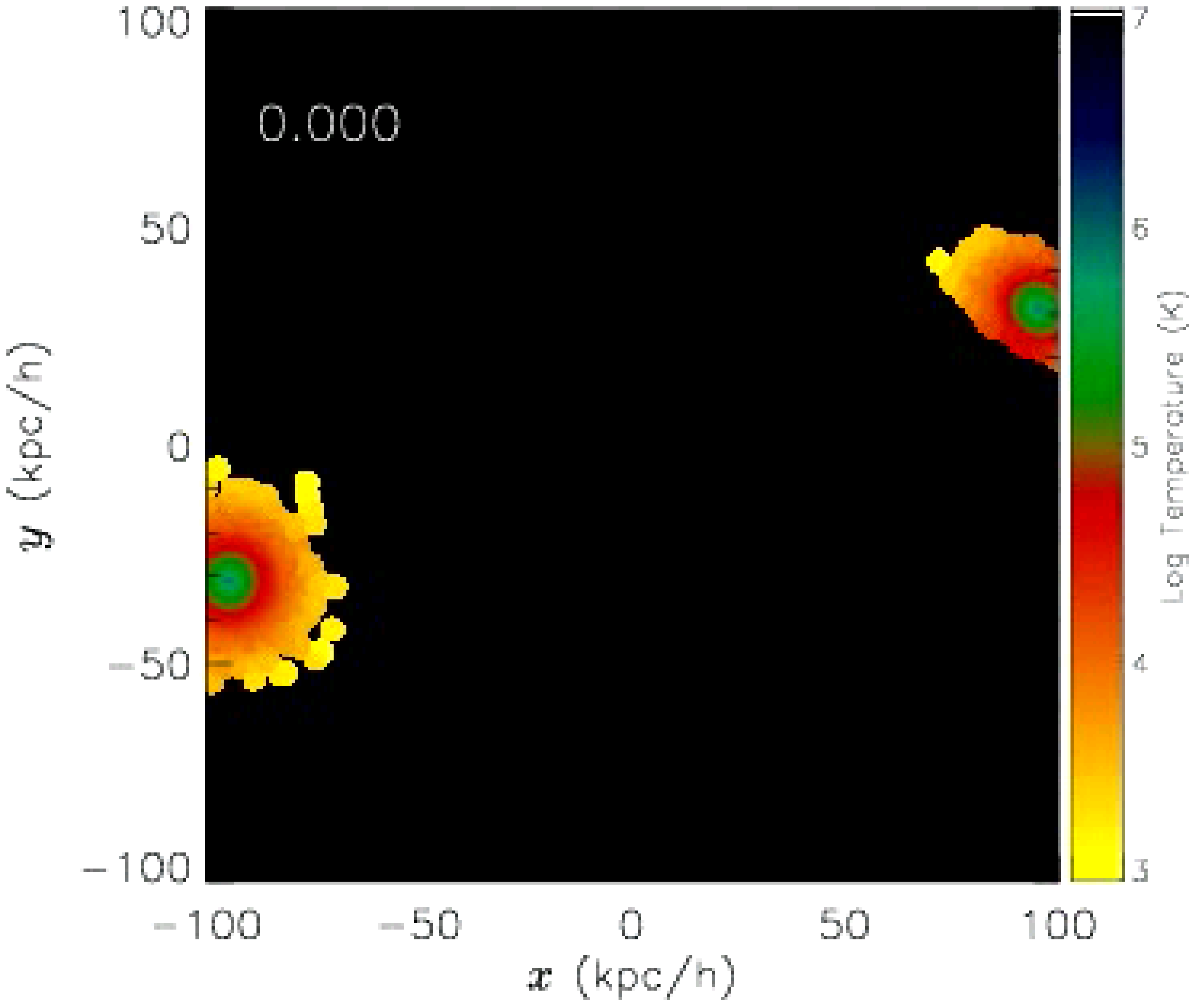
$$e_{1:1}=0.56$$

$$\gamma=0.7.$$



Gas Temperature during Major Merger

7 kpc
slice
through
orbital
plane



10^7 K

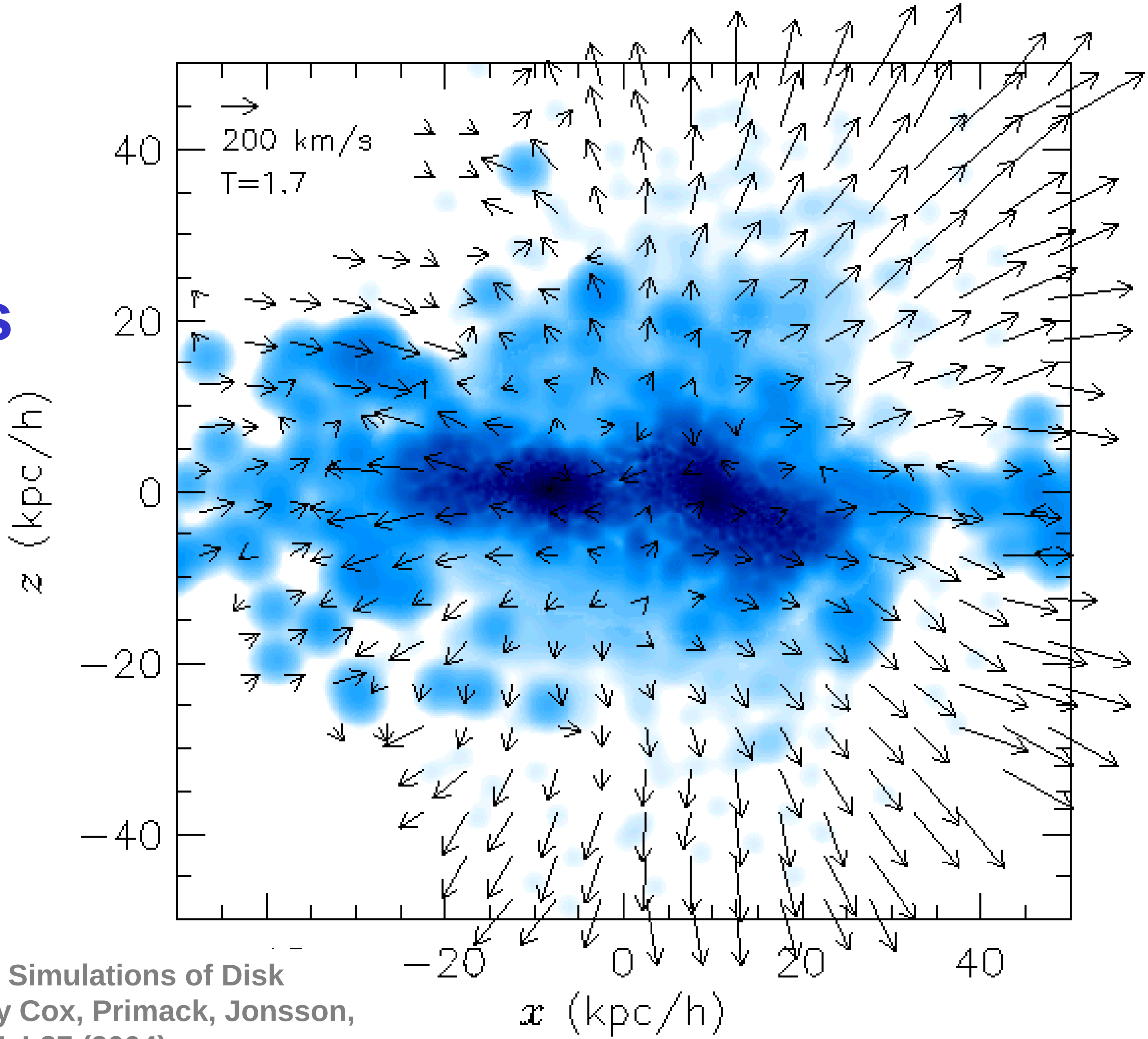
10^6 K

10^5 K

10^4 K

10^3 K

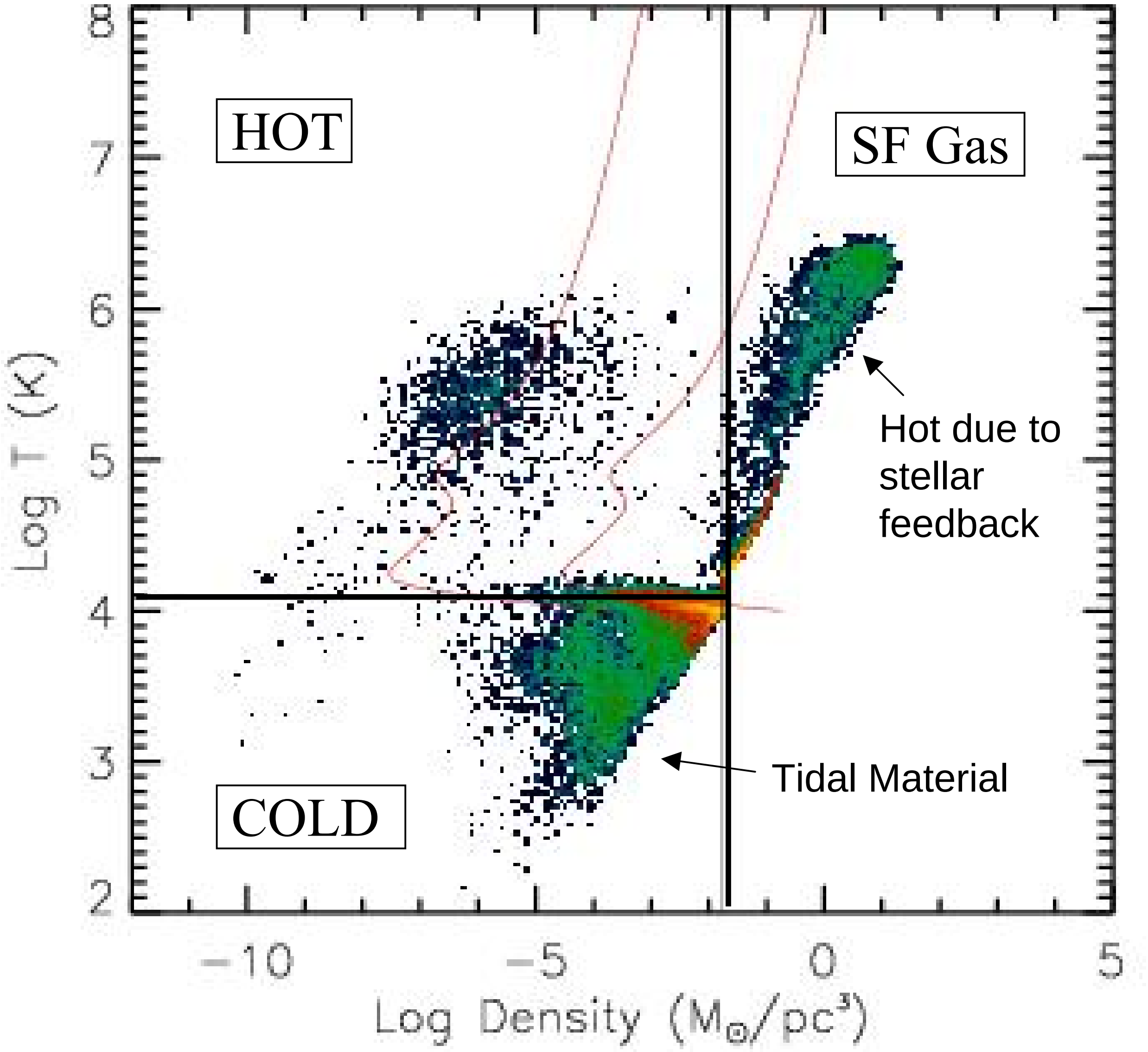
Gas velocity field on color gas density map



7 kpc slice through plane perpendicular to orbital plane

Generating Hot Gas in Simulations of Disk Galaxy Interactions, by Cox, Primack, Jonsson, & Somerville, ApJ, 607, L87 (2004).

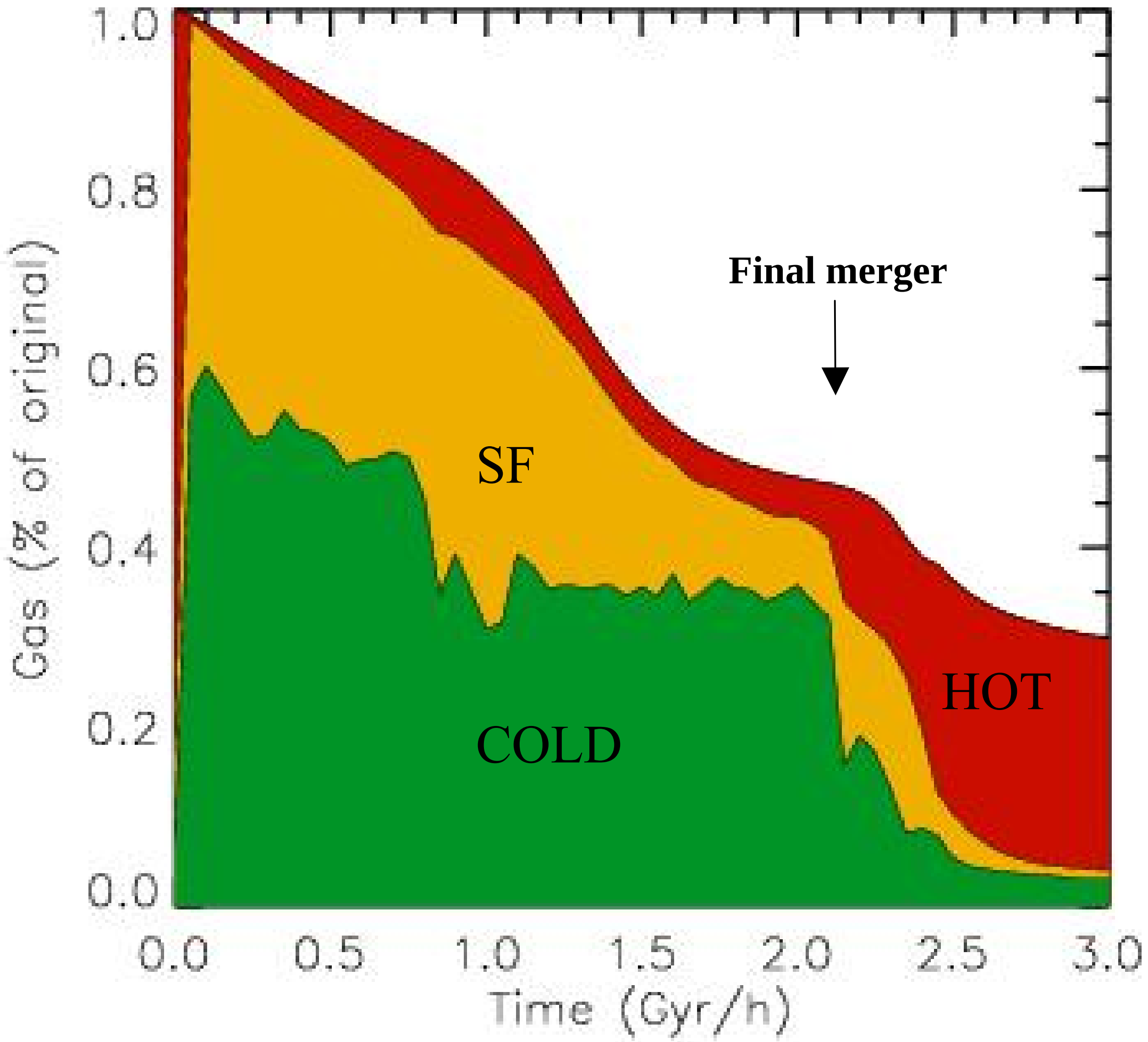
Gas Phases During Simulation



<u>SF Gas</u>
Gas which is above the threshold density for star formation.

Gas below the threshold density for star formation is either
cold (T≤ 1.2 x 10^4K)
or
hot (T>1.2 x 10^4K)

Gas Phases During Simulation

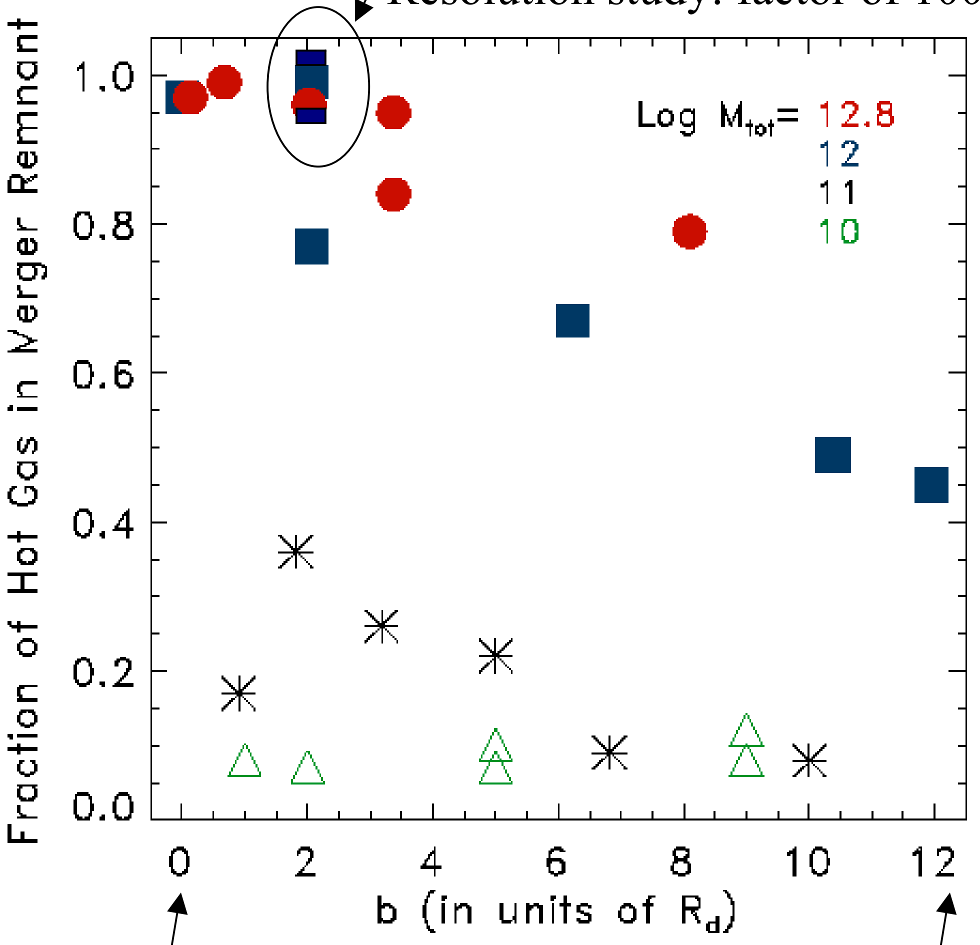


1. SF gas gets efficiently converted to stars.

2. Spherical winds during final merger correspond to transition of
a large amount of gas from cold to hot.

Hot Gas vs. Merger Orbit

Resolution study: factor of 100 in mass resolution

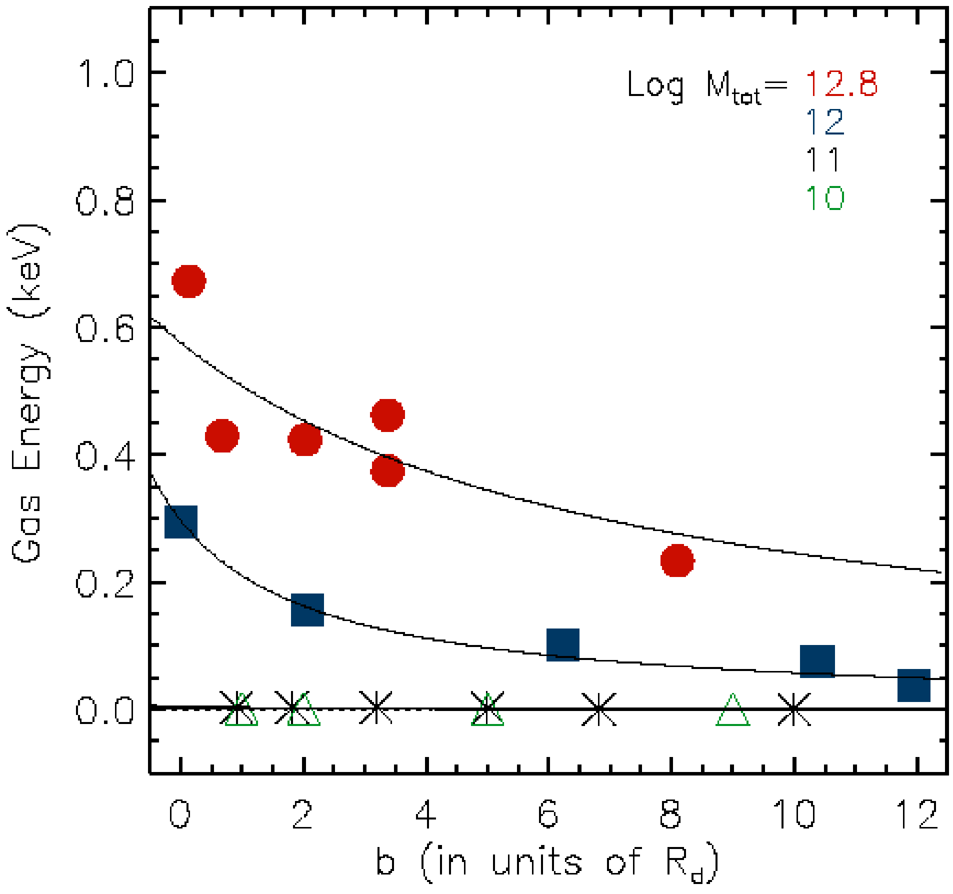


A more radial orbit generates more hot gas in the merger remnant

Radial orbit

Circular orbits

Mergers Pump Kinetic Energy into Gas



Fitting Formula

$$\frac{A}{(b + R_d)}$$

b = impact parameter
Rd = Disk Radial Scale Length
A = free parameter, ~M

Conclusions

- Our results are consistent with Mihos & Hernquist 1994, Mihos & Hernquist 1996, and Springel 2000. We see increased star formation in major and minor mergers, and the suppression of early inflows of gas due to the presence of a bulge. But, due to the newer version of SPH and the higher normalization of star formation, our work suggests they overestimated the gas consumption during mergers.

