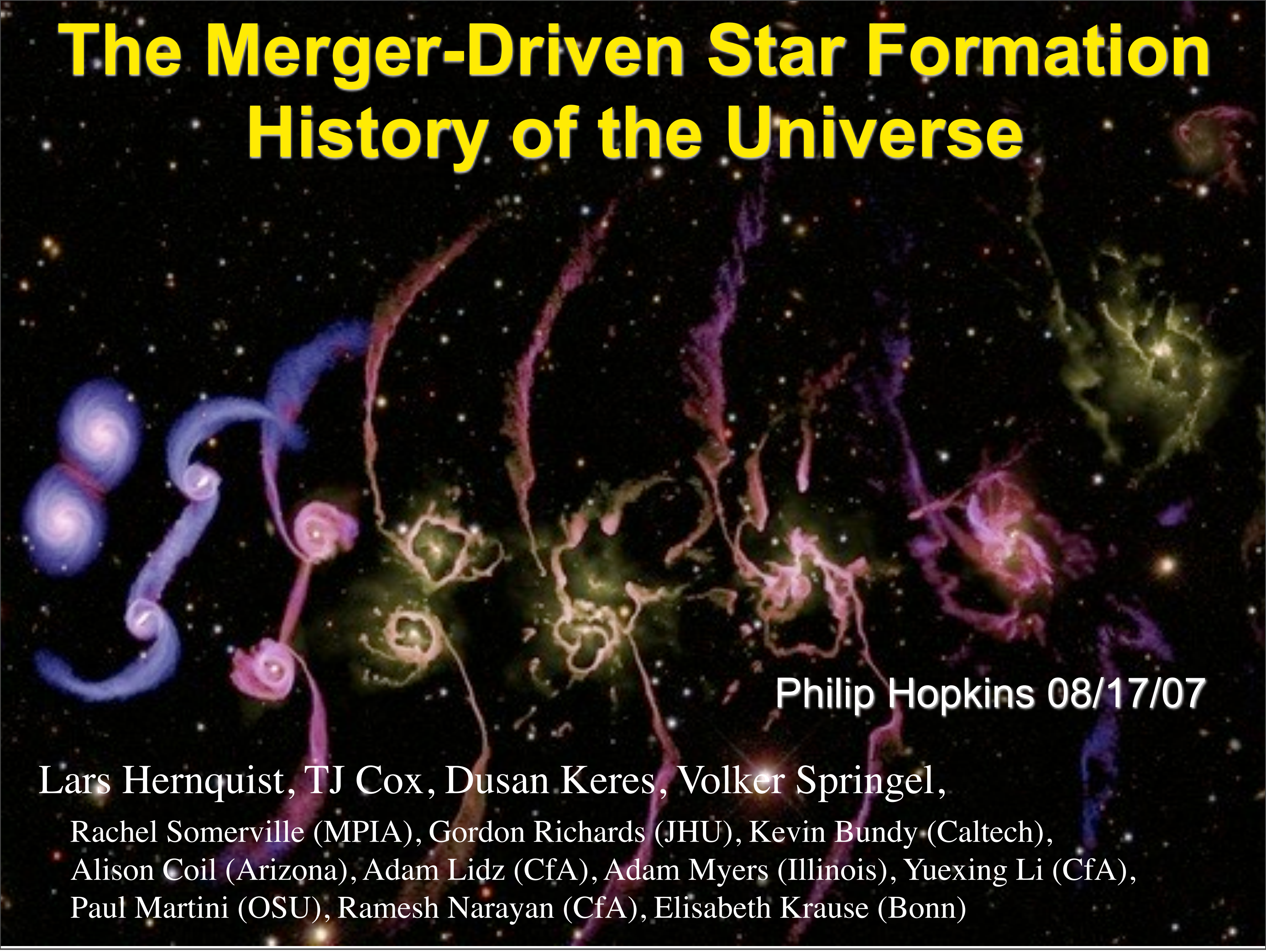
The Merger-Driven Star Formation History of the Universe



Philip Hopkins 08/17/07

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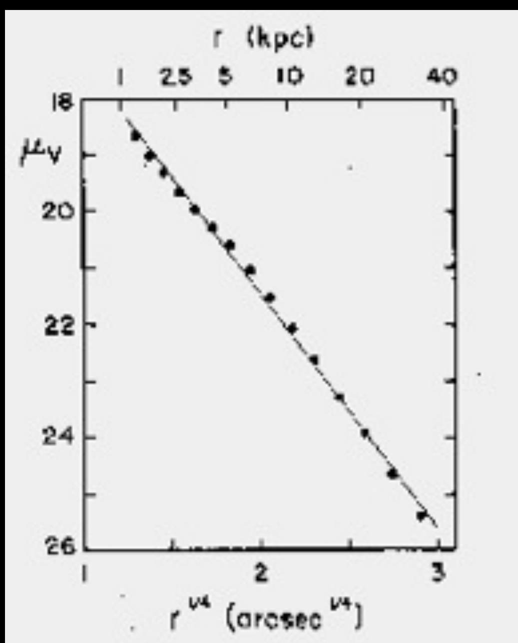
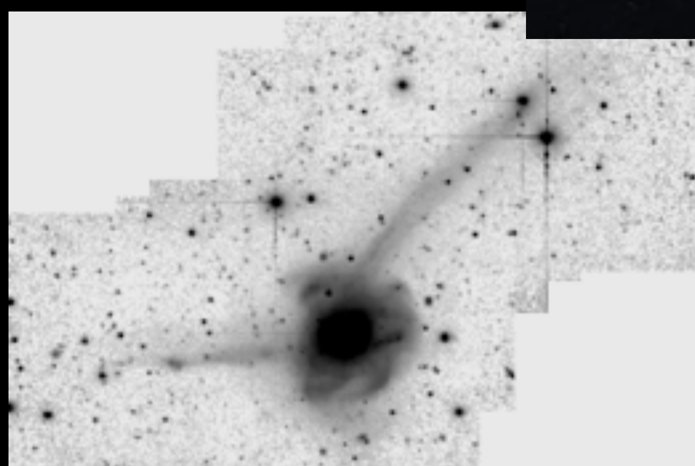
Gas-Rich, Major Mergers

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

HST image of Mice



NGC 7252



Schweizer (1982)

Gas-Rich, Major Mergers

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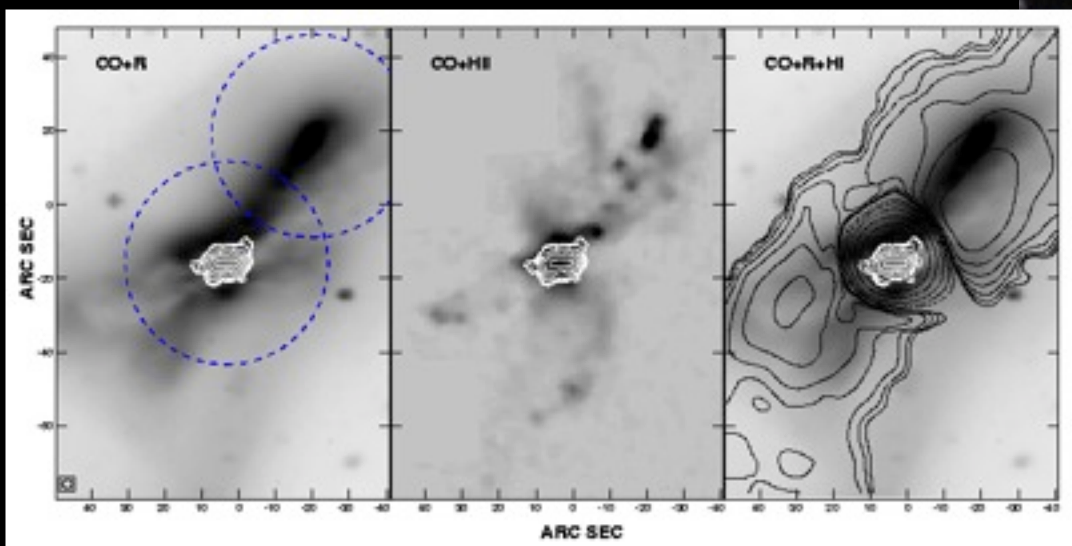

NGC 520 (Arp 157)

Yun & Hibbard (2001)

Gas-Rich, Major Mergers

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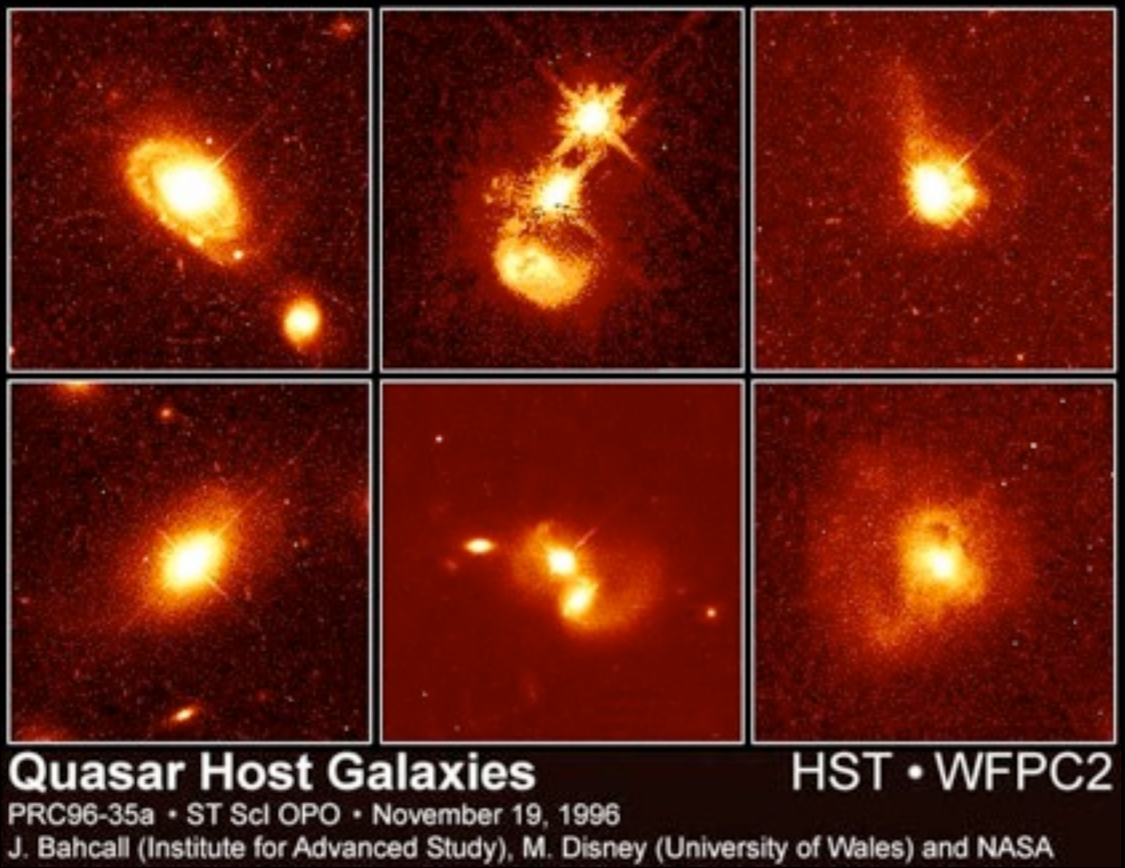
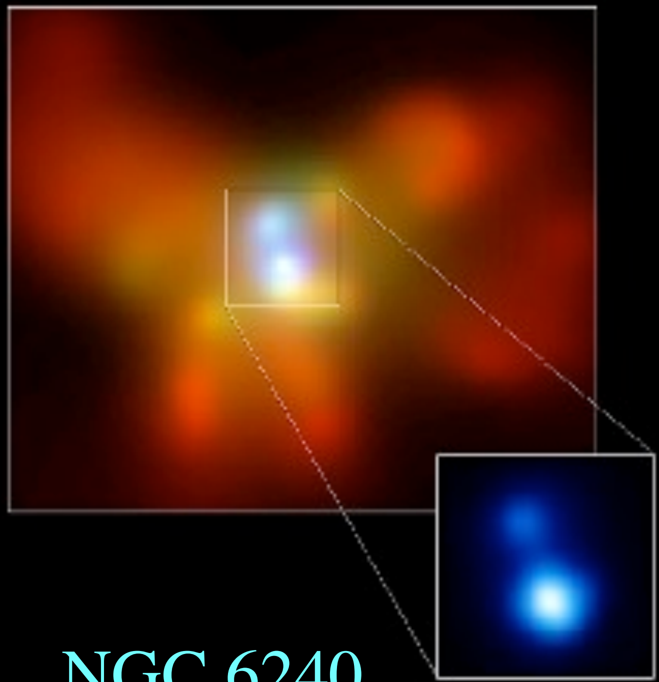


