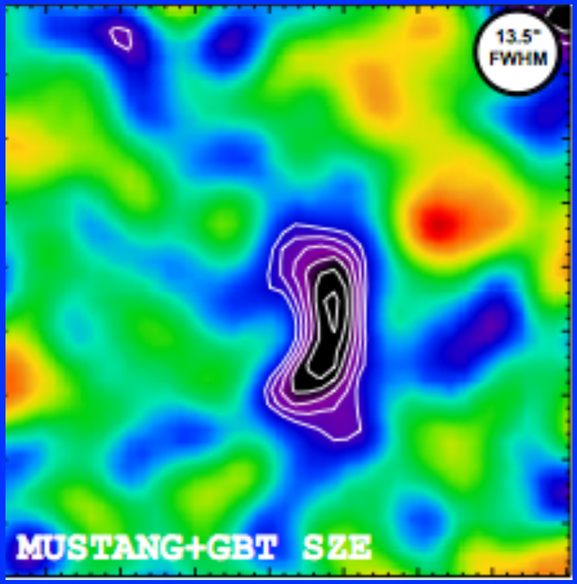
High Resolution SZ Observations with MUSTANG2/GBT and the Dynamics of Clusters of Galaxies



MUSTANG GBT SZ Image of Merger Shock in MACS0744 (Korngut et al.)

Craig Sarazin
University of Virginia

Simulation of SZ from Perseus Radio Bubbles (Pfrommer et al.)

Collaborators

** MUSTANG21.5 Collaboration **

Simulations

Marios Chatzikos (Univ. Kentucky)

Markus Haider (Univ. Innsbruck)

Scott Randall (CfA)

Paul Ricker (Univ. Illinois)

Dan Wik (NASA Goddard)

Radio Bubbles

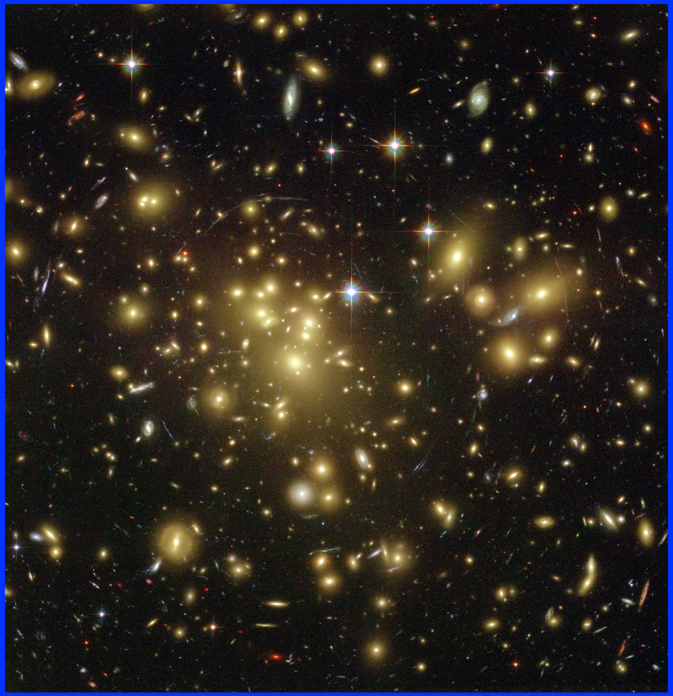
Liz Blanton (Boston Univ.)

Torsten Ensslin (MPA, Garching)

Brian McNamara (Univ. Waterloo)

Christoph Pfrommer (Univ. Heidelberg.

Clusters of Galaxies



- Largest relaxed systems in Universe
- ~2 Mpc in radius
- ~100 bright galaxies, 1000's of faint galaxies
- ~10^{15} $M_\odot$ total mass

Cosmological Probes

Only objects in Universe which are both

- Small enough to be in equilibrium
- Big enough to be fair sample of materials in Universe (e.g., baryonic vs. nonbaryonic matter)

→ Clusters provide strong evidence that we live in a low density Universe ($\Omega_M = 0.3$)

Cosmological Probes

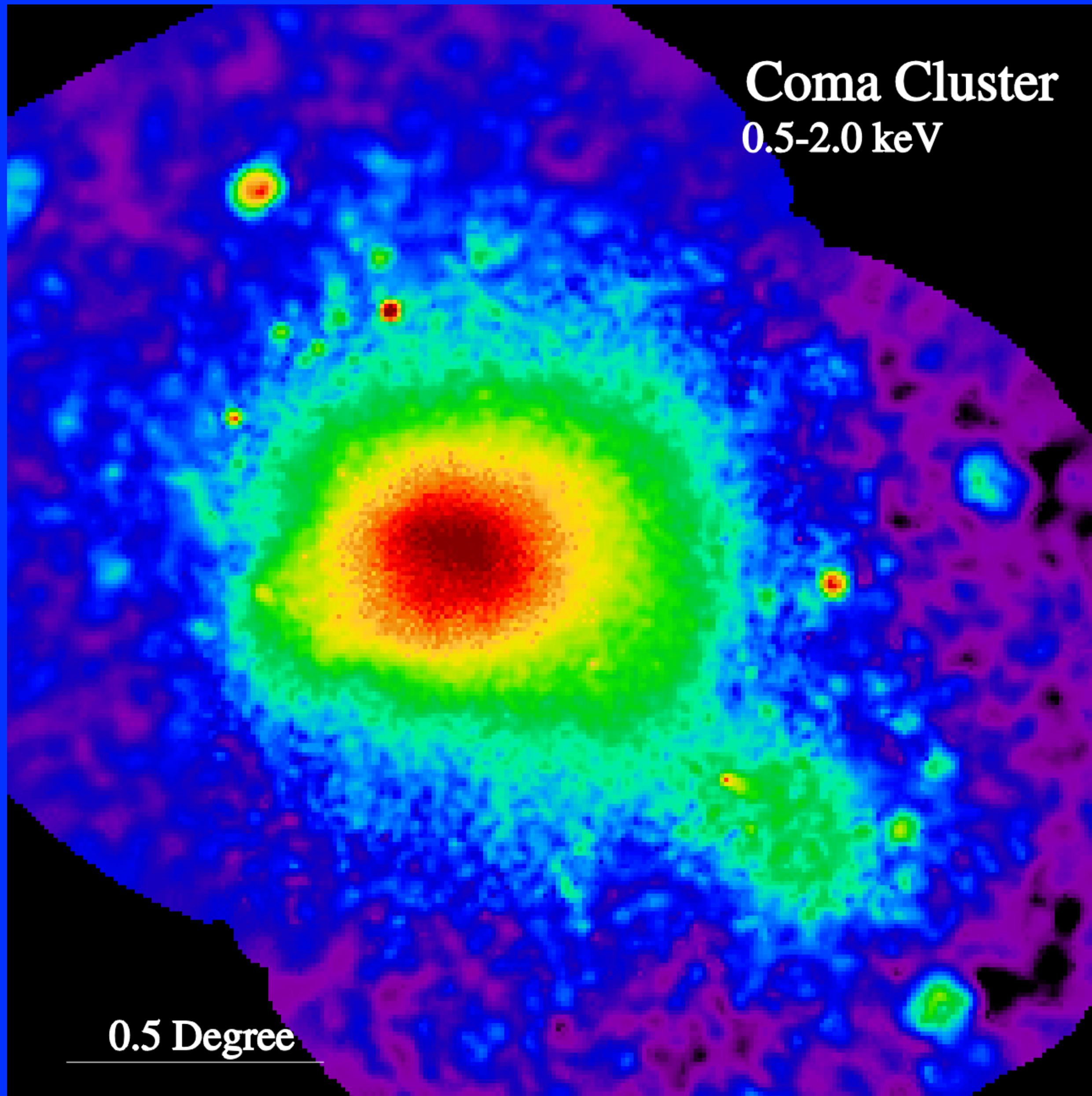
~85% of mass is Dark Matter (DM). Clusters are large and deep gravitational potential wells of DM.

To use for cosmology, we require accurate and relatively easy measures of total cluster mass

Most mass proxies based on equilibrium. How relaxed or dynamical are clusters?

