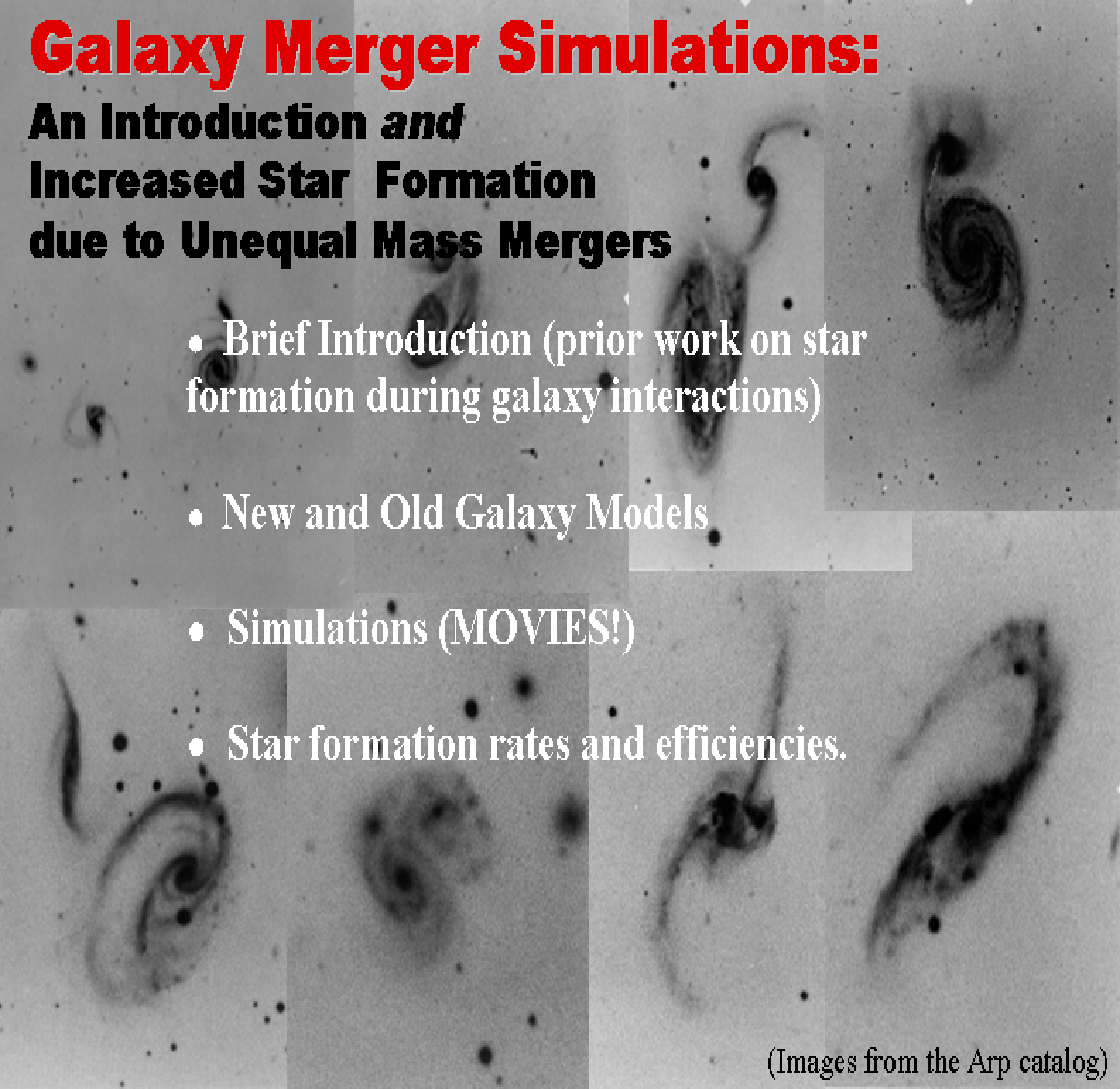
Galaxy Merger Simulations:

An Introduction *and* Increased Star Formation due to Unequal Mass Mergers



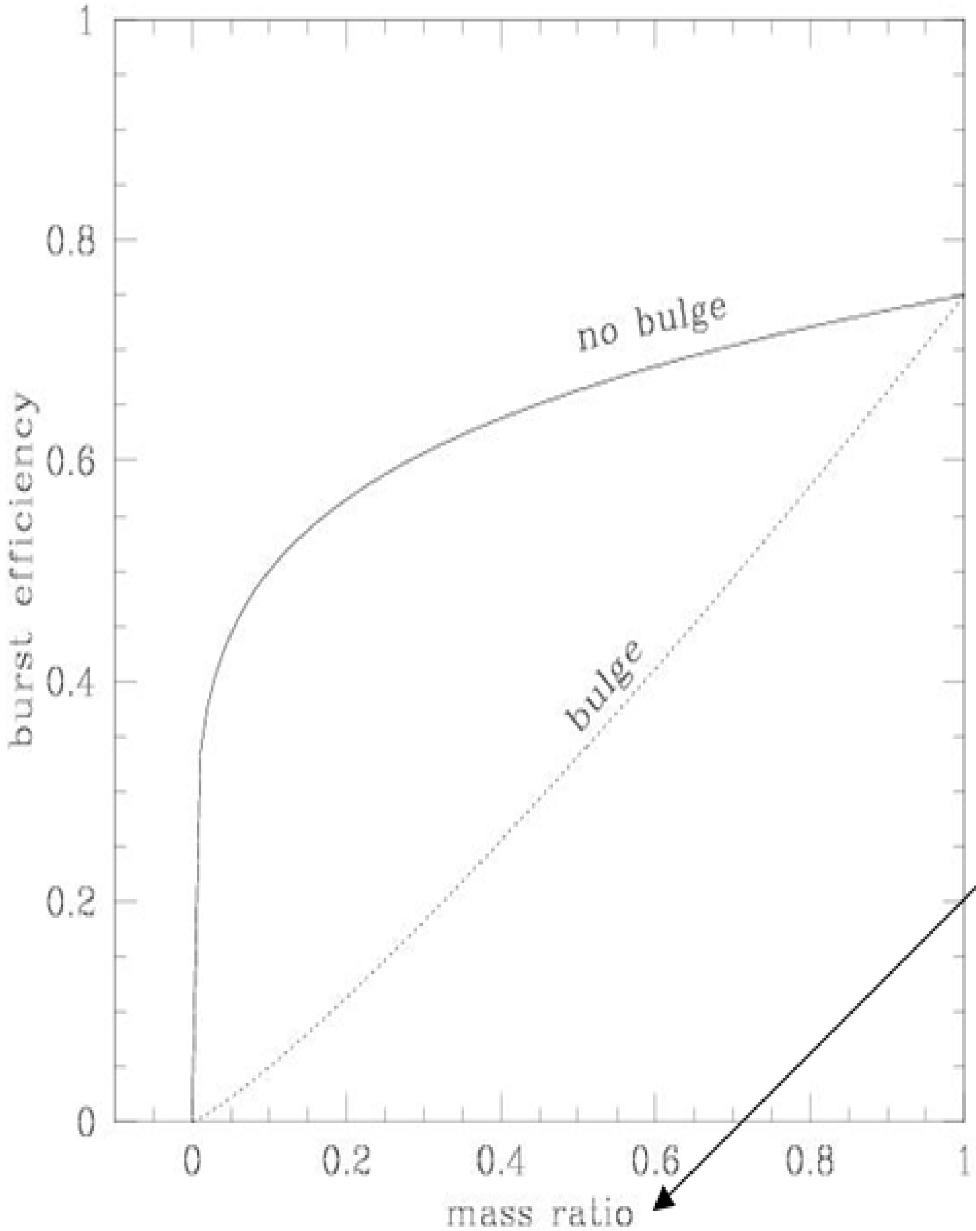
- Brief Introduction (prior work on star formation during galaxy interactions)
- New and Old Galaxy Models
- Simulations (MOVIES!)
- Star formation rates and efficiencies.

