A long time ago in a galaxy far, far away...

($D_L \approx 15.5$ Gpc, $\Delta T \approx 10$ Gyr)

Whence SMGs?

The paper I used for my presentation:
An Evolutionary Model for Submillimeter Galaxies
Sukanya Chakrabarti, Yeshe Fenner, Lars Hernquist, T.J. Cox, Philip F. Hopkins
arXiv:astro-ph/0610860v1
29 Oct 2006

The paper that was actually published:
An Evolutionary Model for Submillimeter Galaxies
Sukanya Chakrabarti, Yeshe Fenner, Lars Hernquist, T.J. Cox, Barbara A. Whitney
The Astrophysical Journal, Volume 688, Issue 2, pp. 972-989
12/2008

Presented by:
Matthijs Smith

What's an SMG?

- SMG = Sub-Millimeter Galaxy
  - Luminous ($L_{IR} \geq 1 \times 10^{12}$ $L_{\odot}$), high redshift ($z \sim 2$) dusty galaxies, probably containing AGN and with a large black hole mass
  - First seen in large numbers by SCUBA
  - Empirically defined as flux $F_{850\ \mu M} \geq 1$ mJy

How do SMGs work?

- SHARC-2 observations say they're gassy ($M_{gas} \sim 10^{10} – 10^{11}\ M_\odot$)
  - They resemble more local ULIRGs
  - They seem to be the result of mergers
- So how do they form, and what do their SEDs look like?
  - The authors make a comparison with the more local, better-known ULIRGs

SMGs vs. ULIRGs

ULIRGs themselves are morphologically complex, indicating merger-driven origins. Previous researchers have tried to explain them with axisymmetric models, but the results of mergers will be more complex than that.

Chakrabarti et al. have previously employed a **self-consistent three-dimensional radiative transfer code** (important term, remember it) to calculate the infrared emission of ULIRGs. They use the same approach here.

To simulate a SMG...

- Our authors calculate optical- to millimeter-wavelength SEDs of simulated gas-rich major mergers using the **self-consistent three-dimensional radiative transfer code**, which treats the scattering, absorption and reemission of photons from dust grains.
- A word of caution: "[W]e defer a derivation of the infrared luminosity function to a future paper, as this depends on a full cosmological model of merger rates, and is outside the scope of this paper"
    - In other words, no full simulation yet of what Spitzer or Herschel are likely to see

So how does this simulation actually work?

- GADGET-2 (free code for massively parallel cosmological N-body simulations)
  - Entropy-conserving formulation of SPH
  - Black holes represented by “sink” particles
    - Bolometric luminosity $L_{bol} = \epsilon_r \dot{M} c^2$
- ISM (major source of infrared radiation) model: one SPH particle = one dense molecular cloud
  - Turbulent pressure ~ 100 × thermal pressure
- Spatial resolution: “a few tens of parsecs in the best cases”

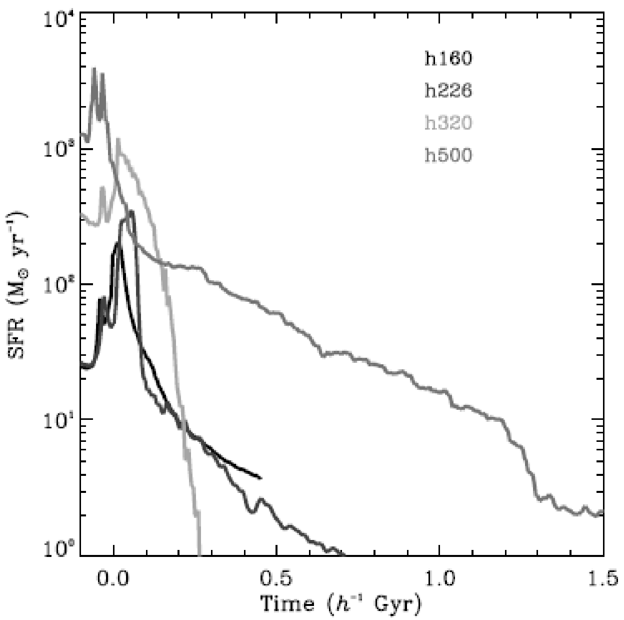
The simulated galaxies

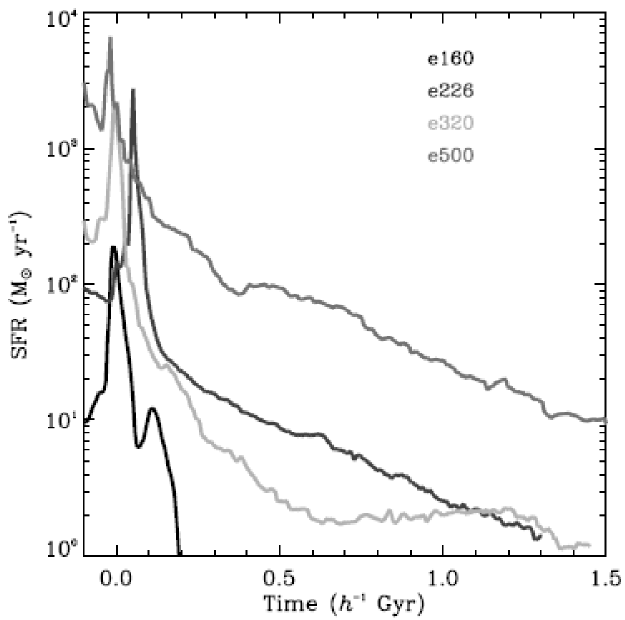
Simulation	M_{vir} ($M_\odot$)	Progenitor Redshift	Orbital Orientation	V_{vir}(km/s)
e160(vc3e)	2.7×10^{12}	0	e	160
h160(A3)	2.7×10^{12}	0	h	160
h226(A4)	7.7×10^{12}	0	h	226
h320(A5)	2.2×10^{13}	0	h	320
h500(A6)	8.3×10^{13}	0	h	500
e226(A4e)	7.7×10^{12}	0	e	226
e320(A5e)	2.2×10^{13}	0	e	320
e500(A6e)	8.3×10^{13}	0	e	500
z3e270(z3A4.5e)		3	h	270
z3h500(z3A6)		3	h	500

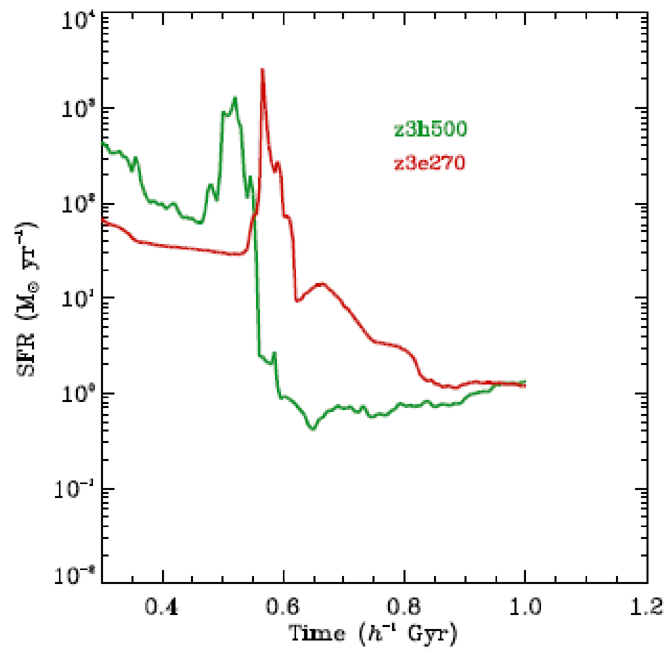
- h = co-planar merger, e = arbitrary inclination, V_{vir} = virial velocity
- The *z* = 3 galaxies were dropped from the final version

Some early results

- Star formation rate (left panel shows the co-planar mergers of varying virial velocity; middle panel shows the non co-planar mergers; right panel shows the (dropped) $z = 3$ mergers)
    - Formation rate proportional to mass, which decreases with redshift z (may be inflated by AGN luminosity)

