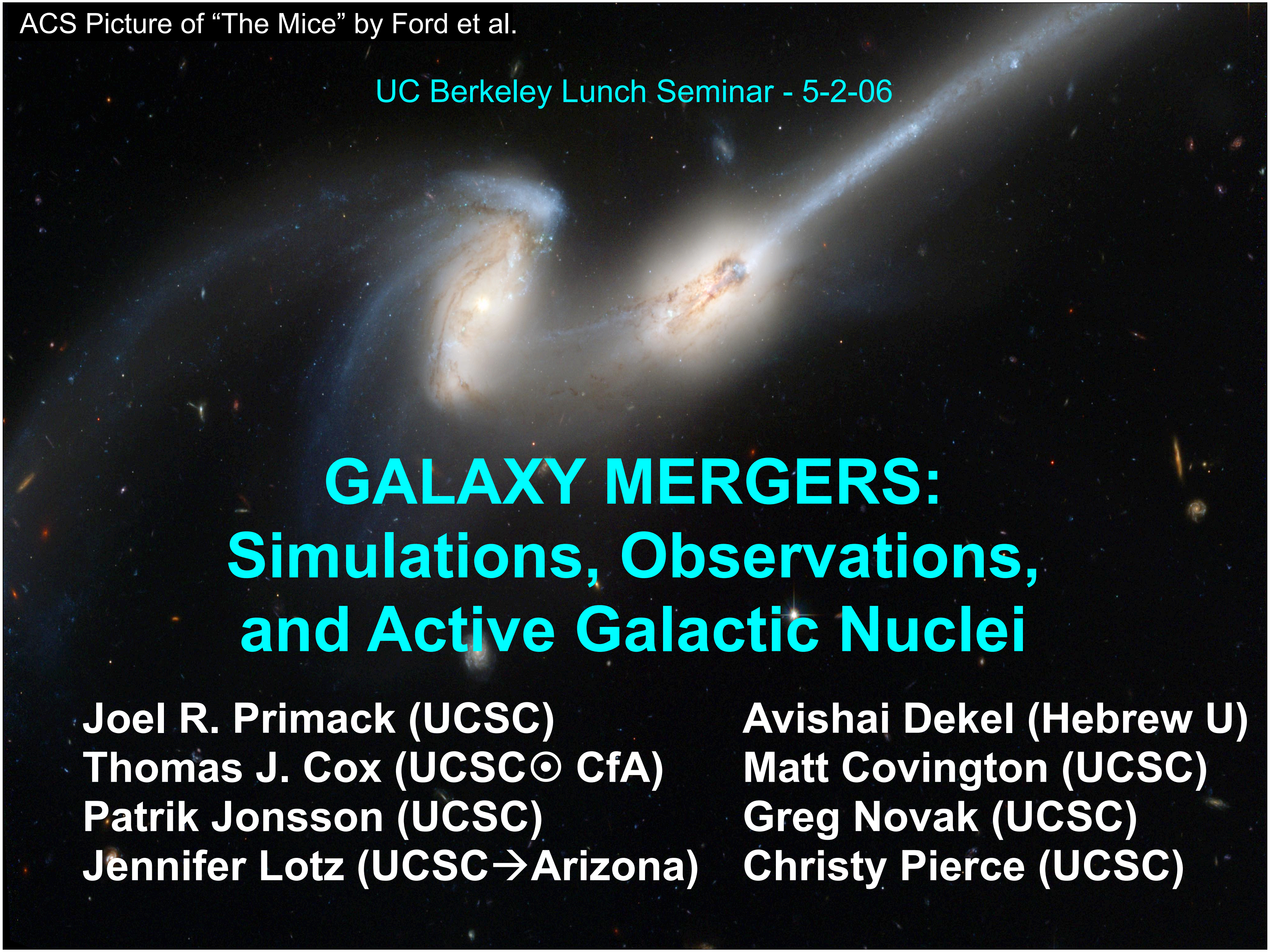


ACS Picture of “The Mice” by Ford et al.

UC Berkeley Lunch Seminar - 5-2-06

GALAXY MERGERS: Simulations, Observations, and Active Galactic Nuclei

Joel R. Primack (UCSC)
Thomas J. Cox (UCSC⊙ CfA)
Patrik Jonsson (UCSC)
Jennifer Lotz (UCSC→Arizona)
Avishai Dekel (Hebrew U)
Matt Covington (UCSC)
Greg Novak (UCSC)
Christy Pierce (UCSC)

Goals of Galaxy Interaction Simulations

Understand the amount of star formation due to galaxy mergers TJ Cox PhD thesis Sept 2004

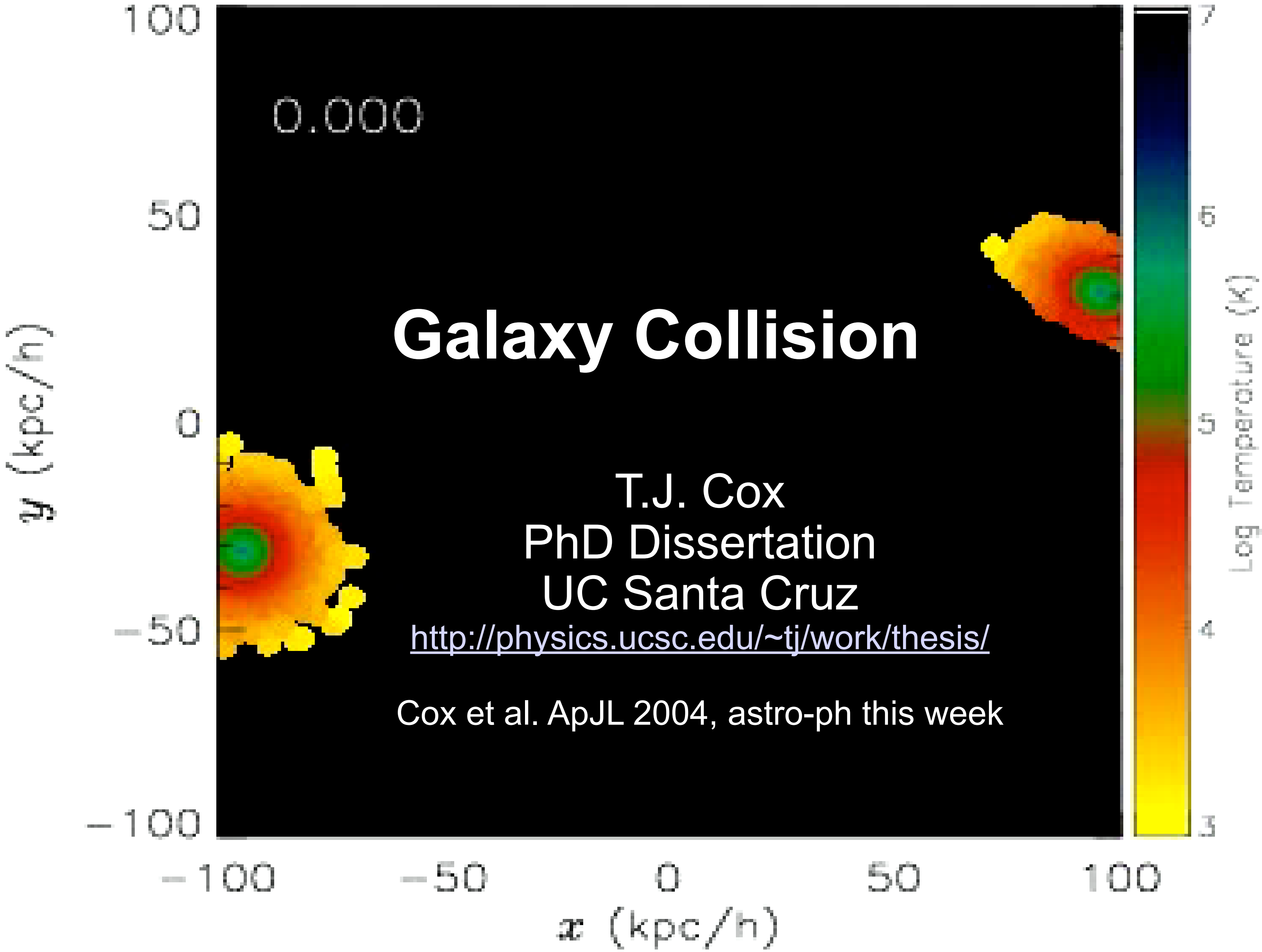
Study properties of merger remnants TJ Cox+05,06

→ DM/stellar/gas distributions Matt Covington

→ Angular momenta and kinematics Greg Novak

Predict appearance of interacting galaxies throughout merger, including dust scattering, absorption, and reradiation Patrik Jonsson PhD thesis Sept 2004, MN in press, MN submitted 2006

Statistically compare to observations (DEEP2 and GOODS: ACS, Chandra, Spitzer, etc.) Jennifer Lotz, Piero Madau, and Primack 2004, AJ; Lotz et al. 05, 06; Pierce et al. 2006, Nandra et al. 2006

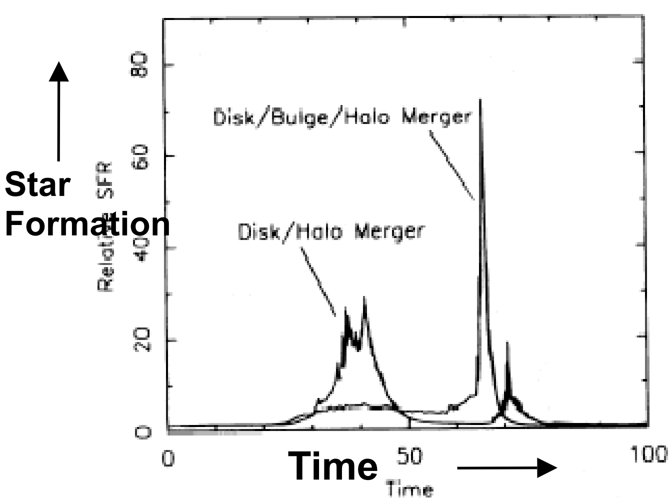


Galaxy Collision

T.J. Cox
PhD Dissertation
UC Santa Cruz
http://physics.ucsc.edu/~tj/work/thesis/

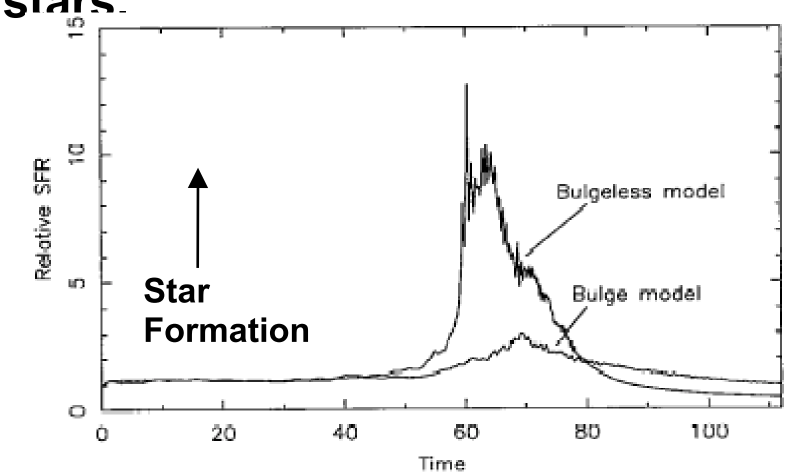
Cox et al. ApJL 2004, astro-ph this week

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 (i.e. the presence of a bulge or not) dictates when the gas is funneled to the center and turned into stars.**

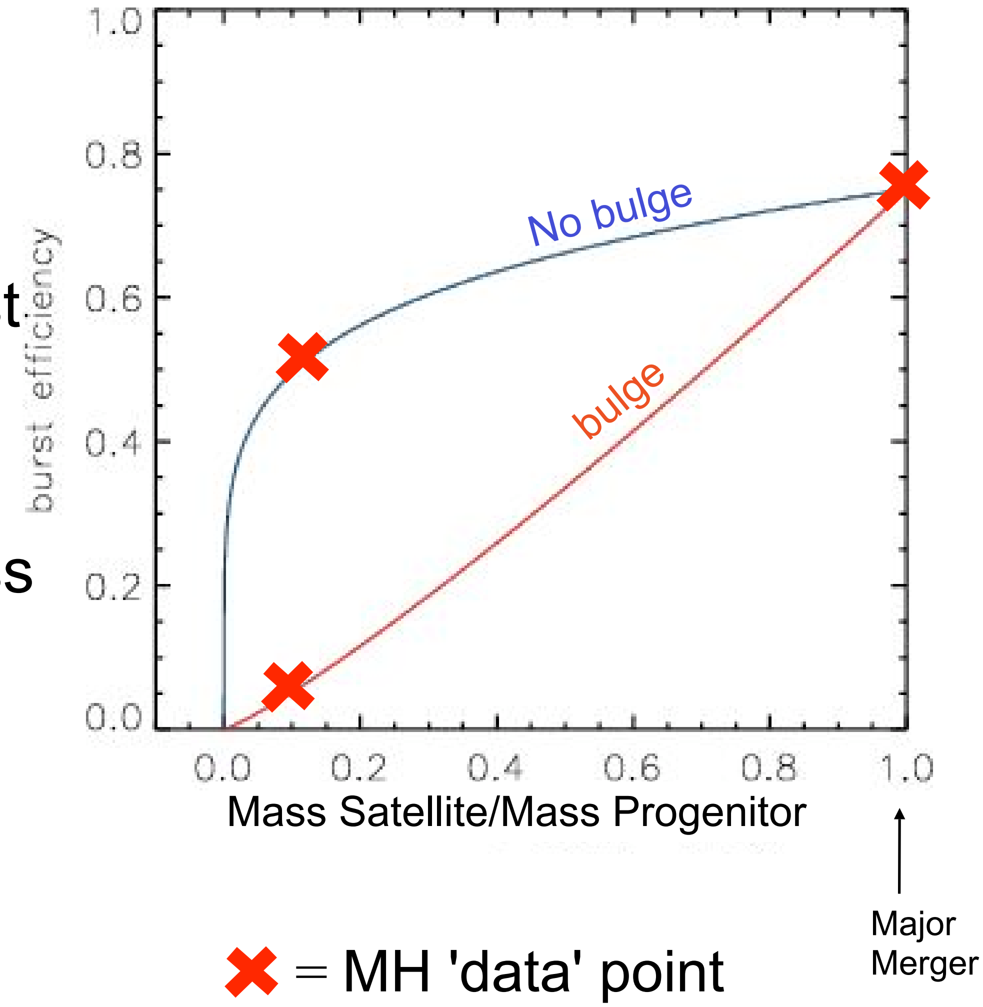
- **Minor mergers (Mihos & Hernquist 1994) (satellite galaxy is 10% of the original disk mass) generate significant bursts of star formation only when there is no bulge in progenitor disk galaxy.**



→ **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)

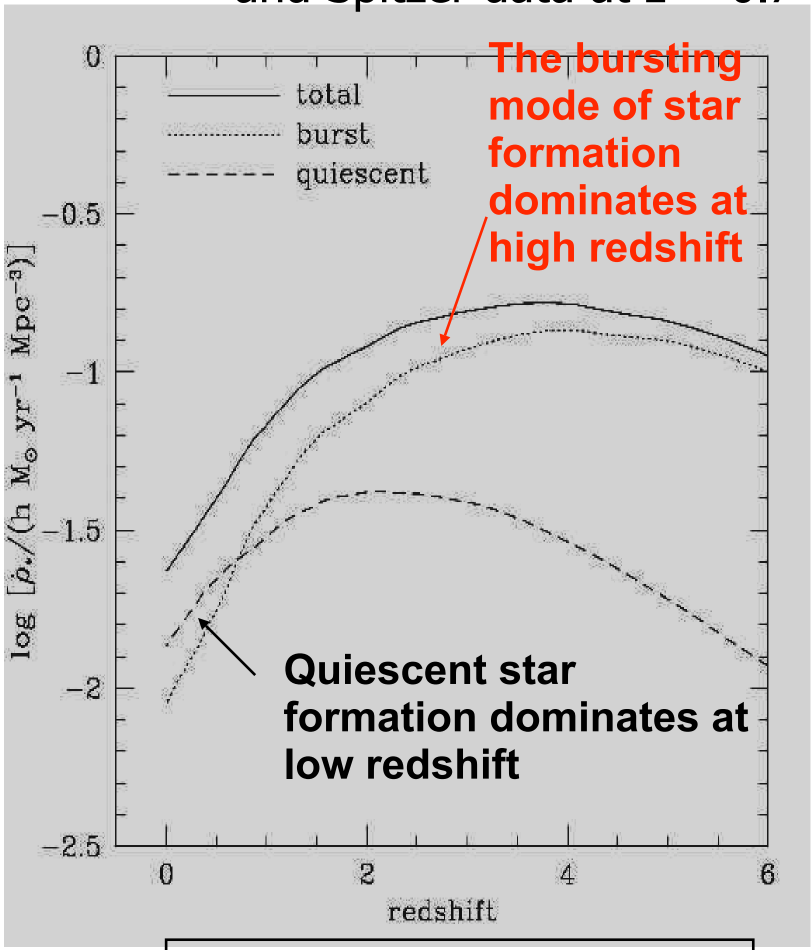
Bell et al 2005 also find that this model also agrees with GEMS and Spitzer data at z ~ 0.7

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

1) Comoving 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 minor mergers



Note: this is redshift, not time!

Our New Work

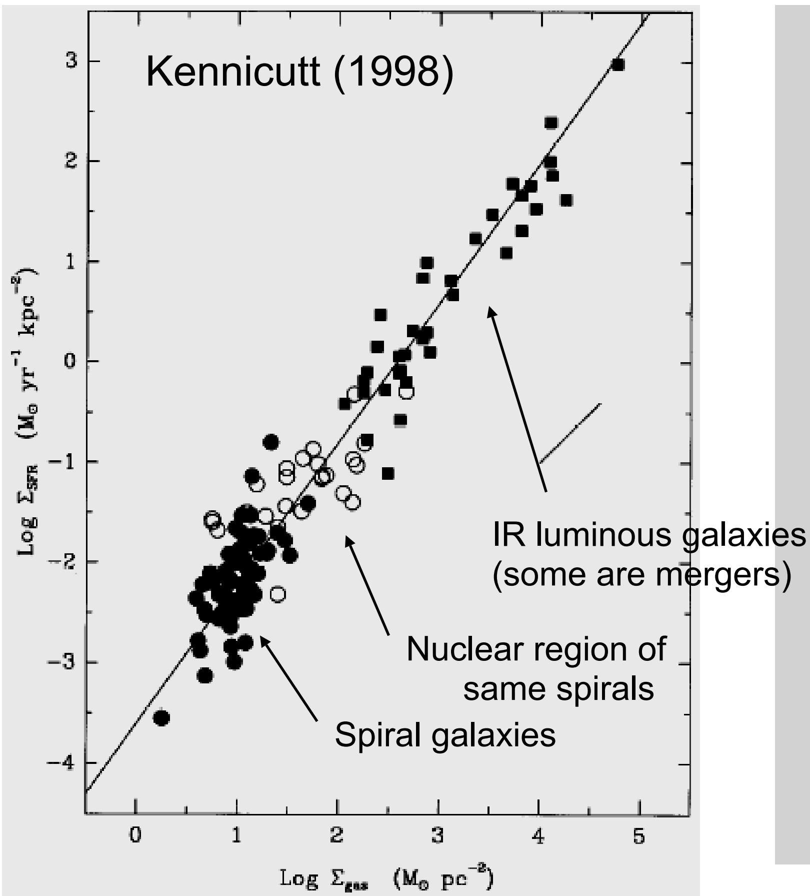
In order to investigate galaxy mergers (and interactions) we build observationally motivated N-body realizations of compound galaxies and simulate their merger using the SPH code GADGET (Springel, Yoshida & White 2000, Springel 2005). These simulations include:

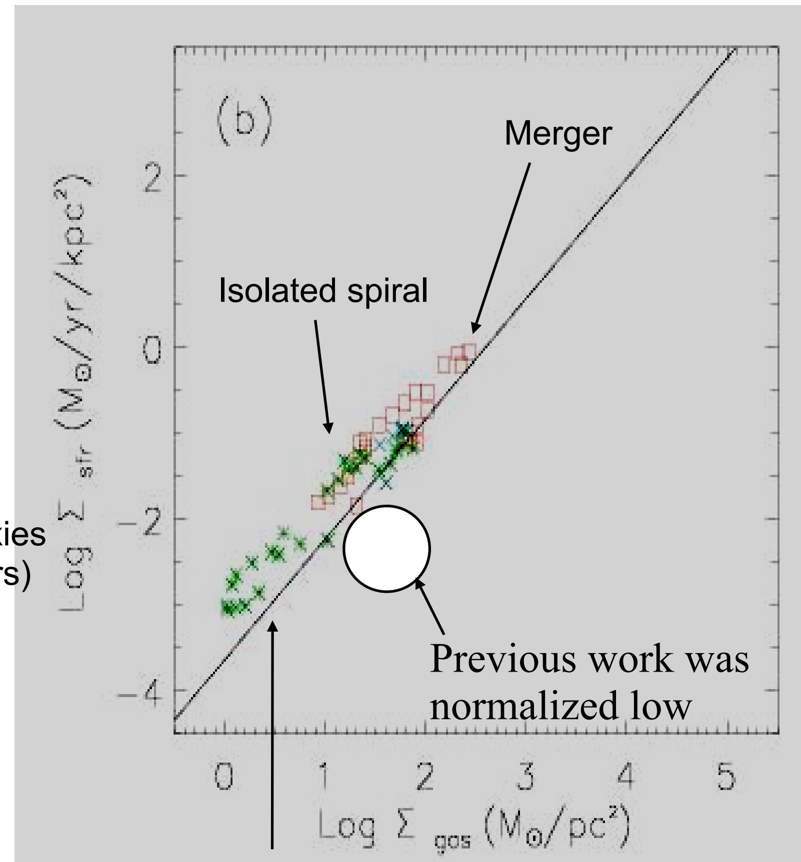
- An improved version of smooth particle hydrodynamics (SPH) which explicitly conserves both energy and entropy (Springel & Hernquist 2002).
- The radiative cooling of gas
- Star formation: $\rho_{sfr} \sim \rho_{gas}/\tau_{dyn}$ for ($\rho_{gas} > \rho_{threshold}$)
- Metal Enrichment
- Stellar Feedback

* Our simulations contain ≥ 170,000 particles per galaxy and the resolution is typically ~100 pc. (Tested up to 1.7×10^6 particles.)

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.





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 and observational data on galaxy properties.

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) and Robertson et al. (2004)

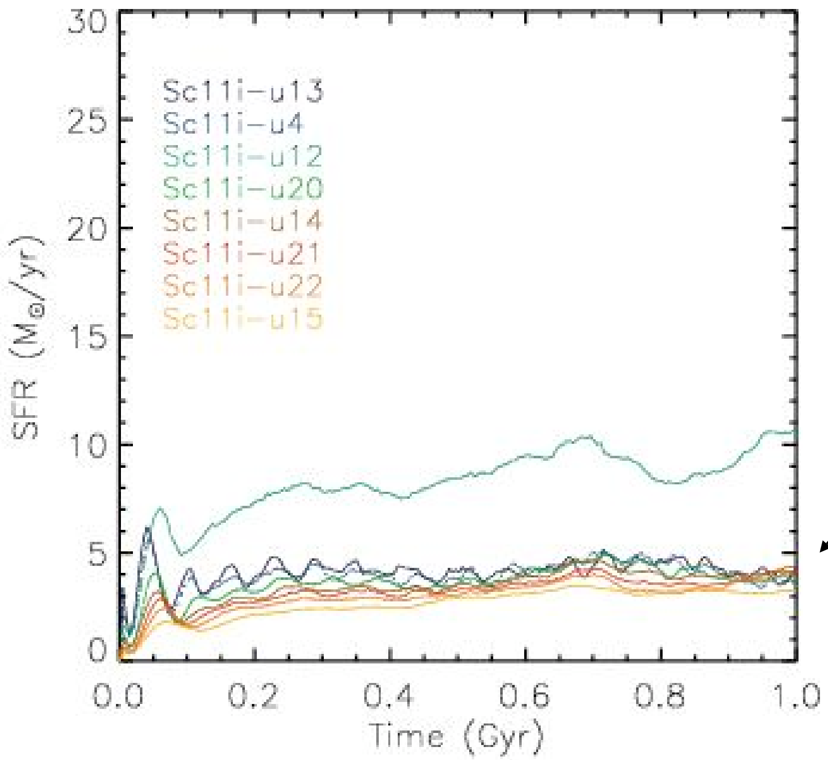
Disk Galaxy Models

- **The Milky Way + Mass Excursions** (40+ Major Mergers)
  A large, *low gas fraction* galaxy has been the starting point for the majority of all merger simulations to-date (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. Model Sc has no bulge and Model Sbc has a small bulge.

- **G models** (13 Major Mergers, 88+ 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, early-type galaxy surveys. The dark mass and concentration are constrained to match the baryonic TF relation.

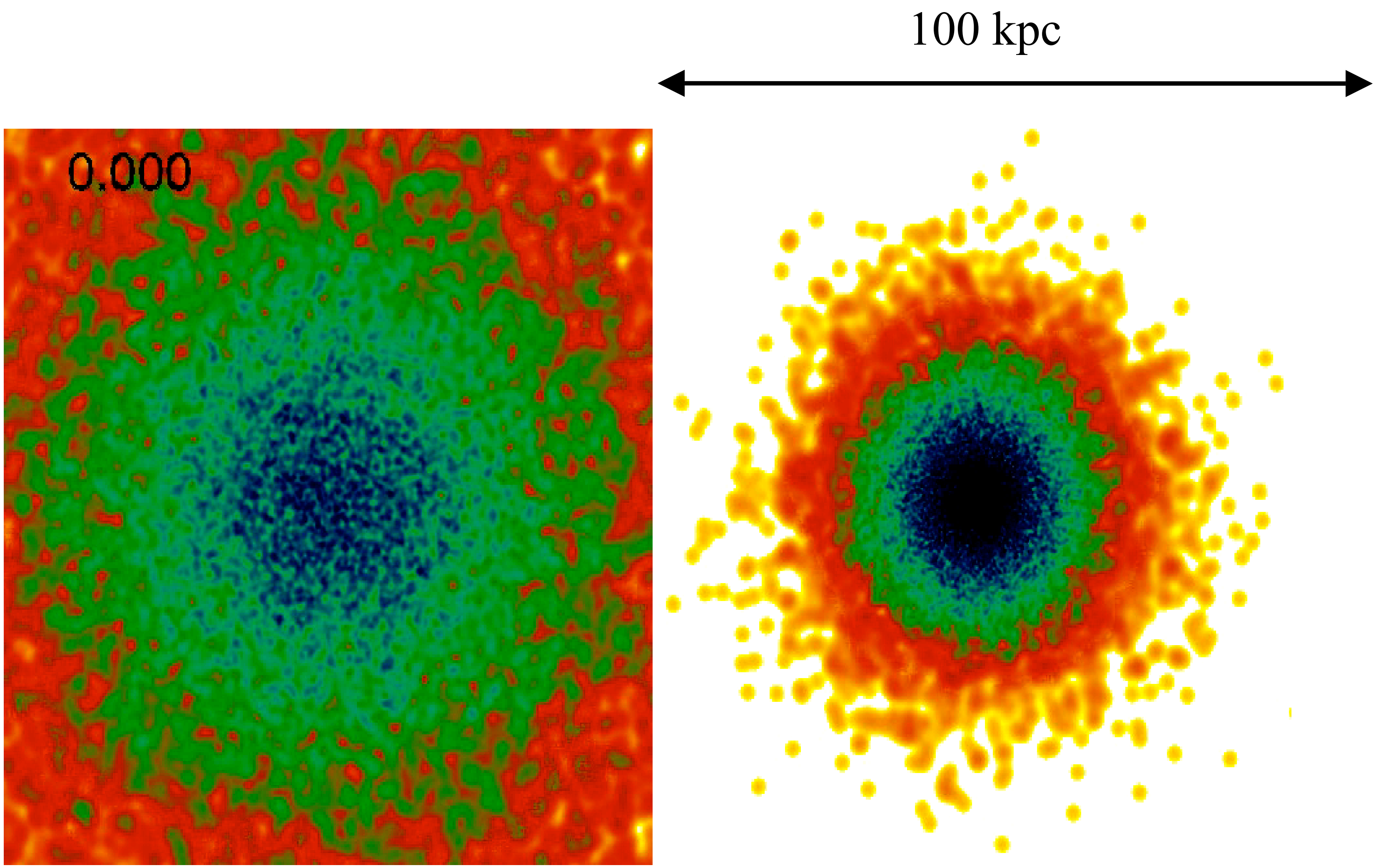
The Star Formation Rate (SFR)



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

→ We can produce and simulate stable disk galaxies.