- The star formation, not surprisingly, is highly dependent upon the amount of cold gas available. As evidence, our Sc-Sc major merger has a maximum star formation rate of ~110 $M_{\odot} Yr^{-1}$ while the MW-like Z major merger with similar orbit has a maximum of ~8 $M_{\odot} Yr^{-1}$ yet these two galaxies are roughly the same mass.

- To a lesser degree, the presence of a bulge and the merger orbit also affect the star formation. Similarly, the initial cold gas distribution (extended or not) changes the relative SF during a burst.

Conclusions (con't)

- Minor mergers of mass ratios greater than 1:5 enhance star formation over that of quiescent galaxies.
- Mergers involving small mass halos are different from mergers between galaxies the size of the Milky way. Star formation tends to ensue for longer periods after the final merger, feedback plays a much larger role and the increase is many-fold over the star formation that would have quiescently occurred. But much gas remains after the merger, and forms a disk.
- Major mergers convert orbital energy to gas thermal energy via shock heating.

In the future, we must:

- Better understand the relationship between angular momentum and star formation.
- Quantify the remnant properties (stellar profiles, dark matter contraction, relationship to the fundamental plane of ellipticals, central gas disks, formation of tidal dwarfs, feeding of central black holes) as a function of everything.
- Compare to observations systematically. Chalenge: need to determine masses of observed interacting galaxies.

Simulations of Dust in Interacting Galaxies

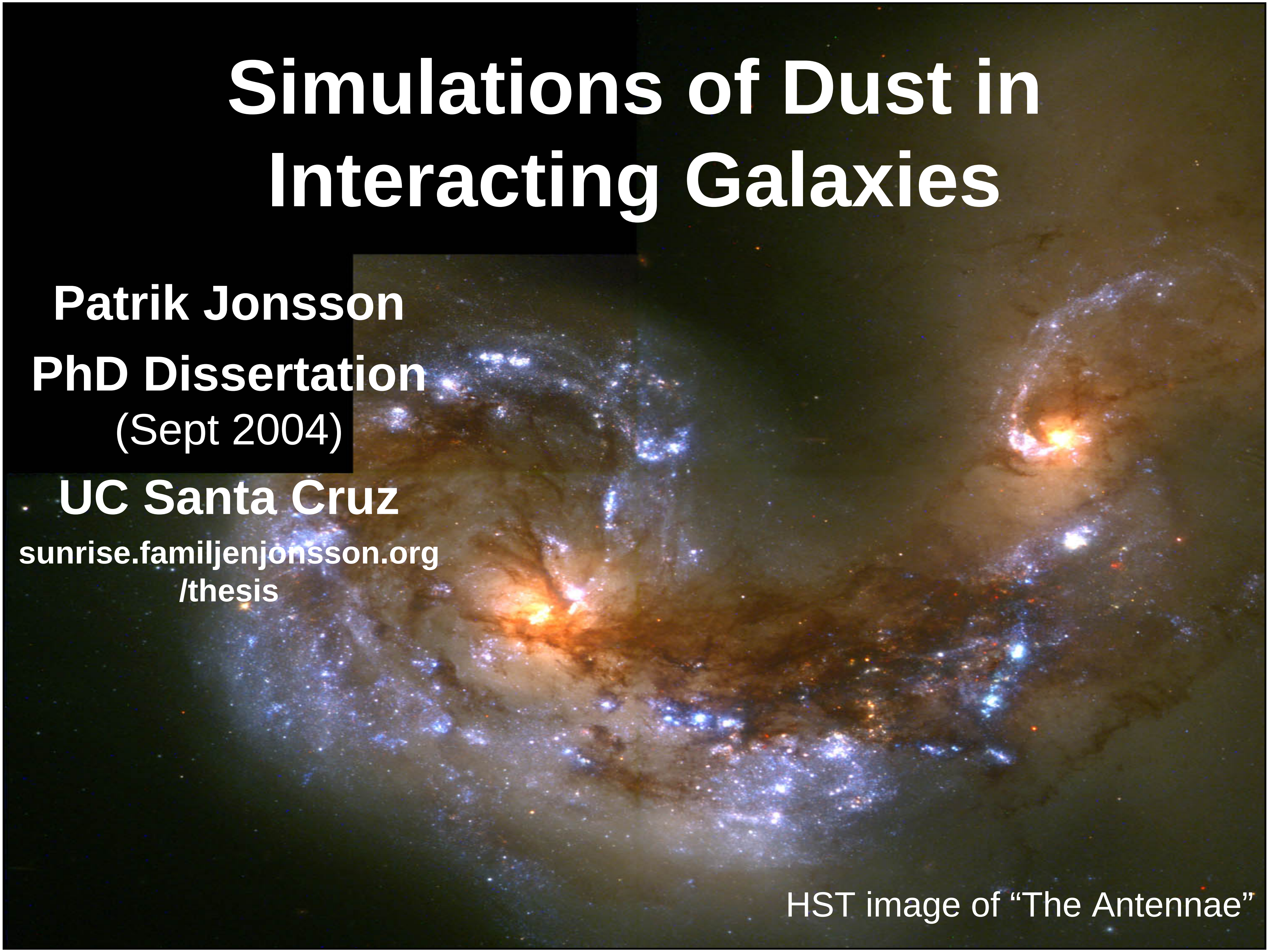
Patrik Jonsson

PhD Dissertation

(Sept 2004)

UC Santa Cruz

sunrise.familjenjonsson.org /thesis



HST image of “The Antennae”

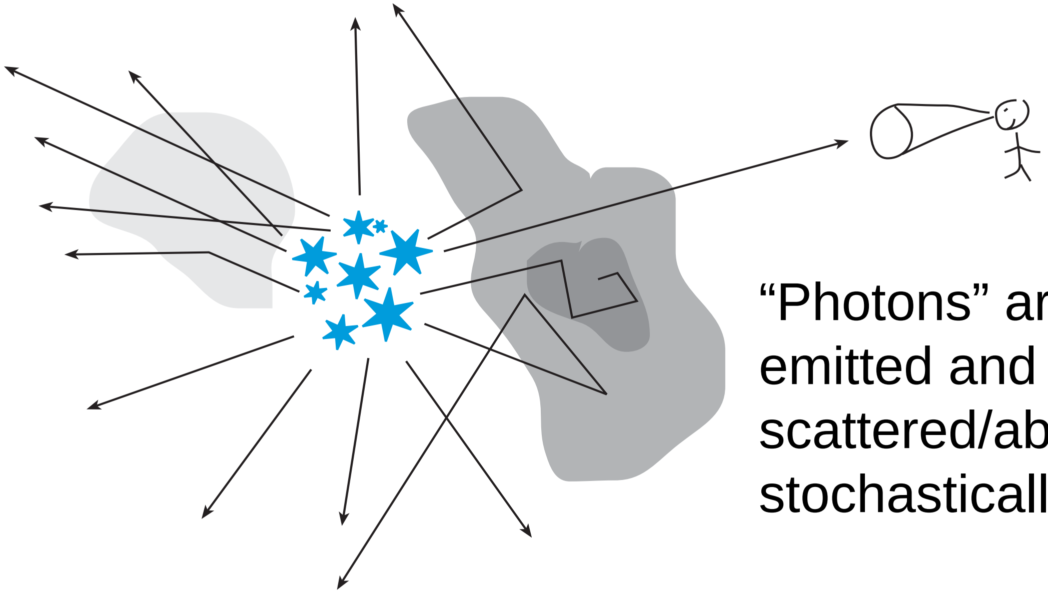
Introduction

- Dust in galaxies is important
  - Absorbs about 40% of the local bolometric luminosity
  - Makes brightness of spirals inclination-dependent
  - Completely hides the most spectacular bursts of star formation
  - Makes high-redshift SF history very uncertain
- Dust in galaxies is complicated
  - The mixed geometry of stars and dust makes dust effects geometry-dependent and nontrivial to deduce
  - Needs full radiative transfer model to calculate realistically
- Previous efforts have used 2 strategies
  - Assume a simple, schematic geometry like exponential disks, or
  - Simulate star-forming regions in some detail, assuming the galaxy is made up of such independent regions
  - Have not used information from N-body simulations

Our Approach

For every simulation snapshot:

- SED calculation
- Adaptive grid construction
- Monte Carlo radiative transfer



“Photons” are
emitted and
scattered/absorbed
stochastically

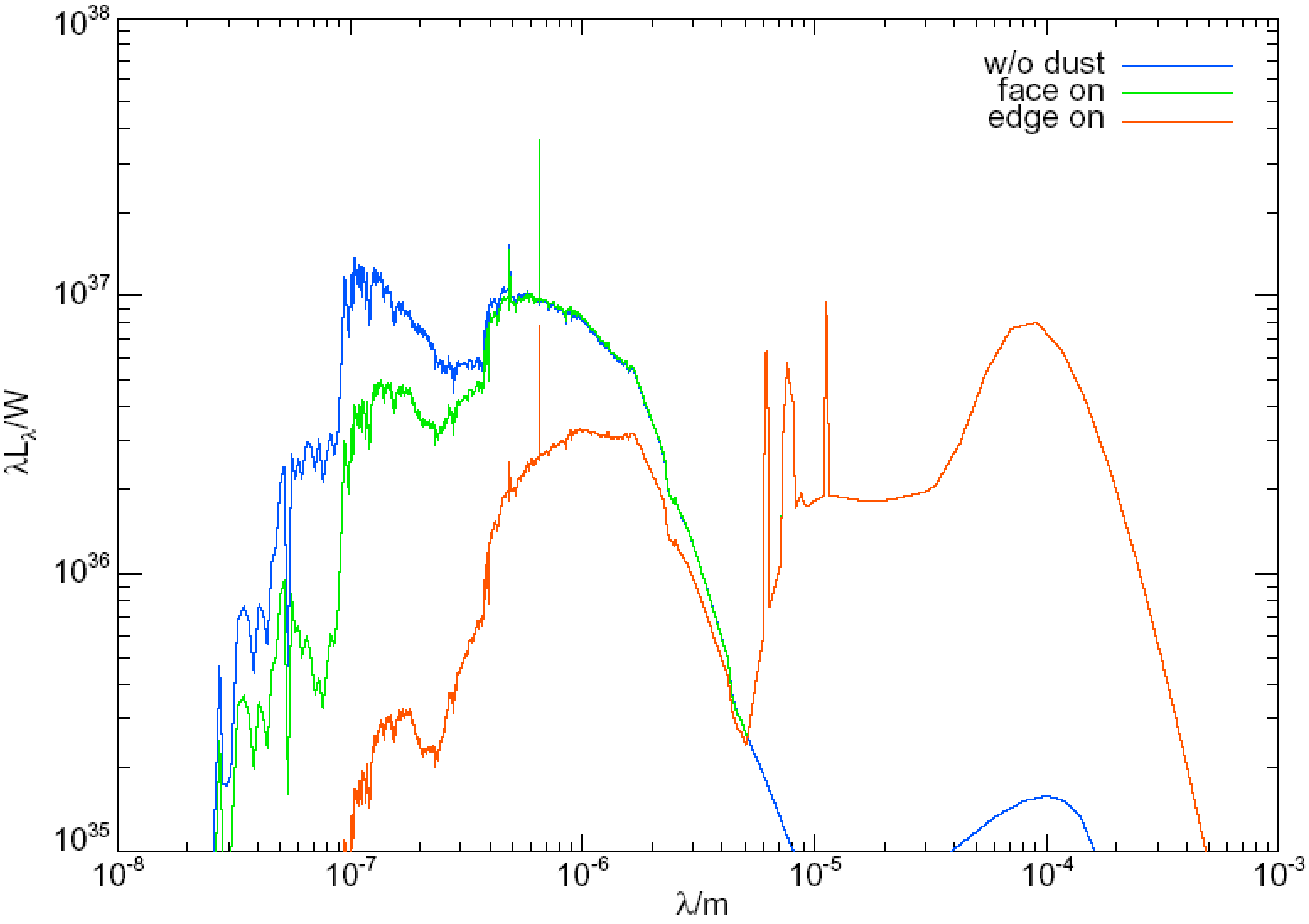
Radiative transfer stage

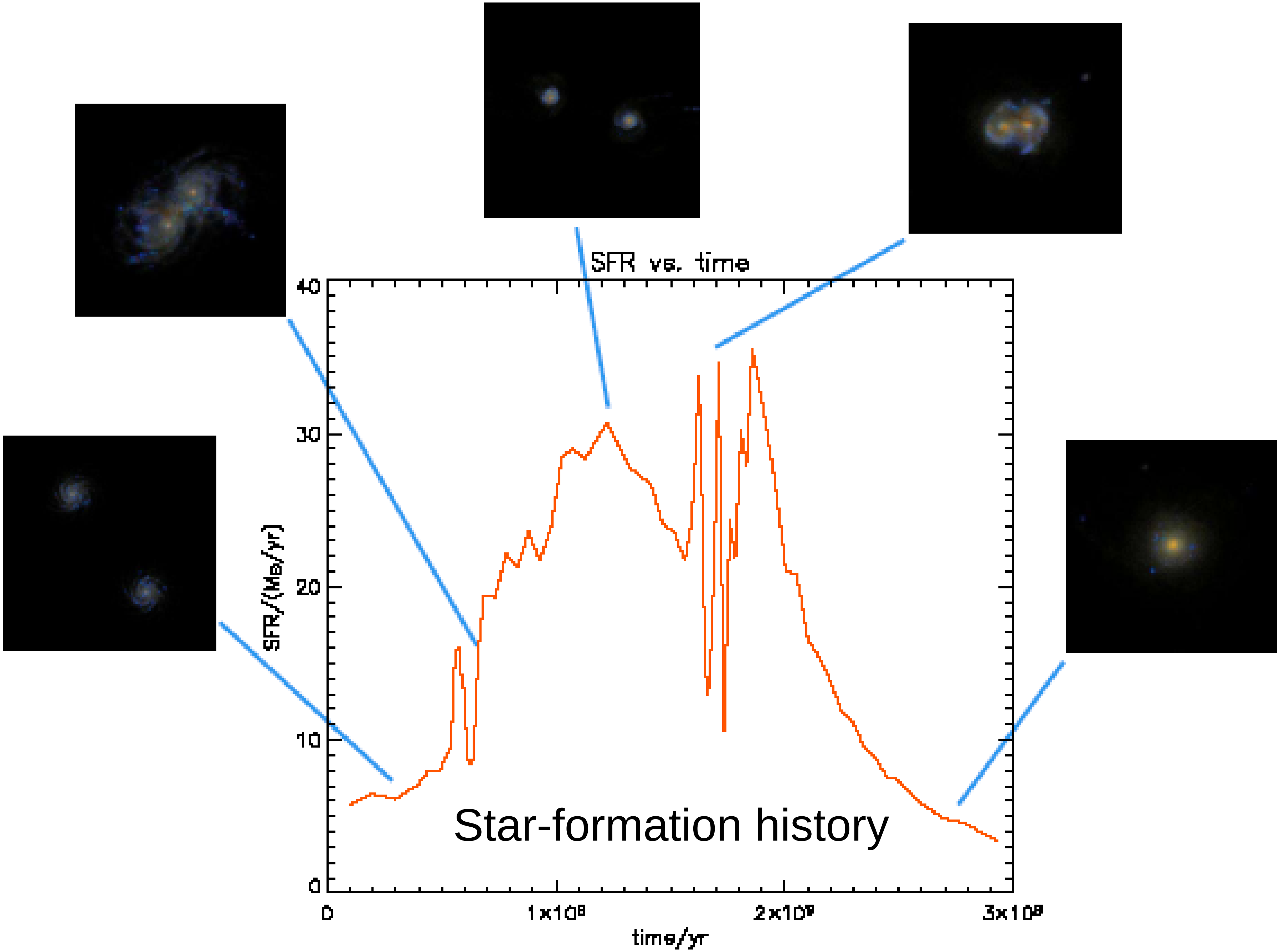
- Run entire SED at once without scattering
- Run with scattering for a single wavelength
- Repeat for all wavelengths desired
- Interpolate SED to full resolution

Outputs

- Data cube for each camera, typically 300x300 pixels x 500 wavelengths
  - Can be integrated to give images in broadband filters
  - Or look at spectral characteristics
- Absorbed energy in grid cells
  - Determines FIR luminosity reradiated by dust
  - Devriendt FIR template SED is added to integrated spectra

