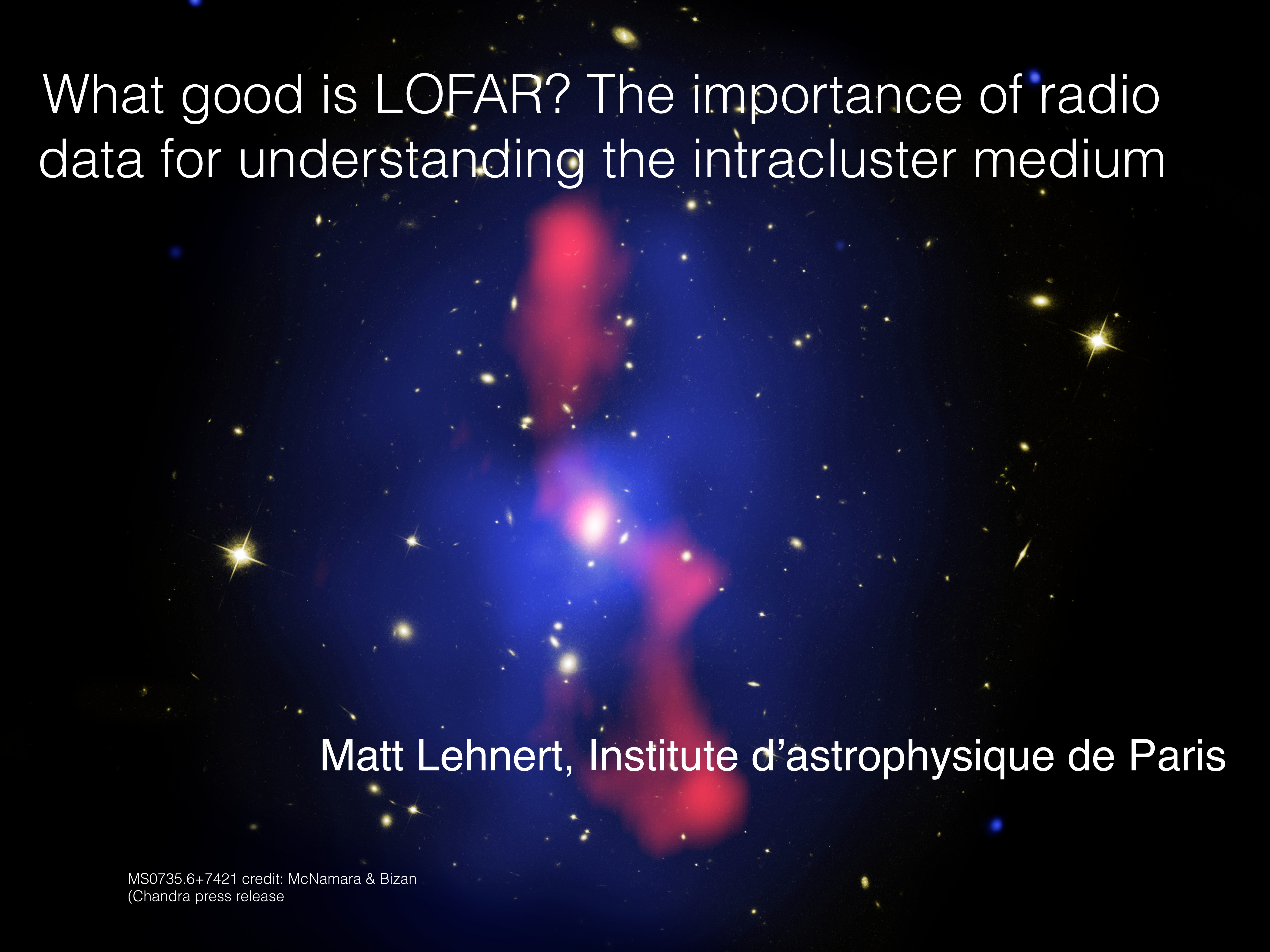
What good is LOFAR? The importance of radio data for understanding the intracluster medium



Matt Lehnert, Institute d'astrophysique de Paris

MS0735.6+7421 credit: McNamara & Bizan
(Chandra press release

Galaxy clusters

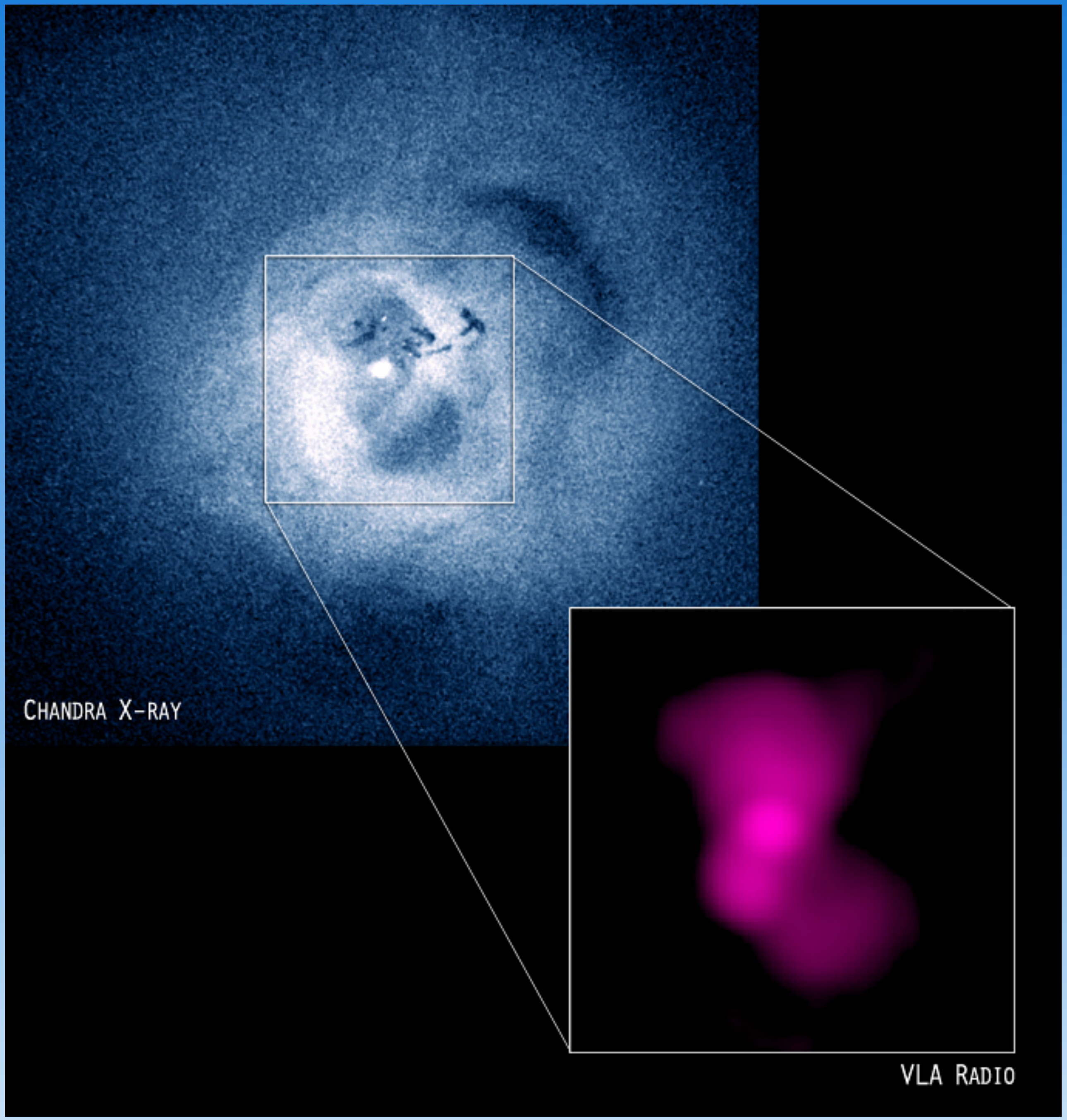
- Largest gravitationally bound structures, ~10^{15} $M_\odot$ and volumes ~100 Mpc^3
- Dark matter, ~80% of mass
- X-ray emitting plasma, ~0.1 to >10 keV, ~15% of mass — the intracluster medium, ICM
- Stars and colder gas, ~3-5%
- Most of the metals are in the ICM
- Entropy budget and cooling times requires +1 keV/Baryon
- Magnetic fields in the ICM can reach 0.1-1.0 μG and $E_{mag,total}$~10^{61} erg
- The total magnetic energy is about that a powerful radio galaxy ejects in kinetic energy per "outburst"