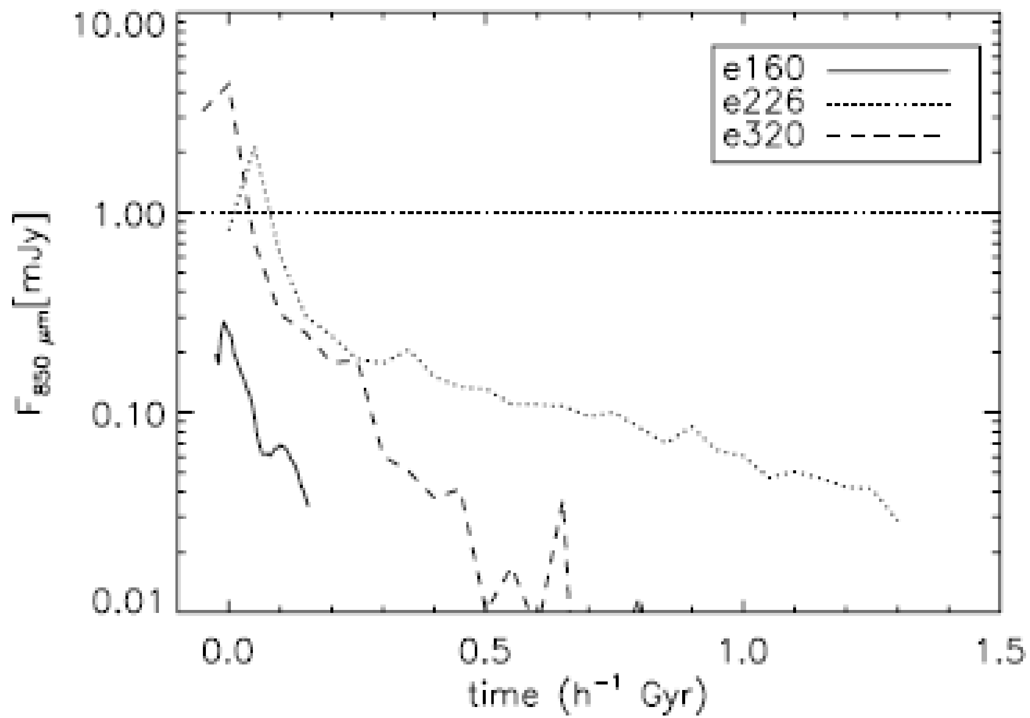






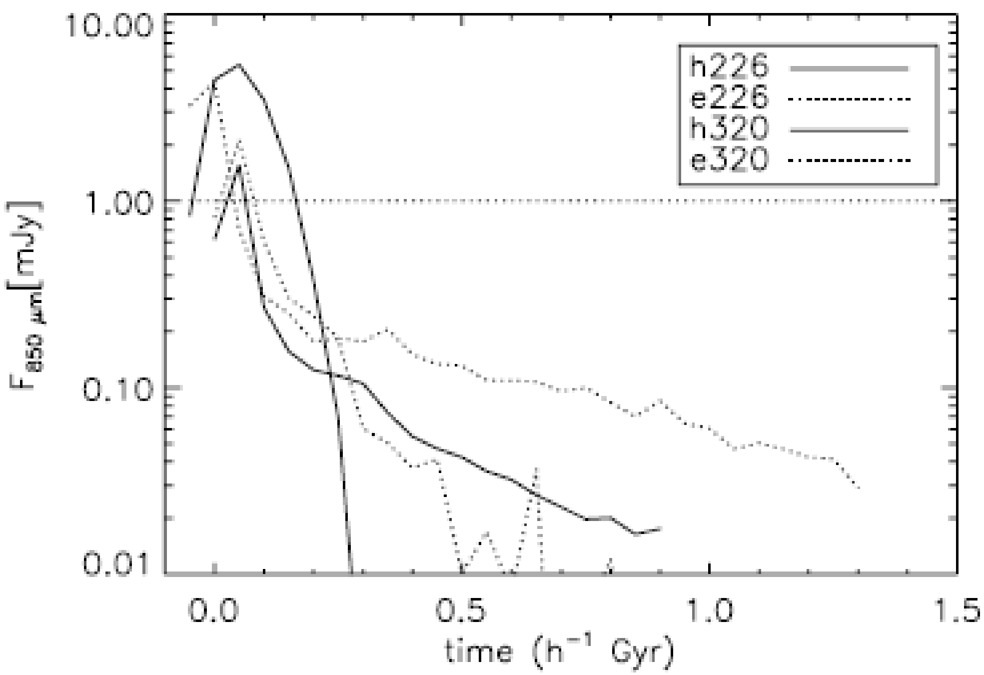
But are these really SMGs?

- Only those above the line are considered true SMGs
- The empirical definition may be flawed; awaiting further refinement from SCUBA-2 and Herschel data
- More mass → higher peak but more rapid decline in flux, less likely to be visible as SMG



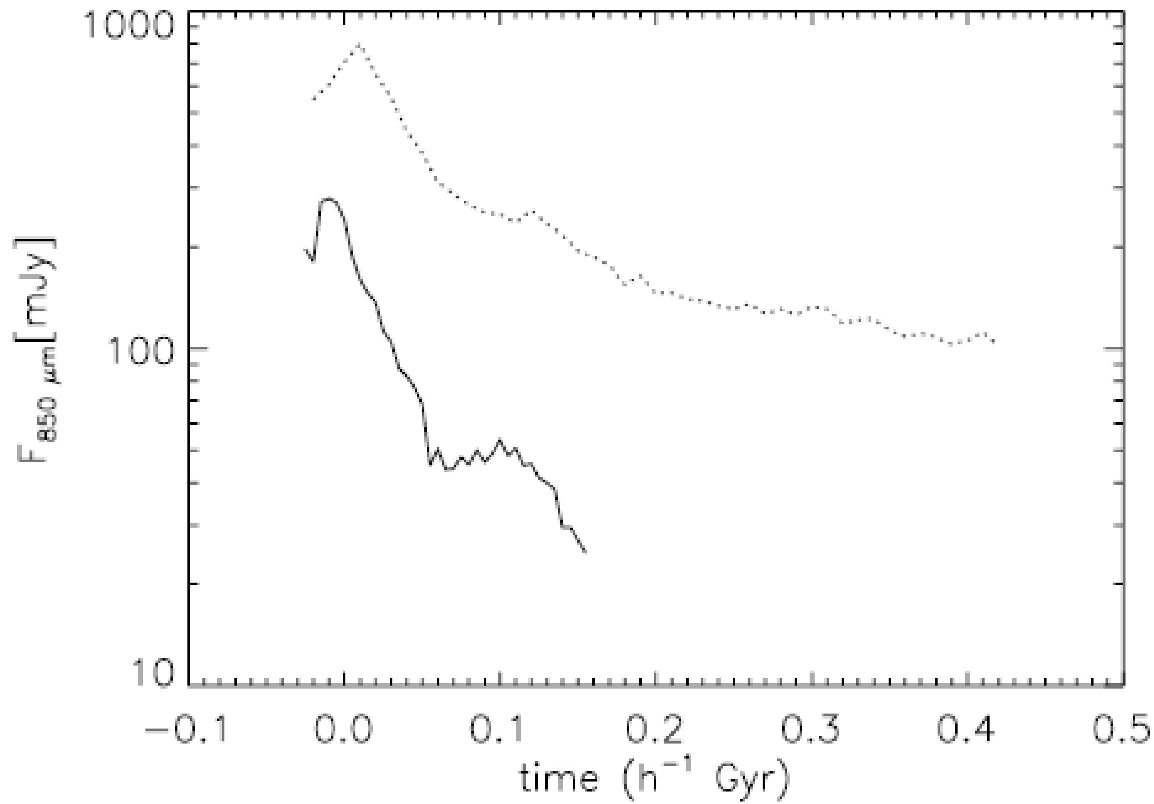
Further complicating factors

- Solid lines: co-planar cases; dotted lines: non co-planar
- Also of significance: different IMF models, ice mantles



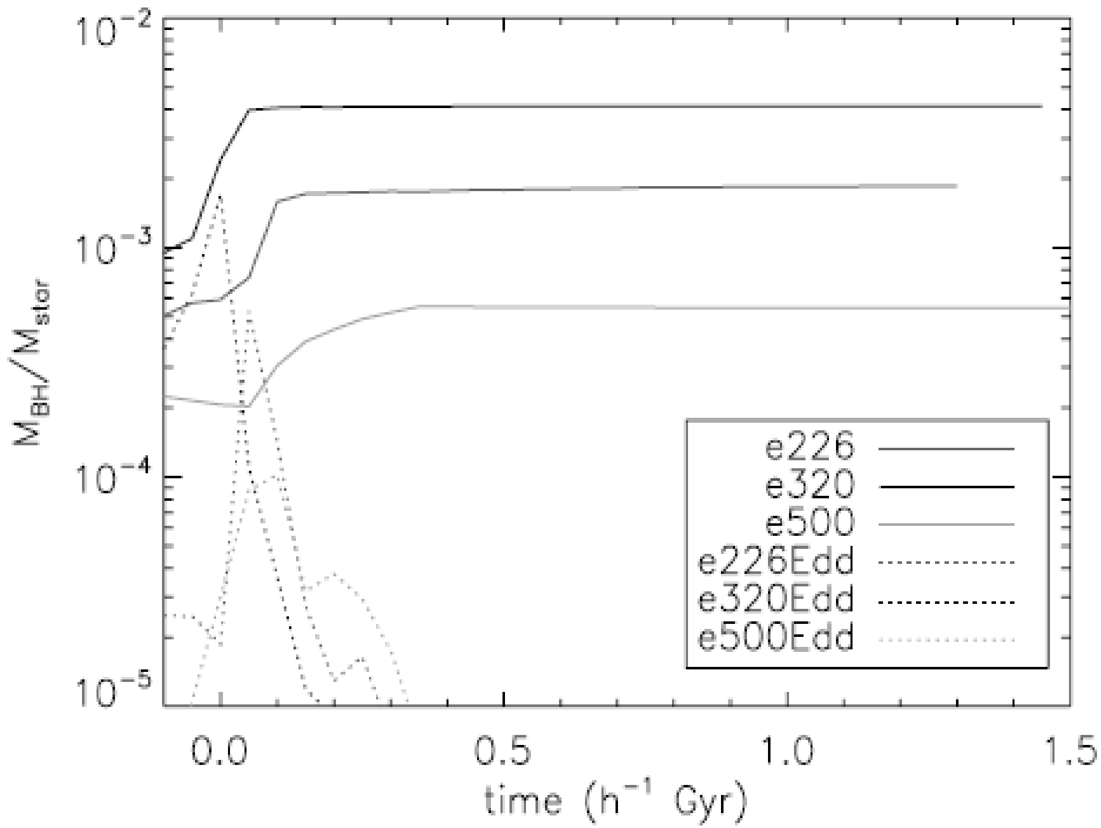
What if they were closer?