Intracluster Gas

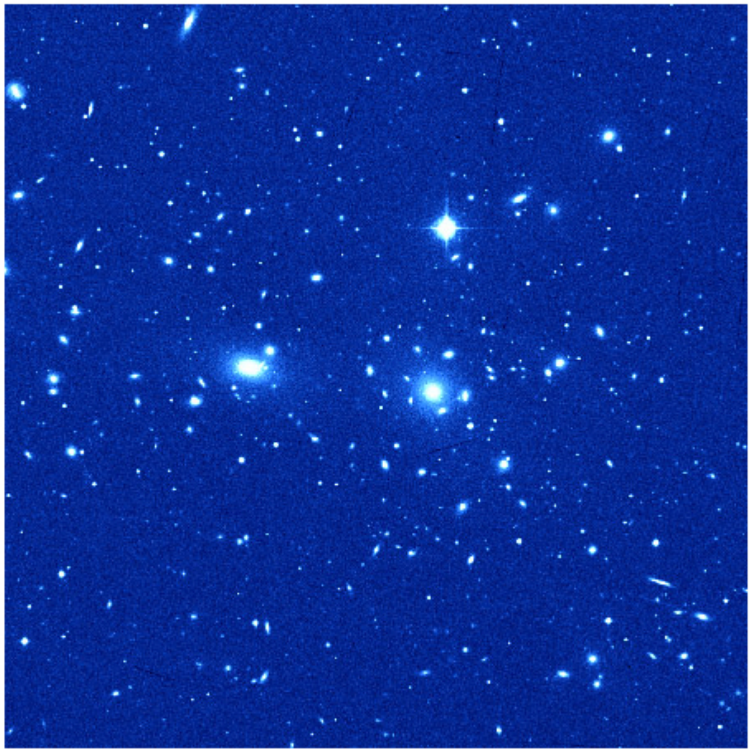
- Majority of observable cluster mass is hot plasma
- Temperature $T \sim 10^8$ K
- Electron number density $n_e \sim 10^{-3}$ cm^{-3}
- 5 x as much mass as all stars and galaxies in cluster
- Mainly H, He, but with heavy elements (O, Fe, ..)
- Mainly emits X-rays
- $L_X \sim 10^{45}$ erg/s, most luminous extended X-ray sources in Universe

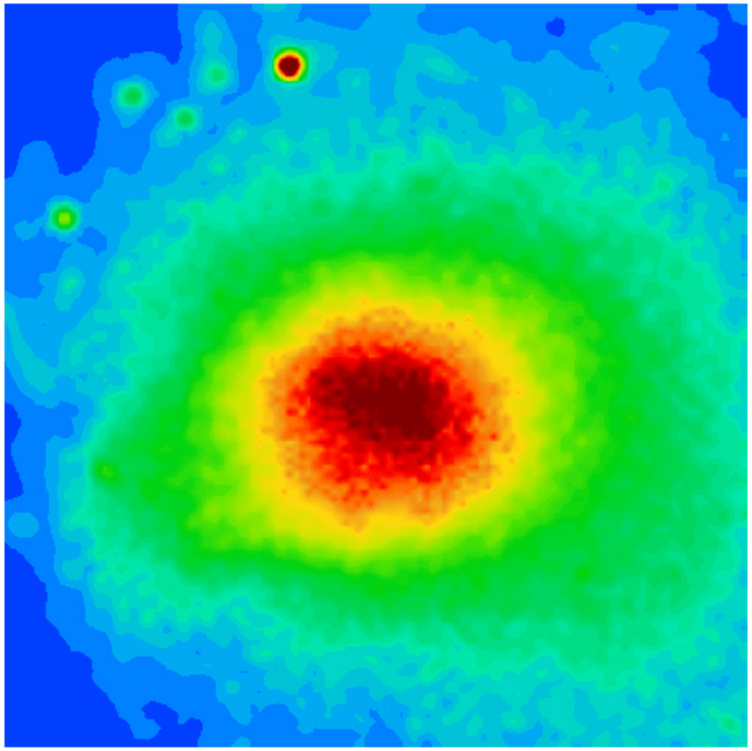

Coma Cluster
0.5-2.0 keV
0.5 Degree

Optical vs. X-ray

Optical

X-ray





Coma cluster

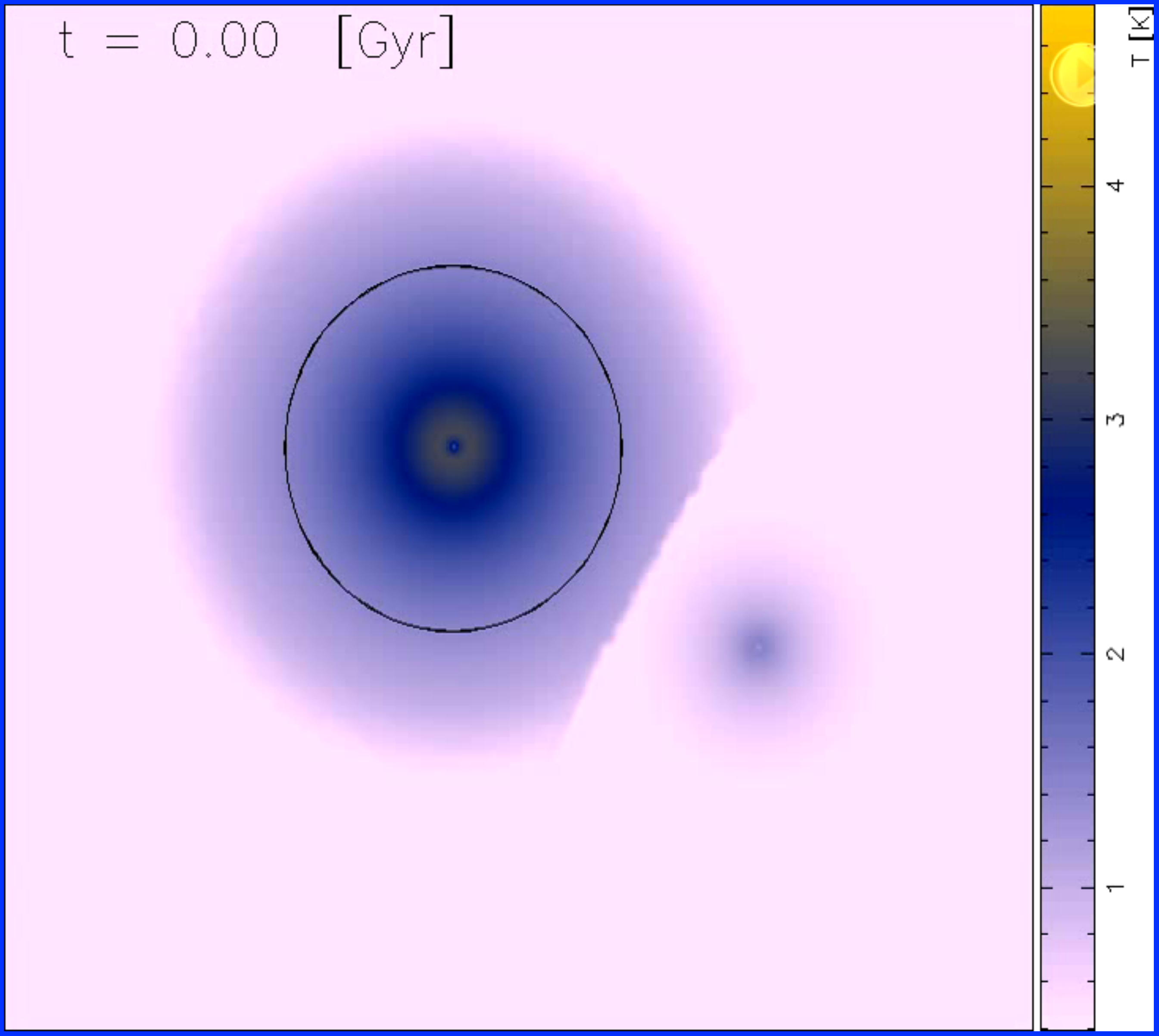
Cluster Mergers

- Clusters form hierarchically

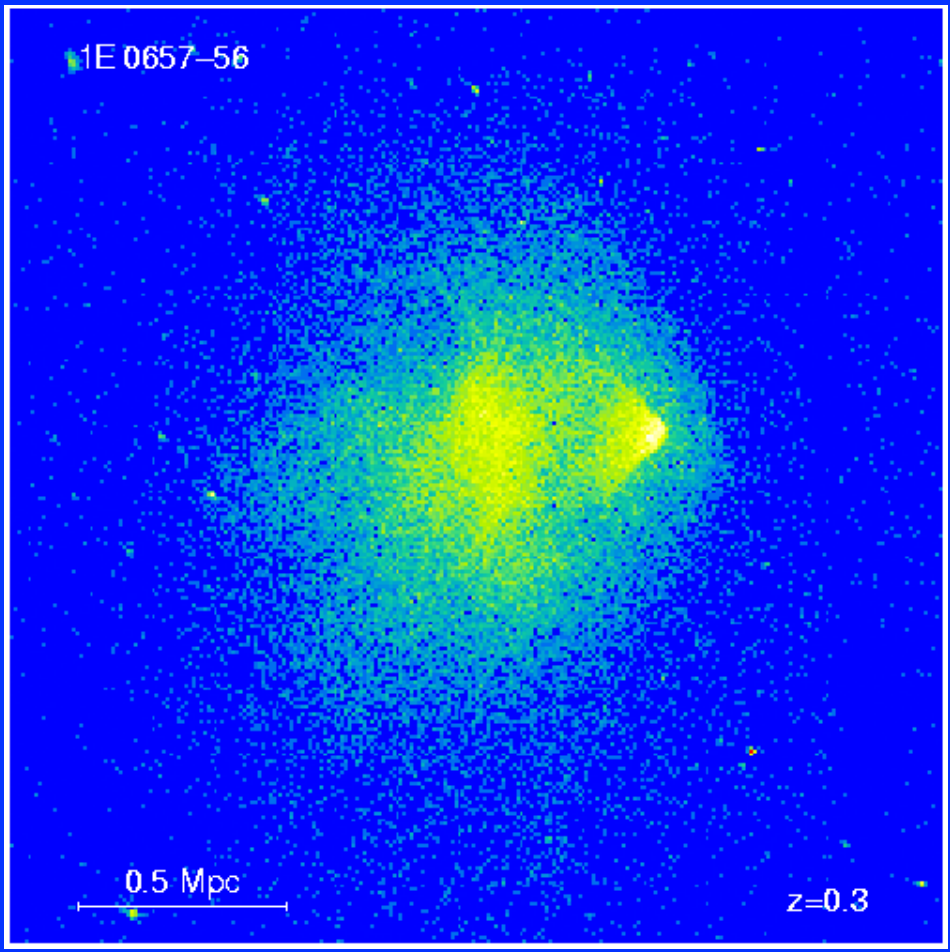
→ Major cluster mergers are most energetic events in Universe since Big Bang

