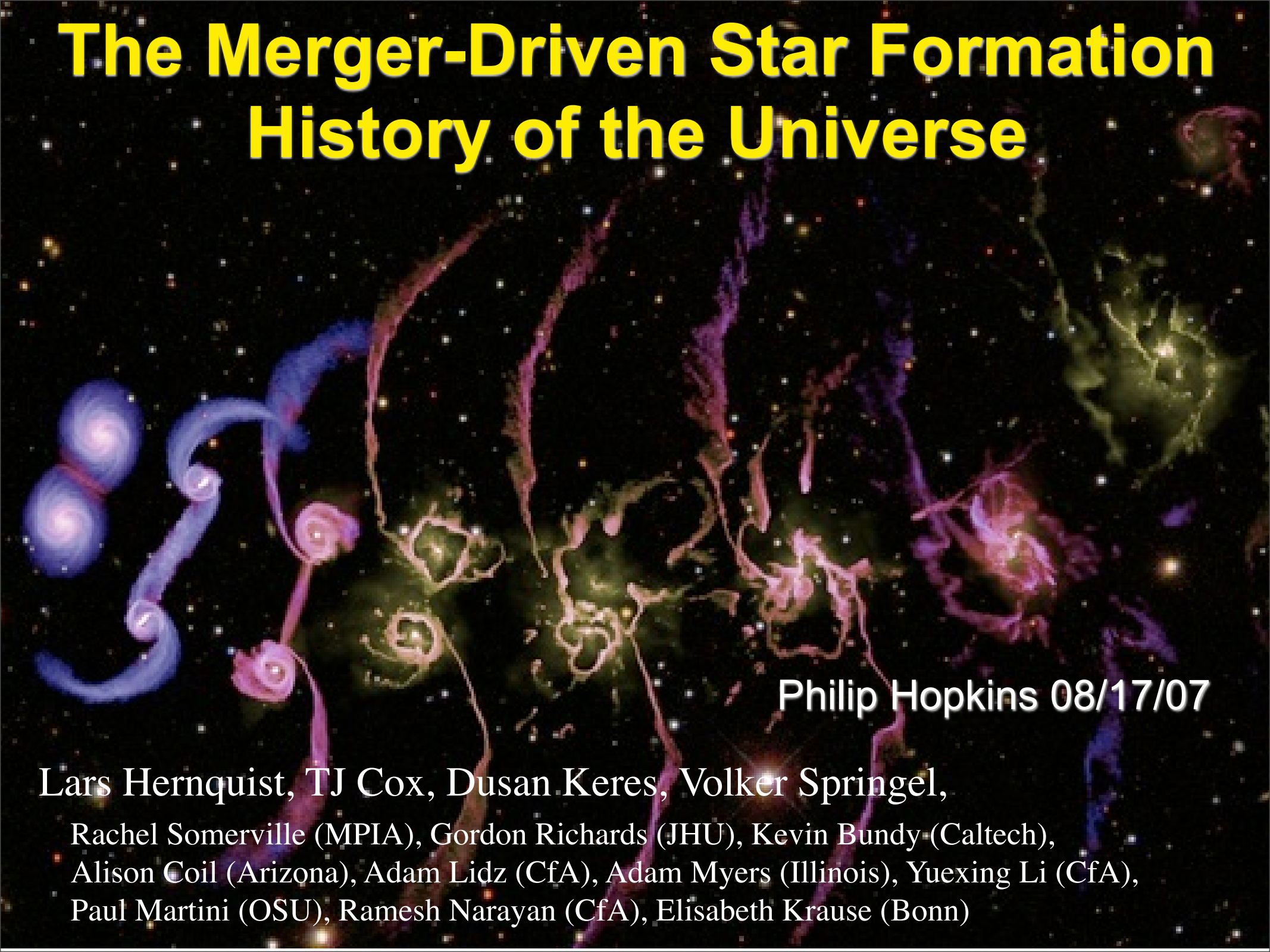


# The Merger-Driven Star Formation History of the Universe

A visualization of the cosmic web, showing a complex network of filaments and clusters of galaxies. The filaments are colored in shades of blue, purple, and green, while the clusters are more densely packed and appear in various colors. The background is dark with numerous small white stars.

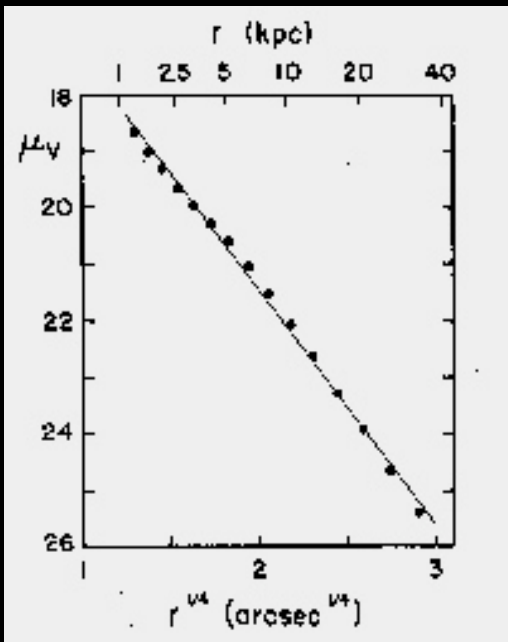
Philip Hopkins 08/17/07

Lars Hernquist, TJ Cox, Dusan Keres, Volker Springel,

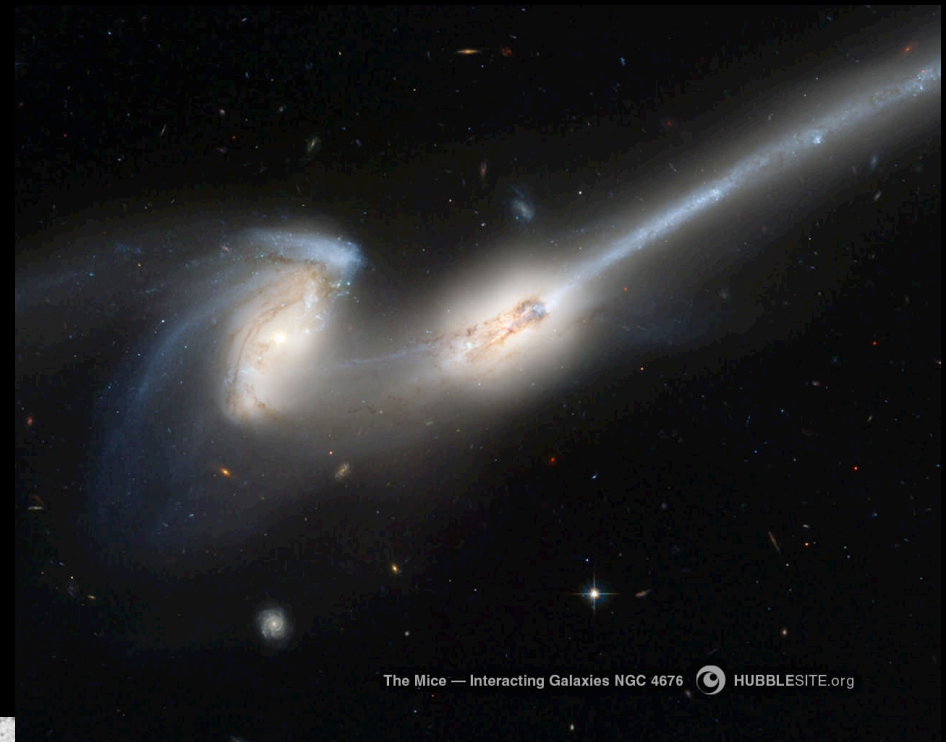
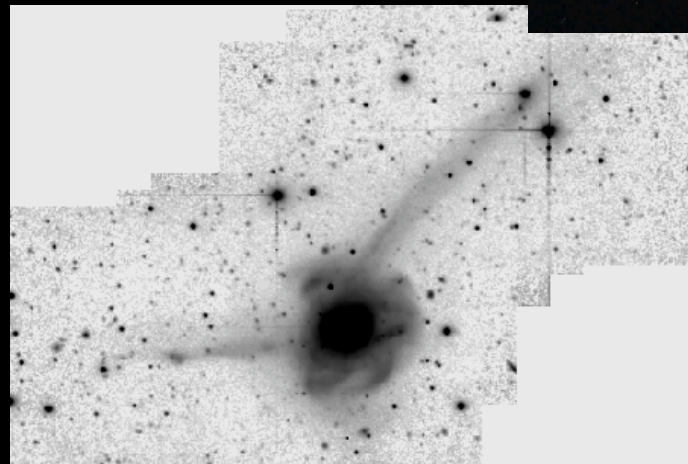
Rachel Somerville (MPIA), Gordon Richards (JHU), Kevin Bundy (Caltech),  
Alison Coil (Arizona), Adam Lidz (CfA), Adam Myers (Illinois), Yuexing Li (CfA),  
Paul Martini (OSU), Ramesh Narayan (CfA), Elisabeth Krause (Bonn)

# Gas-Rich, Major Mergers

- Locally, seen related to:
  - growth of spheroids
  - causing starbursts
  - fueling SMBH growth, quasar activity



NGC 7252

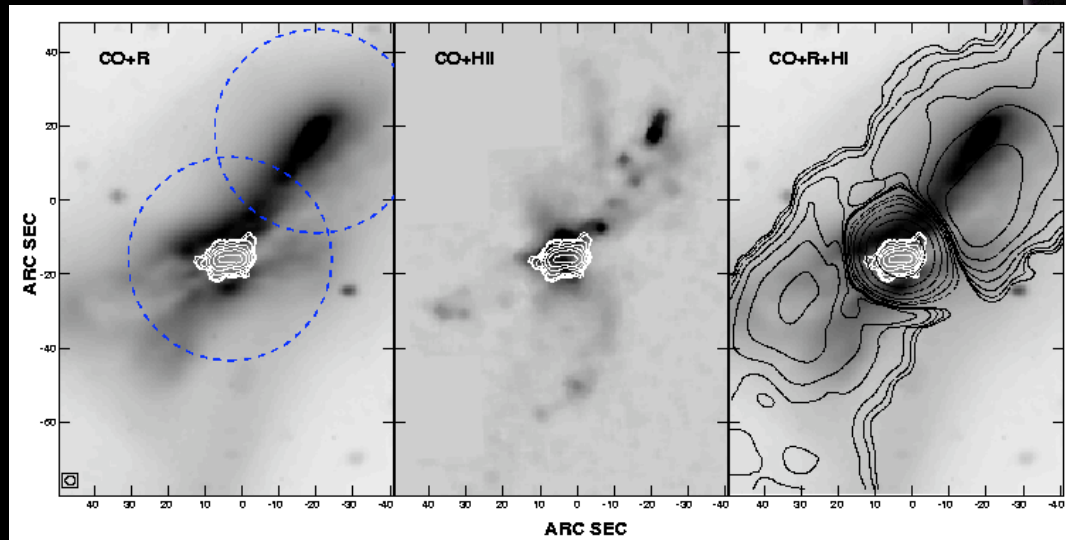
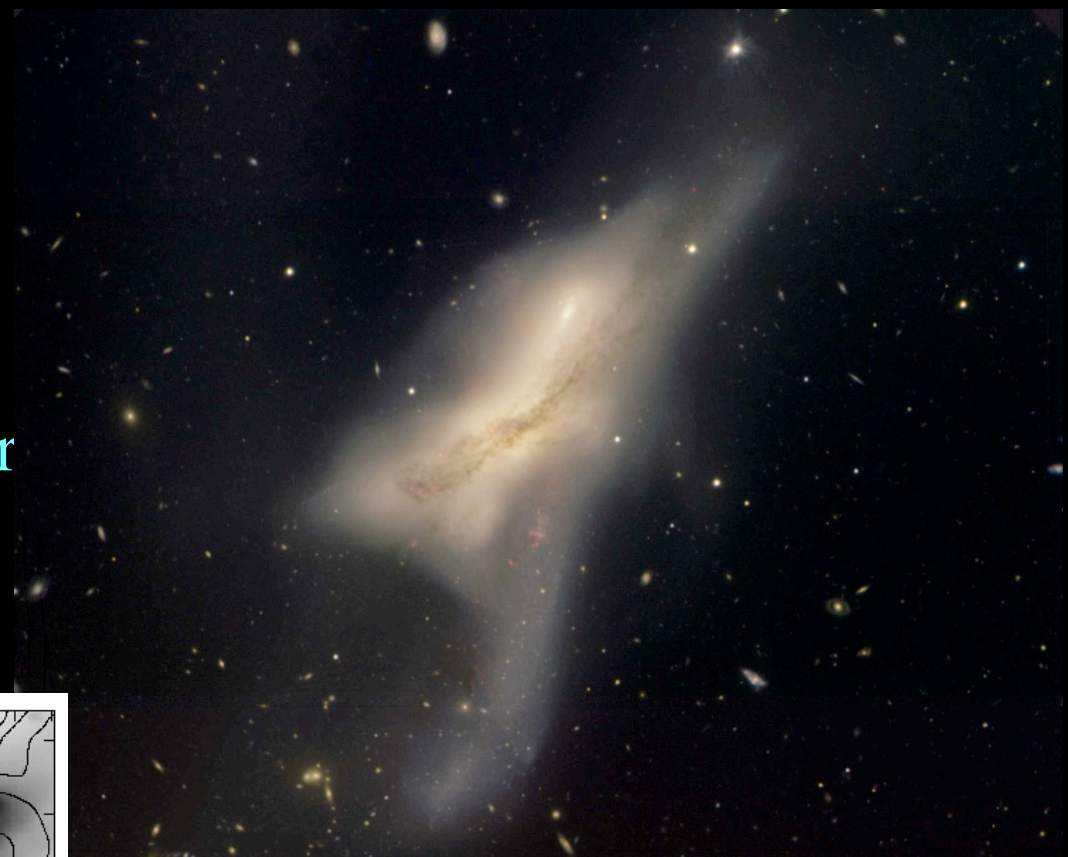


