Star Formation and AGN Heating in Brightest Cluster Galaxies in Cool Cores

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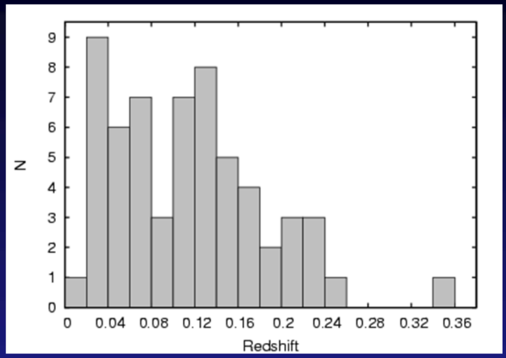
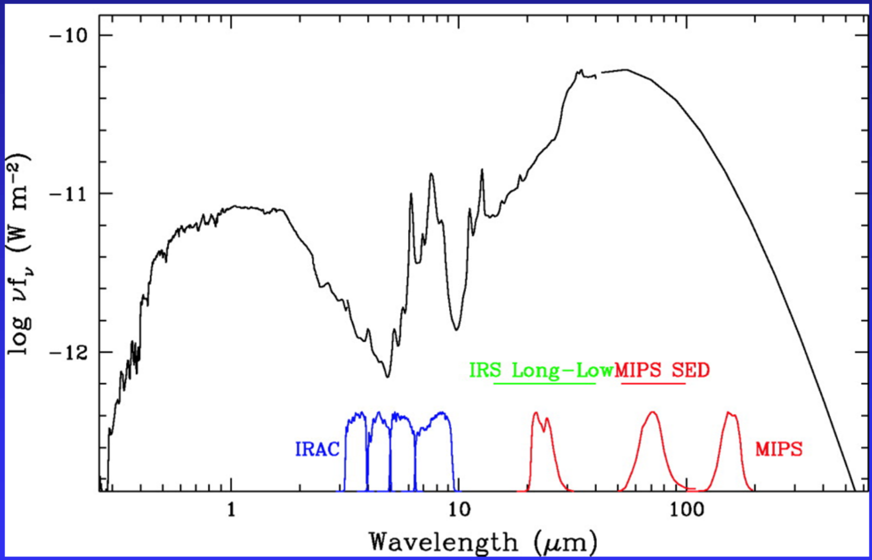
The BCG Sample

- Total of 62 Brightest Cluster Galaxies (BCGs) selected on Cluster X-ray and BCG Hα emission
- The selection tends to favor BCGs in "cool core" clusters
- Obtained Spitzer Observations
  - IRAC Imaging 3.6, 4.5, 5.8, and 8 μm
  - MIPS Imaging 24 and 70 μm



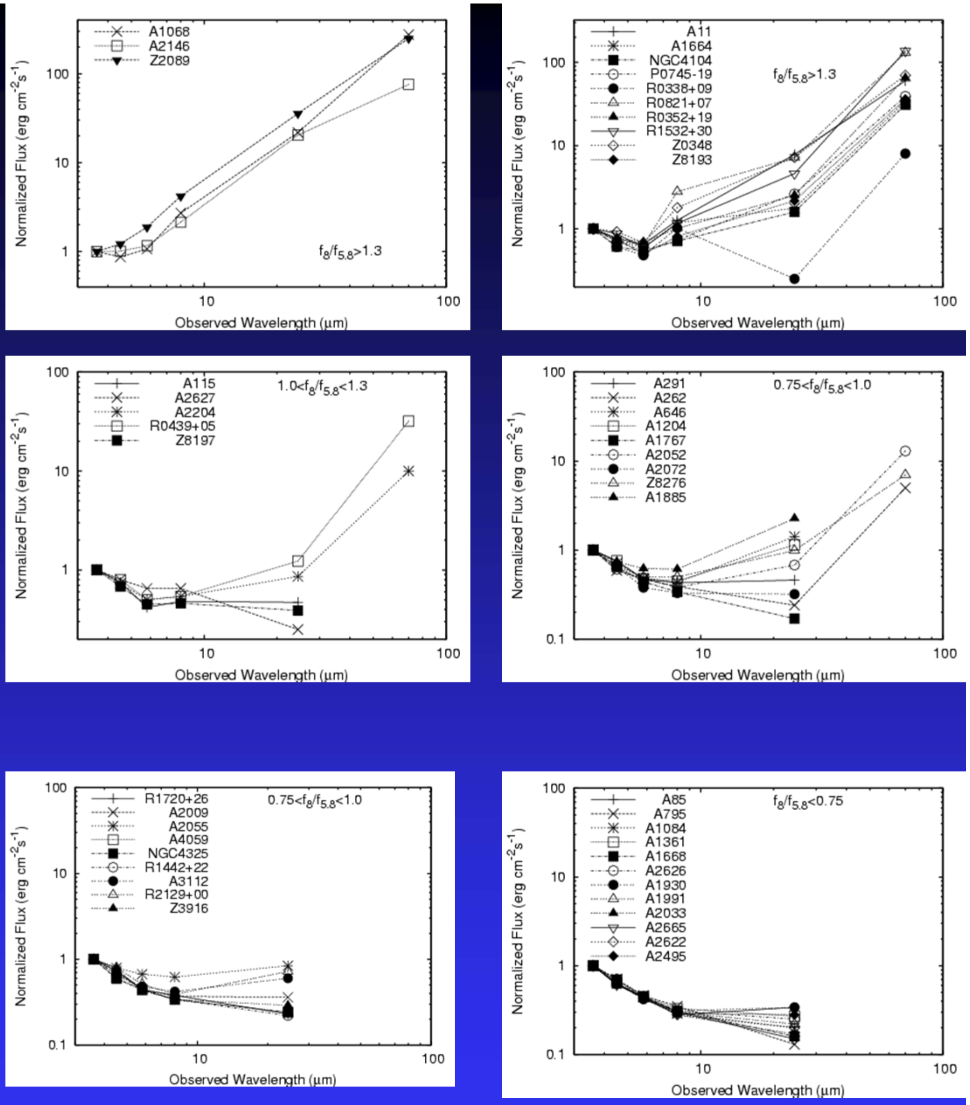
Redshift



Schematic spectrum of star forming galaxy showing location of Spitzer bandpasses (Kennicutt et al 2003).

Spitzer SEDs of 62 BCGs in Cool Cores

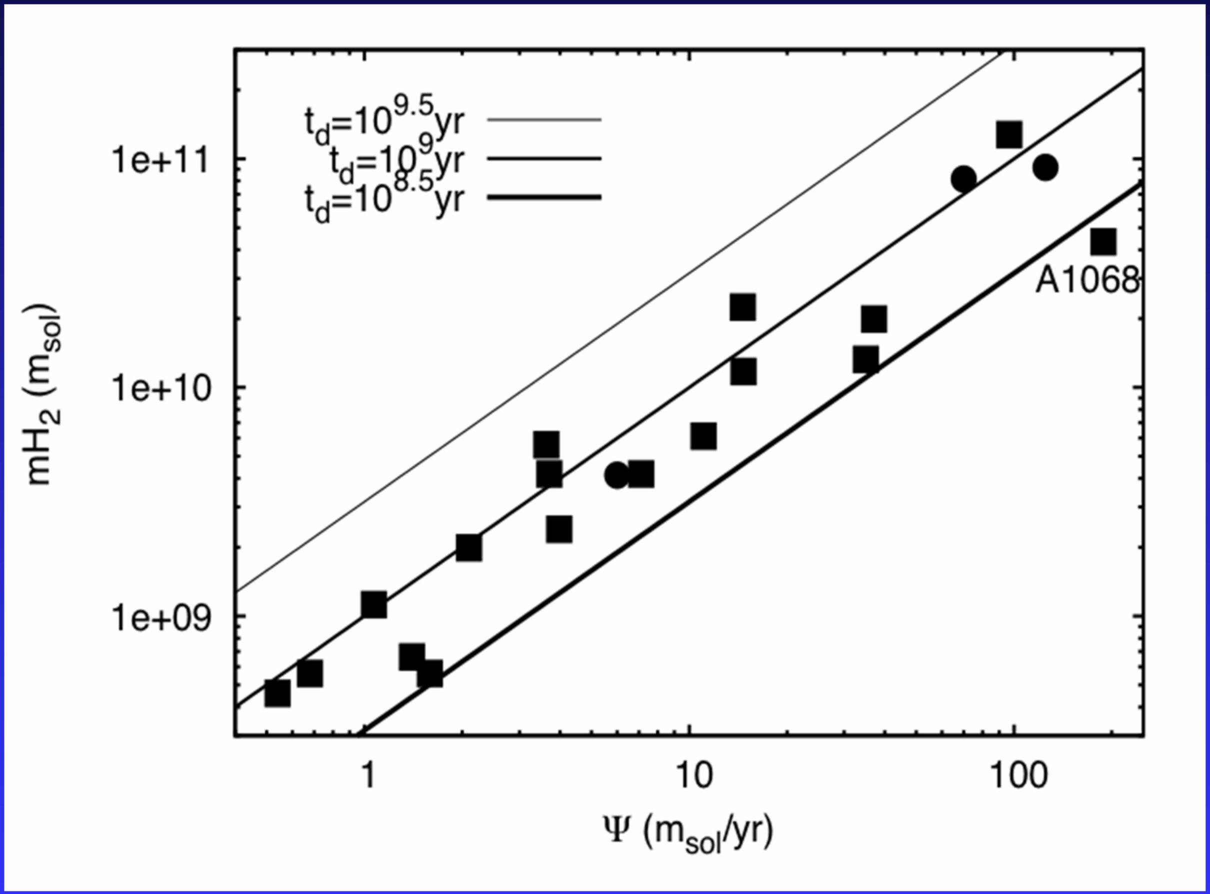
- 50% show IR excess likely due to star formation.
- 3-4 show hot dust due to optically bright AGN



