Advancing Cluster Science with XMM-Newton

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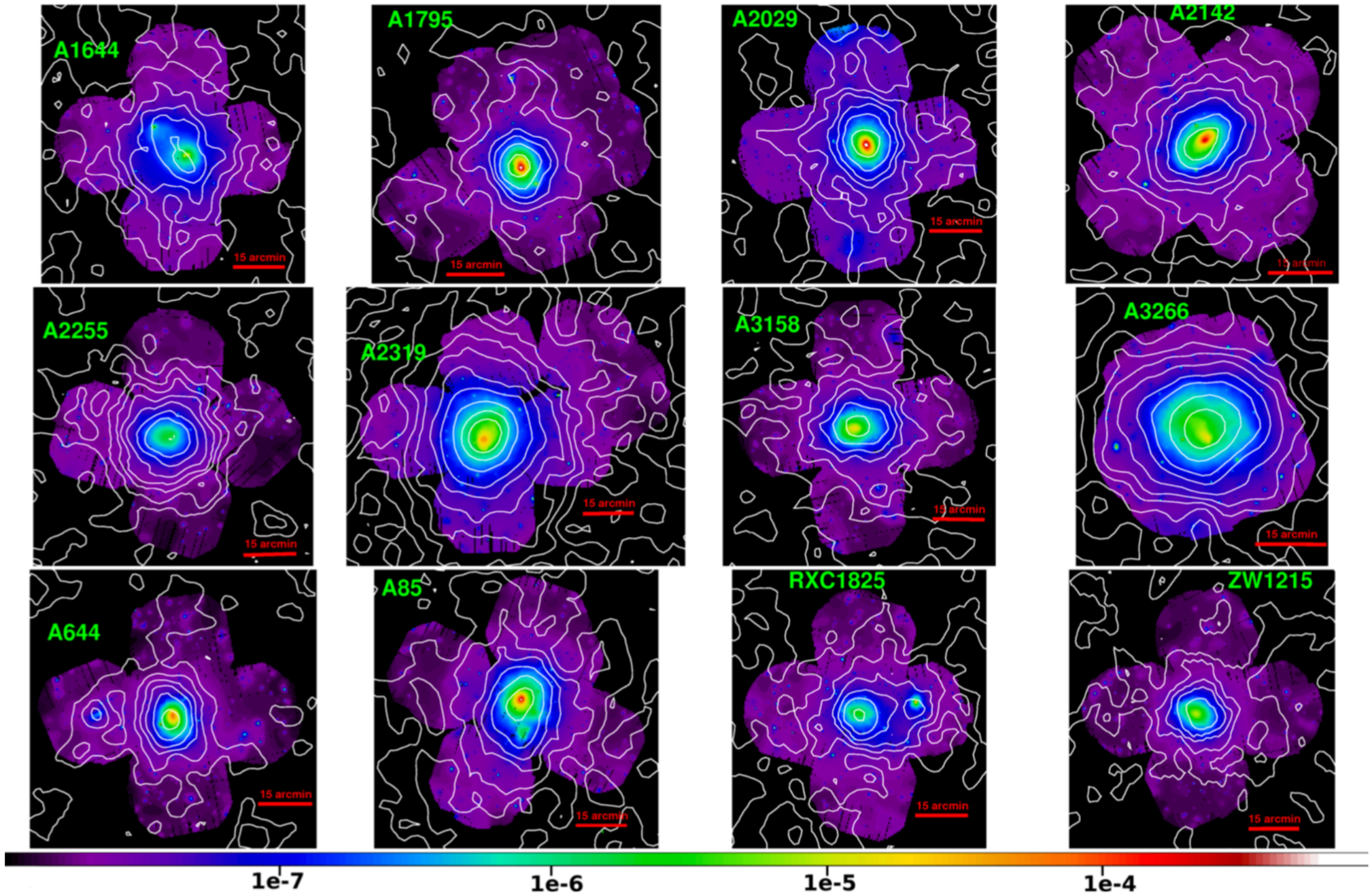
XMM cluster science

- Density and temperature gradients and maps from the core to beyond the virial radius (e.g. X-COP=X-ray Cluster Outskirts Program Eckert+2017)
- Detection and characterization of distant groups (e.g. COSMOS groups, see Giodini+2009)
- Detection and characterization of distant clusters of galaxies, included redshift estimates (!)
- Cosmology with clusters using gas mass, temperatures, and/or hydrostatic mass as mass proxies (e.g. Donahue+2014)

XMM cluster science

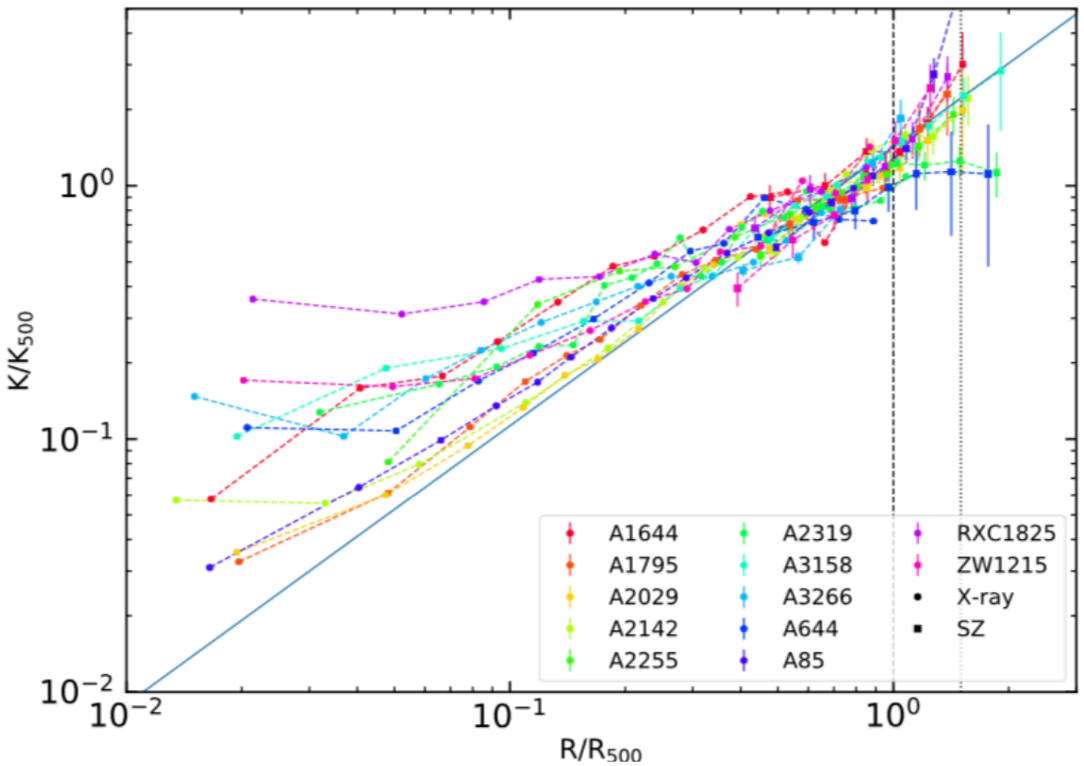
- Clusters have a nearly universal pressure profile (Arnaud+2010) : clusters are self-similar outside their cores
- Even merging ones (e.g. Walker+2019) although pressure is somewhat larger in merging clusters
- Outside of the core and inside the virial radius, radial gradients of cluster gas entropy ($K=kT\ n_e^{-2/3}$) follow the cosmological expectation $\propto r^{1.1}$ (e.g. Voit+2005)
- …but have entropy levels higher than numerical simulations without feedback expect