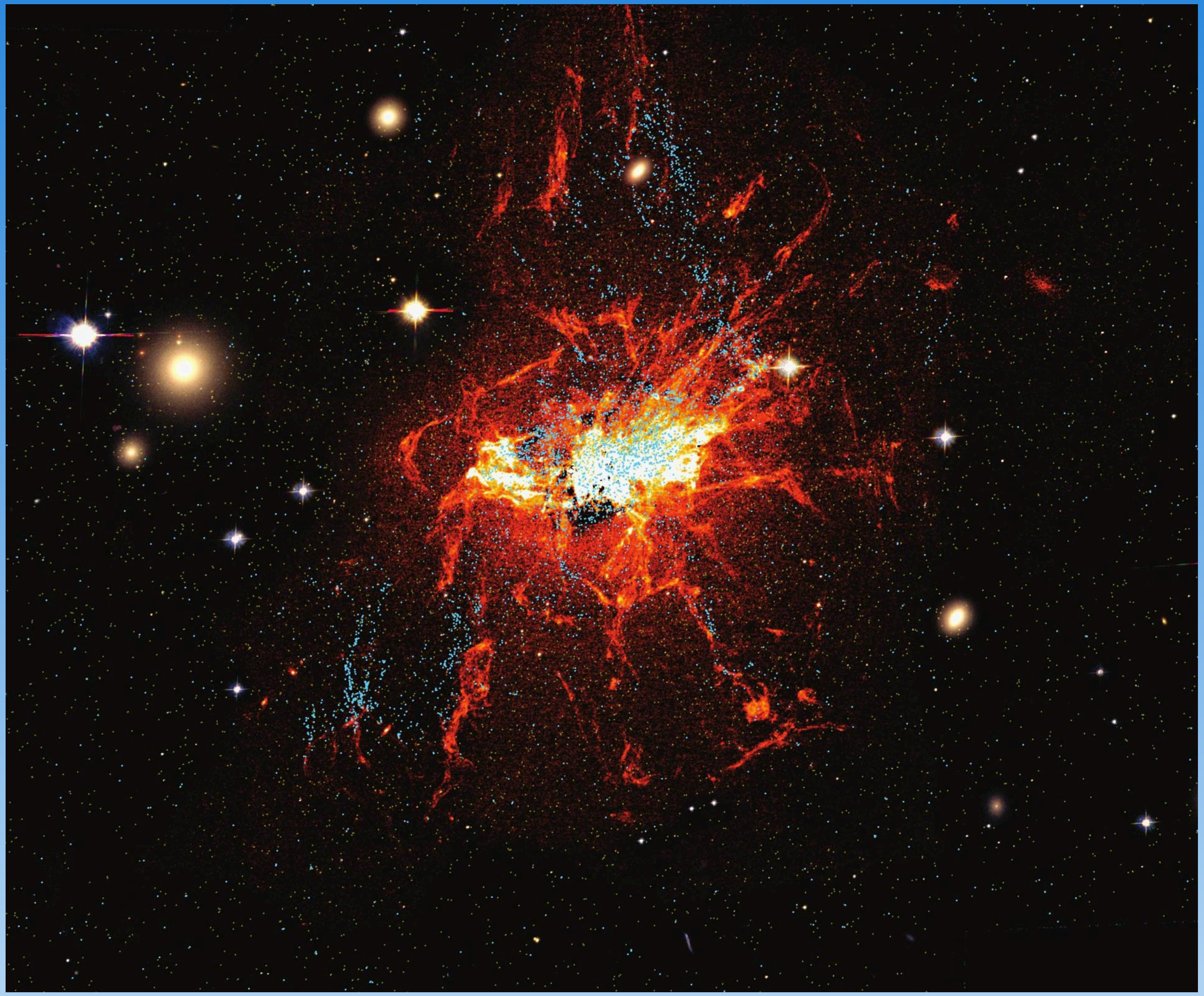
How and when did the ICM come into place with its current characteristics and does its magnetic field strength give us a clue?

Evolution of the ICM

What does the ICM look like today?

