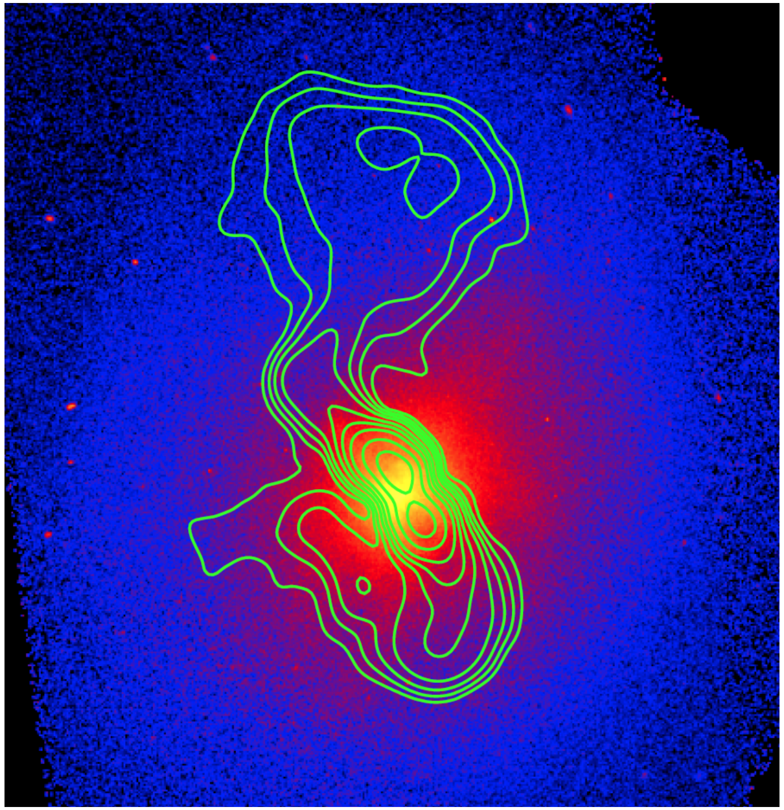
AGN Feedback is Mechanical?
Evidence for Massive Outflows in Hydra A



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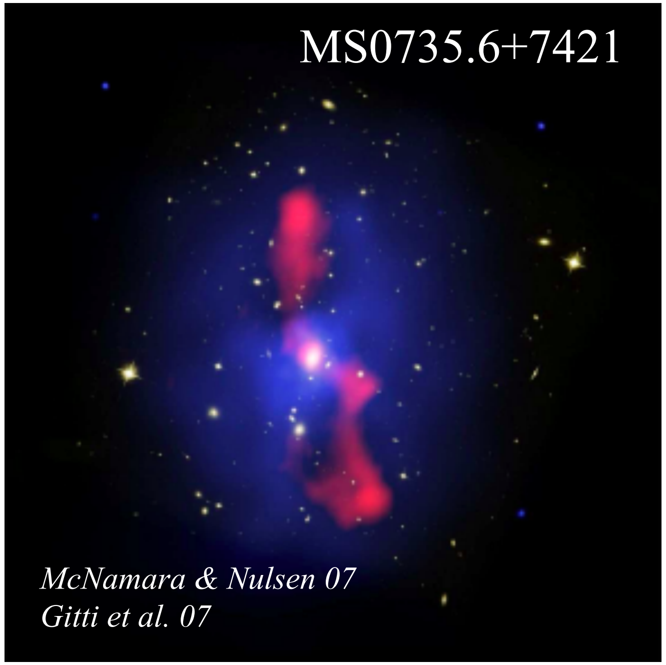
B. McNamara (U Waterloo/SAO),
M. Wise (ASTRON)

Cooling Flow Regulation in Galaxy Clusters

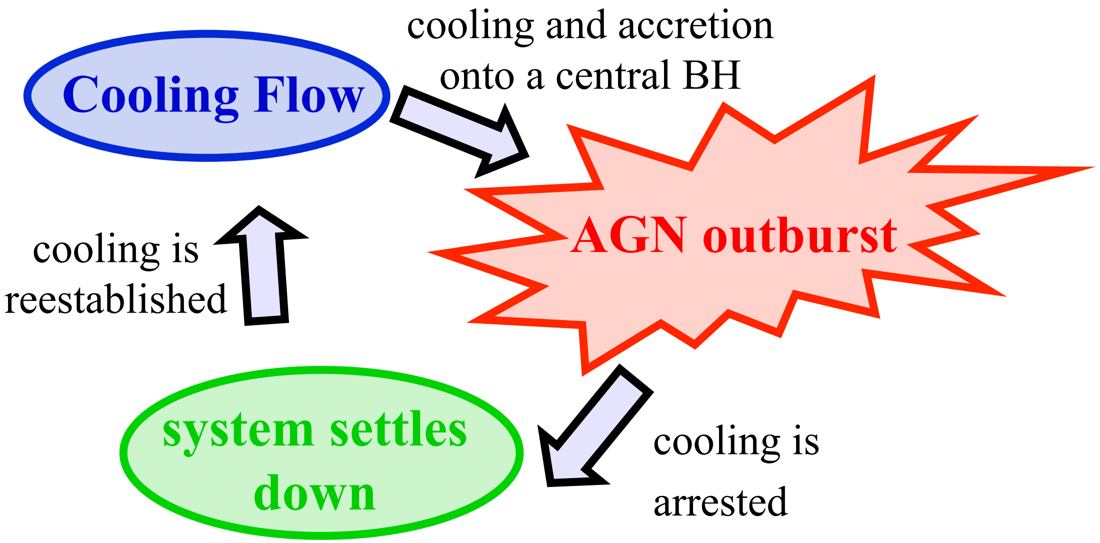


Detection of X-ray cavities and shocks in Chandra images

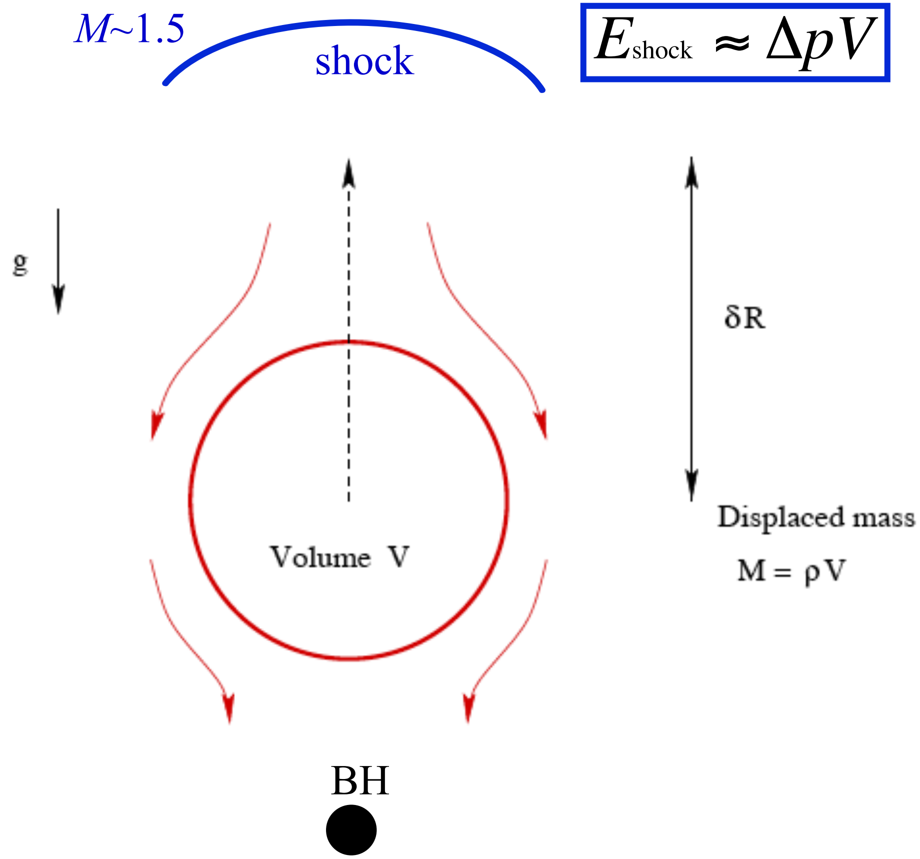
⇒ (recurrent) outbursts from the central AGN

Main candidate to solve the "Cooling Flow Problem":

Feedback by central AGN

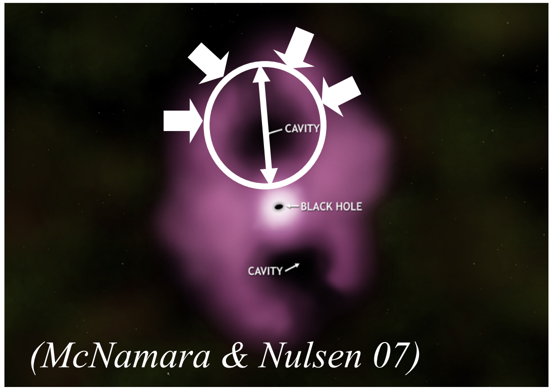


Cavity (+Shock) Heating



$$E_{shock} \approx \Delta pV$$

Shocks difficult to detect, known in a few systems only *(e.g., talks by Forman, Blanton, Randall)*



(McNamara & Nulsen 07)

Enthalpy H lost by the cavity as it rises:

$$E_{cav} \equiv H = E_{int} + pV = \frac{\gamma}{\gamma - 1} pV$$

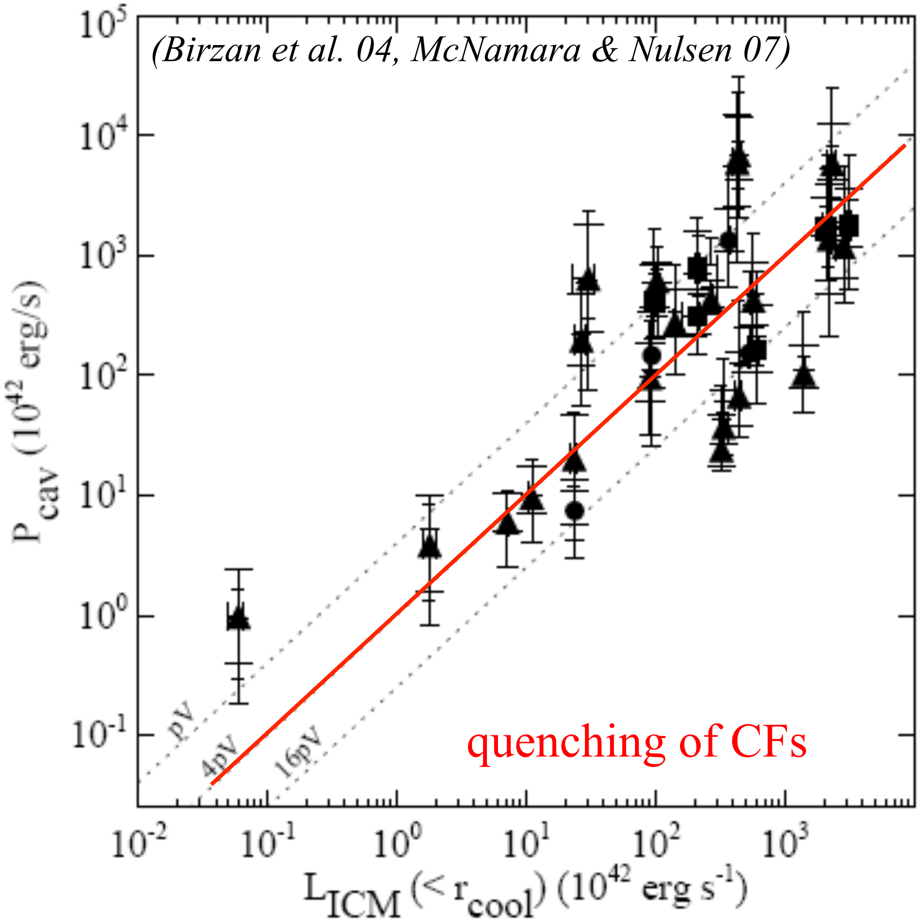
Direct measure of the mechanical energy of AGN outburst:

$$E_{tot} = E_{cav} + E_{shock} = 10^{55} - 10^{62}\,\mathrm{erg}$$

Cavity Heating

It is now widely accepted that AGN in the cD of cool core clusters can reheat the ICM

