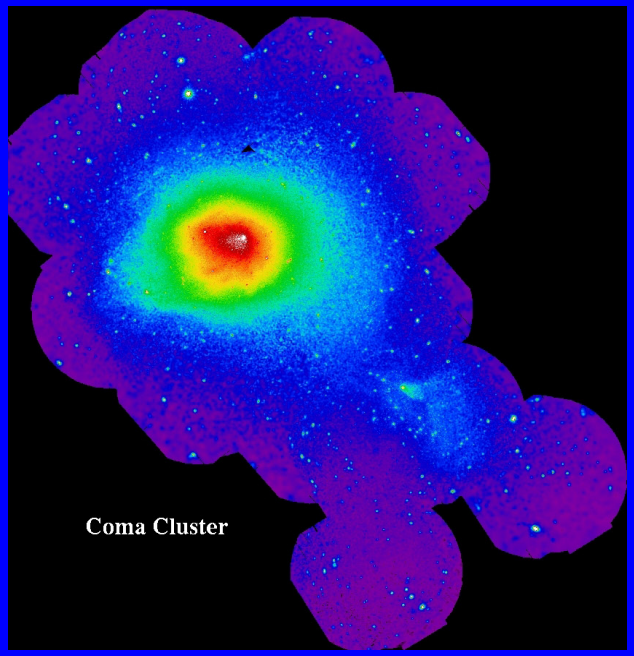
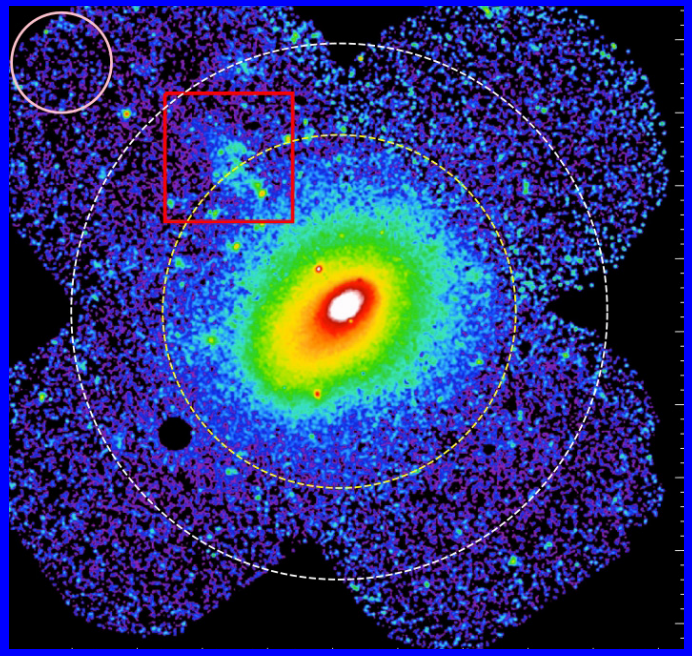
Clusters of Galaxies: Highlights from 20 Years of XMM-Newton



Abell 2142 Filament

Craig Sarazin

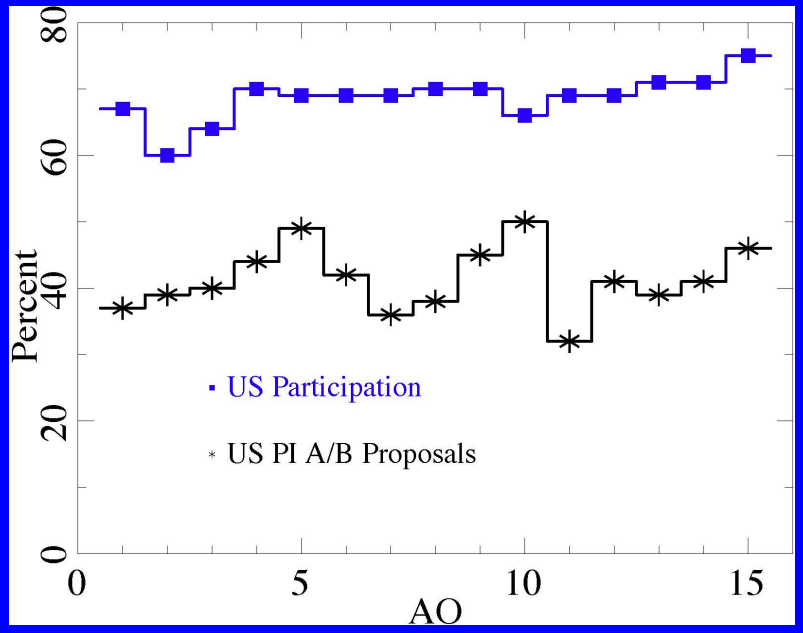
University of Virginia



Coma Cluster

Personal Involvement with XMM

- Proposer, User, Member of TACs
- Chair, NASA XMM-Newton Users' Group, 2009-2017
  - NASA funding for XMM to be cancelled based on 2008 NASA Senior Review
    - Supposedly based on scientific "bang for the buck"



Personal Involvement with XMM

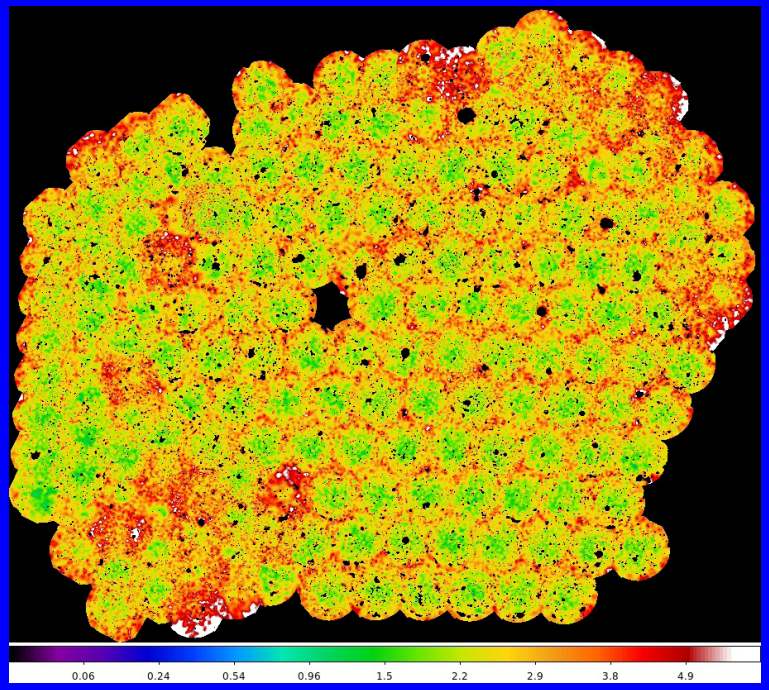
- Proposer, User, Member of TACs
- Chair, NASA XMM-Newton Users' Group, 2009-2017
    - NASA funding for XMM to be cancelled based on 2008 NASA Senior Review
        - Started letter campaign to NASA HQ
        - Some funding restored, special handling in ADAP
        - Regular funding restored by 2010 NASA Senior Review

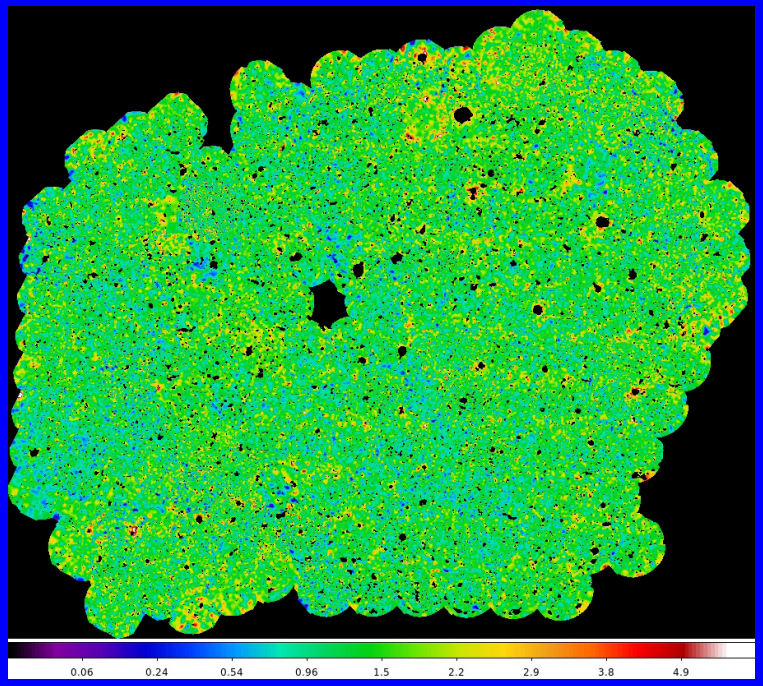
Personal Involvement with XMM

- Proposer, User, Member of TACs
- Chair, NASA XMM-Newton Users' Group, 2009-2017
- Member (US representative), ESA XMM-Newton Users' Group, 2011-2017
  - Initially, substitute for Richard Griffiths (project scientist)
  - ESA Users' Group changing from mainly project people to users
  - Convinced ESA that Chair of US Users' group should be member

ESAS
Extended Source Analysis Software

Many Thanks to Steve Snowden and Kip Kuntz!!





