Hot plasma in galaxy clusters

the X-ray/SZ picture

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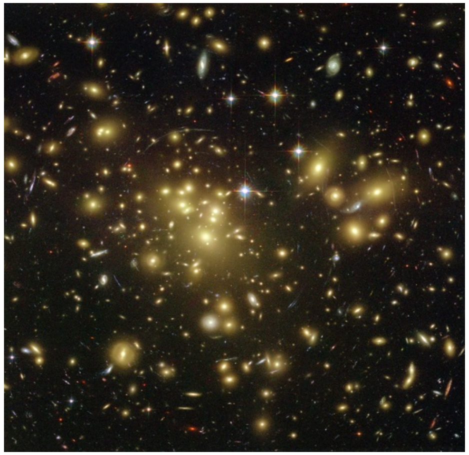
Jan 21th, 2013

What are galaxy clusters?

«Galaxy clusters are significant concentrations of galaxies.»



Basically true, but…

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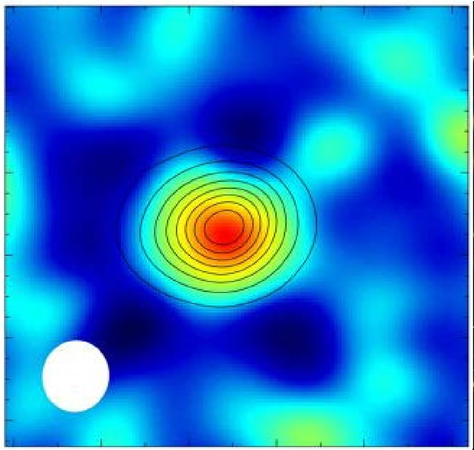
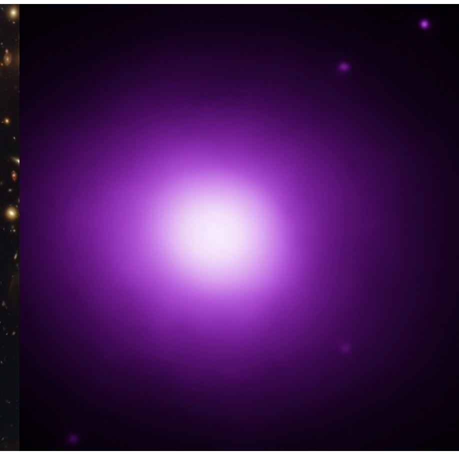
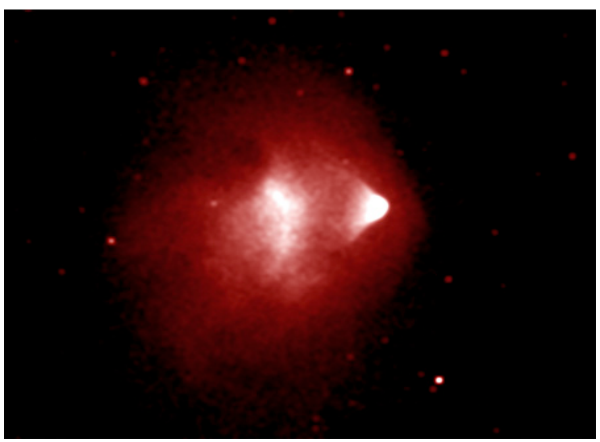


Basically true, but…fairly naive.

What are galaxy clusters?

- **«Galaxy Clusters are the cosmic structures on the high-mass tail of the halo mass function»**
- Large structures (few Mpc) with a fair representation of the cosmic mass budget:
  - ~2% mass in galaxies (10s to 1000s)
  - ~13% in the hot ($10^7 \div 10^8$K), ionized intra-cluster plasma

    (i.e. baryon assembly into galaxies is quite inefficient)
  - ~85% dark matter (historical argument by F. Zwicky)

  Typical masses in excess of $10^{14}\ M_\odot$
- Routine observations of clusters today are performed in a variety of spectral windows:
  - Optical, IR (σ_v , N_{gal})
  - Optical (lensing mass)
  - X-rays (L_X,T_X)
  - Mm/submm (Compton Y)
  - Radio (halos, relics…)
  - …

Clusters: the crossroad of astrophysics and cosmology?

- Measuring distances using clusters as standard rulers
- Growth of cosmic structure from cluster number counts
- Using the gas mass fraction in clusters to measure the cosmic baryon density
- Measuring the large-scale velocity fields in the universe from kinematic SZ Effect
- Constraints from power spectrum

Problem: at the MPc scales, structure assembly and evolution cannot be predicted from pure gravity+cosmology alone.

Q: Given this complication, can we still predict some general properties which bind the cluster population to the underlying cosmology?

A: yes, if we understand the (baryon) physics in galaxy clusters.

Baryons in galaxy clusters

- Assembly into galaxies is inefficient
- Majority of baryonic mass in clusters is hot gas (ICM)
  - Temperature T ~ 10^8 K (~ 10 keV) (heated by gravitational potential)
  - Electron number density $n_e \sim 10^{-3}$ cm^{-3}
  - Mainly H, He, but with heavy elements (O, Fe, ..)
  - Mainly emits X-rays (but also radio and gamma rays), first observed by Uhuru back in the ‘70s
  - $L_X \sim 10^{45}$ erg/s, most luminous extended X-ray sources in Universe
  - Causes the Sunyaev-Zel’dovich effect (SZE) by inverse Compton scattering the background CMB photons

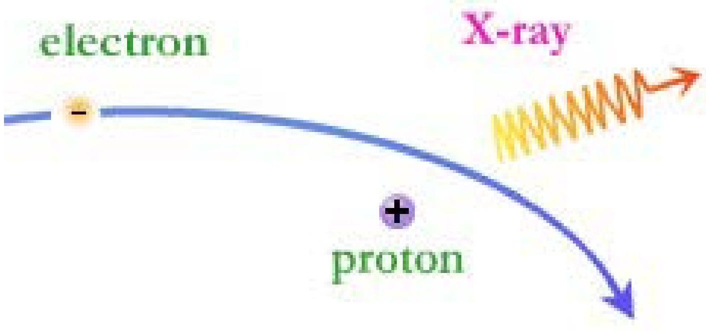
Review on clusters: Voit, Rev.Mod.Phys.77:207-258,2005

Clusters in X-rays

- Thermal bremsstrahlung is the primary source of X-ray emission from clusters due to diffuse intracluster plasma at 10^8K
- Power radiated according to Larmor's formula ($P \propto |a|^2$)
- Total power per unit volume:

$$L \propto nenHT^{\frac{1}{2}}$$

- Very sensitive to substructure, but difficult to push obsvns to cluster outskirts.
- Power per unit freq, unit volume:



$$\varepsilon^{ff}(\nu,i) = \frac{2^5 \pi e^6}{3 m_e c^3}\left(\frac{2\pi}{3k_B m_e}\right)^{1/2} T^{-1/2} Z_i^2 g_{ff}(Z_i,T,\nu) n_e n_i e^{-h\nu/kT}$$

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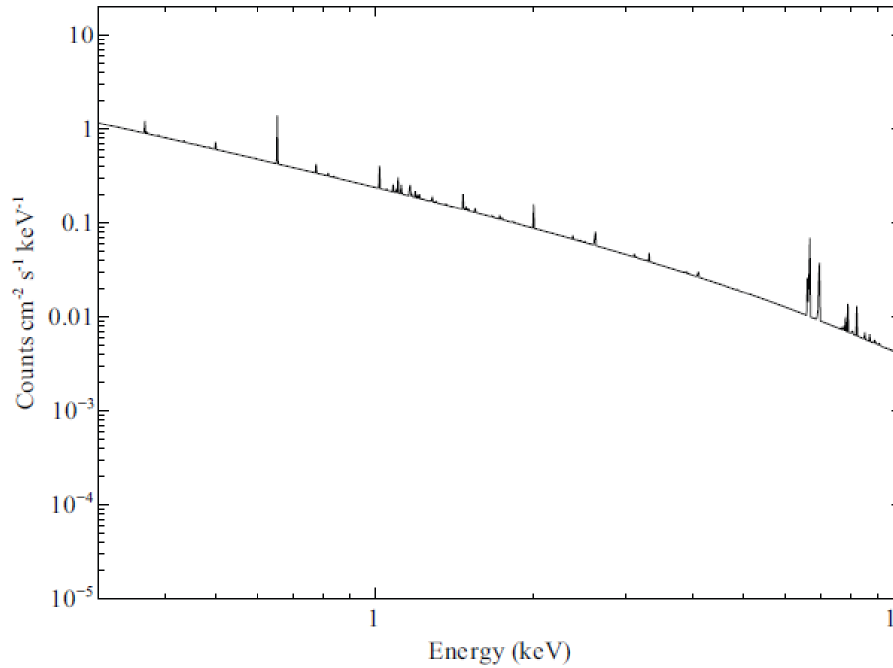

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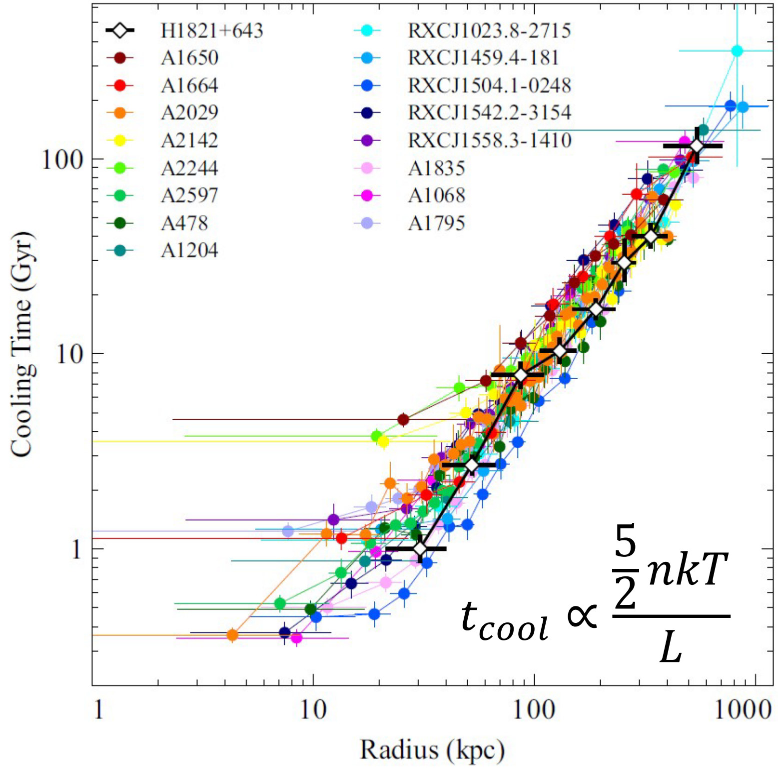