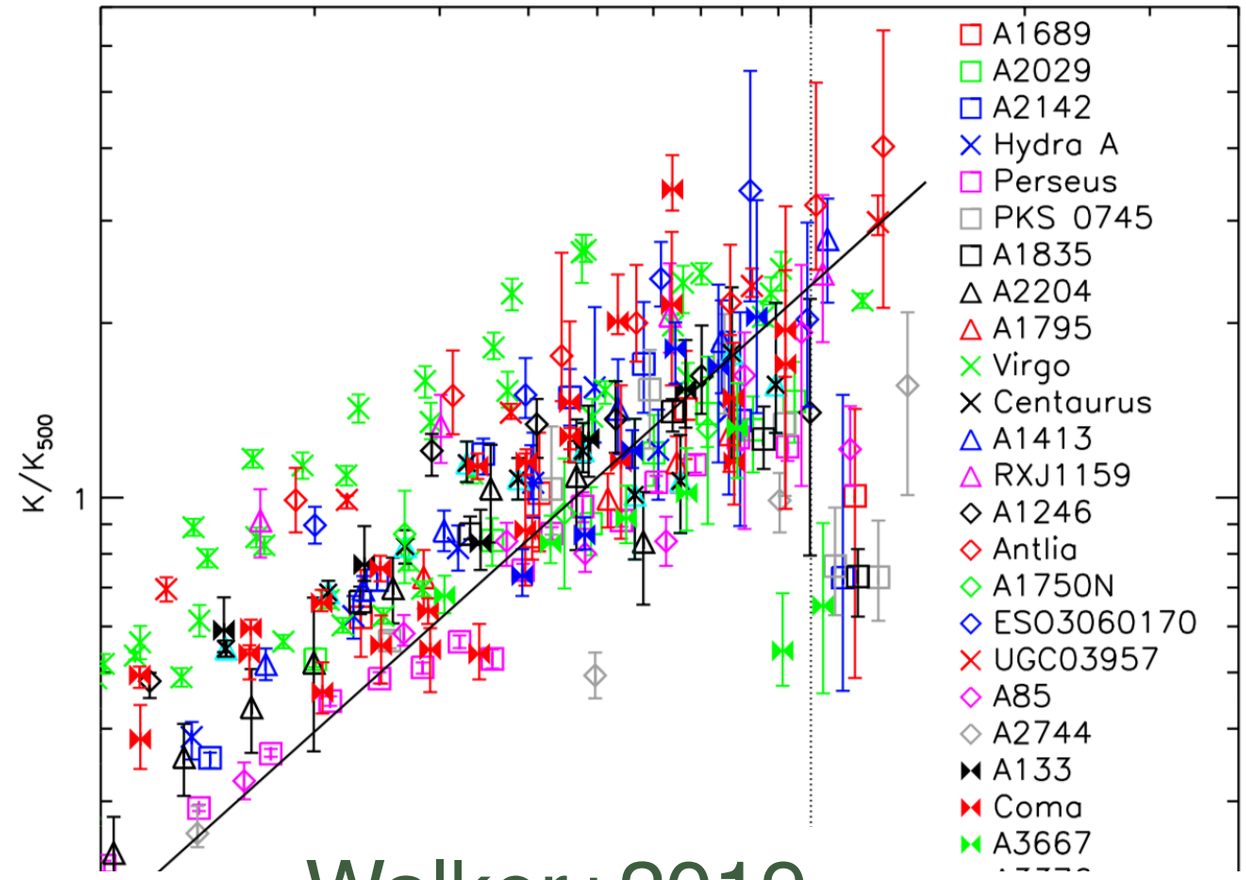
X-COP: XMM (0.7-1.2 keV) images + Planck contours

XMM observations can produce profiles beyond r_{500}

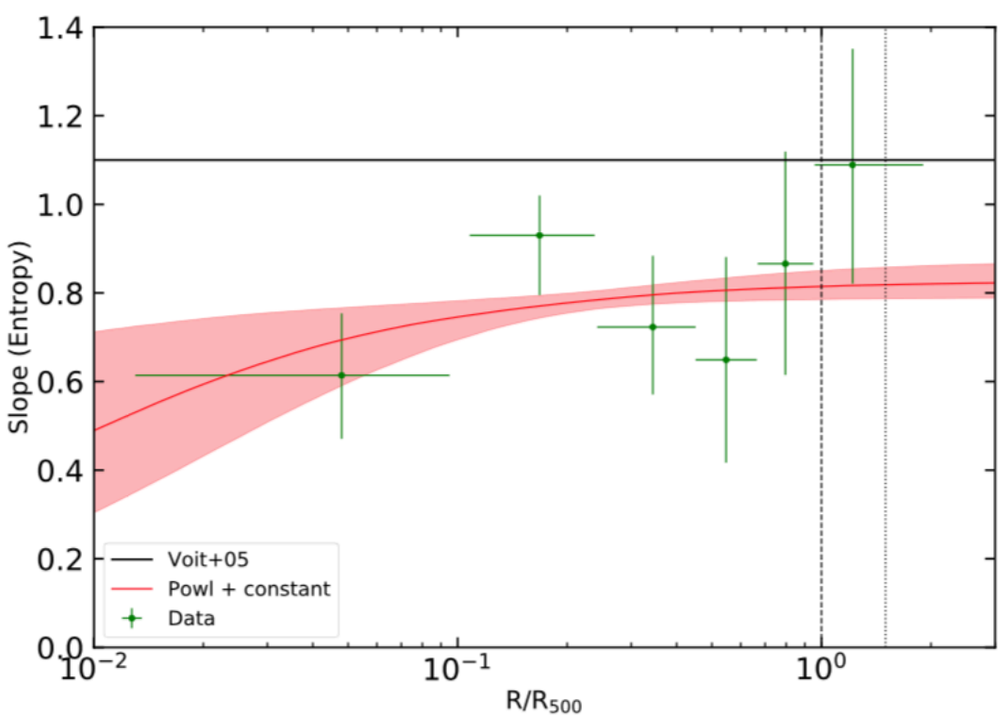
(sample selection: strong Planck signal; close and massive enough for Planck resolution, low Galactic column)