HST image of Mice

Schweizer (1982)

# Gas-Rich, Major Mergers

- Locally seen related to:
  - growth of spheroids
  - causing starbursts (ULIRGs)
  - fueling SMBH growth, quasar activity

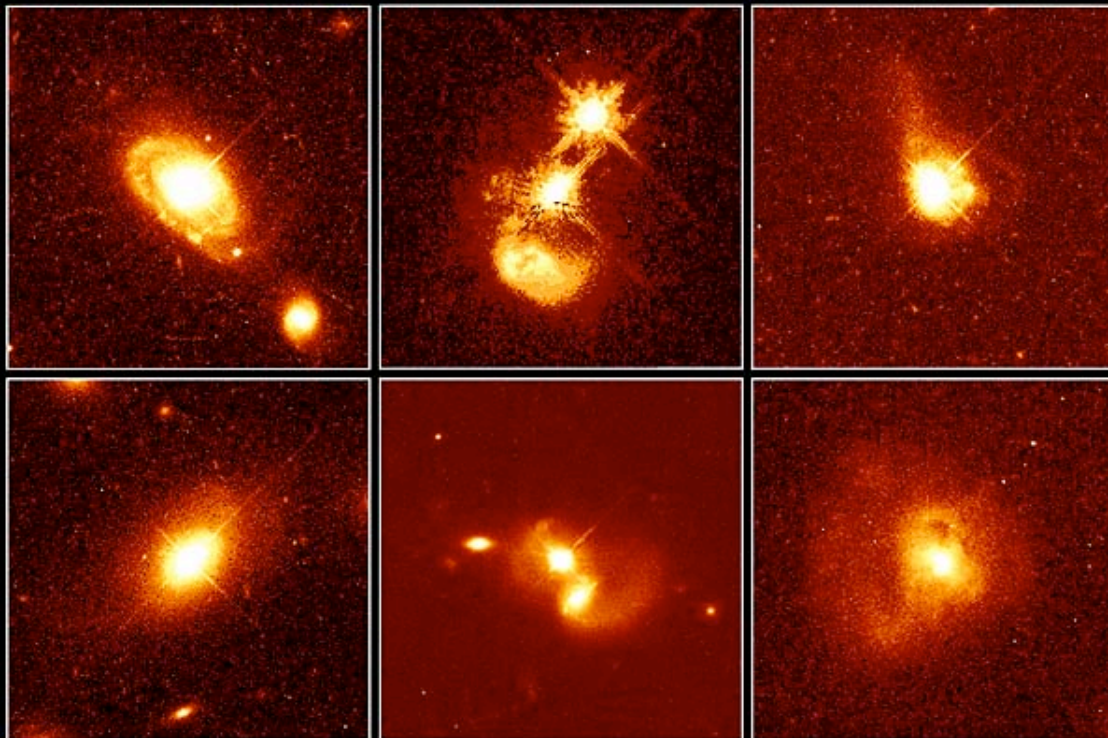


NGC 520 (Arp 157)

Yun & Hibbard (2001)

# Gas-Rich, Major Mergers

- Locally, seen related to:
  - growth of spheroids
  - causing starbursts (ULIRGs)
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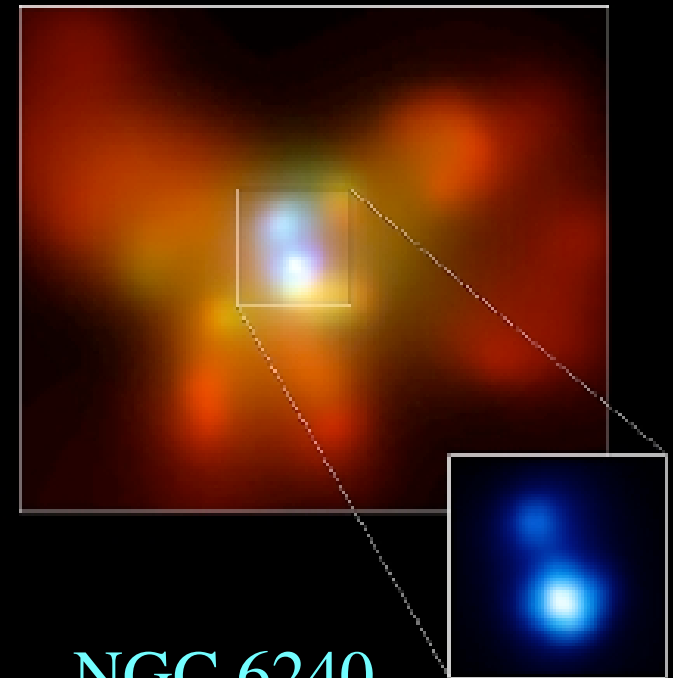
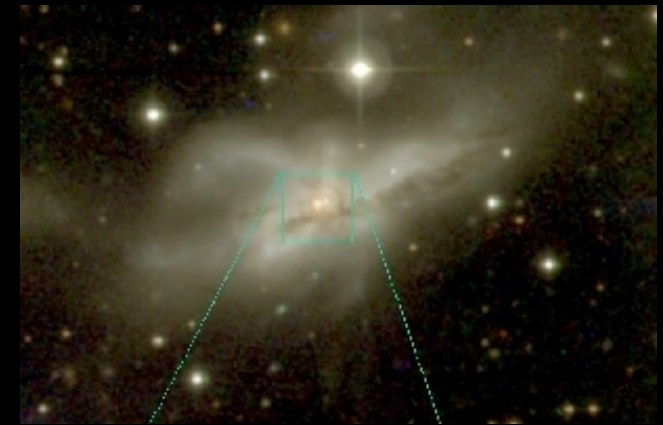
Quasar Host Galaxies

HST • WFPC2

PRC96-35a • ST Scl OPO • November 19, 1996

J. Bahcall (Institute for Advanced Study), M. Disney (University of Wales) and NASA

Komossa et al. (2003)

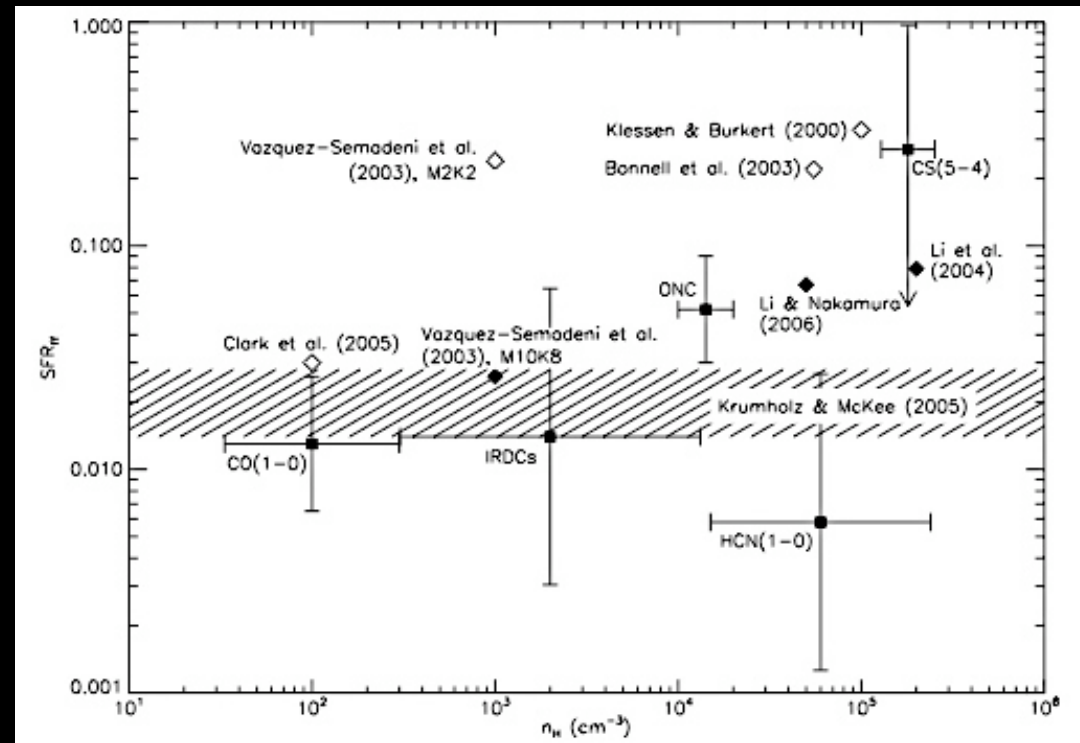


NGC 6240

# Merger-Induced Star Formation

## Why Is It Interesting?

- Most Extreme Environments
  - High Local SFR
  - Quasar/AGN Background
  - Inflows & Outflows
  - Different IMF?



# Merger-Induced Star Formation

## Why Is It Interesting?

- Most Extreme Environments
- Most Extreme Objects Known
  - ULIRGs & HLIRGs
  - $\sim 1000 M_{\text{sun}}/\text{yr}$  in a 200 pc region

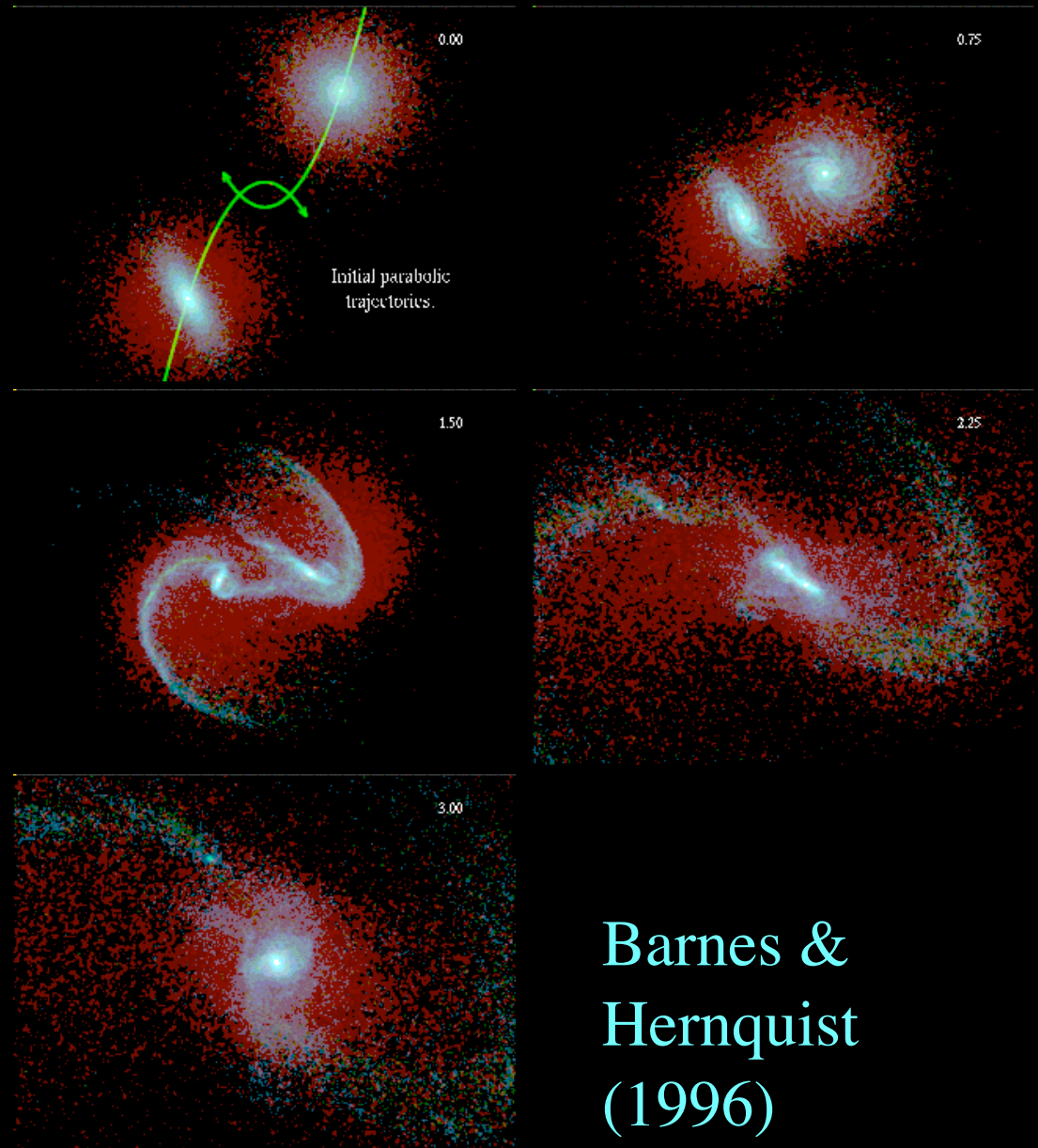
# Merger-Induced Star Formation

## Why Is It Interesting?

- Most Extreme Environments
- Most Extreme Objects Known
- Most Important Stars (...to some of us...)
  - Structure of Ellipticals:
    - Phase space density
    - Rotation
  - Depth of potential  $\rightarrow$  BH mass ( $M_{\text{BH}}\text{-}\sigma$ )
  - “Loss Cone” for SMBH Coalescence

# Physical Mechanism

- Tidal torques  $\Rightarrow$  large, rapid gas inflows (e.g. Barnes et al.)
- Triggers starburst (e.g. Mihos et al.)
- Feeds BH growth (e.g. Di Matteo et al.)
- Merging stellar disks grow spheroid
- **Requirements:**
  - major merger
  - supply of cold gas  
("cold" = rotationally supported)