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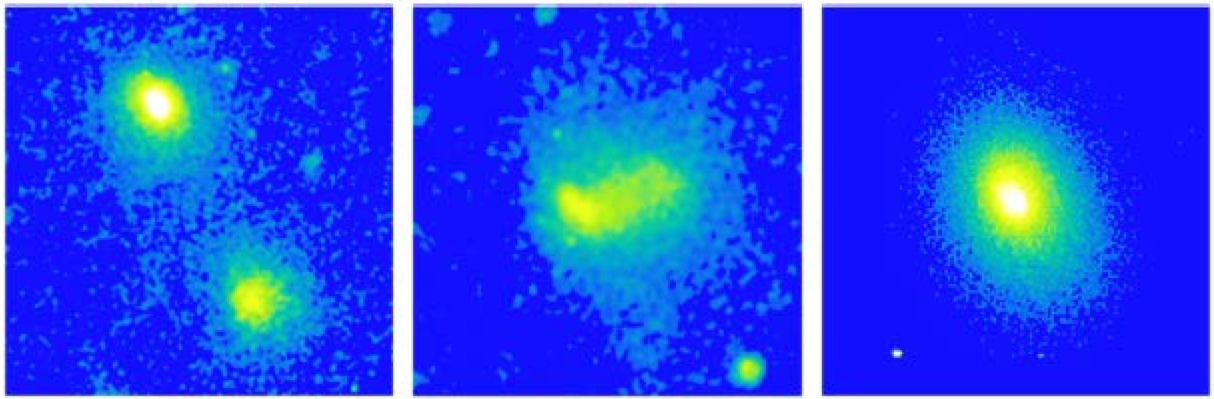
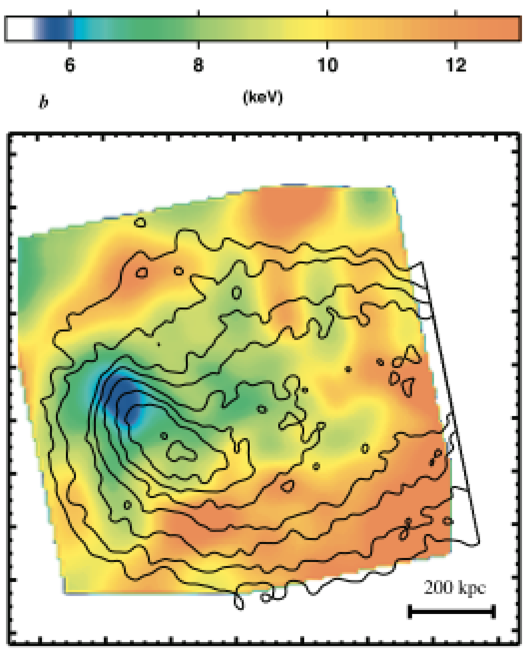
Clusters in X-rays

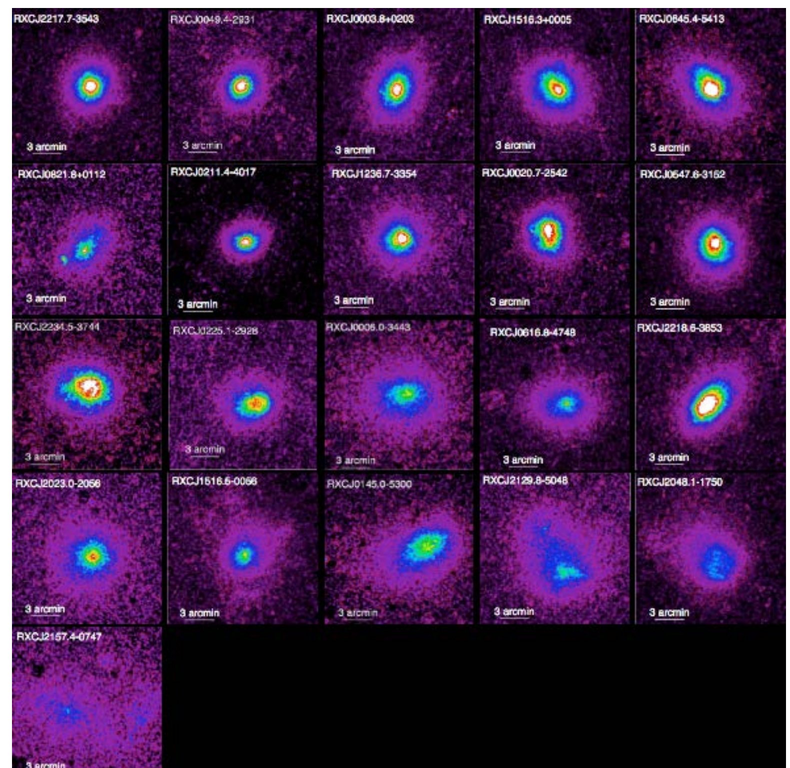
→The «cooling flow» problem was the first strong evidence of complex baryon physics at work in the cores of clusters (feedback from AGNs, multiphase mixing, thermal conduction, heating by cosmic rays, etc.) (Fabian, astro-ph/0512549)

→ Many cluters exhibit ongoing merging activity, deviations from spherical simmetry, traces of nonthermal phenomena…

Clusters in X-rays





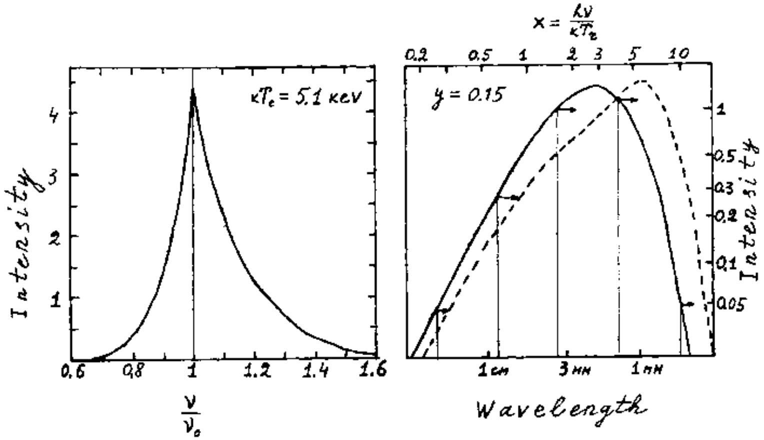


Clusters in the microwaves

Yacov B. Zel’dovich

Rashid Sunyaev

Sunyaev & Zel’dovich
(1969, 1970,1972)



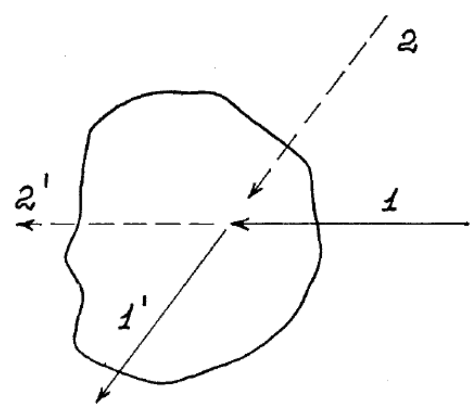


FIG. 2. The scattering of isotropic radiation field by the cloud of electrons.

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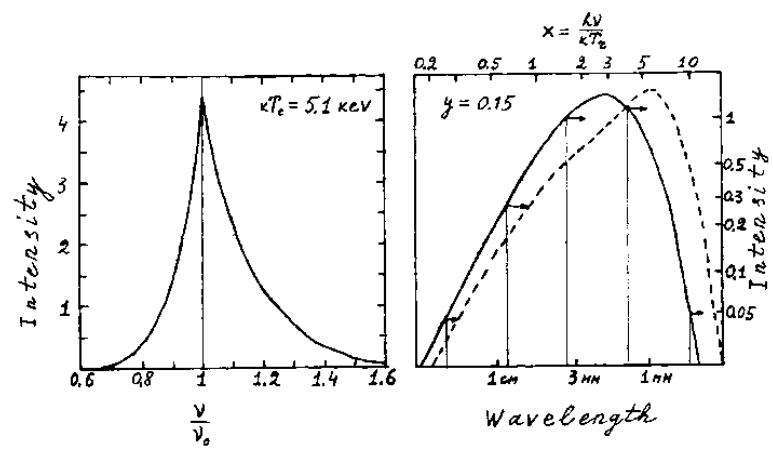


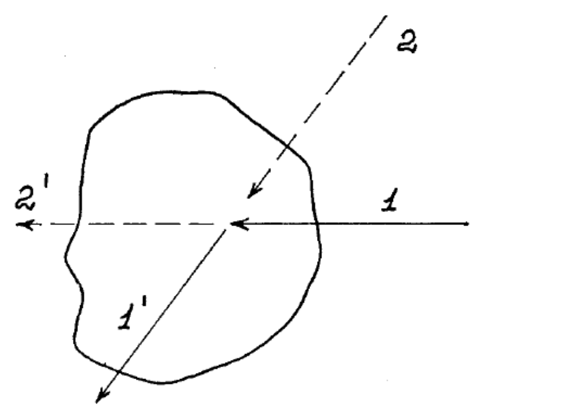
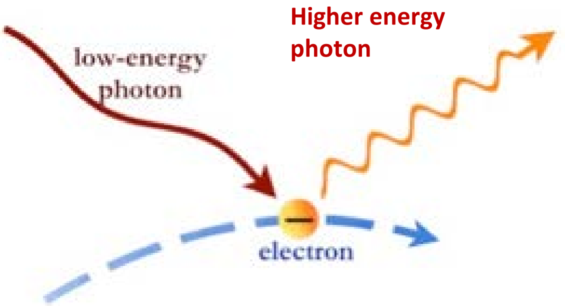


FIG. 2. The scattering of isotropic radiation field by the cloud of electrons.

SZ effect

L'effetto SZ è la distorsione spettrale indotta in una popolazione di fotoni dallo scattering Compton inverso su una popolazione densa e calda di elettroni.



In un ammasso di galassie:

$n_e=10^{-3} e^{-} cm^{-3}$

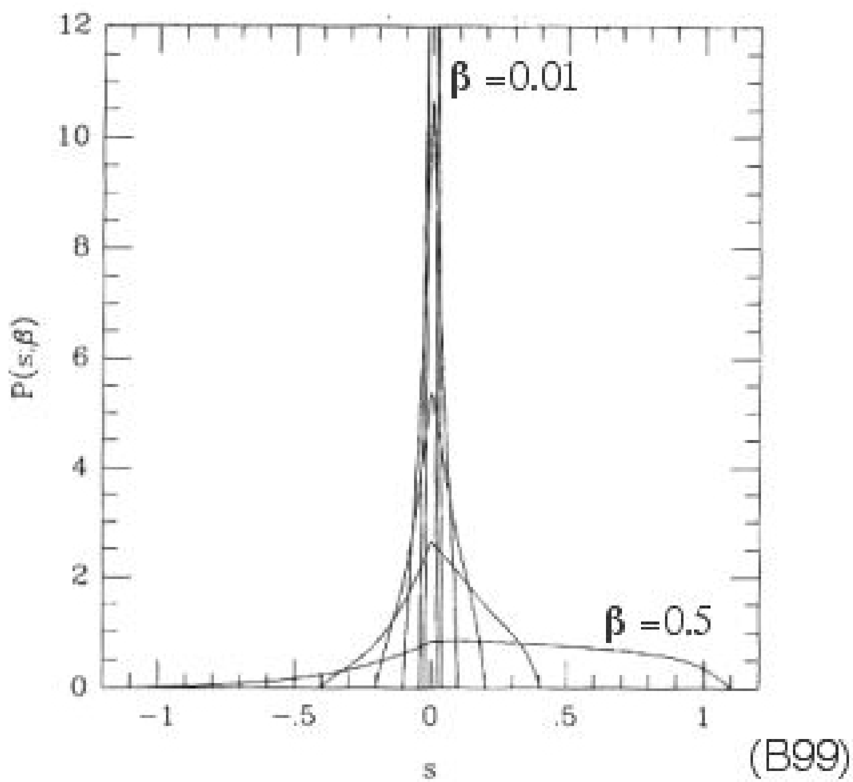
kT_e=5-20 keV

$$\tau_e = \int_{l.o.s} n_e \sigma_T dl \approx 10^{-2}$$

Nucleo di scattering per diffusione di un singolo fotone:

Asimmetrico in s

Distribuzione più larga ad alti β



SZ effect

Convolvendo il nucleo di scattering con la distribuzione iniziale dei fotoni diffusi (spettro della radiazione incidente) si ottiene lo spettro distorto dalla comptonizzazione attraverso il gas.

