Chandra and *XMM-Newton* observations of the merging cluster of galaxies PLCK G036.7+14.9

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Biao Zhang

(University of Science & Technology of China)

L. David, C. Jones, F. Santos, E. O'Sullivan, P. Nulsen, J. Vrtilek, R. van Weeren, R. Kraft (CfA), H. Dahle (U. Oslo), T. Clarke (Naval Research Lab), E. Pointecouteau (U. de Toulouse/CNRS), G. Pratt, M. Arnaud (CNRS), L. Ji (Purple Mountain Obs.), X. Kong (USTC)

Clusters of galaxies: overview

- Largest gravitationally bound systems

  typical mass: ~ 10^{13}-10^{15} $M_{\odot}$ (e.g., Hoekstra et al. 2013)
- Massive clusters still forming present day

  mergers and accretions (e.g., Kravtsov & Borgani 2012)
- Sensitive cosmological probes

  abundance, baryon fraction, high multipole CMB power spectrum, etc.

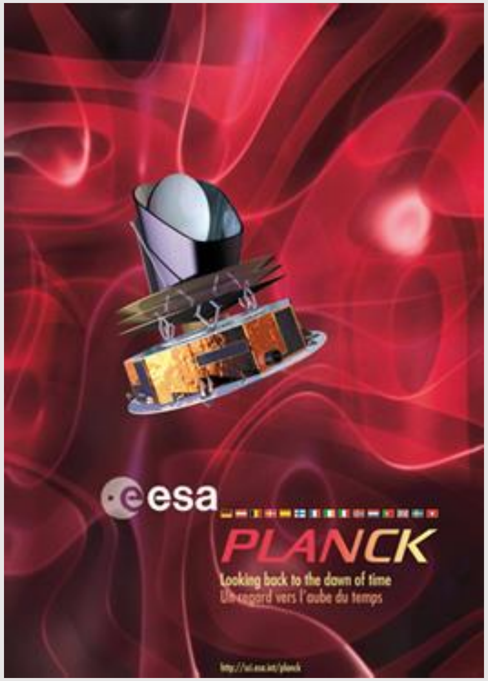
  (e.g., Allen et al. 2011)
- Strong X-ray sources: thermal bremsstrahlung

  L_X ~ 10^{42}-10^{45} ergs s^{-1} (e.g., Sarazin 1988)
- Sunyaev-Zeldovich (SZ) sources: inverse Compton scattering of CMB

  decrement < 218 GHz, increment > 218 GHz (e.g., Birkinshaw 1999)