Komossa et al. (2003)

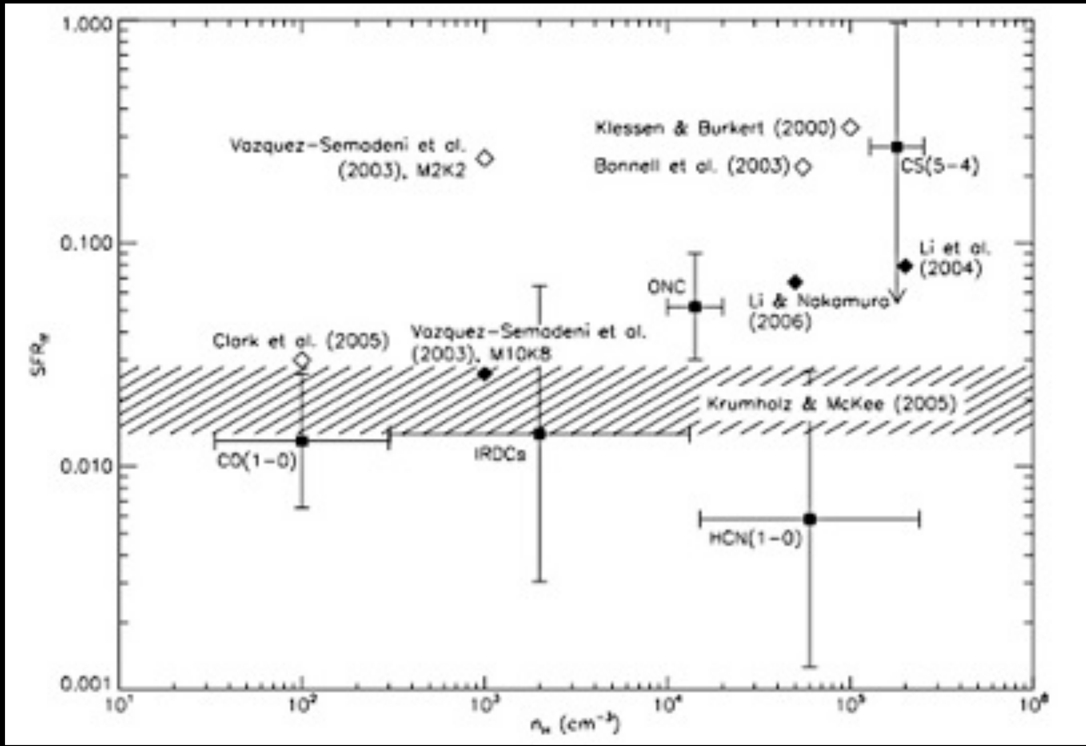


NGC 6240

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
  - ~1000 M_sun/yr in a 200 pc region

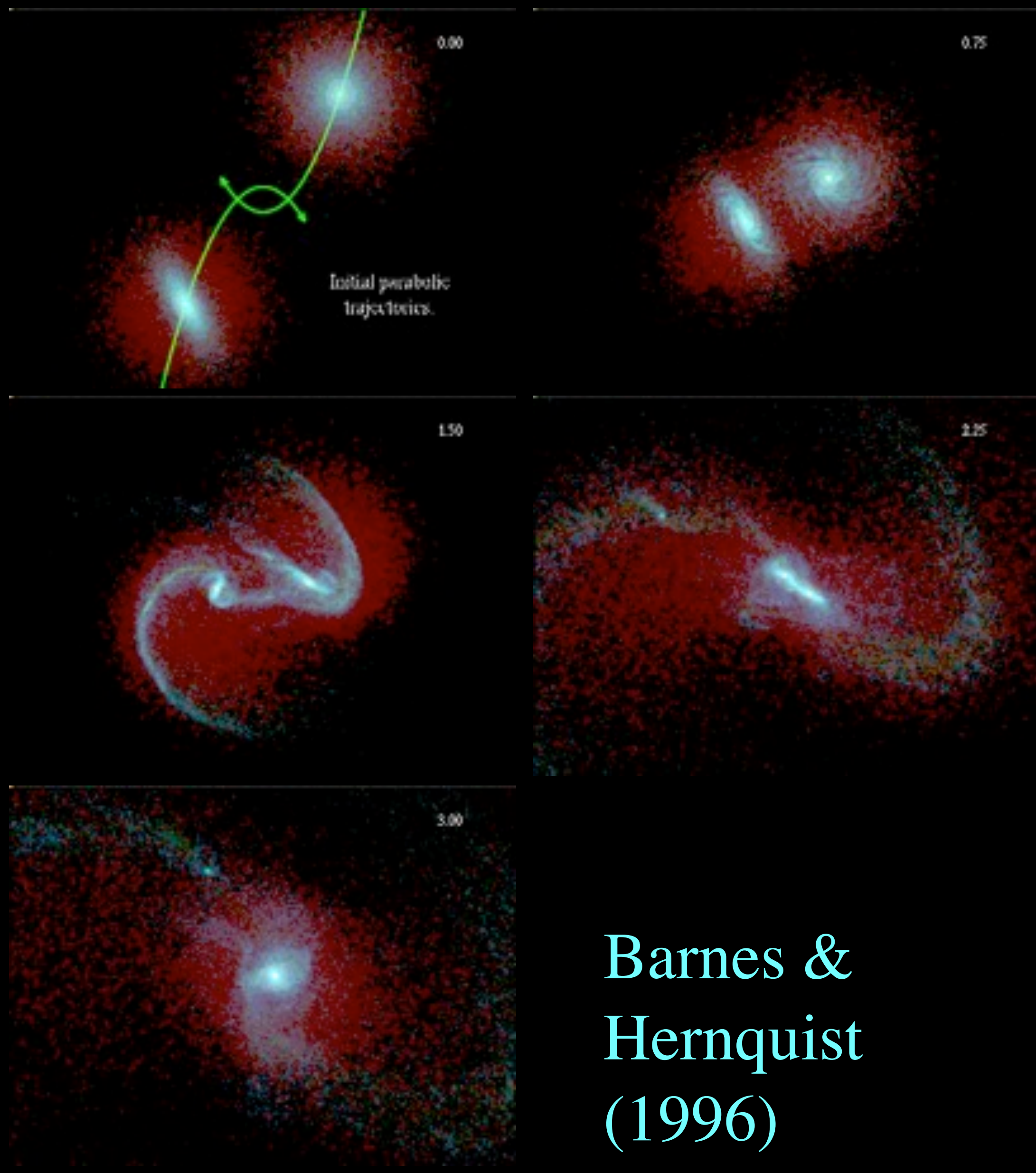
Merger-Induced Star Formation

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 -> BH mass (M_BH-sigma)
  - “Loss Cone” for SMBH Coalescence

Physical Mechanism

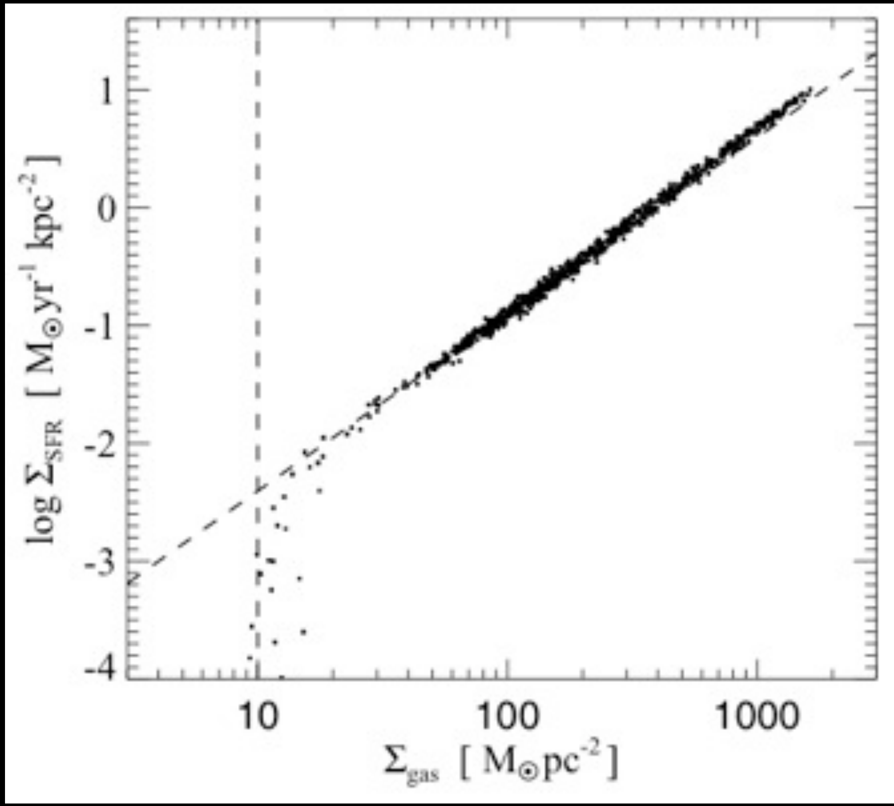
- Tidal torques ⇒ large, rapid gas inflows (e.g. Barnes et al.)
- Triggers starburst (e.g. Mihos et al.)
- Feeds BH growth (e.g. Di Matteo et al.)
- Merging stellar disks grow spheroid
- Requirements:
  - major merger
  - supply of cold gas ("cold" = rotationally supported)

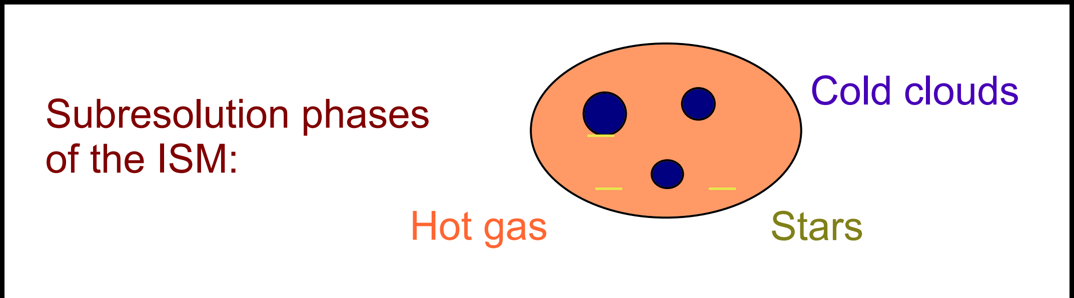


Barnes & Hernquist (1996)

