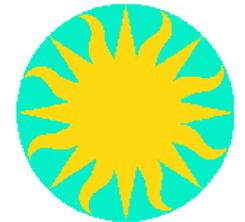


Buoyancy, Uplift, and AGN Feedback: Deep Chandra and XMM-Newton Observations of the Radio Outbursts in NGC 4472 and NGC 1399



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MLGM

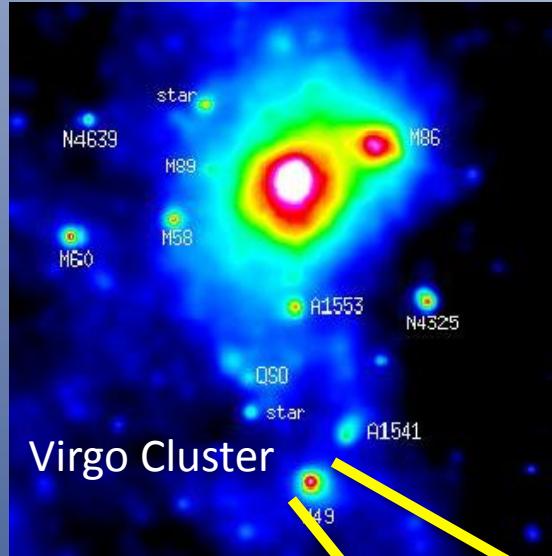
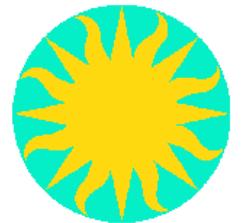


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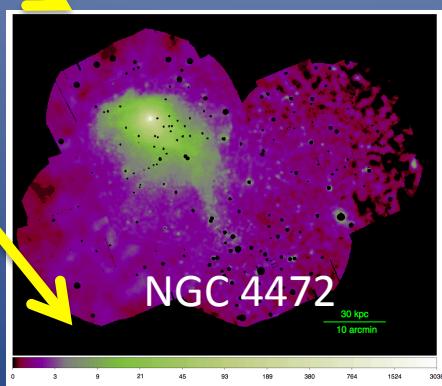
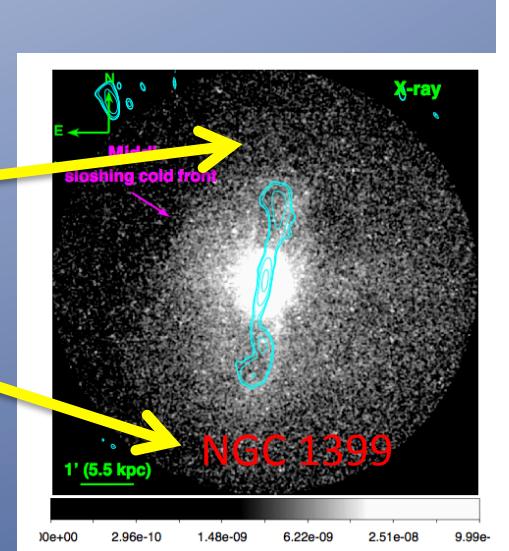
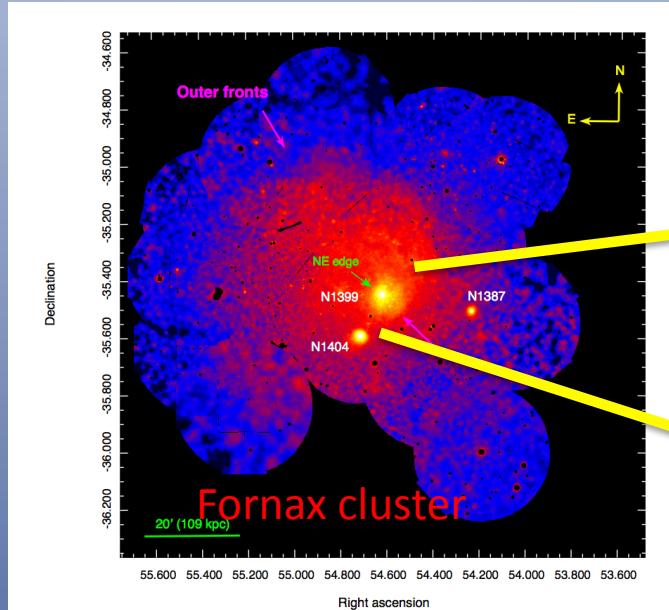


