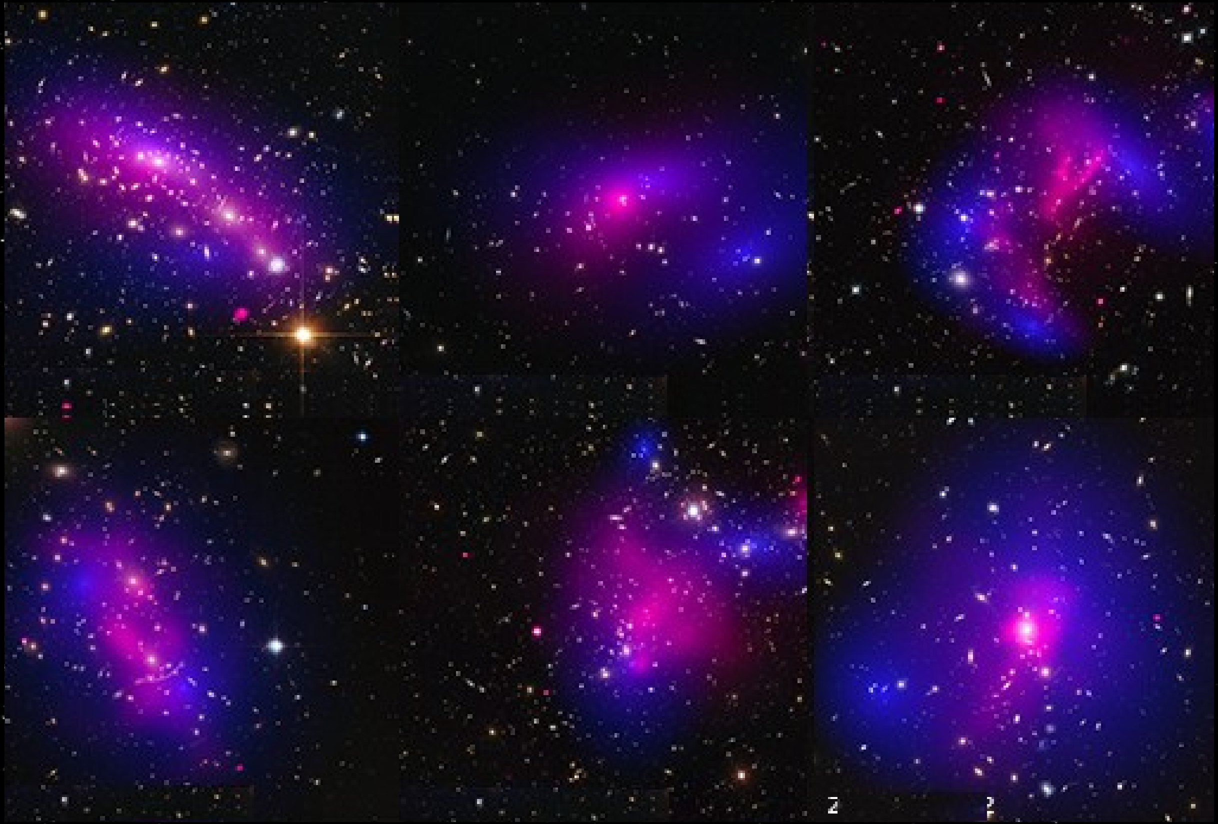
# When galaxy clusters collide



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*February 14, 2024*

# Outline

- **The anatomy of galaxy clusters**
- **The process of galaxy cluster merging**
- **The effects of cluster mergers on the intracluster medium (ICM)**

- **The Abell Supplementary 295 (AS295) and Abell Supplementary 592 (AS592) merging galaxy clusters**
- **Chandra X-ray observations of AS295 and AS592:**
- **Spatial distribution of surface brightness**
- **Thermal properties of the intracluster medium**

- **Comparison of the results with simulations of binary mergers**

# Galaxy clusters – largest objects in the Universe

**Galaxy clusters are collections of hundreds up to thousands of galaxies held together by gravity.**

**Galaxy clusters have:**

- **100-1000 galaxies**
- **1-2 $h^{-1}$ Mpc radius**
- **a total mass of $10^{14}$-$10^{15}$ $M_{\odot}$**
- **5% of its total mass in the form of galaxies**

*Abell 1689. NASA, ESA, J. Blakeslee (NRC), and K. Alamo-Martinez (National Autonomous University of Mexico)*

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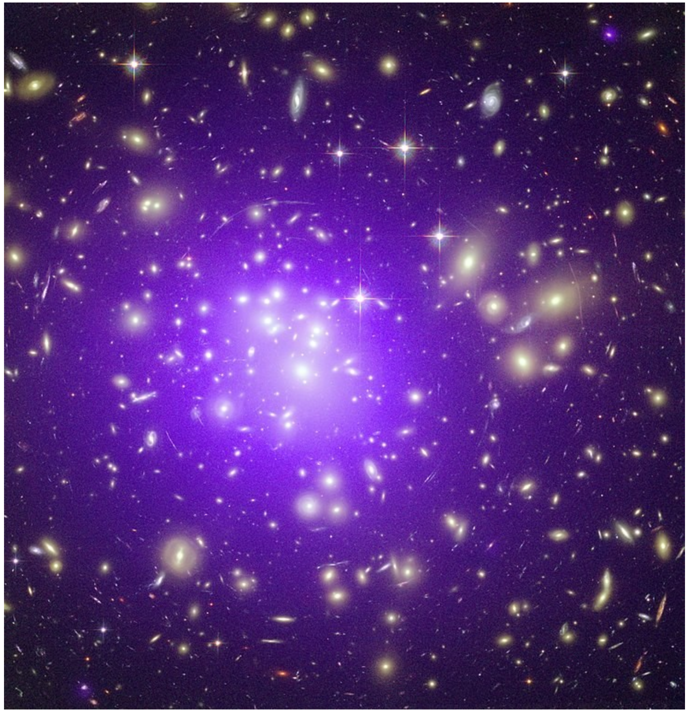
**Galaxy clusters have:**

- **an intracluster medium (ICM), which is a hot (2-14 keV), low density (~$10^{-2}$ electrons $cm^{-3}$) plasma**
- **15% of their total mass in the form of the ICM**



