A Multi-Wavelength Study of BCGs in Cooling Flow Clusters with the MMTF

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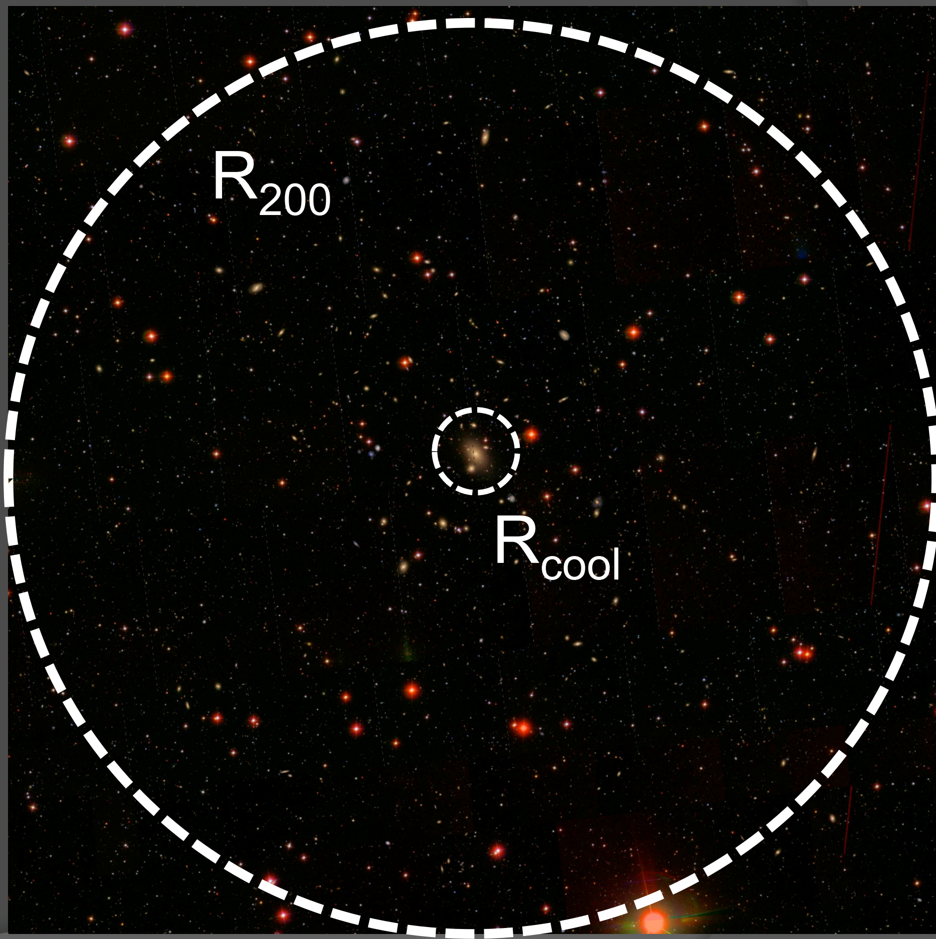
Cooling Flow Clusters

- Massive galaxy clusters have L_X high enough in the central region that the X-ray plasma should cool radiatively in less than a Hubble time.

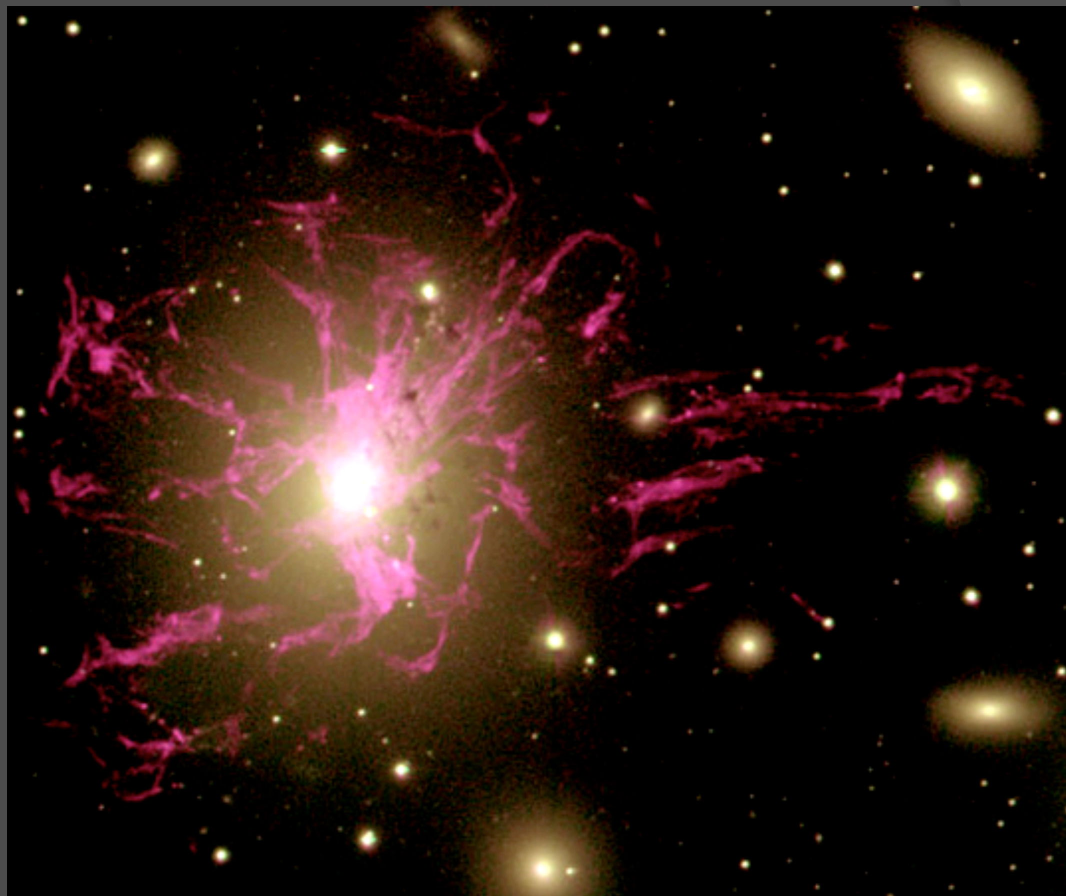
$$\boxed{\dot{M} = \frac{2L\mu m}{5kT}}$$

