The cluster-central type-II QSO in IRAS 09104+4109: Examining the extremes of cooling and feedback

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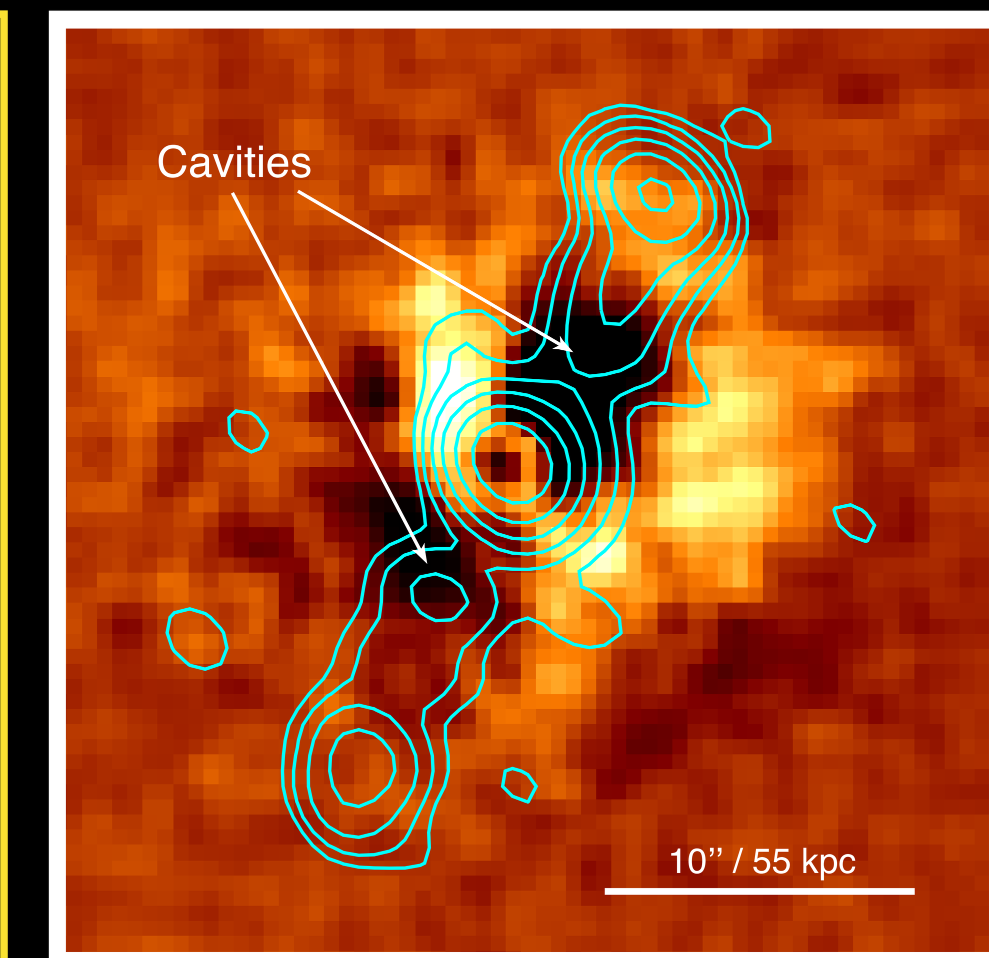
Based on a new 0.55 Ms cycle 23 ACIS-S observation