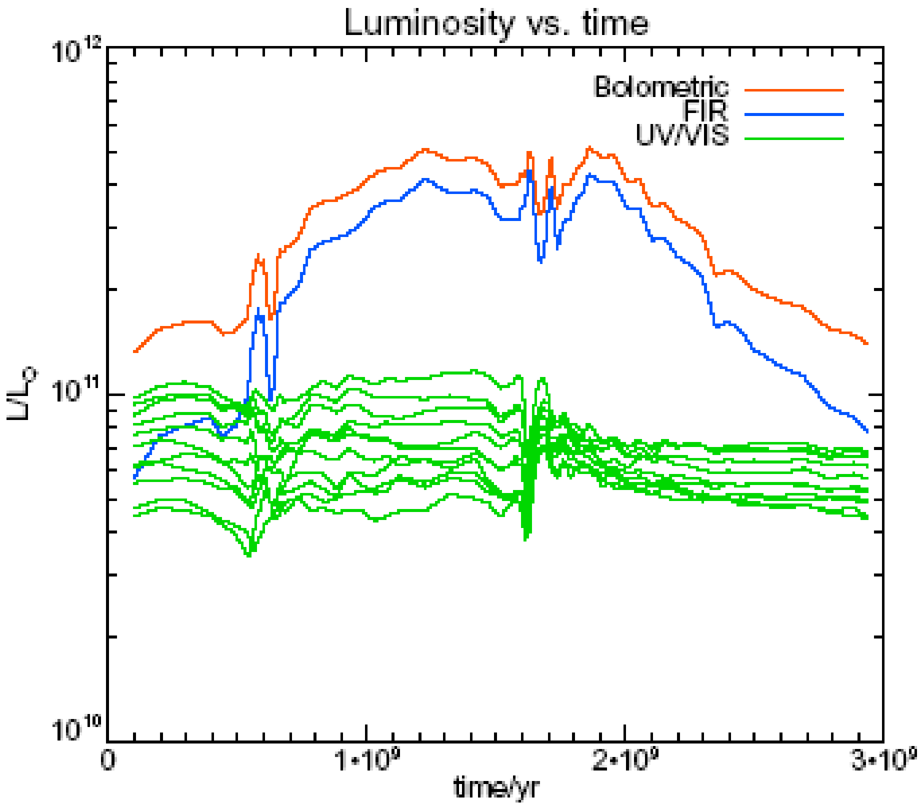
Spectral Energy Distribution

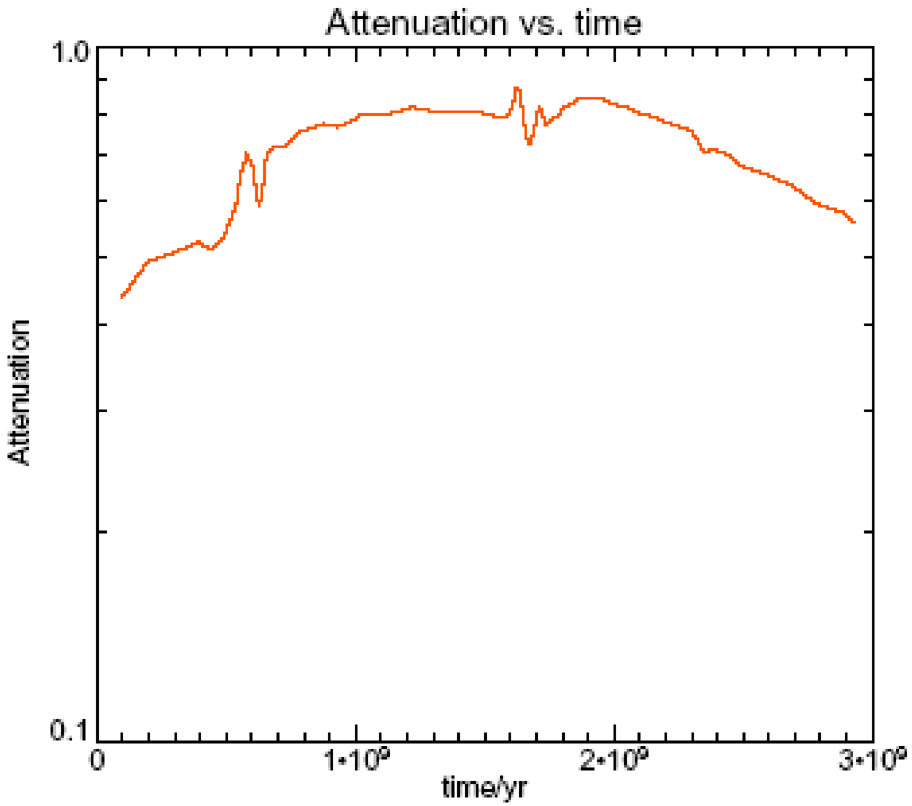




Star-formation history

Luminosities

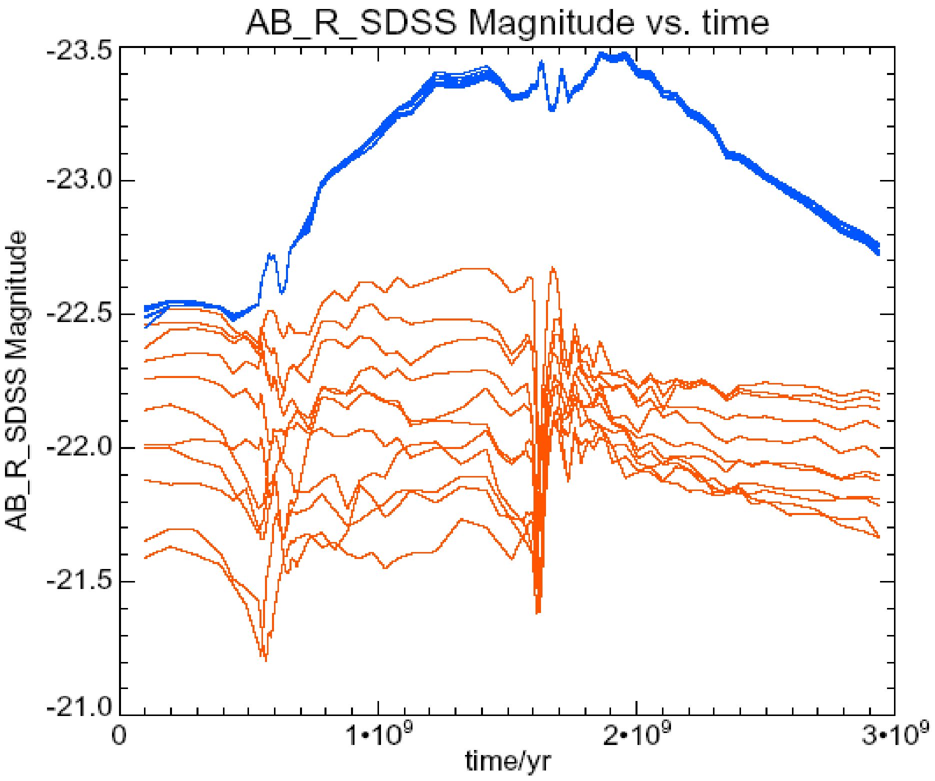


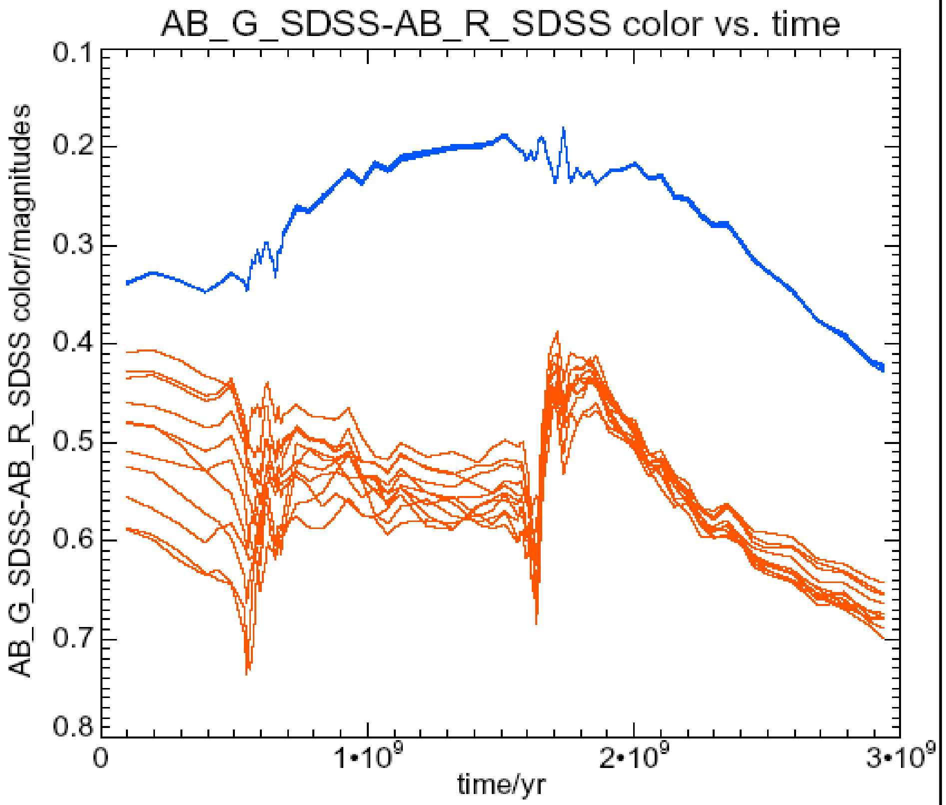


UV/visual luminosity is practically constant over time

Attenuation increases with luminosity

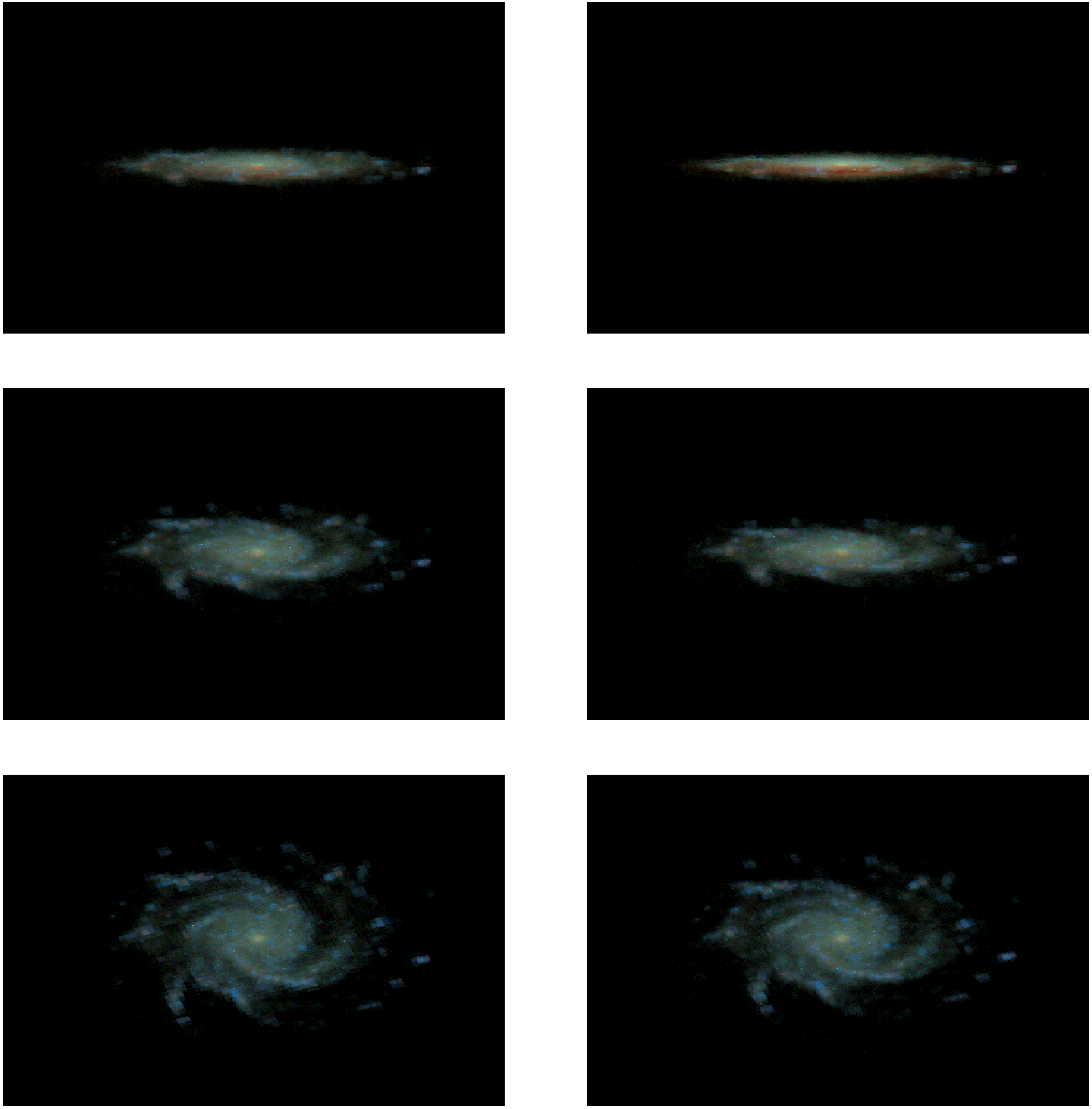
Magnitudes & Colors



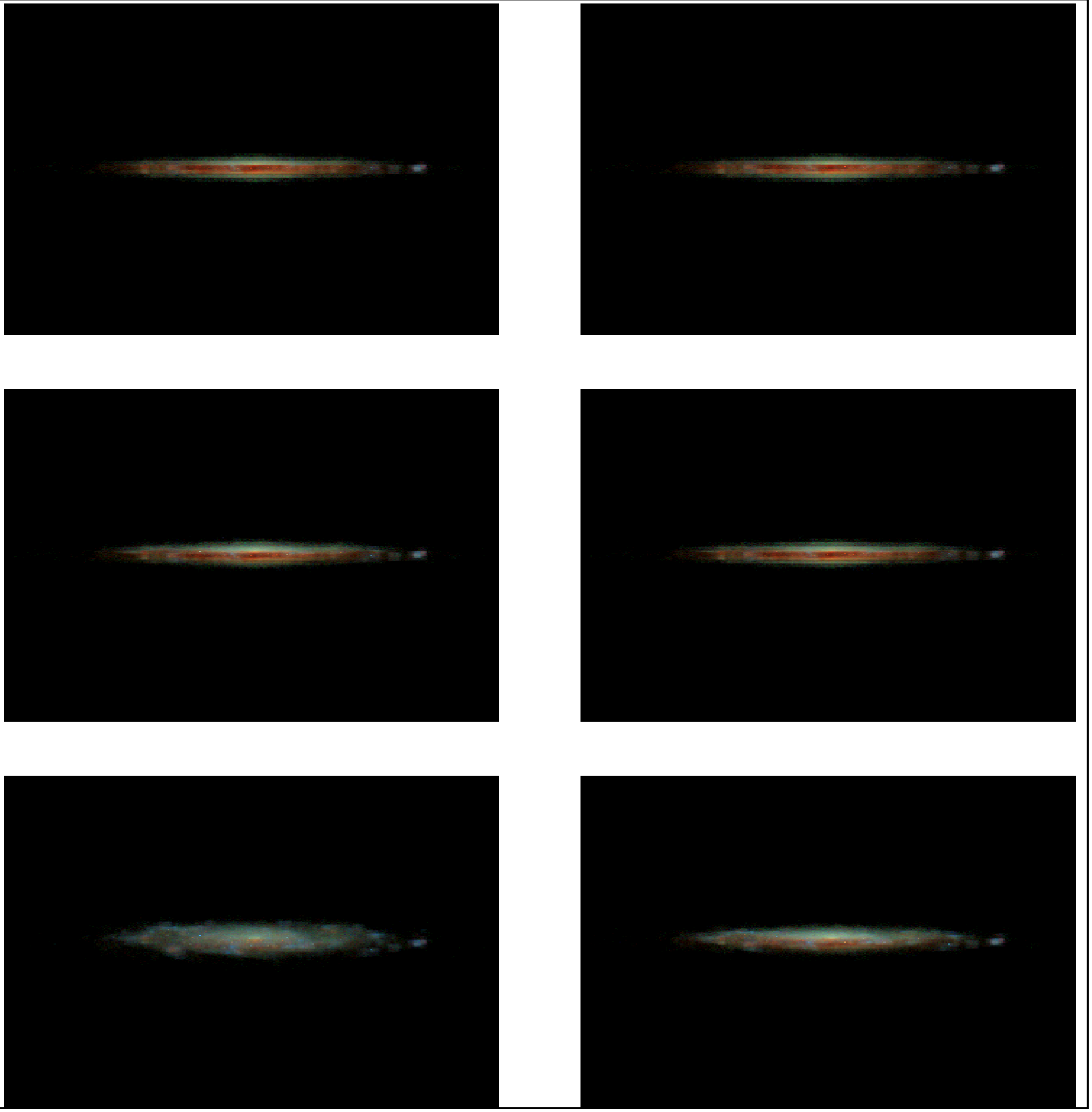


During the transients, the magnitudes and colors with and without dust are **anticorrelated**

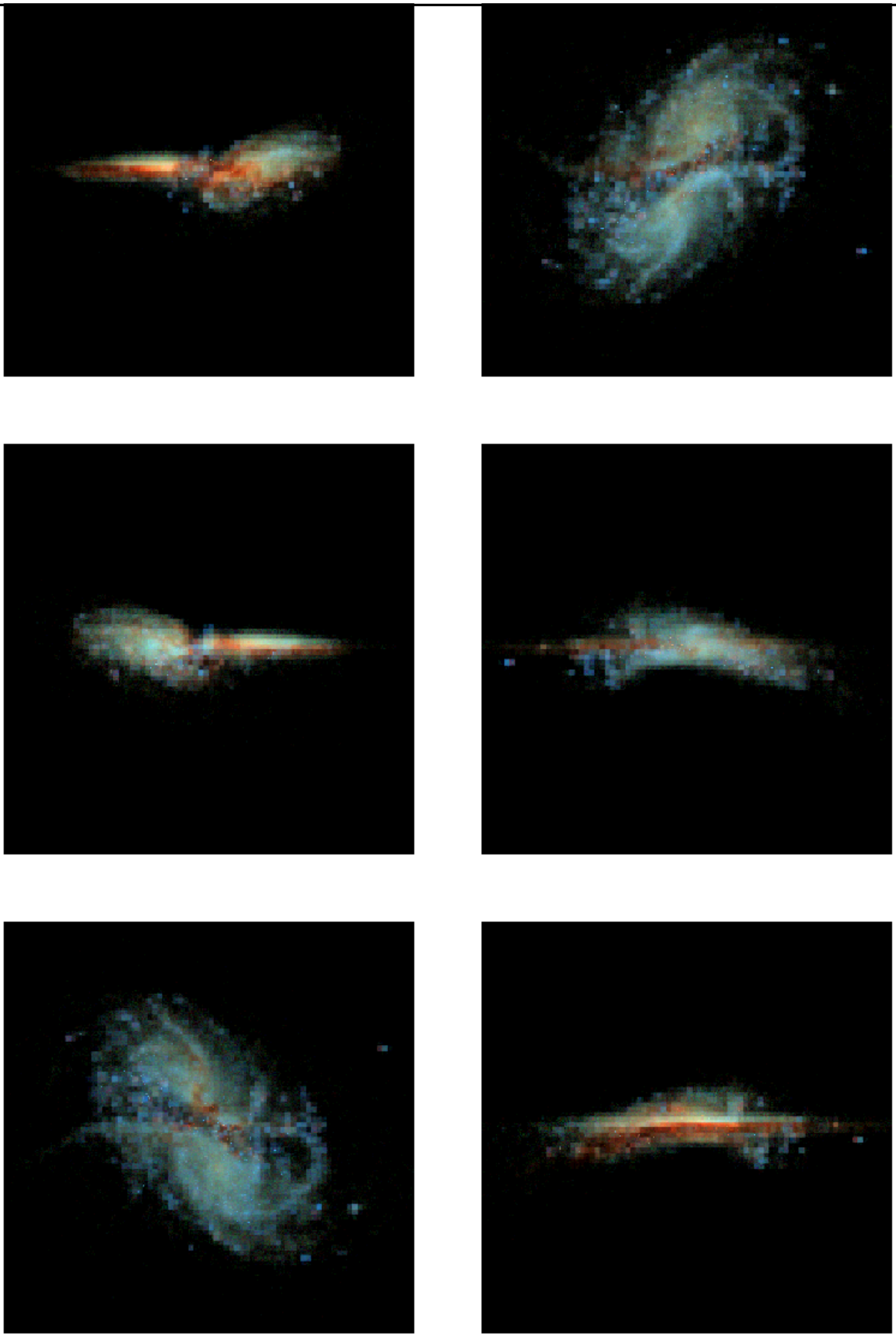
Images of quiescent disk galaxies with effects of dust from Monte Carlo radiative transfer code by Patrik Jonsson



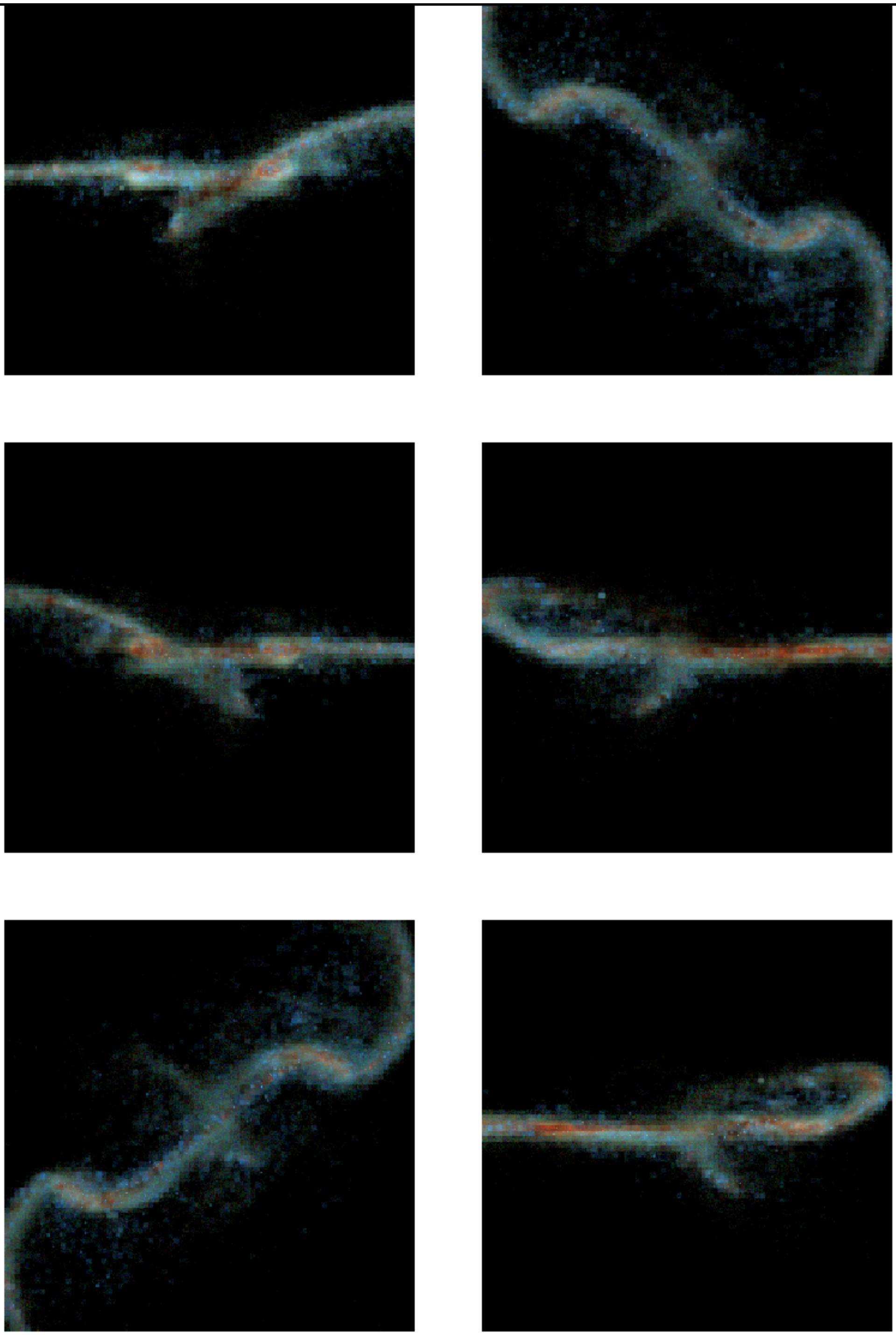
Near edge-on images (with dust) from Monte Carlo radiative transfer code by Patrik Jonsson



