New Constraints on the Origins of Hα Filaments in Cool Core Groups and Clusters

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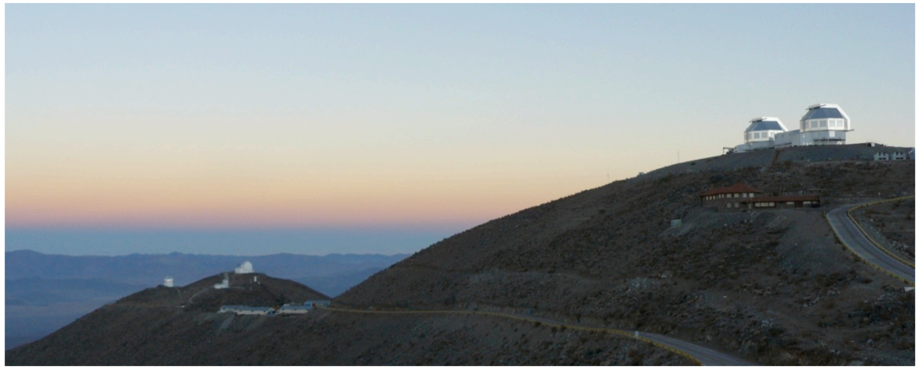
Agenda

- Background & Motivation
  - Cooling flow clusters
  - Maryland-Magellan Tunable Filter



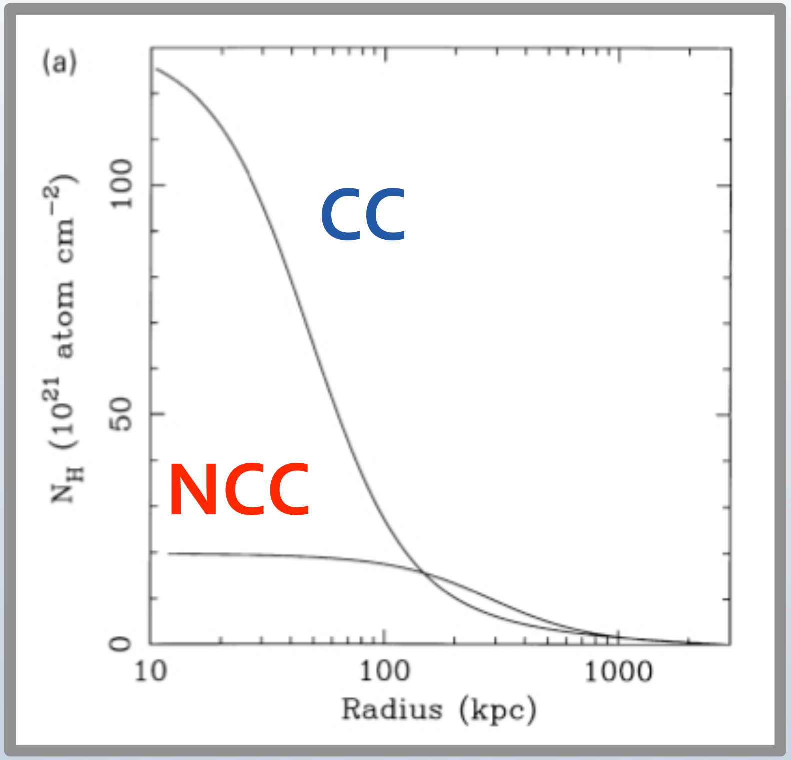
- Results
  - Hα filaments in cooling flow clusters
  - Cooling flow groups
- Interpretation
  - New constraints for cluster formation simulations
- Conclusions & Future Work

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.

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

- Implies cooling rates of ~ 100-1000 $M_\odot$/yr
  - Expect to see plenty of cool gas and star formation
  - The "cooling flow problem"

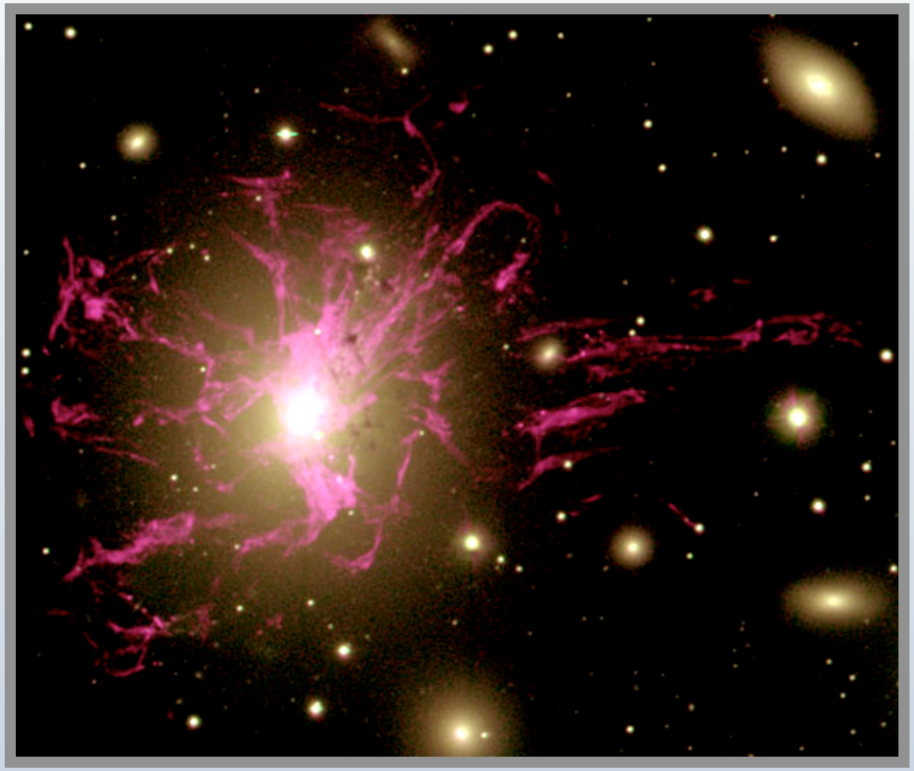


The Cooling Flow Problem

- Solutions:
  - Assume that energy is injected into the core, effectively balancing the energy losses due to radiative cooling.
    - e.g. AGN feedback, mergers, conduction from outer layers…
    - Estimated cooling rates drop by orders of magnitude, to better match the observed values of 1-10 $M_{\odot}$/yr
  - Look for other phases the cooling gas could be in.
    - Neutral gas (radio)
    - Cold molecular gas (mm)
    - Warm molecular gas (IR)
    - Ionized gas (optical)
    - Young stars (UV)