Nel caso più semplice (approssimaz. non relativistica di Kompaneets) la variazione d'intensità della radiazione uscente è espressa dalla relazione

$$\Delta I_\nu = i_0 \frac{x^4 e^x}{\left(e^x - 1\right)^2}\left[x \coth\frac{x}{2} - 4\right] y \qquad i_0 = \frac{2\left(kT_{CMB}\right)^3}{\left(hc\right)^2}, x = \frac{h\nu}{kT_{CMB}}$$

Che descrive l'effetto SZ termico in regime non relativistico.

$$y = \int_{l.o.s} n_e \sigma_T \frac{kT_e}{m_e c^2} dl \approx 10^{-4} \max$$

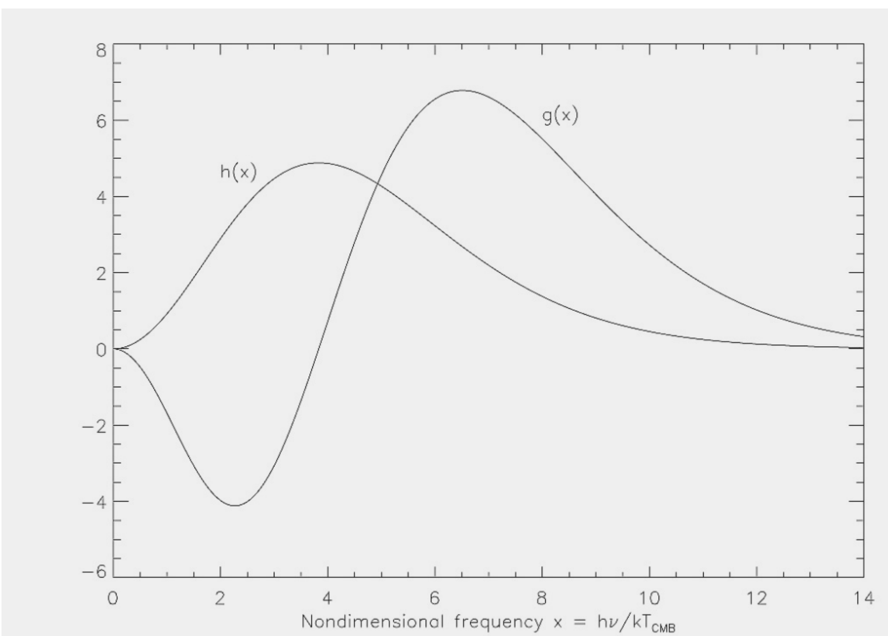
$$\frac{\Delta T_{CMB}}{T_{CMB}} = \left(x \frac{e^x + 1}{e^x - 1} - 4 \right) y$$

Kinetic SZ

Quando il cluster possiede una componente non nulla di velocità peculiare lungo la linea di vista, all'effetto SZ termico si sovrappone una componente cinematica proporzionale, oltre che allo spessore ottico, alla velocità peculiare del cluster e al verso del suo moto lungo la linea di vista.

$$\Delta I_{\upsilon}^{kin} = -i_0 \frac{x^4 e^x}{\left(e^x - 1\right)^2} \beta_c \frac{\tau}{2}$$

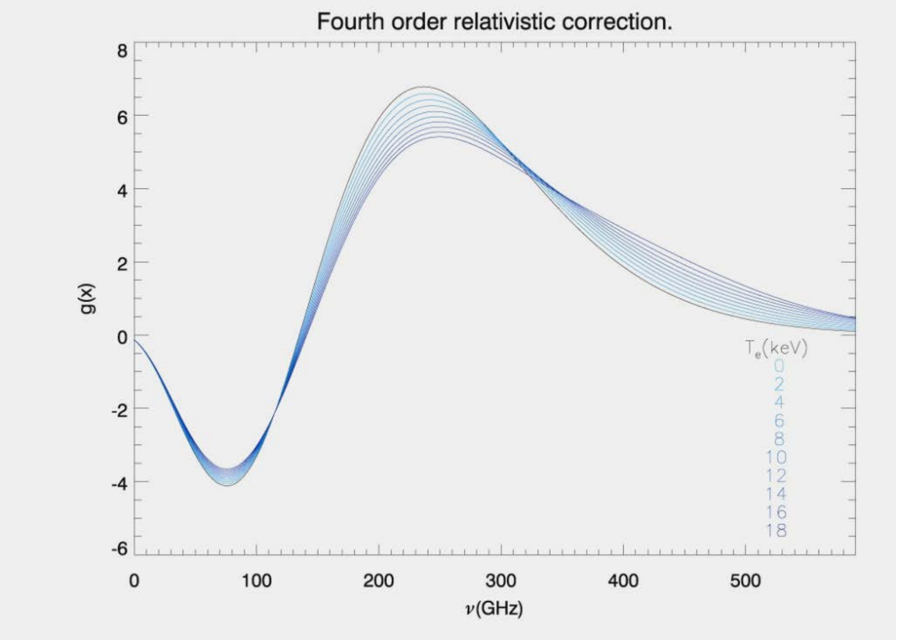
$$\frac{\Delta T_{CMB}}{T_{CMB}} = -\beta_c \frac{\tau}{2}$$



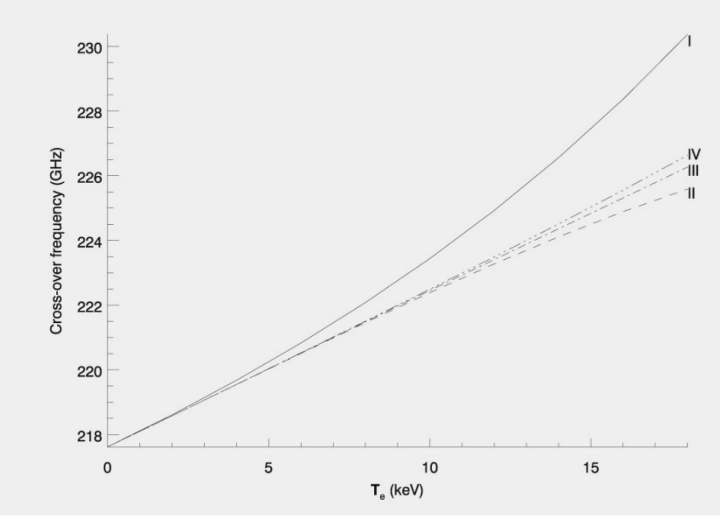
La differente segnatura spettrale consente di discriminare le due componenti quando esse vengano misurate con strumenti multibanda e ad alte frequenze (mm/submm)

Correzioni relativistiche

Indipendentemente dagli approcci (sviluppi perturbativi in kT/mc^2, metodo Monte Carlo per il calcolo della diffusione dei fotoni sugli elettroni del cluster), si dimostra che lo spettro dell'effetto SZ termico acquista più potenza ad alte frequenze e che la frequenza di crossover NON è costante, ma dipende dalla temperatura del gas.



Le correzioni relativistiche possono essere superiori al 10-15% in cluster moderatamente caldi (kT_e>8keV).



Profili di temperatura, densità, pressione

Modello β isotermo

(Cavaliere, Fusco-Femiano, 1976)

$$n_e(r) = n_0\left(1+\frac{r^2}{r_c^2}\right)^{-\frac{3}{2}\beta}$$

Da cui segue per la mappa di comptonizzazione attorno al centro del cluster

$$y(r) = y_0\left(1+\frac{r^2}{r_c^2}\right)^{\frac{1}{2}-\frac{3}{2}\beta}$$

SVM (Vikhlinin et al. ApJ 640, 691 - 2006)

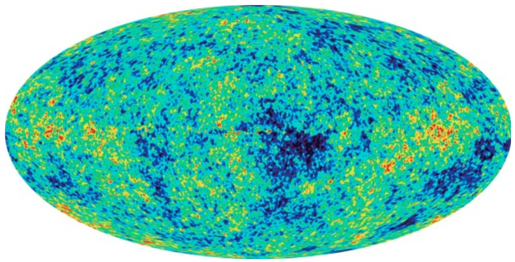
$$n_e(r) = n_0\left[1+\left(\frac{r^2}{r_c^2}\right)^2\right]^{-\frac{3}{2}\beta}\left[1+\left(\frac{r^2}{r_s^2}\right)^{\gamma}\right]^{-0.5\frac{\varepsilon}{\gamma}}$$

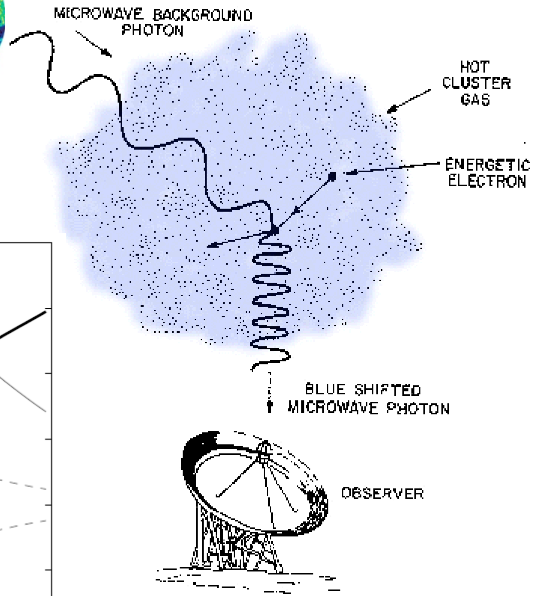
Generalized NFW (Nagai et al., ApJ 668, 1 -2007) (a=1.3,b=4.3,c=0.7)

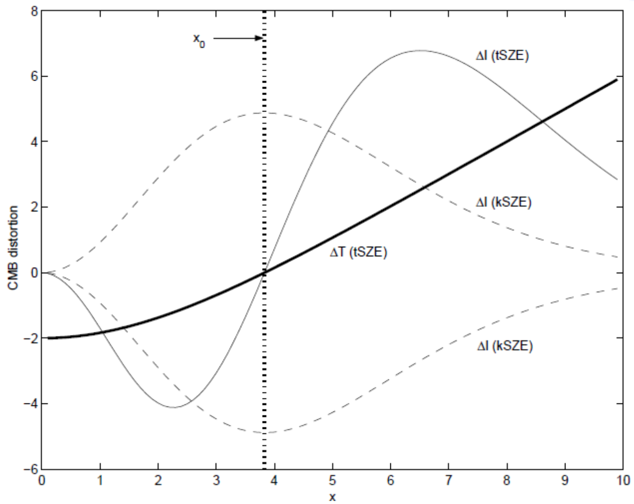
$$p_e(r) = \frac{p_{e,i}}{\left(r/r_p\right)^c\left[1+\left(r/r_p\right)^a\right]^{(b-c)/a}}$$

MA: struttura tri-assiale, clumping, disomogeneità, shocks…

Clusters at microwave frequencies: the Sunyaev-Zel'dovich Effect







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- **Photons are shifted to higher frequencies, providing a unique spectral signature of the CMB distorsion at microwaves.**
- **«Holes in the microwave sky» at radio frequencies, hot spots above ~217 GHz.**
- **Redshift independent, first order in plasma density w.r.t. X-ray brightness: excellent tool to detect (and even discover) clusters at high z.**
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$$\Delta I = \frac{2k^3 T_{CMB}^{\ 3}}{h^2 c^2} \frac{x^4 e^x}{(e^x - 1)^2} \sigma_T \int n_e dl \left[\theta f_1(x) - \beta + R(x, \theta, \beta)\right]$$

$$f_1(x) = x \coth\left(\frac{x}{2}\right) - 4$$

$$x = h\nu / kT_{CMB}$$

$$\theta = kT_e / mc^2$$

$$\beta = V_{pec} / c$$

Sunyaev & Zel'dovich, Comm. Astr. Sp. Phys 4, 173 (1972)

Reviews by:
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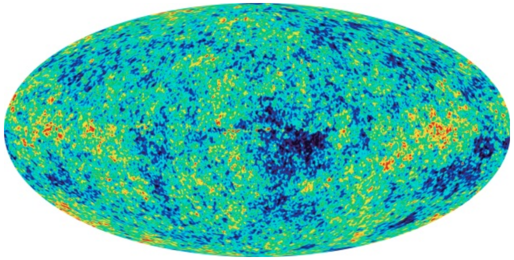