- Should dump 10-100 $M_{\odot} yr^{-1}$ of cool gas on the BCG
  - Not seen!
  - Invoke AGN feedback to prevent cooling…
    - “Housekeeping mode”



Warm Ionized Gas in BCGs

- A distinguishing property of cooling flow clusters is the presence of ionized gas in the BCG.
  - i.e. Perseus A (NGC1275)
- In local Universe, typically see thin, filamentary morphology.
- Hard to build large database due to the rarity of rich clusters
  - i.e. few at a given z

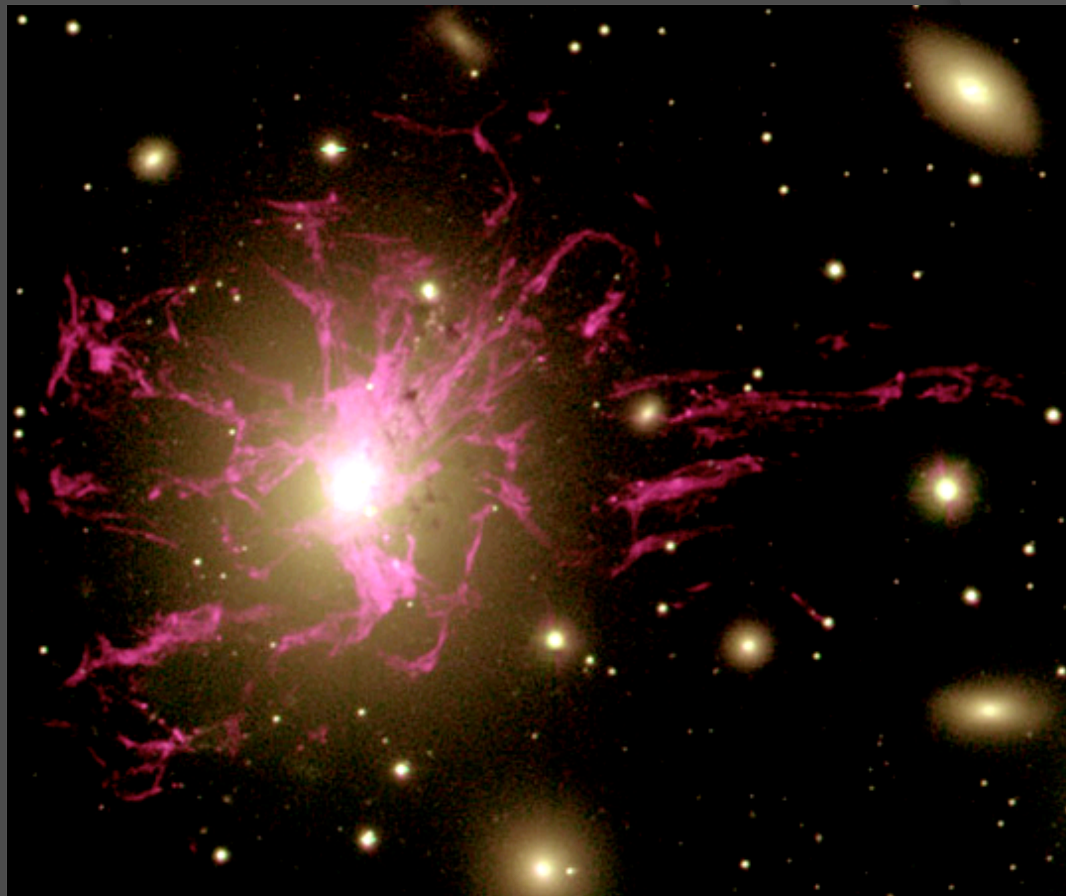


(Perseus A; Conselice 2001)

Warm Ionized Gas in BCGs

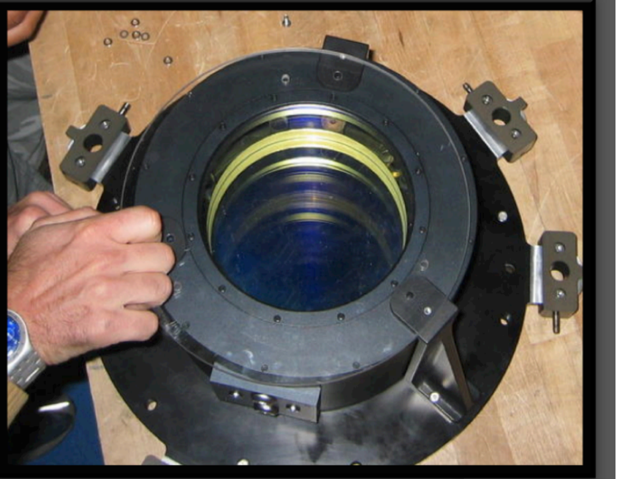
- Several theoretical explanations for the presence and heating of the gas
  - Star formation
  - Buoyant radio bubbles
  - Gas drag in the cooling flow
  - Cosmic ray heating
  - Stripped gas from infalling galaxies

  - But hard to argue for a formation scheme with only 1-2 systems!