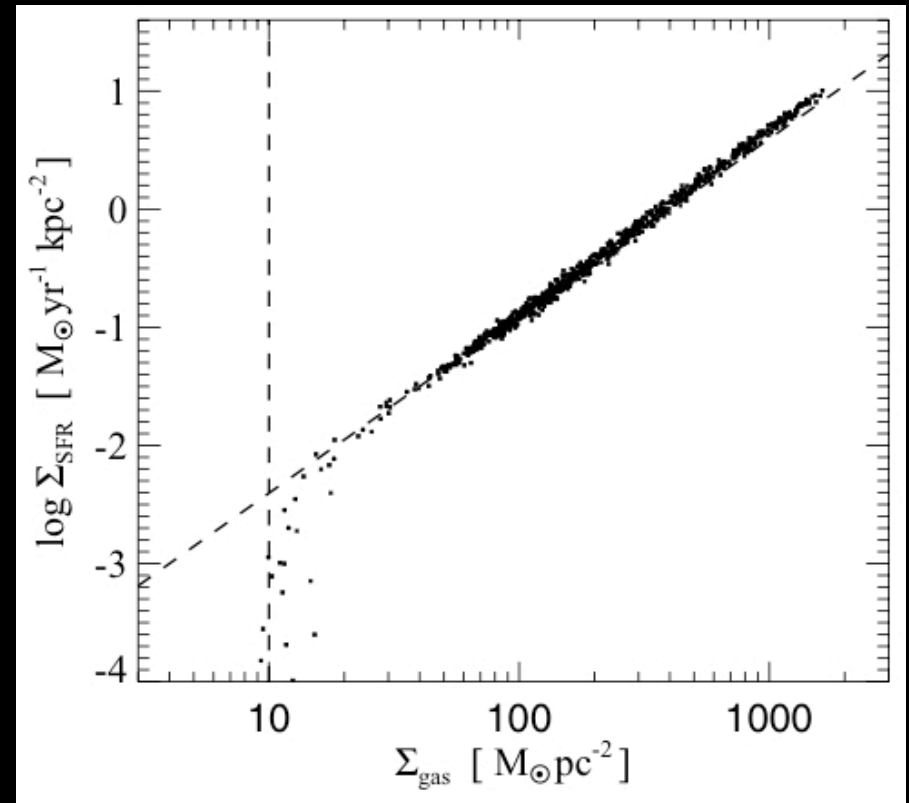


Barnes &  
Hernquist  
(1996)

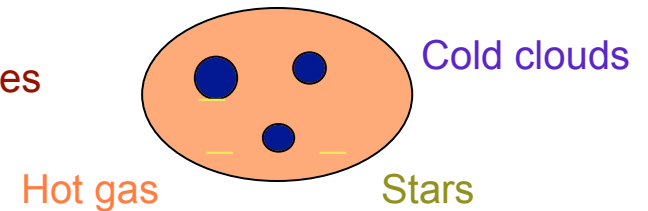


# Testing the Hypothesis

- Simulations: 3-D, time-dependence
- Consider:
  - single, multiple mergers
  - varying mass ratios
  - star formation, supernova feedback & winds (sub-resolution)
  - black hole growth, feedback (sub-resolution)
  - large gas fractions: made possible by SN feedback



Subresolution phases  
of the ISM:



# Caveat: Evolving Highly Gas-Rich Galaxies

10% gas

99% gas

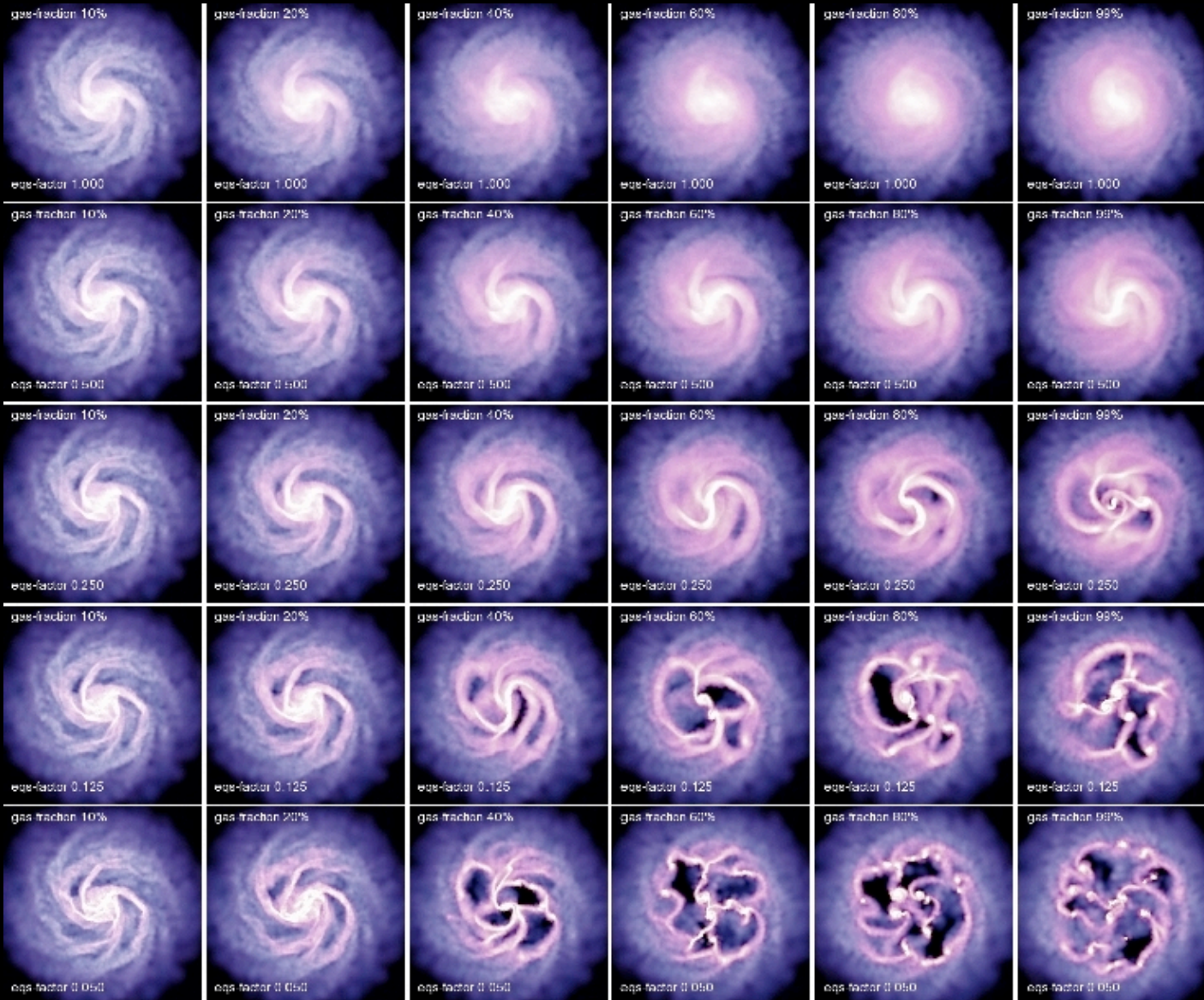


more gas

softer  
EOS

Springel et  
al. (2005)

$\sim 10^5$  K



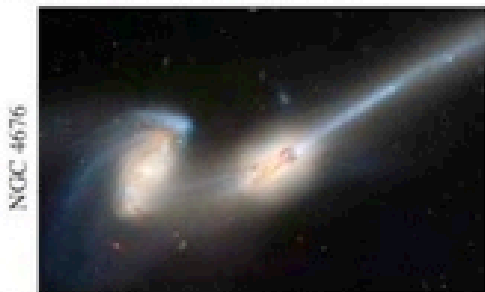
$10^4$  K

T = 0 Myr

Gas

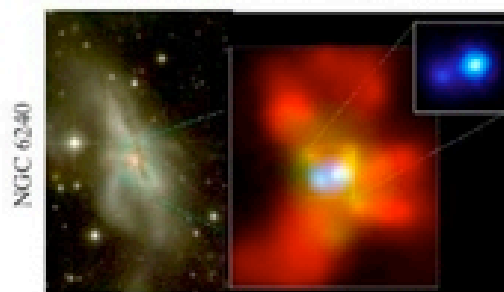


### (c) Interaction/"Merger"



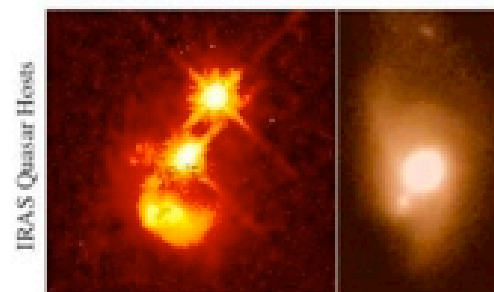
- now within one halo, galaxies interact & lose angular momentum
- SFR starts to increase
- stellar winds dominate feedback
- rarely excite QSOs (only special orbits)

### (d) Coalescence/(U)LIRG



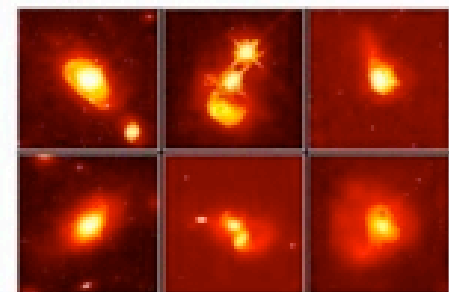
- galaxies coalesce: violent relaxation in core
- gas inflows to center: starburst & buried (X-ray) AGN
- starburst dominates luminosity/feedback, but, total stellar mass formed is small

### (e) "Blowout"



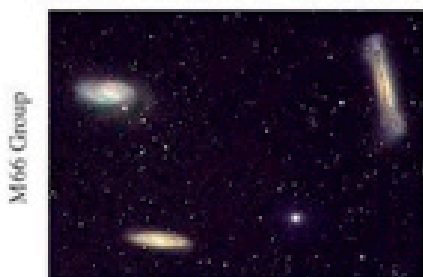
- BH grows rapidly: briefly dominates luminosity/feedback
- remaining dust/gas expelled
- get reddened (but not Type II) QSO: recent/ongoing SF in host high Eddington ratios merger signatures still visible

### (f) Quasar



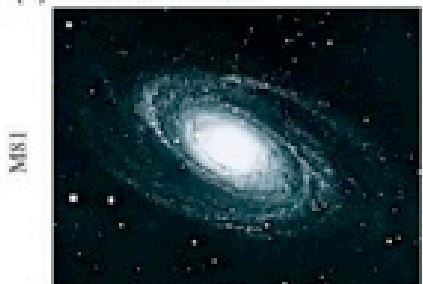
- dust removed: now a "traditional" QSO
- host morphology difficult to observe: tidal features fade rapidly
- characteristically blue/young spheroid

### (b) "Small Group"

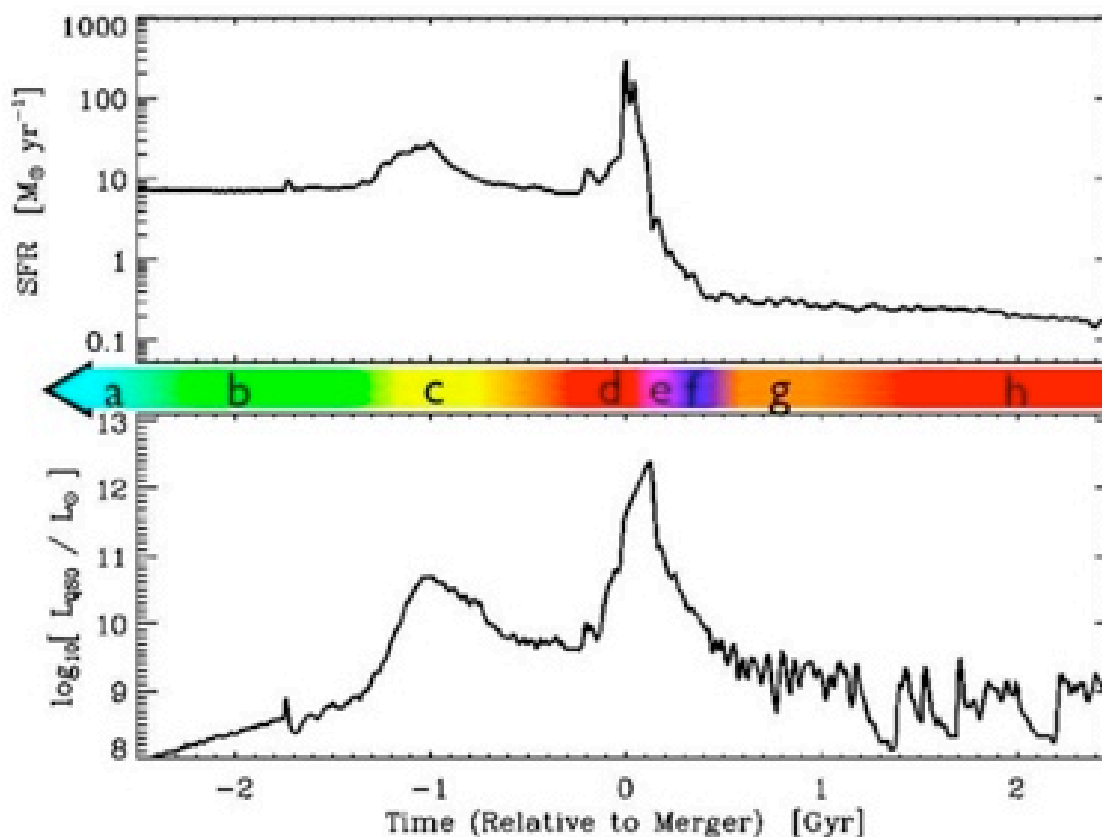


- halo accretes similar-mass companion(s)
- can occur over a wide mass range
- $M_{\text{halo}}$  still similar to before: dynamical friction merges the subhalos efficiently

