The Sunyaev-Zeldovich Effect as a Probe of Black Hole Feedback

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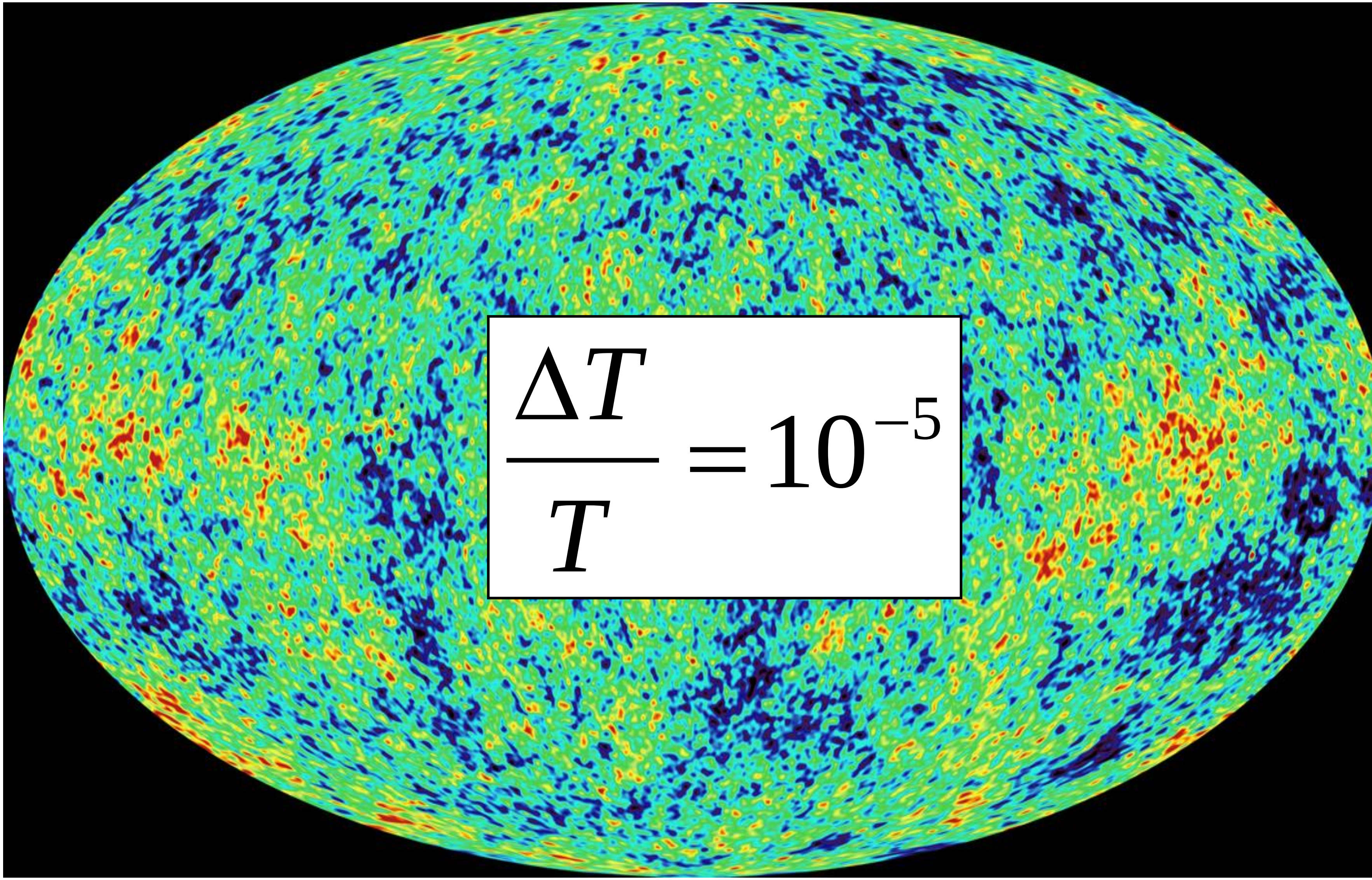
OUTLINE

- The Cosmic Microwave Background
- The Sunyaev-Zeldovich Effect (SZ)
- Black Hole Feedback (AGN Feedback)
- SZ from Black Hole Feedback
- Analytic Model (Chatterjee & Kosowsky 07, ApJL, 661, L113)
- Numerical Simulation (Chatterjee, Di Matteo, Kosowsky & Pelupessy 08, MNRAS, 390, 535)
- Data Analysis (Chatterjee, Ho, Newman & Kosowsky 09, To be submitted in ApJ)
- Conclusion and Future Work