*Abell 1689 ; X-ray: NASA/CXC/MIT/E.-H Peng et al.; Optical: NASA/STScI*

# Galaxy clusters – largest objects in the Universe

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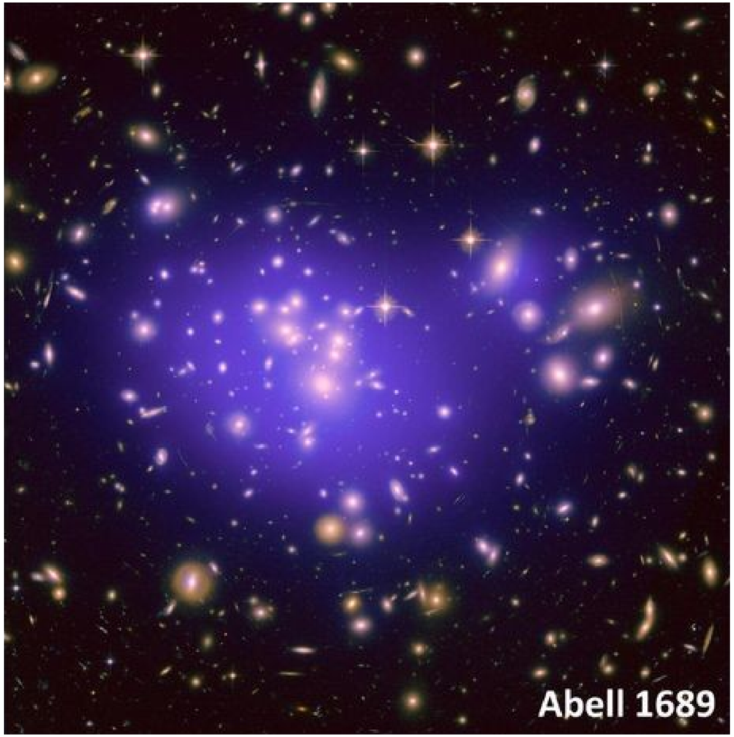
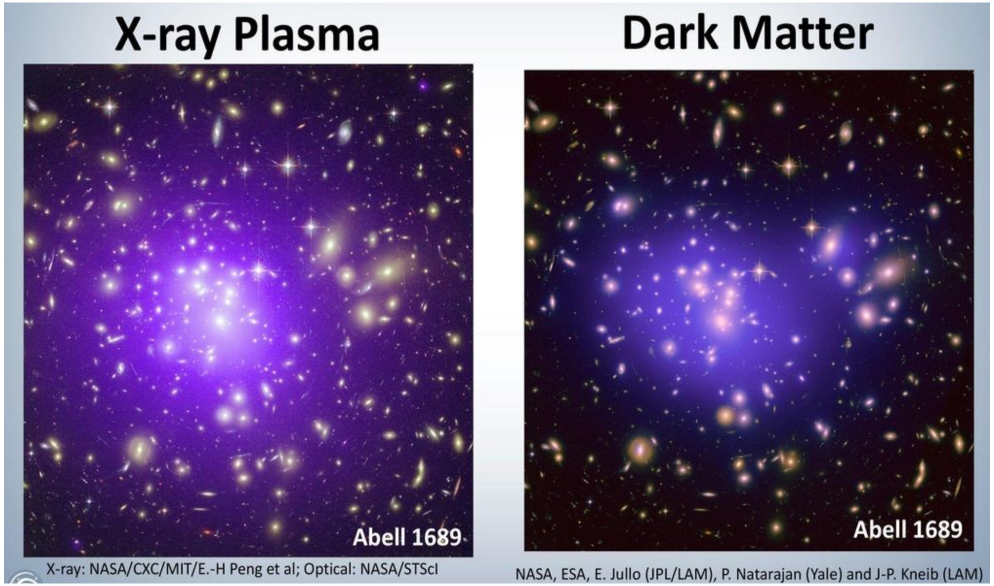
**Galaxy clusters have:**

- 80% of their mass in the form of dark matter



*Abell 1689; NASA,ESA,E. Jullo (JPL/LAM), P. Natarajan (Yale) and J-P. Kneib (LAM)*

# Relaxed galaxy clusters




**Relaxed clusters have:**

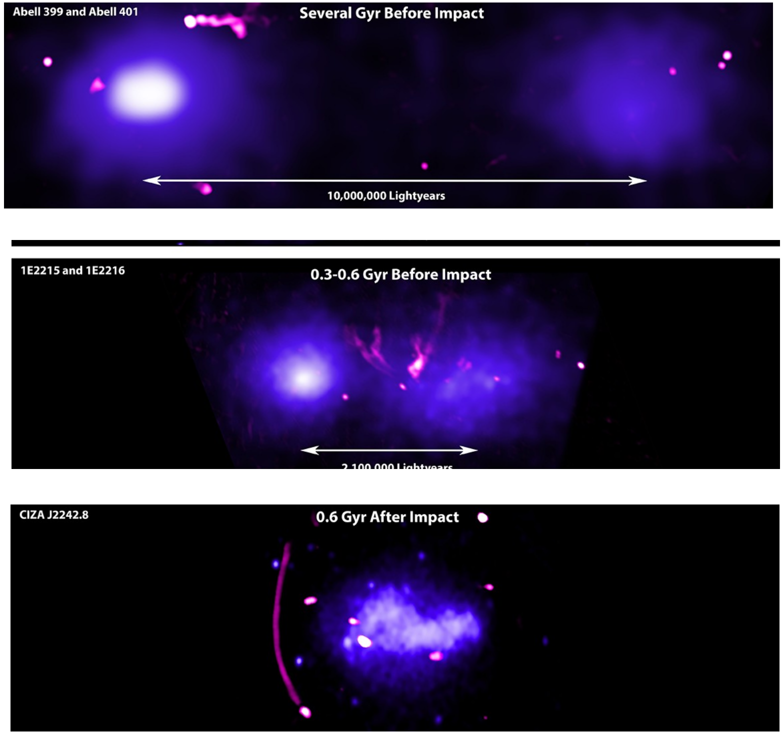
- **Smooth galaxy distribution**
- **Smooth and symmetric X-ray distribution of surface brightness**
- **Central dominant galaxy (at cluster's dynamical centre)**
- **Alignment between galaxies, gas and dark matter**

**~40-70 % clusters in the local universe are relaxed (Andrade-Santos(2017), McDonald (2013))**

# Relaxed and merging clusters – an X-ray view

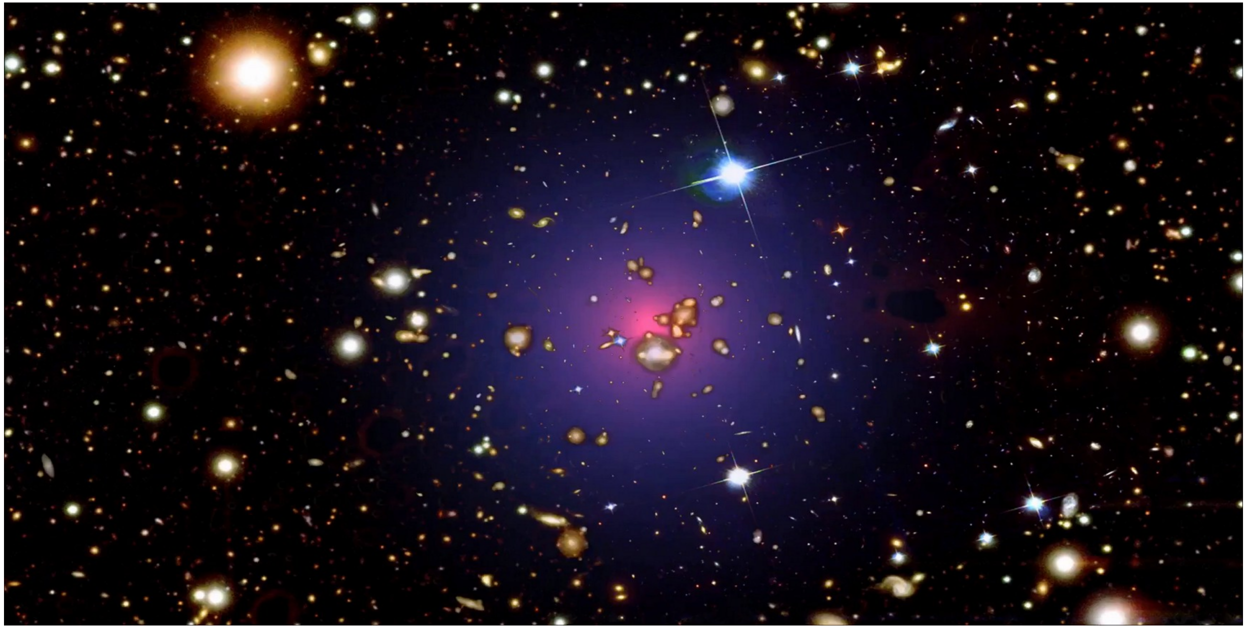
- ~40-70 % clusters in the local universe are relaxed