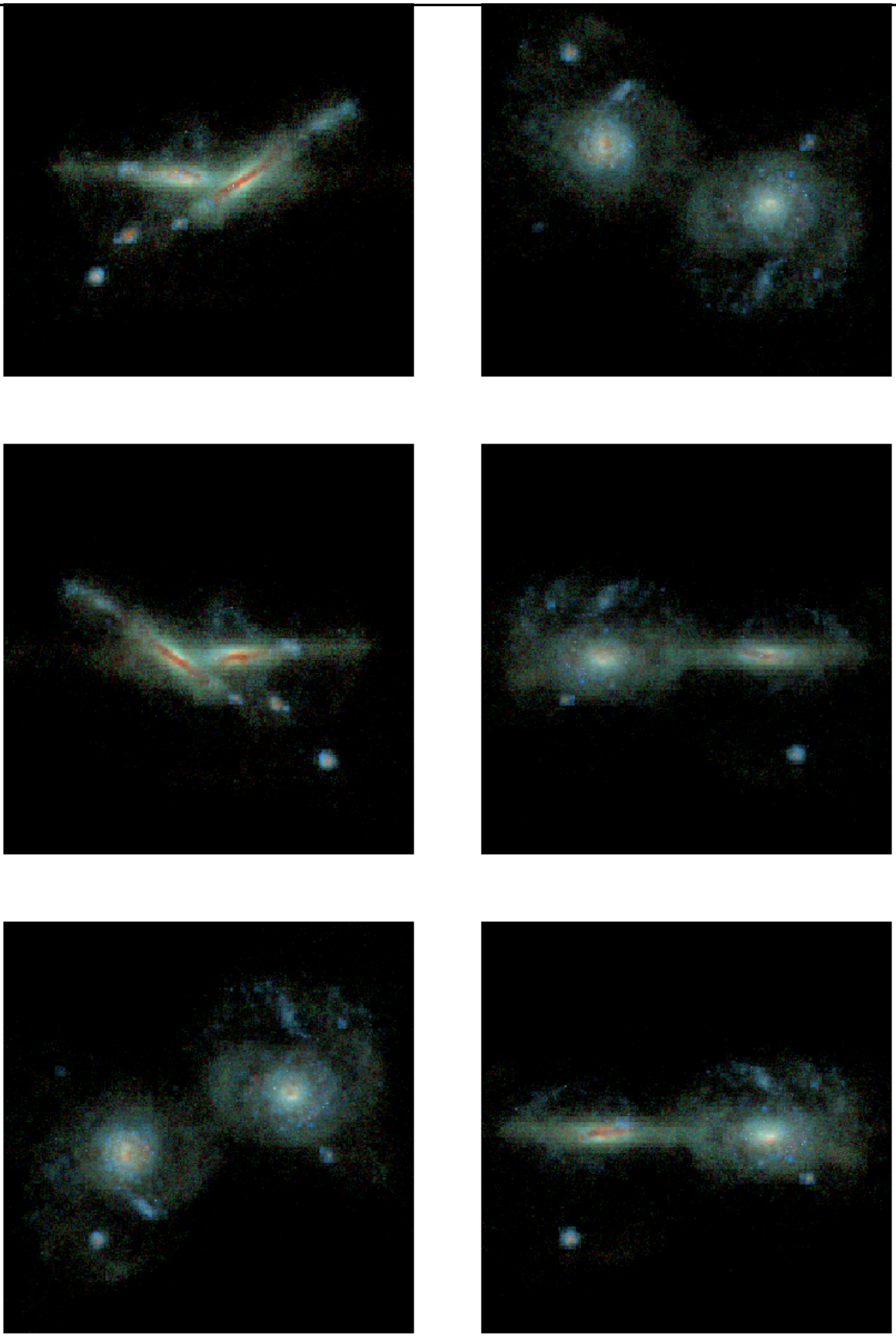
Merger with SEDs and dust: 6 views



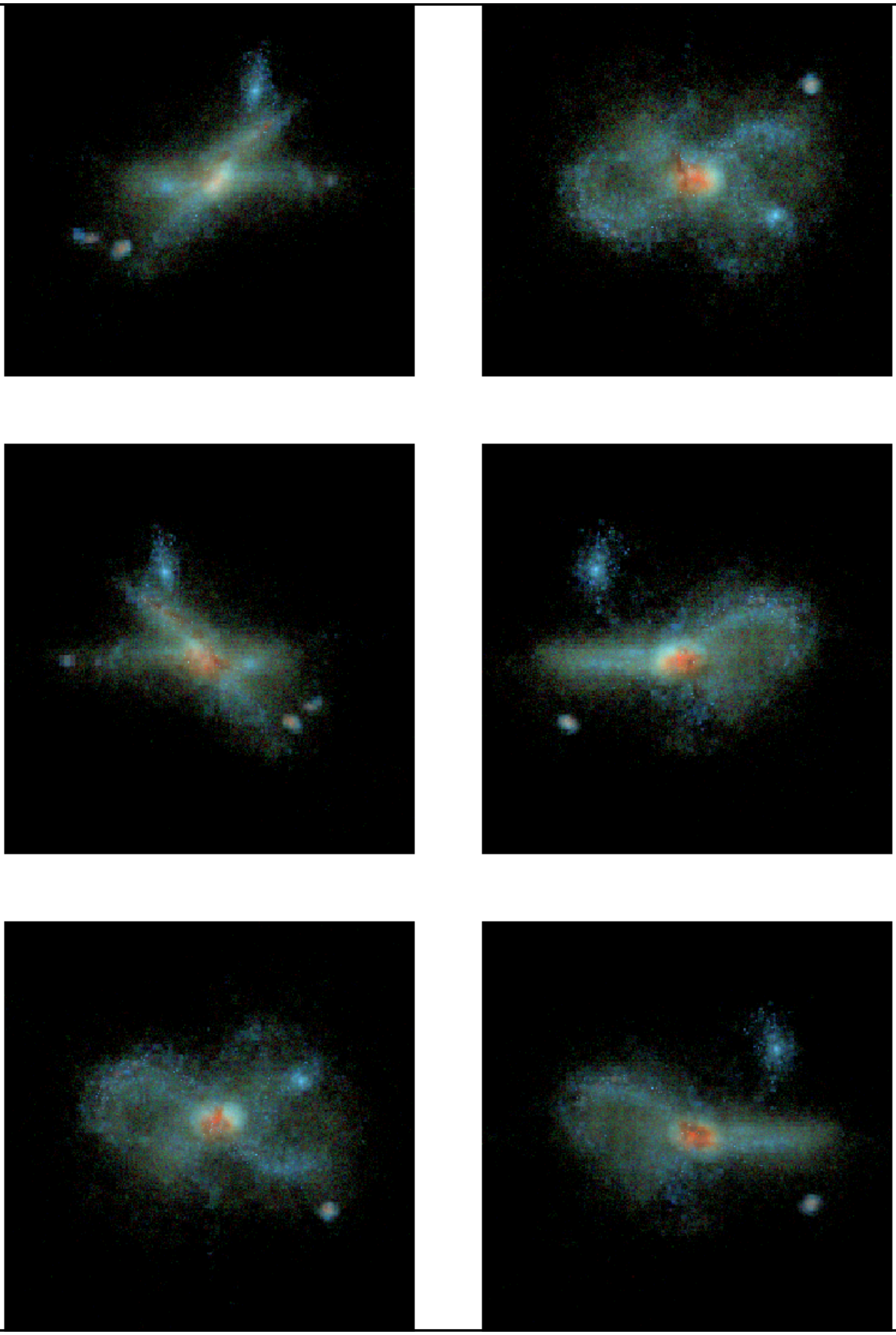
Merger with SEDs and dust: 6 views



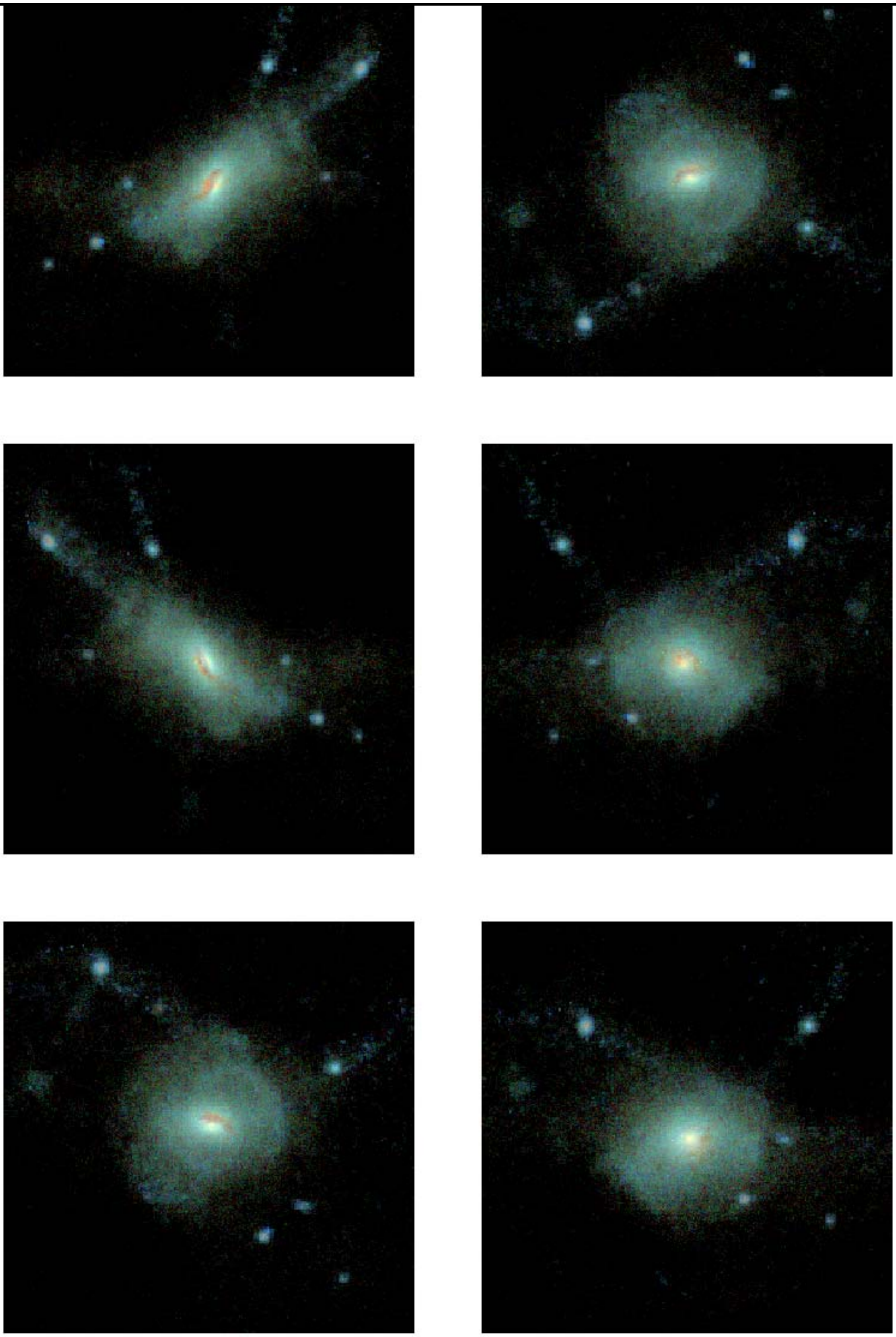
Merger
with
SEDs
and dust:
6 views



Merger with SEDs and dust: 6 views



Merger with SEDs and dust: 6 views



Comparing to IRX-Beta relation

- $\mathrm{IRX}_{1600} = \mathrm{F}_{\mathrm{FIR}}/\mathrm{F}_{1600},$
- UV spectral slope $\beta,$

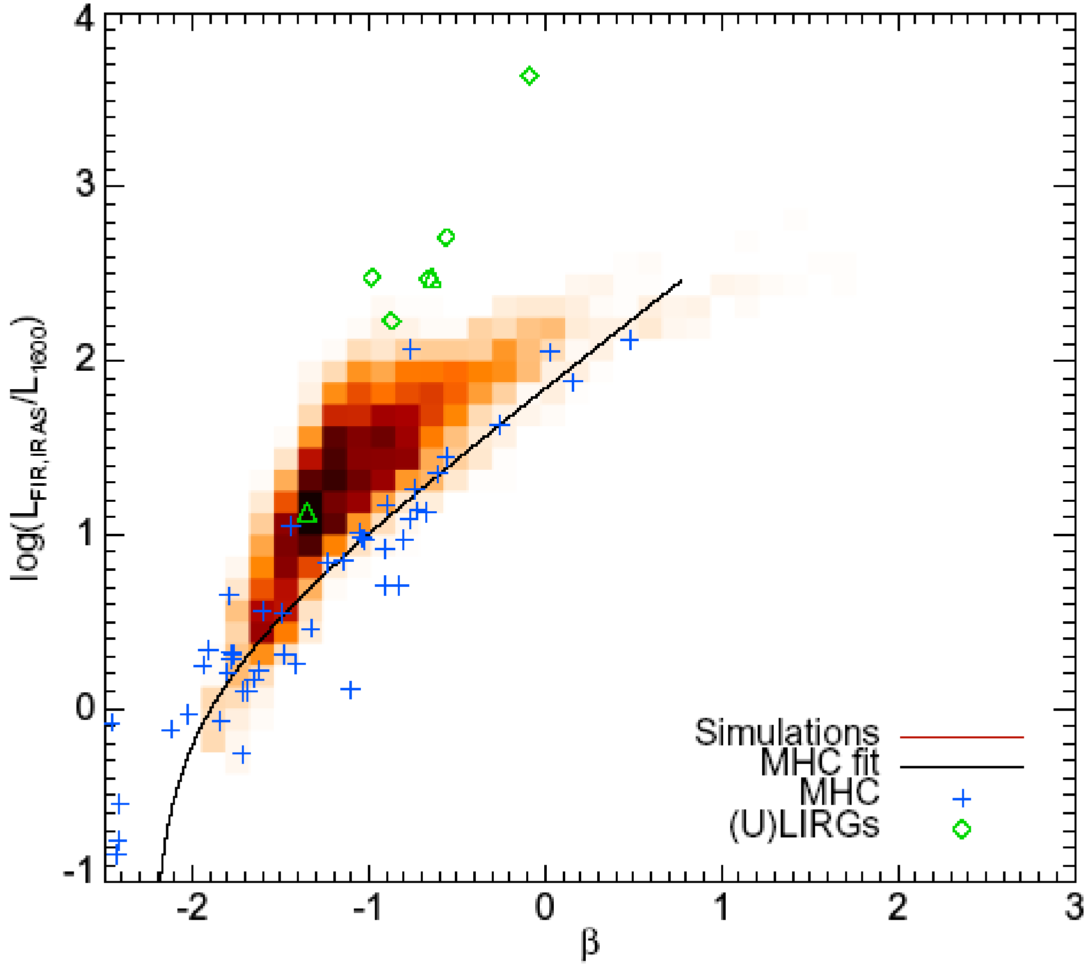
  Determined by fitting $f_\lambda \propto \lambda^\beta.$

- Observed sample is starbursts observed with IUE (Meurer, Heckman, Calzetti 99)
- Also ULIRGS (Goldader 02)

IRX-Beta relation

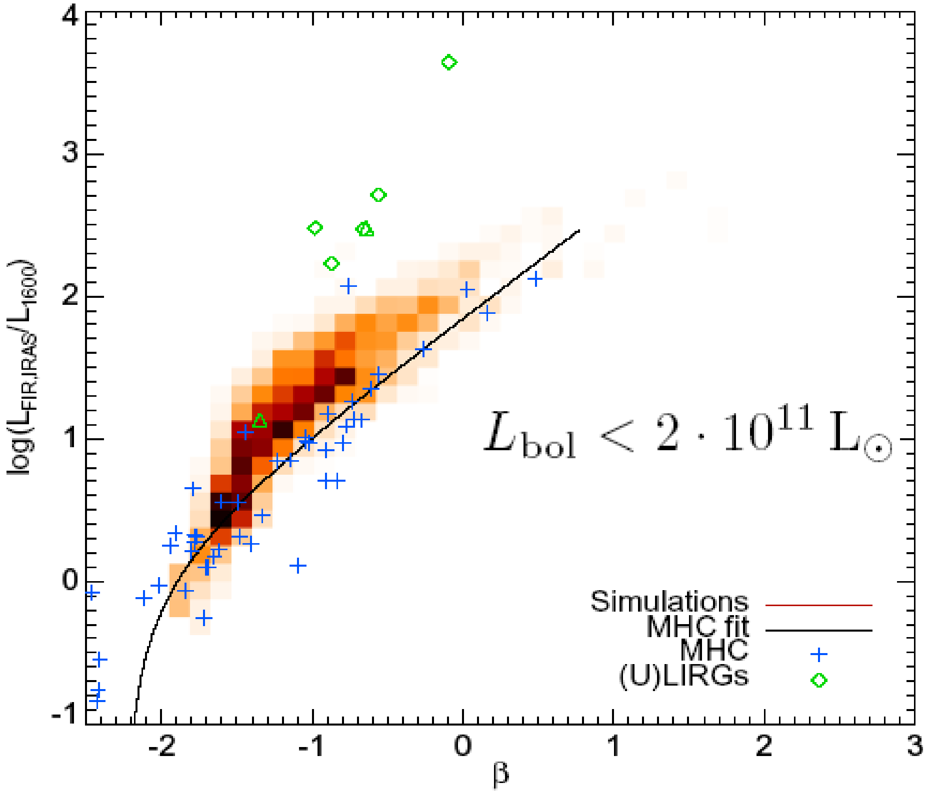
↑

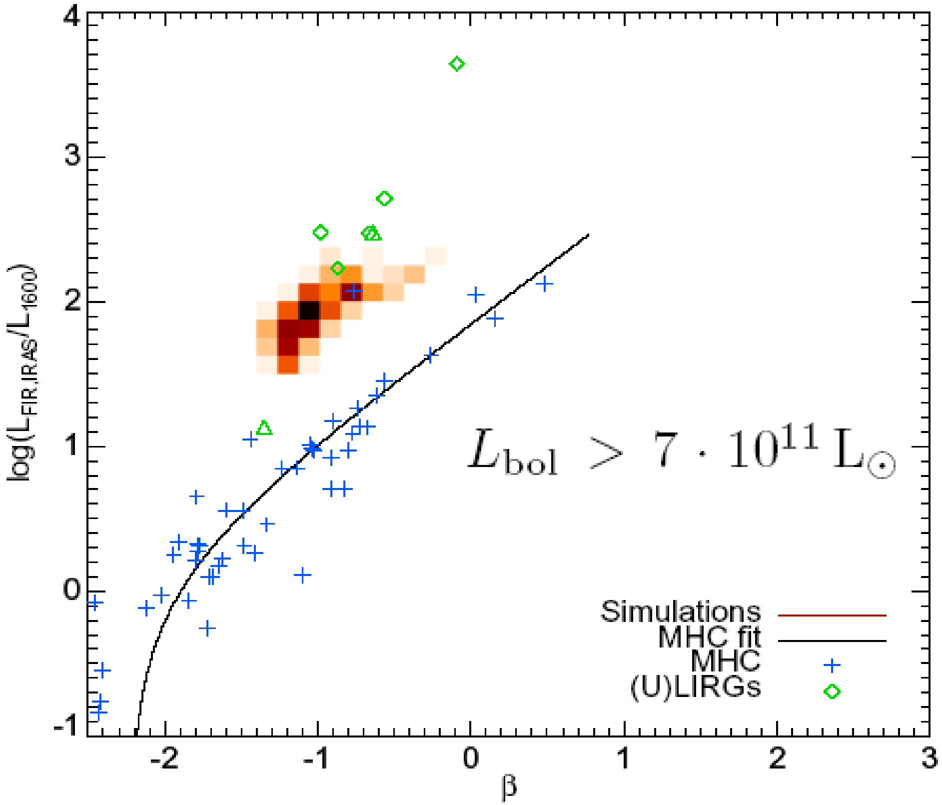
$$\frac{L_{FIR}}{L_{UV}}$$



Observed sample is starbursts observed with IUE (Meurer, Heckman, Calzetti 99) and ULIRGS (Goldader 02). UV continuum slope is β.