- Both representative galaxies are far above the line of flux $F_{850\ \mu M} \geq 1$ mJy
- Nearby SMGs would be equivalent to ULIRGs



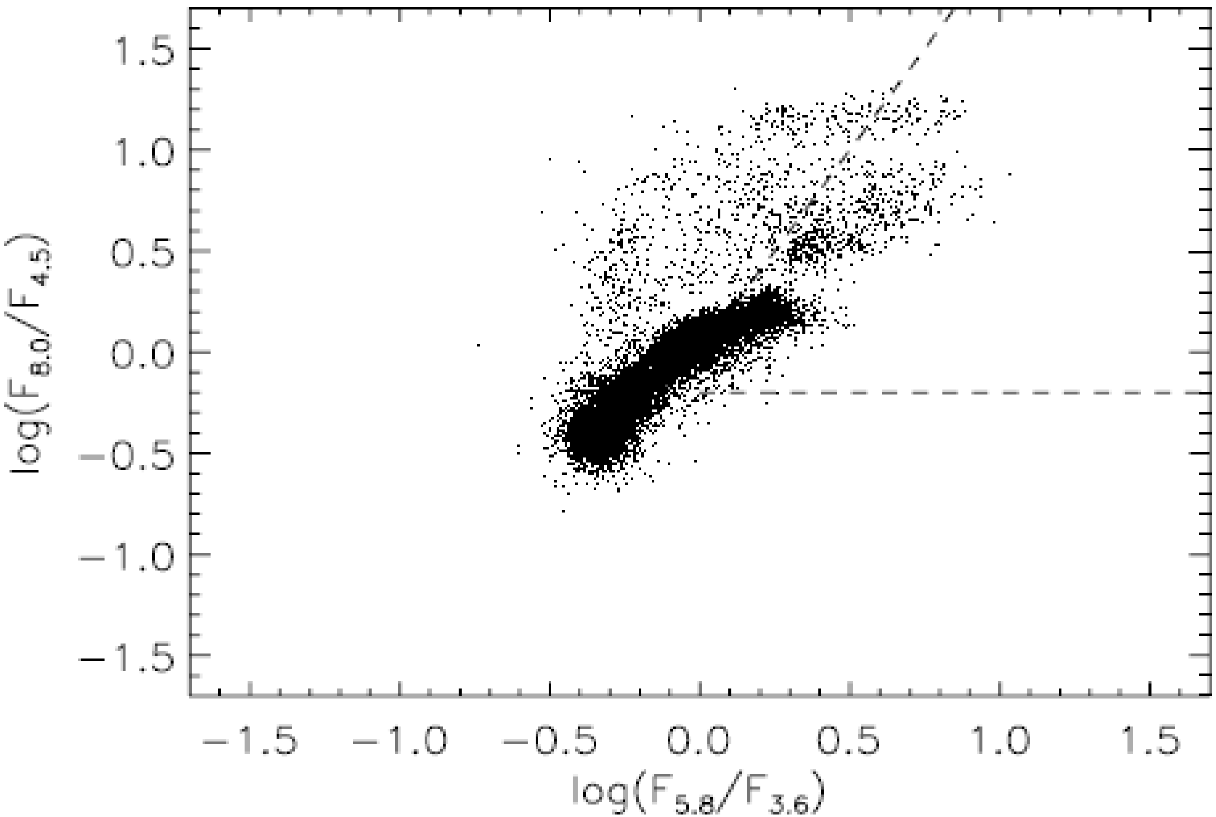
A brief side-note on black holes

- Black hole mass over star mass over time; dotted line assumes Eddington-limited accretion
- HUGE difference; more data needed to be sure
- Early results suggest that Eddington-limited accretion does not apply



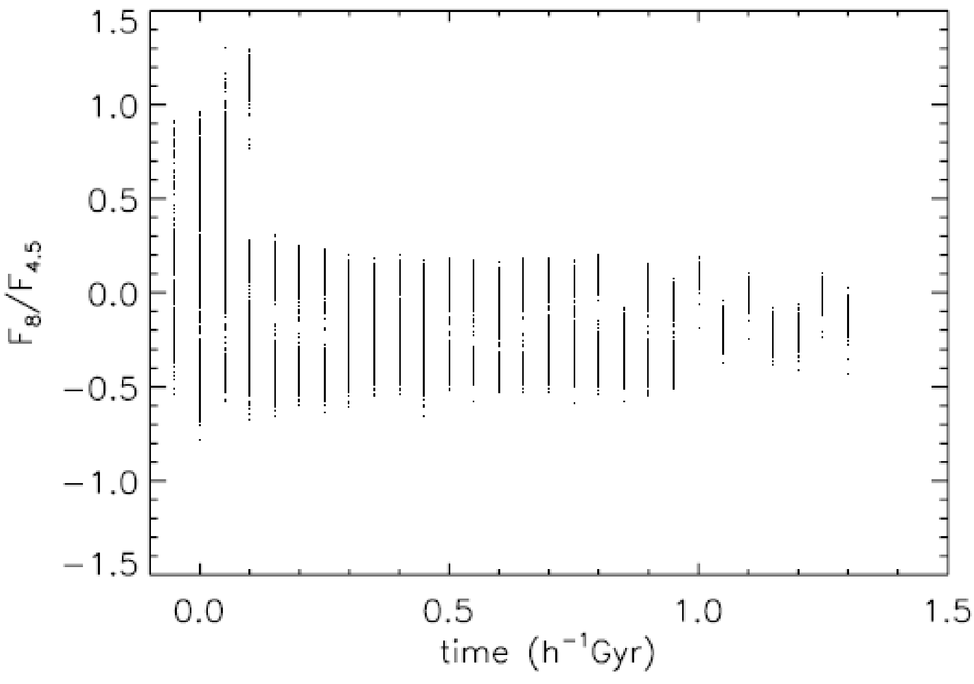
What would Spitzer see?

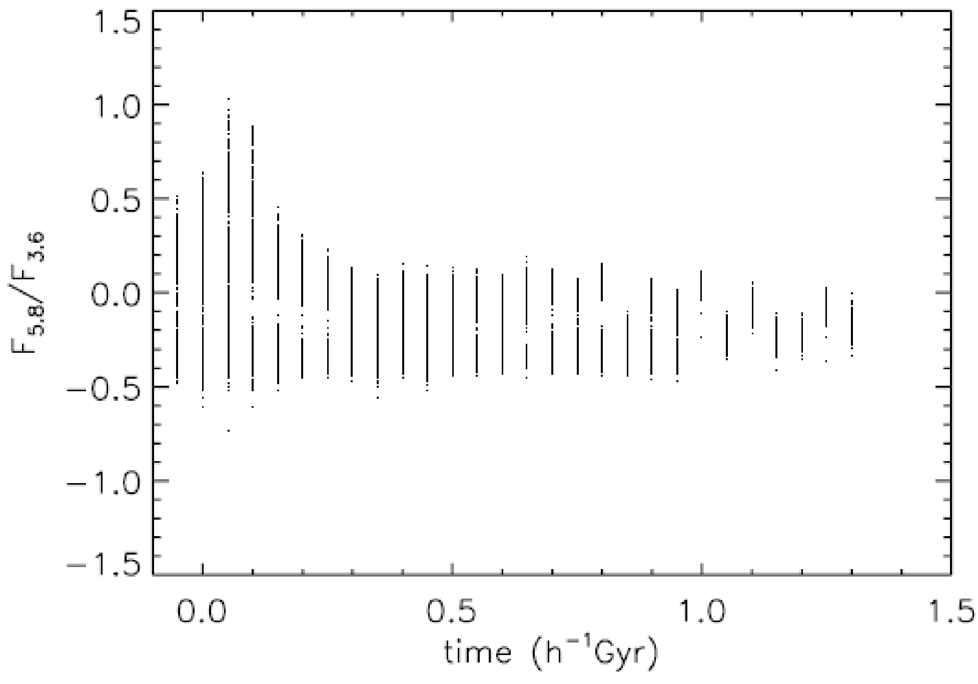
- Color-color plot in IRAC bands (median flux over all viewing angles for each time snapshot constitutes a single data point)
- Dashed lines indicate criteria for picking out obscured AGN
- Encouraging trend: clustering of fluxes in lower left hand area of plot



