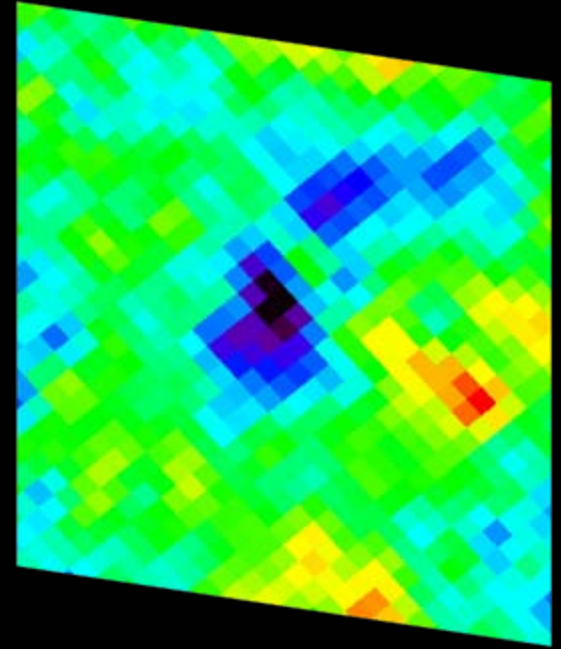


Outstanding Questions for the Standard Cosmological Model
Imperial College, London



MISSING THERMAL ENERGY OF THE UNIVERSE

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Afshordi, Lin, & Sanderson 2005 (1st yr)

Afshordi, Lin, Nagai, & Sanderson 2007(3 yrs)



My idea of public talks in London, prior to today



Galaxy Clusters: Conventional Wisdom

- Largest “relaxed objects” in the Universe
- Contain ~10% of the baryons/dark matter in the Universe

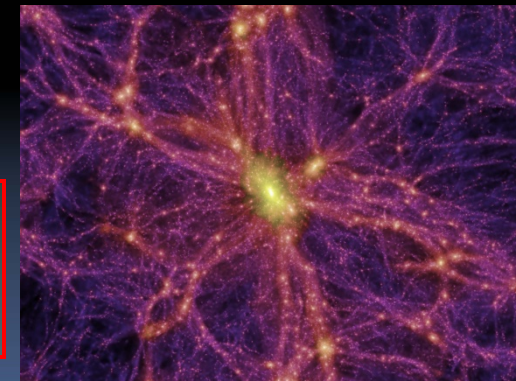
- Most of the cluster baryons are in a shock-heated plasma (10^7 - 10^8 K; 1-10 keV)

→ This plasma contains most of the thermal energy of the Universe

- Representative sample of cosmic baryonic budget



Galaxy Cluster Abell 2218

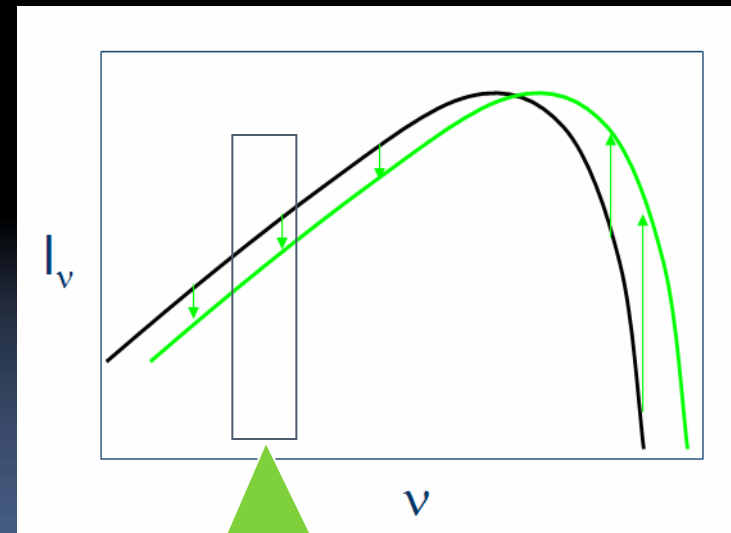
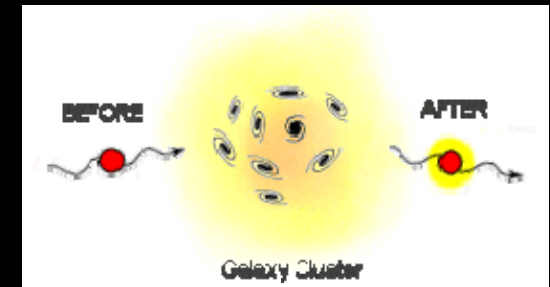