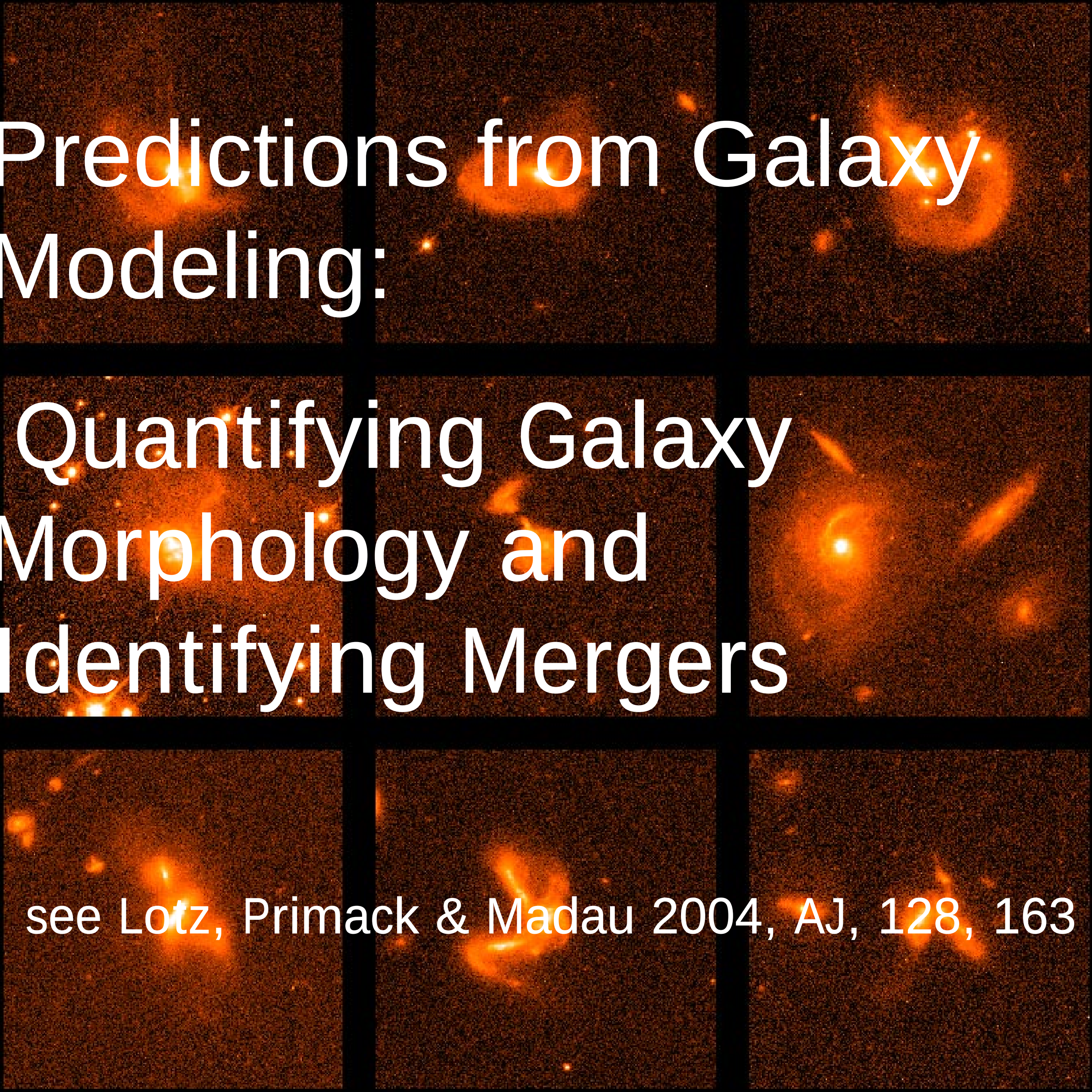
Split by Luminosity





- Simulated lower-luminosity galaxies follow an IRX-β relation similar to the observed MHC99 galaxies

- high-luminosity galaxies occupy the region where U/LIRGs are



Predictions from Galaxy Modeling:

Quantifying Galaxy Morphology and Identifying Mergers

see Lotz, Primack & Madau 2004, AJ, 128, 163

Measuring Galaxy Morphology

- by “eye” - Hubble tuning fork E-Sa-Sb-Sc-Sd-(Irr)

- parametric

  1-D profile fit ($r^{1/4}$, exponential, Sersic)

  2-D profile fit (bulge+disk; GIM2D, GALFIT)

  → doesn’t work for irregular/merging galaxies

- non-parametric

  “CAS” - concentration, asymmetry, clumpiness

  neural-net training

  shaplet decomposition

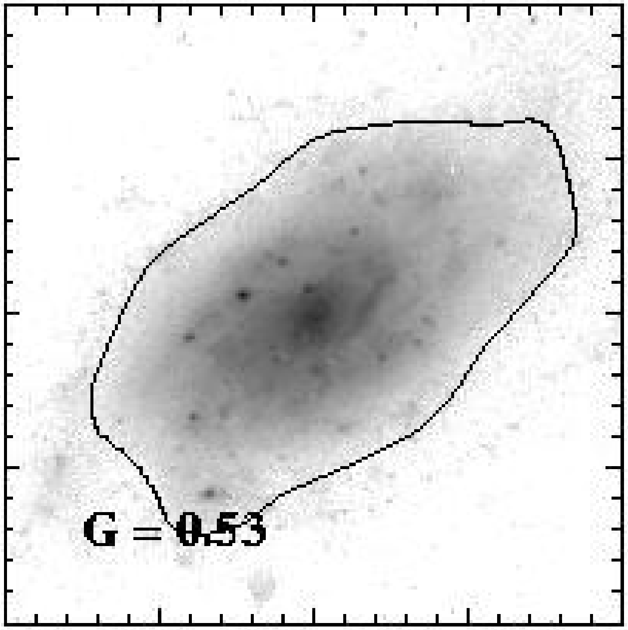
  new: Gini Coefficient (Abraham et al. 2003)

  2nd order moment of brightest regions

The Gini Coefficient

used in economics to measure distribution of wealth in population
→ distribution of flux in galaxy's pixels (Abraham et al. 2003)

G=0 for completely egalitarian society (uniform surf brightness)
G=1 for absolute monarchy (all flux in single pixel)
(G = 0.445 for US in 1999)



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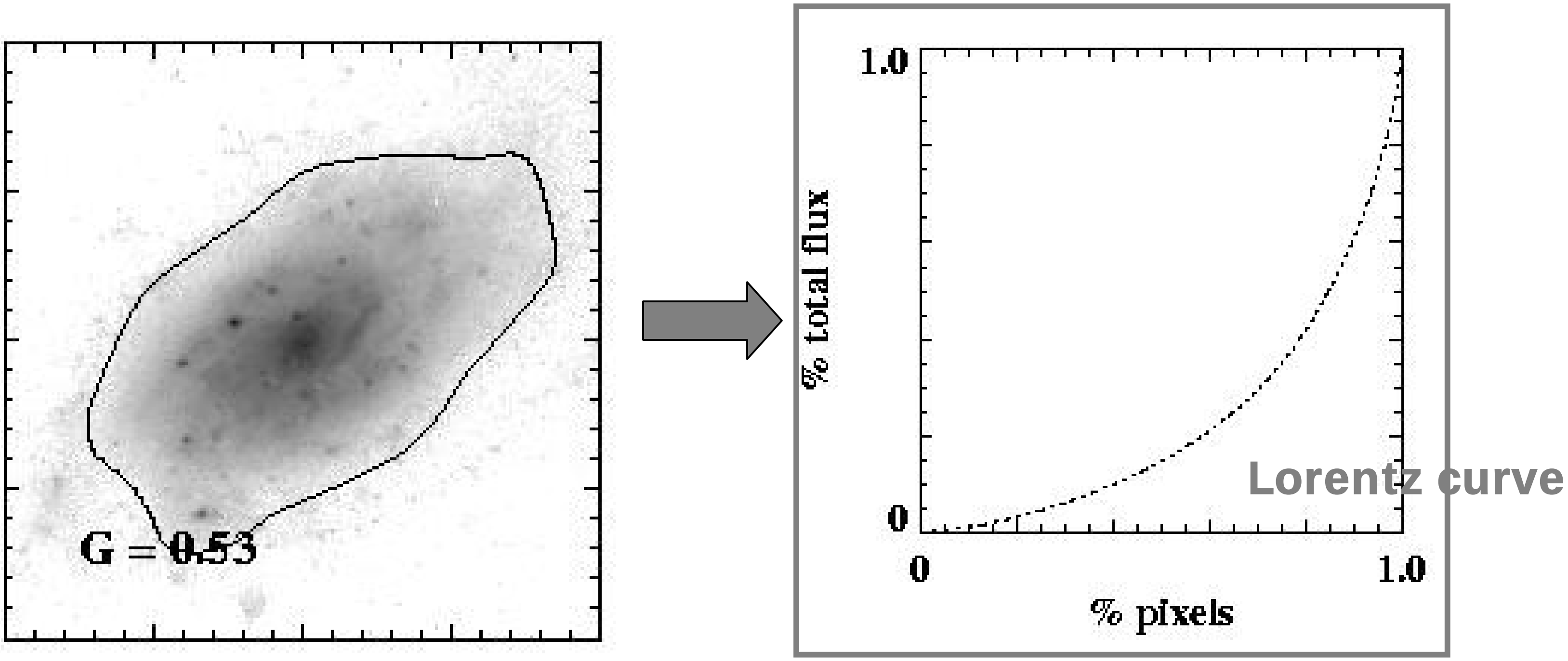

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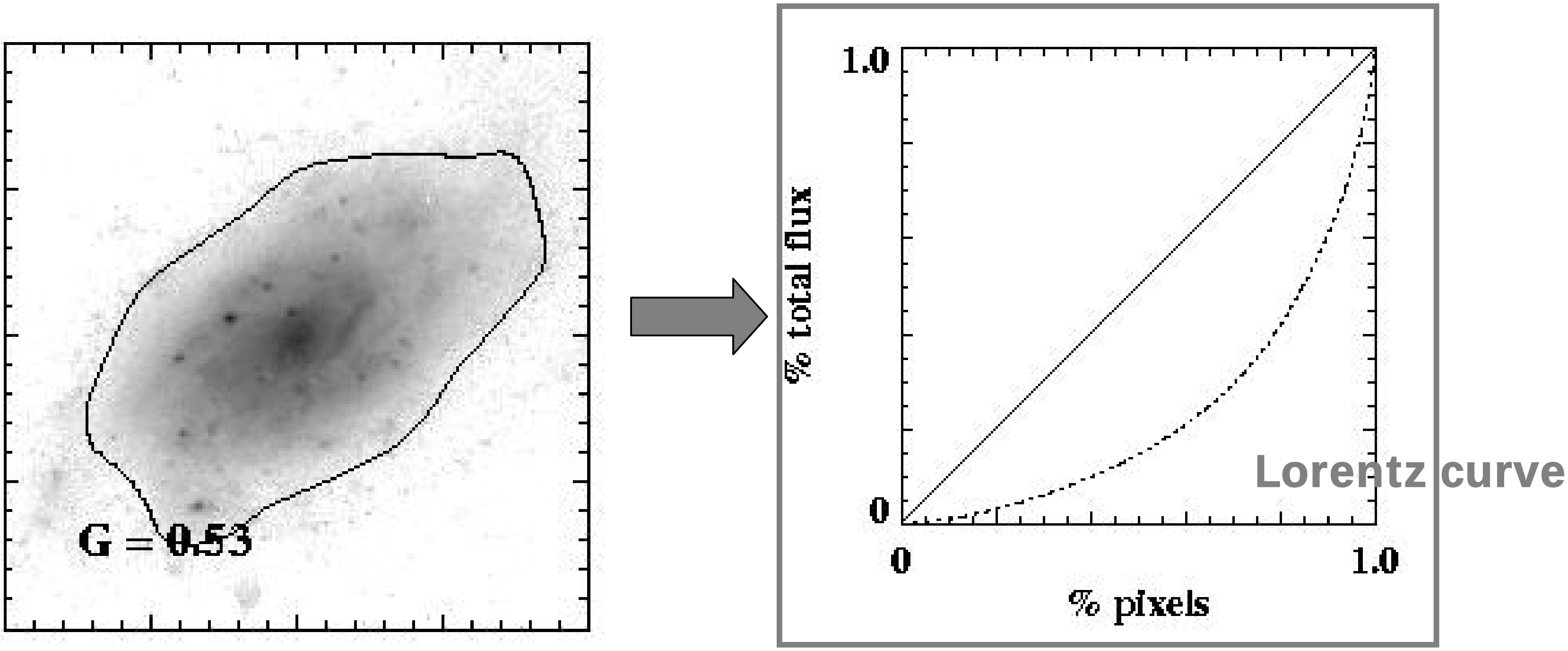

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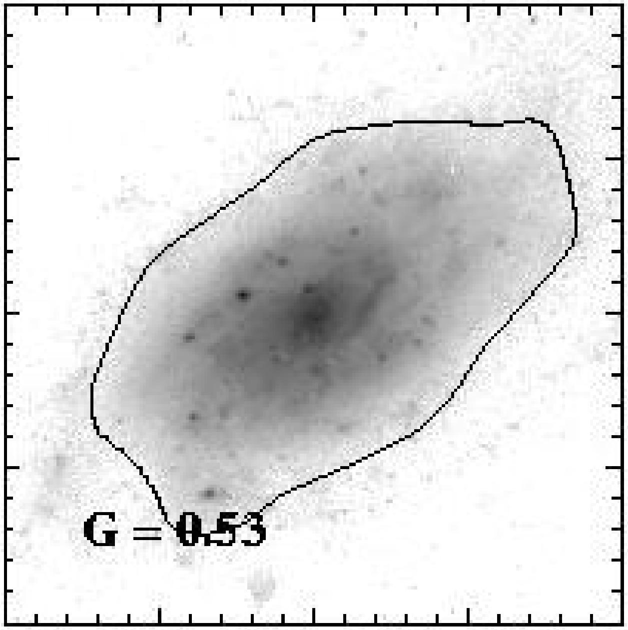

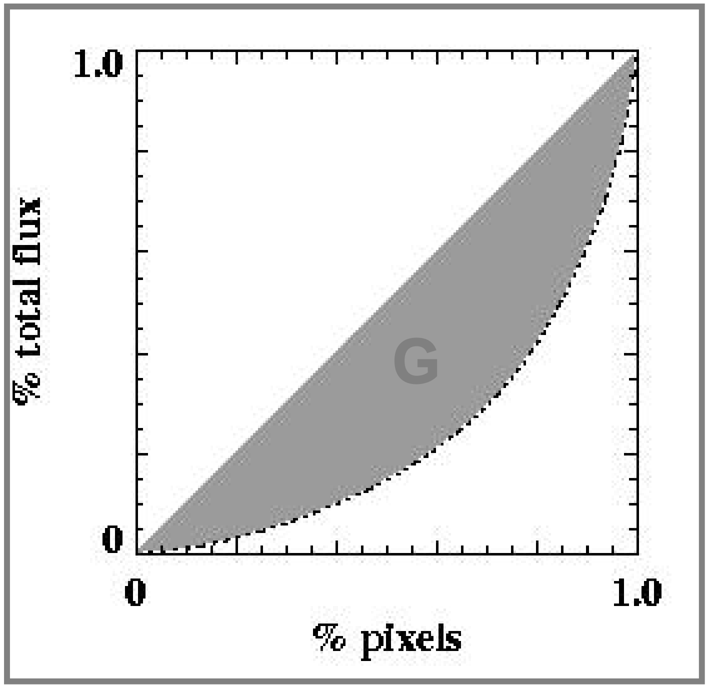

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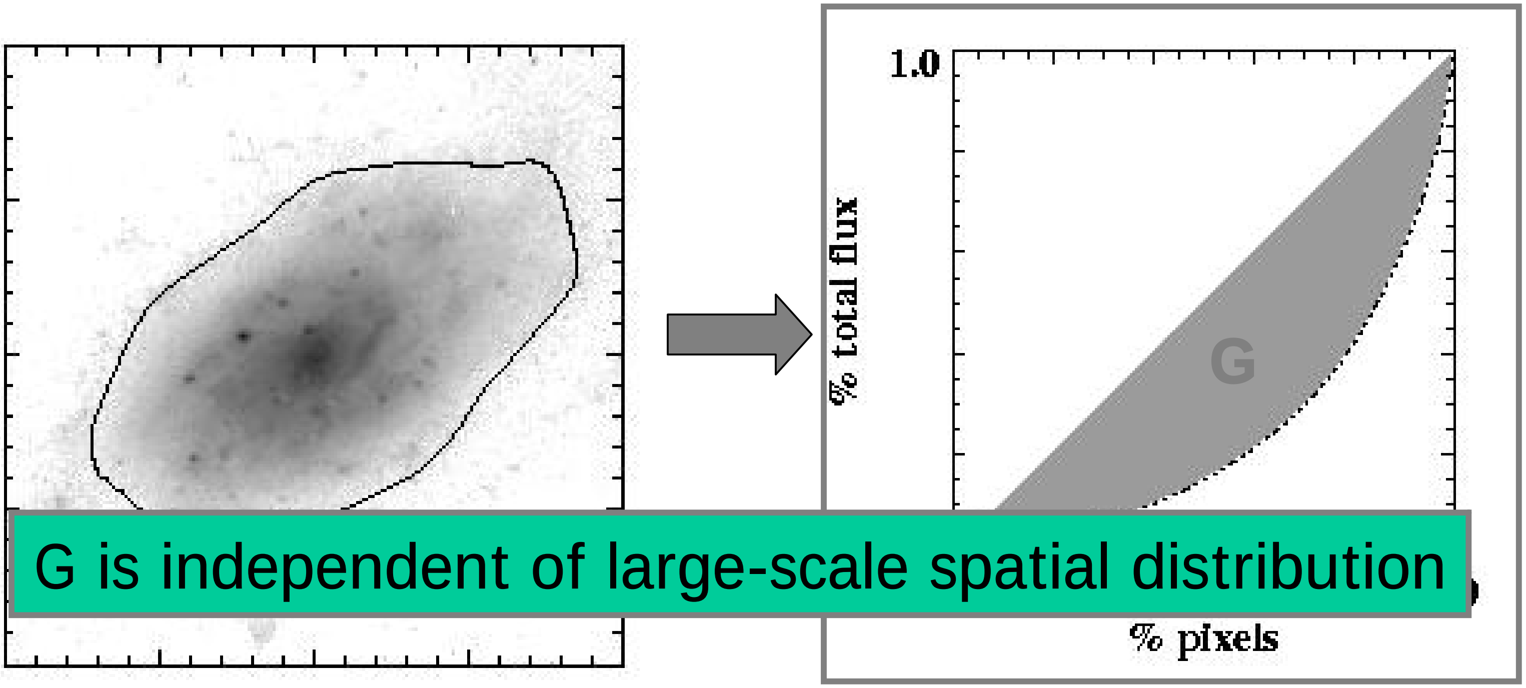
G=1 for absolute monarchy (all flux in single pixel)
(G = 0.445 for US in 1999)



G is independent of large-scale spatial distribution

2^{nd} order moment of light

$M_{total} = \sum_i f_i \cdot r_i^2$ (minimize to find center)

this depends on size + luminosity

→ find *relative* moment of brightest regions

$$M_{20} = \log_{10} \frac{\sum_i^n f_i \cdot r_i^2}{M_{total}}$$ where $$\sum_i^n f_i = 0.2 \sum_i f_i$$

- very similar to C (= log ($r_{80\%}/r_{20\%}$))
  but does NOT assume particular geometry

- more sensitive to merger signatures (double nuclei)

Defining the galaxy map

G + M_{20} depend on which pixels/spatial regions are assigned to galaxy

want this “map” to be insensitive to S/N, surface brightness, and distance/redshift