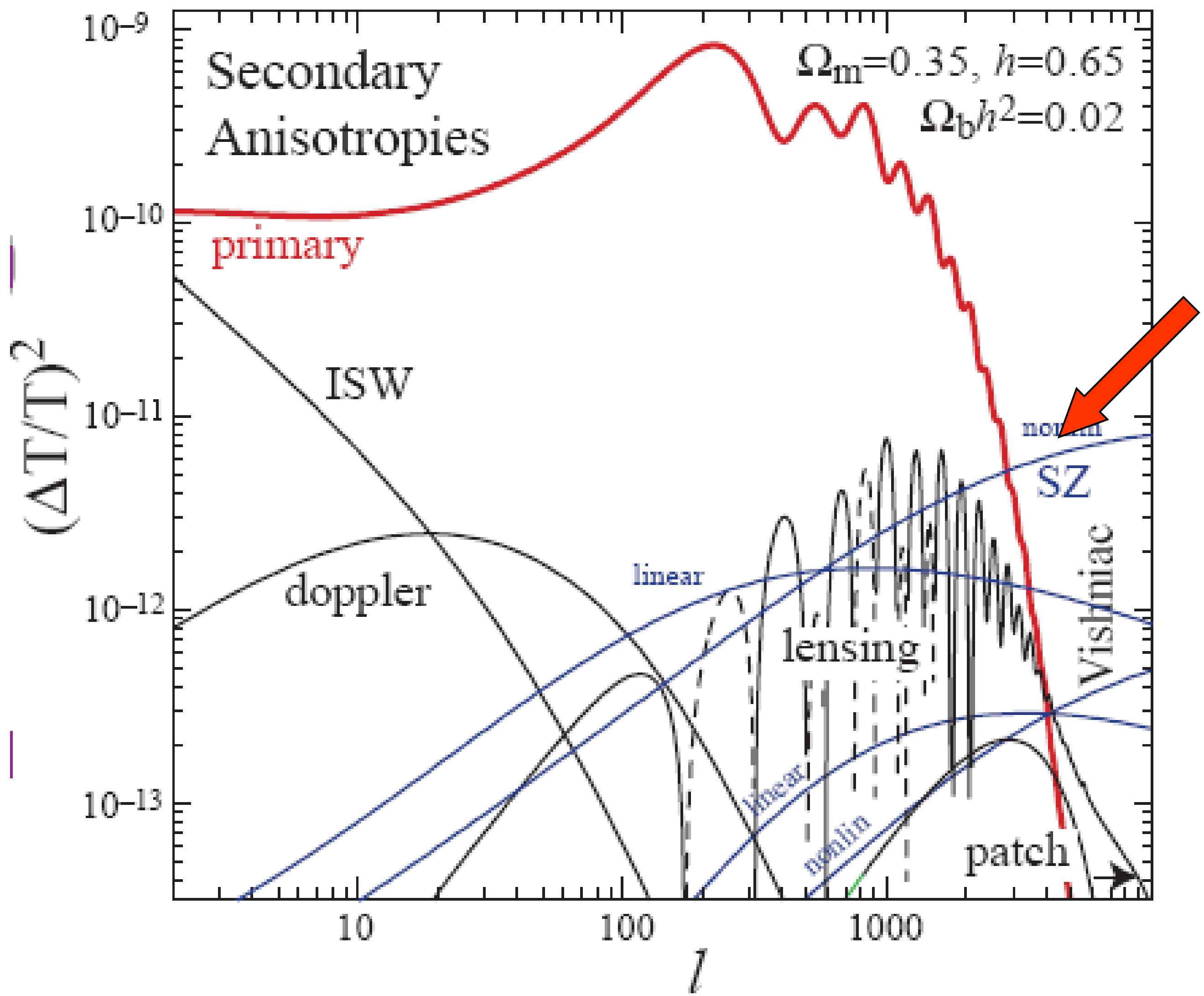
Primary Anisotropy in the CMB



$$\frac{\Delta T}{T} = 10^{-5}$$

Courtesy: WMAP science team

Secondary Anisotropies in the CMB

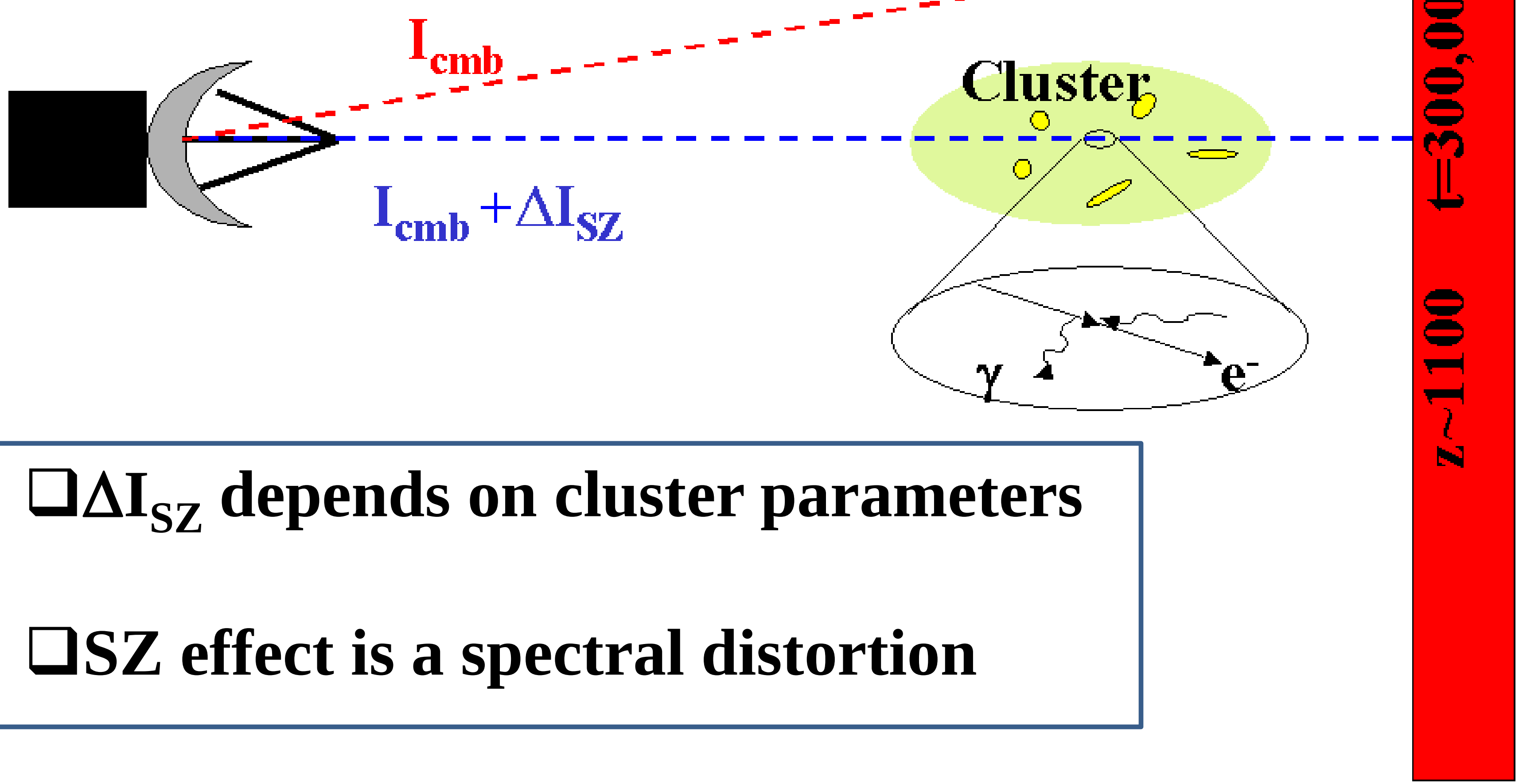


Hu 2000

Sunyaev-Zeldovich Effect

Photo Credit: BIMA group

Inverse Compton scattering of CMB photons by hot electrons in the intracluster plasma



- ❑ ΔI_{SZ} depends on cluster parameters
- ❑ SZ effect is a spectral distortion

Mathematical Description

$$\Delta I = I_0 g(x) y \ldots\ldots\ldots(1)$$

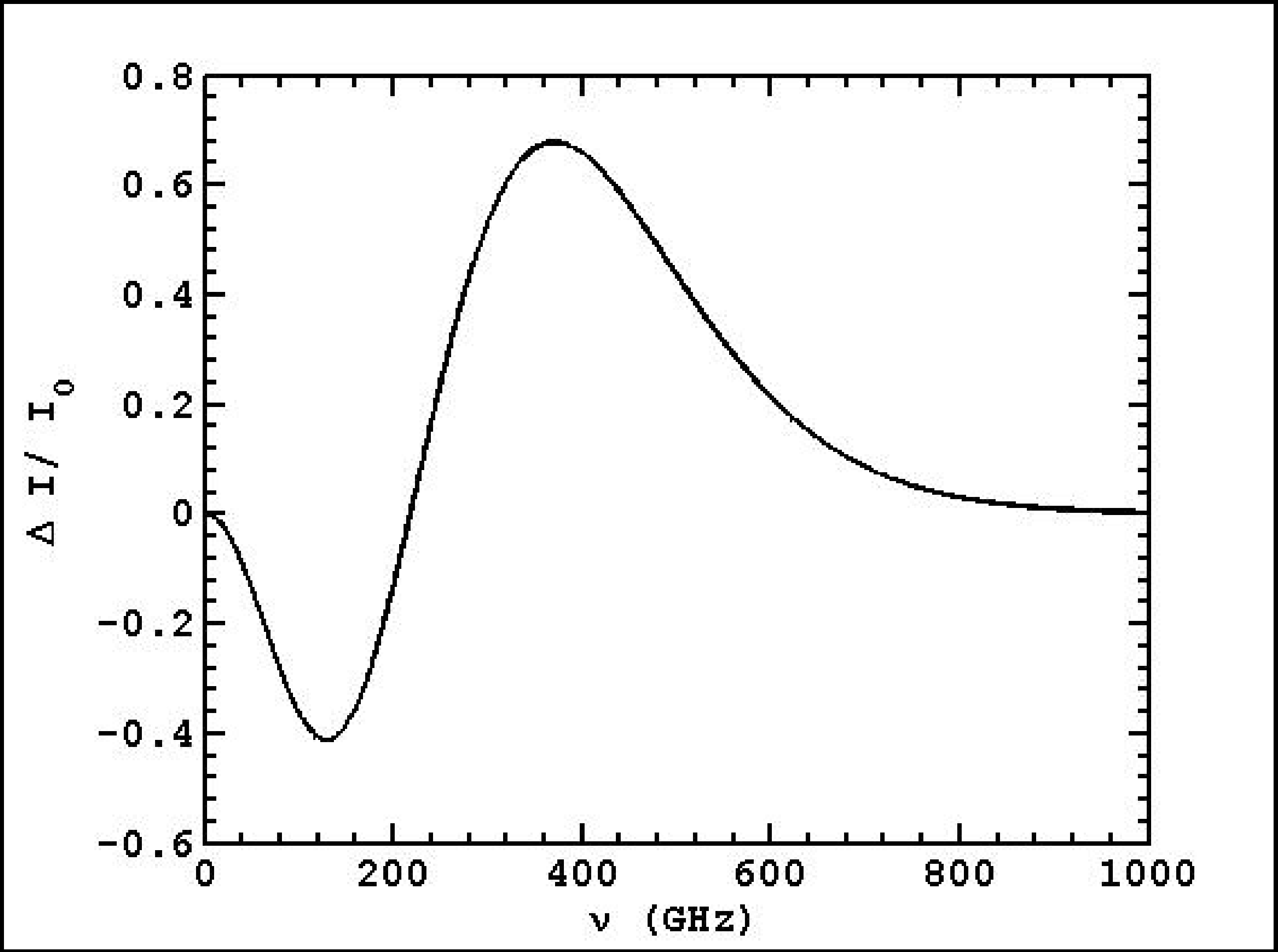
$$\Delta T = T_0 f(x) y \ldots\ldots\ldots(2)$$