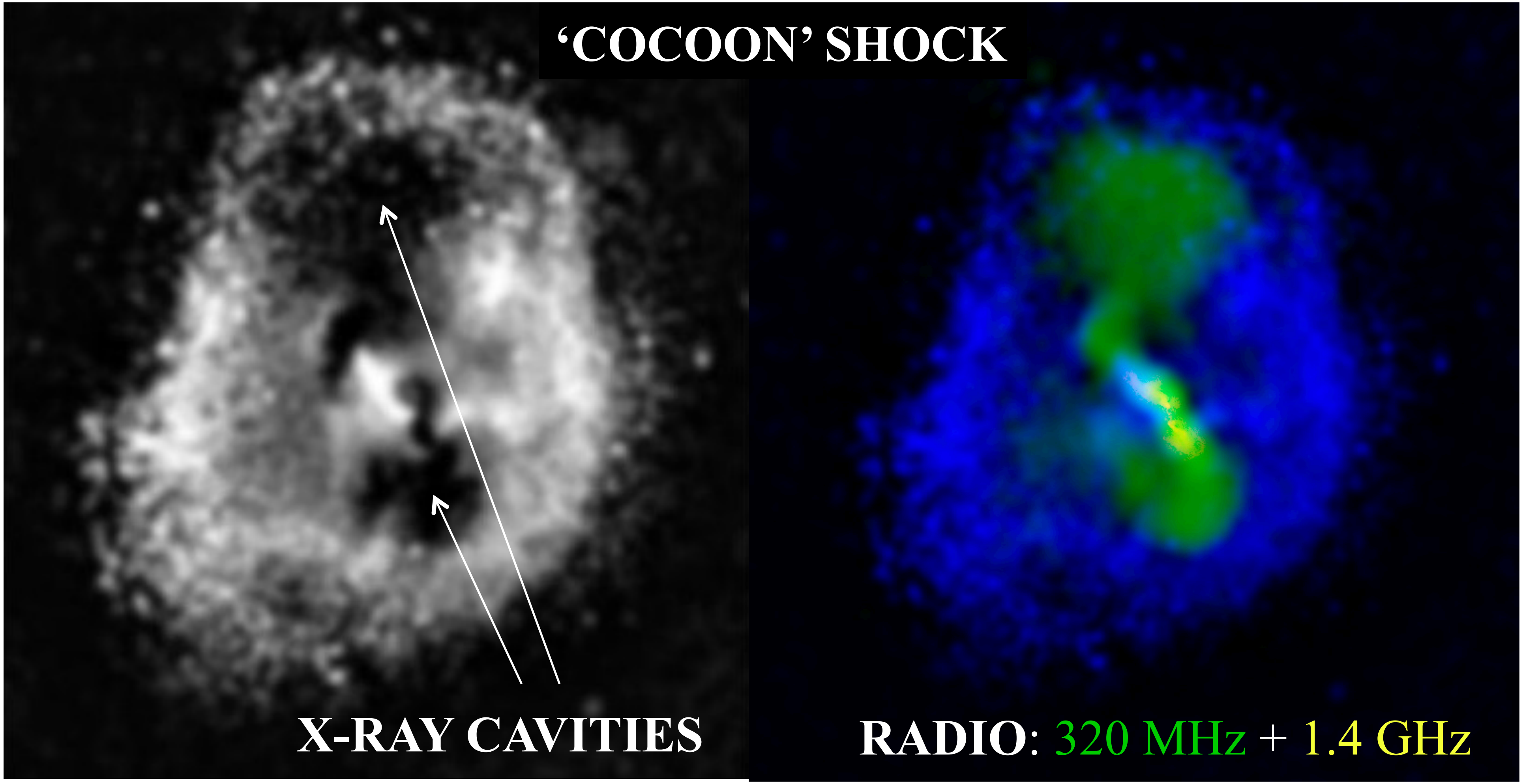
However, details and (side) effects of the feedback loop still poorly understood



Only by studying striking examples can we understand why cooling and star formation proceeds at a reduced rate

➔ coupling AGN feedback / ICM

Hydra A Observed by Chandra (~200 ks)

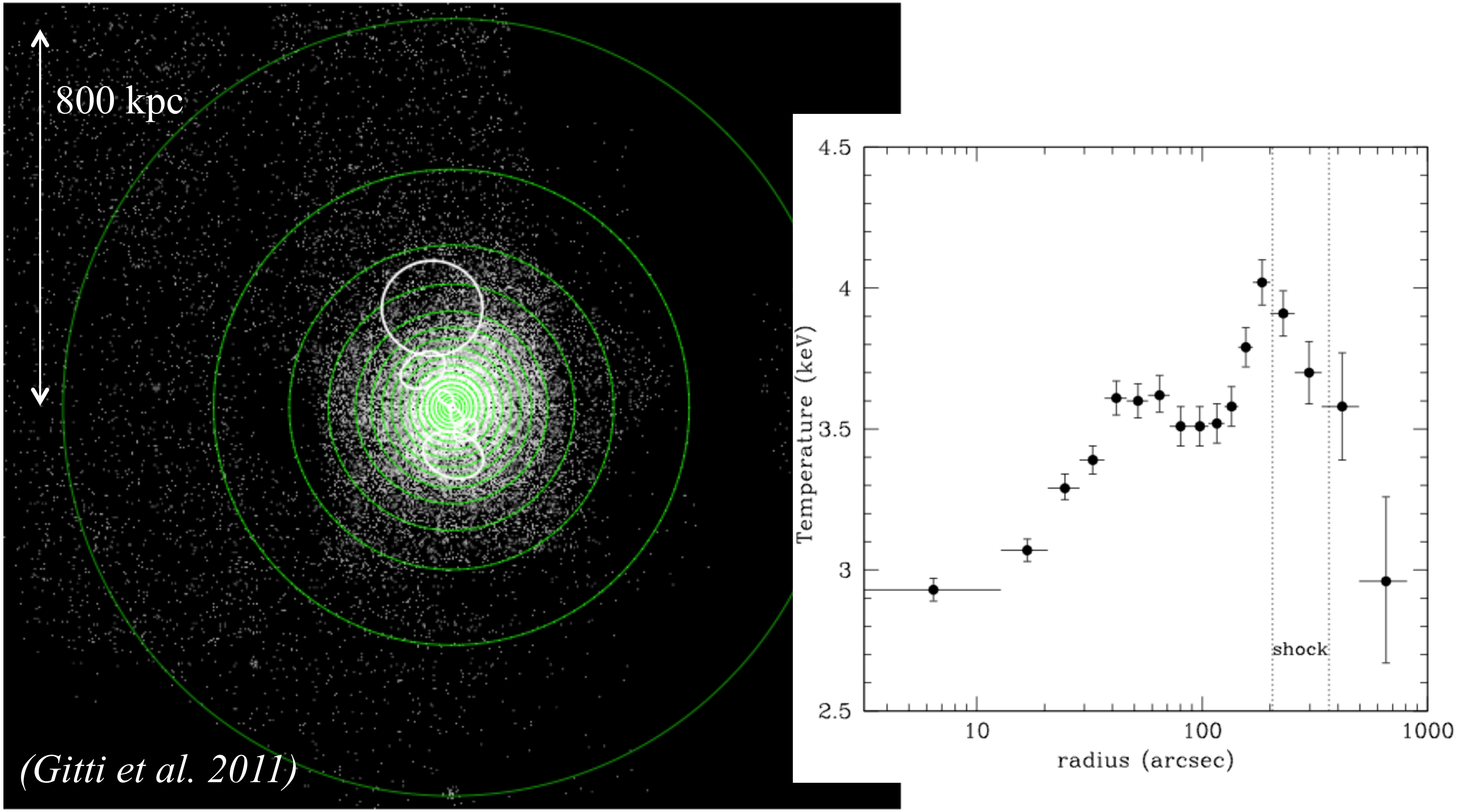


McNamara et al. 2000
Nulsen et al. 2005
Wise et al. 2007
Gitti et al. 2011

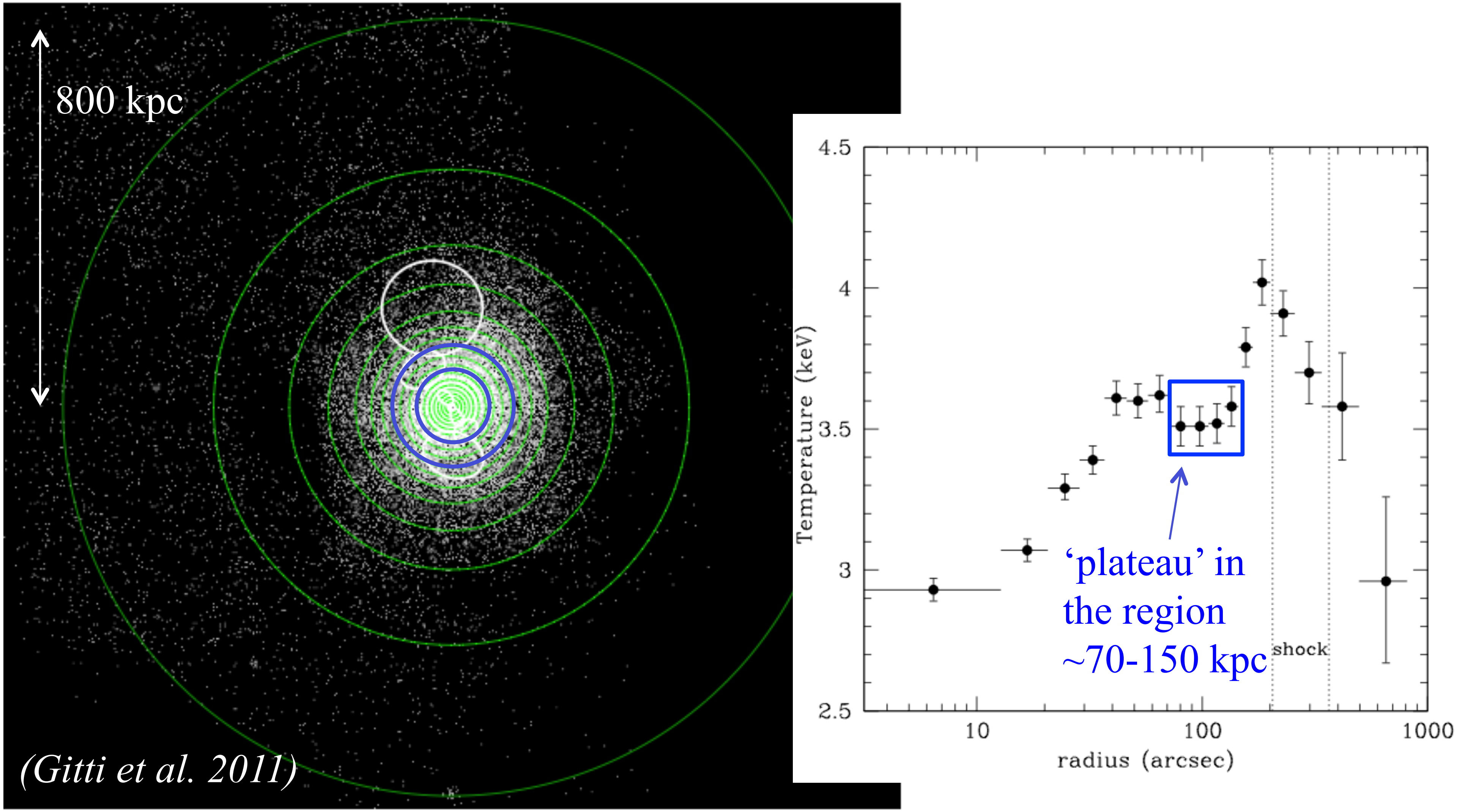
Hydra A is one of the 'prototypes' of cool core clusters with cavities

