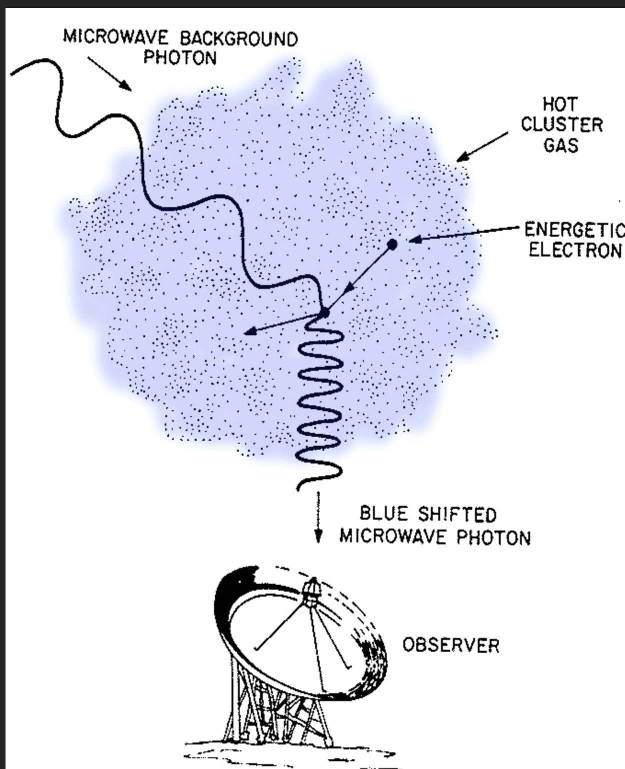
Astrophysics and Cosmology with the Sunyaev-Zel'dovich Effect

Dan Marrone
Hubble/KICP Fellow
University of Chicago

Sunyaev-Zel’dovich Effect

Sunyaev & Zel’dovich (1970, 1972)



From L. van Speybroeck

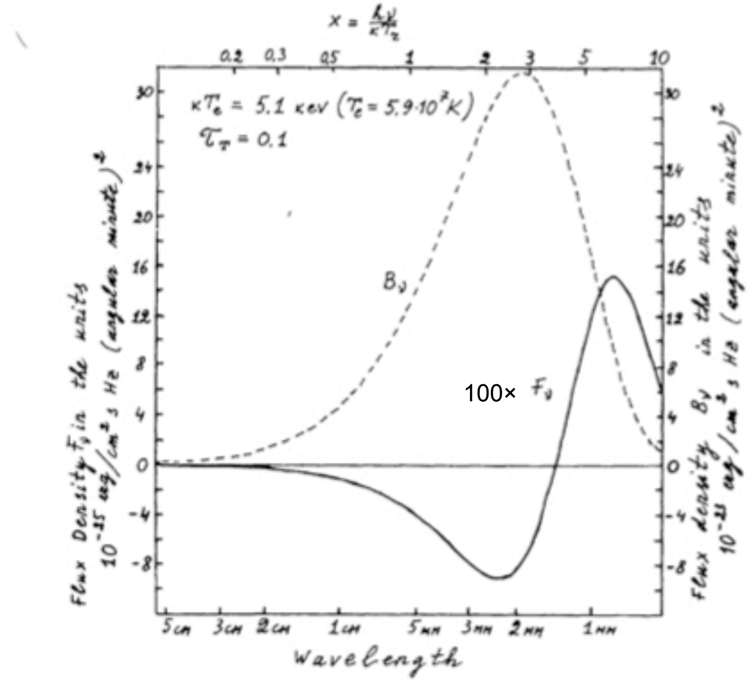


Figure 7 The change of the microwave-background energy density (solid line) in the direction of a cluster of galaxies as a function of the wavelength. The spectrum of blackbody radiation is shown on a different scale for comparison (broken line). The cluster becomes a “positive” radiation source in the submillimeter band, and a “negative” one at longer wavelengths. $T_r = 2.7$ K is assumed.

Sunyaev 1980, ARA&A V18, 537

Sunyaev-Zel'dovich Effect

$$\Delta I_{SZE} = g(x) I_0 y,$$

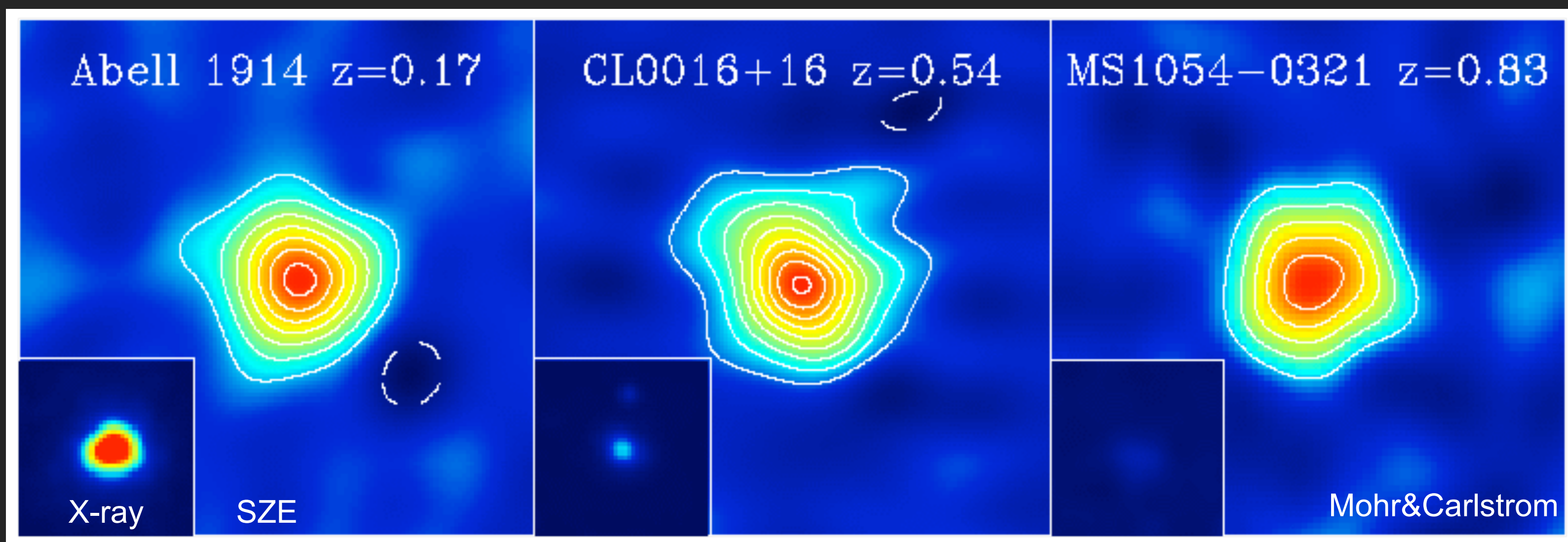
$$y = \int_0^\infty \sigma_T n_e \frac{k_B T_e}{m_e c^2} dl$$

Signal proportional to cluster thermal energy

- Should be an excellent proxy for cluster mass

No cosmological dimming

- Redshift independent cluster detection!
- Compare to $(1+z)^{-4}$ for X-rays
- Allows mass-limited identification of clusters throughout universe



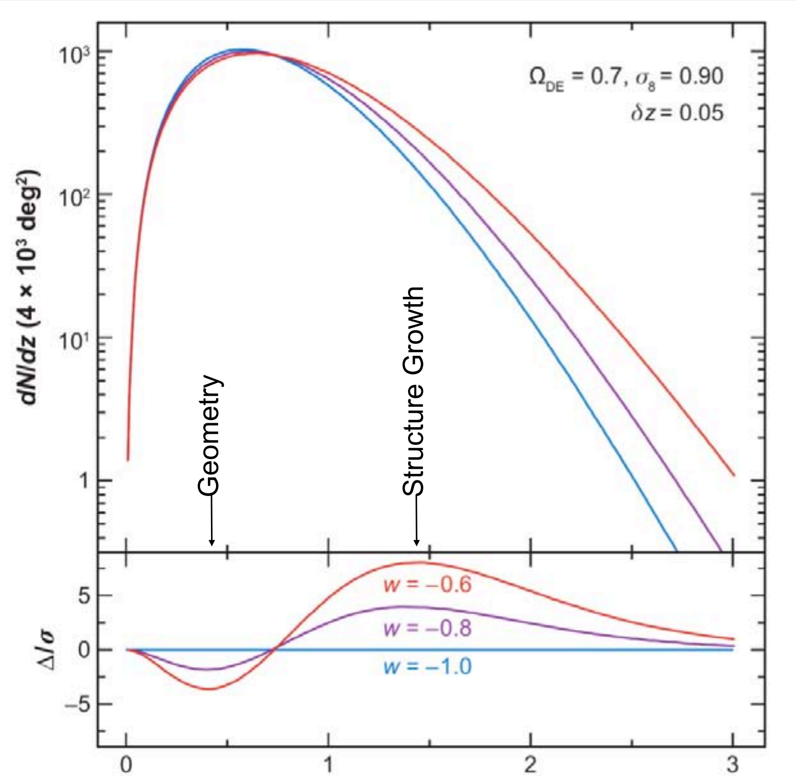
Cosmology: Counting Galaxy Clusters

Abundance of massive things depends sensitively on cosmology

Cluster counts probe dark energy through structure growth, geometry (volume)