Hα Emission in Cool Cores

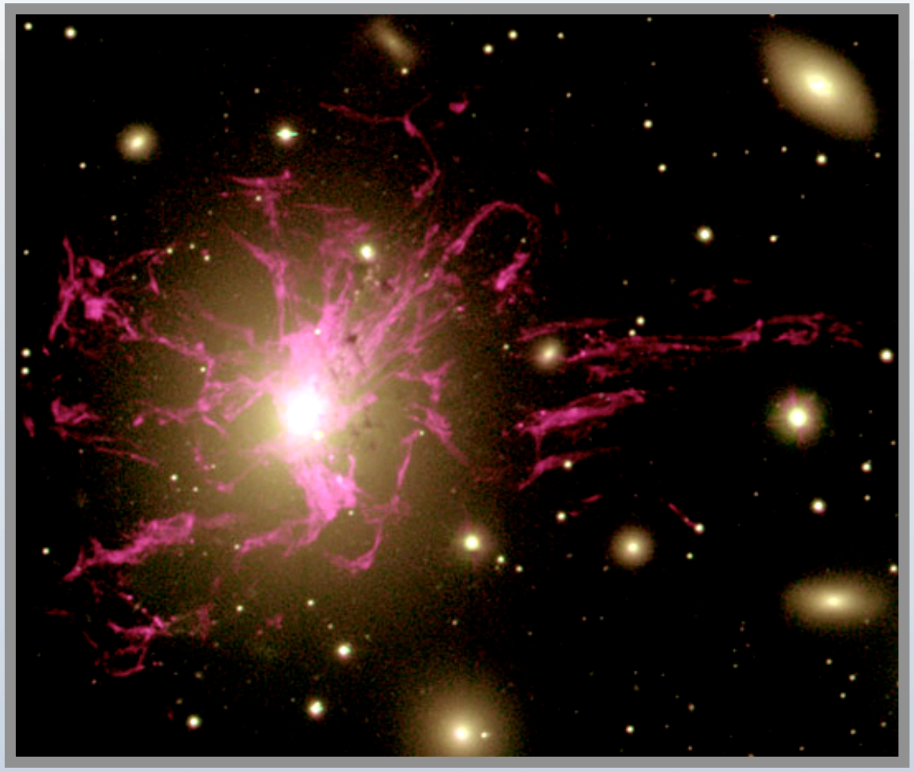
- The presence of warm, ionized gas has been noted in the cores of several cooling flow clusters to date.
  - Typically radial filaments centered on the BCG
  - Surface brightness is too high by orders of magnitude to be ICM cooling through 10^4 K.
  - Unanswered questions:
    - Where did the gas come from?
    - What is the heating source?



Perseus A, Conselice et al. 2001

Hα Emission in Cool Cores

- Potential sources of gas:
  - Stripped from infalling, gas-rich galaxies
  - X-ray cooling flow
  - Buoyant radio bubbles
- Potential sources of heat:
  - Cosmic ray ionization
  - AGN
  - Young stellar populations
  - Conduction from ICM
  - Ionization by ICM X-rays



Perseus A, Conselice et al. 2001

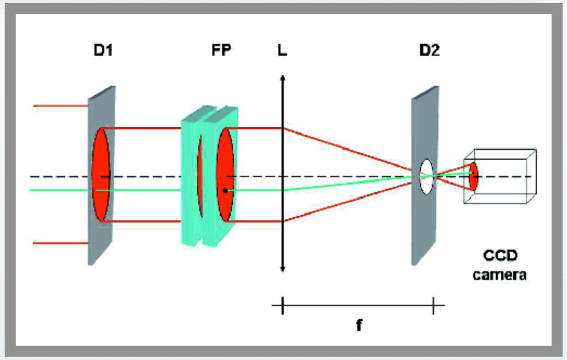
Hα Emission in Cool Cores

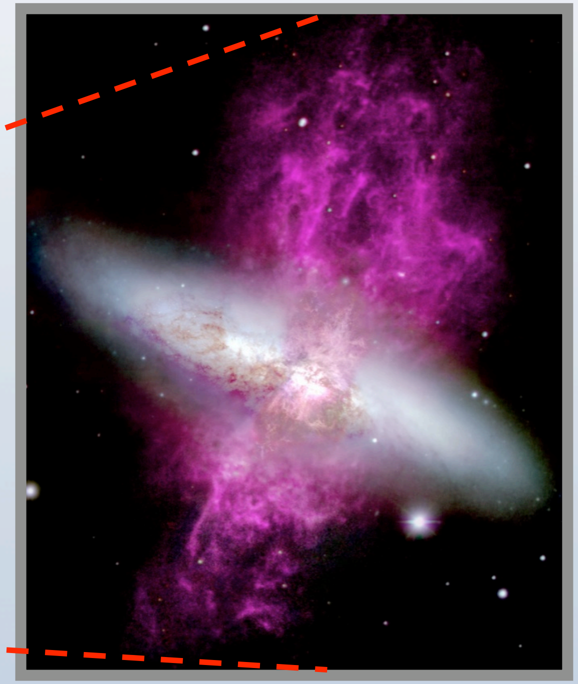
- Very difficult to argue in favor of a specific formation scheme with so few well-resolved examples (Perseus A, M87, …)
- Ideally, would like a large sample of cooling and non-cooling clusters with high-resolution Hα imaging
  - Narrow-band filters – limits redshift range to < 0.03
  - Spectroscopic surveys – limits field of view to central few kpc
    - SDSS fiber is 3″ in diameter → only looking at AGN
  - IFU surveys – typically hard to get both high spatial resolution AND sufficient coverage

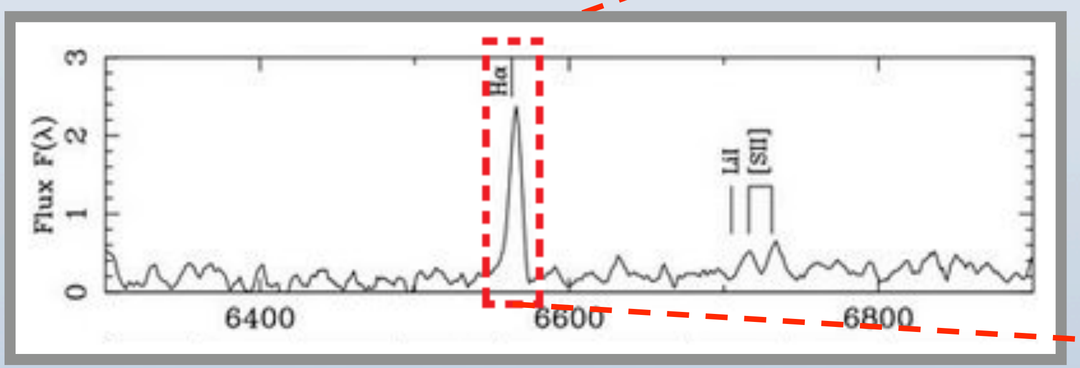
→ Tunable filter surveys

Tunable Filters

- Low spectral resolution ($\Delta\lambda \sim 10$Å)
  - Narrow band filter tunable both in width and central λ
  - Bandwidth is only slightly larger than the width of a typical emission line
    - Isolate a single line, such as Hα
  - Combines excellent spatial resolution and coverage!