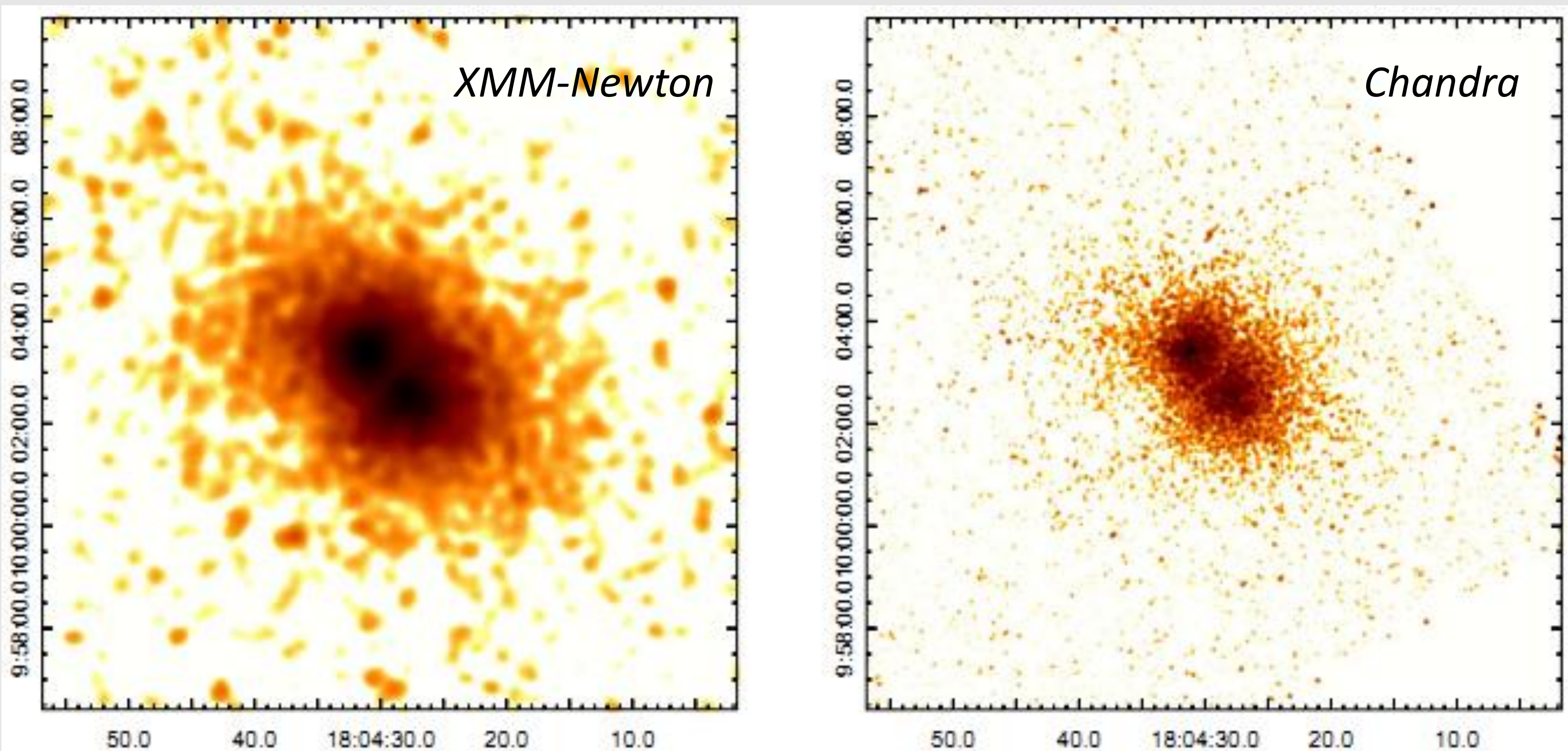
Data

- *Planck*
  first all sky SZ survey
  angular resolution > 5 arcmin
  very efficient at detecting massive clusters
  ESZ catalogue (2011): 189 cluster & candidates
  2014 catalogue: 1227 cluster & candidates
- *Chandra*
  Chandra-Planck Legacy Program: all z<0.35
  clusters (165), > 10000 photons, mass function
- *XMM-Newton*
  most also have *XMM-Newton* observations



Credit: ESA

PLCK G036.7+14.9: X-ray



Two close subclusters: G036N and G036S

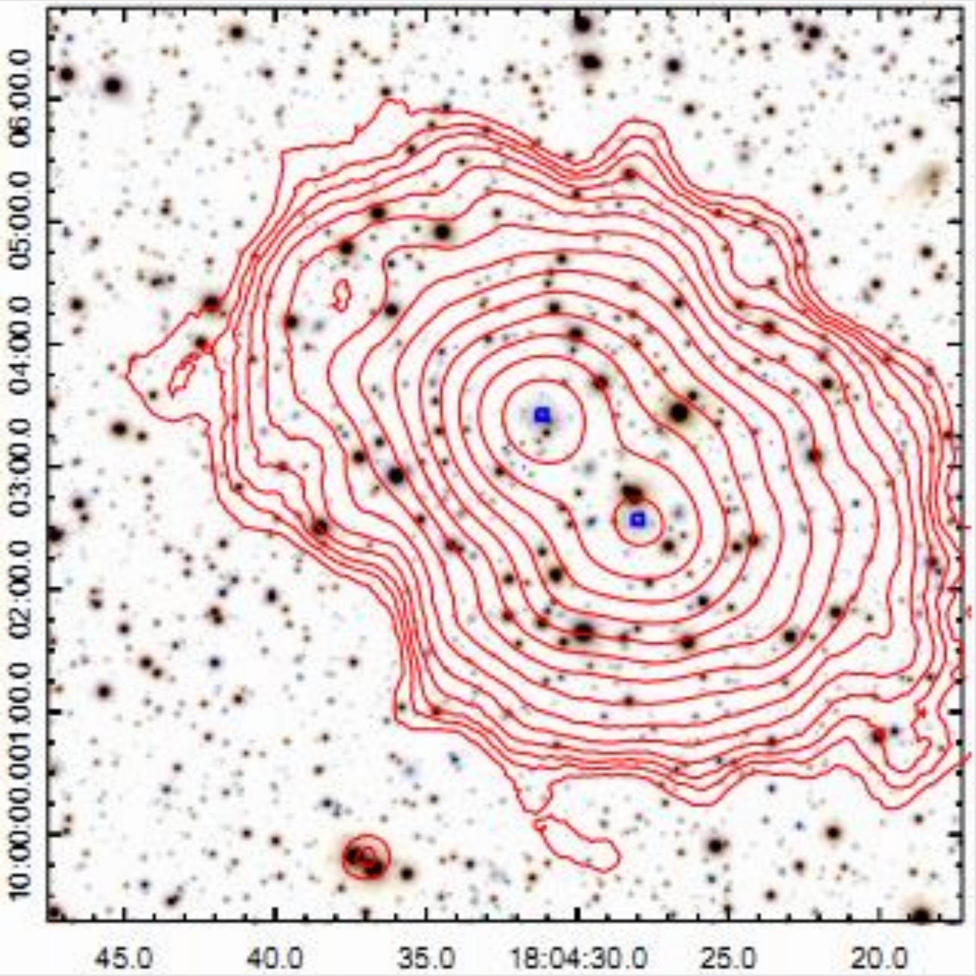
Not resolved by previous ROSAT, optical, or recent *Planck* observations