Relies on well-understood mass-observable relation, selection function

Proposed techniques:
X-ray, SZ, optical surveys



Mohr (2005)

D. P. Marrone
Submillimeter Universe
November 13, 2010

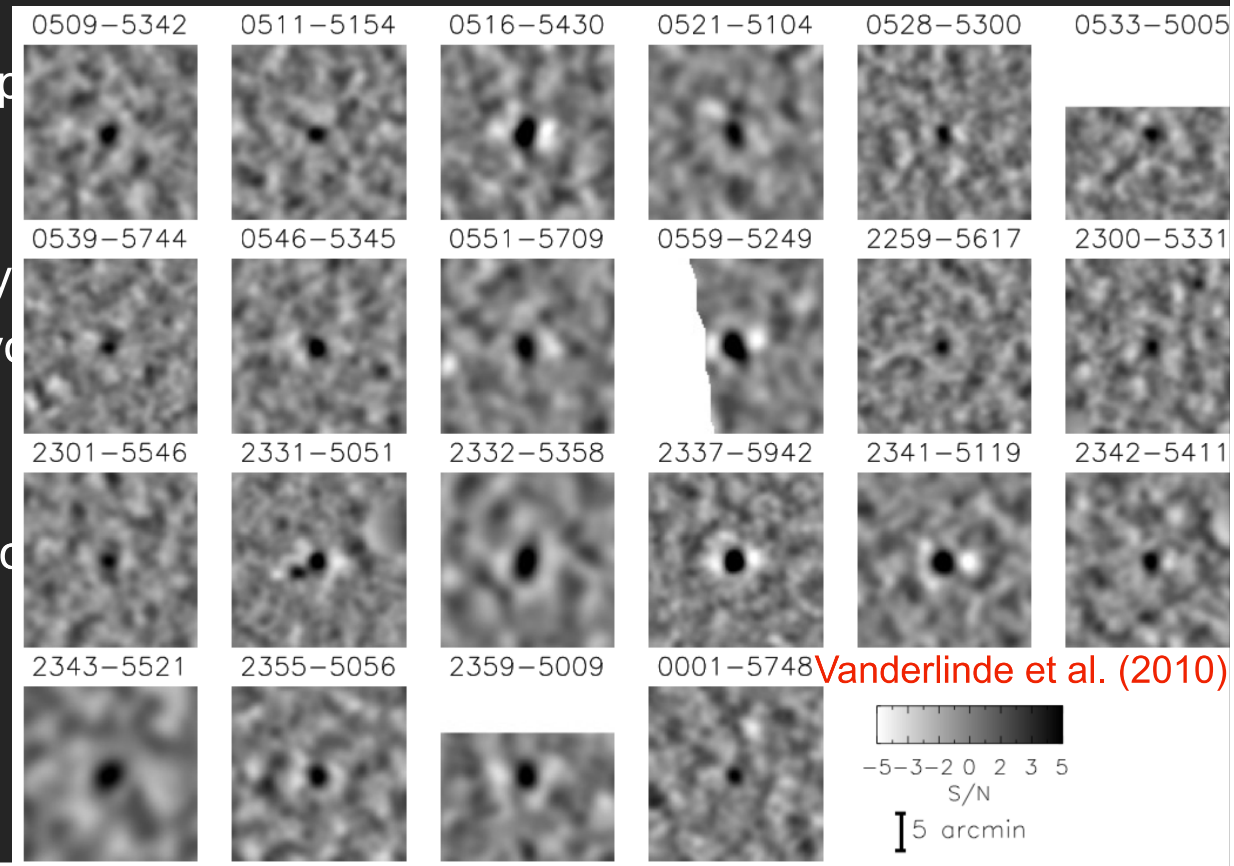
Cosmology: Counting Galaxy Clusters

Abundance of massive things dep
on cosmology

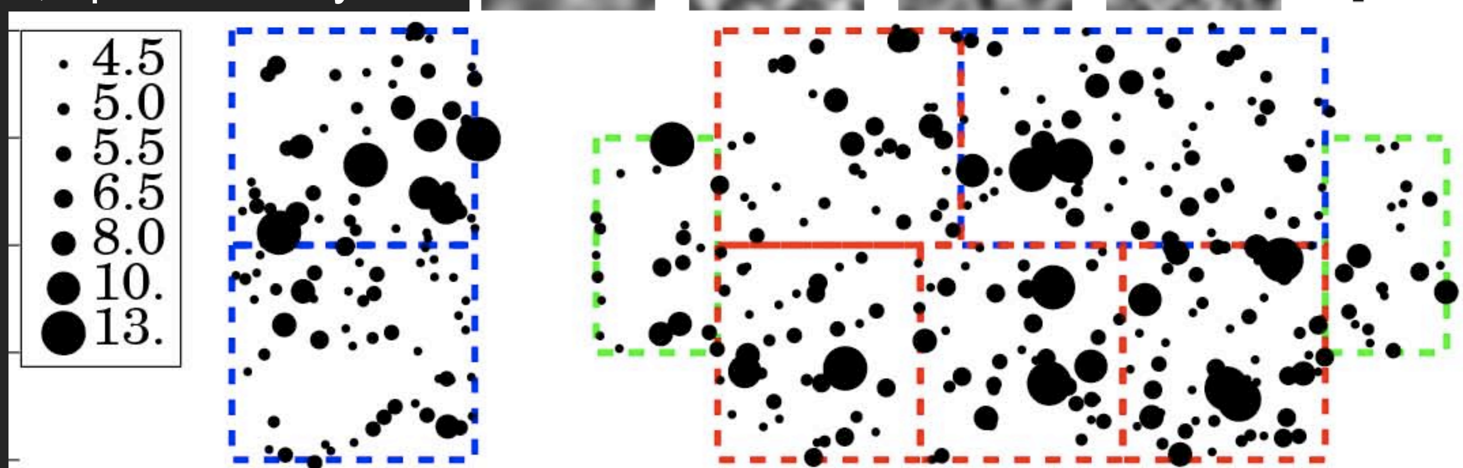
Cluster counts probe dark energy
structure growth, geometry (vo

Relies on well-understood mass-o
relation, selection function

Proposed techniques:
X-ray, SZ, optical surveys



Vanderlinde et al. (2010)



D. P. Marrone
neter Universe
mber 13, 2010

Galaxy Cluster Astrophysics

Astrophysics of galaxy clusters important for surveys, other applications

Simulations reproduce observed clusters fairly well with little astrophysics

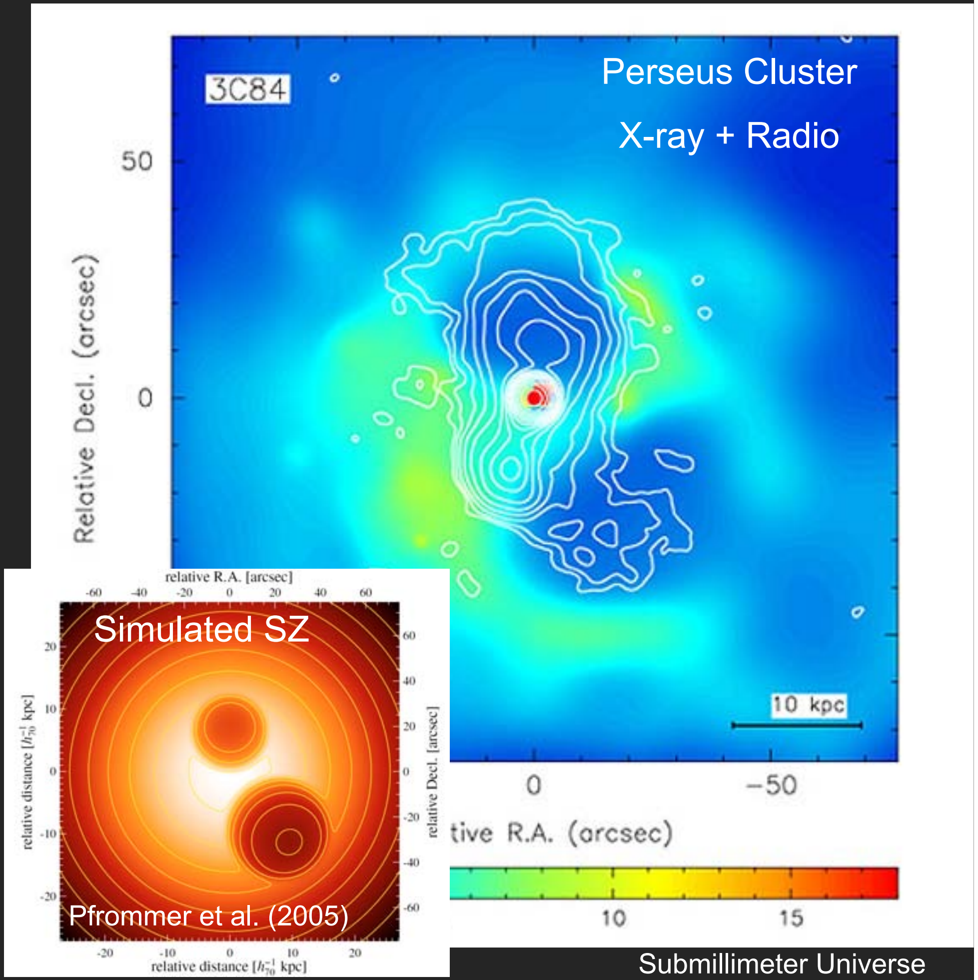
Notable failures in cluster cores (star formation, gas fraction, entropy)