Changes over time

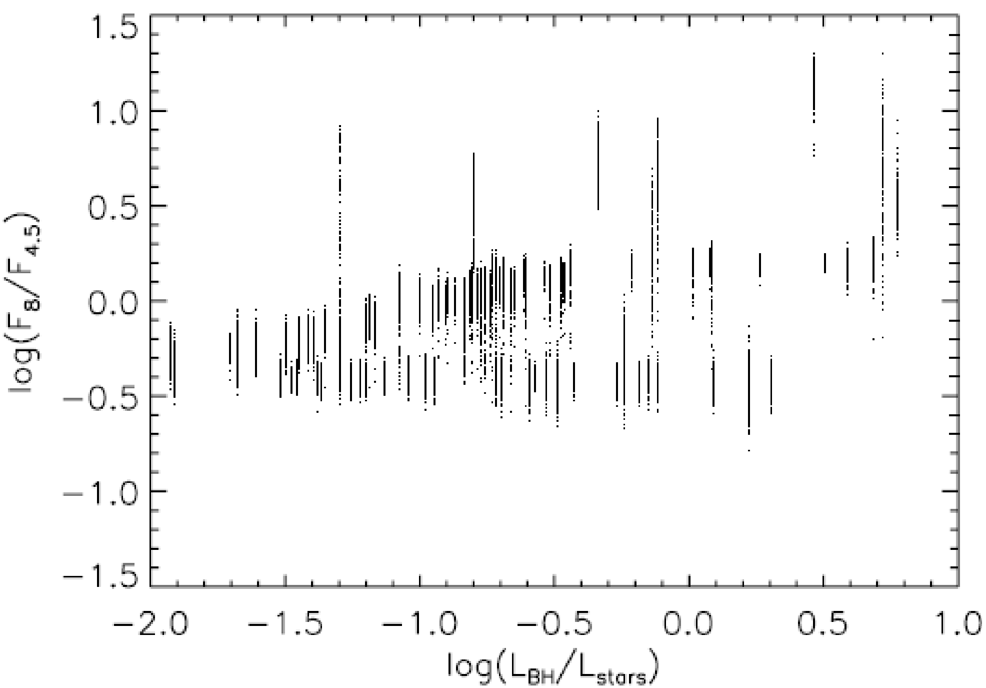
- Dynamical simulation allows for plotting color vs. time, not just color-color
- Clustering seen in last color-color plot is replicated in these plots
  - SMGs spend most of their lifetime in a particular region of color-color space

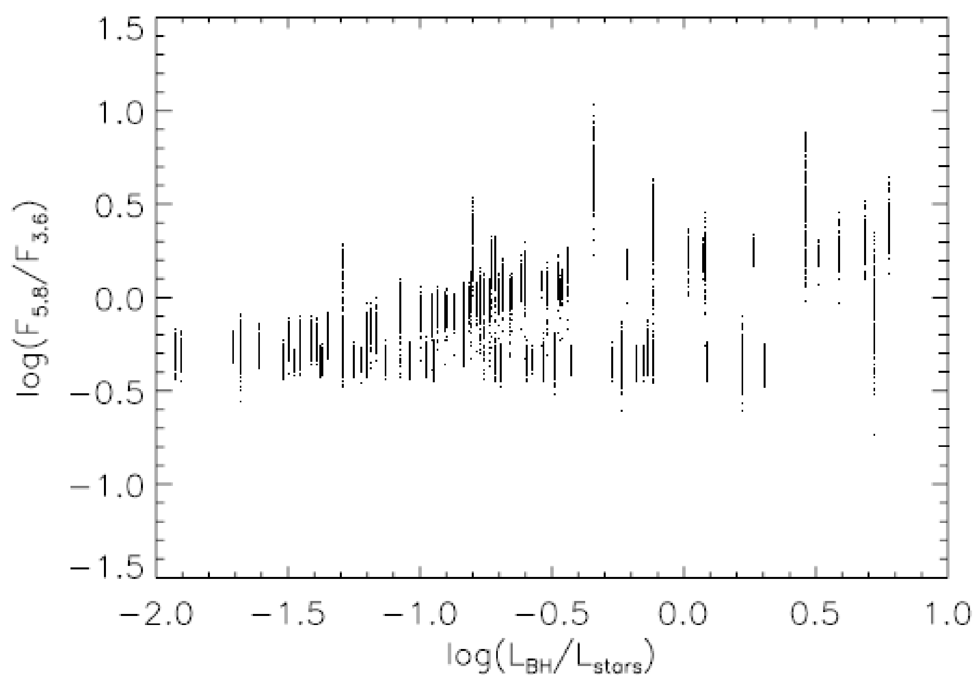




Other contributions

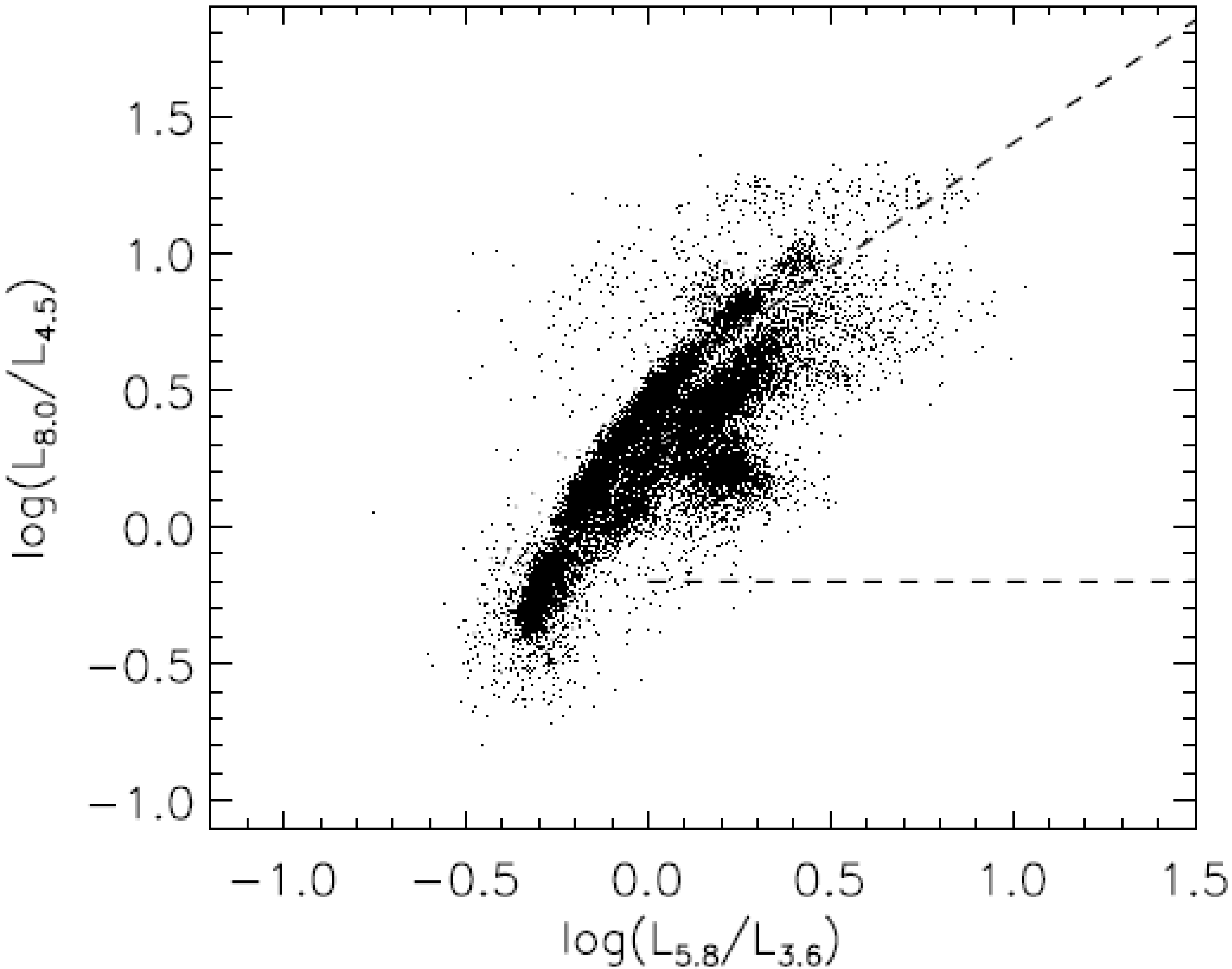
- Black hole luminosity has little overall effect on color of SMGs
  - Data points in upper right-hand corner (red region) → energetic black holes produce red SMGs