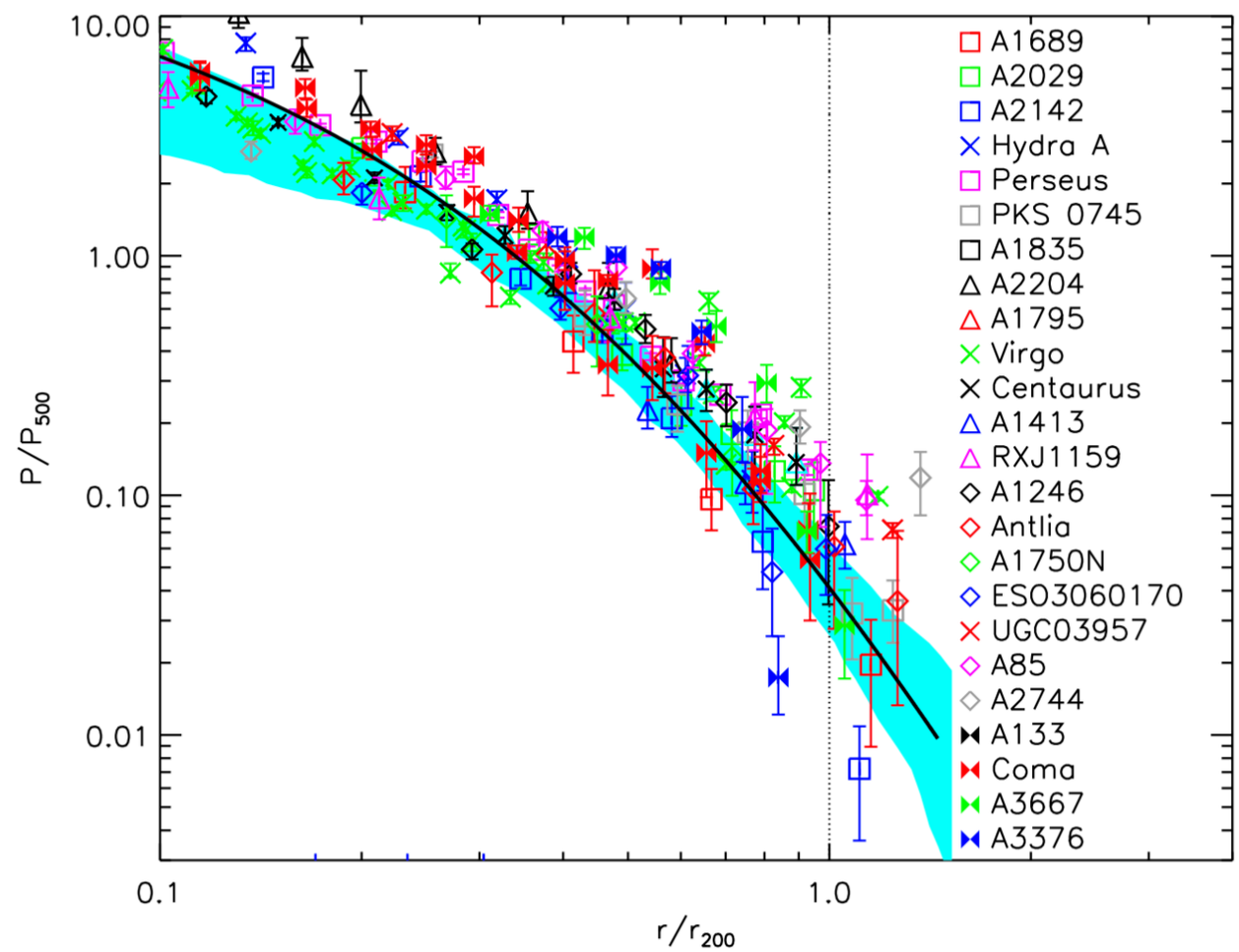


Ghirardini+2019



Walker+2019





Analysis of extended sources

- Backgrounds - bright, varies with position, energy, and time
  - Particle background
  - Photon background
- A PSF scatters light. For an extended source you have light scattered both in and out of the region of interest.

These are challenging data problems and they are not unique to X-ray astronomy.

XMM-Newton EPIC background working group

- In the first ~10 years, XMM observers were offered the possibility of a “custom” blank sky background
- To the uninitiated, this service was … terrifying
- A set of standard backgrounds are available now and the custom service was discontinued in 2013

Carter & Read 2007

Extended Source Analysis

- Steve Snowden and Kip Kuntz (who will talk more tomorrow)
- XMM-ESAS (Extended Source Analysis Software)
- now supplied with XMM SAS analysis tools
  - includes recipes for how to handle background files
  - includes routines to create “cross-arfs” to use in the analysis of extended sources like clusters
  - enabled the use of wide-area ROSAT fields to constrain soft backgrounds

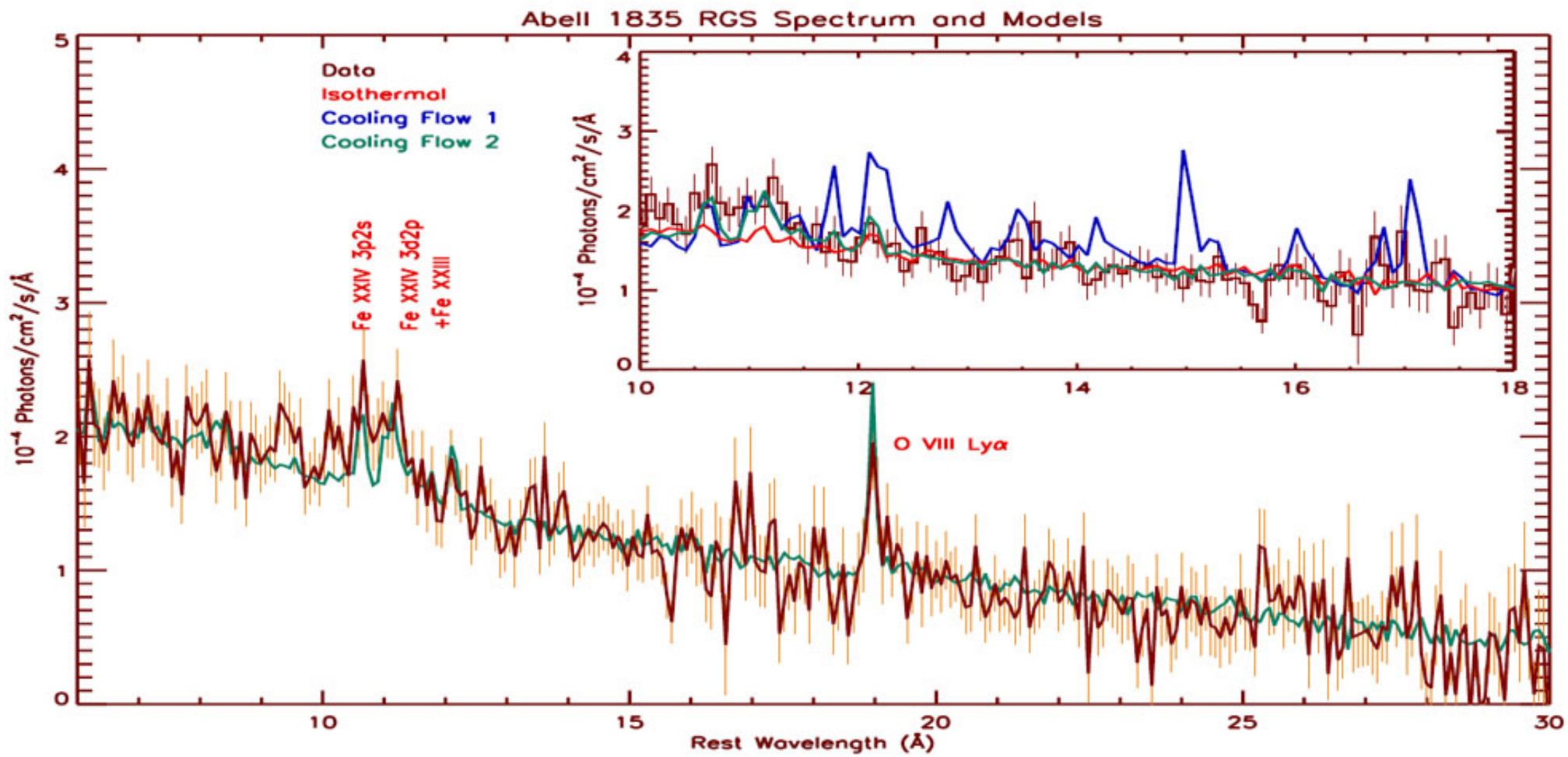
Snowden+2008;
Eckart+2012

other work:

- Andisheh Mahdavi (formerly SFSU) developed a simple XMM pipeline to prepare X-ray spectra products for analysis and a modern statistical analysis code:
- JACO: Joint Analysis of Cluster Observations (Mahdavi+2007, 2008, 2013; O'Sullivan+2012; CLASH papers: Umetsu+2012, Coe+2012, Donahue+2014, Siegel+2018)
- hrothgar MCMC minimizer package (https://sourceforge.net/projects/hrothgar/)

NASA ADP/ADAP + XMM and Chandra data analysis funds

XMM RGS and cooling flows



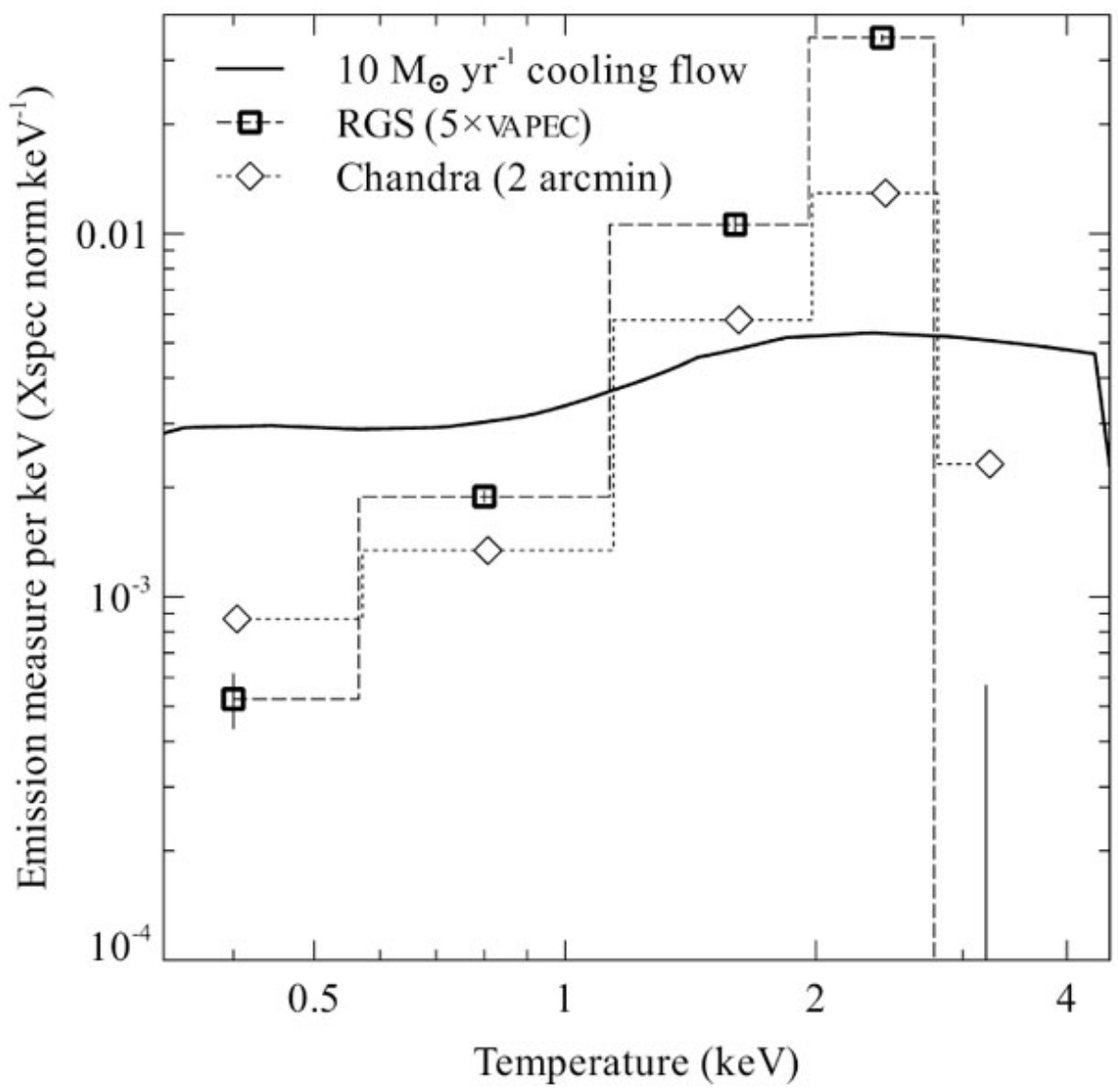
Peterson+2001

The “death” of cooling flows

the cooling flow model in modern context

- baryons in a gravitational potential are shocked to the virial temperature ~ 1-10 keV in a cluster
- later infall shocks to higher entropy, developing an entropy profile with dK/dr > 0, inside-out
- gas radiates, losing thermal energy, lessening pressure; higher density gas radiates the fastest
- the cooler gas radiates even faster
- if there were zero feedback, cooling is inevitable: a few systems show evidence for a “cooling flow” - but only in the very center (Phoenix Cluster, NGC4261, IC4296)