How much will our lack of understanding change cosmology results?

What makes clusters look the way they do?

- AGN feedback
- Cosmic ray pressure
- Magnetic fields
- Gas motions, viscous damping

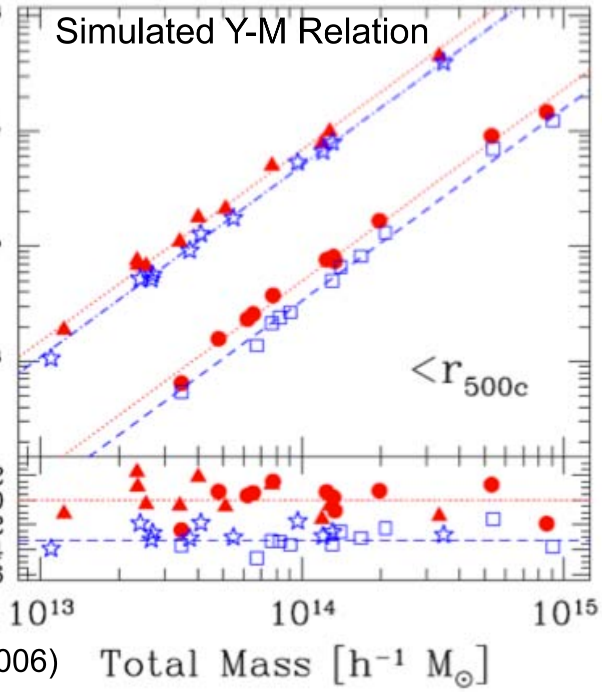
SZ not yet involved in these questions



Cluster Questions

Shouldn't we characterize Y-M scaling
upon which cosmology surveys will rely?

Requires: Representative cluster samples
examined with all available tools



Nagai (2006)

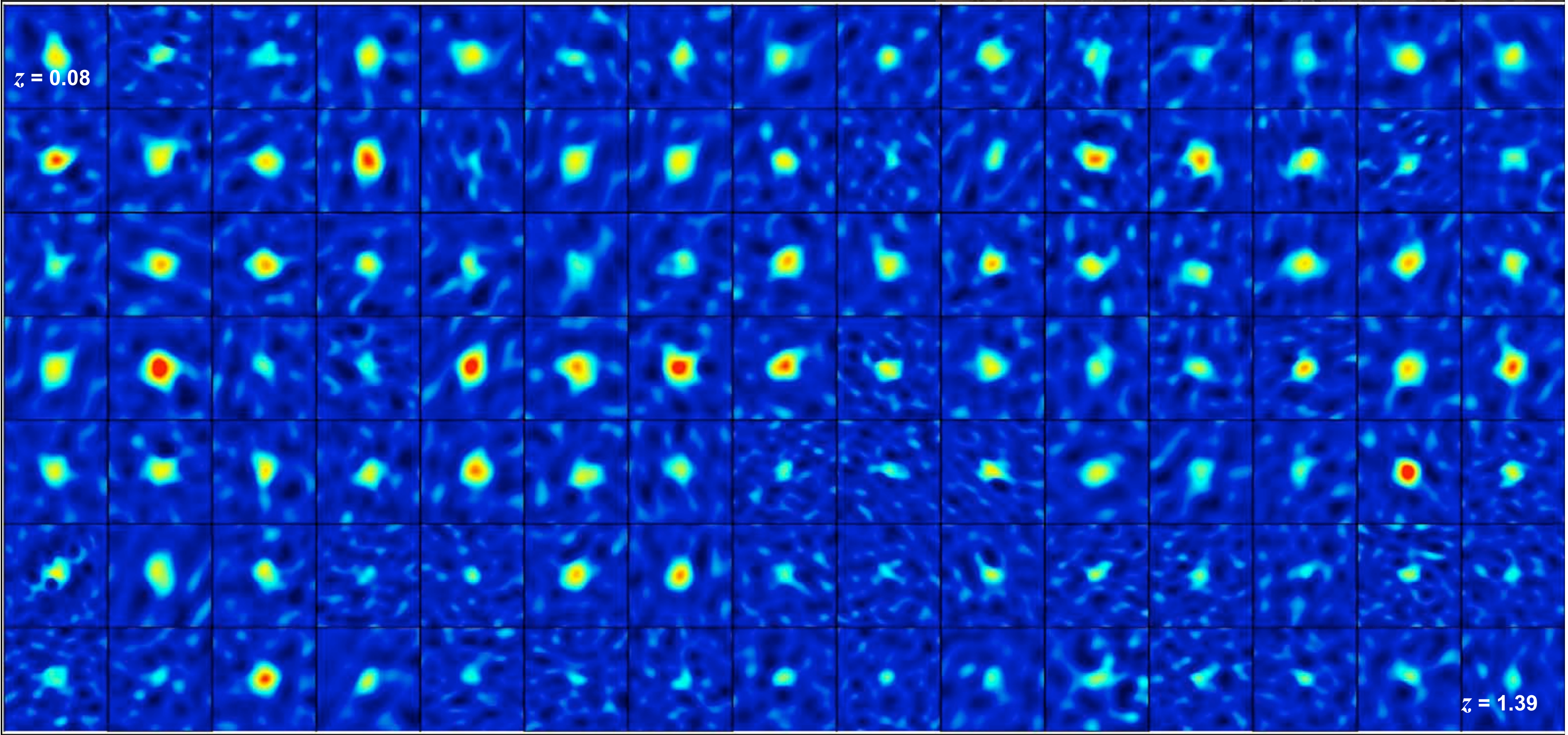
Can we begin to examine cluster
astrophysics with the SZE?

