Star Formation in Brightest Cluster Galaxies in Cool Cores:

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HST FUV: Kieran O'Dea, Alice Quillen (Rochester), Chris O'Dea, Grant Tremblay, Stefi Baum, Brad Snios, Kevin Christiansen, Jake Noel-Storr (RIT), Alastair Edge (Durham), Megan Donahue, Mark Voit (Michigan State)

The Coma Cluster

Chandra Image of the Central Region of the Coma Cluster

Properties of Rich Clusters of Galaxies

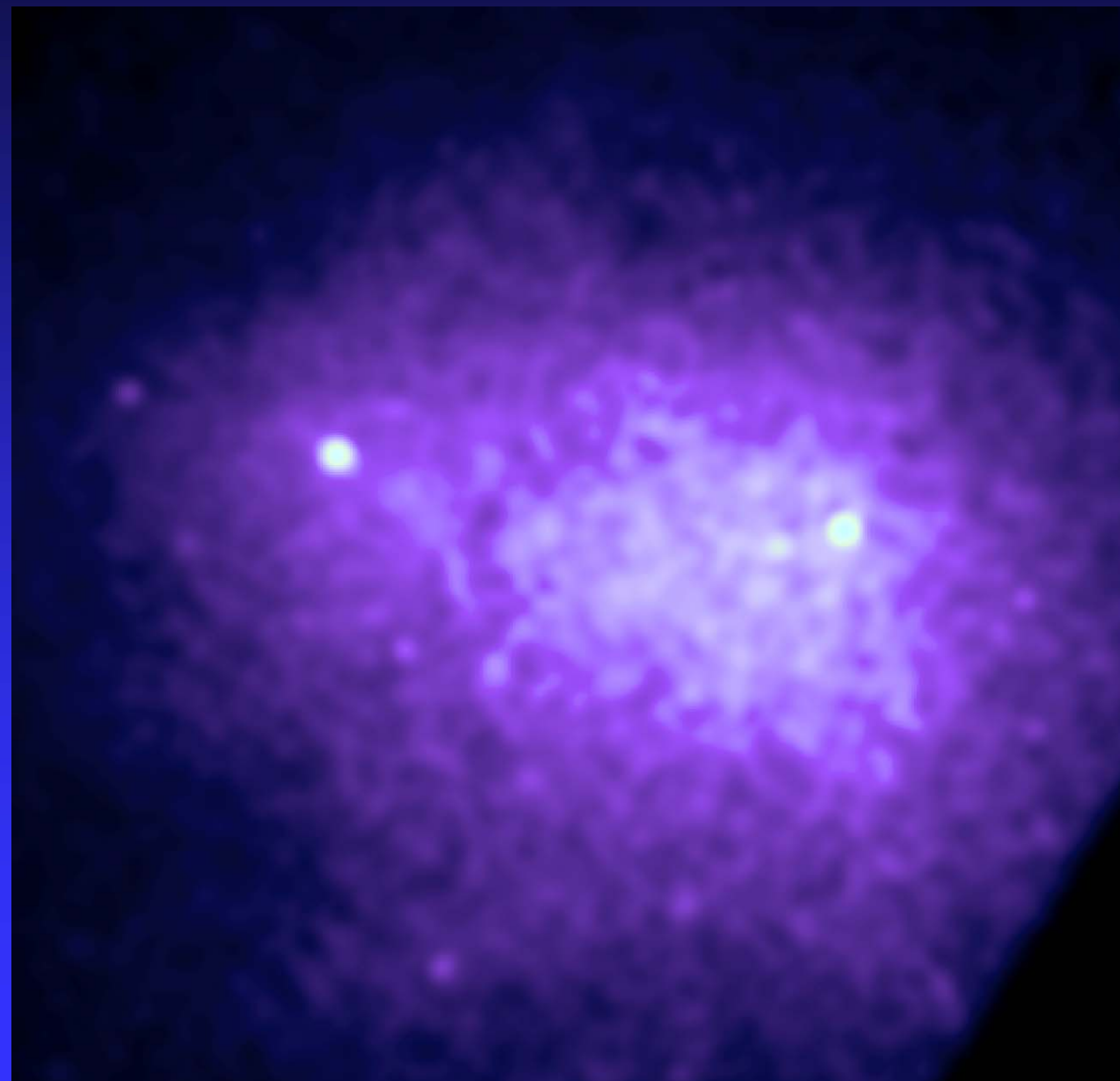
Total Mass ~ 10^{15} M$\odot$

~85% dark

~1% stars

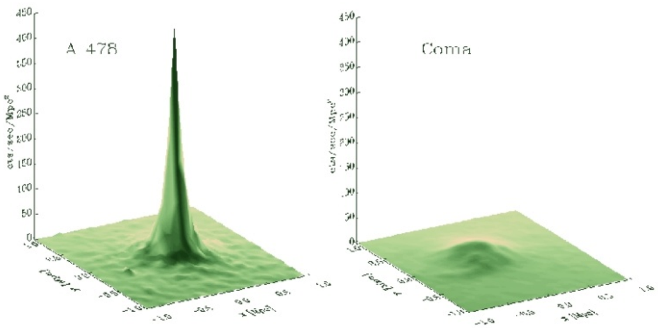
~14% hot gas

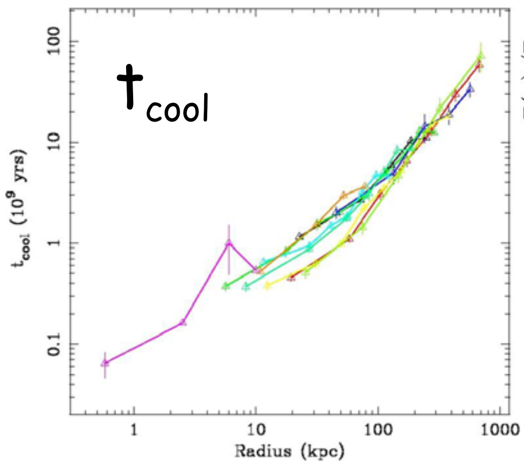
- T ~ 7 x 10^7 K
- N_e ~ 10^{-3} cm^{-3}
- L_x ~ 10^{43} – 10^{45} ergs/s