- Major cluster mergers, two subclusters, $\sim 10^{15}\ M_{\odot}$ collide at ~ 2000 km/s
- E (merger) ~ 10^{64} ergs
- E (shocks in gas) ~ 10^{63} ergs

Temperature



Merging Bullet Cluster

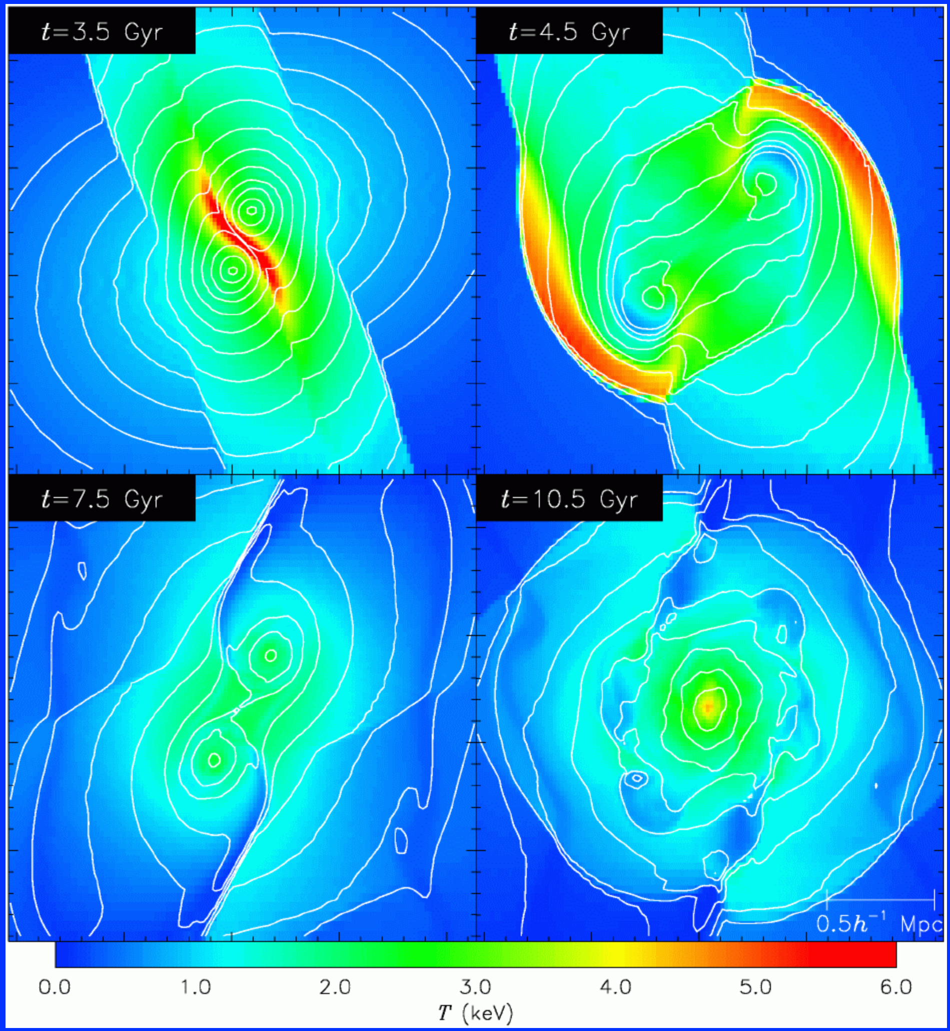


Markevitch et al.

1E0657-56

Merger Shocks

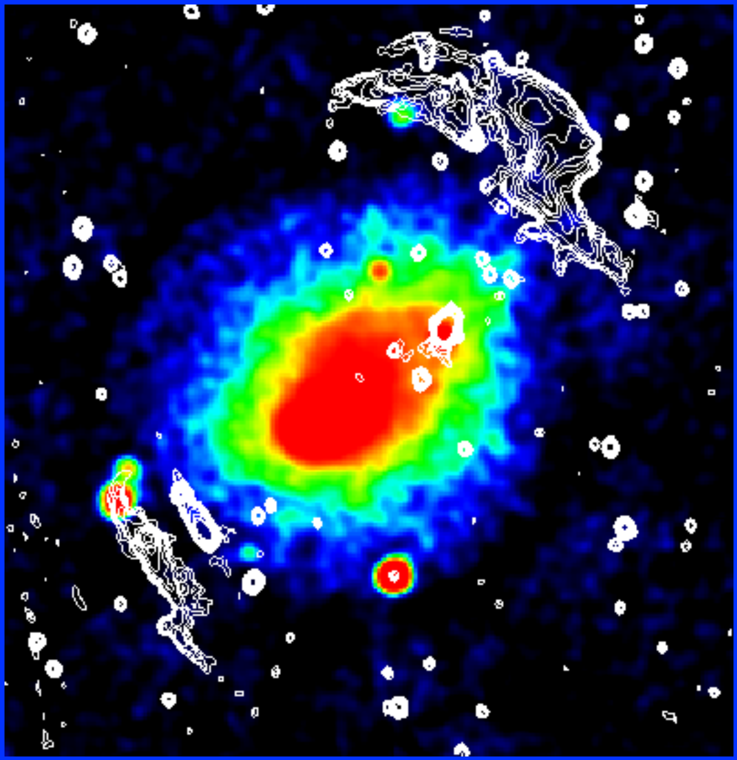
- Typical shock velocity 1000 km/s
- E (shock) ~ 10^{63} ergs
- Main heating mechanism of intracluster gas



(Ricker & Sarazin 2001)

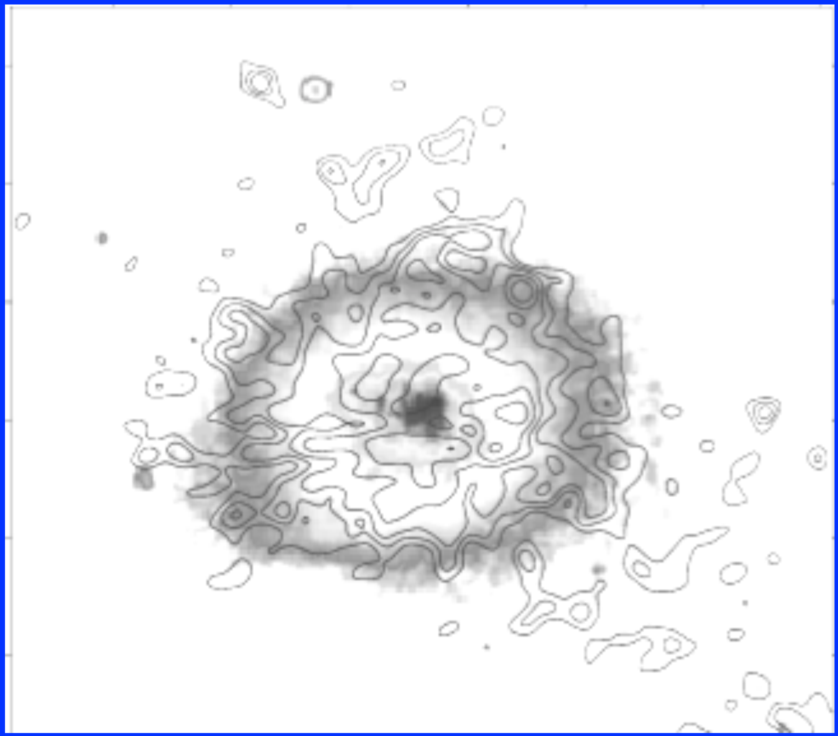
Cluster Radio Halos and Relics

Radio Relics
(shock acceleration?)



Abell 3667
(Röttgering et al.)

Radio Halo
(turbulent acceleration?)



Coma
(Govoni et al.)

Cluster Radio Relics and Halos

- Cluster radio relics: peripheral and elongated
  - Due to merger shock (re)acceleration (?)
- Cluster radio halos: central and symmetric
  - Due to turbulent acceleration behind shocks (?)

Is there a shock at the edge of every cluster relic?