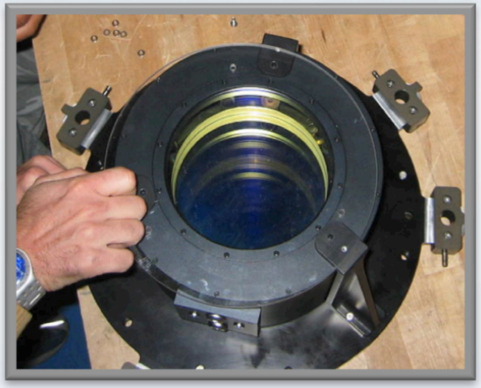






The Maryland-Magellan Tunable Filter

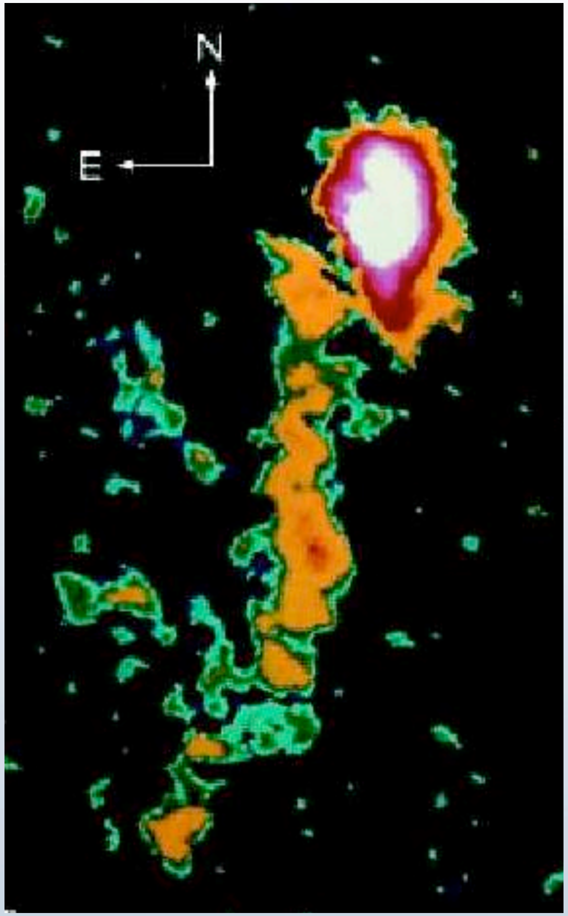
- PI: Sylvain Veilleux
  - 3 nights/yr guaranteed
- On Baade 6.5m telescope in Chile
  - DIQ ~ 0.5″
- Broad wavelength coverage
  - ~5000-9200Å
- Bandwidth tuning
  - ~6-20 Å
- Largest FOV of any FP in operation (27′x27′)

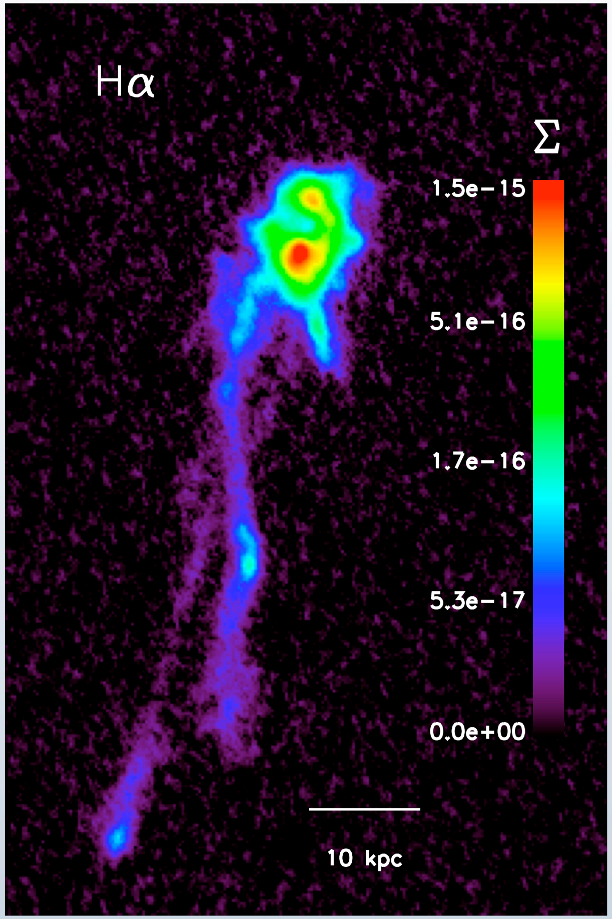


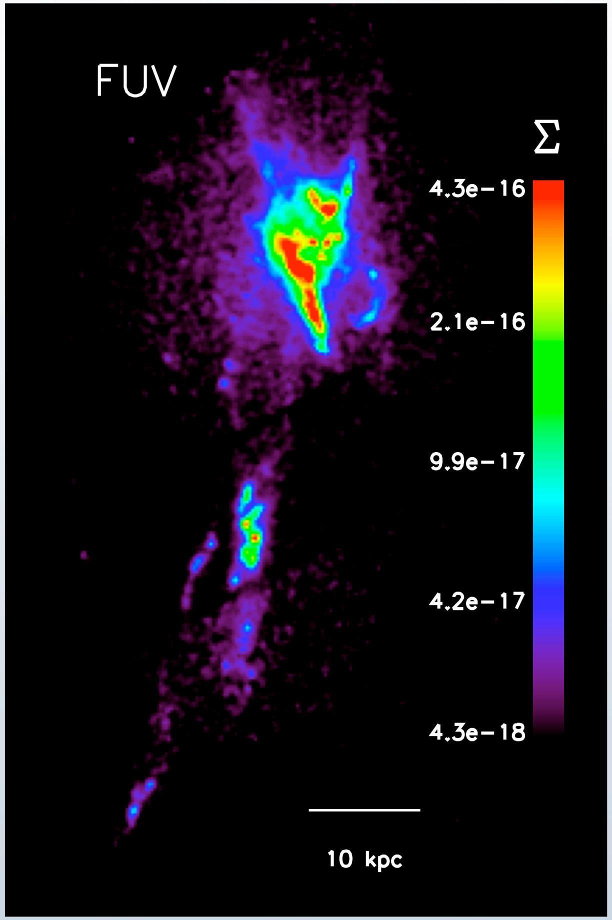
Science Goals

- Census of Hα filaments in cooling flow clusters
  - How common are they? What is the typical morphology?
  - How does Hα emission correlate with other cluster properties?
    - e.g. global/cooling X-ray properties, AGN, BCG, etc.
  - How does the presence of Hα emission depend on environment?
- Important questions:
  - What are the origins of the gas in the ionized filaments?
  - What are the primary sources of ionization?

A Pilot Study – Abell 1795





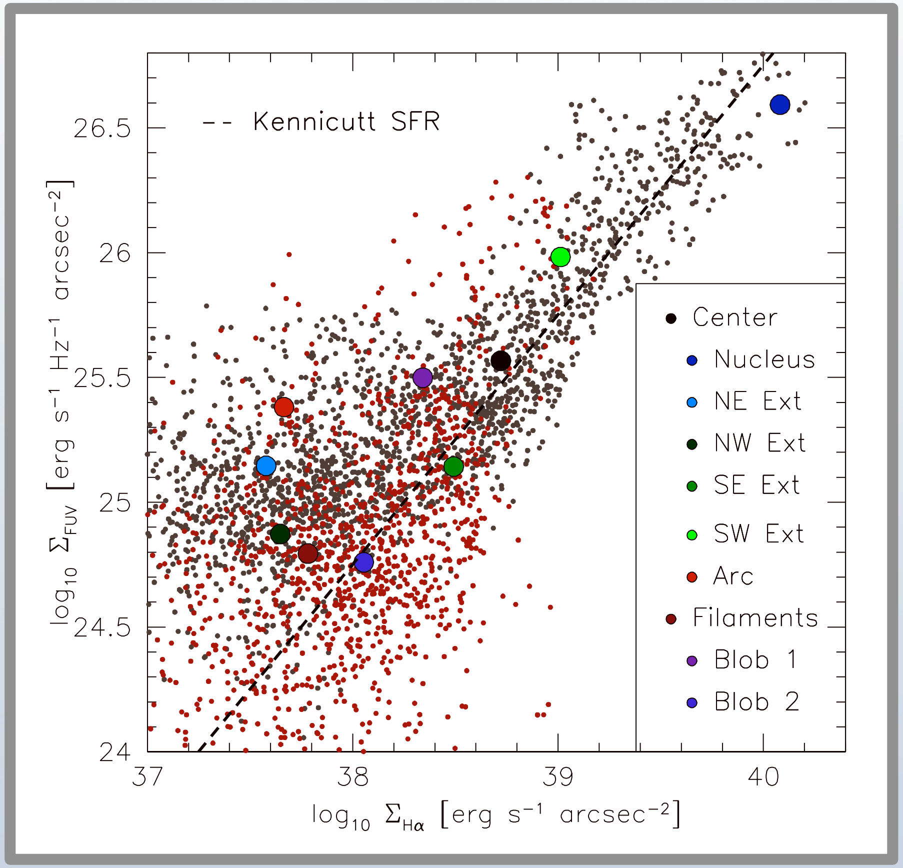


Cowie et al. (1983) McDonald & Veilleux (2009)

A Pilot Study – Abell 1795

- Comparing UV data from HST with MMTF Hα imaging on a pixel-to-pixel basis suggests that star formation may be responsible for the bulk of the observed Hα

- Caveats!
  - High [N II]/Hα ratios
  - Several regions with UV and no accompanying Hα, or vice versa.