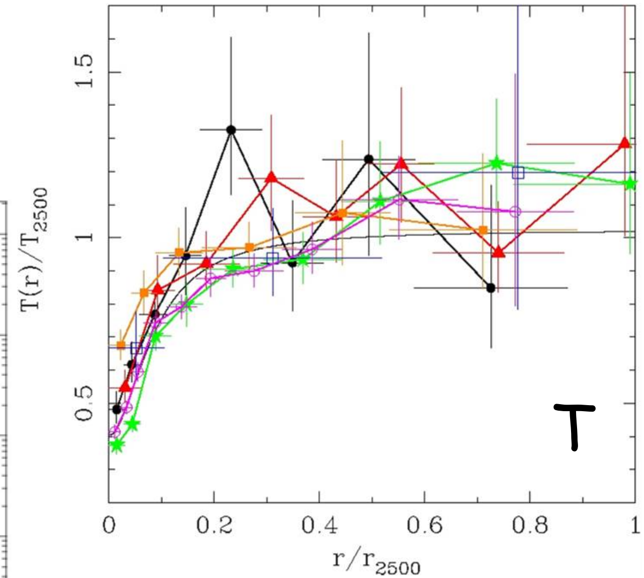


Coma Cluster

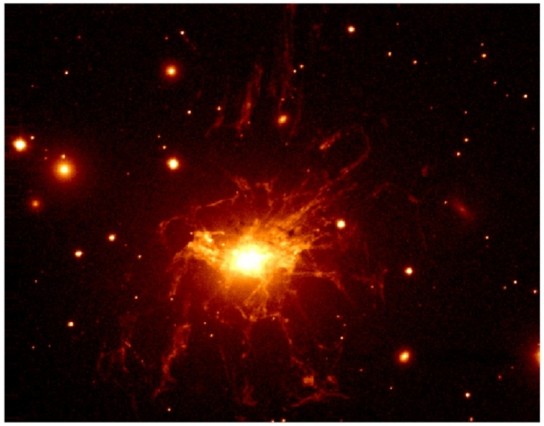
Complex Cool Cores in Clusters





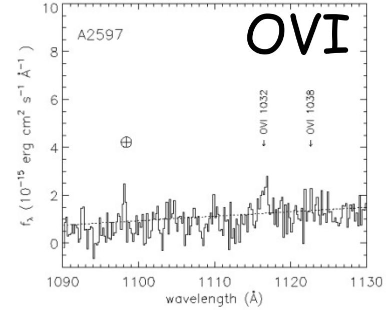


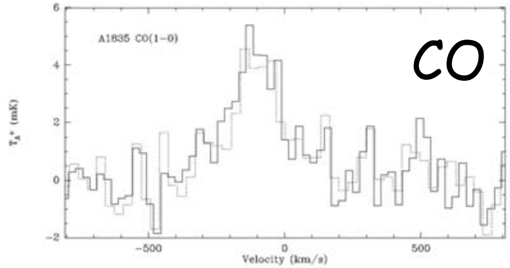
$$\dot{M}_X \approx \frac{2}{5}\frac{L\mu m}{kT}$$



10^4 K

$3\text{x}10^5$ K





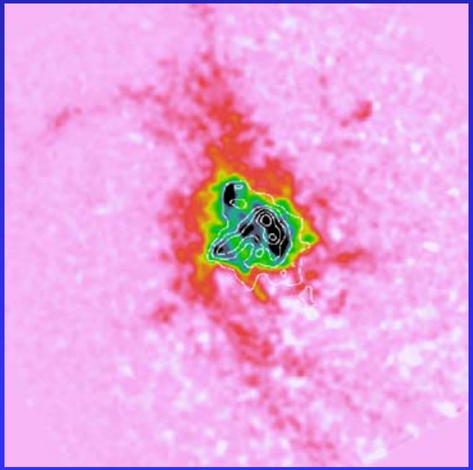
10-100 K

Fabian 2003

Motivation for a Census of Star Formation

- Some form of feedback/heating seems necessary to explain:
  - the lack of intermediate temperature gas in X-ray spectra of the ICM of "cool core" clusters (e.g., Peterson & Fabian 2006, McNamara & Nulsen 2007).
  - the luminosity function of galaxies (e.g., Benson et al 2003; Binney 2004; talk by Bower),
  - the entropy of the ICM (e.g., Voit and Bryan 2001)
- Star formation is likely to be the ultimate sink for any cooling gas in the cool core clusters.
  - We can determine the actual amount of gas which cools.
  - Star Formation provides a constraint on the ability of heating to stop catastrophic cooling in the ICM.
- Thus, we undertook a census of star formation in Brightest Cluster Galaxies (BCGs) using Spitzer.