- Substructure, merger effects
- AGN, galaxy effects

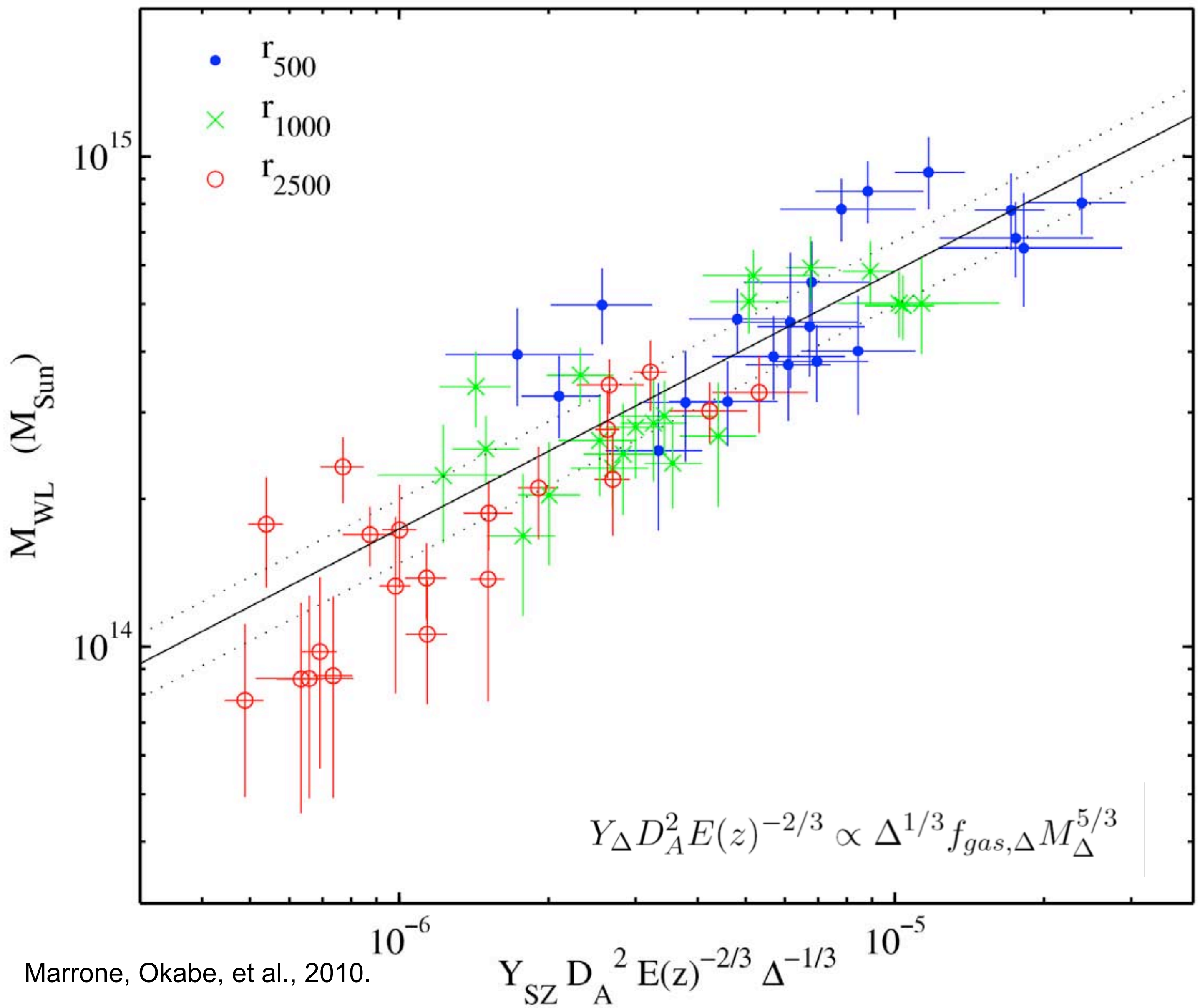
Requires: SZ imaging on large and small scales

Sunyaev-Zel'dovich Array

8-element, SZ-optimized interferometer



Cosmology Calibration: Mass-SZ Relation



Marrone, Okabe, et al., 2010.

LoCuSS

Local Cluster Substructure Survey

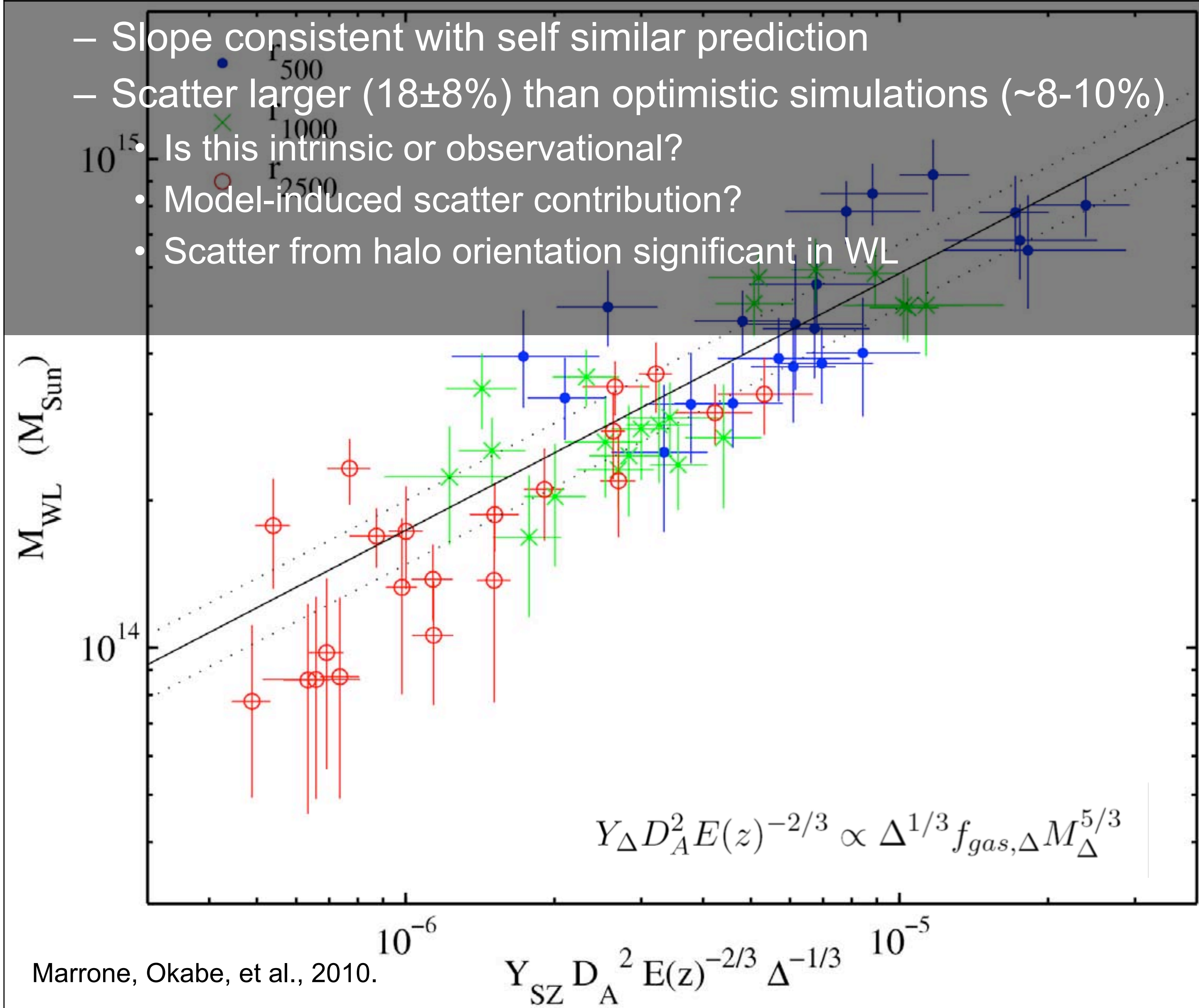
- WL: Okabe et al. (2010)
- SZ: SZA (DPM)

D. P. Marrone
Submillimeter Universe
November 13, 2010

Cosmology Calibration: Mass-SZ Relation

First M_{WL} – Y scaling relation:

- Slope consistent with self similar prediction
- Scatter larger (18±8%) than optimistic simulations (~8-10%)
  - Is this intrinsic or observational?
  - Model-induced scatter contribution?
  - Scatter from halo orientation significant in WL



Marrone, Okabe, et al., 2010.

LoCuSS

Local Cluster Substructure Survey

- WL: Okabe et al. (2010)
- SZ: SZA (DPM)