$$g(x) = \frac{e^x x^4}{(e^x - 1)^2}(x\coth(x/2) - 4)$$

$$f(x) = (x\coth(x/2) - 4) \qquad x = \frac{h\nu}{K_B T_0}$$

$$y = 2\int dl\,\sigma_T n_e(M,z)\frac{K_B T_e(M,z)}{m_e c^2}$$

Sunyaev-Zeldovich Spectrum



Chatterjee : Thesis

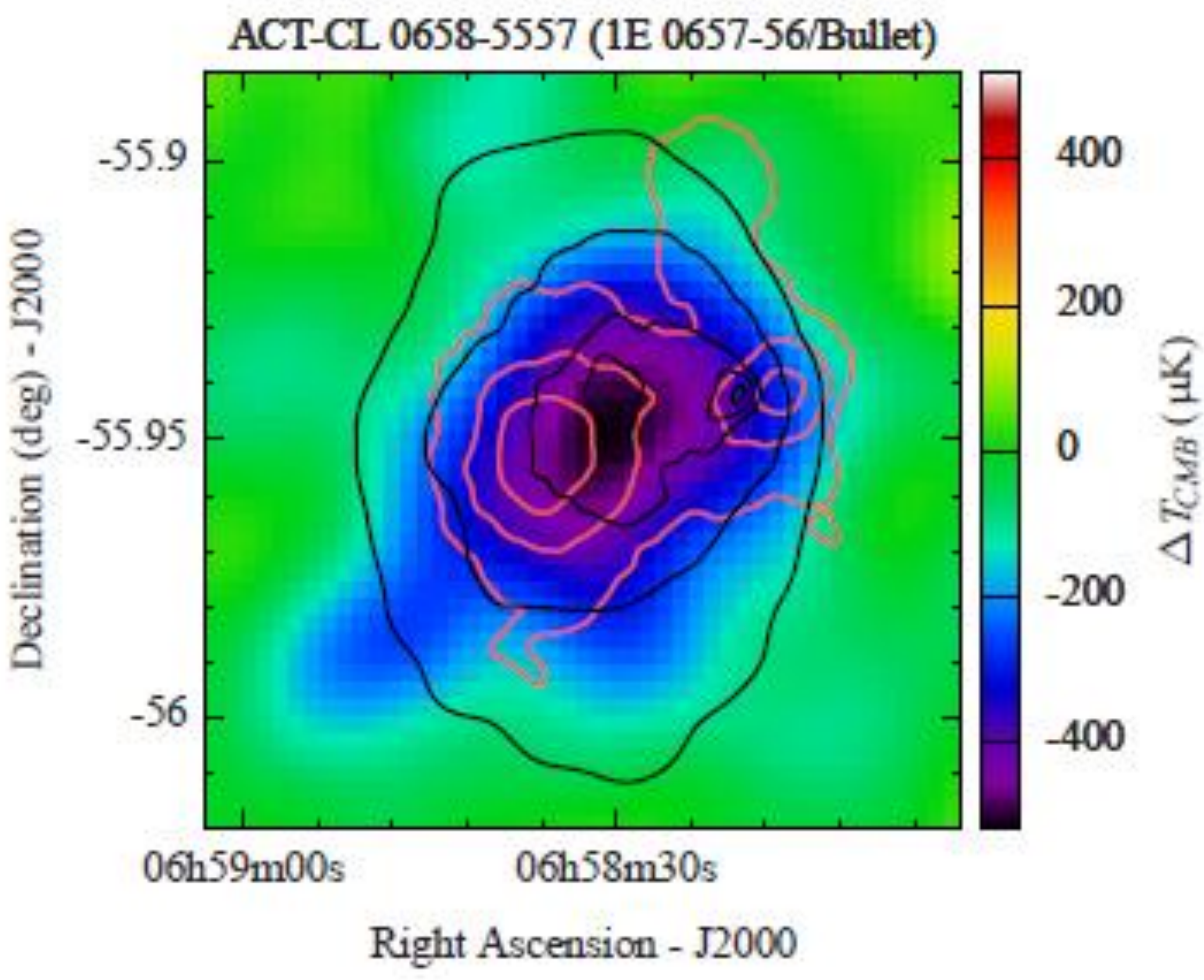
Null Frequency
220 GHz

Galaxy Cluster Facts

- Cluster Temperature: **1-10 kev (10^7-10^8 K)**
- Electron density: **10^{-2} - 10^{-4} /cm^3**
- Y distortion : **10^{-4}**
- ΔT : 100 μK
- Mass : **$10^{14} M_{sun}$-$10^{15} M_{sun}$**

SZ effect is an effective probe for detecting accumulation of hot gas in the universe

Bullet Cluster at 148 GHz



Atacama Cosmology Telescope (Hincks et al. 2009)

Black: X-ray contours; Orange: Weak Lensing contours;

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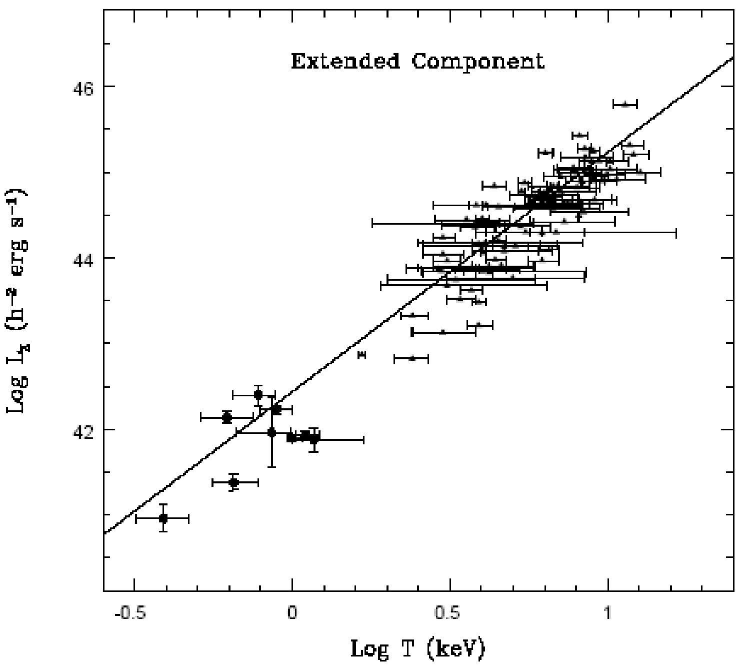
Lx-T Relation in Clusters

- Gas in clusters are heated: cluster potential well
- Self- similar models suggest $L_X \sim T^2$ for the gas in clusters.
- But observations show $L_x \sim T^3$ roughly.
- Departure from self-similar