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)

Molecular Gas Mass ~ Star Formation Rate

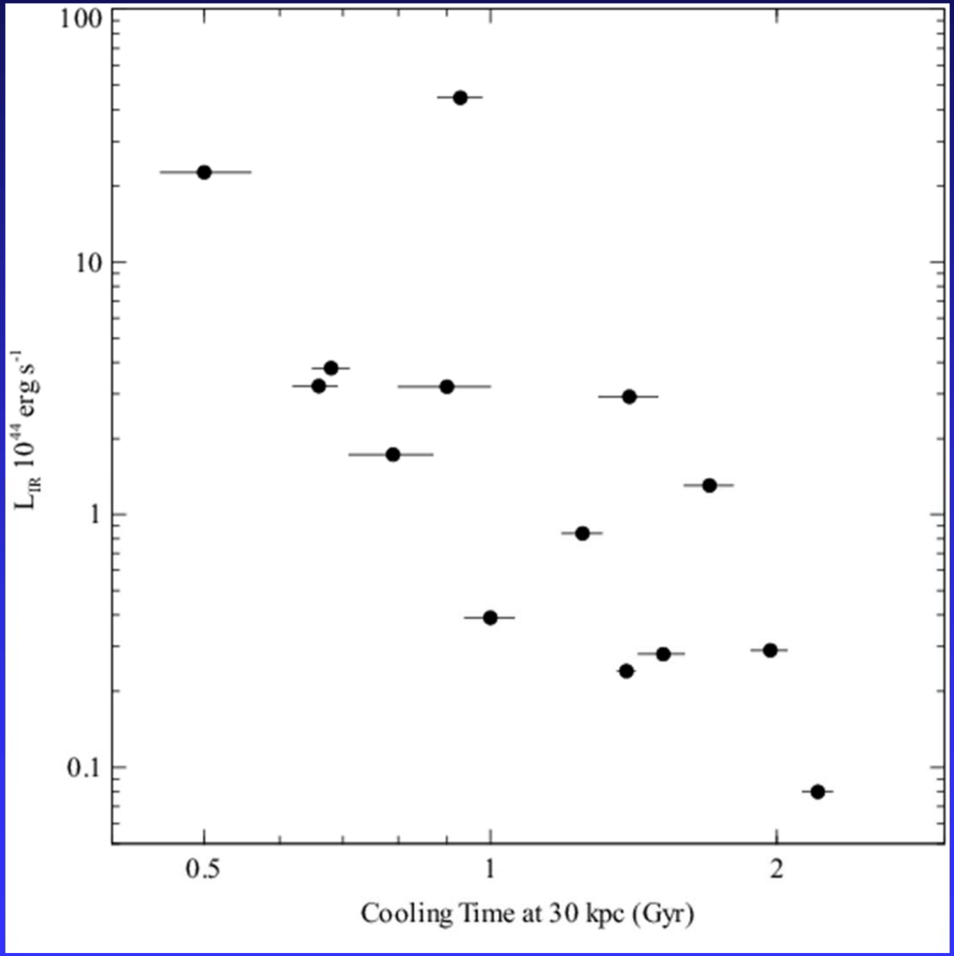
- Molecular gas reservoir 10^8 to
- 10^{11} Mo
- Gas depletion time scale ~ 1Gyr



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)