(Images from the Arp catalog)

Merger Induced Star Formation

(according to Mihos&Hernquist 1994/6 and Somerville, Primack & Faber 2001)

The fraction of gas, originally in a disk, converted to stars during the merger simulation.



Merger Ratio

Merger Induced Star Formation

(according to Mihos&Hernquist 1994/6 and Somerville, Primack & Faber 2001)

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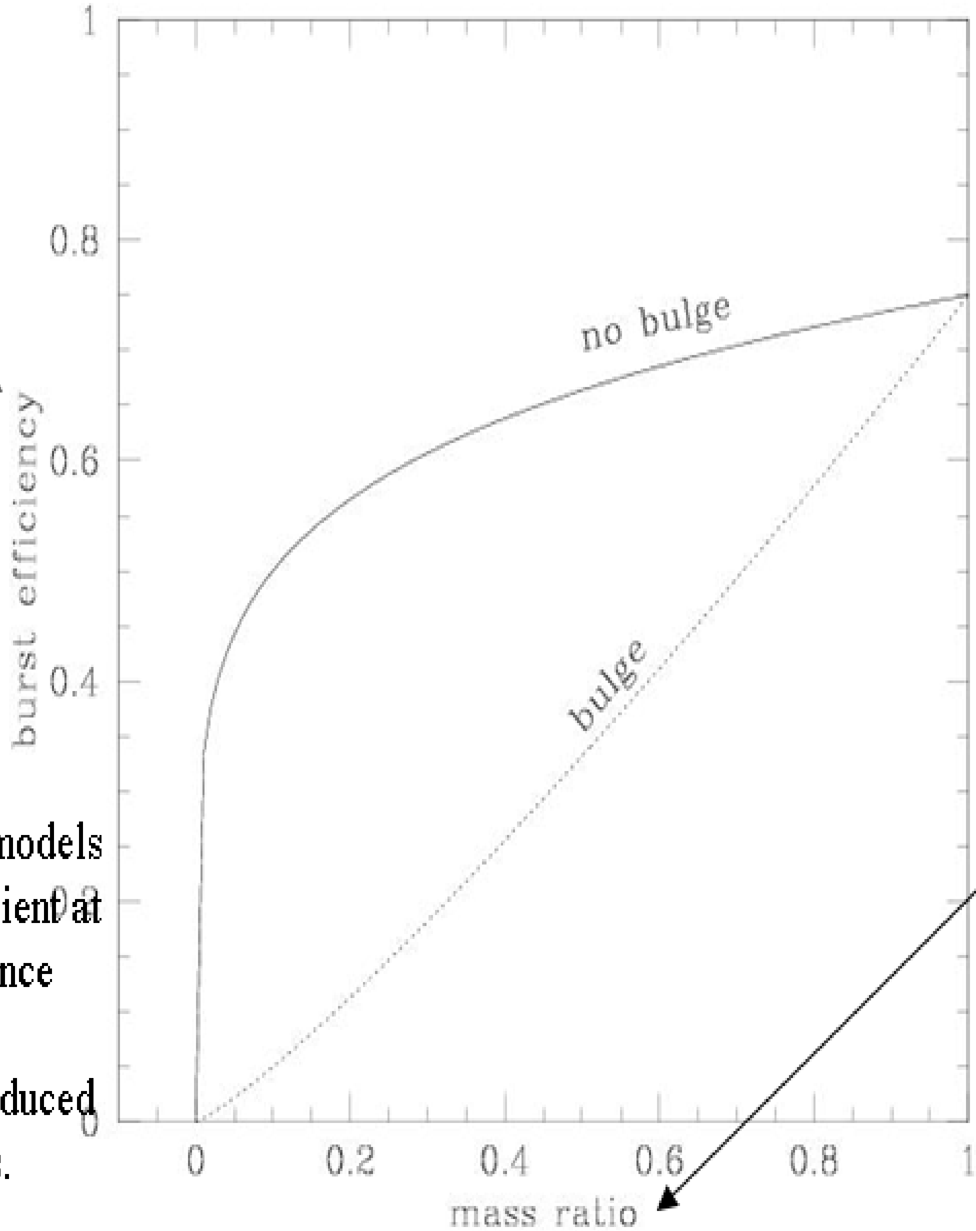

WARNING

Their quiescent models were very inefficient at forming stars, hence almost all star formation was induced by merger events.

Merger Induced Star Formation

(according to Mihos&Hernquist 19

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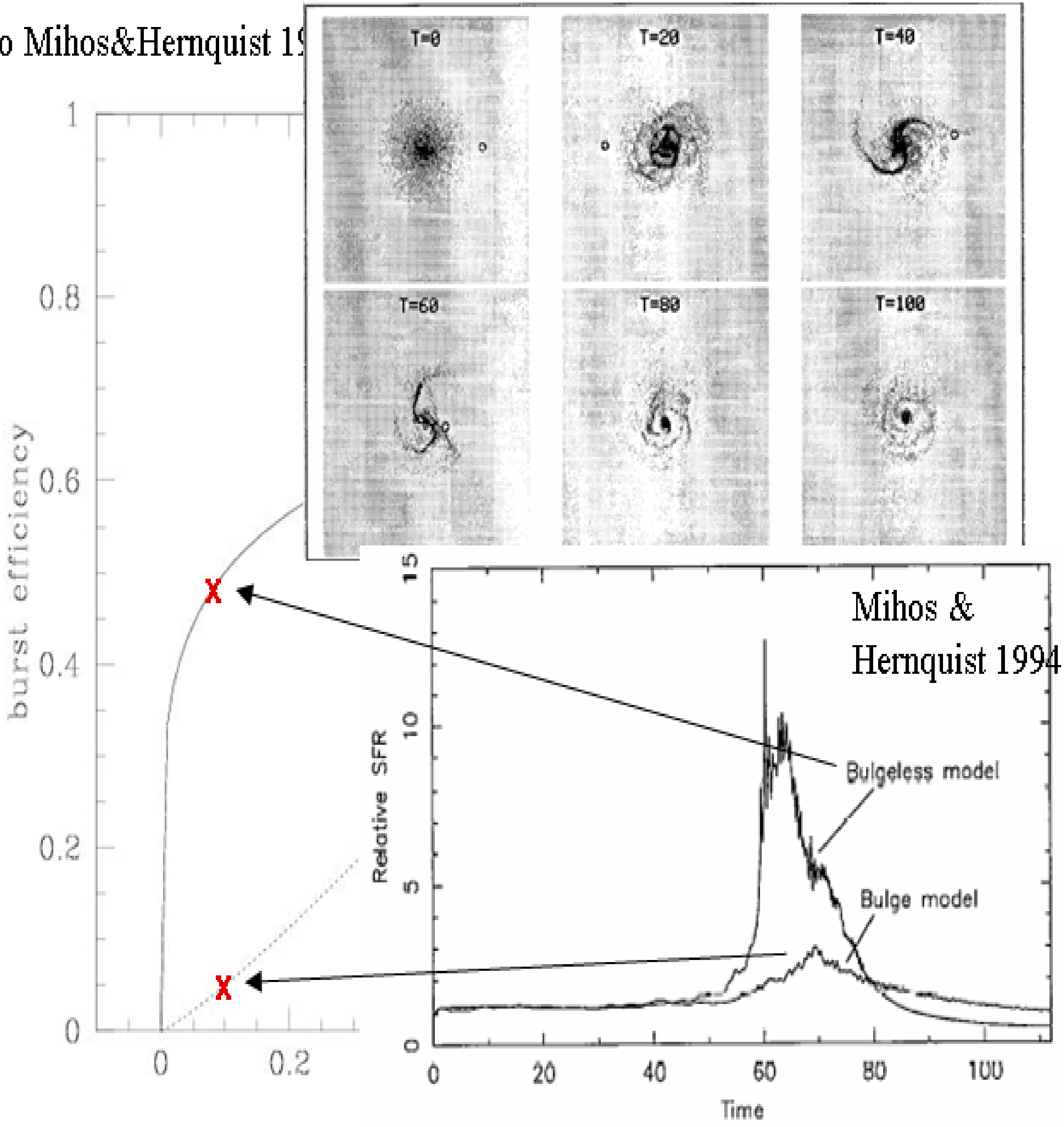