Mulchaey & Zabludoff 98



$$LogL_X = (42.44 \pm 0.11) + Logh^{-2} + (2.79 \pm 0.14) LogT$$

Recently confirmed by Andersson et al. 2009 with XMM

The Cooling Flow Problem

- X-ray surface brightness peaks at cluster centers
- Cooling is maximum at cluster centers
- Cooling inflow due to pressure gradient
- Lack of expected cooling flow

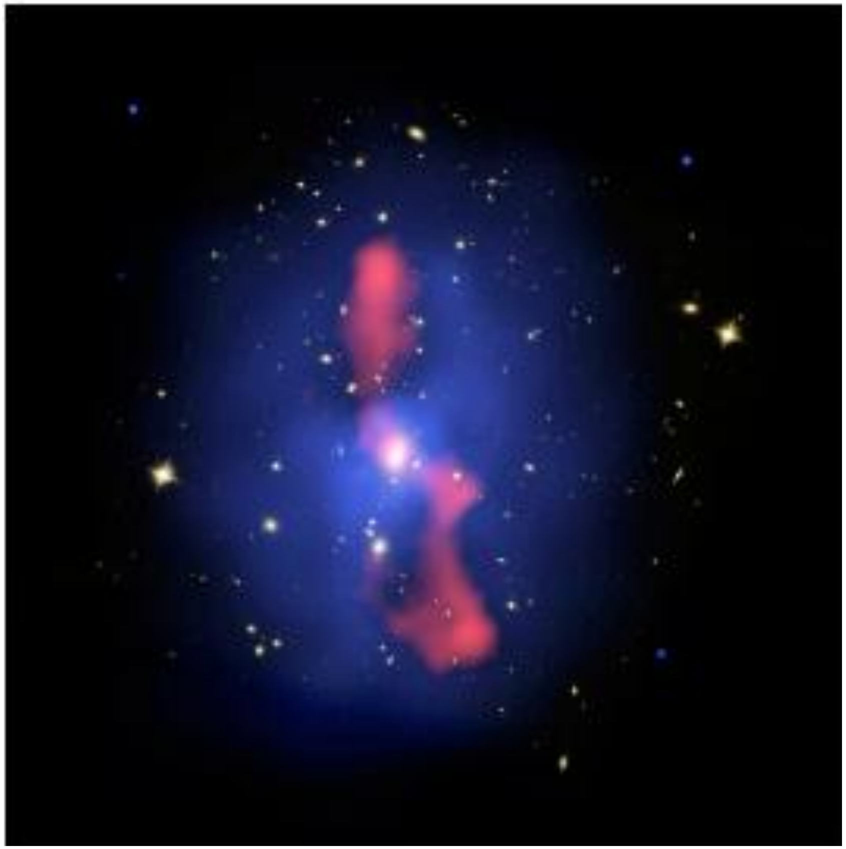
See Peterson & Fabian 2006 for a review

The Missing Piece (Feedback from AGN)

(e.g. Binney & Tabor 1995)

- Non-Gravitational heating mechanism in clusters
- Lack of cooling flow

Black Hole Feedback in Galaxy Cluster



HST image of MS0735.6 + 7421 cluster
Chandra X-ray image in blue
VLA radio image in red

McNamara & Nulsen 2007

Study of hot gas in black hole environments via SZ distortion

(Natarajan & Sigurdsson 99, Platania et. al 02, Lapi et. al 03)

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Theoretical Model

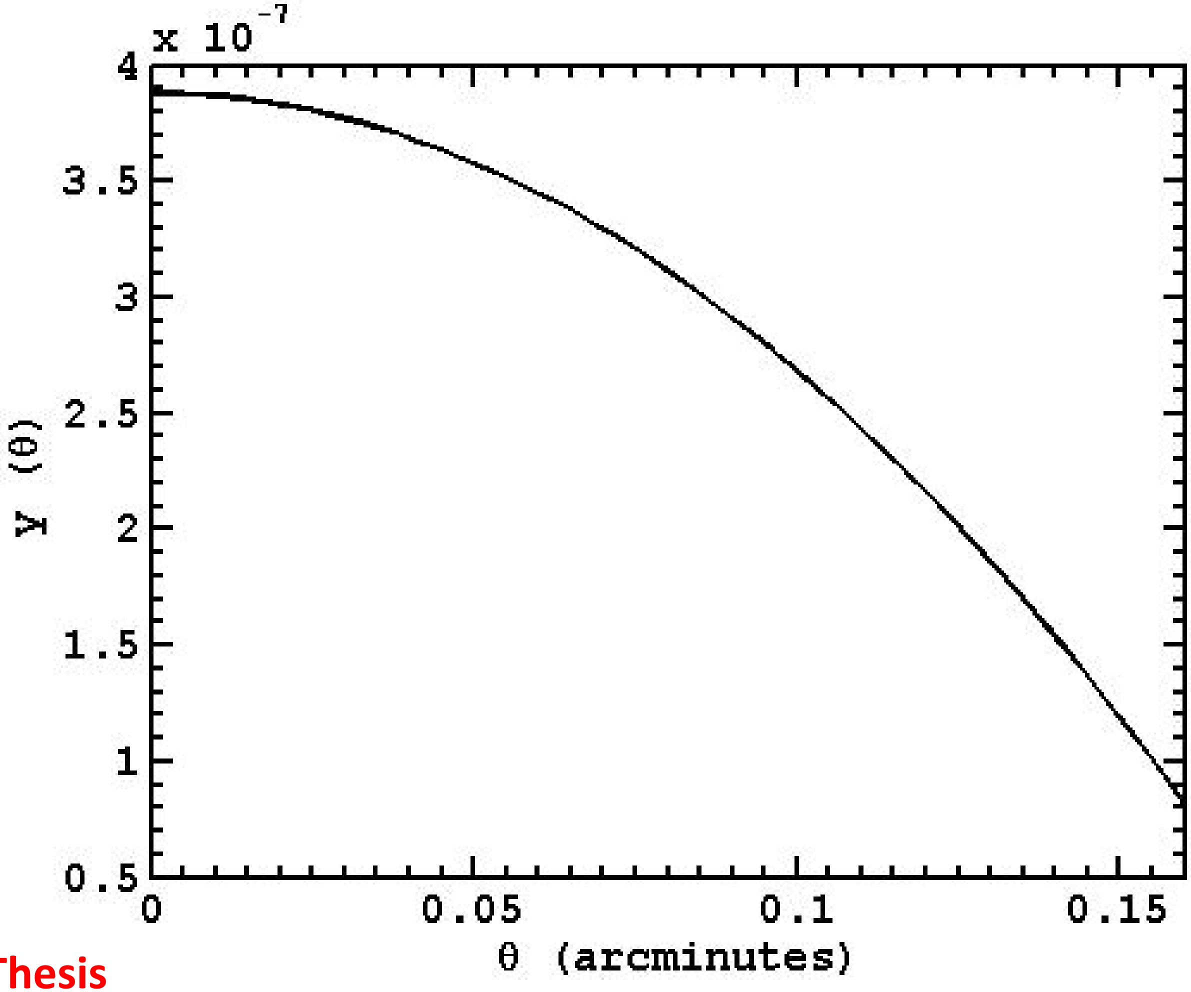
➢ The energy outflow from an AGN

⇒ **Scannapieco & Oh 2004**

- Energy is ejected into the IGM in the form of a spherical bubble.
- This bubble expands as a blast wave into the surrounding medium. (Sedov-Taylor solution)
- The radius and temperature of the bubble is given as a function of time.
- Uniform temperature and density within the bubble