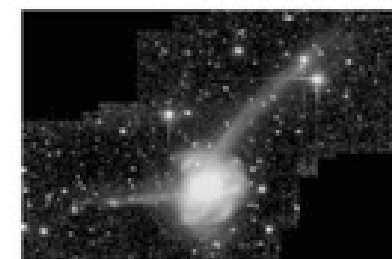
### (a) Isolated Disk



- halo & disk grow, most stars formed
- secular growth builds bars & pseudobulges
- "Seyfert" fueling (AGN with  $M_b > 23$ )
- cannot redden to the red sequence

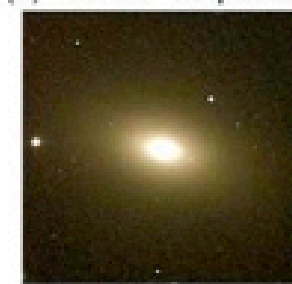


### (g) Decay/K+A

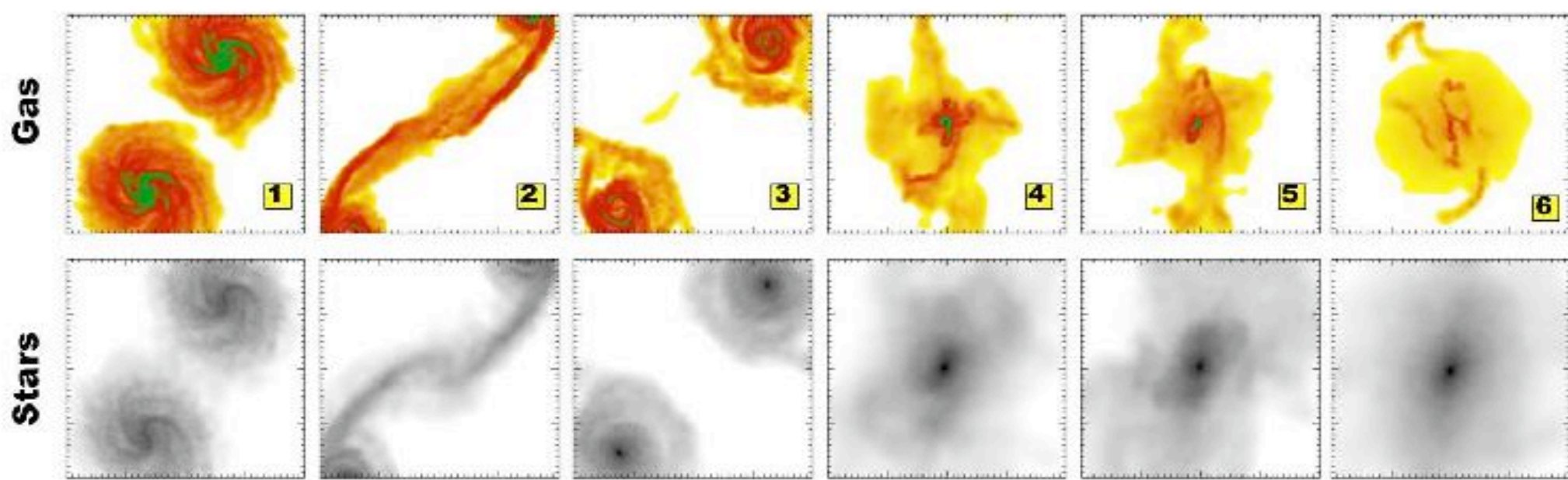
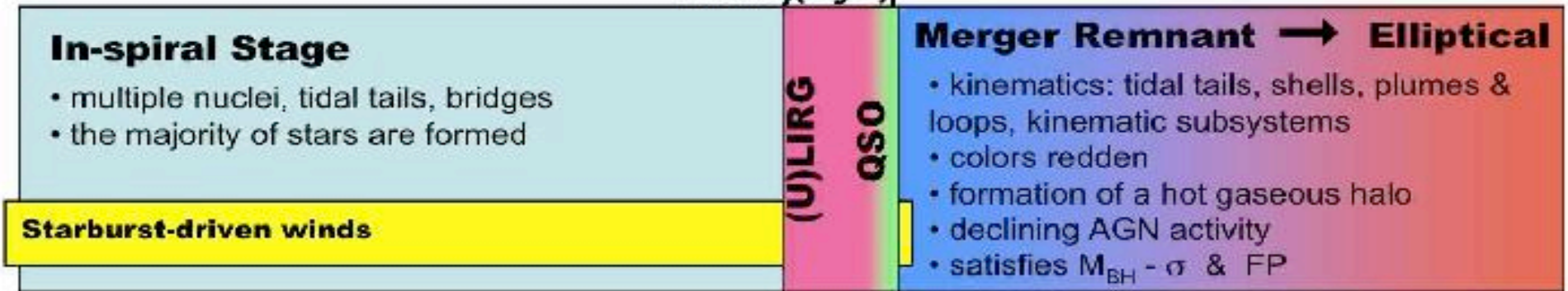
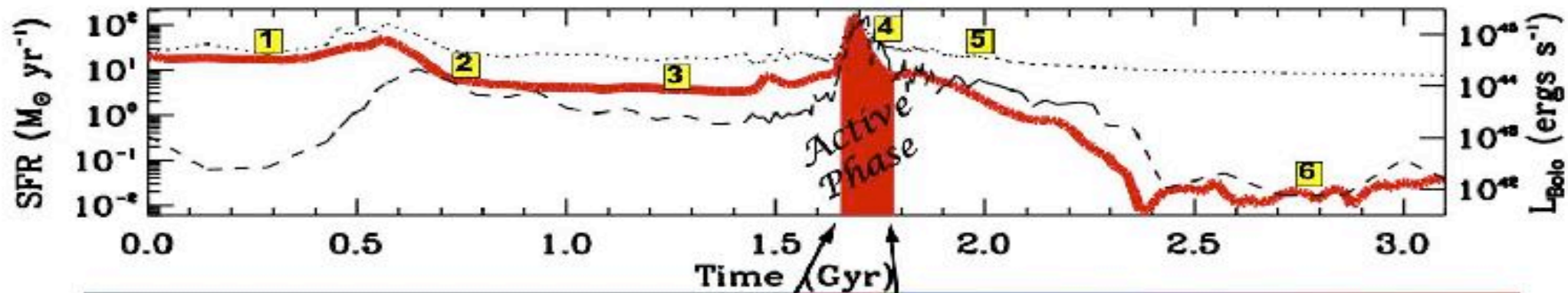


- QSO luminosity fades rapidly
- tidal features visible only with very deep observations
- remnant reddens rapidly (E+A/K+A)
- "hot halo" from feedback sets up quasi-static cooling

### (h) "Dead" Elliptical

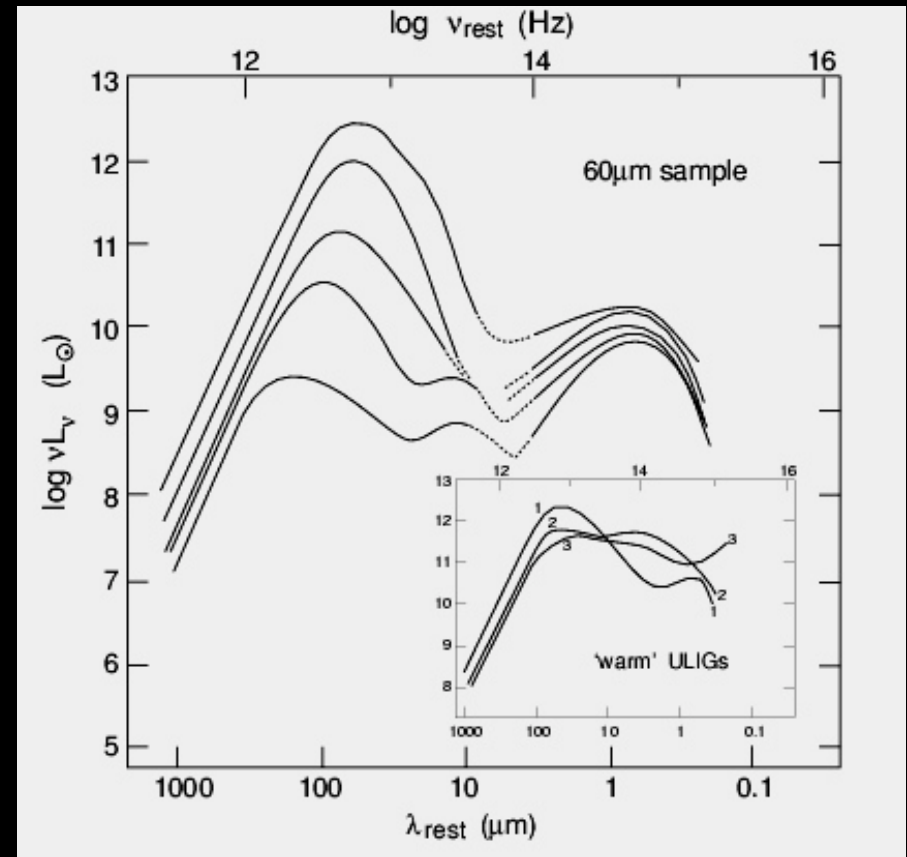


- star formation terminated
- large BH/spheroid - efficient feedback
- halo grows to "large group" scales: mergers become inefficient
- growth by "dry" mergers



# Starbursts, Remnant Color Evolution

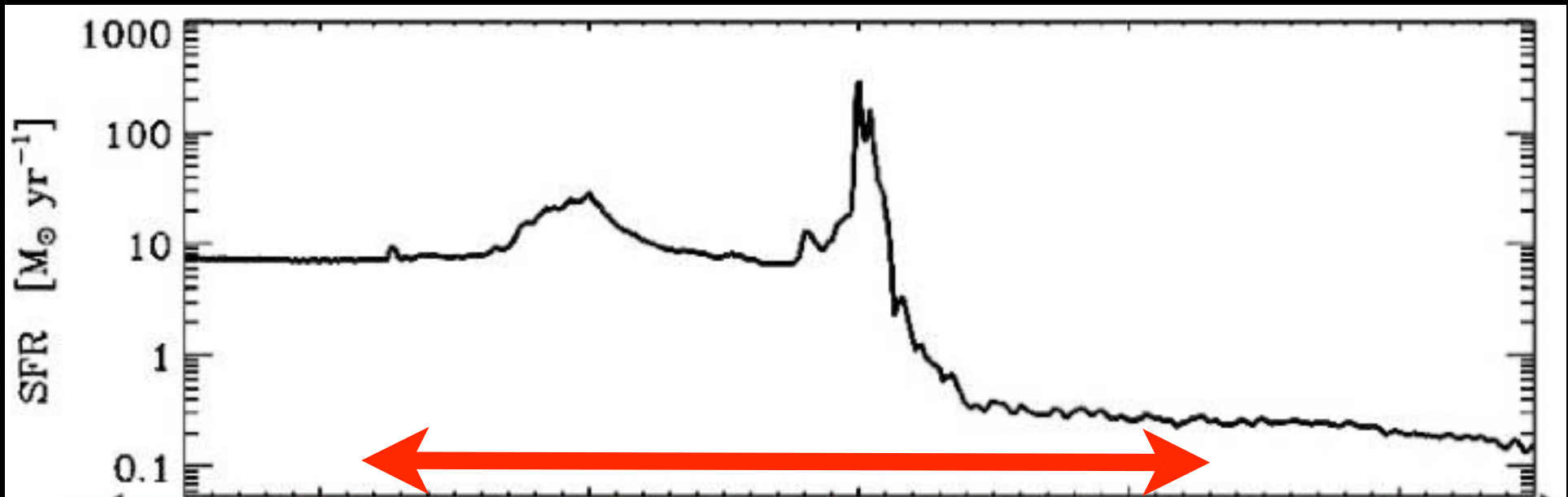
- Large enhancements in SFRs;  $L_{\text{bol}}$  similar to ULIRGs
- Radiative transfer  $\Rightarrow$  IR colors like SMGs; evolution from cold to warm ULIRGs (Li et al., Chakrabarti et al. astro-ph/0610860)
- Star formation in remnant quenched:
  - gas depletion
  - SN driven winds (but limits on outflow rates)
  - AGN feedbackDominant process depends on mass, gas content ...
- Remnant reddens rapidly



Sanders & Mirabel (1996)

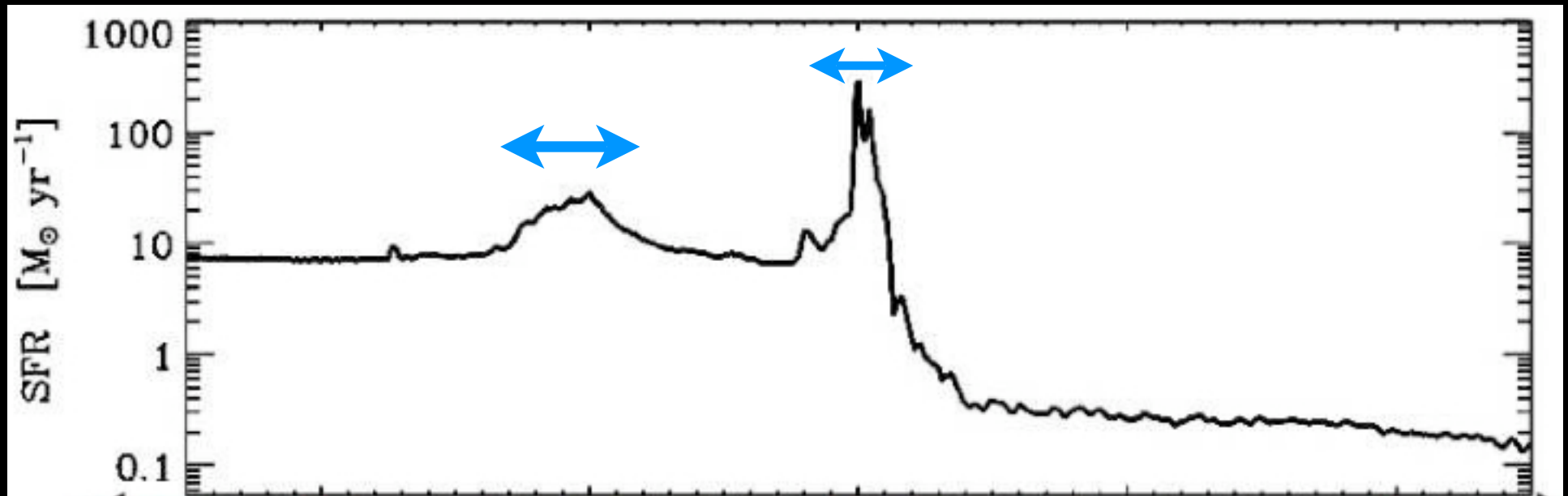
# Merger-Induced Star Formation: What Does It Mean?