Cosmology Calibration: Mass-SZ Relation

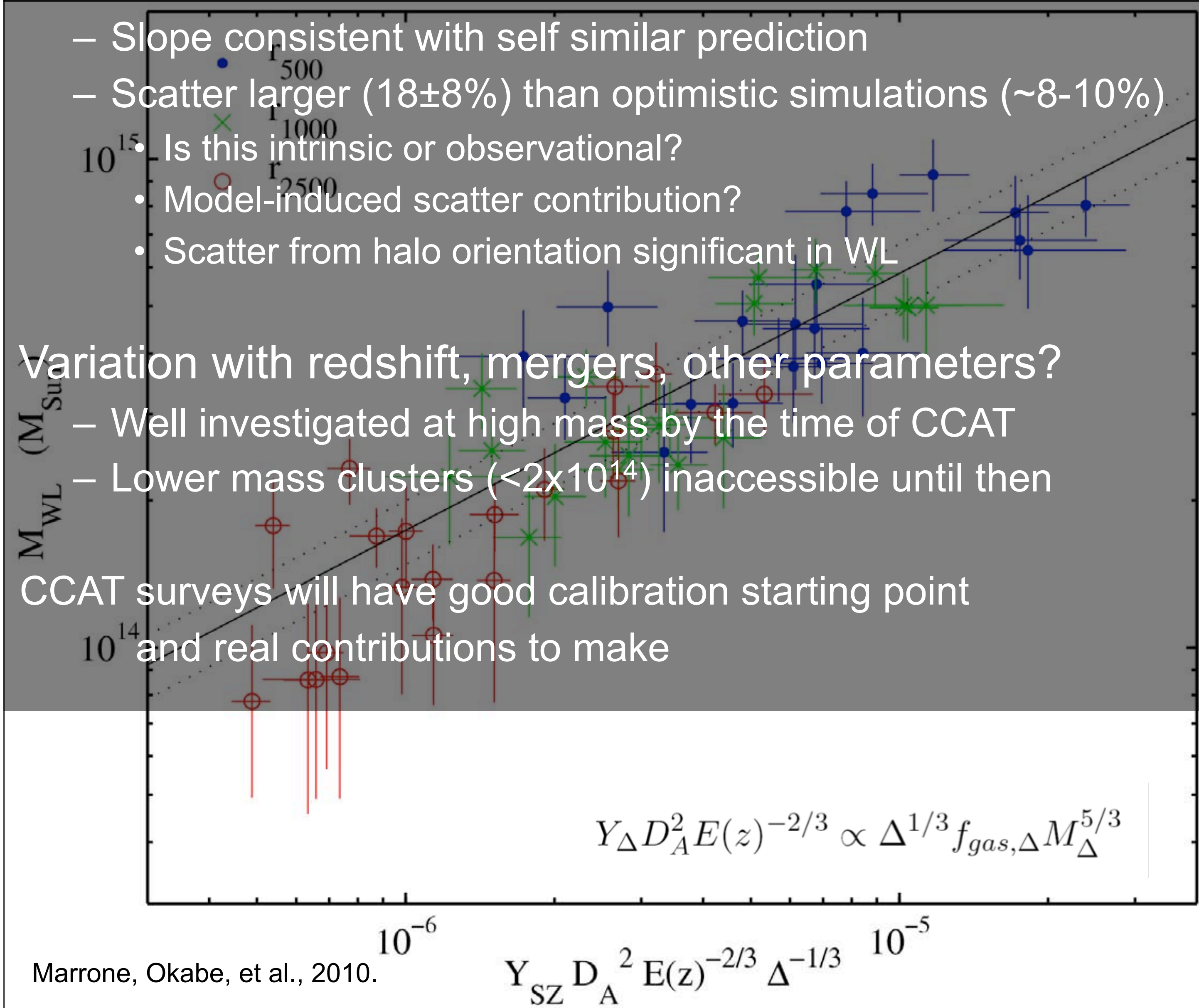
First M_{WL} – Y scaling relation:

- Slope consistent with self similar prediction
- Scatter larger (18±8%) than optimistic simulations (~8-10%)
  - Is this intrinsic or observational?
  - Model-induced scatter contribution?
  - Scatter from halo orientation significant in WL

Variation with redshift, mergers, other parameters?

- Well investigated at high mass by the time of CCAT
- Lower mass clusters (<2x10^{14}) inaccessible until then

CCAT surveys will have good calibration starting point and real contributions to make



Marrone, Okabe, et al., 2010.

LoCuSS

Local Cluster Substructure Survey

- WL: Okabe et al. (2010)
- SZ: SZA (DPM)

Galaxy Cluster Astrophysics

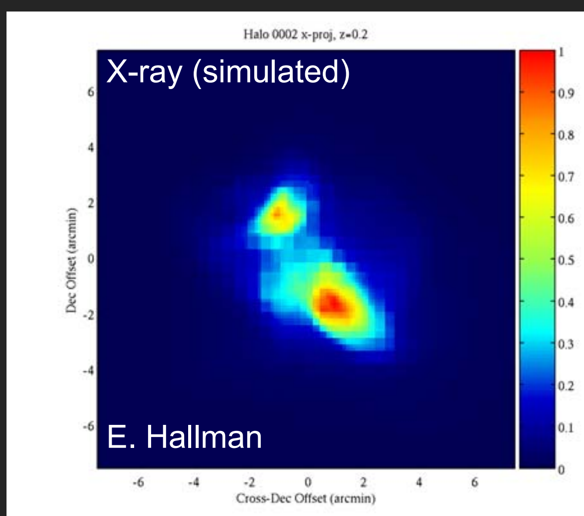
X-ray + SZ trace same ICM gas in different ways

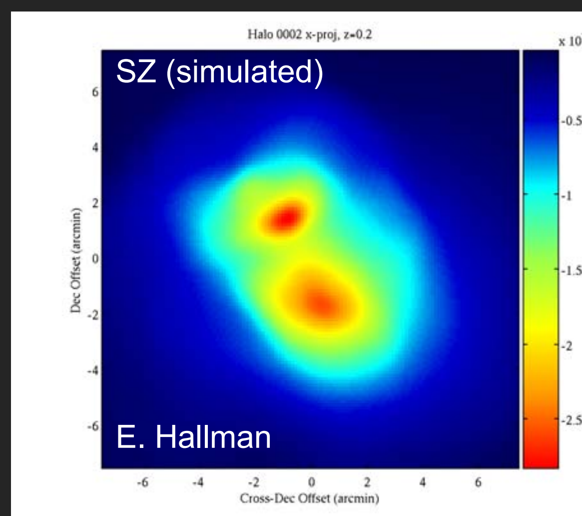
X-ray:

- $S_{X,band} \sim n_e^2$
  - Core (and cool gas)
- Photon spectrum → T_{ew}
- CXO/XMM resolution 1-15”
- Insensitive to large scales
- Inefficient for high-z searches

SZ:

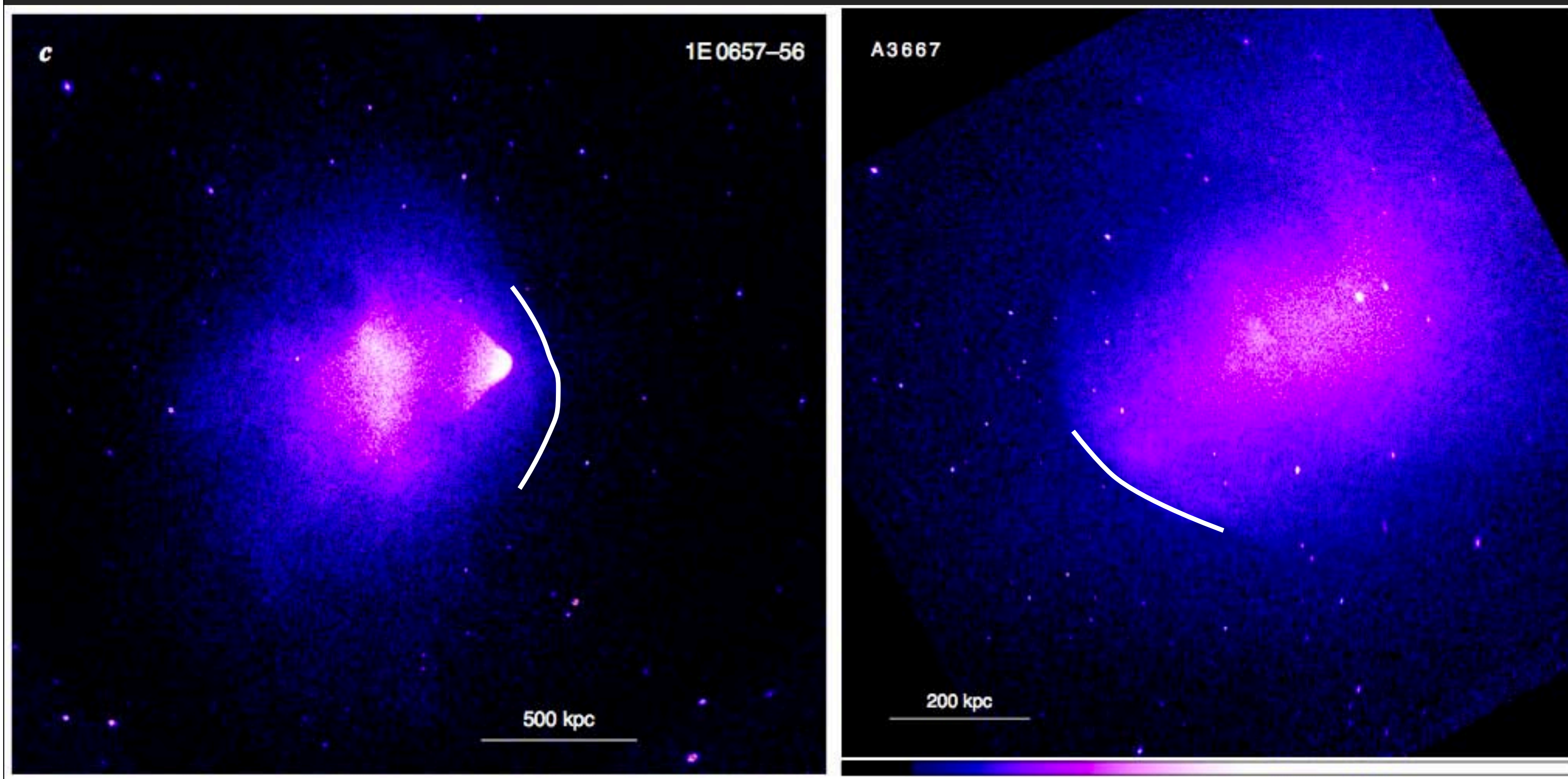
- $Y \sim n_e T_{mw}$
  - Gas to r_{vir}, hot gas
- $Y/\sqrt{S_X} \sim T_{mw}$
- Undiminished at high redshift
- Resolution typically limited