➔ pixels with $\mu > \mu(r_p)$ are assigned to galaxy

Petrosian radius r_p based on curve of growth

$$\eta = \frac{\mu(r_p)}{\langle \mu(r < r_p) \rangle} \equiv 0.2$$

insensitive to S/N + surface brightness dimming

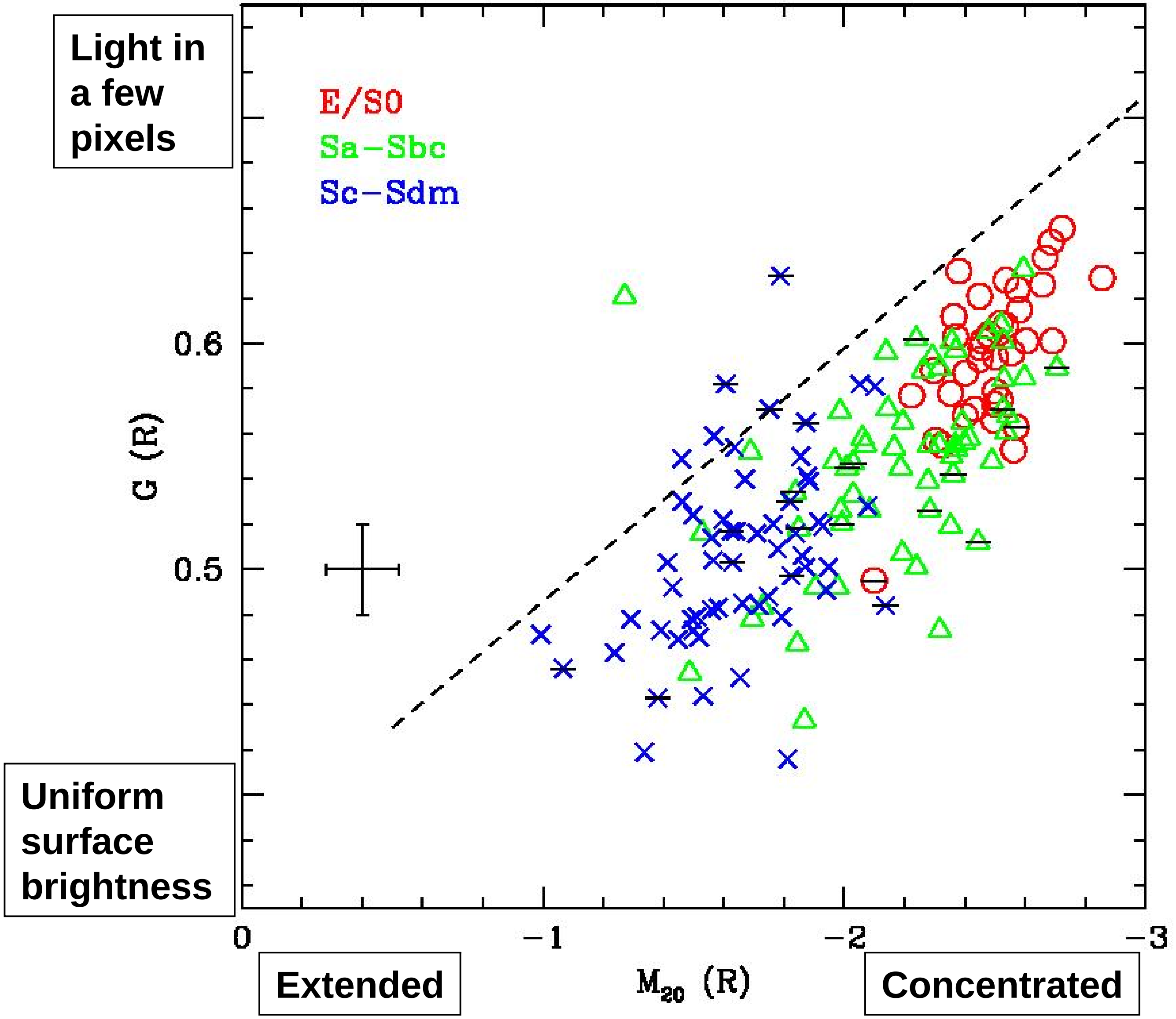
Local Galaxy G-M20 relation

Frei et al 1996: ~100 bright local Hubble types
B/g (~4500 AA) + R/r (~6500 AA)

SDSS DR1: ~50 local bright (u<14) galaxies
u (~3600 AA), g (~4700 AA), r(~6200 AA)

Borne et al 2000: ~100 HST WFPC2 z < 0.2 ULIRGs
F814W (~ 6500 AA rest-frame)