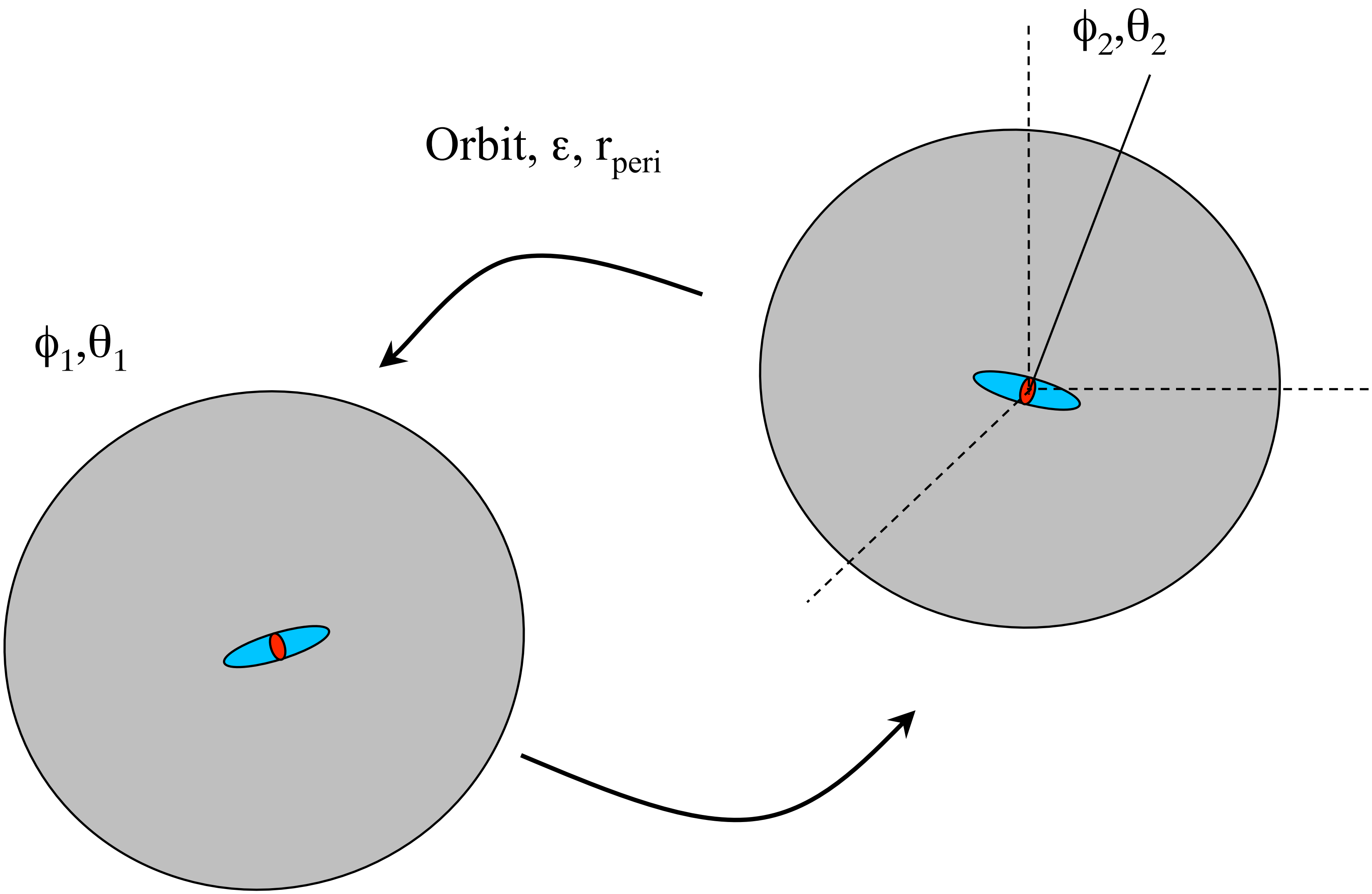
Stable Disk



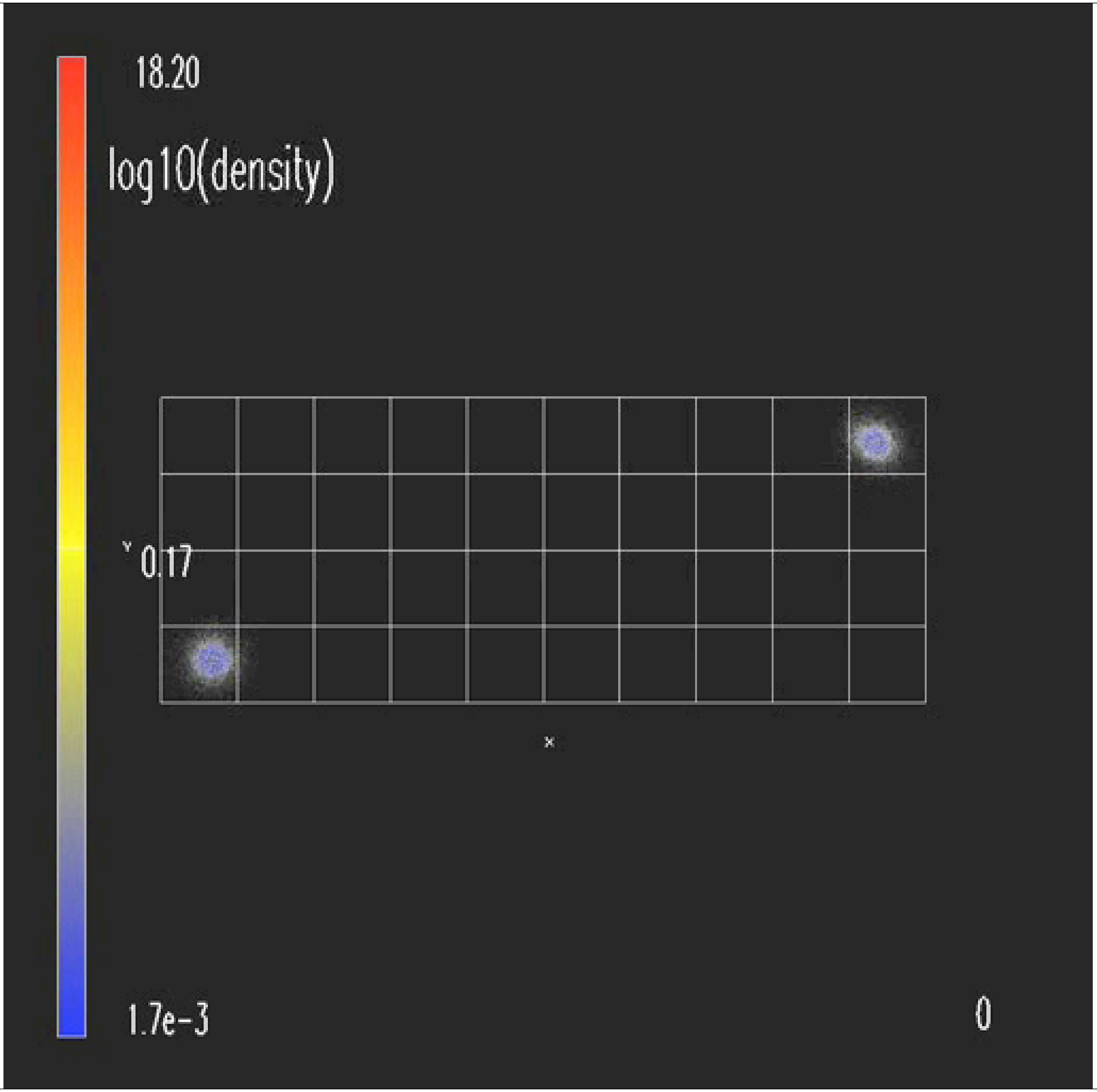
Gas

Star

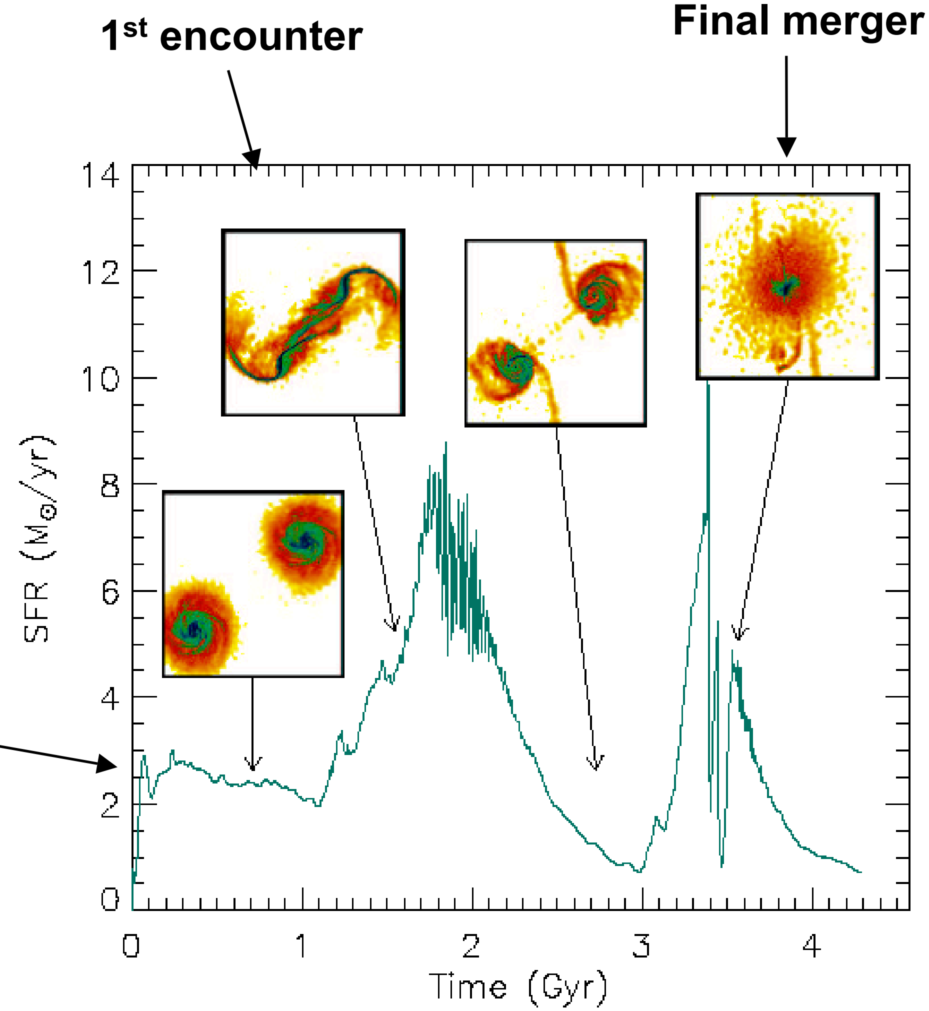
Now Let's Merge Two Disks



Gas Particles color-coded by density



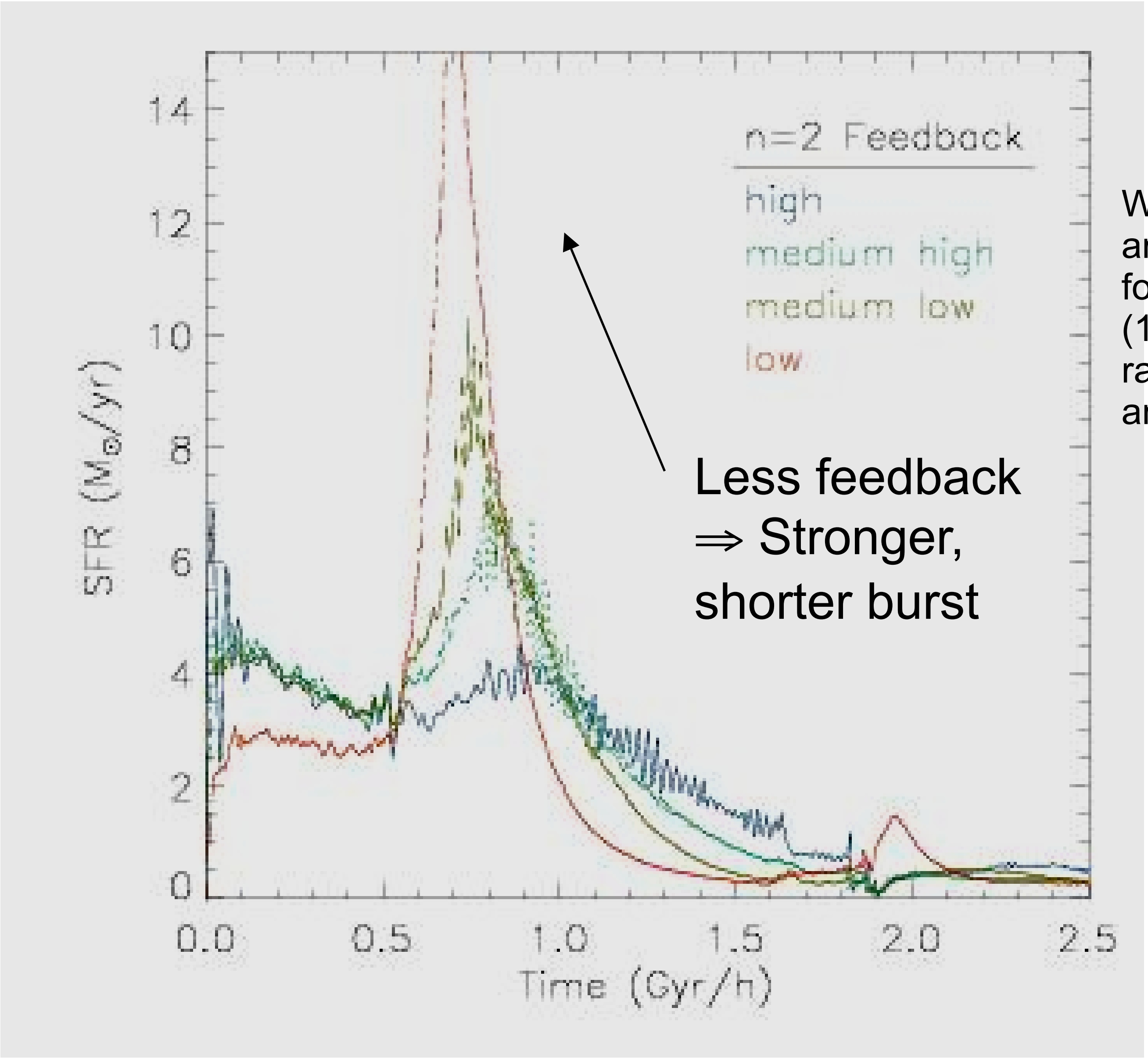
Major Merger Morphology and Resulting Star Formation



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

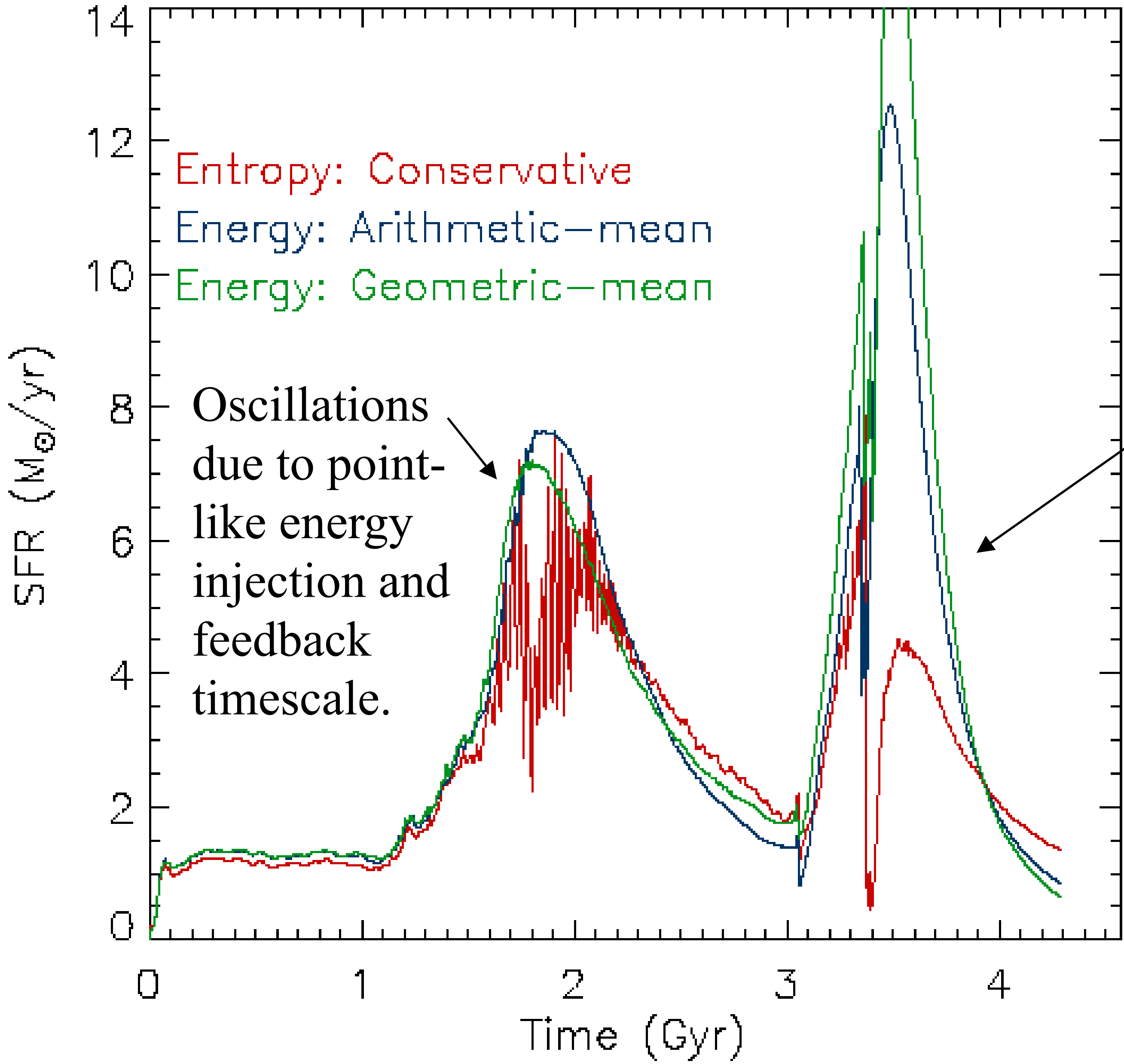
Prograde parabolic orbit, initial separation 250 kpc, pericentric distance 7 kpc

SFR vs. Free Parameters



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.

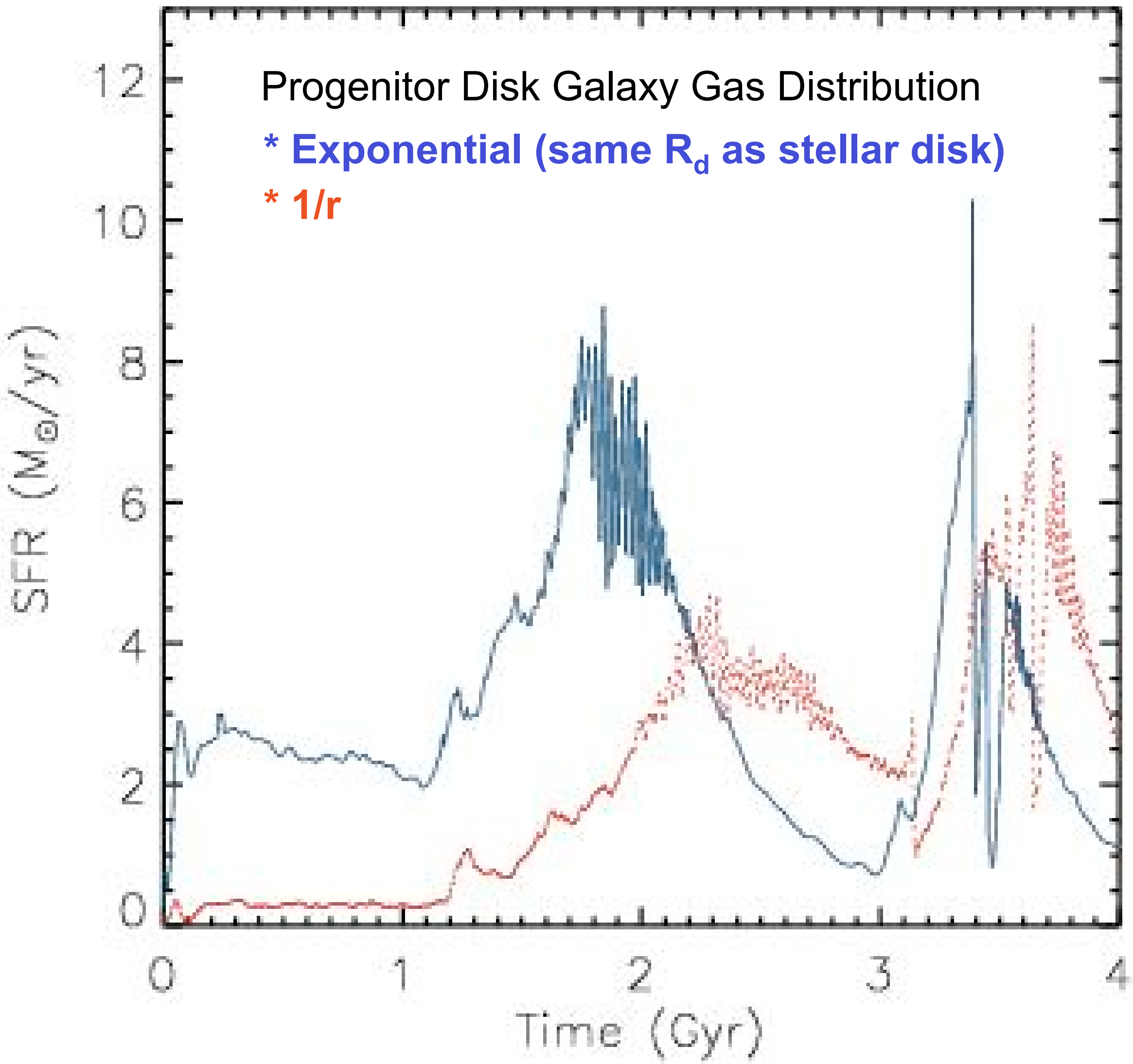
SPH & Star Formation



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



Total Gas Consumption:
76%
55%

Peak SFR / Quiescent SFR
~5
~30

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

Now some minor mergers...

Merger Mass Ratios

G3G3: Major merger between two G3's

G3G1: Minor merger between G3 and smaller G1

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

Projected Gas Density
in the orbital plane

Projected Stellar Density
in the orbital plane

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

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/

Projected gas density

Projected stellar density

left: Projected gas density

right: Projected stellar density

XY, the orbital plane

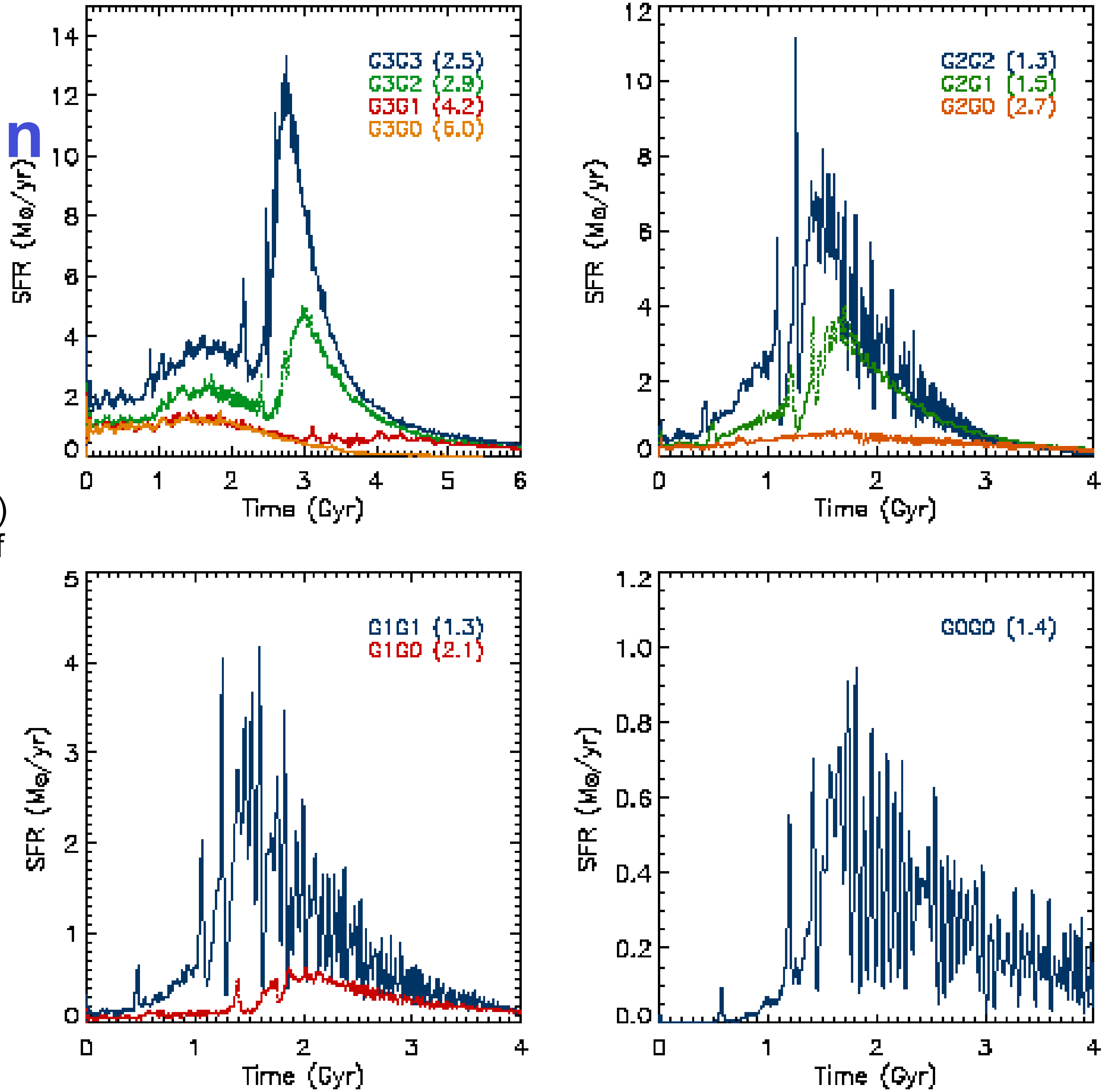
Isolated Disk (Sbc) Galaxy
Run: execute/G3G1-u3
T.J. Cox & Patrik Jonsson, UC Santa Cruz
UC Santa Cruz, 2004

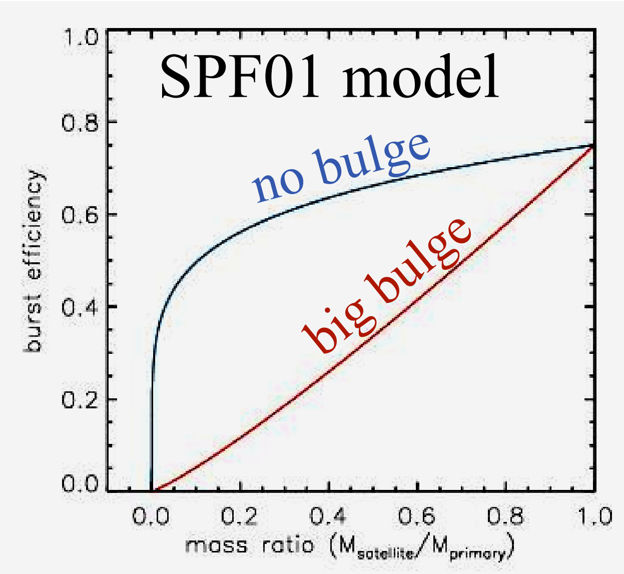
G3G1: **1:6** prograde minor merger

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

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!





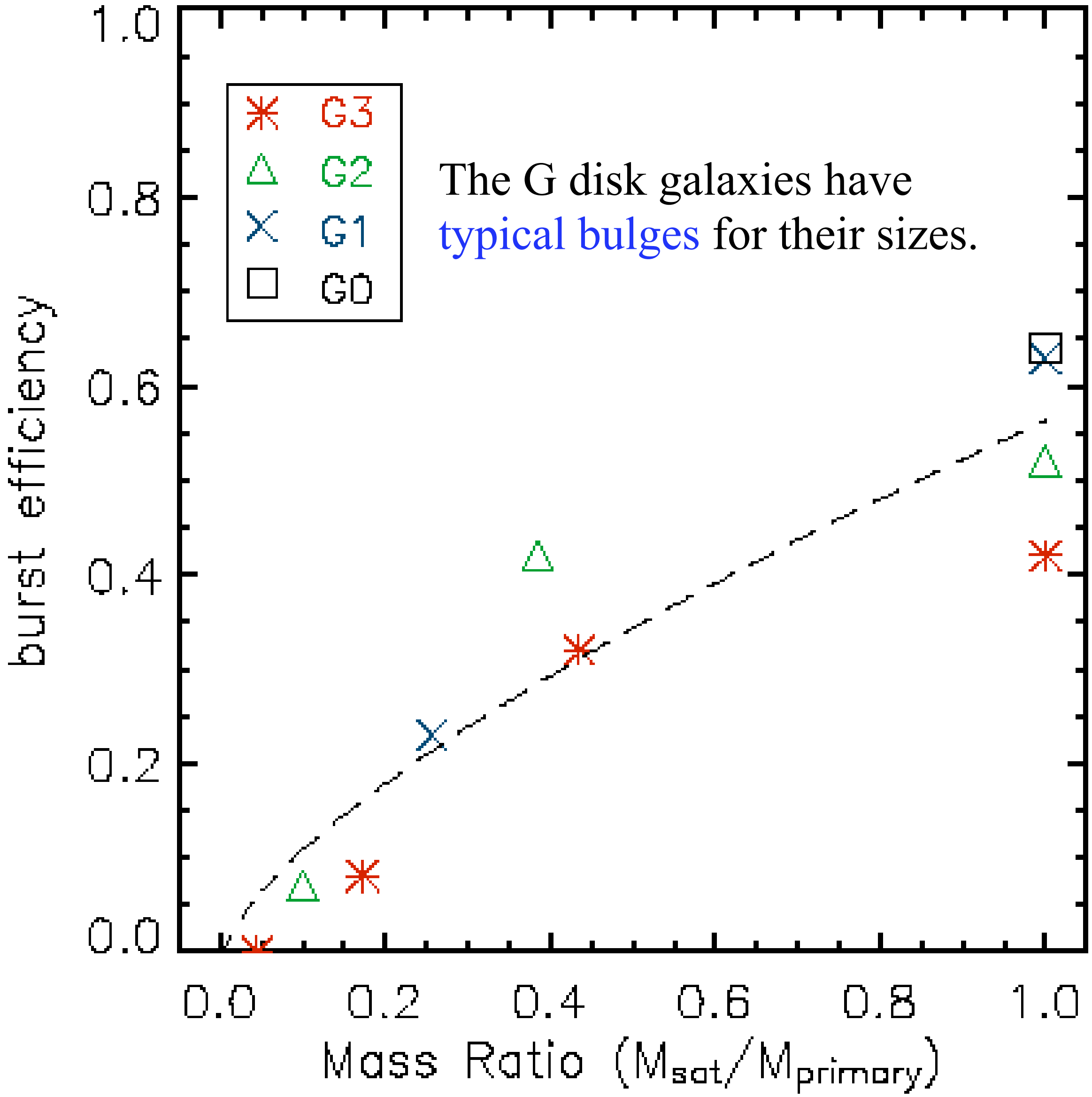
The quiescent star formation has been subtracted.

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

$e_{1:1}$=0.56

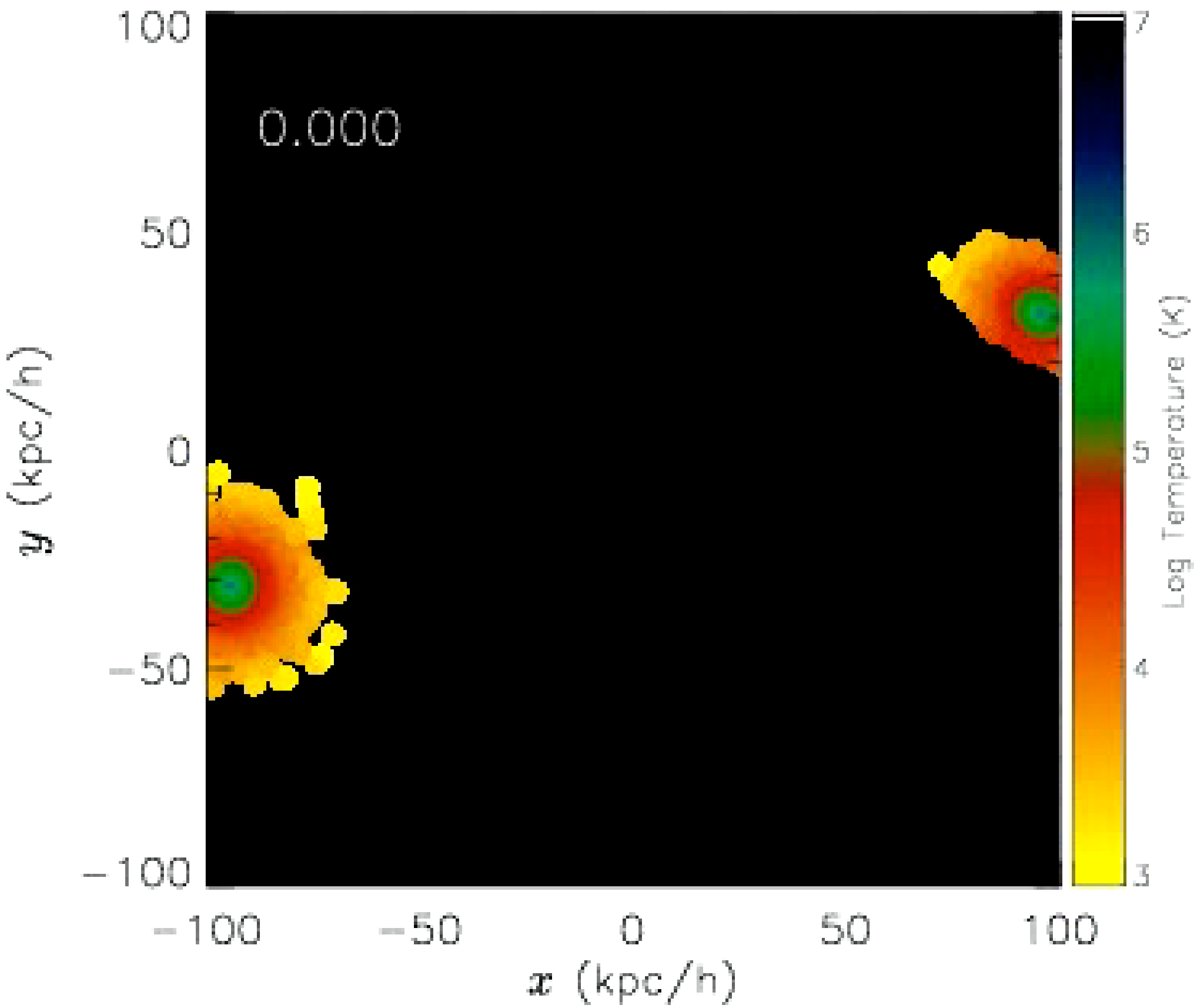
γ=0.7

Burst Efficiency



Gas Temperature during Major Merger

7 kpc slice through orbital plane



10^7 K

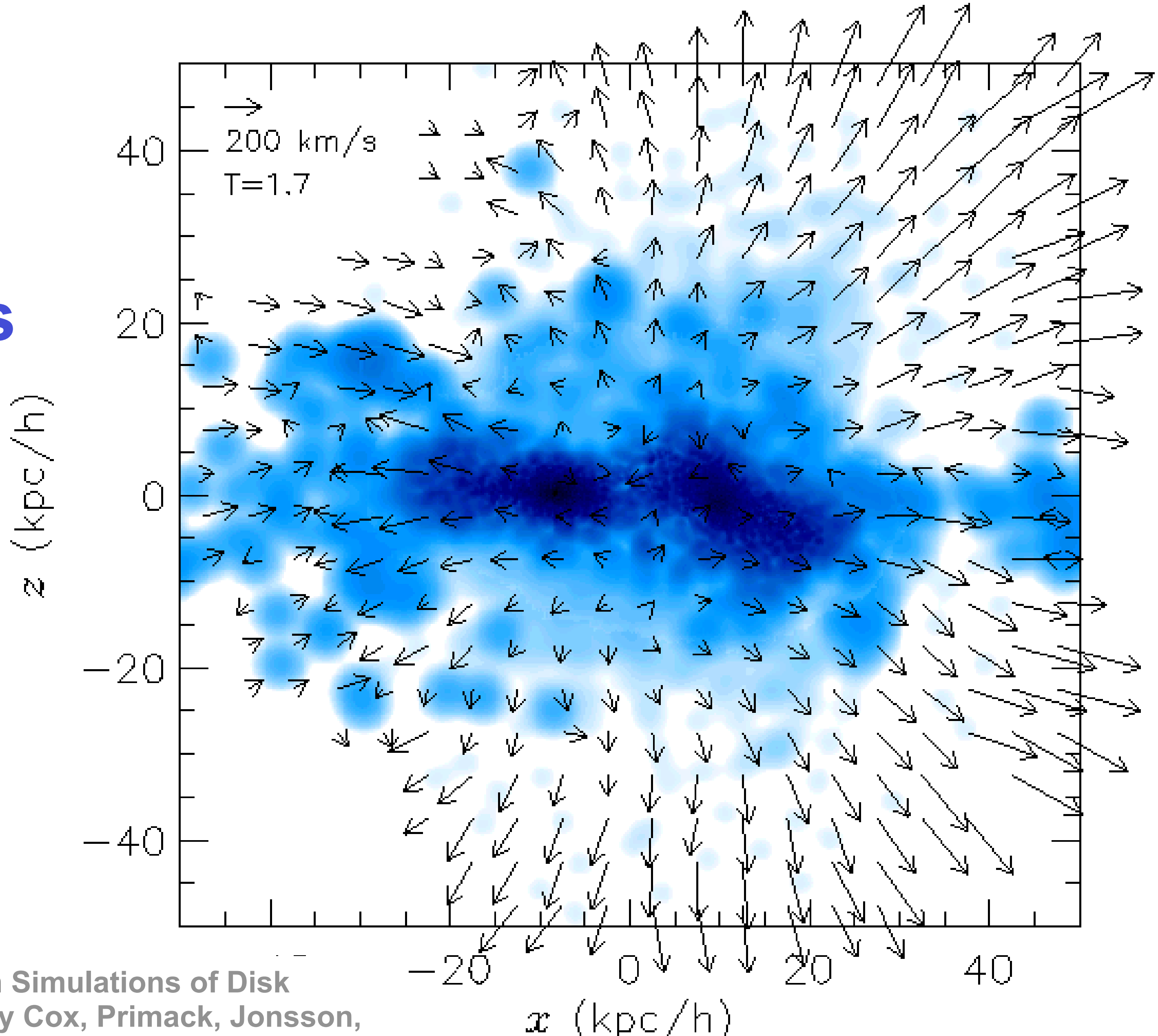
10^6 K

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).