Ebeling et al. 2002

PLCK G036.7+14.9: optical

- X-ray contours rather regular
- BCGs close to the X-ray centroids
- Early stage of merging

NOT+*XMM-Newton*+BCGs



X-ray mass measurements

- Assumptions: (e.g., Sarazin 1988)

  spherical symmetry

  hydrostatic equilibrium

- Total mass:

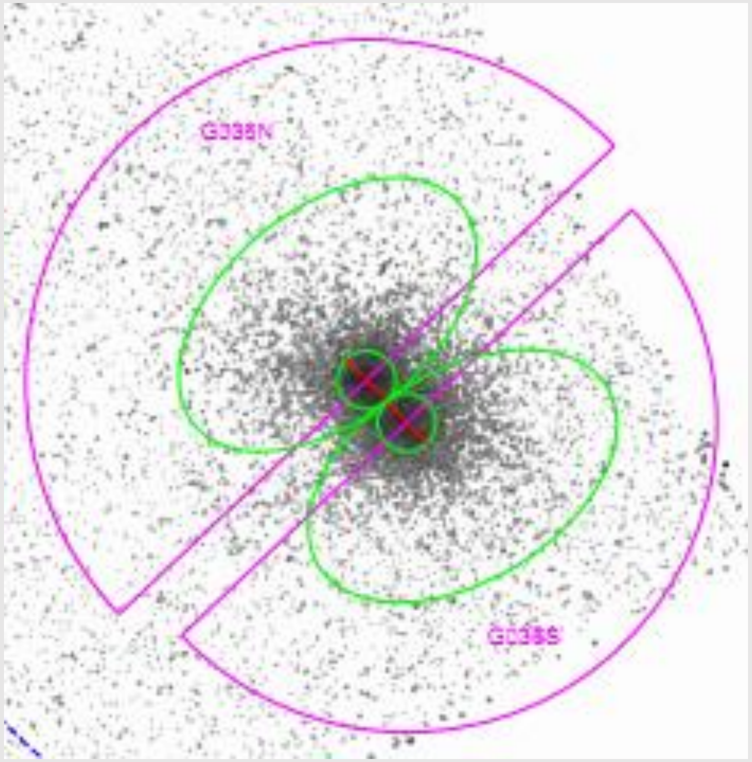
$$M(r) = -\frac{kTr}{G\mu m_p}\left(\frac{d\ \ln n_e}{d\ \ln r} + \frac{d\ \ln T}{d\ \ln r}\right),$$

- Surface brightness profile:

$$S(r) = S_0\left[1 + \left(\frac{r}{r_c}\right)^2\right]^{-3\beta+1/2},$$

- Temperature profile:

$$T_{3D}(r) = T_0 \frac{\left(\frac{r}{r_{cool}}\right)^{a_{cool}} + \frac{T_{min}}{T_0}}{1 + \left(\frac{r}{r_{cool}}\right)^{a_{cool}}} \frac{\left(\frac{r}{r_t}\right)^{-a}}{\left[1 + \left(\frac{r}{r_t}\right)^b\right]^{c/b}},$$



Vikhlinin et al. 2006

Systematic uncertainties

- Hydrogen column density
- Redshift
- Background subtraction
- Other calibration issues