McDonald & Veilleux (2009)

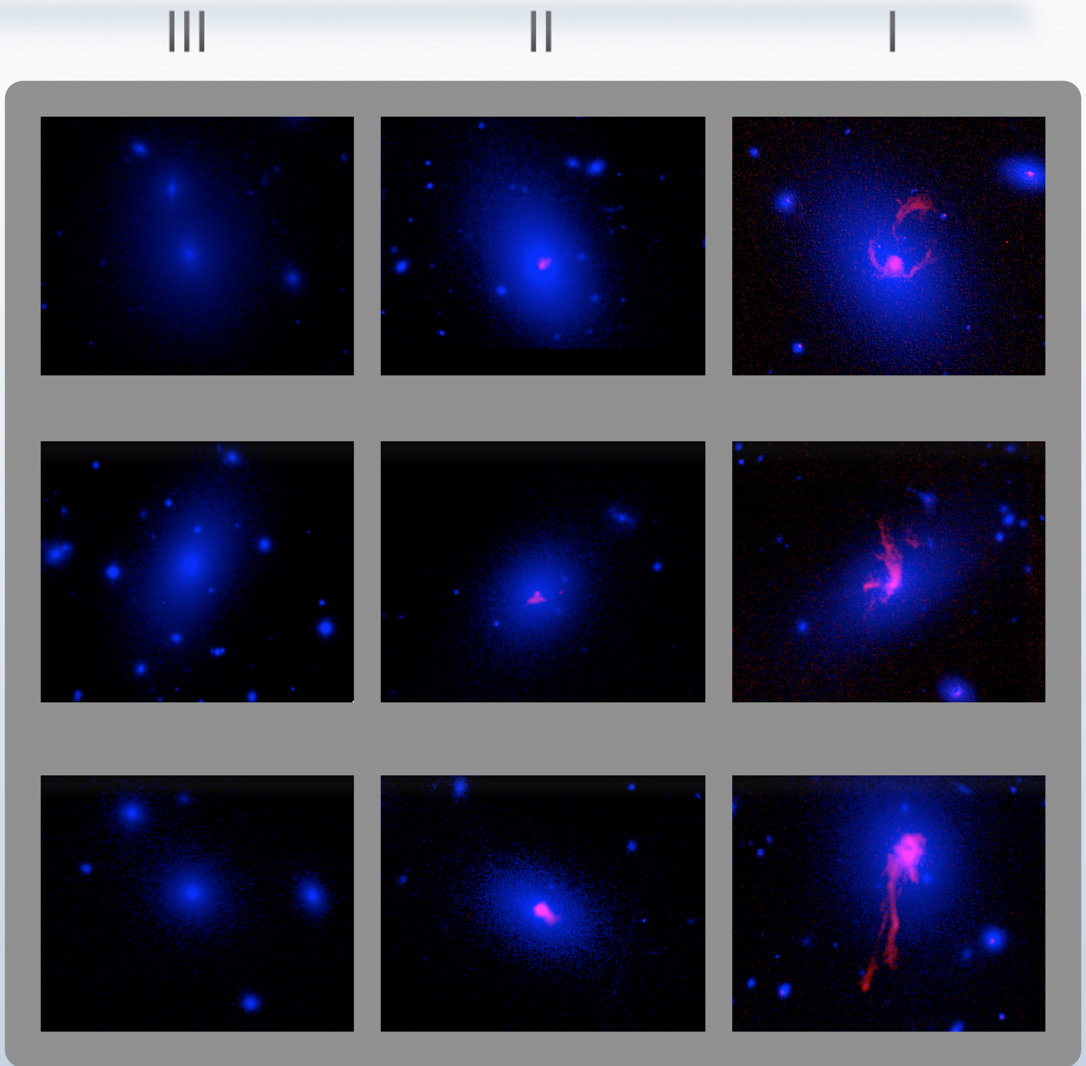
A Multiwavelength Database

- Sample of 23 galaxy clusters, drawn from White et al. (1997)
- Covering a full order of magnitude in T_X, M_X, L_X, dM/dt
- Excellent wavelength coverage:
  - 21/23 have CXO X-ray imaging
  - 19/23 have GALEX/XMM-OM near-UV imaging
  - 23/23 have ~r-band and Hα imaging
  - 23/23 have 2MASS near-IR imaging
  - 18/23 have VLA 1.4 GHz fluxes
- Supplemented with 10 groups, drawn from Sun et al. (2009)
  - Increase baselines by order of magnitude in T_X, M_X

Results – Hα in Clusters

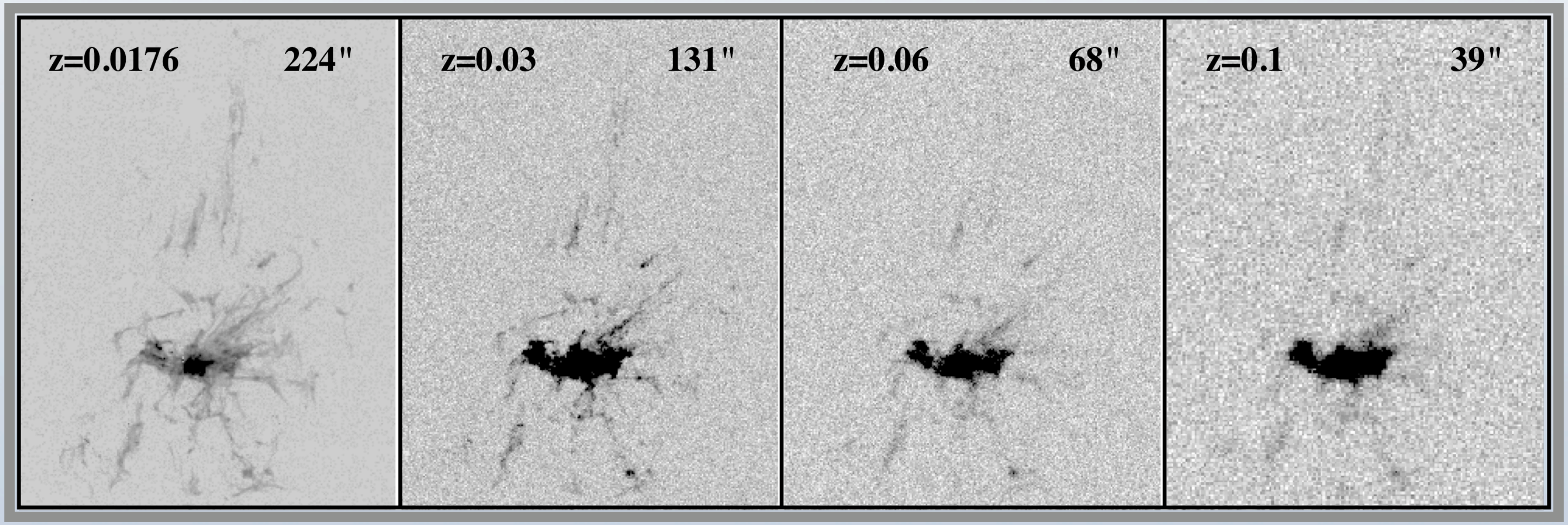
- Sample can be divided into three morphological classes