- A. All star formation during/associated with a merger



# Merger-Induced Star Formation: What Does It Mean?

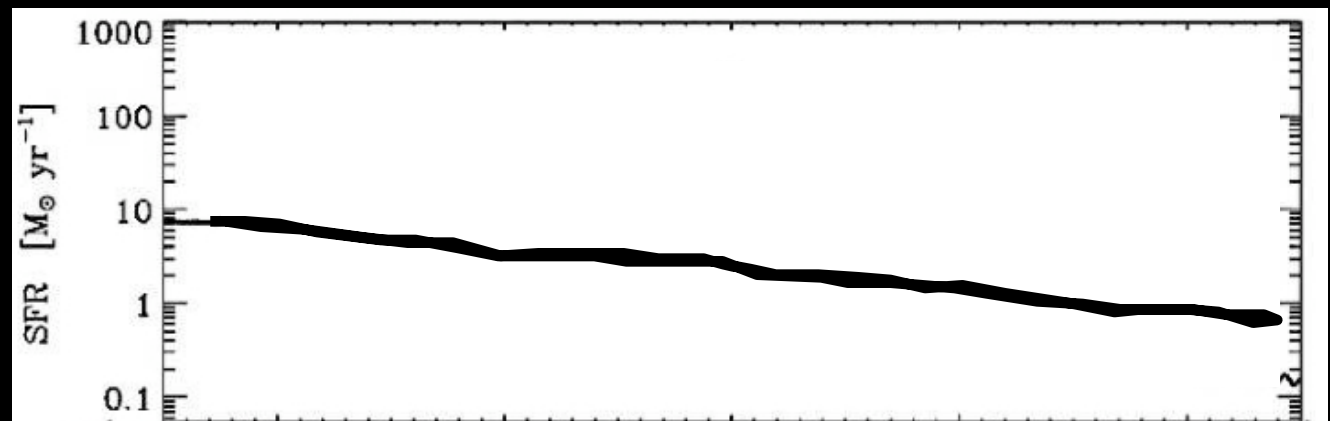
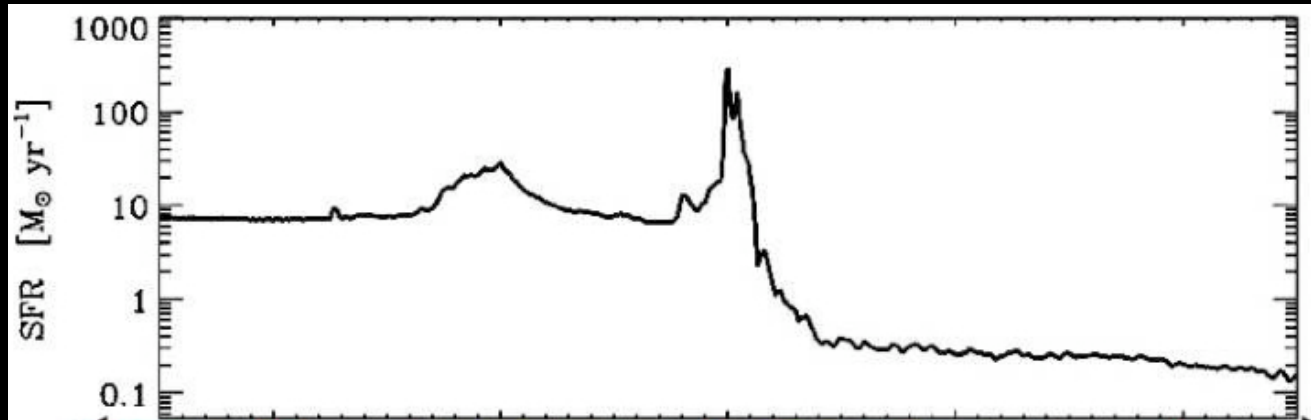
- A. All star formation during/associated with a merger
- B. Centrally-concentrated star formation during the “active” phase(s)





# Merger-Induced Star Formation: What Does It Mean?

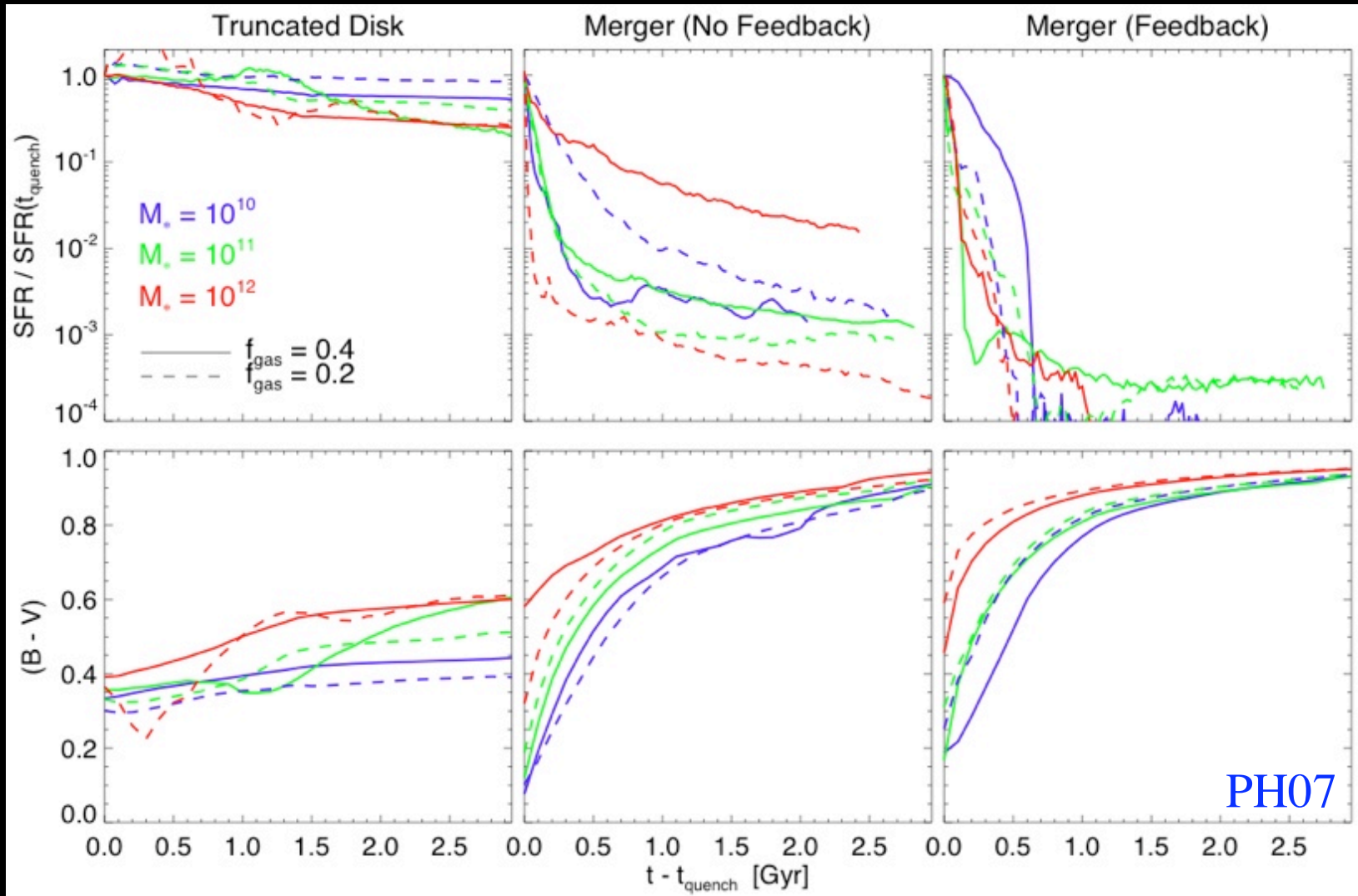
- A. All star formation during/associated with a merger
- B. Centrally-concentrated star formation during the “active” phase(s)
- C. Star formation beyond the “isolated” system



– Primarily affect the shape of the SFH, not total stellar mass!

# SFR/Color Evolution of Merger Remnants

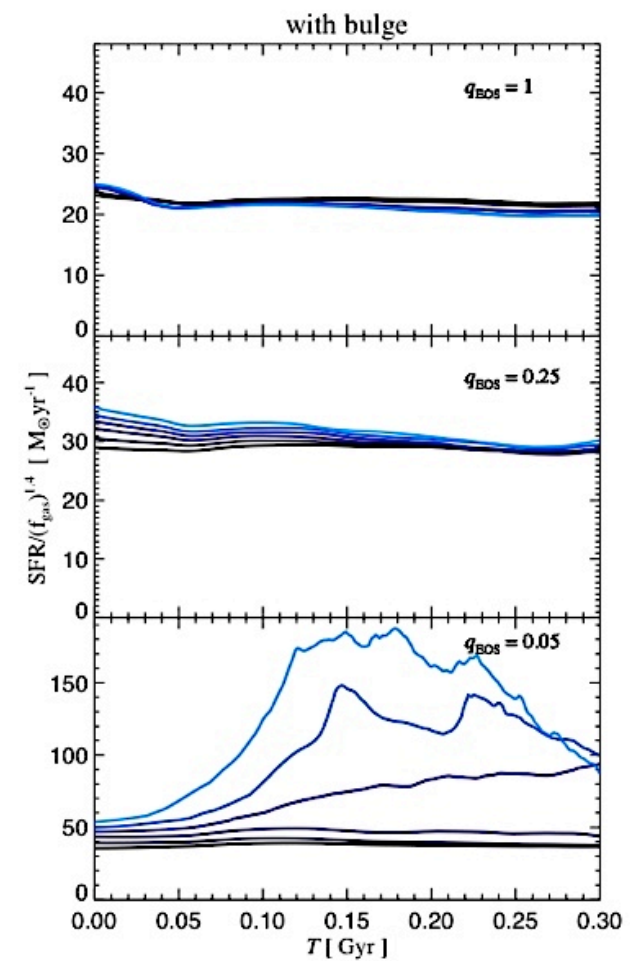
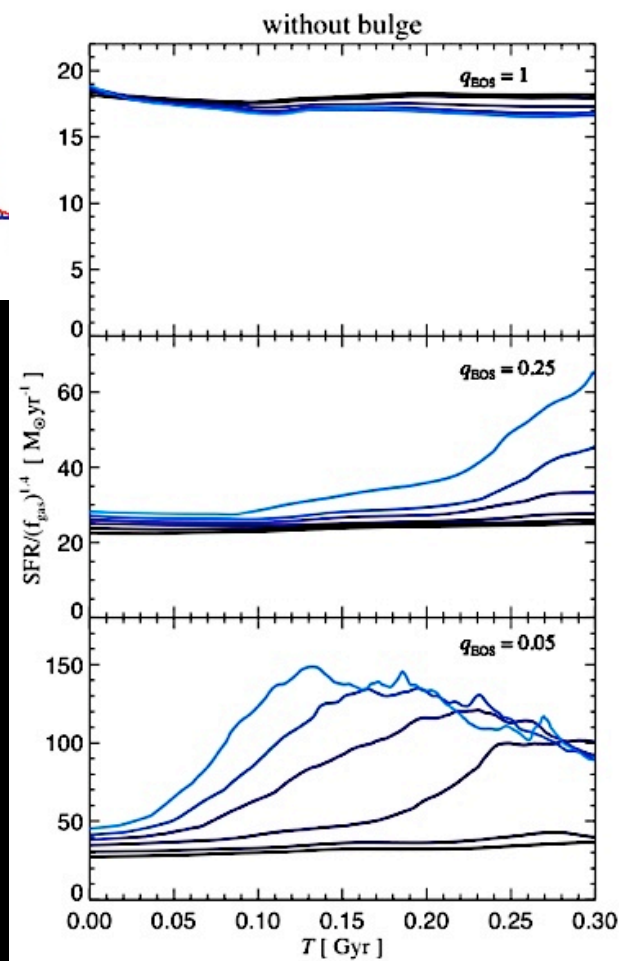
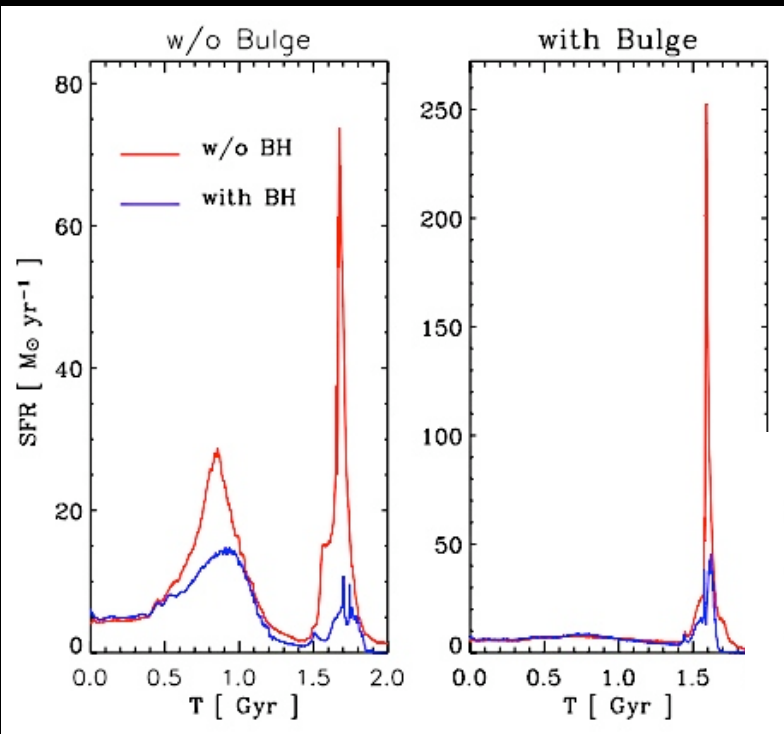
- Merger efficiently exhausts gas; feedback can expel what remains > remnant rapidly reddens



