Anisotropies in the Cosmic Microwave Background

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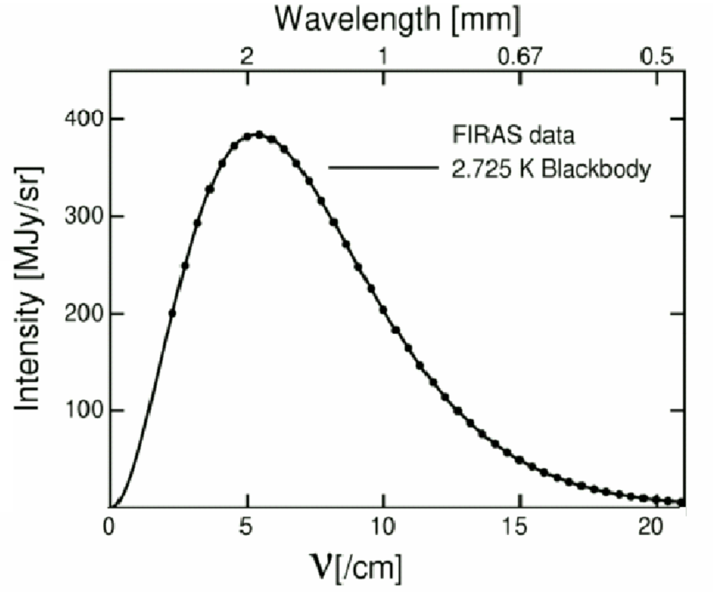
Scheme

- The Cosmic Microwave Background
- The Sunyaev-Zeldovich Effect (SZ)
- Current S-Z experiments
- Cosmology from S-Z studies
- Small angle SZ
- SZ from Quasar Feedback

The Cosmic Microwave Background

Confirmation of Big Bang Cosmology

- Predicted by George Gamow in the 1940's
- Relic radiation from the Big Bang
- A signature of the smaller, hotter, denser phase of the universe.
- Penzias and Wilson discovered this radiation in 1964



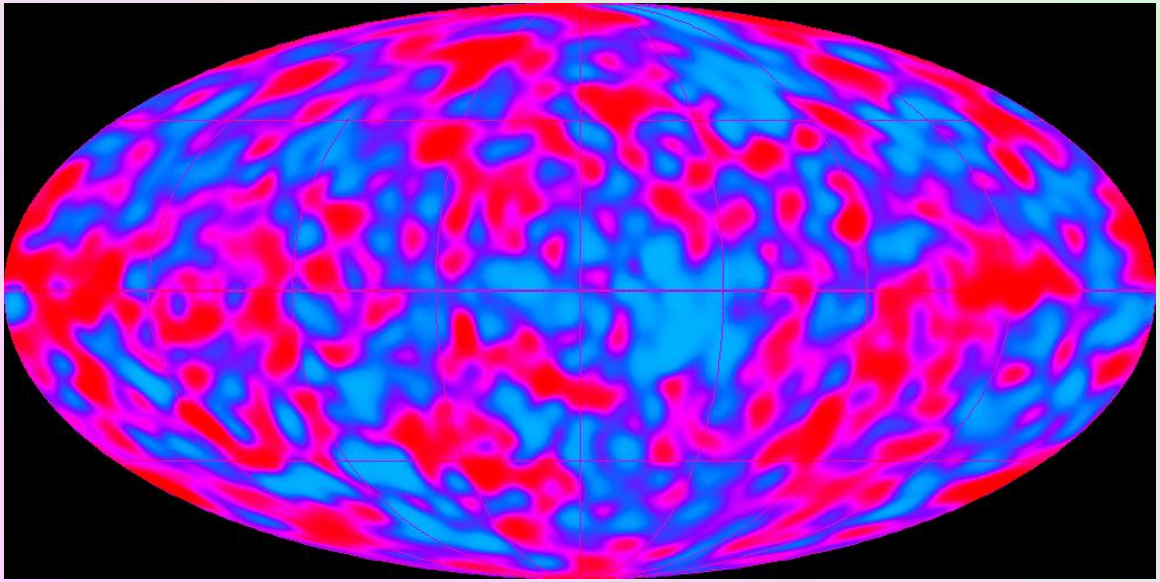
Perfect blackbody at 2.73 K (COBE 1990).

Physics Behind the CMB

- Universe was filled with a plasma of baryons and photons.
- Tightly coupled by Thompson scattering.
- Universe at the ionization temperature of Hydrogen, neutral atoms started forming. (Recombination)
- Shortage of free electrons. (Scatterers)
- Photons free streamed to today's CMB sky : Surface of Large scattering.