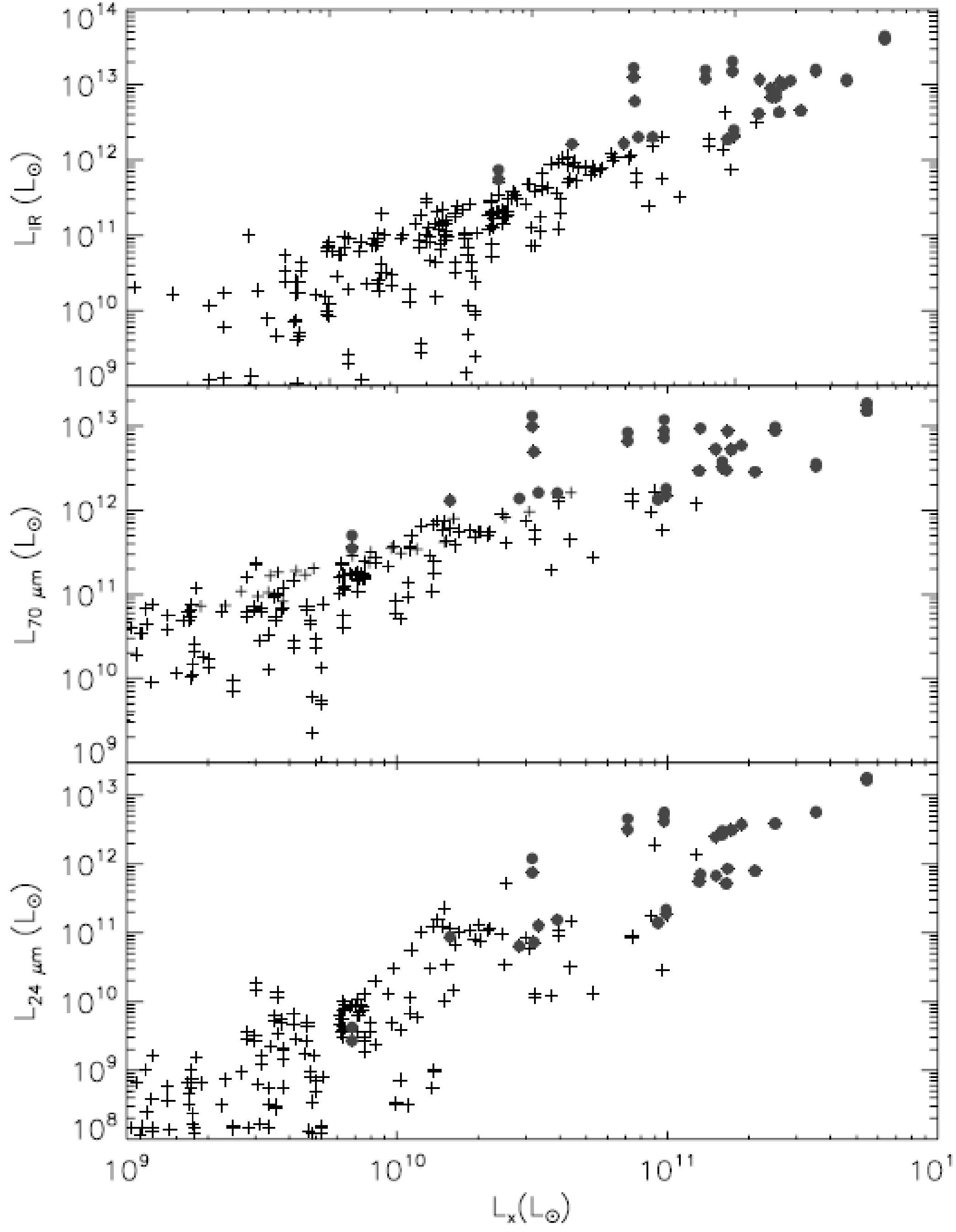
Other contributions

- Squares designate spectrum with inclusion of phenomenological PAH emission model
- PAH emissions create noticeable redshift
  - Notice bias towards AGN region

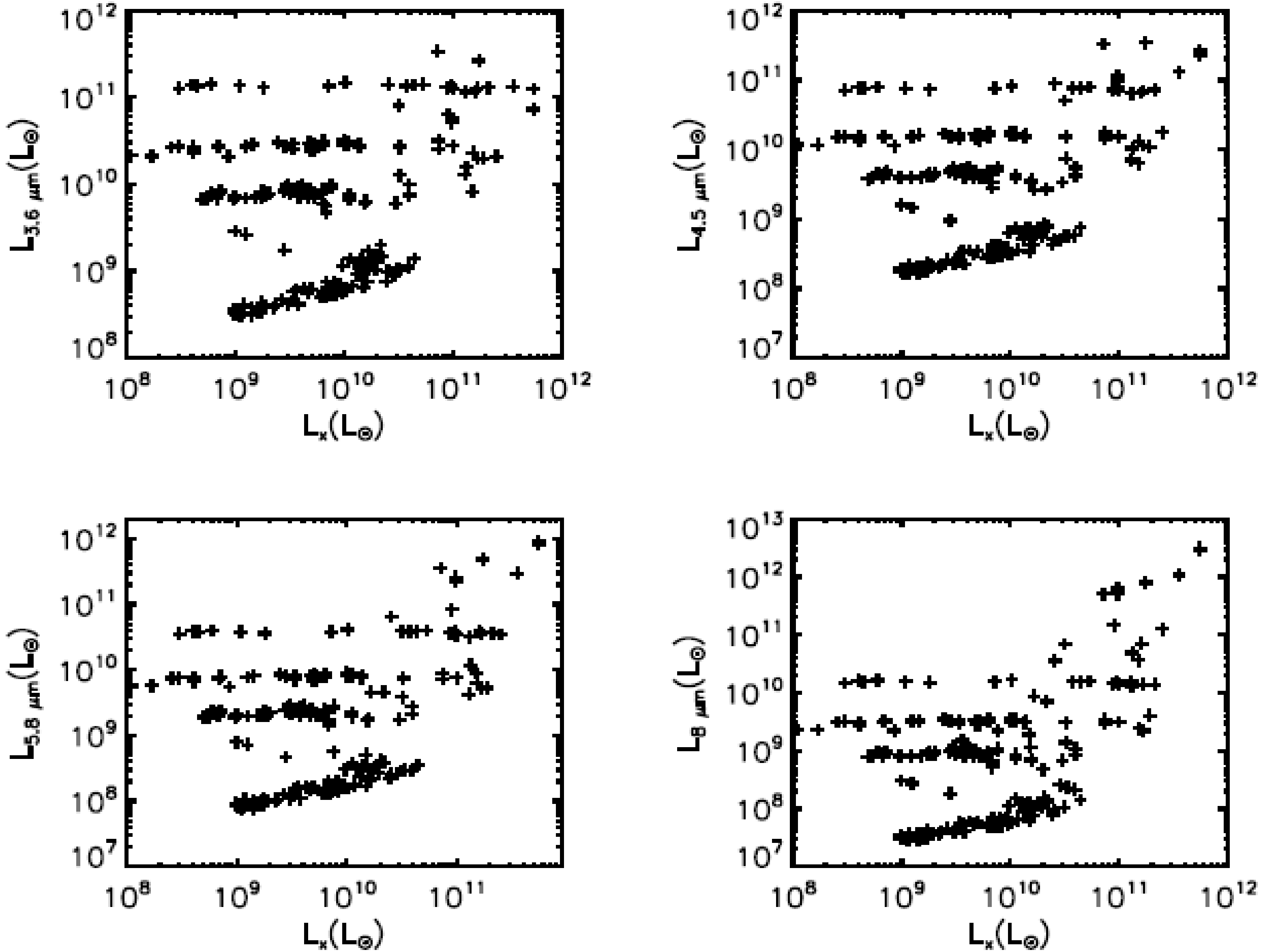


Infrared/X-Ray correlations

- Top: total IR luminosity; middle: 70 *μ*m; bottom: 24 *μ*m
- Low L_X → quiet black hole, distributed IR radiation sources → cool galaxy
- High L_X → energetically active black hole dominates as radiation source → hot galaxy, AGN
  - Brighter than ULIRGs
- Testable by Herschel



Rejected data (absent from final version of paper, included here for completeness's sake)



Infrared/X-Ray correlations

(This slide was based on the previous slide of incorrect data, and has been included for historical accuracy)

- Longer wavelengths show best correlations to X-Ray luminosity; shorter wavelengths indicate that behavior is more complex than first suspected
  - Too many sources of noise (PAH emission, dust opacity/scattering)
- Visible curves in graphs arise from discrete simulations, i.e. actual observations (which probe a continua of masses) will not show discrete curves

Time for the pretty pictures!

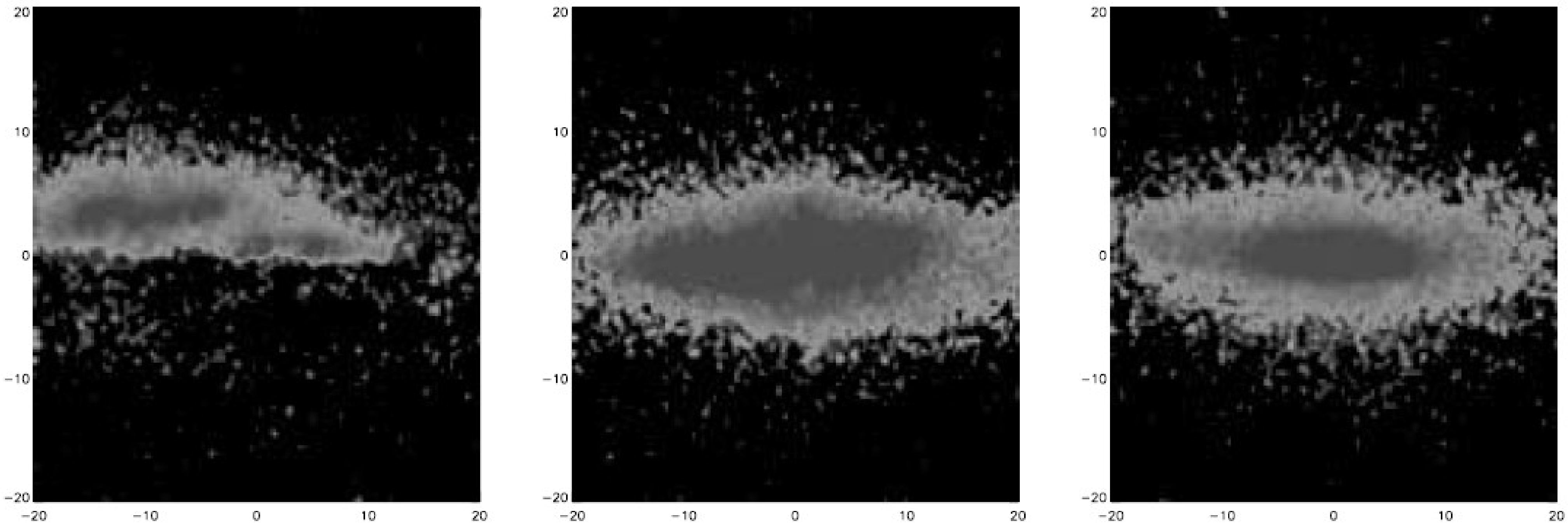


Photo Album of the Lifetime of an SMG produced in a co-planar merger (h320) in observed 3.6 μm band, (a) Pre-merger phase, (b) Close to Main Feedback Phase, (c) After Main Feedback Phase