- Details depend on quasar and stellar feedback prescriptions

# Mergers Drive Strong Gas Inflows, Fueling Starbursts and BH Growth

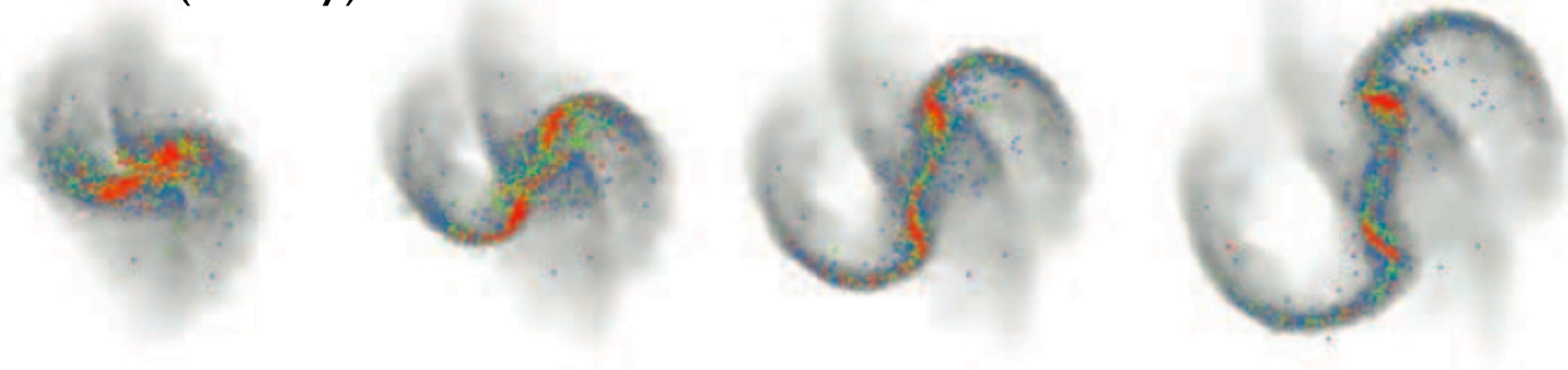
SYSTEM CHANGES RAPIDLY; BUT STATISTICS ARE WELL-BEHAVED



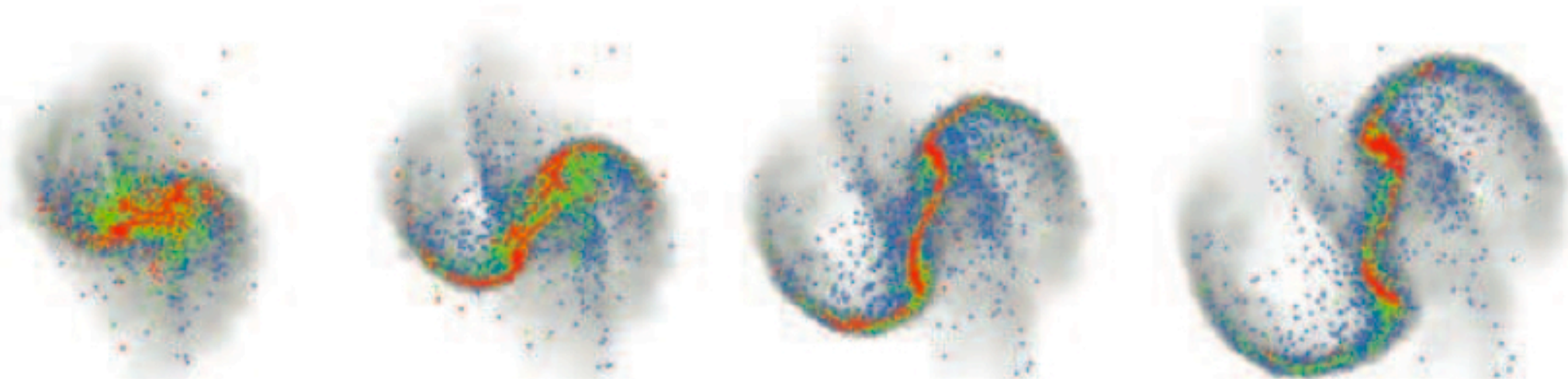
# Mergers Drive Strong Gas Inflows, Fueling Starbursts and BH Growth

SYSTEM CHANGES RAPIDLY; BUT STATISTICS ARE WELL-BEHAVED

SFR = f(density)

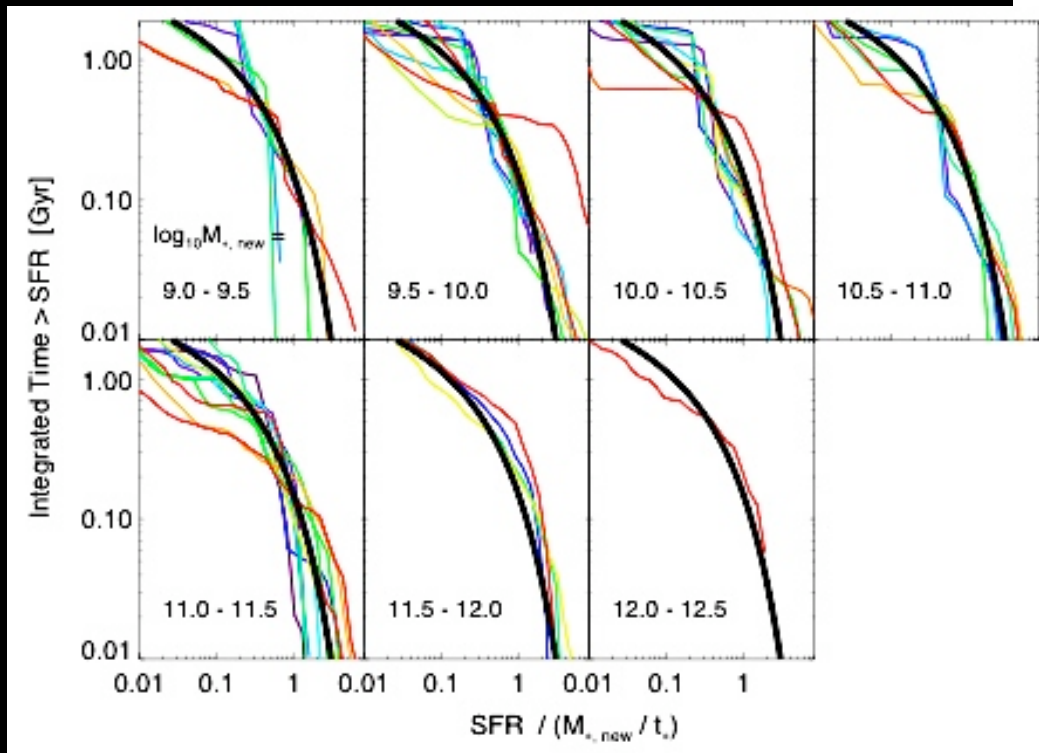
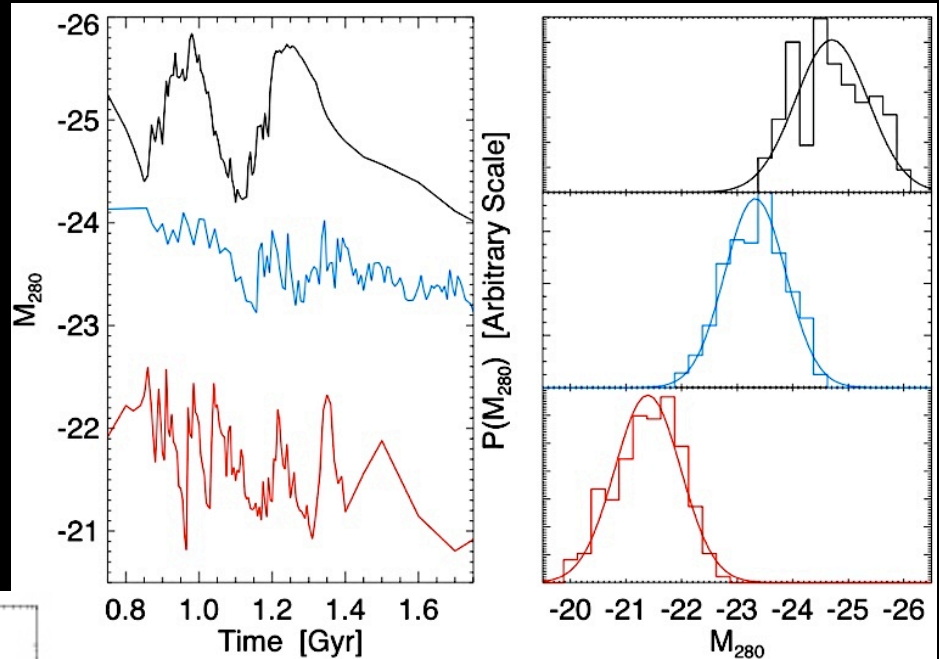
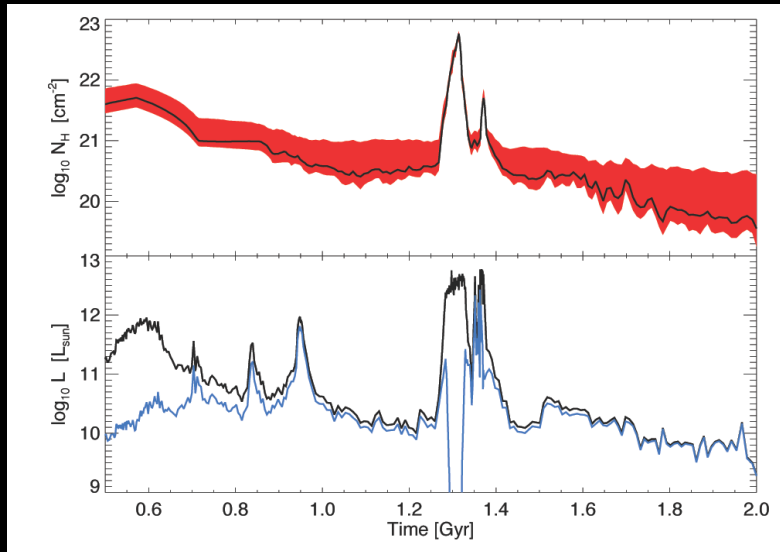


SFR = f(density, mach number)