Local Galaxy G-M20 relation



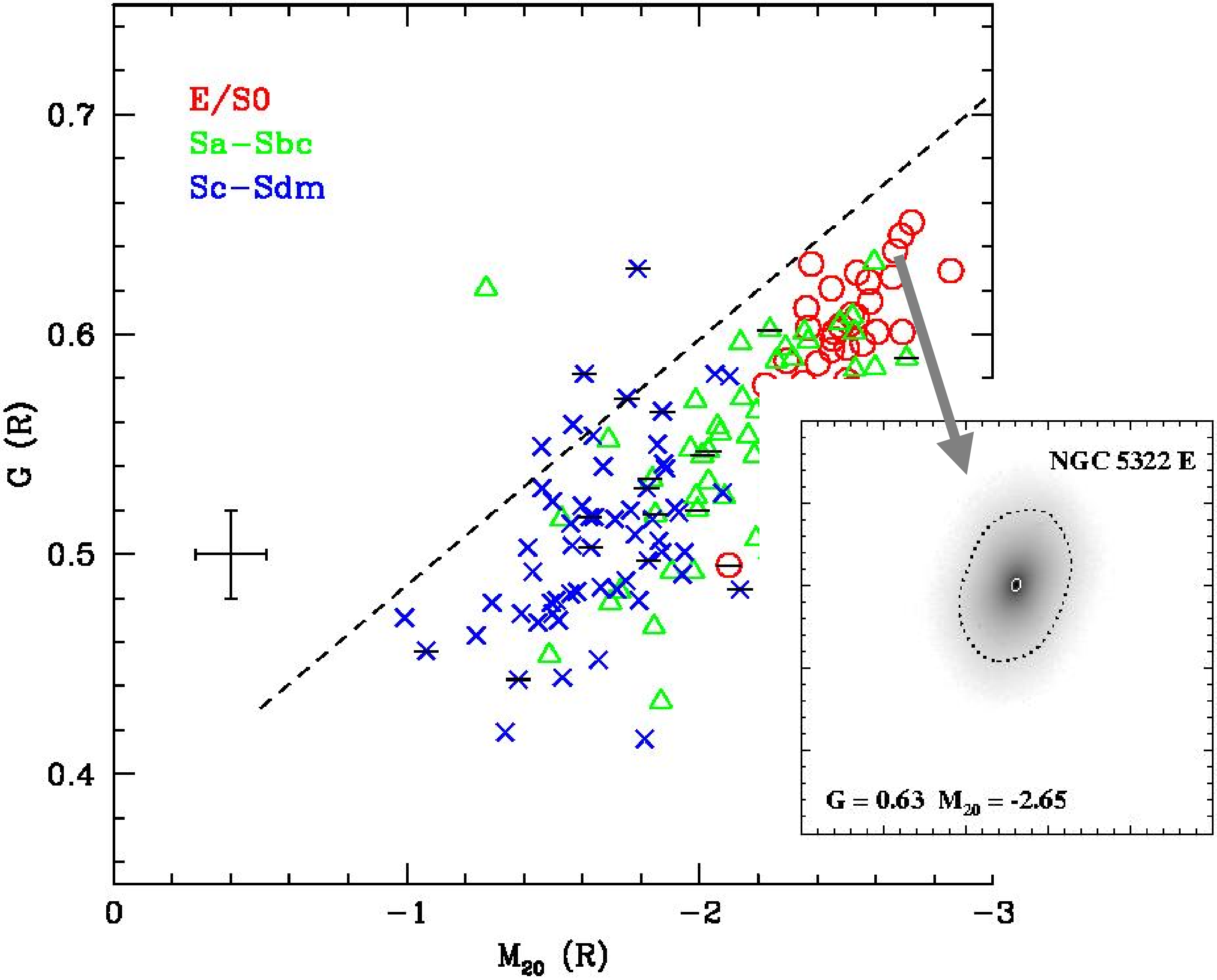
Light in a few pixels

Uniform surface brightness

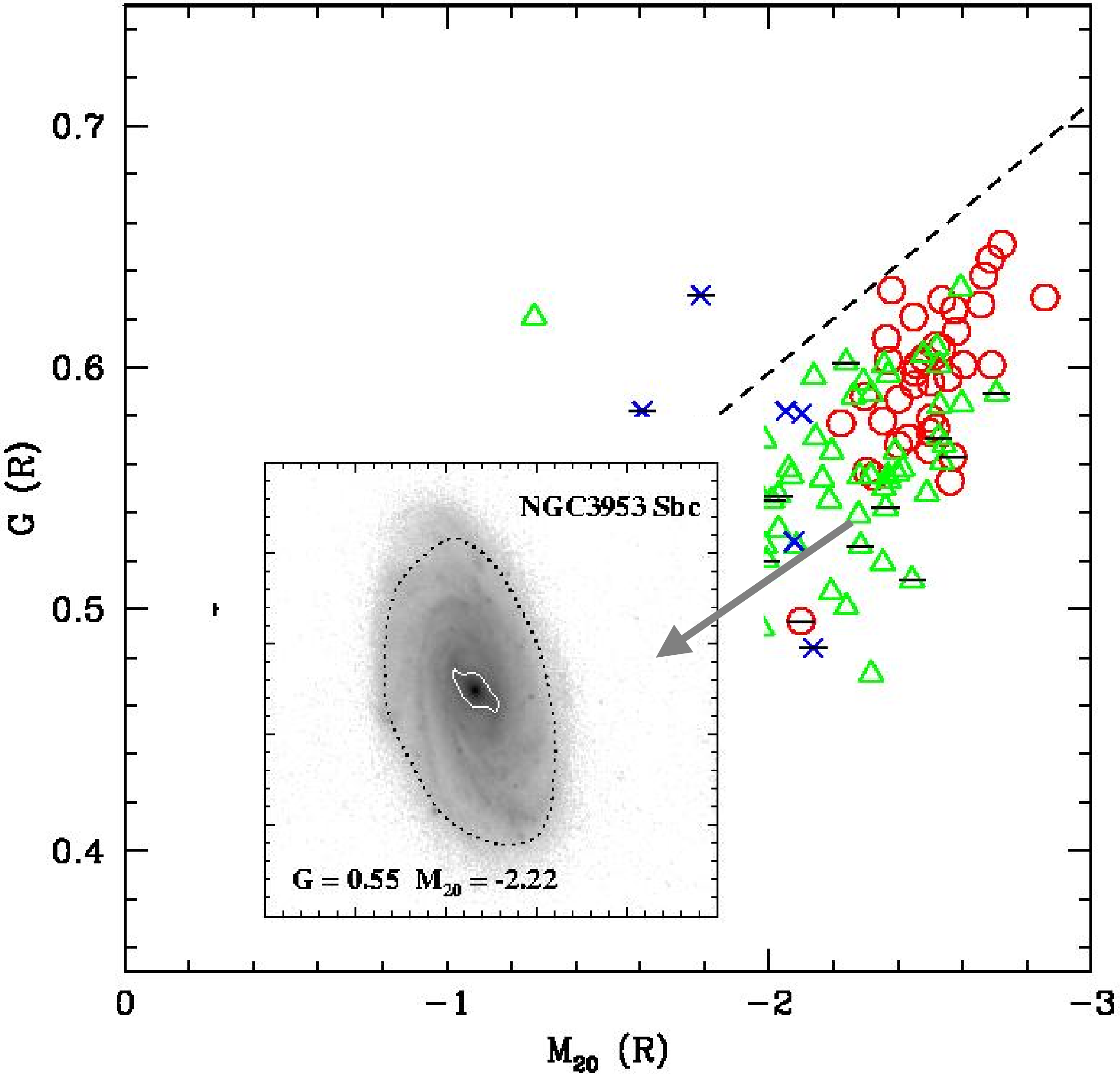
Extended

Concentrated

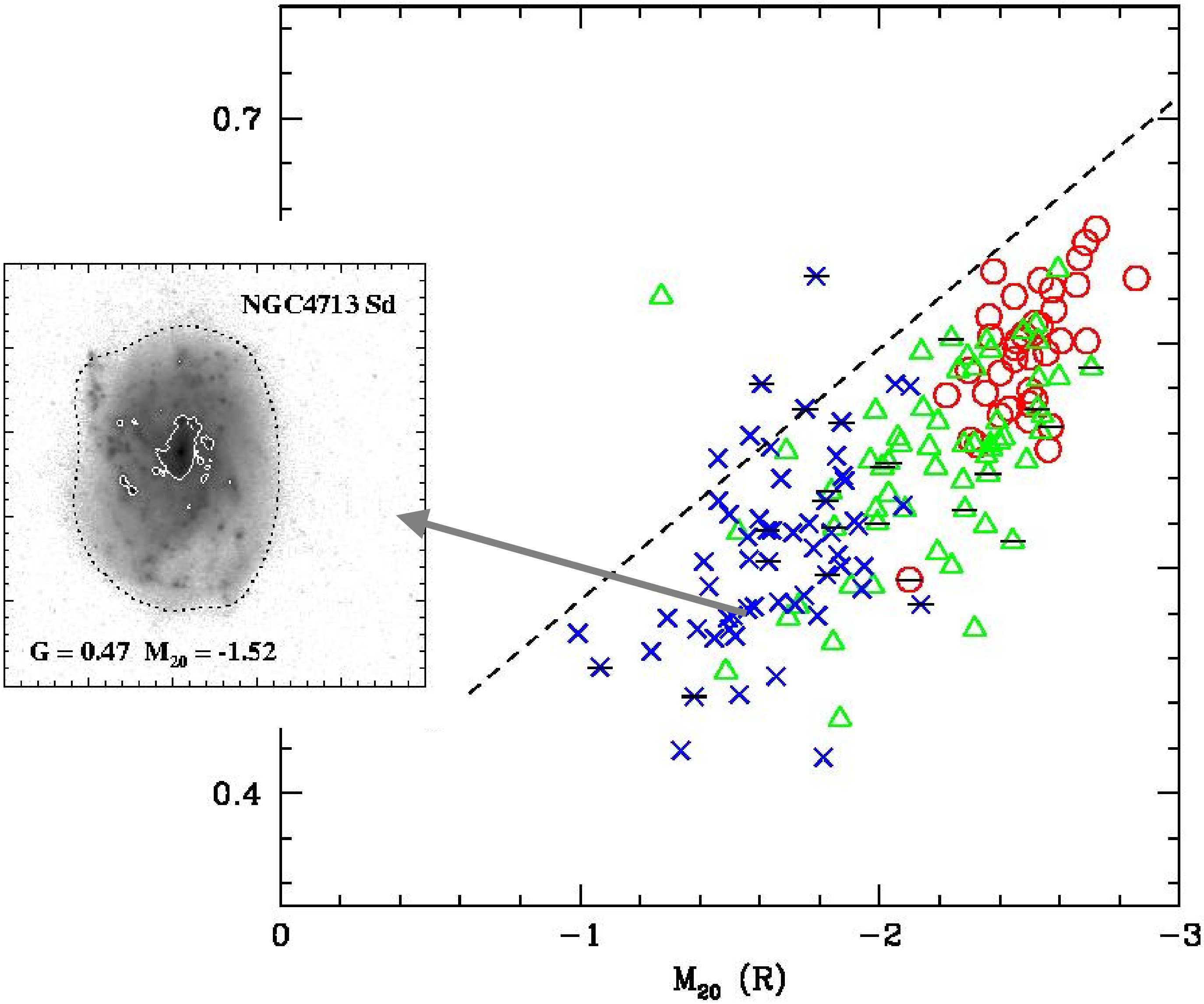
Local Galaxy G-M20 relation



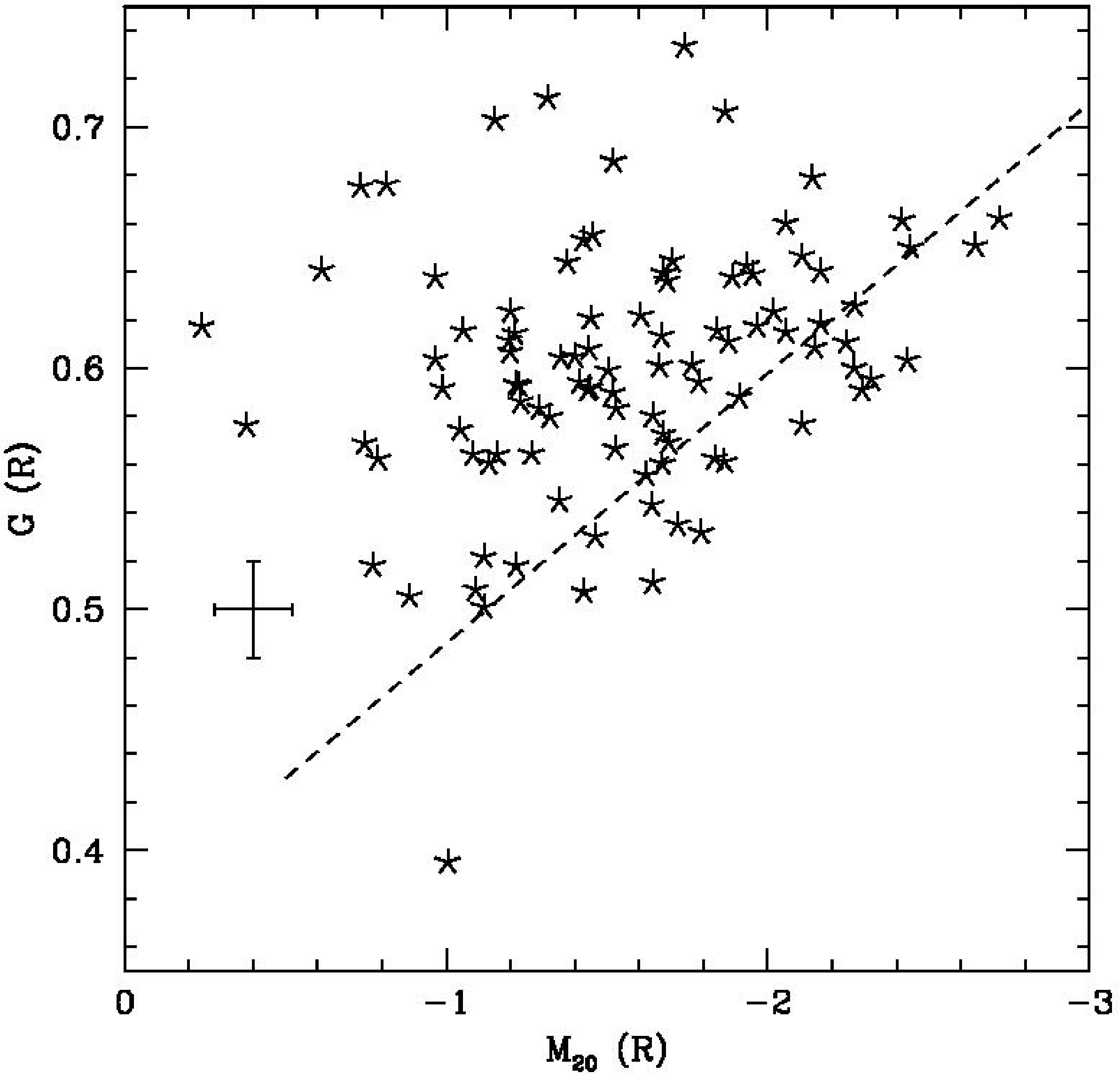
Local Galaxy G-M20 relation



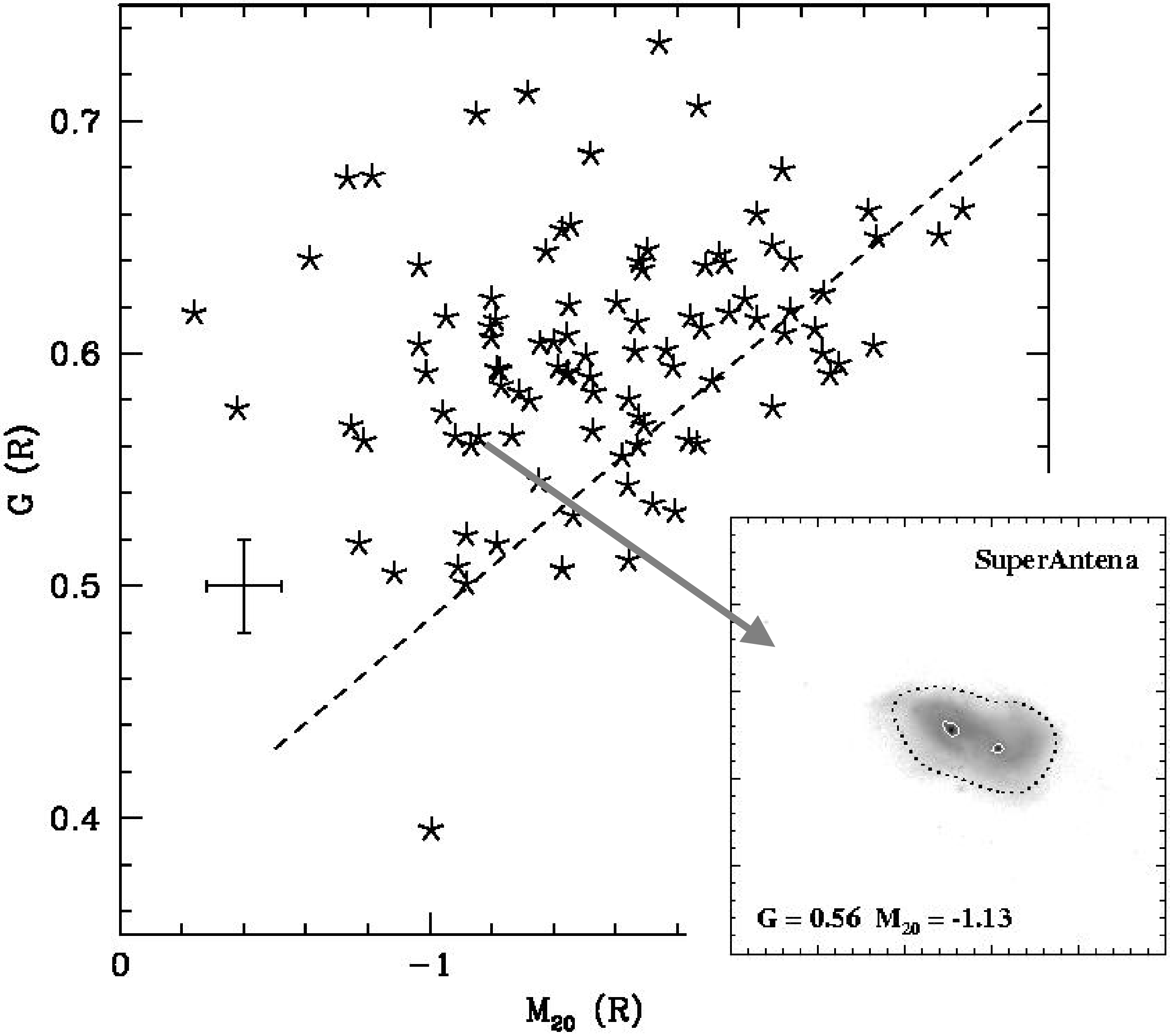
Local Galaxy G-M20 relation



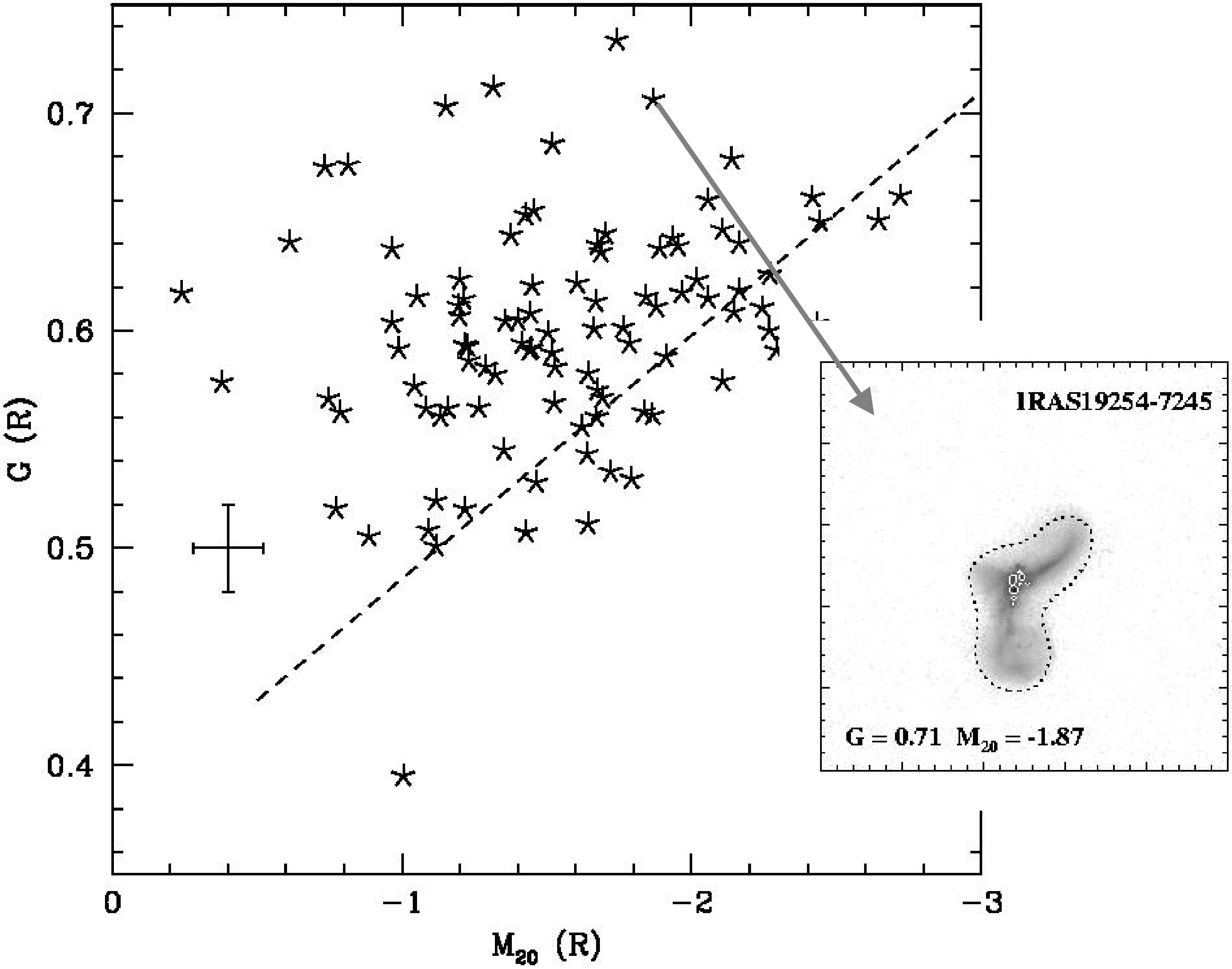
Local Galaxy G-M20 relation



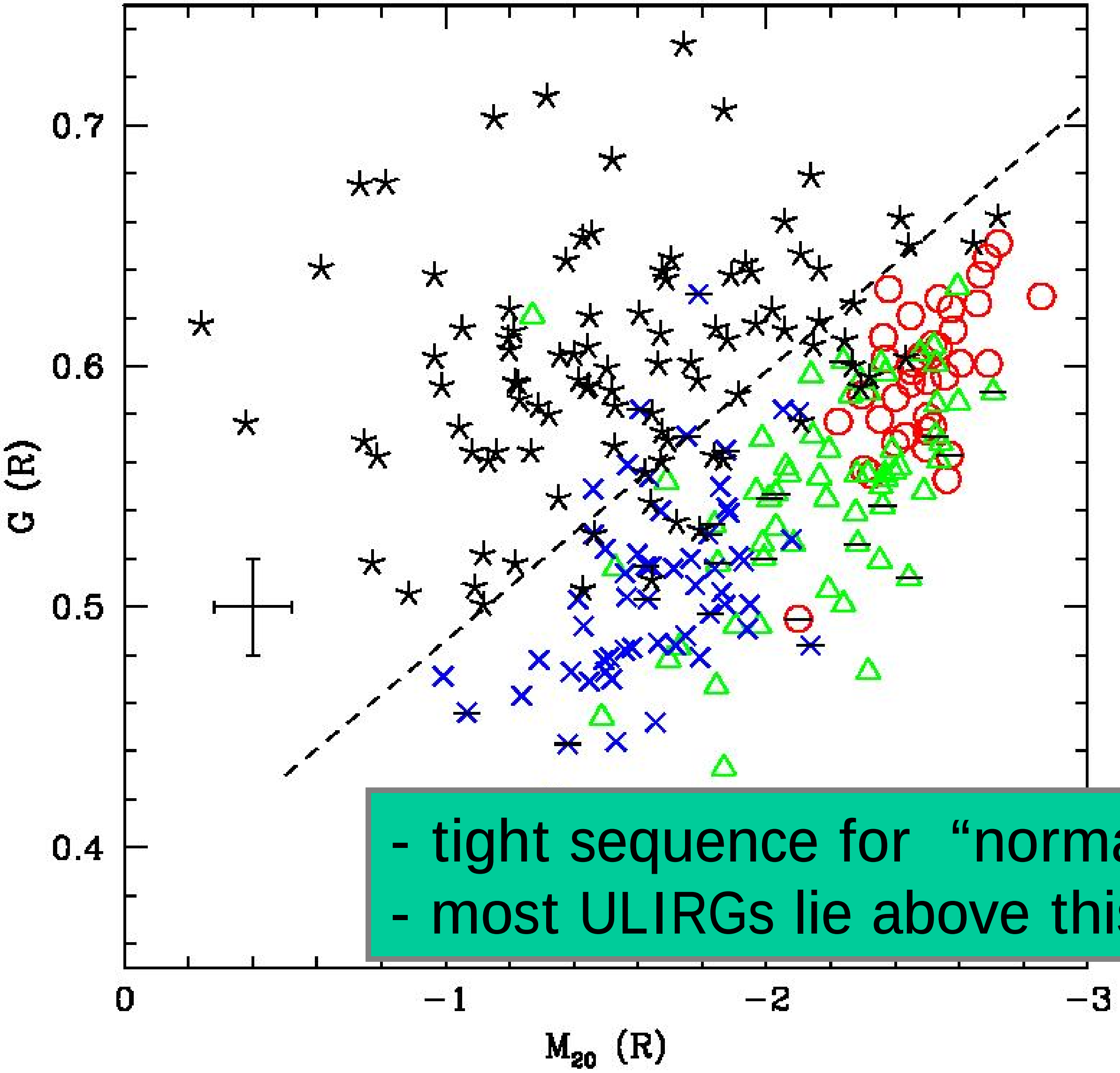
Local Galaxy G-M20 relation



Local Galaxy G-M20 relation



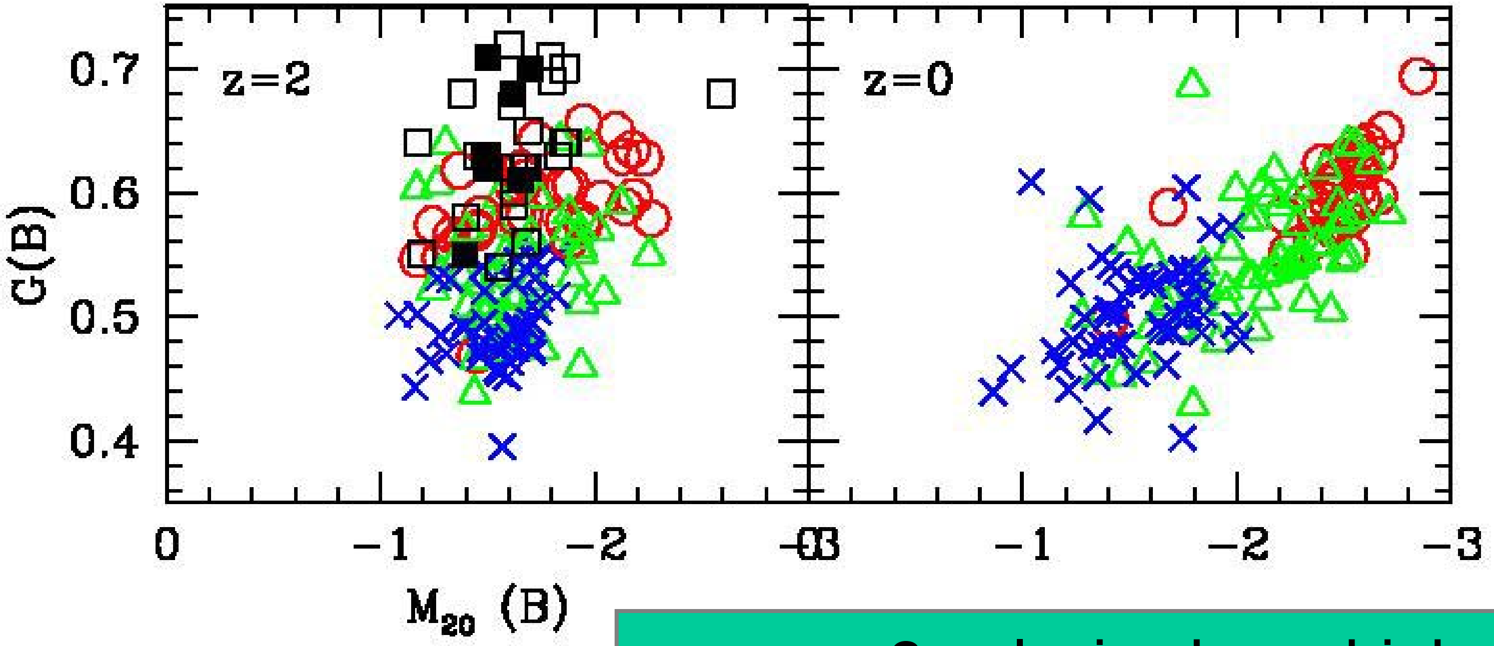
Local Galaxy G-M20 relation



- tight sequence for “normal” galaxies
- most ULIRGs lie above this sequence

Lyman break galaxy morphologies

- NICMOS HDFN z= 2-3 LBG sample (Dickinson et al)
  F110W+F160W (~3200-4500 AA rest-frame)



many z~2 galaxies have high G

Modeling Merger Morphologies

T.J. Cox's simulations of colliding disks (gas, stars, DM)
+ P. Jonsson's pop. synthesis + radiative transfer code

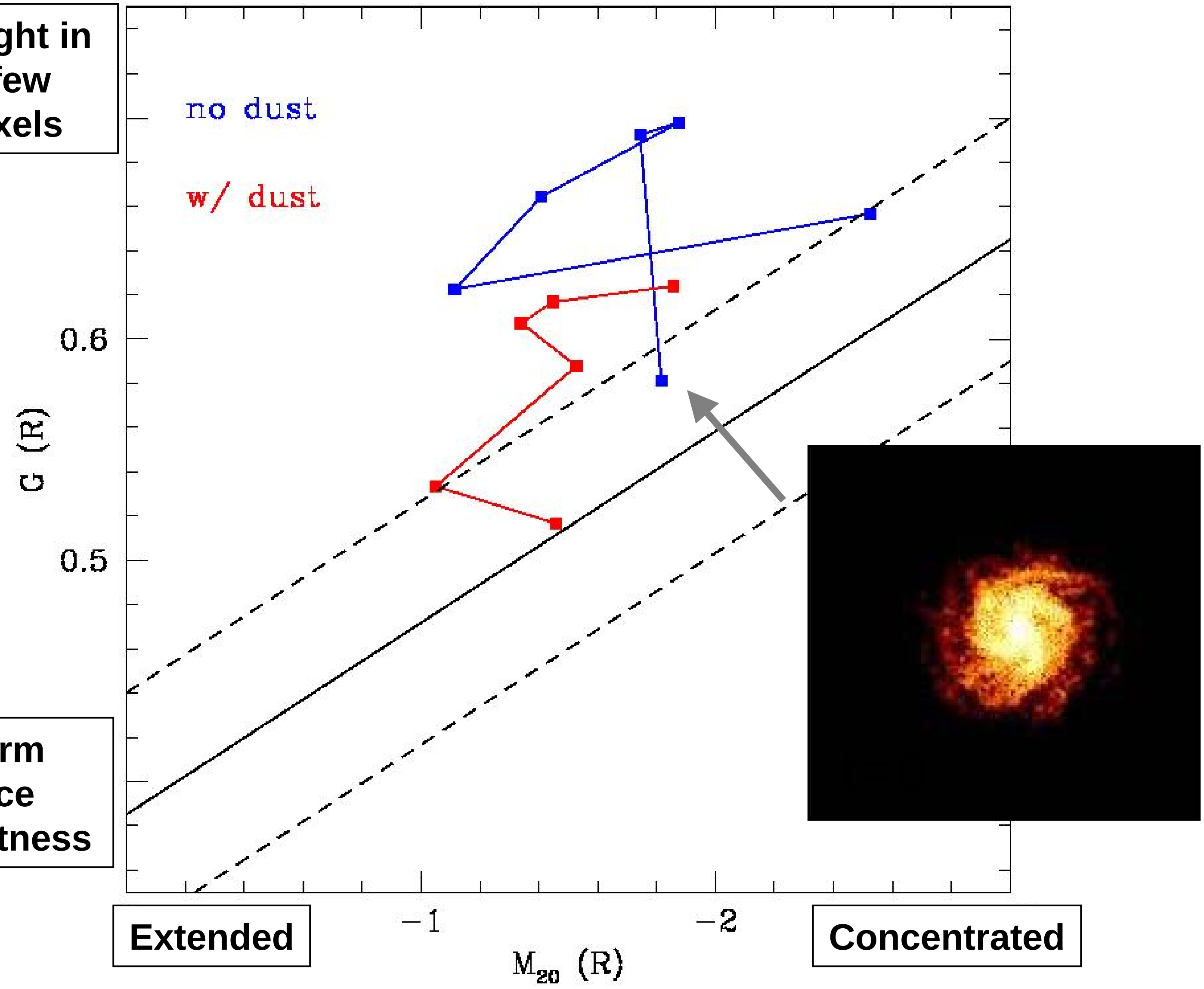
→ multi-wavelength images of simulations

→ can predict merger morphologies + morph. evolution

will test merger mass ratios,
orbital parameters,
initial galaxy conditions (B/D, gas fraction, ...),
dust models