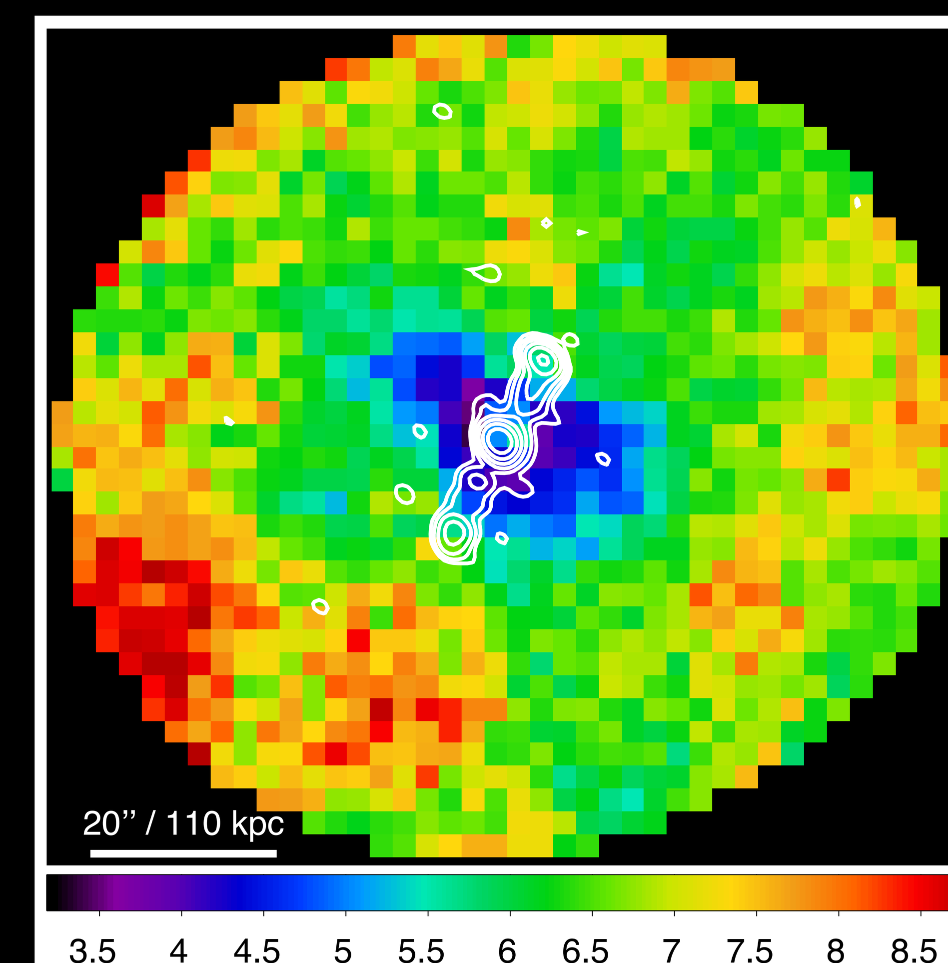
[plus O'Sullivan et al. 2021, MNRAS, 508, 3796 and O'Sullivan et al. 2012, MNRAS, 424, 2971]

Introduction

In the nearby Universe the thermal equilibrium of galaxy groups and clusters is maintained by heating from the jets of their central radio galaxies. At higher redshifts these AGN are expected to be quasars, emitting most of their energy as radiation, with limited impact on the hot intra-cluster medium (ICM). To understand why jet-mode feedback now dominates, we need to understand the conditions which trigger quasar mode. IRAS 09104+4109 (z=0.44) is one of only a handful of low-redshift examples of obscured (type II) quasars in cool-core clusters. The star-formation and jet activity history of its Hyper Luminous Infrared Galaxy (HyLIRG) BCG suggest that the AGN recently (120-160 Myr) realigned its axis and shifted into quasar mode. Cooling from the ICM is evident; the dominant elliptical is surrounded by ionized gas filaments and has one of the most extended molecular gas distributions known in any cluster, with ~4.5x10^{10} M$_\odot$ of cold gas along the length of the old, fading radio jets. We are currently working with a new, deep (~550 ks) Chandra ACIS-S observation of this unique system, focussing on the conditions around the AGN to answer two critical questions:

- Why does this cluster host a central QSO?
- What triggered its transition from jet to quasar mode?