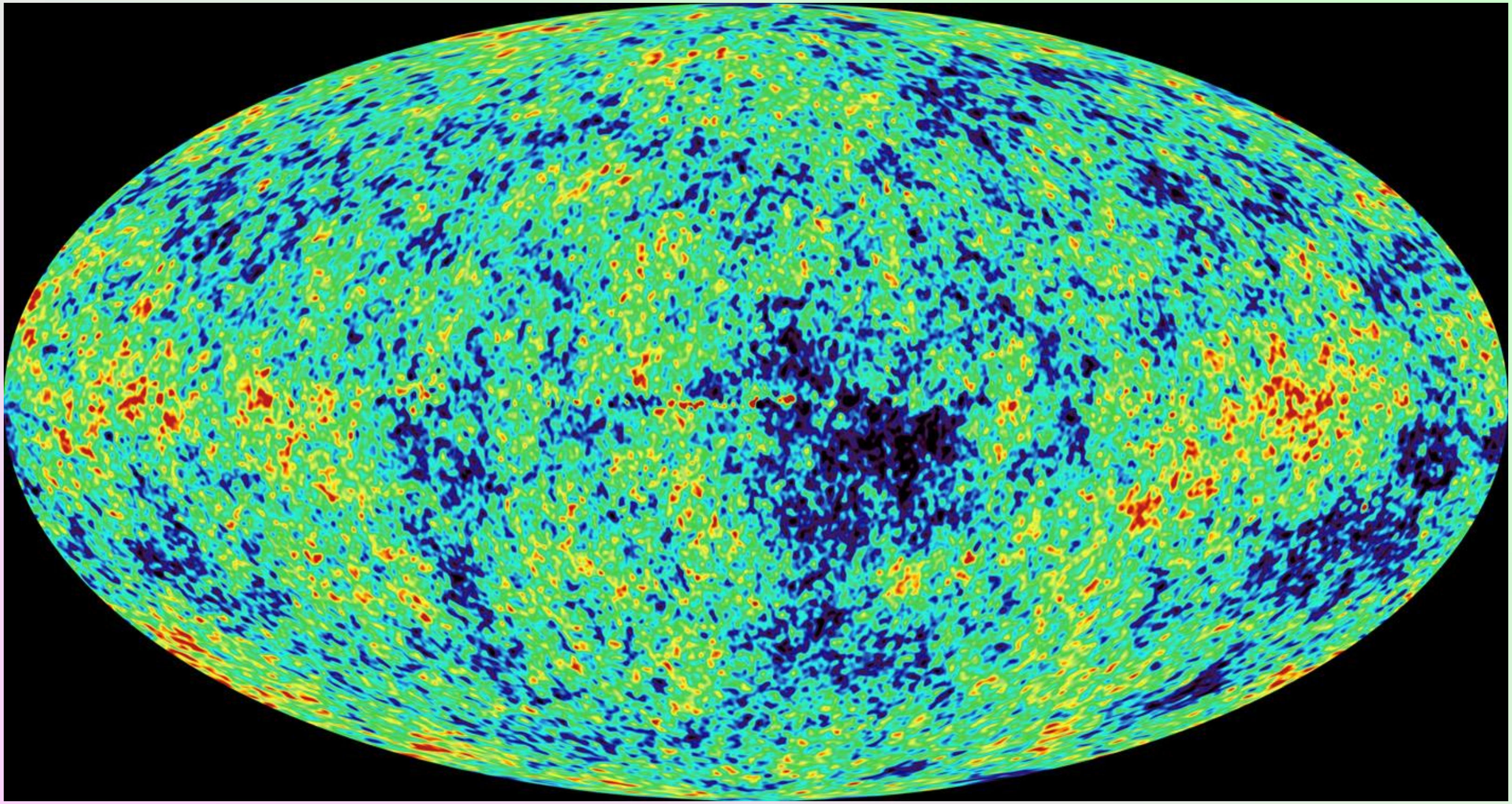
Fluctuations in the CMB

- 350000 years after the Big Bang
- Redshift ~ 1100, Temp ~ 3000 K
- Fluctuations of one part in100000 in the CMB.



COBE MAP

TEMPERATURE MAP FROM WMAP



Angular Resolution of COBE : 7 minutes
Angular Resolution of WMAP: 15 arc minutes

Primary anisotropy in the CMB

- Fluctuations in the gravitational potential causes anisotropy via the Sachs Wolfe effect.
- Arises from acoustic oscillations in a plasma of Baryons and Photons under Gravity.
- Interplay between pressure and Gravity.
- Photons at maximum compression will be hotter and at maximum expansion will be cooler.
- Doppler shifts induces an additional anisotropy.
- Precisely measured by the WMAP satellite.

Secondary Anisotropies

- Fluctuations in the CMB due to its interaction with matter in the late Universe.
- Dominant in much smaller scales.
- Current state of the art CMB experiments are using it to constrain Cosmology.

- **Rees Scaima effect**
- **Gravitational Lensing of the CMB**
- **Integrated Sachs Wolfe effect**
- **Ostriker Vishniac effect**
- **Sunyaev-Zeldovich effect**

The Power spectrum

The fluctuations in temperature can be expanded in Spherical harmonics

$$\frac{\delta T}{T}(\theta,\phi) = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} a_{lm} Y_{lm}(\theta,\phi)$$