y-Distortion from the Model

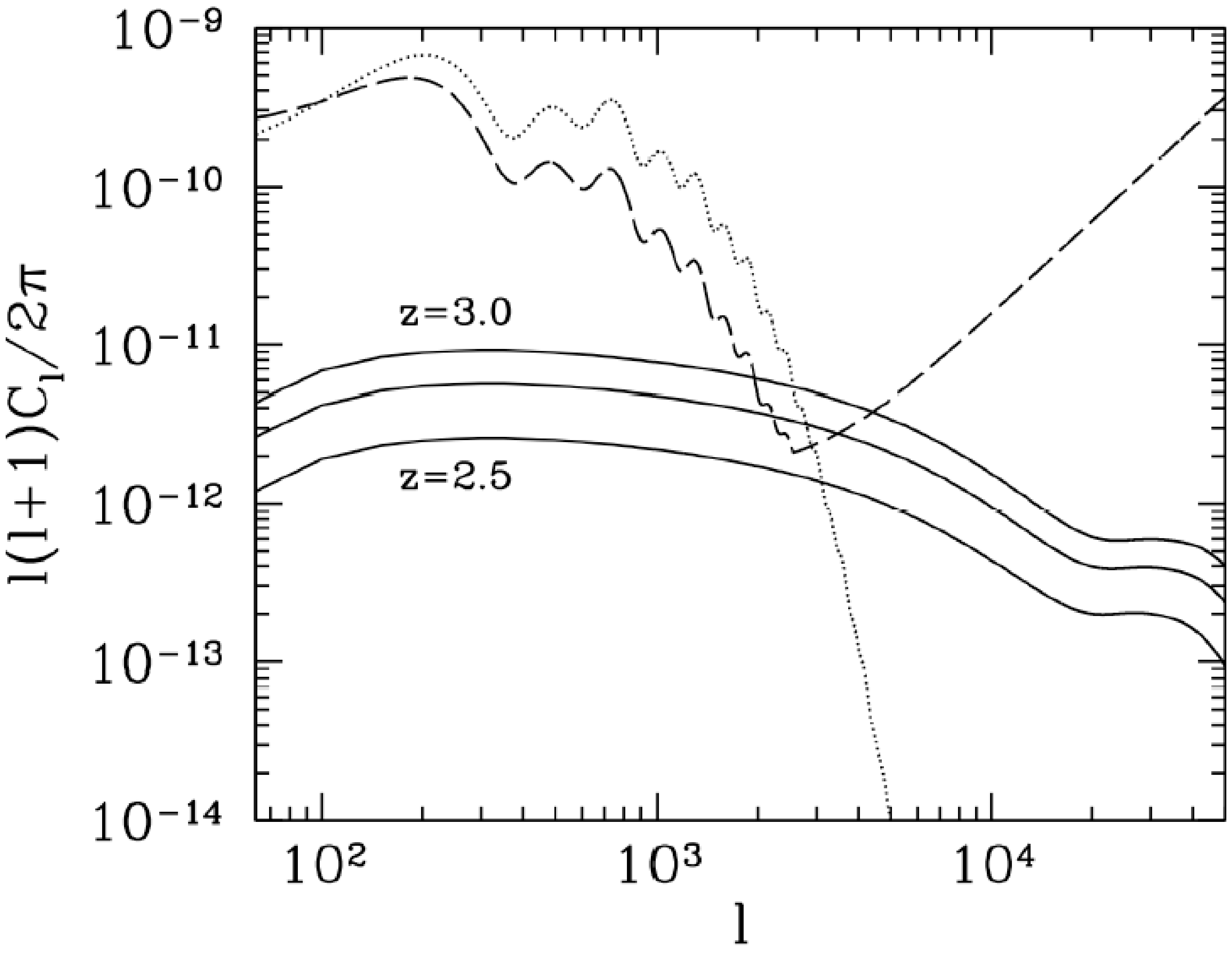
$$y(\theta) = \frac{4\sigma_T K_B}{m_e c^2} T_e n_e R_s \left[1 - \frac{D_A^2 \theta^2}{R_s^2}\right]^{1/2} .$$



Chatterjee : Thesis

Power Spectrum of y-distortion

- Need the number density of AGNs
- Use halo model to get number density of halos
- Each dark matter halo hosts an AGN
- All the AGNs eject their energy at redshift (z_{in})
- Assume a mass range of halos (M_{min}-M_{max})
- $M_{BH} \sim 0.0001 M_{halo}$ **(Marconi & Hunt 03; Dubinski et al. 96)**
- Expansion into spherical harmonics.
- Angular Power spectrum



Chatterjee & Kosowsky 2007

Power Spectrum to Signal

Assume a Gaussian Beam

$$\left\langle \frac{\delta T}{T}^2 \right\rangle = \frac{1}{4\pi} \sum_l (2l+1) W_l^2 C_l,$$

$$W_l = \exp(-l^2\sigma^2/2).$$

Frequency (GHz)	Resolution (arcseconds)	Temperature (μK)
145	60	-2.18
220	60	0.09
265	60	1.63

Chatterjee & Kosowsky 2007

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Simulation

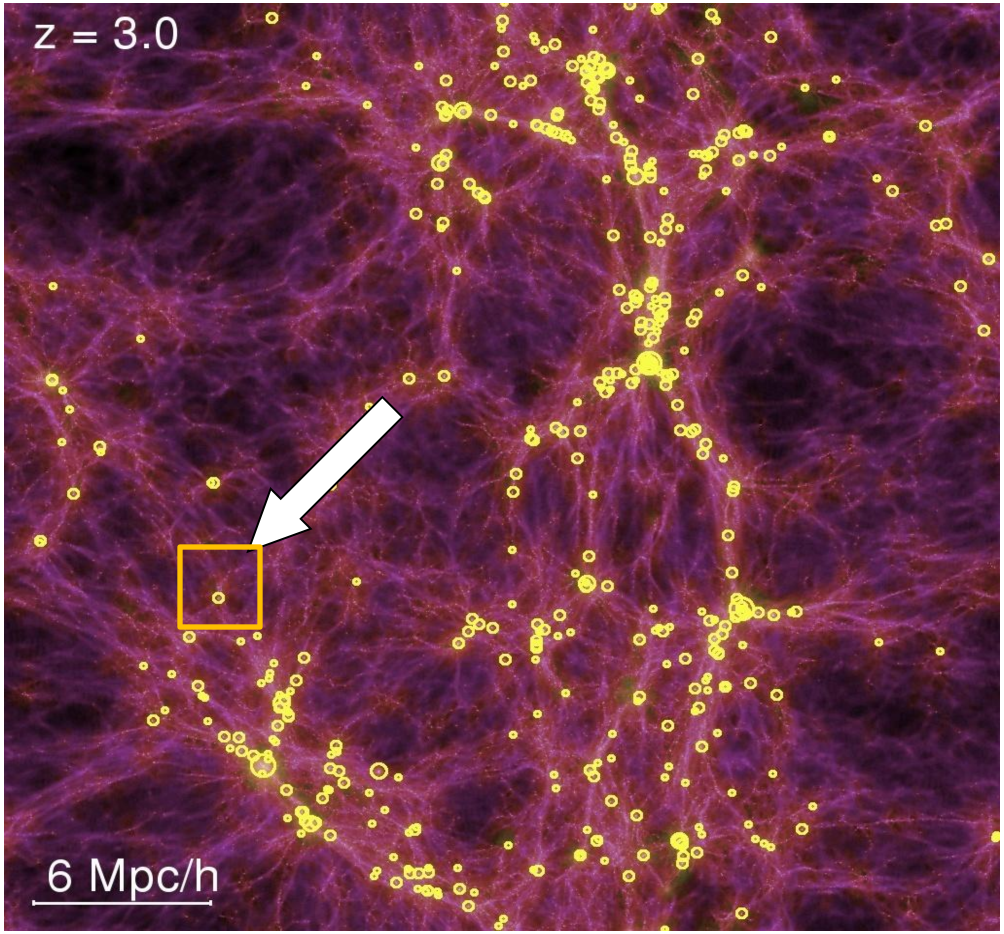
DiMatteo et al. 2008

- **N-body (Tree Particle-Mesh)**
- **Hydro (Smoothed Particle Hydrodynamics)**
- **Particles : $2x486^3$**
- **Box : 33.75 h^{-1} Mpc**
- **Star formation, Supernova & AGN feedback**
- **Dark Matter mass: $2.75x10^7 h^{-1} M_{sun}$**
- **Gas mass: $4.24x10^6 h^{-1} M_{sun}$**