XMM XXL-South VLP before and after ESAS processing

ESAS
Extended Source Analysis Software

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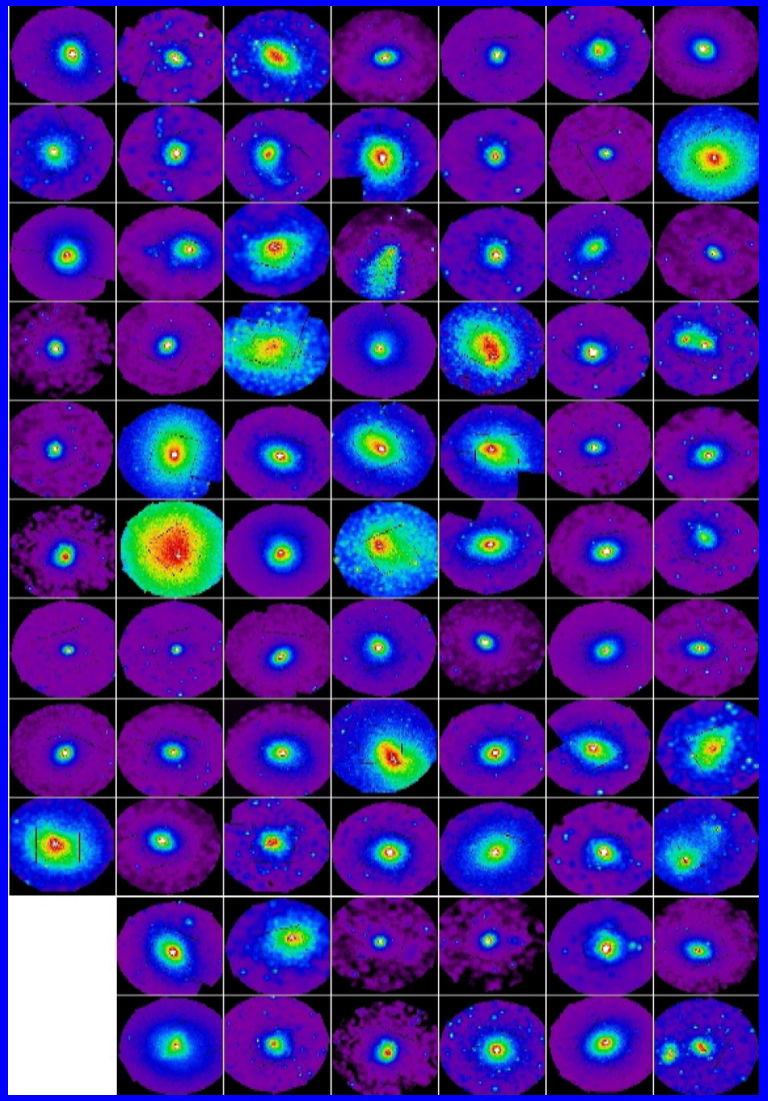

ESAS
Extended Source Analysis Software

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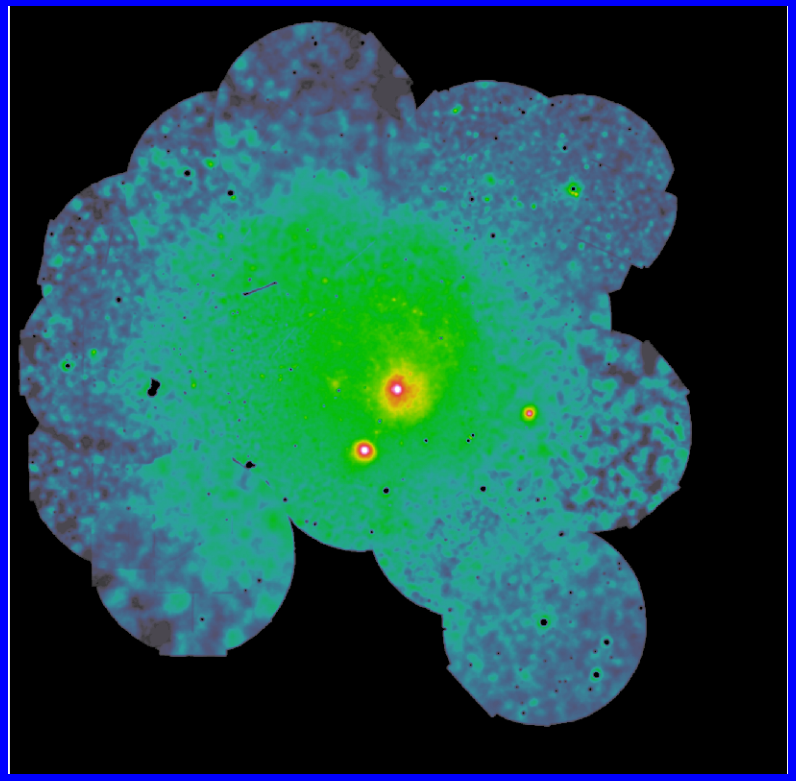
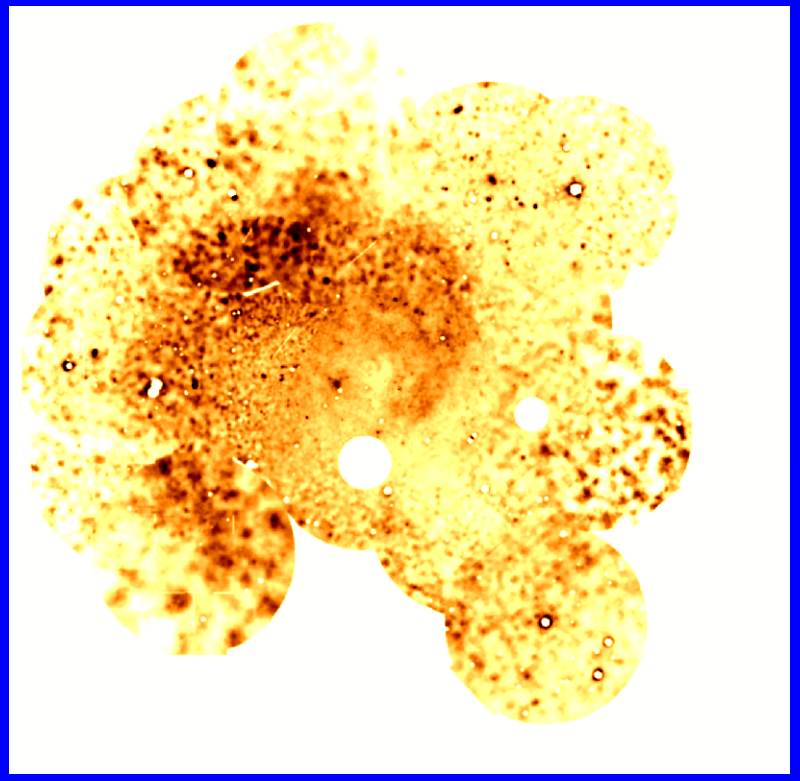




4 sloshing cold fronts in Fornax Cluster (Su et al. 2017)

Some Scientific Highlights

Probably badly selected!

Solution of "Cooling Flow Mystery”

Cooling Flow Mystery:

cluster cores:

lots of gas (100’s $M_{\odot}$/yr) cools by 2-3.

BCGs:

cool, cold gas and star formation

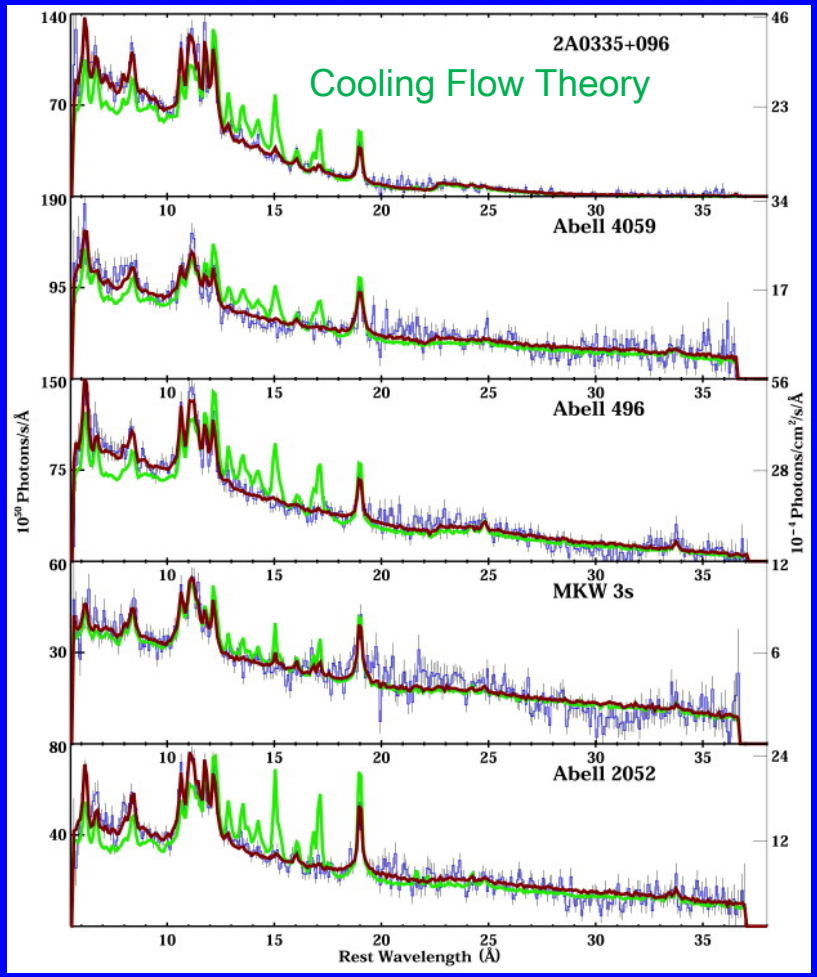
But .. . rates ~5% of X-ray cooling

Solution of ”Cooling Flow Mystery”

Solution:

XMM RGS spectra show that low energy X-ray lines from cooling gas are missing from clusters (Peterson et al. 2003)

Most of the gas which starts to cool is reheated by radio AGN “feedback”



Solution of ”Cooling Flow Mystery”

Some gas DOES cool down

(RGS spectra; Morris & Fabian 2005; Werner et al 2006)