Systematic uncertainties

Radius, Gas mass, Total mass, and Gas Mass Fraction

Region	Method	Parameter[a]	$\Delta = 2500$	$\Delta = 500$	$\Delta = 200$
G036N		r_Δ	$0.52 \pm 0.01(0.55 \pm 0.02)$	$0.99 \pm 0.03(1.03 \pm 0.03)$	$1.38 \pm 0.04(1.43 \pm 0.04)$
		$M_{g,\Delta}$	$1.42 \pm 0.28(1.51 \pm 0.32)$	$3.00 \pm 0.62(3.12 \pm 0.70)$	$4.33 \pm 0.91(4.49 \pm 1.02)$
	XMM-Newton	M_Δ	$2.25 \pm 0.18(2.69 \pm 0.29)$	$3.20 \pm 0.28(3.60 \pm 0.29)$	$3.46 \pm 0.32(3.85 \pm 0.32)$
		f_Δ	$6.32 \pm 1.41(5.63 \pm 1.38)$	$9.42 \pm 2.21(8.69 \pm 2.16)$	$12.57 \pm 3.02(11.71 \pm 2.97)$
		r_Δ	$0.55 \pm 0.03(0.53 \pm 0.03)$	$1.10 \pm 0.06(1.07 \pm 0.05)$	$1.56 \pm 0.08(1.51 \pm 0.07)$
	Chandra	$M_{g,\Delta}$	$1.51 \pm 0.32(1.48 \pm 0.31)$	$3.22 \pm 0.69(3.19 \pm 0.68)$	$4.65 \pm 0.99(4.60 \pm 0.99)$
	baseline[b]	M_Δ	$2.77 \pm 0.46(2.52 \pm 0.38)$	$4.44 \pm 0.67(4.08 \pm 0.59)$	$5.02 \pm 0.73(4.61 \pm 0.65)$
		f_Δ	$5.49 \pm 1.29(5.92 \pm 1.36)$	$7.29 \pm 1.78(7.83 \pm 1.89)$	$9.31 \pm 2.32(10.02 \pm 2.49)$
		r_Δ	$0.54 \pm 0.04(0.54 \pm 0.03)$	$1.20 \pm 0.10(1.15 \pm 0.06)$	$1.85 \pm 0.23(1.66 \pm 0.10)$
	Chandra	$M_{g,\Delta}$	$1.45 \pm 0.33(1.52 \pm 0.35)$	$3.47 \pm 0.77(3.46 \pm 0.80)$	$5.51 \pm 1.33(5.09 \pm 1.21)$
	with soft[c]	M_Δ	$2.59 \pm 0.65(2.63 \pm 0.41)$	$5.75 \pm 1.47(5.04 \pm 0.73)$	$8.80 \pm 3.55(6.07 \pm 1.11)$
		f_Δ	$5.71 \pm 1.53(5.81 \pm 1.40)$	$6.21 \pm 1.76(6.91 \pm 1.75)$	$6.70 \pm 2.38(8.49 \pm 2.35)$
		r_Δ	$0.54 \pm 0.03(0.52 \pm 0.03)$	$1.06 \pm 0.06(1.03 \pm 0.05)$	$1.50 \pm 0.08(1.45 \pm 0.07)$
	Chandra	$M_{g,\Delta}$	$1.46 \pm 0.31(1.42 \pm 0.30)$	$3.09 \pm 0.66(3.03 \pm 0.65)$	$4.46 \pm 0.94(4.37 \pm 0.93)$
	back*0.95[d]	M_Δ	$2.55 \pm 0.41(2.30 \pm 0.34)$	$3.96 \pm 0.64(3.57 \pm 0.53)$	$4.43 \pm 0.69(4.01 \pm 0.58)$
		f_Δ	$5.77 \pm 1.37(6.22 \pm 1.43)$	$7.89 \pm 1.99(8.50 \pm 2.09)$	$10.12 \pm 2.61(10.94 \pm 2.75)$
		r_Δ	$0.52 \pm 0.02(0.54 \pm 0.03)$	$1.10 \pm 0.05(1.08 \pm 0.07)$	$1.63 \pm 0.09(1.55 \pm 0.09)$
	Chandra	$M_{g,\Delta}$	$1.43 \pm 0.31(1.49 \pm 0.35)$	$3.21 \pm 0.74(3.22 \pm 0.77)$	$4.88 \pm 1.16(4.70 \pm 1.12)$
	back*1.05[e]	M_Δ	$2.36 \pm 0.27(2.56 \pm 0.44)$	$4.37 \pm 0.55(4.20 \pm 0.75)$	$5.74 \pm 0.98(4.92 \pm 0.81)$
		f_Δ	$6.06 \pm 1.41(5.87 \pm 1.47)$	$7.40 \pm 1.81(7.69 \pm 2.08)$	$8.60 \pm 2.28(9.59 \pm 2.62)$
G036S[f]		r_Δ	$0.52 \pm 0.02(0.56 \pm 0.02)$	$0.98 \pm 0.03(1.06 \pm 0.04)$	$1.37 \pm 0.05(1.48 \pm 0.06)$
		$M_{g,\Delta}$	$1.68 \pm 0.33(1.79 \pm 0.31)$	$3.36 \pm 0.67(3.56 \pm 0.63)$	$4.74 \pm 0.94(5.02 \pm 0.90)$
	XMM-Newton	M_Δ	$2.36 \pm 0.23(2.95 \pm 0.32)$	$3.13 \pm 0.31(3.90 \pm 0.41)$	$3.38 \pm 0.34(4.24 \pm 0.47)$
		f_Δ	$7.10 \pm 1.42(6.07 \pm 1.13)$	$10.72 \pm 2.27(9.12 \pm 1.77)$	$14.03 \pm 3.04(11.85 \pm 2.39)$