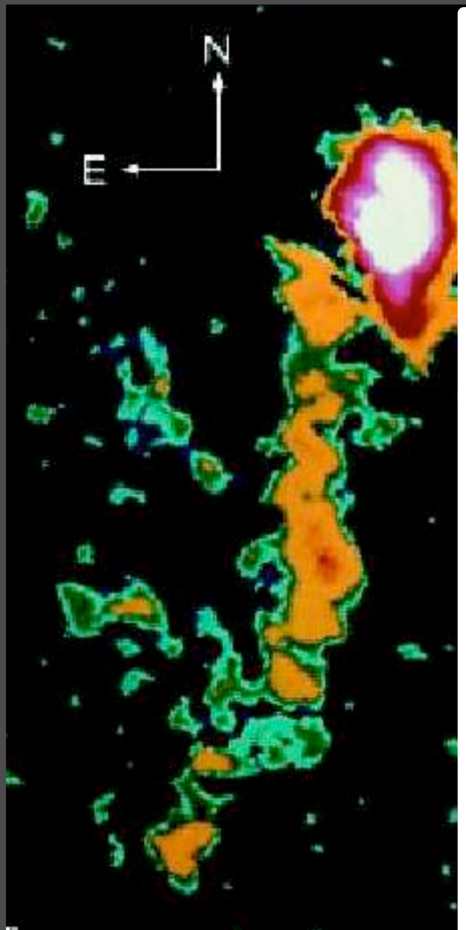
(Perseus A; Conselice 2001)

