Title: Observations with CBI2 and application of an improved SZ model

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Abstract:

Oxford Physics

A Model for Large-Scale SZ Observations

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In collaboration with
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Steve Myers
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Dick Bond and
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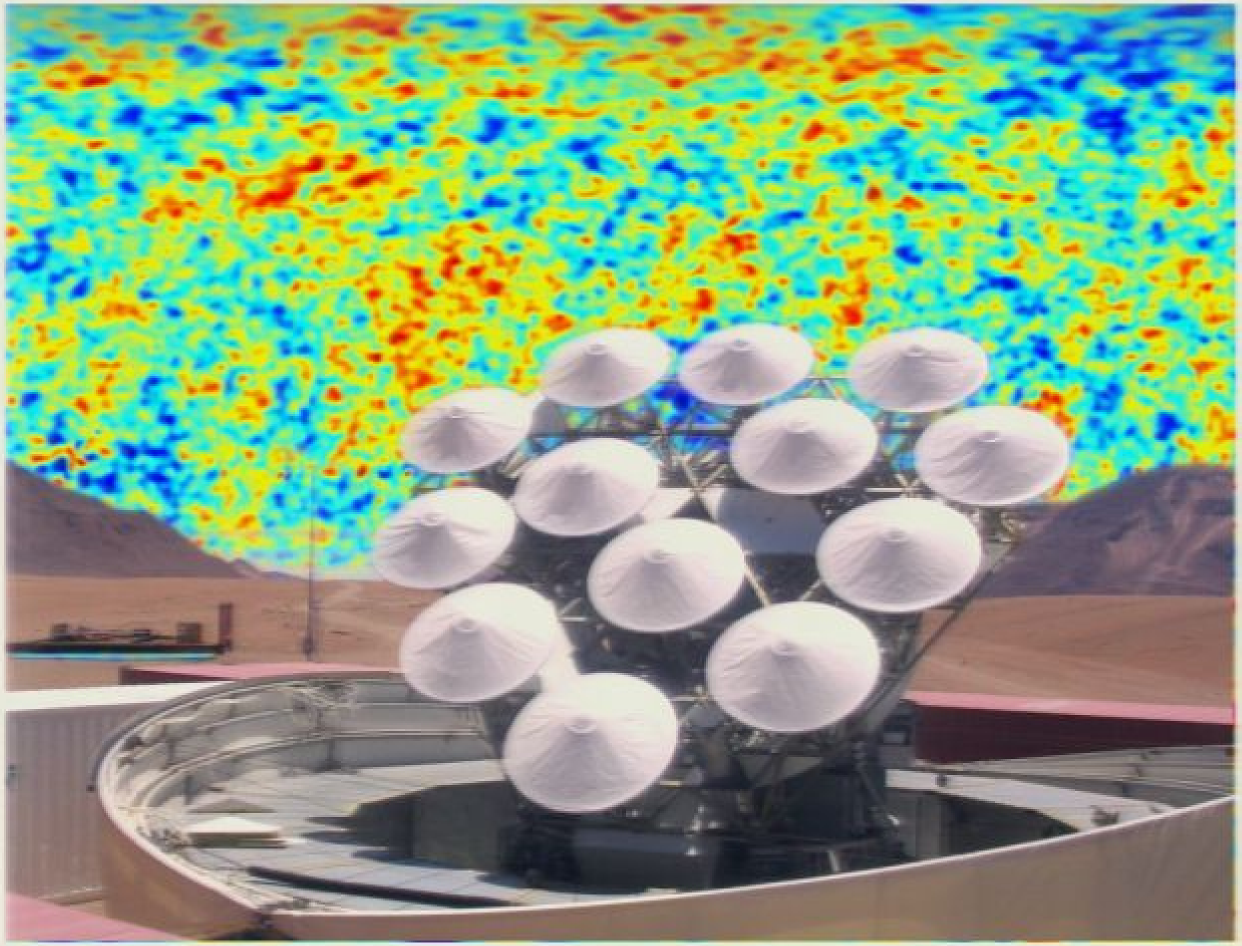
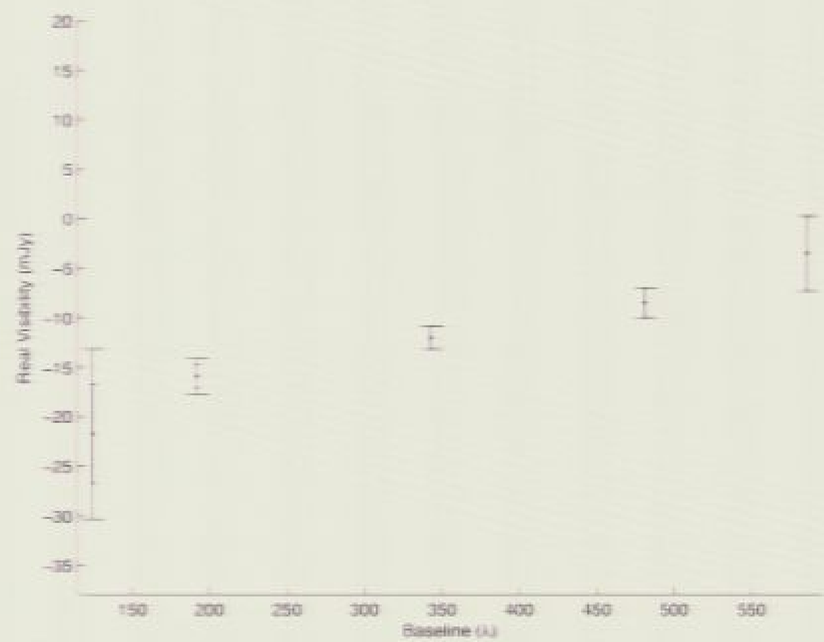