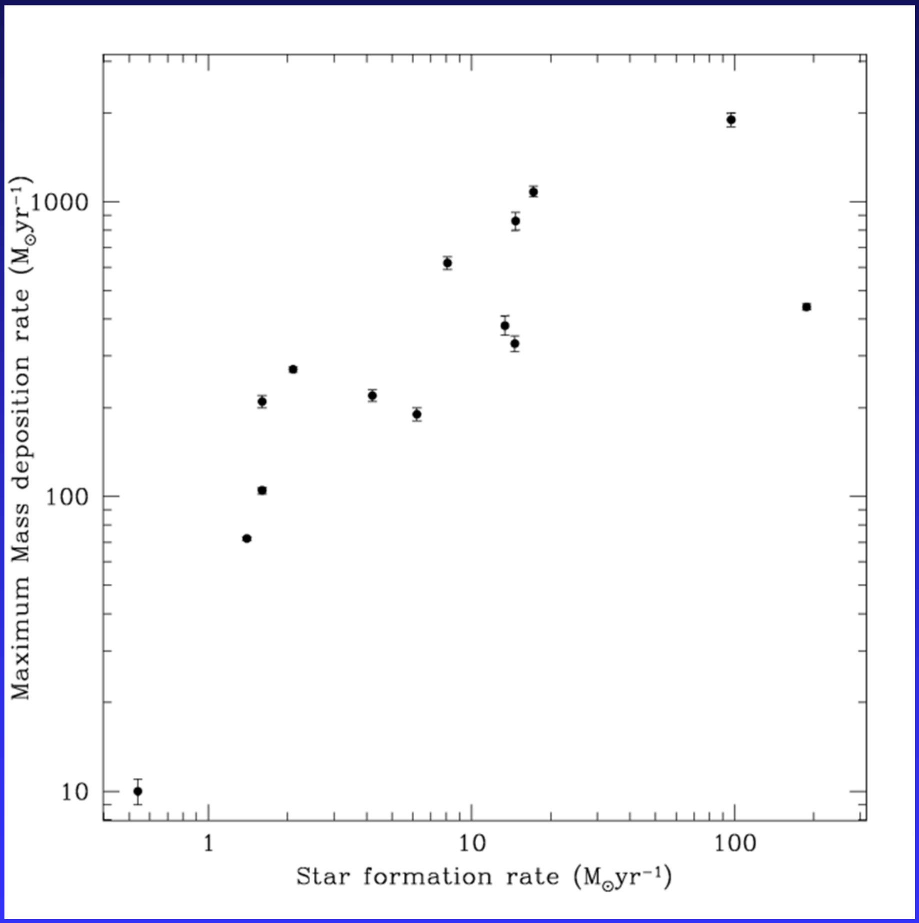
IR Luminosity ~ X-ray Cooling Time

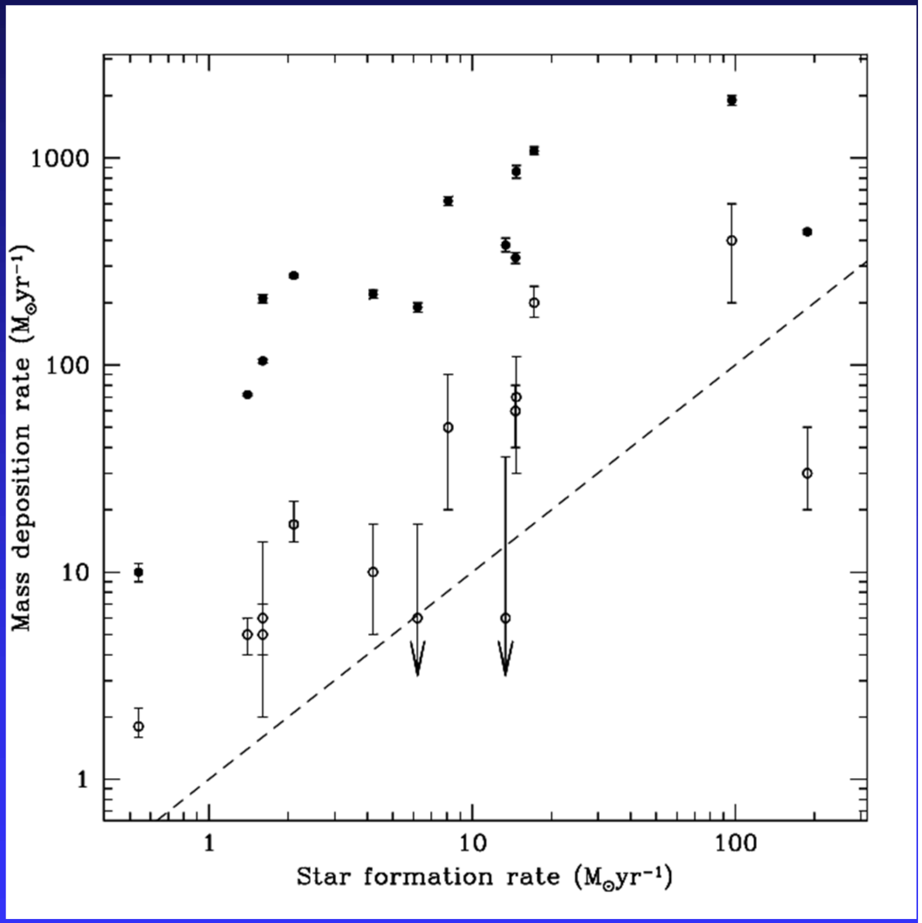
- BCGs have higher IR luminosity in clusters with shorter cooling times.
- Suggests the gas forming stars has cooled from the hot ICM.



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)

Fixed Fraction of the Hot Gas Cools

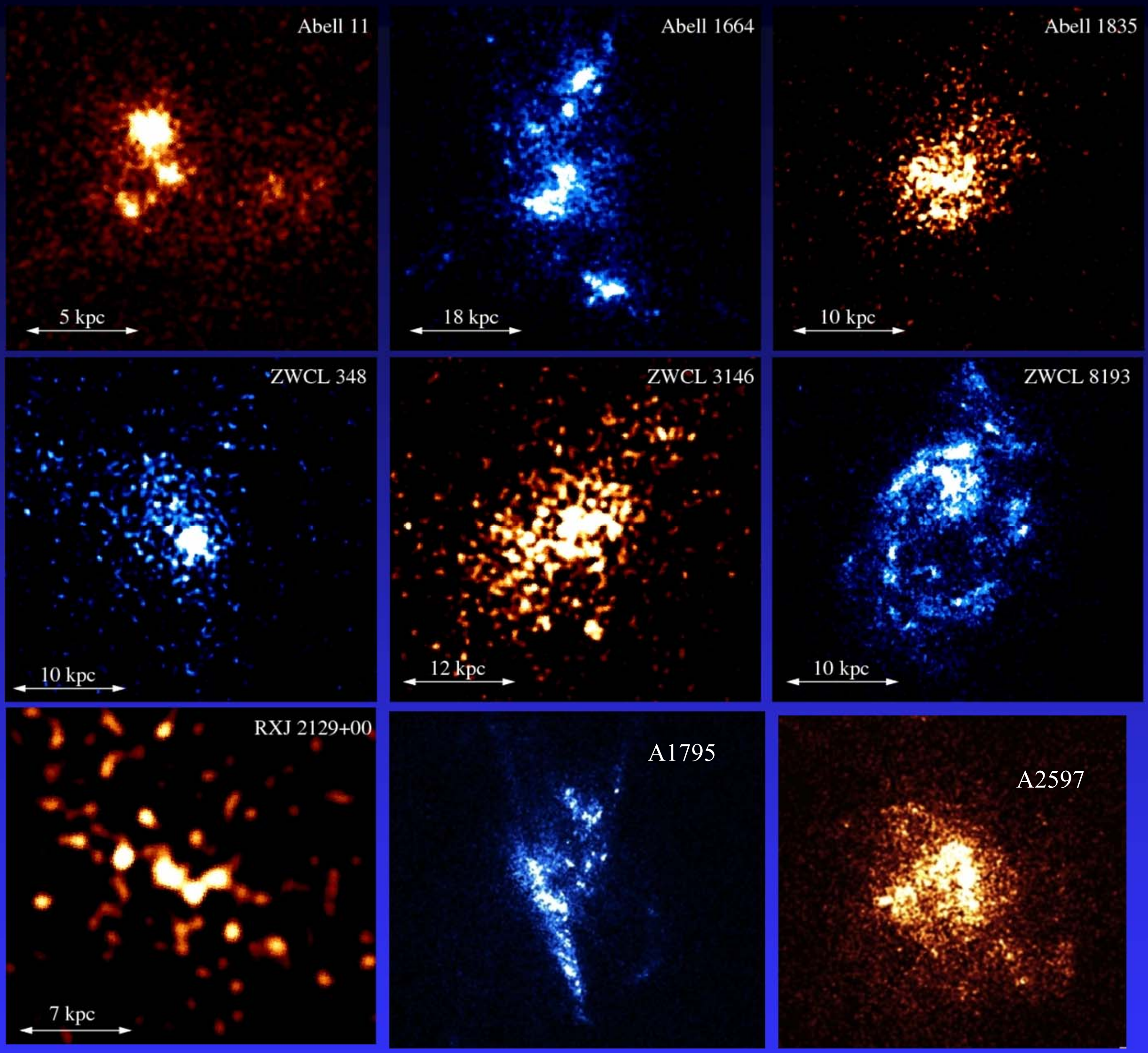




X-ray derived mass deposition rate upper limits vs. estimated star formation rates. The closed circles correspond to maximum mass deposition rates, M_I, if heating is absent, derived from X-ray images. (O'Dea et al. 2008, ApJ, 681, 1035)

Star Formation

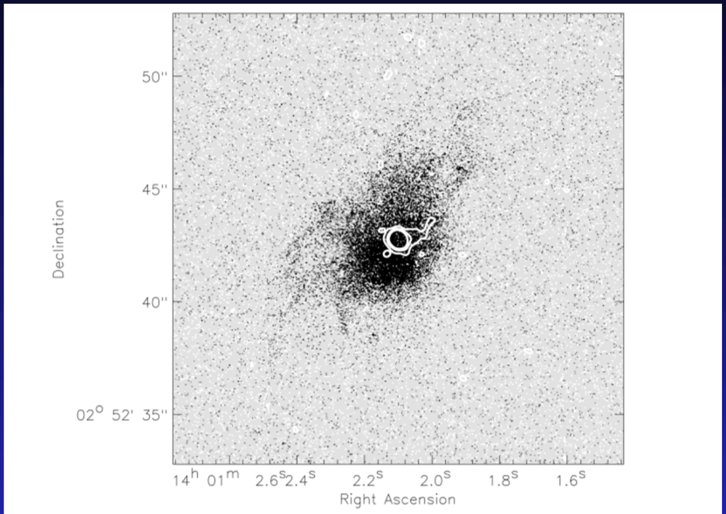
- Extended star formation (~10-30 kpc) found so far in all BCGs with a mid-IR excess.
- FUV derived SFR are a factor of a few less than the IR-estimated rates, probably due to internal extinction.
- Clumpy and Filamentary star formation. Disks are rare.

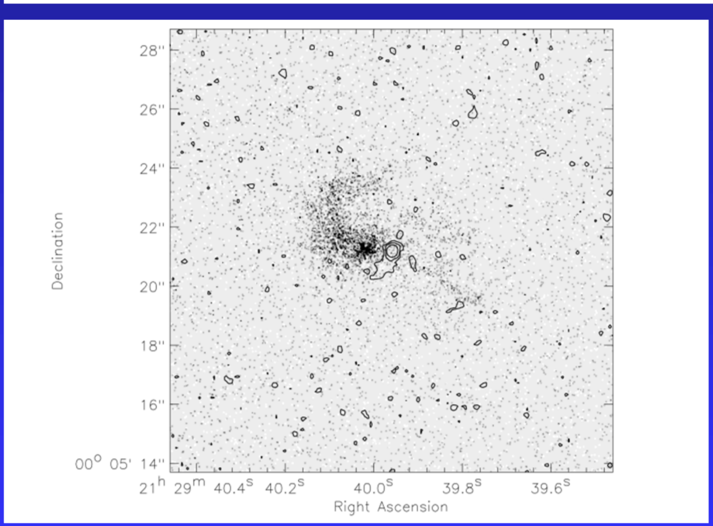


HST FUV emission (~1500 Å rest frame, ½ orbit) of BCGs with MIR excess (O'Dea et al 2004,ApJ, 612,131, and 2010, ApJ, 719, 1619)

Weaker Radio Sources Associated with Stronger Star Formation?