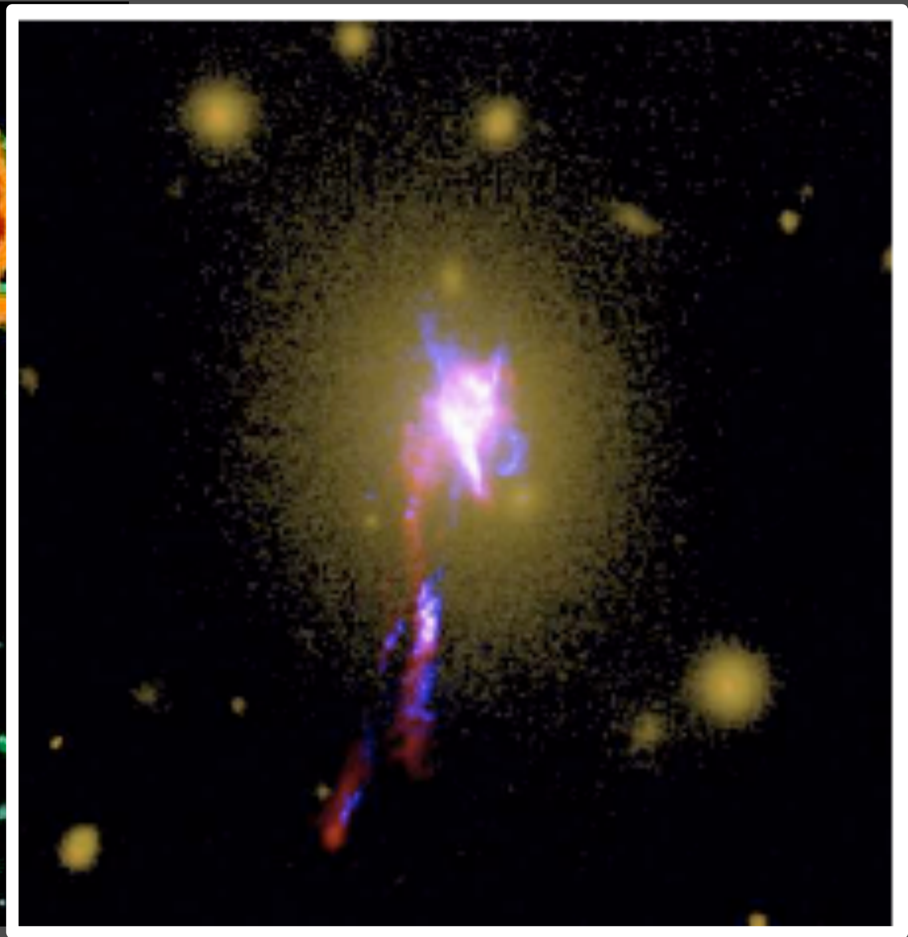
The Maryland Magellan Tunable Filter

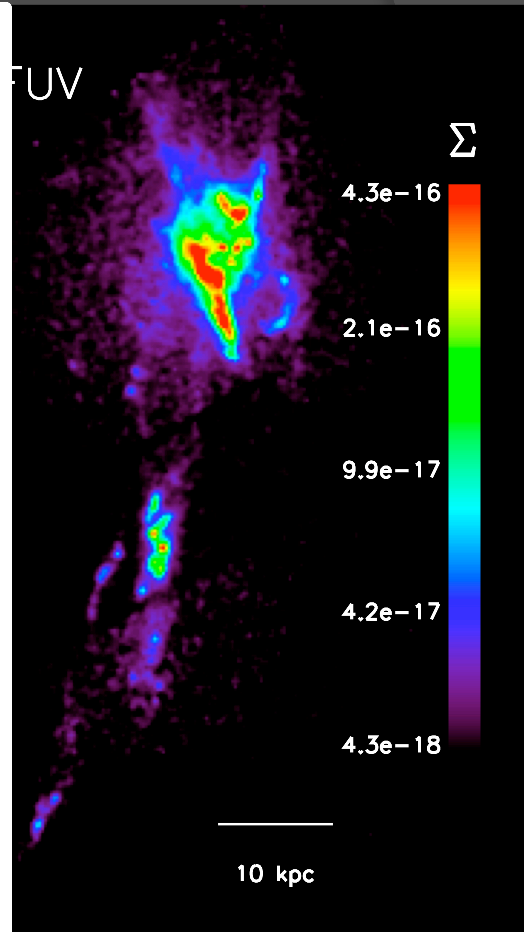


- PI: Sylvain Veilleux
  - 3 nights/yr guaranteed
- On Baade 6.5m telescope in Chile
  - DIQ ~ 0.4” - 0.7”
- Wavelength coverage ~ 5000 - 9200Å