X-ray Spectroscopy and Temperatures and Emission Measures



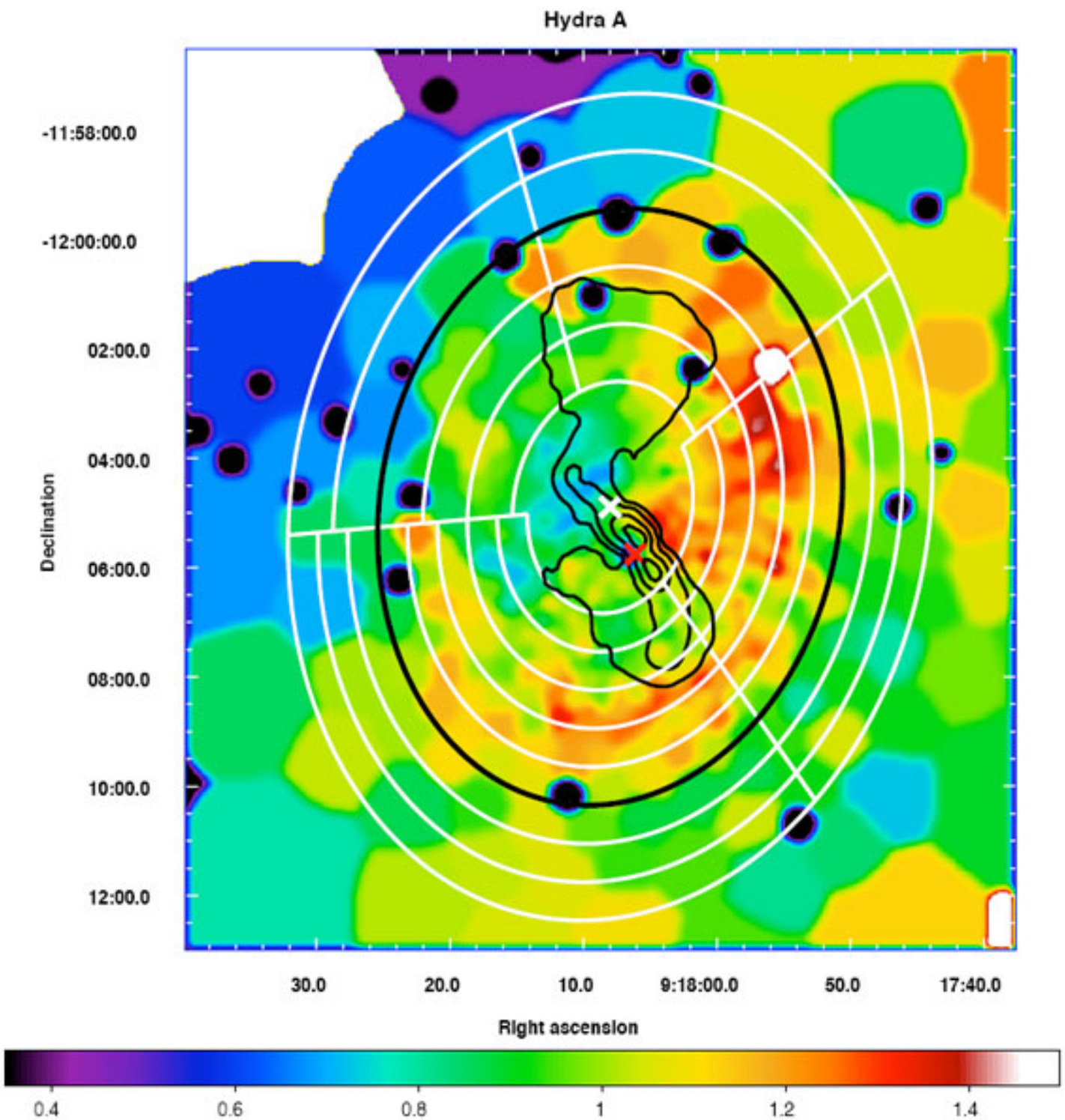
Model of a 10 solar mass/year cooling flow, solar metallicity

Data: inner 2' of Centaurus

Sanders+2008

the cooling flow model was too simple

- it does not account for non-gravitational heat sources that can increase when the cold gas supply is large, and reduce when there is less cold gas (“feedback”):
  - Galactic winds from stellar populations (particularly SN 1a-generated winds)
  - AGN winds and jets



Hydra A

Pressure map, smoothed, average radial profile divided out

Simionescu + 2009

Radio contours from Lane+2004

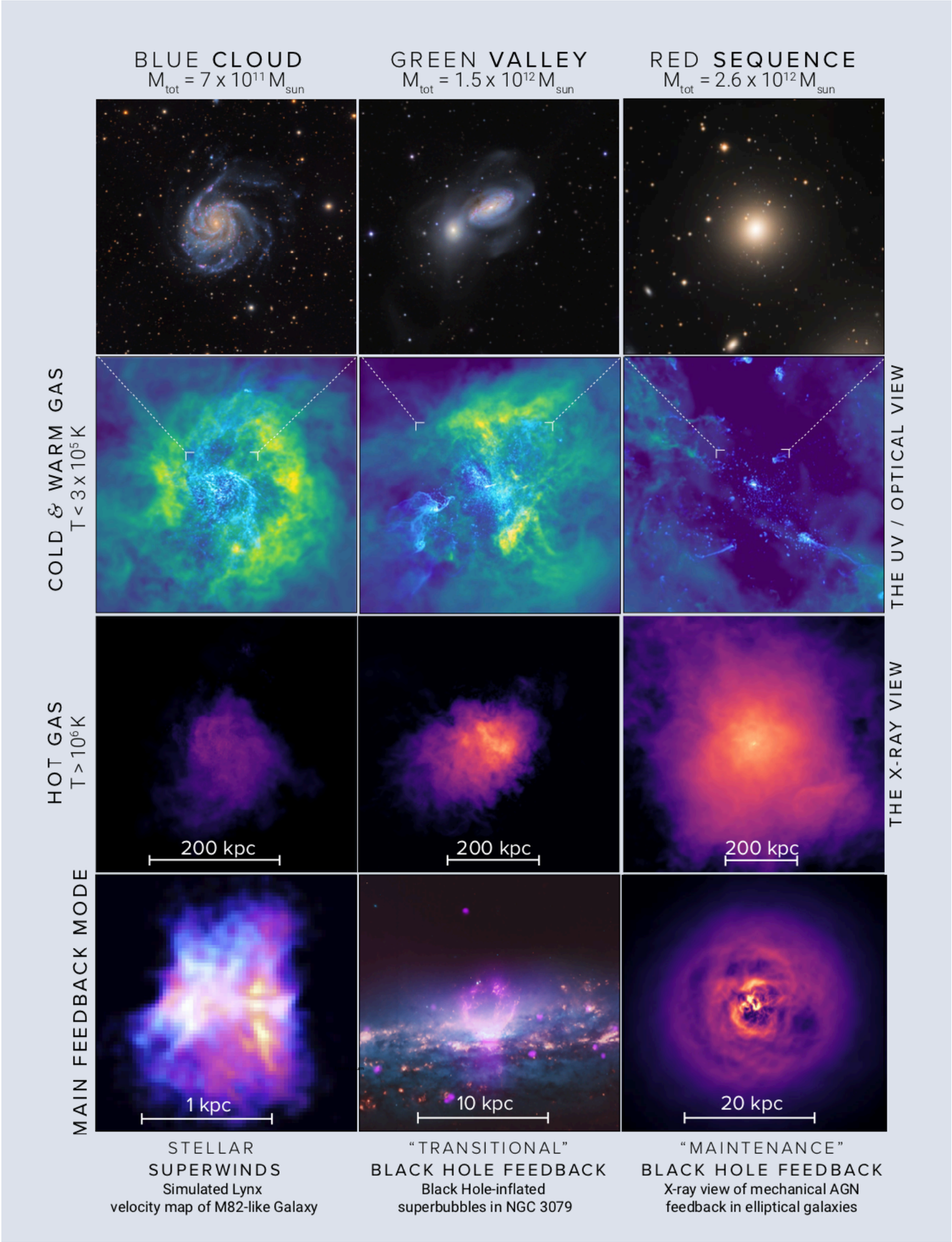
the physics of feedback

- “cooling flows” (e.g. the connection of the thermal instability in the gaseous halo of the cluster or the galaxy to the activity of the central black hole) are still relevant
- could be the dominant process for short times, close to the SMBH (e.g. Phoenix cluster)
- but AGN feedback in clusters and star+AGN feedback in galaxies must be taken into account in simulations and theory to reproduce observations