Taylor 1996
Lane et al. 2004

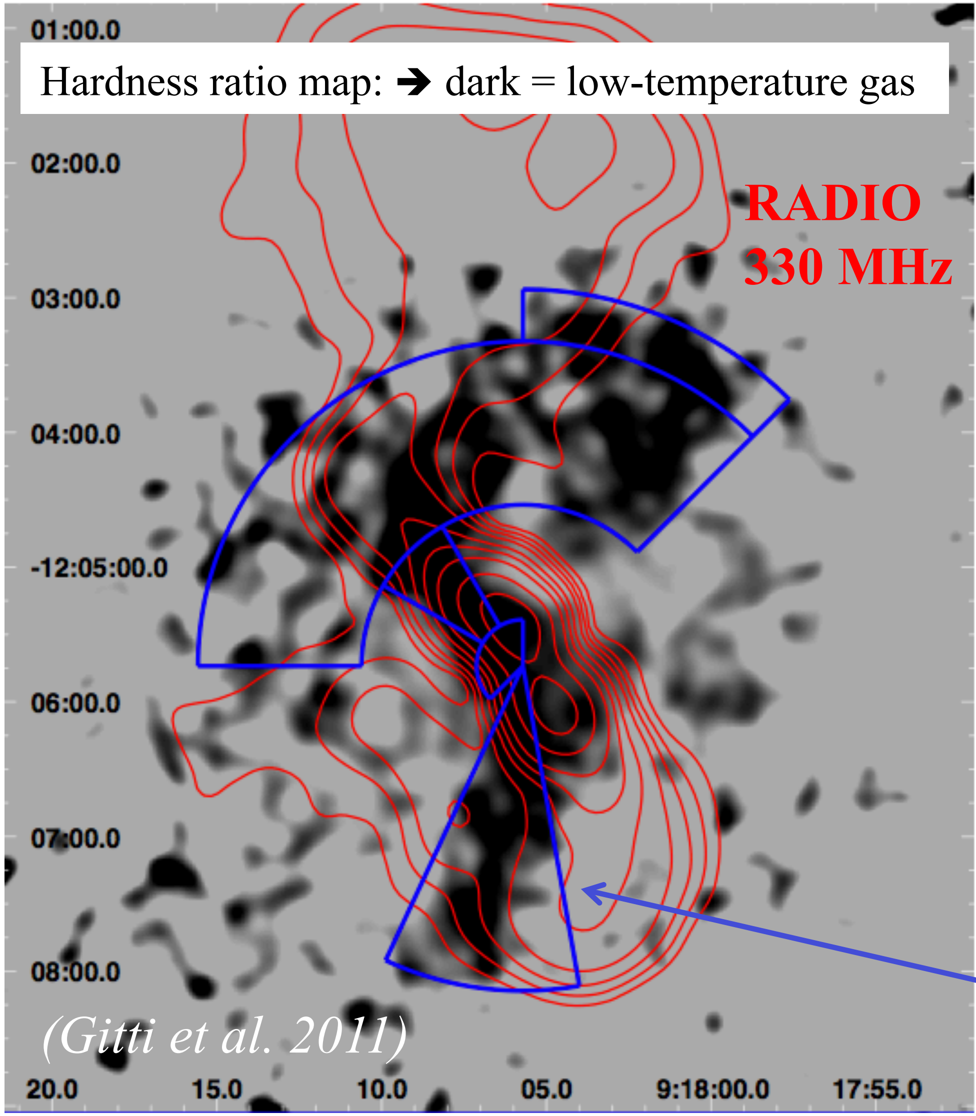
Hydra A: Global Cluster Temperature Profile

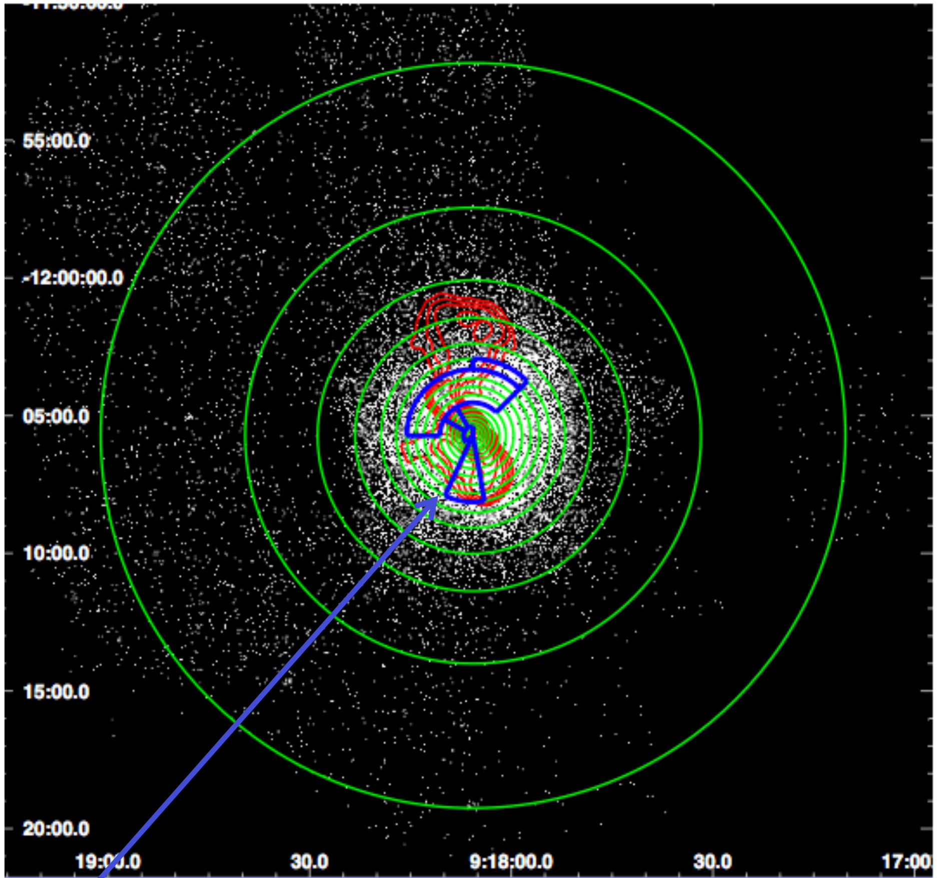


Hydra A: Global Cluster Temperature Profile



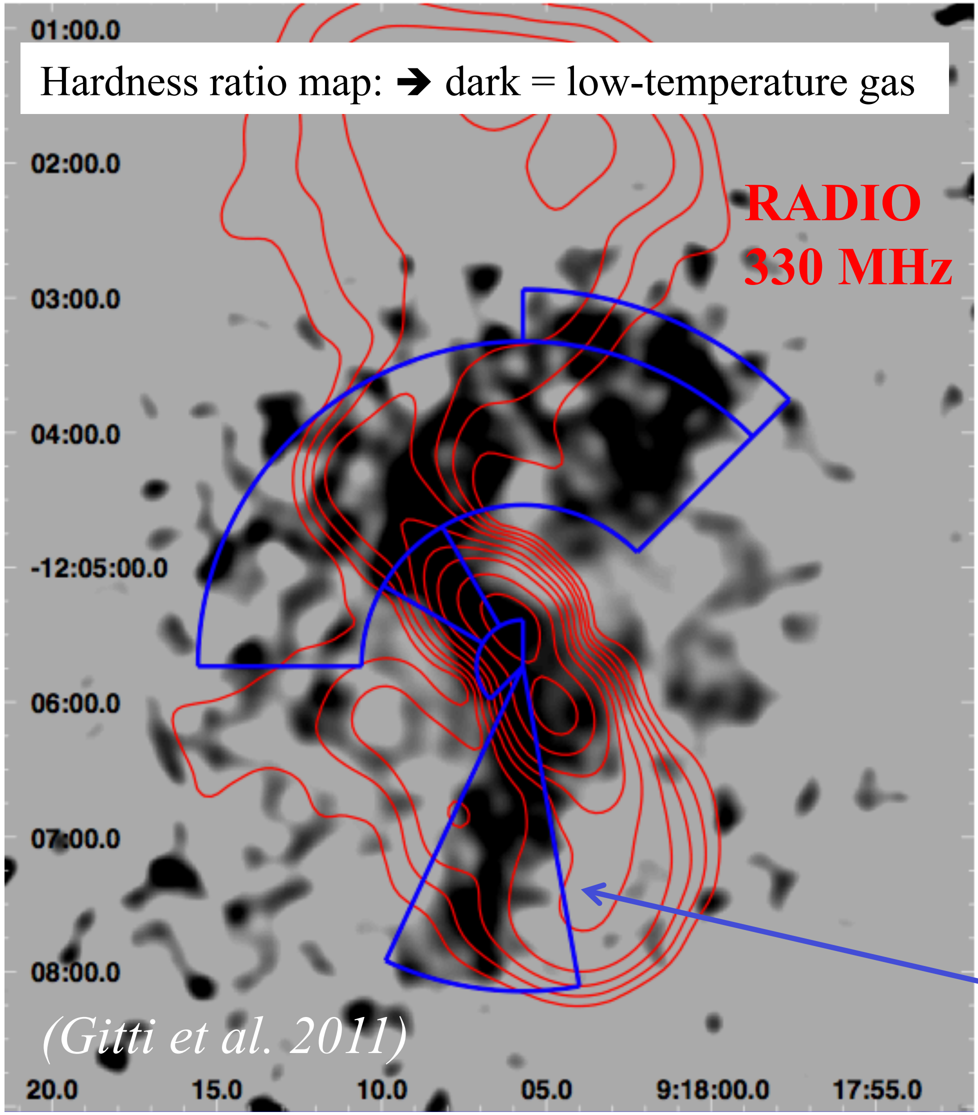
Hydra A: Global Cluster Temperature Profile
Evidence for Cool Filaments