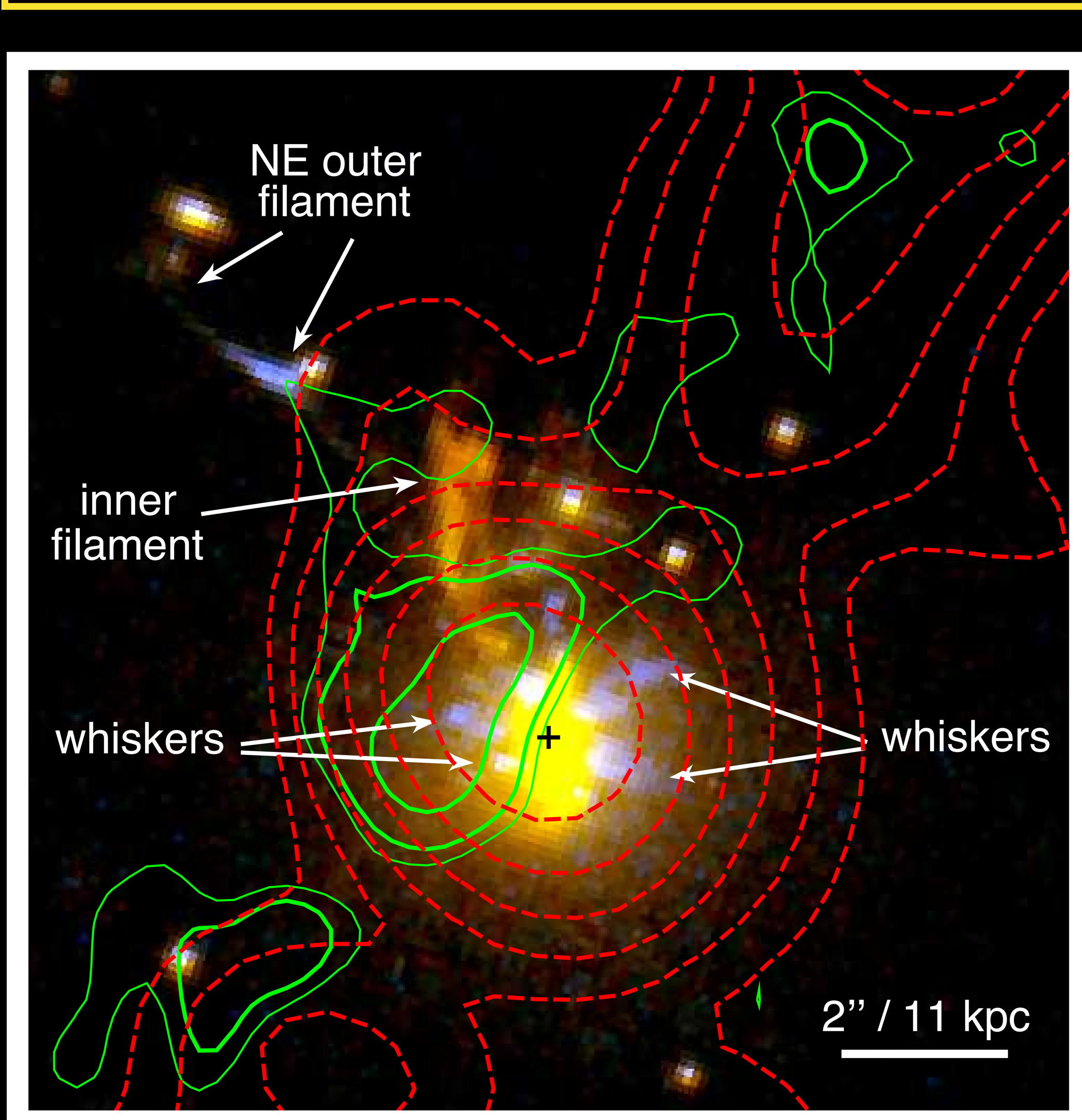


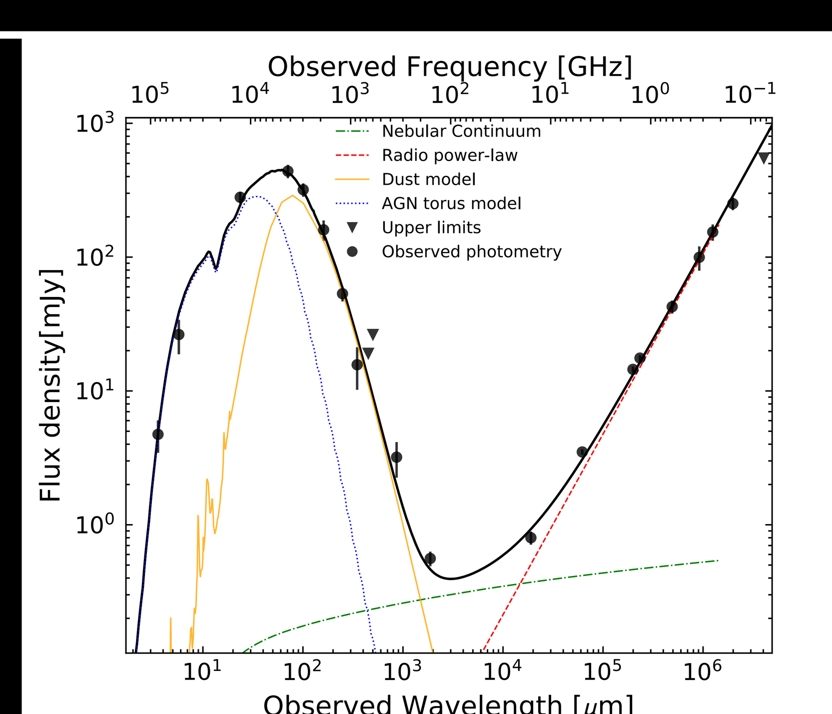
Left: *Chandra* ACIS-S+I 0.5-2 keV residual map, after subtraction of the best fitting cluster + central point source model, overlaid with GMRT 1.28 GHz contours.

Right: *Chandra* ACIS-I temperature map (in keV) showing the asymmetry of the cooling region. The map is based on 1000 net count spectra from 2-30" radius extraction regions. Uncertainties are 7-17%, increasing with radius. GMRT 1.28 GHz contours are overlaid.