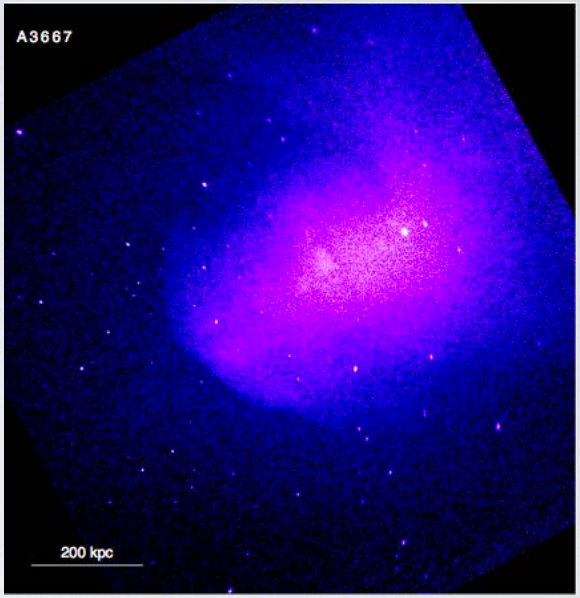
Cluster Astrophysics: Shocks+Fronts

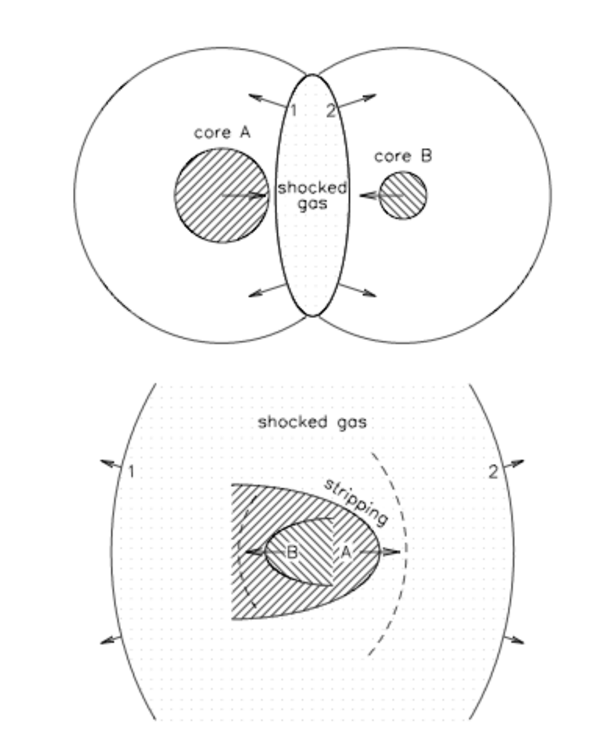
- Clusters only grow through collisions, accretion
  - These processes shape their final appearance, establish mass scalings
  - They also leave long-lived marks



COLD FRONTS

- Sharp discontinuities in density and temperature, with hotter gas in the more diffuse region.
- Approximately isobaric, but *pressure difference depends on velocity of front.*
- Caused by sloshing cool cores and remnants of cool cores in merging systems.

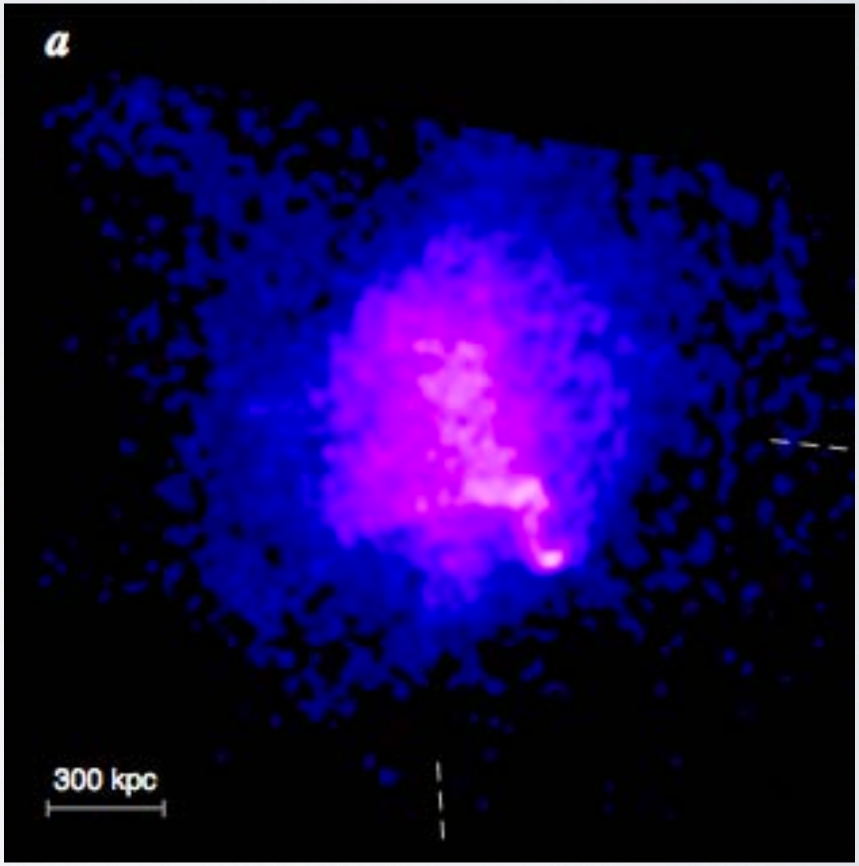




Markevitch and Vikhlinin (2007)

SHOCK FRONTS

- Created during mergers, move quickly out of core into diffuse outer regions.
- Crucial for maintaining SZ vs. mass relation after major merger.
- Only ~2 discovered in X-ray.
- Large pressure difference (since the dense gas is hotter), so easy to see in SZ.

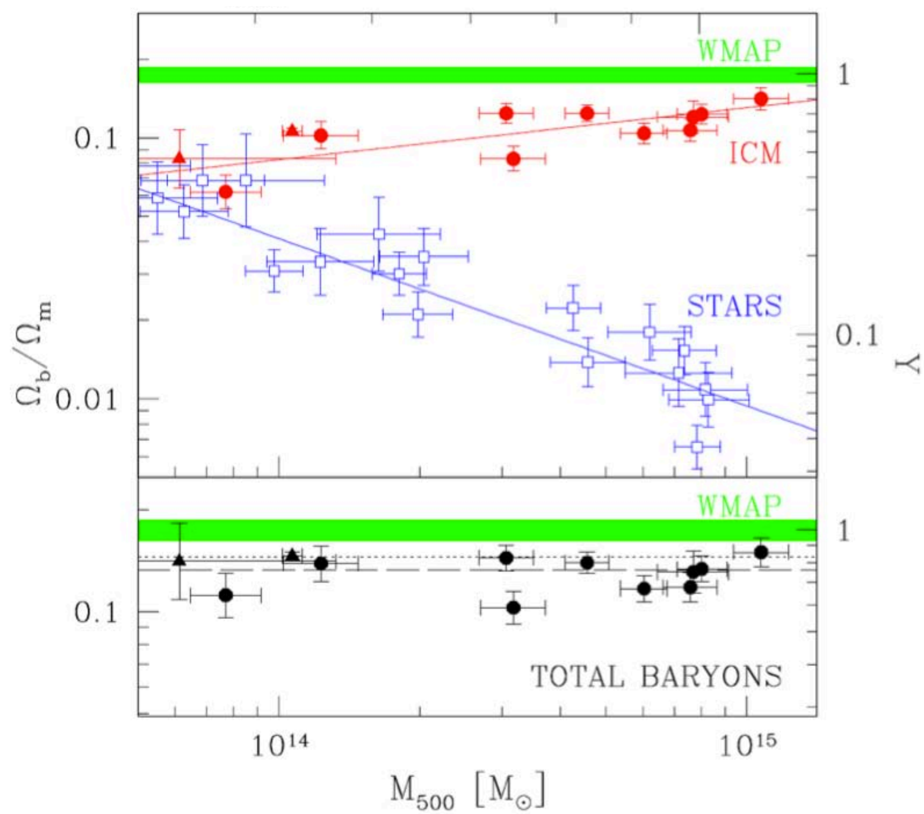


Markevitch and Vikhlinin (2007)

Cluster Astrophysics: Missing Baryons

- Universal baryon fraction is well-measured
  - Galaxy clusters (ICM+stars) apparently have fewer baryons than expected
  - Where are they?