  I. Thin, extended filaments
  II. Nuclear, slightly extended emission
  III. No emission

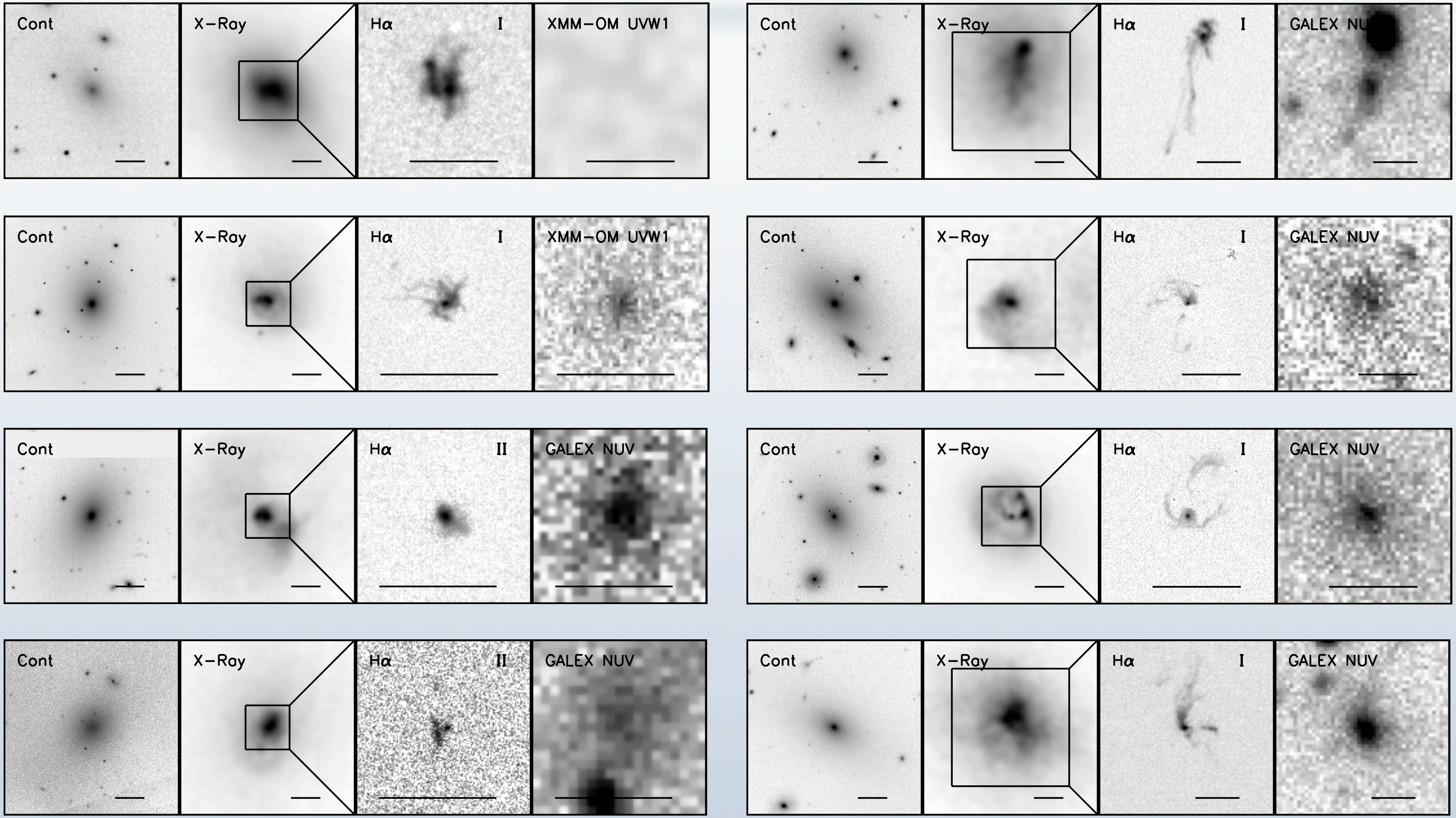


In the Context of Per A…

- The complex morphology of the ionized filaments in Perseus A is typical of the clusters in our sample
  - Larger distances make it very difficult to resolve filaments and see low surface brightness features