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





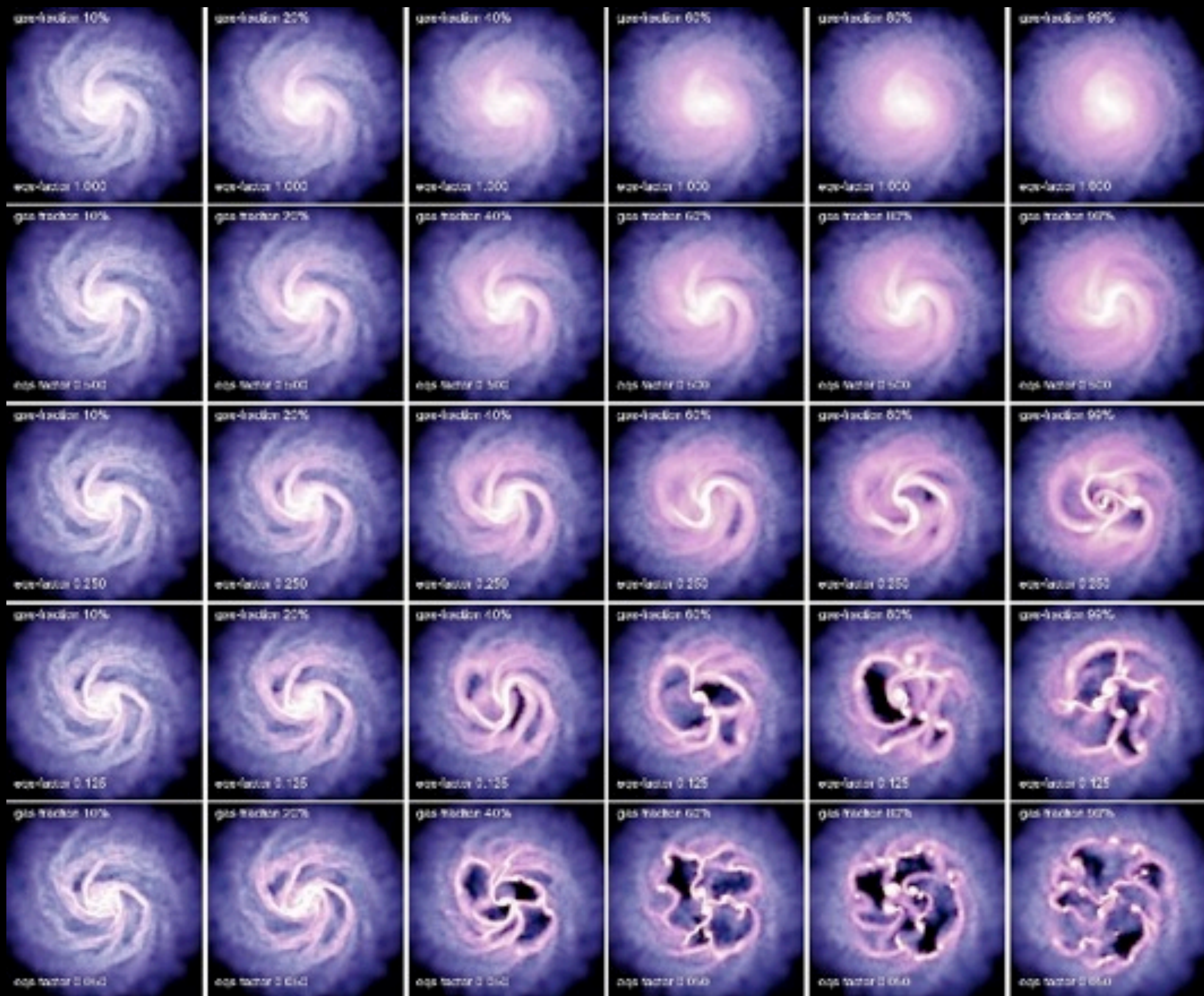
Caveat: Evolving Highly Gas-Rich Galaxies