Conclusions so far

- 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, an 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 versus in the quiescent galaxy.

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 than 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.

Work in progress:

- 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.

Spatial, velocity, and angular momentum distribution of dark matter, stars, and gas in merger remnants:

Comparison with Planetary Nebulae and Globular Clusters – "Dark-Matter Haloes in Elliptical Galaxies: Lost and Found" Avishai Dekel et al., *Nature, 437,* 707 (2005)

Comparison with PNe and SAURON – in progress by UCSC grad student Greg Novak working with Primack.

Semi-analytic models of merger remnant properties (e.g., M*, $r_{1/2}$, σ_v, gas) – in progress by UCSC grad student Matt Covington working with Primack. Massive major mergers lie in fundamental plane, lower mass disky remnants do not.

Comparison with Planetary Nebulae and Globular Clusters – "Dark-Matter Haloes in Elliptical Galaxies: Lost and Found"
Dekel et al., *Nature, 437,* 707 (2005)

We show what's wrong with the conclusions drawn by Romanowsky et al.:

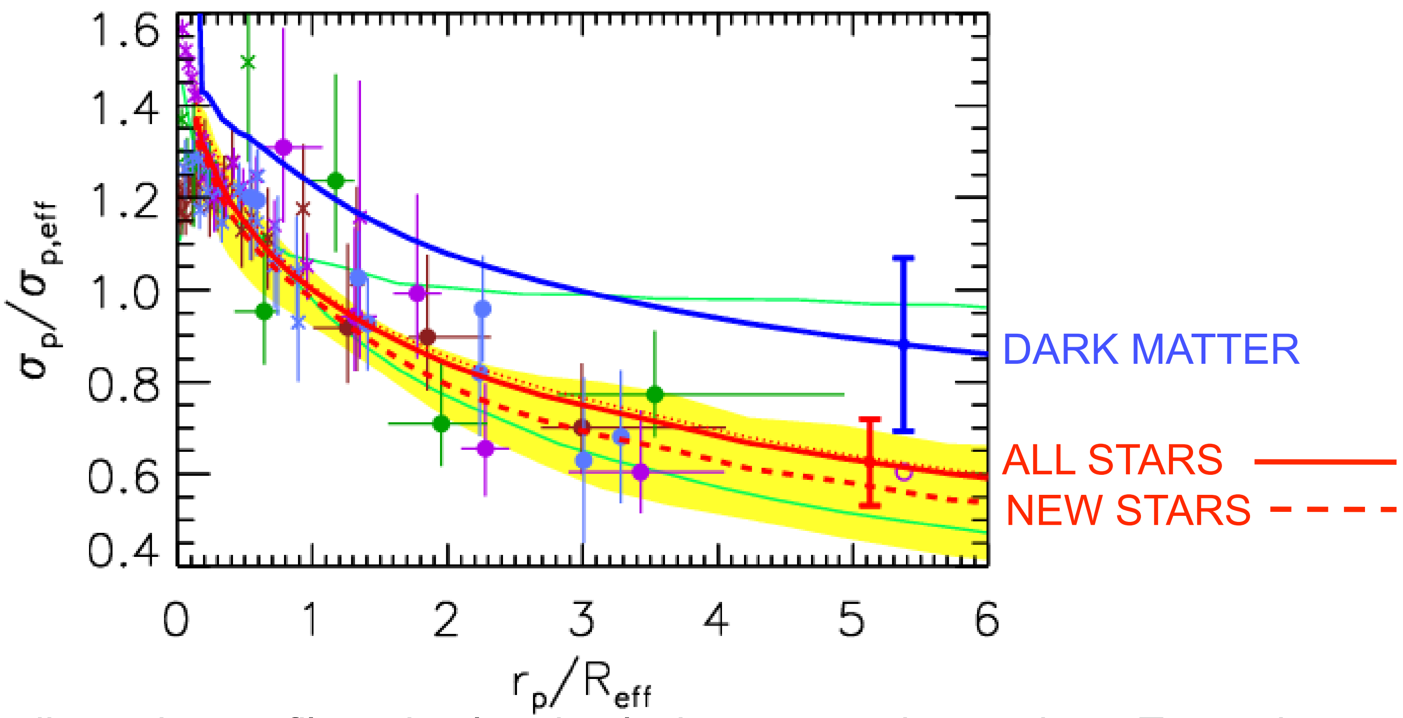
Romanowsky, Douglas, Arnaboldi, Kuijken, Merrifield, Napolitano, Capaccioli, & Freeman,

"A Dearth of Dark Matter in Ordinary Elliptical Galaxies" *Science* **301**, 1696 (2003)

Abstract: The kinematics of the outer parts of three intermediate-luminosity elliptical galaxies were studied with the Planetary Nebula Spectrograph. The galaxies' velocity-dispersion profiles were found to decline with the radius, and dynamical modeling of the data indicates the presence of little if any dark matter in these galaxies' halos. This unexpected result conflicts with findings in other galaxy types and poses a challenge to current galaxy formation theories.

Note that more recent X-ray and Globular Cluster data imply massive dark matter halos in at least two of these galaxies. They thus conflict with this claim and and are consistent with our simulations.

Comparison with Planetary Nebulae and Globular Clusters – "Dark-Matter Haloes in Elliptical Galaxies: Lost and Found"
Dekel et al., *Nature, 707,* 437 (2005) astro-ph/0501622



Projected velocity dispersion profiles: simulated galaxies versus observations. Ten major merger remnants are viewed from three orthogonal directions and the 60 profiles are stacked such that the stellar curves ("old"+"new") match at Reff. Dark matter (blue) versus stars (red), divided into "old" (dotted) and "new" (dashed). The < 3 Gyr "new" stars mimic the observed PNs. The shaded areas and thick bars mark 1σ scatter, partly due to triaxiality. The Romanowsky galaxies are marked green (821), violet (3379), brown (4494) and blue (4697). The surface densities shown for NGC 3379 and 4697 almost coincide with the simulated profile. Green lines refer to the R03 models with (upper) and without (lower) dark matter.

MERGER REMNANTS LIE IN THE FUNDAMENTAL PLANE

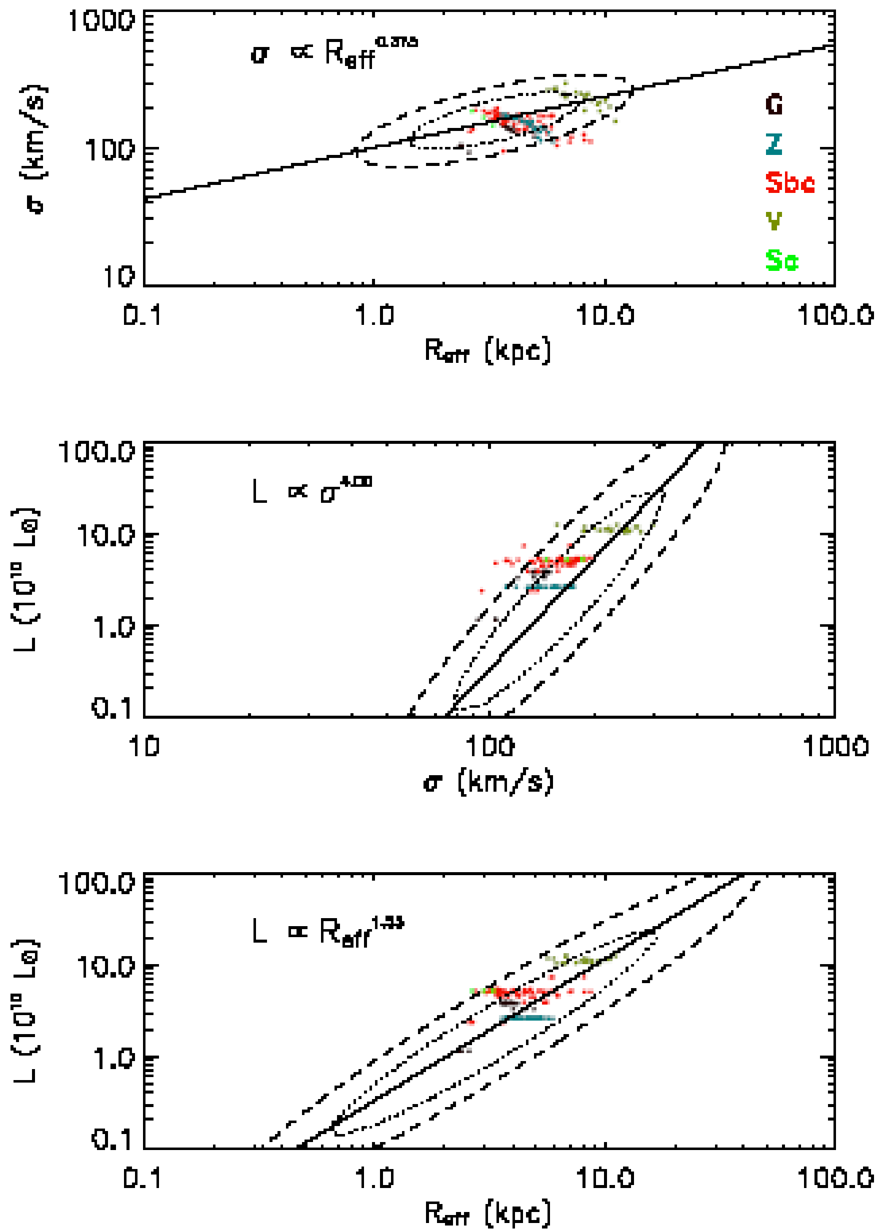
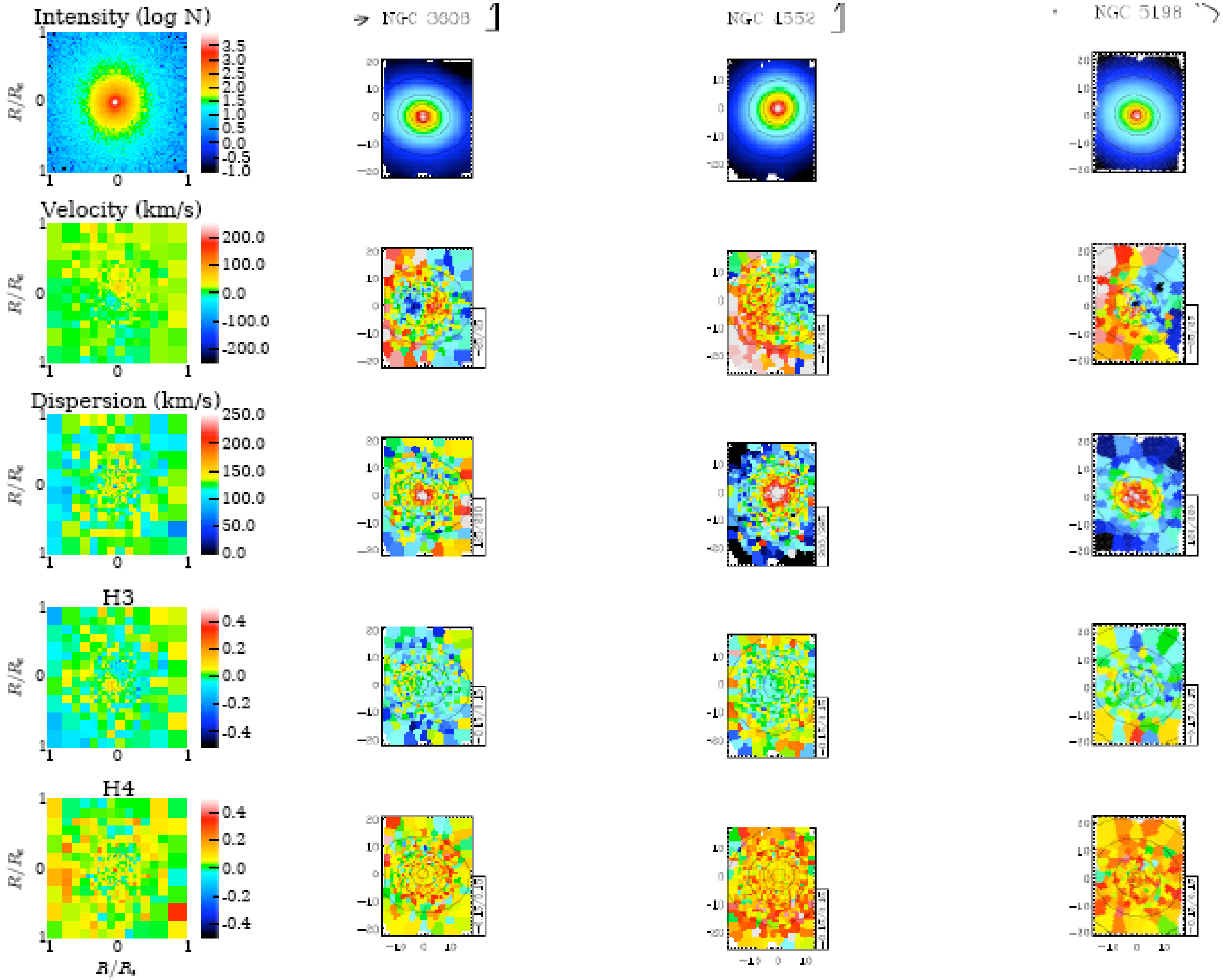


Figure 11. The global structure properties of the simulated merger remnants (symbols, colored by the merger type) in comparison with the Fundamental Plane distribution of elliptical galaxies in SDSS (1 and 2 contours). The dispersion velocity is measured in the central regions. The luminosity is derived from the stellar mass assuming an effective M/L = 3.

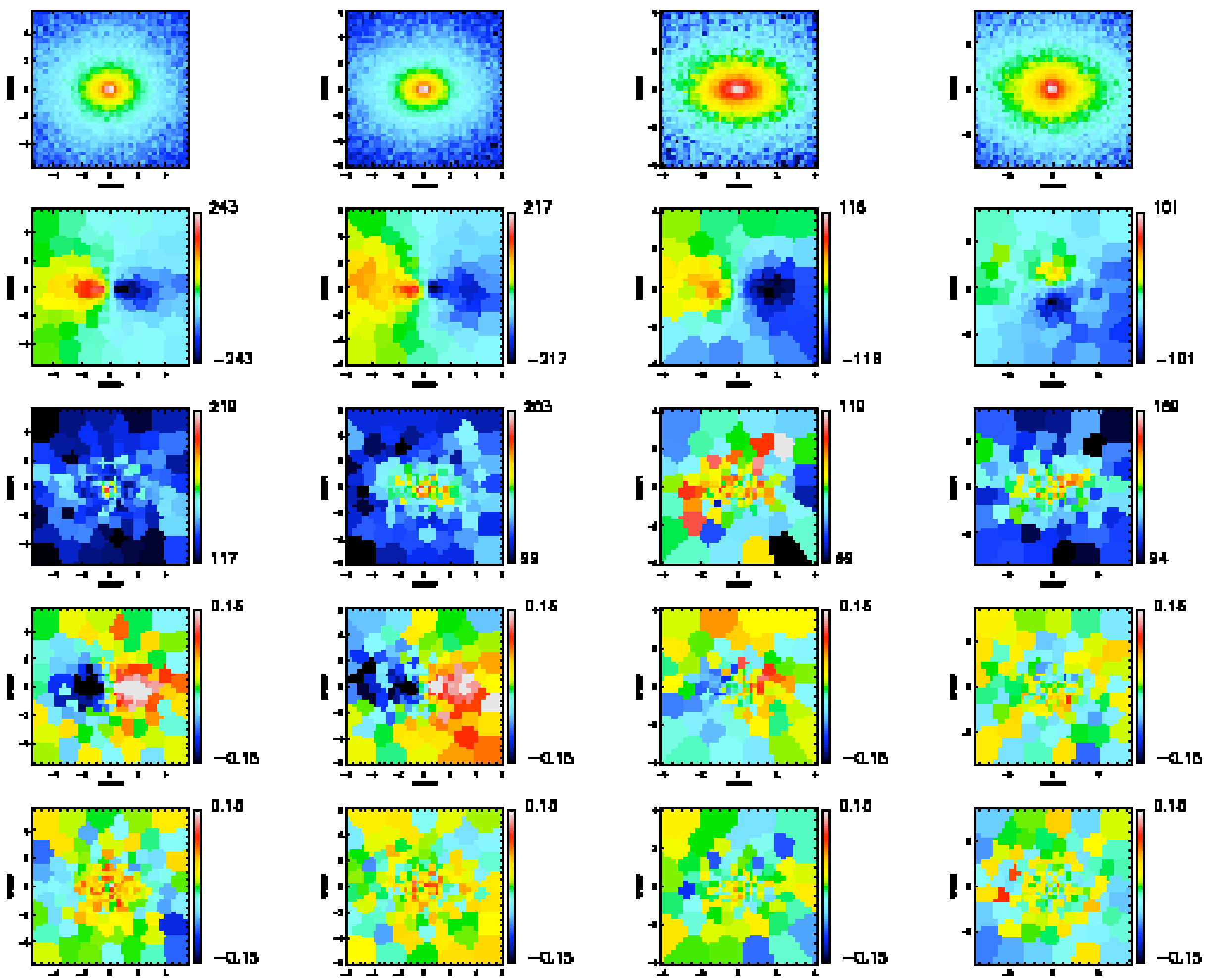
From Supplementary Information online with Nature article, also at astro-ph/0501622. Based on work by Matt Covington with Joel Primack at UCSC.

SAURON Data (from Emsellem et al. 2004)

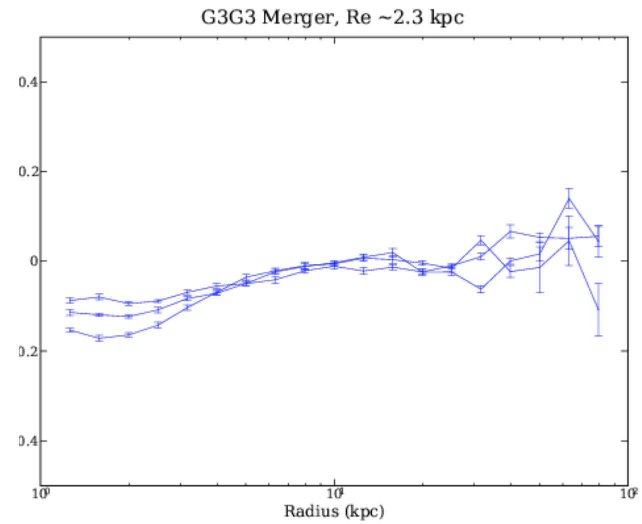


Comparison with PNe and SAURON – in progress by UCSC grad student Greg Novak working with Primack, Cox, Jonsson, and Faber.

Three views of G3G3 merger, plotted like SAURON data.



H4 vs. radius for G3G3 merger



The simulations produce realistic stellar velocity fields, in that the H4 parameter of the old stars is typically < 0.05 in absolute value, as observed for the stellar spectral lines.

The H4 of the PNe of the two galaxies for which we have the data produce larger |H4| .

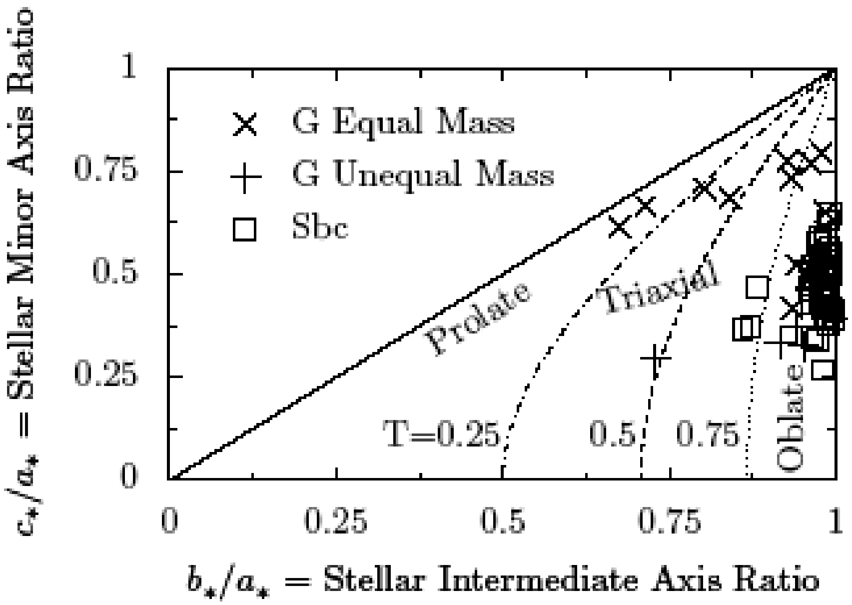
These larger |H4| are reproduced by the young stars of the simulations. This suggests that the observed (bright) PNe are indeed young.

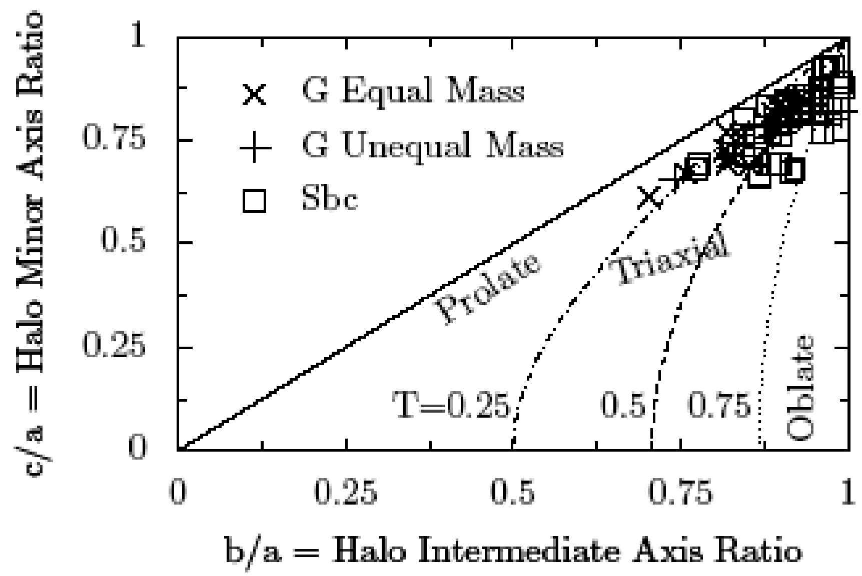
The conclusions so far regarding the SAURON comparison are:

1) Binary hydrodynamic major mergers form qualitatively convincing replicas of the SAURON "fast rotators". We are modeling NGC 6240, with its close SMBH binary.

2) Binary gas-poor major-mergers spiral galaxy and binary gas poor elliptical-elliptical mergers cannot form the SAURON "fast rotators." They have too little rotation and get the V-H3 correlation wrong.

3) Binary gas-poor major-mergers spiral galaxy and binary gas poor elliptical-elliptical mergers may be able to form the SAURON slow rotators, if slow rotators are significantly more elliptical on average than is indicated by the SAURON survey. Greg Novak is running various types of multiple mergers to try to form galaxies like the SAURON slow rotators.

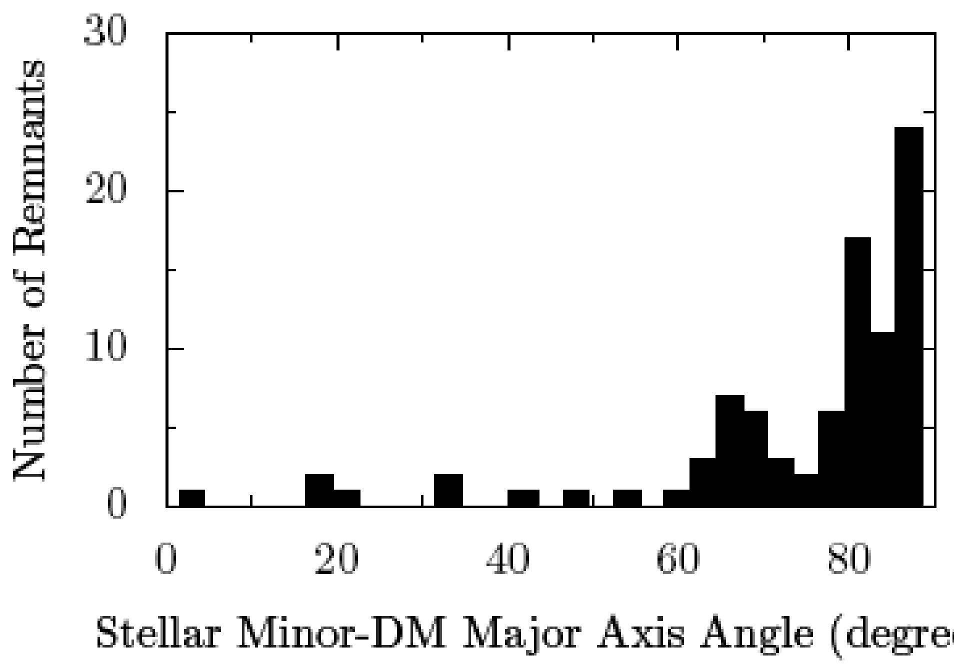




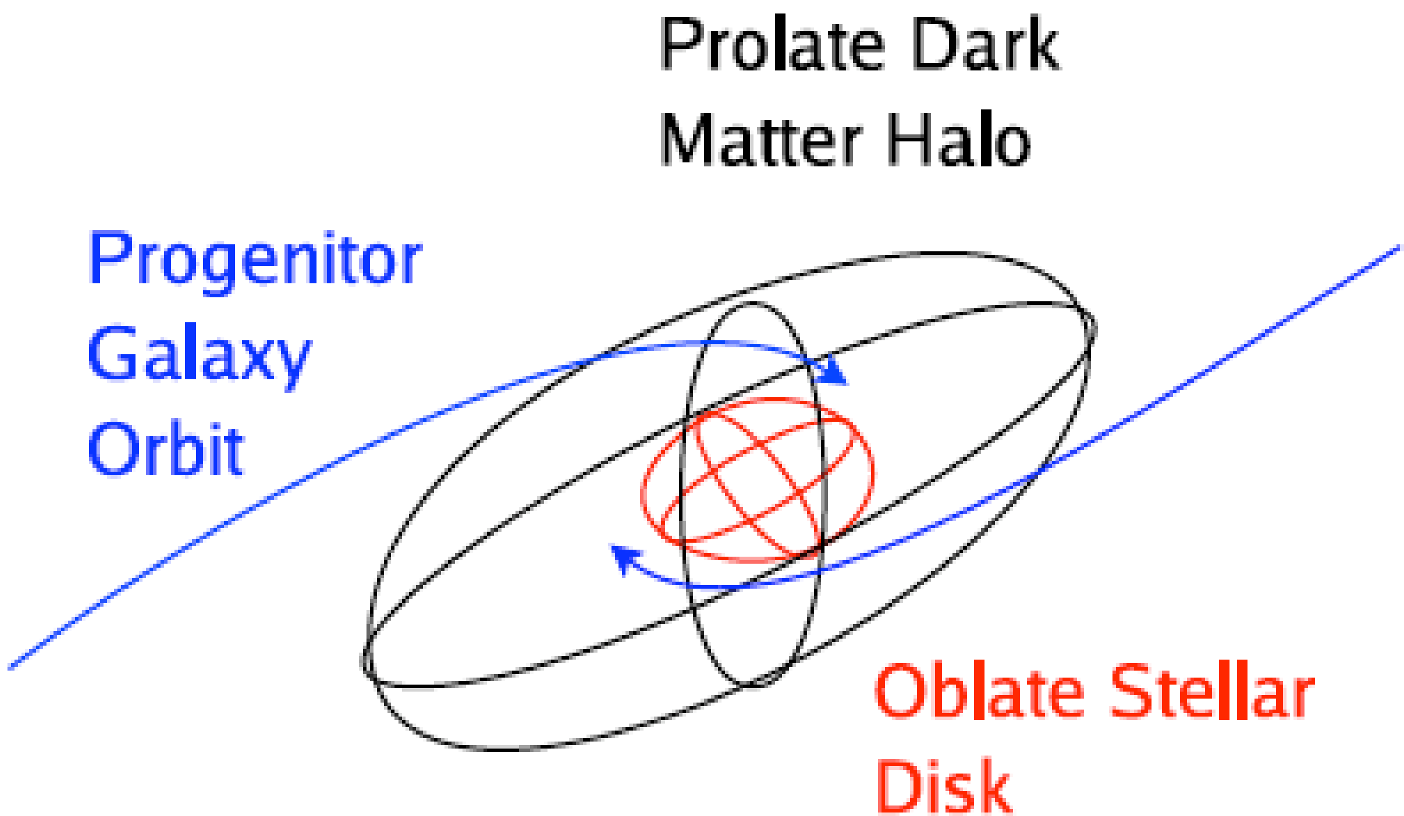
The stellar ellipsoids are mostly oblate but the dark matter halo is usually triaxial or prolate.

The stellar minor axis usually aligns with the angular momentum axis, which aligns with the dark matter smallest axis, perpendicular to the dark matter major axis.

Novak, Cox, Primack, Jonsson, & Dekel, ApJ Letters in press, astro-ph/0604121



Why does the short (rotation) axis of the visible elliptical galaxy align with the long axis of its dark matter halo?
The long axis of the halo is along the merger axis, while the angular momentum axis is perpendicular to that axis.