The hot intracluster medium: Chandra X-ray observations

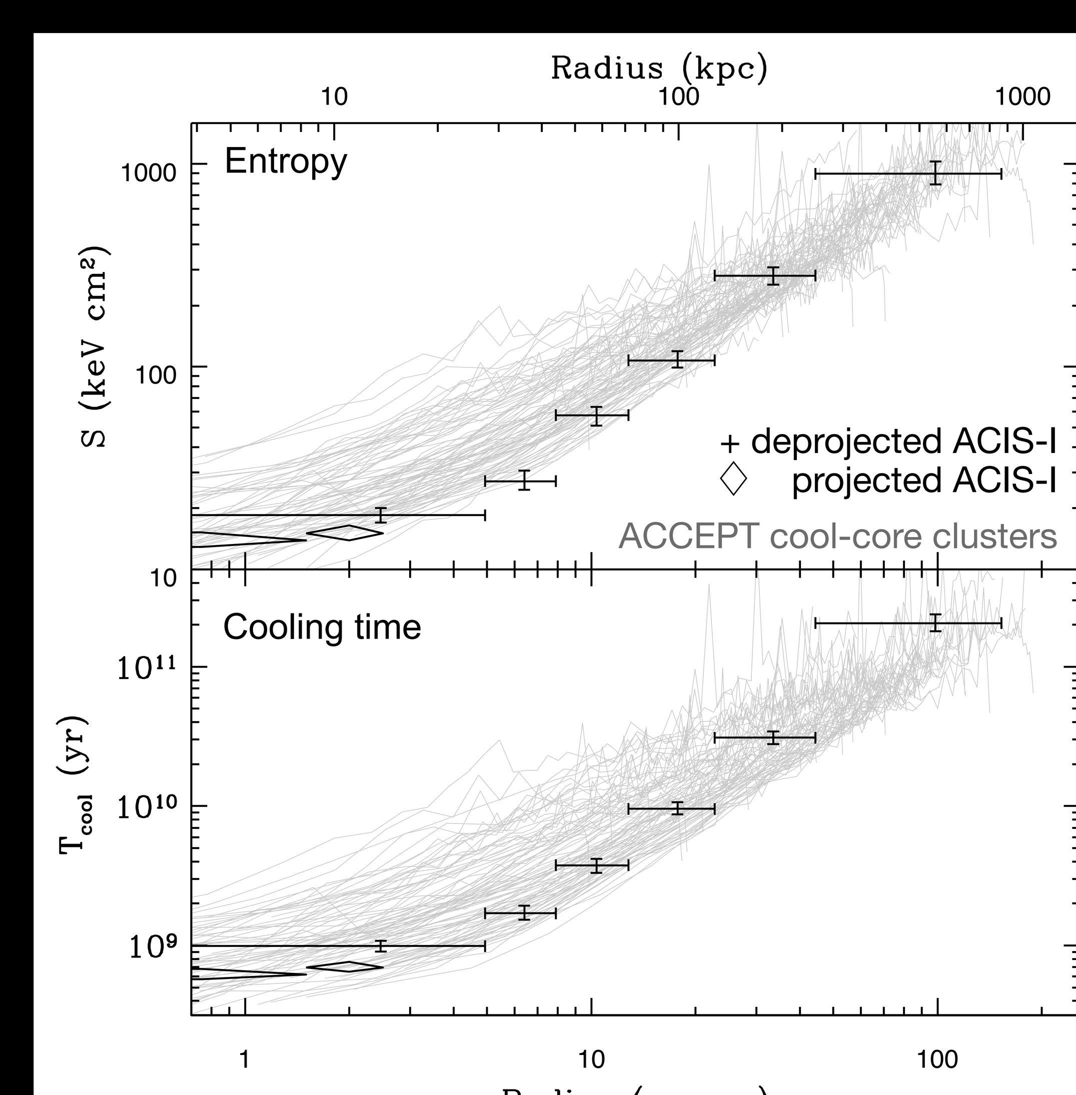
- Observed by *Chandra* in cycles 1 [10 ks ACIS-S], 10 [75 ks ACIS-I] and 23 [~550 ks ACIS-S after cleaning].
- Surface brightness modelling reveals the large-scale spiral residual ⇛ sloshing from a recent minor cluster merger.
- Steep spectrum radio jets are old, inactive for the last 120-160 Myr ⇛ timescale of switch from radio to quasar mode.
- Cavities along the line of the old radio jets (see above left), enthalpy ~7.7x10^{60} erg comparable to cooling losses.
- Asymmetric cool core (see kT map, above right), coolest gas orthogonal to radio jets ⇛ evidence against uplift?
- Cavities partially enclosed by compressed gas rims, brightest region correlated with inner optical filament (below left).
- ACIS-I data shows low central entropy (~3 keV cm^2) and short central cooling time (~620 Myr), see profiles below..
- ICM is thermally unstable ($t_{cool}/t_{free\text{-}fall}$<25 and t_{cool}/t_{eddy}~1) out to 70 kpc ⇛ matches extent of ionized & molecular gas.