- Bandwidth ~ 6 - 20Å
  - Low resolution
- FOV ~ 27’ x 27’
  - Largest FOV of any FP currently in operation
- Data reduction pipeline fully operational.

Abell 1795 – A Pilot Study







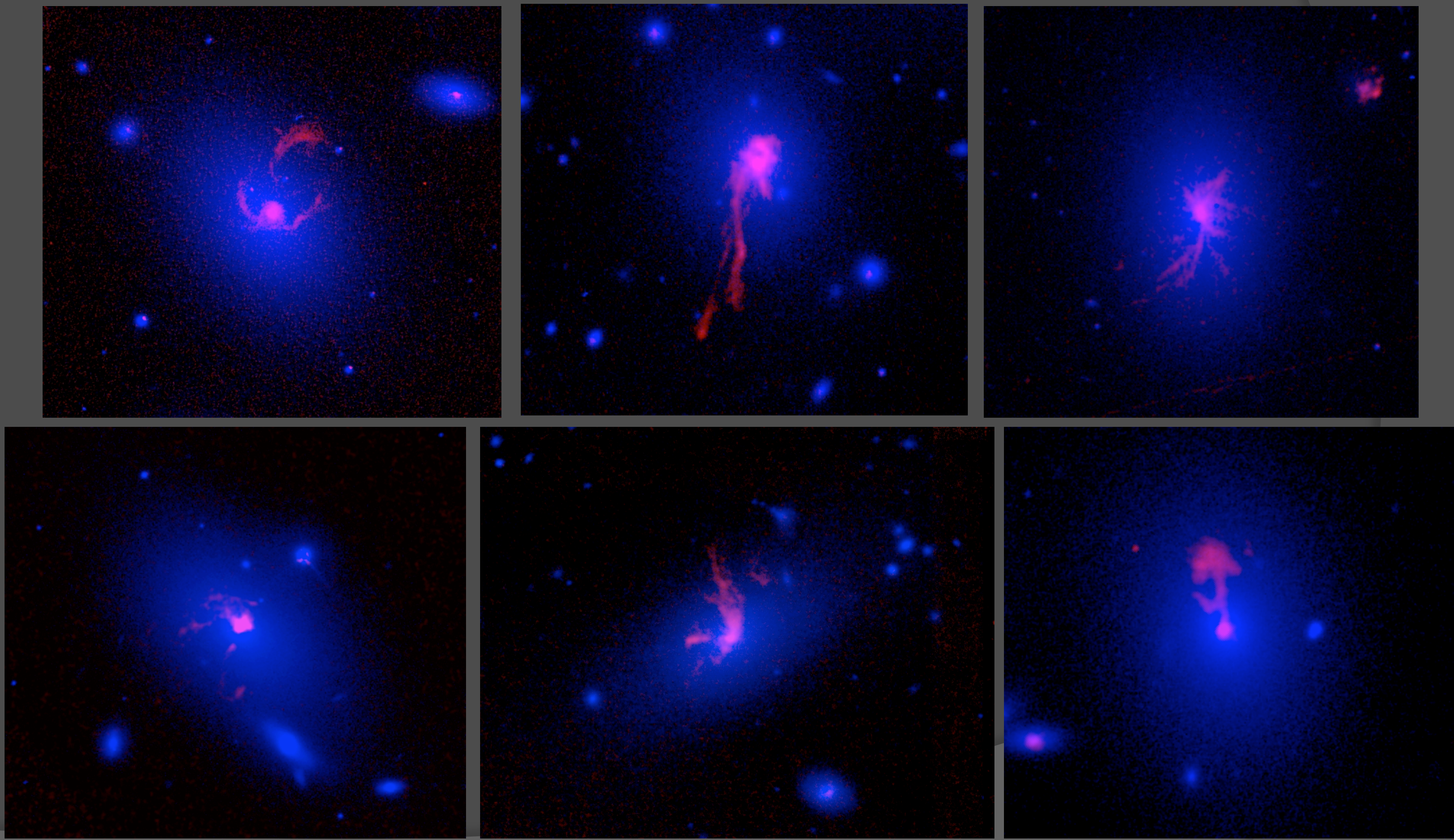
Cowie et al. (1983) McDonald & Veilleux (2009)