Novak, Cox, Primack, Jonsson, & Dekel,
ApJ Letters in press, astro-ph/0604121

Simulations of Dust in Interacting Galaxies

Patrik Jonsson
UCSC

HST image of “The Antennae”

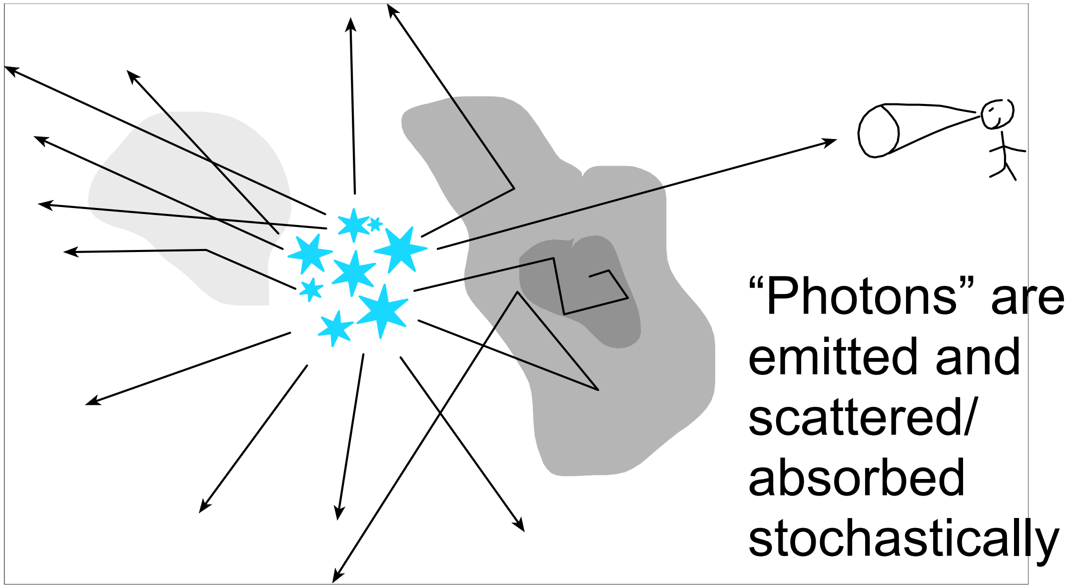
Introduction

- 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



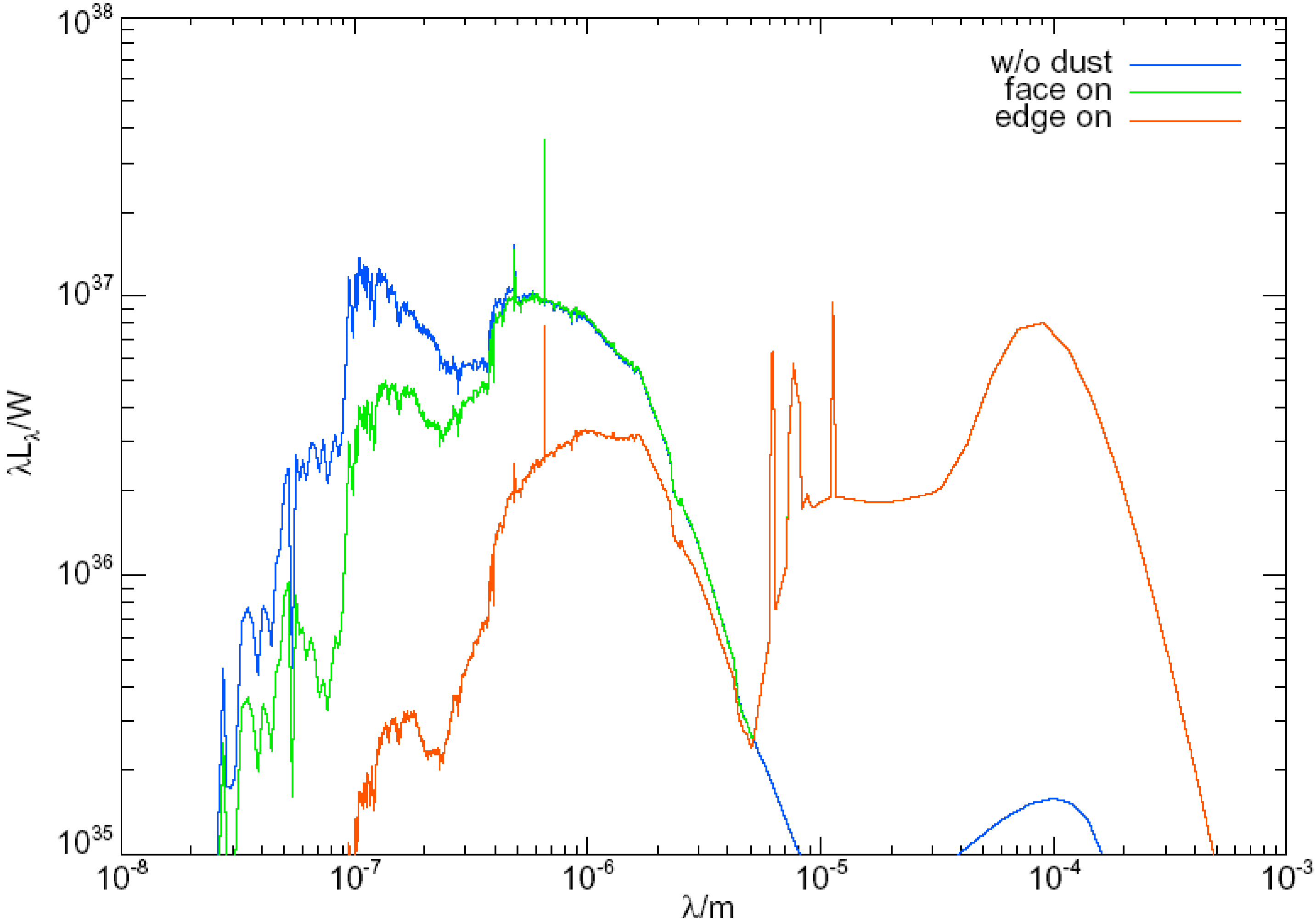
Radiative transfer stage

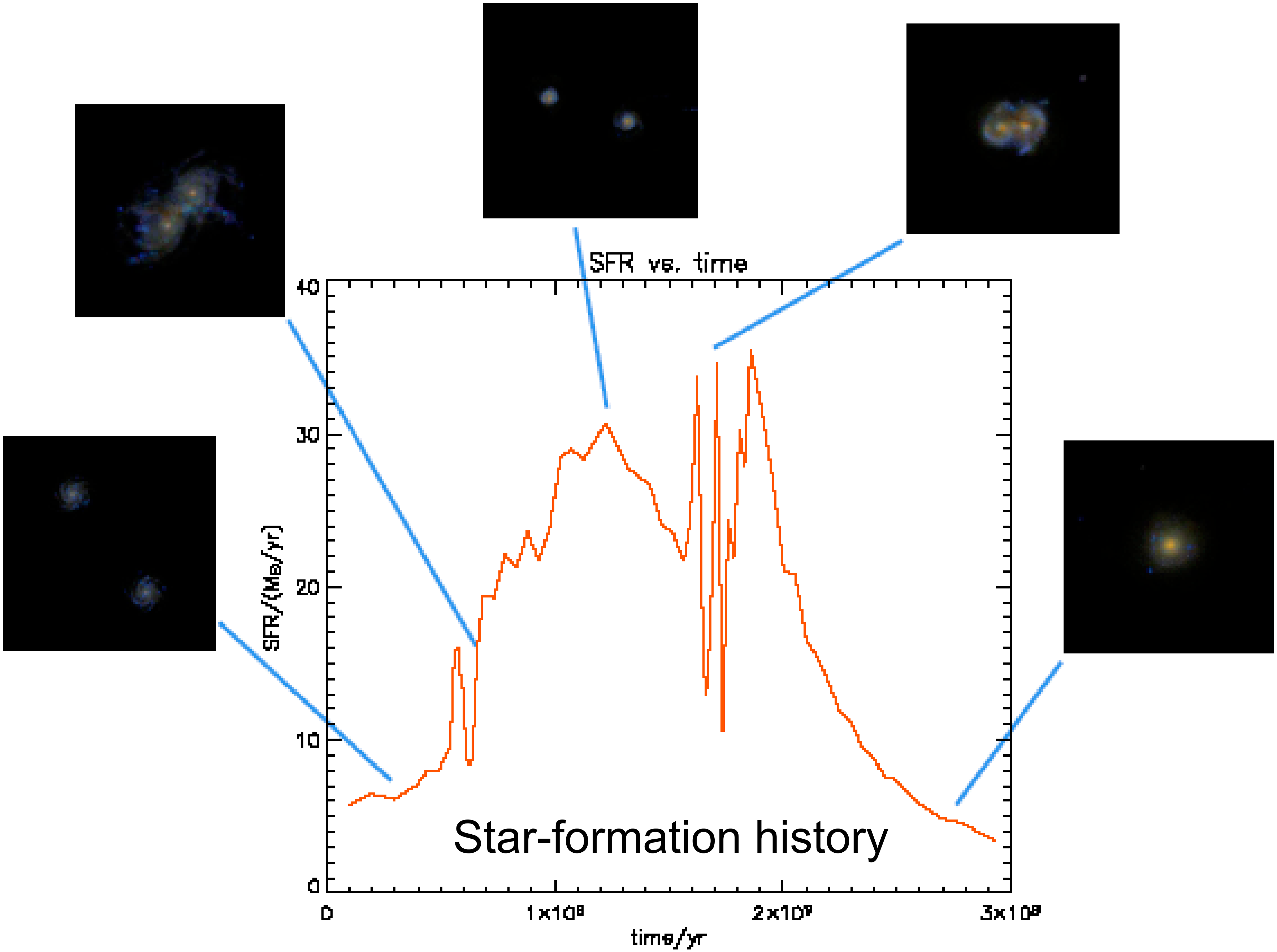
- Run entire SED at once without scattering
- Run with scattering for a single wavelength, or for many (`polychrome')
- Repeat for all wavelengths desired - code includes Ly alpha, beta
- Interpolate SED to full resolution

Outputs

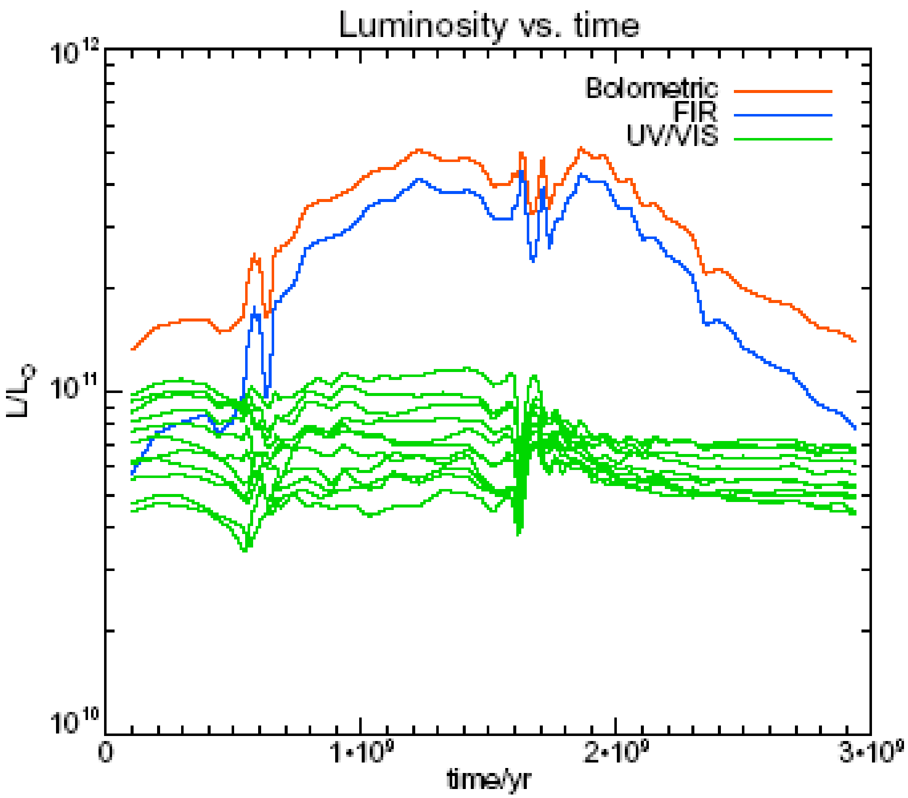
- Data cube for each camera, typically 300x300 pixels x 500 wavelengths
  - Can be integrated to give images in broadband filters
  - Or look at spectral characteristics
- Absorbed energy in grid cells
  - Determines FIR luminosity reradiated by dust
  - Devriendt FIR template SED is added to integrated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

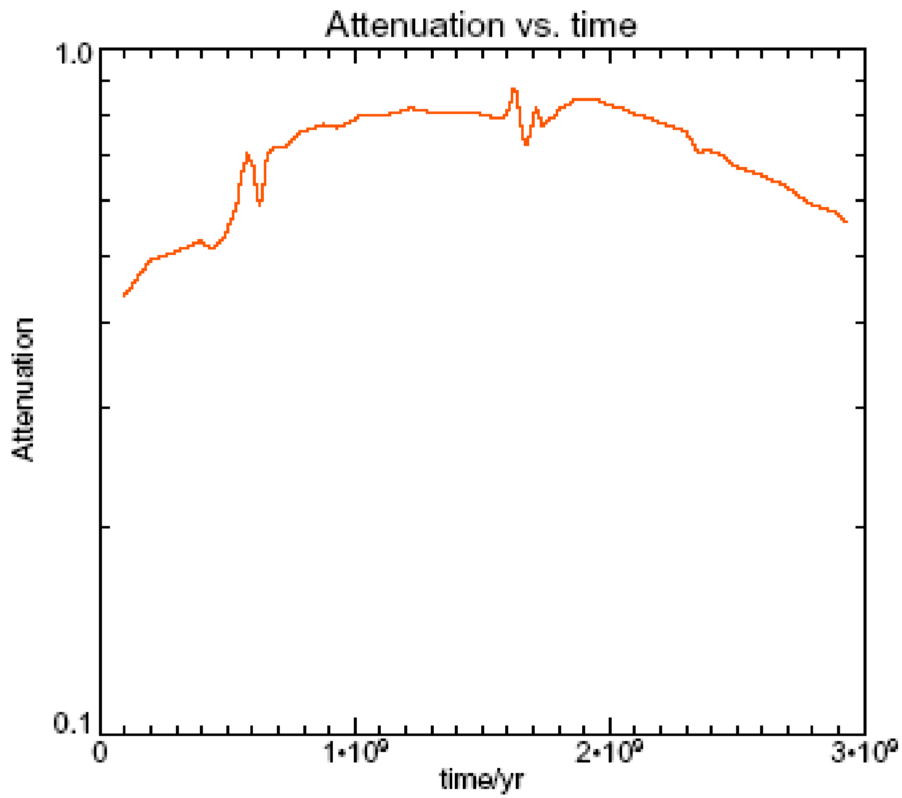
Spectral Energy Distribution




SFR vs. time
SFR/(Ms/yr)
time/yr
0
10
20
30
40
0
1x10⁹
2x10⁹
3x10⁹
Star-formation history

Luminosities

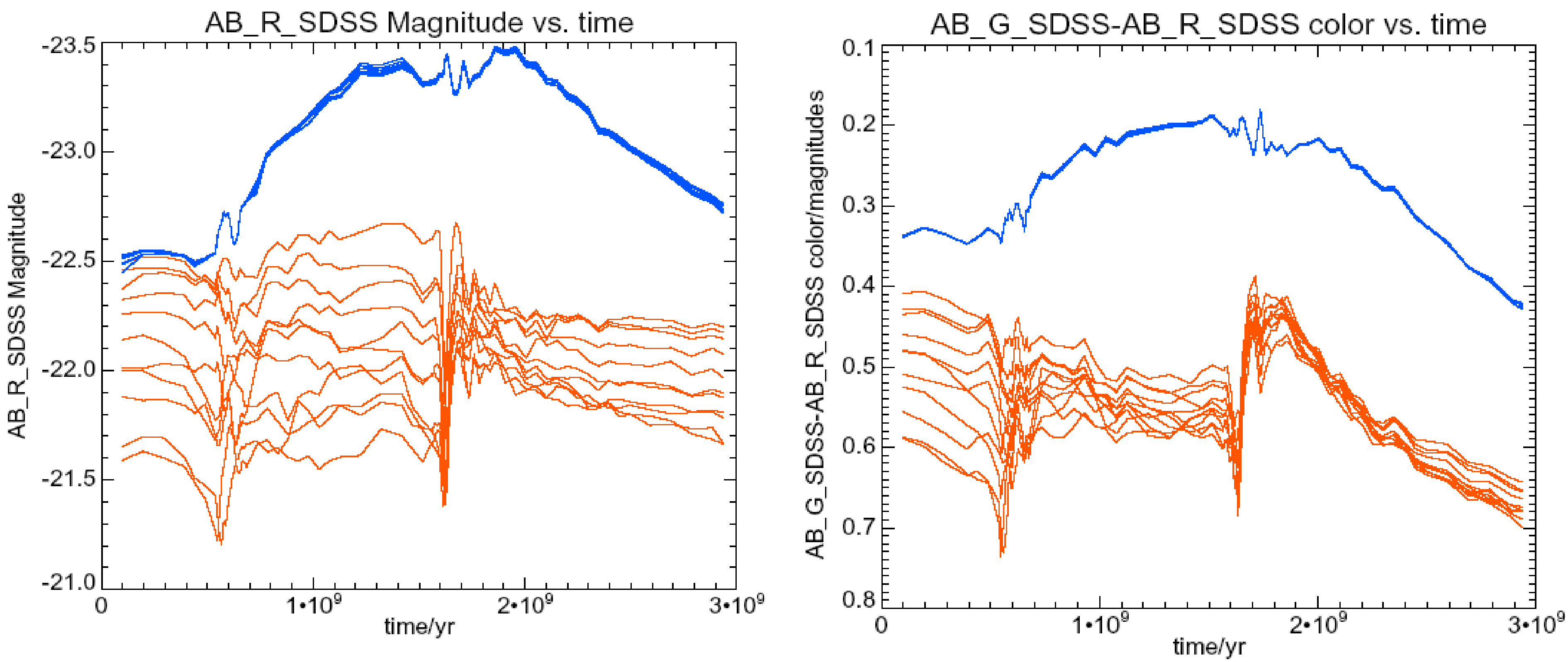




UV/visual luminosity is practically constant over time

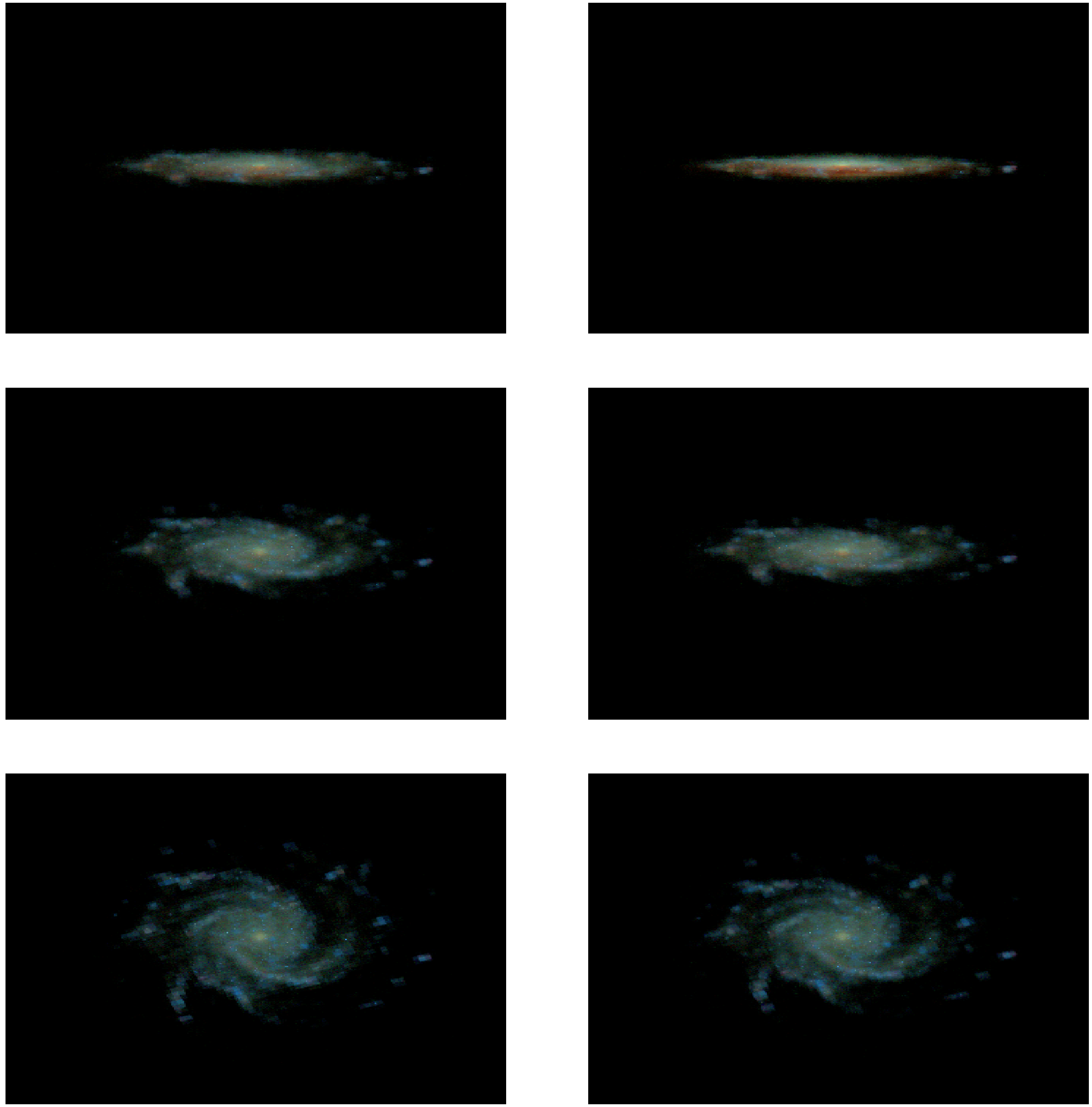
Attenuation increases with luminosity

Magnitudes & Colors



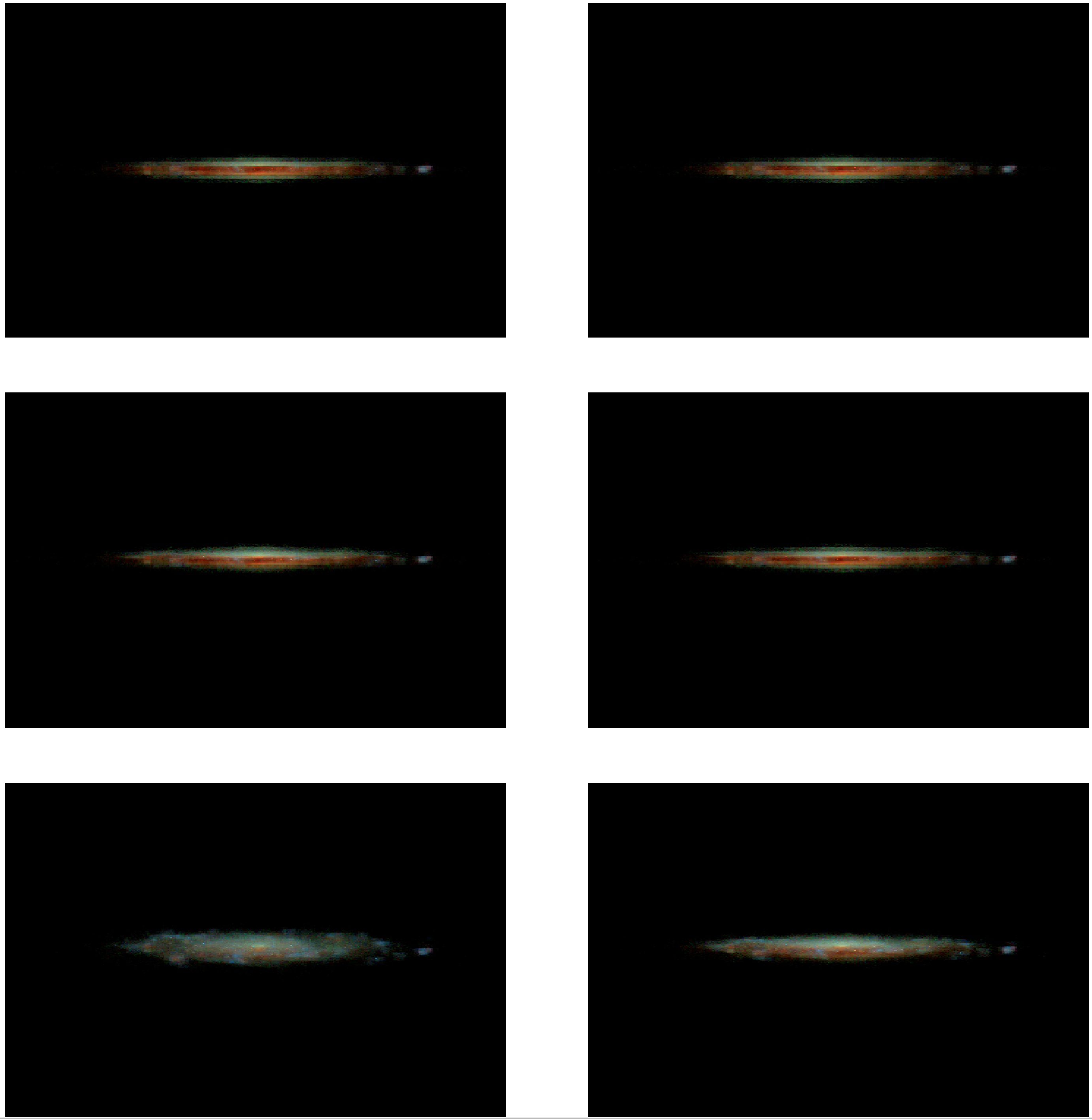
During the transients, the magnitudes and colors with and without dust are **anticorrelated**

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

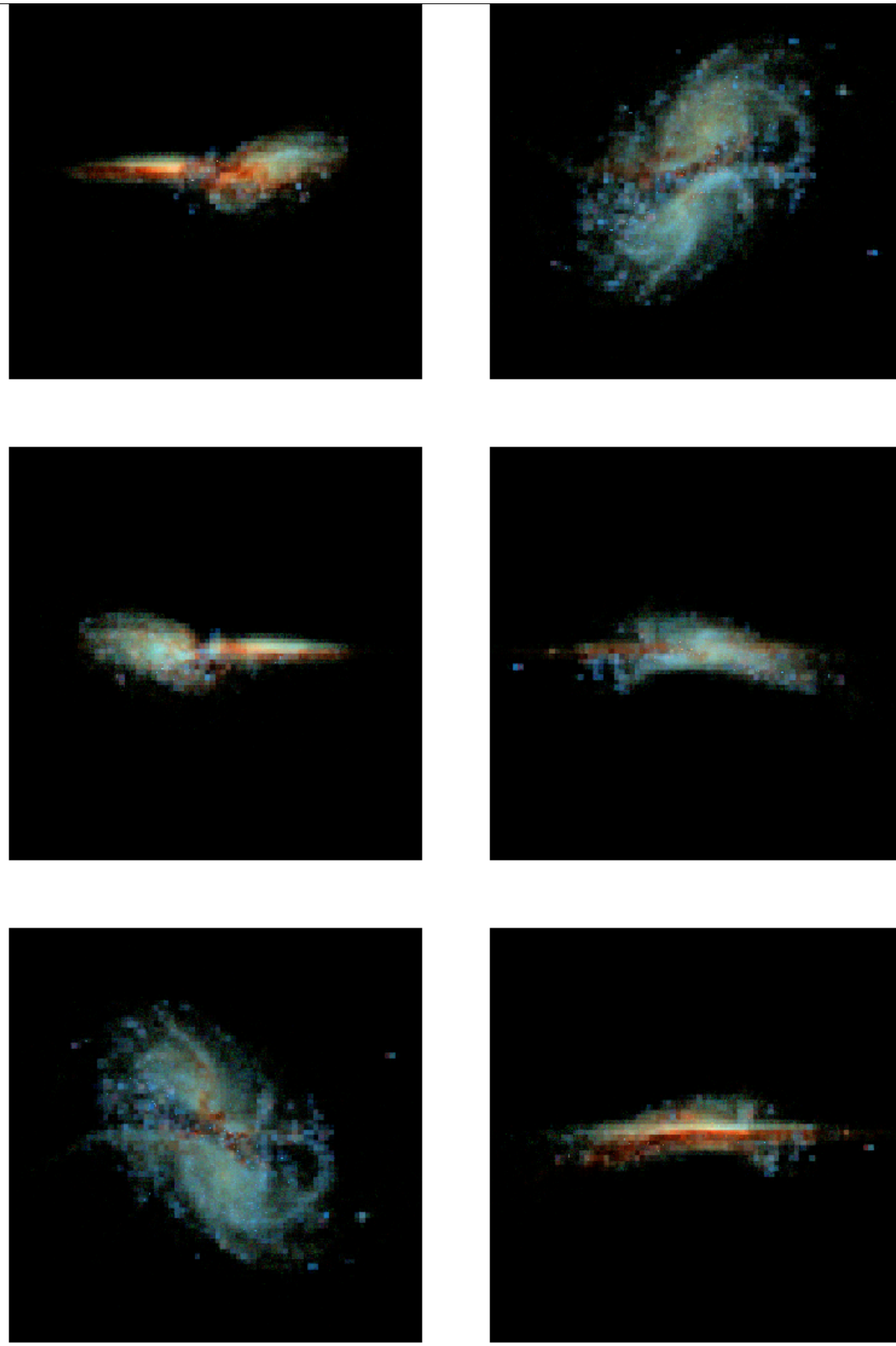


Near edge-on images (with dust) from *Sunrise* Monte Carlo radiative transfer code by Patrik Jonsson.

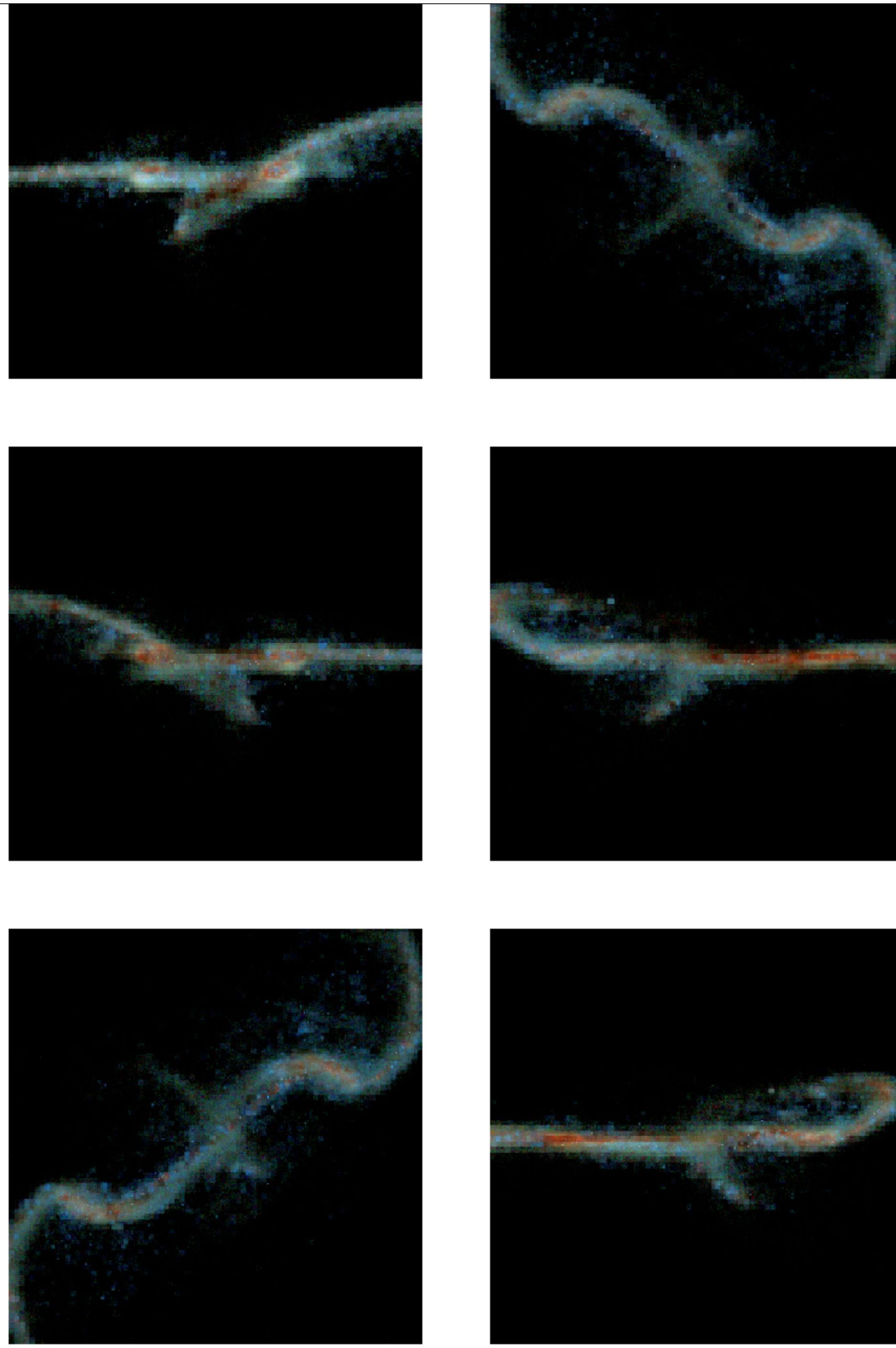
These were run with no radial metallicity gradient, but our latest work shows that observed radial gradients predict attenuation vs. inclination in agreement with observations.