- A1835 and RXJ2129+00 exhibit weak kpc scale jets which show no relation to the FUV or Lyα. The other 5 BCGs studied by O'Dea et al 2010 show only faint unresolved steep spectrum radio sources
- These sources have weaker radio sources and higher star formation rates than the more power radio sources in A1795 and A2597.





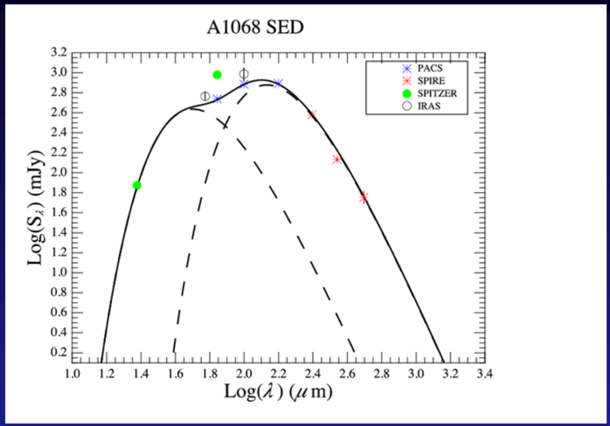
VLA radio contours on grey scale Lyα (Top) A1835. (Bottom) RXJ 2129+00 (O'Dea et al. 2010).

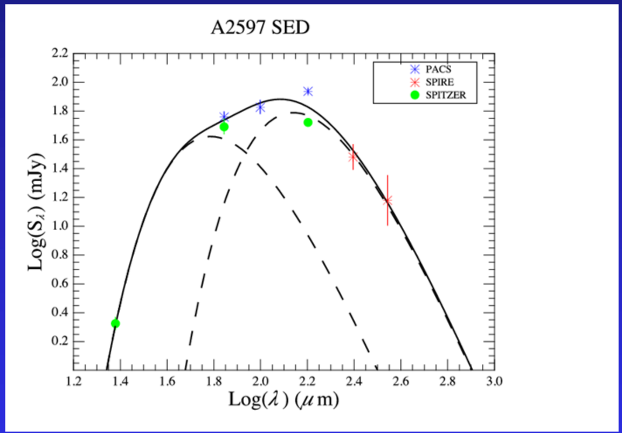
DUST SEDs

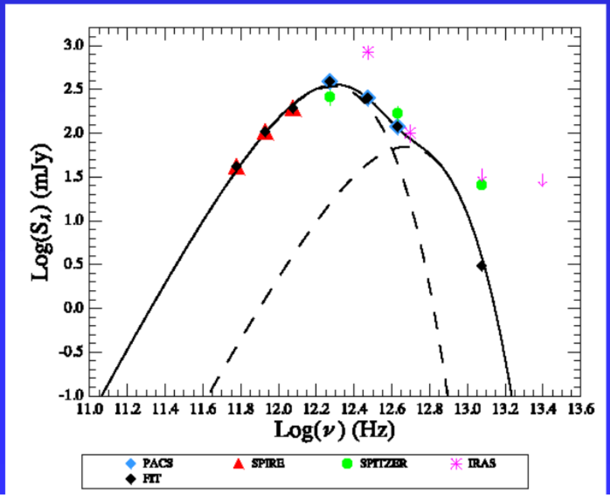
SED requires dust at two temperatures: ~ 20 K and ~50 K. The lower temperature is consistent with the gas temperature from CO.

Cold dust mass ~10^7 to 10^8 $M_☉$ consistent with CO mass for gas/dust ~ 100 (most of the mass in the colder component).

Agreement of temperature and mass estimates suggest that dust is embedded in the star forming gas.







Infrared SED of A1068 (top) and A2597 (middle), NGC4696 (bottom). IRAS, Spitzer, PACS, and SPIRE photometry are shown along with a two temperature modified-BB fit. (Edge et al 2010, Mittal et al. 2011)

A2597: Star Formation Amidst AGN Feedback

PhD Thesis by Grant Tremblay

A2597 SED

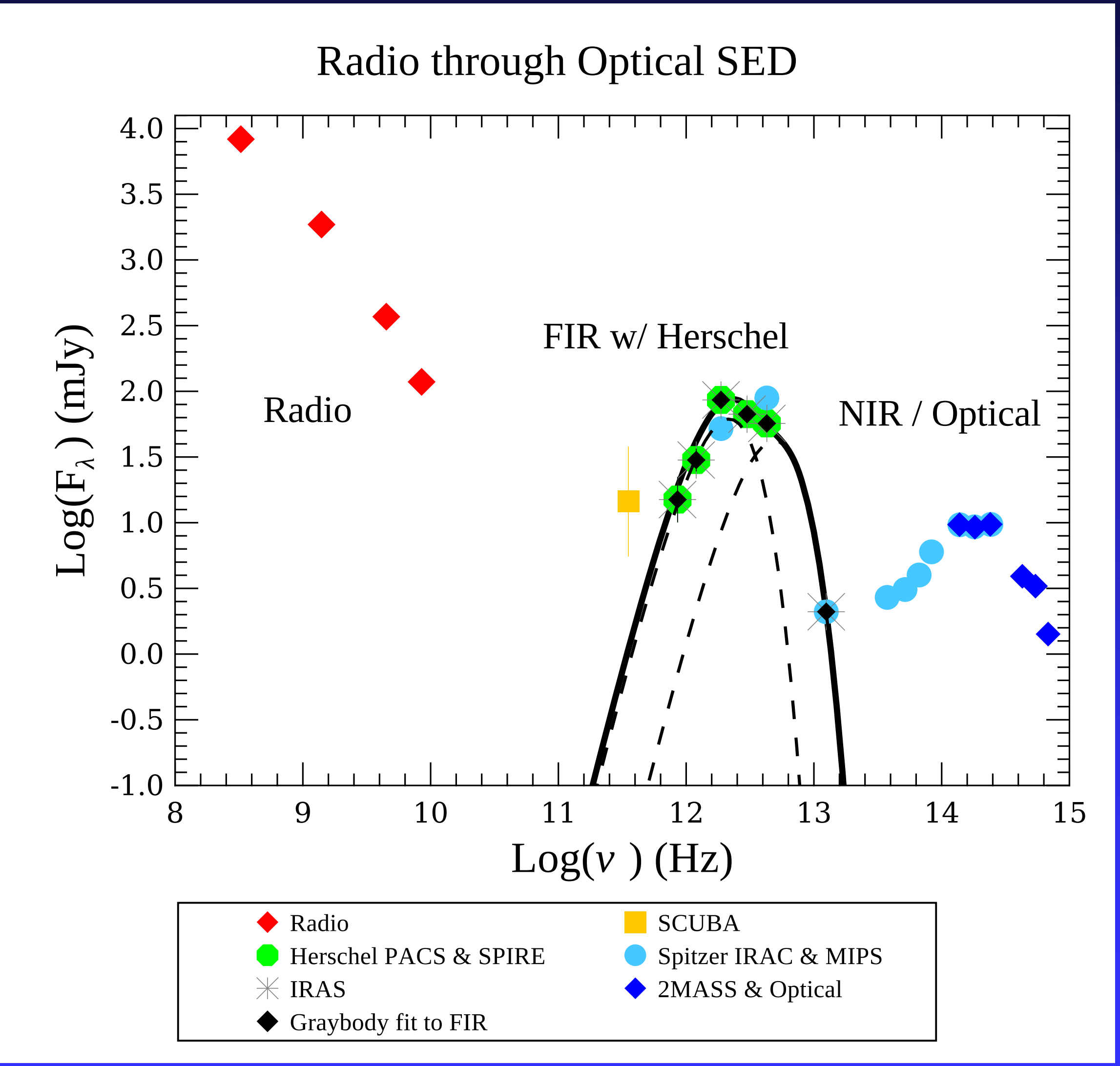
Data consistent with two component fit (could be range of T).