A Multi-Wavelength Database

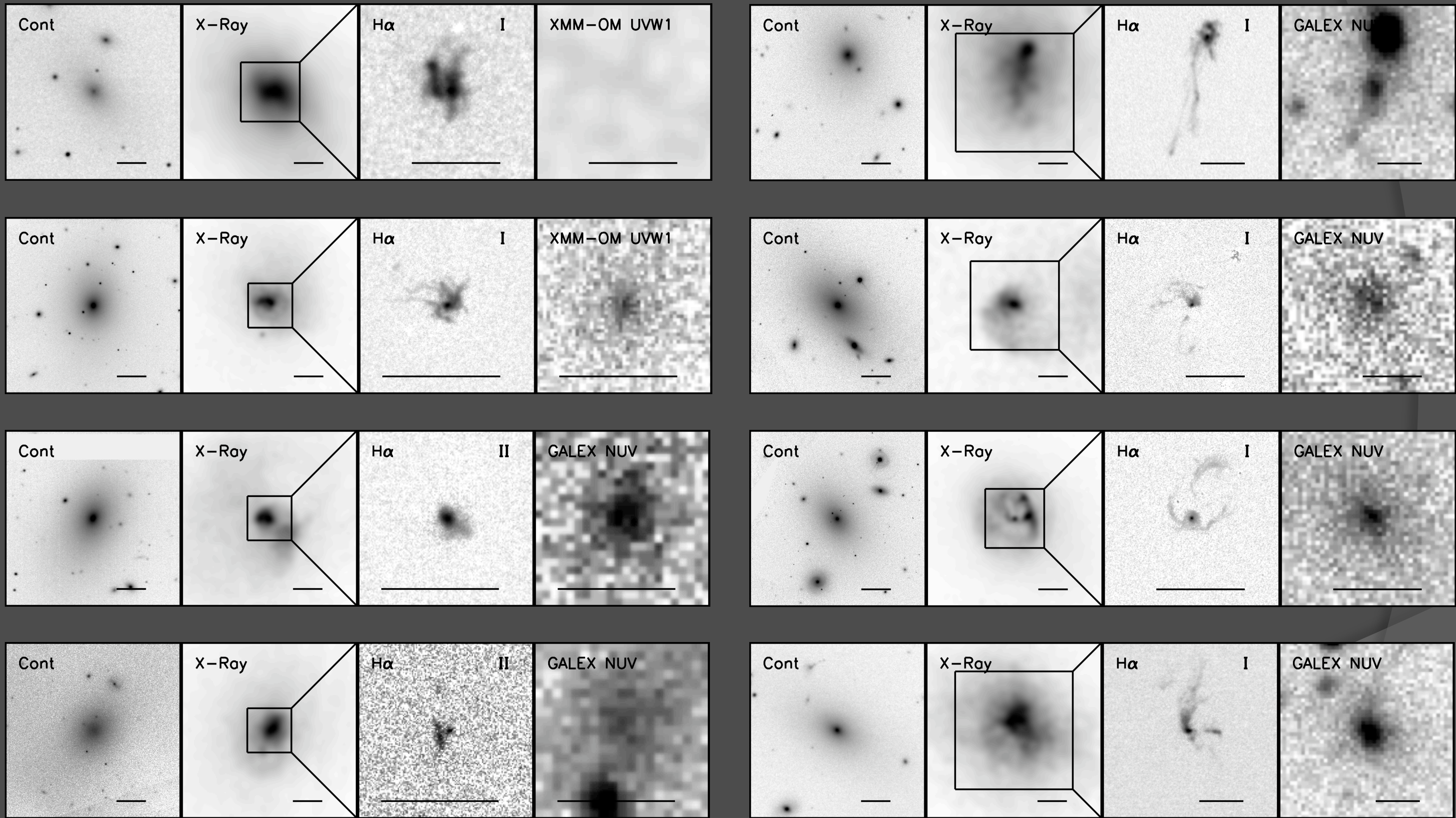
- Sample of 23 galaxy clusters with a wide variety of properties
  - 1-2 orders of magnitude range in dM/dt, L_x, M_x, T_x
  - 23/23 have Hα & NIR imaging from MMTF and 2MASS.
  - 19/23 have X-Ray & UV imaging
    - X-ray from Chandra (19/23)
    - UV from GALEX & XMM-OM (21/23)
  - 18/23 have VLA 1.4 GHz fluxes

(1) Name	(2) z	(3) E(B-V)	(4) T_X	(5) $\dot{M}_{class}$
Abell 0085	0.0557	0.038	6.5	108
Abell 0133	0.0569	0.019	3.5	110
Abell 0478	0.0881	0.517	6.8	736
Abell 0496	0.0329	0.132	4.8	134
Abell 0644	0.0704	0.122	6.5	136
Abell 0780	0.0539	0.042	4.7	222
Abell 1644	0.0475	0.069	5.1	12
Abell 1650	0.0846	0.017	5.1	122
Abell 1795	0.0625	0.013	5.3	321
Abell 1837	0.0691	0.058	2.6	12
Abell 2029	0.0773	0.040	7.4	431
Abell 2052	0.0345	0.037	3.4	94
Abell 2142	0.0904	0.044	10.1	369
Abell 2151	0.0352	0.043	2.9	166
Abell 3158	0.0597	0.015	5.3	9.6
Abell 3376	0.0597	0.056	3.5	6.3
Abell 4059	0.0475	0.015	-	-
Ophiuchus	0.0285	0.588	8.6	41
Sersic 159-03	0.0580	0.011	2.4	288
Abell 2580[a]	0.0890	0.024	4.3	95
Abell 3389[a]	0.0267	0.076	2.0	22
Abell 0970[b]	0.0587	0.055	4.1	20
WBL 360-03[b]	0.0274	0.028	1.8	10