Perseus Cluster

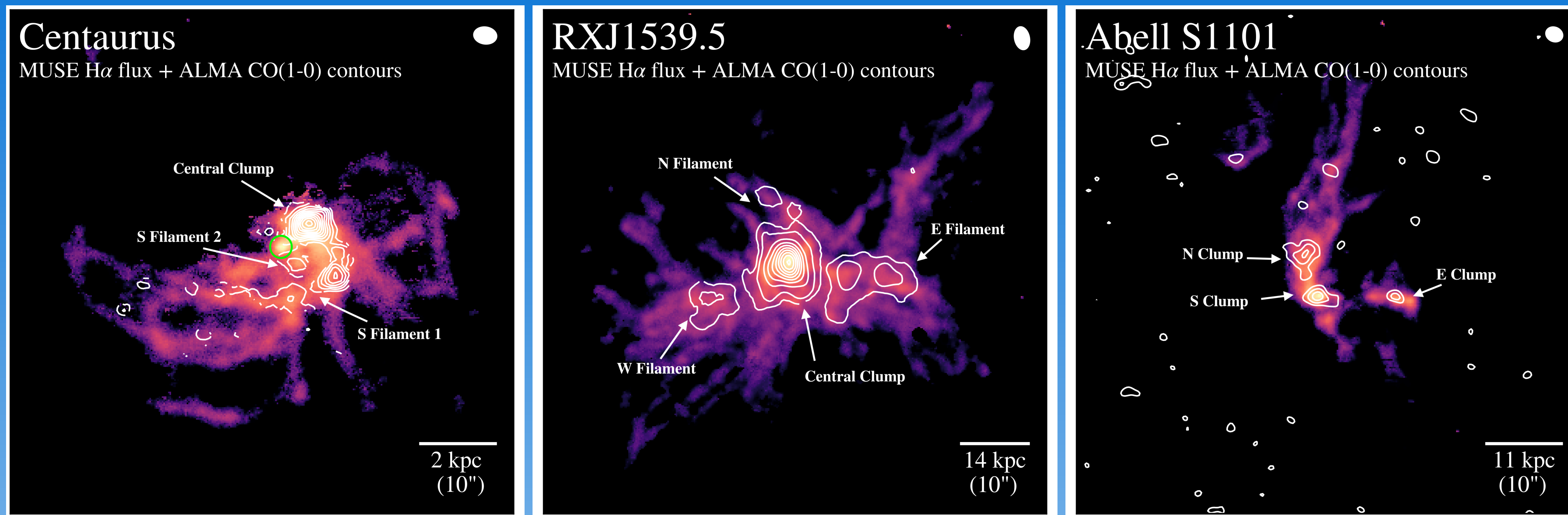


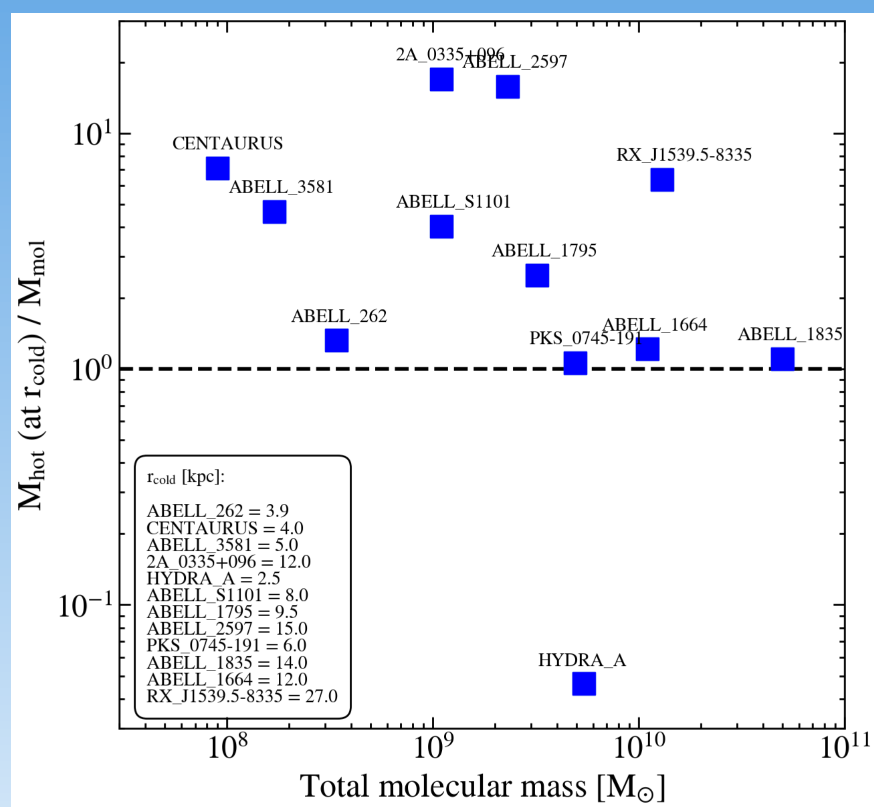


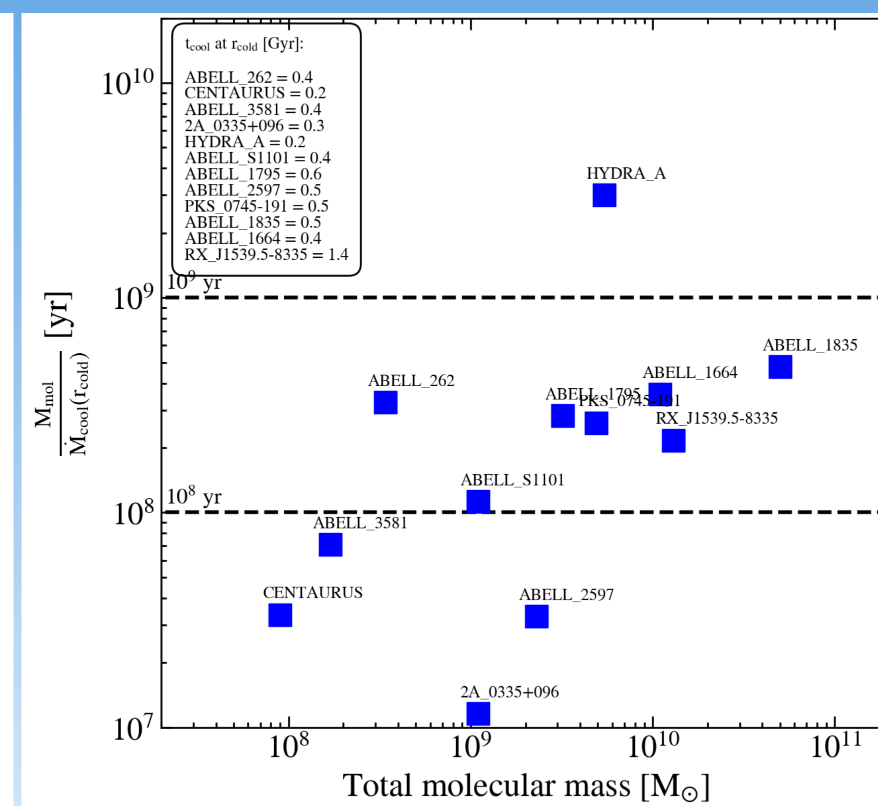
Intimate relation between the hot X-ray emitting gas and the radio emission with the warm ionized gas and molecular gas. Radio jets appear to balance the global cooling.

Fabian et al. & Taylor et al.; Lim et al. 2010

Warm and cold gas in clusters



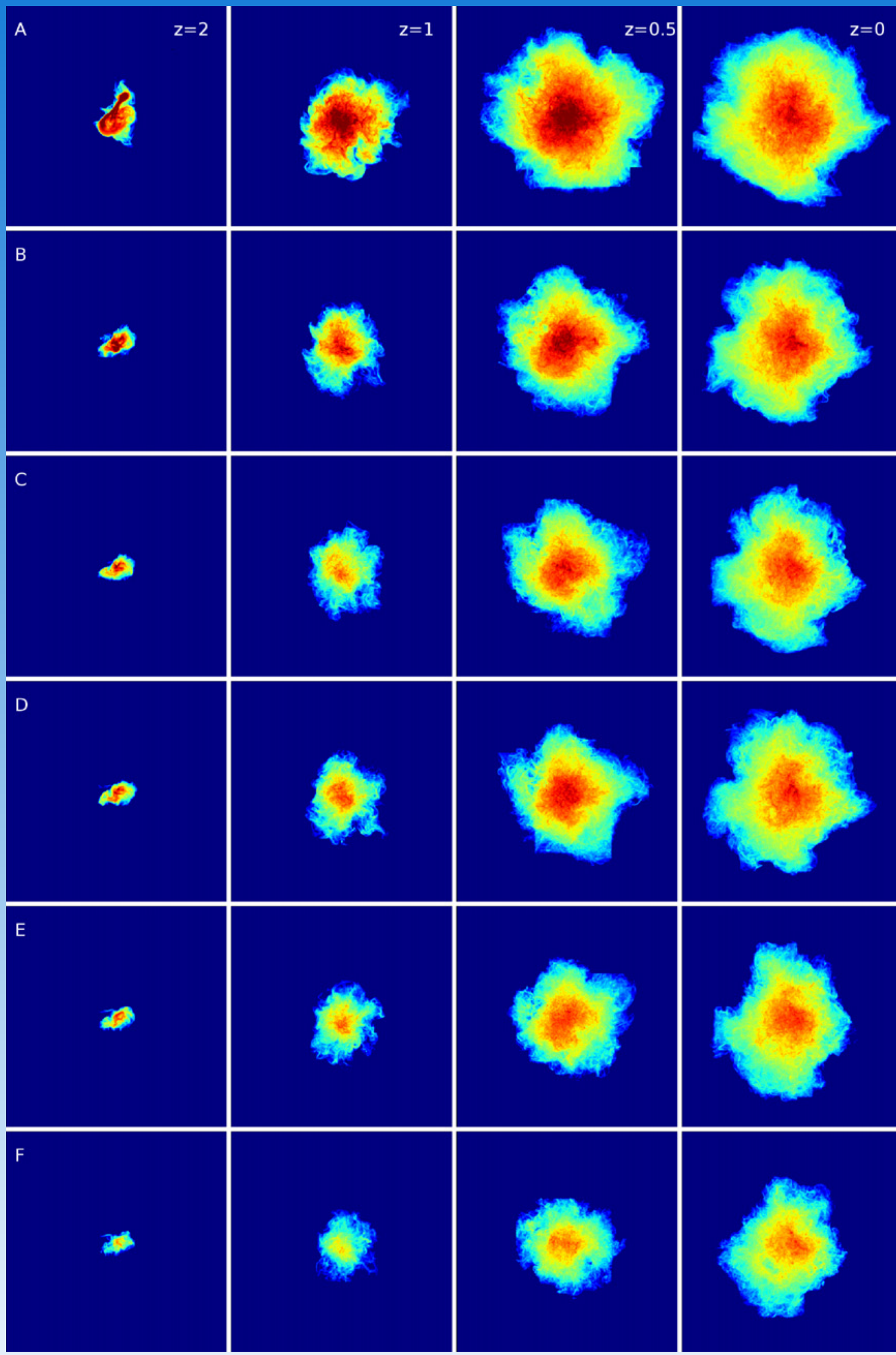




Within the region of the molecular gas deep in the core, the molecular gas is significant and likely formed recently … not long lived.