10% gas

99% gas

more gas

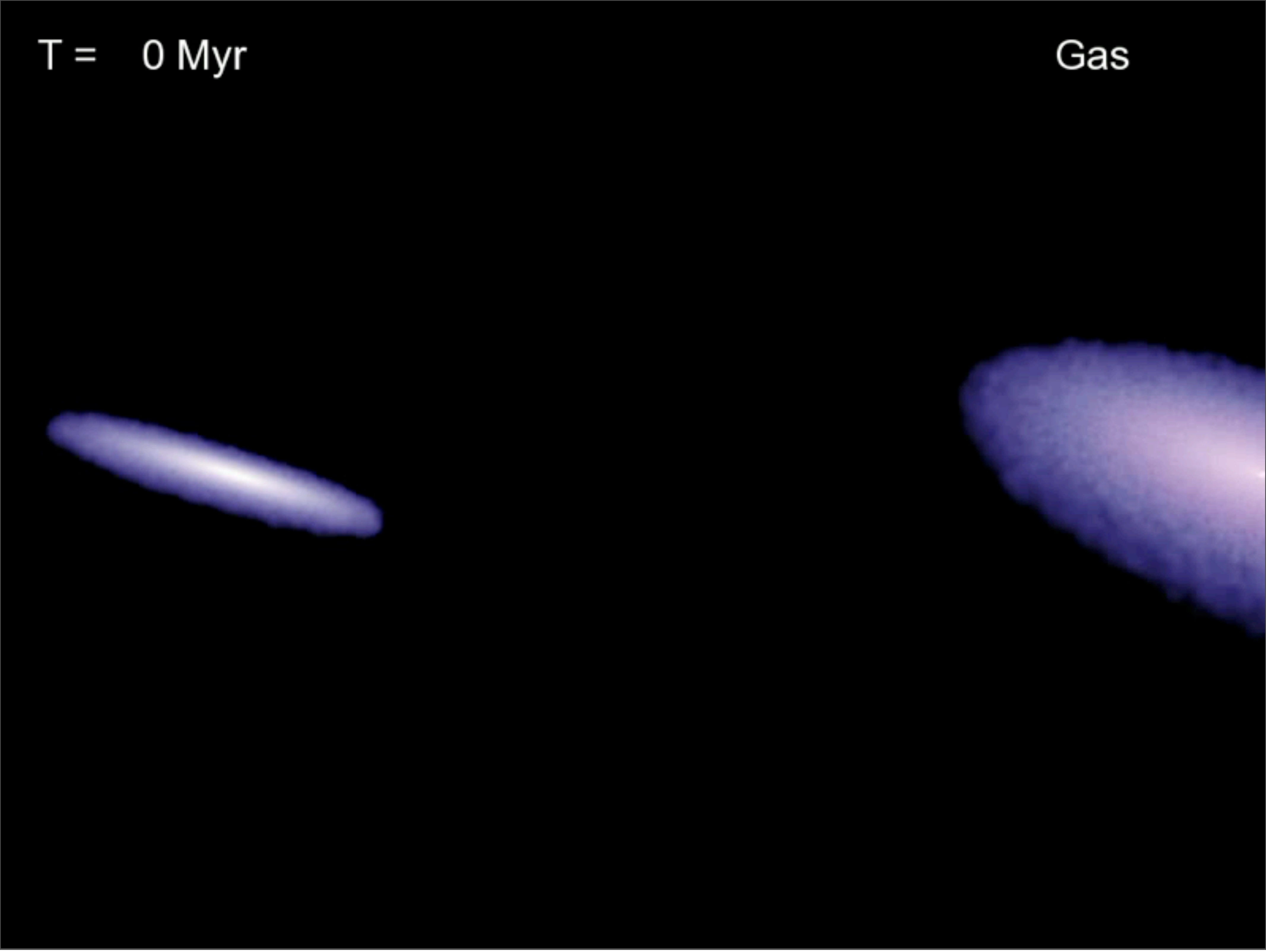
~ 10^5 K

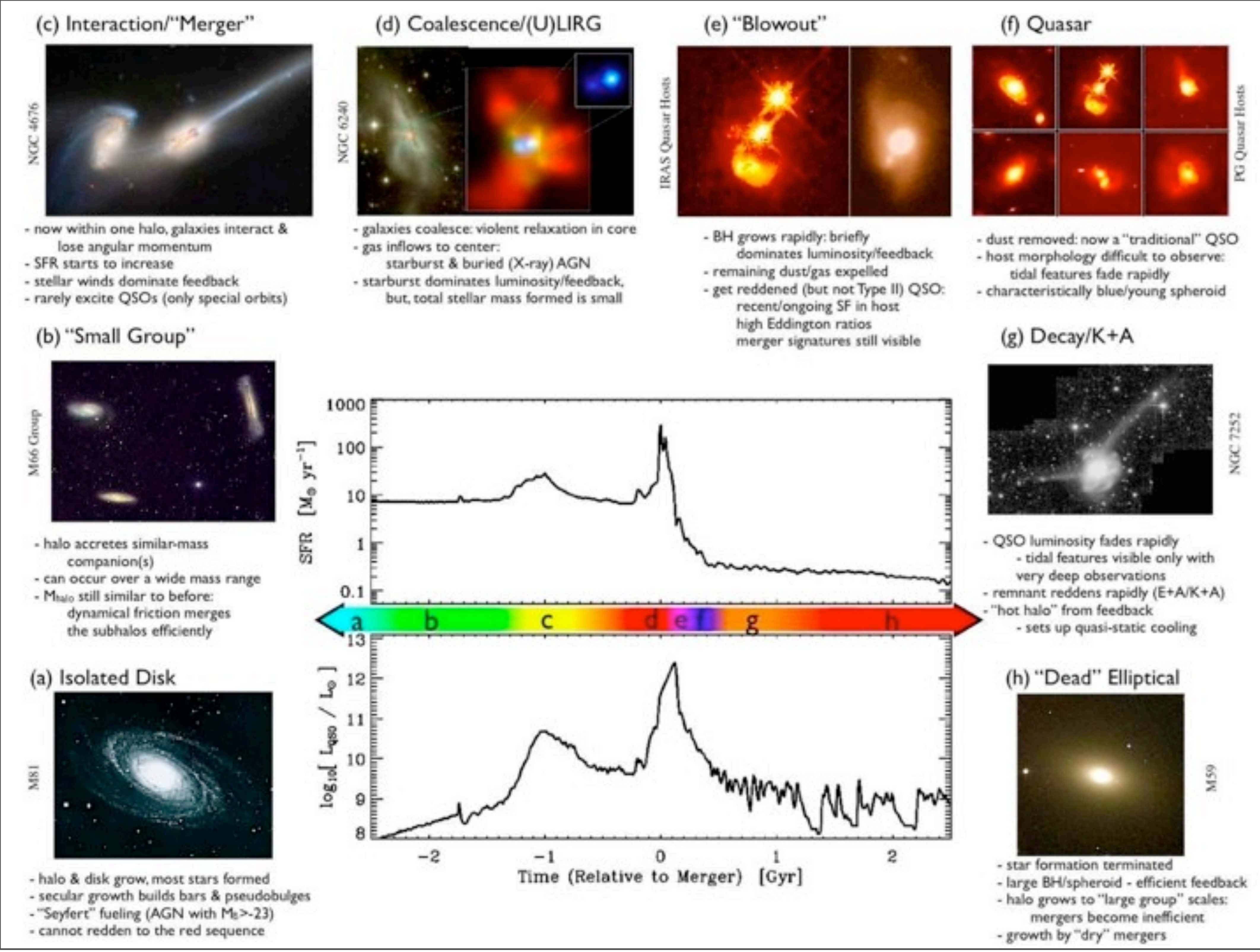


10^4 K

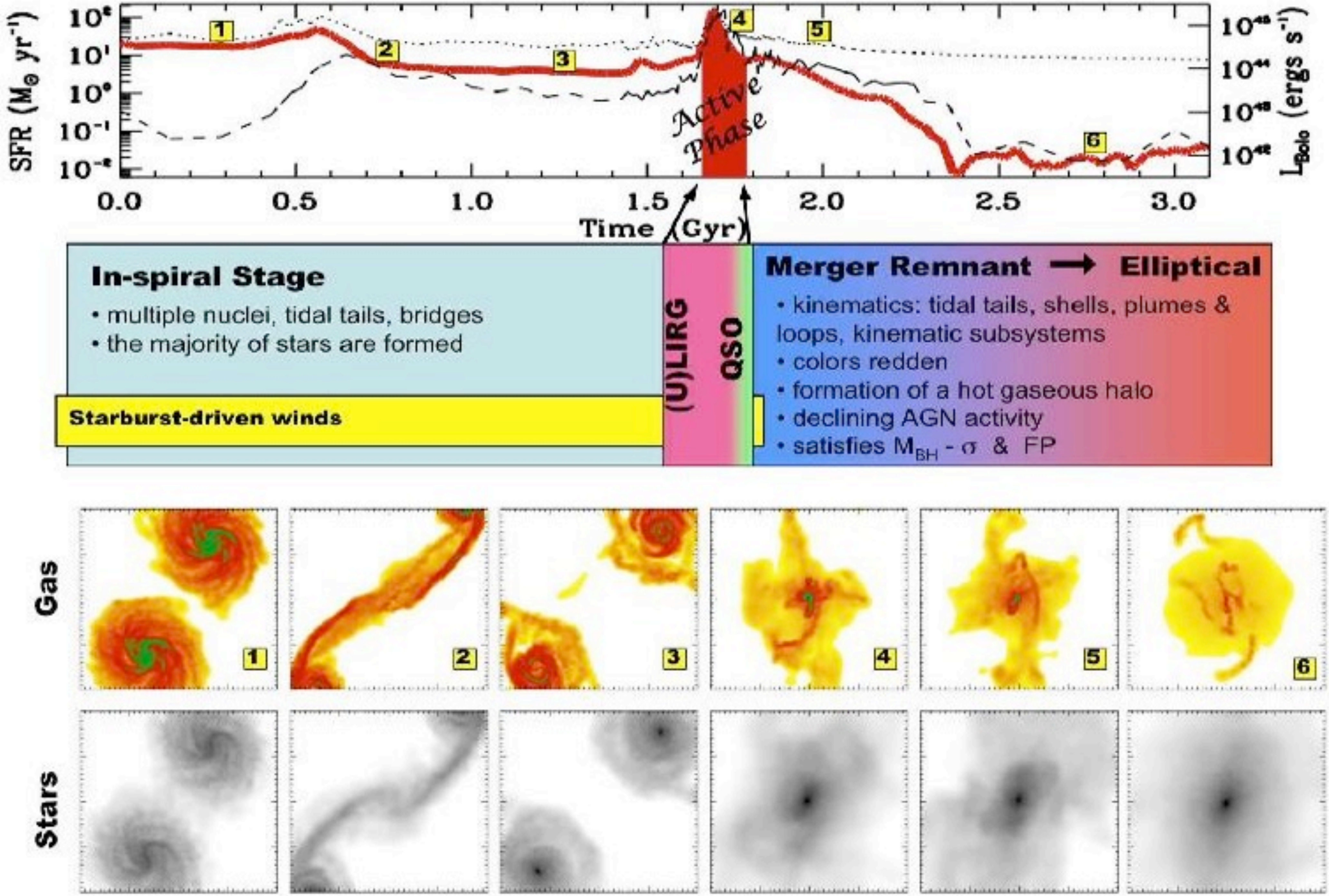
softer EOS

Springel et al. (2005)


T = 0 Myr
Gas



(c) Interaction/"Merger"
NGC 4676
- 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
NGC 6240
- 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"
IRAS Quasar Hosts
- 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
PG Quasar Hosts
- dust removed: now a "traditional" QSO
- host morphology difficult to observe: tidal features fade rapidly
- characteristically blue/young spheroid
(b) "Small Group"
M66 Group
- halo accretes similar-mass companion(s)
- can occur over a wide mass range
- M_{halo} still similar to before: dynamical friction merges the subhalos efficiently
(g) Decay/K+A
NGC 7252
- 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
(a) Isolated Disk
M81
- halo & disk grow, most stars formed
- secular growth builds bars & pseudobulges
- "Seyfert" fueling (AGN with M_B>-23)
- cannot redden to the red sequence
(h) "Dead" Elliptical
M59
- star formation terminated
- large BH/spheroid - efficient feedback
- halo grows to "large group" scales: mergers become inefficient
- growth by "dry" mergers
SFR [$M_\odot$ yr^{-1}]
1000
100
10
1
0.1
a b c d e f g h
$\log_{10}$[L_{QSO} / $L_\odot$]
13
12
11
10
9
8
−2
−1
0
1
2
Time (Relative to Merger) [Gyr]

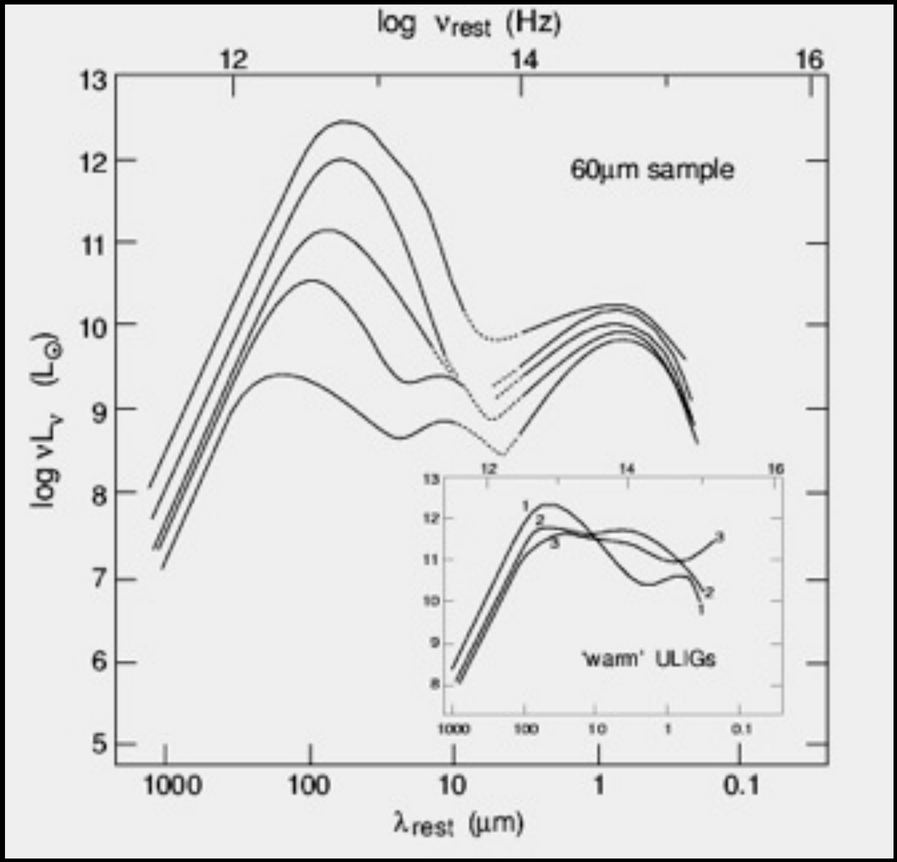


SFR ($M_\odot$ yr^{-1})
L_{Bolo} (ergs s^{-1})
Time (Gyr)
Active Phase
1
2
3
4
5
6
In-spiral Stage
• multiple nuclei, tidal tails, bridges
• the majority of stars are formed
Starburst-driven winds
(U)LIRG
QSO
Merger Remnant → Elliptical
• kinematics: tidal tails, shells, plumes & loops, kinematic subsystems
• colors redden
• formation of a hot gaseous halo
• declining AGN activity
• satisfies M_{BH} - σ & FP
Gas
Stars

Starbursts, Remnant Color Evolution

- Large enhancements in SFRs; L_{bol} similar to ULIRGs
- Radiative transfer ⇒ 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 feedback

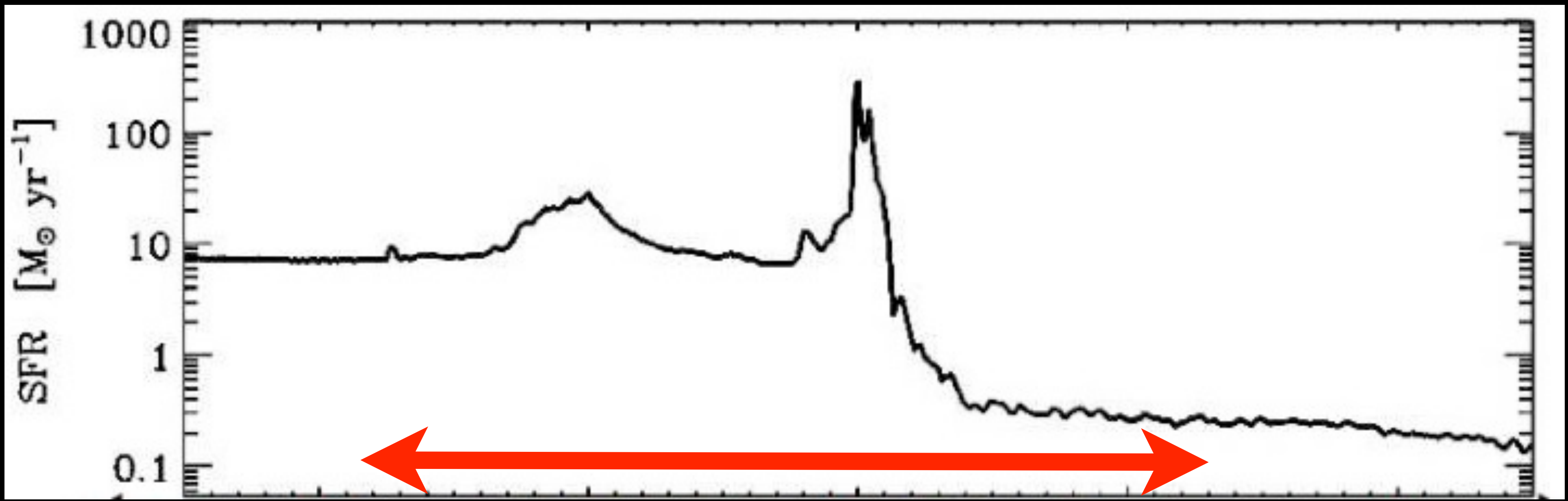
  Dominant process depends on mass, gas content …
- Remnant reddens rapidly



Sanders & Mirabel (1996)

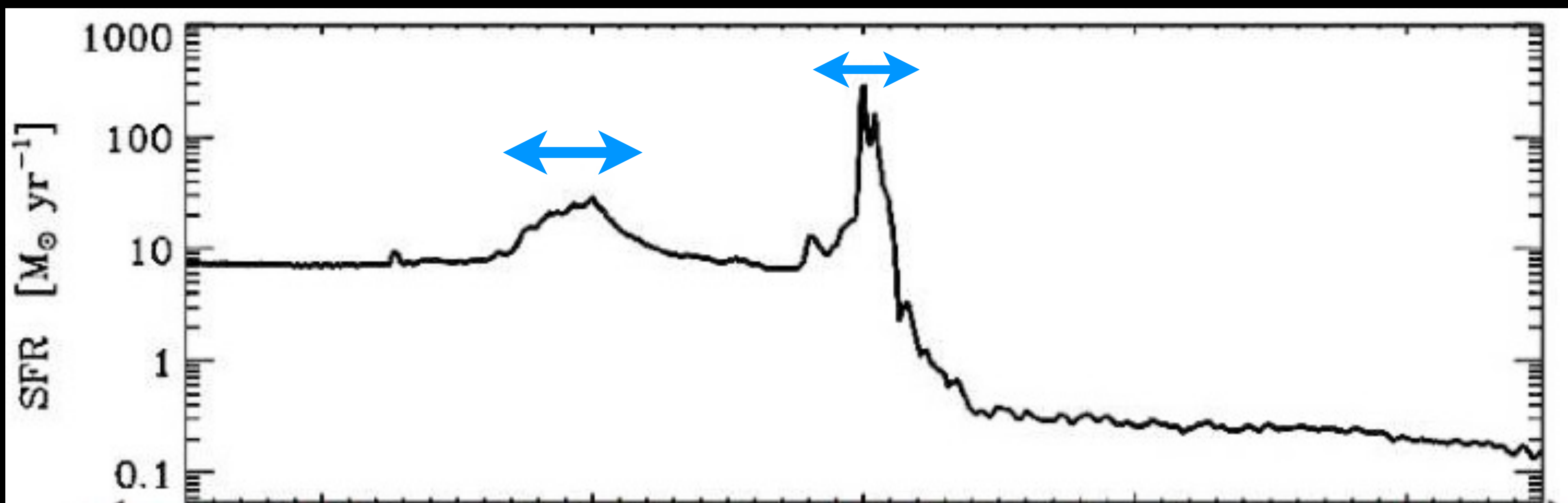
Merger-Induced Star Formation:
What Does It Mean?