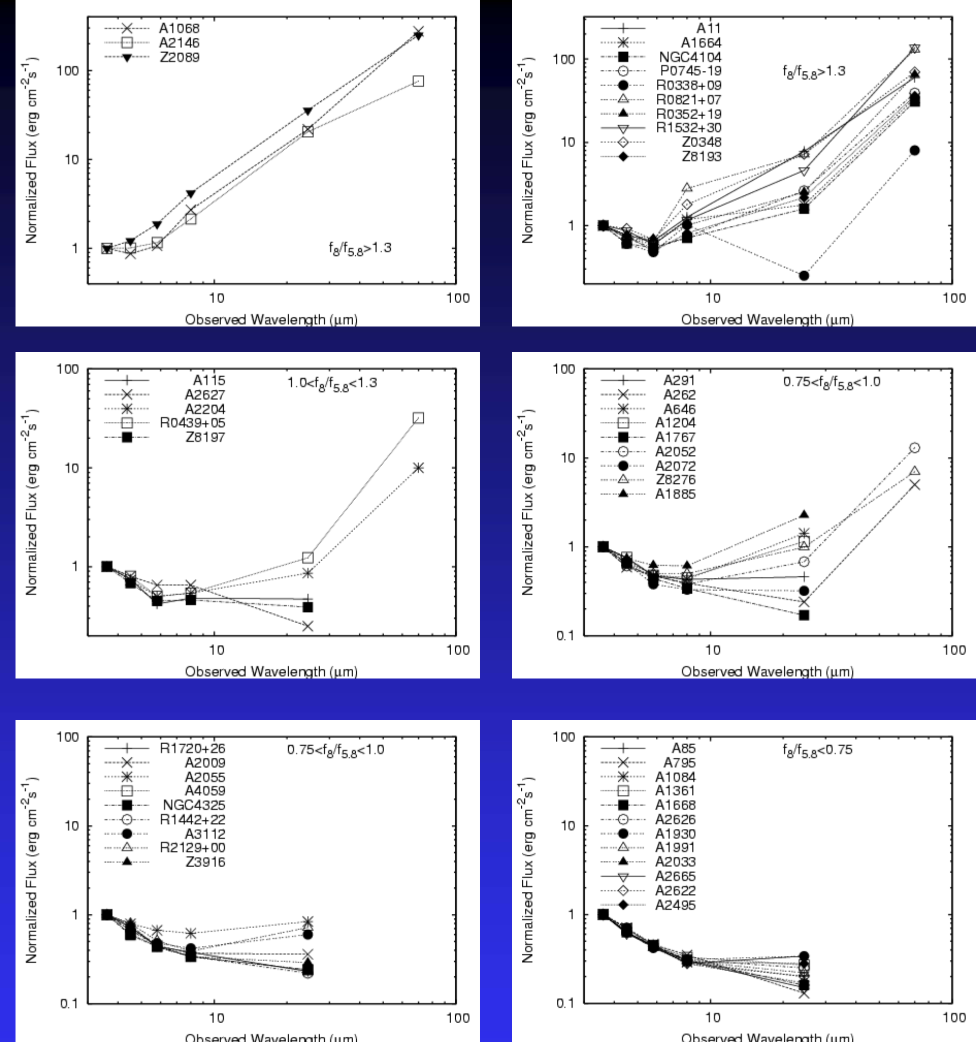
Van Gogh 1889



A2597. Color image of smoothed Lyα emission line with contours of FUV continuum. (O'Dea, Baum, Koekemoer, Mack, & Laor 2004)

Spitzer SEDs of 62 BCGs in Cool Cores

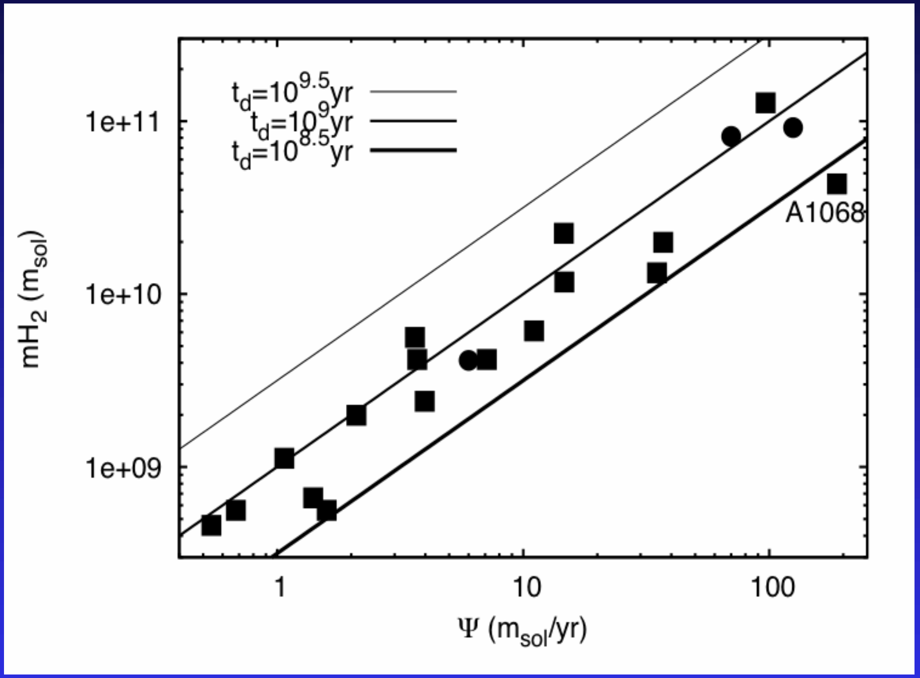
- ~1/2 have an IR excess: $F_{8\mu m}/F_{5.8\mu m} > 0.75$ and/or detection at 70 μm
- 4 sources are likely AGN dominated in the IR (A1068, A2146, Zw2089, R0821+07) as indicated by hot dust seen in the near-IR and/or high [OIII]/Hβ in the optical spectrum.
- The IR excess in the non-AGN BCGs is powered by star formation.
- Estimated SFR ≤1 to 100 M_o/yr. (But highest SFR have contribution from AGN). These BCGs are certainly star *forming*, but not star *bursting*.