Cold: : T~47 K, M~1.7x10^5 Mo

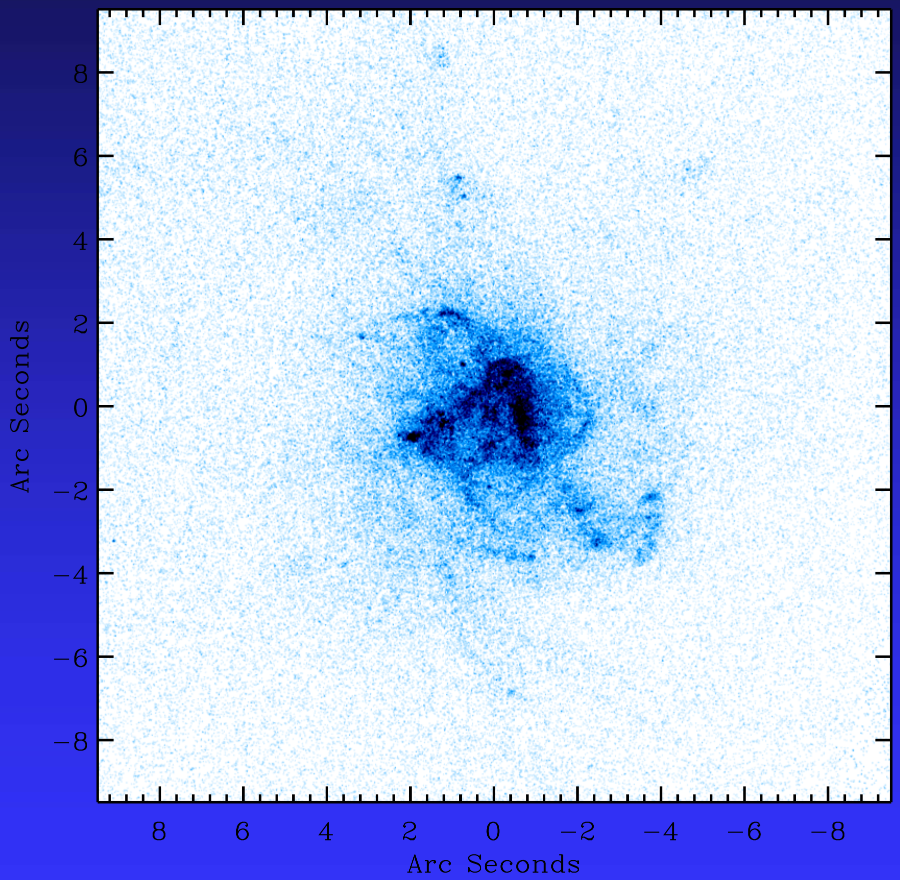
Colder: T~20 K, M~1.3x10^7 Mo

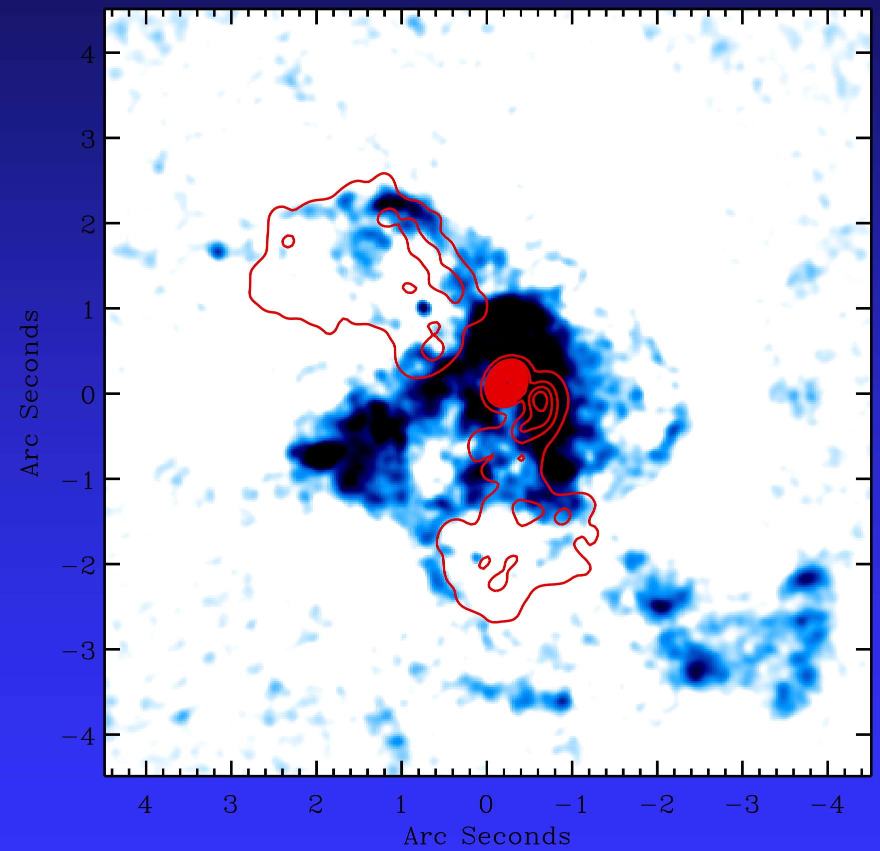
SFR ~ 3 M_o/yr

Herschel PACS and SPIRE photometry combined with additional data (Tremblay+ 2012b, MNRAS, 424, 1042).



Relationship between the Radio Source and Star Formation

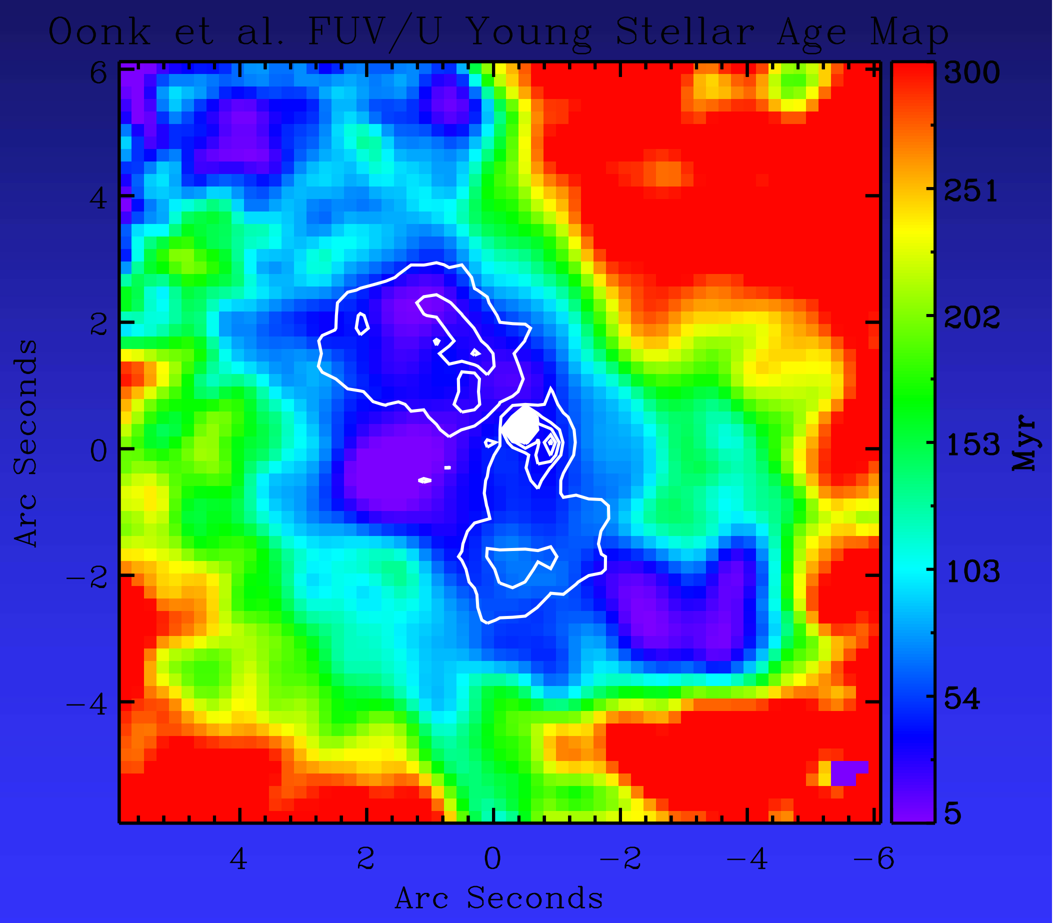




A2597. (Left) HST SBC F150LP FUV continuum image (Oonk et al. 2010). (Right) Blow up of "residual" image which emphasizes filamentary structures (Tremblay+2012b)