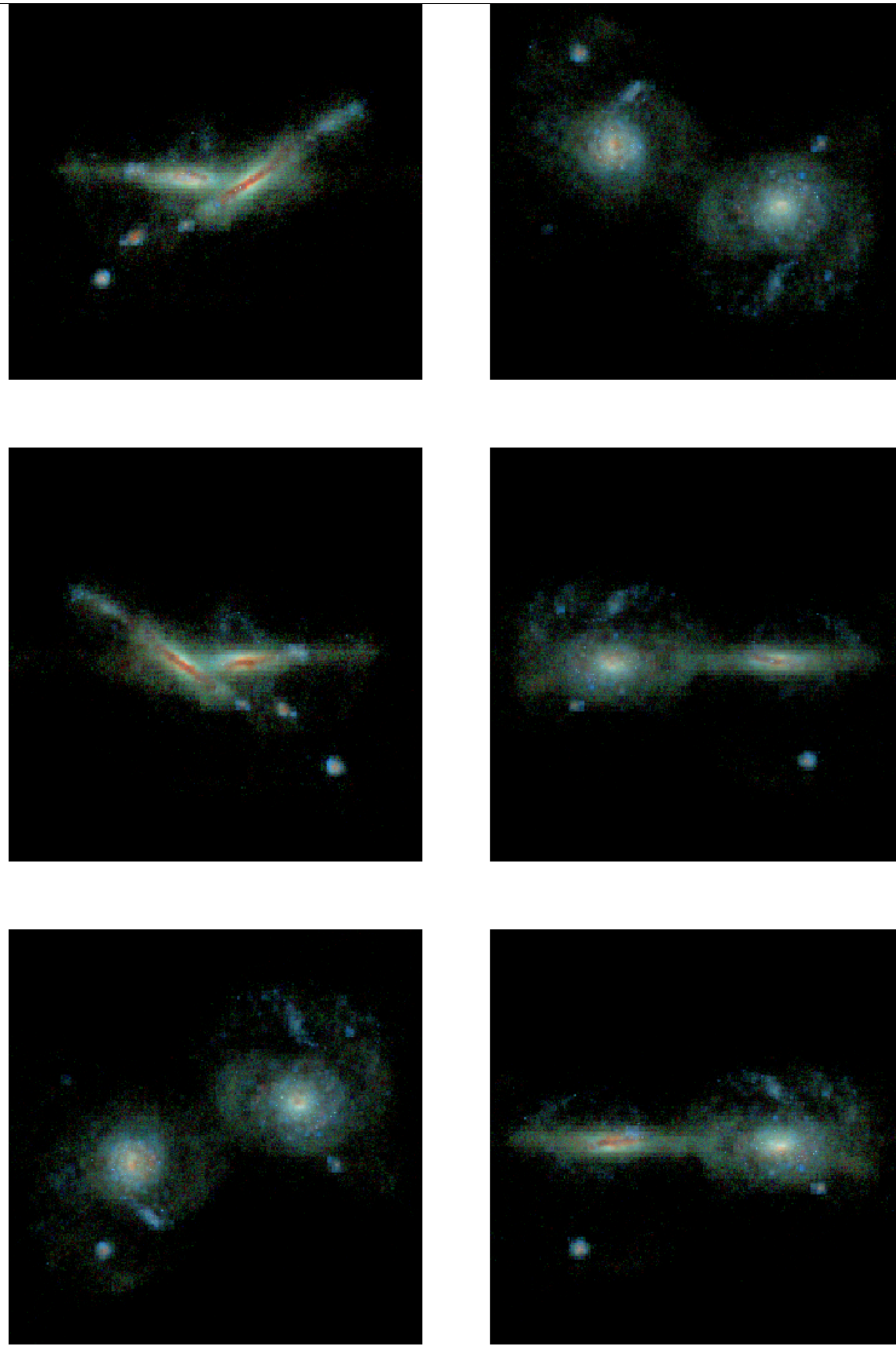
Merger
with
SEDs
and dust:
6 views



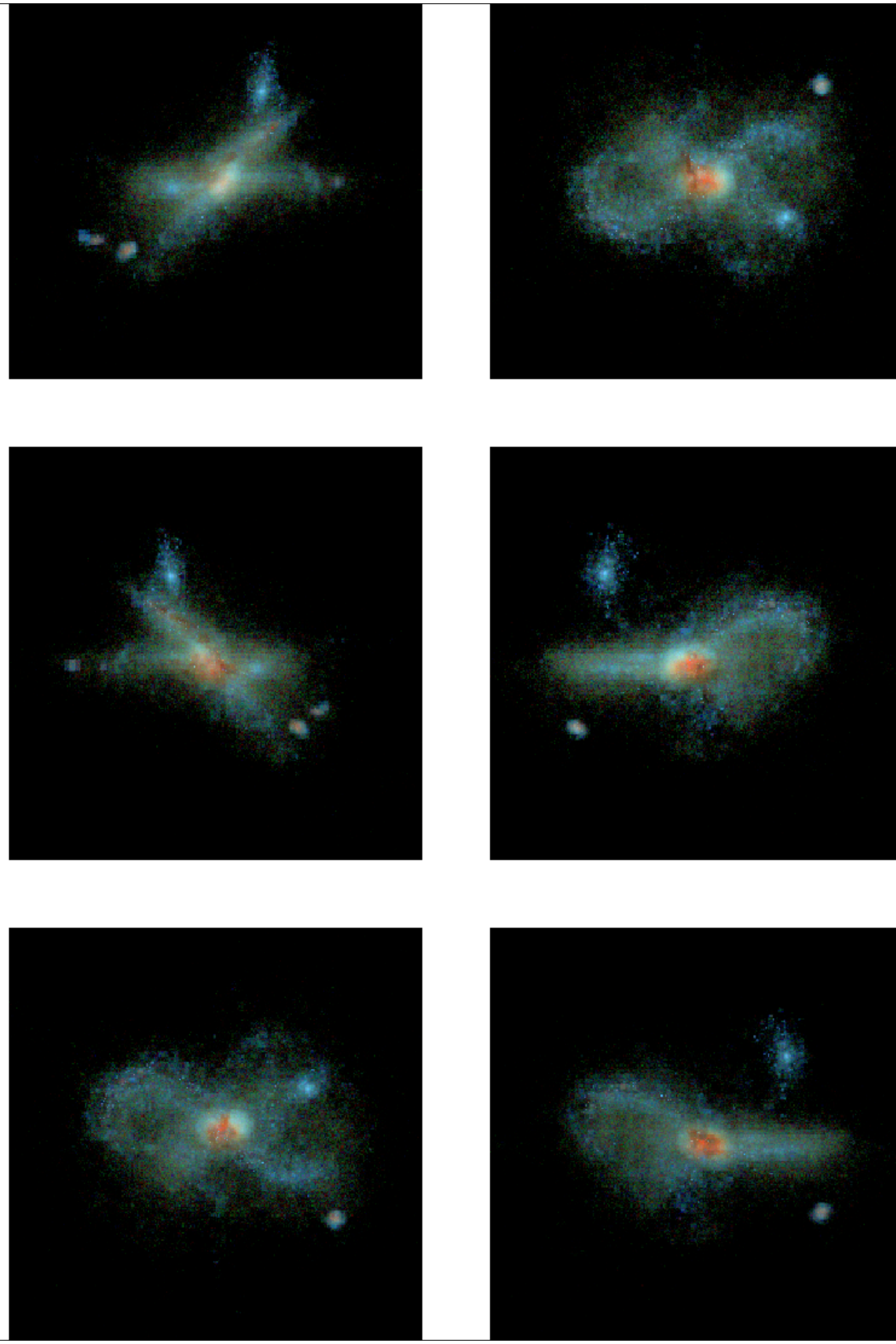
Merger with SEDs and dust: 6 views



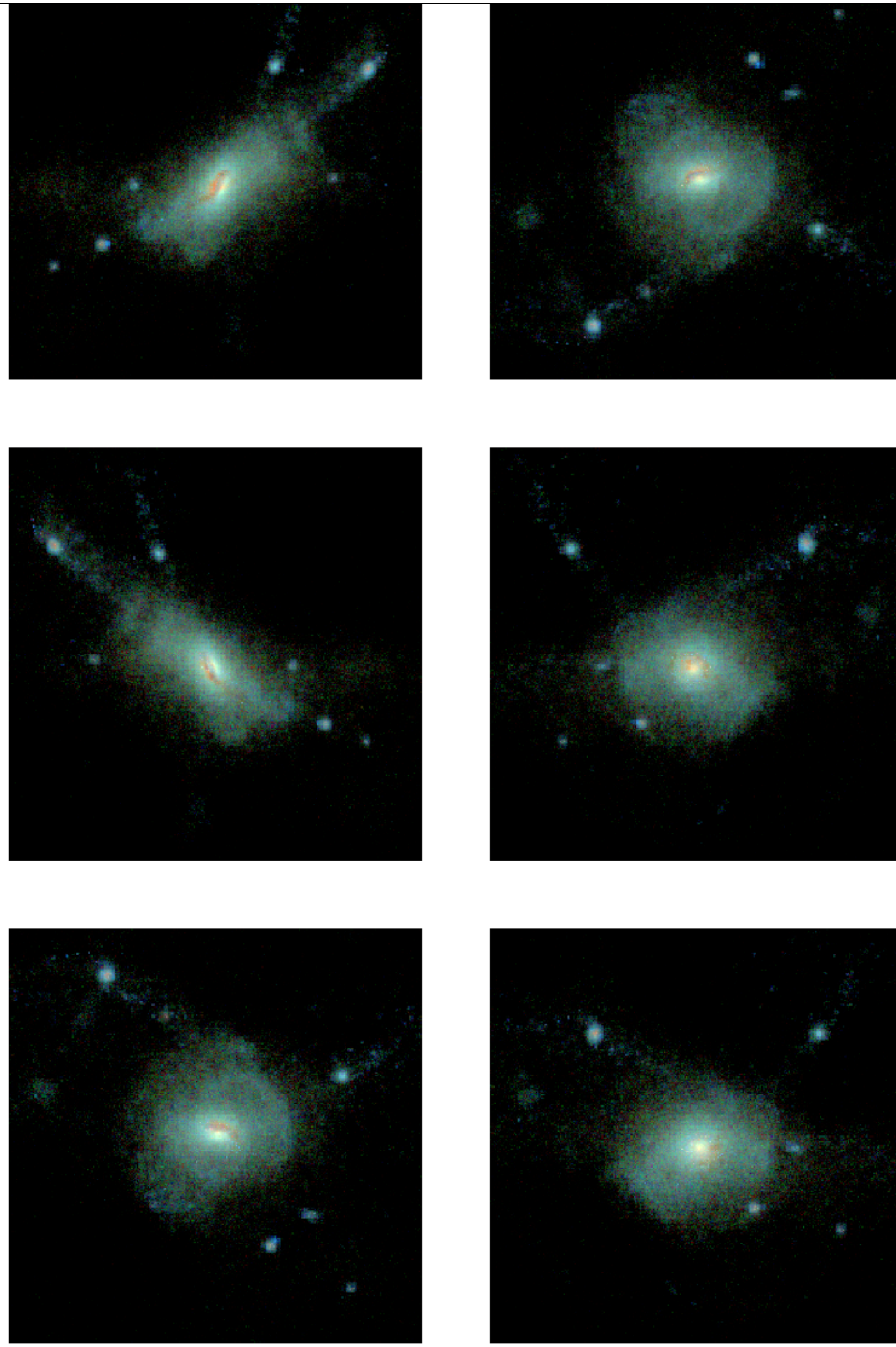
Merger with SEDs and dust: 6 views



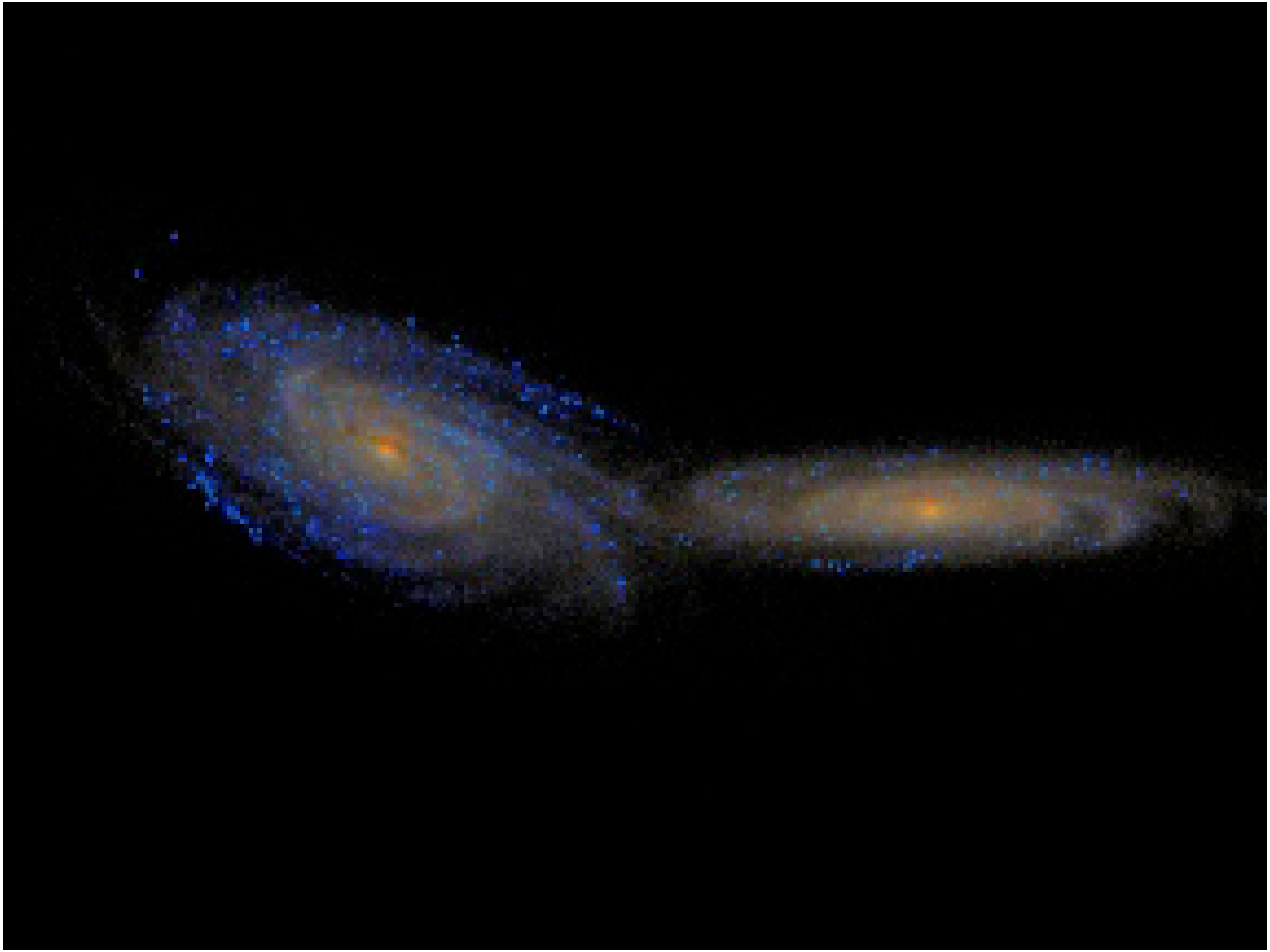
Merger with SEDs and dust: 6 views

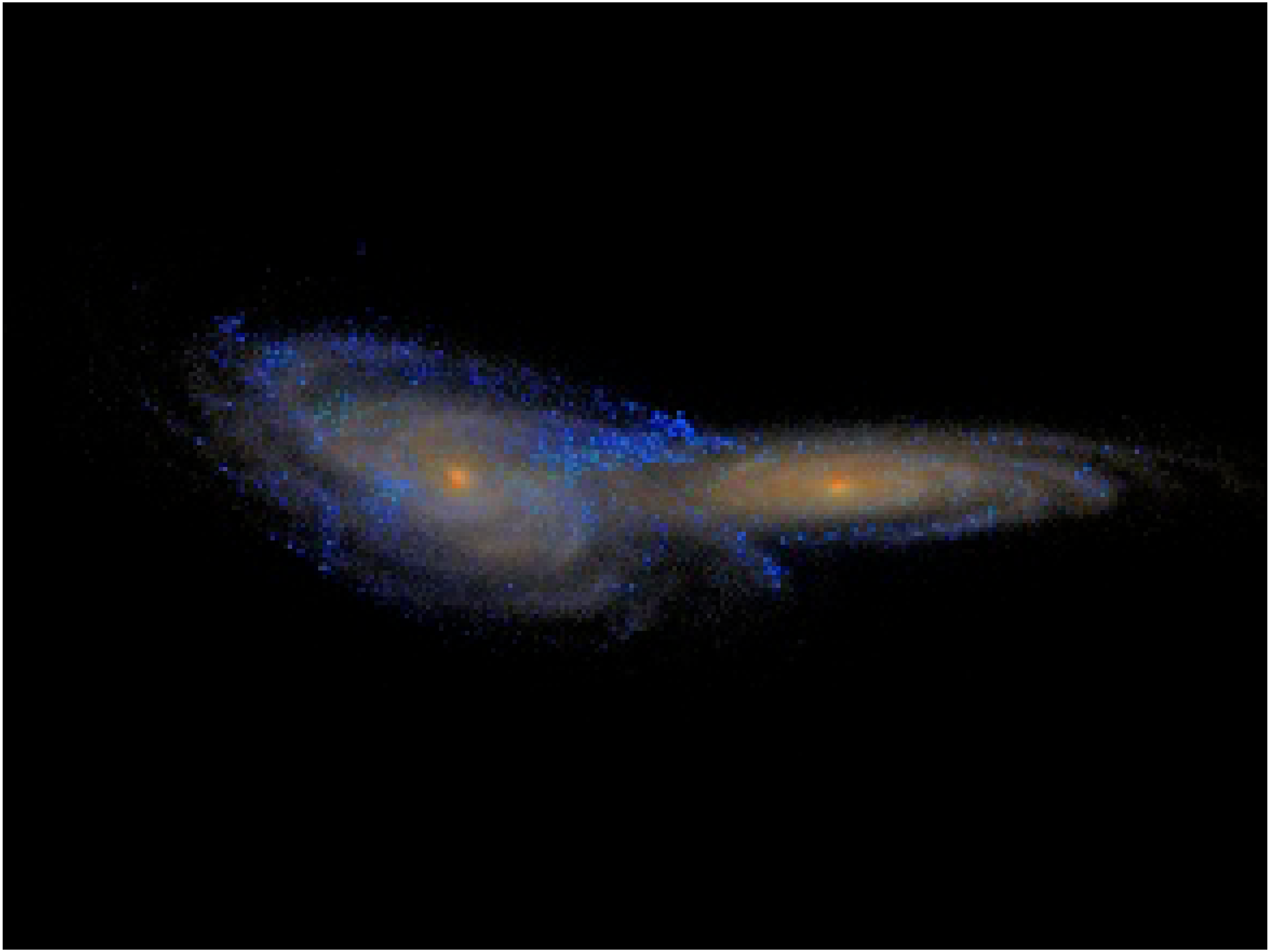


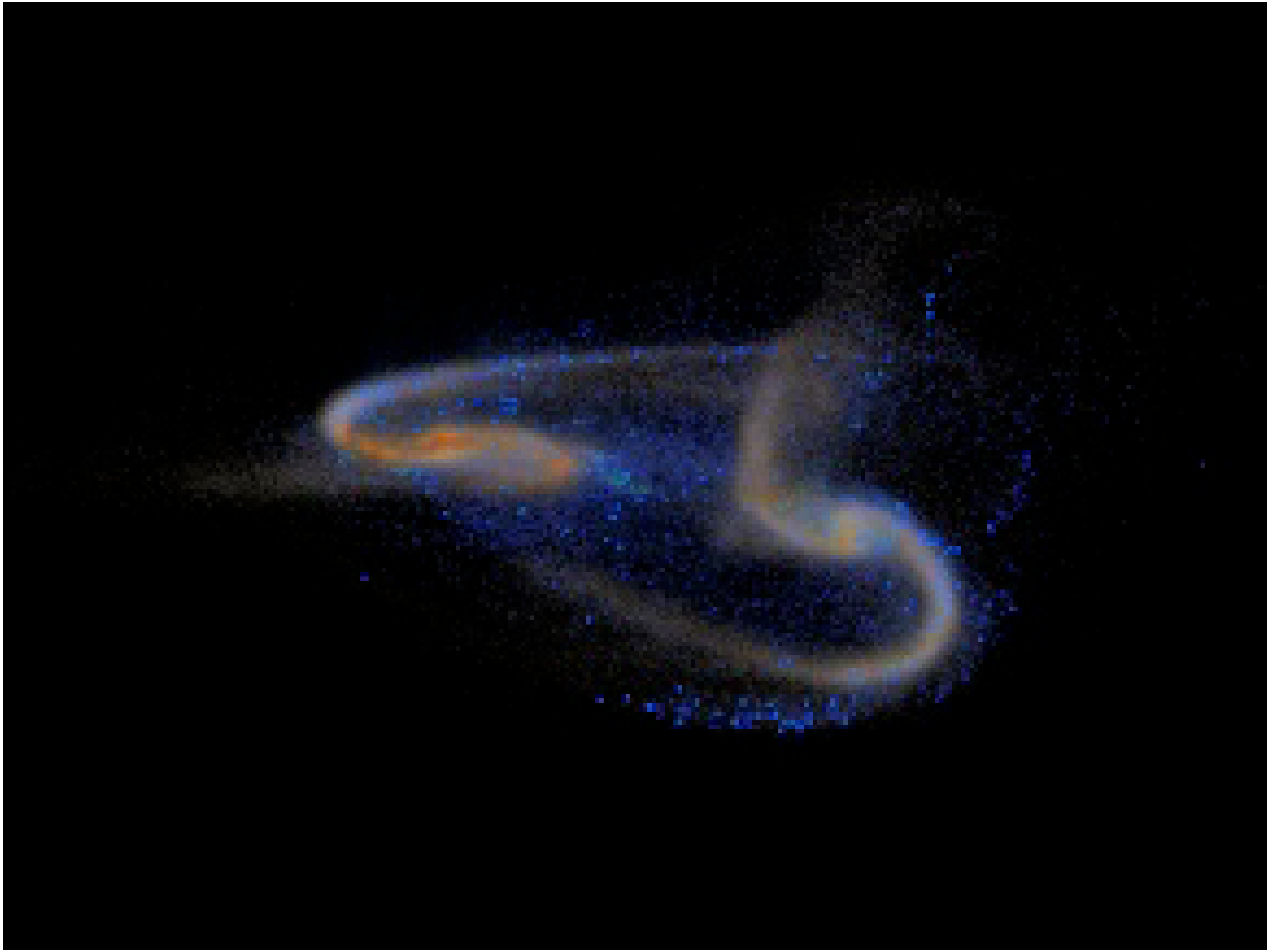
Merger with SEDs and dust: 6 views

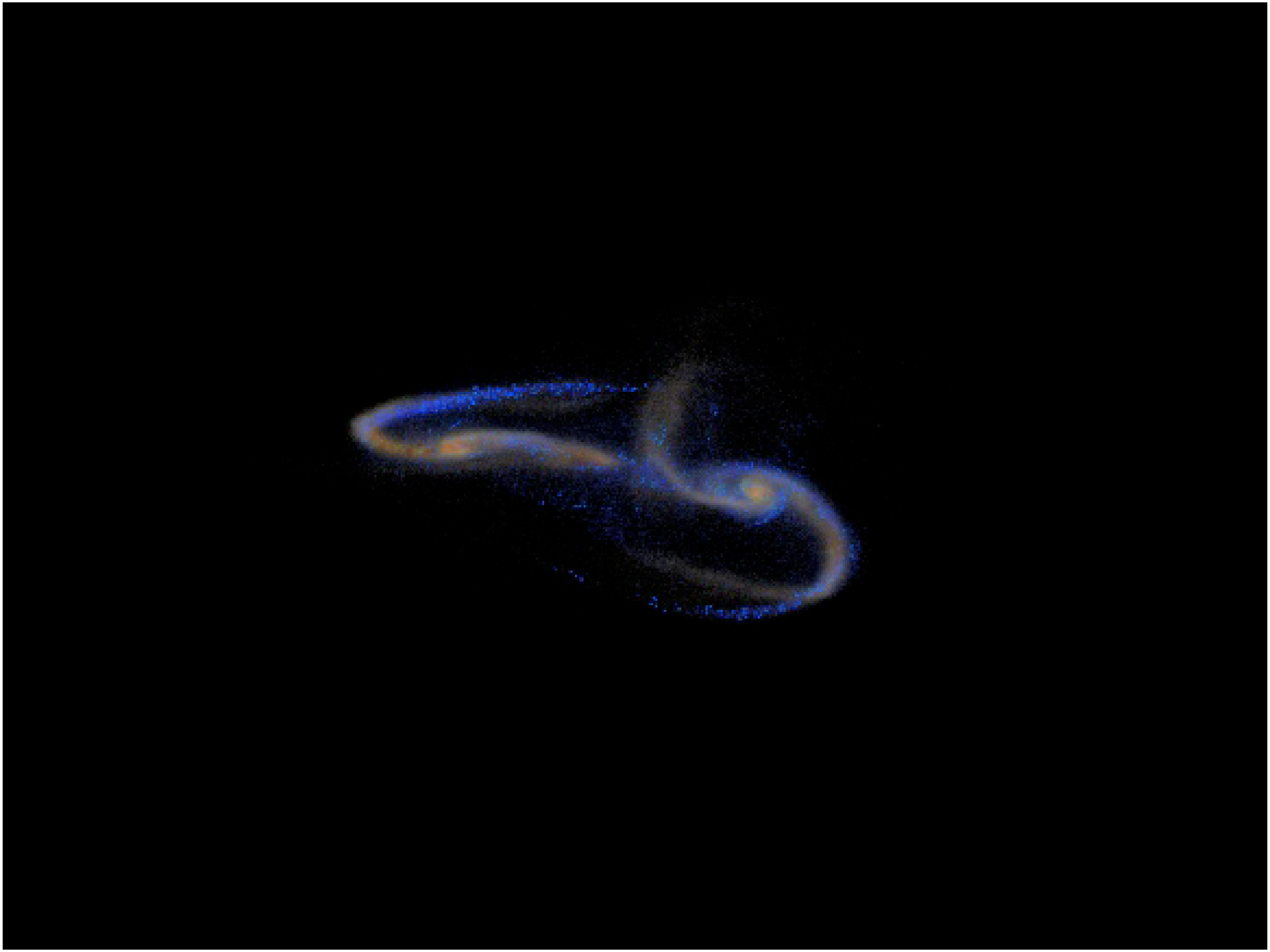


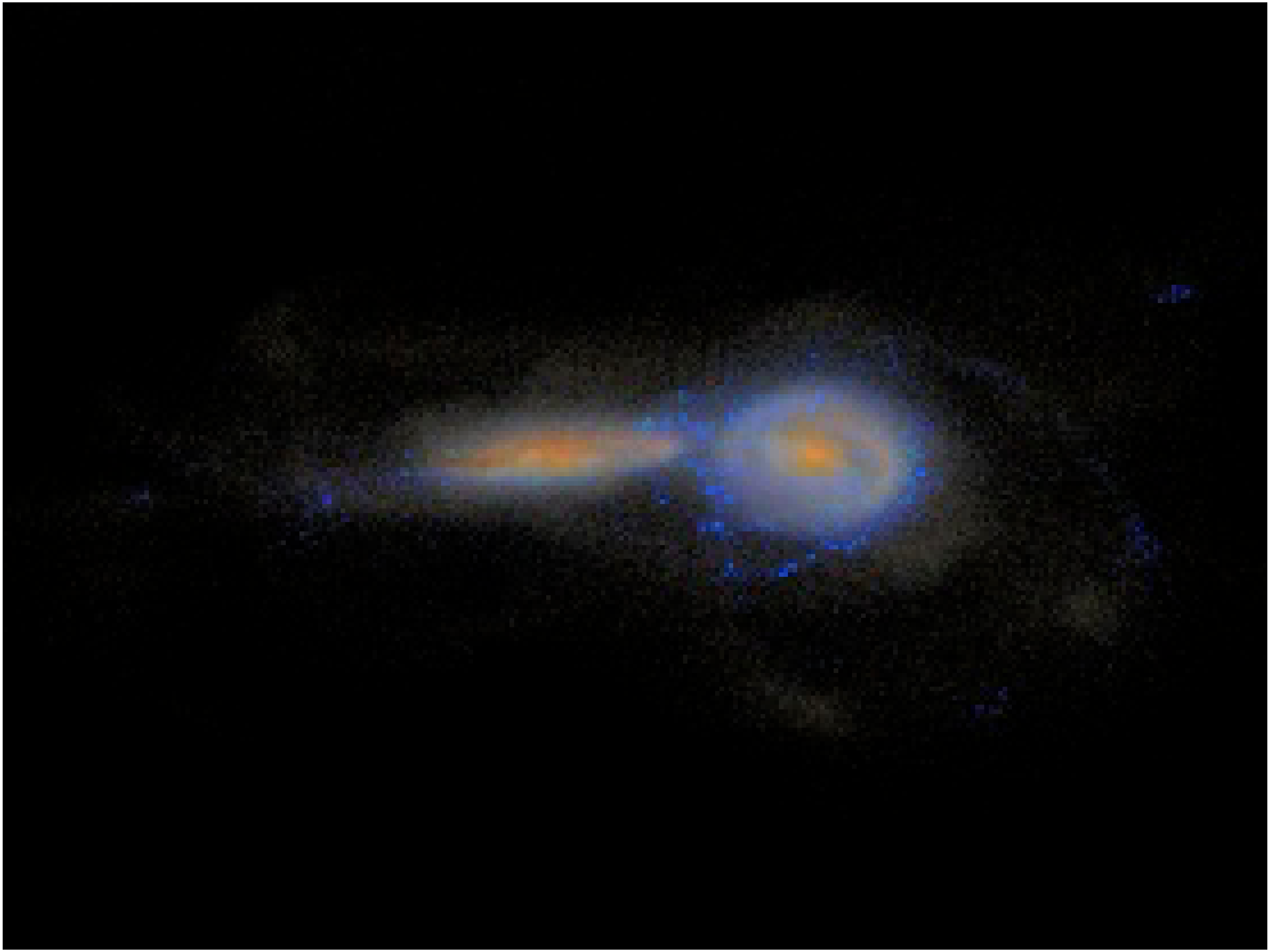
This and the following images show a merger between two Sbc galaxies, each simulated with 3x the mass resolution of the previous ones. The images are color composites of u, r, and z-band images.