Olivares et al. 2019

Simulations of the evolution of B-field energy density

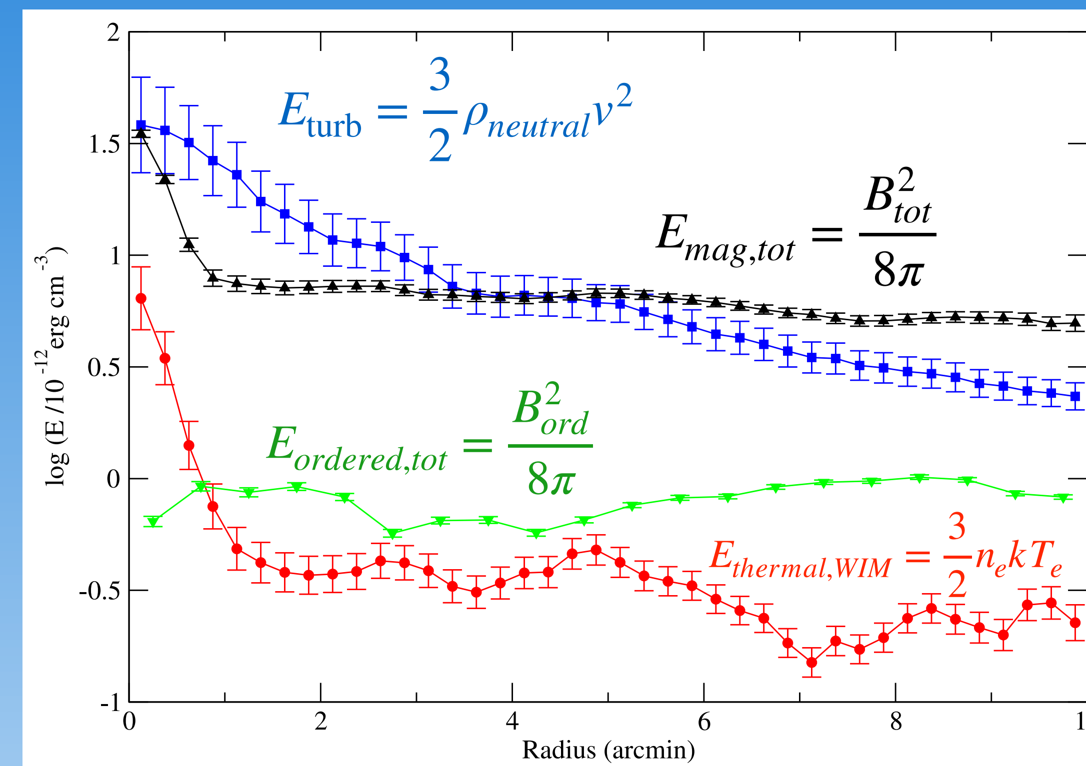


10^8 erg cm^{-2}

10^{12} erg cm^{-2}

8 x 8 Mpc, mergers and random ICM motions spread field from AGN

IC 342

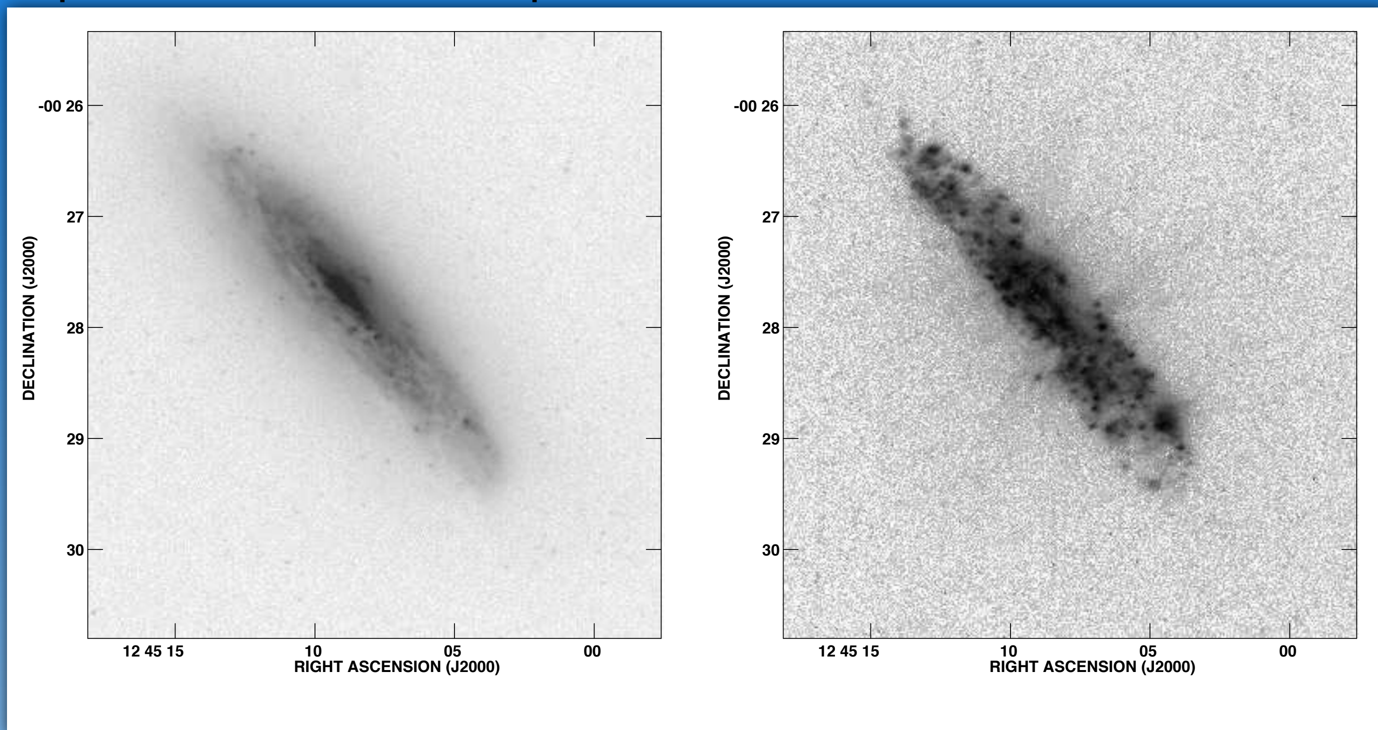


~1-10 μG

Xu et al. 2010; Beck 2015

Starburst galaxies eject B-fields

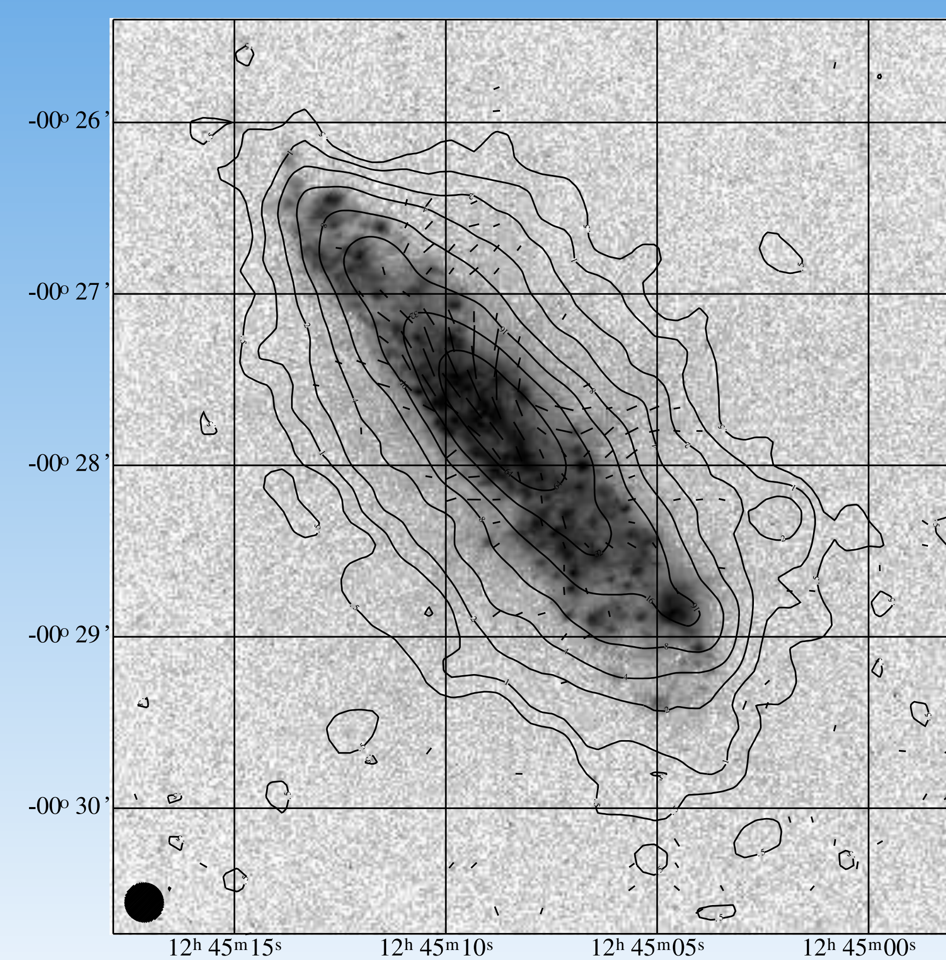
Optical and H-alpha emission



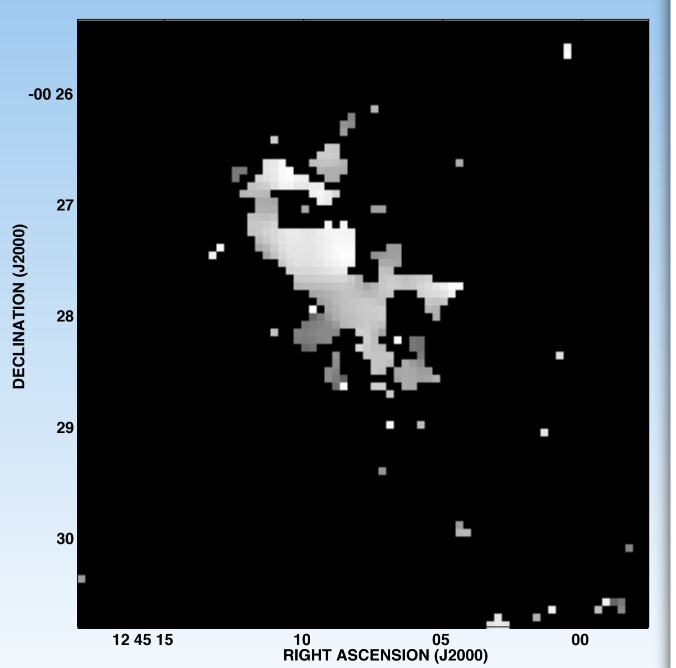
The extent, polarization, RM, and spectral index suggests that the B-field has been ejected … fields surprisingly well ordered