# Mergers Drive Strong Gas Inflows, Fueling Starbursts and BH Growth

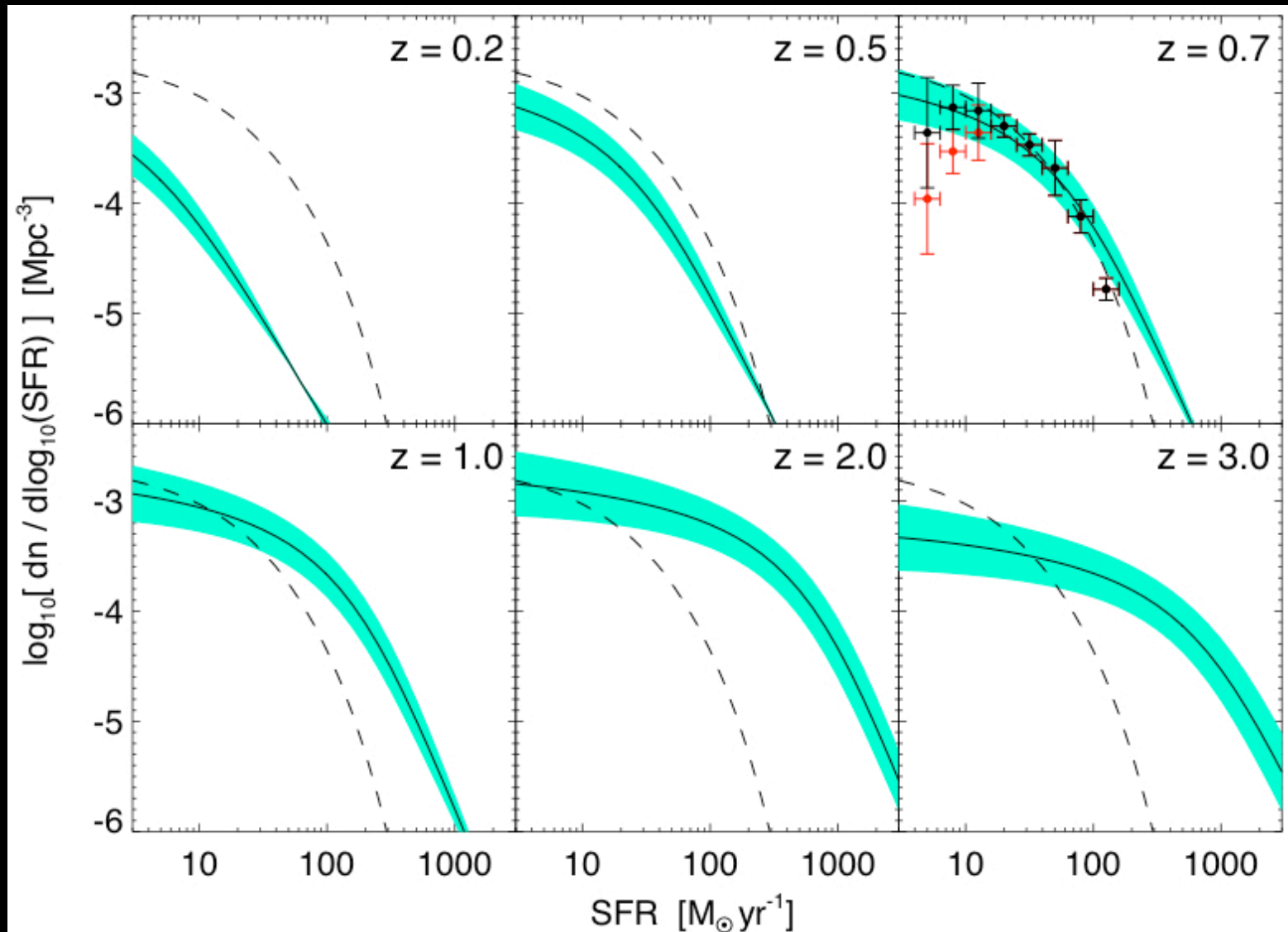
SYSTEM CHANGES RAPIDLY; BUT STATISTICS ARE WELL-BEHAVED



- Probability of seeing given merger at some SFR
  - characteristic SFR  $\sim$   $(M_{\text{gas}} \text{ at final merger stages}) / (x \text{ dynamical times})$
- + Radiative transfer = IR+UV luminosities

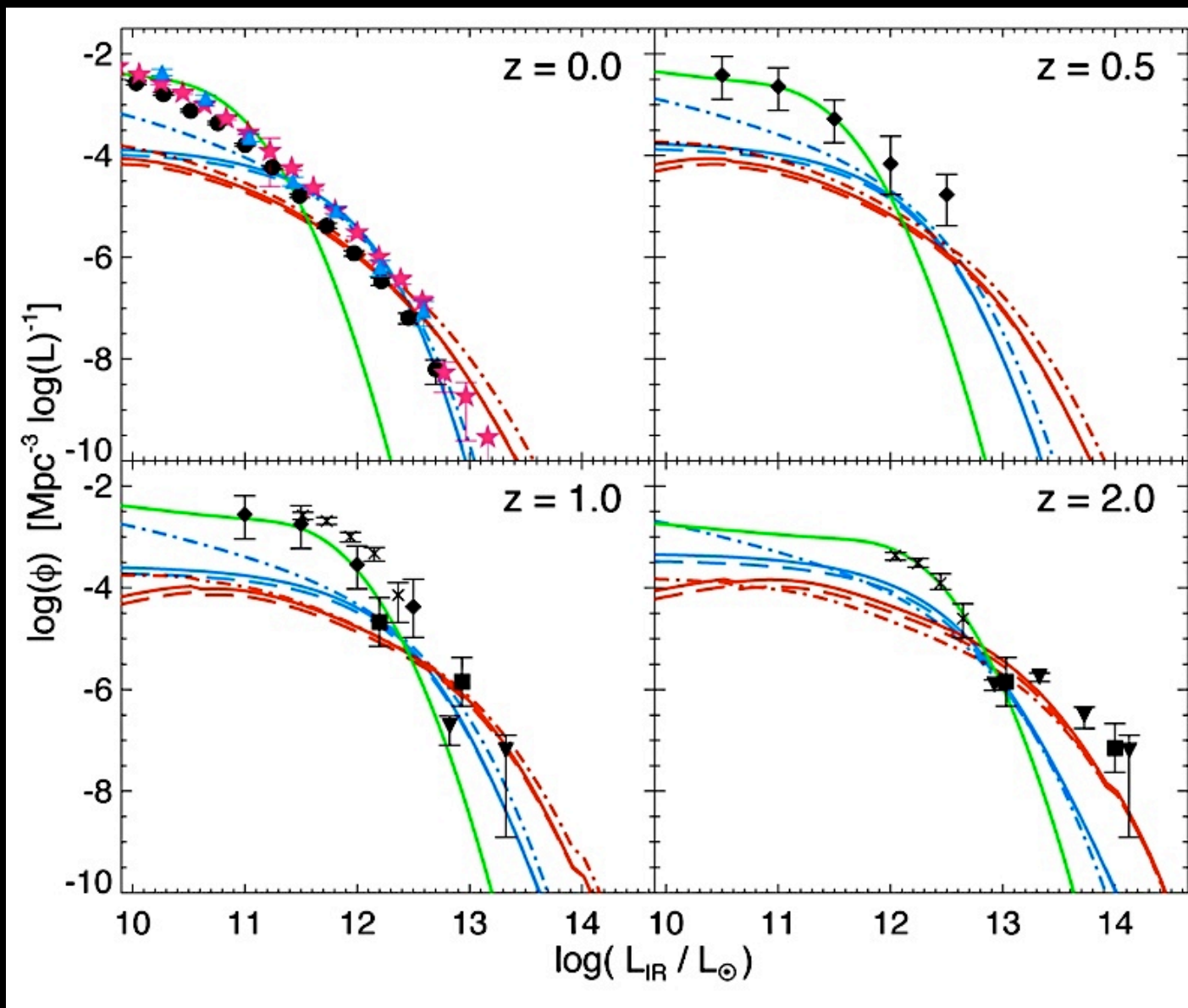
# The Cosmological Context

- Convolve with cosmological models: know merger rates, etc.



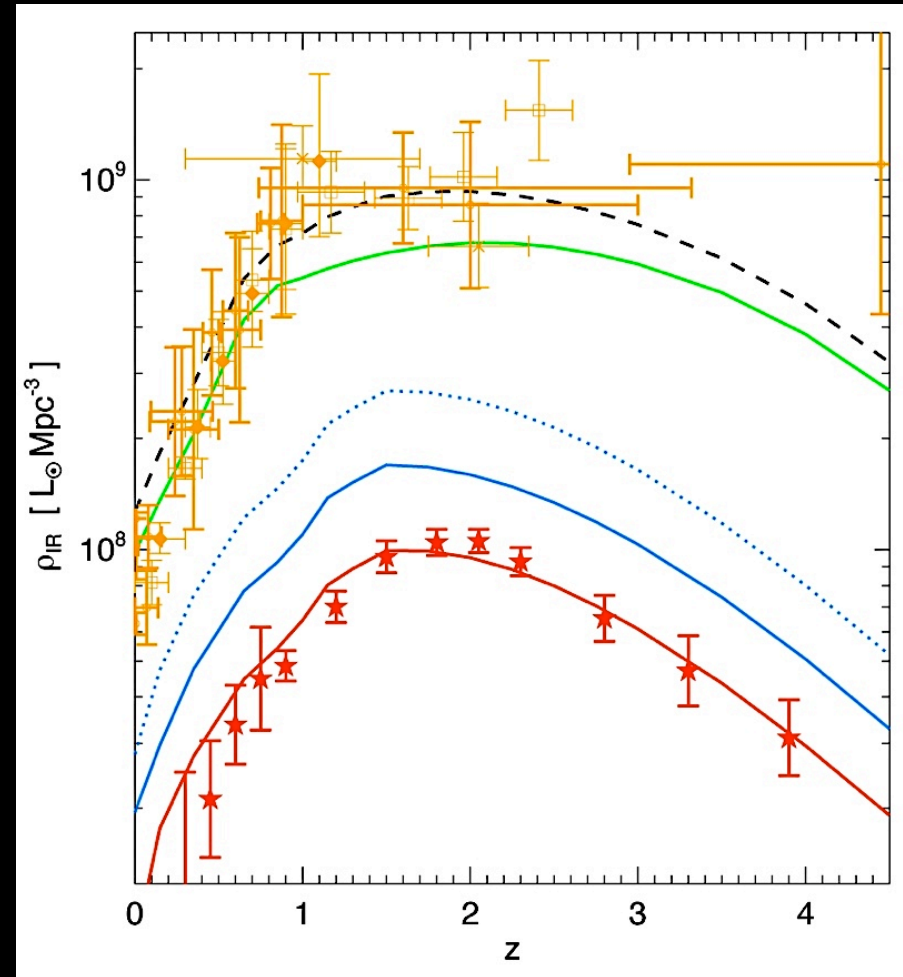
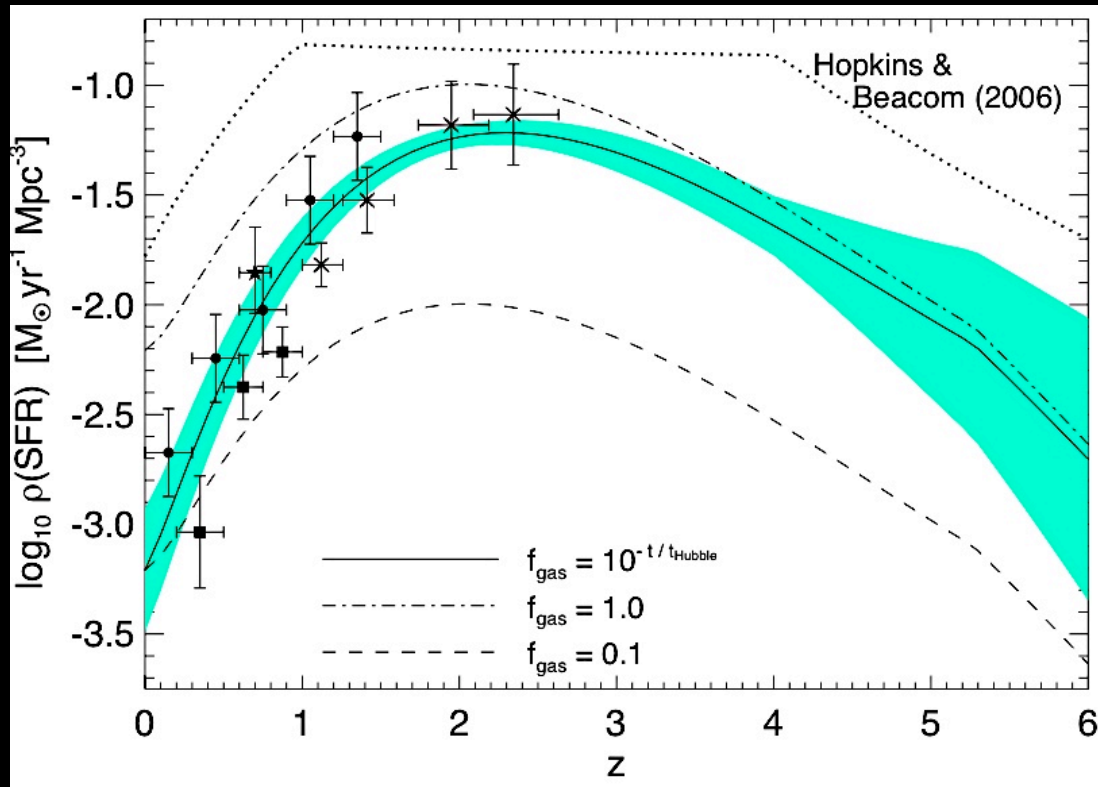
# The Cosmological Context

- Convolve with cosmological models: know merger rates, etc.