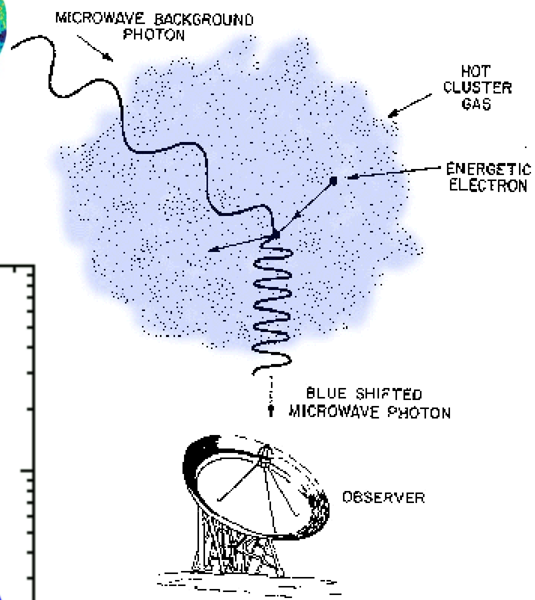

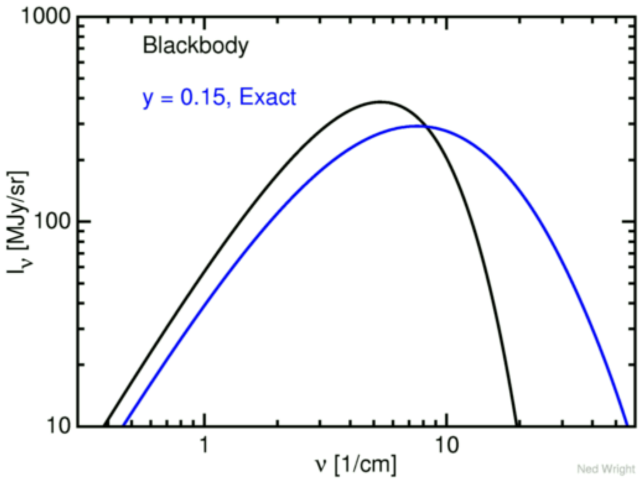

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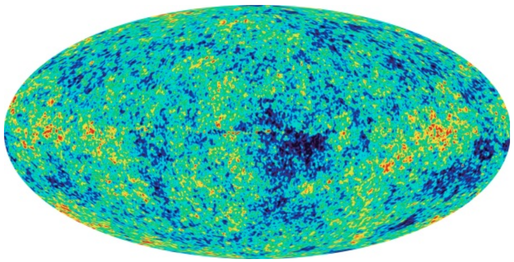

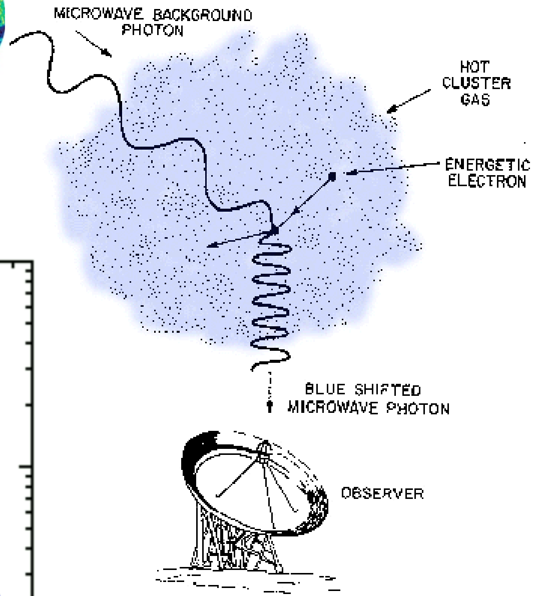

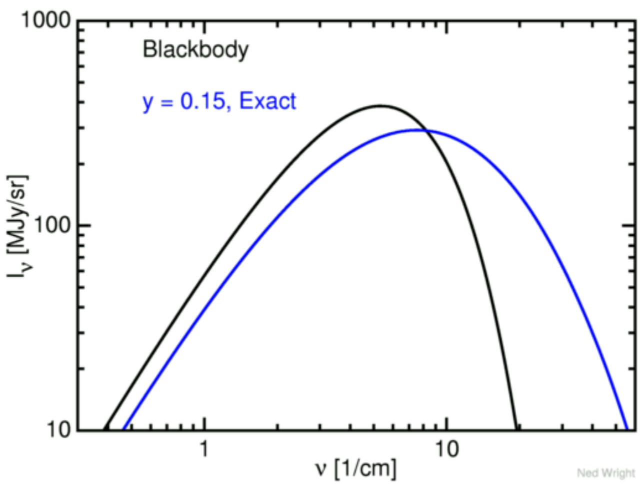

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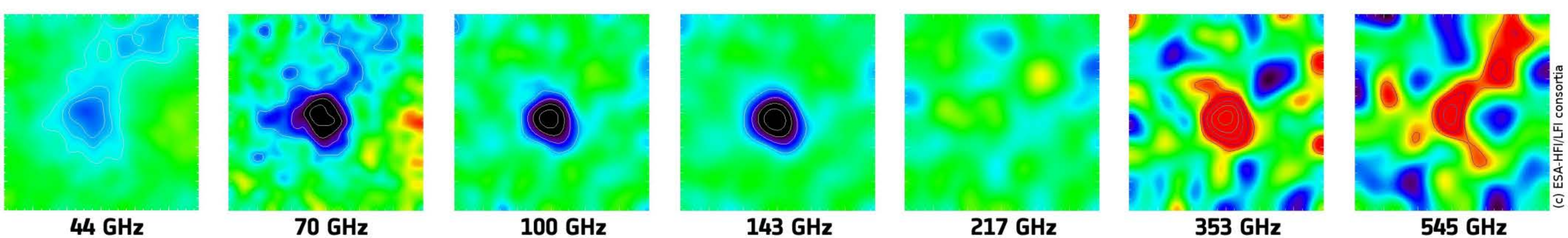
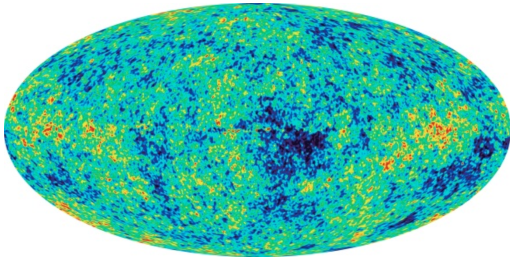
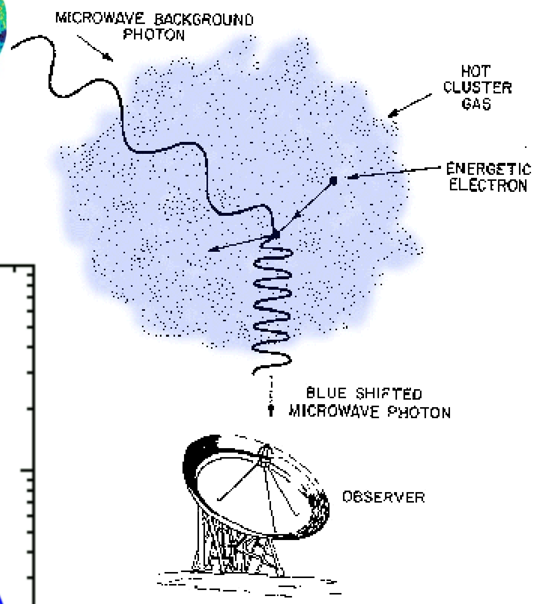
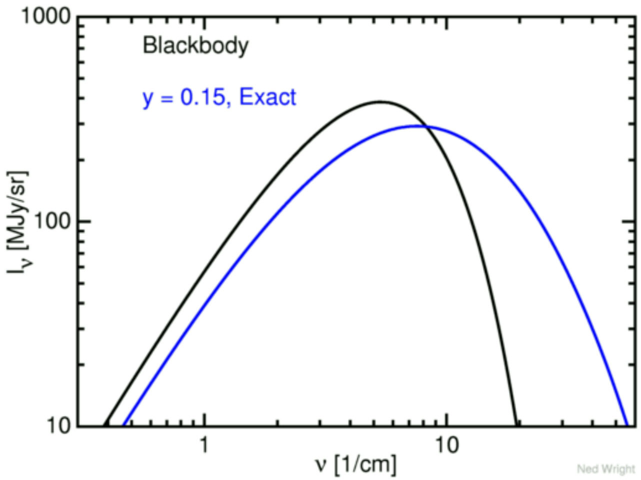


The spectral signature: Multifrequency view of Abell 2319 by Planck

Clusters at microwave frequencies: the Sunyaev-Zel'dovich Effect







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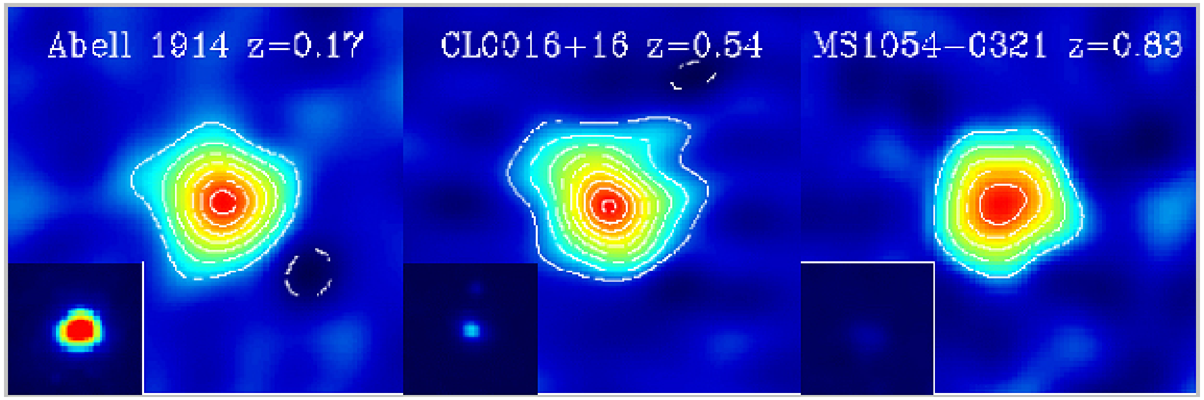


The redshift magic: OVRO/BIMA 30GHz maps with X-ray counterparts

Clusters come regoli standard

Variazione d'intensità del fondo cosmico in direzione di un ammasso:

$$\Delta I = i_0 g(x) \frac{kT_{e0}}{m_e c^2} \sigma_T n_0 d_A \int w_n w_T d\left(l / d_A\right)$$