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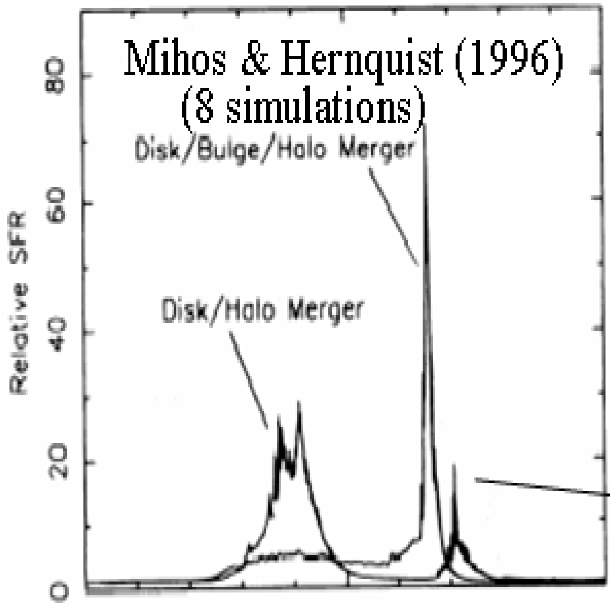

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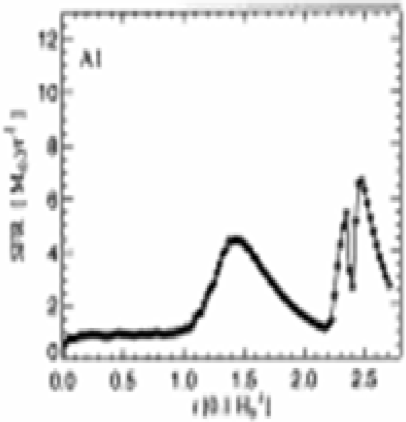
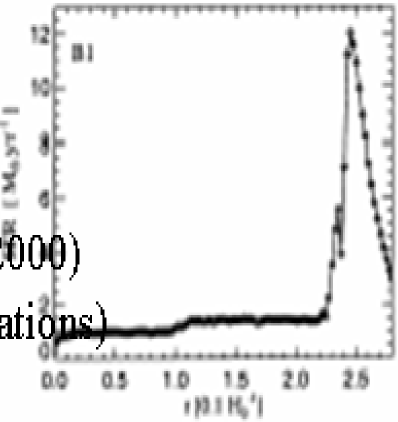
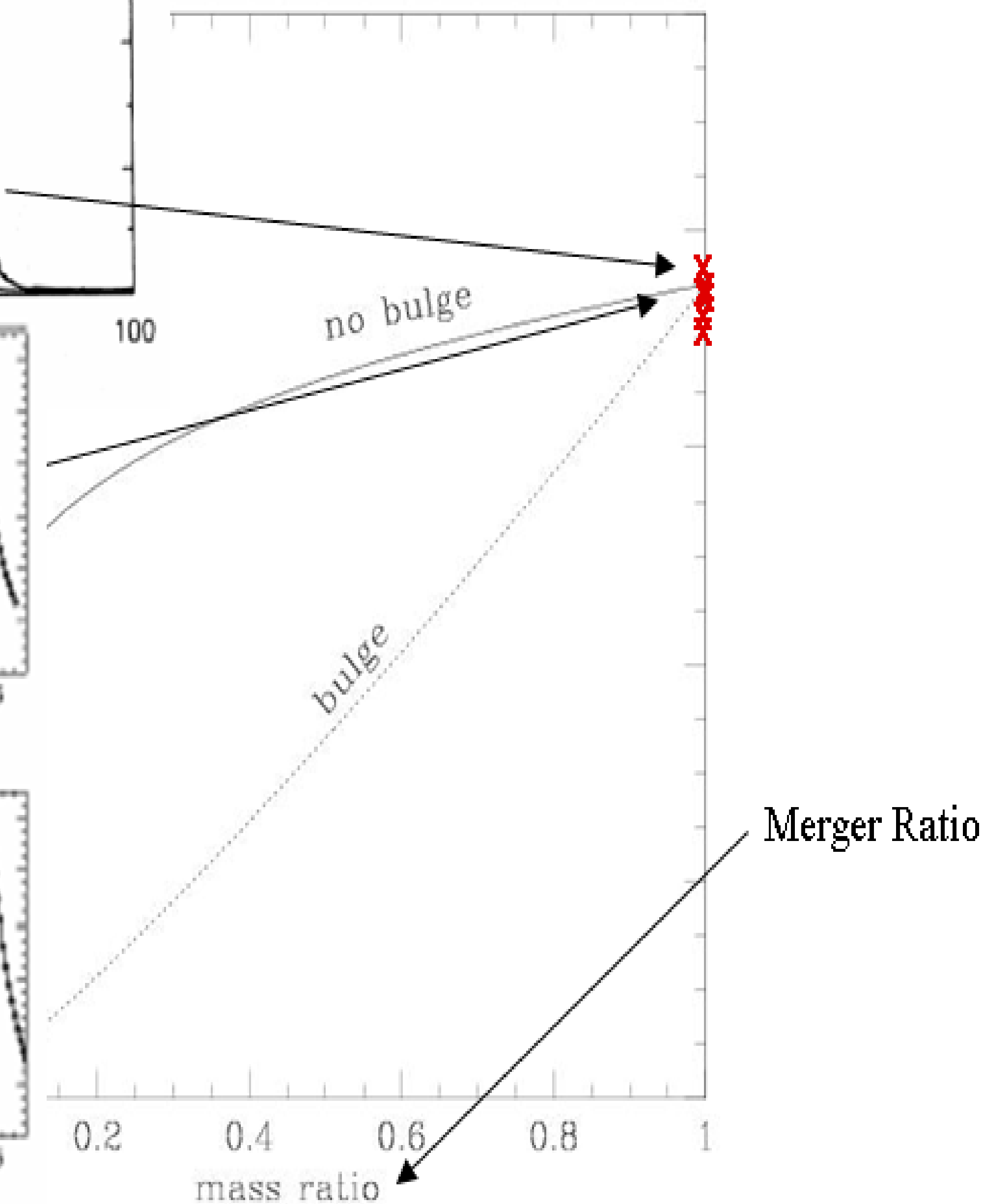




Springel (2000)
(6 simulations)



Galaxy Models: Then and Now

- **The Milky Way** (22 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).