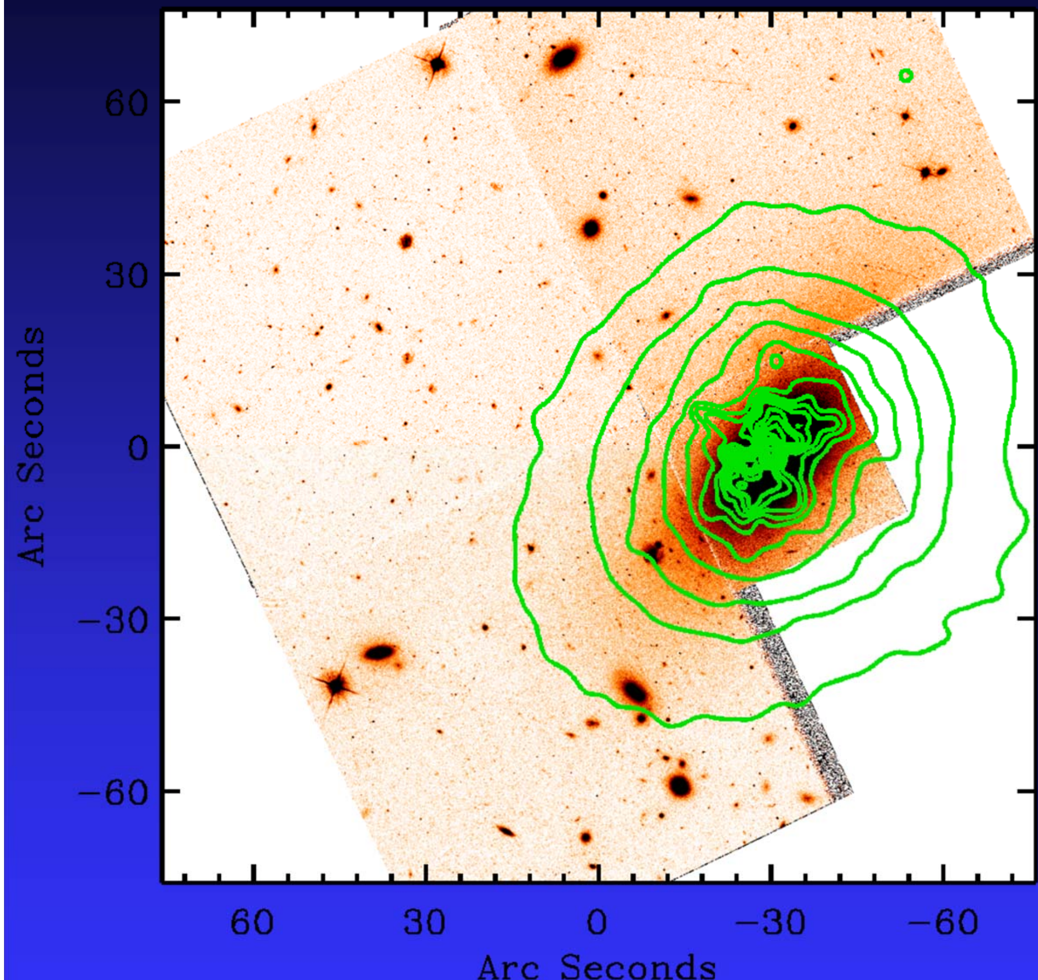
Stellar Ages Decrease Toward the Radio Source

Stellar ages range from ~300 Myr on larger scales to ~ 5 Myr on smaller scales (associated with the radio source).

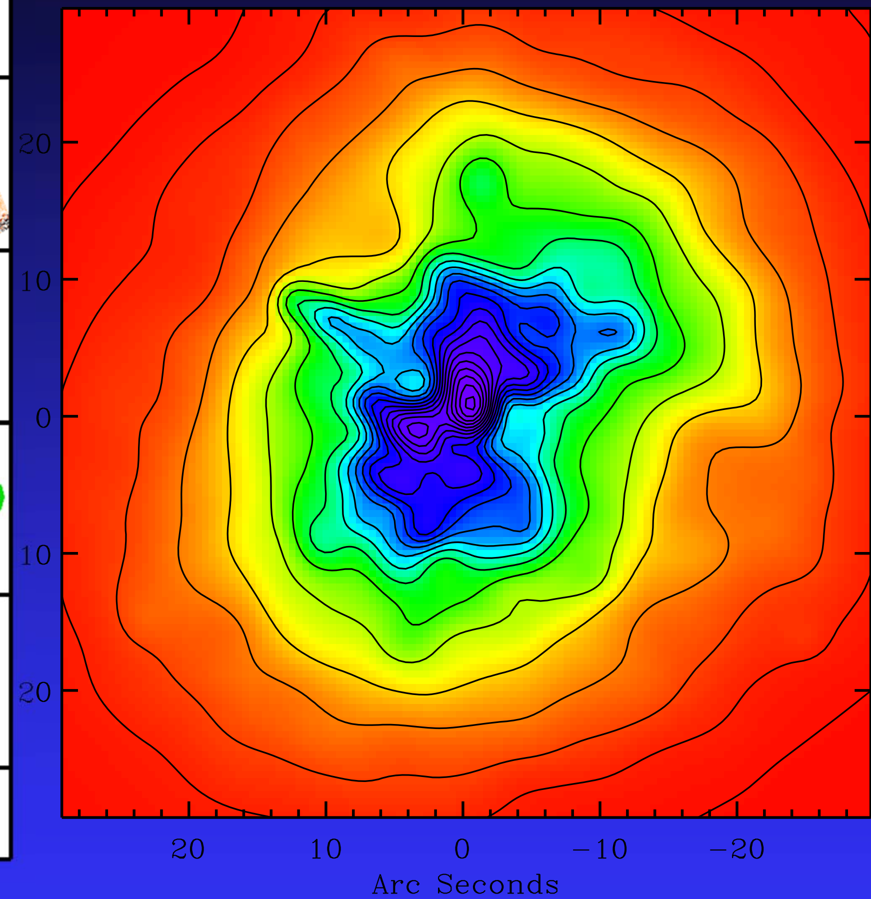


Single Stellar Population age map from Oonk et al (2010) derived by comparing FUV/U colors with Bruzual &Charlot (2003) models. VLA 8.4 GHz contours overlayed in white (Tremblay+2012b).

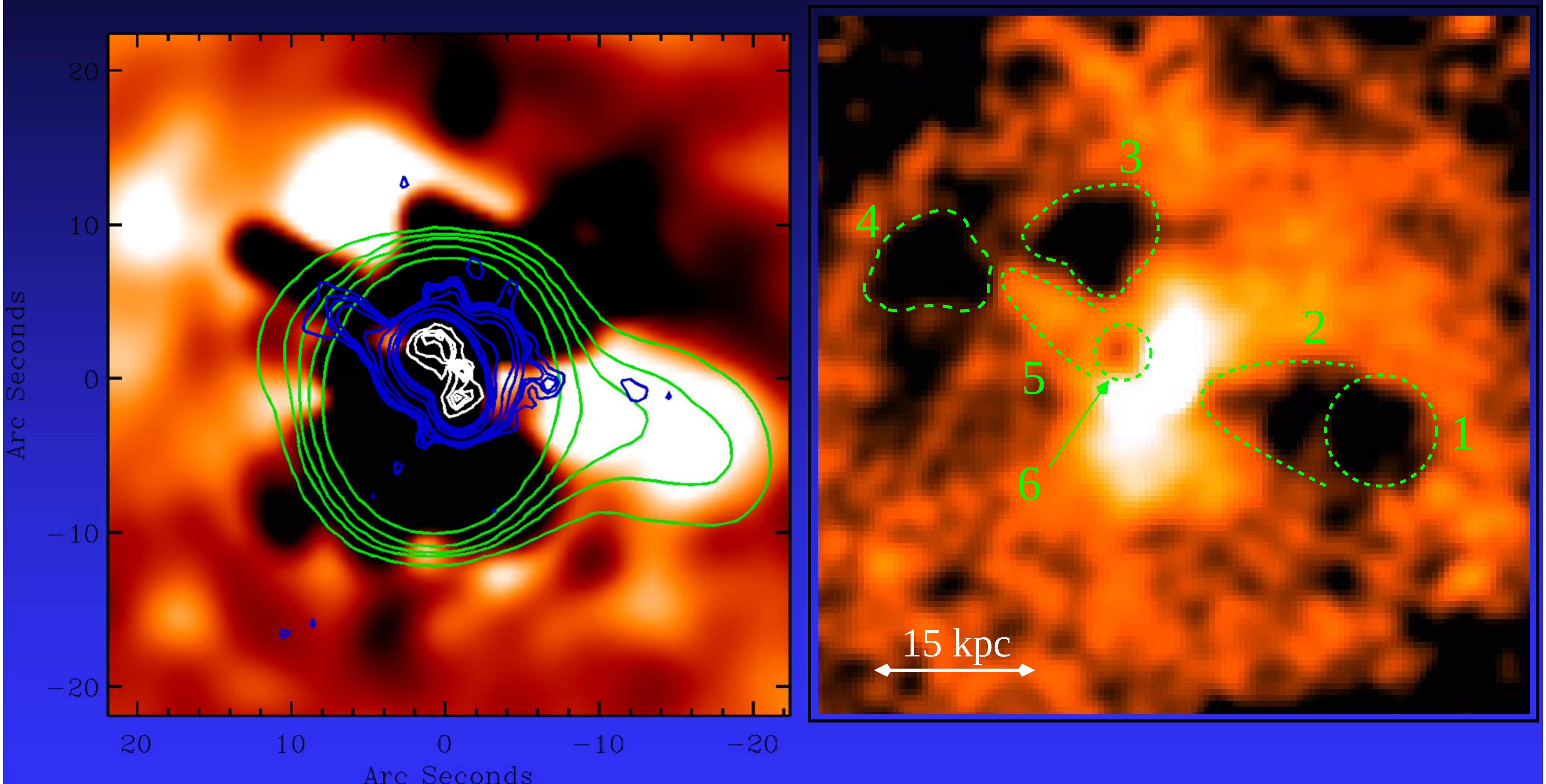
X-ray is Complex on Scale of BCG.