Millennium Simulation
Springel et al. 2005

Sunyaev-Zel'dovich (SZ) effect

- Scattering of CMB photons off hot electrons in the Intracluster medium
- Probes the **thermal energy** distribution of electrons in the Intra-Cluster Medium:

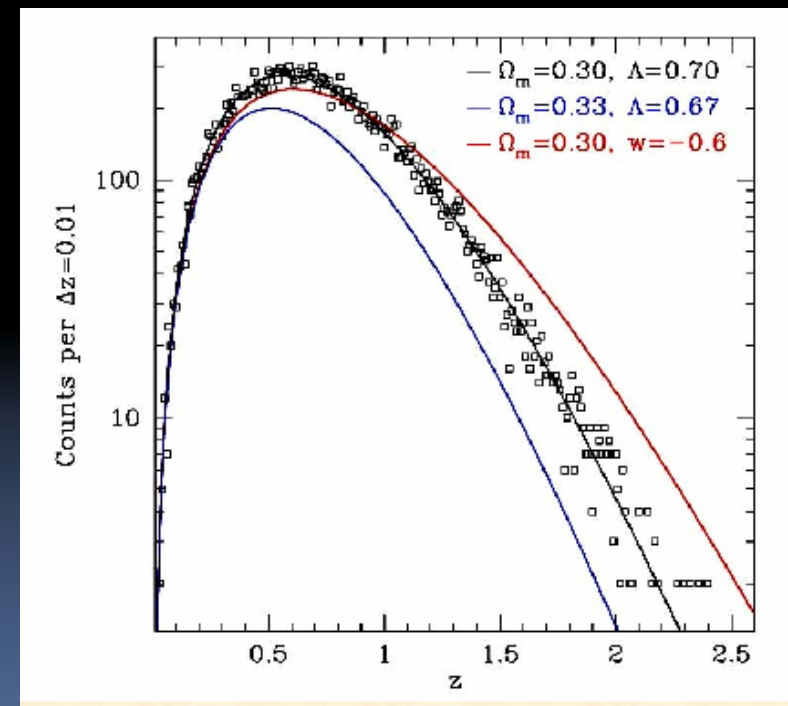
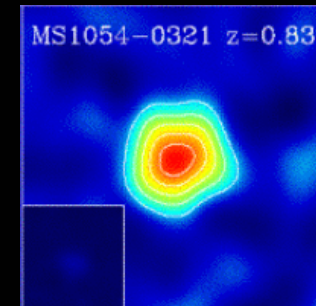
$$\delta T_{SZ}(\hat{n}) \propto \int dr P_e(r\hat{n})$$
- SZ flux is redshift independent
- Positive (negative) at large (small) frequencies



WMAP sees here

SZ Cluster Surveys

- SZ clusters can be detected up to high redshifts
- Their number counts probe Dark Energy/Cosmology
- Many SZ surveys are underway: APEX, SZA, ACT, SPT, Planck, ...
- Can they deliver?
Calibration of SZ-Mass relation, Gasphysics, ...