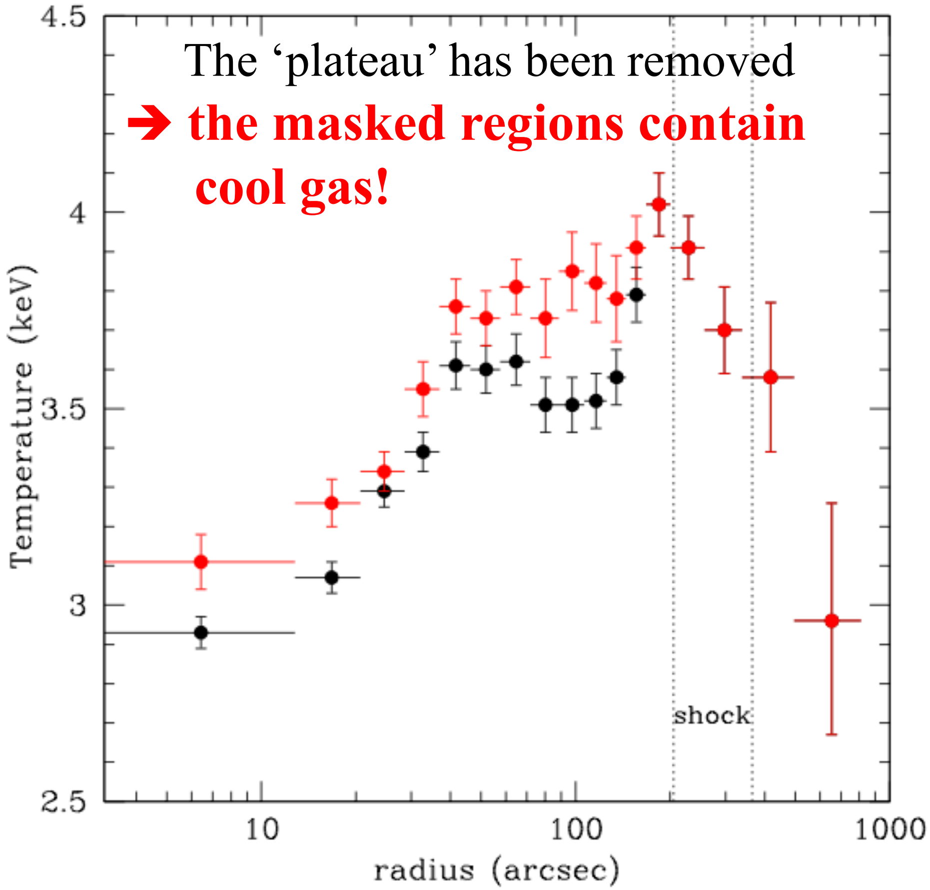




Sectors excluded in the new calculation
of the global cluster temperature profile

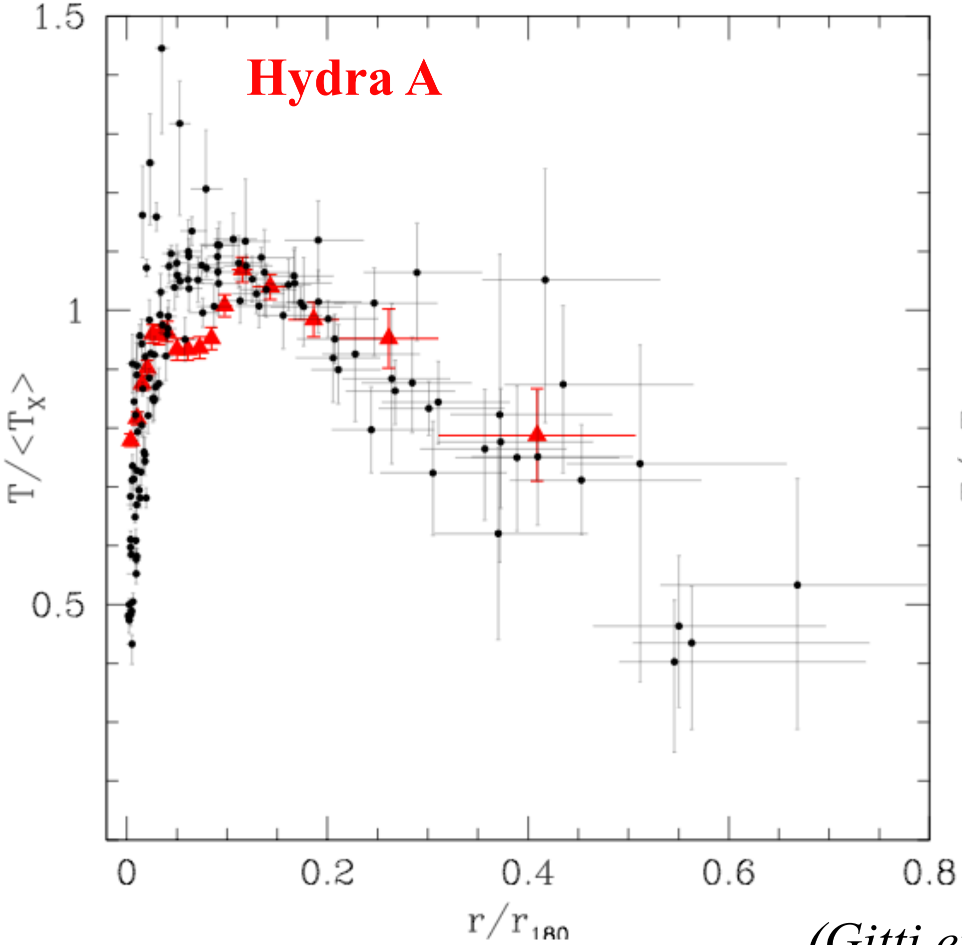
Hydra A: Global Cluster Temperature Profile
Evidence for Cool Filaments

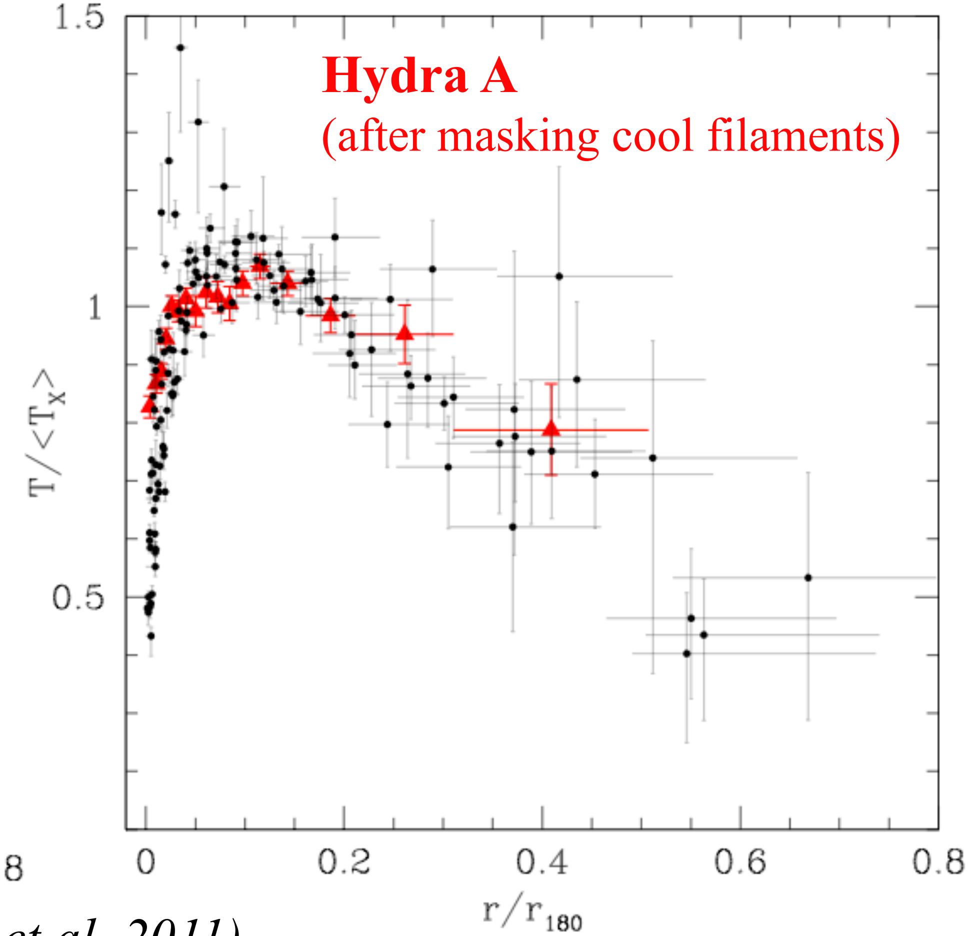




Sectors excluded in the new calculation of the global cluster temperature profile