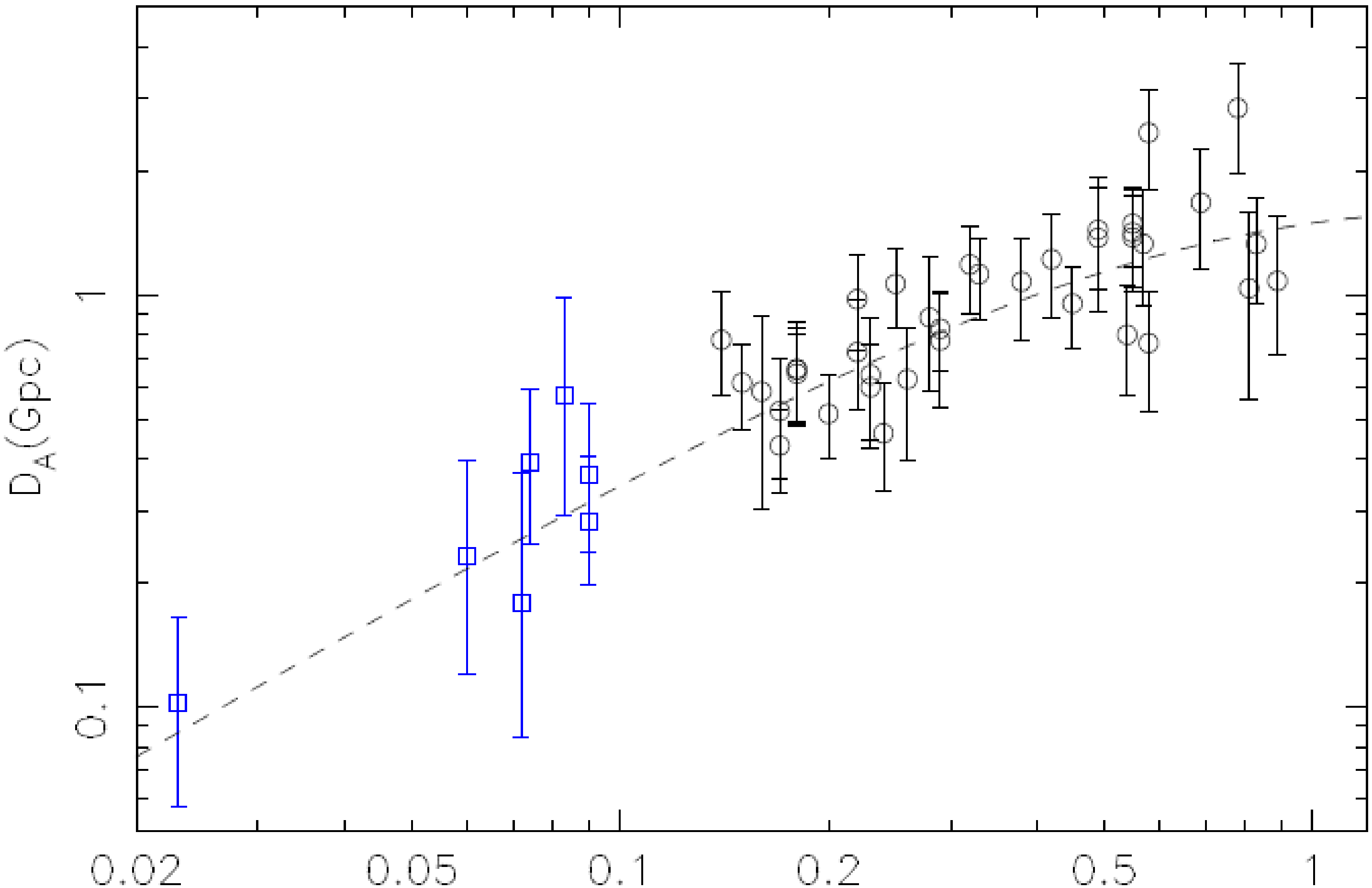
Brillanza superficiale X (1÷10 keV)

$$b_X = \frac{X_0 n_0^2 d_A}{4\pi(1+z)^3} \int w_n w_X d(l / d_A)$$

Da cui, eliminando n_0:

$$d_A = \frac{1}{4\pi(1+z)^3} \left(\frac{X_0}{\sigma_T^2 b_X} \right) \left(\frac{\Delta I}{i_0 g(x)} \right)^2 \left(\frac{m_e c^2}{kT_{e0}} \right)^2 \left(\frac{Q_X}{Q_m^2} \right)$$

$$H_0 d_A = \frac{c}{(1+z)\sqrt{|k|}} S\left(\sqrt{|k|} \int_0^z \left[(1+z')^2 (1+\Omega_M z') - z'(2+z')\Omega_\Lambda \right]^{-1/2} dz' \right)$$



D_A (Gpc)
1
0.1
0.02
0.05
0.1
0.2
0.5
1

SZ observations from MITO: the Coma cluster

SZ on A1656 by MITO

$$\Delta T_0(143\mathrm{GHz}) = (-184 \pm 39)\ \mu\mathrm{K}$$

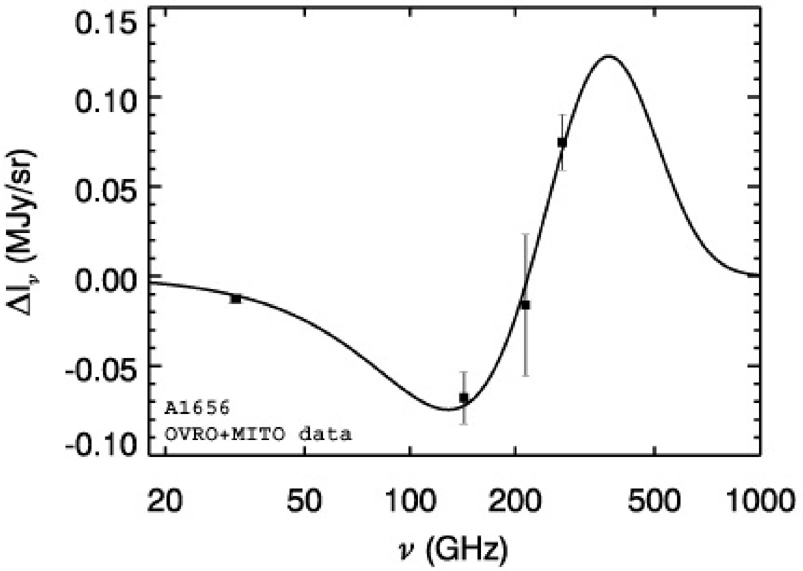
$$\Delta T_0(214\mathrm{GHz}) = (-32 \pm 79)\ \mu\mathrm{K}$$

$$\Delta T_0(272\mathrm{GHz}) = (+172 \pm 36)\ \mu\mathrm{K}$$

$$\Rightarrow \tau_0 = (5.05 \pm 0.84) \cdot 10^{-3}$$

De Petris, ..LL.. et al. Ap.JL **574**, 119 (2002)

Savini, ..LL.. et al. New Astr. **8**, 7, 727 (2003)

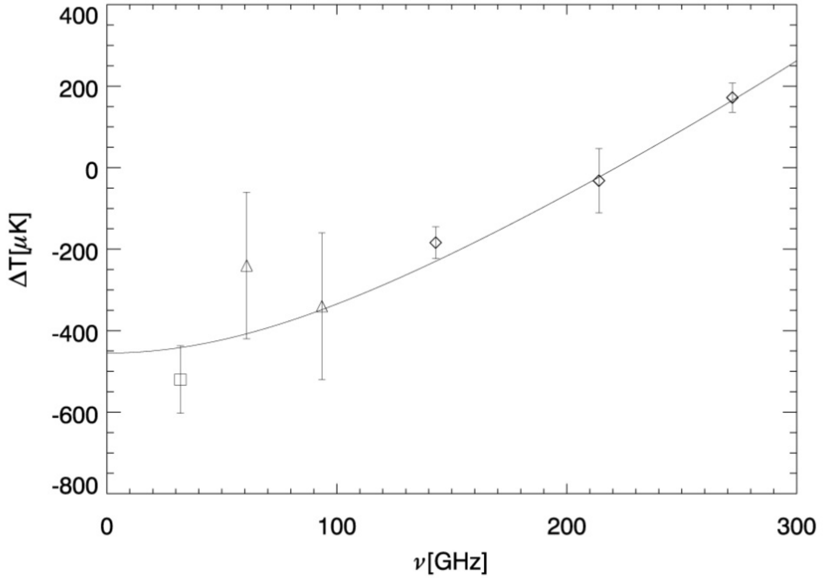


SZ on A1656 by OVRO+WMAP1+MITO

First SZ spectrum with 6 frequencies:

$$\Rightarrow \tau_0 = (5.35 \pm 0.67) \cdot 10^{-3}$$

Battistelli, ..LL..et al.,ApJ 598, L75 (2003)



SZ observations from MITO: the Coma cluster

SZ on A1656 by MITO

$$\Delta T_0(143\text{GHz}) = (-184 \pm 39)\,\mu\text{K}$$

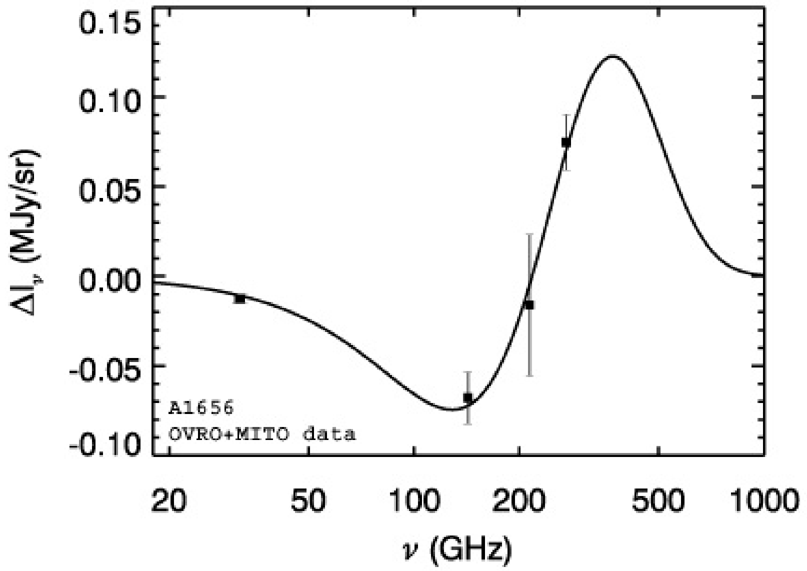
$$\Delta T_0(214\text{GHz}) = (-32 \pm 79)\,\mu\text{K}$$

$$\Delta T_0(272\text{GHz}) = (+172 \pm 36)\,\mu\text{K}$$

$$\Rightarrow \tau_0 = (5.05 \pm 0.84) \cdot 10^{-3}$$

De Petris, ..LL.. et al. Ap.JL **574**, 119 (2002)

Savini, ..LL.. et al. New Astr. **8**, 7, 727 (2003)



SZ on A1656 by OVRO+WMAP1+MITO

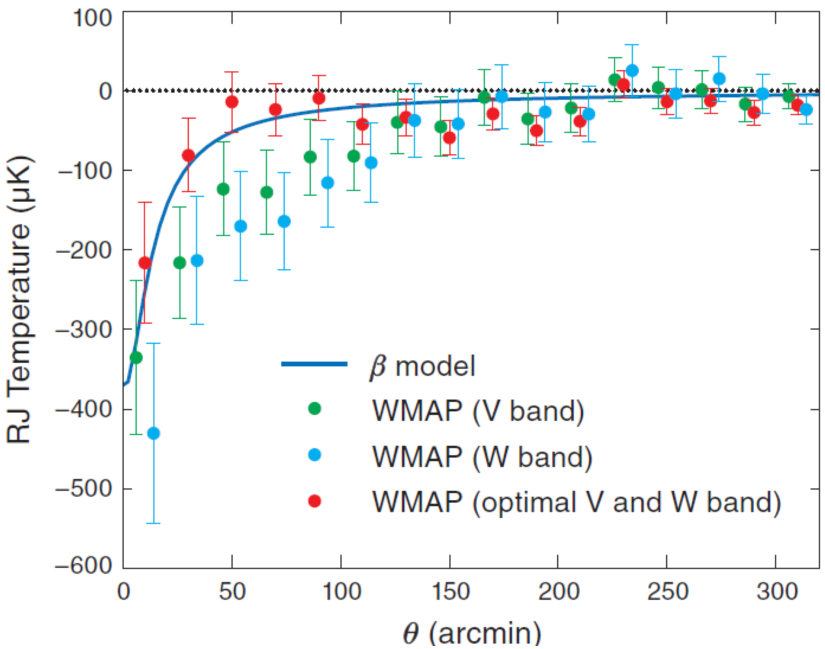
First SZ spectrum with 6 frequencies:

$$\Rightarrow \tau_0 = (5.35 \pm 0.67) \cdot 10^{-3}$$

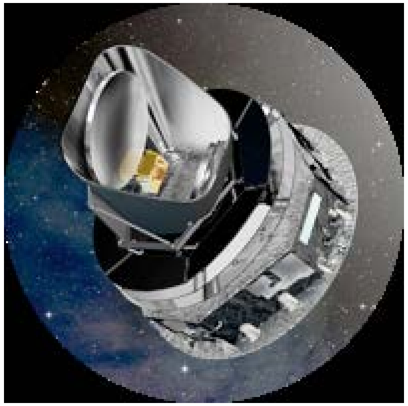
Battistelli, ..LL..et al.,ApJ 598, L75 (2003)