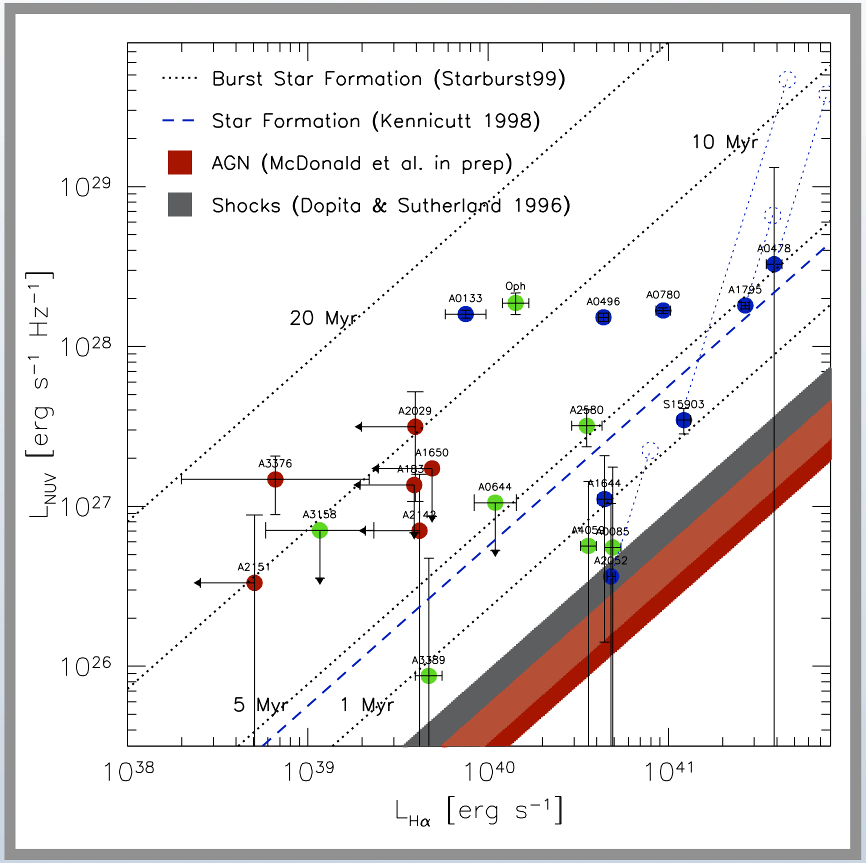
Results – Hα in Clusters



McDonald, Veilleux, Rupke and Mushotzky 2010

Results – NUV vs Hα

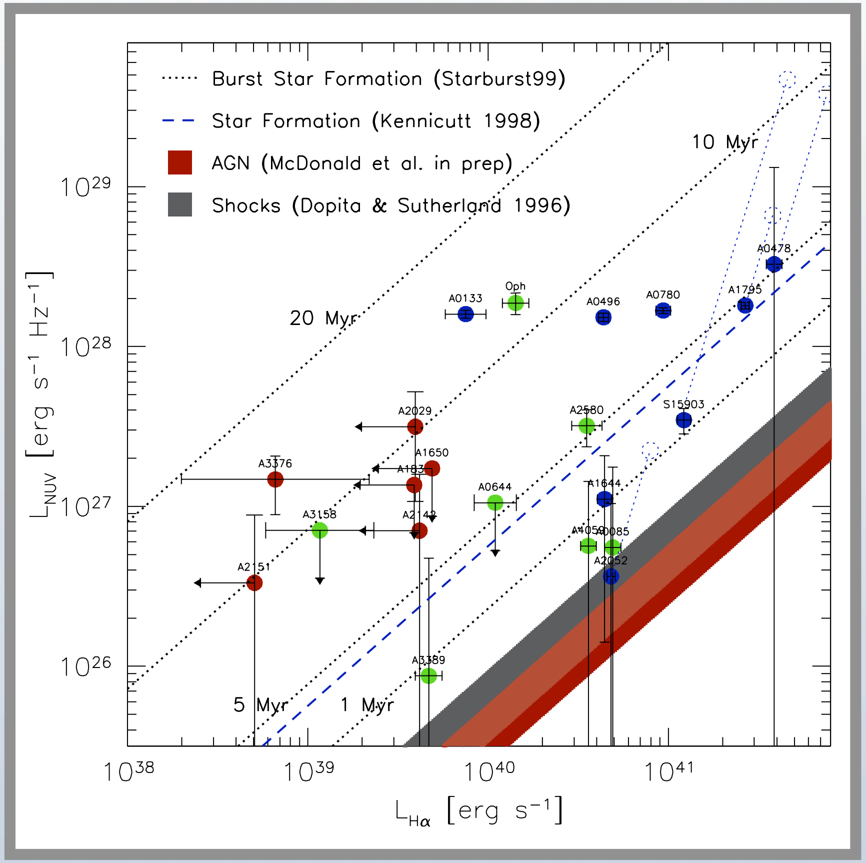
- Using GALEX & XMM-OM near-UV imaging, can examine relationship between UV and Hα emission.
  - Must remove UV contribution from older stars, via 2MASS J-band imaging
- Strong deviations from Kennicutt-like star formation
  - Could be due to burst-like star formation
  - More probably, the Hα emission is not linked to star formation



McDonald et al. 2010a

Results – NUV vs Hα

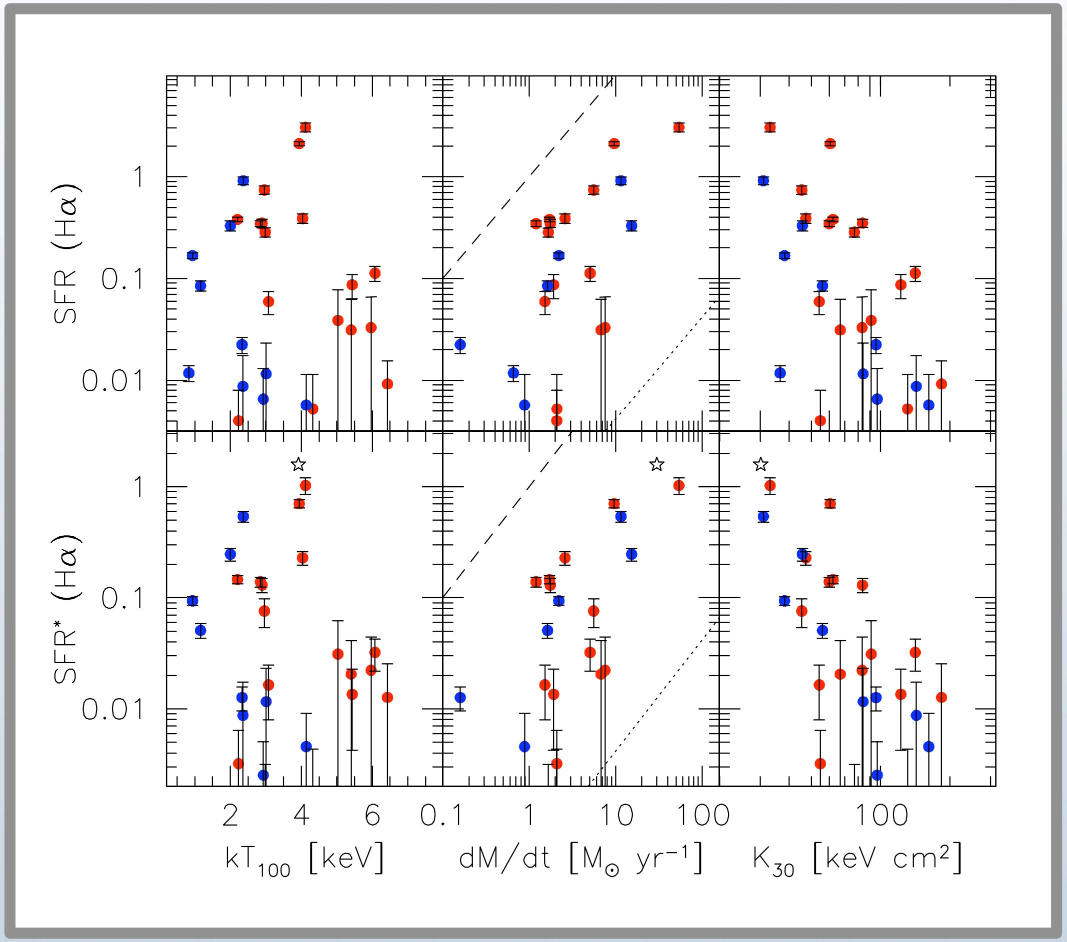
- Without higher resolution UV imaging, too difficult to say whether star formation is a viable heat source
  - Ideally, would like to look at UV/Halpha ratio pixel-by-pixel as we did for Abell1795
  - Will address this in McDonald et al. 2011 with high-resolution UV imaging from HST for 21 clusters.



McDonald et al. 2010a

Results – A link to cooling?

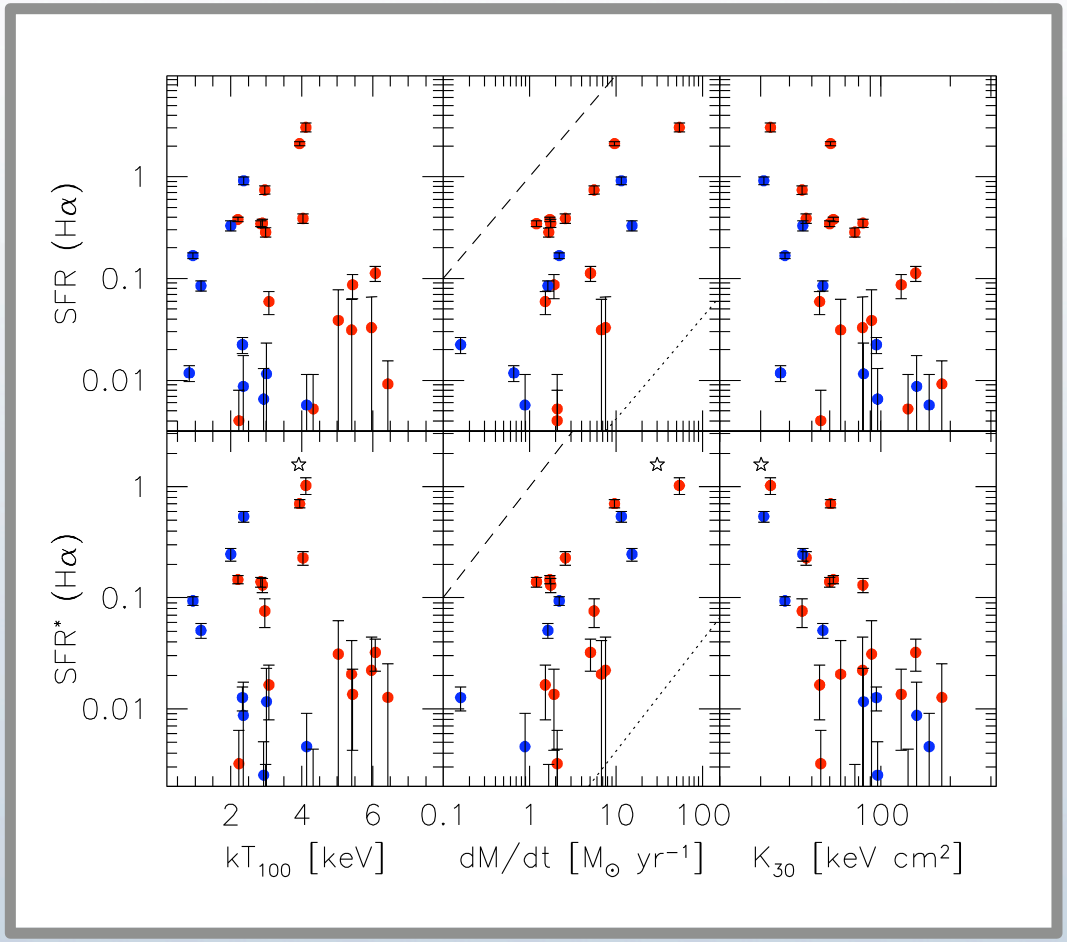
- Using archival X-ray data, we can look for a link between the Hα emission and the properties of the cluster/group core.
  - Red points: Clusters
    Blue points: Groups
  - Strong correlations between Hα luminosity and:
    - ICM temperature
    - Cooling rate (dM/dt)
    - Specific entropy