- **MW Mass Excursions** (20+ Major Mergers)
  Smaller or larger versions of the above, with slightly higher gas fractions.

- Semi-NEW **Sbc/Sc models** (50+ Major Mergers – see Patrik's Talk)
  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. The dark halo is adiabatically contracted (as above) and hence these galaxy have a rotation velocity larger than that suggested by the baryonic Tully-Fisher (TF) relation (Bell & de Jong 2000).

- NEW **G models** (13 Major Mergers, 18 Minor Mergers)
  Properties extracted from SDSS galaxies plus other local, early-type galaxies. The dark mass and concentration are constrained to match the baryonic TF relation.

G Galaxy Properties

	G3	G2	G1	G0
Total Mass, M_{vir} (10^{11} $M_{\odot}$)	116.0	51.0	20.0	5.0
Concentration, $c=R_{vir}/r_s$	6	9	12	14
Spin Parameter, λ	0.05	0.05	0.05	0.05
Disk Mass Fraction, m_d	0.035	0.026	0.024	0.019
Disk Scale Length, R_d (kpc)	2.85	1.91	1.48	1.12
Disk Scale Height, z_0 (kpc)	0.40	0.38	0.30	0.22
Disk Spin Fraction, j_d	0.015	0.010	0.010	0.010
Gas Mass Fraction, m_g	0.011	0.009	0.010	0.012
Gas Fraction, f	0.196	0.242	0.286	0.375
Gas Scale Multiplier, α	3.0	3.0	3.0	3.0
Gas Spin Fraction, j_g	0.012	0.010	0.013	0.019
Bulge Mass Fraction, m_b	0.008	0.003	0.002	<0.001
Bulge 3D Scale Length, R_b (kpc)	0.37	0.26	0.20	0.15
N	240,000	150,000	95,000	51,000
N_{dm}	120,000	80,000	50,000	30,000
N_{gas}	50,000	30,000	20,000	10,000
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Simulations

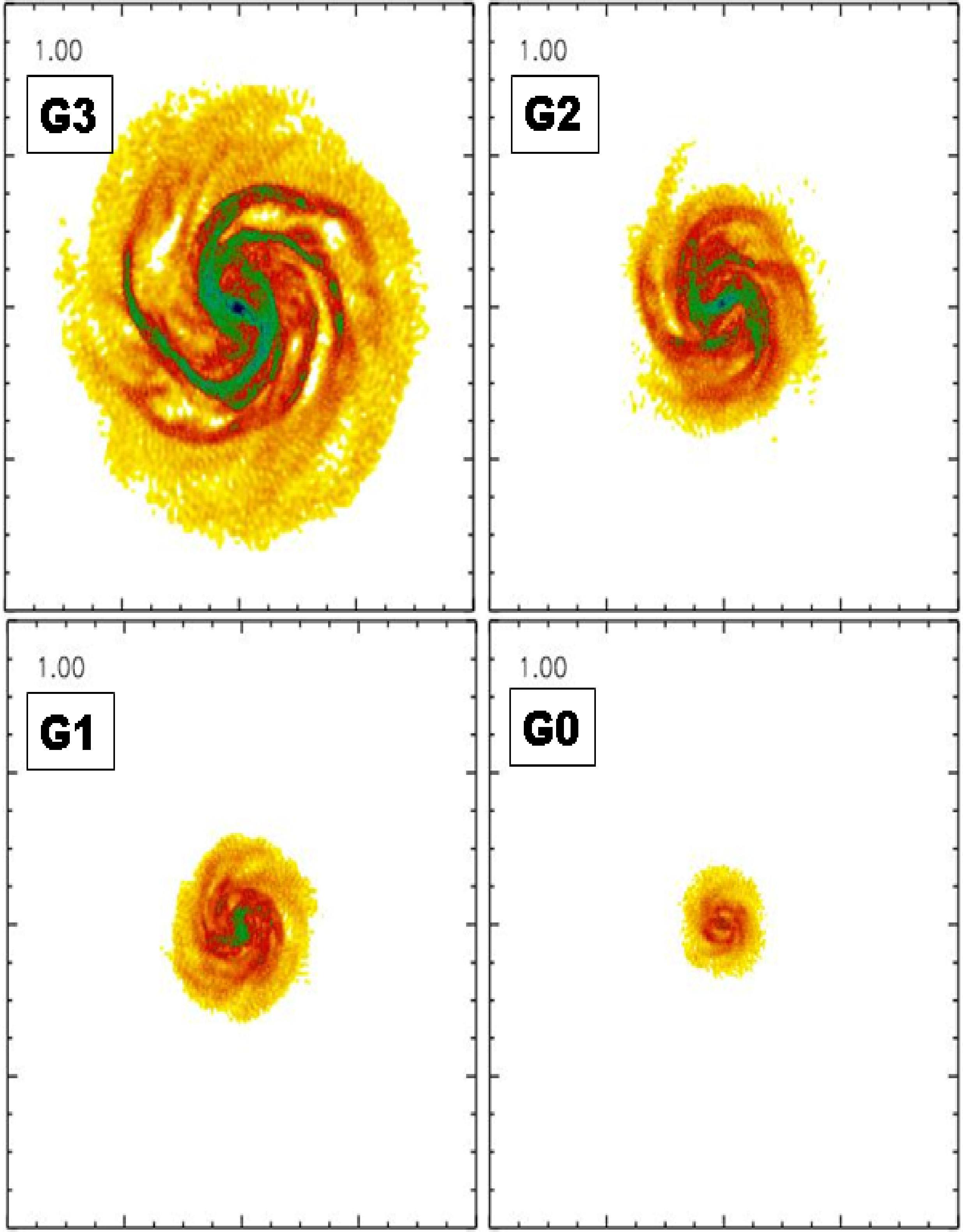
In order to investigate galaxy mergers (specifically minor mergers) we build observationally motivated N-body realizations of compound galaxies and simulate their merger using the N-body code GADGET (Springel, Yoshida & White 2000). These simulations include:

- An improved version of smooth particle hydrodynamics (SPH) with 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 ($\rho_{gas} > \rho_{threshold}$), tuned to match the observations of Kennicutt (1998)
- Metal Enrichment
- Stellar Feedback

Projected Gas Density

for G models after 1 Gyr evolution.