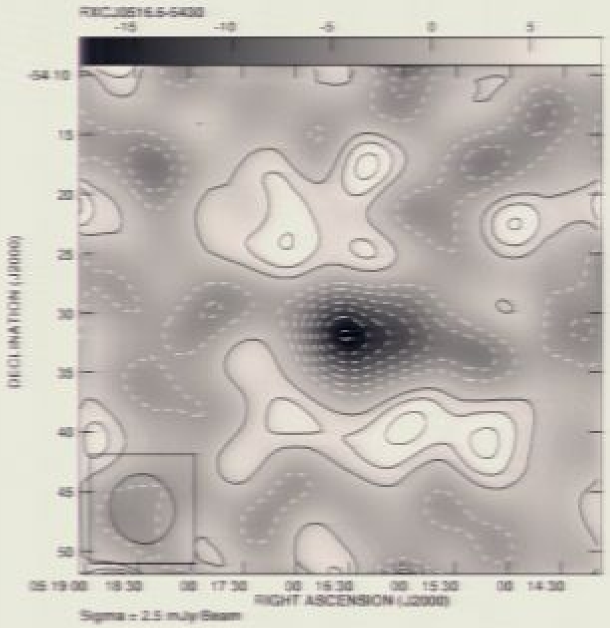
CBI2 SZ Observations

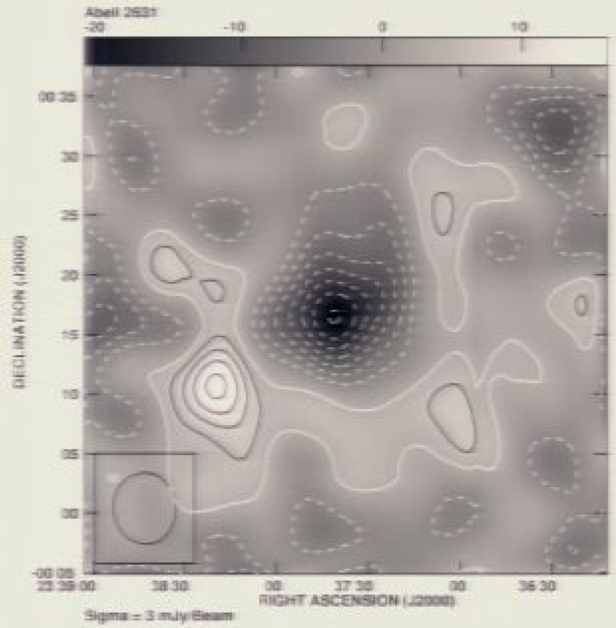
- Upgrade of previous CBI experiment
- Larger (1.4m) dishes provide greater sensitivity on the longes[t] baselines
- Better signal to noise for pointe[d] SZ on large scales away from CMB contamination
- 31 GHz Interferometer – we measure and fit for the visibilities