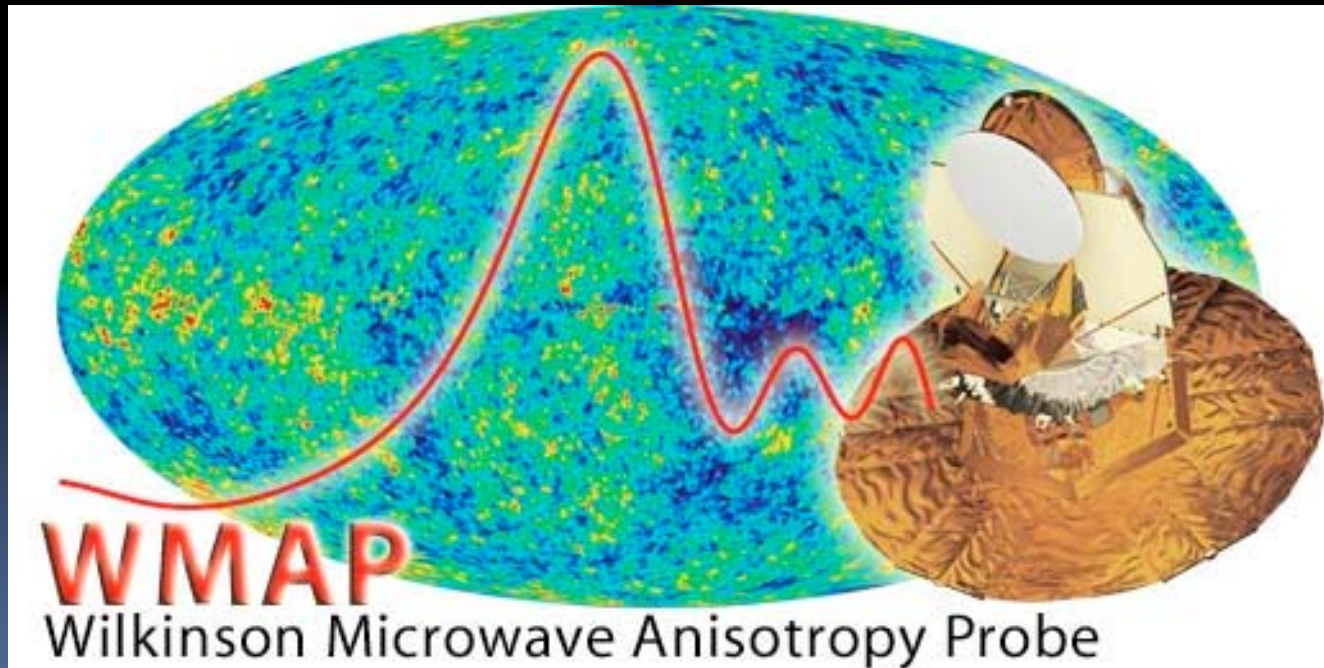


Courtesy of John Carlstrom

Imperial College, London

SZ effect in WMAP

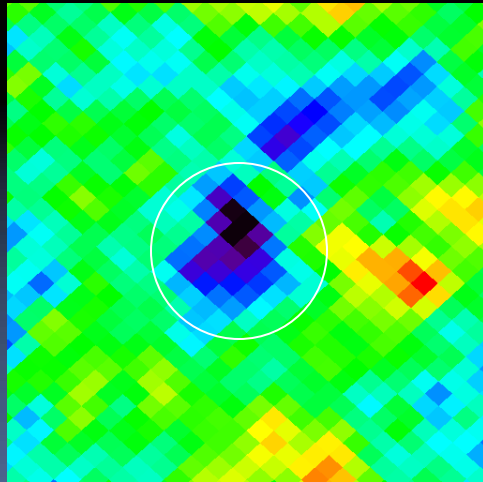
- (just to get a head start)



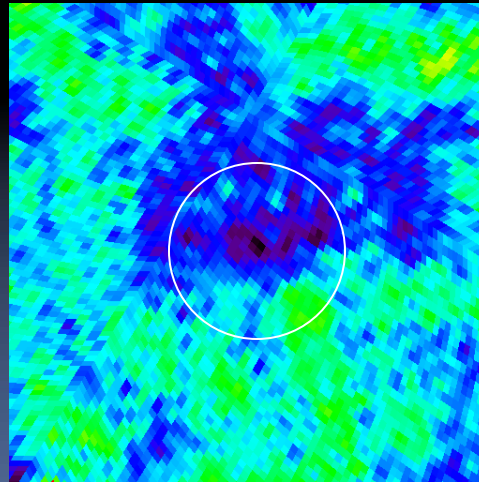
WMAP SZ clusters ...