$B_{tot} \sim 7.1 \mu G$ or ~1/2 that of the disk

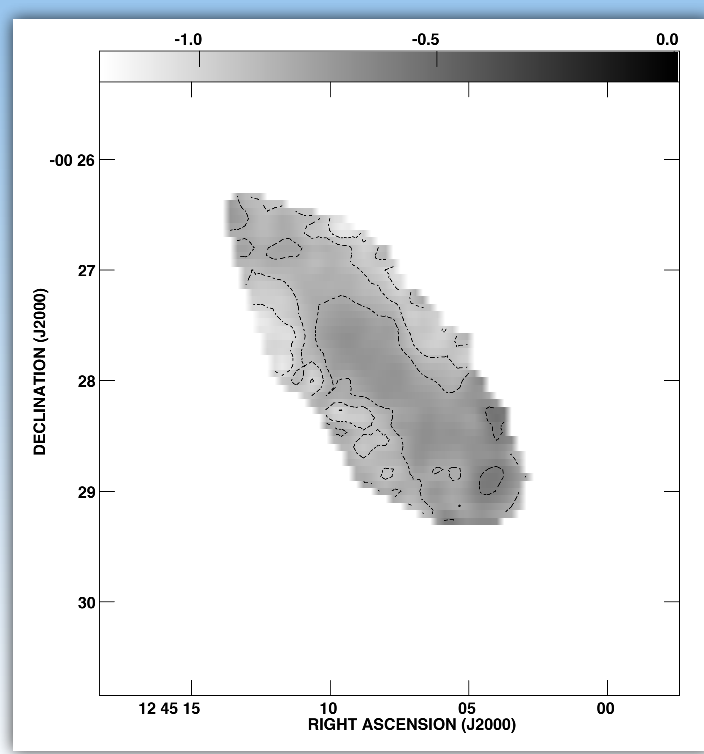
Polarization and map



RM = -39 to 39 rad m^{-2}



$\alpha^{1.43}$ 4.89



Dahlem, Petr, Lehnert, Heckman, & Ehle1997

Evolution of the ICM

AGN have enough power and likely $B^2/8\pi$

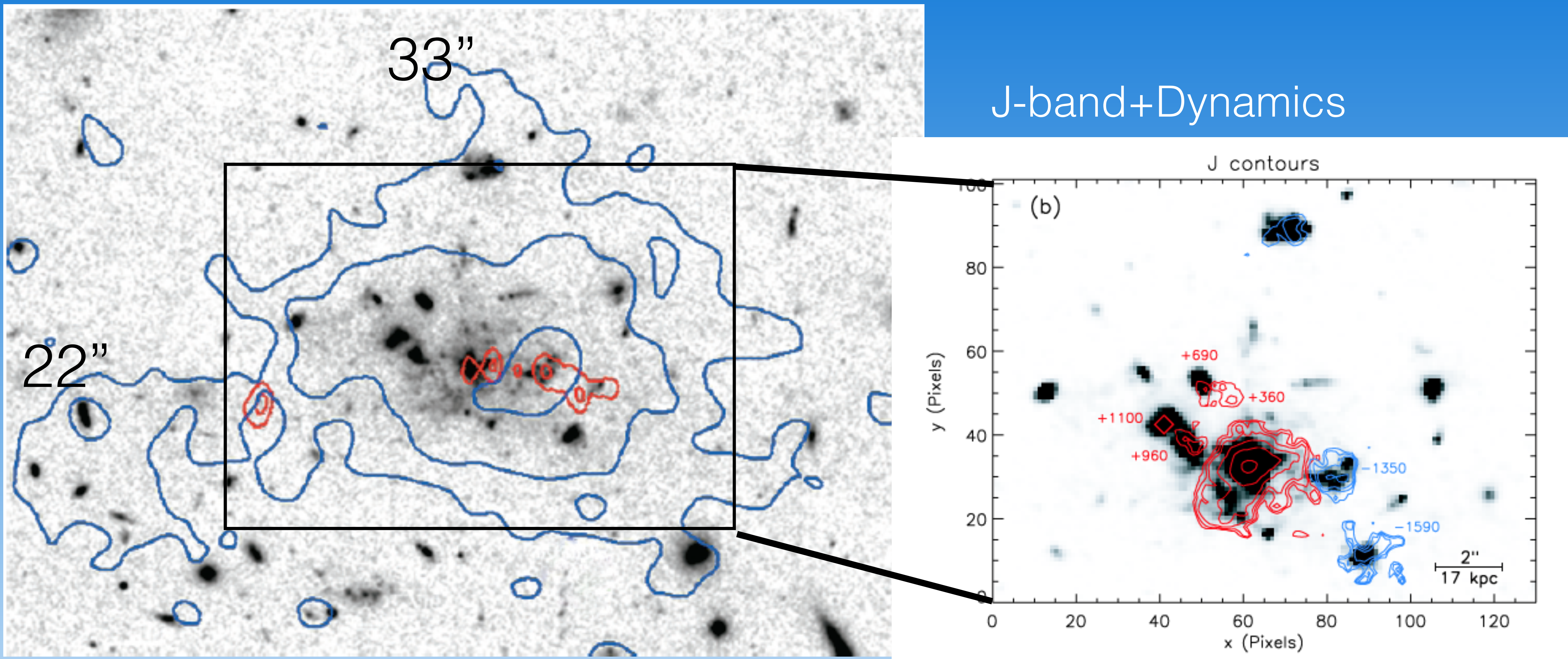
Galaxies eject B-fields, metals, and energy

Maybe *in situ* observations will help decide?

The “Spider web”

Ly-alpha + HST F814W

J-band+Dynamics



Best studied radio galaxy embedded in a photo-cluster at z=2.16 … radio galaxy massive, $M^{*}\sim$few 10^{11} $M_{\odot}$, giant Ly-alpha halo … x-ray emission …