The X-ray Universe 2017 – Galaxy Clusters and Feedback IV
June 9, 2017

NGC 4472 (M49) and NGC 1399 (BCG of Fornax cluster)



- Lies at the outskirts (1.35 Mpc – roughly virial radius) of the Virgo cluster ($d_L \sim 17$ Mpc)
- Most massive galaxy in local Universe
- Complex interaction with Virgo cluster and cavities coincident with lobes (Irwin and Sarazin 1995, Biller+2004, Kraft+2011)

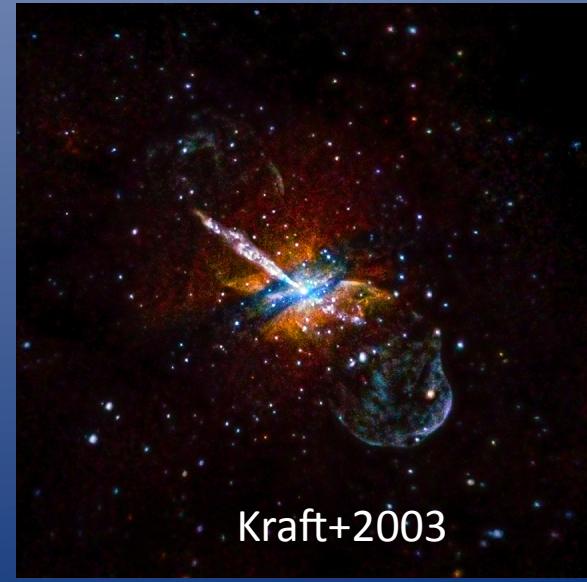
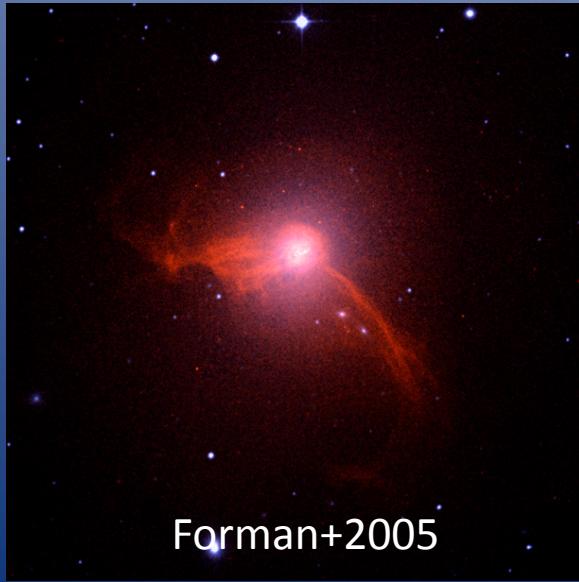


- Slightly further ($d_L \sim 20$ Mpc) than Virgo cluster
- Central BCG of a large (1.5 keV) group
- Multiple sloshing fronts (NGC 1404 merger) and cavities – some with radio plasma and at least one ‘ghost’ cavity