- Three close-by clusters in the WMAP₃ map

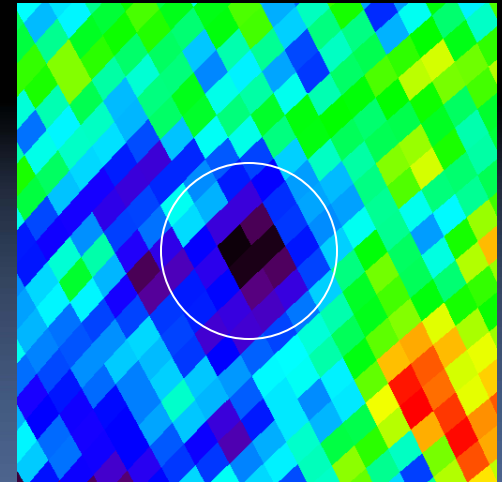
Abell 2319



Abell 1656



Abell 133

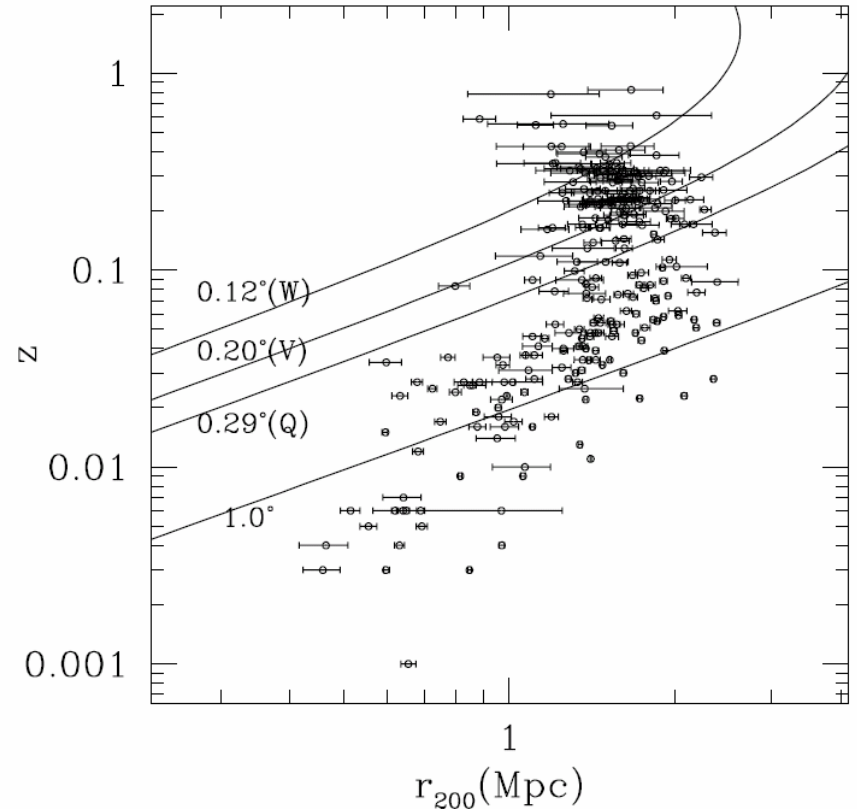


Model-independent reconstruction of pressure profile

(Afshordi, Lin, Nagai, & Sanderson 2007, MNRAS in press)

- WMAP 3-yr maps
 - Q, V, W (41-92 GHz)
 - $N_{\text{res}} = 9$ (pixel size $\simeq 0.1$ deg)
- 260 clusters
 - measured X-ray temperature