Confirmed by WMAP7

(Komatsu et al., ApJS 2011)



Cluster studies today:
Blind SZ detections & hi res SZ mapping


Planck


ACT


SPT


Apex


Mustang (GBT)

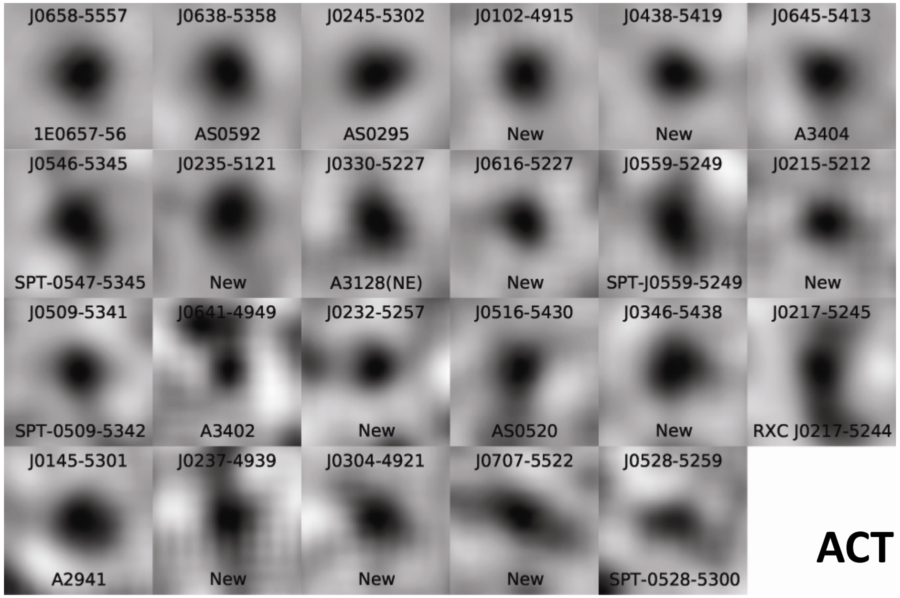

CARMA


AmiBA

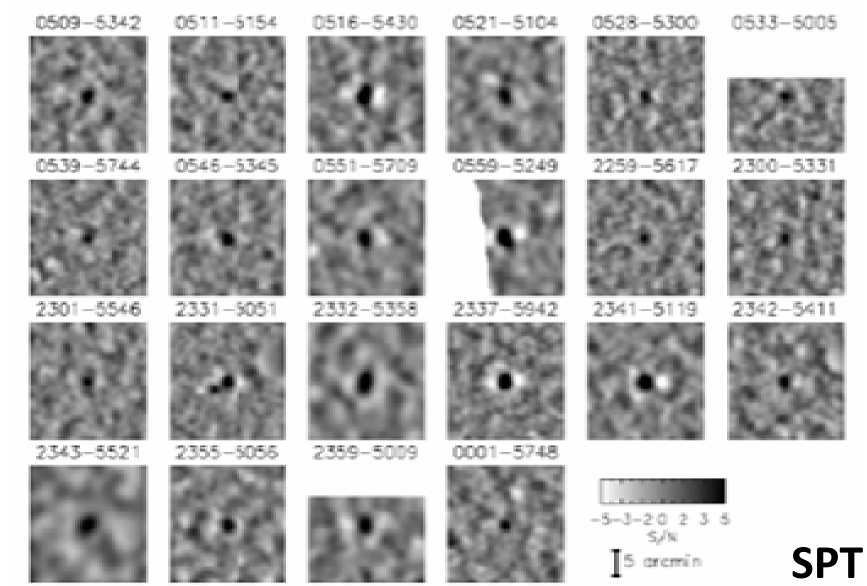

AMI

Cluster studies today:

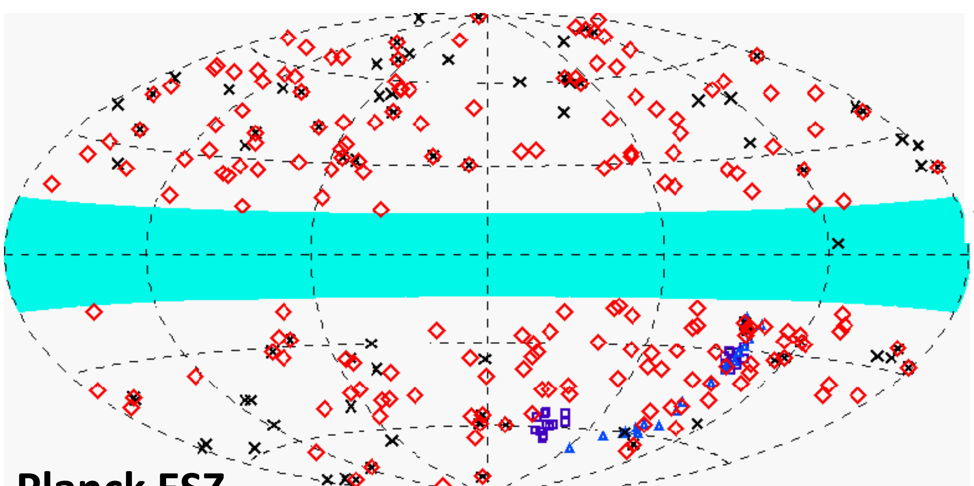
Blind SZ detections & hi res SZ mapping



Marriage et al., ApJ 737, 71 (2011)

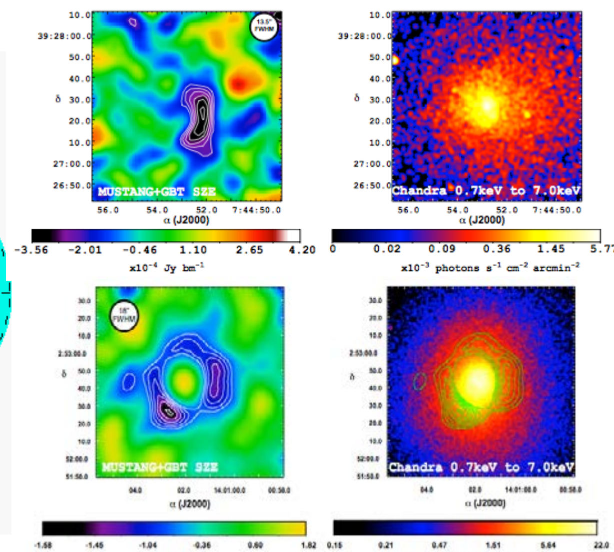


Vanderlinde et al., ApJ 722, 1180 (2010)



Planck ESZ

(early paper no. VIII)



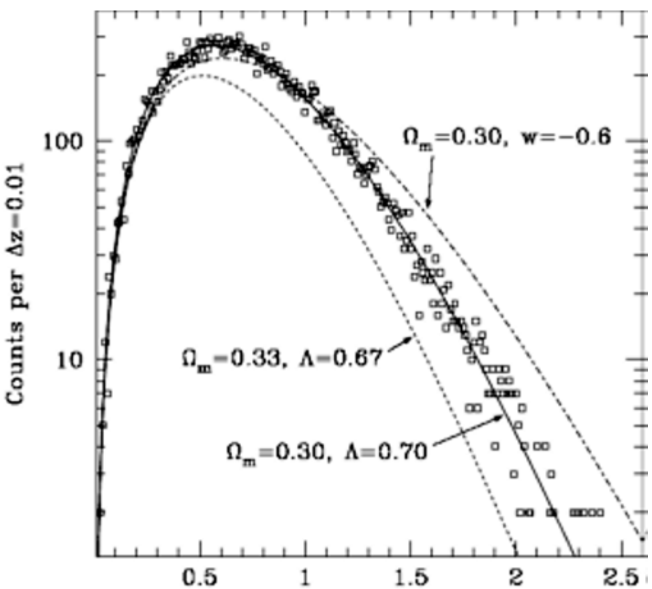
Mustang

Korngut et al., ApJ 734,10 (2011)

Cluster studies today:

Cluster scaling relations and the quest for the perfect mass proxy

• How many clusters of mass M exist in a given cosmology at redshift z?
• What is the probability that a cluster of mass M at redshift z will have temperature T_x (or some other observable)?



$$\frac{dN}{d\Omega dz} = \frac{dV}{d\Omega dz} \times \int_{M_{min}}^{\infty} dM \frac{dn}{dM}$$

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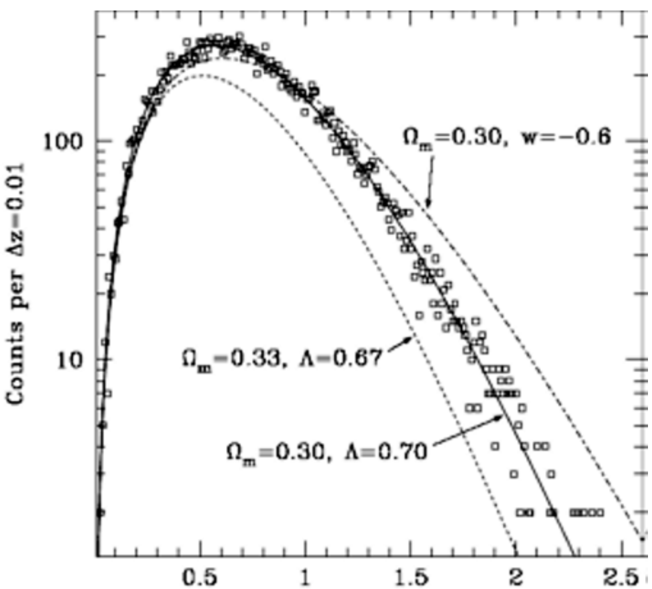


$$\frac{dN}{d\Omega dz} = \frac{dV}{d\Omega dz} \times \int_{M_{min}}^{\infty} dM \frac{dn}{dM}$$

Comparison of mass-proxies + hydro sims can help identify which ones work best, but also provides insights in the relevant cluster physics.

How many «inferred» masses?