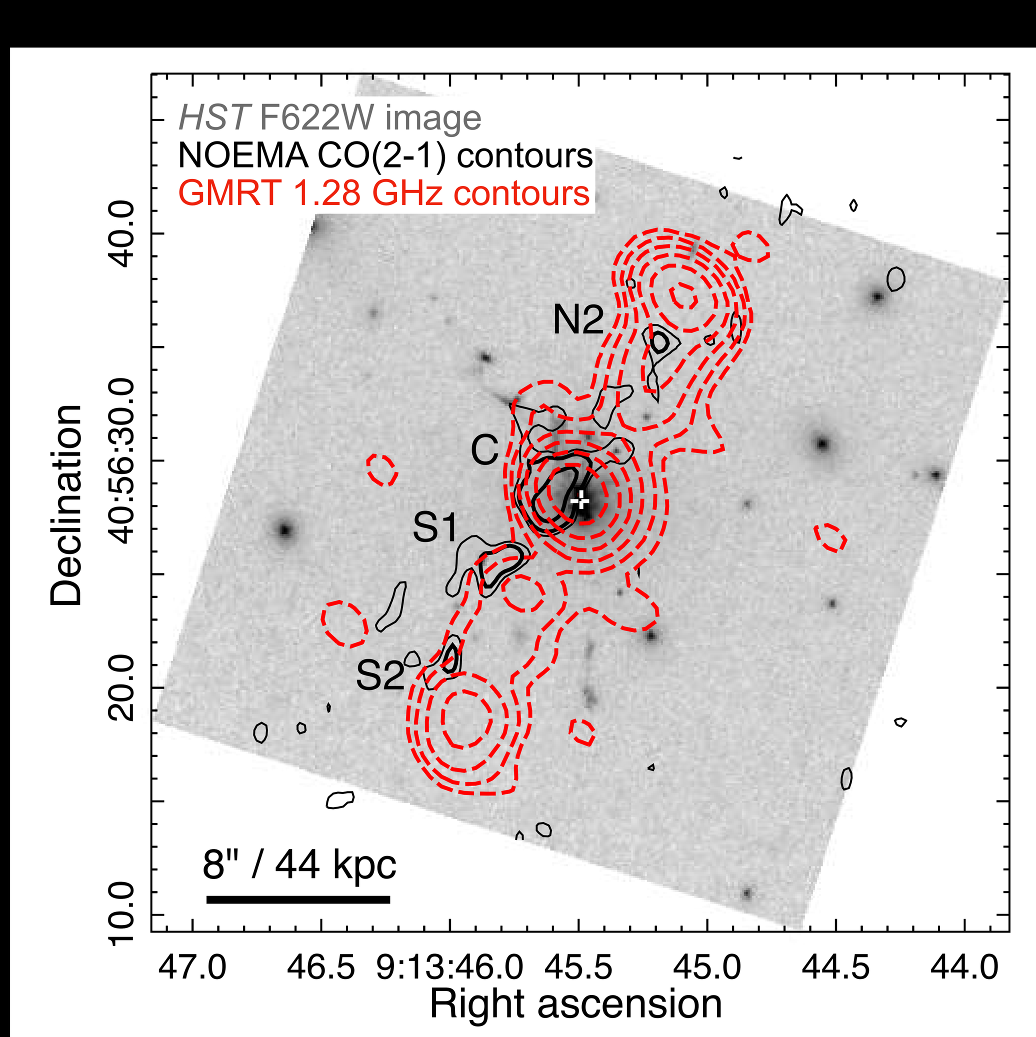
Left: *HST* PC2 814W & 622W false colour image of the BCG showing warm ionized gas filaments and whiskers. Contours show GMRT 1.28 GHz continuum (red) and NOEMA CO(2-1) emission.