- However, clusters are not static objects; they move and collide with each other.
- A galaxy cluster may suffer more than one merging process during its lifetime
- The merging process lasts between Myrs to Gyrs depending on cluster velocities, masses, etc.
- Mergers have a profound effect on the properties of the resulting merged cluster
- Mergers is the main mechanism through which clusters grow



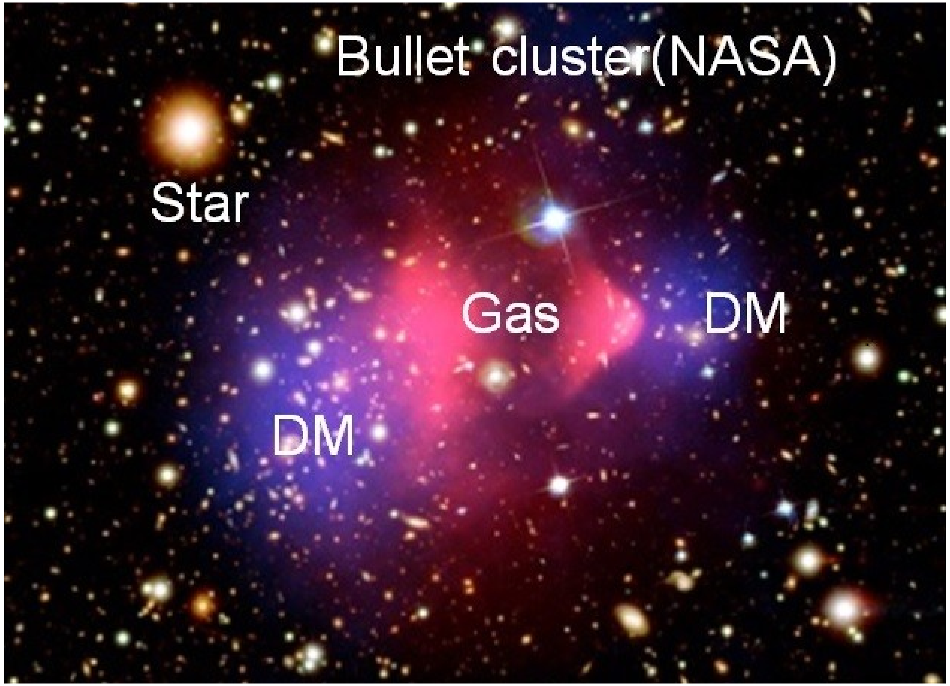

Credit: X-ray: NASA/CXC/RIKEN/L. Gu et al;

# Merging Galaxy Clusters



# Merging galaxy clusters – Why study them?

- Understand the merging process in itself
- Study cluster physics – mergers affect the properties of the different cluster components
- Understand cluster formation and evolution
- Study the properties of dark matter

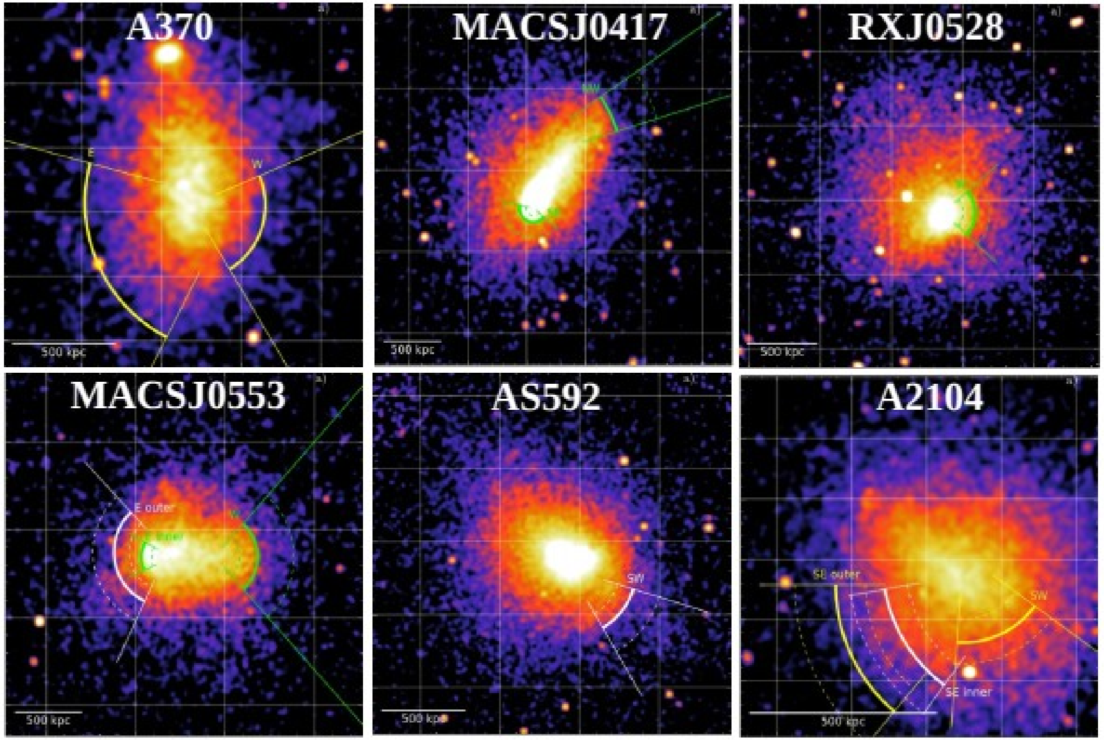


# Merging clusters – How to detect them?

**Typical signatures of merging clusters are:**

- **an irregular morphology**

- **contact edges between regions of gas with different entropies**

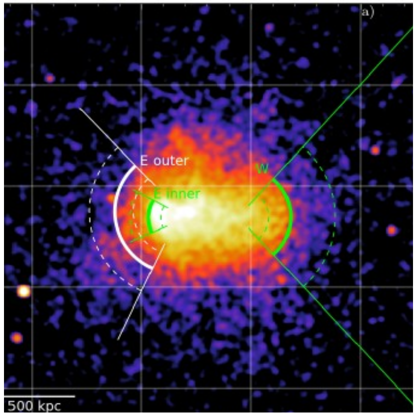


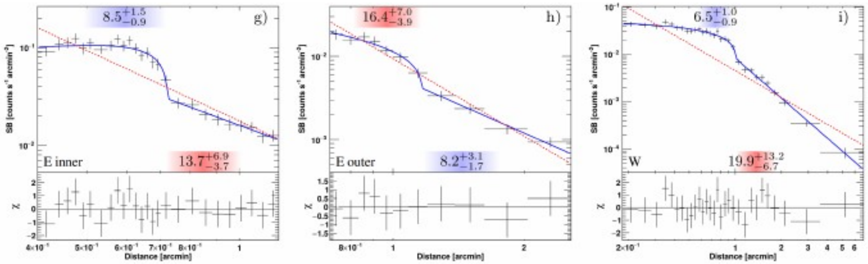

*Botteon, A., Gastaldello, F., & Brunetti, G. 2018, MNRAS, 476, 5591*

# Impact of mergers on the intracluster medium

## Contact edges between regions of gas with different entropies

- Cold fronts - high surface brightness region is cooler than lower one
- Shocks – high surface brightness region is hotter than lower one
- Across the brightness discontinuity, cold fronts have continuous pressure, while shocks have a pressure jump