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



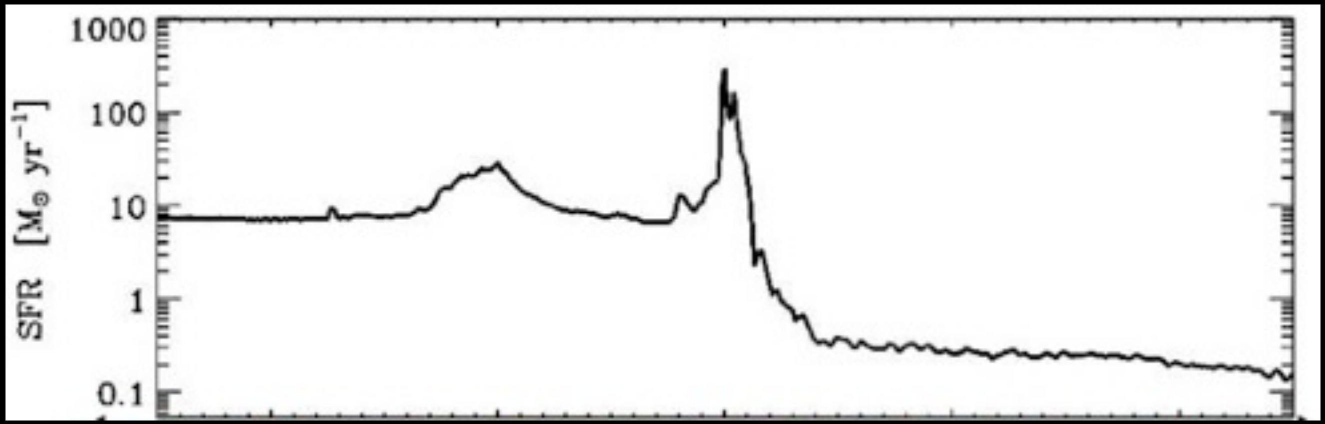
Merger-Induced Star Formation: What Does It Mean?

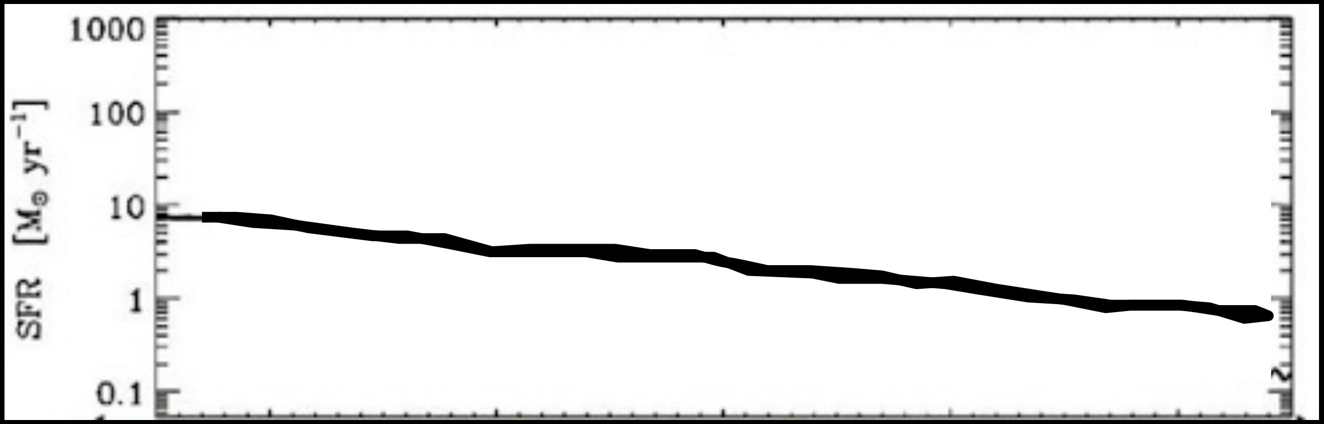
- A. All star formation during/associated with a merger
- B. Centrally-concentrated star formation during the “active” phase(s)



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

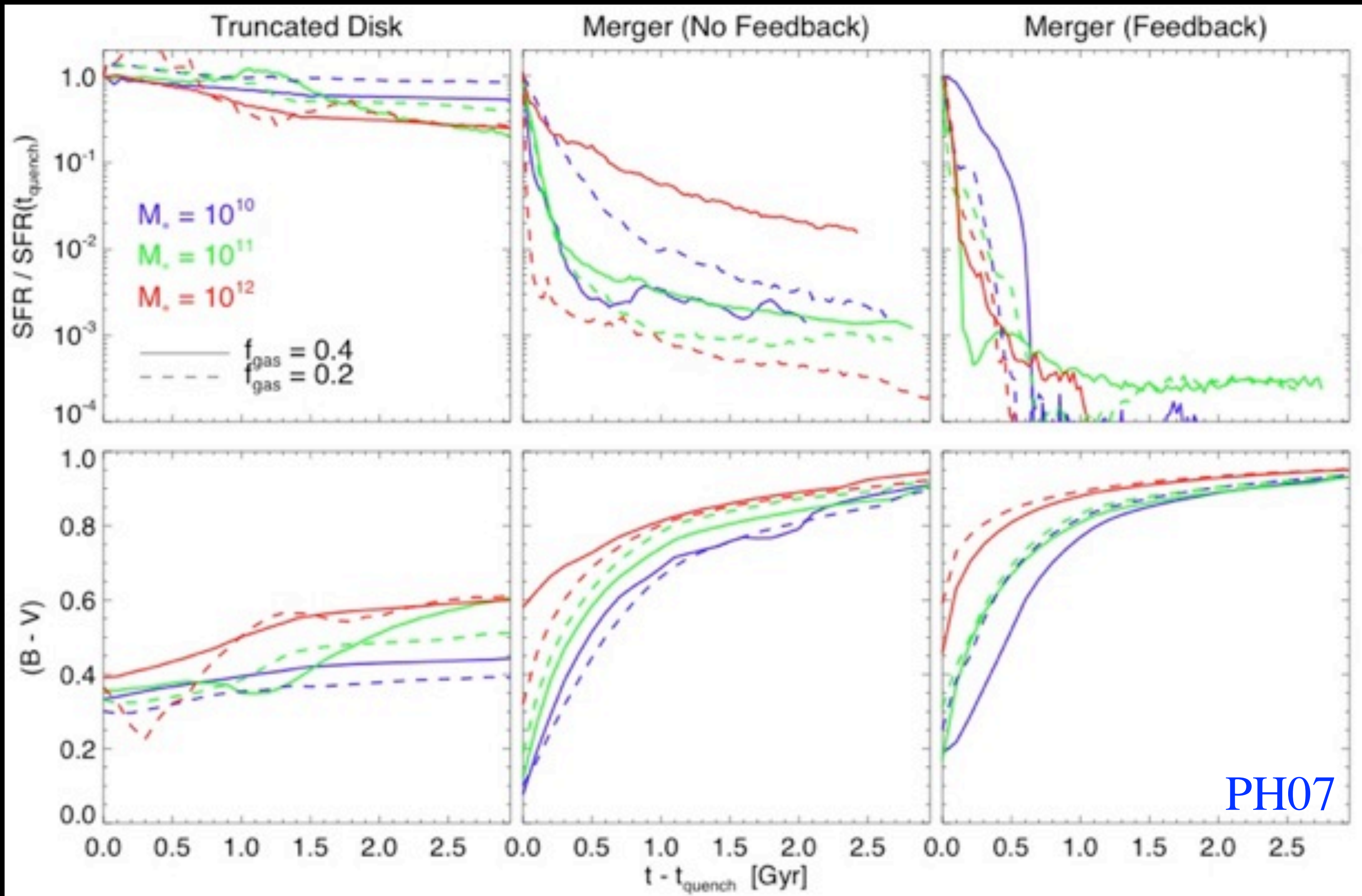




– Primarily affect the shape of the SFH, not total stellar mass!

SFR/Color Evolution of Merger Remnants

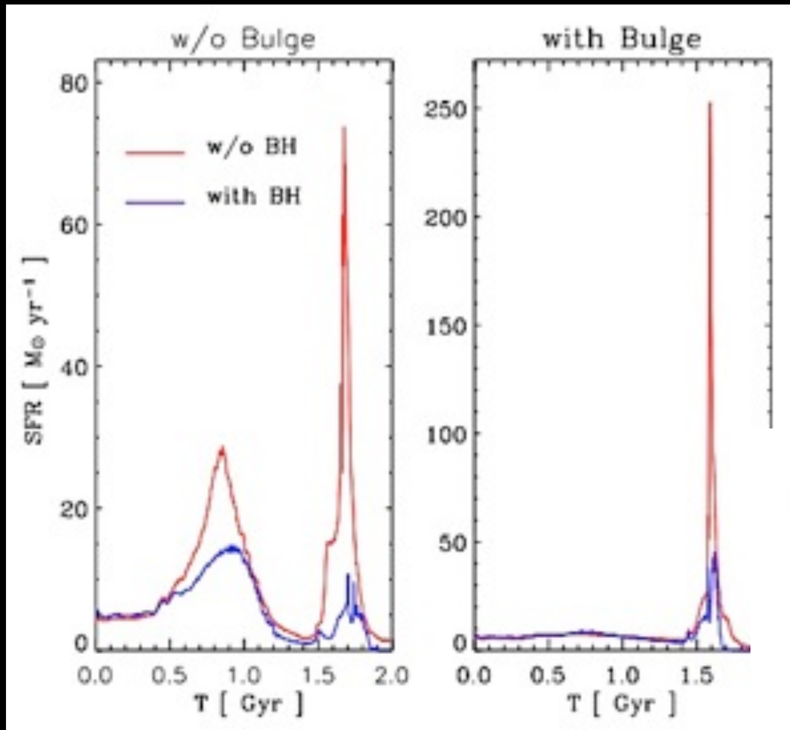
- Merger efficiently exhausts gas; feedback can expel what remains > remnant rapidly reddens