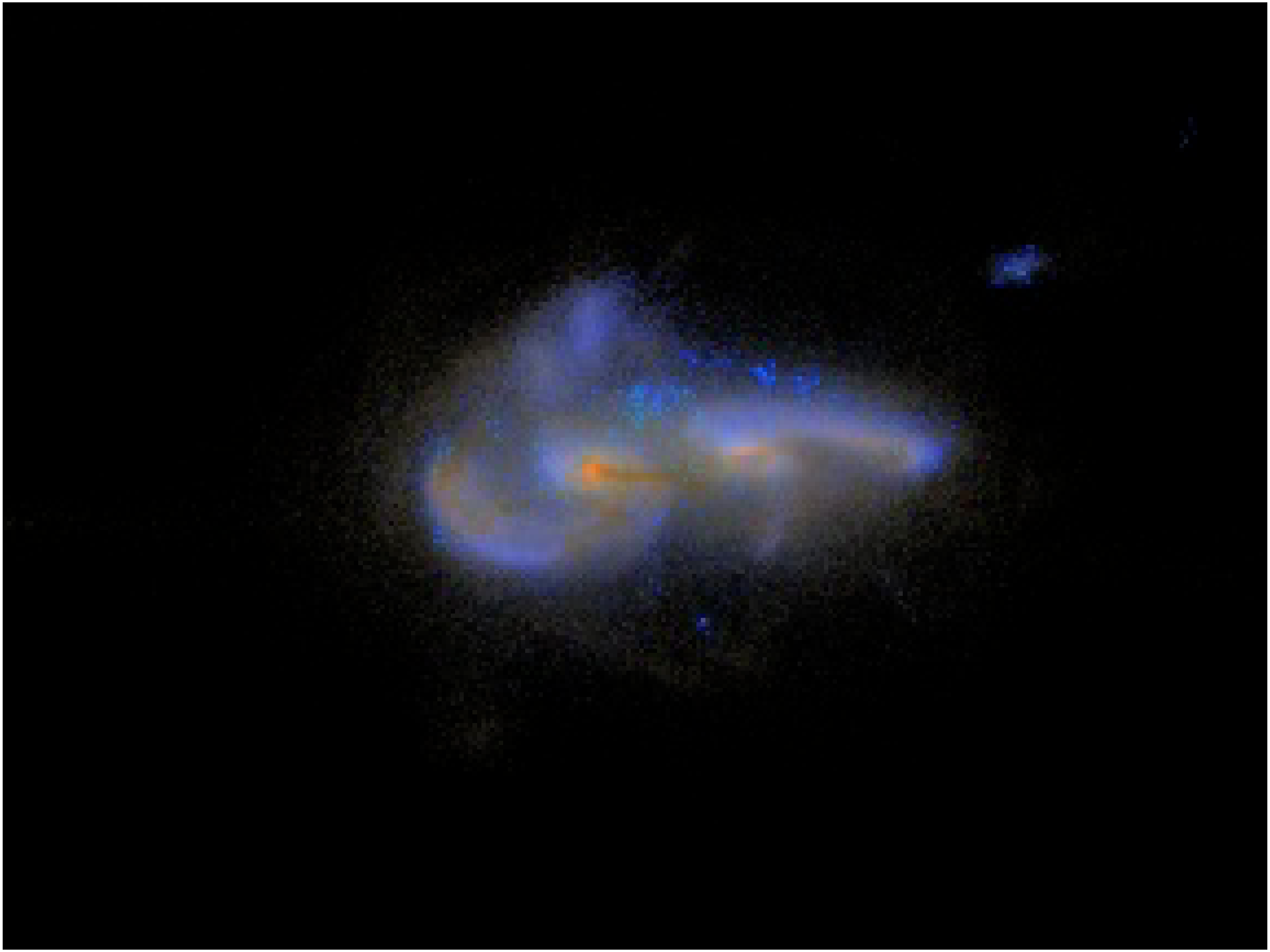


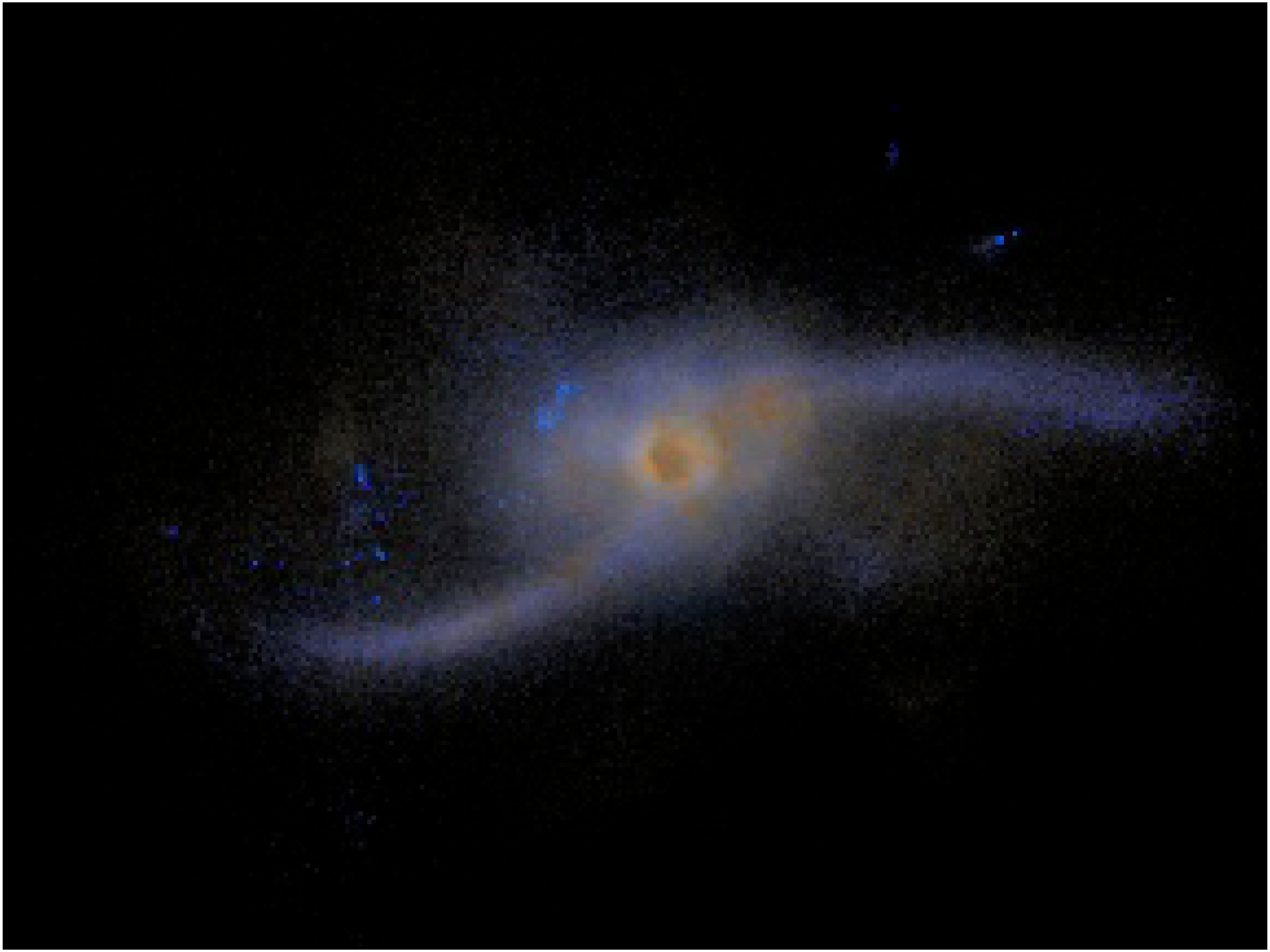


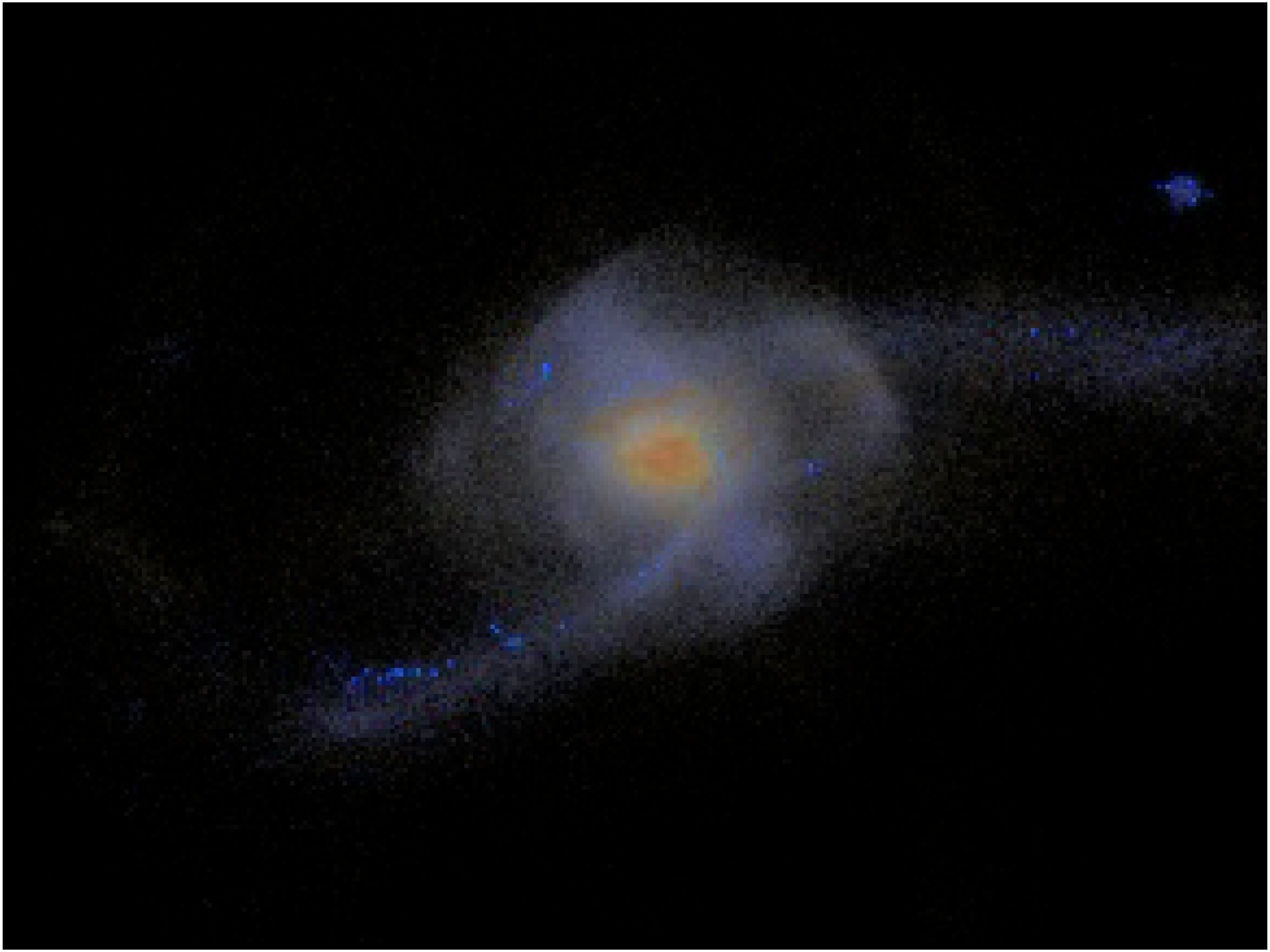


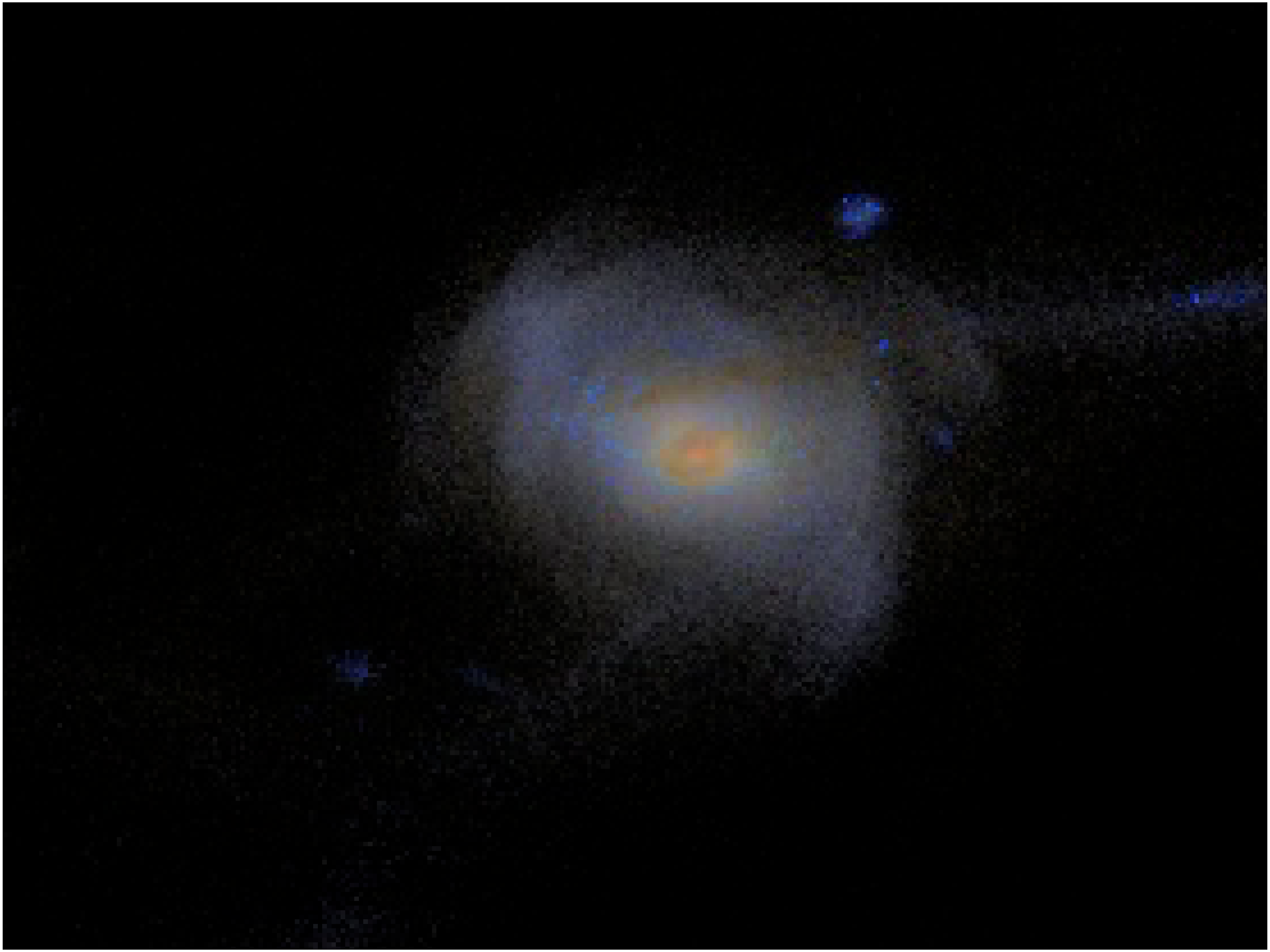


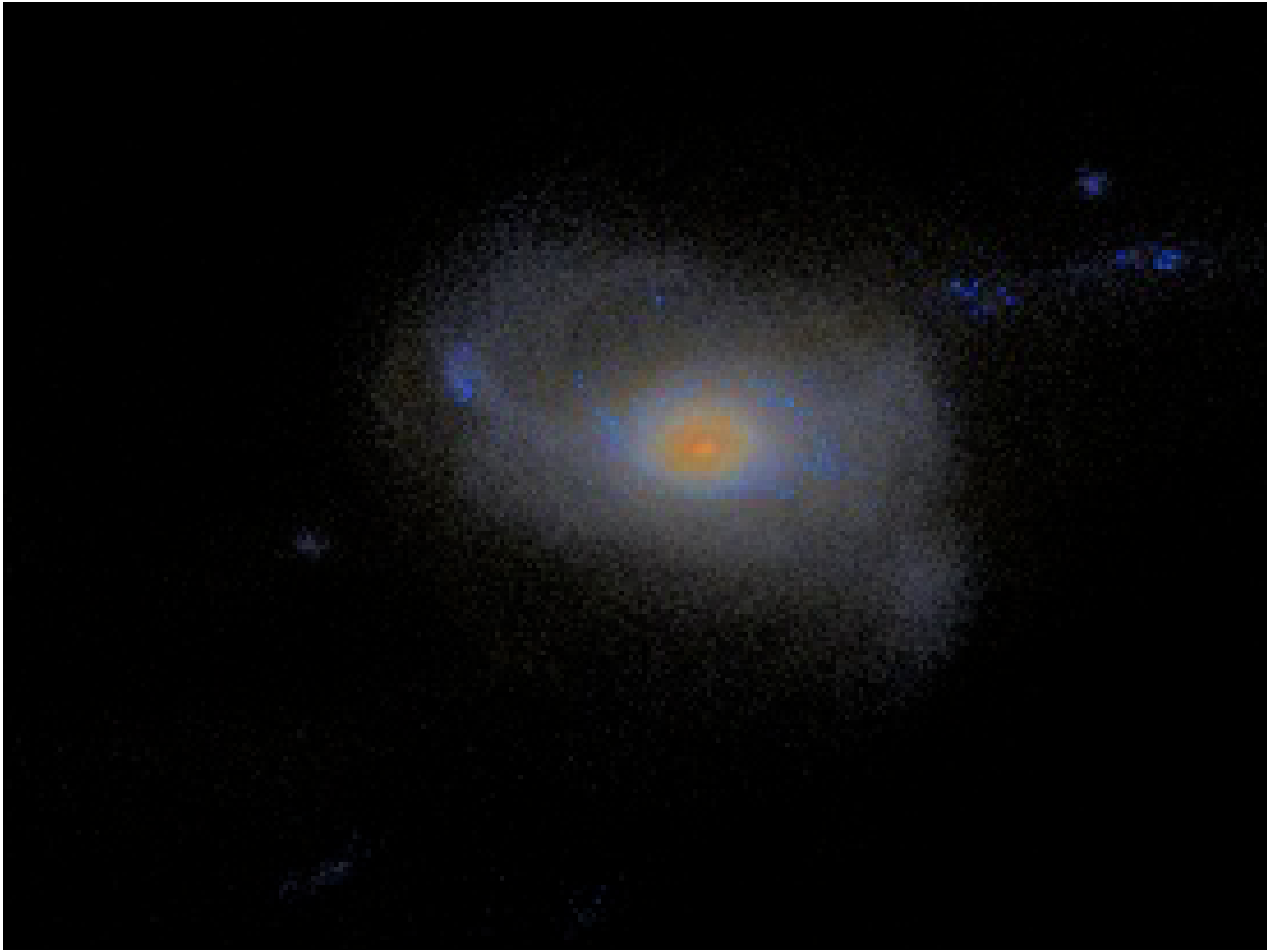


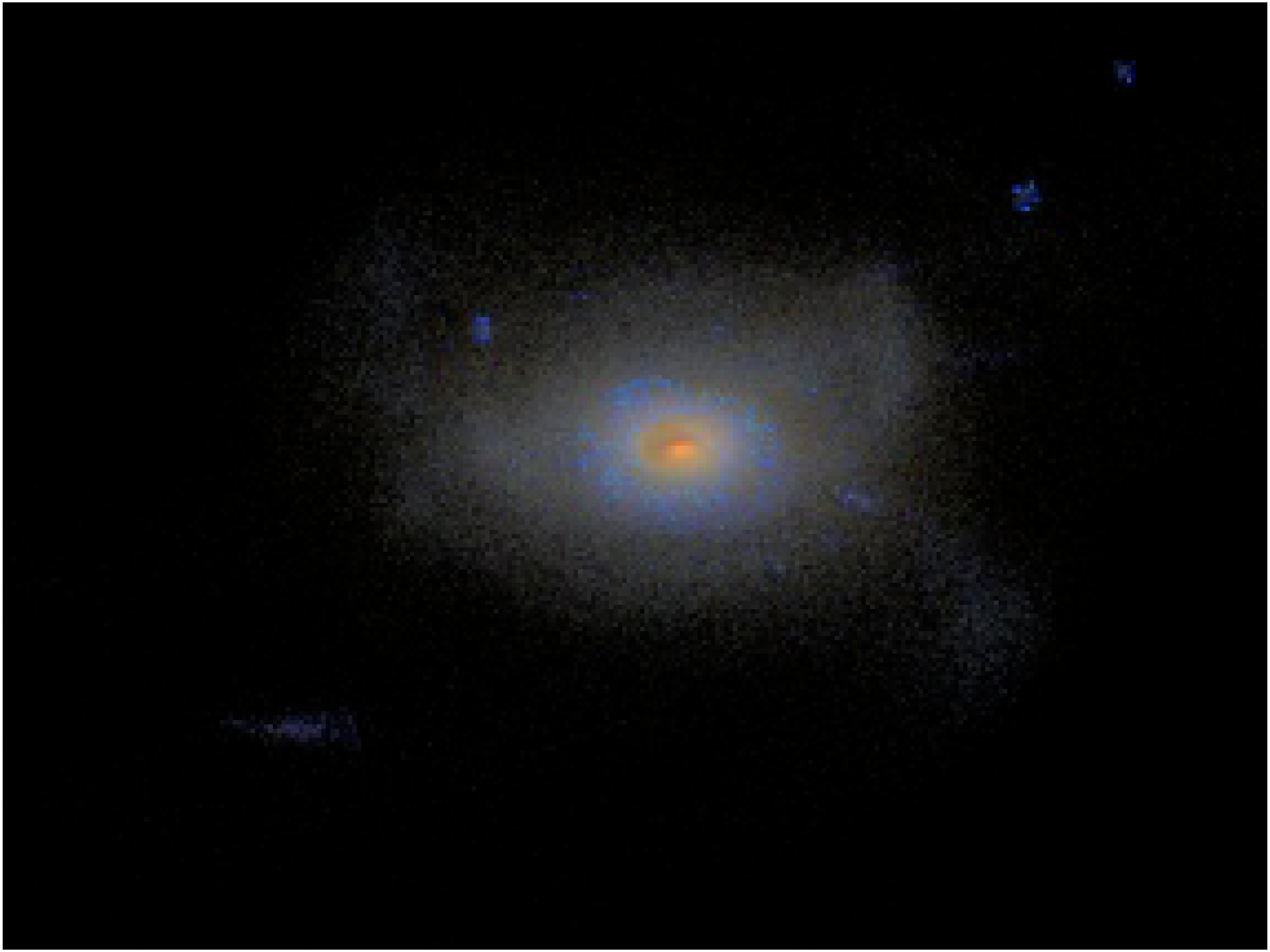












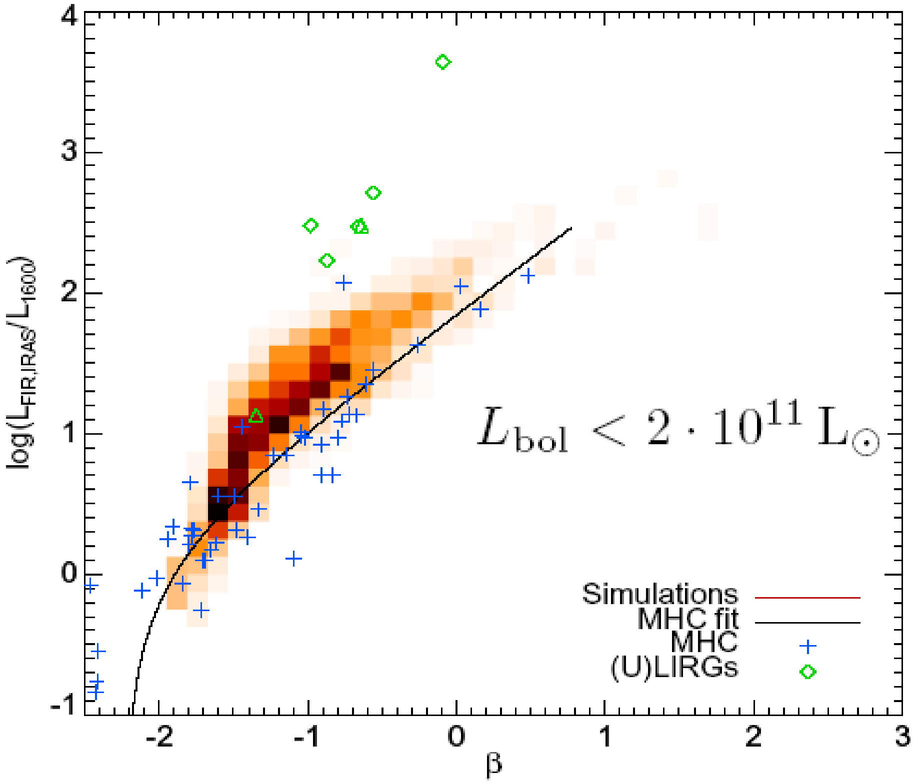
Comparing to IRX-Beta relation

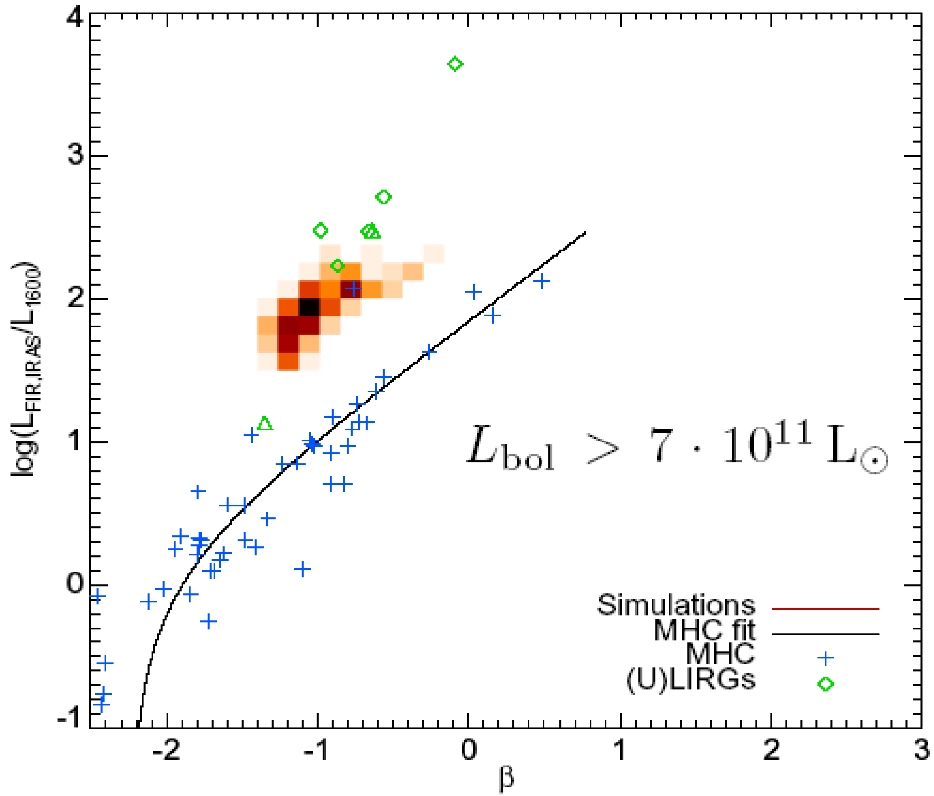
- $\mathrm{IRX}_{1600} = \mathrm{F}_{\mathrm{FIR}}/\mathrm{F}_{1600},$
- UV spectral slope $\beta,$

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

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

Split by Luminosity



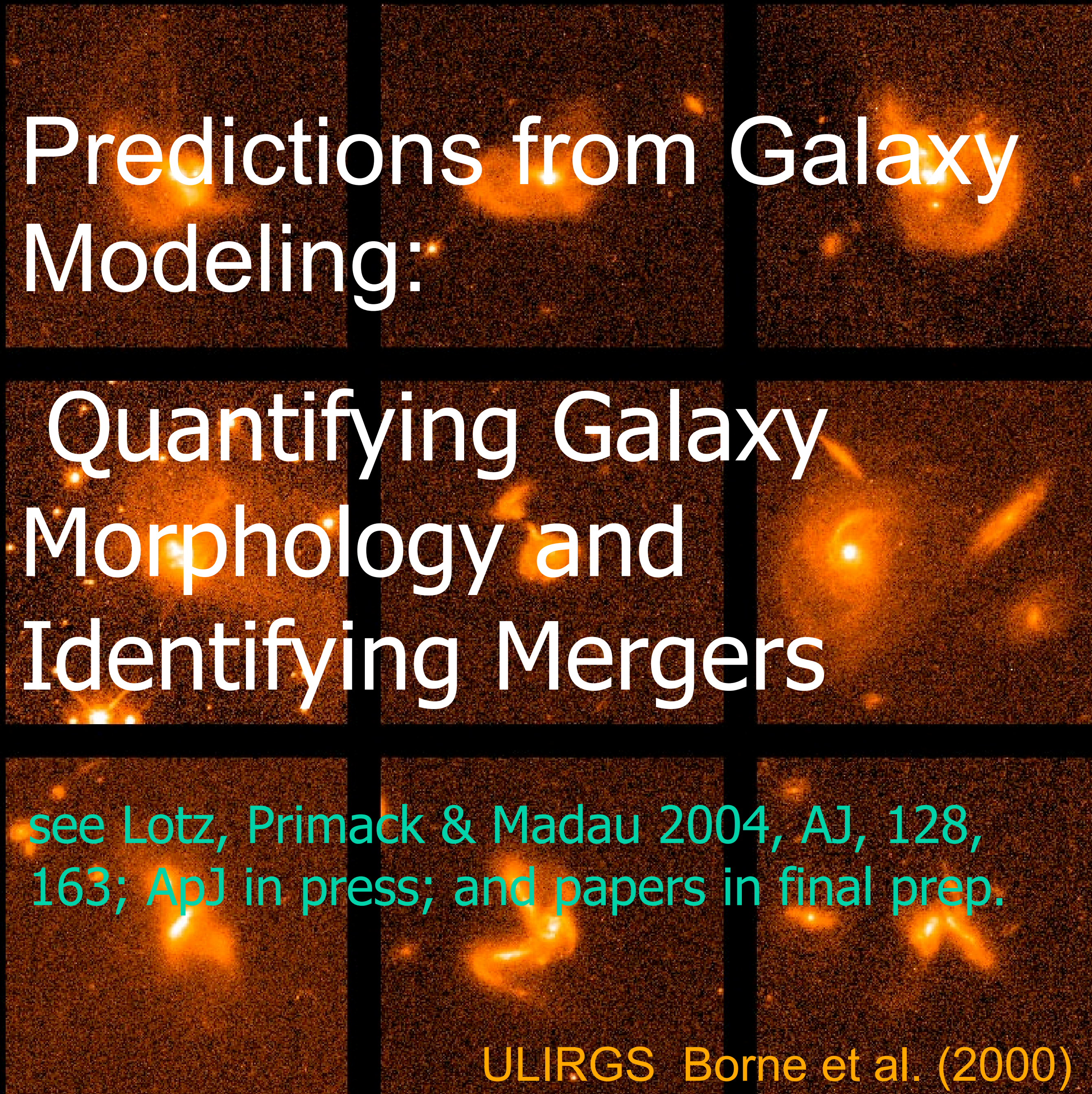


- Simulated lower-luminosity galaxies follow an IRX-β relation similar to the observed MHC99 galaxies
- Higher-luminosity galaxies occupy the UIRG region
- Note that these were predictions: no parameter fitting!

Predictions from Galaxy Modeling:

Quantifying Galaxy Morphology and Identifying Mergers

see Lotz, Primack & Madau 2004, AJ, 128, 163; ApJ in press; and papers in final prep.