HST WFPC2 F702W and Chandra X-ray contours (Tremblay+2012b)

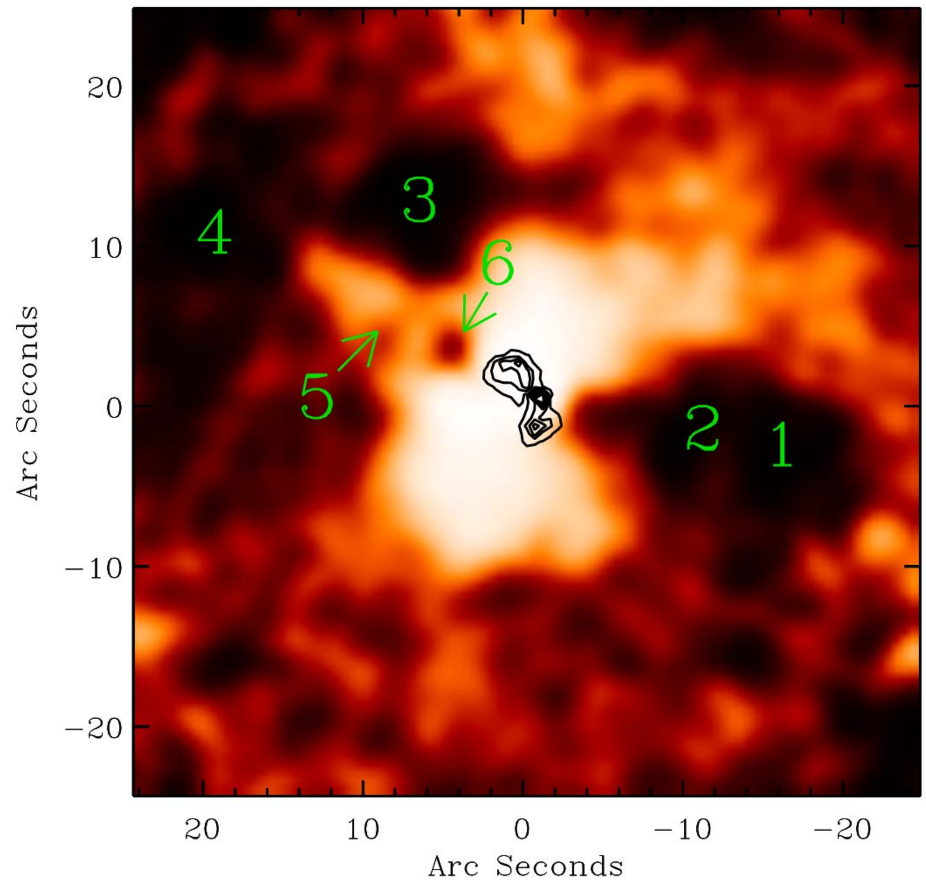


Adaptively smoothed Chandra Image (Tremblay+2012b)



(Left) Chandra residual Image with VLA contours Green: 330 MHz, Blue: 1.3 GHz, White: 8.4 GHz Residual Image. (Right) Unsharp Mask Image labeling features. (Tremblay+2012b)

Tremblay et al. 2012b



CAVITY AGE DATING

SOUND CROSSING $$t_{c_s} = \frac{R}{c_s} = R\sqrt{\frac{\mu m_{\rm H}}{\gamma k T}}$$

BUOYANT RISE $$t_{\rm buoy} \simeq \frac{R}{v_t} \simeq R\sqrt{\frac{SC}{2gV}}$$

CAVITY REFILL TIME $$t_{\rm refill} = 2\sqrt{\frac{r}{g}}$$

Label (1)	Name (2)	R (D) (kpc) (3)	r (kpc) (4)	pV ($\times 10^{57}$ erg) (5)	t_{c_s} ($\times 10^7$ yr) (6)	$t_{\rm buoy}$ ($\times 10^7$ yr) (7)	$t_{\rm refill}$ ($\times 10^7$ yr) (8)	Shape assumed (9)
1	M01 western ghost cavity	24	4.8	3.1	2.7	8.8	6.6	Sphere
2	C05 X-ray tunnel	(18)	1.5 & 5.25	2.6	...	...	...	Cone
3	M01 northern ghost cavity	21	6.6	7.0	2.7	6.1	7.3	Sphere
4	Eastern ghost cavity	35	3.6	0.79	3.8	17.8	6.9	Sphere
5	Cold filament	(15)	...	...	...	...	...	...
6	Filament base cavity	9	2.3	0.30	1.1	2.7	2.8	Sphere

ESTIMATED TIMESCALES HAVE INTERESTING IMPLICATIONS

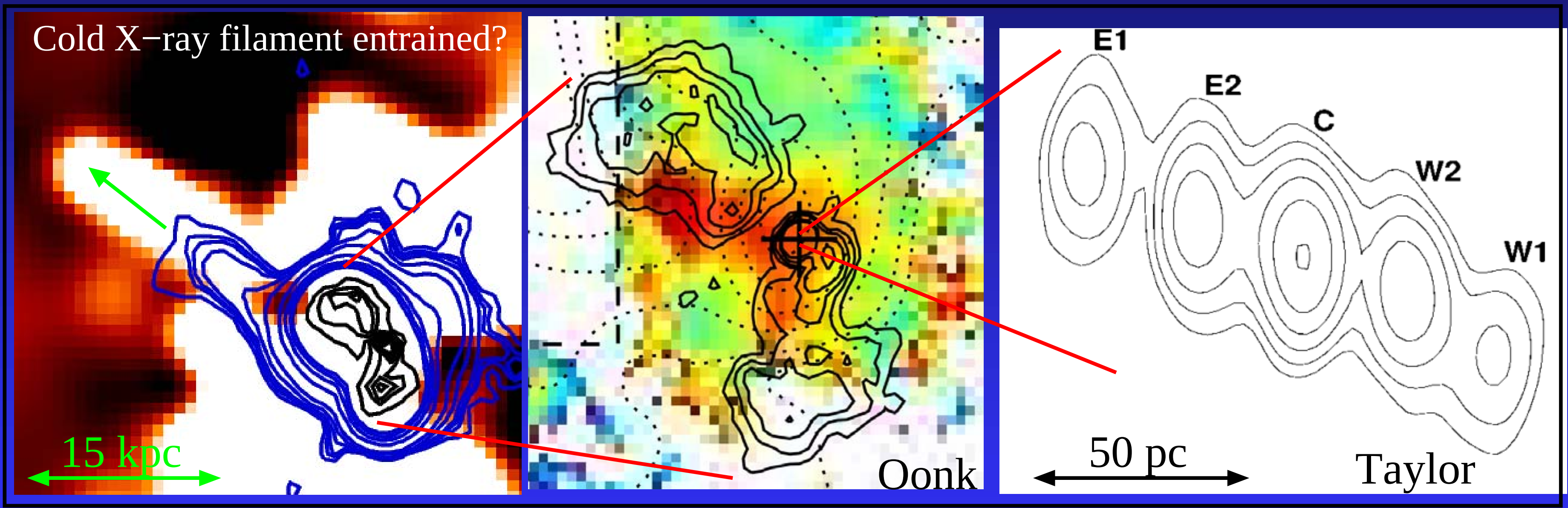
cooling time	est. X-ray cavity ages	est. radio structure ages	single stellar population ages
1 Gyr @ 40 Msol/yr w/in 40 kpc (*Chandra*, *XMM*, *FUSE* consistent)	~10 to ~90 Myr (Tremblay, Birzan)	~50-100 Myr for 330 GHz	as young as ~5 as old as ~500 Myr (for the young stellar population, FUV derived)