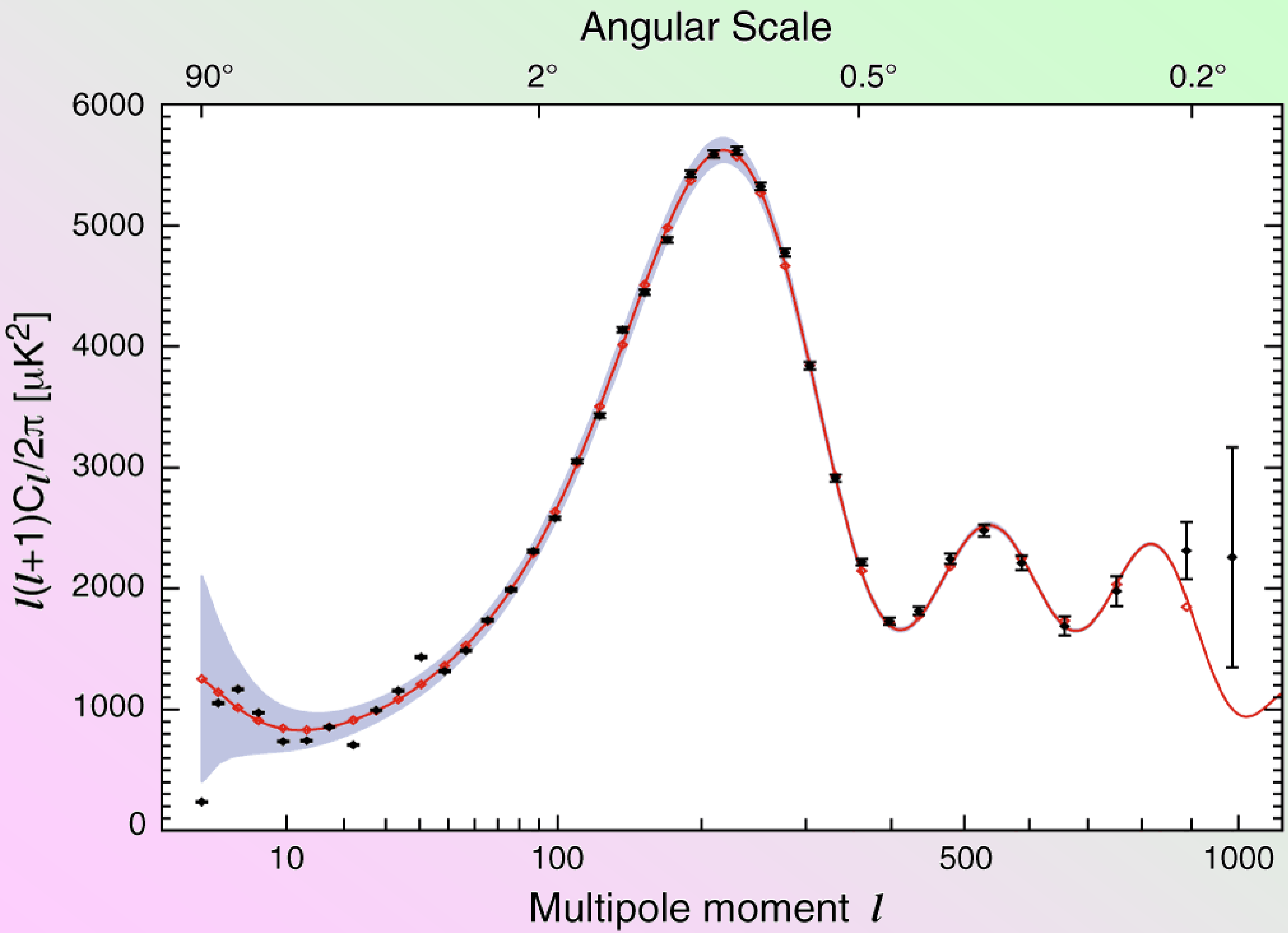
The correlation function is given by

$$C(\theta) = \frac{1}{4\pi} \sum_{l=0}^{\infty} (2l+1) C_l P_l (Cos\theta)$$

The fluctuation in temperature

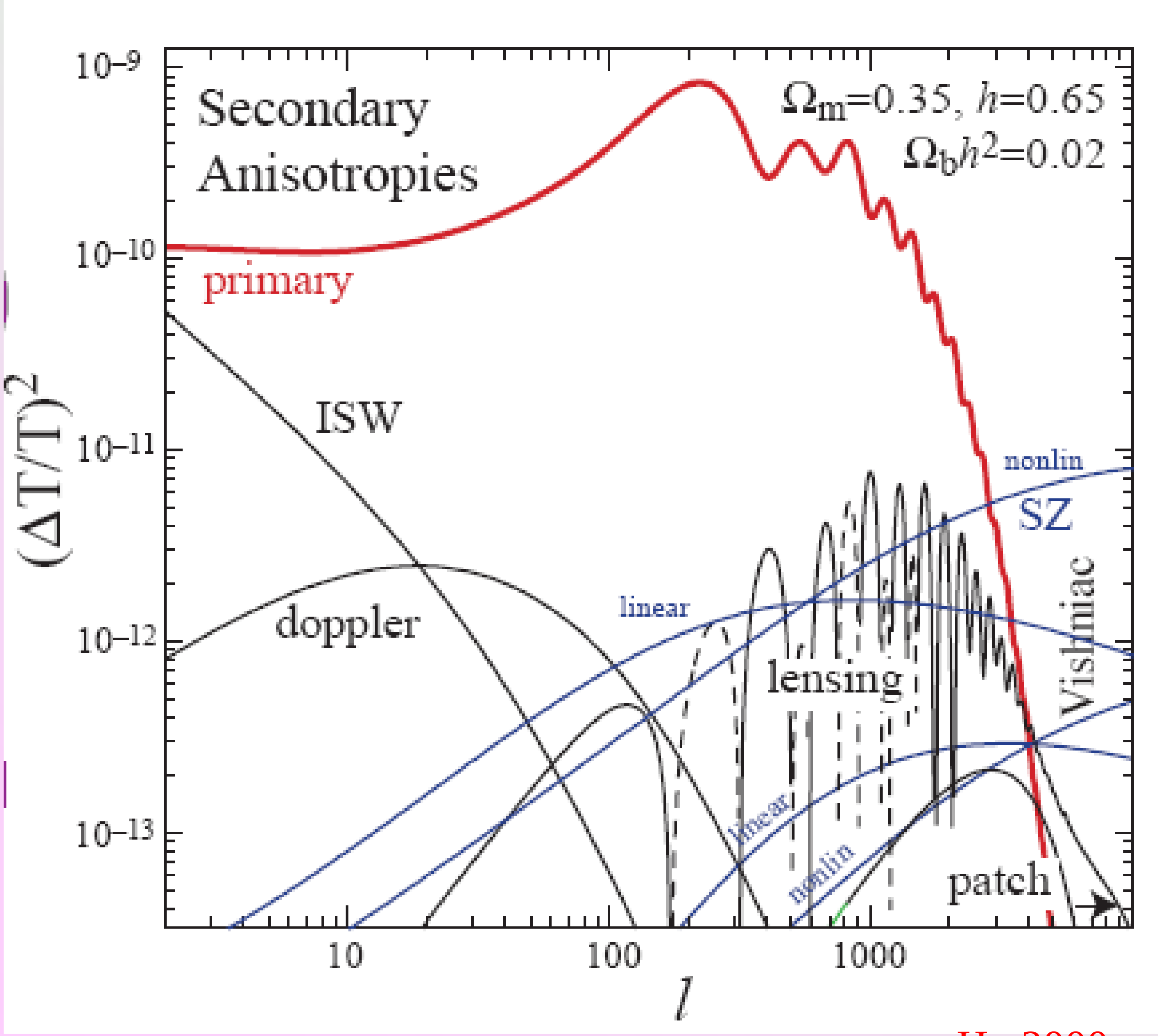
$$\Delta T = \left(\frac{l(l+1)}{2\pi} C_l\right)^{\frac{1}{2}} \langle T \rangle$$

ANGULAR POWER SPECTRUM OF PRIMARY ANISOTROPY



Hinshaw et. al 2006

ANGULAR POWEWR SPECTRUM

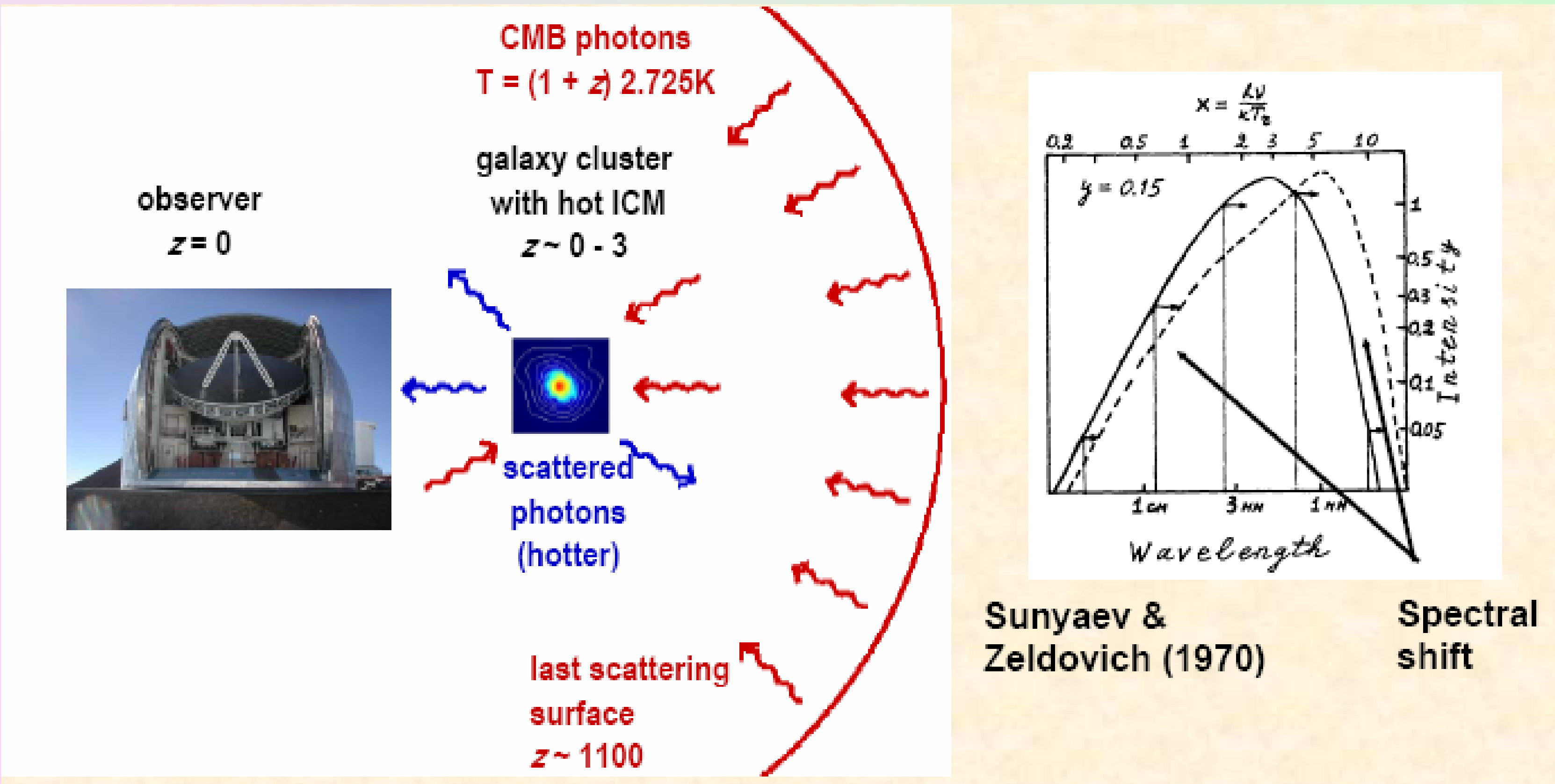


Hu 2000

The Sunyaev-Zeldovich effect

- Inverse Compton scattering of the Cosmic Microwave Background Photons by hot electrons present in galaxy clusters.
- Departure from a blackbody.