McDonald et al. 2010b

Results – A link to cooling?

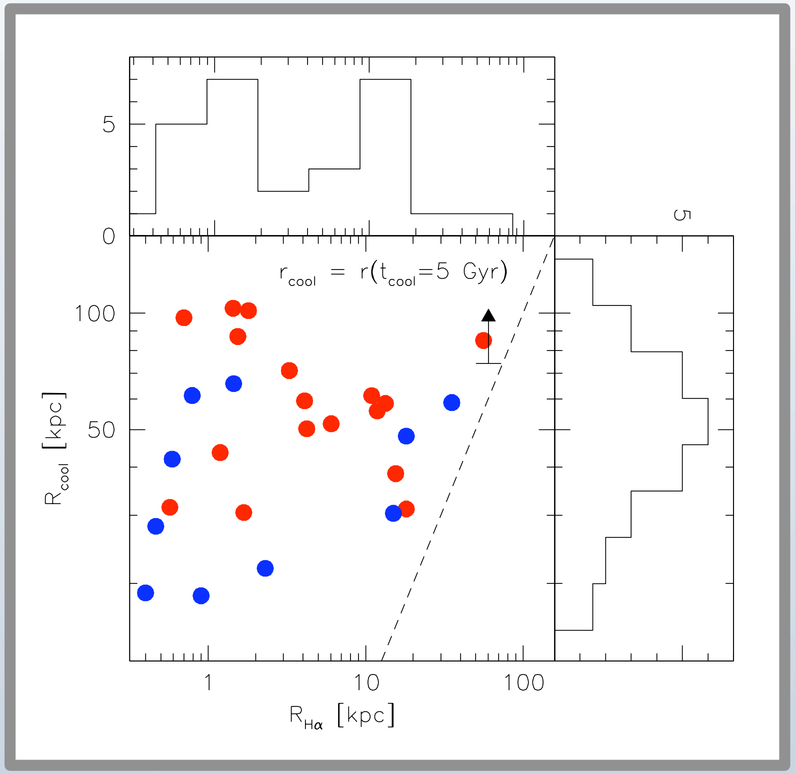
- Hard limit on the formation of optical filaments at $T_{(<100kpc)} = 4.5$ keV
- The Hα luminosity is an order of magnitude too high to be single recombination
- Also, an order of magnitude too low to be star formation induced by cooling flow.



McDonald et al. 2010b

Results – A link to cooling?

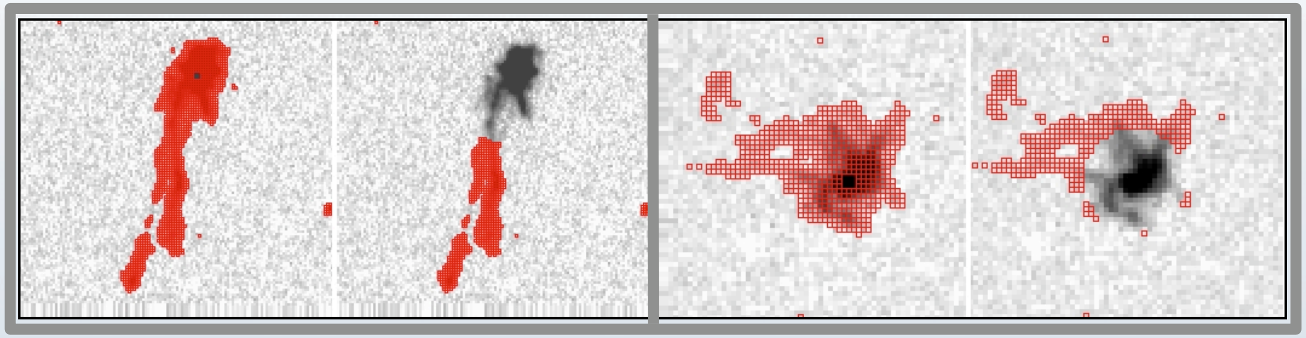
- The radius at which the ICM is cooling in less than 5 Gyr is also correlated with the maximum radius of Hα emission.
  - Filaments never extend beyond the cluster cooling radius.
  - Suggests a link between the Hα filaments and the X-ray cooling flow.



McDonald et al. 2010b

Results – A link to cooling?