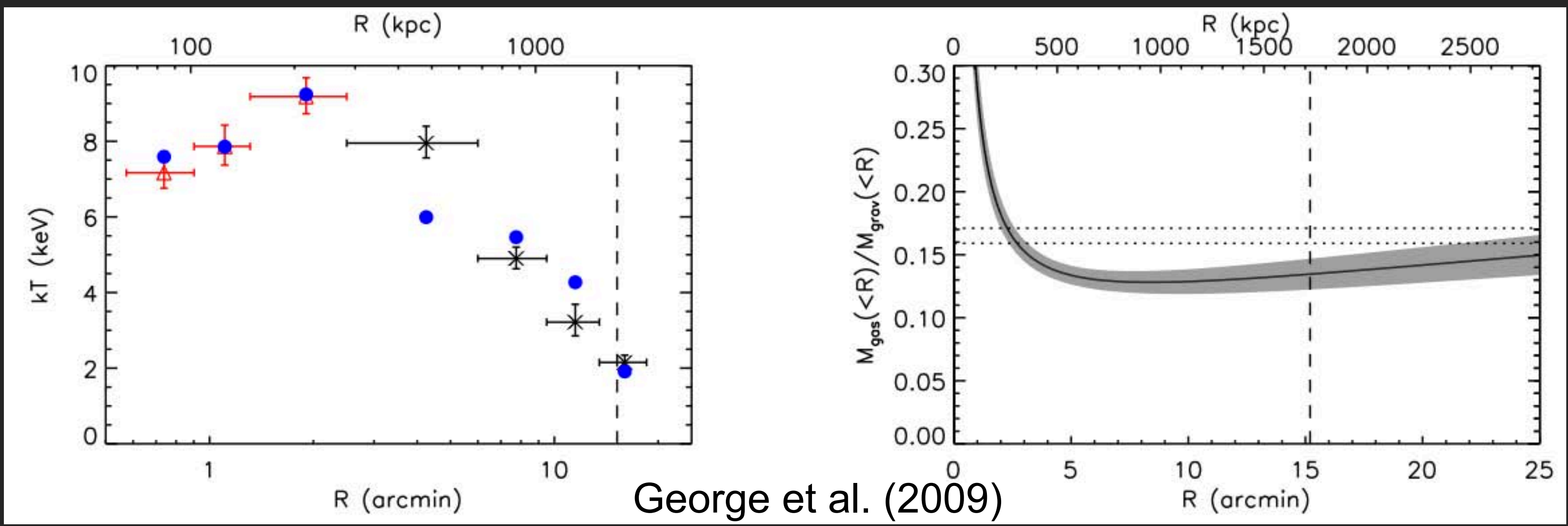
Gonzalez, Zaritsky, Zabludoff 2007



Cluster Astrophysics: Missing Baryons

- Universal baryon fraction is well-measured
  - Galaxy clusters (ICM+stars) apparently have fewer baryons than expected
  - Where are they?

- X-ray measurements difficult at large radius
  - Suzaku beginning to provide some constraints

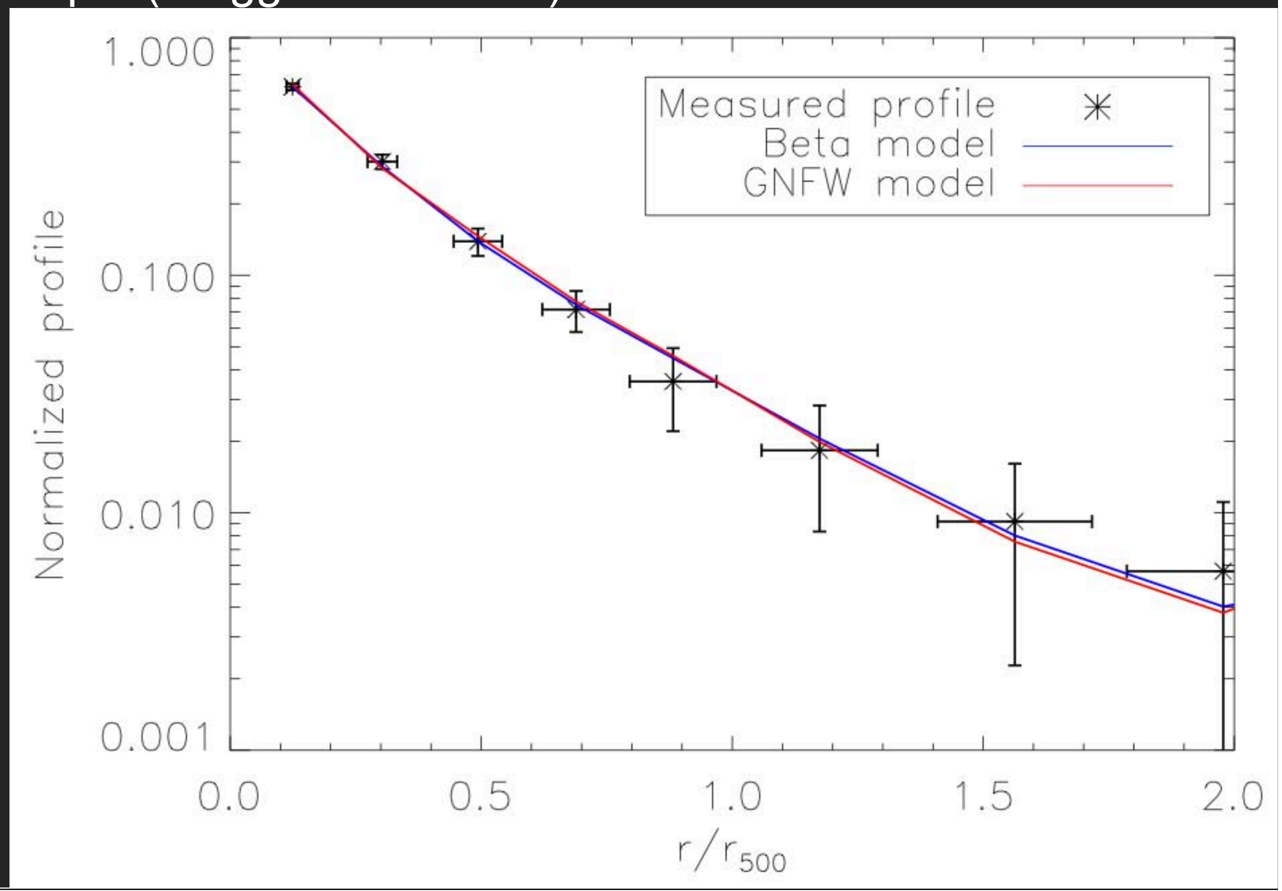


George et al. (2009)

Cluster Astrophysics: Missing Baryons

- Universal baryon fraction is well-measured
  - Galaxy clusters (ICM+stars) apparently have fewer baryons than expected
  - Where are they?

- SZ More naturally probes large radius
  - SPT has made limited attempts (Plagge et. al 2010)
  - Stacking required: CMB



Cluster Astrophysics: Missing Baryons

- Universal baryon fraction is well-measured
  – Galaxy clusters (ICM+stars) apparently have fewer baryons than expected
  – Where are they?