Observed SEDs of the 62 BCGs, grouped by color. (Top Left). 3 BCGs likely AGN dominated. (Top Right). $F_{8\mu m}/F_{5.8\mu m} > 1.3$, all detected at 70μm. (Left Middle). $0.98 < F_{8\mu m}/F_{5.8\mu m} < 1.3$. (Right Middle). $0.75 < F_{8\mu m}/F_{5.8\mu m} < 0.98$. (Left and Right Bottom). $F_{8\mu m}/F_{5.8\mu m} < 0.75$. (Quillen et al. 2008, ApJS, 176, 39)

Correlation of Molecular Gas Mass and Star Formation Rate

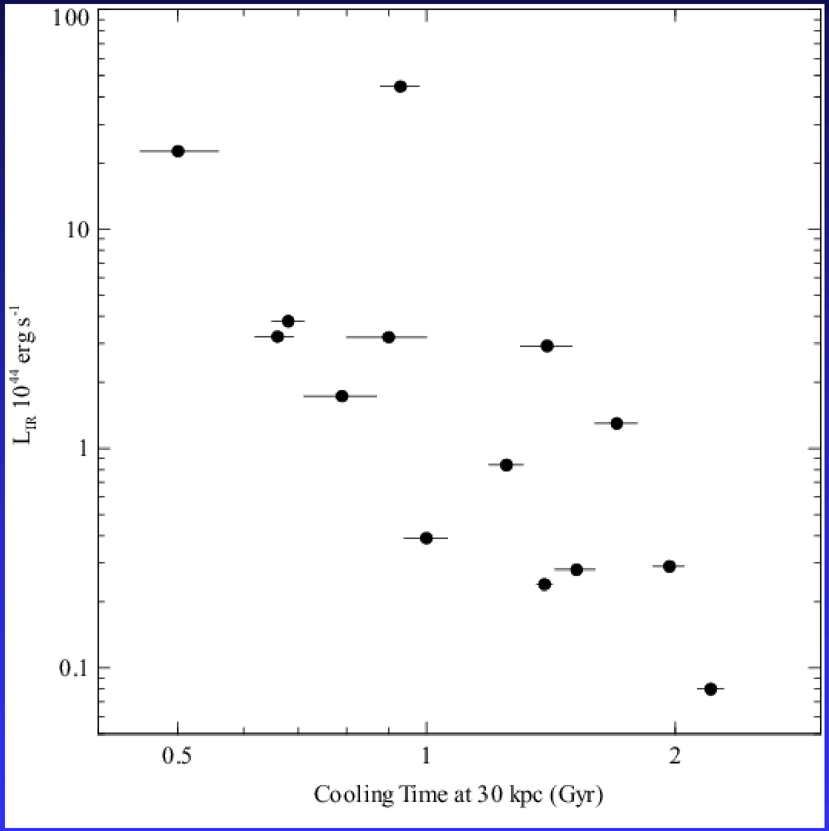
- Star formation rate <1 to ~100 $M_\odot$/yr.
- Star formation rate is proportional to the mass of molecular gas.
- Gas depletion time scale is ≤ 1 Gyr consistent with gas depletion time scale in normal star forming galaxies (e.g., Young et al. 1986).
- 4-6 Gyr since last major cluster merger, so there may not have been enough time for a steady state to be set up (cooling leads to cold gas leads to star formation).