Consistent with smaller but non-zero cool gas, cold gas, and star formation

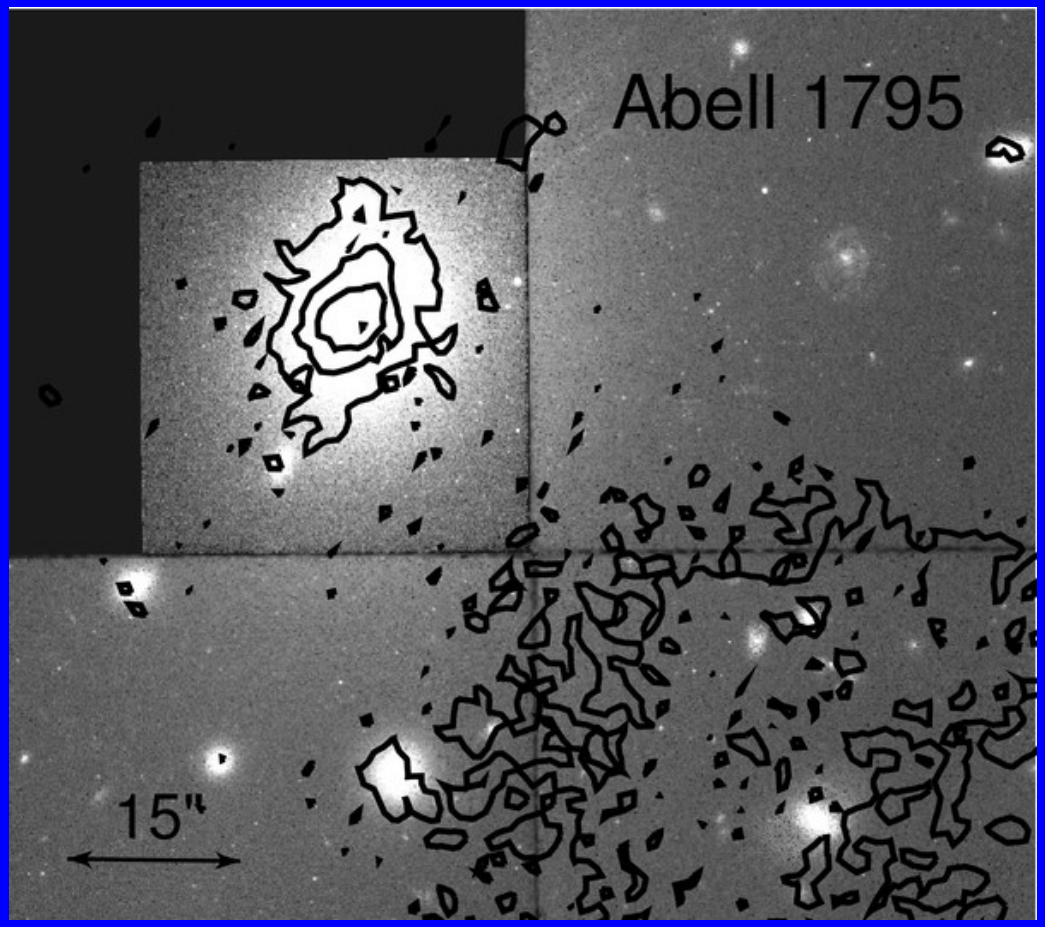
RGS Spectra of Cluster Cores

RGS: Key feature is high resolution spectra of extended emission

- Measurements or limits on velocities, velocity dispersion, turbulence
  - Line wavelengths, lines width, line optical depths (Churazov et al. 2004; Gastaldello & Molendi 2004; Sanders et al. 2010,2011; Sanders & Fabian 2013)
- Abundances of lighter elements (e.g., Sanders et al. 2007)

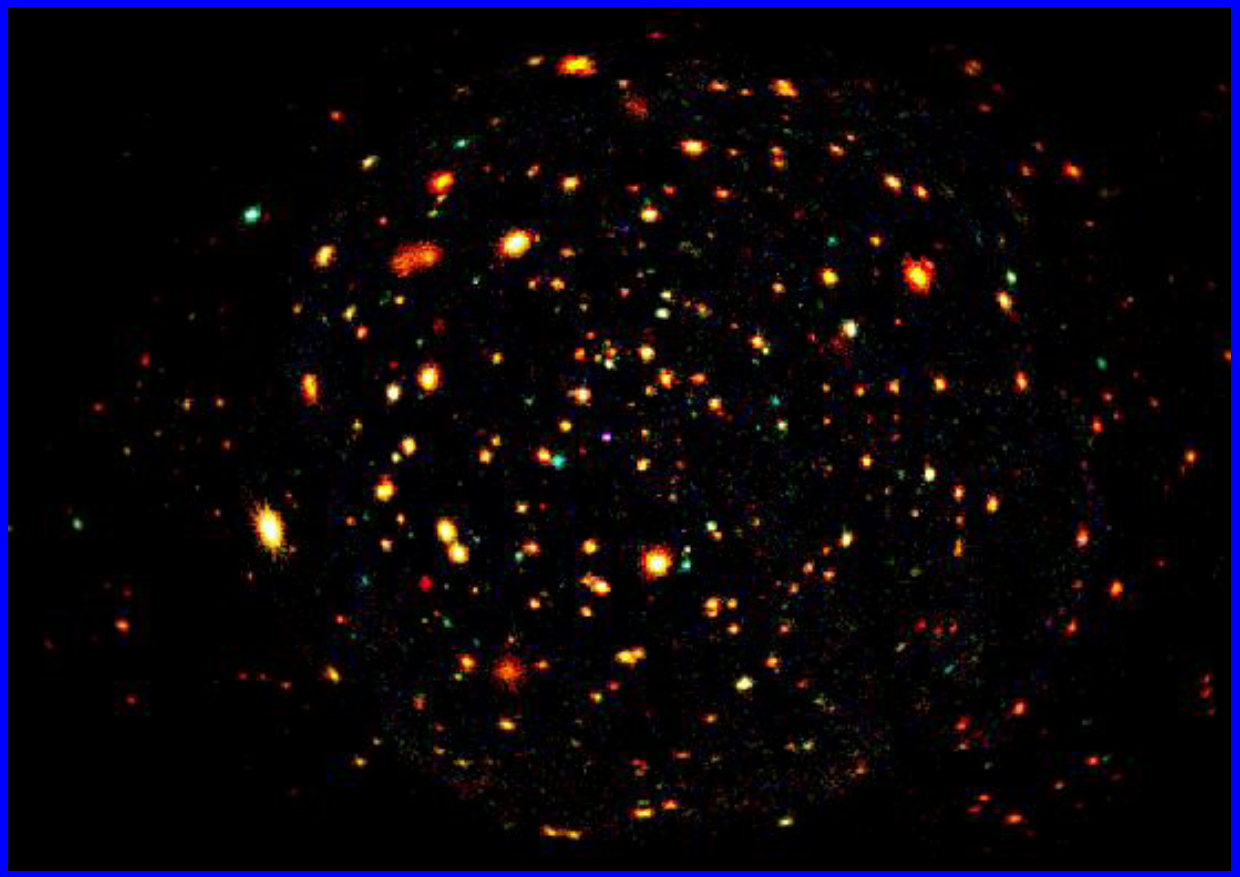
Star Formation in Cool Cores

OM UV observations of star formation in cluster cool core BCGs (Hicks & Mushotzky 2005; Donahue et al. 2010)