ULIRGS Borne et al. (2000)

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

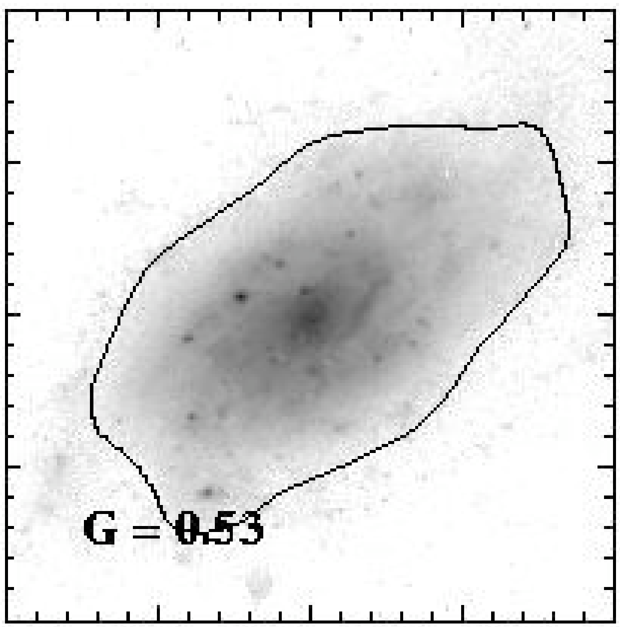
- non-parametric
  "CAS" - concentration, asymmetry, clumpiness
  neural-net training
  shaplet decomposition

  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)

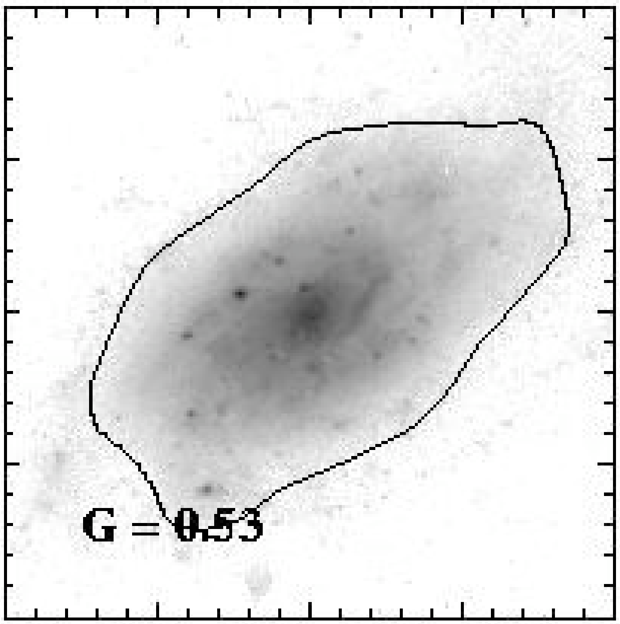
G=0 for completely egalitarian society (uniform surf brightness)
G=1 for absolute monarchy (all flux in single pixel)
(G = 0.445 for US in 1999)

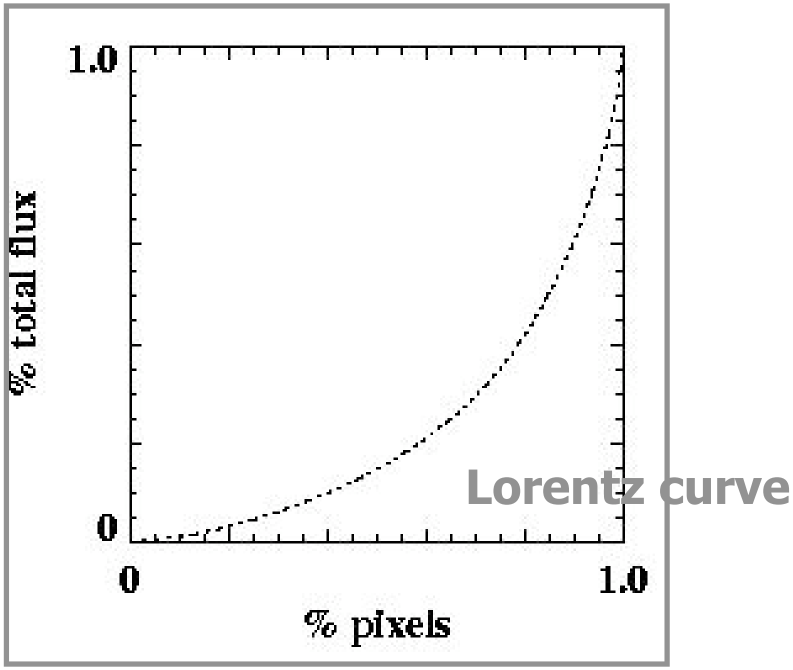


The Gini Coefficient

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)

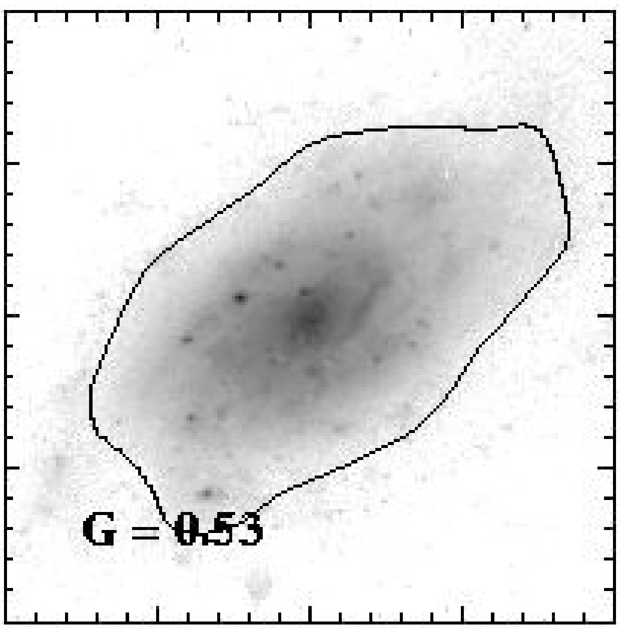


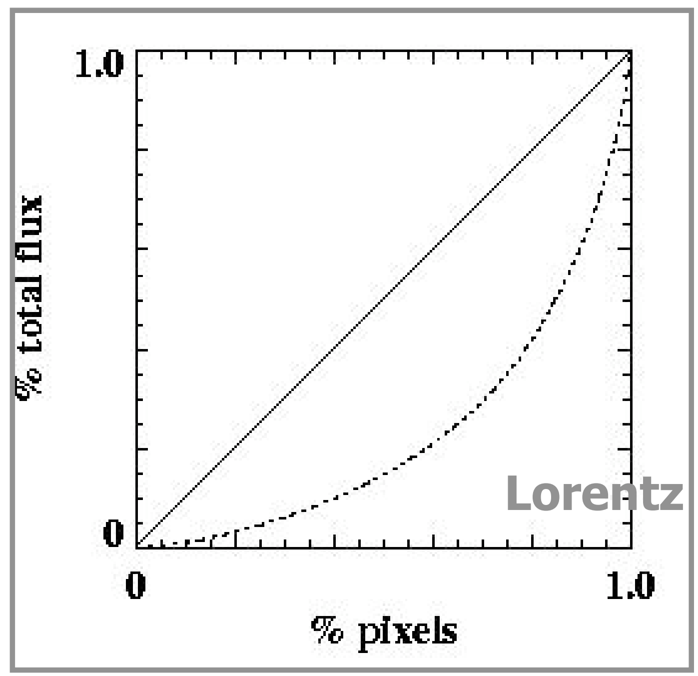


The Gini Coefficient

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)

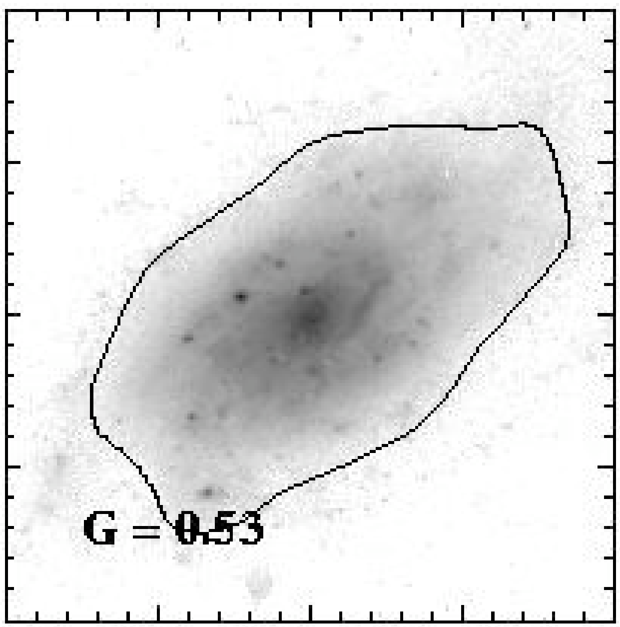


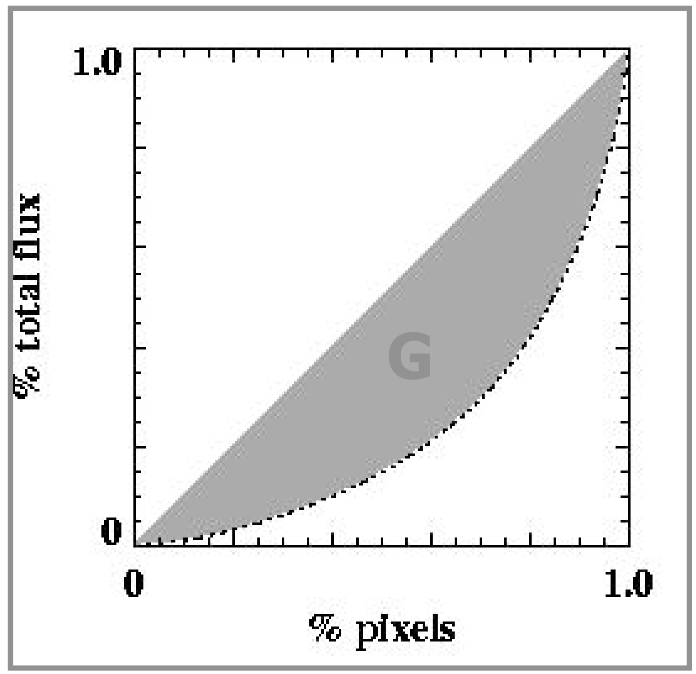


The Gini Coefficient

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)

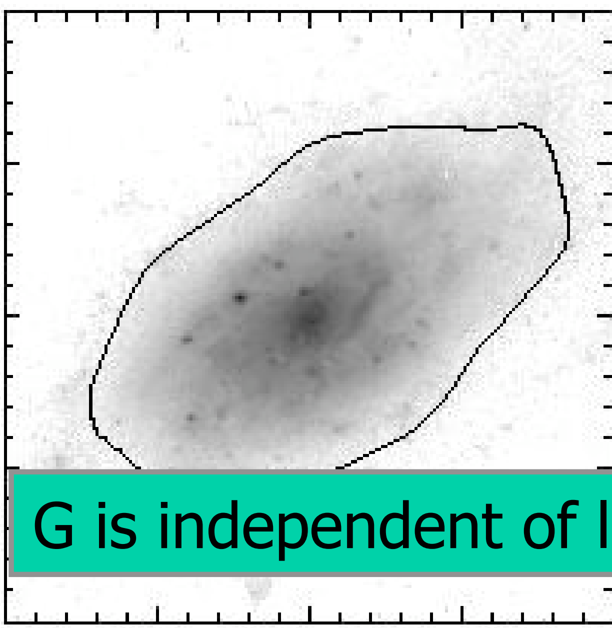


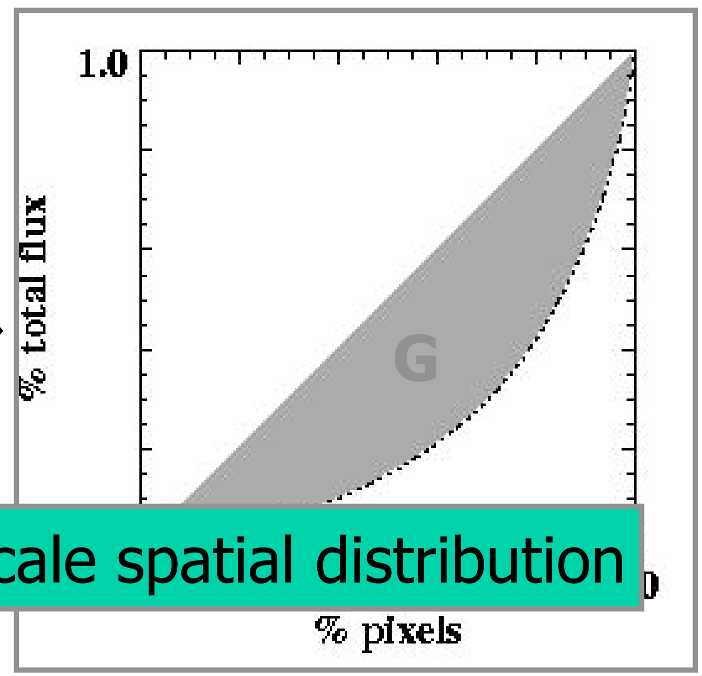


The Gini Coefficient

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)





G is independent of large-scale spatial distribution

2^{nd} order moment of light

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

this depends on size + luminosity

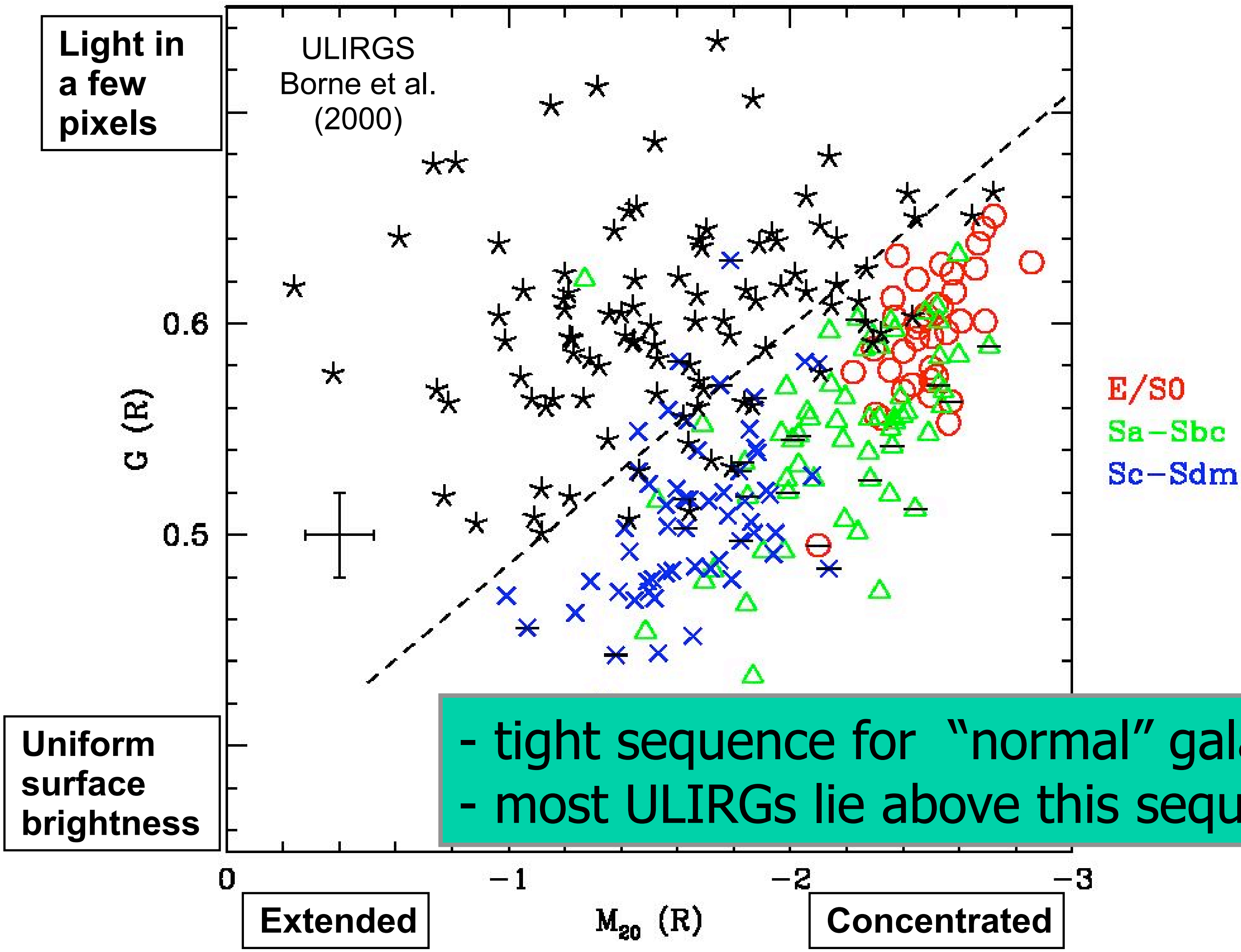
→ find relative moment of brightest regions

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

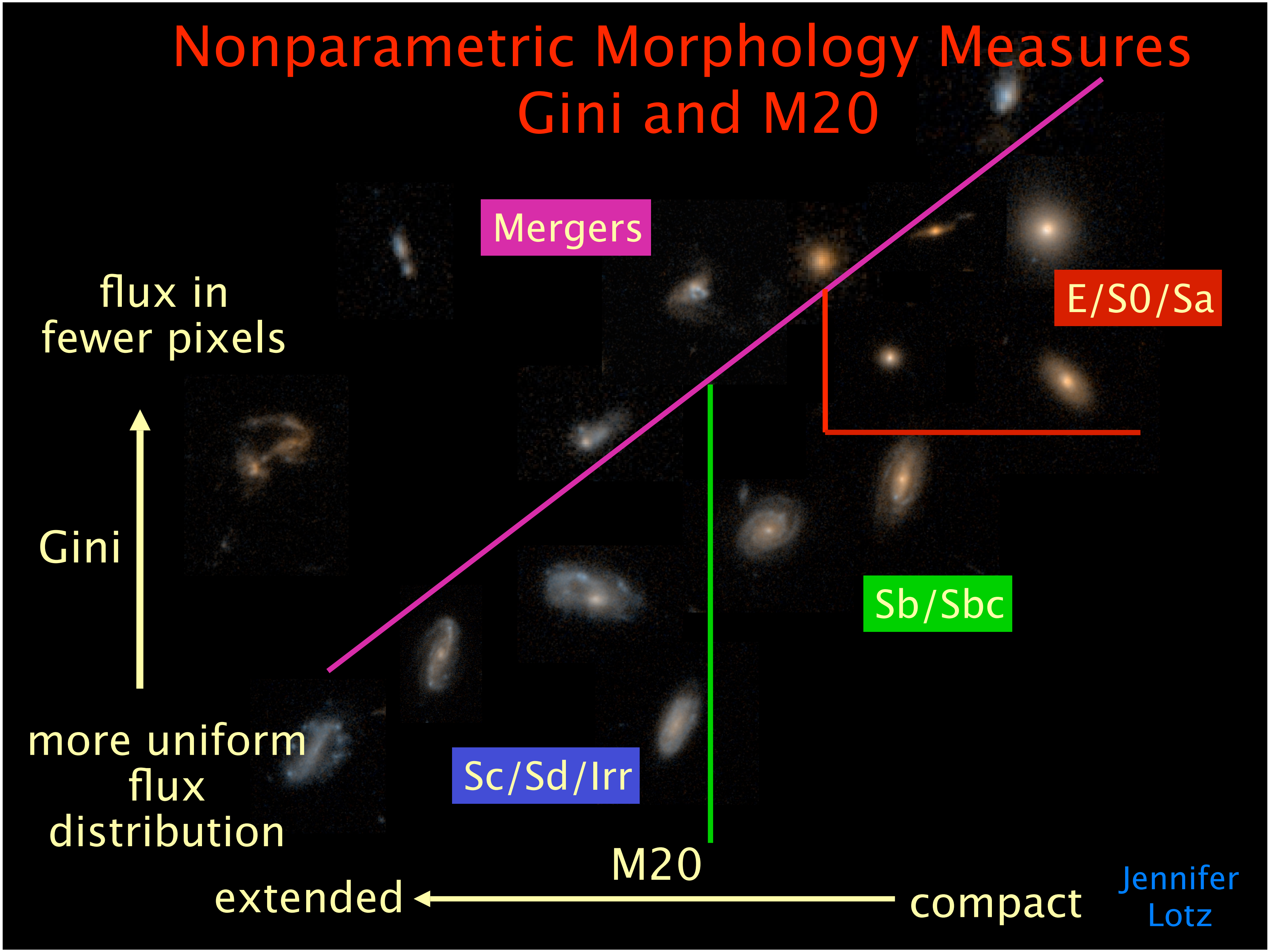
- very similar to $C = \log (r_{80\%}/r_{20\%})$
  but does NOT assume particular geometry

- more sensitive to merger signatures (double nuclei)

Local Galaxy G-M20 relation



- tight sequence for "normal" galaxies
- most ULIRGs lie above this sequence


Nonparametric Morphology Measures
Gini and M20
Mergers
E/S0/Sa
flux in
fewer pixels
Gini
more uniform
flux
distribution
Sb/Sbc
Sc/Sd/Irr
M20
extended
compact
Jennifer
Lotz

Modeling Merger Morphologies

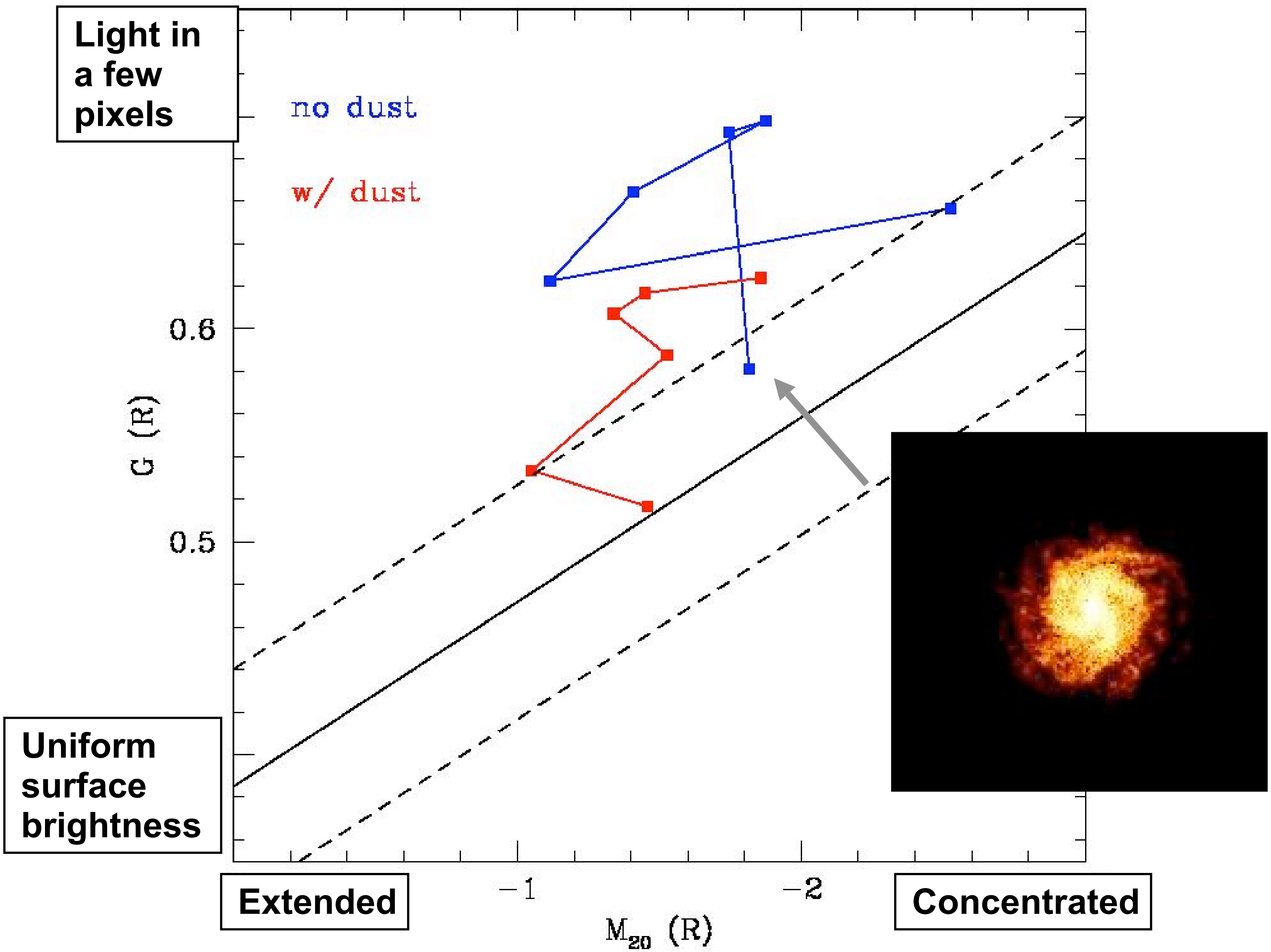
T.J. Cox's simulations of colliding disks (gas, stars, DM)
+ P. Jonsson's radiative transfer + pop. synthesis code

→ multi-wavelength images of simulations

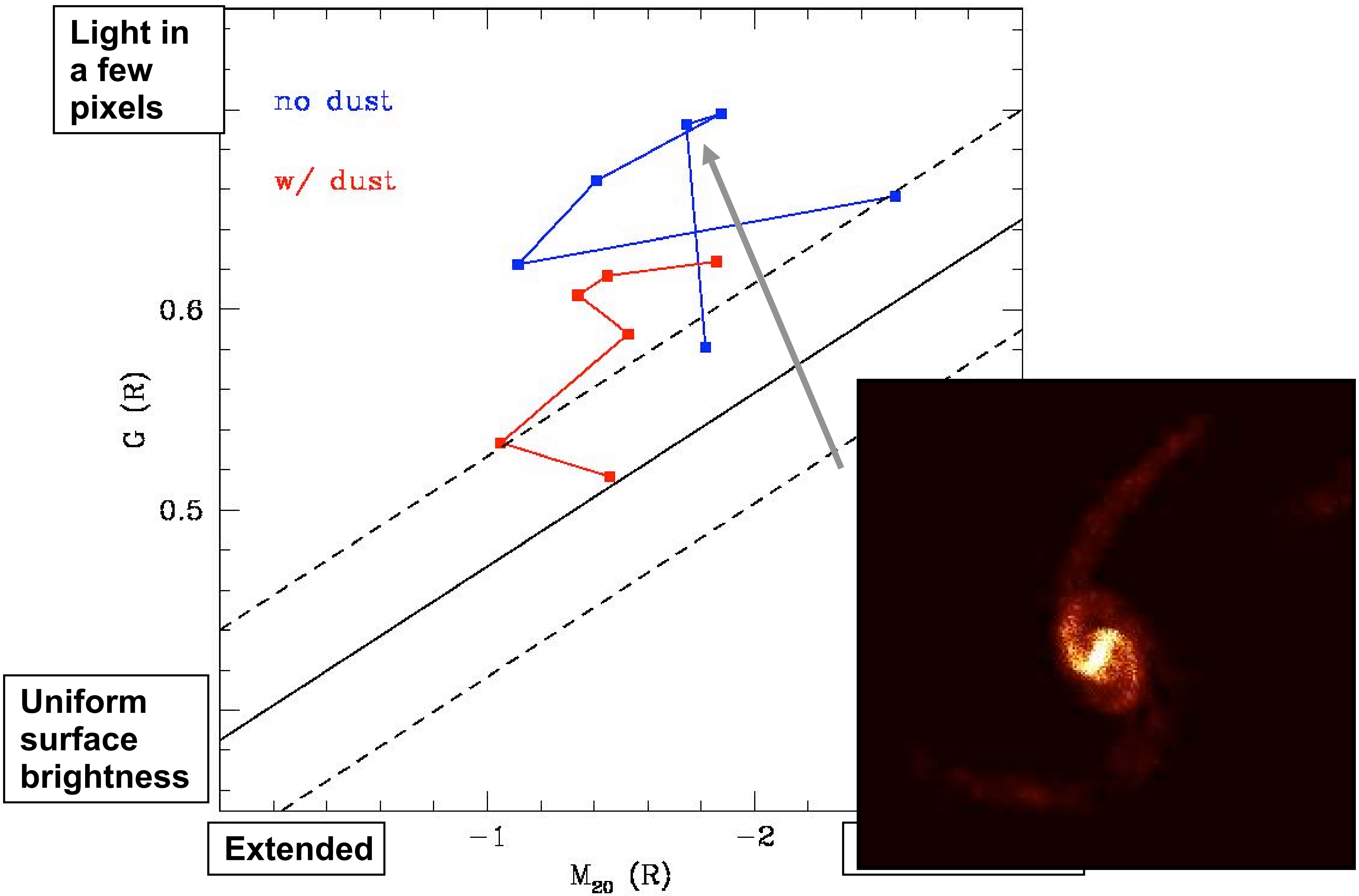
→ can predict merger morphologies + morph. evolution