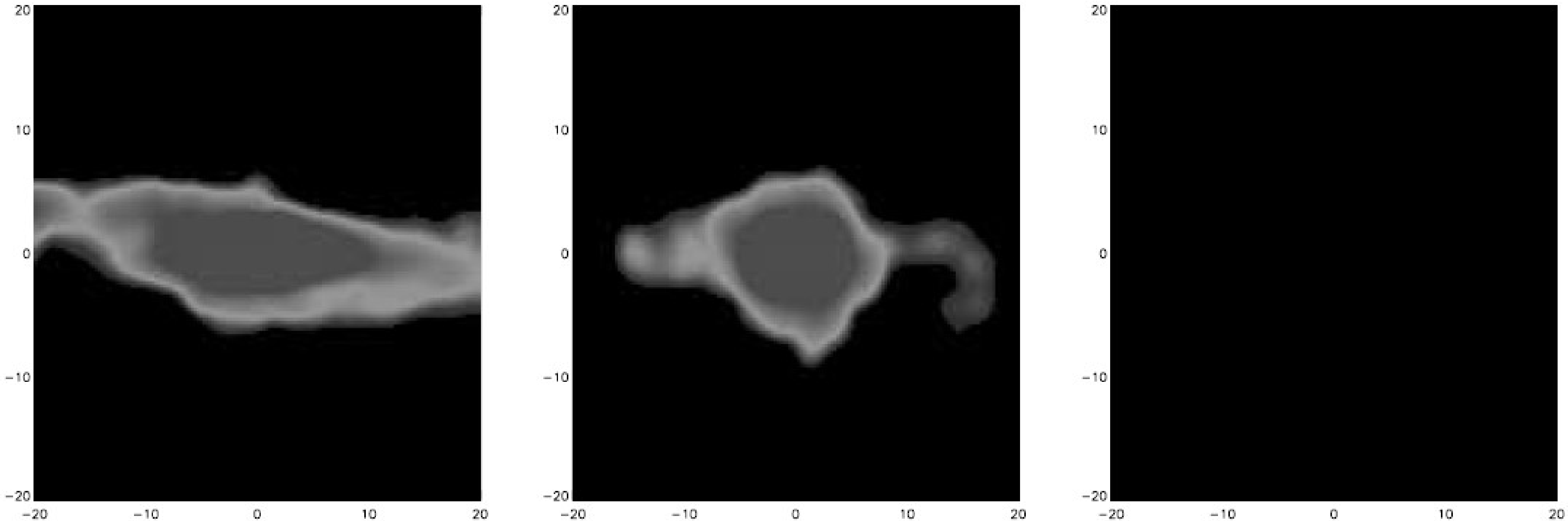
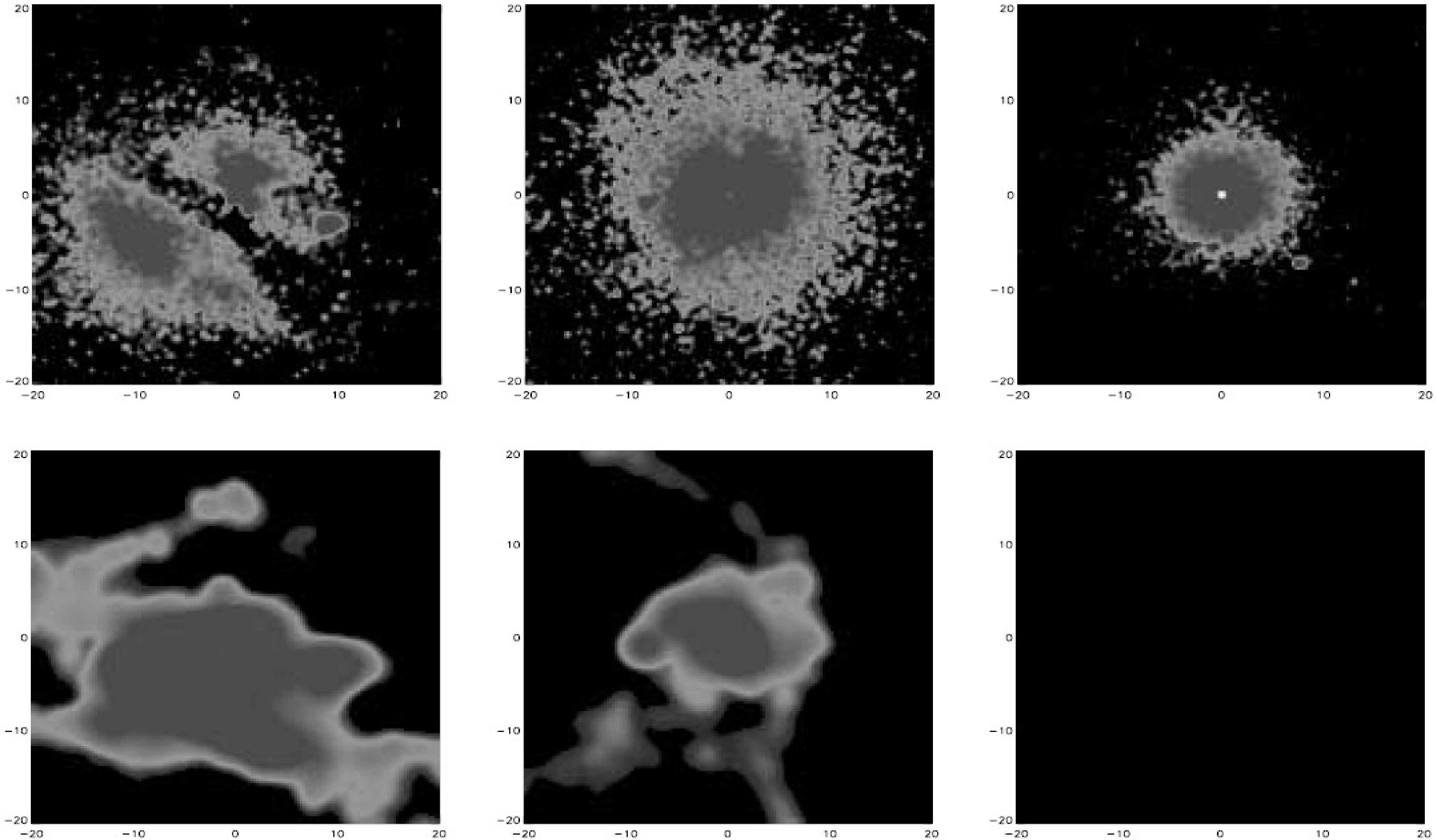
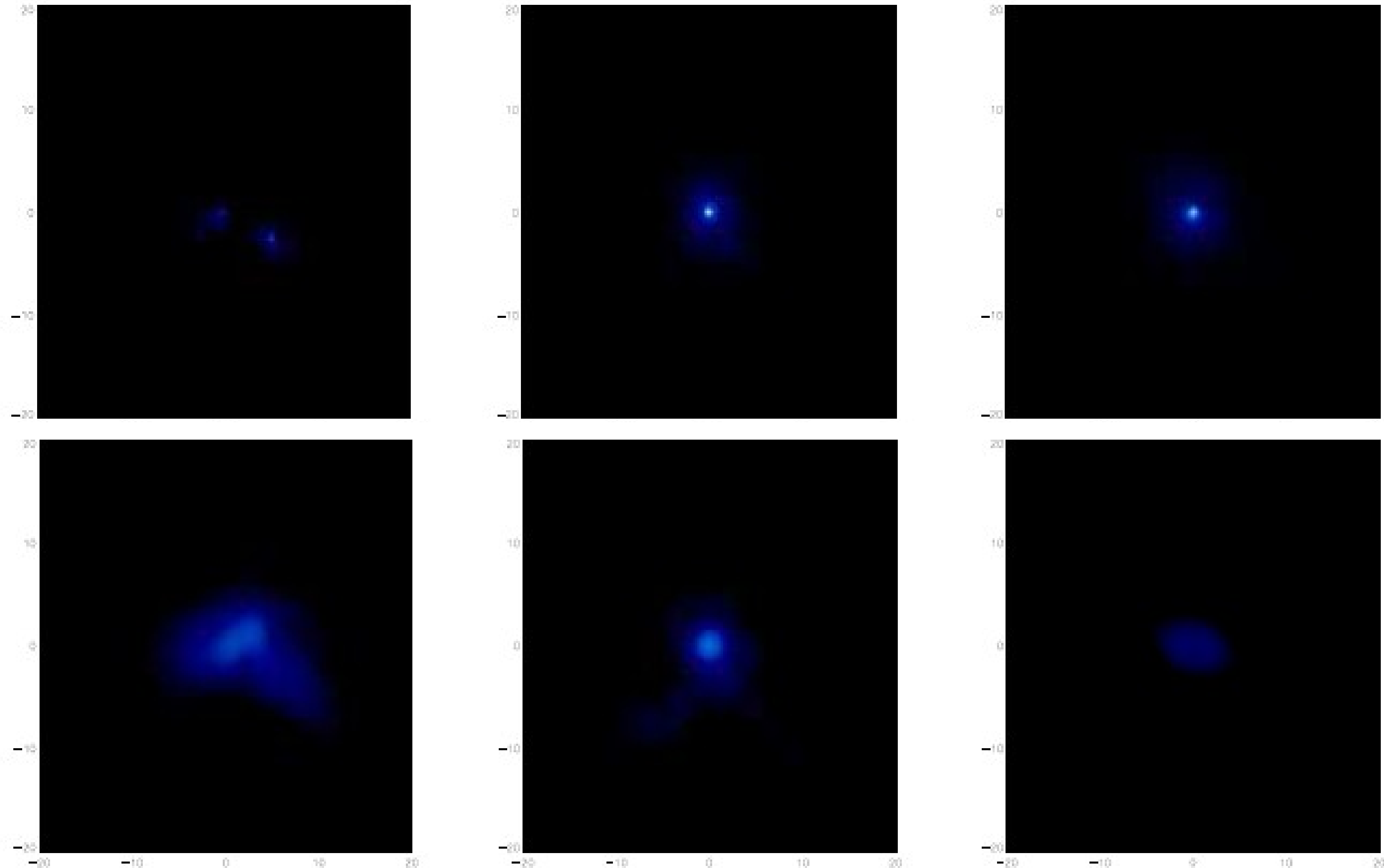