- SZ More naturally probes large radius
  – SPT has made limited attempts (Plagge et. al 2010)

- Limitations of CMB “Noise” can be overcome with CCAT
  – True single-object pressure profiles

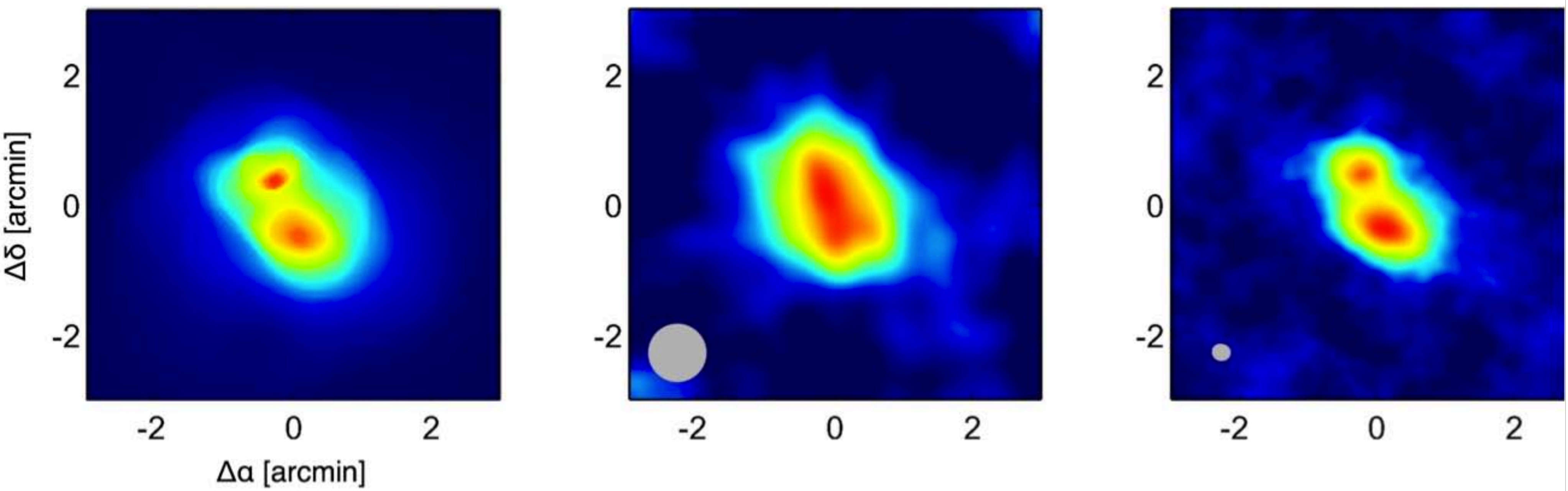
High-Resolution, Sensitivity SZ Effect Imaging

CARMA Heterogeneous array interferometry

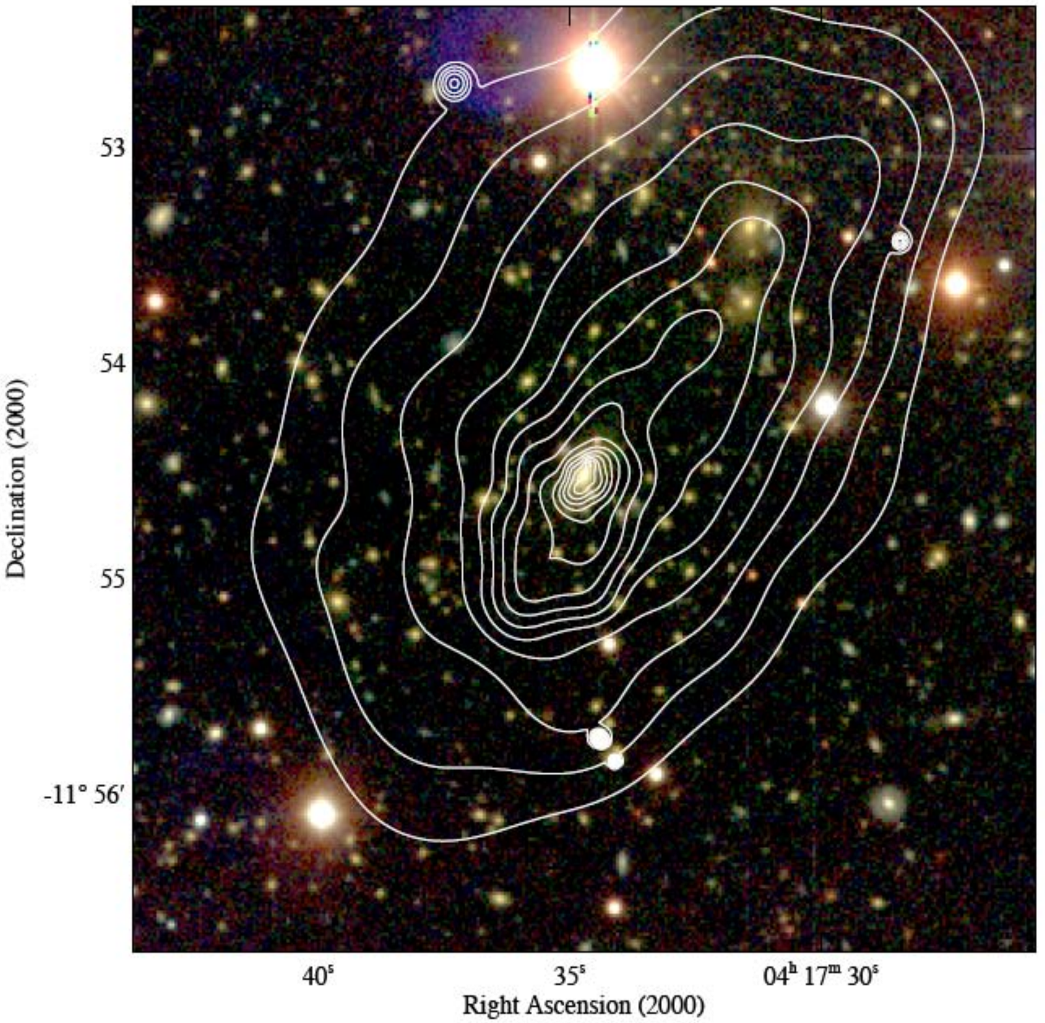
- Different telescopes for different angular scales
- CARMA+SZA – 23 elements
  - 6 x 10.4 m
  - 9 x 6.1 m
  - 8 x 3.5 m

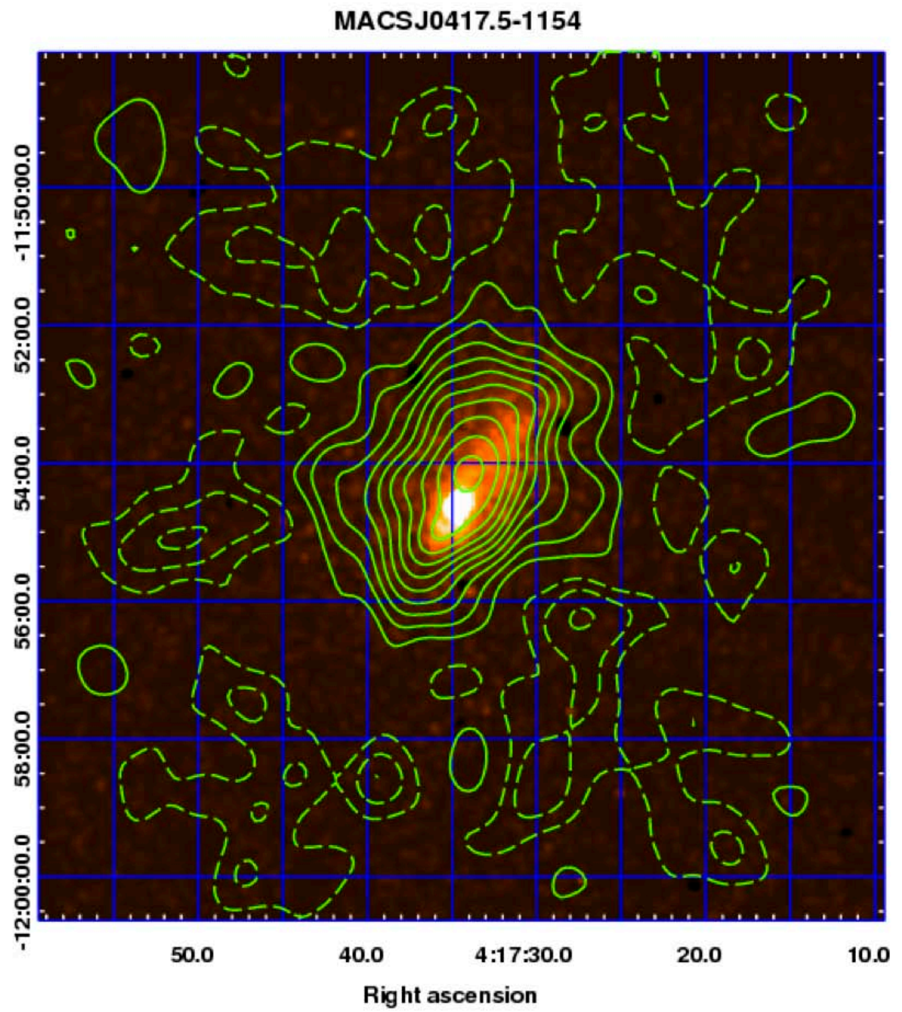
Sensitivity, angular resolution, dynamic range all significantly improved

Detailed (10-30”) cluster imaging becomes possible



SZ Effect Imaging: MACS0417





SZ Effect Imaging: CCAT

- CMB removal advantage will make huge difference at large radius
- Collecting area and speed will give first(?) look at virial shock