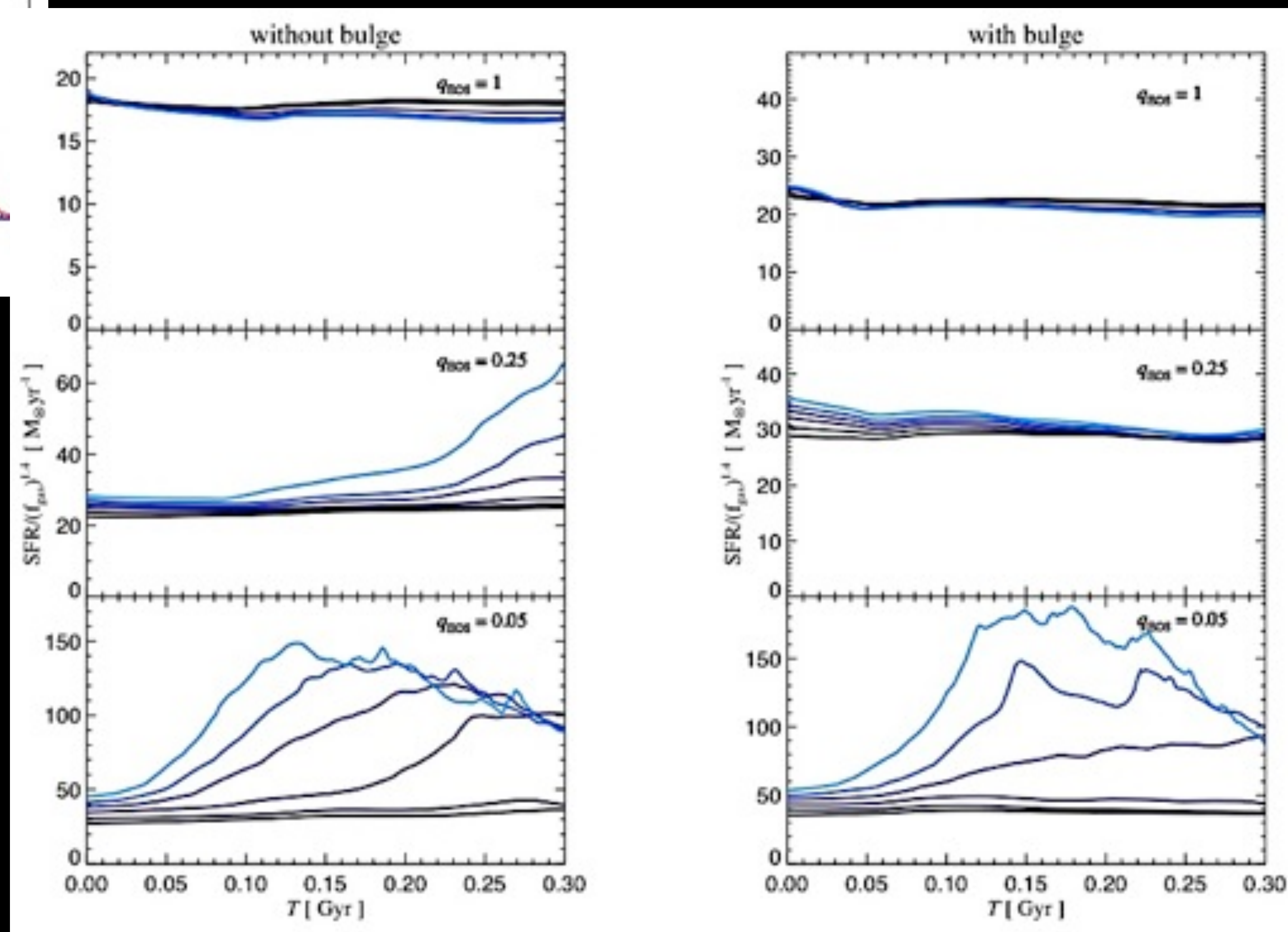


- Details depend on quasar and stellar feedback prescriptions

Mergers Drive Strong Gas Inflows, Fueling Starbursts and BH Growth

SYSTEM CHANGES RAPIDLY; BUT STATISTICS ARE WELL-BEHAVED





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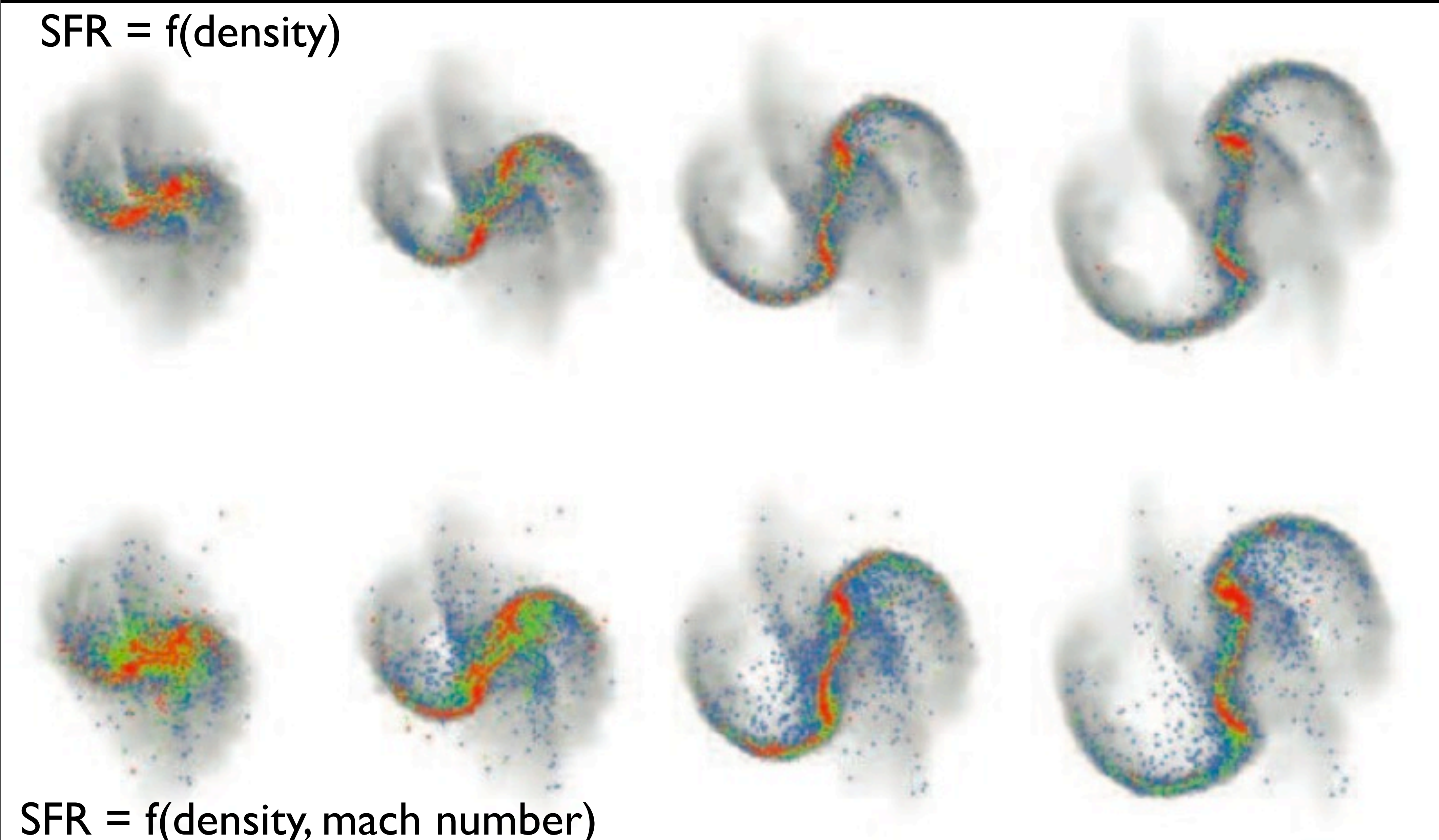

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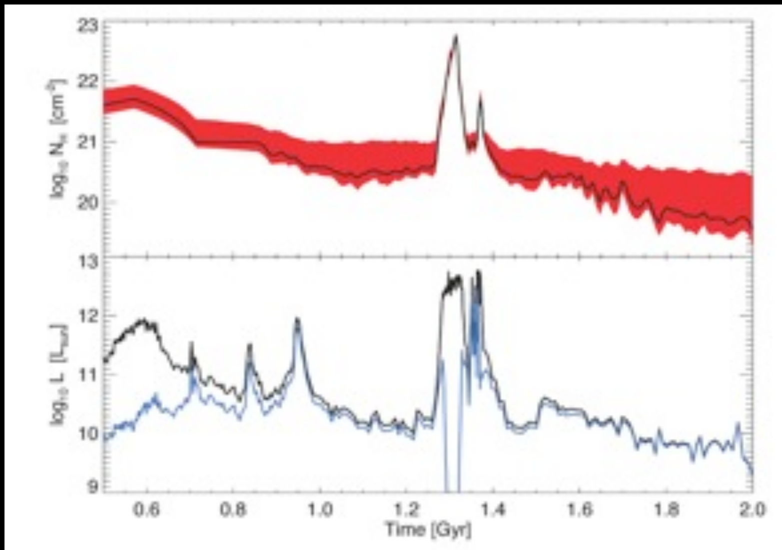
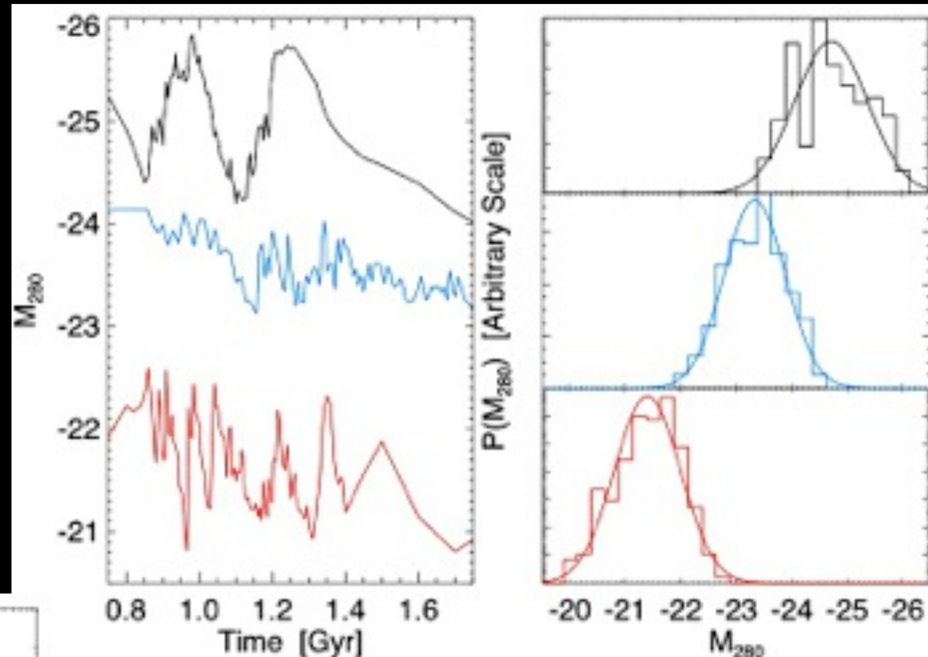
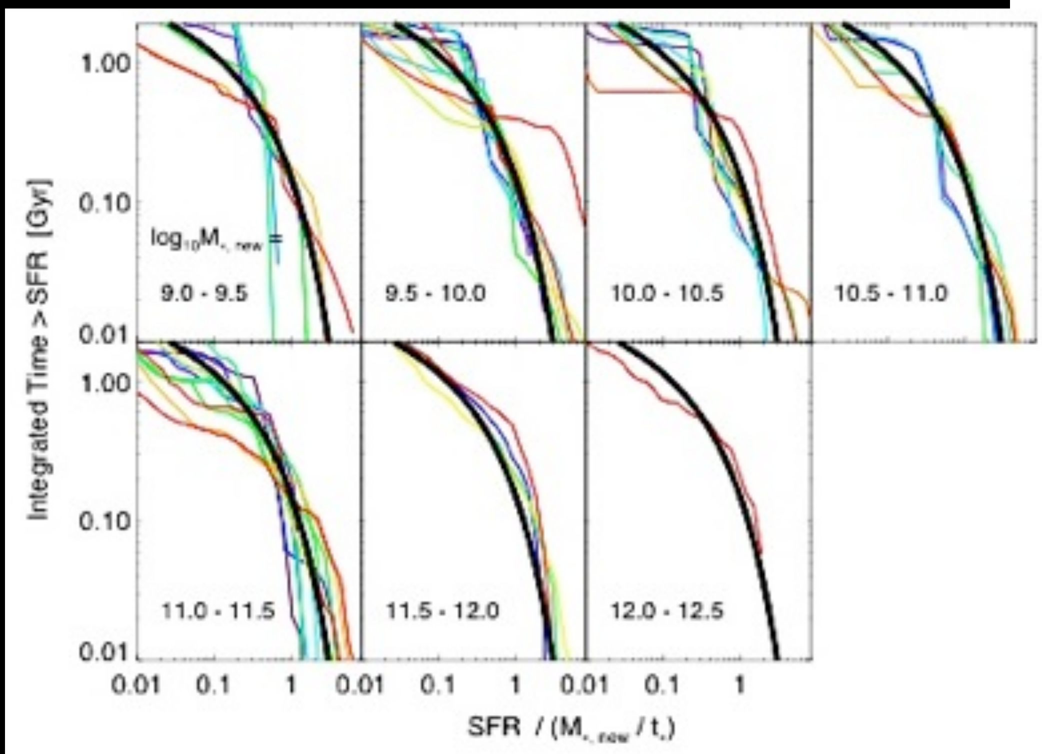