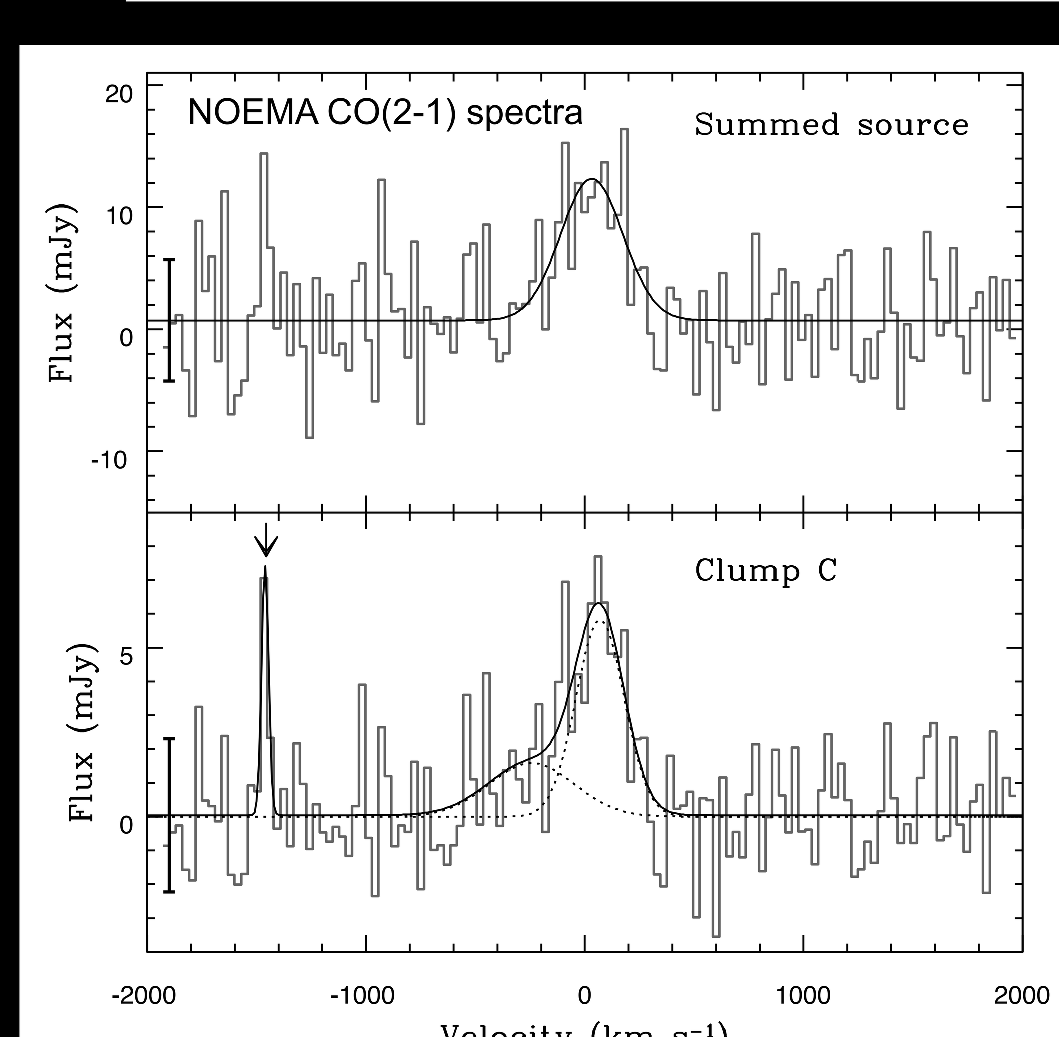
Right: IR/radio SED based on GMRT, VLA, NOEMA, SCUBA2, *Herschel* and *Spitzer* data



Optical and IR observations

- *HST* (left) traces warm ionized gas filaments around the BCG.
- Red colour of Inner filament indicates strong [OIII] 5007Å emission (also [OII], Calzadilla et al. 2022).
- BCG underwent first burst of star formation 70-200 Myr ago (Bildfell et al. 2008, Pipino et al. 2009, overlaps jet shutdown).
- SED fit (above) ⇛ New burst began 25±13 Myr ago.
- Current SFR ~110 M$_\odot$ yr^{-1} (Farrah et al 2016).
- From SED, AGN radiative luminosity ~4.60x10^{46} erg s-1.