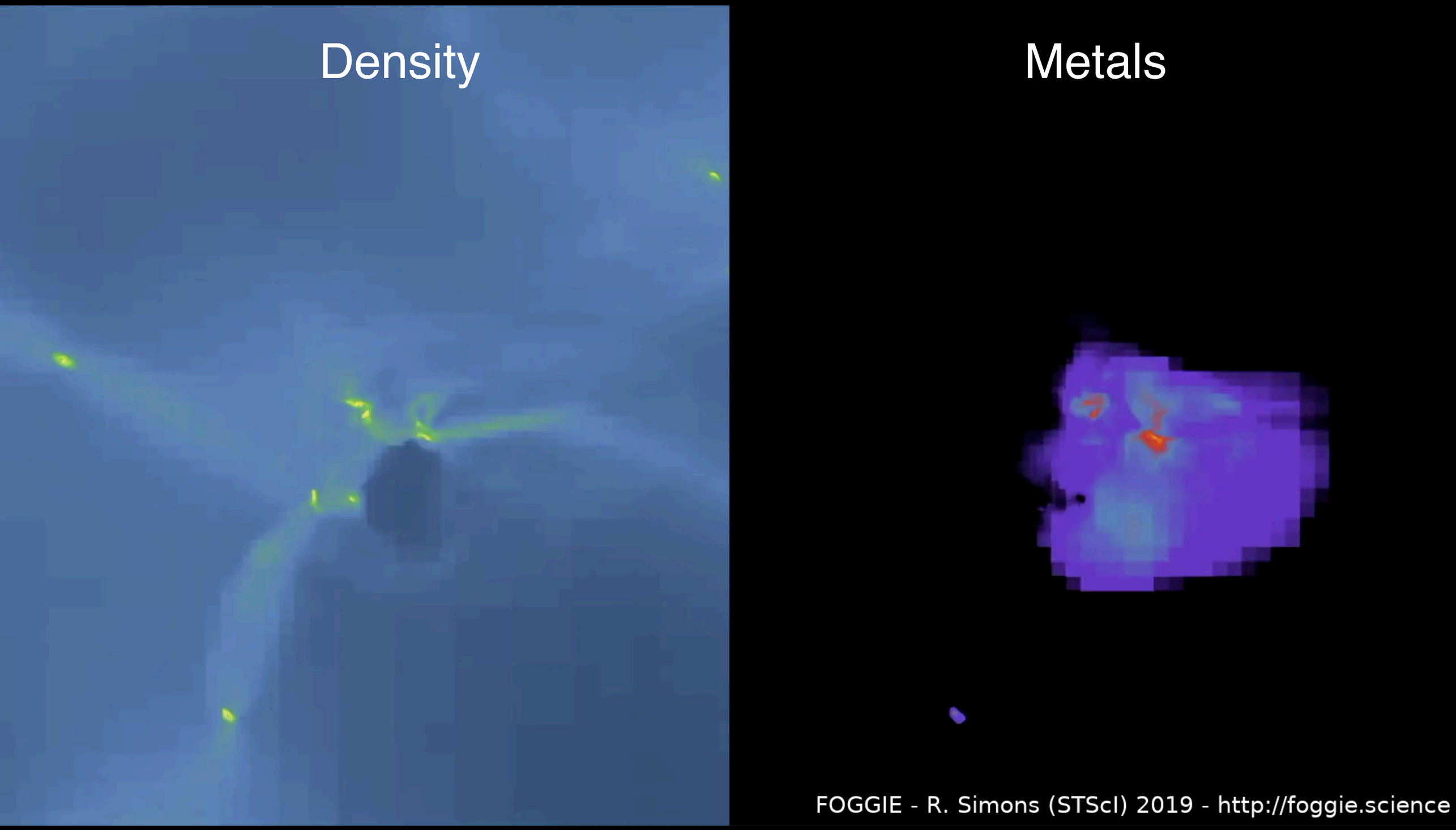
gaseous halos are ridiculously sensitive to the details of feedback

- Most of the cosmological simulations attempting to reproduce the effects of feedback have:
  - a. Succeeded in reproducing the star formation histories and stellar contents of galaxies, particularly low-mass galaxies
  - b. Failed in reproducing the properties of the gaseous halos, where most of the baryons live.

NB: I am using “CGM” to mean the hot gas surrounding a galaxy whether it’s in a cluster, group or in a field


BLUE CLOUD
$M_{tot} = 7 \times 10^{11} M_{sun}$
GREEN VALLEY
$M_{tot} = 1.5 \times 10^{12} M_{sun}$
RED SEQUENCE
$M_{tot} = 2.6 \times 10^{12} M_{sun}$
COLD & WARM GAS
$T < 3 \times 10^5$ K
HOT GAS
$T > 10^6$ K
MAIN FEEDBACK MODE
THE UV / OPTICAL VIEW
THE X-RAY VIEW
200 kpc
200 kpc
200 kpc
1 kpc
10 kpc
20 kpc
STELLAR SUPERWINDS
Simulated Lynx velocity map of M82-like Galaxy
"TRANSITIONAL" BLACK HOLE FEEDBACK
Black Hole-inflated superbubbles in NGC 3079
"MAINTENANCE" BLACK HOLE FEEDBACK
X-ray view of mechanical AGN feedback in elliptical galaxies

Stellar Feedback in a Milky-Way in an 85 kpc FOV, co-moving



The hot CGM affected by feedback: circulates, puffs up (increases in entropy), but does not “leave” (z=5.5-0.3; video credit R. Simons (STScI))