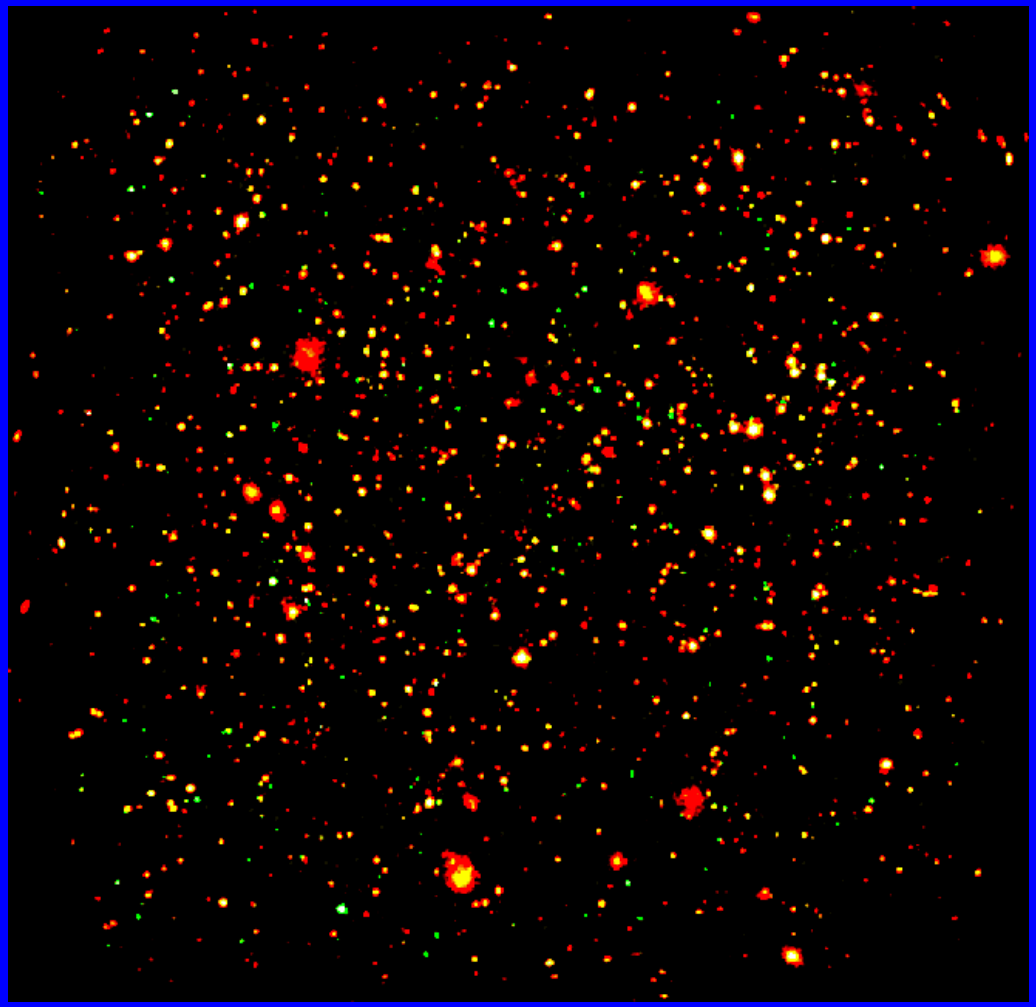
Cluster Surveys

Lockman hole



Cluster Surveys

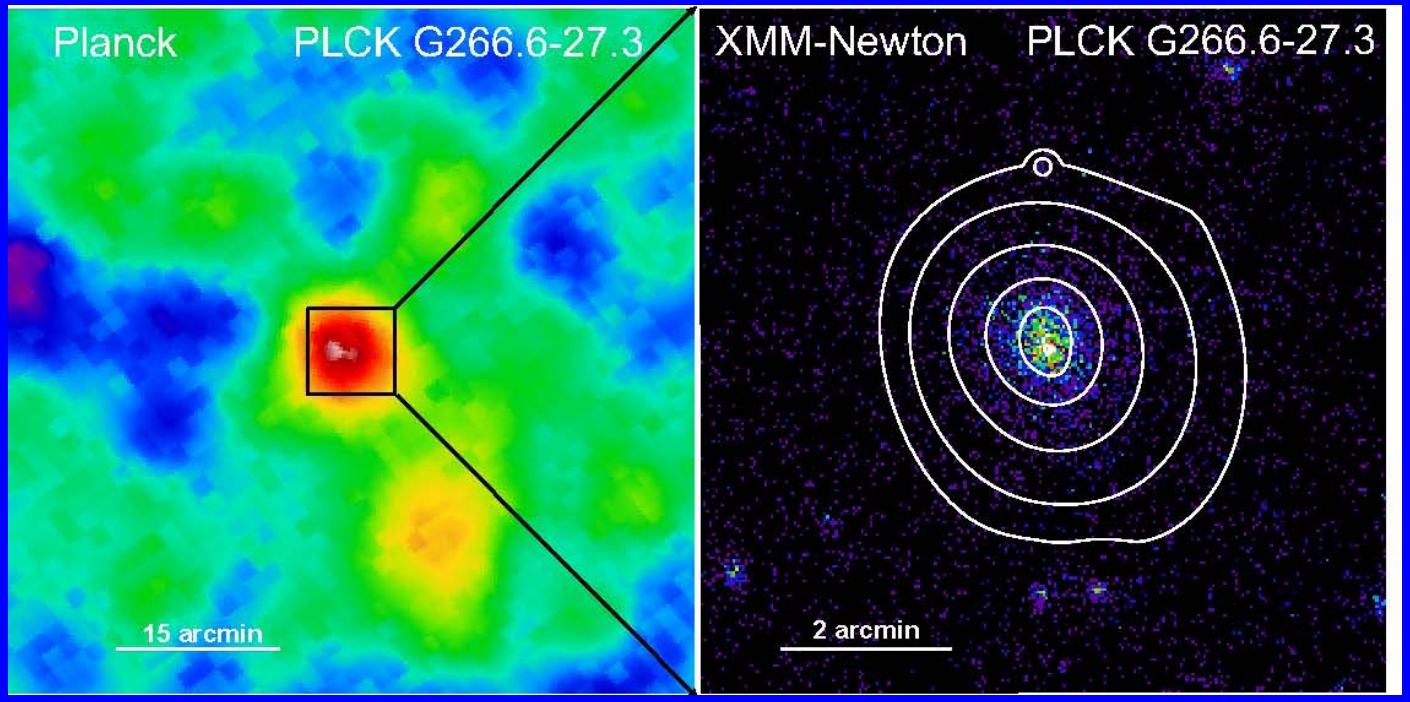
- XMM-LP (Böhringer et al. 2007)
- COSMOS



Cluster Surveys

XMM follow-up of Planck clusters

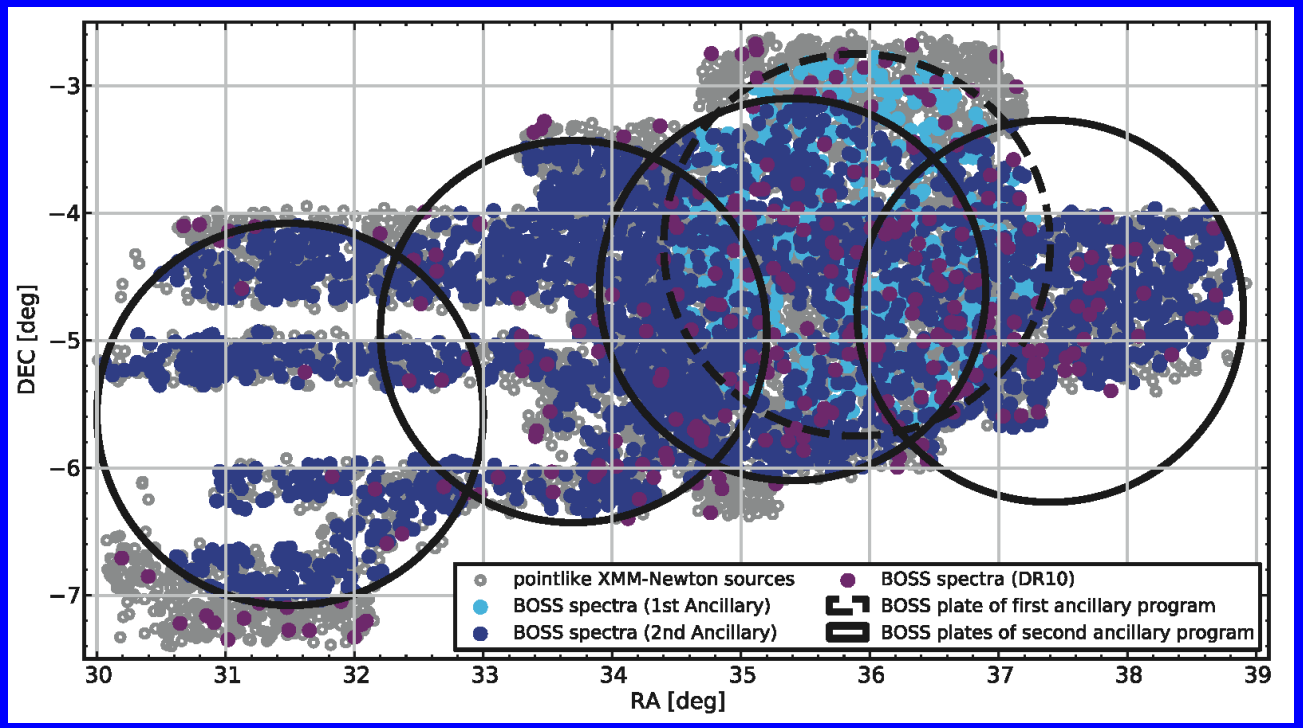
- XMM confirmed Planck-detected cluster candidate PLCK G266.6-27.3, z = 0.94 high mass 8e14 for high redshift



Cluster Surveys

XMM XXL North and South

- 2 fields, 25 deg^2 each
- 7 Msec, 540 observations



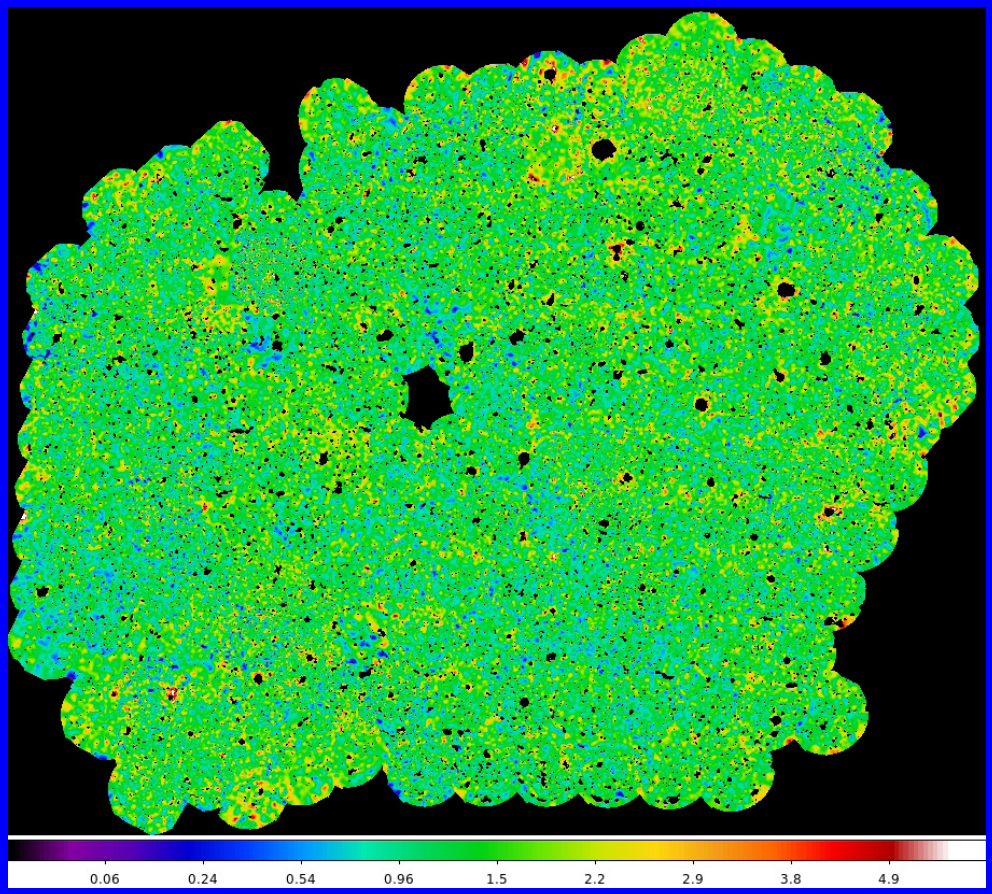
North

Cluster Surveys

XMM XXL North and South

- 2 fields, 25 deg^2 each
- 7 Msec, 540 observ.

South



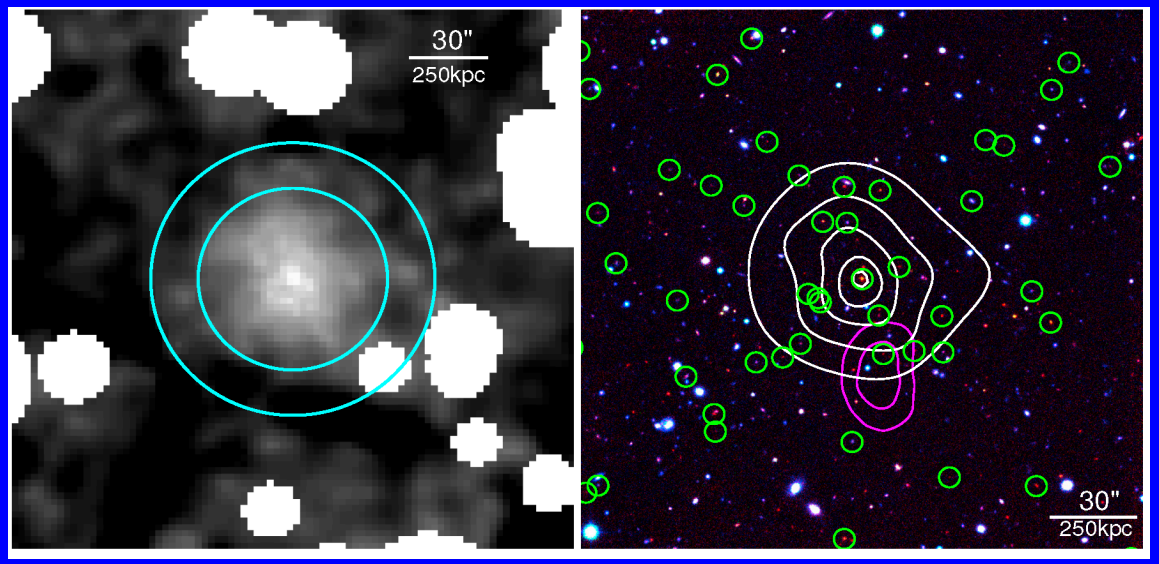
Cluster Surveys

- Extremely Expanded HIghest X-ray FLUx Galaxy Cluster Sample (eeHIFLUGCS)
- XMM-SERVS. 12 deg^2, 50 ksec
- Stripe 82 is a 31 deg^2, ~6 ksec

High Redshift Clusters

XMM ideal to detect, verify, and study highest z clusters, due to collecting area and soft X-ray sensitivity