Molecular gas mass (from CO) vs. estimated star formation rate (SFR) for the BCGs. We estimate the SFR from the IR luminosity following Bell (2003). The solid lines show gas depletion time scales. (O'Dea et al. 2008, ApJ, 681, 1035)

IR Luminosity vs. Cooling Time

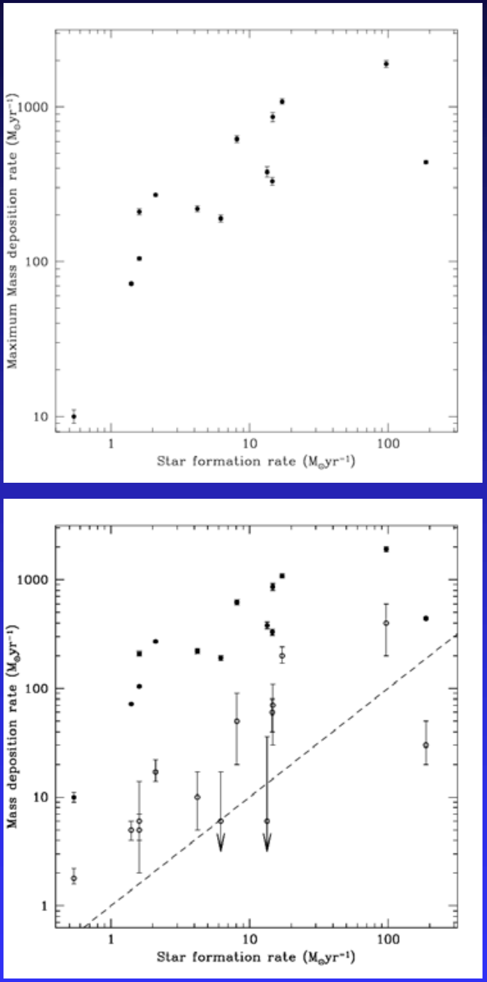
- BCGs have higher IR luminosity in clusters with shorter cooling times for the hot ICM.
- The gas at a few x10^7 K and ~25 K are related.
- This is consistent with gas cooling from the hot ICM to molecular gas and forming stars.
- This correlation is not destroyed, and possibly even maintained by heating?



IR luminosity vs X-ray derived cooling time for the hot ICM at a radius of 30 kpc. BCGs have higher IR luminosity in clusters with shorter cooling times. (O'Dea et al. 2008, ApJ, 681, 1035)

Correlation of Mass Accretion Rate and Star Formation Rate

- The estimated mass accretion rate from cooling gas is proportional to the estimated star formation rate.
  - This suggests that the cooling ICM is the source of the star forming gas.
- However, the SFR is a factor of 30-100 (reduce by factor ~5 to account for difference in volumes) smaller than the maximum (imaging) mass accretion rate, but within a factor of a few of the "spectroscopic" m-dot.
- This suggests the re-heating mechanism on average supplies most (~90%) of the energy radiated by the hot ICM.
- The heating mechanism cannot be turned off for a time longer than the gas cooling time.
  - operates with a high duty cycle (i.e., active most of the time) and is is very effective over a range of size scales.