Implementation of AGN Feedback

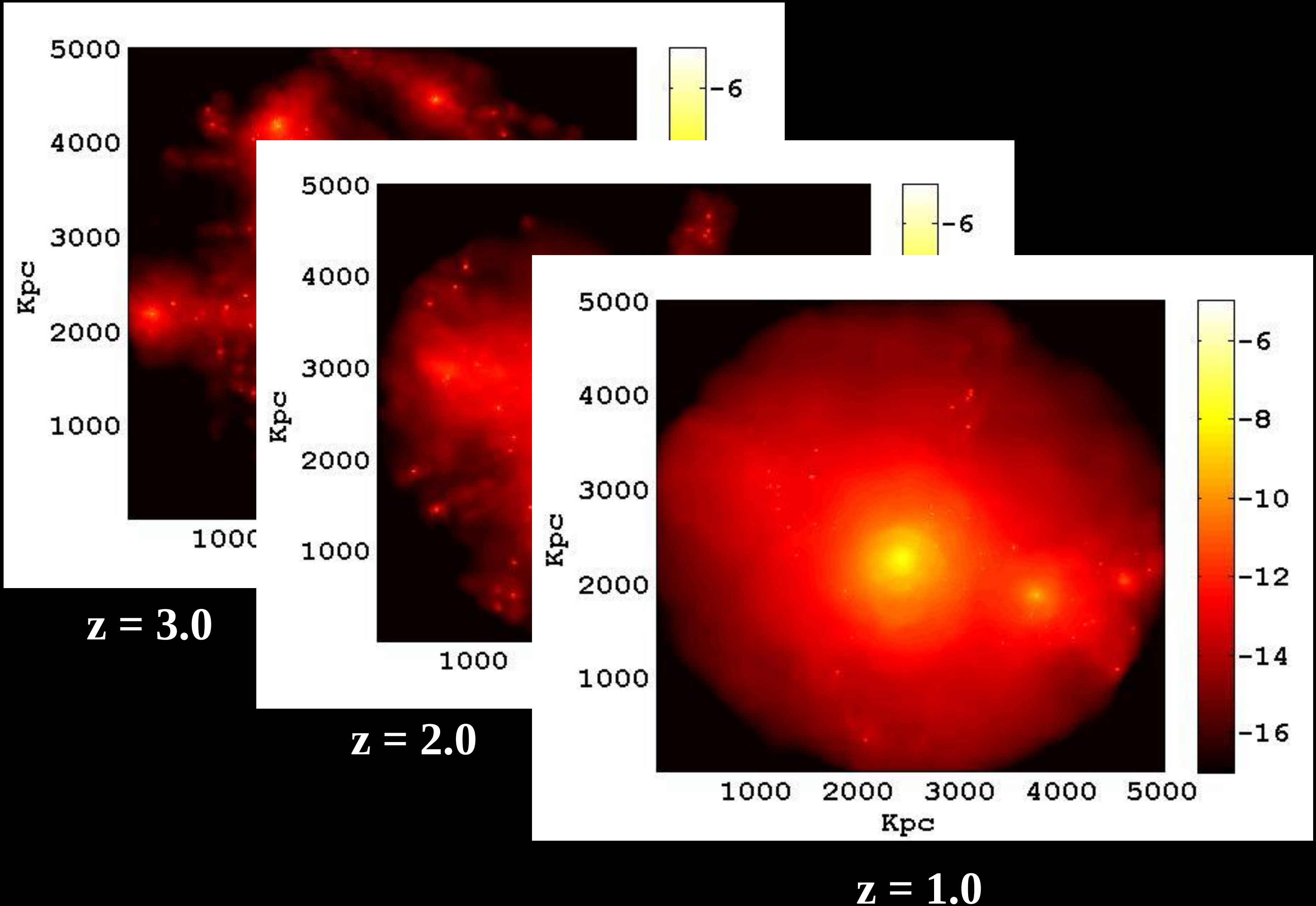
- **Black holes are introduced in halos above a mass threshold of 10^{10} solar masses**
- **The densest SPH particle is converted to a black hole particle of seed mass $10^5 h^{-1} M_{sun}$**
- **Black holes grow via accretion and merging**
- **Accretion model: Bondi –Hoyle-Lyttleton parameterization**
- **10% of the mass energy is radiated**
- **Energy is radiated isotropically**
- **0.5% of the mass energy (5% of the radiated energy) couples as feedback energy**

Simulation Box



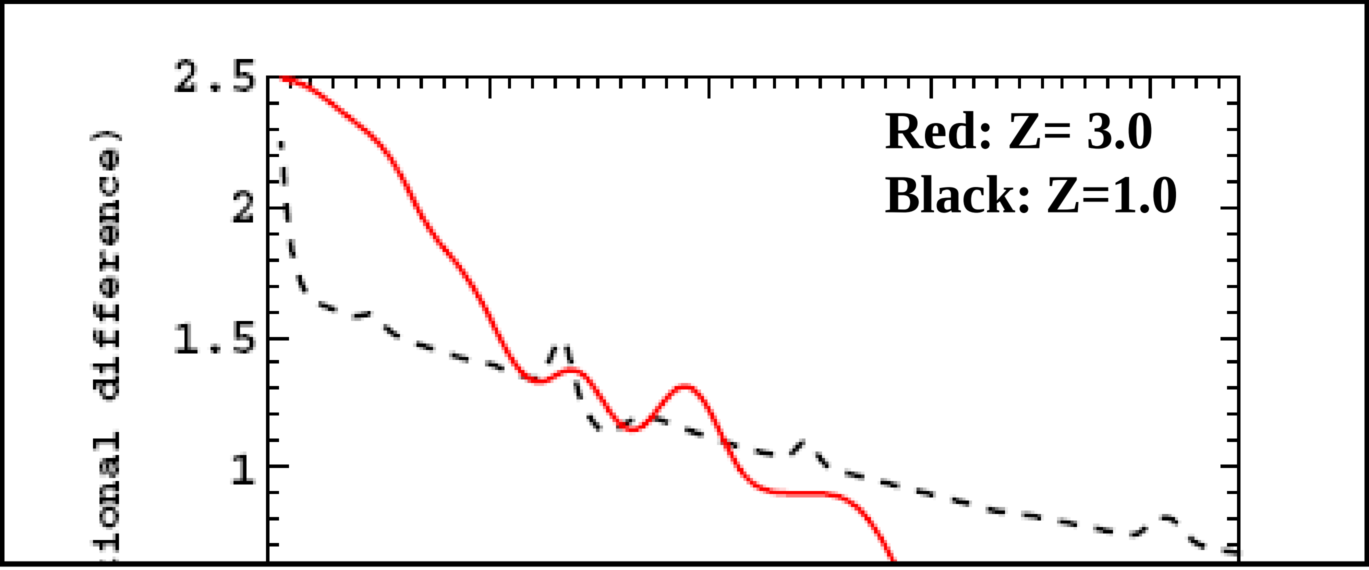
DiMatteo et al. 2008

SZ map around individual black hole



Chatterjee et al. 2008

Fractional Change of the SZ signal



- **The SZ effect is enhanced due to AGN feedback**
- **The enhancement is more centrally concentrated at higher redshifts**
- **The effect is predominant at angular scales within 5-20 arcseconds**