Hα Filaments in BCGs

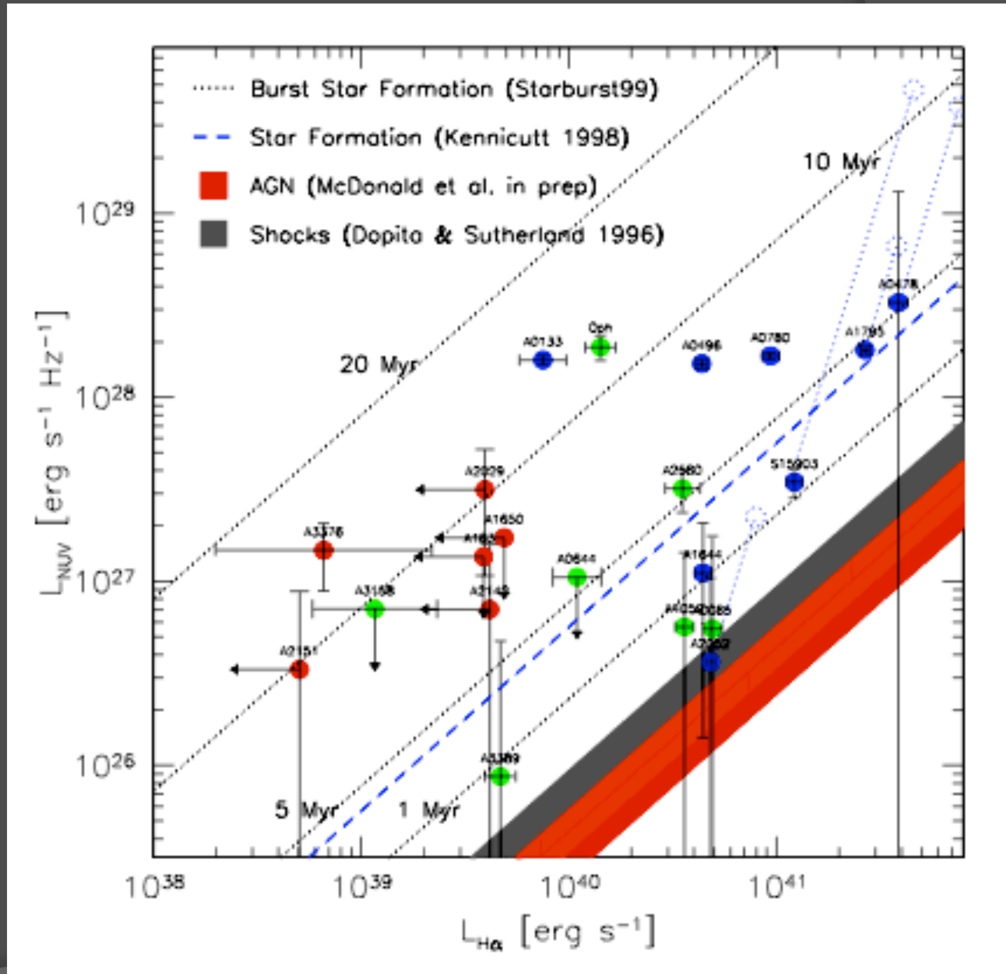


A Multi-Wavelength Database



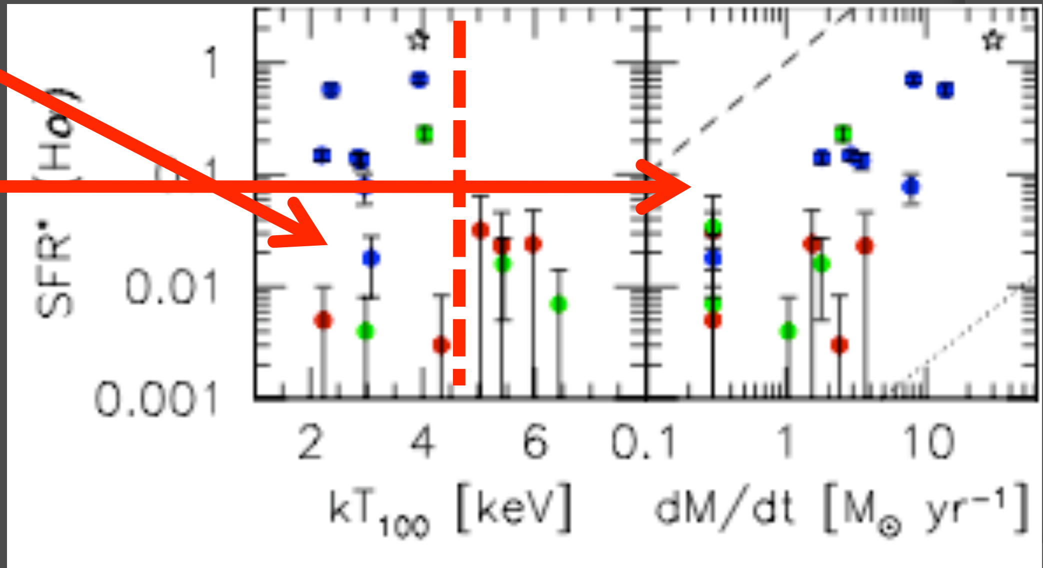
Hα vs NUV – The Complete Sample

- While several clusters are consistent with heating from young stars, there is a lot of scatter in this relation!
  - Other mechanisms may be more important:
    - Cosmic ray heating
    - Conduction from ICM
    - Mechanical energy from a shearing flow
  - Too difficult to pursue this without higher quality data
    - FUV data from HST
    - Long-slit spectra along filaments



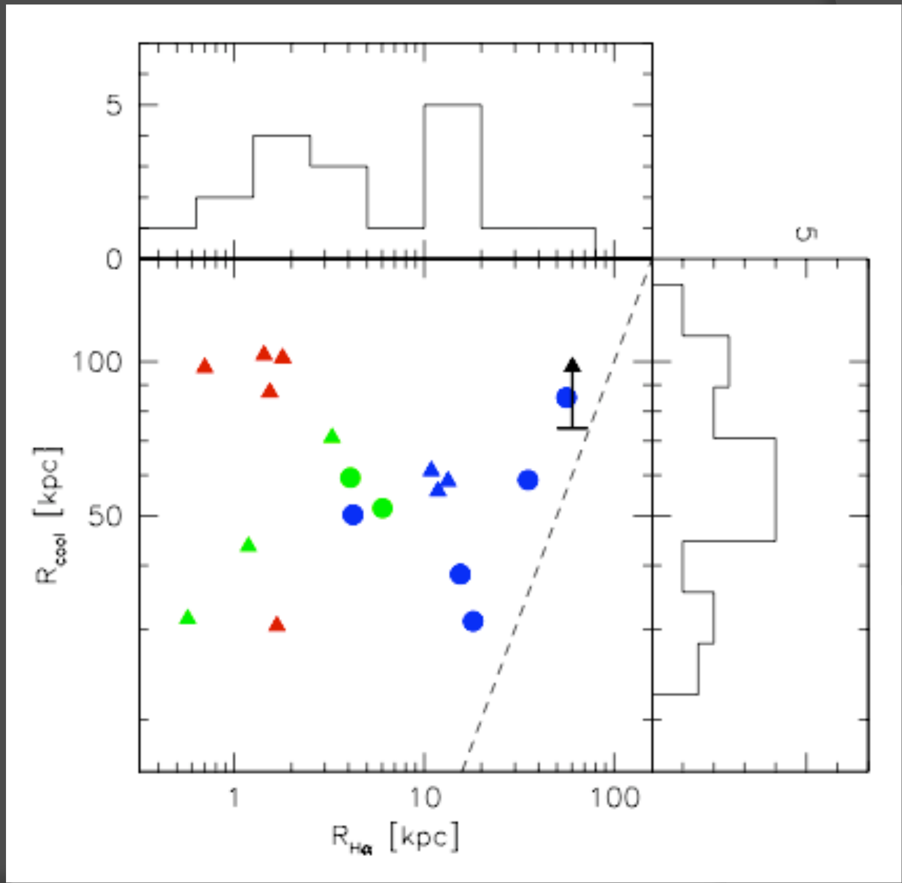
X-Ray Properties of ICM

- Appears to be a temperature threshold at which Hα filaments are able to form:
  - kT < 5 keV
- Strong correlation between cooling rate and the UV or Hα flux.
  - Too little Hα flux to be stars forming out of cooling gas, too much to be purely recombination