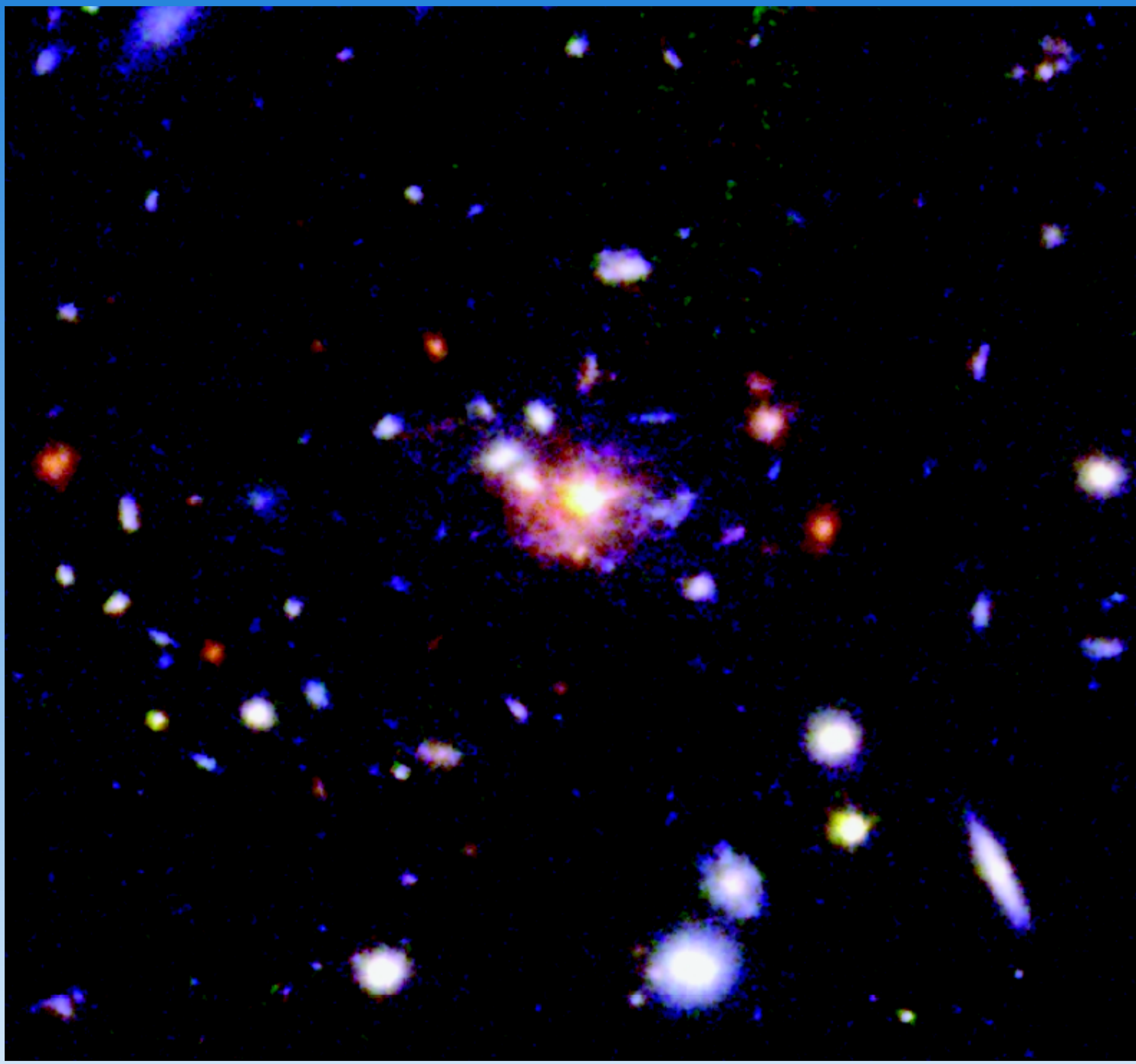
Galaxies whizzing around …

Jets are powerful … $\sim10^{61}$ erg into the galaxy and CGM & ~binding energy of a massive halo

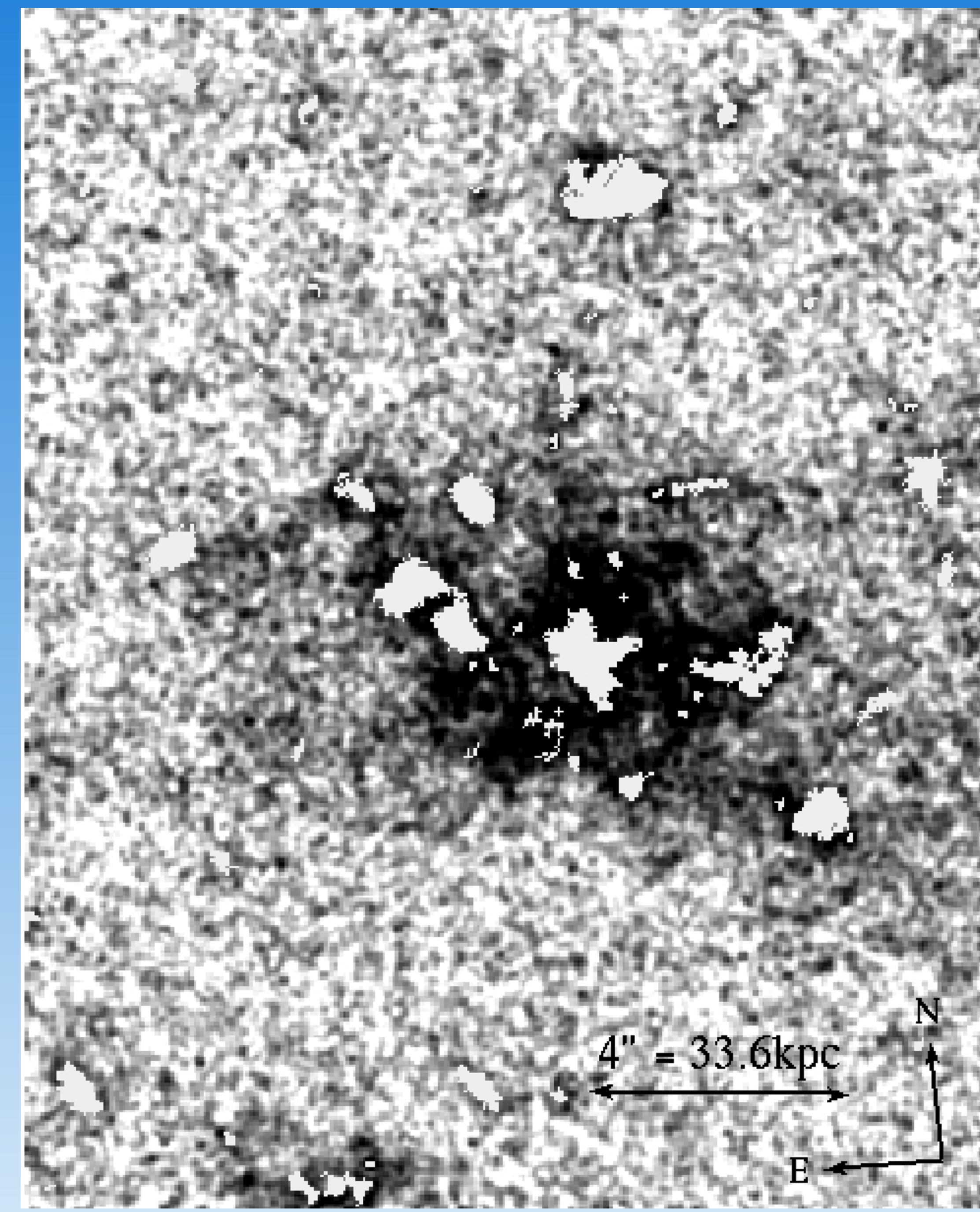
Miley et al. 2006; Kuiper et al. 2012; Carilli et al. 2002

The “Spider web”star formation in its halo

$g_{475}+I_{814}+J_{110}+H_{160}$



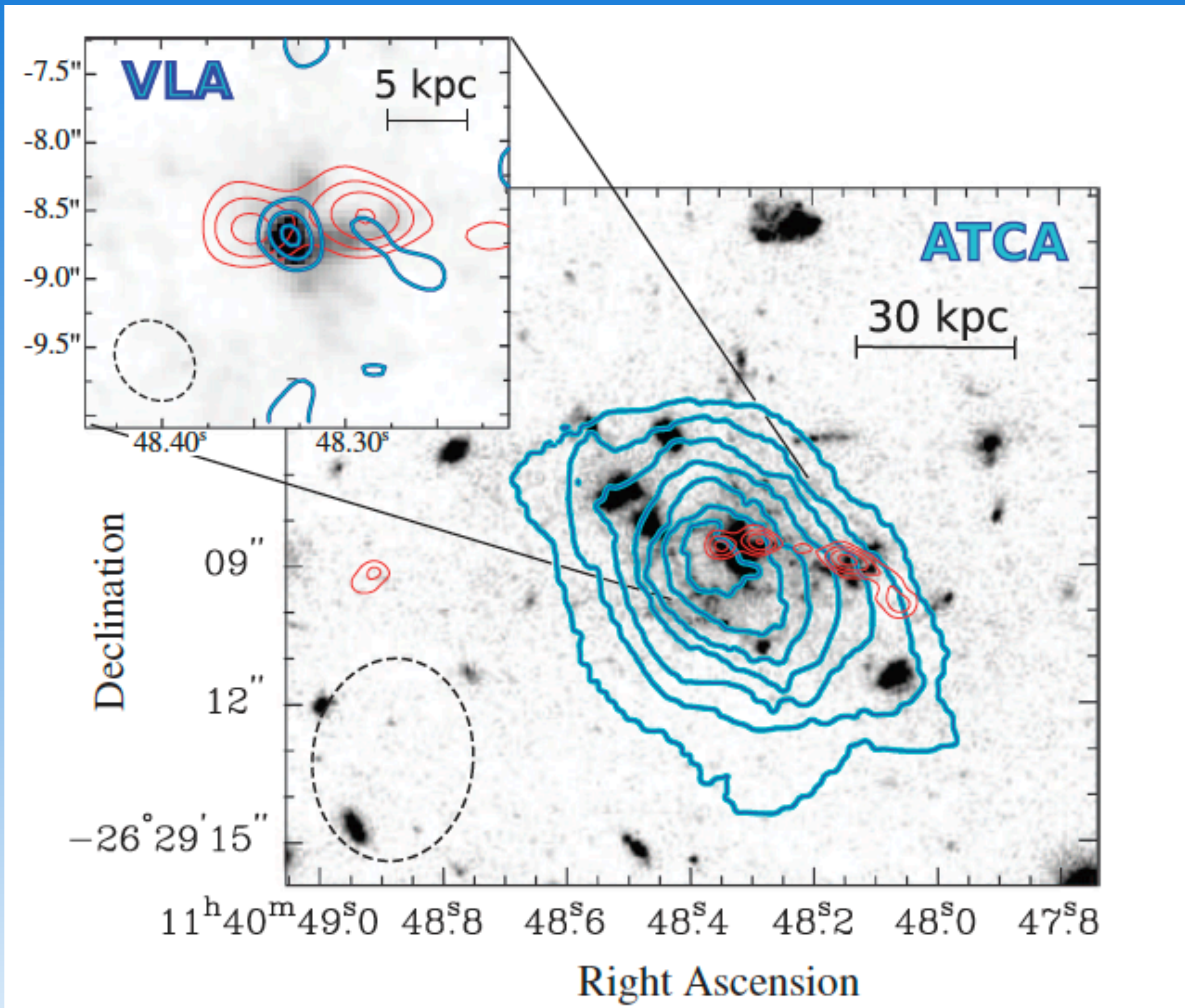
g_{475} with galaxies removed to emphasize diffuse light



Hatch et al. (2006) estimate SFR~140 $M_{\odot}$ yr^{-1} in the extended diffuse light. Ruled out faint cluster galaxies, neb cont., scattered QSO light, etc.