Chatterjee et al. 2008

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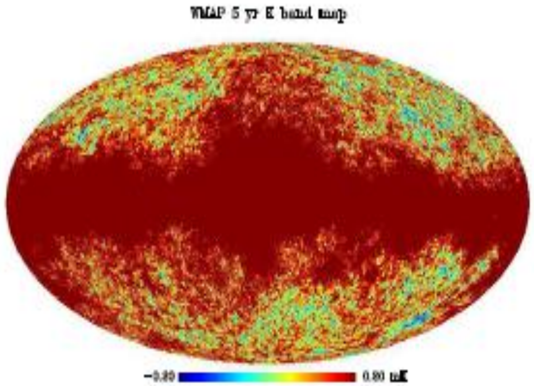
Detection Schemes

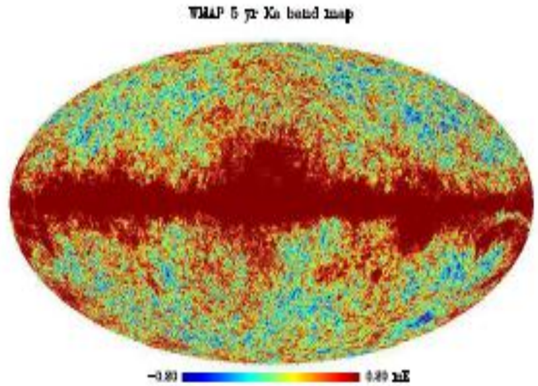
- **Direct Observations by future millimeter wave telescopes**
  - Spatially resolve the source
  - Prospects are marginal with Atacama Large Millimeter Array (ALMA), Cornell Caltech Atacama Telescope (CCAT)
- **Stacking Microwave Maps in the direction of known Quasars.**
  - Cross-correlate quasars from Optical surveys with CMB maps

Cross-Correlation Of SDSS and WMAP

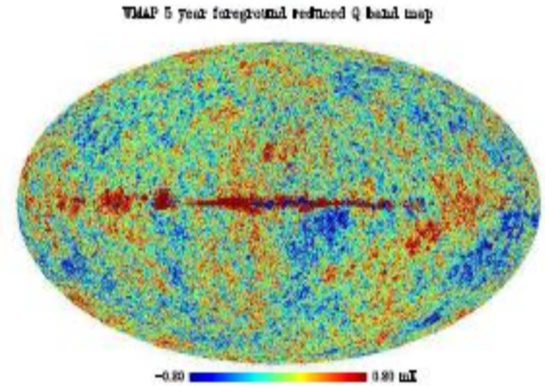
K: 23 GHz



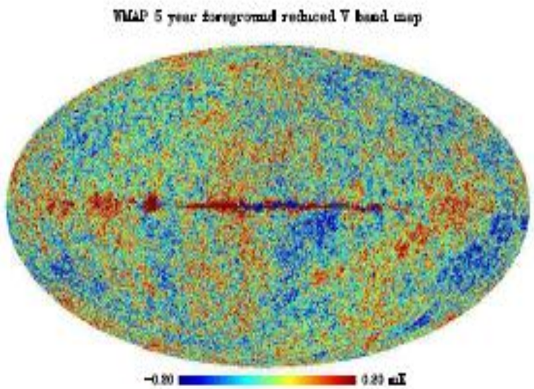
Ka: 33 GHz

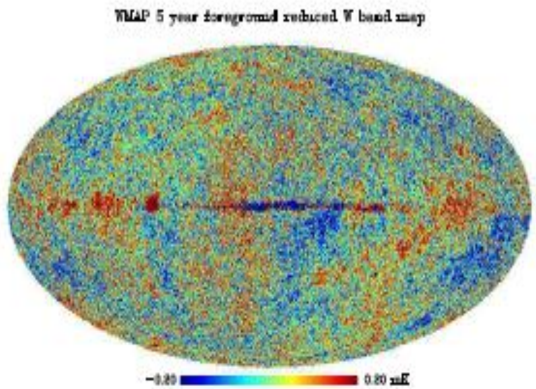


Q: 41 GHz



V: 61 GHz

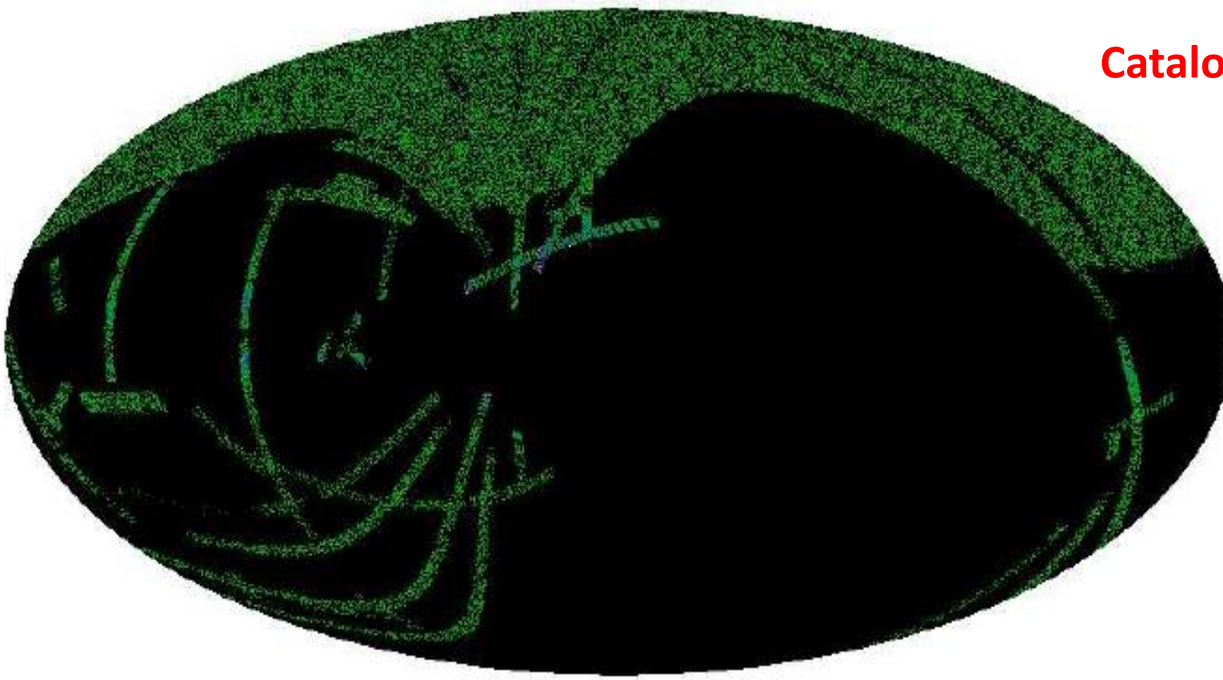




W: 94 GHz

At WMAP frequencies we look for anti-correlation of temperature with QSOs

(Data credit: WMAP Science team): Figure (Chatterjee : Thesis)



Catalog : Ho et al. 2008

Chatterjee et al. 2009 (To be submitted in ApJ)

$$\Delta T = \frac{\sum_i N_i T_i}{\sum_i N_i}$$

N_i = Number of QSOs in the ith pixel

T_i=Temperature of the ith pixel

Systematics

- **Galactic foregrounds: Synchrotron, Free-Free, Dust**
(Foreground reduction+ dust masks)