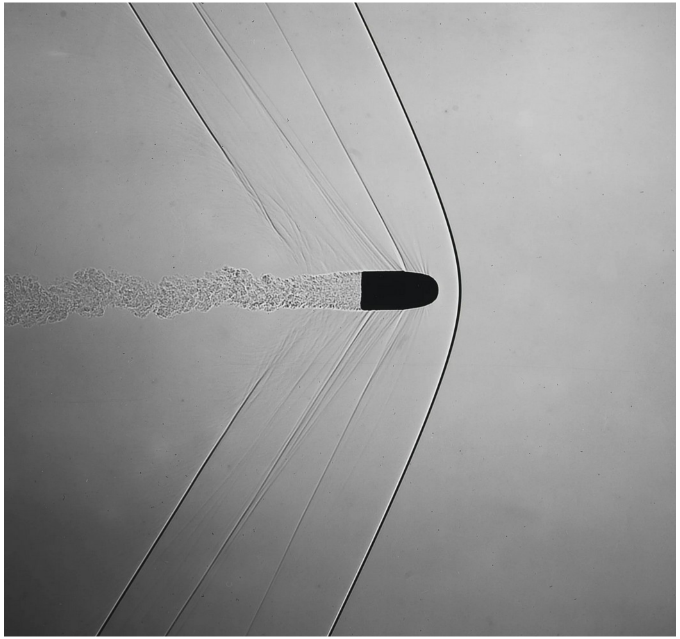




- **Merger shocks heat and compress the intracluster medium**
- **Mergers produce a temporary boost of gas temperature and X-ray luminosity**
- **Mergers mix the intracluster medium/Disrupt cool cores**

**Cluster mergers are sought-after objects used to study the cluster formation process, the nature of DM and its interaction with ICM.**

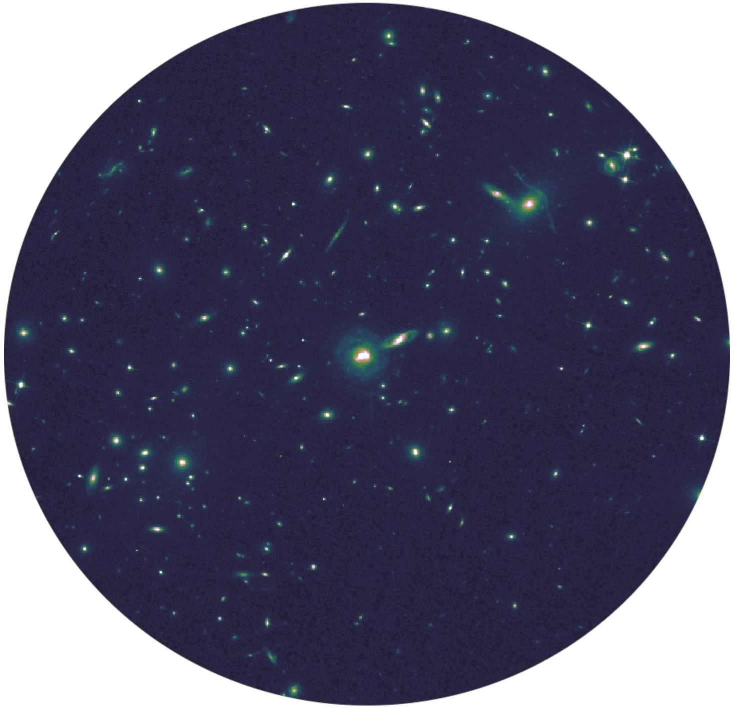
# Cold fronts and shocks

Credit: National Geographic (Tina Magas, MyShot)



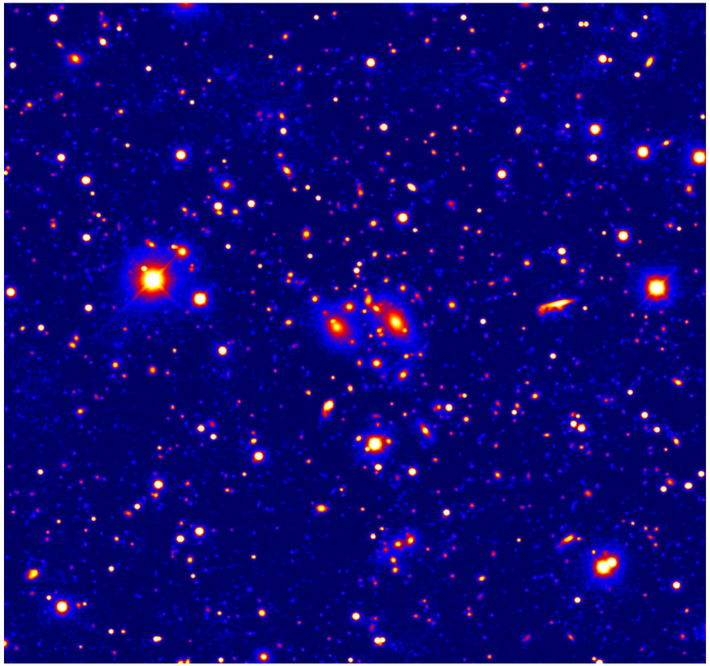
Harold E. Edgerton, Bullet Shock Wave, 1970

# The AS295 and AS592 cluster – the galaxies



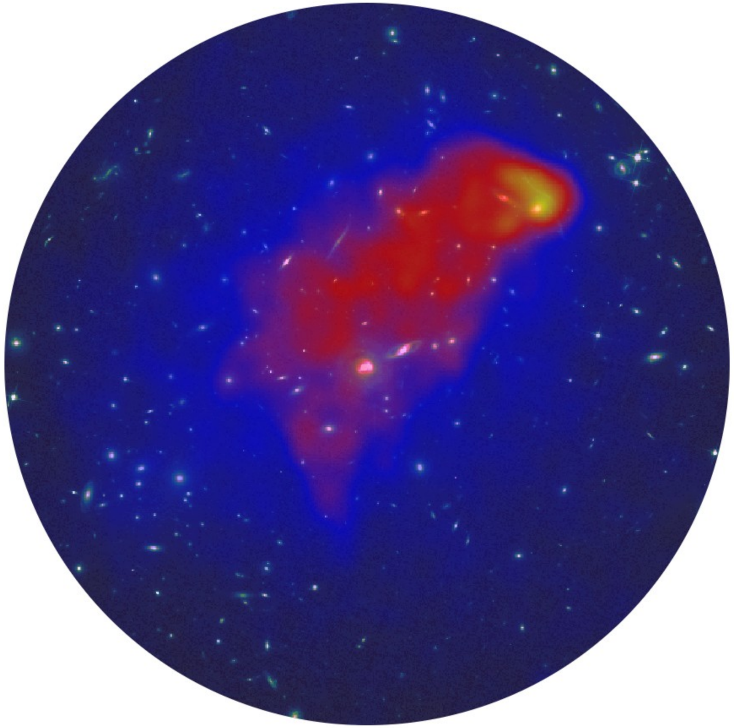
AS295. Hubble Space Telescope; P.I. F. Pacaud

- low redshift systems (z=0.3 AS295 and z=0.22 AS592)
- Massive clusters: 10.4±2.6 x $10^{14}$ $M_{\odot}$ (AS295) and 12.5±3.2 x $10^{14}$ (AS592) $M_{\odot}$ (dynamical mass) Hasselfield2013
- binary merging clusters
- discovered optically
- X-ray and radio follow-up observations



AS0592 – CTIO g-band optical image (Menanteau, F.)