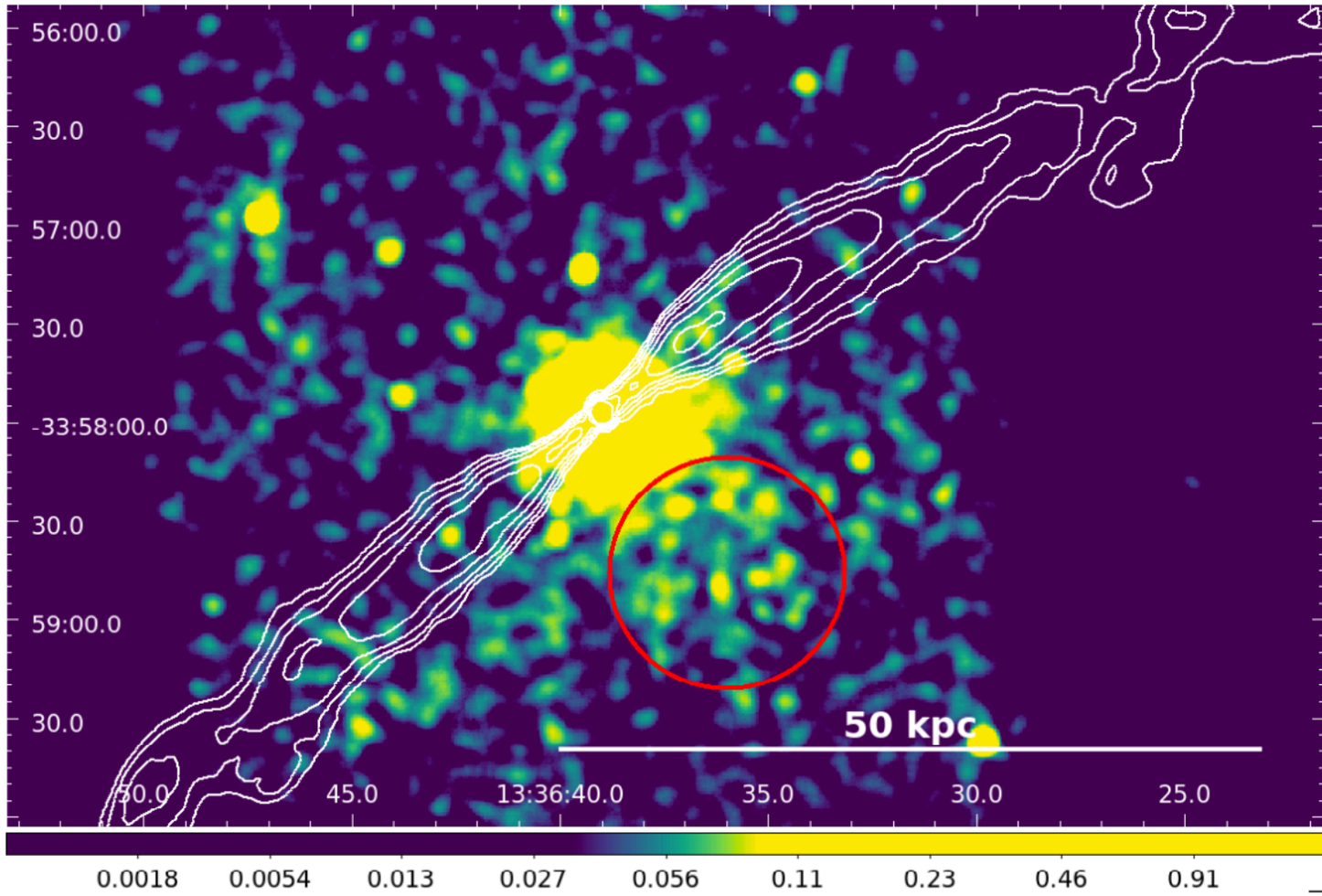
Recent XMM results

- Previous: X-COPS: XMM (+SZ) gas profiles
- A bubble around a nearby radio galaxy lobe
- Discoveries of X-ray groups associated with OVI absorbers

IC4296

z=0.0125; d=49 Mpc from SBF method (0.256 kpc/“)