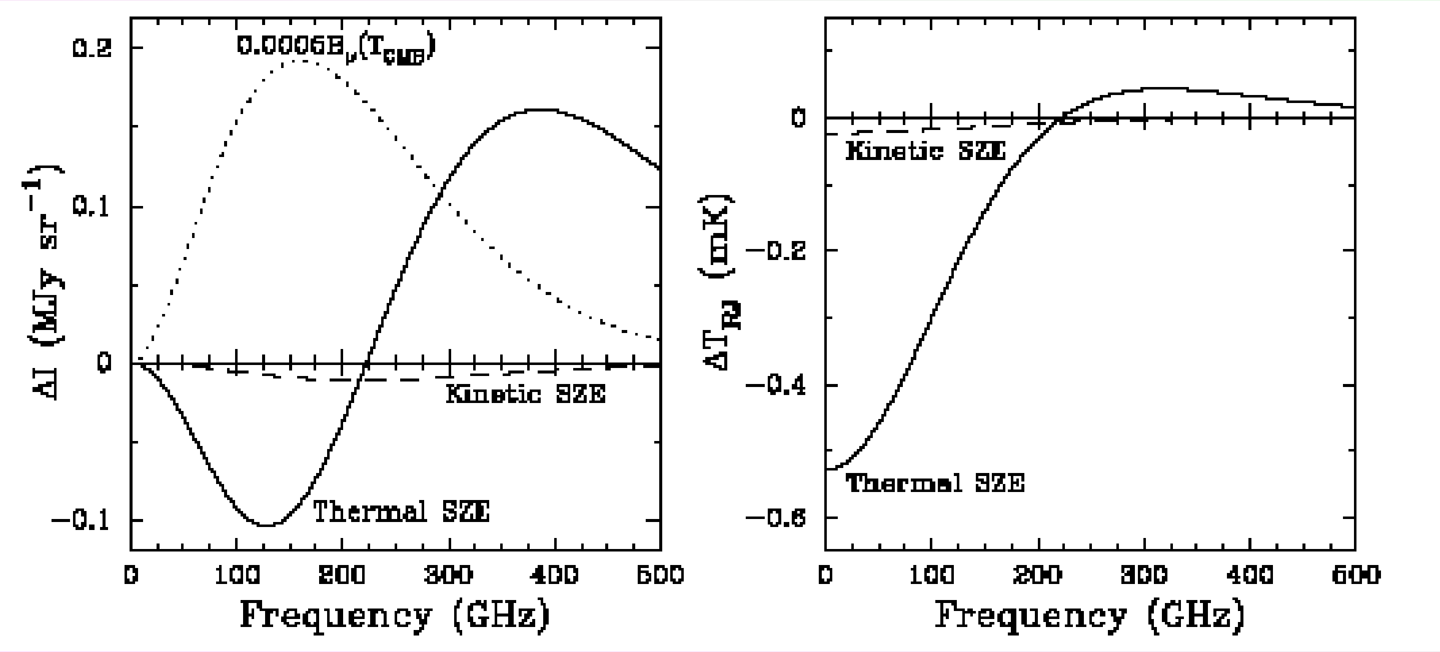
Photo credit: J. Glenn



Thermal and Kinetic SZ

- SZ effect can be of two types.
  - Thermal SZ : Departure from a Black Body
  - Kinetic SZ: Net Doppler shift of the CMB due to peculiar velocities of clusters.

Carlstrom et.al 2002



Current S-Z experiments

Atacama Cosmology Telescope

- Maps 400 sq degrees of sky area
- 3 frequency bands (145 GHz, 220 GHz, 265 GHz)
- Arc minute angular resolution
- 2 μ K sensitivity per pixel
- Timeline (Summer2007)

Collaborations

NSF Physics, NSF Astronomy
Program in International Research and Education

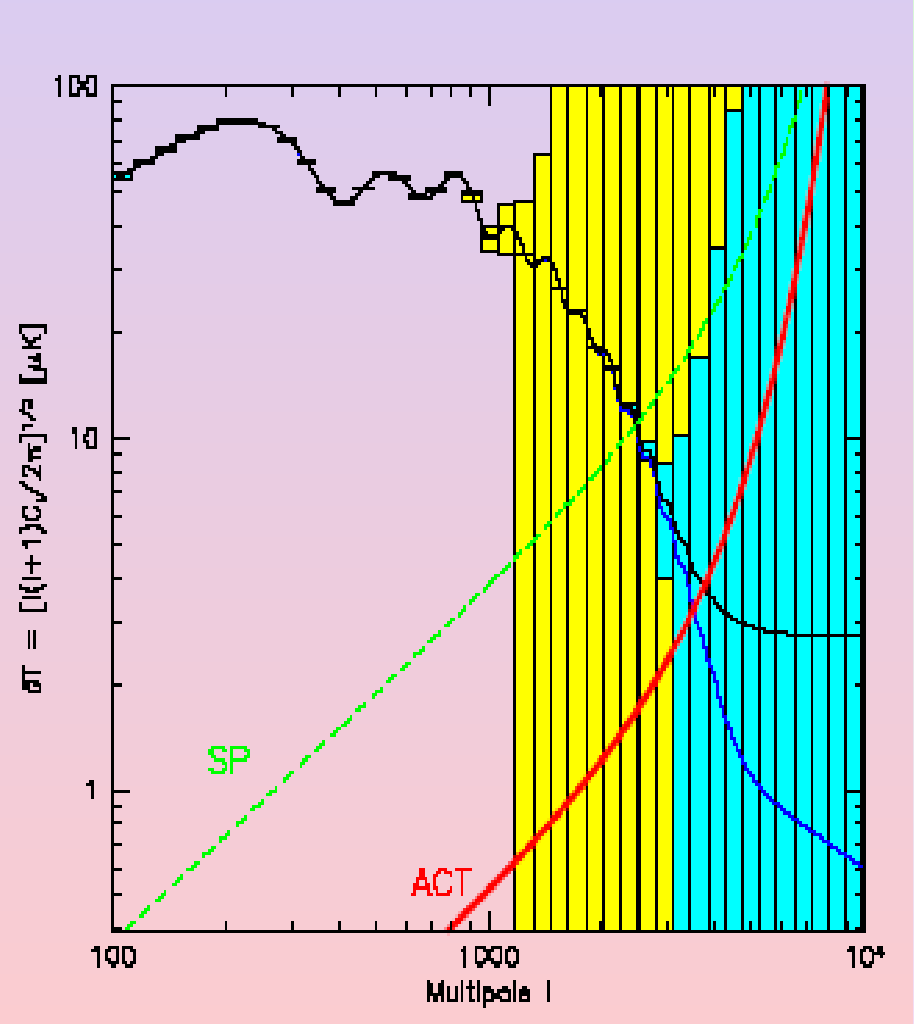
http://www.physics.princeton.edu/act/

CARDIFF,UK, COLUMBIA
HAVERFORD, INAOE,MEXICO
KWAZALU-NATAL,SA, LLNL
NASA JPL, NIST
UPENN, PRINCETON (PI : L.Page)
PITTSBURGH, RUTGERS
UNIVERSITY OF CAPE TOWN,SA
UMASS,CATOLICA,CHILE
YORK COLLEGE