# The AS295 and AS592 cluster – the intracluster medium

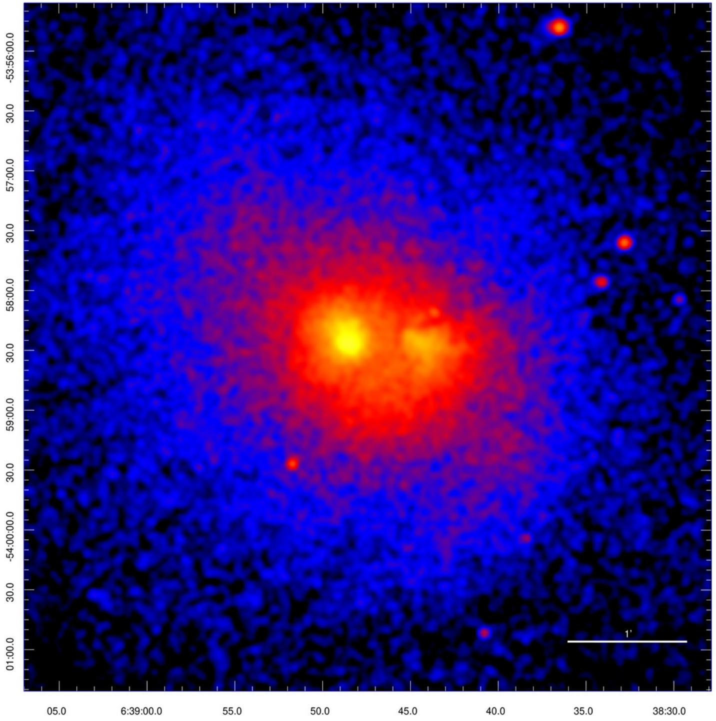


AS295. Hubble Space Telescope; P.I. F. Pacaud; Chandra (yellow-red-blue colormap )

- **irregular morphology of surface brightness**
- **possible merger axis:**

  AS295-SE-NW direction

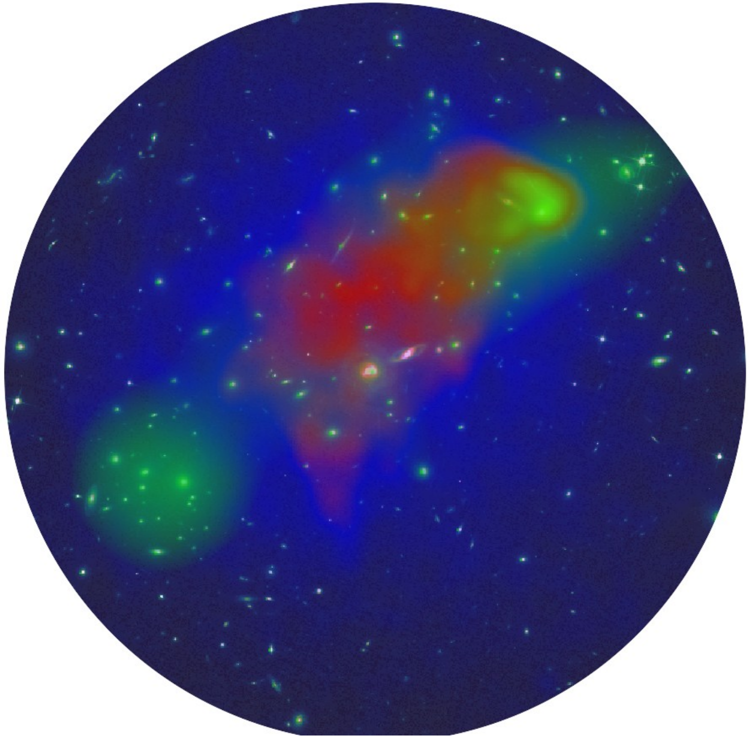
  AS592-SW-NE direction
- **Binary structure for both systems**
- **Bullet-like morphology for secondary in both clusters**




*Chandra image of AS0592 (PI: Kraft, R., Smith, G.). Gaussian smoothed, 0.5-2.0 keV, exposure corrected, background subtracted image.*

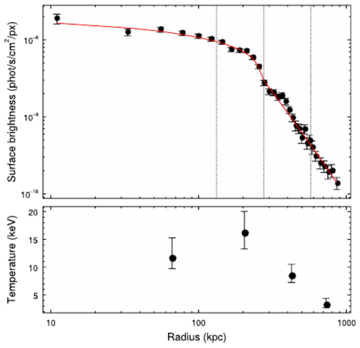
# The AS259 cluster – the dark matter

- **The two peaks in the total mass distribution confirms the binary nature of the merger**
- **The mass peak in the NW coincides with the secondary**
- **A clear offset between the mass peak and the bulk of the  gas in primary**

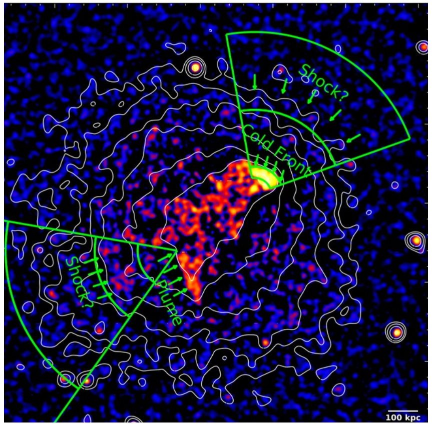


*AS295. Hubble Space Telescope; P.I. F. Pacaud; Chandra (yellow-red-blue colormap ); surface mass-density distribution (green) – Cibirka et al. (2018)*

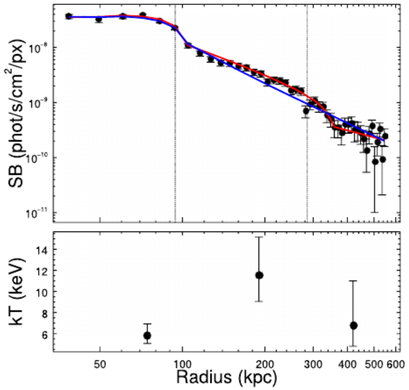
# Surface brightness discontinuities



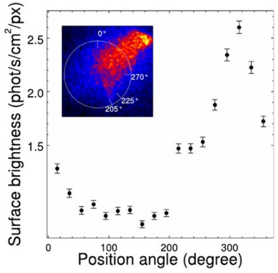

- Possible reverse shock
- Amplitude of density jump is 1.35 ± 0.003
- Amplitude of temperature jump is $1.89^{+0.61}_{-0.45}$

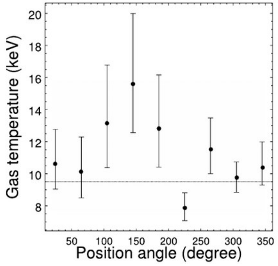



Unsharp-masked X-ray image




- Cold front at 90 kpc, with a temperature jump of 0.5±0.18
- Weak evidence for the presence of a shock ahead the cold front