(Highly?) Supersonic inflation of the Radio lobes



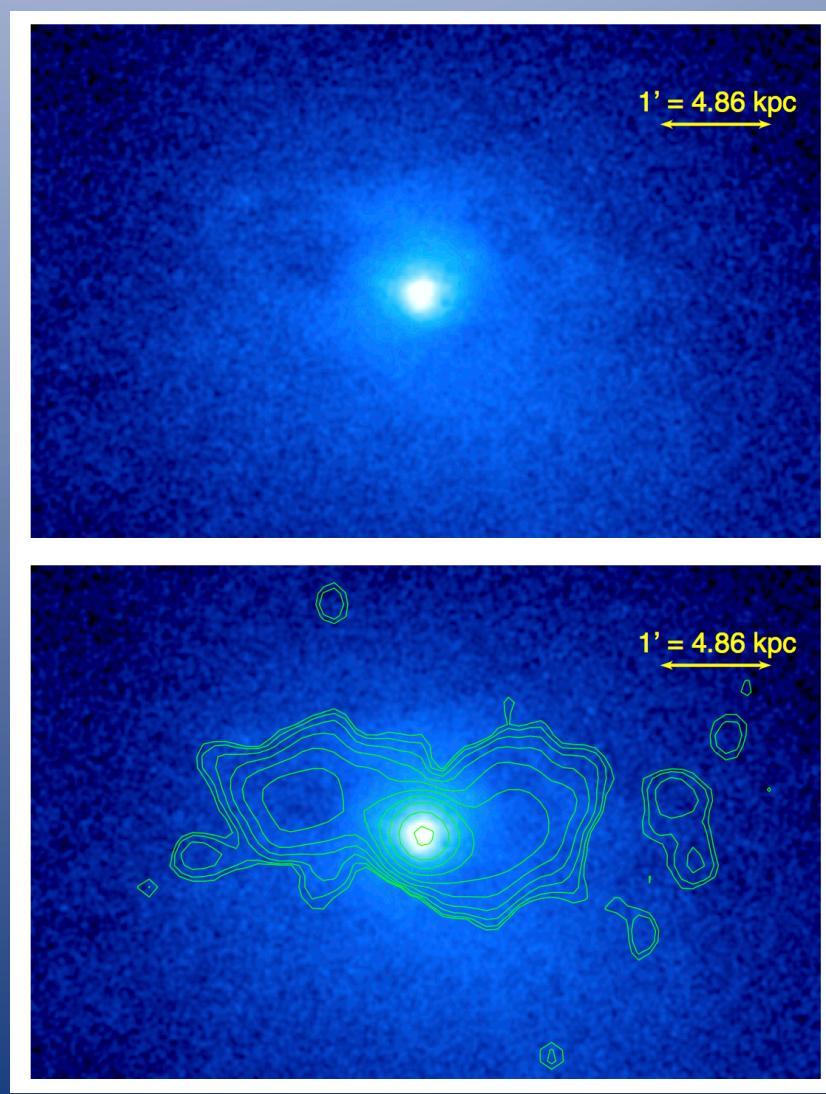
- Surface brightness discontinuities in the X-ray gas around radio lobes often indicative of shocks.
- Supersonic outflow from AGN believed to play key roles in thermodynamic evolution of cluster gas (McNamara and Nulsen 2007 and many others)