Hydra A: Scaled Temperature Profile

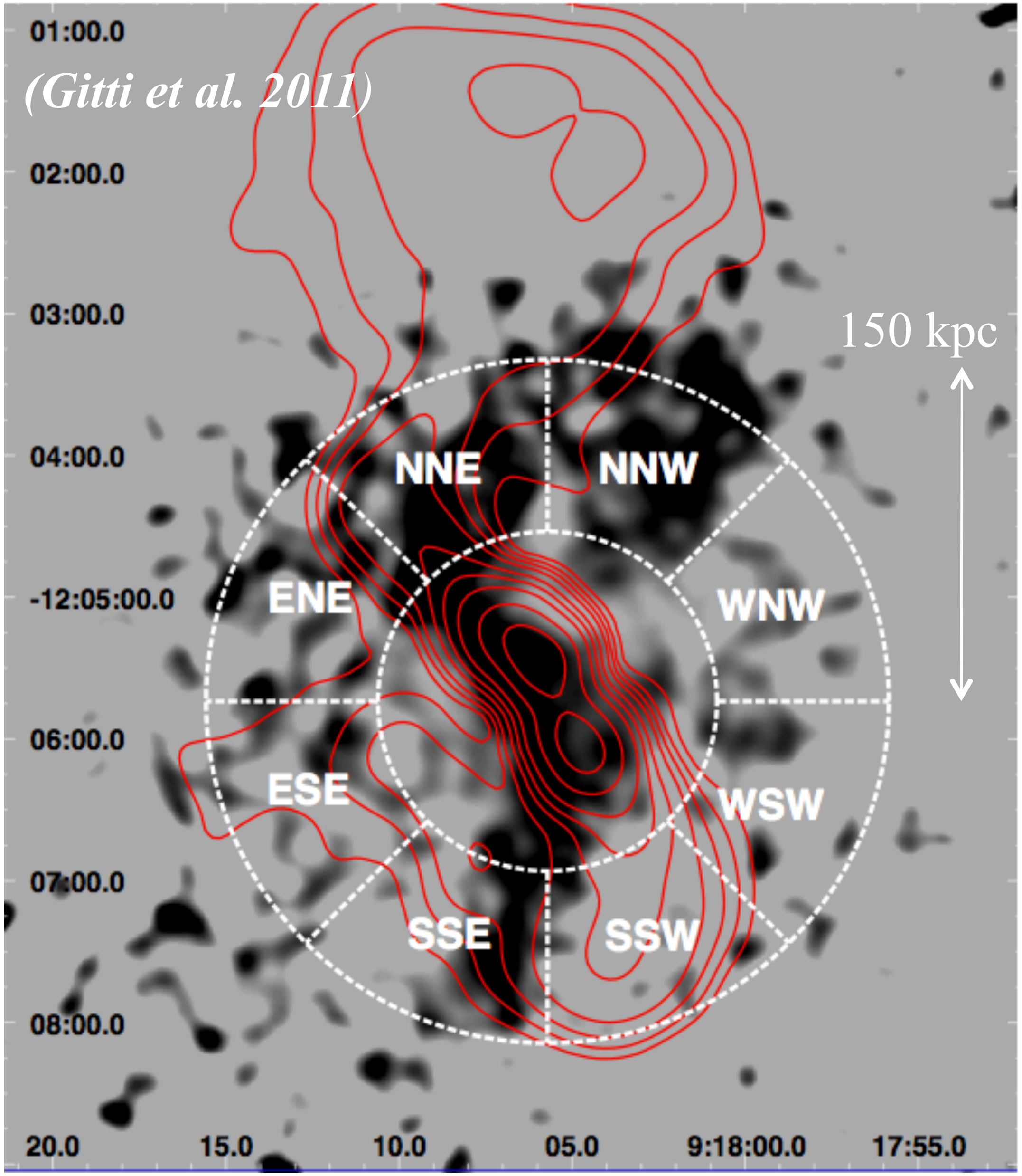




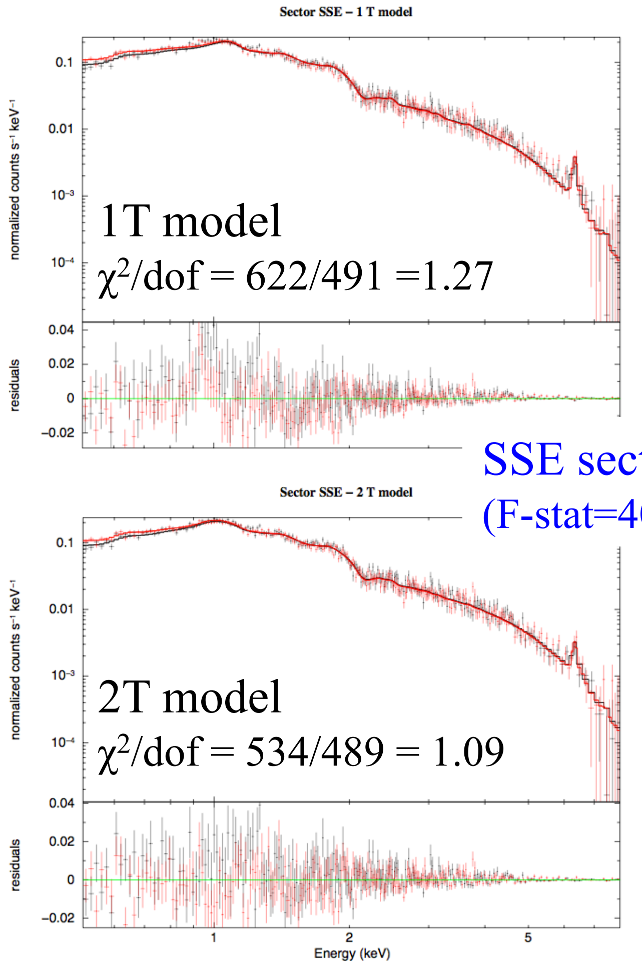
(Gitti et al. 2011)

General shape of temperature profiles observed for relaxed clusters *(Vikhlinin et al. 2005)*

Hydra A: Spectral Properties of the Cool Gas

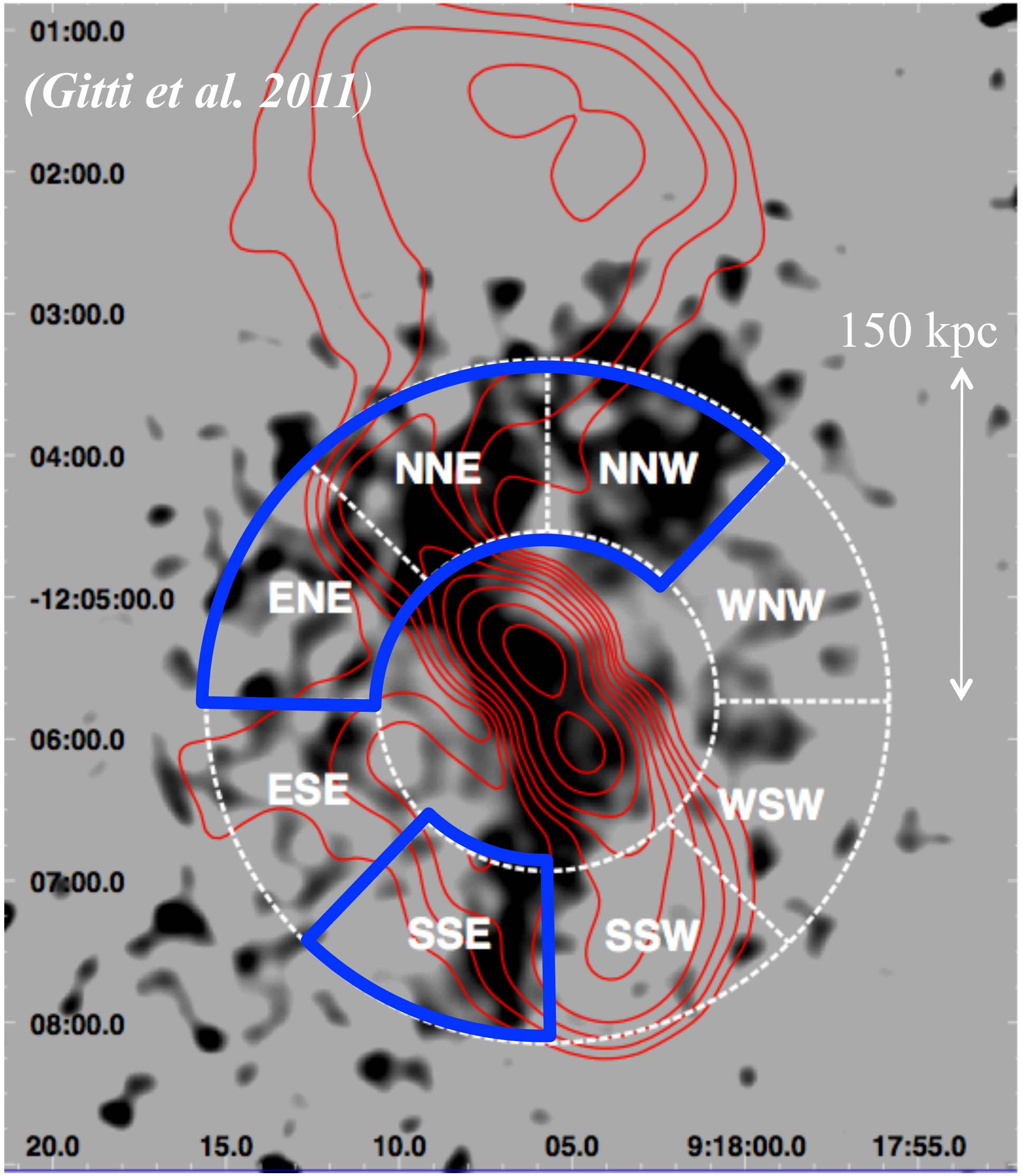


Spectra extracted in each sector, then fit with different plasma model: compare 1T model vs. 2T model



SSE sector (F-stat=40.3)

Hydra A: Spectral Properties of the Cool Gas



Spectral evidence for multi-phase gas along the X-ray filaments:

$$\begin{cases} kT_{hot} \sim 4.0 \text{ keV} \\ kT_{cool} \sim 1.6 \text{ keV} \end{cases}$$

(see also central Hα filament, *McDonald et al. 2010)*

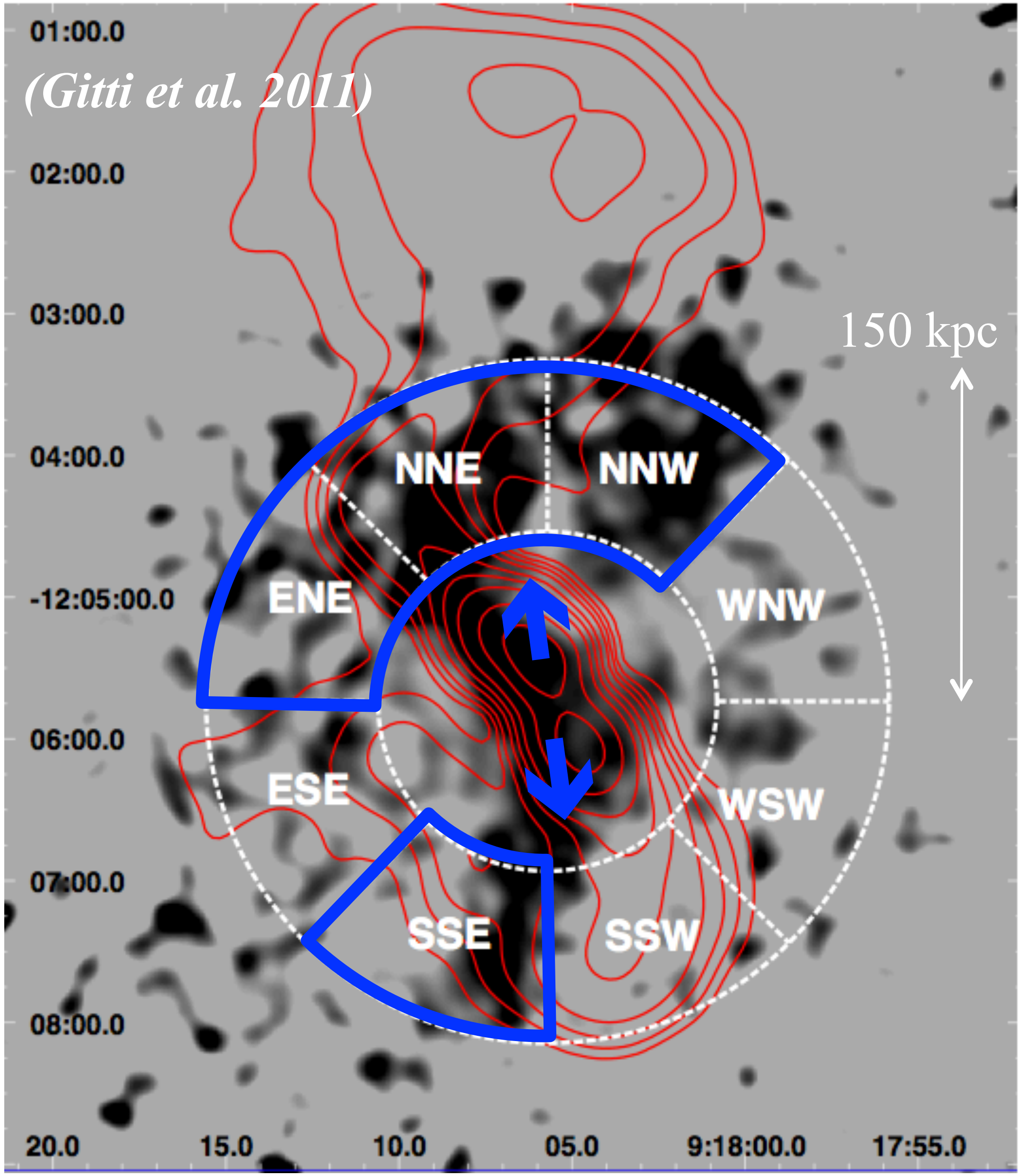
In 70-150 kpc region:

$$M_{cool} \sim 10^{11} M_{\odot}$$

(~**60%** of mass inside 30 kpc)

Where does it come from?