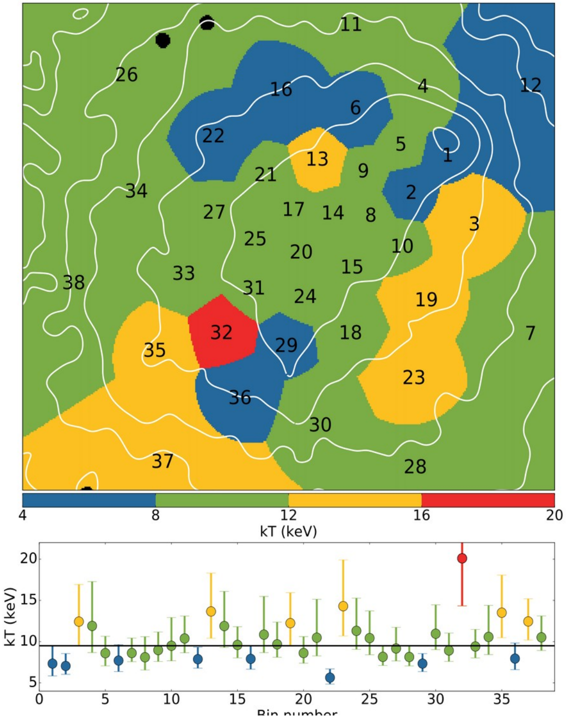



# Thermal distribution of the intracluster medium

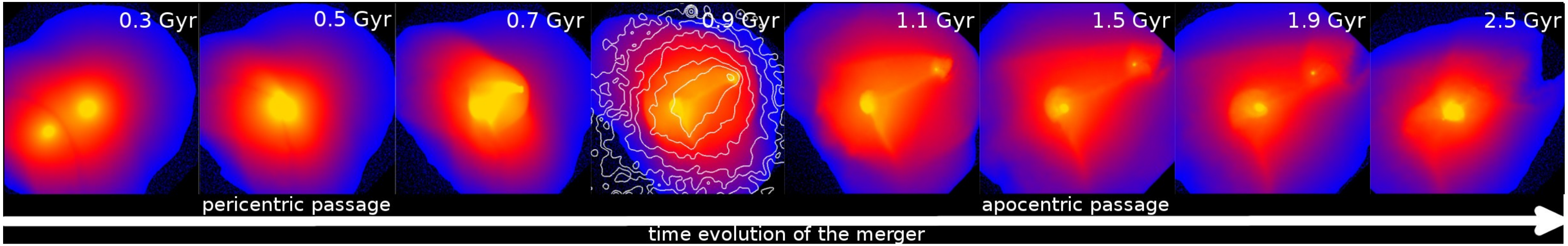
- **The primary has a gas temperature of 9.5 keV**

- **The secondary has cool gas associated with it**

- **The hottest region is in the proximity of the primary**



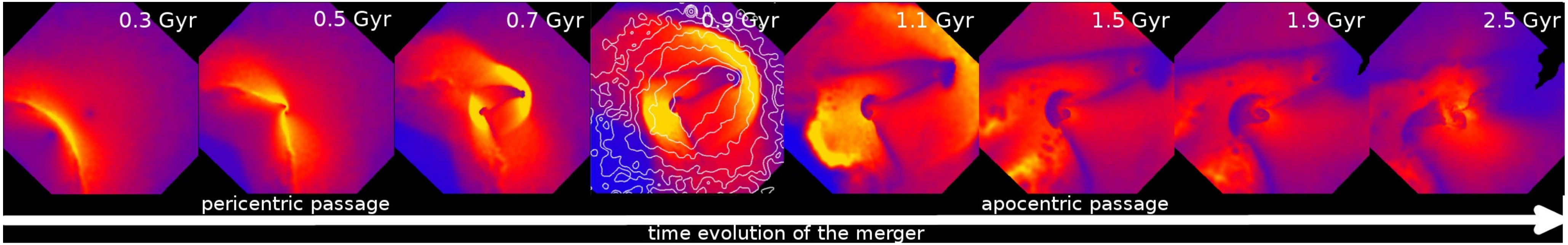
# Simulations of binary cluster mergers – surface brightness




**Binary cluster merger simulations predict:**

- **an elongated distribution of the surface brightness along the direction of merger**
- **the formation of several contact discontinuities**

# Simulations of binary cluster mergers – temperature




**Binary cluster merger simulations predict:**

- **the formation of a cold front in front of secondary shortly before pericentric passage**
- **the formation of two outwardly propagating shocks shortly before the first pericentric passage**
- **the formation of a plume of gas emerging from primary**
- **the formation of a sloshing cold front close to the primary core**