Hydrostatic (X, SZ):

$$\frac{dp_{gas}(r)}{dr} = -\rho_{gas}(r)\frac{G\,M_{tot}(<r)}{r^2} = \frac{k_B}{\mu\, m_p}\frac{d[\rho_{gas}(r)\,T_X(r)]}{dr}$$

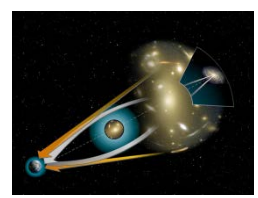
$$M_{tot}(<r) = -\frac{k_B\,T(r)\,r}{G\,\mu\,m_p}\left(\frac{d\ln\rho_{gas}}{d\ln r} + \frac{d\ln T}{d\ln r}\right)$$

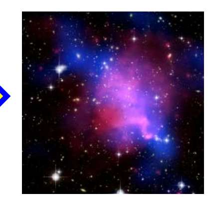
μ ~0.6: mean molecular weight; m_p: proton mass

Dynamical (opt):

$$M(r) = -\frac{r\sigma_r^2(r)}{G}\left[\frac{d\ln\sigma_r^2}{d\ln r} + \frac{d\ln\nu}{d\ln r} + 2\beta\right]$$

Lensing (opt):





Proxies: L_X, T_X, Y_X, Y_{SZ}, N_{200}, other?

$$Y_{S,\Delta} = \frac{\sigma_T}{m_e c^2}\frac{\mu}{\mu_e}\left(\frac{\sqrt{\Delta}G H_0}{4}\right)^{2/3} E(z)^{2/3} f_{gas,\Delta} M_{tot,\Delta}^{5/3}$$

Cosmology with cluster counts/masses

Cluster counts (observations)

$$\frac{dN}{d\Omega dz} = \frac{dV}{d\Omega dz} \times \int_{M_{min}}^{\infty} dM \frac{dn}{dM}$$

Halo mass function + matter power spectrum (Cosmology)

$$\frac{dn_M}{d\ln\sigma^{-1}} = \sqrt{\frac{2}{\pi}} \frac{\Omega_M \rho_{cr0}}{M} \frac{\delta_c}{\sigma} \exp\left[-\frac{\delta_c^2}{2\sigma^2}\right].$$

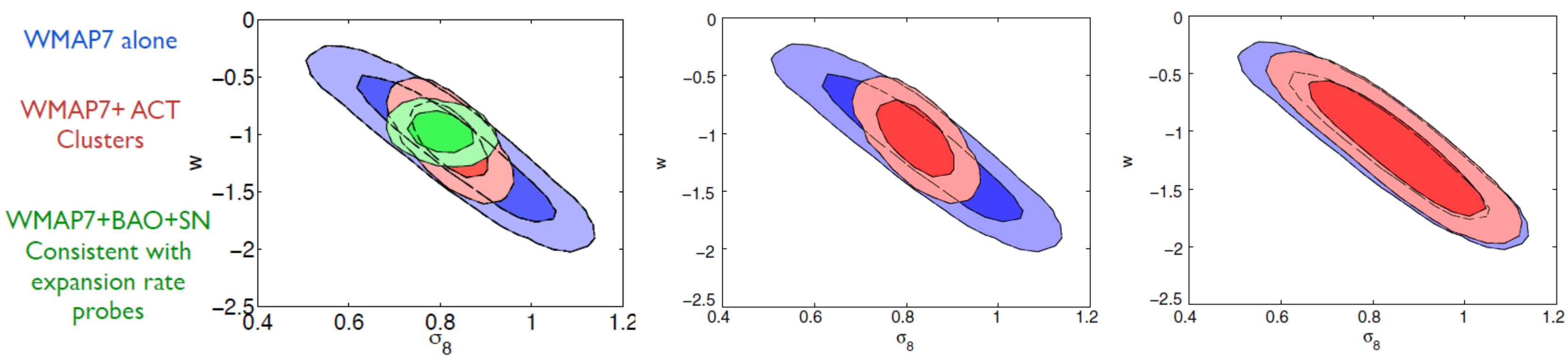
(Press-Schechter, 1974)

$$\frac{dn_M}{d\ln\sigma^{-1}} = A_J \frac{\Omega_M \rho_{cr0}}{M} \exp[-|\ln\sigma^{-1} + B_J|^{\epsilon_J}]$$

(Jenkins, 2001)

$$\sigma^2(M,z) = \frac{D^2(z)}{(2\pi)^3} \int P(k)|W_k(M)|^2 d^3k,$$

Variance on mass scale M
(constraints on σ_8, Ω_m, Ω_Λ, w, …)



Constraints from ACT-detected SZ clusters, see Sehgal et al., ApJ 732, 44 (2011)

Calibration of SZ scaling relations through the ACCEPT catalogue

$$K(r) = \frac{k_B T_X(r)}{n(r)_e^{2/3}} \qquad K(r) = K_0 + K_{100}\left(\frac{r}{100kpc}\right)^{\alpha}$$

Entropy plateau correlated with central cooling time (Donahue et al. 2005),
Proven by bimodality in K_0 distribution (Cavagnolo et al. 2009)

MCMC fits to 289 cluster profiles:
GNFW pressure profile → Y
SVM for electron density → M

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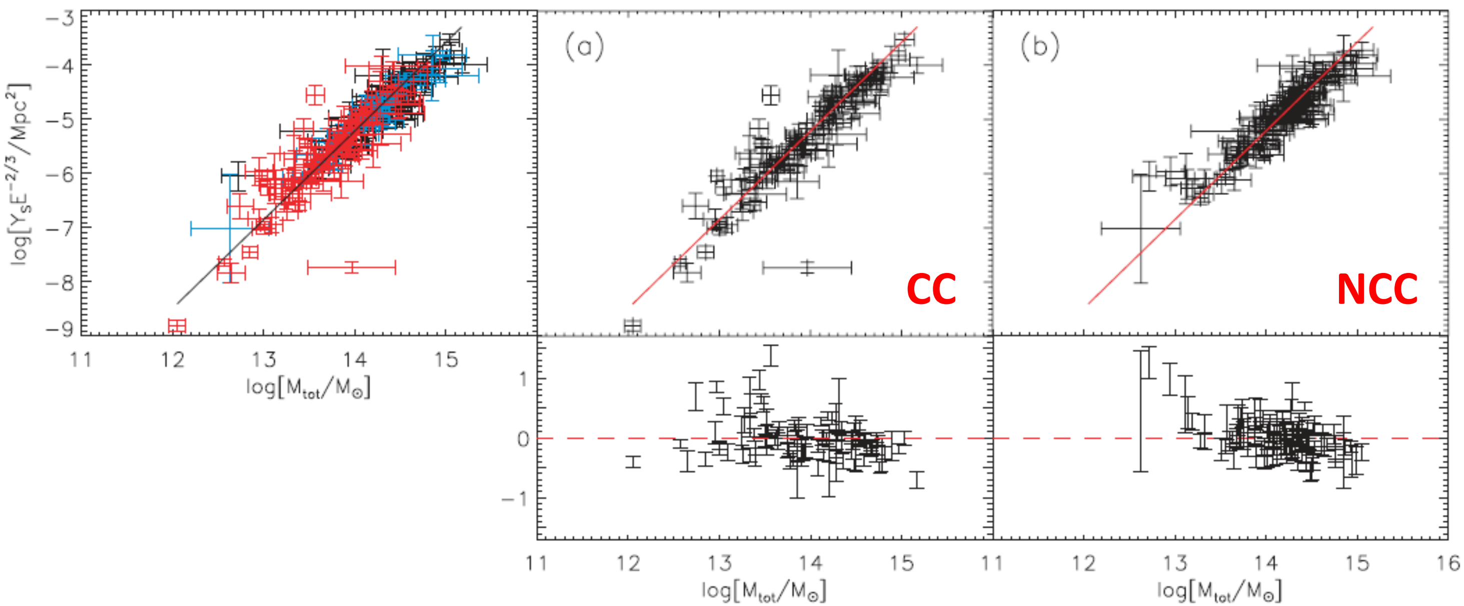
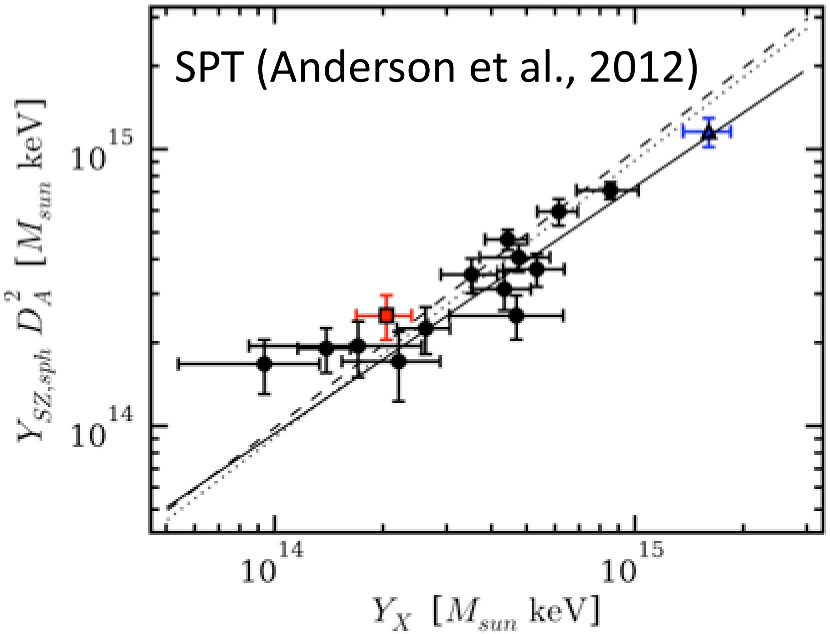
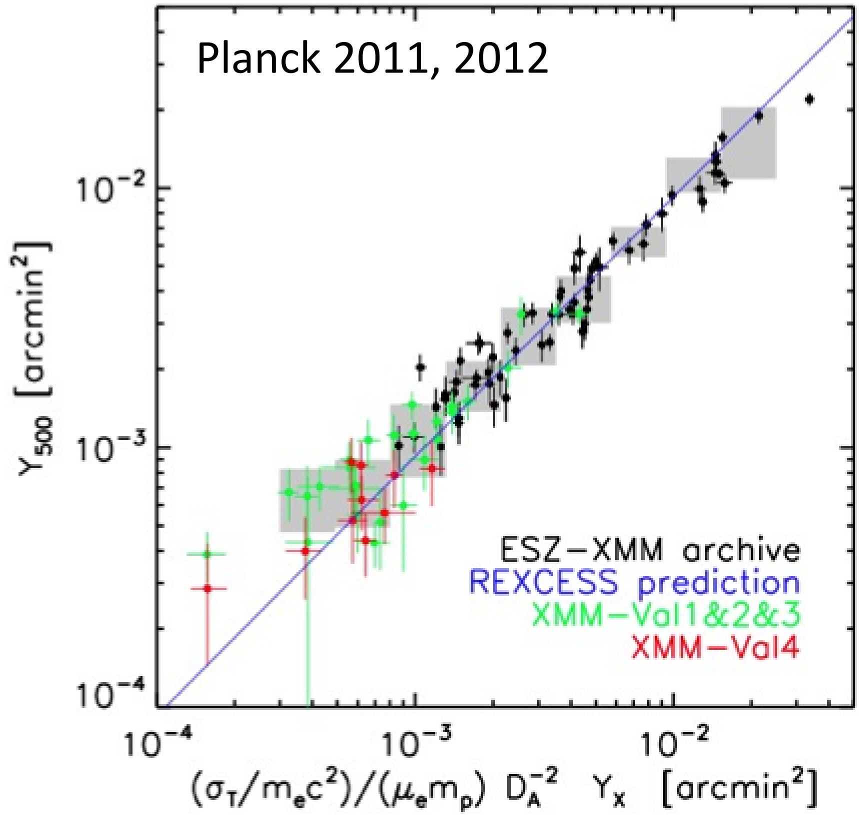
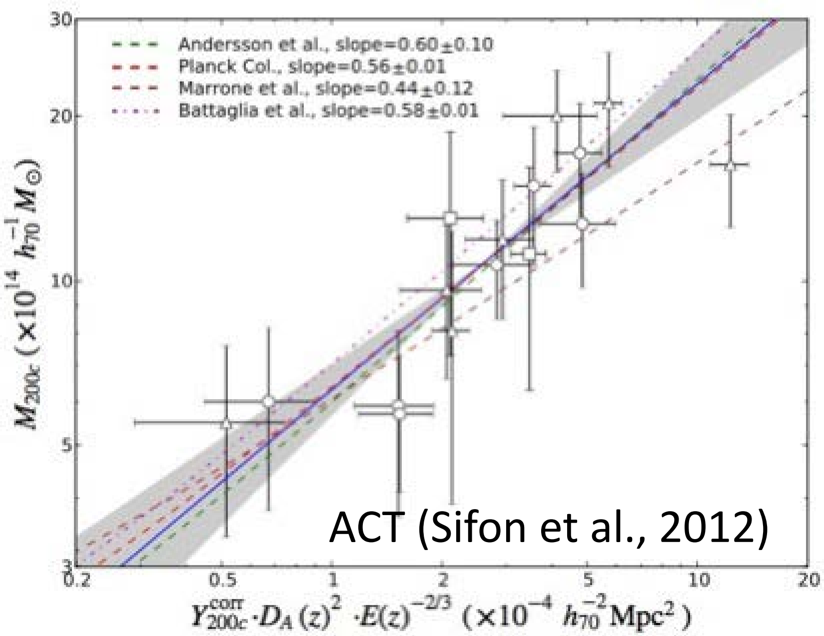
$$Log\left(Y_S E^{-2/3}\right) = (1.648 \pm 0.070) Log M_{tot} - (28.35 \pm 0.96)$$