SOUTH POLE TELESCOPE
PI : J. Carlstrom
UNIVERSITY OF CHICAGO
And other institutes

Cosmology from SZ surveys

Primary anisotropies at lower angular scales

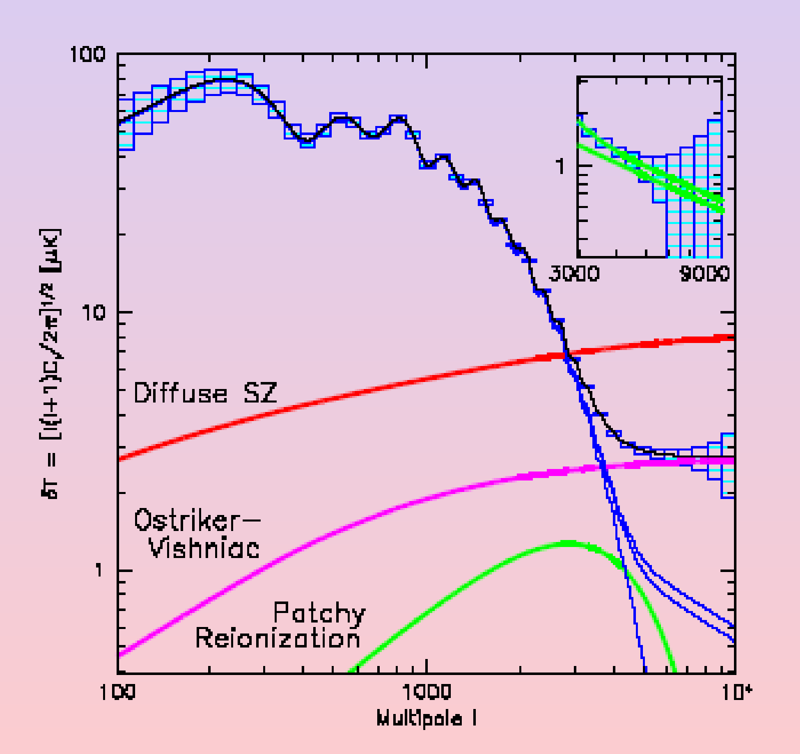


Error bars for WMAP (yellow)
PlANCK (aqua)

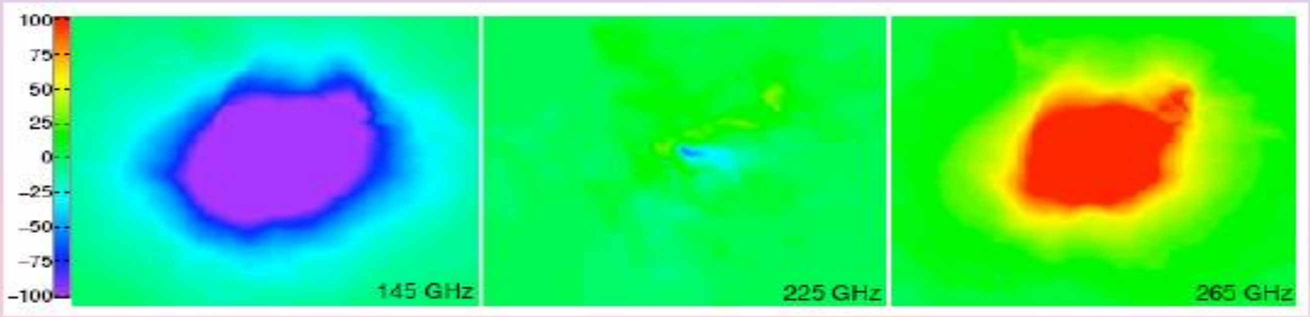
A.de.Oliviera-Costa for
the ACT proposal

A.de.Oliviera-Costa for the ACT proposal

S-Z effect continued

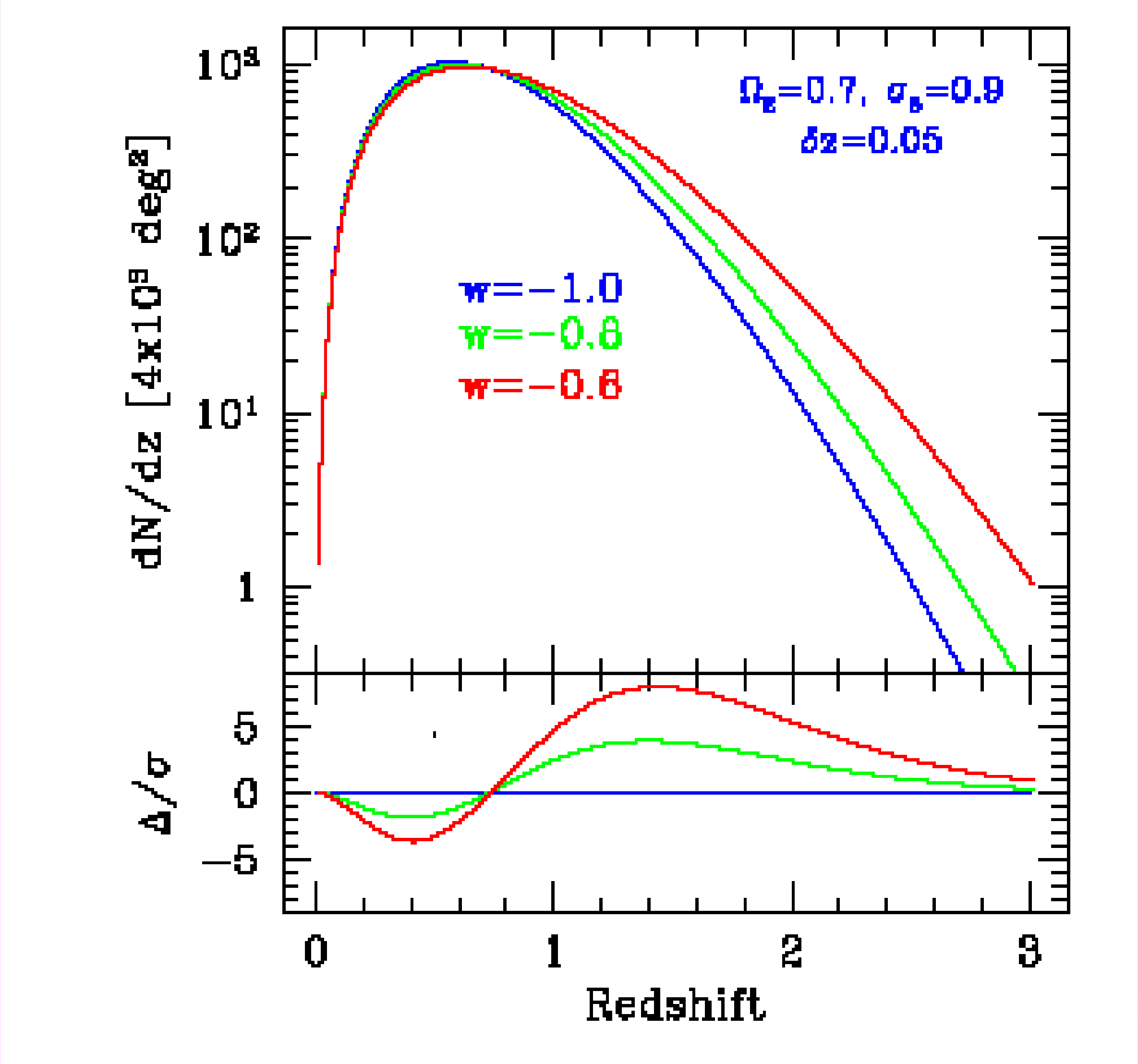


- S-z effect can be used to detect clusters
- Constrain Cosmology
- Study Cluster Physics