XLSSC 122 z=2.0 (Mantz et al. 2018) Highest z X-ray selected

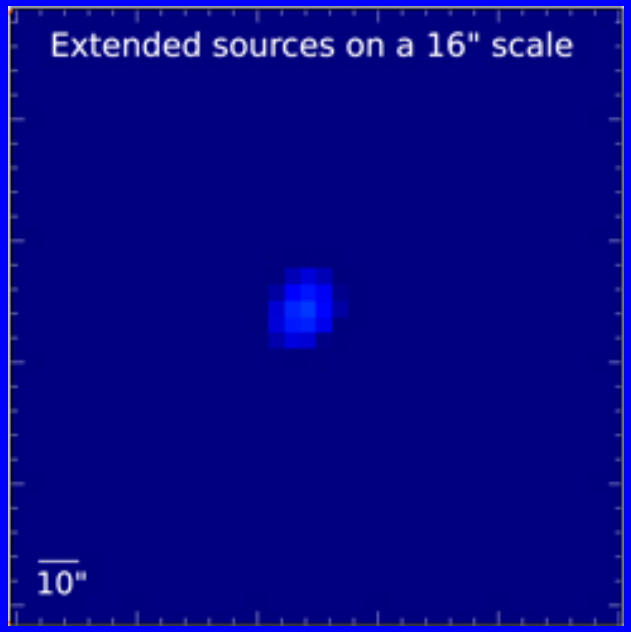


XXM

Galaxies and CARMA SZ

High Redshift Clusters

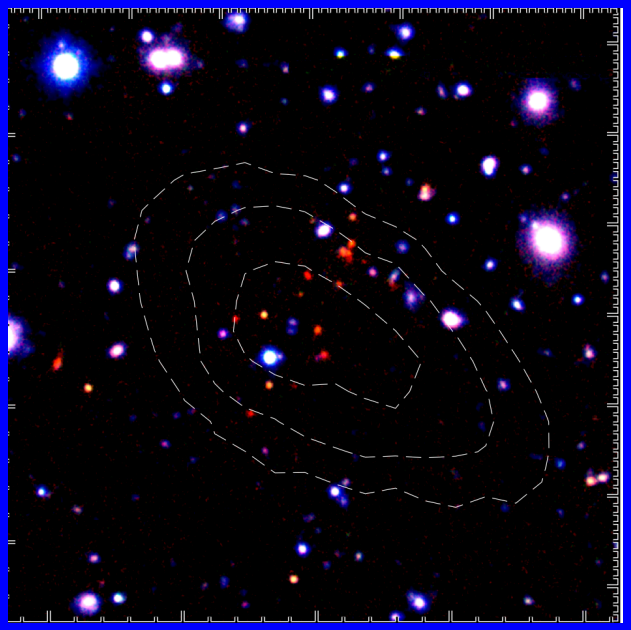
CL J1001+0220 z=2.506 , highest z cluster with ICM X-ray detection (Wang et al. 2016)?



XXM/ Chandra (mainly XMM)

High Redshift Clusters

CL J1449+0856 z=2.07 (Gobat et al. 2011)



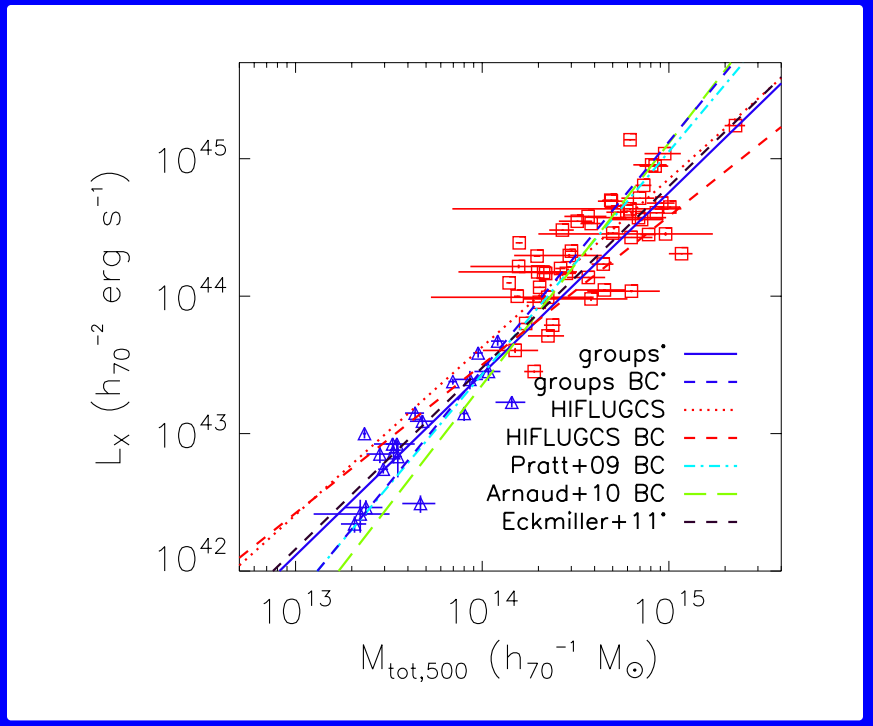
XXM contours on optical/IR color image

Hot ICM in clusters very early!!

Cluster Scaling Relations

Clusters are very important cosmological probes. But, … many applications require that the total mass of the cluster be known. For large sample, easier to measure other properties (e.g., X-ray luminosity). Need to scale these to mass (e.g., Kotov & Vikhlinin 2005; Maughan et al. 2006; Zhang et al. 2006; Croston et al. 2008; Juett et al. 2010; Gonzalez et al. 2013; Kettula et al. 201; Lovisari et al. 2015; O'Sullivan et al. 2018).

Scaling relation steepens from clusters to groups (Lovisari et al. 2015)

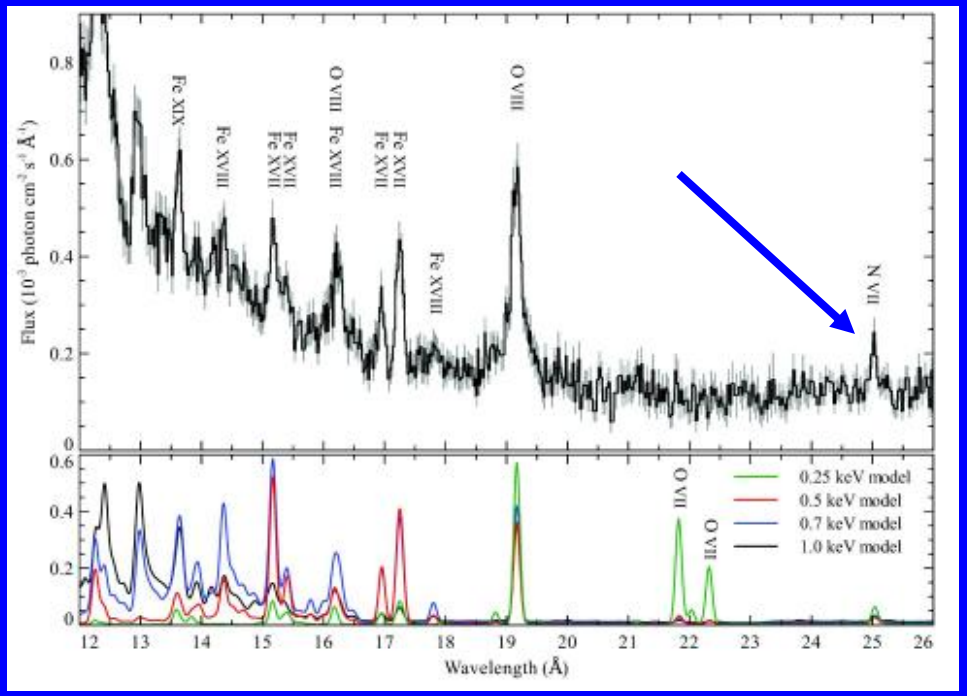


Abundances in Clusters

XMM:

EPIC: Large collecting area, broad band, good spectral resolution

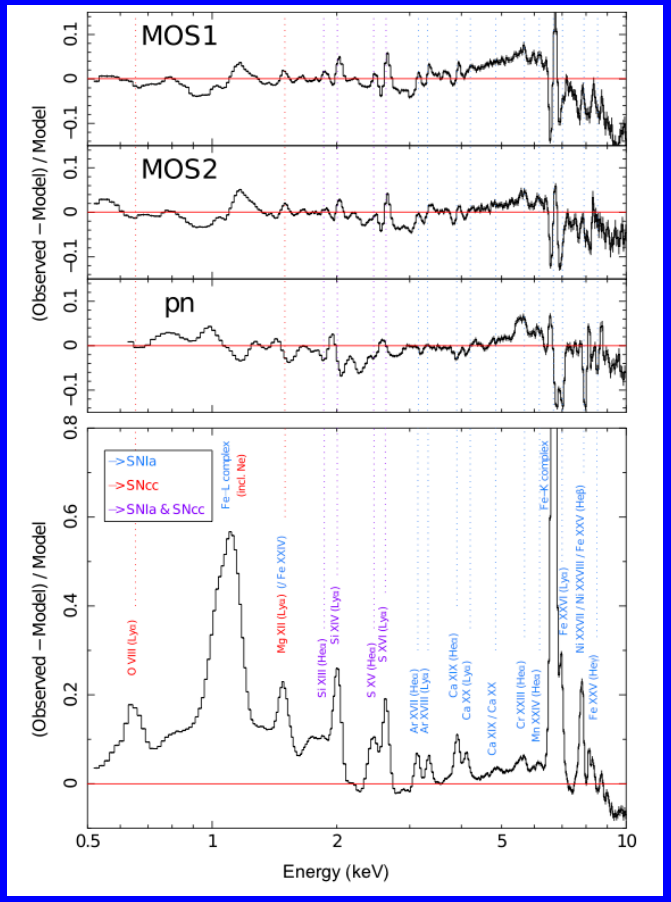
RGS: Works for extended sources

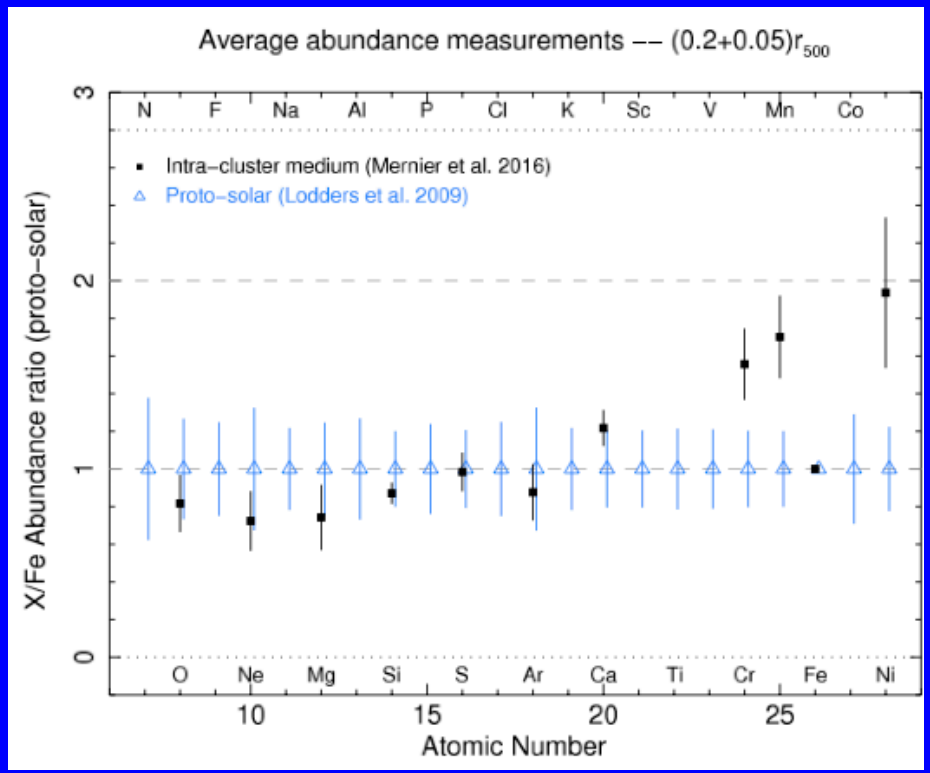


N VII detection Centaurus clusters with RGS (Sanders et al. 2007)

Abundances in Clusters

XMM RGS and EPIC CHEERS Sample, 44 clusters (Mernier et al. 2016)



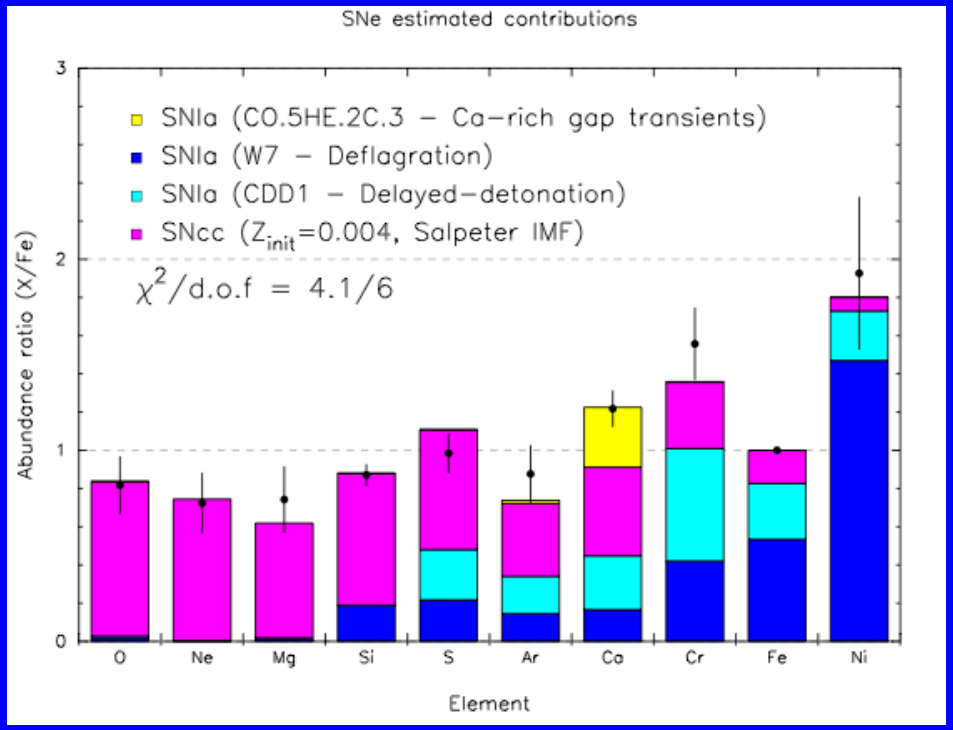


Abundances in Clusters

XMM RGS and EPIC CHEERS Sample

- Core-collapse SNe
- SNIa – both Deflagation and Delayed Detonation
- "Ca-rich gap transient" SNIa

Early enrichment, before clusters formed



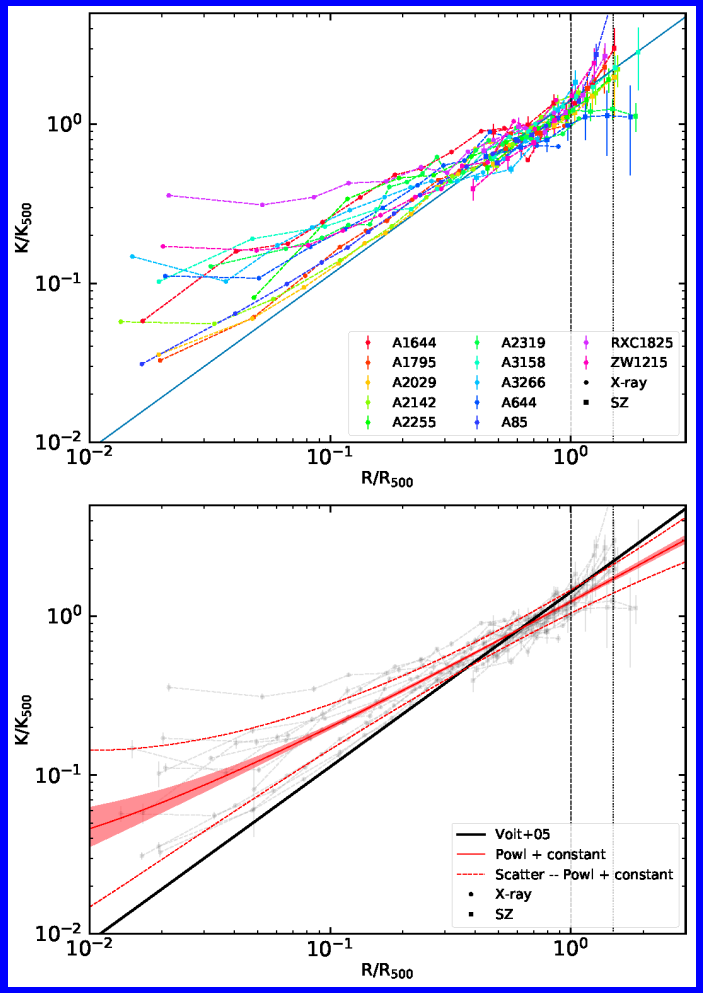
Abundances in Clusters

- Measure abundances
  - at large radii in nearby clusters (e.g., Urban et al. 2011)
  - In clusters at high redshifts

Cluster Gas and Mass Profiles

Gas density, temperature, pressure, entropy vs. radius

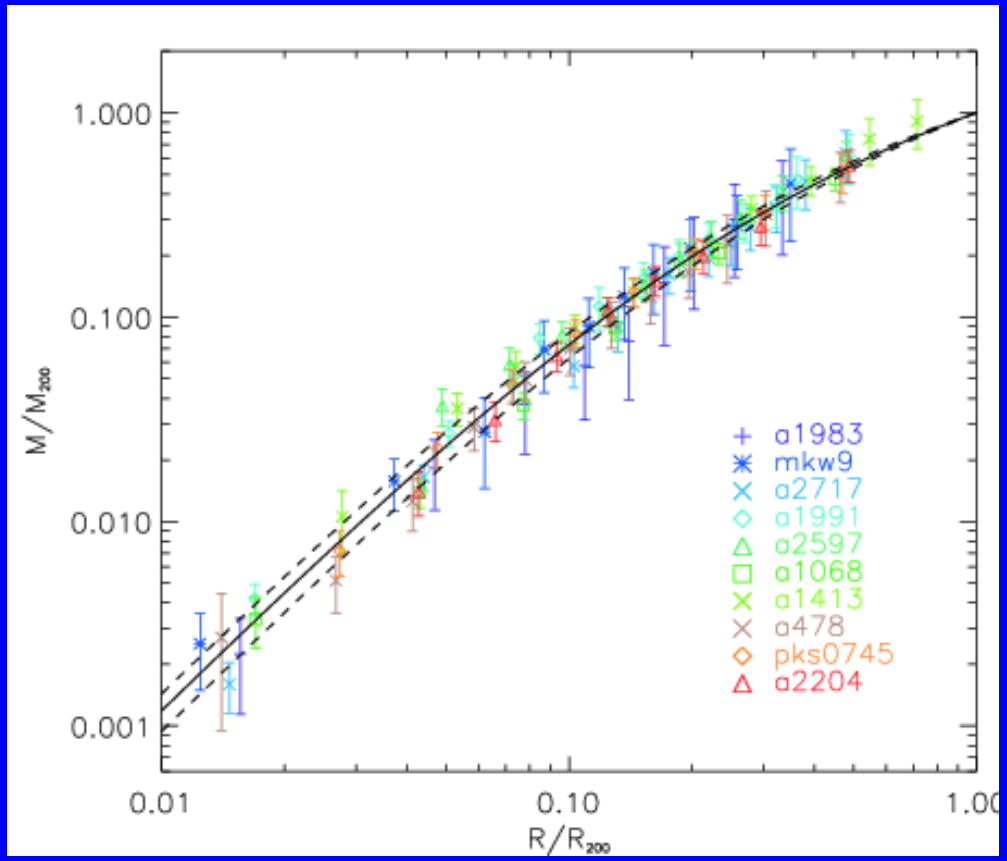
- Entropy profiles
  - Flatten at center due to AGN feedback
  - Flatten at outside due to clumping?