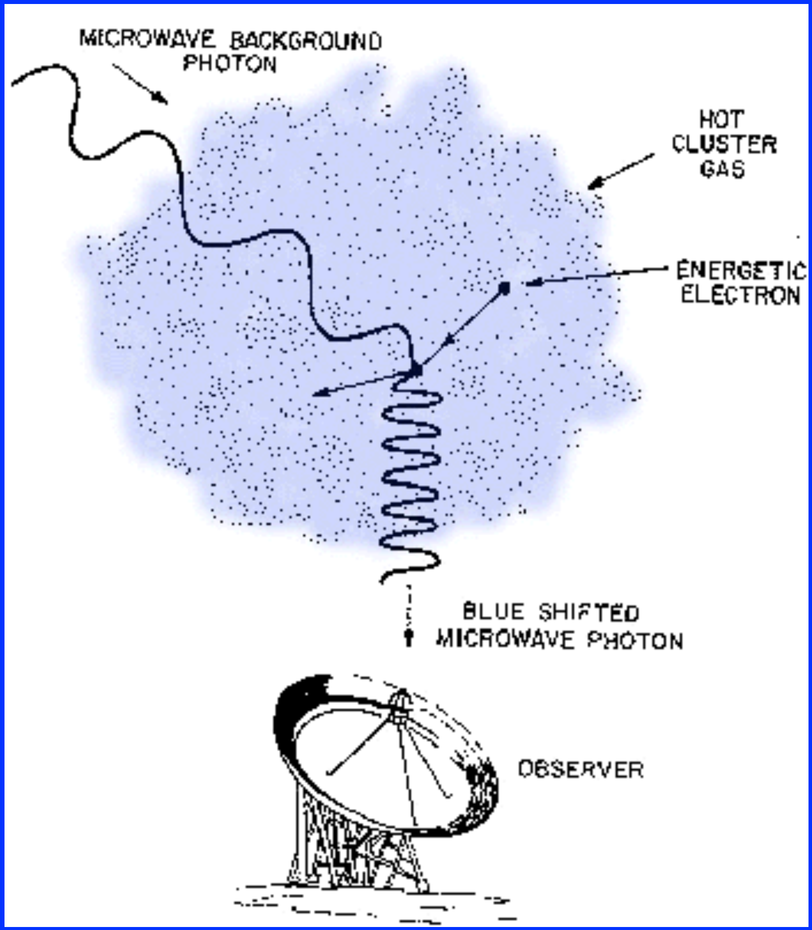
Are cluster halos always located between shocks?

Sunyaev - Zel' dovich (SZ) Effect

Another way to study intracluster gas in clusters

- Free electrons in hot gas scatter CMB radiation which passes through a cluster
  - Typically, only ~0.3% of photons scattered
  - Need background source with lots of photons
- Cosmic Microwave Background from Big Bang
  - Behind Everything!

Sunyaev - Zel’dovich (SZ) Effect

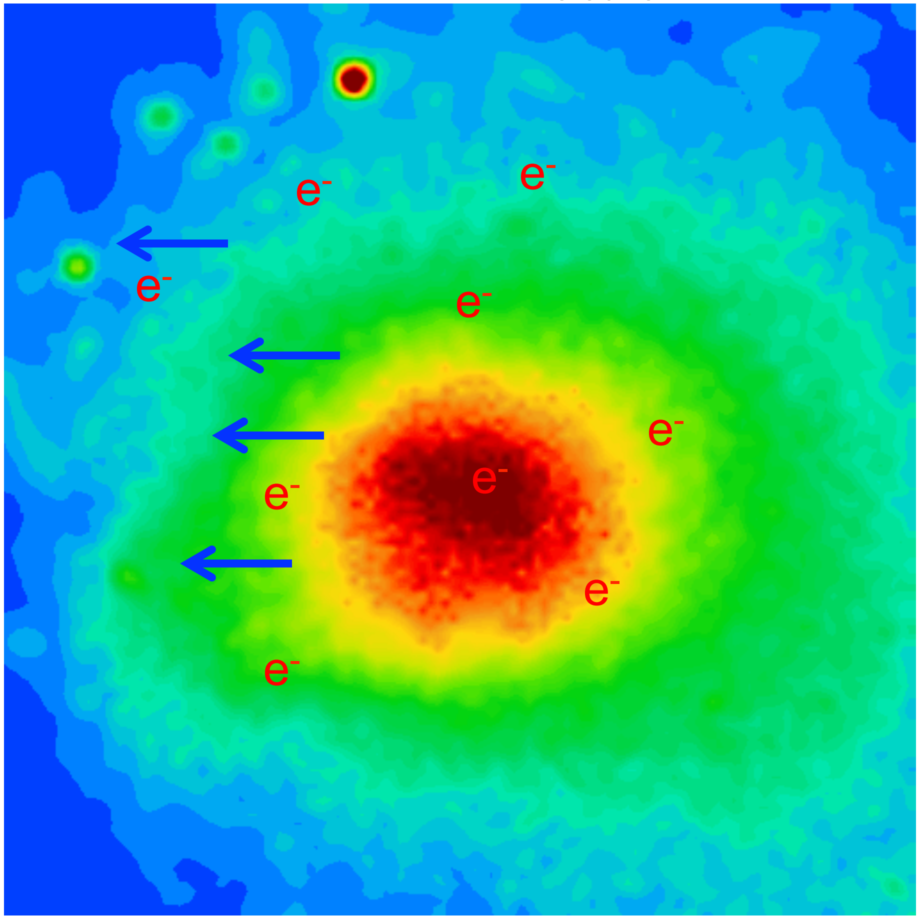


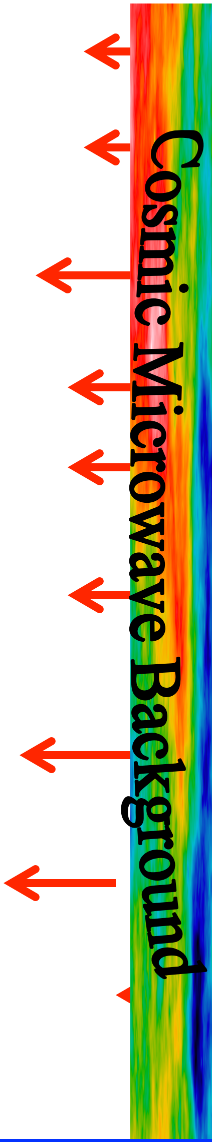
Thermal SZ Effect

- Temperature electrons in cluster $T_e \sim 10^8$ K
- Temperature of CMB photons $T_{CMB} = 2.73$ K
- Photons get energy from electrons