# The Cosmological Context: Global SFH

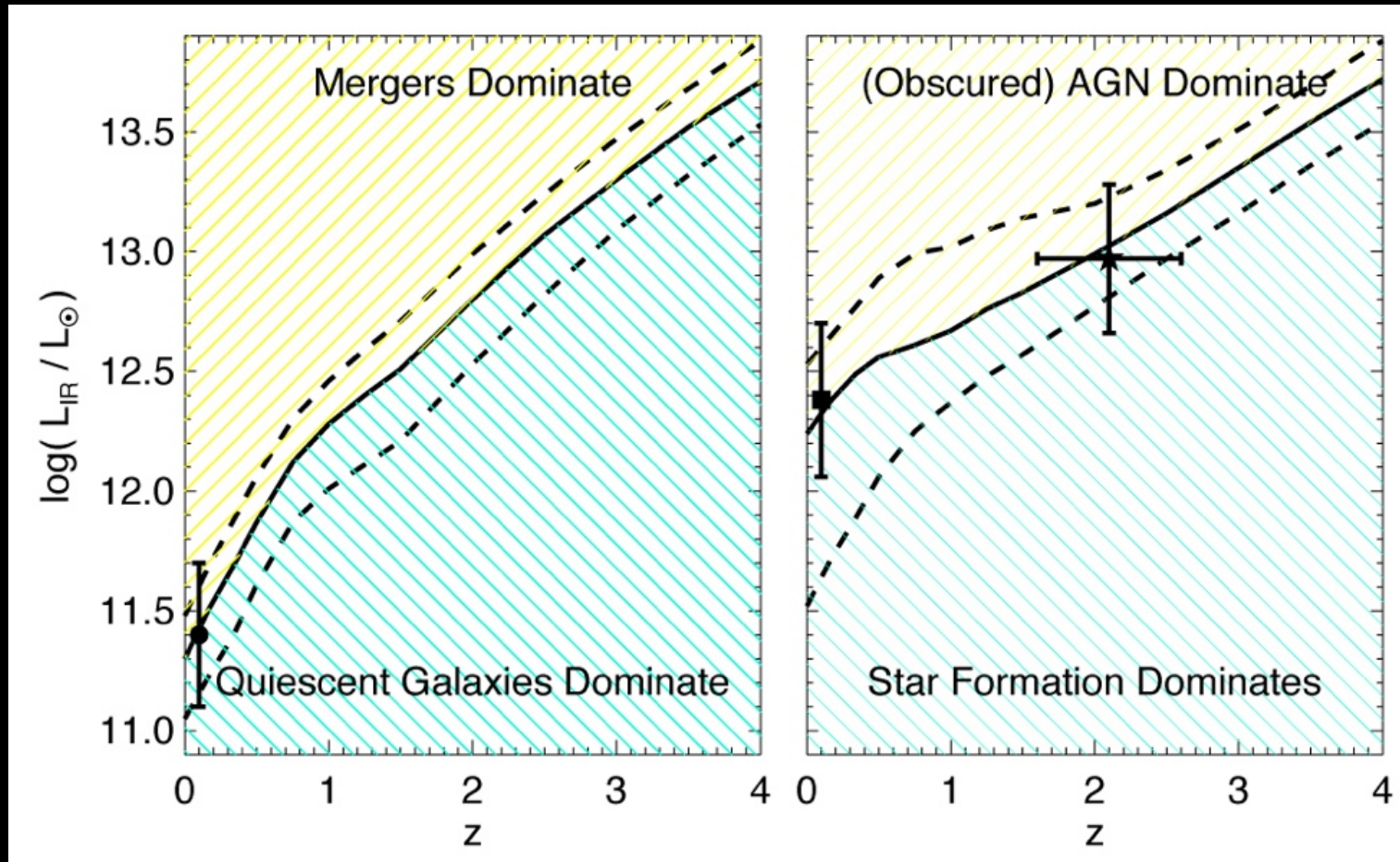
- Mergers are an important, but \*never dominant\* contributor to the global SFR density
- Most stars (>~ 90%) are formed in “quiescent” disks



Observations: Bell+05; Brinchmann+98;  
Perez-Gonzalez+05

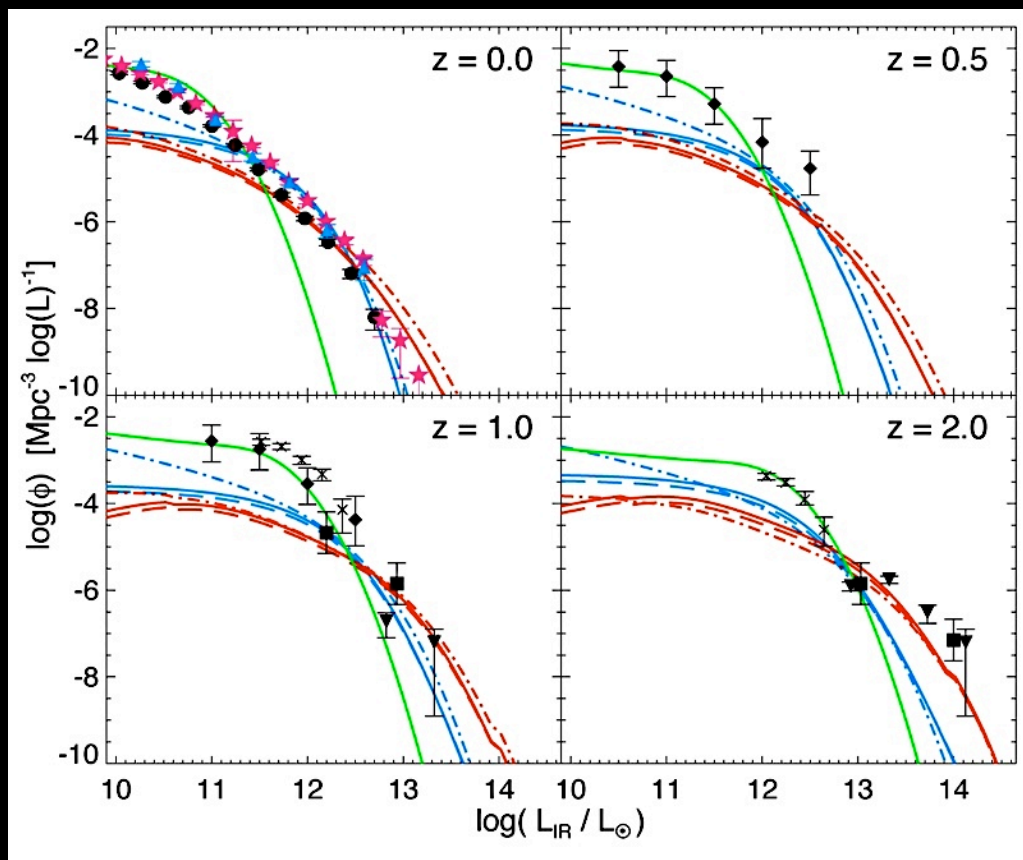


# The Cosmological Context: Mergers vs. Disks

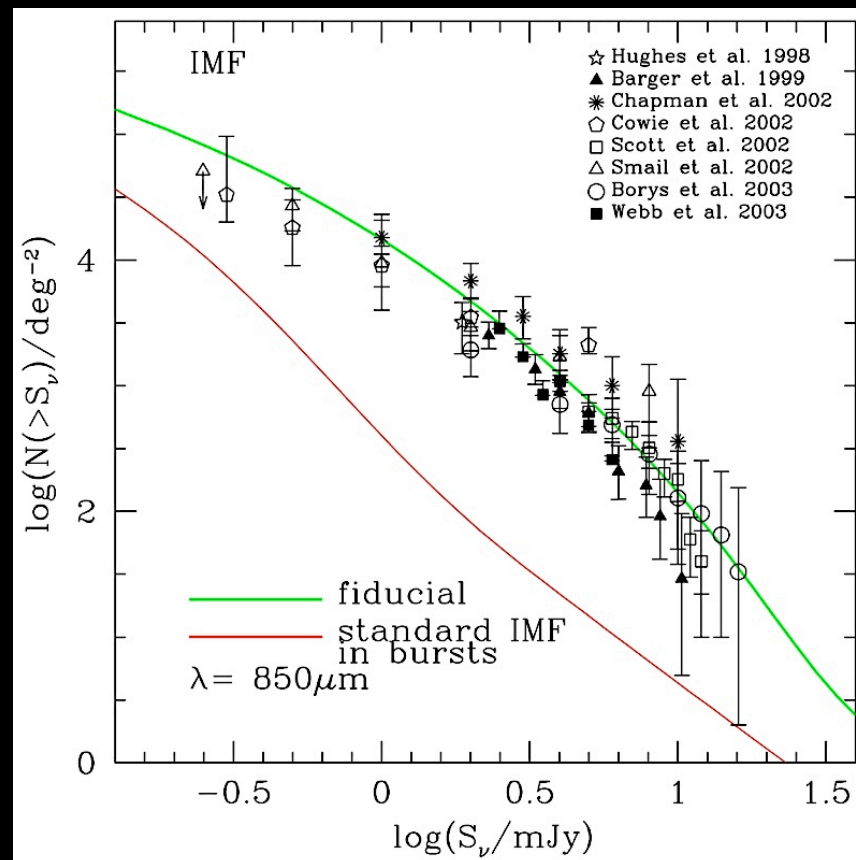


- Important caveats:
  - Where do AGN contribute?
  - How does AGN obscuration evolve?
  - How well do we really know IR luminosities?

# The Cosmological Context: The Ugly Truth



PH07



Baugh et al. 2005

- Lots of tradeoffs between how much SF occurs “pre” & “in” mergers
- We aren’t the ones who should be estimating the IMF & feedback “needed”!

# Conclusions

- Most extreme sources & many high-redshift galaxies are making stars in extreme starburst environments
  - Most stars are still made in disks
  - Where mergers dominate depends strongly on redshift
  - Need to know how scaling laws (Kennicutt) behave
- If Kennicutt/Schmidt law applies, SFR in these systems is largely determined by how much gas is available at the final starburst
  - Set by efficiency in progenitor disks!
  - Sensitive to feedback: how efficiently can dense gas clump and runaway at high- $z$ ?
- Theorists need to know:
  - How does SF feedback couple \*as a function of scale\*?
  - Do SF properties depend on environment?

10% gas

99% gas

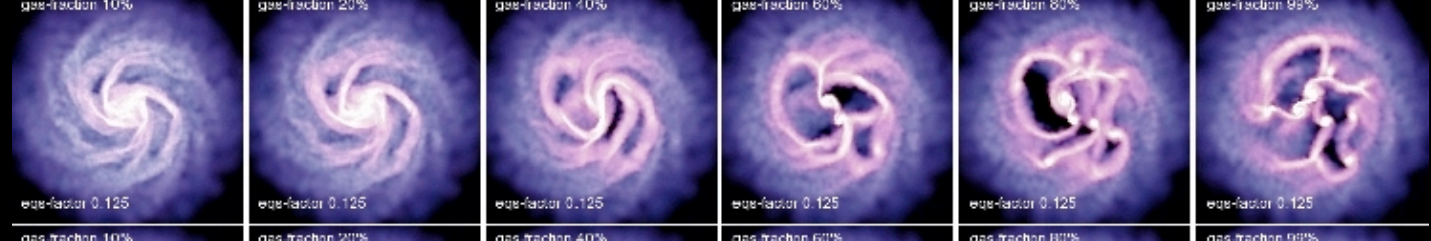
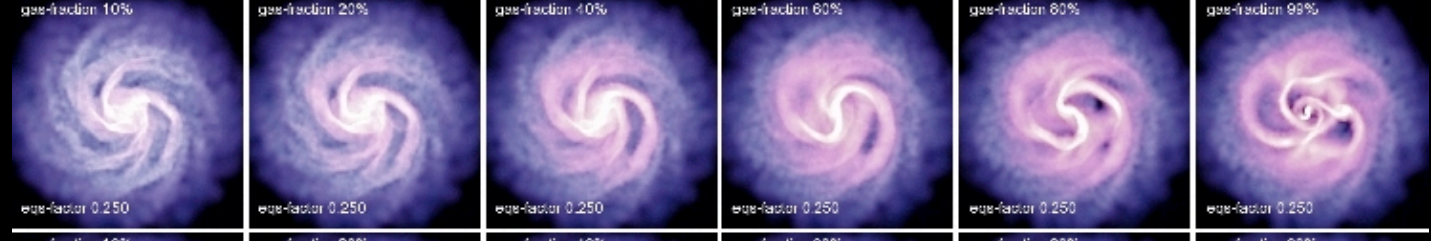
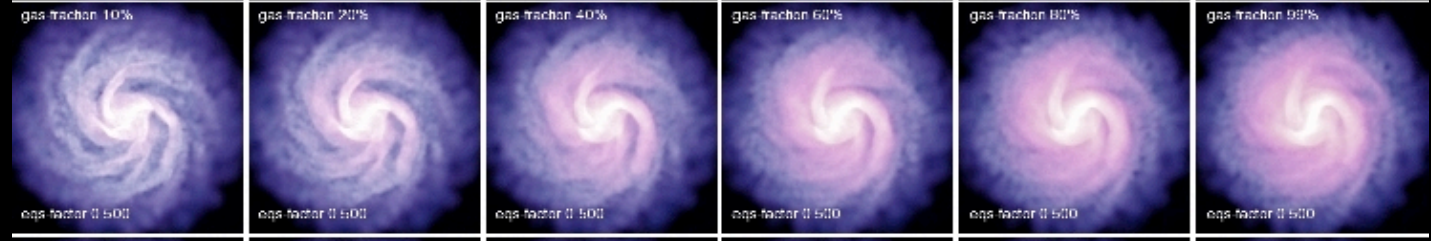
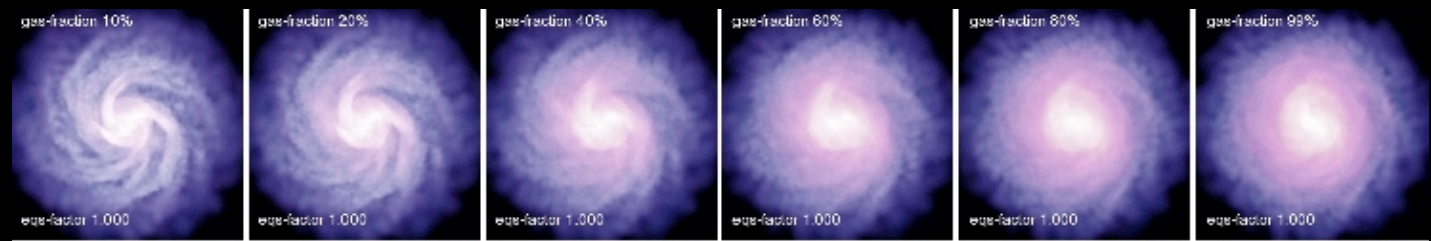


more gas



softer  
EOS

$\sim 10^5$  K



$10^4$  K