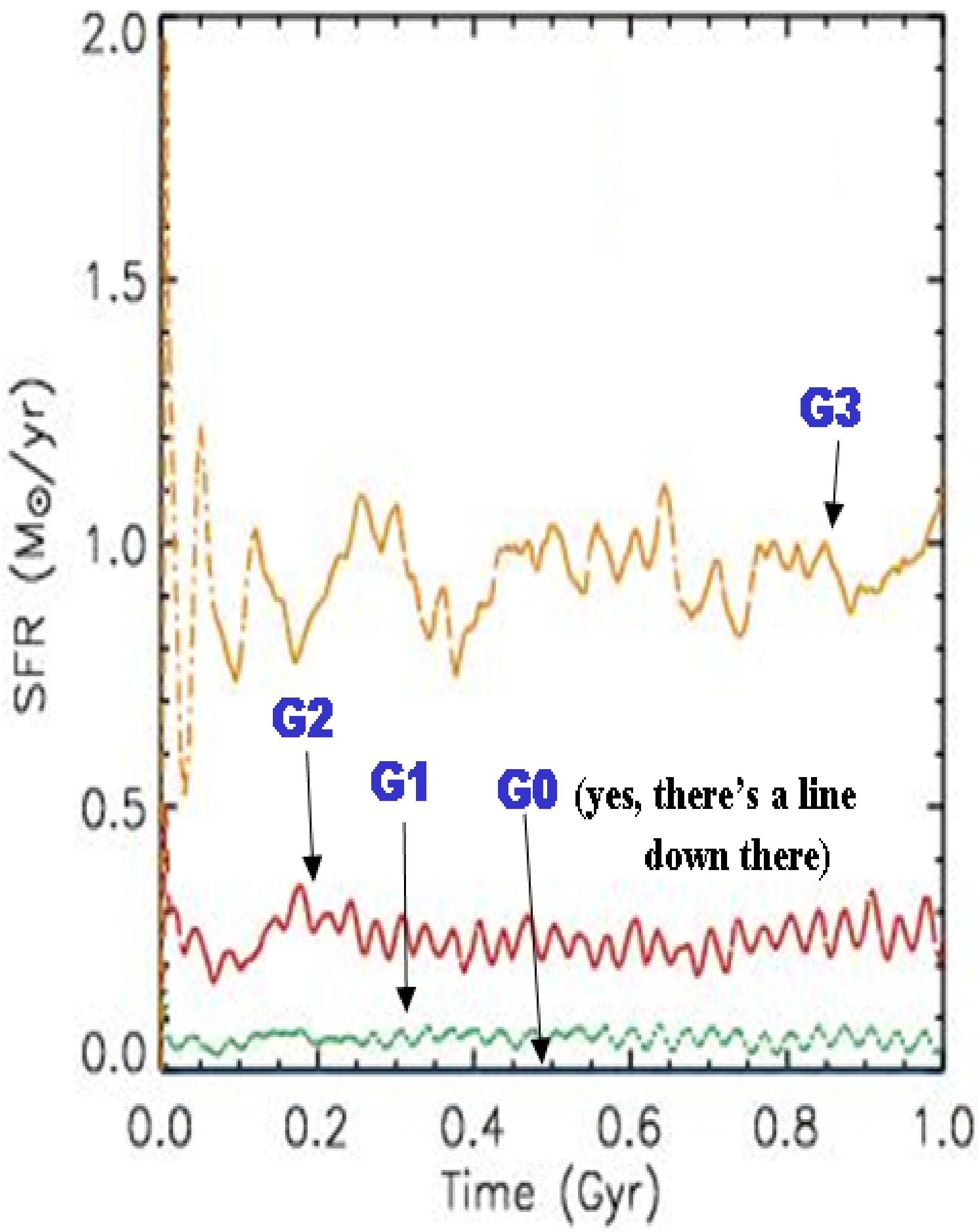
* green surface density corresponds to gas which is currently forming stars



Star Formation in Isolated Galaxies

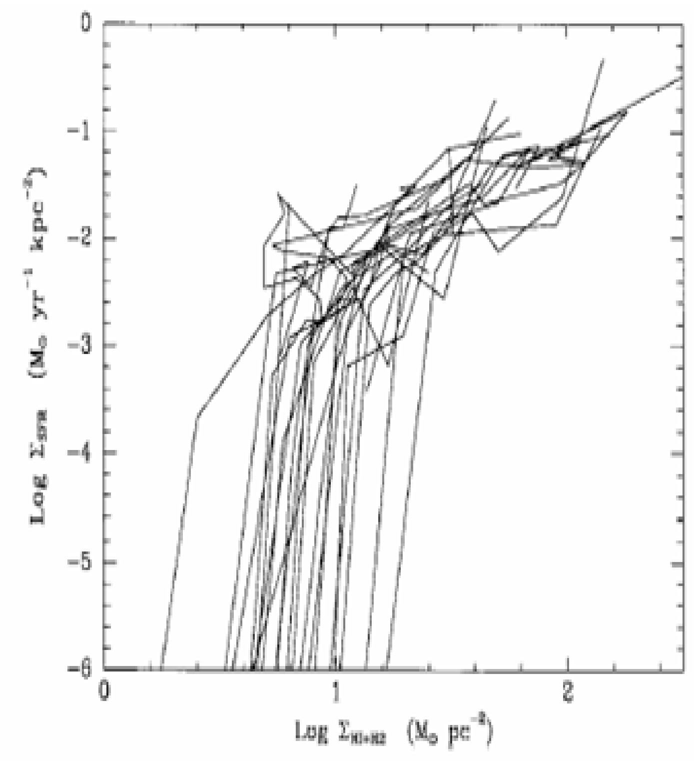
* Gas consumption: 6% for the largest galaxy G3 to <1% for G0.

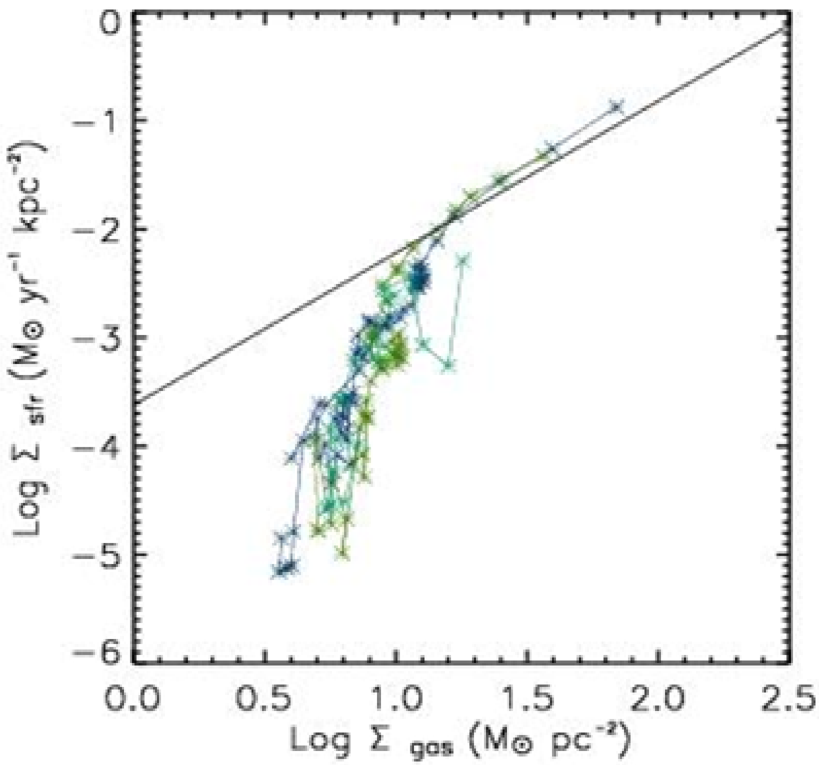
* Star Formation Rate: stable in all models 6% for the largest galaxy G3 to <1% for G0.