Ghirardini et al. (2019)

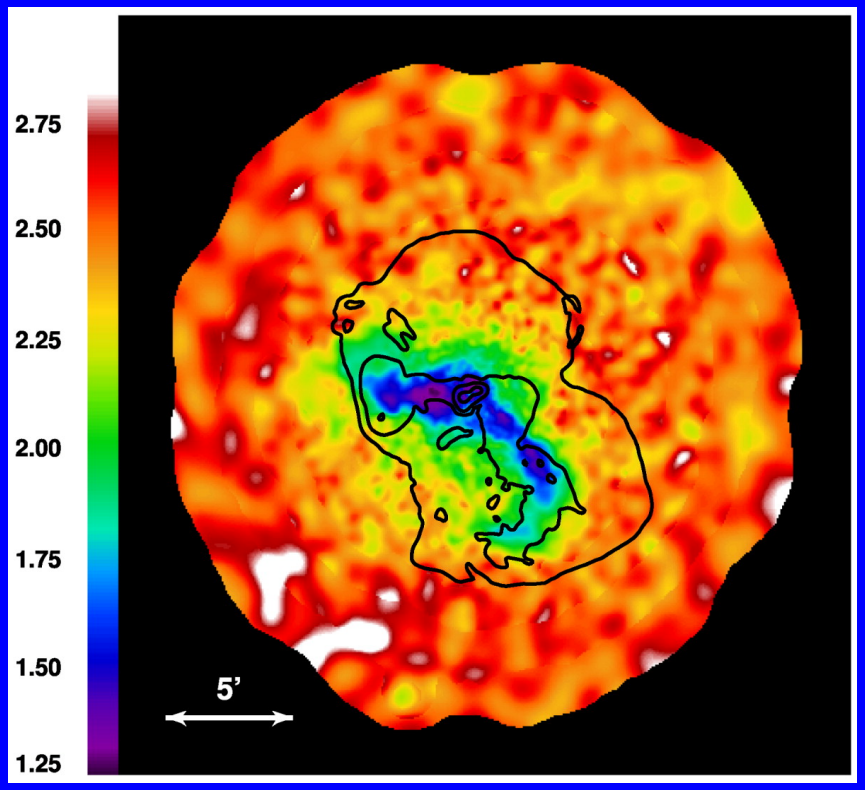
Cluster Gas and Mass Profiles

- Total mass profiles
  - Universal, ~NFW

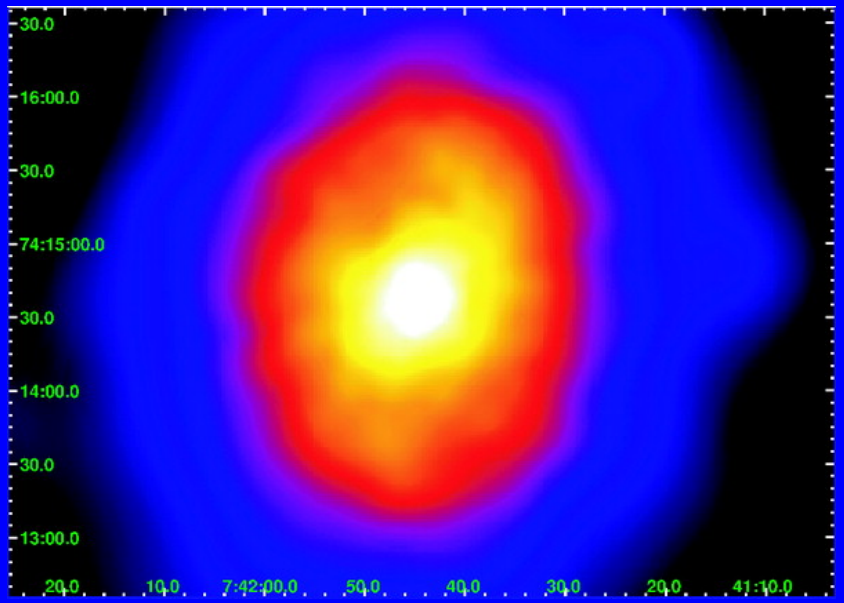


Pointecouteau et al. (2005)

Radio Galaxy Feedback



M87
XMM Temperature and
radio contours
(Forman et al. 2005)

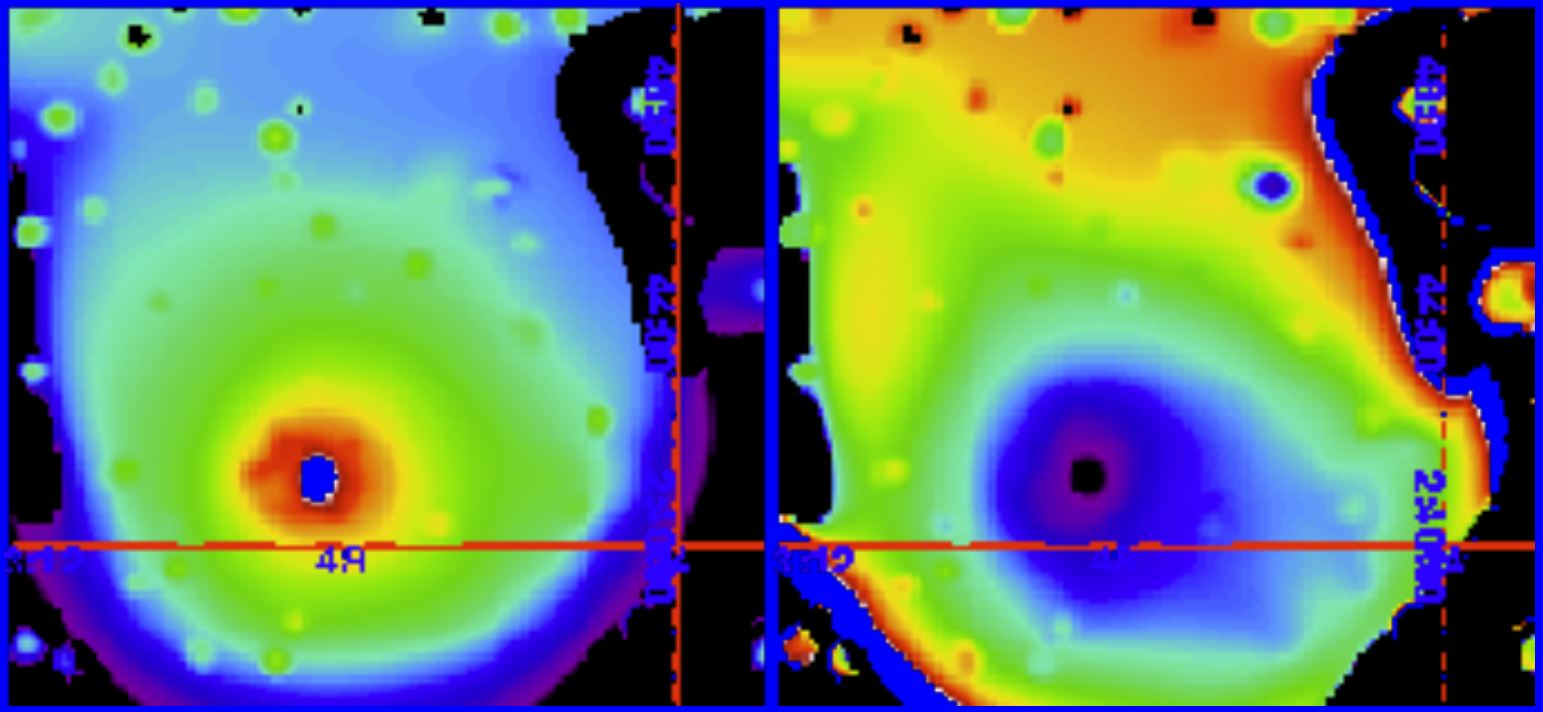


MS 0735+7421
XMM Image
(Gitti et al. 2007)

Maps of Gas Physics

X-ray SB and spectrum → gas density , T, abundances →

- Pressure maps → dynamics of gas
- Entropy maps → thermal history of gas



Entropy and pressure maps (Finoguenov et al. 2004)

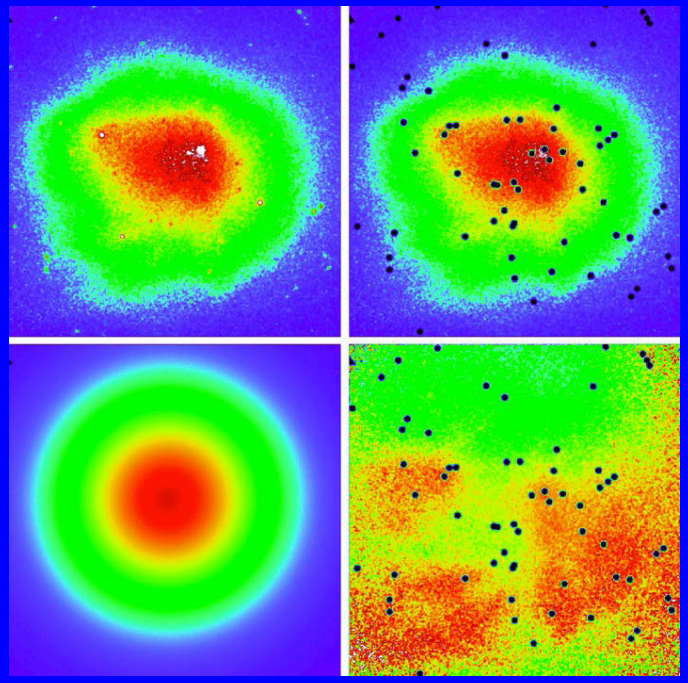
Maps of Gas Physics

Fluctuations:

Surface brightness, pressure, entropy →

Power spectrum and nature of turbulence

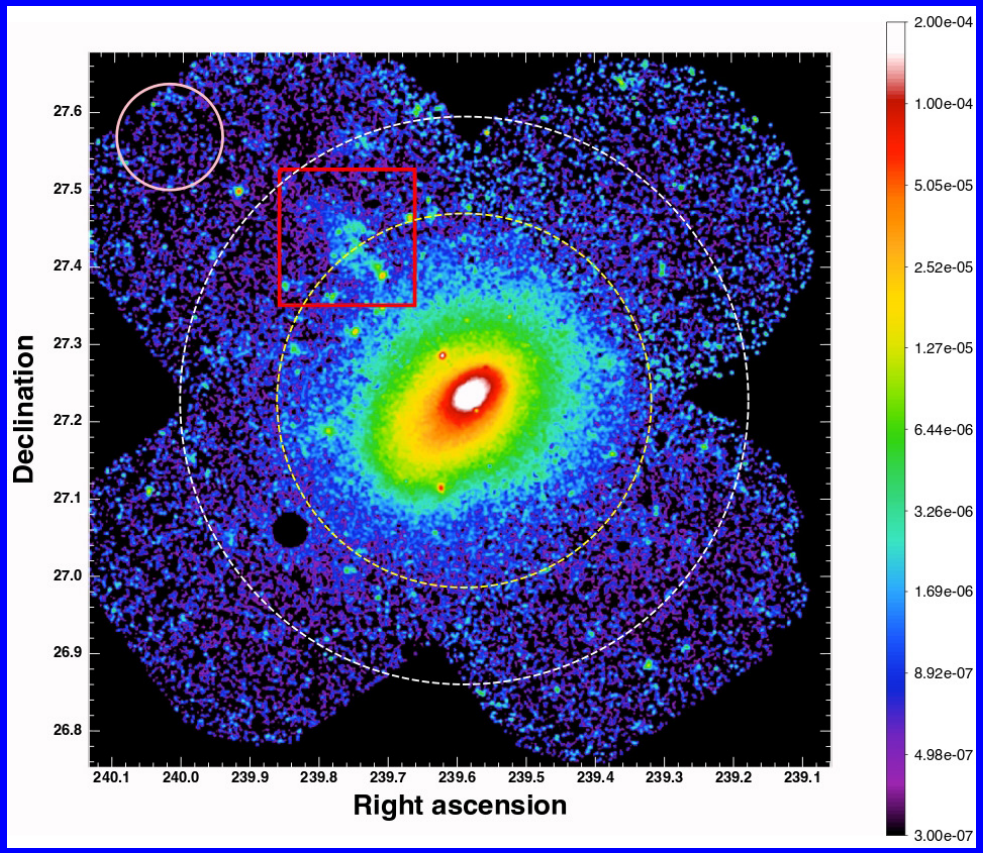
(e.g., Churazov et al. 2012; Sanders & Fabian 2012)