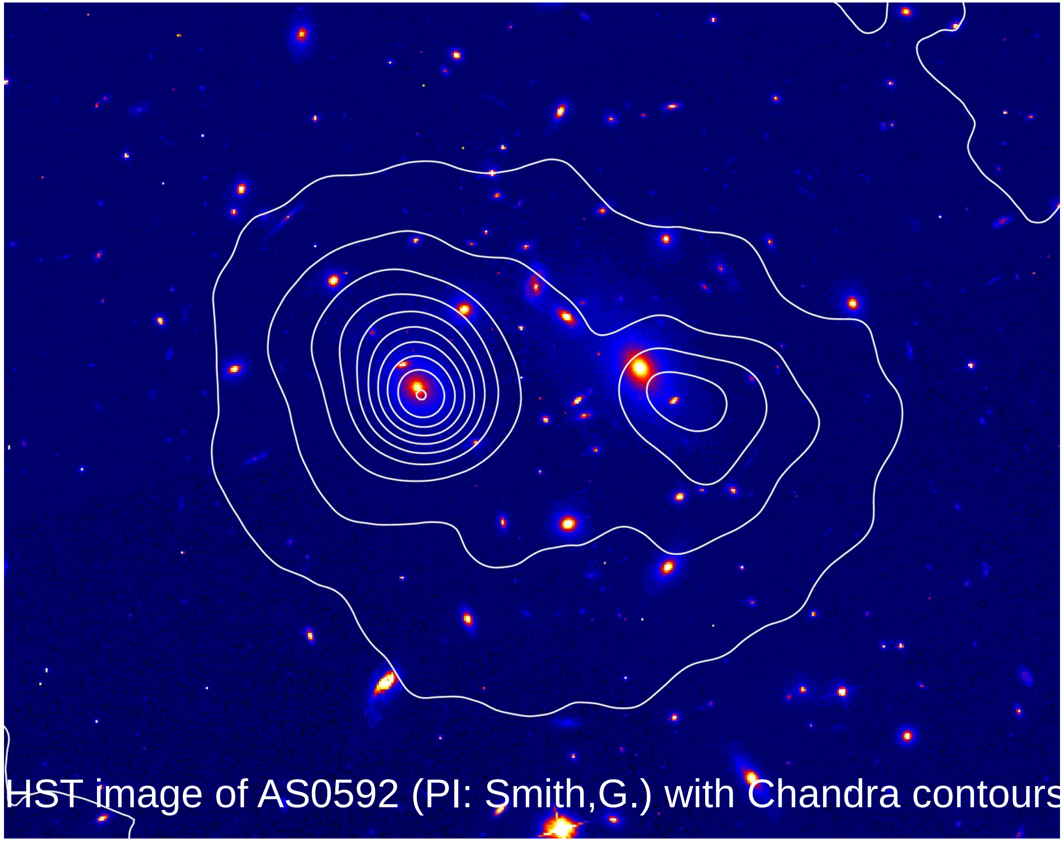
# Conclusions – AS295 galaxy cluster

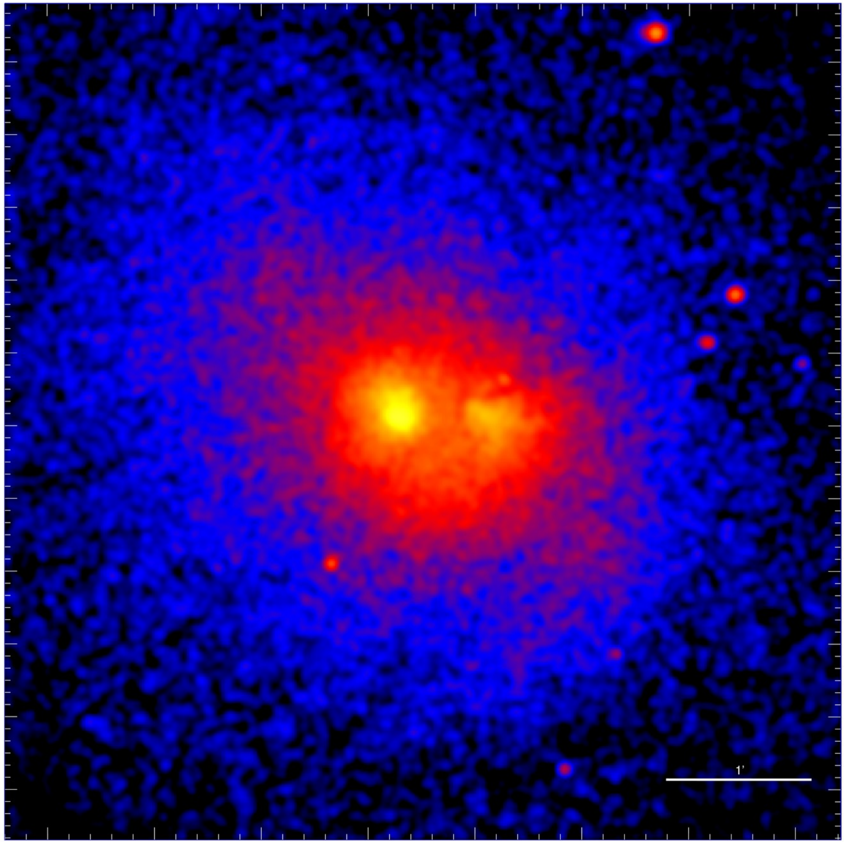
## AS295 galaxy cluster

- **is a low mass-ratio, off-axis, binary merging system, with the secondary close to the first apocentric passage**
- **shows signs of mergers in the ICM such as a cold front and a plume of cool gas**
- **shows weak signs for the presence of shocks: a reverse and possibly a bow shock**
- **shows a significant spatial offset between the peak of the gas and that of the dark matter in primary**

AS295 is a promising candidate for studies of the nature of dark matter and the merging process

# AS592 - Optical and x-ray surface brightness distribution


HST image of AS0592 (PI: Smith,G.) with Chandra contours

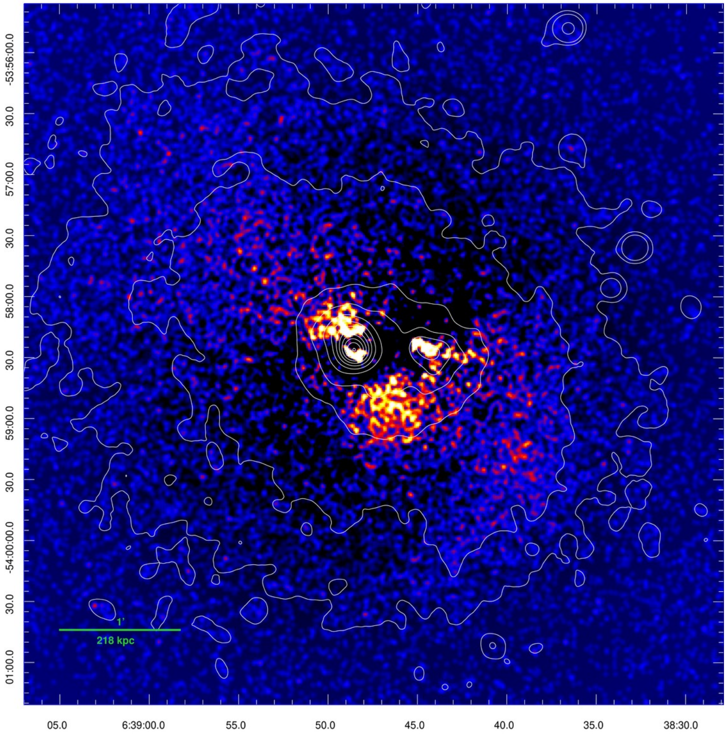


# Searching for surface brightness features

- irregular morphology of surface brightness

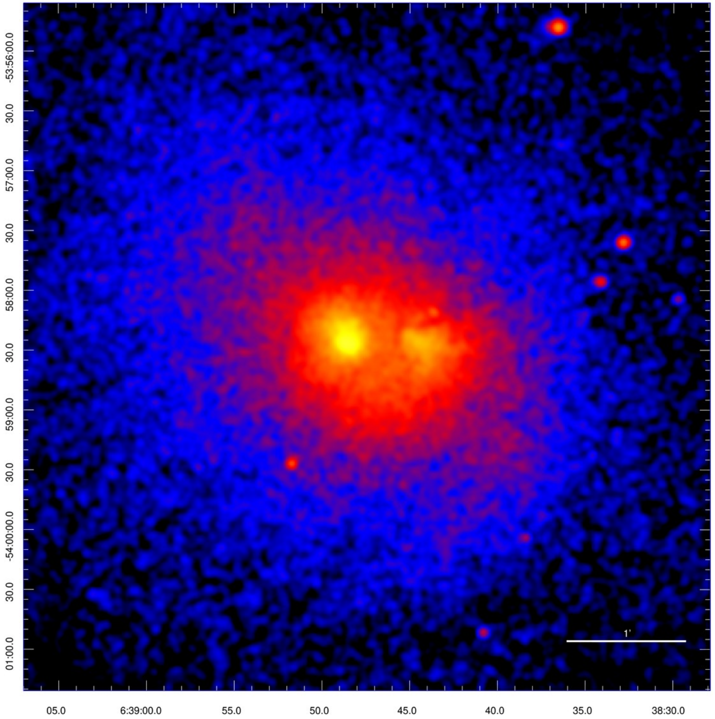
- possible merger axis is in the SW-NE direction