Isolated Star Formation

Kennicutt (1998) determined that the surface density of star formation was very tightly correlated with the surface density of gas over a remarkably wide range of gas densities and in a wide variety of galactic states. We use this 'law' to calibrate our star formation parameters by requiring isolated disk galaxies to follow the Kennicutt law.





Merger Mass Ratios

Now that we have stable galaxy models which span a range in mass we simulate mergers between pairs of galaxies.

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: 1:3 Minor Merger

Projected Gas Density

Projected Stellar Density

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
in the orbital plane

Projected Gas Density
perpendicular to 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

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Movie: 1:6 Minor 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:
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Projected stellar density
in the orbital plane

Projected stellar density
perpendicular to orbital plane

Projected Stellar Density

left: XY, the orbital plane

right: XZ

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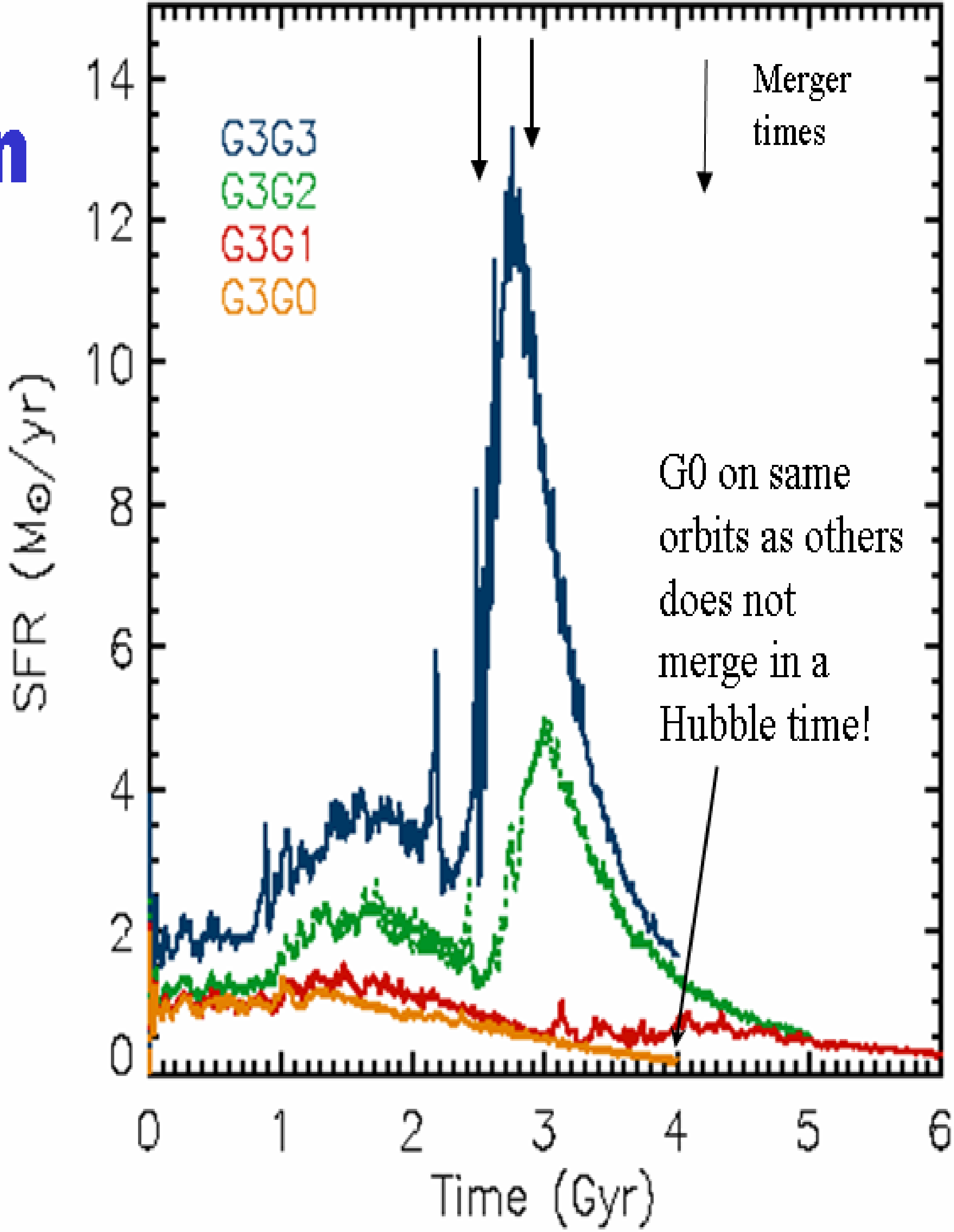
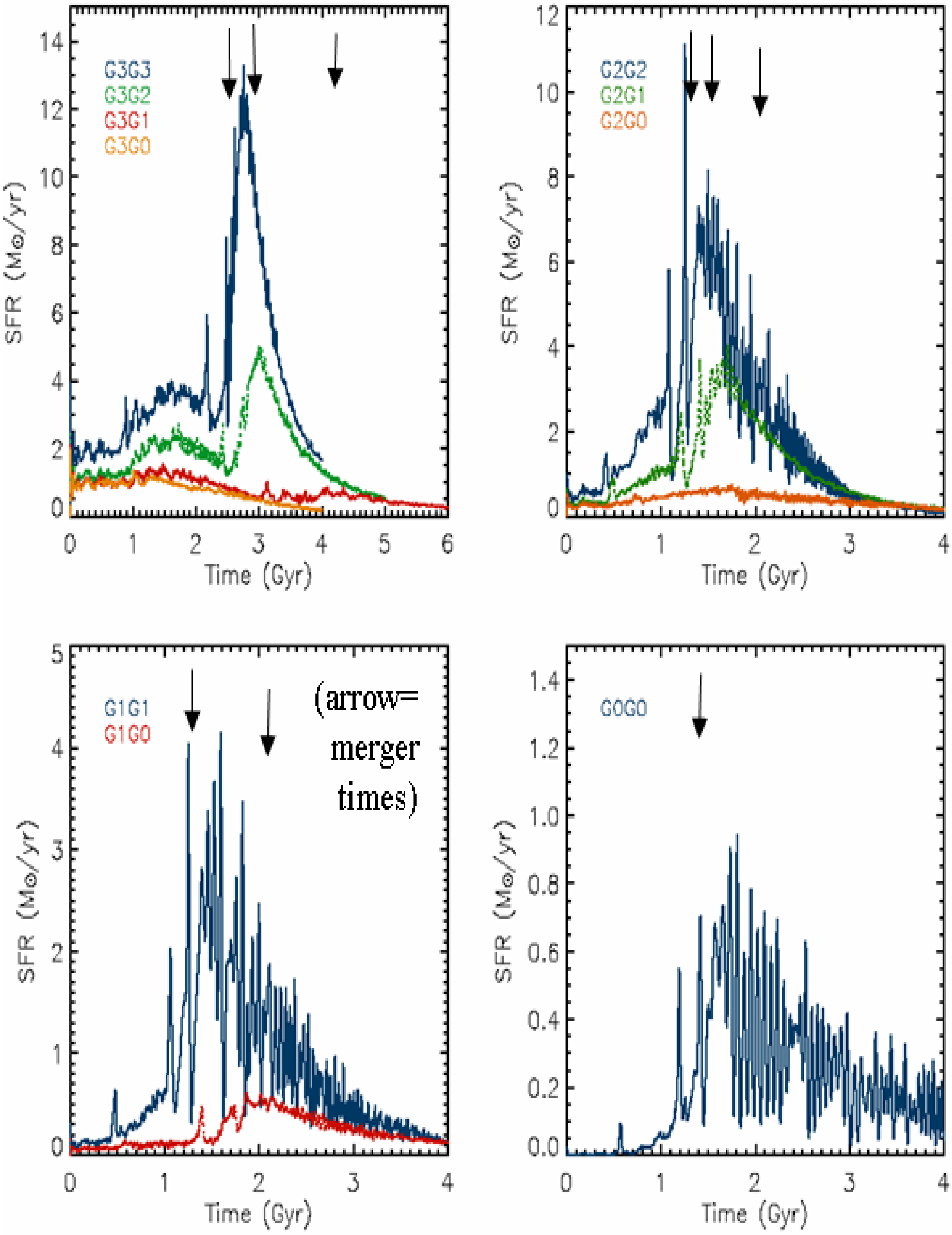
Star Formation in G3 Mergers