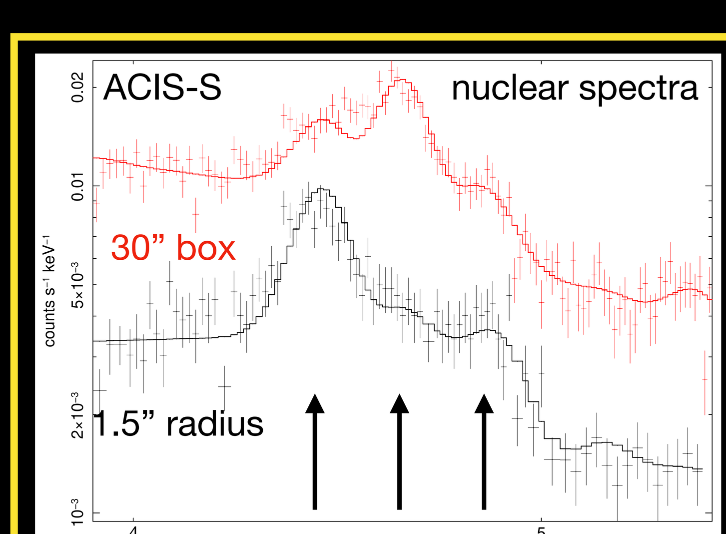


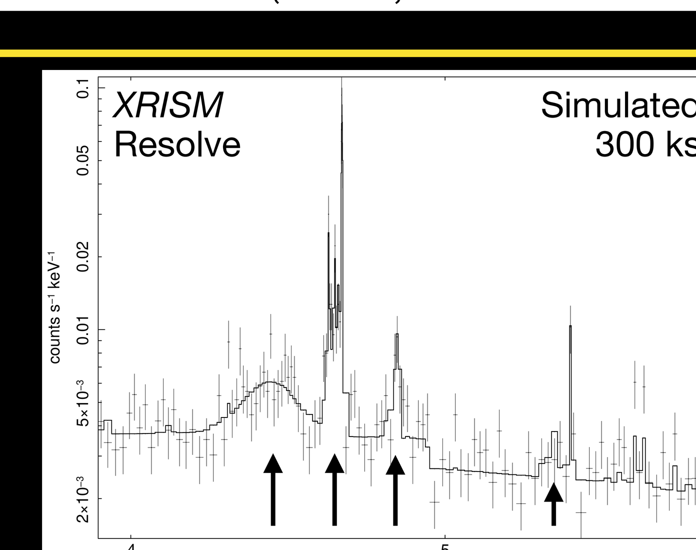


The cold component: NOEMA CO(2-1) observations

Cluster-central AGN are thought to be fueled largely by molecular gas cooled from the ICM. We therefore observed IRAS 09104+4109 with NOEMA in 2018-19 for a total of 4 hours, targeting the CO(2-1) line. This revealed:

- ~4.5x10^{10} M$_\odot$ of molecular gas in clumps along the radio jets (above left).
- CO found out to ~55 kpc radius ⇛ one of the most extended CO distributions seen in any BCG.
- Central clump (C) contains >50% of the molecular gas, and overlaps the base of the inner optical filament and "whiskers" ⇛ strongest cooling northeast of BCG core?
- No velocity gradient in the molecular gas along the jets ⇛ no uplift, or aligned in plane of sky?
- Negative velocity tail in clump C (see spectrum above right) ⇛ gas falling into the BCG, feeding quasar?





Our Current work

focusses on the spectral analysis of the new, deep ACIS-S observations, with goals of:

1) Measuring ICM thermodynamic properties in the central 5.5 kpc (1") to investigate conditions in the immediate environment of the quasar.

2) Mapping the larger-scale temperature and abundance distribution to search for evidence of uplift by the radio jets or Compton cooling of gas in the radiation cones of the quasar.

3) Determining gas properties at the position of the optical filaments and molecular gas clumps, to see if these are special locations for cooling.

Future plans

Several previous studies have attempted to use the X-ray data to constrain the physical properties and orientation of the AGN, based on the 6.4 keV FeKα line. This is complicated by the ICM emission, which contributes Fe XXV (6.7 keV) and Fe XXVI (6.9 keV) lines. At CCD resolutions, these overlap and must be jointly constrained (see ACIS-S spectra above left). Calorimeter data has the sensitivity and resolution to separate the lines, providing stronger physical constraints. A simulated 300 ks *XRISM* Resolve exposure is shown above right, with a broadened FeKα line clearly separated from the ICM Fe and Ni lines (arrows indicate redshifted line energies).