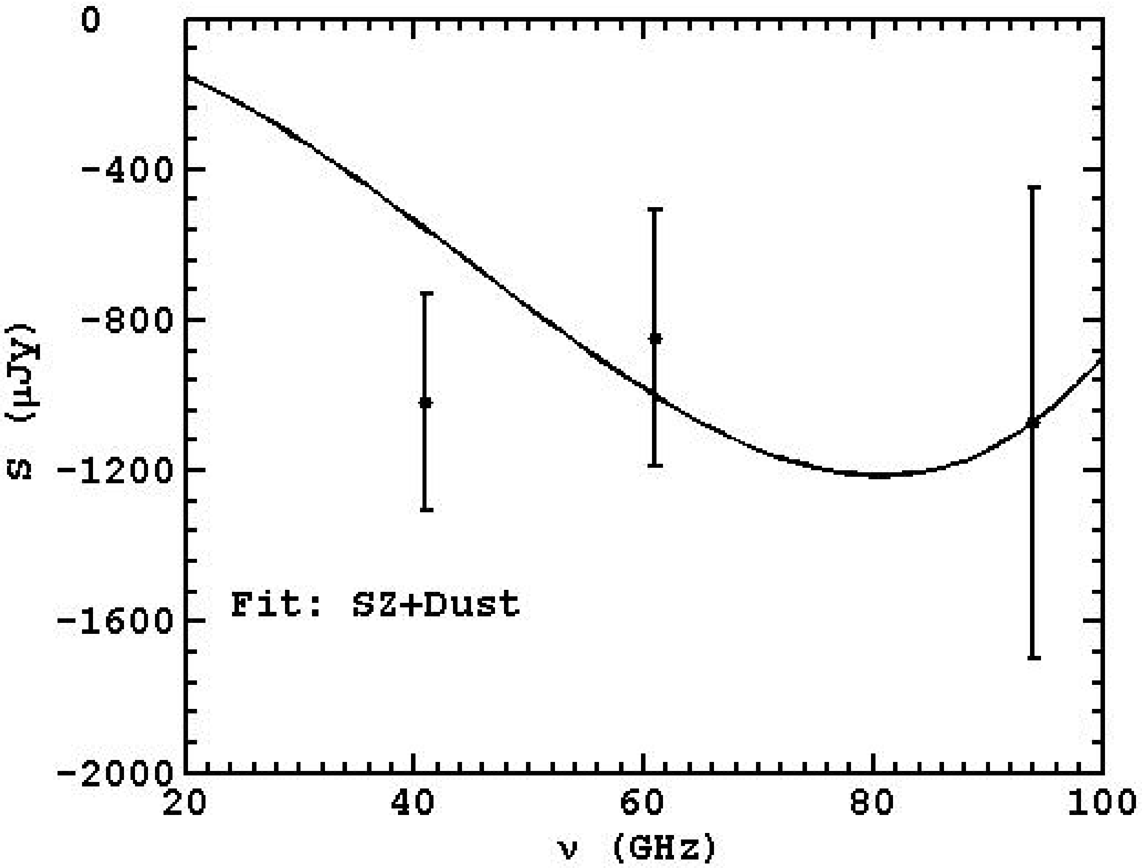
- **Radio sources**
(Radio masking by matching with radio catalogs)

- **Primary CMB** (Spatial filter)

- **Detector noise** (Filter)

- **SZ from galaxy cluster:**
(Estimated by cross-correlating with luminous red galaxies)

Cross-Correlation Spectrum



$$y = (5.8 \pm 1.8) \times 10^{-7}$$

Chatterjee et al. 2009 (To be submitted in ApJ)

We see a deficit in the flux (anti-correlation)

Significance of Correlation

- Randomize positions of QSOs (1000 realizations)

- 0.1% (Q) , 1.3% (V) 6% (W) of the random cases have more prominent anti-correlation than the observed data

- QSOs are significantly correlated with temperature pixels in WMAP

Interpretation of Results

Object	Expected Signal from WMAP
Clusters	10s mJy **(Diego & Partridge 2009)**
AGN feedback	10-100 μJy
Observed	1 mJy

- **QSOs tend to be in halos of mass $3x10^{12}M_{sun}$ at redshift 1.0** **(Coil et al. 2007)**
- **If a fraction (~10%) of QSOs reside in halos of bigger size it can explain the observed signal**
- **AGNs put more energy into the IGM**
(e.g. Natarajan & Sigurdsson 1997)
- **Need future high resolution experiments (ACT/SPT) to resolve galaxy clusters and have better constraint**

Conclusion

- **We show that the SZ effect is an effective tool in quantifying feedback energy from AGN**

- **The resulting signal obtained from analytic model of AGN feedback is of the order of a μK**

- **Predominant at angular scales of 10-15 arcseconds**

- **We perform one of the first high resolution SZ simulations of AGN feedback**

- **The highest mass black holes produce an SZ distortion of ~ μK**

Conclusion (Contd….)

- Marginal prospects of detection with future high resolution mm wave telescopes

- We show that cross-correlation with optical quasars and CMB maps provides another route of detection

- We perform the first cross-correlation analysis with SDSS QSOs and WMAP CMB maps.

- The result is consistent with SZ

- Better constraints expected from ACT/SPT

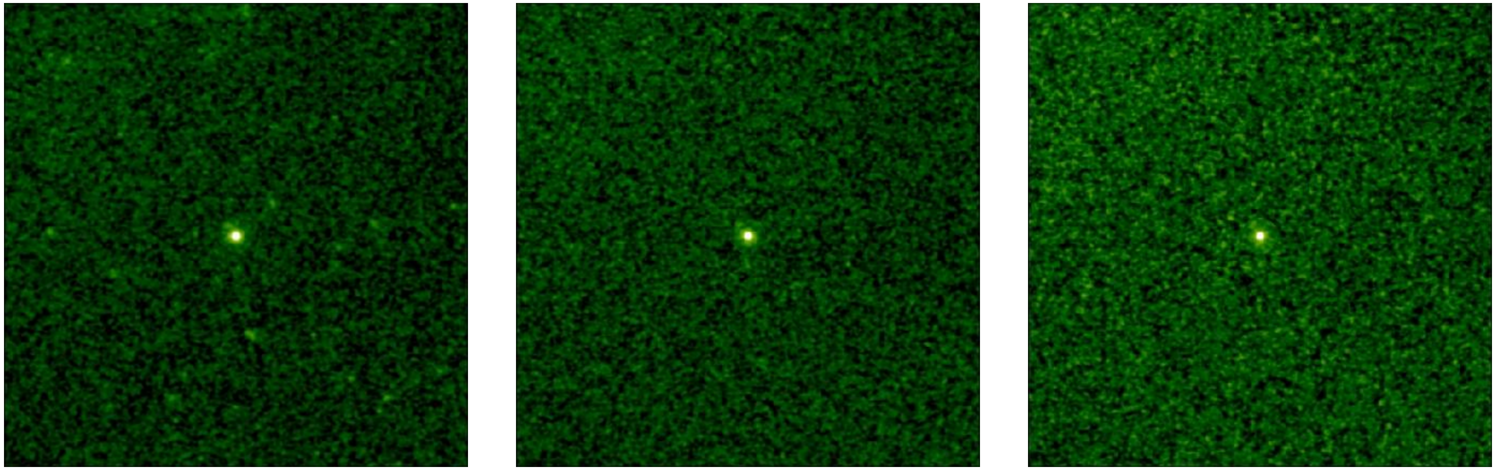
We have used a traditional tool in cosmology, namely the CMB …

… to study an astrophysical phenomenon, namely the feedback from AGNs, which has substantial impact on theories of structure formation.

Structure formation itself is an important question in cosmology!

Future Work

❖Studying the X-ray signal from the simulation and comparing with observations



Chatterjee et al. 2009 (in prep)

❖Stacking Galaxy clusters from X-ray and Optical catalogs to investigate the SZ effect

❖Detecting the signal with ACT

Special Thanks to

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Thank You


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Astrophys.
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