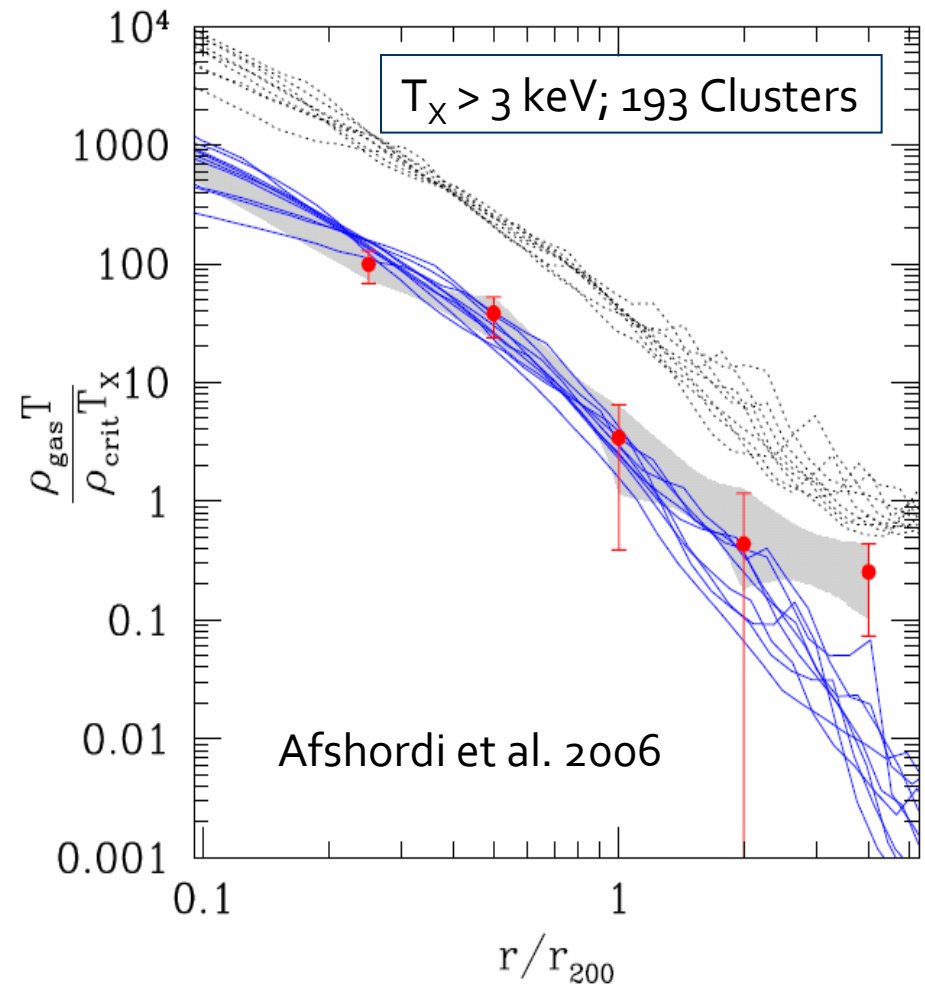
$$r_{200} = (1.16 \text{ Mpc}) \left(\frac{H(z)}{100 \text{ km/s/Mpc}} \right)^{-1} \left(\frac{T_X}{5 \text{ keV}} \right)^{1/2}$$