- 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.
- The burst strength increases with merger mass ratio, with the 1:6 merger (red) generating very little increase in SF at all.
- Small mergers are tricky!



Star Formation in all Prograde Mergers

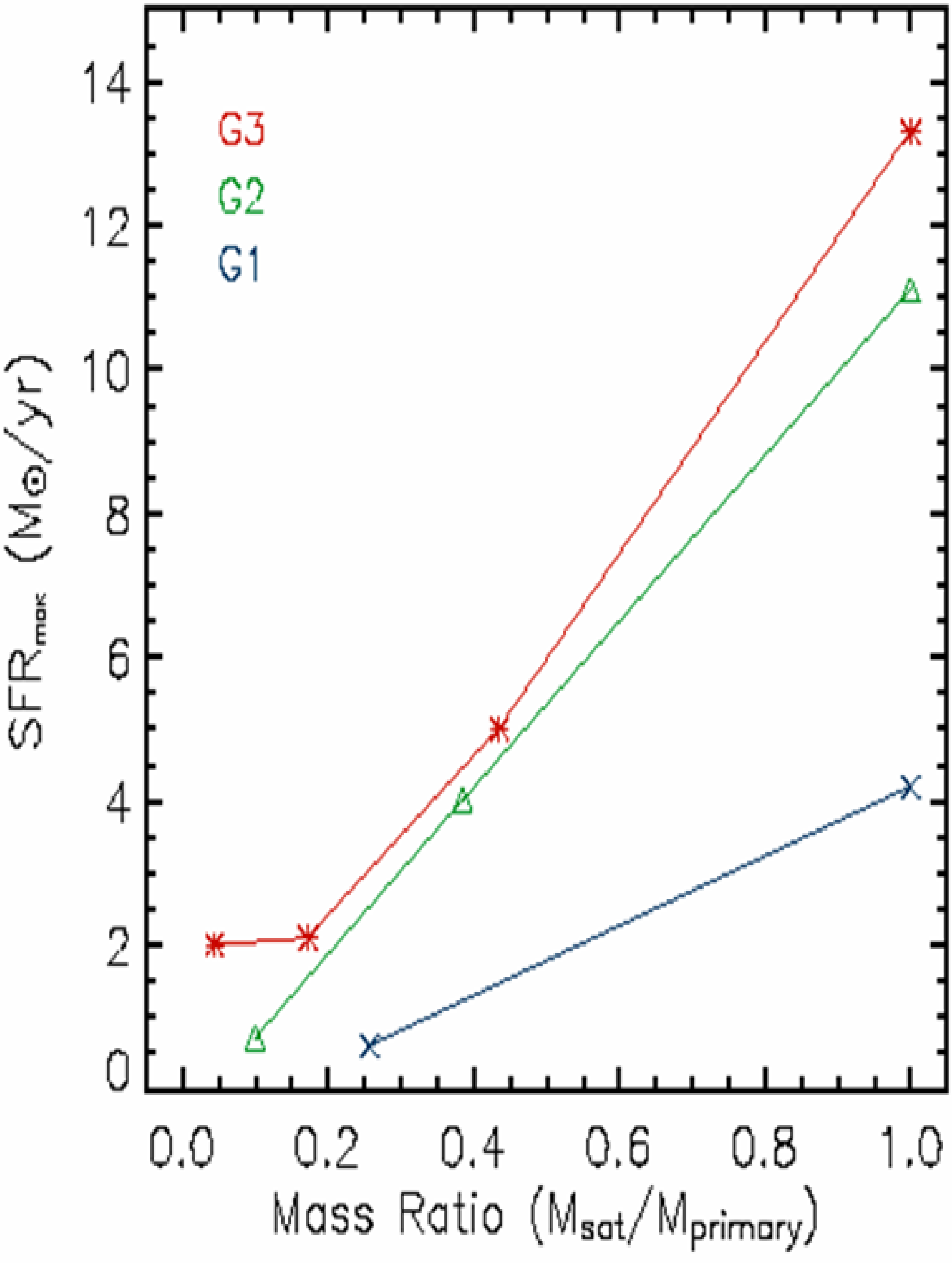
- Trends in star formation are similar to those in the G3 case.
- The maximum star formation decreases with progenitor mass.
- Small accretion events lead to little increased SF, with a preliminary dividing line at 1:5.
- Mergers with small mass progenitors (G1 or G2) have long tails of SF after the merger is over.