$M = 10^{15} M_{\odot}$, $T = 9$ keV simulated cluster (Sehgal, Holder, AK 2005)

Cosmolgy with Clusters



W= equation of state Parameter for Dark Energy

Mohr 2004

Other interesting Science

- Other cosmological parameters from cluster number counts and SZ power spectrum.
- Peculiar velocities of clusters from KSZ.
- Cosmological parameters from velocities of clusters.
- Gravitational lensing of the CMB
- Small angle SZ to understand the role of Baryonic Physics.

Small Angle SZ

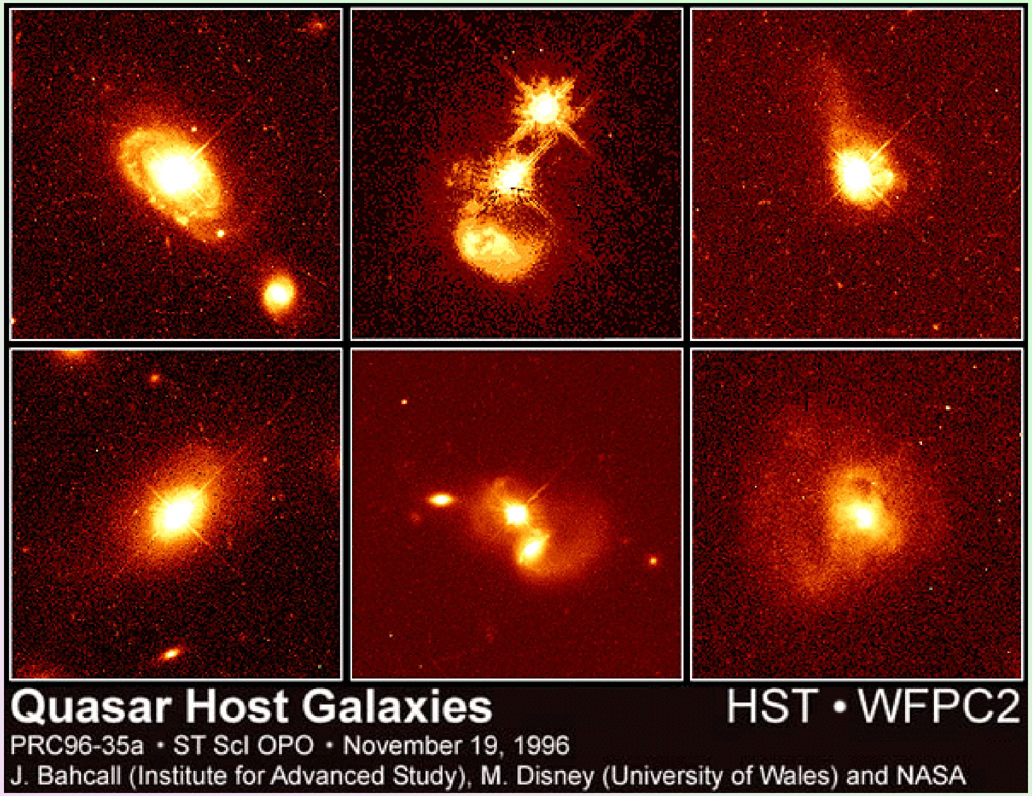
Different signals

- SZ distortion from first stars (Oh et.al 03)
- SZ distortion from Galactic winds (Majumdar et. al 01)
- Effervescent heating by quasar bubbles (Roychowdhury et.al 05)
- SZ distortion from Quasar bubbles

  (Natarajan & Sigurdsson 99, Platania et. al 02, Lapi et. al 03, Chatterjee & Kosowsky 07)

Quasars

- Very energetic distant objects.
- They are powered by super massive(10^6 - 10^9 M_{sun}) black holes
- A particular Active Galactic Nuclei.
- Quasars reside in the centers of massive galaxies.

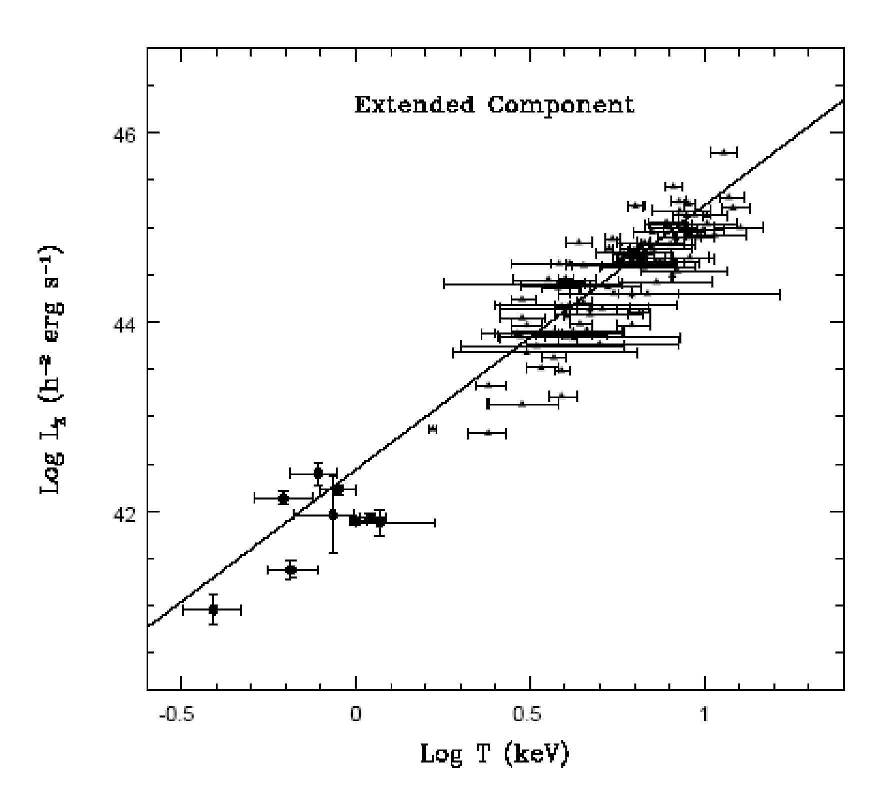


Sunyaev-Zeldovich Effect from Quasar Feedback

Lx-T relation in clusters

Mulchaey & Zabludoff 98

- Self similar models suggest $L_X \sim T^2$ for the gas in clusters.
- But Observations show $L_x \sim T^3$ roughly.
- What is the source of this discrepancy ??