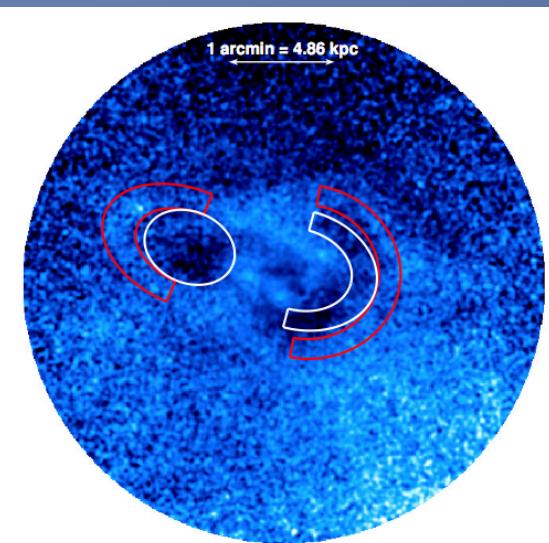
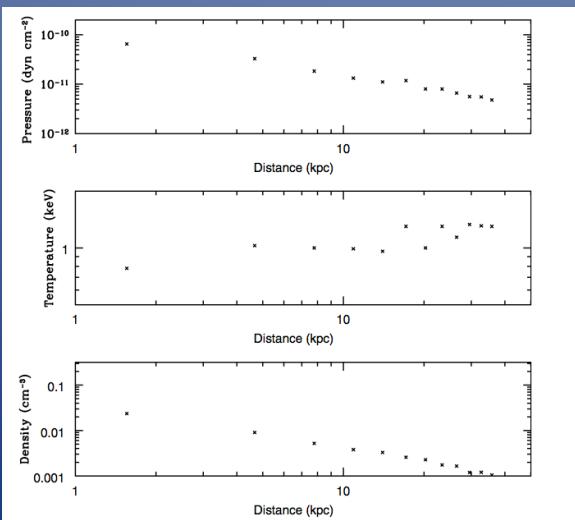
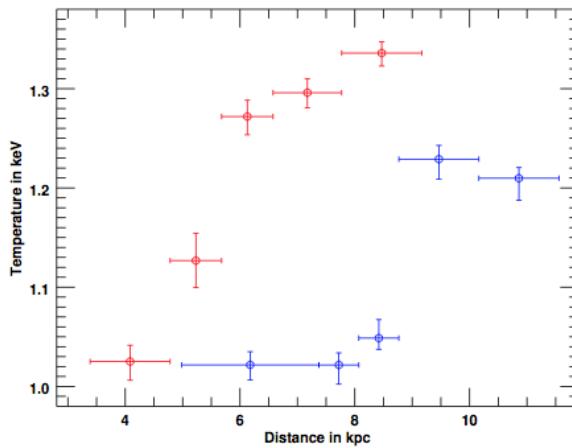
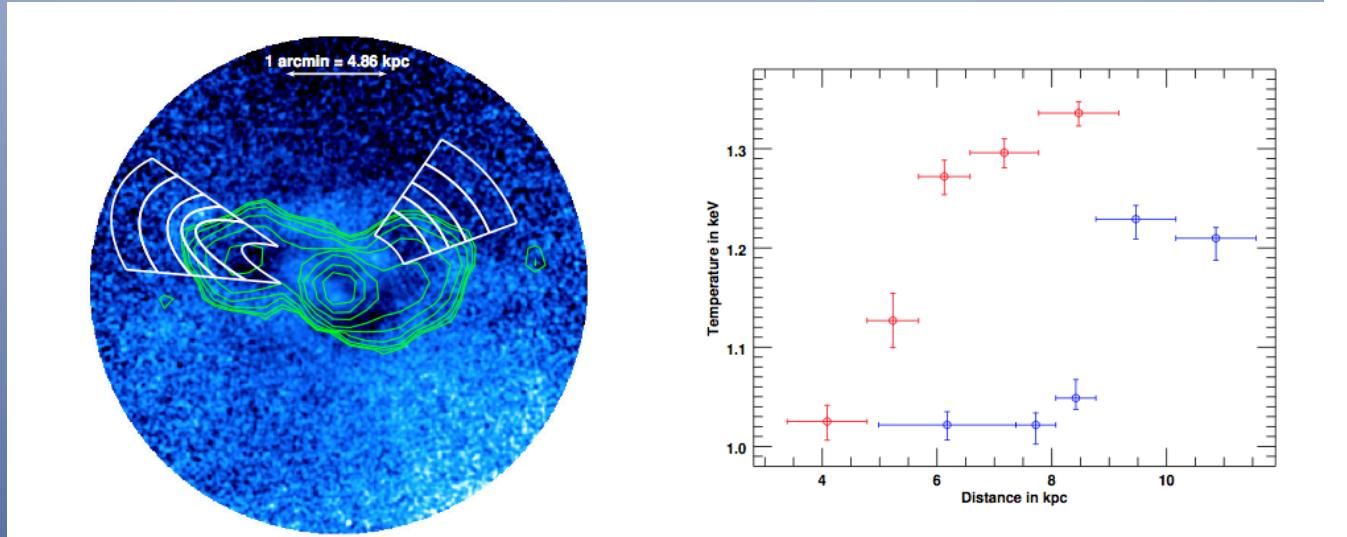
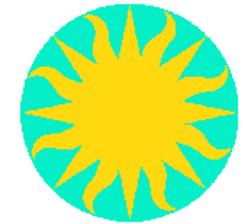
Deep Chandra (375 ks) Observation of NGC 4472



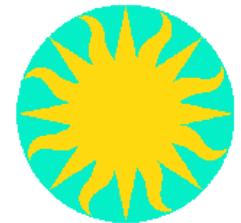
- Deep Chandra observation (LP) to study gas dynamics (Su+ in preparation) and AGN outburst (Gendron Marsolais+2017)
- Radio source is relatively weak – 3 orders of magnitude fainter than M87
- Clear evidence of cavities in the X-ray data, and bright X-ray rims around the radio lobes