X-Ray Properties of ICM

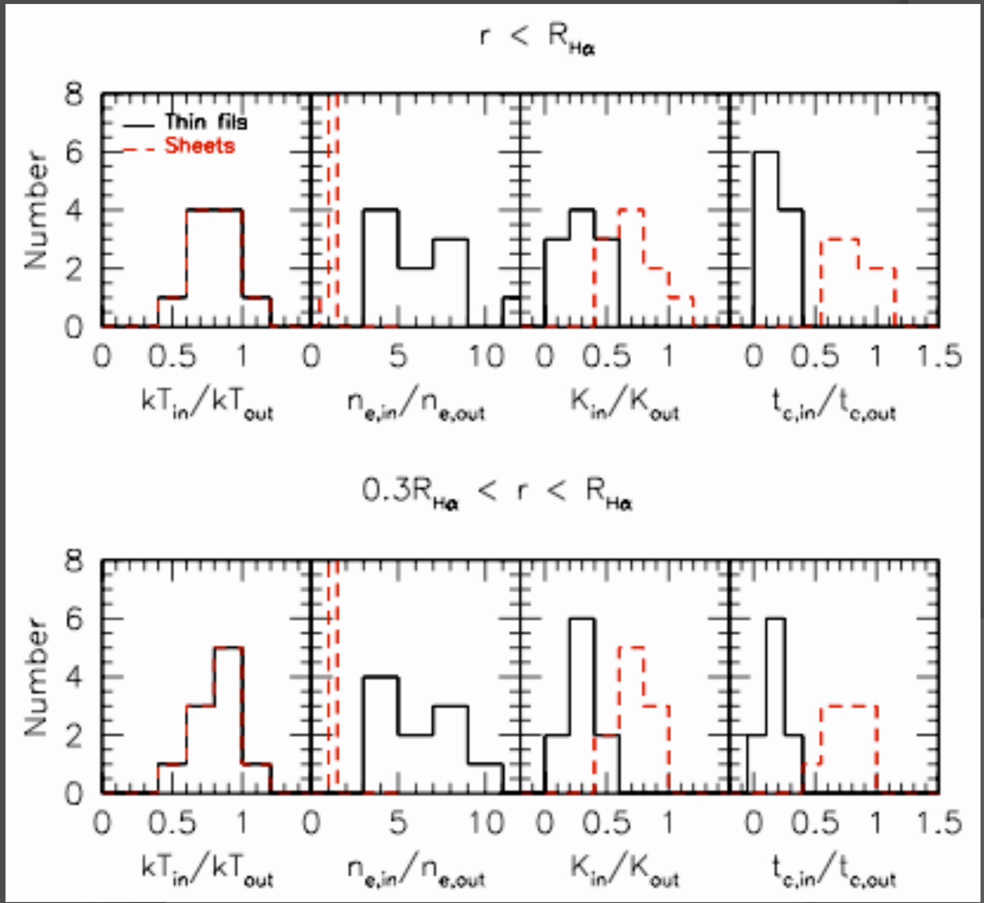
- The Hα emission never extends further than the cooling radius of the ICM!
  - Combined with the correlation between cooling rate (dM/dt) Hα flux in filaments, suggests that the warm gas is linked to the cooling flow.



X-Ray Properties of Filaments

- We can also extract X-ray spectra coincident with the Hα filaments
  - Filaments have:
    - Low temperature
    - High density
    - Low entropy
    - Short cooling time

→ Direct link between warm gas and X-ray cooling flow!



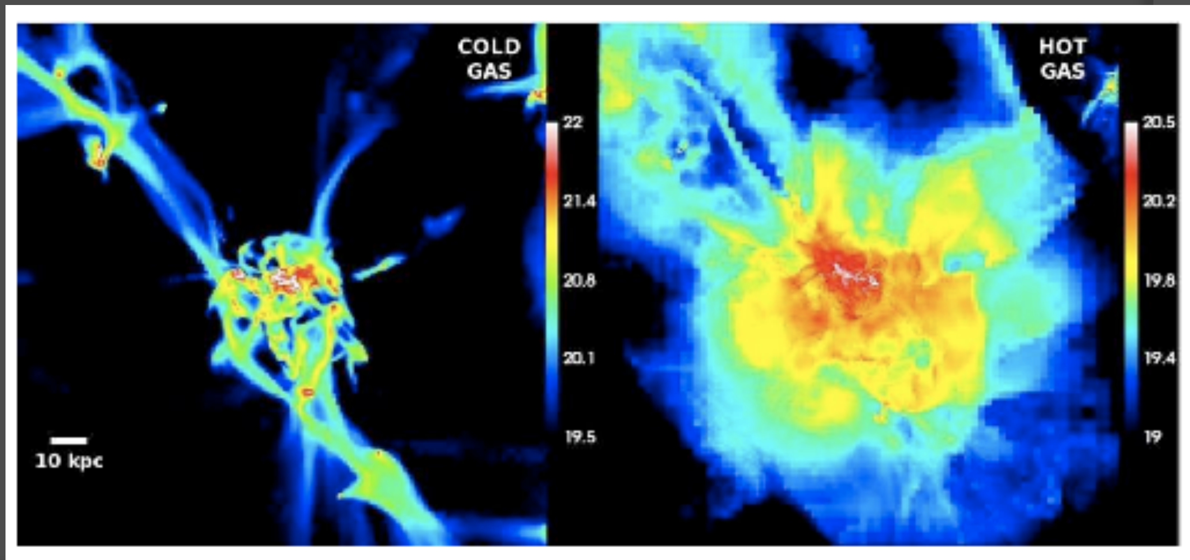
Summary of Results

- The X-ray and Hα morphologies are similar in cases where we see optical filaments
- There is a strong correlation between the mass of warm gas in filaments and the mass of gas cooling out of the X-ray
- The warm filaments only extend as far as the X-ray cooling radius
- The cooling time of the X-ray gas coincident with the warm gas is ~10x less than the surrounding ICM

➔ **The Hα emission is linked to the cooling ICM!**

Interpretation of Results

- Hα filaments trace the X-ray cooling flow!
  - Inside of R_{cool}, ICM cools rapidly, collapsing into thin streams which fall onto the BCG at the cluster potential minimum
    - Morphology of warm and hot gas resemble that seen in recent high-resolution hydro sims of gas cooling by Ceverino et al.
    - Heating probably due to a combination of star formation in filaments, conduction from ICM and drag heating.



Work in Progress

- High resolution far-UV survey with HST
  - Are stars forming in the gas filaments?
  - How does the SFR compare to the X-ray cooling rate?
- Extension to galaxy groups
  - Is there a lower mass/temperature limit for the presence of Hα?
- Long-slit spectra of extended filaments and BCGs
  - What ionization processes can be excluded?
  - What are the kinematics of the filaments?
  - Further classification of AGN
- High resolution sub-mm imaging of clusters
  - What is the distribution of the cold molecular gas?
  - Is the amount of cold gas consistent with the cooling flow hypothesis?