Thermal SZ Effect in Clusters

Coma Cluster $T_{electron} = 10^8$ K

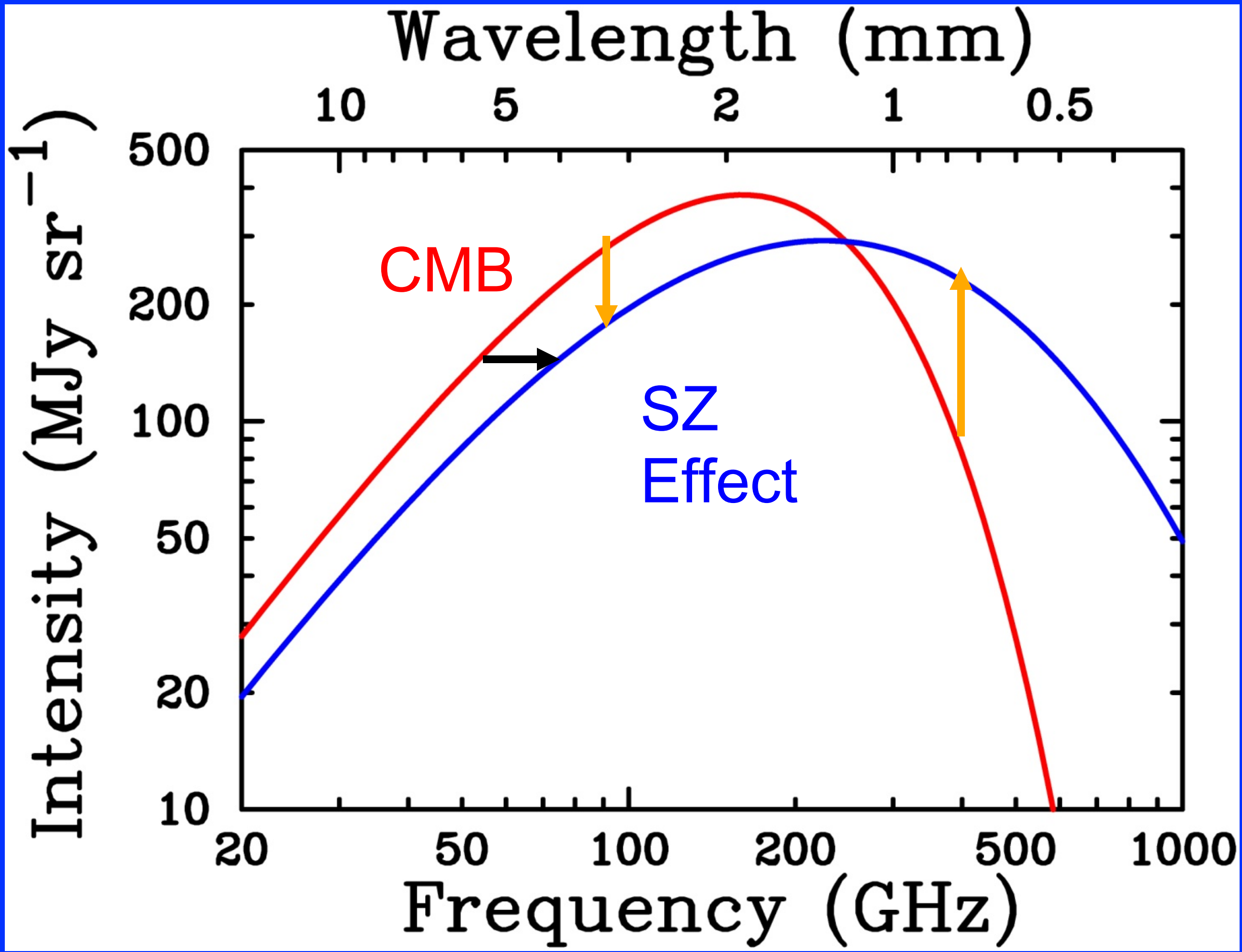




Thermal SZ Effect

- Temperature electrons in cluster $T_e \sim 10^8$ K
- Temperature of CMB photons $T_{CMB} = 2.73$ K
- Photons get energy from electrons
  - Number of photons conserved
  - Shift BB spectrum to higher energies and frequencies
- Paradoxically, reduces intensity at low frequencies

Thermal SZ Effect



Thermal SZ Effect: Barometer?

$$\Delta I_\nu \propto y \equiv \int \sigma_T n_e \frac{kT_e}{m_e c^2} dl \propto n_e k T_e = P_e$$

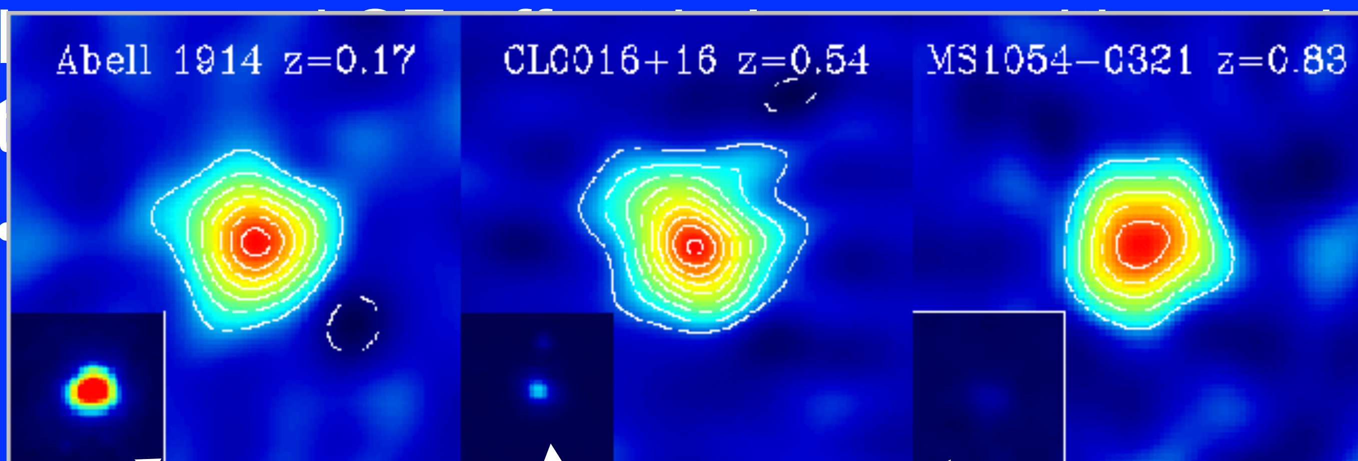
- Effect measures integral of pressure
- Integrated over entire cluster

$$Y \equiv \int y dA \propto \int n_e k T_e \, dl \, dA \propto \frac{3}{2} n_e k T_e V = TE$$

- Integrated effect over entire cluster measures total thermal energy of electrons

SZ vs. X-ray Observations

- X-ray: mainly measures density $I_X \propto \int n_e^2 \Lambda(T_e)\, dl$
  - Not directly related to dynamics
- SZ measures pressure
- SZ is distance and redshift independent
- … namics
- … energy



X-ray images

Pressure – the Key to Cluster Dynamics & Mass

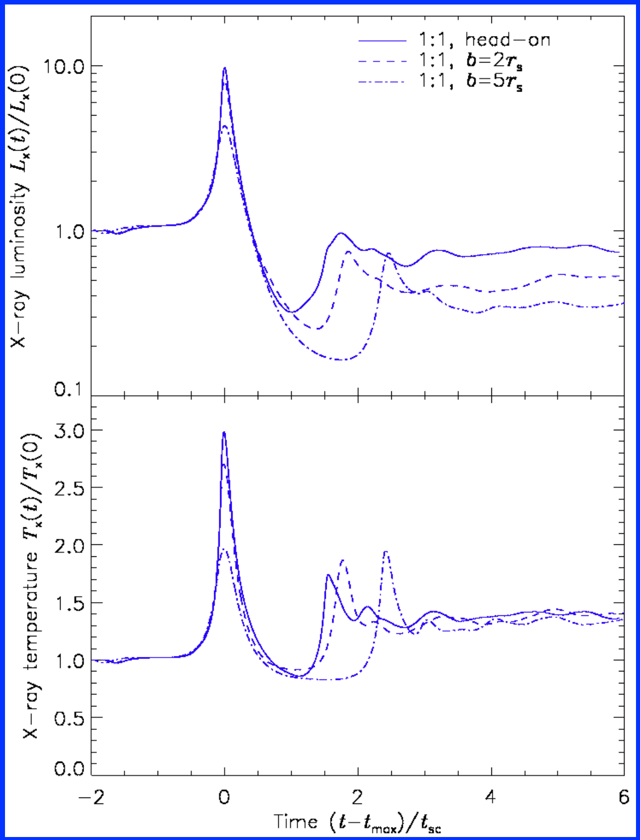
- Pressure and gravity drive gas dynamics
- Pressure directly related to mass through hydrostatic equilibrium

$$\nabla P = -\frac{GM\rho}{r^2}$$

- SZ: can derive mass, and directly detect how dynamics affects mass

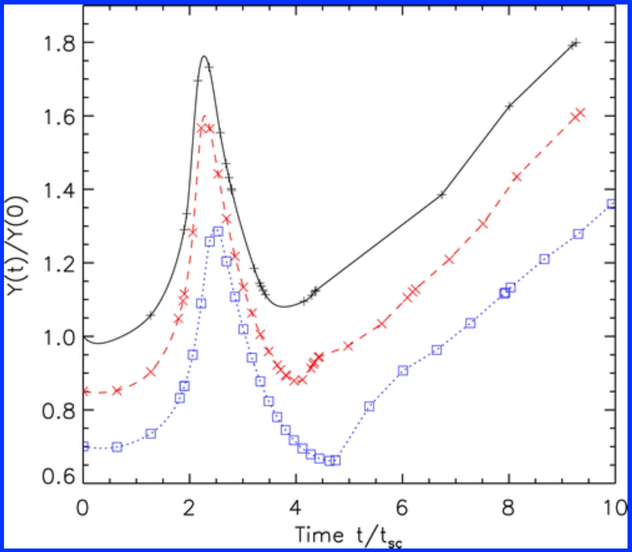
Merger Boosts

Bigger in X-ray



(Ricker & Sarazin 2001; Randall et al. 2002)

Smaller in Integrated SZ



Easier to see in
High Resolution SZ images

(Wik, Sarazin, & Randall 2008)