Evidence for Extended Gas Dredge-Up



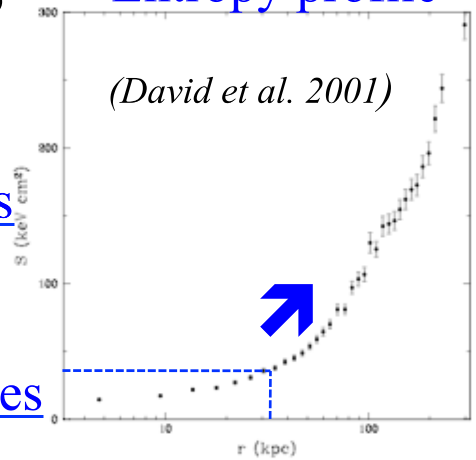
$M_{\mathrm{cool}} \sim 10^{11}\ M_{\odot}$

$S_{\mathrm{cool}} = kT\, n_e^{-2/3}$

~ 30 keV cm^2

the cool gas was lifted from the central ~30 kpc in the rising lobes

Entropy profile



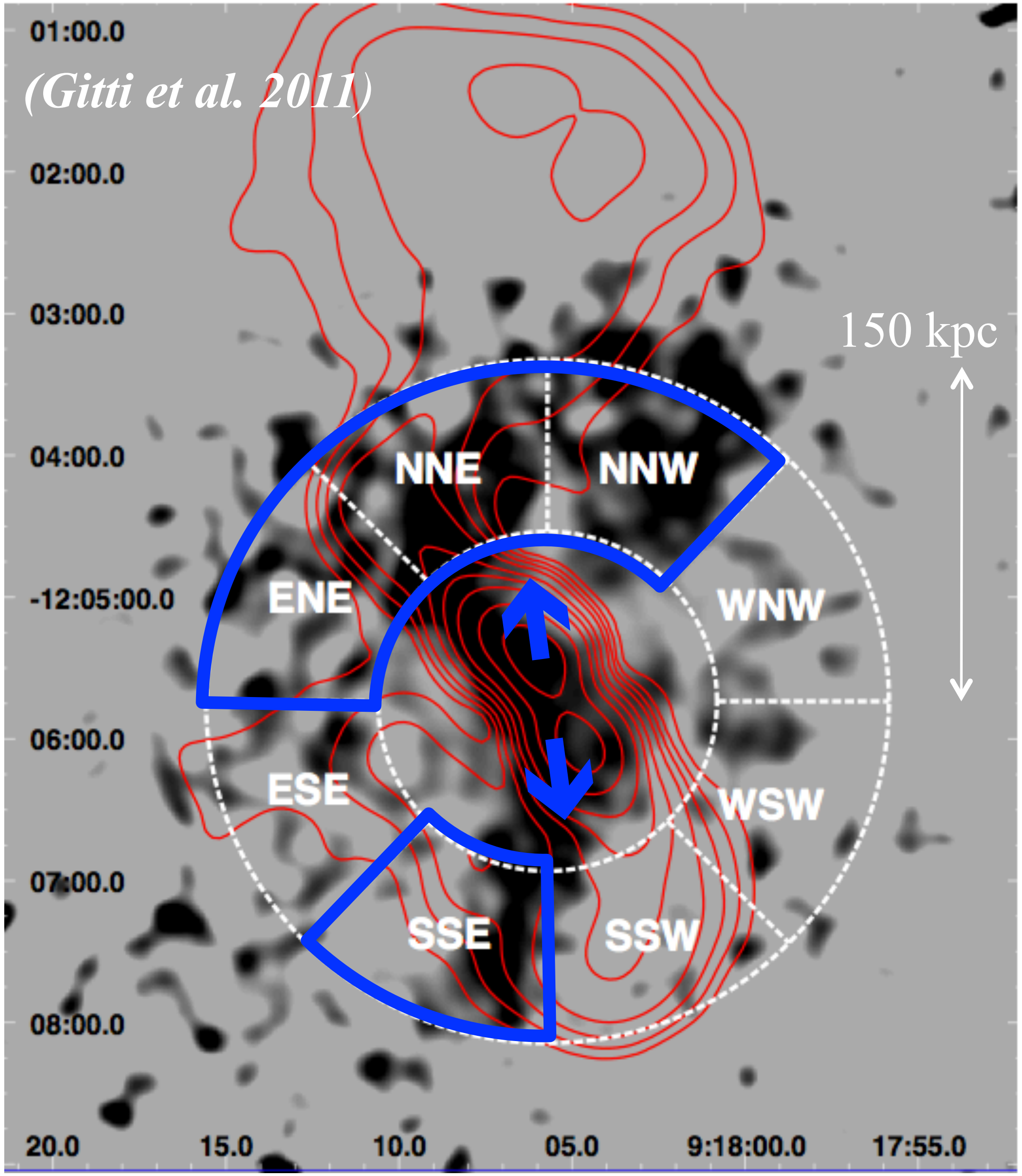
Energy required to lift the gas = variation in grav. potential energy

$$\Delta E = \frac{M_{\mathrm{cool}}\, c_s^2}{\gamma} \ln\left(\frac{\rho_i}{\rho_f}\right) \approx 2.2 \times 10^{60}\,\mathrm{erg}$$

Comparable to the work required to inflate the cavity systems:

$pV_{\mathrm{cav}} = 4 \times 10^{60}$ erg *(Wise et al. 2007)*

Evidence for Extended Gas Dredge-Up



In 70-150 kpc region:

$$M_{\mathrm{cool}} \sim 10^{11}\, M_{\odot}$$

~60% of mass inside 30 kpc

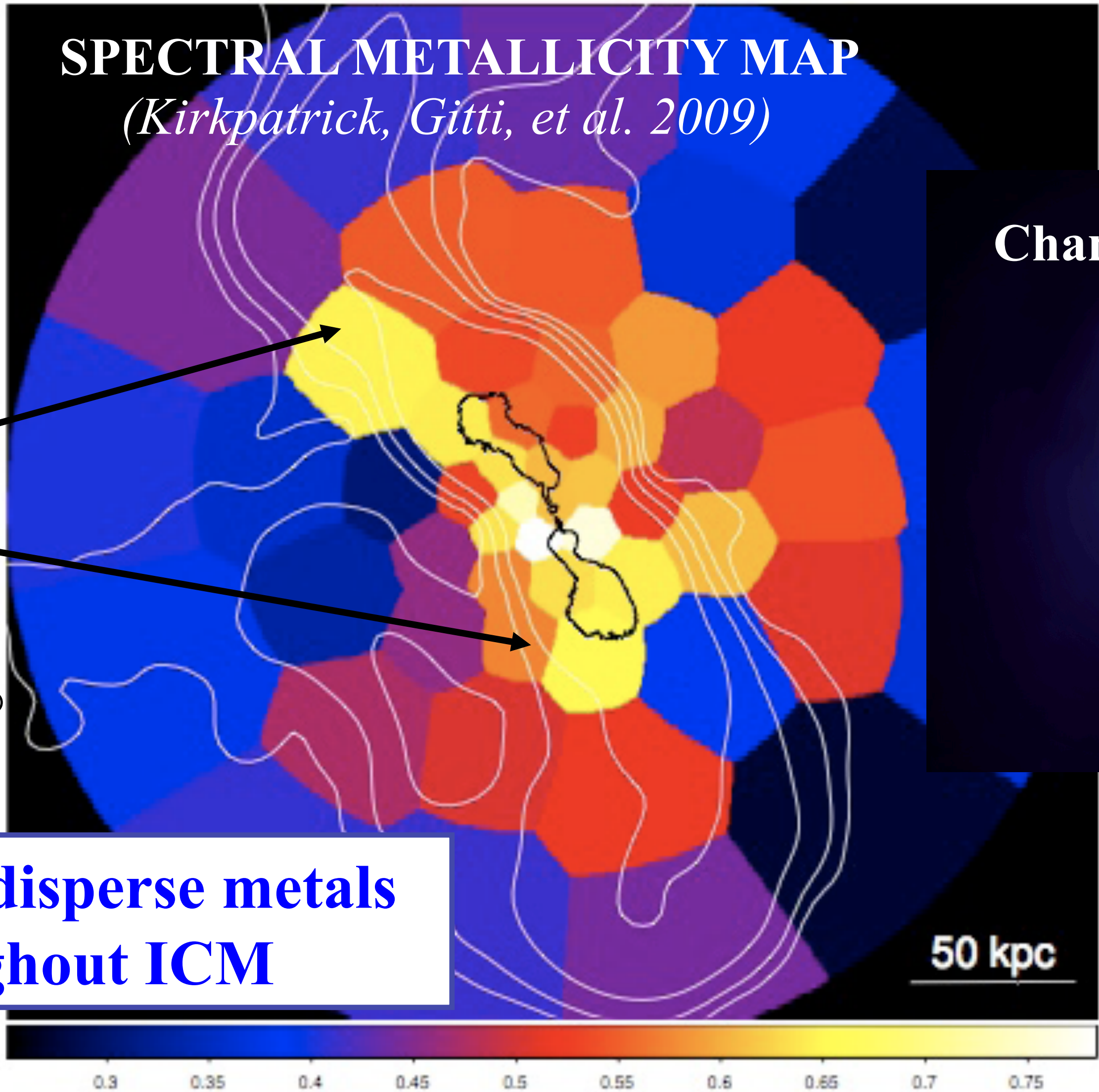
(see also M87: *Simionescu et al. 2008, Werner et al. 2011*)

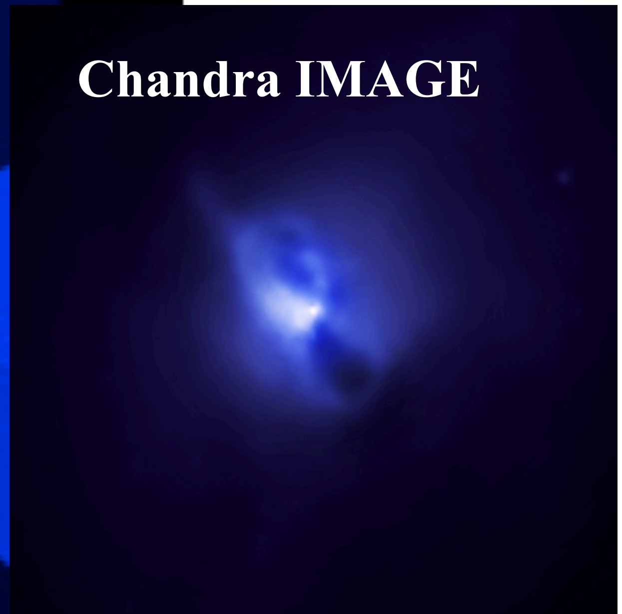
By studying the cavity system *(Wise et al. 2007)*:
continuous (or series of) bursts from the AGN over past **200-500 Myr**

$\Downarrow$

Outflows of ~few 100s $M_{\odot}$/yr that can reduce the net inflow of cooling gas