Photo Album of the Lifetime of an SMG produced in a co-planar merger (h320) in observed 450 μm band at same times as in 3.6 μm band. Times beyond the last phase would be black, i.e., would show no emission in SCUBA. This shows that more of the emitted energy is distributed to the shorter wavelengths as AGN feedback clears out the obscuring material.



Non co-planar merger (e320) in 3.6 μm and 450 μm bands



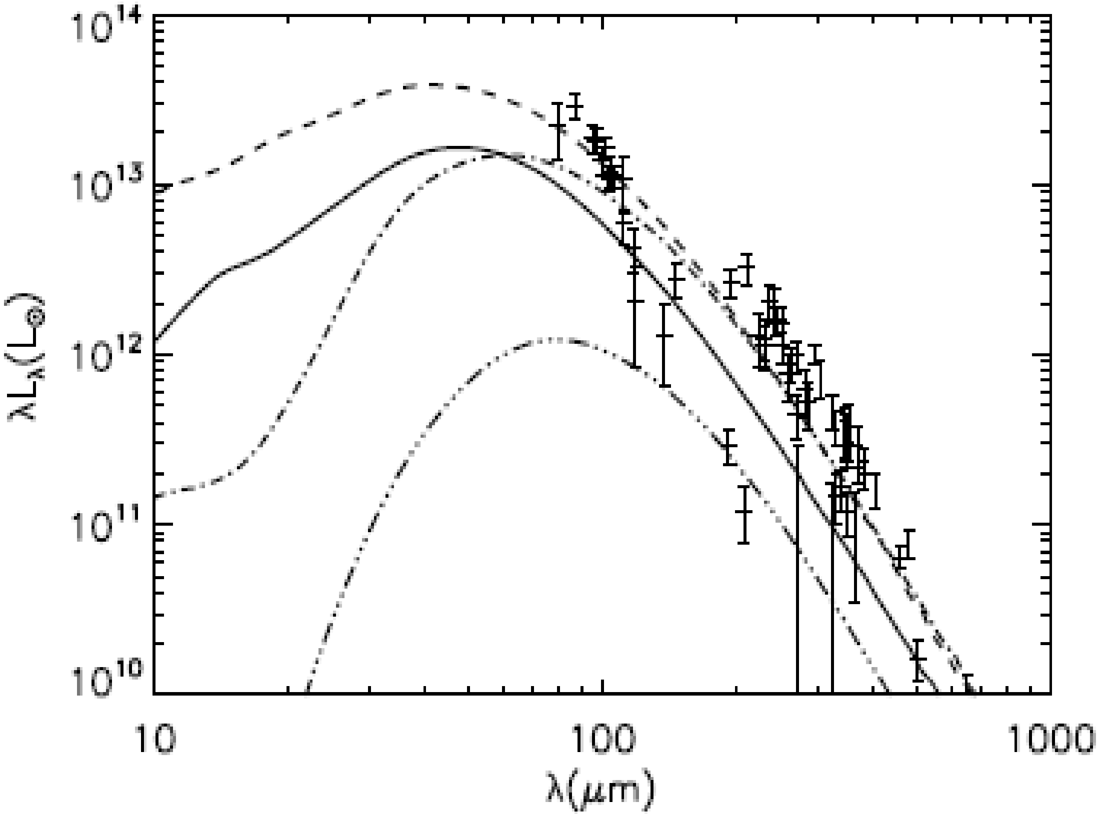
z=3 scaled merger (z3e226) in 3.6 μm and 450 μm bands
(absent from final version of paper)

Is this what they *really* look like?

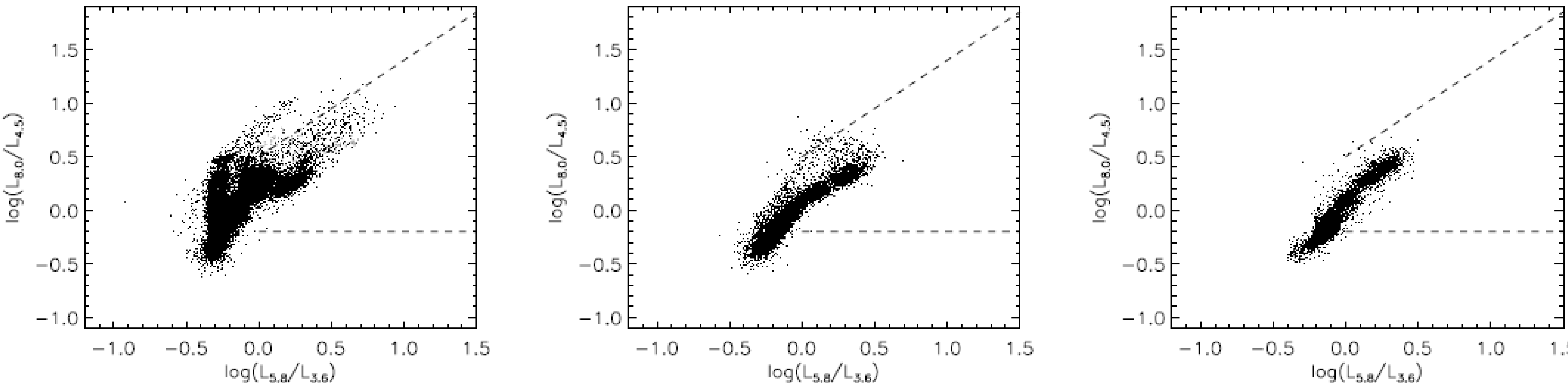
- Tempting to speculate about the differences in morphology between $z = 0$ and $z = 3$ mergers and potential to witness differences in morphology in high-res images
  - Not clear that if images alone, even of HST resolution, can determine whether models for SMGs with disk properties of $z = 0$ systems would be favored over those with properties of $z = 3$ systems
- Testing IRAC and IR/X-Ray predictions will require a large number of observations in a narrow redshift slice
- To compare 850 μm fluxes to observations, it will be necessary to disentangle the effects of lensing, and of multiple counterparts contributing to wide SCUBA field 850 μm flux, and to understand current observational biases
  - To quote the authors: “We defer this study to a future paper.” Shucks!

But wait!

- Comparison to SHARC-2 and SCUBA data
- Dash-double-dotted line is the h160 simulation, solid line is e226, dashed line is e320, and dash-dotted line is e500; all are shown close to the peak of their sub-mm bright phase
- Not too bad!