Modeling Merger Morphologies

Light in a few pixels

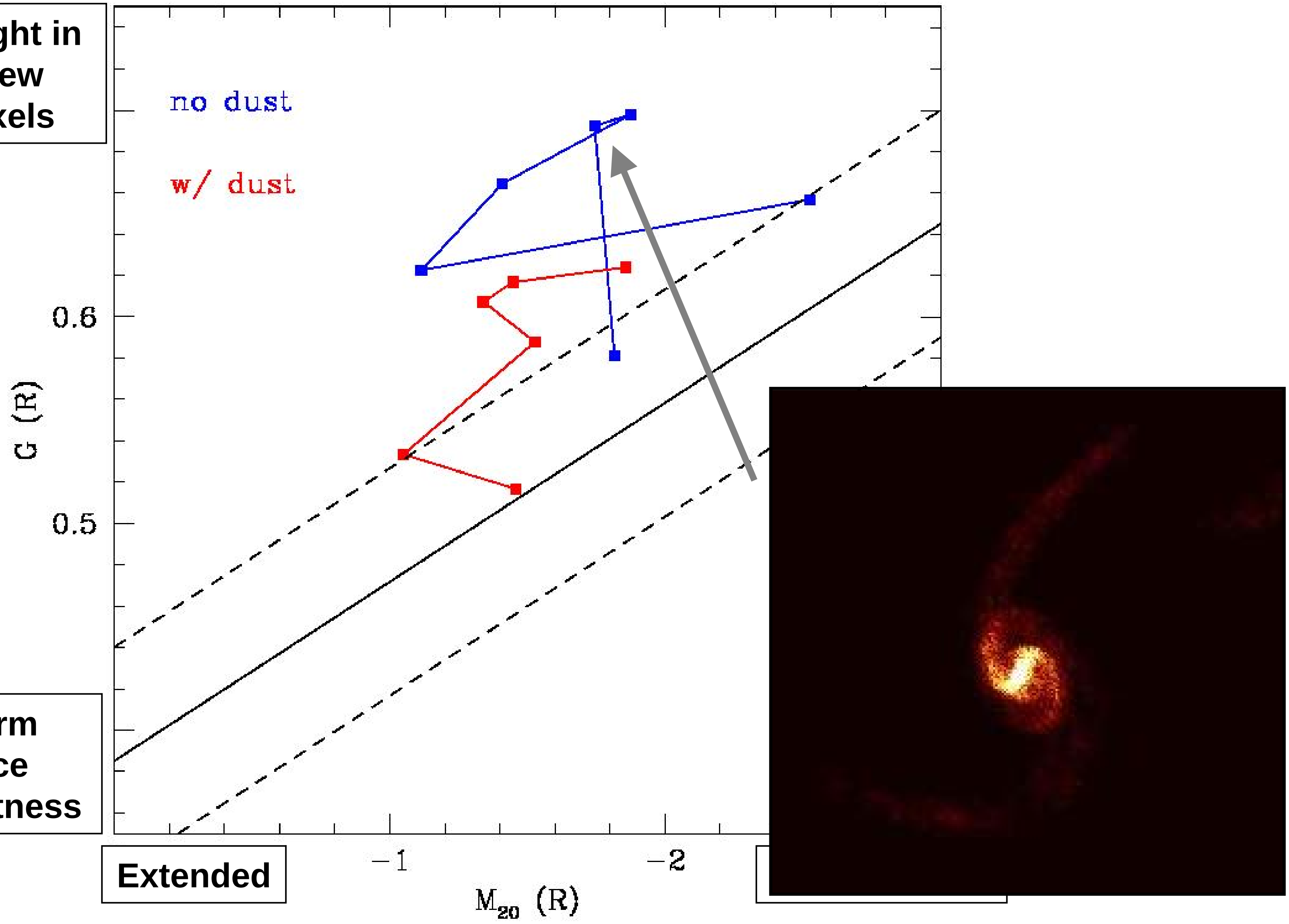


Uniform surface brightness

Extended

Concentrated

Modeling Merger Morphologies

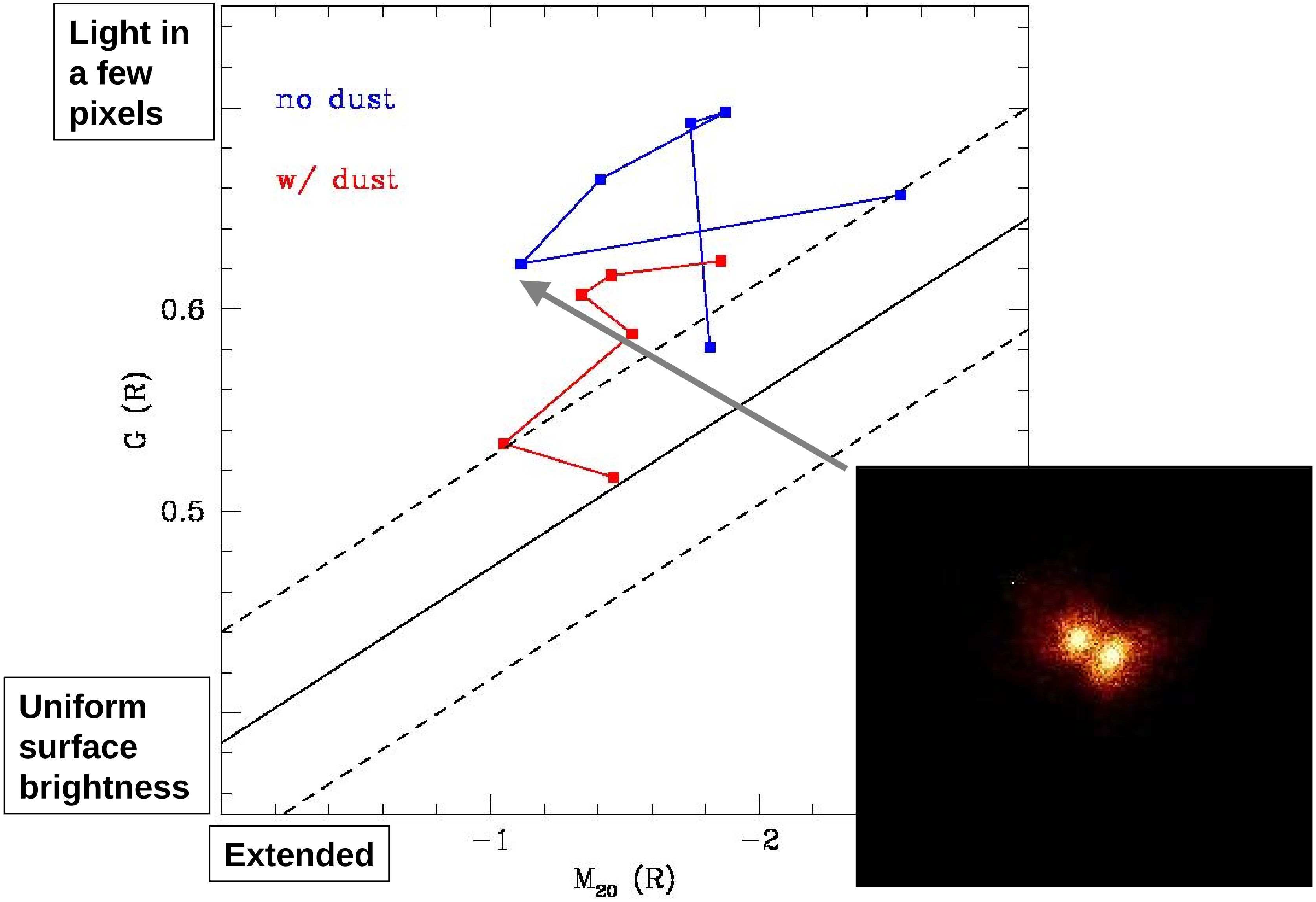


Light in a few pixels

Uniform surface brightness

Extended

Modeling Merger Morphologies

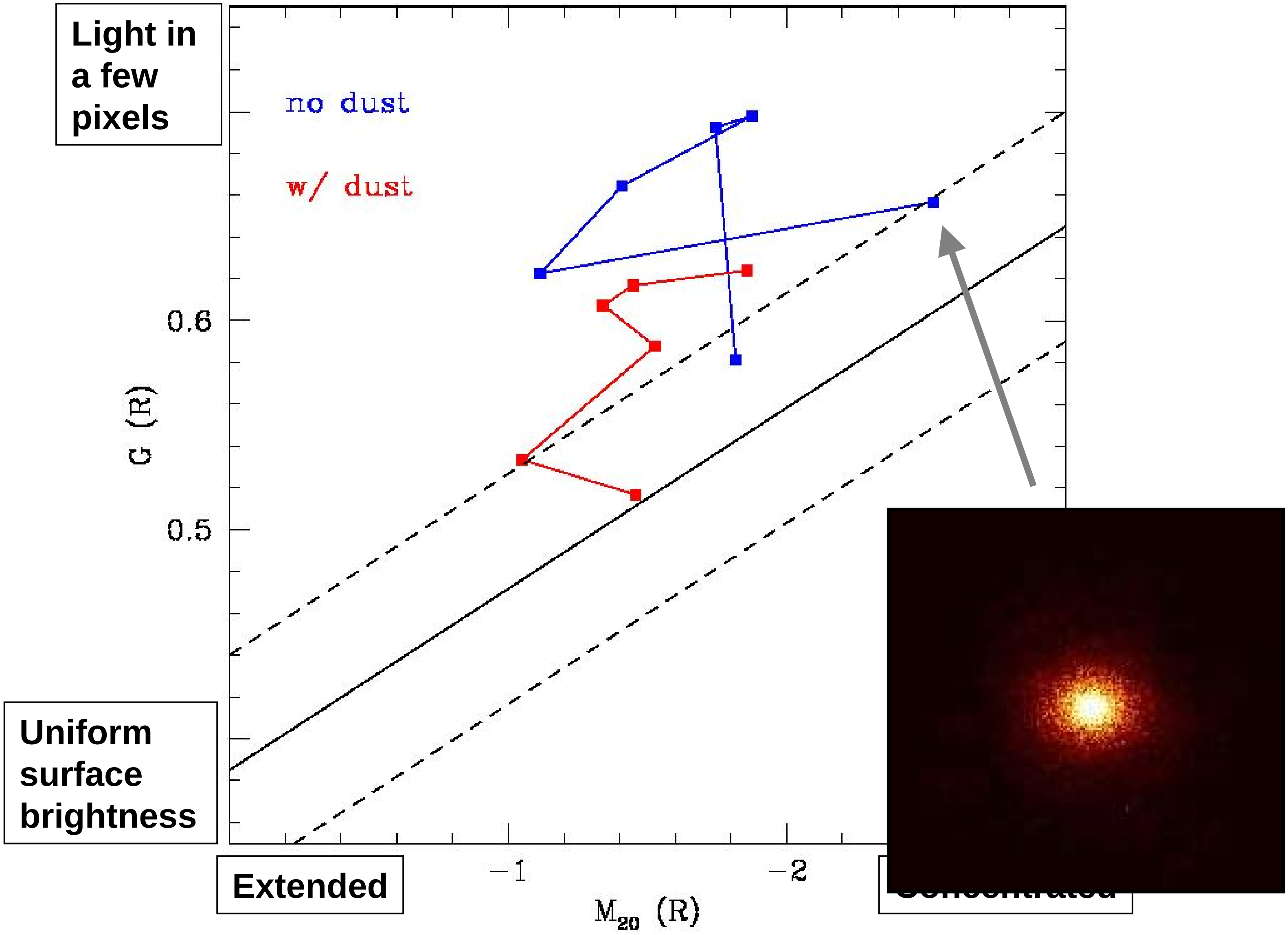


Light in a few pixels

Uniform surface brightness

Extended

Modeling Merger Morphologies



Light in a few pixels

Uniform surface brightness

Extended

Concentrated

Modeling Merger Morphologies

E/S0

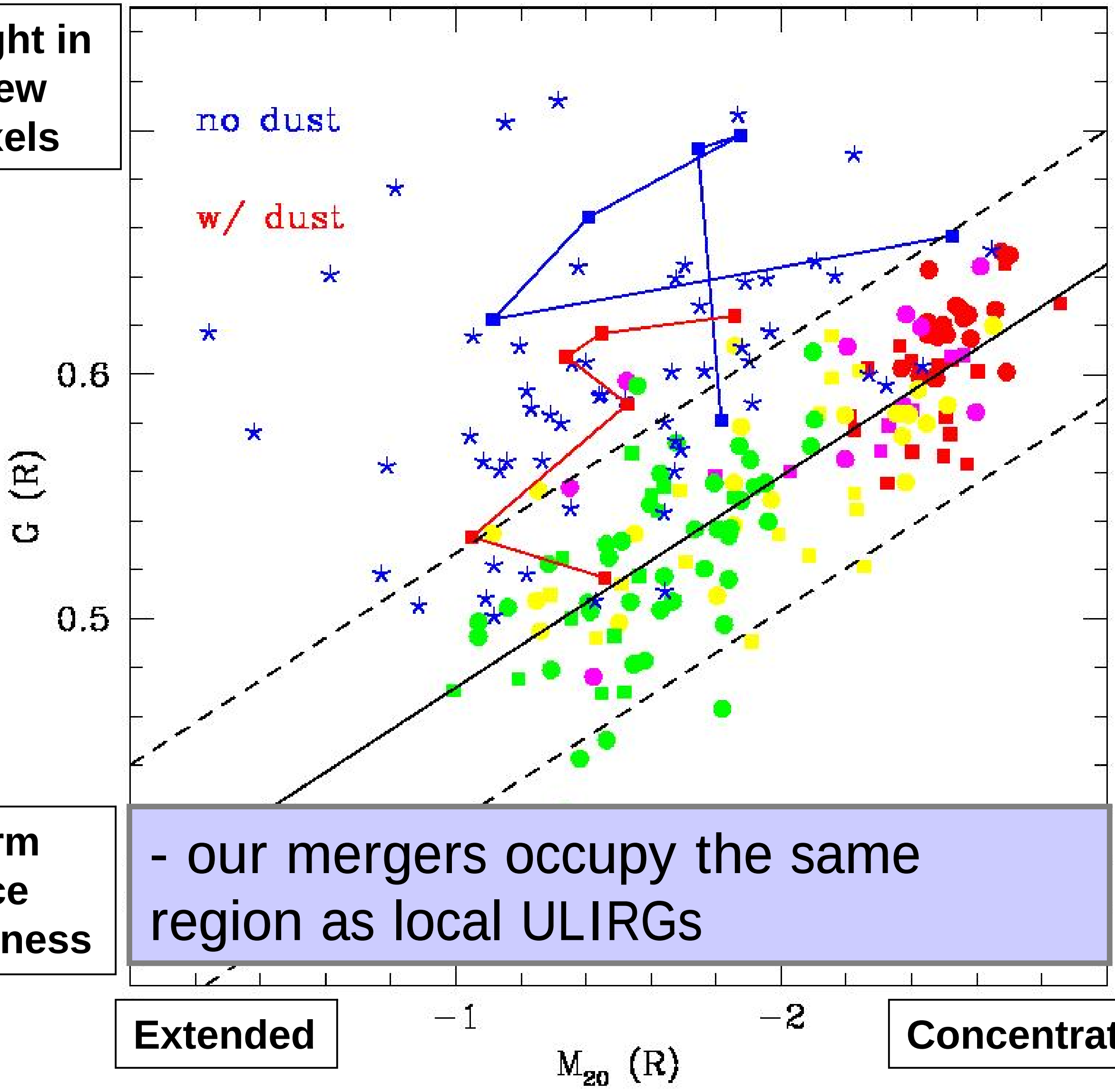
Sa/Sab

Sb/Sbc

Sc/Scd

ULIRGs

Light in a few pixels



Uniform surface brightness

- our mergers occupy the same region as local ULIRGs

Extended

Concentrated

Major Merger Simulations + Morphologies

How well do galaxy-merger simulations predict
ULIRG/ merger remnant morphologies?

Sbc-Sbc prograde-prograde collision
- with bulges
- extended gas disks

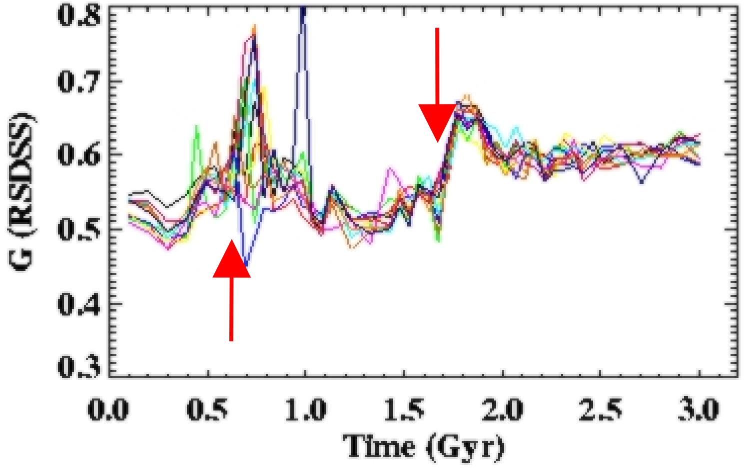
Star-formation + moderate feedback
Salpeter IMF, solar metallicity assumed

with and without dust

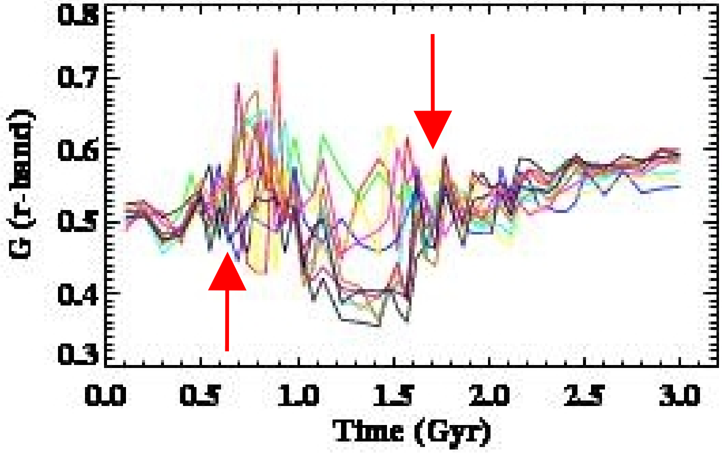
images from 10 cameras, 12 bandpasses
(Galex FUV/NUV, SDSS, 2MASS, IRAC)

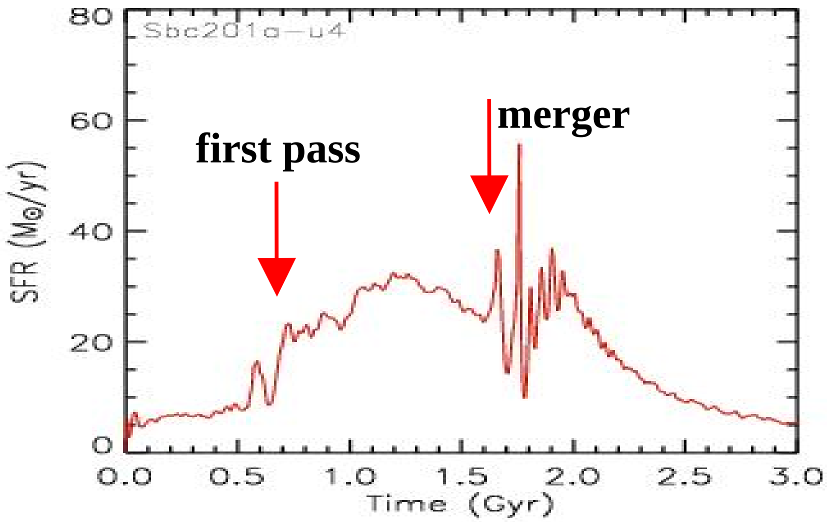
Gini Coefficient v. Time

No Dust



With Dust



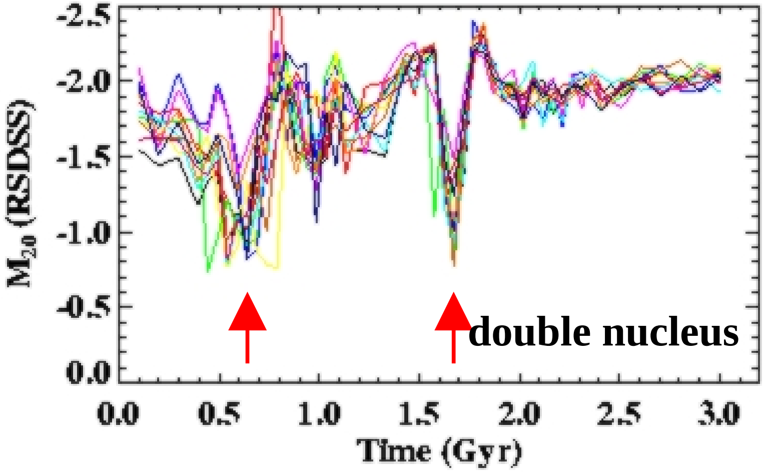


first pass

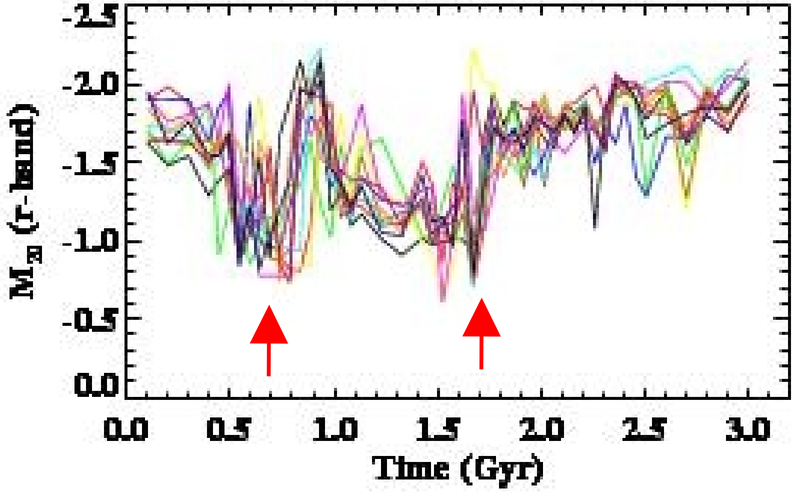
merger

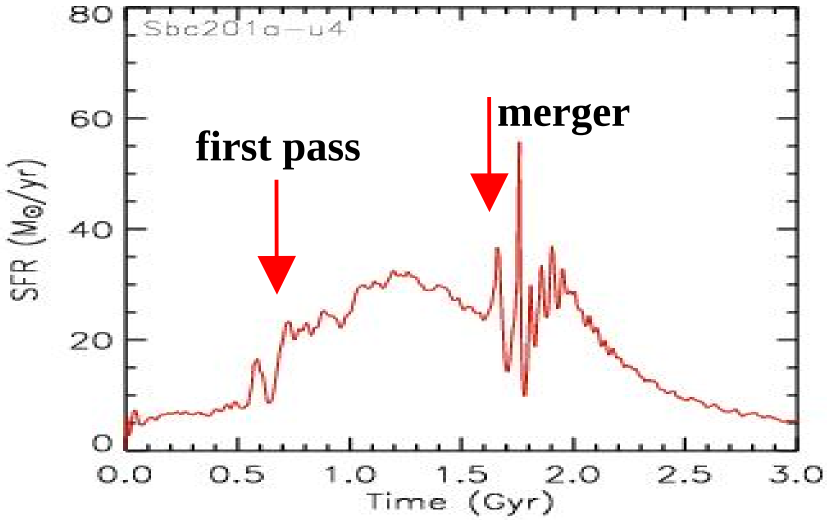
M20 v. Time

No Dust



With Dust





Conclusions

- There is a degeneracy between star formation and feedback parameters. Are there observations which break this degeneracy?

- Mergers enhance star formation but not as much as previous work suggested (because of newer, entropy-conserving version of SPH and Kennicutt normalized star formation)

- Burst efficiency depends strongly on initial gas distribution. (What are *realistic* disk galaxy gas distributions at various redshifts?)

- Major mergers can generate hot gas depending on initial galaxy sizes and orbital parameters. This hot gas is due to the merger process (shocks) in addition to stellar wind and supernova energy input.

- Morphological comparisons between simulated mergers and observations support the idea that ULIRGs are interacting galaxies and ellipticals are merger remnants. Emission-selected galaxies at z=1.5 resemble those at z=4 using the Lotz, Primack, & Madau statistics.

….. much more work needs to be done (i.e. the fun has just begun)

The Future

- Do more realistic initial conditions alter our story at all? What are disks like at high redshift to feed into future merger simulations of high redshift mergers?

- Detailed observations of individual merger remnants. Angular momentum distribution of halo, stars and gas in merger remnants. Semi-analytic models of merger remnant properties (e.g., $r_{1/2}$, σ_v) – in progress by UCSC grad student Matt Covington working with Primack.

- Analytically parameterize star formation efficiency in mergers (and non-mergers) as a function of merger ratio and initial galaxy properties, feed this into SAMs for a more complete understanding of the role mergers play in driving global star formation.

- Compare the morphology of simulated mergers, including the effects of dust, to observations using Lotz, Primack, & Madau 2004. Can we calibrate automated procedures to better determine mergers at high redshift? Can we calibrate spectra? Line-widths?