Temperature Analysis – Rims are cool



Radio bubble energetics

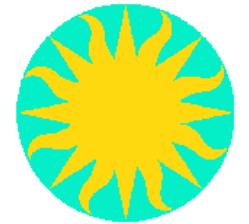


	Eastern Lobe	Western Lobe
Volume	$8 \times 10^{65} \text{ cm}^3$	$1.1 \times 10^{66} \text{ cm}^3$
Distance from lobe to SMBH	4.6 kpc	3.7 kpc
n_{H} at lobe center	$9 \times 10^{-3} \text{ cm}^{-3}$	$1.2 \times 10^{-2} \text{ cm}^{-3}$
T at lobe center	1.16 keV	1.13 keV
P at lobe center	$3.7 \times 10^{-11} \text{ dyn cm}^{-2}$	$4.7 \times 10^{-11} \text{ dyn cm}^{-2}$
Bubble enthalpy ($H=4pV$)	$1.1 \times 10^{56} \text{ ergs}$	$2.2 \times 10^{56} \text{ ergs}$
Age	20.5 Myr	16.5 Myr
Power	$1.7 \times 10^{41} \text{ ergs s}^{-1}$	$4.1 \times 10^{41} \text{ ergs s}^{-1}$
Uplift Mass	$6.3 \times 10^6 M_{\text{Solar}}$	$1.7 \times 10^7 M_{\text{Solar}}$
Uplift energy	$0.7 \times 10^{56} \text{ ergs}$	$1.8 \times 10^{56} \text{ ergs}$
$\Delta E/H$	0.65	0.82

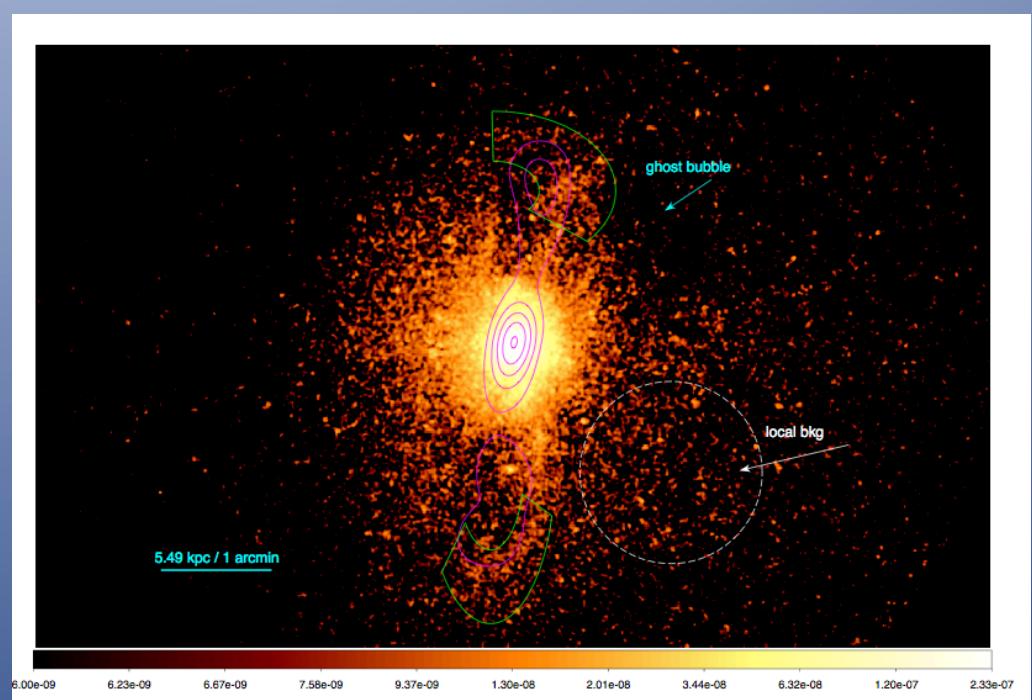
$$\Delta E = \frac{M_{\text{cool}} c_s^2}{\gamma} \ln \left(\frac{\rho_i}{\rho_f} \right)$$

Uplift energy (Reynolds+2008)
 where ΔE is the energy, M_{cool} is the mass of cool gas uplifted, c_s is the sound speed of the gas (assume isothermal), γ is the adiabatic index (5/3), and ρ_i and ρ_f are the ambient gas densities at the initial and final positions of the uplifted rims, respectively.

Radio bubble energetics in NGC 1399?