Pressure – the Key to Cluster Dynamics & Mass

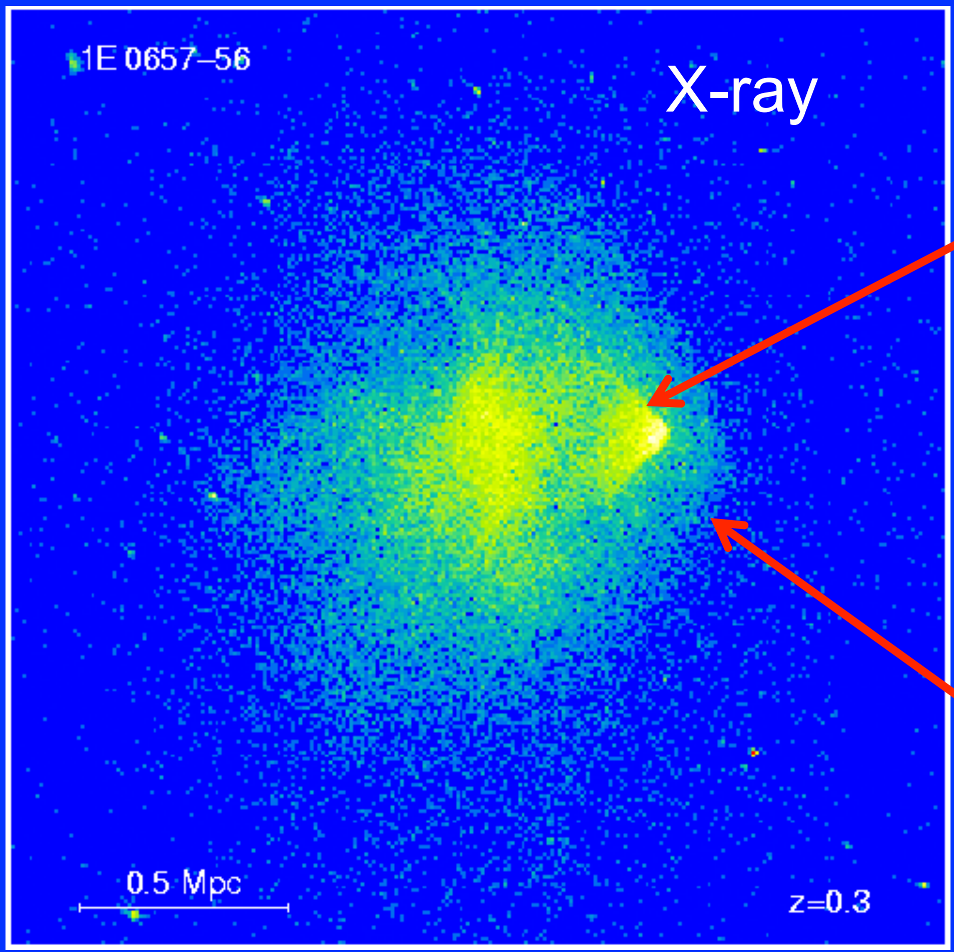
- Pressure and gravity drive gas dynamics
- Pressure directly related to mass through hydrostatic equilibrium

$$\nabla P = -\frac{GM\rho}{r^2}$$

- SZ: can derive mass, and directly detect how dynamics affects mass
- Shocks = pressure discontinuities
  - Pressure jump unbounded
  - Compression < 4

SZ much better for finding shocks than X-ray

Bullet Cluster 1E0657-56



Contact interface
("cold front")
not a shock

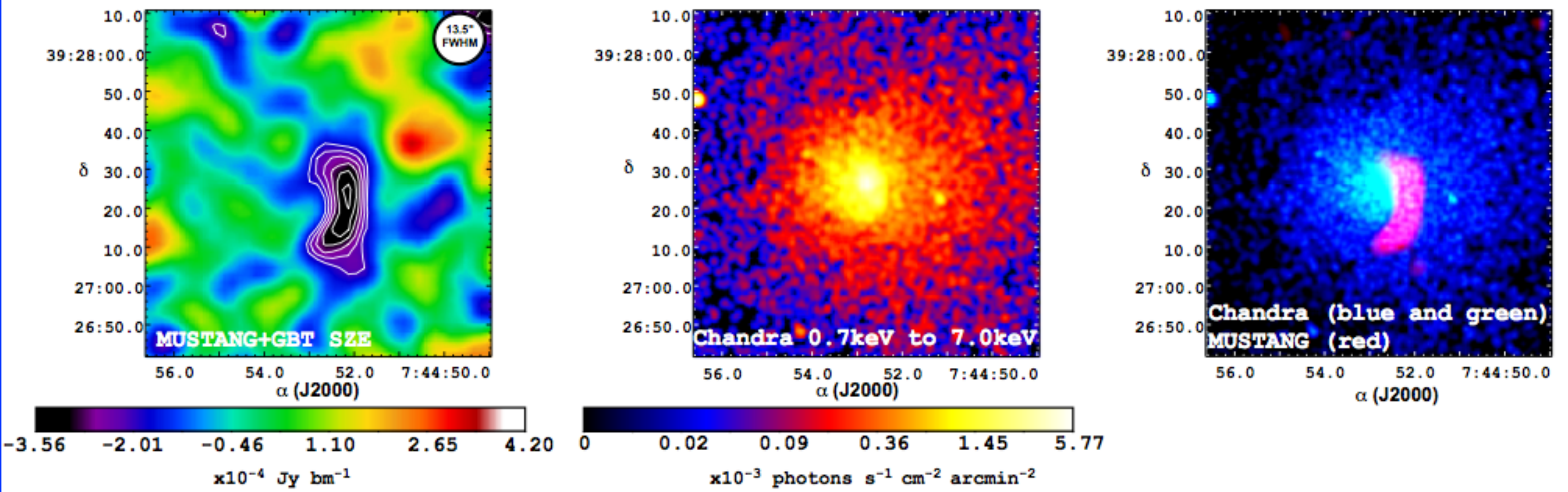
Strongest known
merger shock

1E0657-56 (Markevitch et al.)

MACS0744+3972

previously unknown & unexpected weak (Mach ~1.2) shock near the core of this cluster

MUSTANG SZ Chandra X-ray



(Korngut et al. 2011)

Pressure – the Key to Cluster Dynamics & Mass

- Pressure and gravity drive gas dynamics
- Pressure directly related to mass through hydrostatic equilibrium

$$\nabla P = -\frac{GM\rho}{r^2}$$

- SZ: can derive mass, and directly detect how dynamics affects mass
- Shocks = pressure discontinuities
  - Pressure jump unbounded
  - Compression < 4

Require high spatial resolution SZ measurements

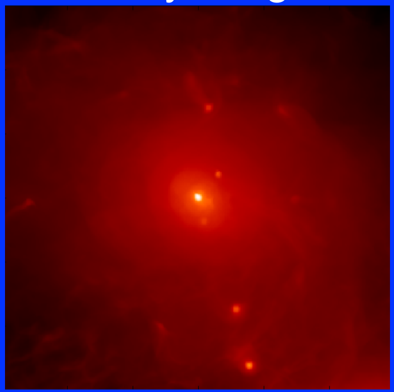
Pressure Fluctuations and Turbulence

Prediction from numerical simulations:

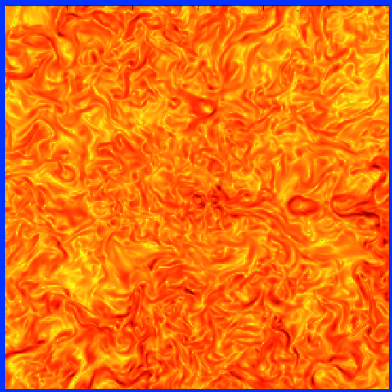
After the passage of shocks, the ICM is turbulent for ~10^8 years

- Turbulence accelerates relativistic electrons in cluster radio halos
- How much does turbulence contribute to pressure support in clusters, undermining hydrostatic equilibrium?

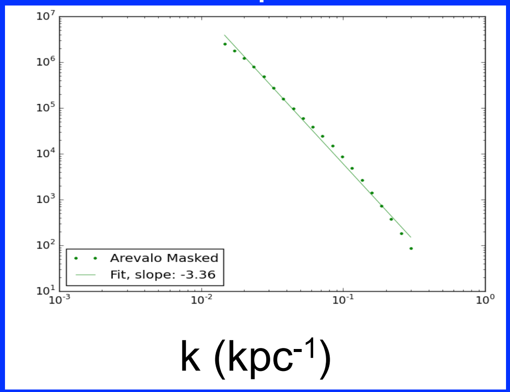
X-ray image



SZ Fluctuations



Power Spectrum



(Haider et al. 2015)

Kinetic SZ Effect

Due to bulk motion of subcluster

- Measure velocity relative to CMB = average of observable Universe = “absolute velocity”
- Not fooled by distance/redshift differences

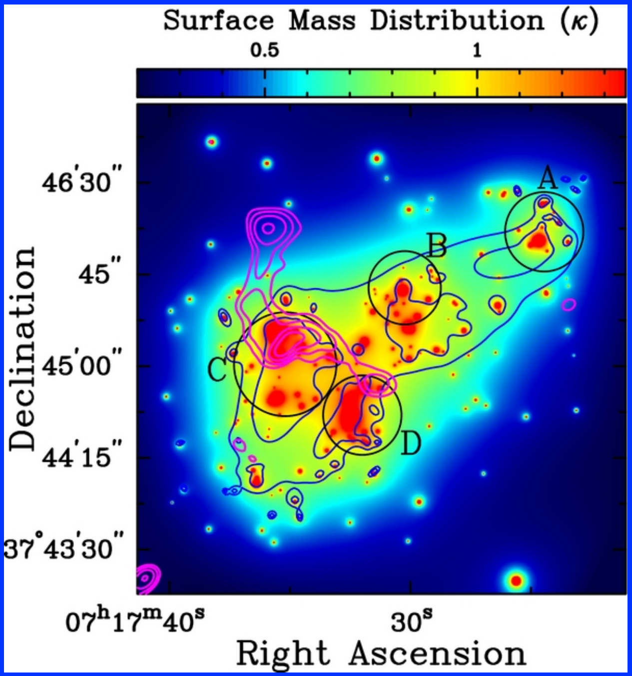
MACS J0717.5+3745

MUSTANG+Bolocam

v_r (B) ≈ +3600 km/s

agrees with optical

(Mroczkowski et al. 2012)



SZ Observations of Cluster Radio Bubbles

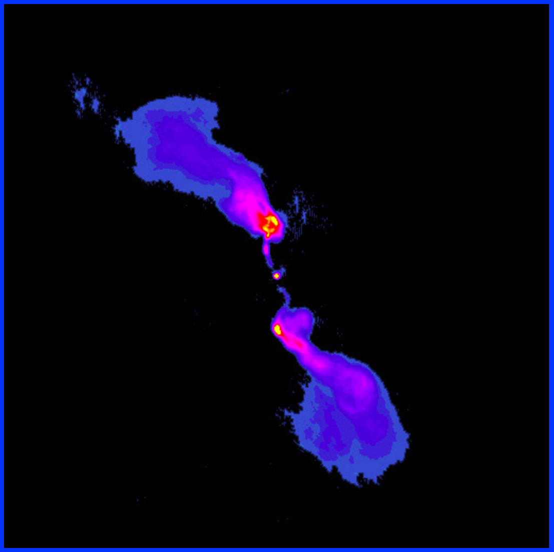
Perseus Chandra X-ray and radio

Perseus GBT SZ?