Hatch et al. 2008; 2011

Star-formation and CO(1-0) in the Spiderweb halo



We found the molecular gas, $M_{H2}=10^{11}$ $M_{\odot}$, from CO(1-0) supporting the extended SF on ~100 kpc scale

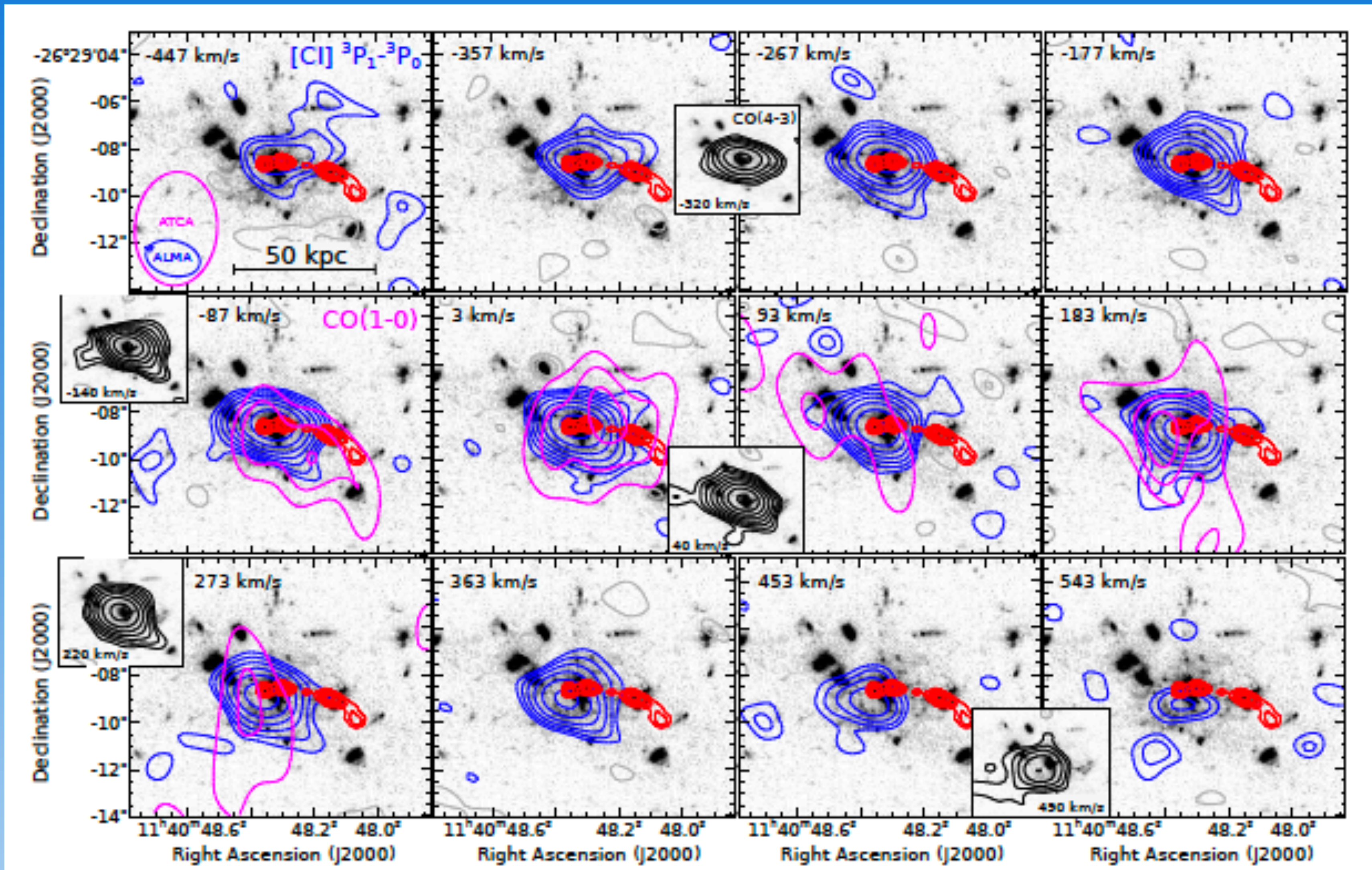
2/3 emission extended

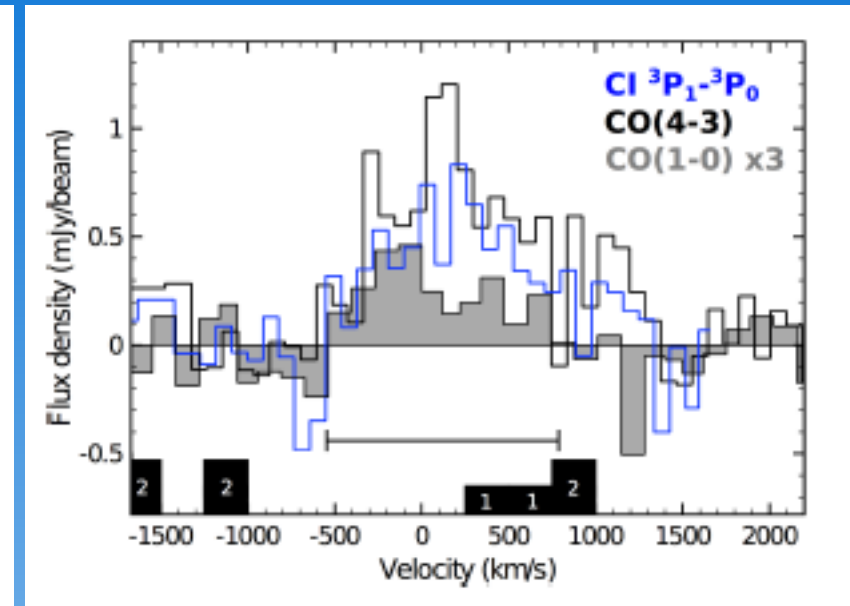
VLA data rule out fainter galaxies and the image has no negative “noise” over the MRC 1138-242

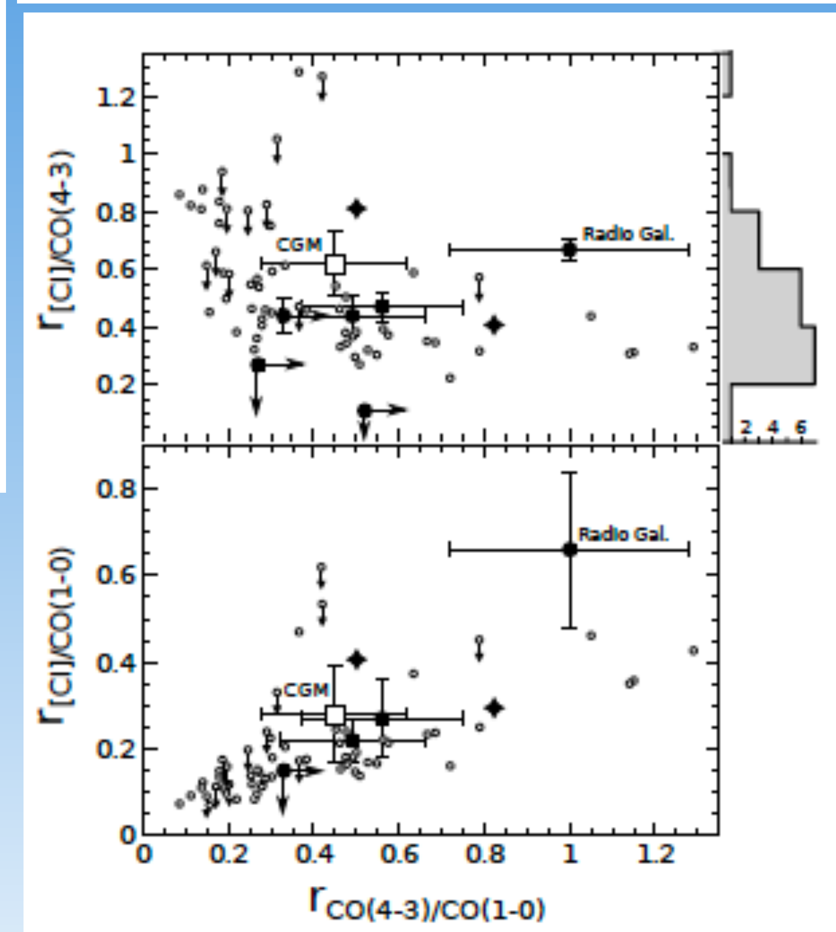
About 30% of the ICM is in molecular gas!