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

Possible Answers

- X-ray observations of cluster show non-gravitational heating.
- Different sources of non gravitational heating
- Quasar feedback into the Inter Galactic Medium ⇒ Potential source
- Theoretical prediction of its effect on structure formation.
- Robust observational evidence via the Sunyaev-Zeldovich effect (SZ effect)

Theoretical Model

- The energy outflow from a Quasar

  ⇒ (Scannapieco & Oh 04)

  - Energy is ejected into the IGM in the form of a spherical bubble.
  - This bubble expands as a shock front into the surrounding medium.
  - The radius and temperature of the bubble is given as a function of time. (Sedov-Taylor solution)
  - The density of the surrounding medium is taken to be the mean baryonic density of the universe.
  - All the Quasars eject their energy at a single redshift.

Contd…….

- Calculation of the y distortion
  - The temperature inside the bubble is taken to be constant
  - The density inside the bubble is taken to be constant and equal to the density of the surrounding medium
  - The y distortion

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

  - Gives a simple line of sight integral
  - Cooling time is of the order of Hubble time

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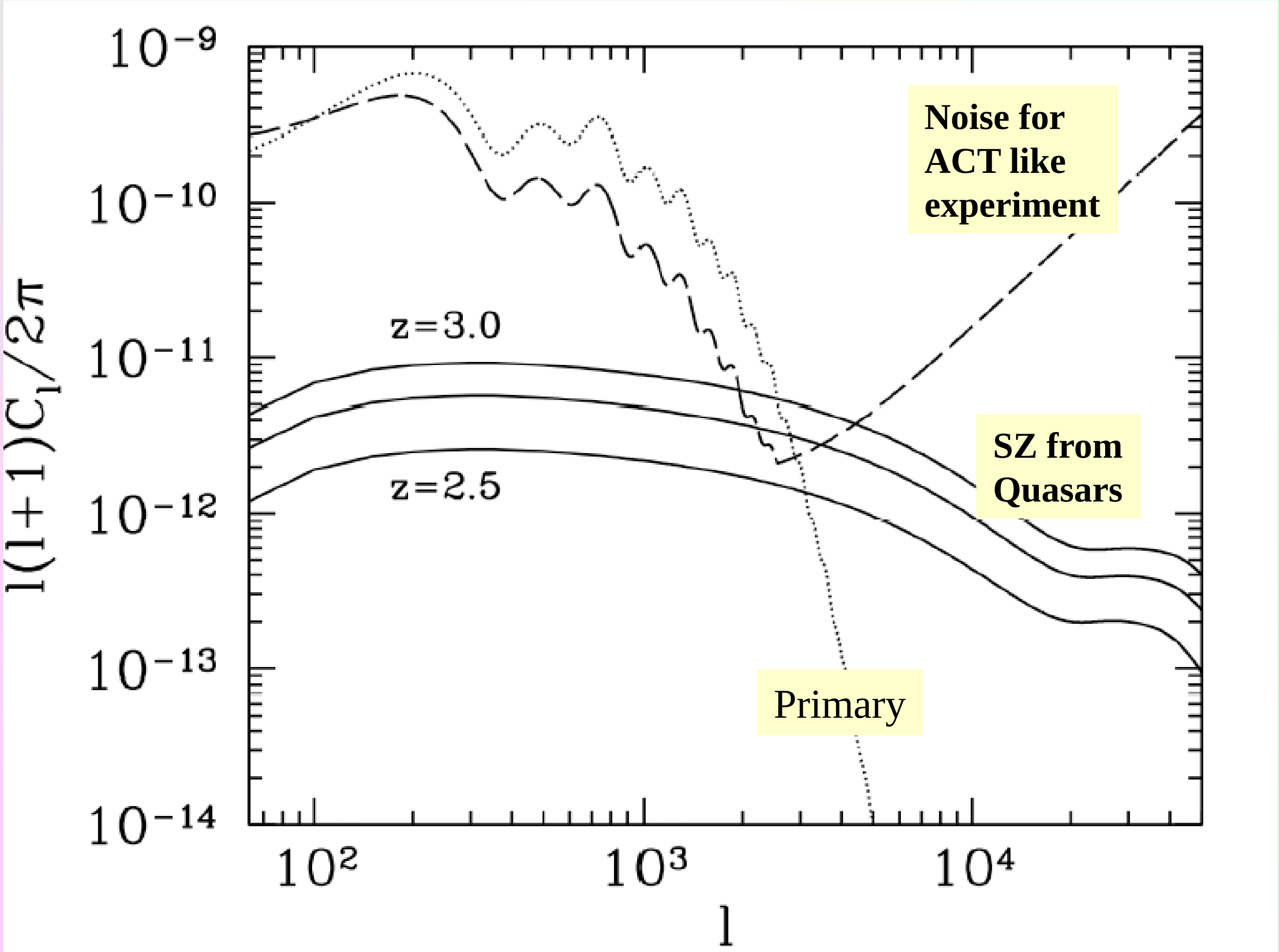
- **The number density of quasars**
  - Each halo hosts a quasar.
  - Number density of halos from the Sheth-Tormen mass function. (Sheth & Tormen 99)
  - The minimum black hole mass to power quasar is assumed to be 10^7 solar masses.
  - M_{BH}/M_{bulge} =0.002 (Marconi & Hunt 03) $M_{halo}/M_{bulge} = 20$ (Dubinski, Mihos & Hernquist 96) minimum $M_{halo} = 10^{11}$ M_{sun}.
- **The Power spectrum of y distortion.**
  - Expansion into spherical harmonics.
  - Angular Power spectrum

Chatterjee & Kosowsky 07 (Accepted for publication in ApJ Letters)