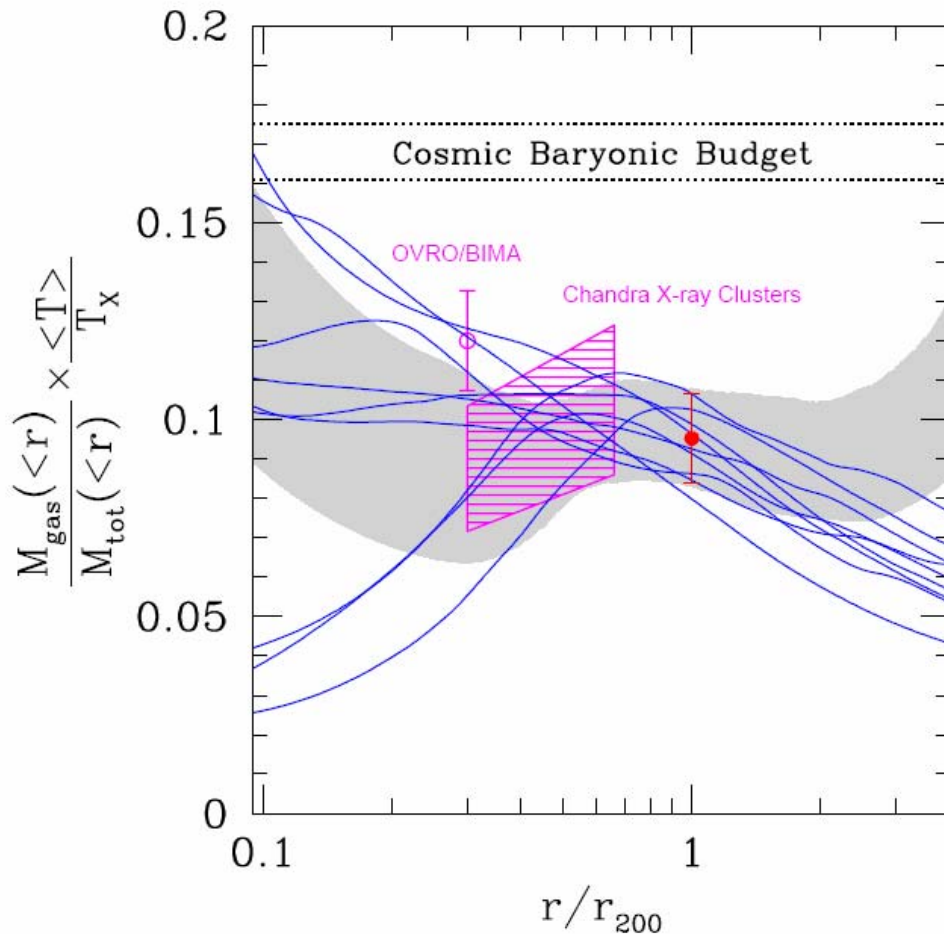
Universal Pressure Profile

- ρ_{DM}/ρ_{crit}
- Hydro-Simulations
- WMAP 1- σ region ($P_{gas} > 0$)
- WMAP best fit

1. First **direct measurement** of ICM pressure profile
2. **Excellent agreement** between simulations and observations



Missing Thermal Energy of the Intracluster Medium



— Hydro-Simulations

■ WMAP 1- σ region ($P_{\text{gas}} > 0$)

● WMAP best fit

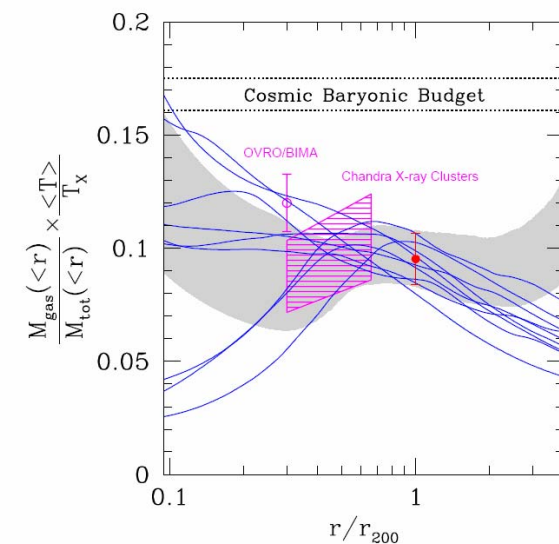
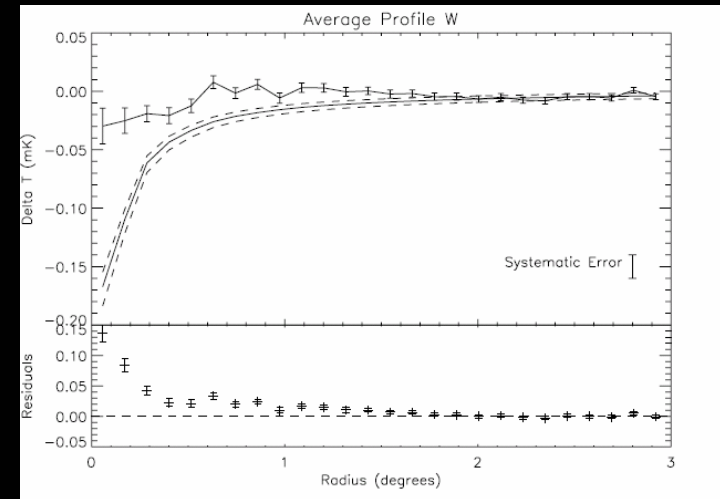
- X-ray and SZ observations are **both missing ~35% of baryons**
- Simulations also lose the same fraction into cold gas