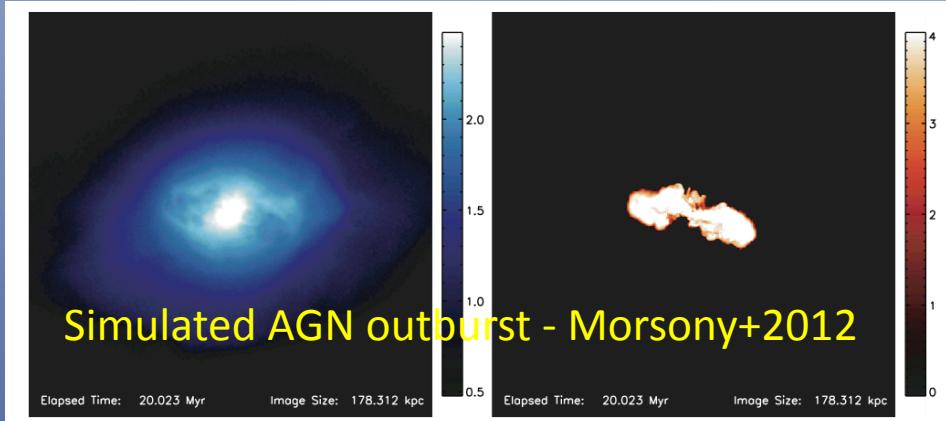


	Northern Lobe	Southern Lobe
Distance from lobe to SMBH	6.4 kpc	3.7 kpc
T at lobe center	1.3 keV	1.4 keV
Bubble enthalpy (H=4pV)	1.5×10^{56} ergs	1.4×10^{56} ergs
Age	33.3 Myr	36.7 Myr
Power	1.5×10^{41} ergs s ⁻¹	1.2×10^{41} ergs s ⁻¹
Uplift Mass	1.8×10^7 M _{Solar}	1.3×10^7 M _{Solar}
Uplift energy	1.0×10^{56} ergs	0.9×10^{56} ergs
$\Delta E/H$	0.65	0.69



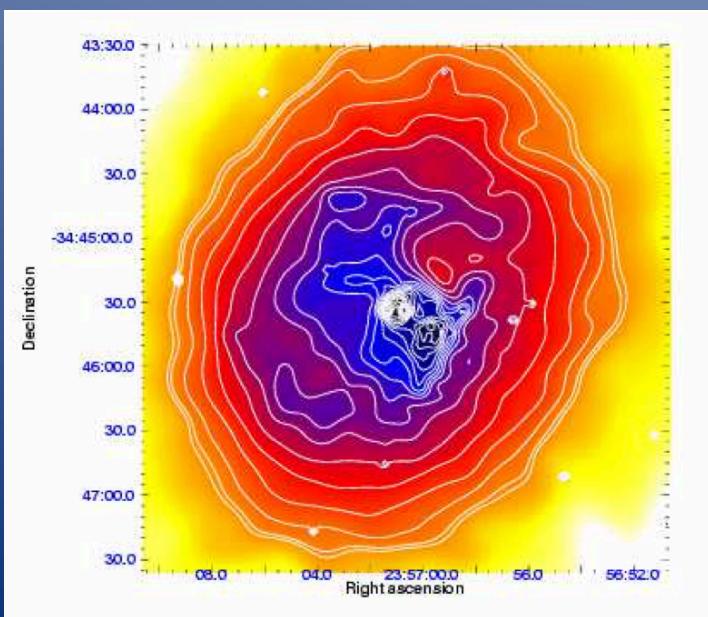
Chandra image of NGC 1399 – the central galaxy in the nearby ($d_L \sim 20$ Mpc) Fornax cluster

Other examples – both observed and simulated!



Energy of uplifted gas ranges from a few percent to a significant fraction of the outburst energy

Abell 4059 – Reynolds+2008



Hydra A – Gitti+2011



Summary and Conclusions



- X-ray rims around radio bubbles in NGC 4472 and NGC 1399 are cool – consistent with uplift and not shocks (Gendron-Marsolais+2017, submitted, Su+2017a,b, submitted)
- The uplift energy is a significant fraction of the outburst energy – *can this be usefully tapped to heat the core?* Could also efficiently transport metals to halo
- Higher resolution VLA observations of NGC 4472 lobes (PI: Gendron Marsolais)
- Next generation low frequency radio observatories (LOFAR, SKA) and future X-ray missions (Athena) likely to transform our view of radio bubble dynamics, turbulence, and buoyancy