Comis,..LL.. et al., MNRAS 418, 1089 (2011)

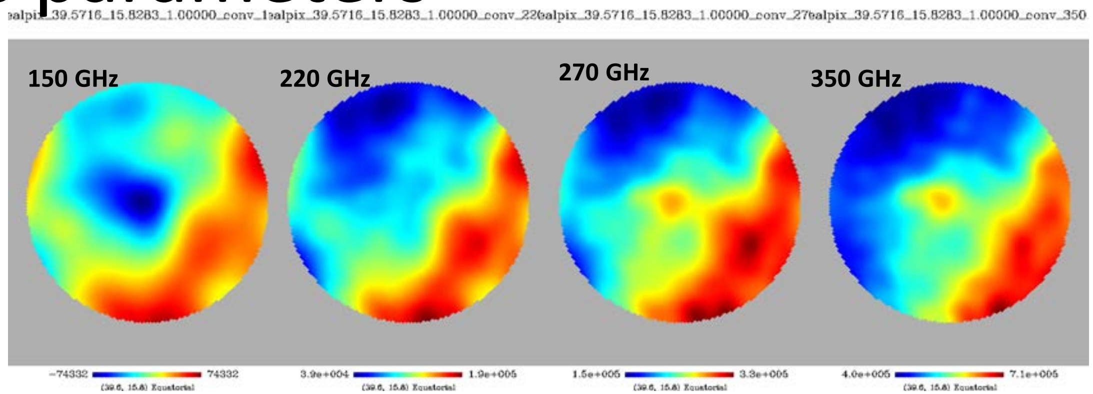




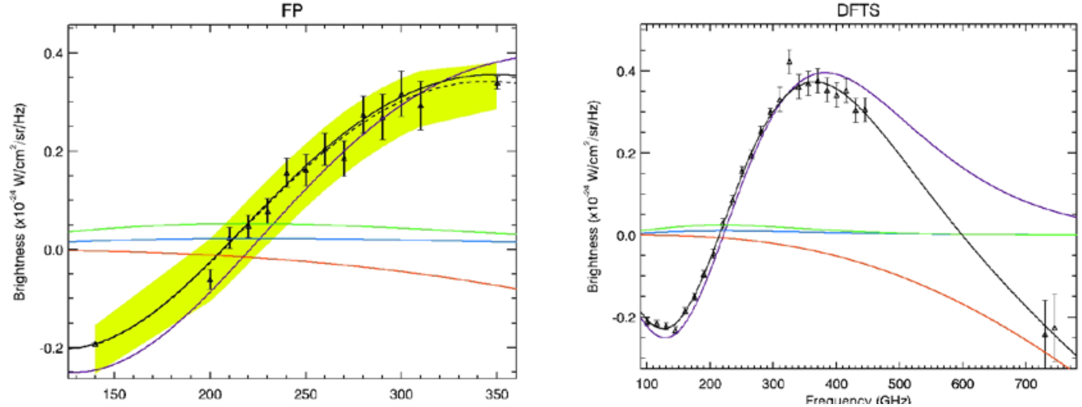


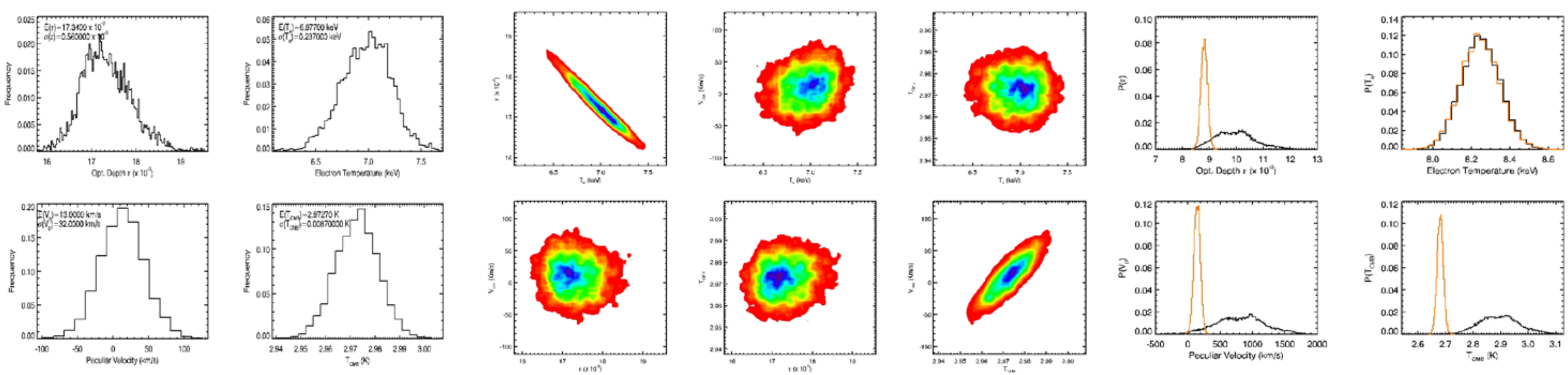
X-ray vs SZ proxies in good agreement,
(but SZ has less observational bias)

Spectral measurements of SZ effect gas parameters



- Maps: SZ spectrum + noise model + obs strategy + contamination
- MCMC Estimate of cluster parameters
- Evaluate degeneracies
- Compare to highly sensitive photometers of the present generation



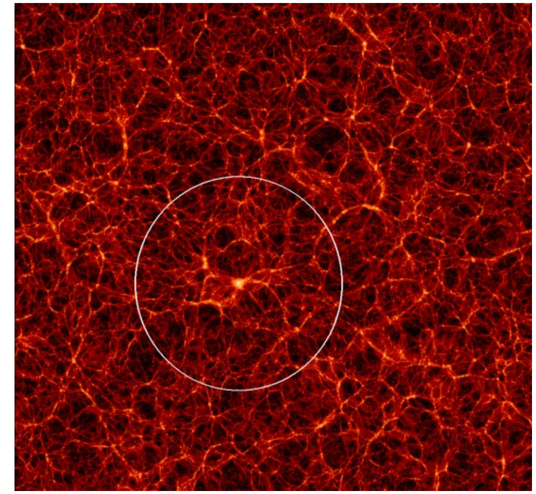


The other side of the coin: cluster hydrodynamical simulations

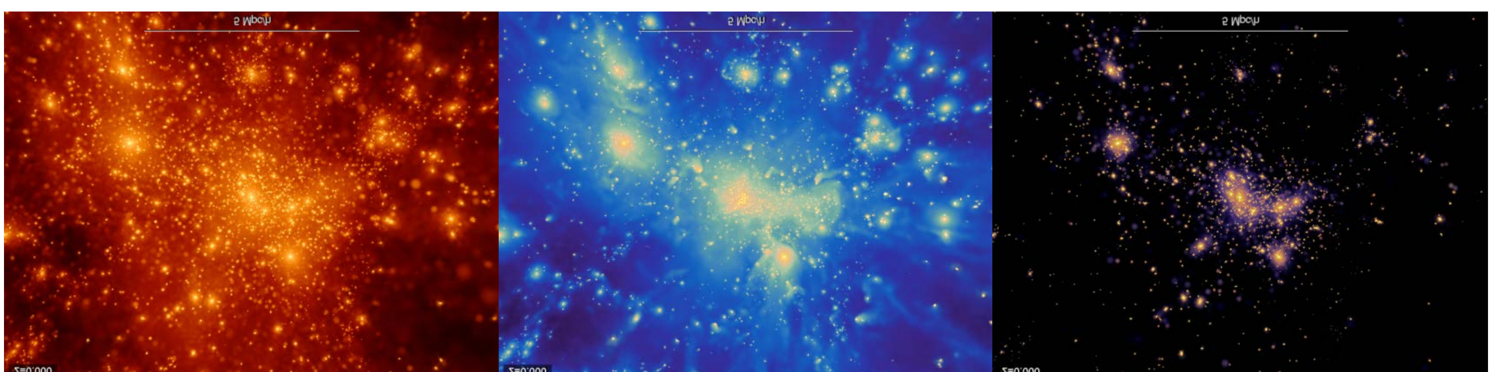
- In the recent past, significant tradeoffs between volume/mass resolution (i.e. constant number of particles), no radiative processes: evolution driven by gravity only, baryon structures added through semi-analytic «prescriptions».

- Now enough computational power to improve mass resolution and add realistic gas physics (NR, cooling, star formation) into limited volumes

- Forecast structure aspect and evolution in presently unexplored regimes (low mass, high z systems, «bullet-like» objects, protoclusters, etc.)



http://astro.ft.uam.es/marenostrum/



http://music.multidark.org

Multidark – MUSIC2

Sembolini,..LL.. et al., accepted in
MNRAS (astro-ph/1207.4438)

- About 300 «resimulated» clusters from MN and MD hydrodynamical simulations, including gas heating, cooling, star formation, feedback and other NR processes
- Explores halo mass function from group to massive cluster regime, z up to 1 (but higher z available)
- Scaling relations, evolution, fgas, relaxed/disturbed objects
- Even more mass definitions!
- Topics:
  - angular momentum: can differential KSZ constrain halo growth?
  - Bulk flows through KSZ
  - pressure profiles: is there a «standard pressure profile» as claimed by low-z, massive clusters observations?
  - Protoclusters: how do they behave? What can they teach us?
  - Forecast for upcoming instruments (CCAT, etc.)
- A few theses available!

A final note: why clusters?

In 15 years we switched from cluster blob-ology to «true» cluster cosmology.

This required a lot of open-minded work, some improvements in our tools and a truly panchromatic, multiscale view of clusters (I even met a Spitzer guy at a cluster conference!)

We still miss a lot of things:

- deep full-sky surveys;
- complete catalogs;
- mass proxies (and possibly a real understanding of «mass» in clusters);
- galaxy populations and their evolution in clusters;
- gas heating: where, and how, and when, and how long;
- ICL;
- BCGs;
- turbulence in the ICM;
- high z supermassive clusters: the «pink elephant» joke.

In a few words (Jim Gunn's quote): «***We do not understand baryons. Baryons are hard.***»

We learn about clusters because we want to do ''cluster cosmology''.

Indeed we MAY come to learn something about cosmology through clusters one day,

Regardless…it will always be worth our time.

AND ALL WERE IN THE WRONG!

Good Presentation Should Be Susceptible to Only One Interpretation

It was six men of Indostan
To learning much inclined,
Who went to see the Elephant
(Though all of them were blind.)
That each by observation
Might satisfy his mind.

The First (side) "Is very like a wall!"

The Second (tusk) "Is very like a spear!"

The Third (trunk) "Is very like a snake!"

The Fourth (knee) "Is very like a tree!"

The Fifth (ear) "Is mighty like a fan!"

The Sixth (tail) "Is very like a rope!"

And so these men of Indostan
Disputed loud and long,
Each in his own opinion
Exceeding stiff and strong
Though each was partly in the right,
And all were in the wrong!

From John Godfrey Saxe, "The Blind Men and the Elephant", *Clever Stories of Many Nations Rendered in Rhime*, 1865.

Six blind men and an elephant:
a pictorial view of John Godfrey Saxe's version of the famous Indian legend,
and (IMHO) a lesson about modern cluster science.

Suggested reading

- Rephaeli, ARA&A 33, 541 (1995)
- Birkinshaw, Phys. Rep. 310,97 (1999)
- Carlstrom et al., ARA&A 40, 643 (2002)
- Rosati et al., ARA&A 40, 539 (2002)
- Voit, Rev. Mod. Phys. 77, 207-258 (2005)