35 ± 8% of Baryons are missing from the Intracluster Medium!

- **Where are the rest of baryons?**
 - stars are $< 10\%$
 - intracluster stars (only 2-3%)
 - warm gas: 10^5 - 10^6 K (soft X-ray excess: but why doesn't it cool?; **c.f. talk by Kaastra**)
 - cold starless clouds (**c.f. talk by Combes**)
 - thermal evaporation from the cluster (Loeb 06: but this is suppressed by B-field: Medvedev 07)

Is there a discrepancy between X-ray and SZ?

- Lieu, Mittaz, & Zhang 2006 and Bielby & Shanks 2007 find that β -model fits to X-ray cluster observations overpredict WMAP SZ signal by many σ 's
- We find that X-ray and SZ gas fractions are systematically low but consistent

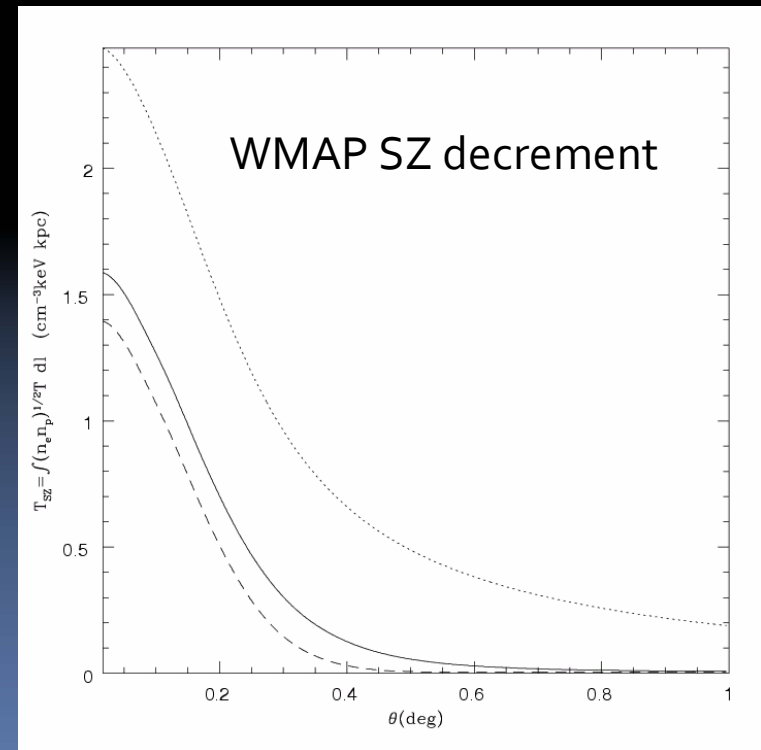
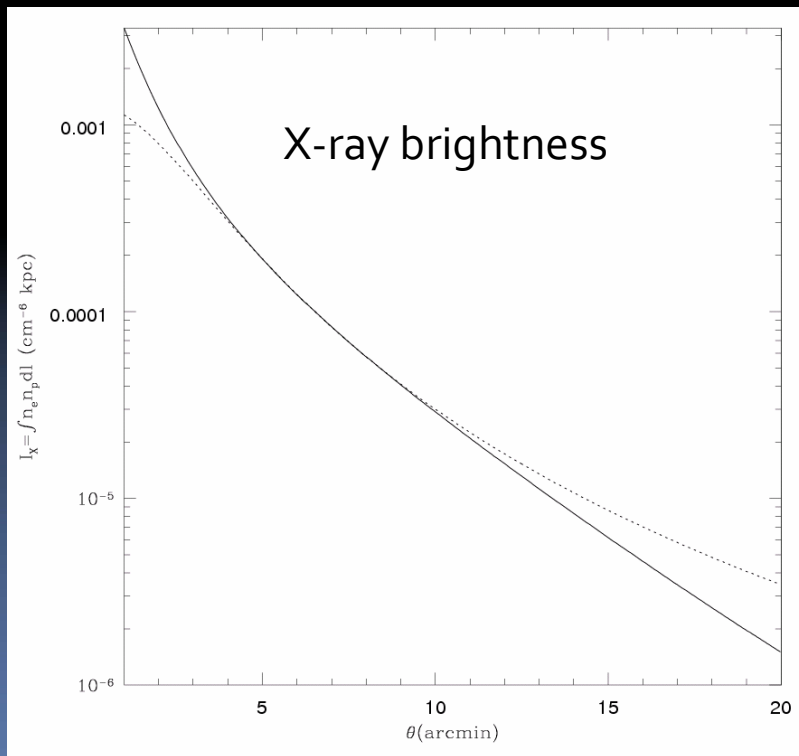