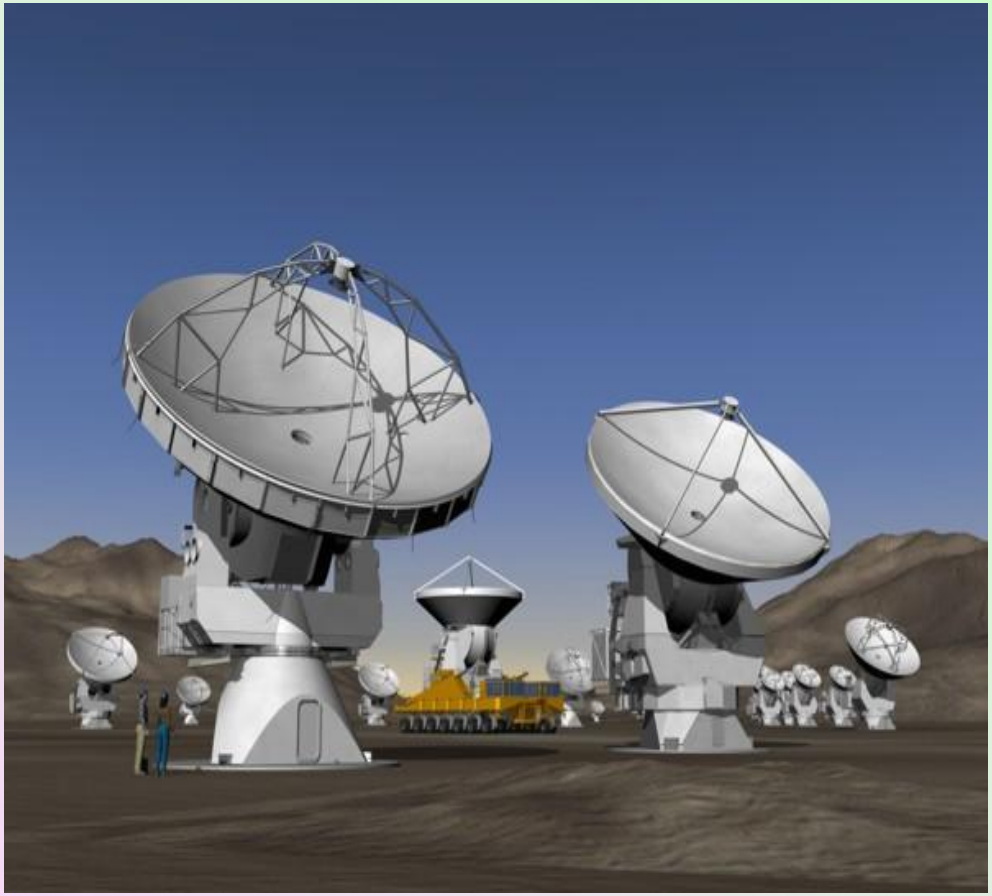
Signal for a Gaussian beam

Frequency (GHz)	Resolution (arcseconds)	Temperature (μK)
145	60	2.18
220	60	0.09
265	60	1.63
145	15	2.32
220	15	0.11
265	15	1.75
145	5	2.35
220	5	0.11
265	5	1.78

(Chatterjee & Kosowsky 07)

Atacama Large Millimeter Array

- 64 x 12m antenna's
- 12 x7m antenna's (Atacama Compact Array)
- 40 – 900 GHz (7mm -0.35 mm) 10 bands.
- Resolution 10 mili arc seconds
- Timeline (2012)



ALMA SENSITIVITIES FOR AN INTEGRATION TIME OF AN HOUR

Frequency (GHz)	Resolution (arcseconds)	Baseline (Km)	Sensitivity (mK)
145	15	.0284	2.41
145	5	.0853	21.74
220	15	.0187	1.76
220	5	.0562	15.84
265	15	.0156	1.63
265	5	.0467	14.63

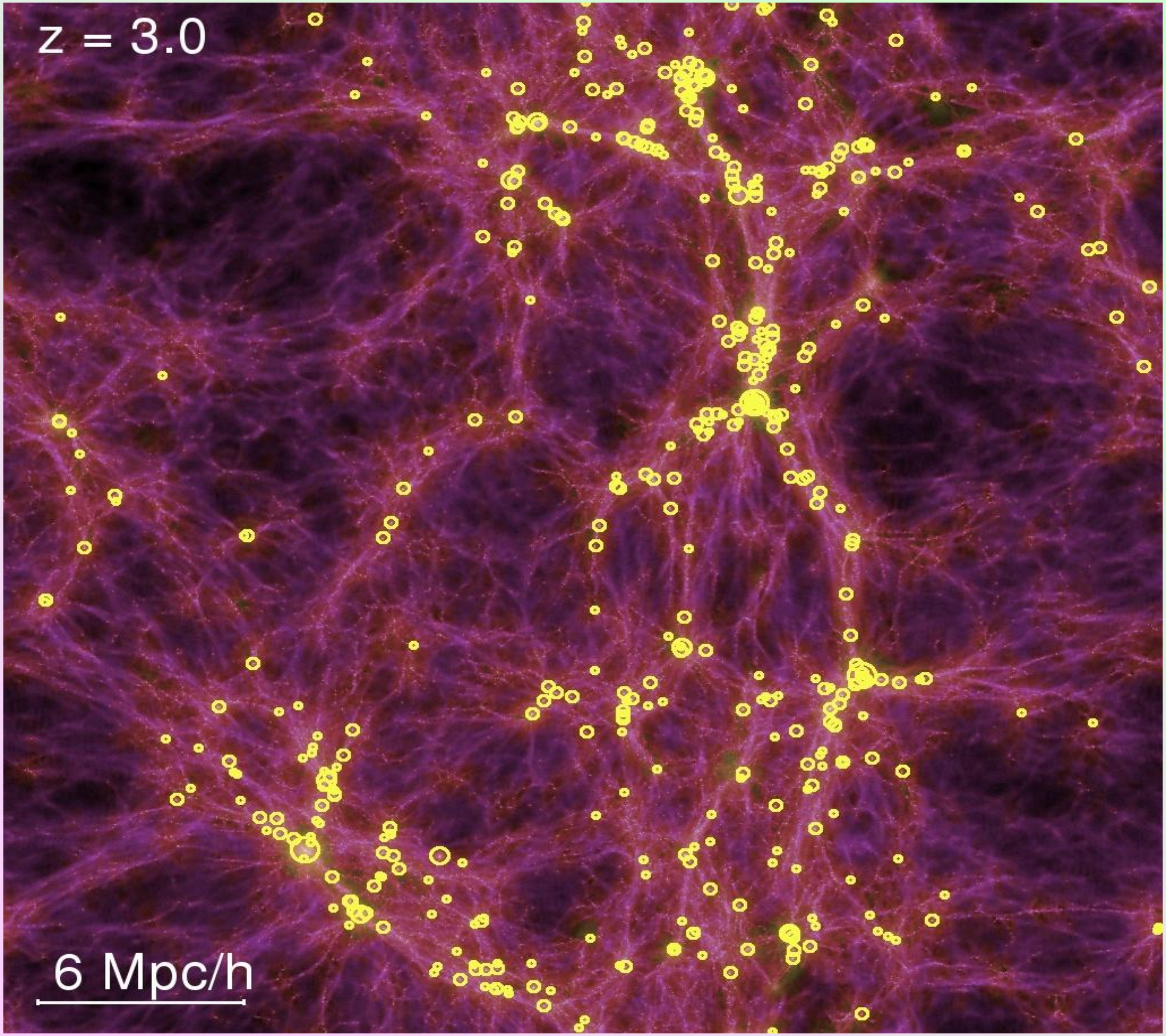
(Chatterjee & Kosowsky 07)

Prospects of Detection

- Deep Observations by ALMA
  - Spatially resolve the sources
  - Get rids of confusion noise.
- Stacking Microwave Maps in the direction of known Quasars.
  - 50 photometrically detected Quasars from Sloan Digital Sky Survey (Richards et. al 2006)
  - For 200 square degrees there are 10000 Quasars.
  - For a noise of 10 micro Kelvin per Pixel we have a signal to noise of ~0.2
  - For 10000 Quasars it will be a 20 sigma detection.
  - Needs Multi-frequency observations to tackle confusion

Future Work

- Analytic model has approximations.
- Needs to compare with galaxy simulation results.
- Ongoing work with Tiziana Di-Matteo (CMU).
- Simulation with AGN feedback (Smoothed particle Hydro+N Body) GADGET 2
- Dark matter particles taken as collisionless fluid particles.
- Gas represented by fluid particles with smoothed Kernel Function.
- Use simulation results to create SZ maps.



Dimatteo et.al 07 (In Prep)

Conclusions

- Both primary and secondary anisotropies in the CMB are useful probes of Cosmology
- Current state of the art CMB experiments are targeted towards SZ.
- Useful probe of Cosmology (cluster scales) as well as Baryonic physics (small scales).
- Quasar feedback seems to be an interesting signature.
- Current and future Sub-mm experiments are potentially capable of detecting the signal.
- Needs calibration and detailed modeling.