Radio Sources in Central Galaxies in Cool Cores

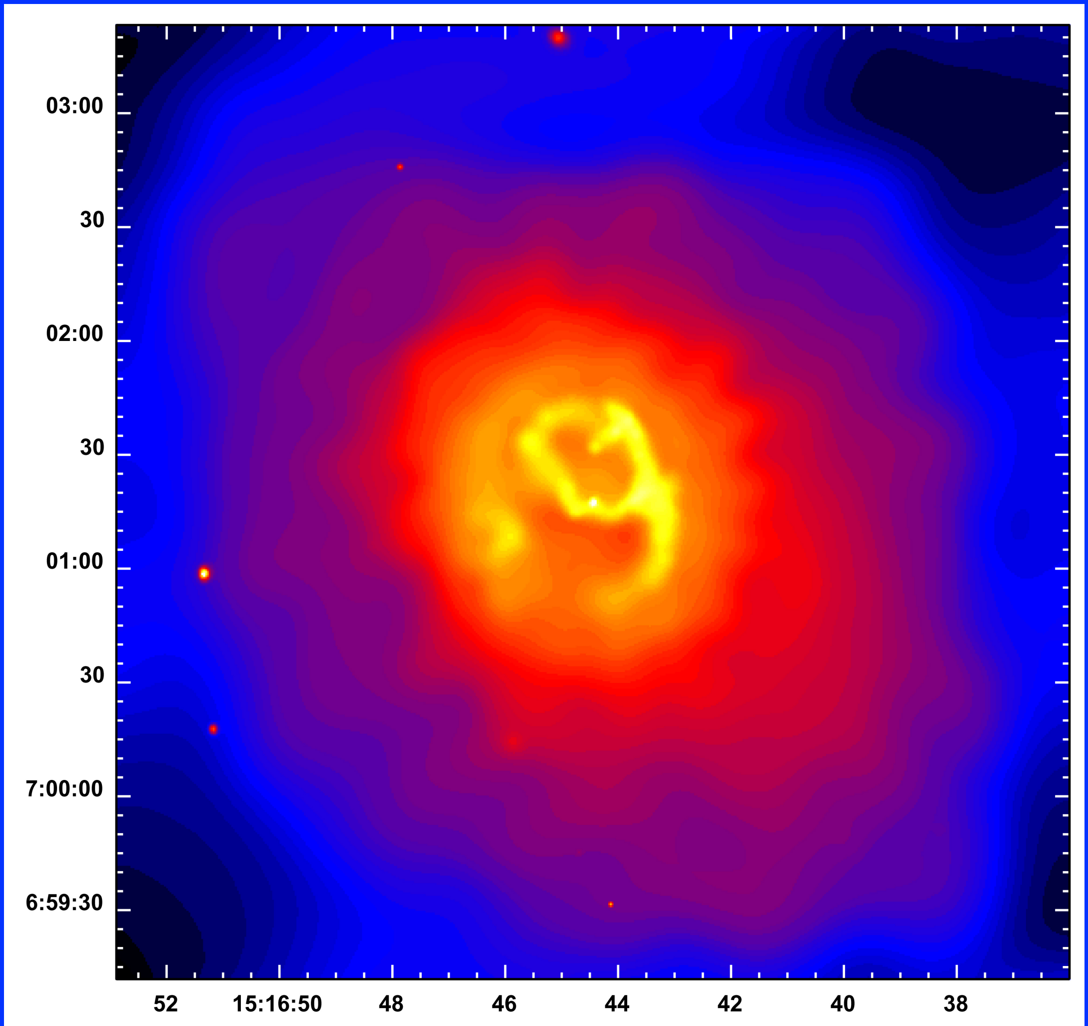
- > 70% of cooling core cDs are radio sources
- Many of nearby, bright radio sources: Virgo A, Perseus A, Hydra A, Cygnus A, . . .
- Radio lobes = X-ray holes

  "Radio Bubbles"
- Radio jets inflate bubbles



Hydra A VLA

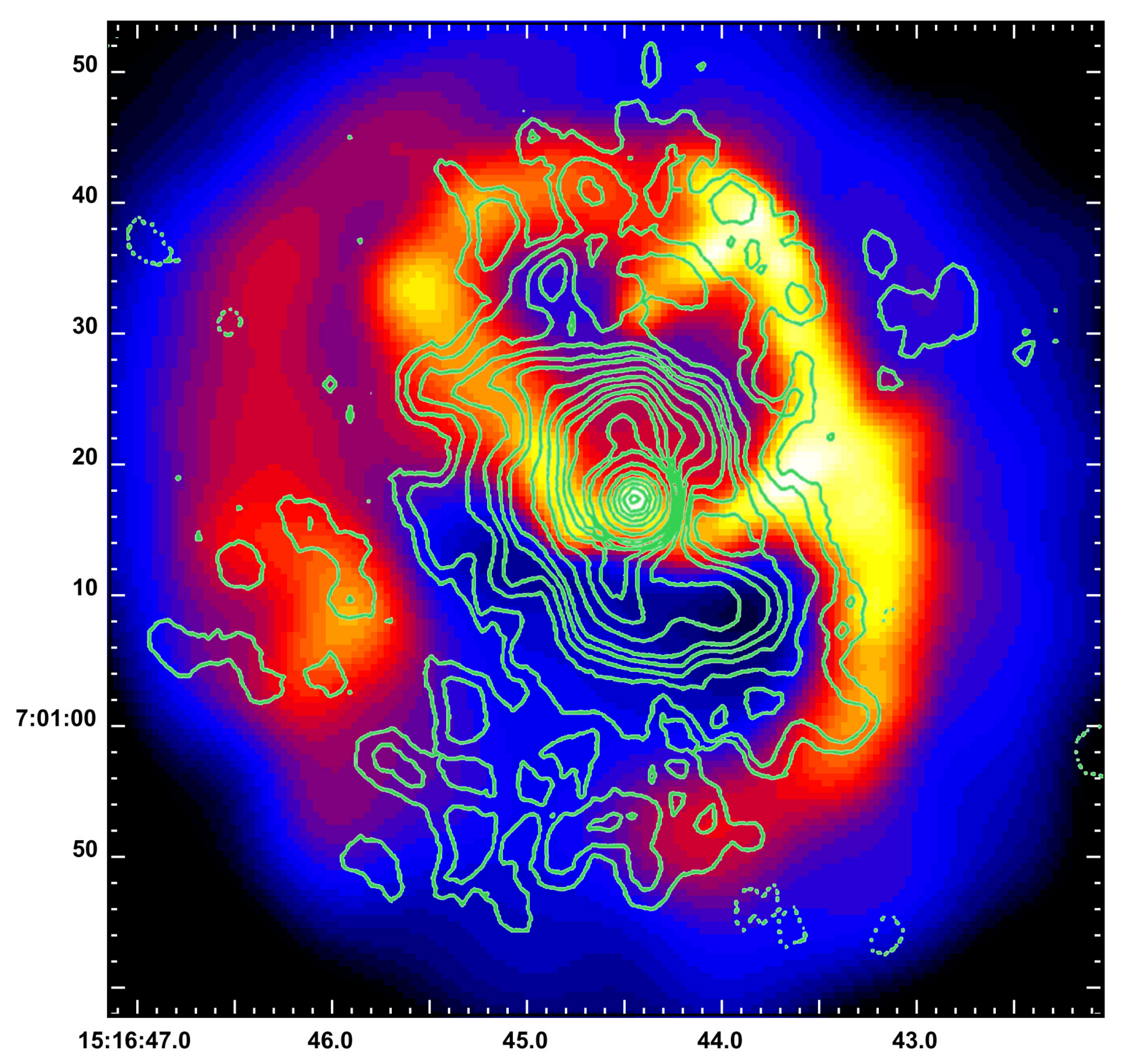
A2052 (Chandra)



(Blanton et al. 2001)