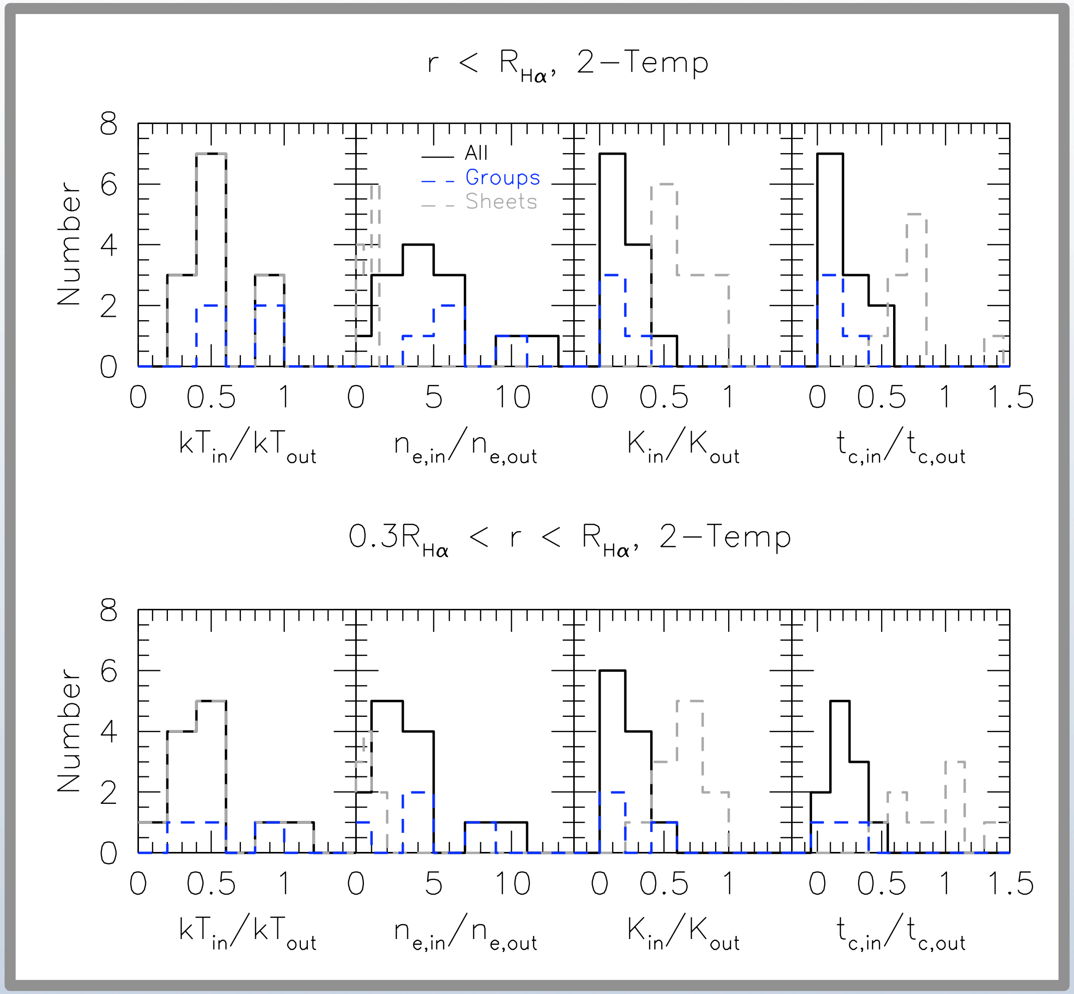
- Utilizing the high-spatial resolution of CXO, we can extract X-ray spectra on- and off-filament.



- Extract spectra in four regions:
  - On-filament
    - $0 < r < R_{H\alpha}$
    - $0.3R_{H\alpha} < r < R_{H\alpha}$
  - Off-filament
    - $0 < r < R_{H\alpha}$
    - $0.3R_{H\alpha} < r < R_{H\alpha}$

Results – A link to cooling?

- Compared to surrounding ICM, on-filament gas is:
  - Colder
  - More dense
  - Cooling MUCH faster (10x)
- Independent of:
  - Filament geometry
  - Radial binning
  - Total mass



McDonald et al. 2010b

Summary of Results

- Soft X-ray and Hα morphologies are similar
- The X-ray cooling rate and Hα luminosity are correlated
- The optical filaments extend to the X-ray cooling radius, but no further
- The cooling time of the ICM spatially coincident with the Hα emission is 10x shorter than the surrounding ICM

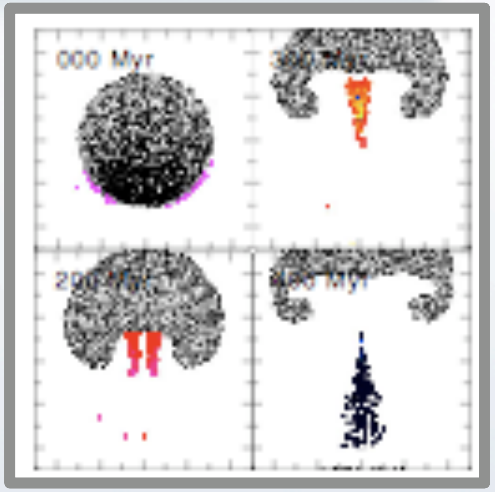
→ **The Hα emission is linked to the cooling ICM!**

Interpretation of Results

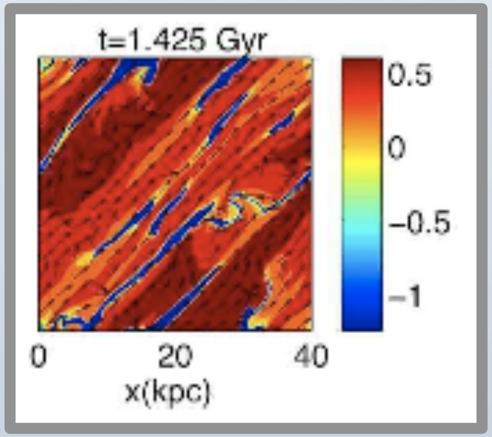
- Sources of gas in filaments
  - **Starburst/AGN driven wind**
    - ✖ Presence of filaments is not dependent on the presence of an AGN
    - ✖ Filaments are much too thin
  - **Stripped from merger/interaction**
    - ✖ Presence of filaments is not dependent on the presence of near neighbour
    - ✖ Would expect to trace the gas to the galaxy being stripped, in some cases
  - **Sloshing of cool material about cluster core**
    - ✖ Does not require emission to be centered on BCG
    - ✖ Would expect to see 'fronts' of ionization, perpendicular to motion

Interpretation of Results

- Two viable mechanisms for producing Hα filaments
  - Buoyant radio bubbles
    - **Pro**: models produce thin, radial filaments
    - **Pro**: radio-loud BCGs tend to have Hα emission
    - **Con**: hard to justify several filaments with different directions and similar surface brightness
    - **Con**: X-ray-Hα correlations should be secondary to BCG/AGN-Hα correlations
  - Radially-infalling X-ray cooling flow
    - **Pro:** several X-ray-Hα correlations
    - **Pro:** models produce thin, radial filaments
    - **Pro**: only see Hα in systems with cooling flows
    - **Con**: should we see Hα emission detached from center (start of infall) ? t_{dyn} vs t_{cool} ?



Revaz et al. (2008)



Sharma et al. (2010)

Ionization Source

- Regardless of how the cool gas arrives in filaments, we require a heat source to produce the high observed Hα surface brightness
  - Viable sources of heating include:
    - Photoionization by young stars
      - Probably not dominant in most cases
    - Cosmic ray heating
      - AGN is excellent source of cosmic rays, plus would explain the AGN-Hα correlation
    - Conduction from ICM
      - Would be consistent with the strong link between the Hα and X-ray emission
  - Need optical spectra of emission-line gas in order to make progress on this problem (McDonald et al 2011 in prep)

New Constraints for Models

- Typically very thin, extended, radial filaments
  - Average length/width ratios of ~ 35
- In general filaments are not heated by star formation
  - Need to explore other methods such as conduction, cosmic rays, drag heating, etc.
- Strong correlations between Hα and X-ray
  - $R_{H\alpha} \leq R_{cool}$
  - $T_{<100kpc} < 4.5$ keV
  - $L_{h\alpha}$ correlates with dM/dt, K_{50kpc}
- X-ray cooling is strongly enhanced in Hα filaments
  - t_{cool} (out) ~ 10 × t_{cool} (in)
- Optical filaments tend to form in low-entropy systems with relatively high gas mass fractions
  - No obvious correlation with global mass/temperature

Conclusions

- Warm, ionized gas (Hα) is present in the cores of a large (2/3) fraction of cooling flow clusters
  - 50% in filaments, 50% nuclear
- The Hα emission is strongly correlated with the cooling ICM
  - Suggests that we are observing directly the gas that has cooled out of the X-ray
- Star formation is, in general, an inadequate source of ionization in the filaments
  - Conduction or cosmic rays seem more promising
- The formation of Hα filaments is independent of the global mass/temperature of the group/cluster
  - Amount of feedback scales with system mass to balance cooling
  - The cooling efficiency is highest in low-mass systems

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