X-ray mass vs. SZ mass

- X-ray:

XMM-Newton: $M_{X,500} = (5.91 - 8.00) \times 10^{14}\ M_\odot$

Chandra: $M_{X,500} = (6.66 - 9.85) \times 10^{14}\ M_\odot$

- SZ: $M_{SZ,500} = (5.11 - 5.96) \times 10^{14}\ M_\odot.$

Planck Collaboration XXIX, 2014

- Interpretation:

$Y_{SZ} = AM^\eta,$ $(M_n^\eta + M_s^\eta)^{1/\eta}.$ $M_n \approx M_s;\ \eta = 1.79$

1). Early stage of the merger

2). *Planck* does not resolve the two subclusters and interprets the whole cluster as a single cluster

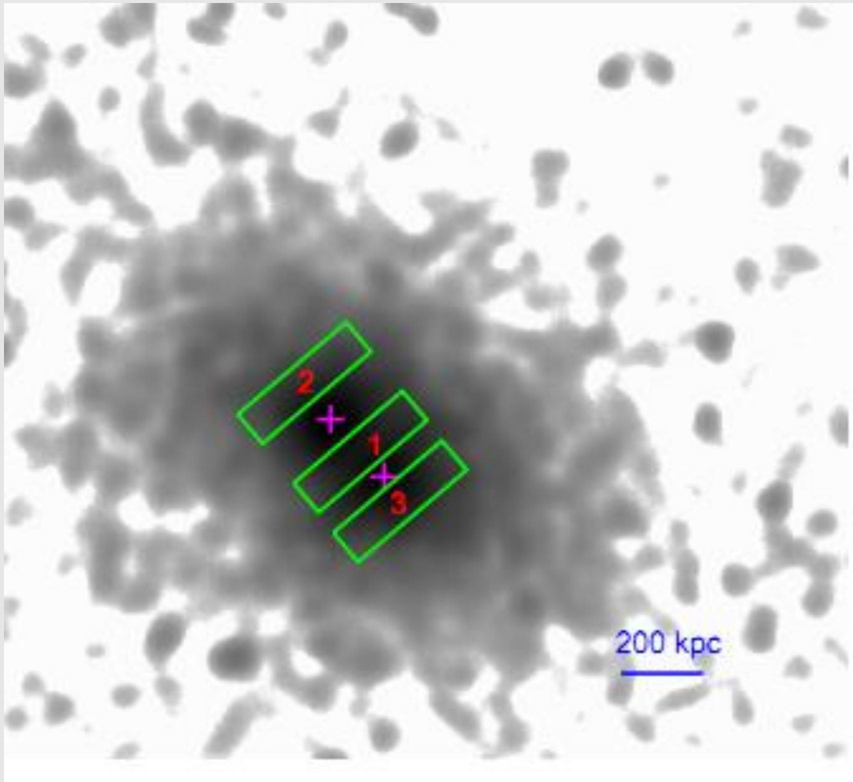
Dynamical state

- Shocked gas in the middle

$$\frac{1}{C} = \frac{2}{\mathscr{M}^2(\gamma+1)} + \frac{\gamma-1}{\gamma+1},$$

$$\frac{1}{C} = [\frac{1}{4}(\frac{\gamma+1}{\gamma-1})^2(\frac{T_2}{T_1}-1)^2 + \frac{T_2}{T_1}]^{1/2} - \frac{1}{2}\frac{\gamma+1}{\gamma-1}(\frac{T_2}{T_1}-1),$$