Some final pictures



IRAC color-color plot in observed frame, with all simulations placed at (a) z = 0.3, (b) z = 1, (c) z = 2. Crosses designate the continuum and squares the combined spectrum, i.e., the continuum and the PAH model

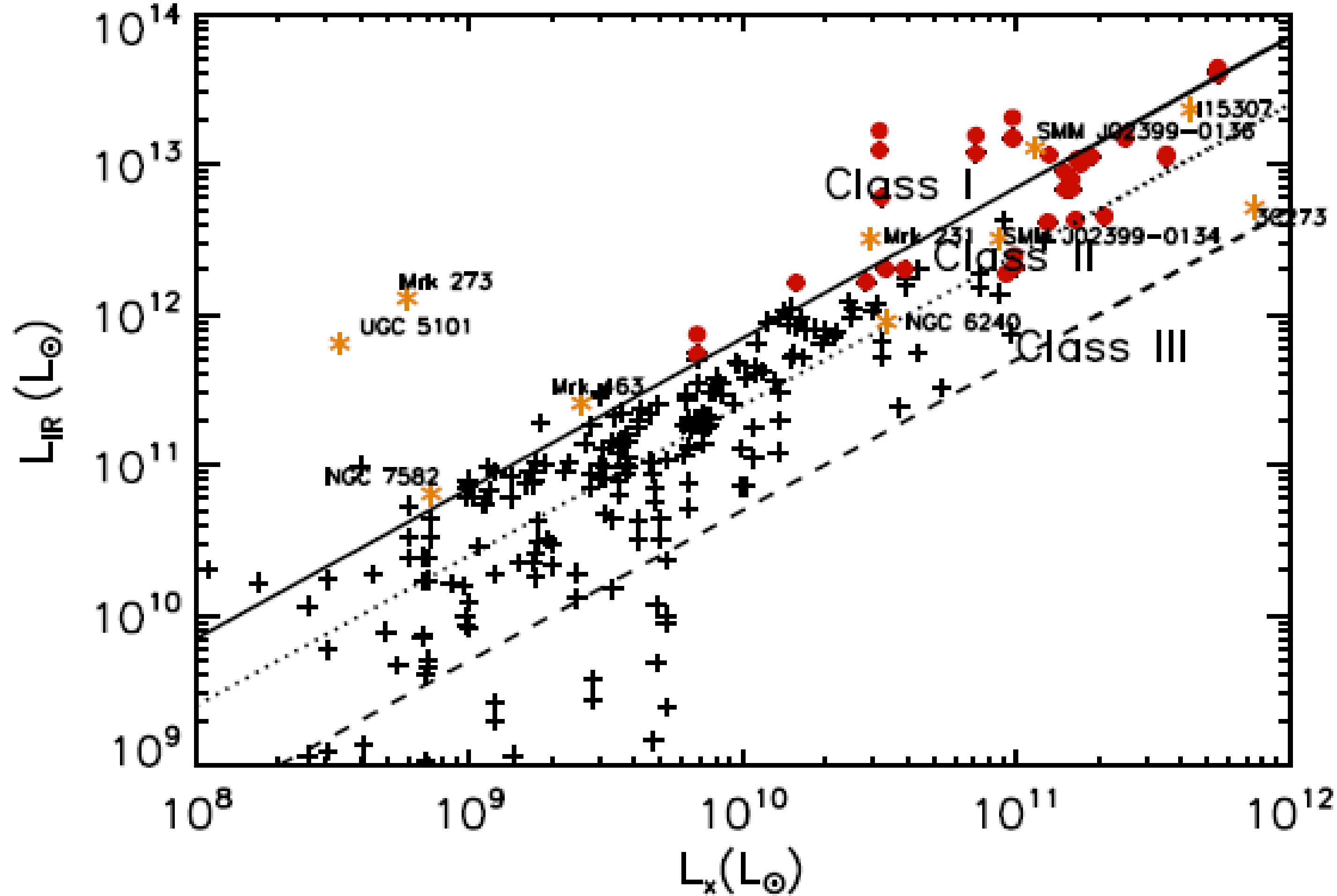
Hopefully, this is what Spitzer will see when we start looking

Conclusions

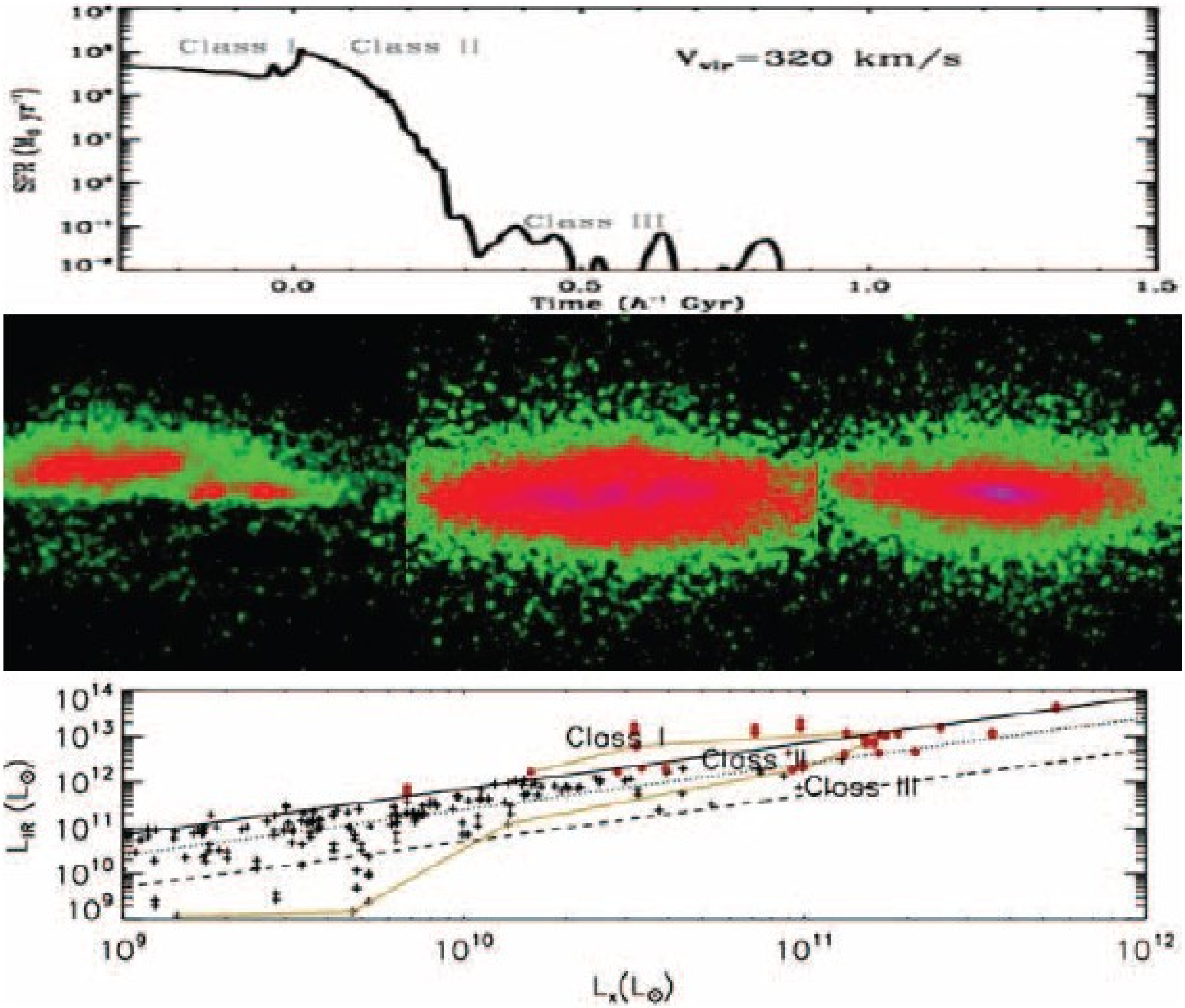
- Simulated gas-rich major mergers with black hole feedback naturally lead to the sort SMGs we have observed
- Black holes in SMGs grow rapidly, not in accordance with assumptions of Eddington-limited accretion
- Observed clustering in IRAC color-color space can be explained by merger traits and SMG evolution
- Similarities between ULIRGs and SMGs, which can be extrapolated to higher redshifts
- Correlations between far-IR and X-Ray emissions, which will be directly testable by Herschel and possibly Spitzer
- Differences in brightness between IRAC and SCUBA bands explained by co-planar vs. non co-planar mergers

Conclusions

- SEDs in good agreement with recent multiwavelength photometry
- Observed 850 μm flux explained as function of X-Ray luminosity (i.e. black hole luminosity)
- Classification scheme for SMGs: $L_{IR} \geq 70\ L_X$ is Class I, $L_{IR} \geq 25\ L_X$ is Class II, $L_{IR} \leq 5\ L_X$ is Class III
  - Can be interpreted as evolutionary scheme: SMG passes from pre-merger stage to quasar phase to merger remnant



The Class I, Class II, Class III designation scheme for SMGs: $L_{IR} \geq 70\ L_X$ is Class I, $L_{IR} \geq 25\ L_X$ is Class II, $L_{IR} \leq 5\ L_X$ is Class III. Points shown in red are those that have $F_{850\ \mu m} \geq 1$ mJy at $z = 2$; i.e., would be empirically designated as SMGs. Yellow asterisks show observed sources from the literature


Class I
Class II
Vvir=320 km/s
Class III
0.0
0.5
1.0
1.5
Time
Class I
Class II
Class III
10^{14}
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
L_{IR} ($L_{\odot}$)
10^{9}
10^{10}
10^{11}
10^{12}
L_x($L_{\odot}$)

Frequently cited papers

Springel, V. & Hernquist, L, 2003a, MNRAS, 339, 289 [SH03]

Weingartner, J., & Draine, B.T., 2001, ApJ, 548, 296 [WD01]

Kovacs, A., Chapman, S.C., et al., 2006, accepted to ApJ, Astro-ph/0604591

Chakrabarti, S., Cox, T.J., Hernquist, L., Hopkins, P.F., et al., 2006a, accepted to ApJ, astro-ph/0605652

The End

(But not the end of the scandal...)