Maximum Star Formation Rate

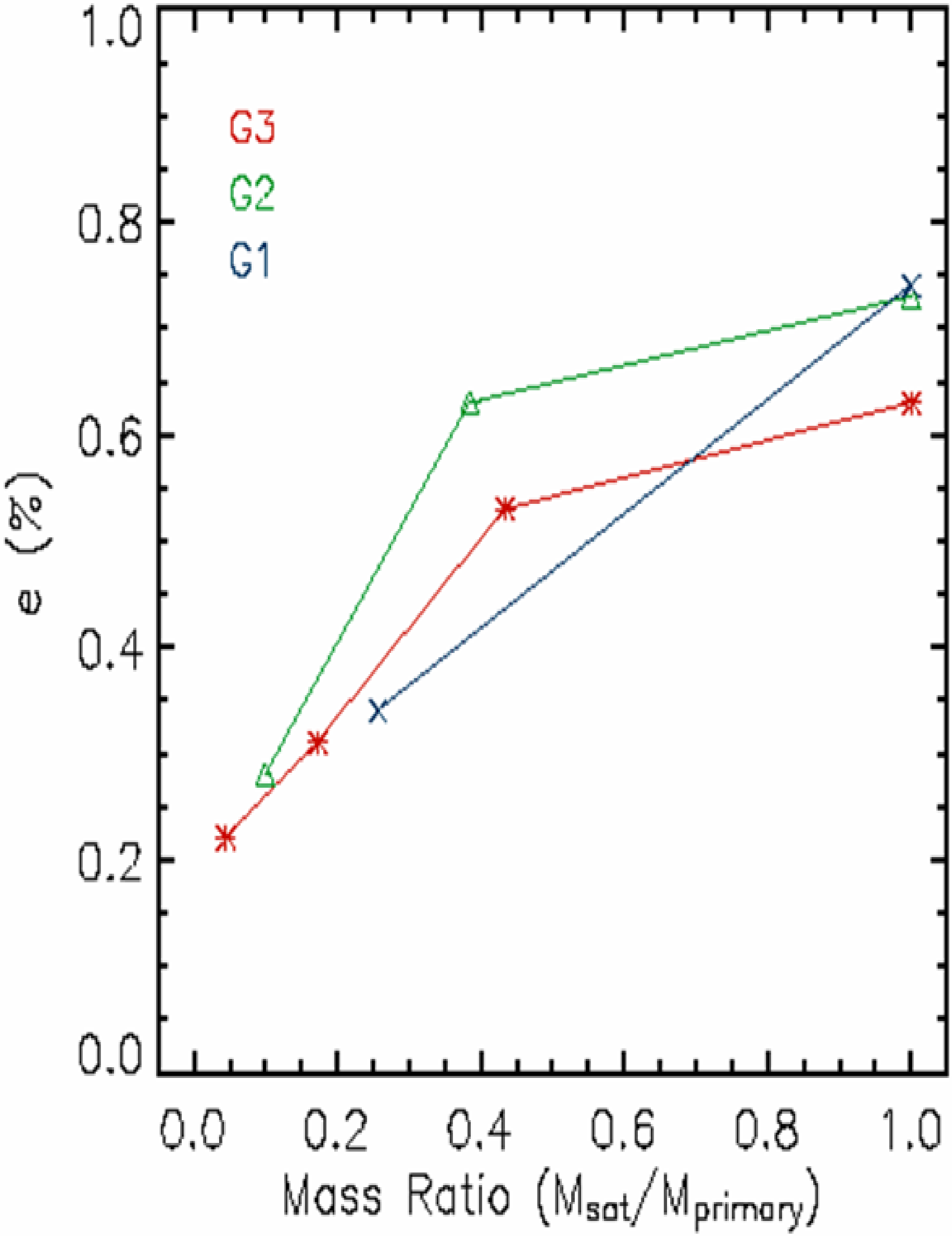
• Maximum star formation rate (usually a peak directly after the final merger) during the simulation.

• Major mergers are more violent star forming events than minor mergers.



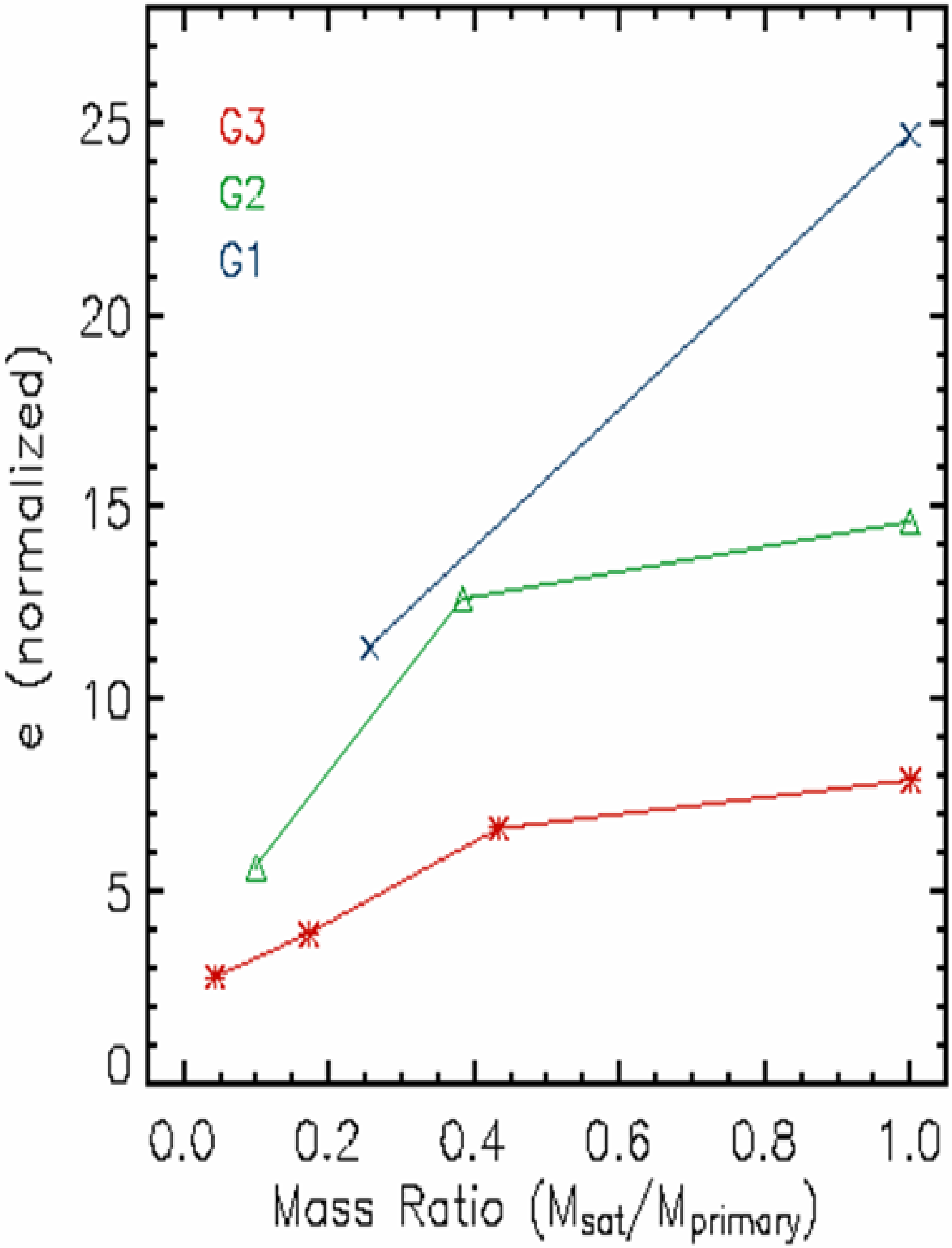
Star Formation Efficiency

- 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).



Normalized Star Formation (or burst) Efficiency

The largest star formation events, major mergers between large galaxies, only modestly increase the amount of star formation, while mergers between small galaxies greatly enhance the amount of star formation than would have otherwise (with no interaction) have occurred.



Conclusions

- Our results are consistent with Mihos & Hernquist 1994. We see increased star formation due to the minor merger and the suppression of early inflows of gas due to the presence of a bulge.
- Mergers with mass ratios greater than 1:5 enhance star formation over that of quiescent galaxies.
- Simulations which had different orbits (retrograte) or galaxies with different internal structure (bulgeless) show that the star formation history (maximum rate and efficiency) depends on everything, and hence a fair amount of parameter space must be explored.
- Are our initial orbits reasonable? Would the smaller merger ratios generate star formation increases if they were on circular orbits?
- Mergers between small mass halos is different than mergers between galaxies the size of the Milky way. Star formation tends to ensue for longer periods after the final merger and the increase is many-fold over the star formation that would have quiescently occurred.