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

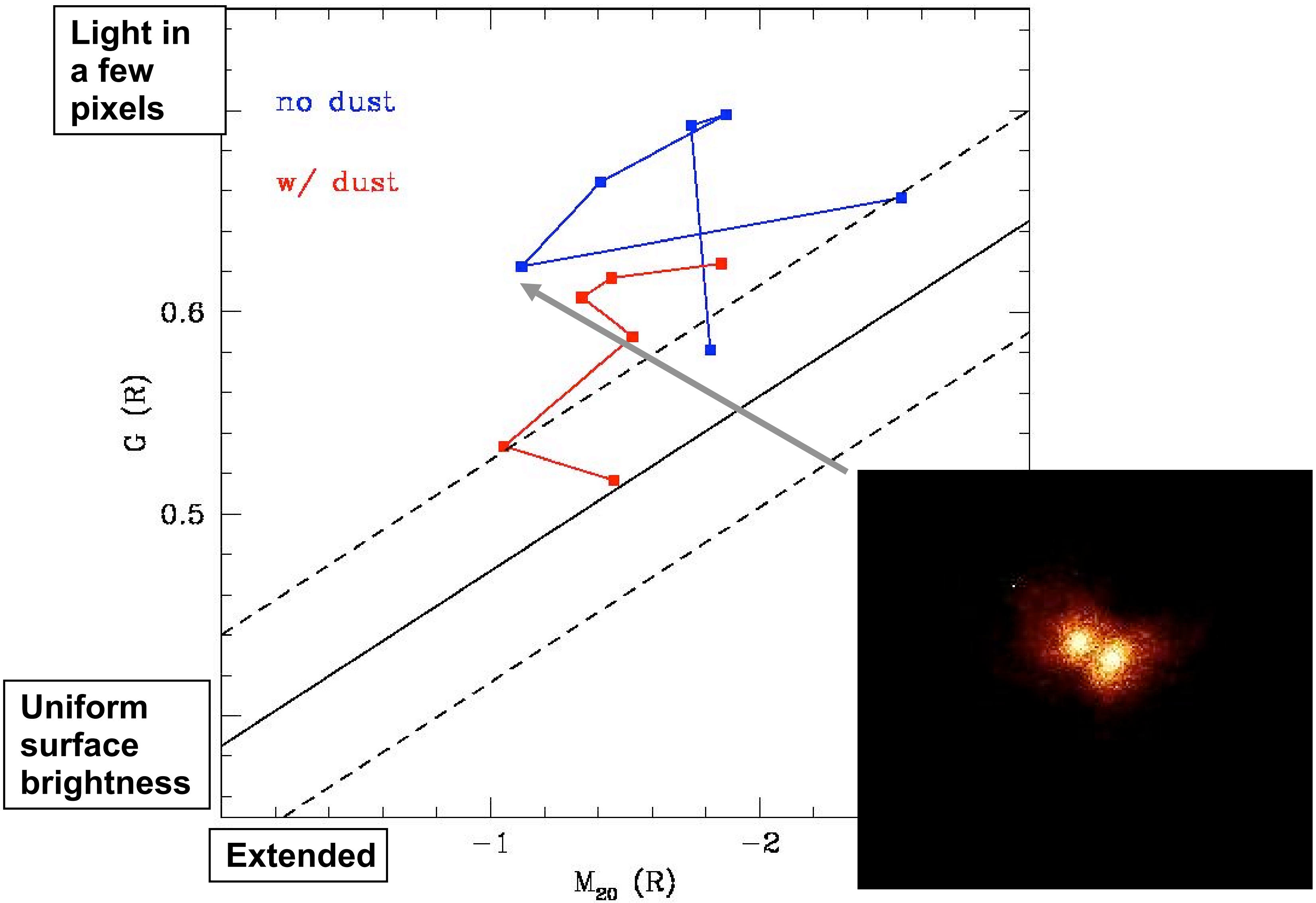
Modeling Merger Morphologies



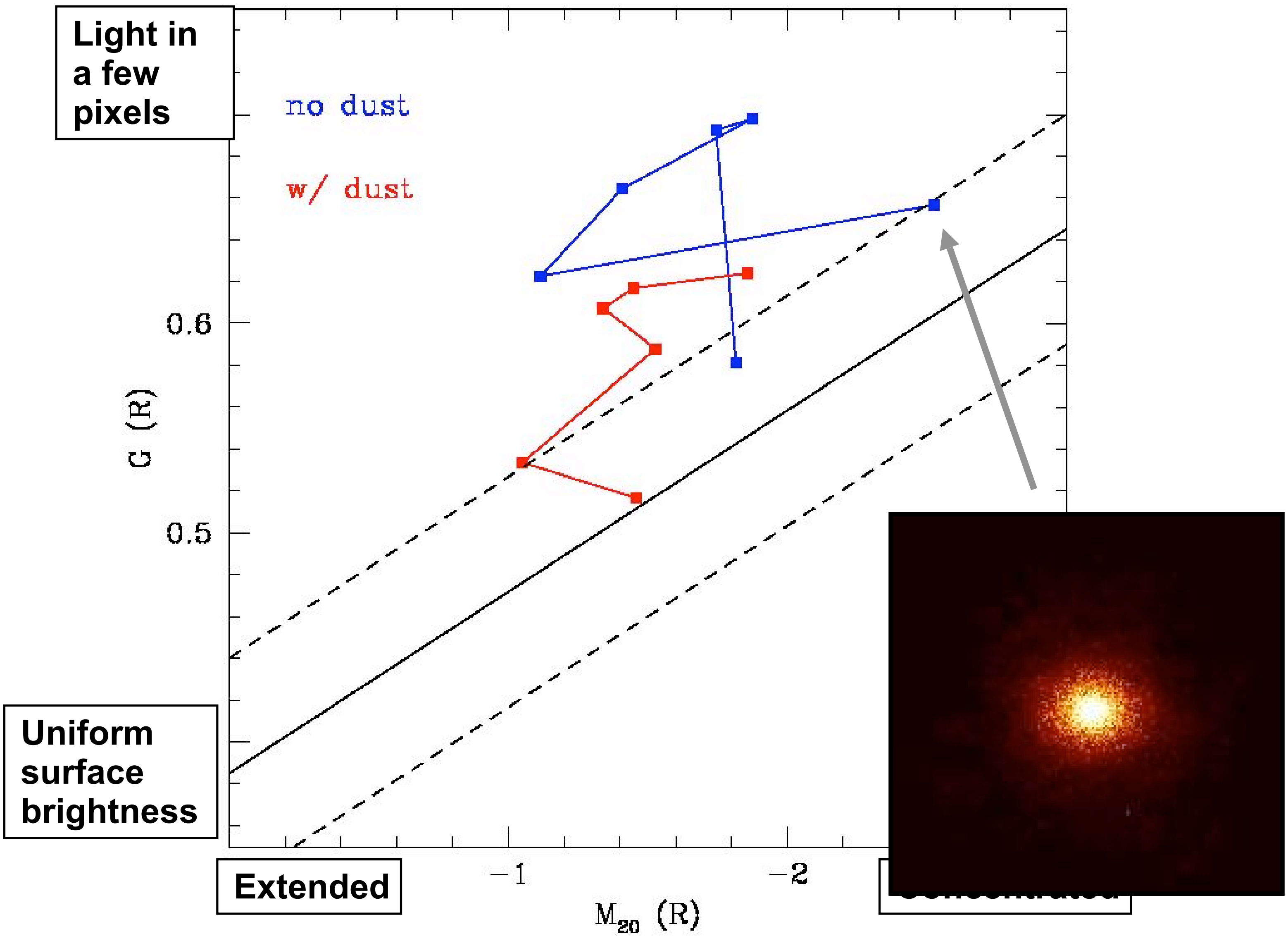
Modeling Merger Morphologies



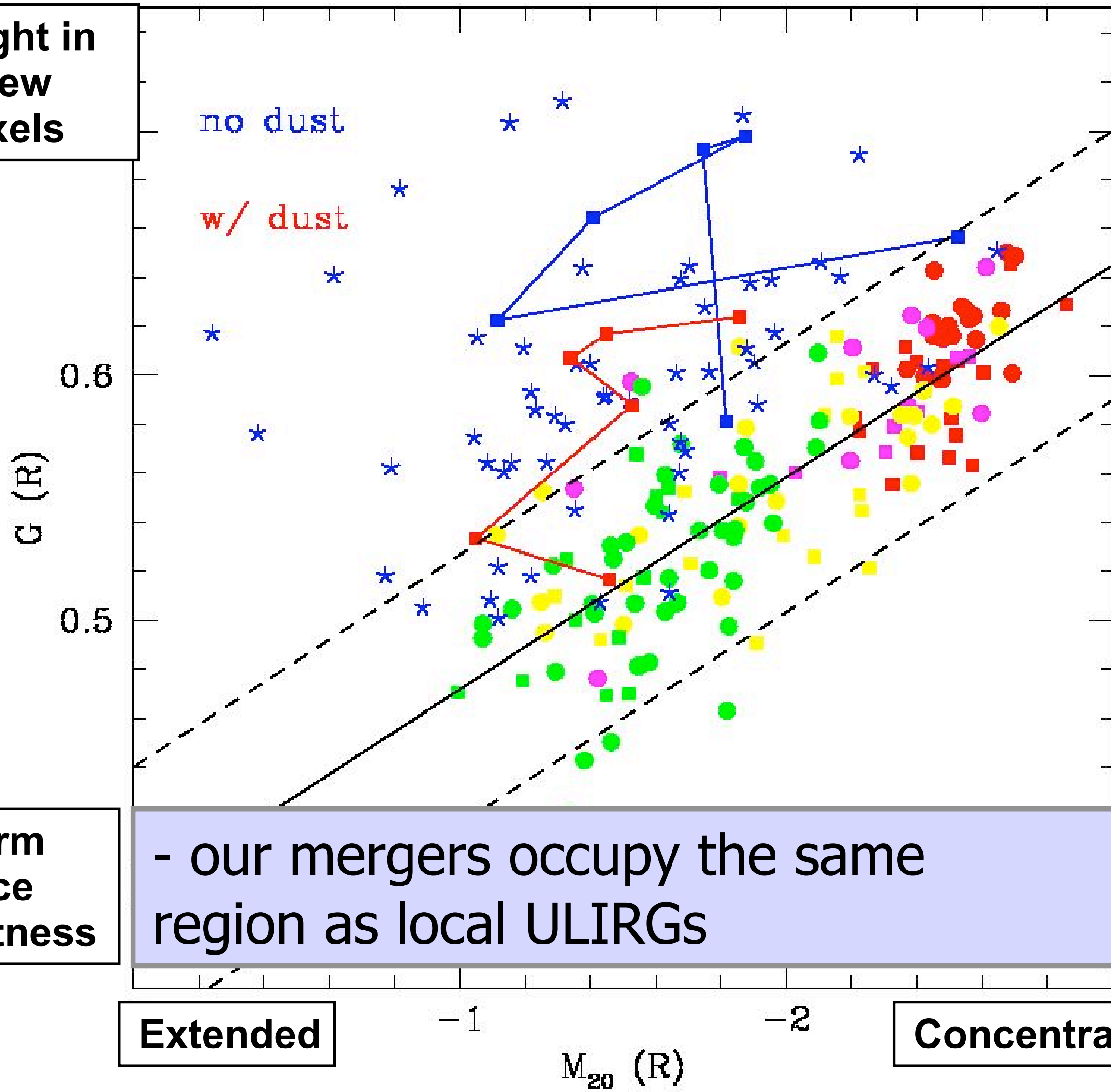
Modeling Merger Morphologies



Modeling Merger Morphologies



Modeling Merger Morphologies



Light in a few pixels

Uniform surface brightness

Extended

Concentrated

E/S0

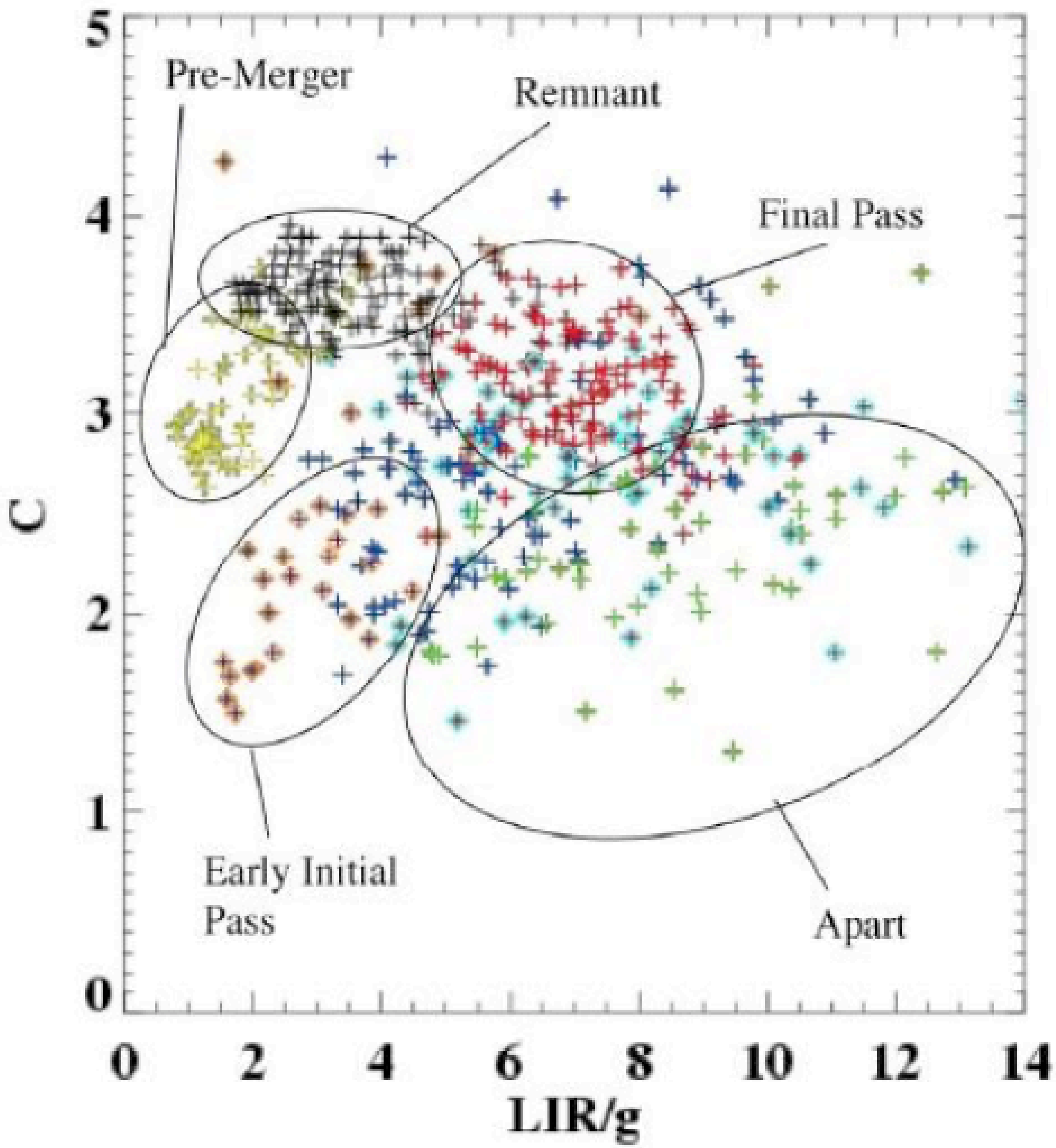
Sa/Sab

Sb/Sbc

Sc/Scd

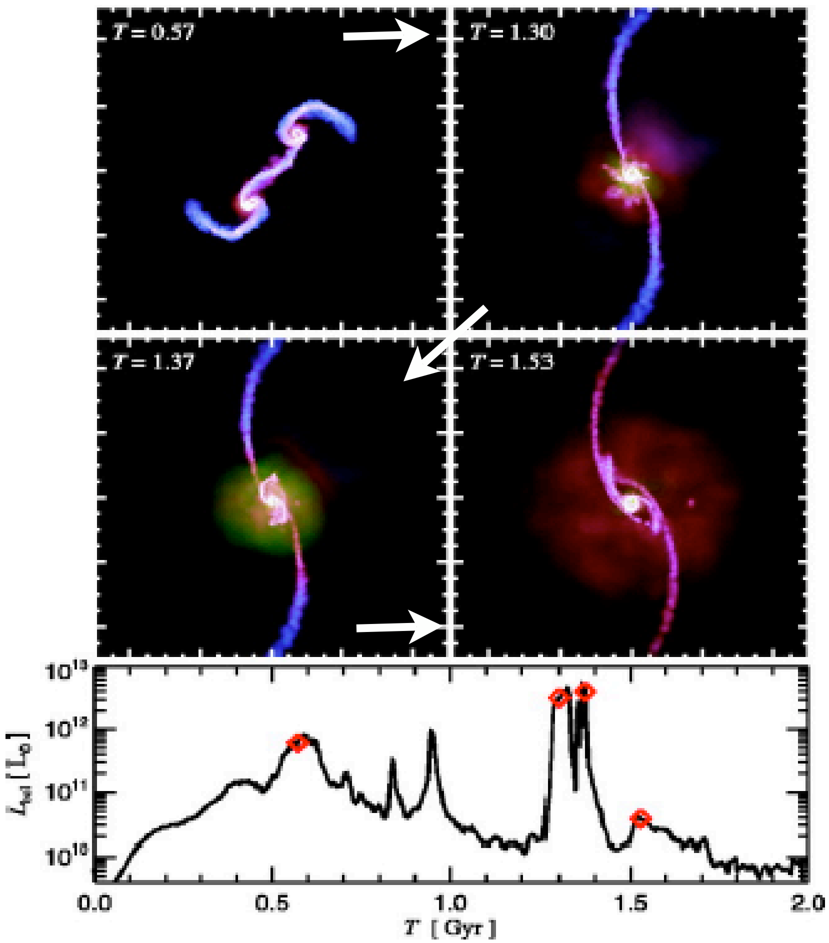
ULIRGs

- our mergers occupy the same region as local ULIRGs



Using morphology and IR - optical color, it's possible to determine the merger stage of simulated galaxies (senior thesis of Seth Cottrell, supervised by Lotz and Primack). We're now applying these techniques to a larger sample of simulations, and to observations. This will enable accurate measurement of merger rates.

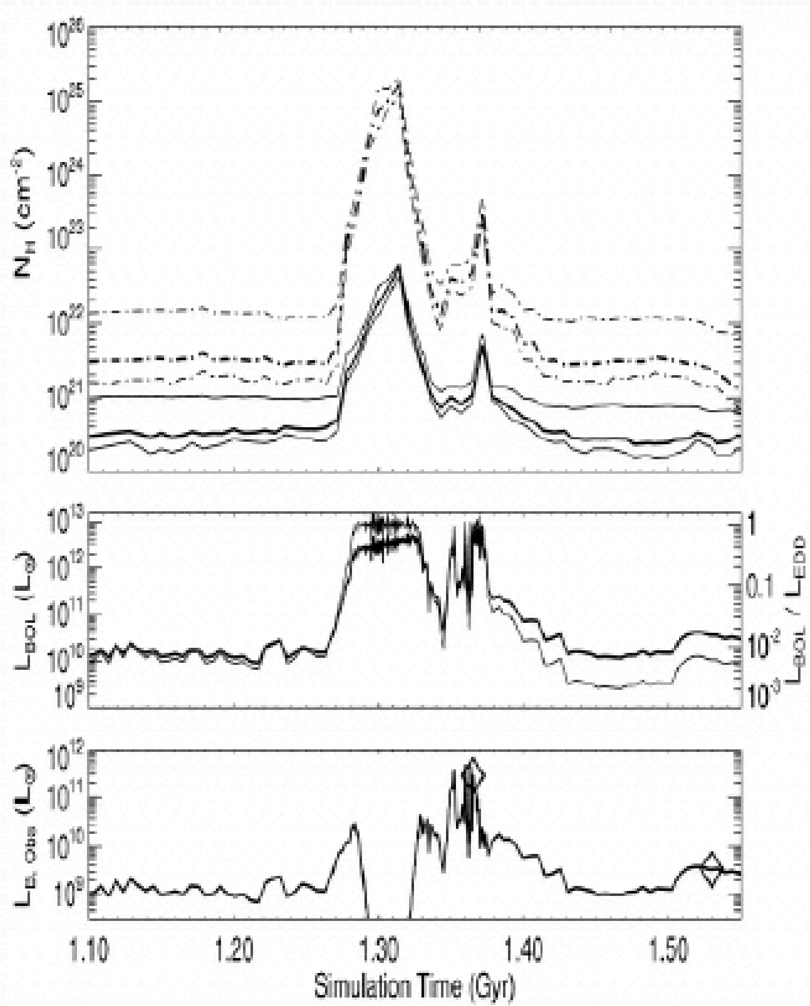
Merger Simulations with Supermassive Black Holes



(Hopkins et al. 2005, ApJ, 625, L71)

- Mergers of gas-rich disk galaxies hosting SMBHs
- Snapshots: gas densities at time (T) since interaction began
- Plot: intrinsic bolometric luminosity (diamonds match snapshots)
- Morphology most disturbed at T~1.30-1.37 Gyrs.
- AGNs turn on at T~1.30 Gyr.

Simulations: Attenuation

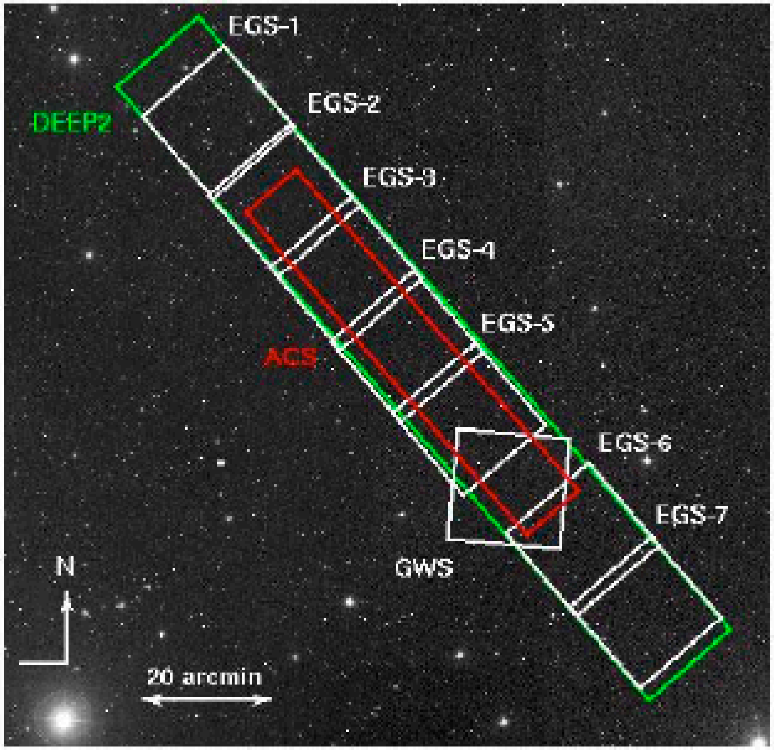


(Hopkins et al. 2005, ApJ, 625, L71)

- Top: column density to nucleus
- Middle: AGN intrinsic bolometric luminosity
- Bottom: observed B-band luminosity of AGN
- B band is highly attenuated during period of greatest morphological disturbance

Comparison with Observational Data

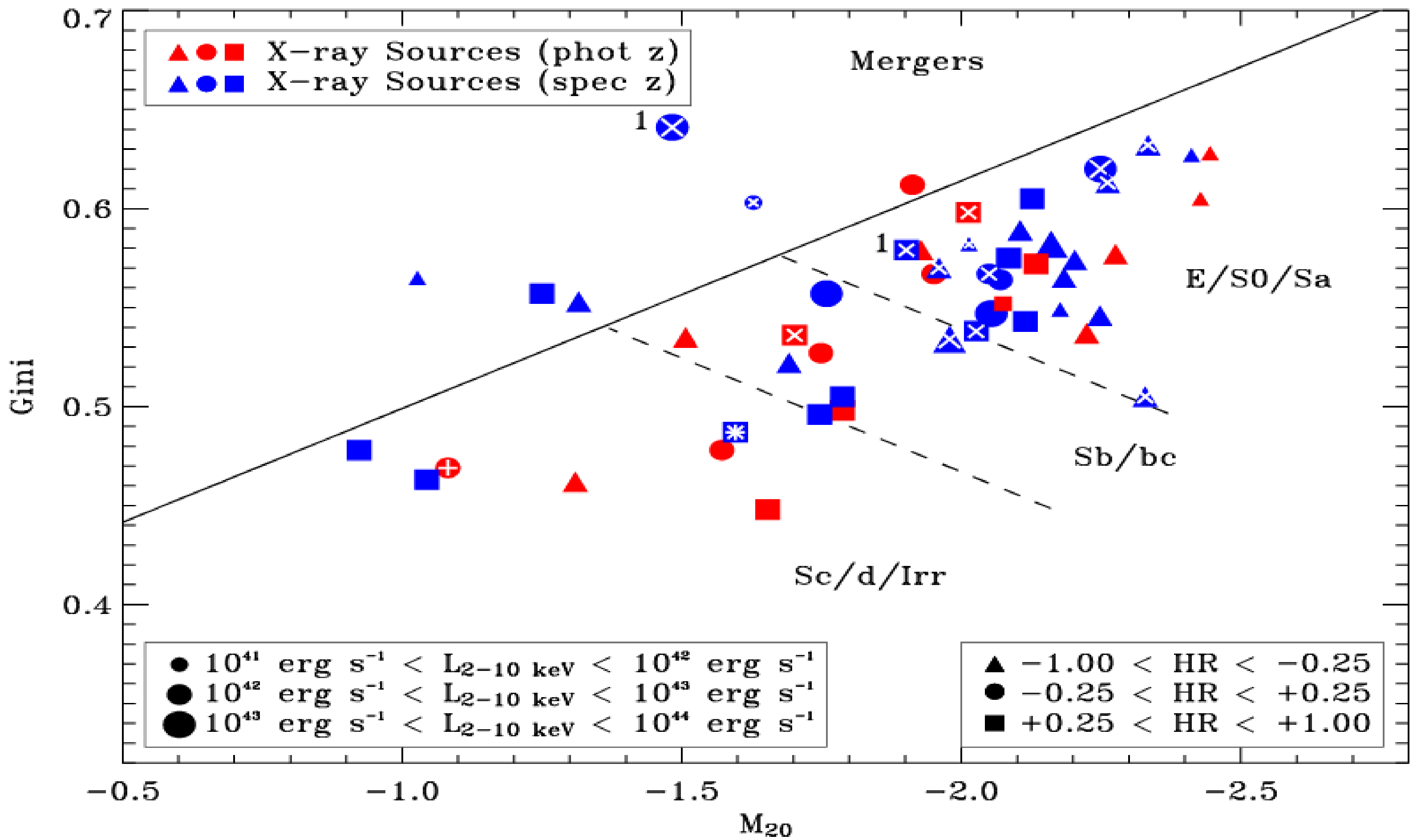
Extended Groth Strip (EGS)



(http://astro.ic.ac.uk/Research/Xray/egs/
)

- EGS: ~0.5 deg^2 (green area)
- ACS: ~0.33 deg^2 (red area)
- IRAC: ~0.5 deg^2 (full EGS)
- Chandra: ~3.75 sq. arcmin. (Groth Westphal Strip; extra pointings now available)
- Canada-France-Hawaii Telescope Legacy Survey: photometric redshifts
- DEEP2 spectroscopic redshifts

Morphological distribution of EGS X-ray selected AGN



The highest fraction of EGS galaxies hosting AGN are early-types, not mergers. This suggests that the AGN activity is delayed, rather than occurring mainly during and immediately following mergers as the Hopkins et al. simulations predicted. (Christy Pierce et al., to be submitted soon to ApJ Letters).

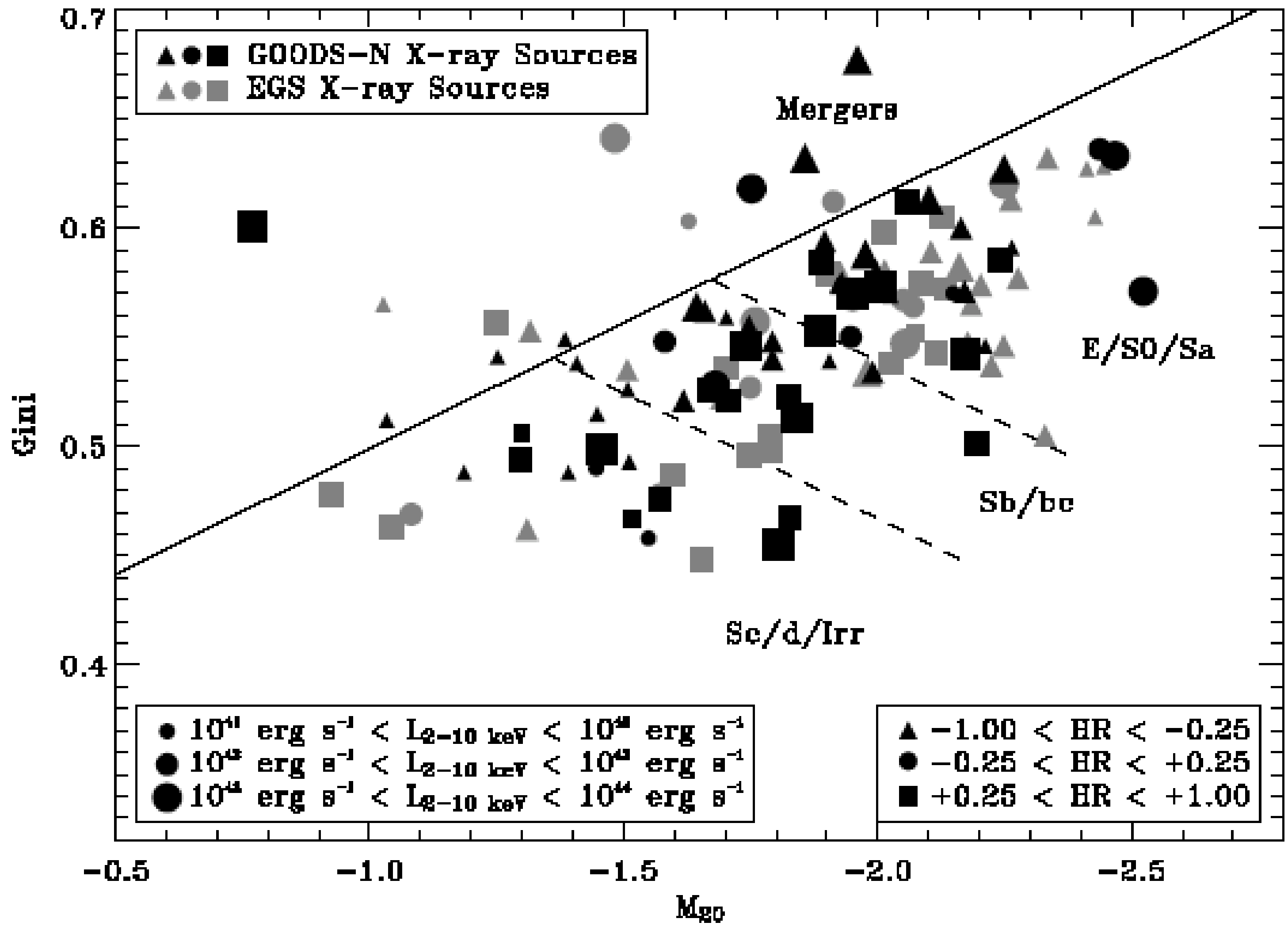
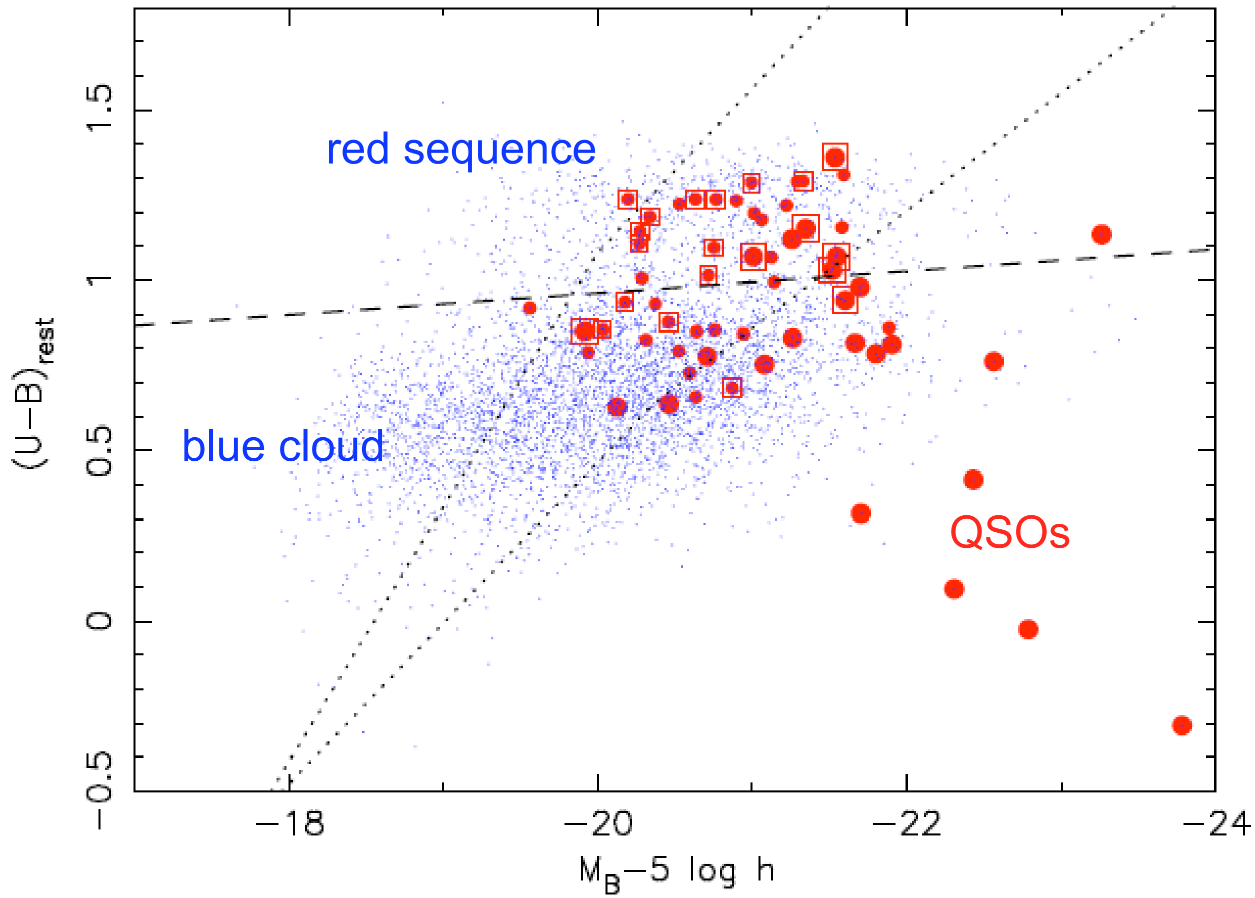


Fig. 1.— *Chandra* sources from GOODS-North (black symbols) and the EGS (grey symbols). Symbol size indicates $L_{2-10\ \mathrm{keV}}$ of the AGN. Host galaxies meet the following criteria: $I < 23.5$, $0.2 \leq z < 1.2$, $\langle S/N \rangle$ per pixel ≥ 2.5, $rp \geq 0.3$, and not flagged as a star by SExtractor. Spectroscopic and photometric redshifts are used. Morphologies are measured from the V band for $0.2 \leq z < 0.6$ and from the I band for $0.6 \leq z < 1.2$. The lines are as defined by Lotz et al. (2006).

Color-Magnitude Diagram of EGS X-ray selected AGN



Rest-frame U-B colour is plotted against the B-band absolute magnitude for DEEP2 comparison galaxies (small blue dots) and X-ray sources (filled red circles) in the EGS in the range $0.7 < z < 1.4$. Squares around the symbols indicate hard X-ray sources, and more luminous systems ($L_X > 10^{43}$ erg s^{-1}) are plotted with larger symbols. The dashed line separates red and blue galaxies, and the dotted lines show the DEEP2 completeness limits at $z = 1.0$ and $z = 1.4$.
(Kirpal Nandra et al., to be submitted soon to ApJ Letters.)

Conclusions, Ongoing Work, & Questions

- 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).

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

- 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, supernova, and AGN energy input.

- Morphological comparisons between simulated mergers and observations support the idea that ULIRGs are interacting galaxies and ellipticals are merger remnants. The fraction of emission-selected galaxies that are merger candidates is **~15%** at z=1.5 and z=4 using the Gini and M20 statistics (Lotz et al., 2005, submitted) – this fraction is in rough agreement with prediction of Somerville, Primack, Faber (2001)'s favored starburst SAM.

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

- Compare with data on Lyman break selected emission line galaxies at high redshift. Do more realistic initial conditions alter our story at all?

- Detailed observations of individual merger remnants. Spatial, velocity, and angular momentum distribution of halo, stars and gas in merger remnants. Comparison with **Planetary Nebulae** (Dekel, et al. 2005) and **SAURON** – in progress by UCSC grad student **Greg Novak** working with Primack. Semi-analytic models of merger remnant properties (e.g., $\mathbf{M^*}$, $\mathbf{r_{1/2}}$, $\sigma_{\mathbf{v}}$) – 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. (Cox 2004, Cox et al. 2005, and in prep.)

- Compare the **morphology** of simulated mergers, including the effects of dust, to observations using Lotz, Primack, & Madau 2004. (Lotz, Jonsson, Primack, et al. 2005, in prep.) Can we calibrate automated procedures to better determine mergers at high redshift? Can we calibrate line-widths?

- When do **AGN** turn on during mergers? Models: Hernquist, Springel, DiMatteo, Hopkins, Cox. Use optical morphology and IR luminosity to determine merger status and stage, and X-rays to see AGN – in progress by UCSC grad student **Christy Pierce** working with Primack, using GOODS and DEEP2 data. Hopkins et al. predictions **not** confirmed.

THE END

Thanks for your patience!