IGM Filaments between Clusters and in Cluster Outskirts

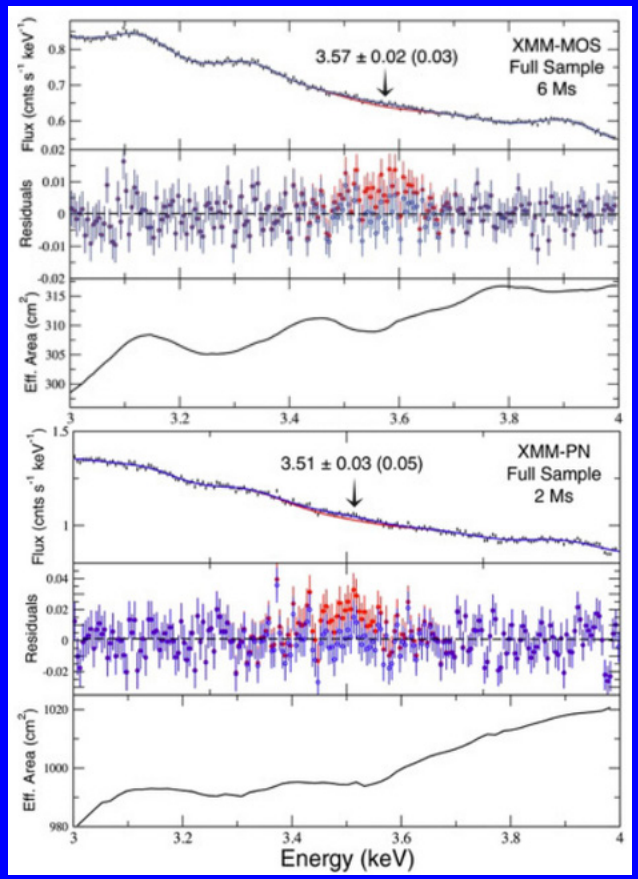
e.g. Coma (Durret et al. 2003), A85 (Kaastra et al. 2003), Abell 3395/Abell 3391 (Alvarez et al. 2018)

800 kpc X-ray tail from merging group in Abell 2142 (Eckert et al. 2014)



Possible Detection of Dark Matter Decay Line

- X-ray line at 3.57 keV in stacked spectra of 73 galaxy clusters (Bulbul et al. 2014; Boyarsky et al. 2014, 2015)



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Decay of 7 keV sterile neutrino warm dark matter particle?

Possible Detection of Dark Matter Decay Line

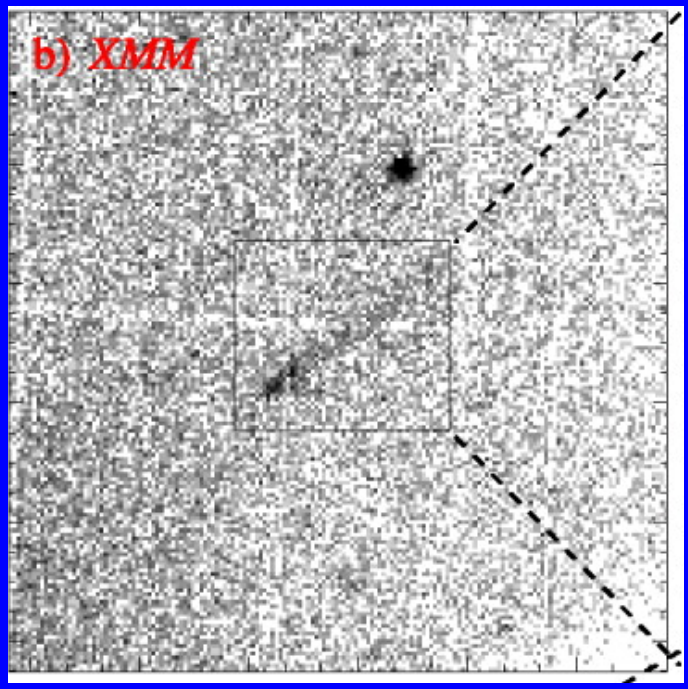
X-ray line at 3.57 keV in stacked spectra of 73 galaxy clusters (Bulbul et al. 2014; Boyarsky et al. 2014, 2015)

Decay of 7 keV sterile neutrino warm dark matter particle?

S XVI charge-exchange line? K XVIII lines?

Others

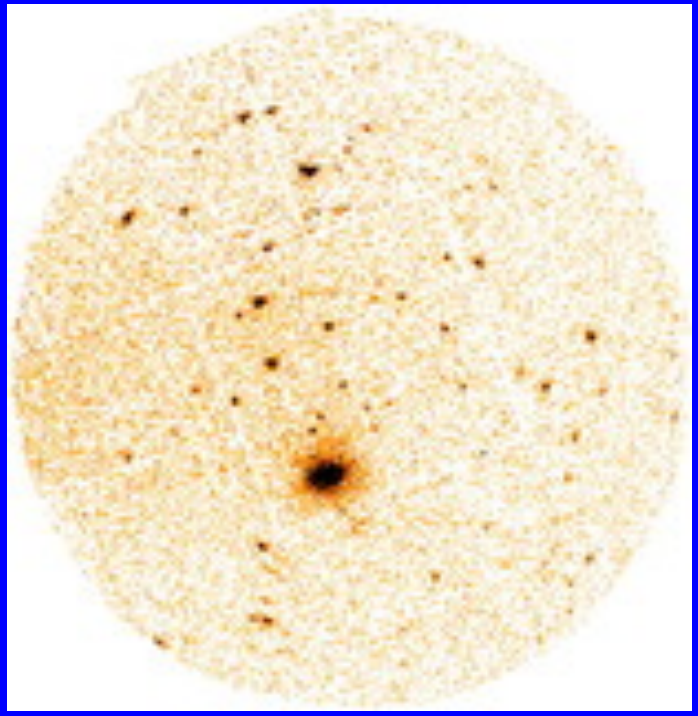
- Tails from Stripping Galaxies
  - Sakelliou et al. (2005), Machacek et al. (2005)



A2627 (Sun et al. 2006)

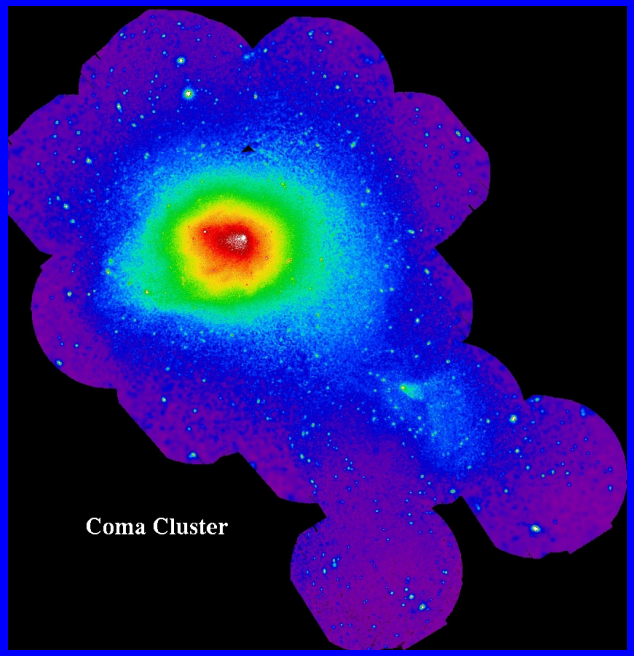
Others

- Tails from Stripping Galaxies
- Fossil cluster at z=0.281?
    - merged cluster where central BCG has eaten most of the central large galaxies
    - extended, hot, luminous ICM, L_X , T_X, mass like rich cluster
    - rich population of dwarf galaxies



Gastaldello et al. 2007

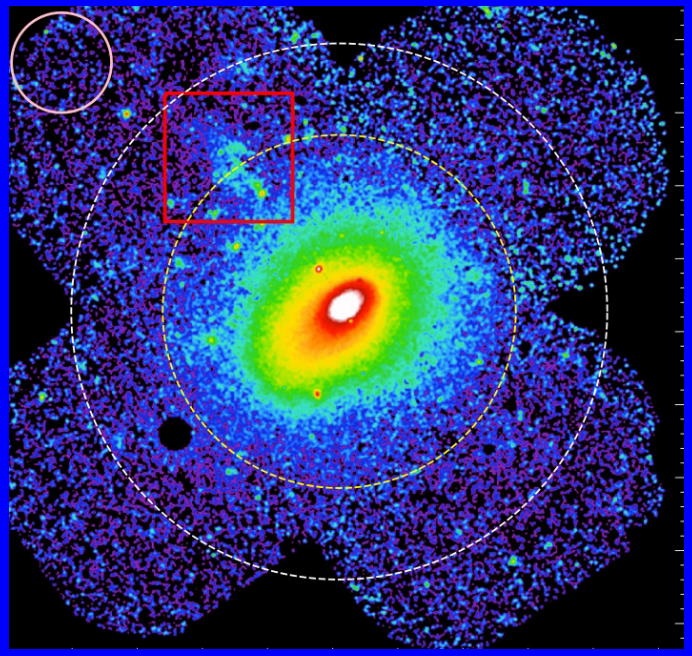
Here's hoping for many more years of great science from XMM-Newton!!



Abell 2142 Filament

Craig Sarazin

University of Virginia



Coma Cluster

end