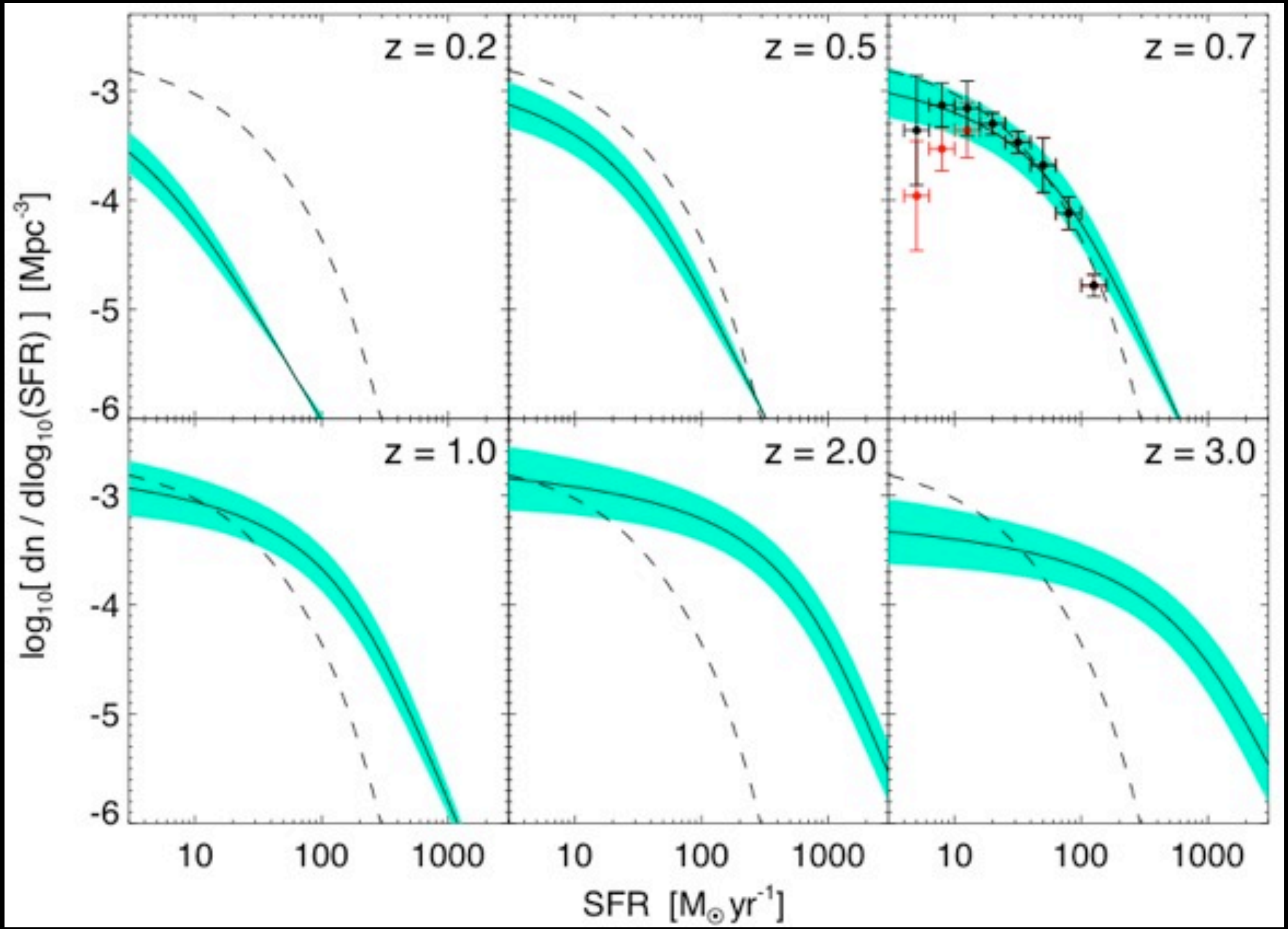




- Probability of seeing given merger at some SFR
    - characteristic SFR ~ (M_gas at final merger stages) / (x dynamical times)
- + Radiative transfer = IR+UV luminosities

The Cosmological Context

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



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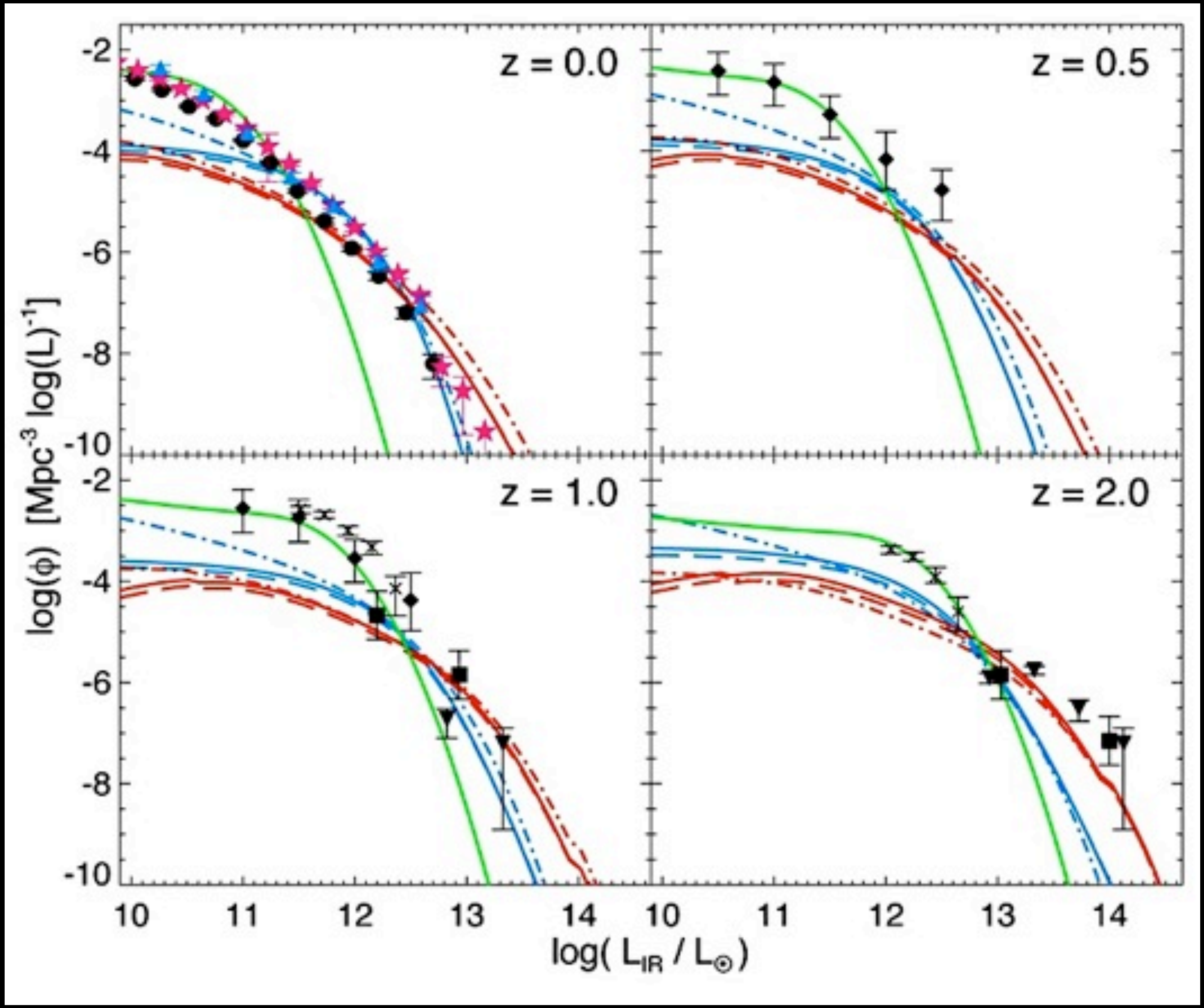
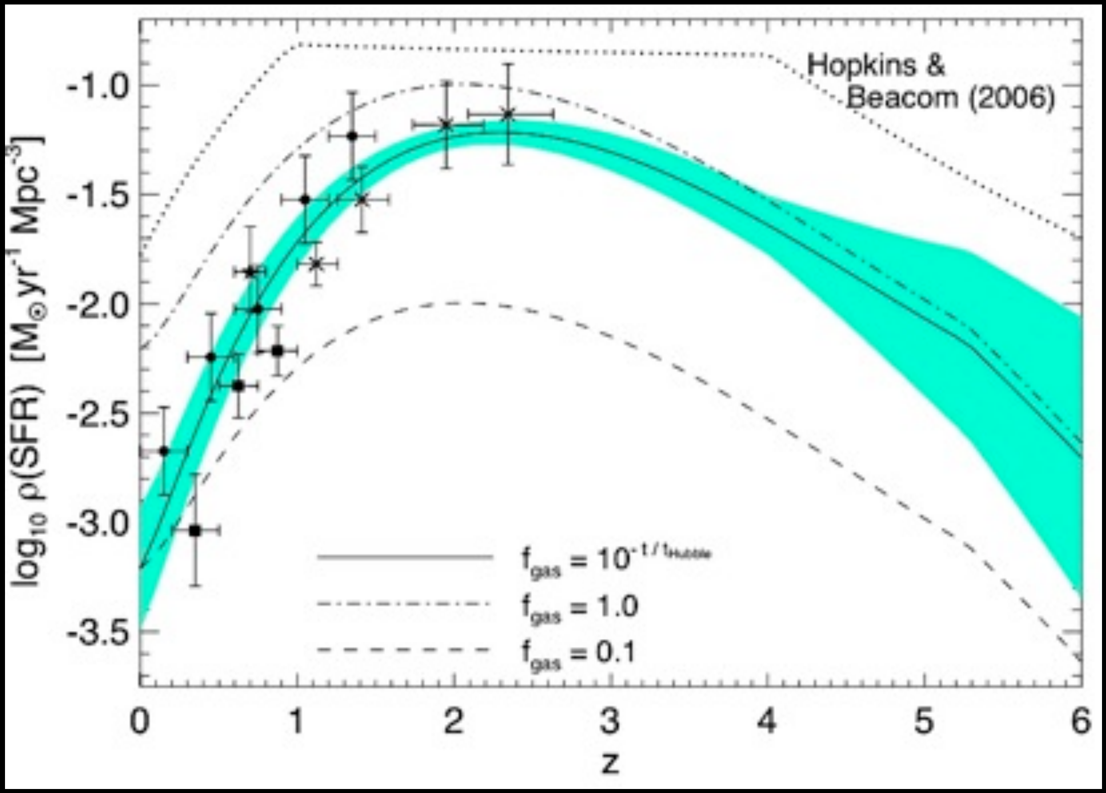
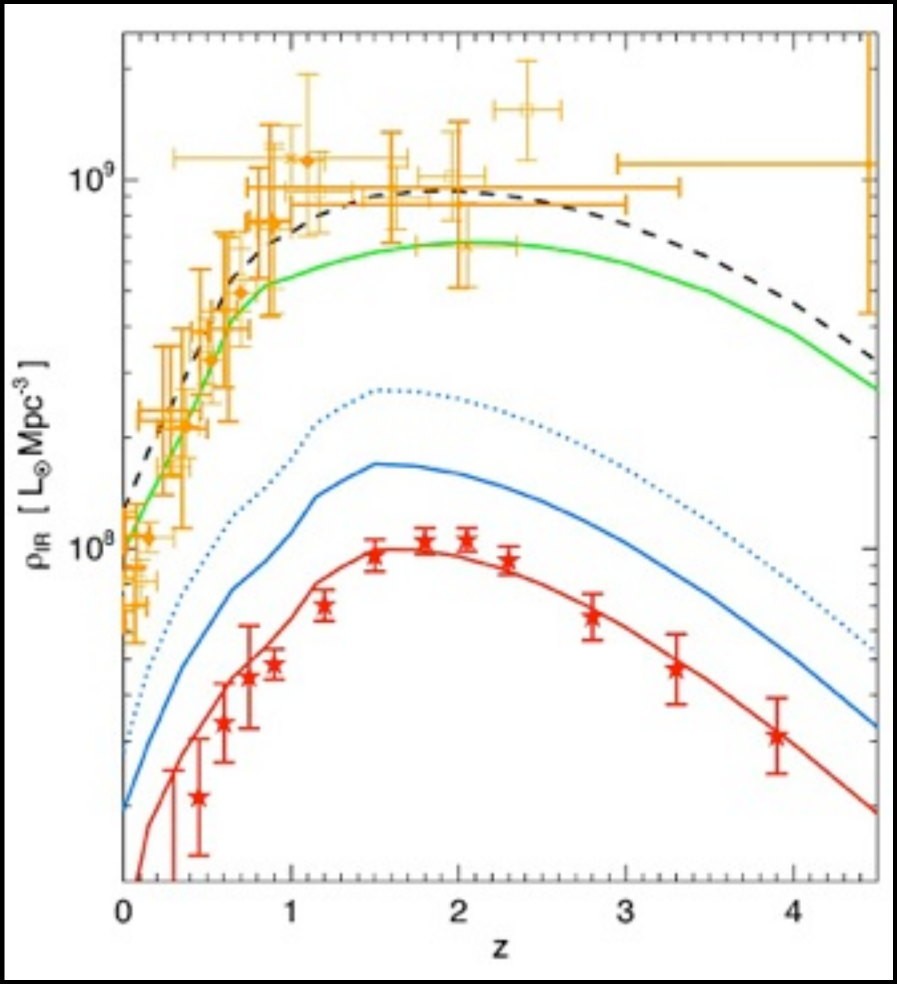