Hydra A: Metal Enriched Outflows





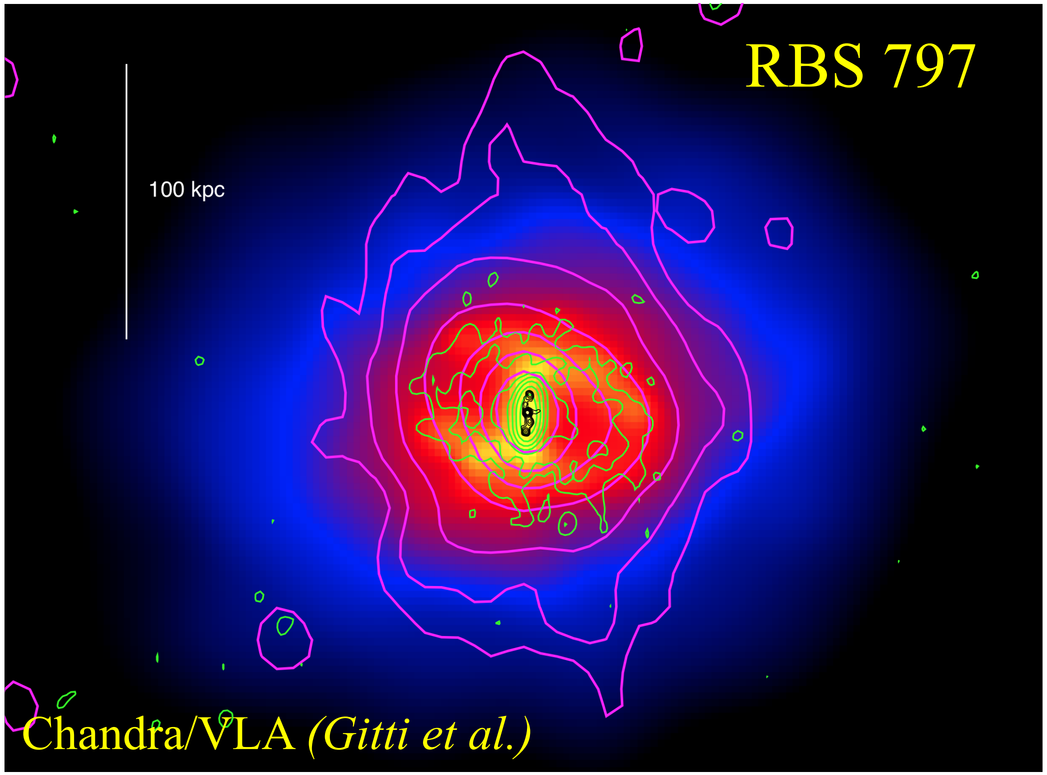
Iron enriched outflows

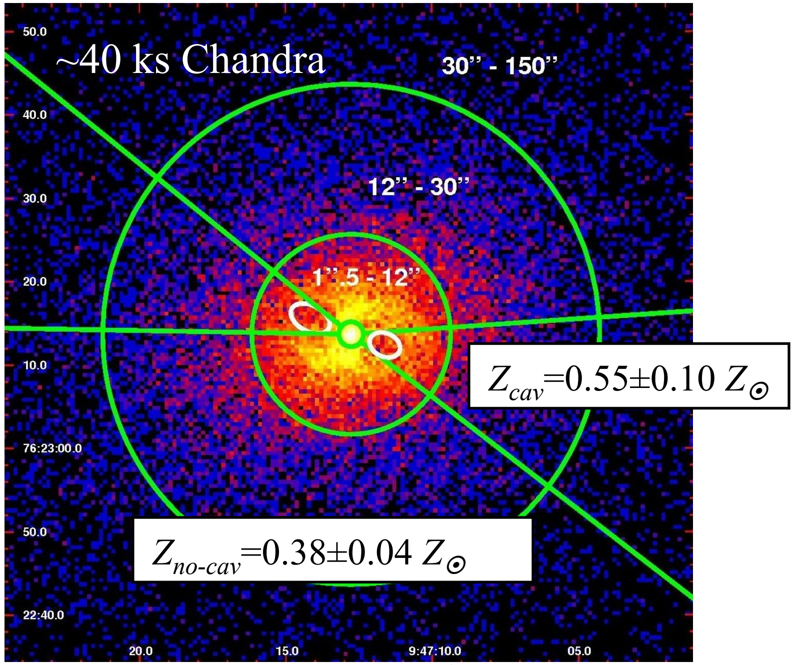
ΔM_{Fe}=2-7×10^7 $M_{\odot}$
R~120 kpc

AGN-Jets disperse metals throughout ICM

see also Fe-map by *Simionescu et al. 2009*

Metal Enriched Outflows





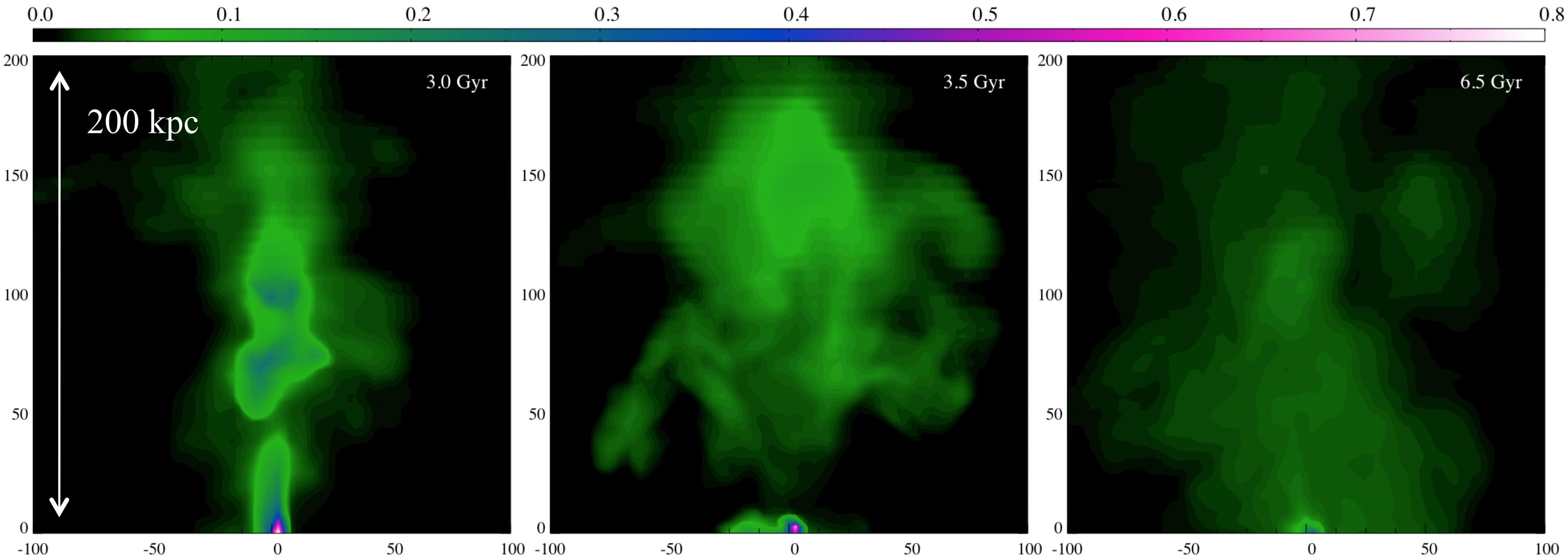
see A. Doria poster !

RBS 797: indication of higher metallicity in the cavity directions *(Doria et al. in prep.)*, as in other systems e.g. M87, MS0735 *(Million et al. 2010, Kirkpatrick et al. 2011)*

➔ **metal-enriched outflows driven by the AGN**

Metal Enriched Outflows

Theoretical modeling of AGN feedback predict the massive subrelativistic bipolar outflows and buoyant bubbles to produce a metal uplift along the jet axis *(e.g., Pope et al. 2010, Gaspari et al. 2011)*



Emission-weighted iron abundance maps for a simulated AGN outflow model at three times *(Gaspari et al. 2011)*

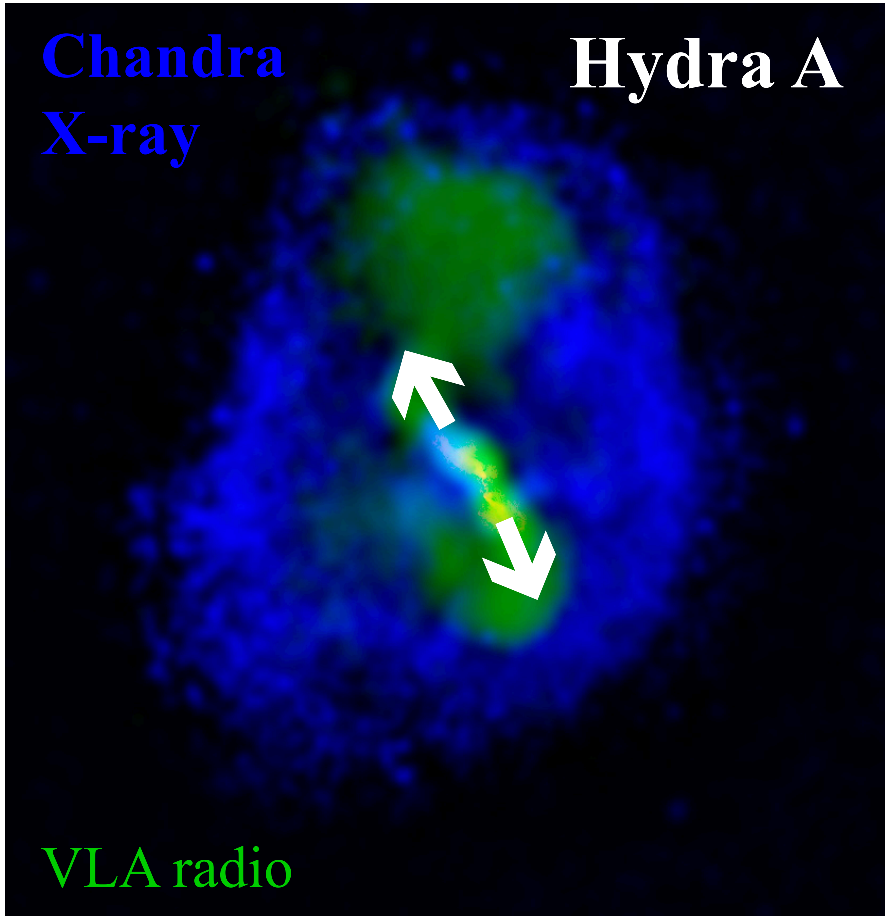
Summary

• The powerful radio source is able to **lift low-entropy, metal-rich gas from the central region and distribute it** throughout the X-ray atmosphere of the cluster

• The AGN feedback is acting not only by directly heating the gas, but also by **removing a substantial amount of potential fuel for the central supermassive black hole**

• Uplift provides a significant channel for the dissipation of outburst energy

(Gitti et al. 2011, ApJ, 732, 13)



$\Rightarrow$ **Indication of mechanical AGN feedback through collimated, massive outflows**