- surface brightness excess to the south of the two clusters

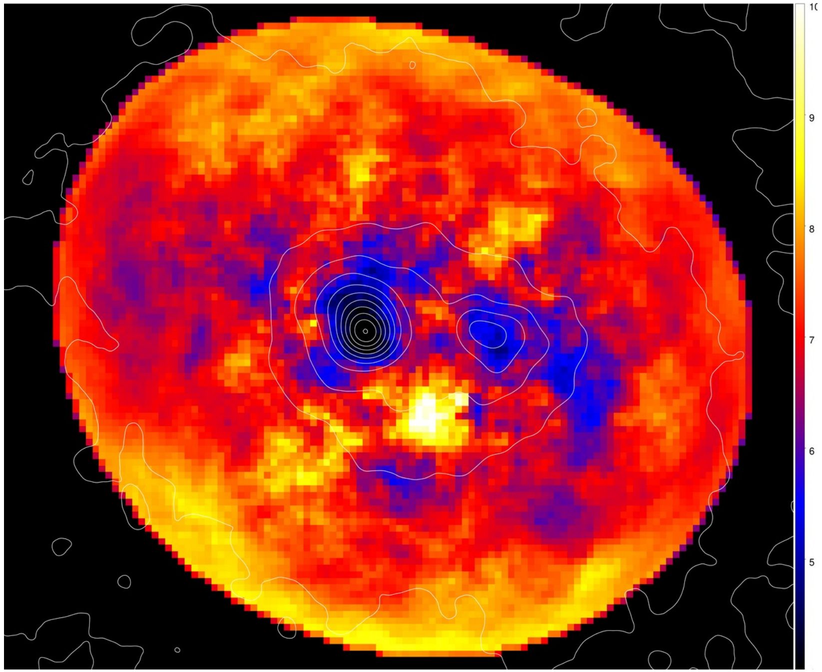



*AS0592 – residuals obtained after subtracting a beta model*

# Intracluster medium temperature

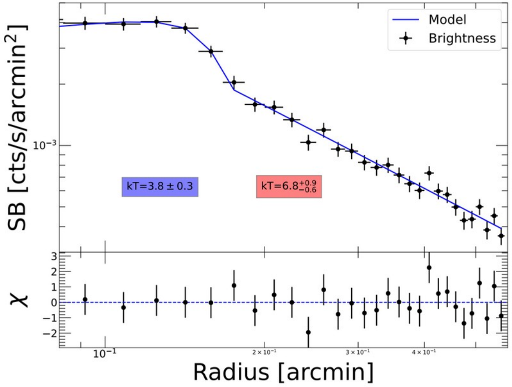



- **Cluster global temperature: 9.68 ± 0.33 keV**
- **Cool cores associated with both subclusters**
- **The temperature in the primary drops to ~4 keV**
- **Hottest region to the south of the clusters with kt ~10 keV**

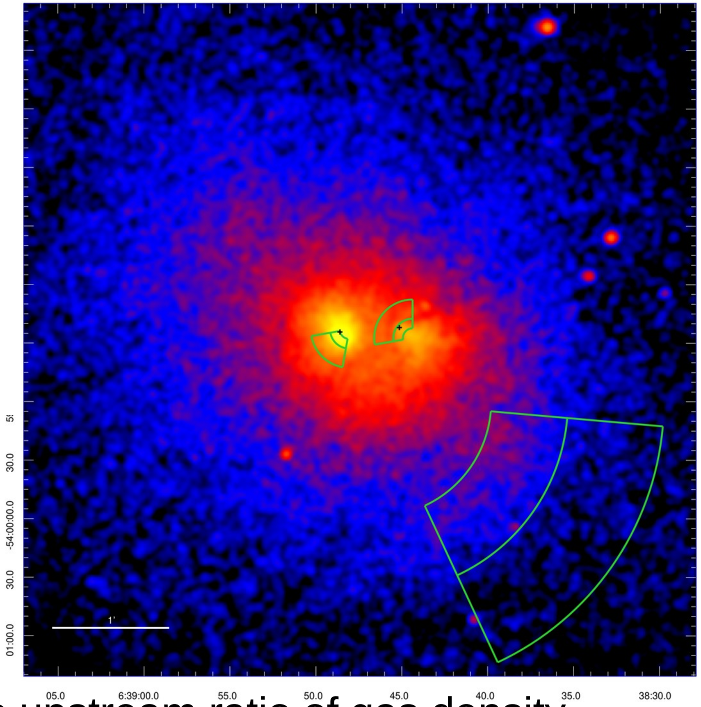


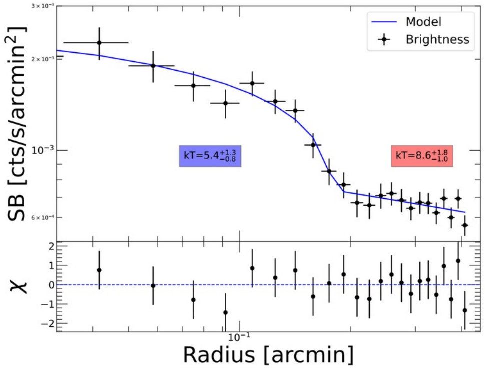

*AS0592 temperature map based on the Adaptive Circular Binning algorithm*

# Surface brightness discontinuities

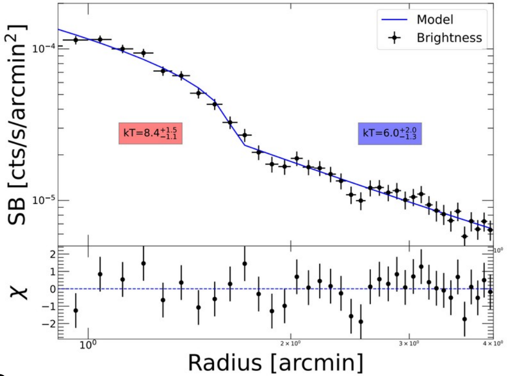



- $R_{ne}$ = 1.86 ± 0.16
- $R_{kT}$ = 0.56 $^{+0.09}_{-0.07}$



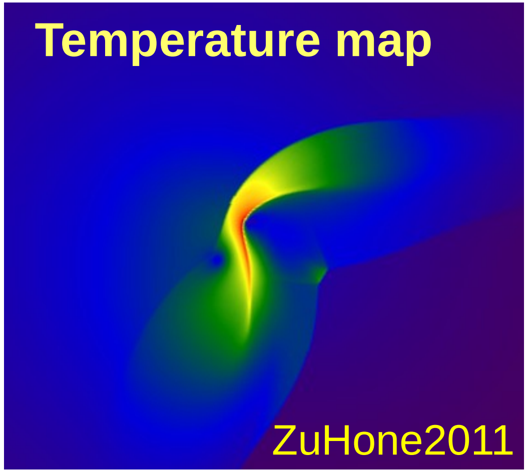

- $R_{ne}$ =2.6±0.7
- $R_{kT}$= 0.63 $^{+0.20}_{-0.12}$



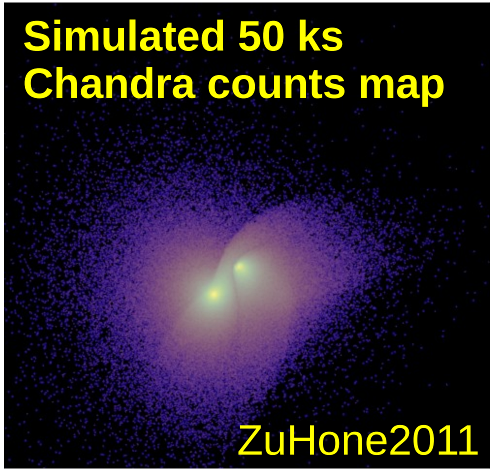

- $R_{ne}$ =1.84±0.12
- $R_{kT}$= 1.4 $^{+0.53}_{-0.35}$

- $R_{ne}=n_d/n_u$ -downstream to upstream ratio of gas density
- $R_{kT}$ $=kT_d/kT_u$ -downstream to upstream ratio of gas temperature

# AS0592 cluster possible merger scenario




Merger simulation
binary merger
3:1 mass ratio
b=1000 kpc




**AS0592 - an off-axis, binary merger, with secondary at first pericentric passage?**

- Sloshing of the primary's core in the cluster's gravitational potential
- The bullet-like morphology of the secondary
- The hot region to the south of the two cluster cores
- The shock behind the secondary

# Conclusions - AS592 galaxy cluster

**The AS0592 galaxy cluster:**

- **is a massive, low redshift, binary merging cluster**
- **shows clear signs of merging in its surface brightness distribution: an irregular morphology, two cold fronts in the cores and a shock**
- **is a  hot cluster with cool cores associated with the two subclusters**
- **shows the properties of a low mass-ratio, off-axis, binary merging system, with the secondary close to the first apocentric passage**

# Conclusions

**The AS295 and AS592 merging galaxy clusters:**

- **are massive, low redshift, binary merging clusters**
- **shows clear signs of merging in its surface brightness distribution: irregular morphology, cold fronts and a shocks**
- **the two clusters are caught at different moments during merging**