The Cosmological Context: Global SFH

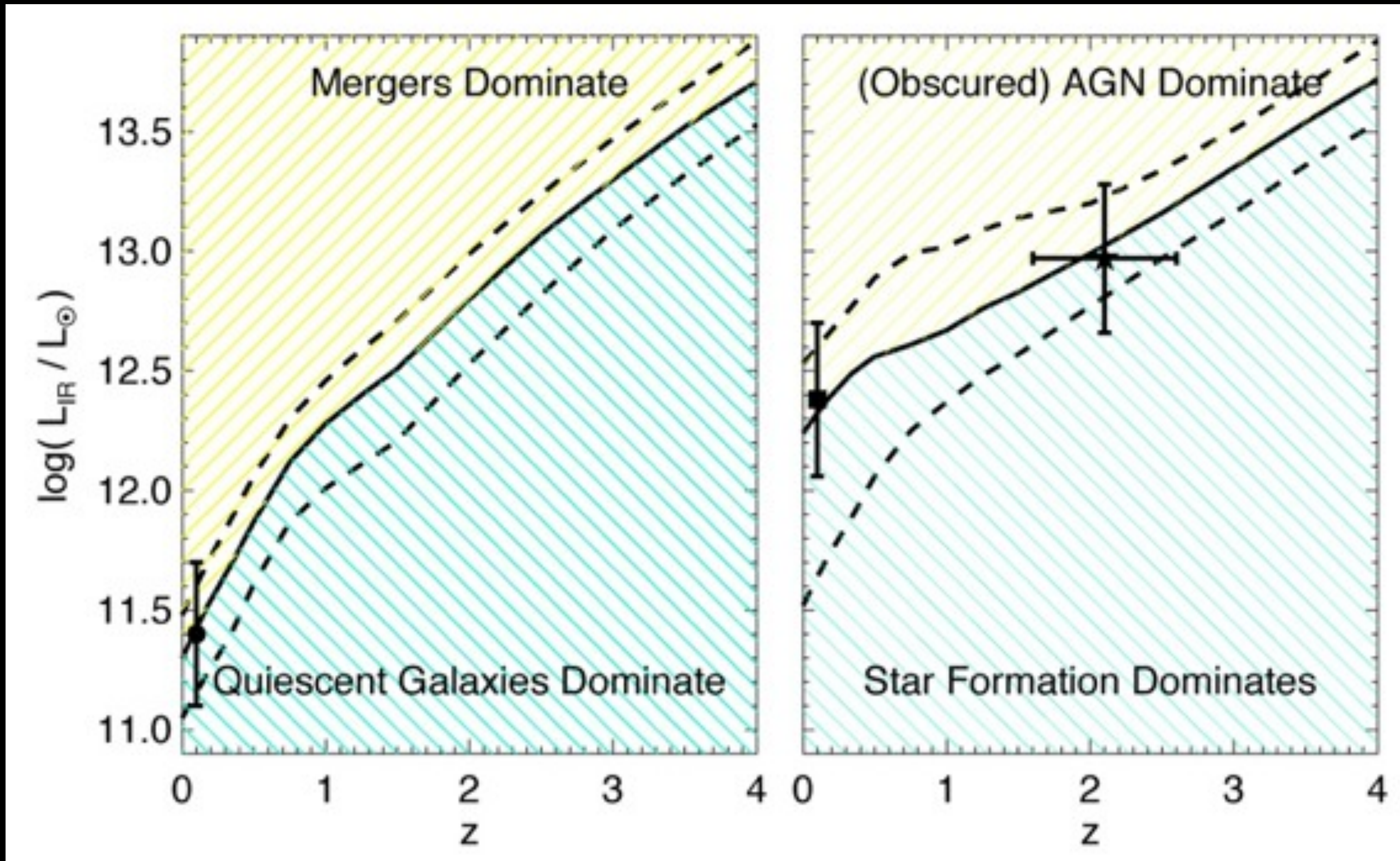
- Mergers are an important, but *never dominant* contributor to the global SFR density
- Most stars (>~ 90%) are formed in "quiescent" disks





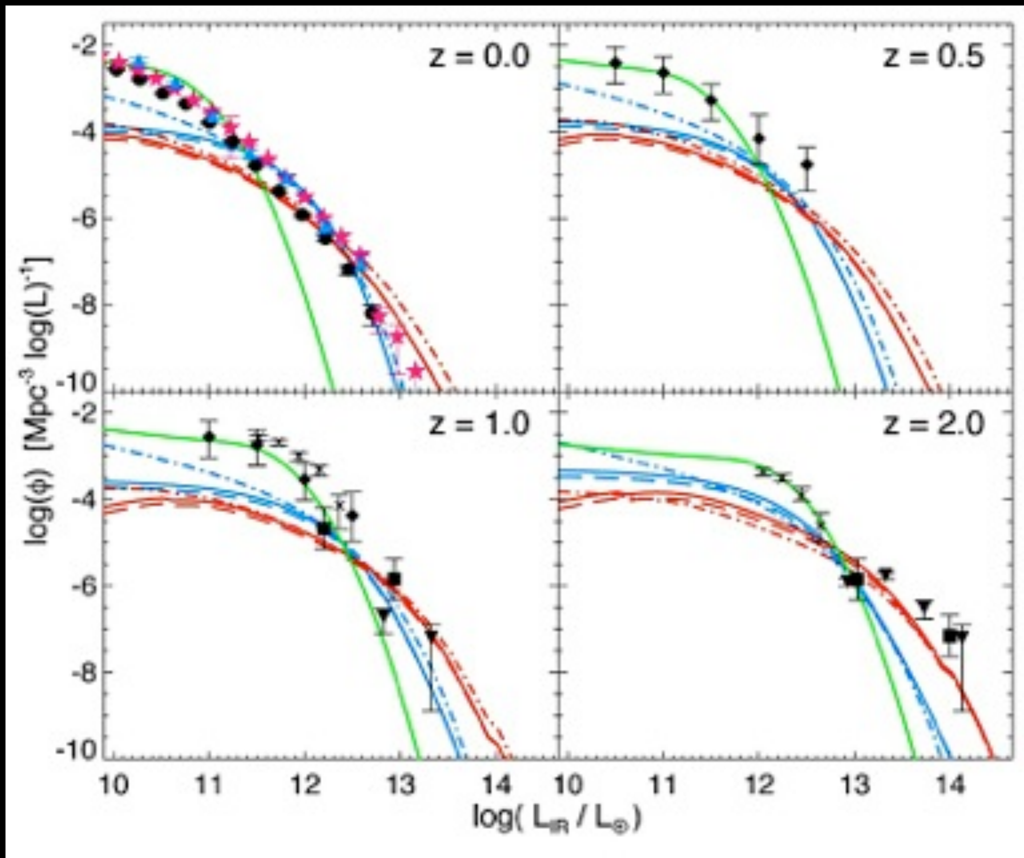
Observations: Bell+05; Brinchmann+98; Perez-Gonzalez+05

The Cosmological Context: Mergers vs. Disks

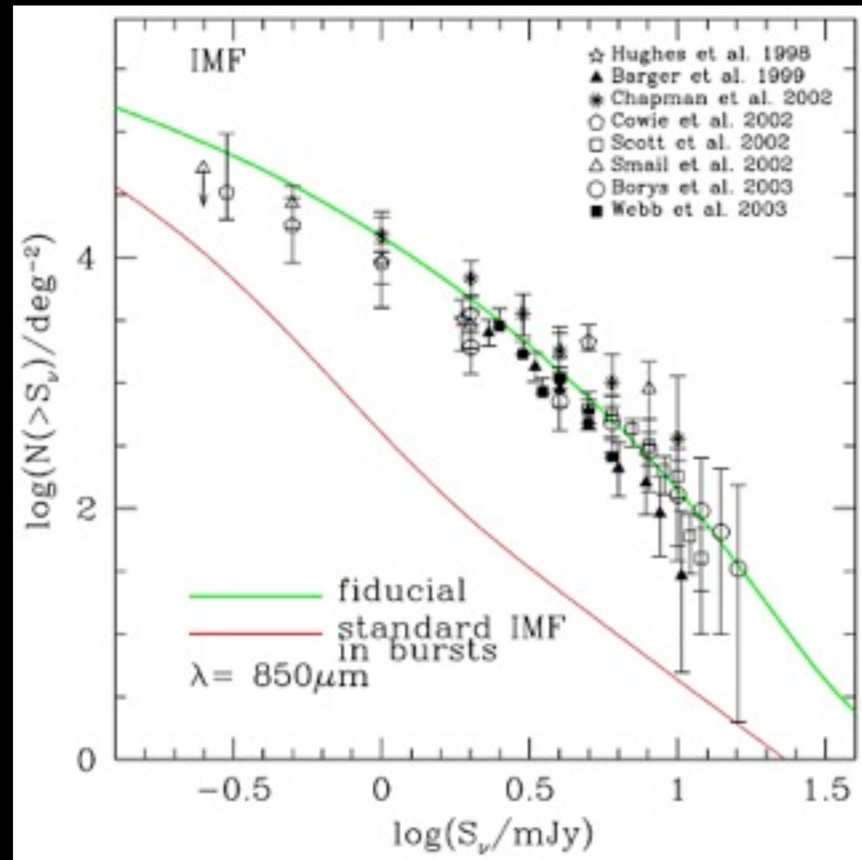


- Important caveats:
  - Where do AGN contribute?
  - How does AGN obscuration evolve?
  - How well to we really know IR luminosities?

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?