Thank you

Hydra A: Hα Filaments

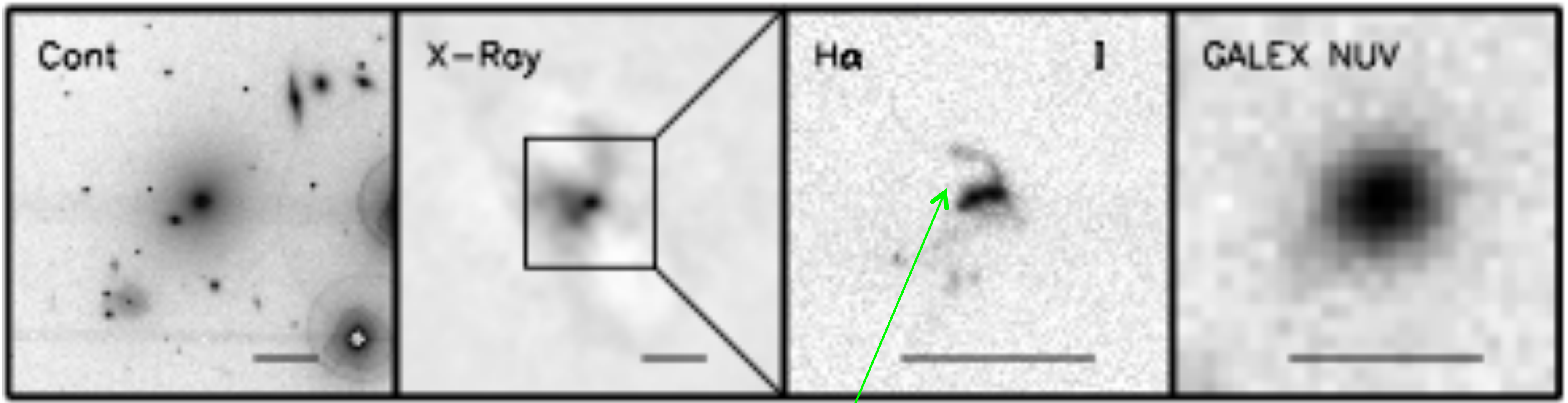
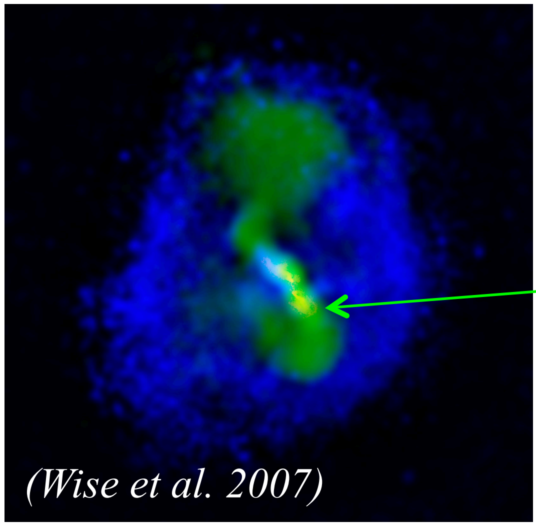


Figure 4. Multi-wavelength data for the 21 clusters in our sample with NUV (*GALEX*, *XMM-OM*) and Hα (MMTF) data. From left to right, the panels are: (1) MMTF red continuum image, (2) unsharp masked *Chandra* X-ray image, (3) MMTF continuum-subtracted Hα image, and (4) *GALEX*/*XMM-OM* NUV image. The horizontal scale bar in all panels represents 20 kpc. The X-ray and red continuum images are on the same scale and the Hα and NUV data are on the same zoomed-in scale. The square region in the X-ray panels represents the field of view for the zoomed-in Hα and NUV panels.

(McDonald et al. 2010)

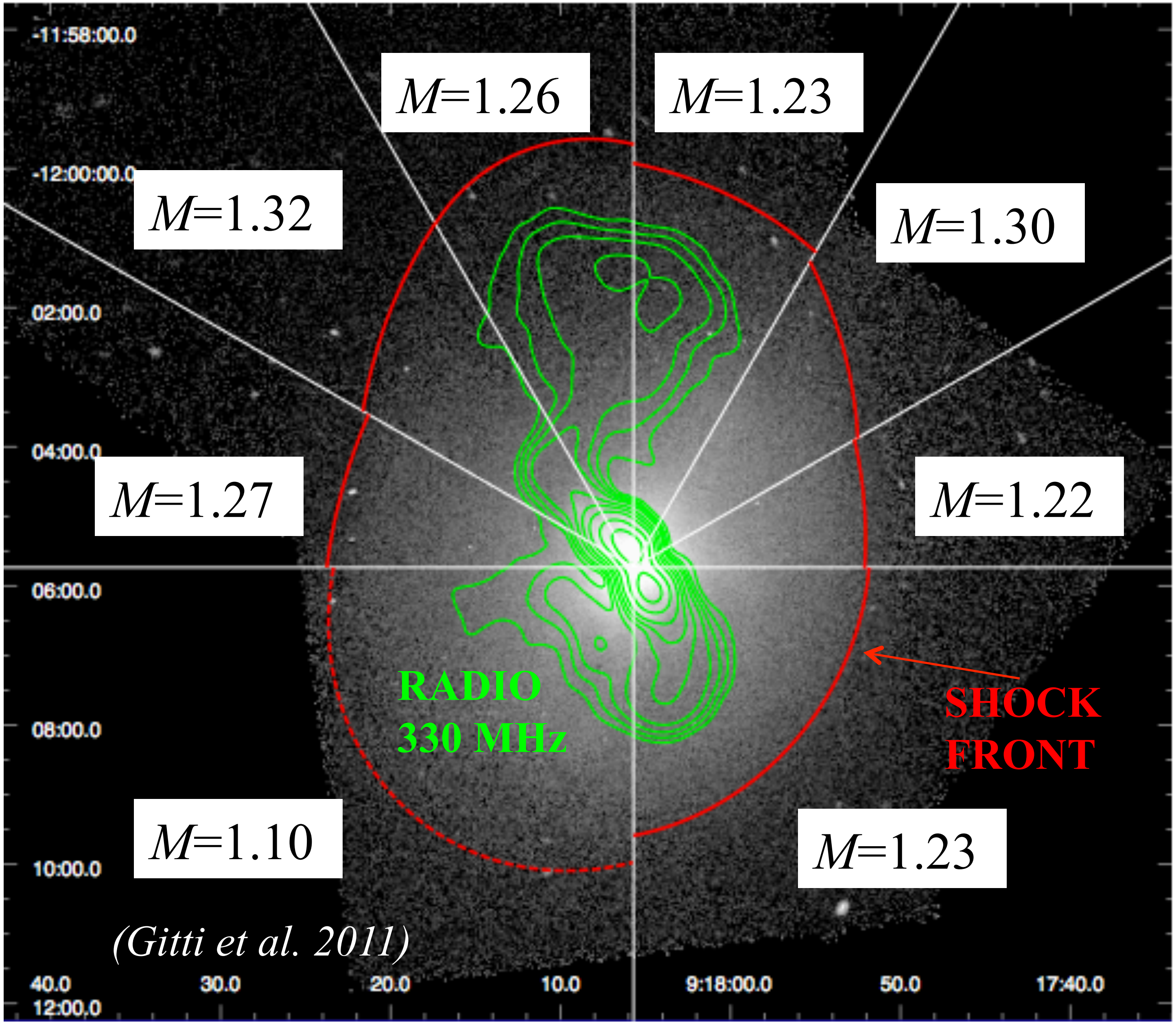


The arcing Hα filament appears to be spatially correlated with the radio jet ($R_{\mathrm{H}\alpha} \sim 11$ kpc)

$$F_{\mathrm{H}\alpha,\,\mathrm{fil}} = 0.16 \times 10^{-14}\,\mathrm{erg} \cdot \mathrm{s}^{-1} \cdot \mathrm{cm}^{-2}$$

$$F_{\mathrm{H}\alpha,\,\mathrm{tot}} = 1.60 \times 10^{-14}\,\mathrm{erg} \cdot \mathrm{s}^{-1} \cdot \mathrm{cm}^{-2}$$

Hydra A: Large-Scale Shock Front



Shock model properties:

- Mach ~ 1.2-1.3
- Energy = 9×10^{60} erg
- Age = 1.4×10^{8} yr

(Wise et al. 2007)

Hydra A: Temperature across the Shock

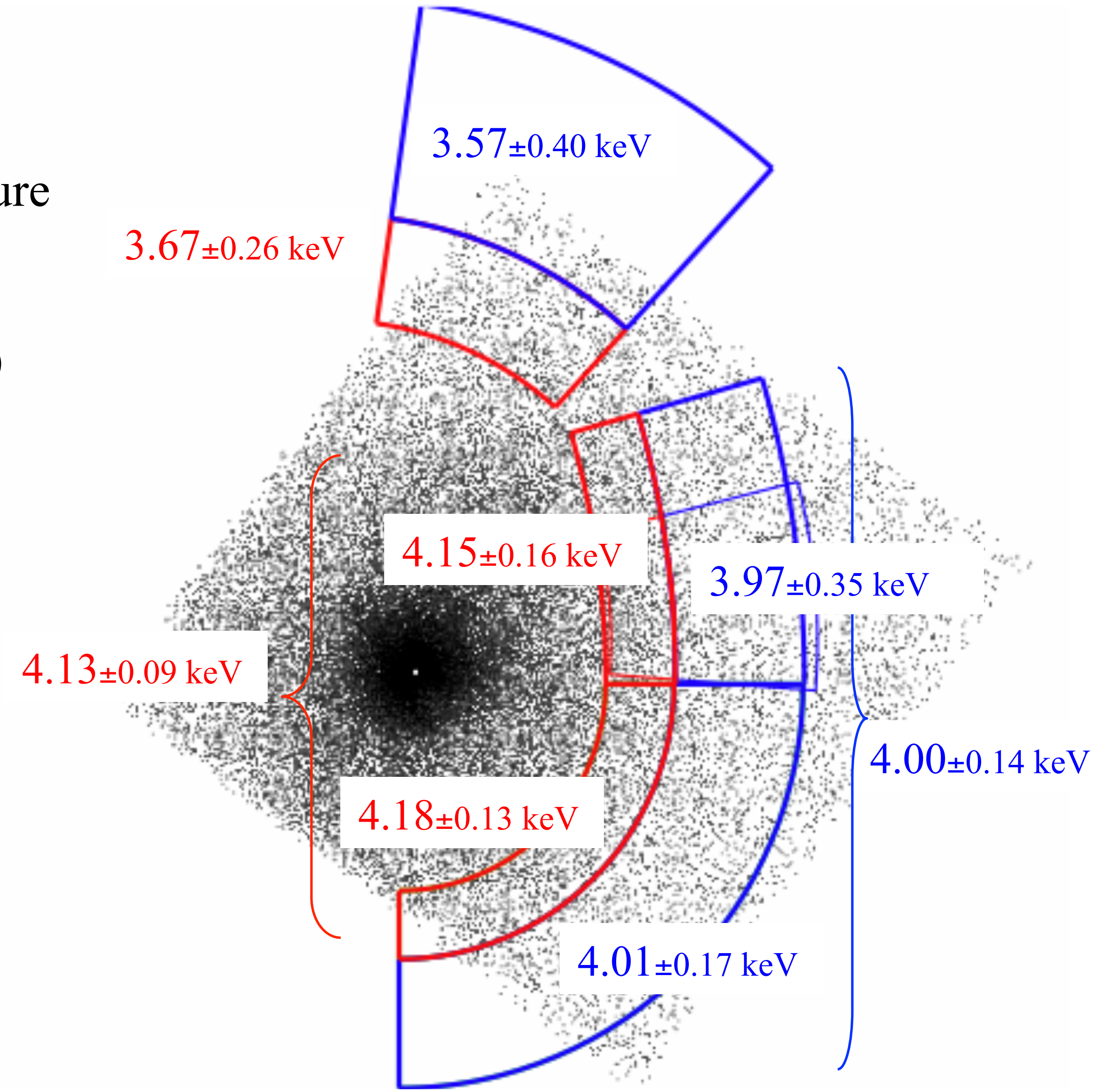
Shock model predicts the emission-weighted temperature to rise across the front by ~10-15% for Mach number *M*~1.2-1.3 *(Nulsen et al. 2005)*

Extract and fit spectra in the post-shock region and in the pre-shock region

➔ compare *kT* (keV) :

$$kT_{\text{post-shock}} > kT_{\text{pre-shock}}$$

BUT large error bars due to limited statistics!



Hydra A: Temperature across the Shock