$L_r \sim 10^{24}$ W/Hz at 1.4 GHz

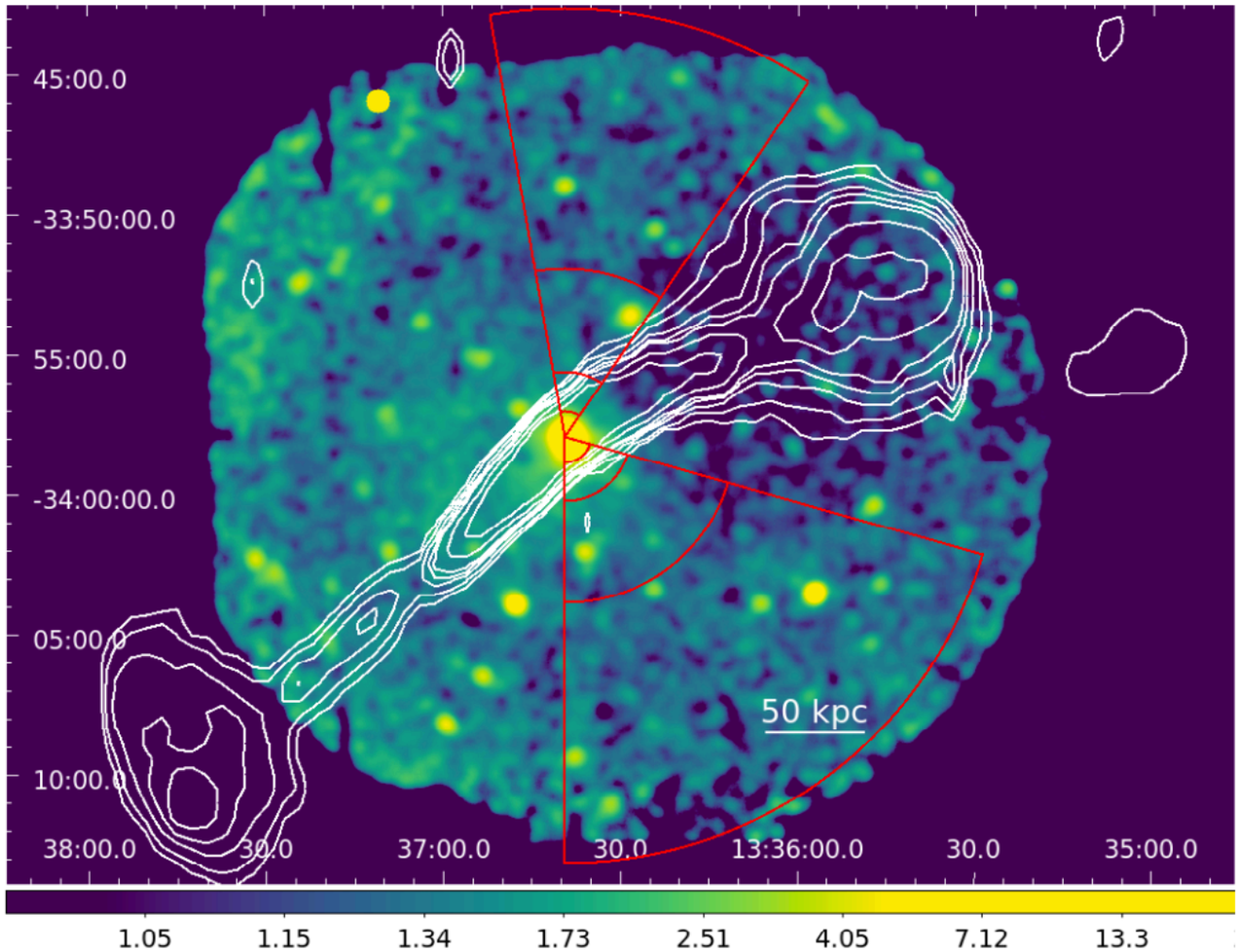


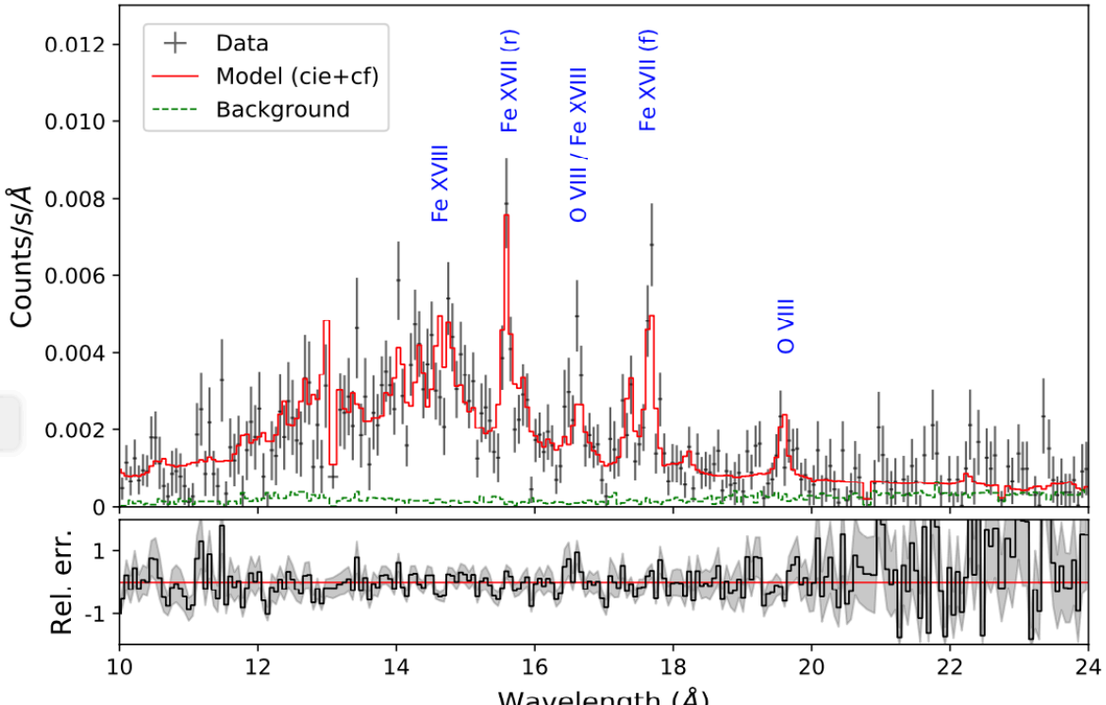
Chandra observation f/ Lakchaura+2018; VLA image from Grossova+2019

IC 4296

The PdV=4pV work required to excavate one lobe is ~3.7E59 erg

$$\dot{M} \sim 2 - 4\ \mathrm{M}_\odot\ \mathrm{yr}^{-1}$$





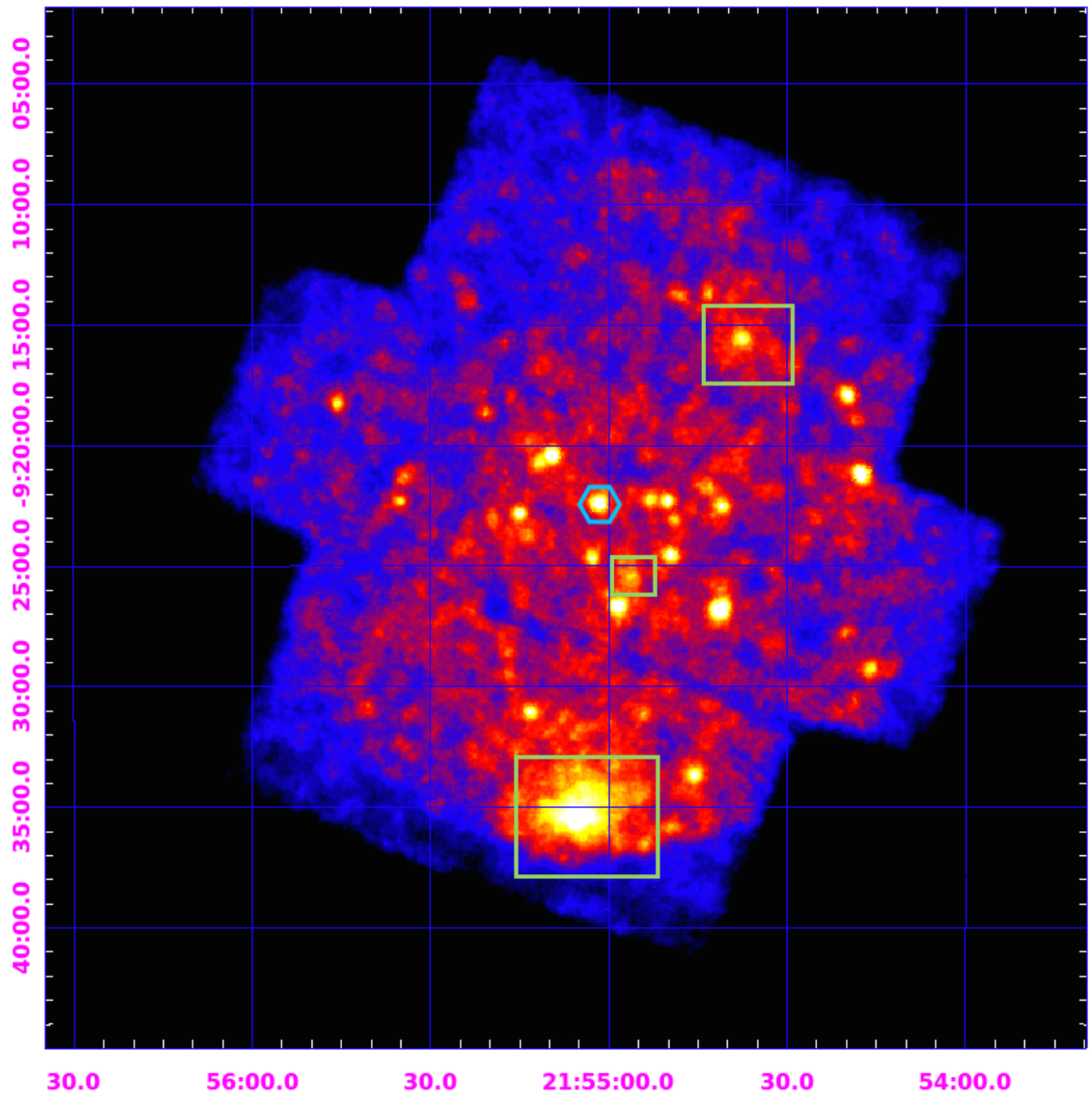
XMM: EPIC & RGS (Grossova+2019)

XMM & QSO absorption line systems: detecting circumgalactic hot gas in emission (!?)

HST-COS has detected (low-z) broad OVI and broad Lyman-alpha absorption line systems lacking any clear galaxy counterpart (Stocke+2014)

Example: broad absorption at z~0.077 in the PHL1811 UV spectrum

X-ray Virgo-like counterpart at z=0.080 ~1 Mpc off the line of sight



XMM Cluster Science

- XMM has enabled fundamental discoveries about clusters of galaxies and cosmology through clusters in the last 20 years.
- XMM is not done: it has unique capabilities for studying the hot gas - the hot CGM - around massive galaxies in ALL environments, enabling tests of feedback over a wide range of mass scales
- XMM's sensitivity can be used to discover and/or place stringent constraints on hot gas measured or suggested by other techniques (SZE, quasar absorption lines, lensing, galaxy velocity studies): perhaps the review panels can be encouraged to accept more scientific risk in their portfolios.