X-ray derived mass deposition rate upper limits vs. estimated star formation rates. The closed circles correspond to maximum mass deposition rates, M_I, if heating is absent, derived from X-ray images. (O'Dea et al. 2008, ApJ, 681, 1035)

HST FUV Images of Star Formation

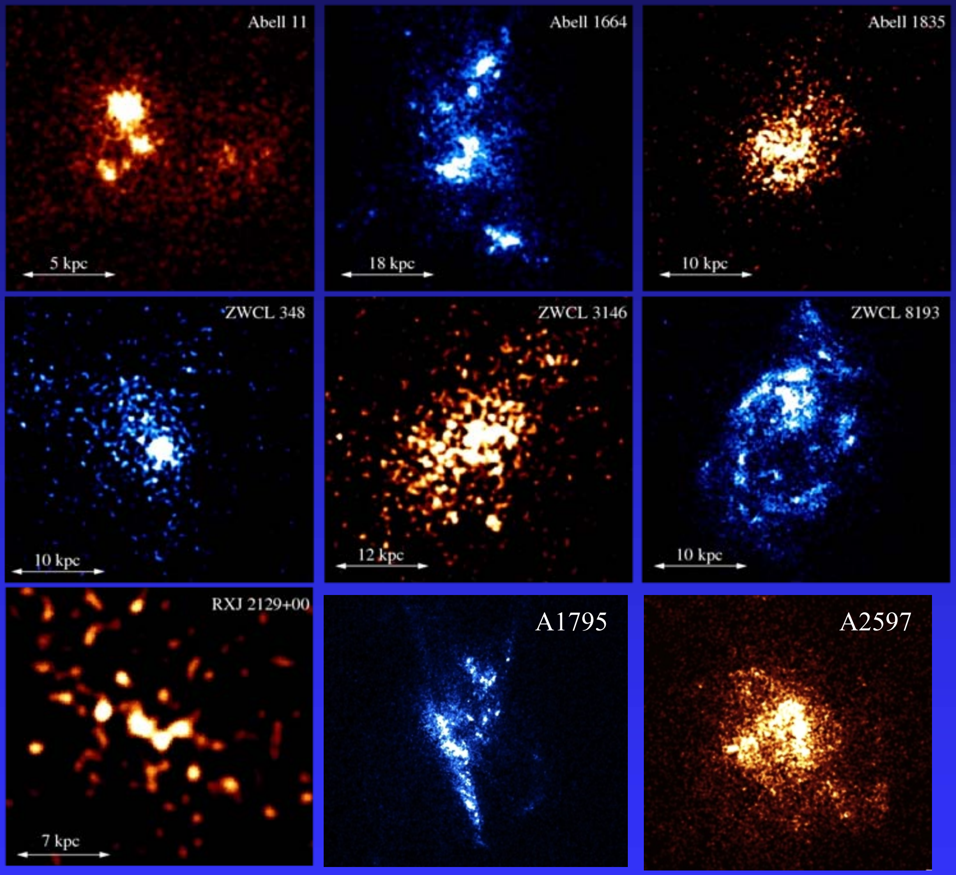
All BCGs with a MIR excess show FUV continuum extended on scales of ~10-30 kpc.

This suggests MIR excess is indeed associated with on-going star formation.

The emission consists of small clumps and filaments (details are influenced by dust).

The spatial extent is consistent with Schmidt-Kennicutt (but no disks?)

SFR are ~ 1-12 M_o/yr which is a factor of ~ 3 to 14 smaller then inferred in the IR, consistent with internal extinction.



HST FUV emission (~1500 Å rest frame, ½ orbit) of BCGs with MIR excess (O'Dea et al 2004,ApJ, 612,131, and 2010, ApJ, 719, 1619)

Summary

- Spitzer reveals that BCGs in cool core clusters show star formation in the range ~1-50 solar masses per year. This is 1-2 orders of magnitude less than the "imaging" m-dots, but within a factor of a few of the "spectroscopic" m-dots.
- HST reveals that the star formation occurs on scales of ~10-30 kpc.
- The gas depletion time scales are ≤ 1 Gyr.
- Star formation rates are higher in BCGs with shorter ICM cooling times.

Implications/Speculation

- Heating reduces the amount of cooling gas, but some gas does still manage to cool and form stars. Depending on assumptions, this could provide a few percent of the BCG stellar mass.
- So heating does not dominate everywhere all the time, though on average heating needs to dominate to keep the star formation rates low.
- The star formation seems to proceed in a relatively "normal" way. Perhaps AGN feedback mainly affects the hot gas while the dense molecular clouds are decoupled from the AGN feedback?