AGN DUTY CYCLE - outbursts last ~10 Myr with repetition intervals ~100 Myr

STAR FORMATION HAS BEEN ONGOING THROUGHOUT THE FEEDBACK-DRIVEN EXCAVATION OF X-RAY STRUCTURE

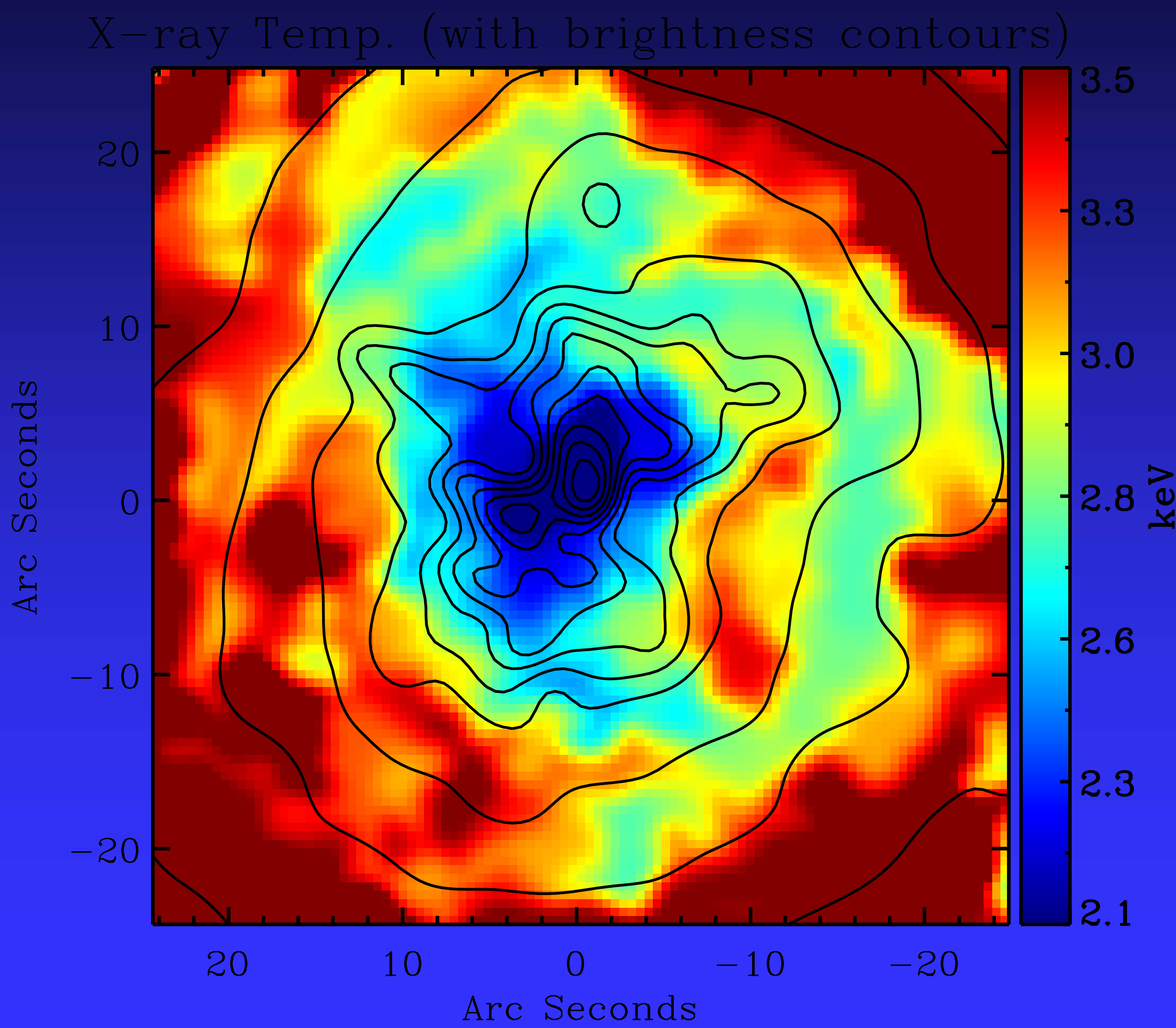
Origin of Cold Filament?

Dredge−up of low entropy gas along jet propagation axis?



(Left) VLA 8.4 GHz (Black) and 1.3 GHz (Blue) on residual Chandra X-ray. (Center) VLT Sinfoni P-α velocity dispersion with 8.4 GHz radio image from Oonk et al (2010) . (Right) VLBA image of symmetric jet from Taylor et al. (1999). (Tremblay+2012a, MNRAS, 424,1026)

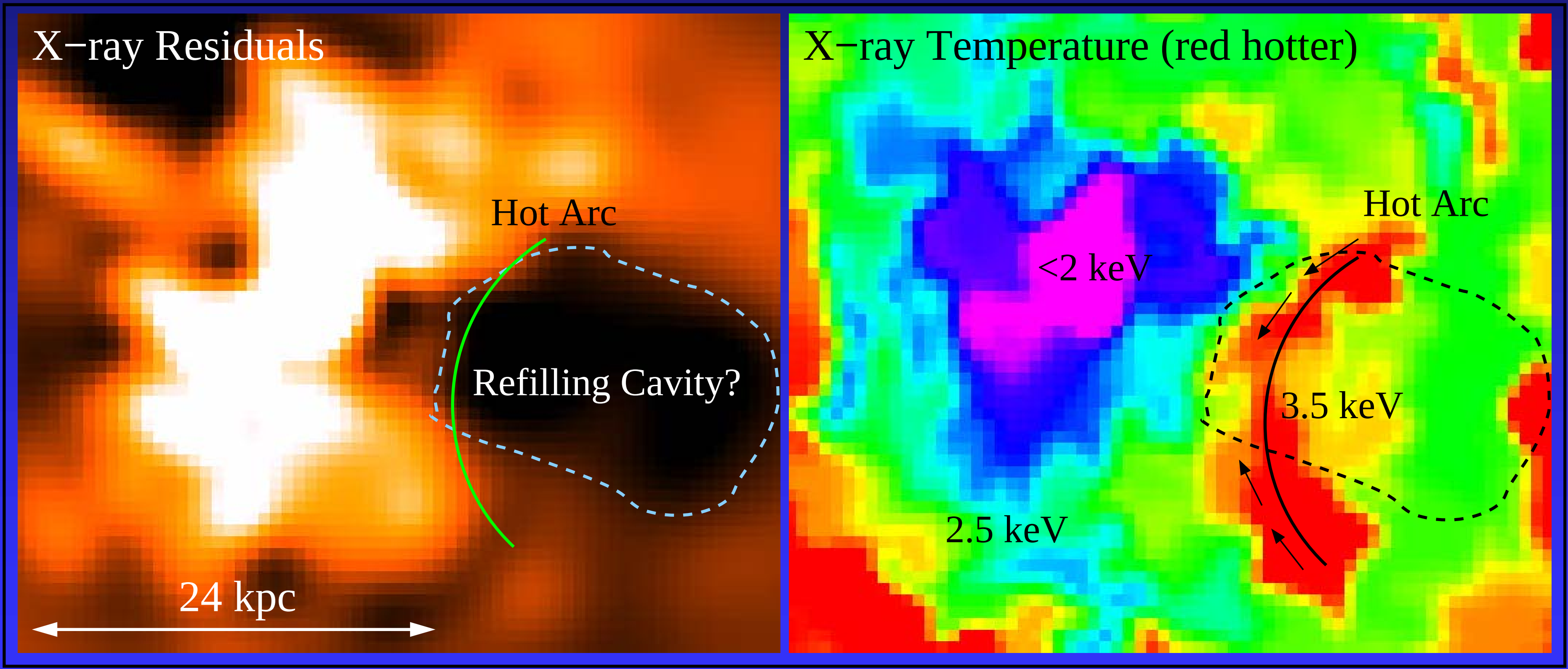
Discovery of "Hot Arc"



X-ray Temperature Map (Tremblay+ 2012a)

Is gas in Hot Arc heated when it refills in the wake of the bubble?

ICM heated as it rushes to refill buoyant cavity wake?



(Tremblay+ 2012a).

A2597 Summary

- X-ray morphology is complex on the scale of the BCG
- Radio source is complex, changing axis twice.
- 3 large bubbles, 1 small bubble
- Bubble power comparable to cooling luminosity
- Bubble energy dissipated quasi-continuously?
- Star formation on-going during heating, now more centrally condensed?
- Discovery of cold filament (dredged up by radio source?)
- Discovery of “hot arc” which may indicate gas heated by refilling in the wake of SW bubble.

The End