Emonts, MDL et al. 2016, Science

Star-formation and dense gas in the Spiderweb halo







$$M_{H_2} = 1.0 \pm 0.4 \times 10^{11} (\alpha_{CO}/4)\ M_\odot$$
$$M_{[CI]} \sim 8.9 \pm 1.4 \times 10^{6}\ M_\odot$$
$$X_{CI}/X_{H_2} \sim 1.5 \pm 0.6 \times 10^{-5} (\alpha_{CO}/4)$$

Excitation is similar to galaxies

[CI] abundance similar to MW, it's metal-enriched

If tidal debris, it has dissipated a lot of energy

Emonts, MDL, et al. 2018, MNRAS

Ram pressure stripping

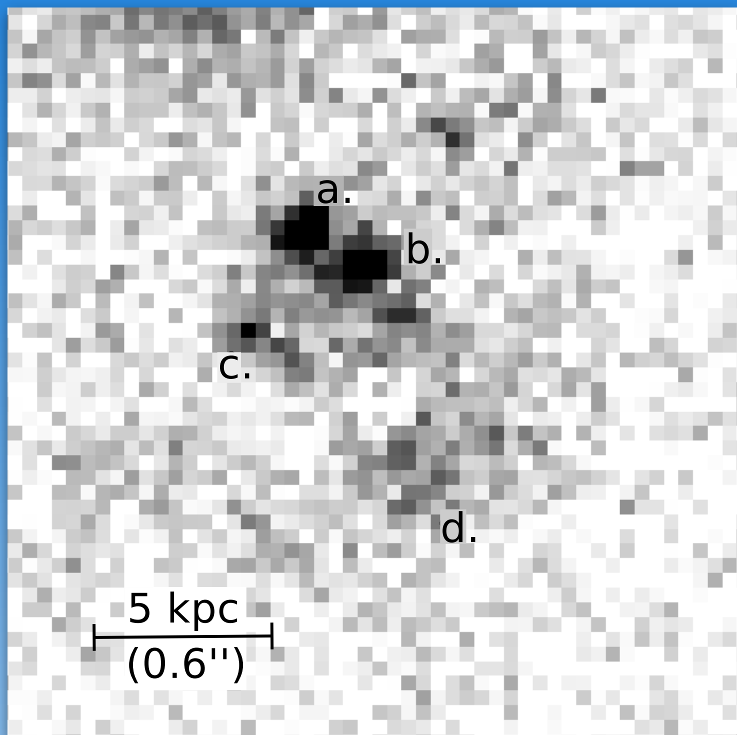
Hot ICM gas provides pressure as the galaxy moves through the cluster …

$P_{ram} = \rho_{hot} v_{galaxy}^2$ (Gunn & Gott 1972)

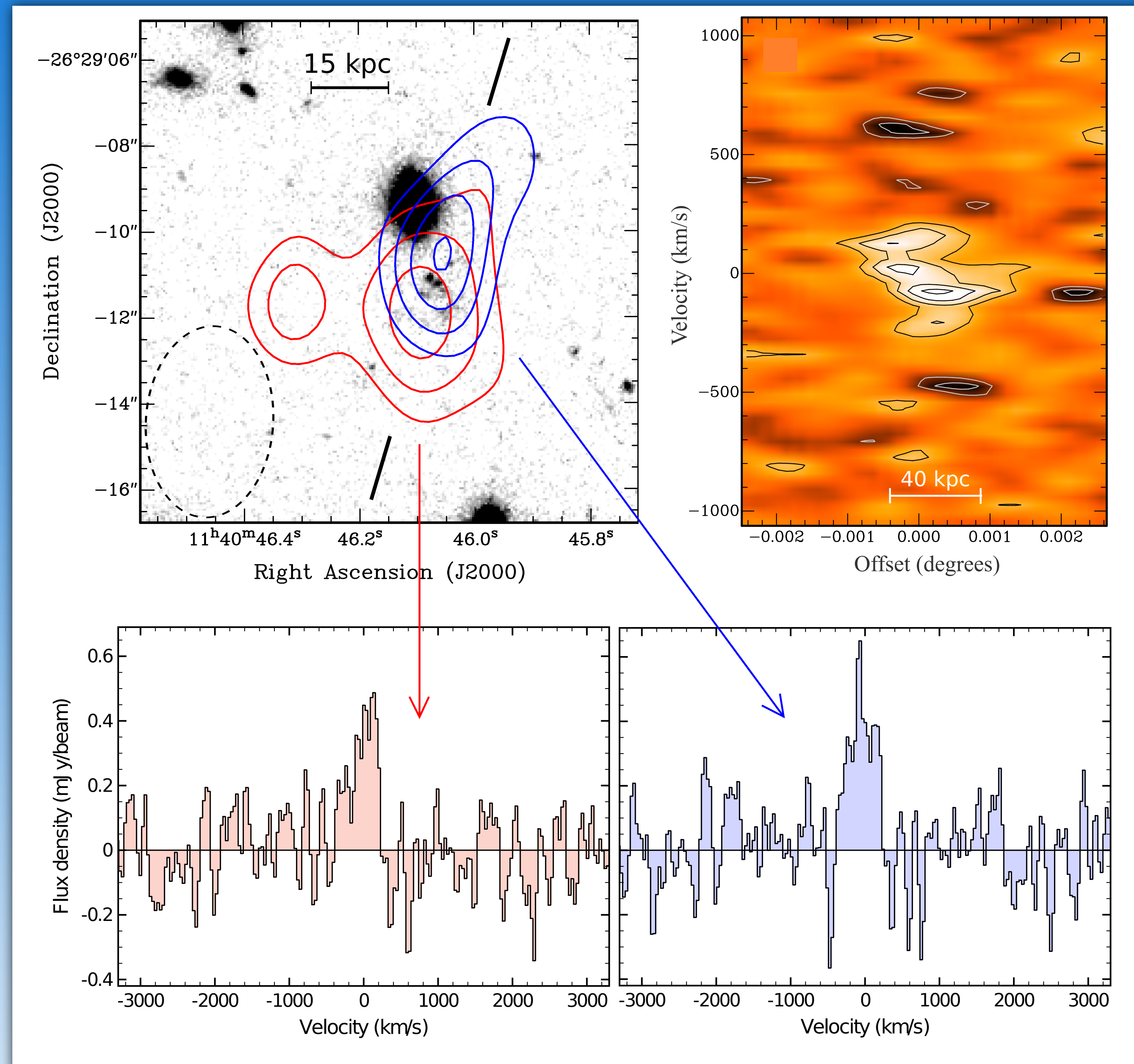
Combined Chandra (blue) & HST; Ming Sun, Serge Meunier

Large molecular disks at high redshift, HAE229

HST F814W of HAE229



Deep observations with ATCA



Massive disk in the MRC1138-242 proto-cluster with M_{mol}=2.0±0.2 x 10^{11} $M_{\odot}$ and $f_{mol}=M_{mol}/(M_{mol}+M_{\star})\approx 30\%$. $M_{\star}\approx$3-5 x 10^{11} $M_{\odot}$, and we are discovering more

Why doesn't ram pressure stripping remove this gas? Is the ICM mostly warm and cold, not hot? $P_{ram} = \Sigma_{phases}\ ff_{phase,v}\ \rho_{phase} v_{gal}^2$

Dannerbauer, Lehnert, Emonts, et al. 2017

Some final thoughts ... no real conclusions

The ICM requires about 1 keV or more per baryon to have its observed entropy. Both AGN and SB provide the necessary entropy

Already RM against distant radio lobes suggest an ionized magnetized medium but can we detect the radio sources and diffuse radio emission from proto-clusters?

Can we detect the first extended radio emission at low frequencies …

$$\nu_{rest-frame} = \nu_{obs} \times (1+z)$$

LOFAR, with its capability of detecting low surface brightness emission is the perfect facility to attempt this experiment