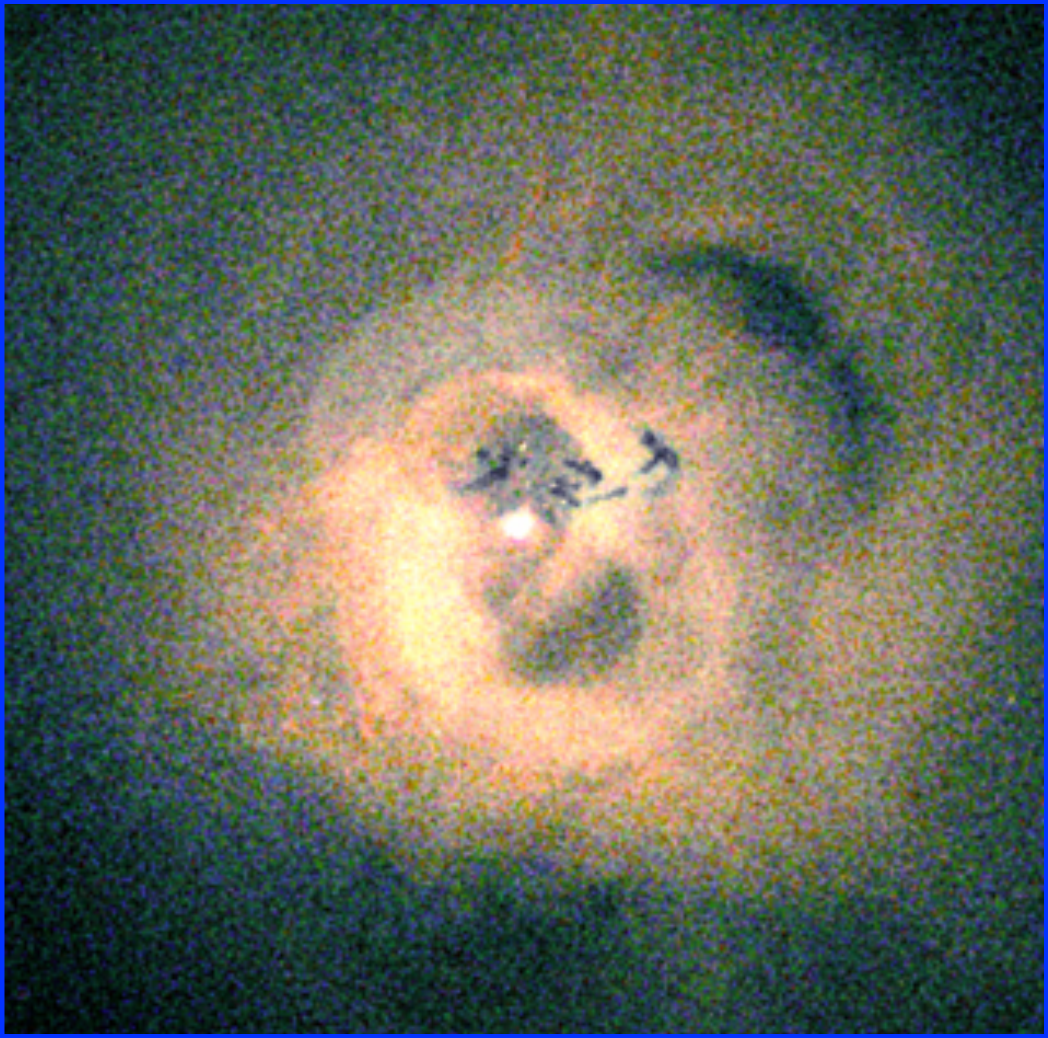
X-ray holes & shells

Radio bubbles – 3C317



Radio Contours

Perseus



Chandra (Fabian et al.)

Radio Bubbles as Calorimeters

- Most bubbles expand subsonically
  - Exceptions: e.g., MS0735 has shocks around bubbles
- Pressure in bubble ≳ pressure in X-ray shell
- Total energy = internal + work done + shock

$$E_{tot} = \frac{1}{(\gamma-1)}\mathrm{PV} + \mathrm{PdV} + E_{shock} = \frac{\gamma}{(\gamma-1)}\mathrm{PV} + E_{shock}$$

Internal bubble energy

Work to expand bubble

Radio Bubbles as Calorimeters

- Radio-mode feedback works (energetically)
  - Solves cluster “cooling flow problem”
  - Limits formation of most massive galaxies
    - But, how does energy go from radio source into X-ray gas??
- Pressure in bubbles ≈ 20 x equipartition radio pressure
- Most of energy in radio lobes ≠ radio plasma
- What are radio lobes made of?
  - Magnetic fields?
  - Low energy relativistic electrons or ions?
  - Diffuse, hot thermal gas?
  - ??

Thermal SZ Effect

If bubbles are full of thermal gas, there will be no holes in the SZ image!

Mildly relativistic gas:

Weaker SZ → weak holes, different spectrum

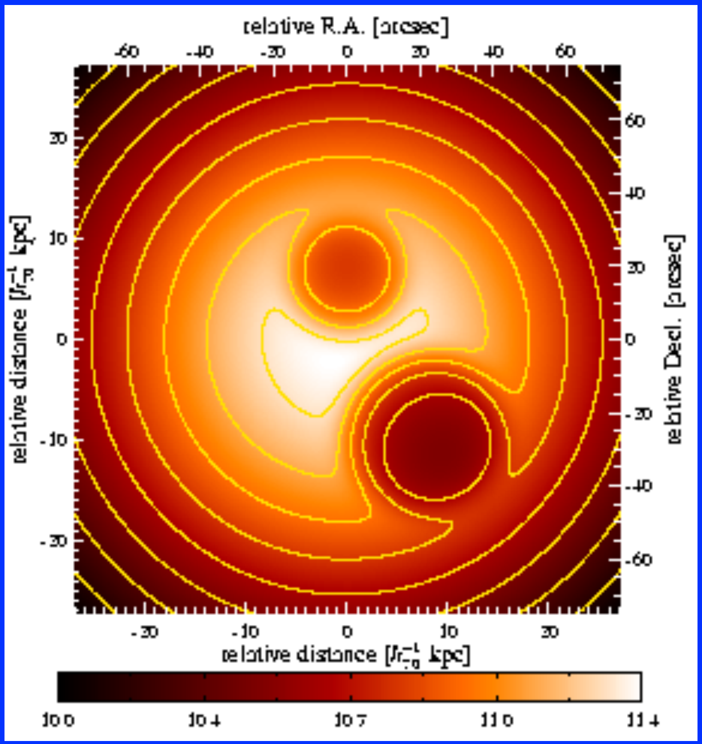
Highly relativistic gas or B:

No SZ effect → strong holes

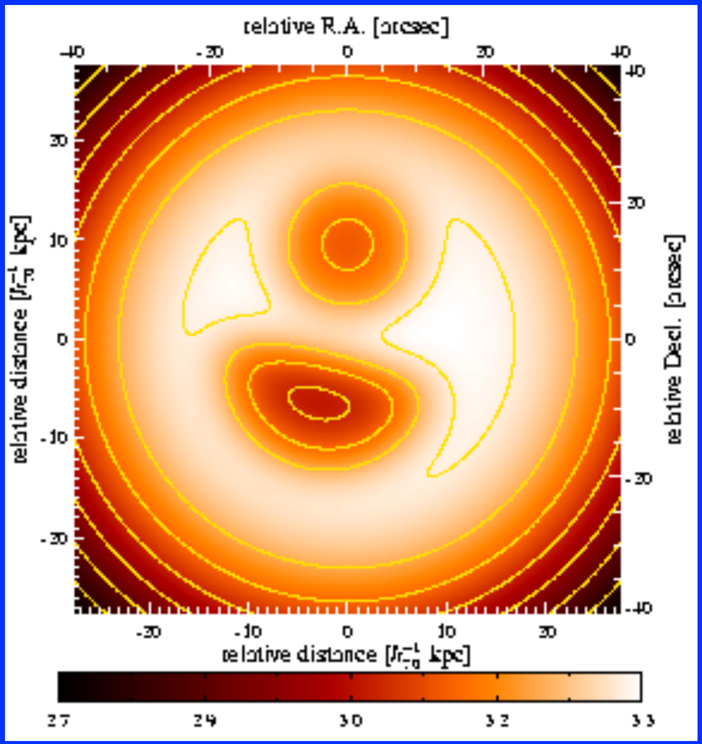
Depth of holes and spectrum → determine energy in thermal gas, low energy CR electrons, and ultra-relativistic material

(Pfrommer et al. 2005)

Simulated Observations with GBT



Perseus



A2052

(Pfrommer et al. 2005)

Conclusions

- High spatial resolution SZ images provide:
  - Dynamical state of clusters
    - Required for use as cosmological probes
  - Merger shocks
    - Are cluster radio relics and halos due to shocks?
  - SZ fluctations give energy in turbulence
- SZ images of cluster radio bubbles determine
  - What are radio sources made of?
  - Constrain mechanism of radio mode feedback in clusters (today) and massive galaxies (at high redshift)

MUSTANG2 on the GBT!!