(e.g., Sarazin 2002)



- Dynamical model

$$d_0 \approx [2G(M_n+M_s)]^{1/3}(\frac{t_{\rm coal}}{\pi})^{2/3},$$

$$v^2 \approx 2G(M_n+M_s)(\frac{1}{d}-\frac{1}{d_0})[1-(\frac{b}{d_0})^2]^{-1},$$

$$d = \frac{d_p}{\cos\theta},$$

$$v = \frac{v_r}{\sin\theta},$$

$$t_{\rm coal} \approx t_{\rm age} + \frac{d}{v},$$

$$t_{\rm merge} \approx \frac{r_n + r_s - d}{v},$$

(see also Sarazin 2002; Sauvageot et al . 2005)

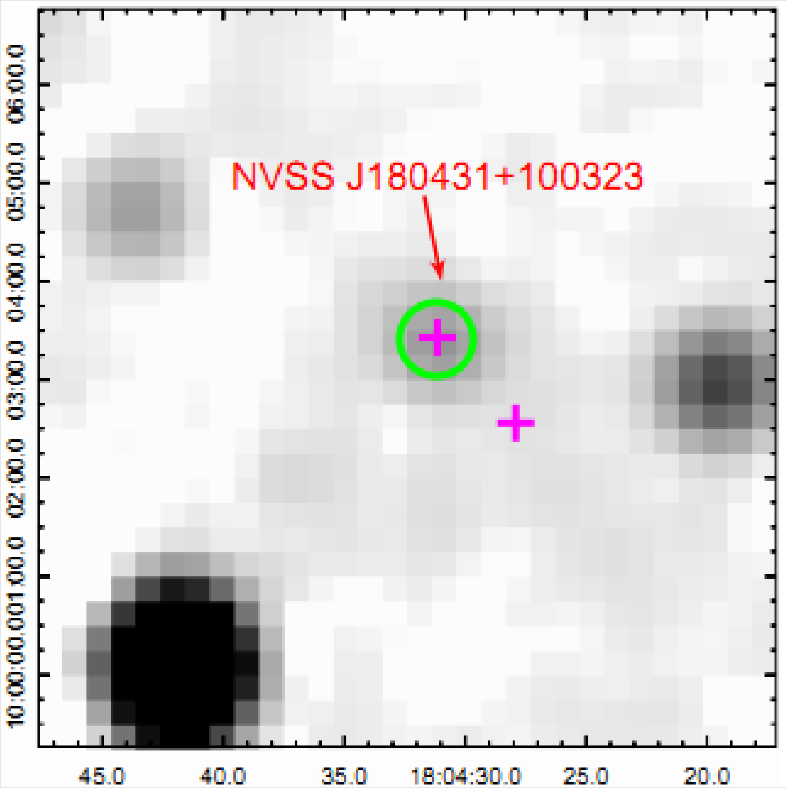
$$\theta \approx 80^\circ,\ t_{\rm merge} \approx \ 0.8\ \mathrm{Gyr}$$

Core properties

- Small (~27 kpc), moderate (t_{cool}=2.6-4.7 Gyr) cool-core in G036N
- Very weak cool-core at most (t_{cool}=5.7 -10.3 Gyr) in G036S (e.g., Hudson et al. 2010)
- Less likely caused by the ongoing merger
- Unresolved radio source in G036N, feedback in action?

  (e.g., McNamara & Nulsen 2007)
- High resolution radio data and deep X-ray data to tell

NVSS



Conclusion

- Detailed spatial and spectral analyses to study the mass, dynamical state and core properties.
- The cluster is undergoing a major merger by G036N and G036S.
- The merger is probably at an early stage, and is largely along the line-of-sight.
- The X-ray mass is higher than the SZ mass, due to that *Planck* does not resolve the two subclusters and interprets the whole cluster as a single cluster.
- G036N hosts a moderate cool-core, while G036S hosts a very weak cool-core at most, which is less likely caused by the ongoing merger.

Thank you!