Isothermal β -model overpredicts gas pressure in cluster outskirts

cluster Abell 133

..... β -model (Lieu et al. 06) 3+1 parameters (brightness+temp)

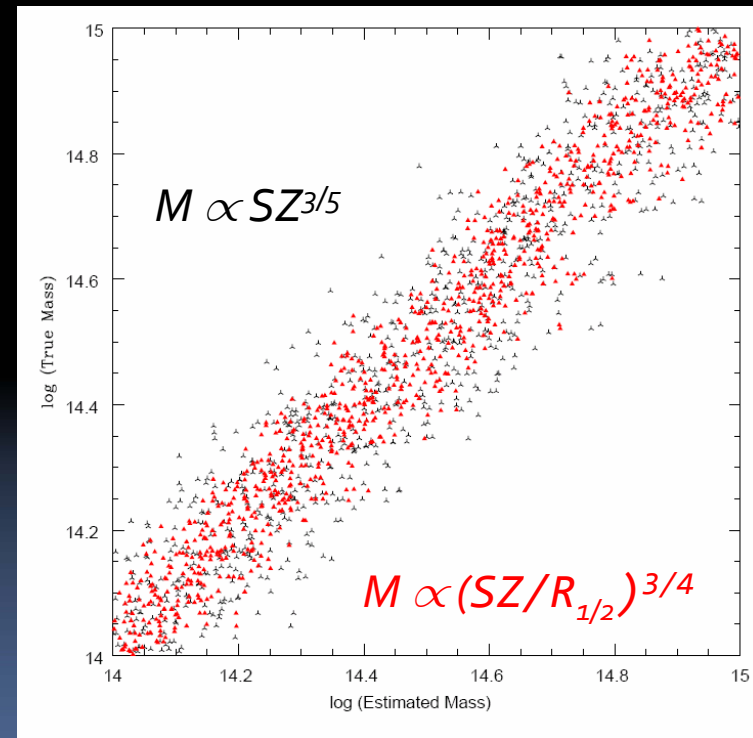
_____ (Vikhlinin et al. 06) 9+9 parameters (brightness+temp)



Fundamental Plane of SZ clusters

(Afshordi 2007, in preparation)

- **< 10% systematic error** in mass is required for reliable cosmology (Francis, Bean & Kosowsky 05)
- Using **SZ half-light** radius can decrease the error in mass estimates by 30%



Conclusions

- SZ clusters are sensitive probes of cosmology
- First direct measurement of cluster pressure profile
- ~Mystery: 30-40% of cluster gas is missing!
- X-ray and SZ are consistent, but beware of extrapolations that may fail (e.g. β -model)