CBI2 SZ Observations

- CBI2 observations target the large scale SZ
- Out-skirts of clusters are resolved at redshifts between 0.1 and 0.3
- SZ provides good constraint on gas to virial radius
- Combine with X-ray data to gain hold on cluster gas properties and mass



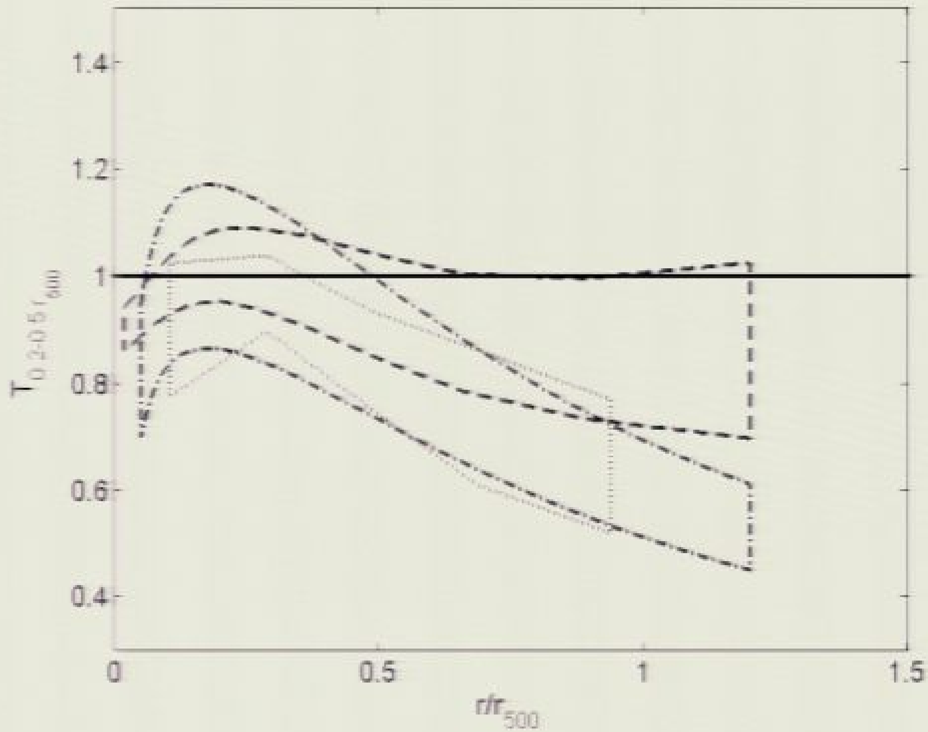


CBI2 SZ Observations

- Cluster observations were chosen based on known X-ray clusters - for example REFLEX-DXL ($z \sim 0.3$, Zhang et al. 2006, 2008) and REXCESS ($z \sim 0.15$, Boehringer et al. 2007) samples.
- We perform a joint analysis of the CBI2 SZ and published X-ray data
- We currently use published X-ray surface brightness data from XMM-Newton observations – powerful constraint of the electron density and cluster gas in the inner regions
- Further analysis will include X-ray spectral temperature data and perhaps weak lensing, however requires further development of the pipeline.

Motivation

- There is clearly a need to go beyond the Isothermal Beta model to reproduce observed temperature profiles
- The Beta model also gives divergent SZ for common beta parameter values
- Spectral X-ray observations show a range non-isothermal temperature profiles in the cluster out-skirts (Zhang et al. 2008, Pratt et al. 2006, Vikhlinnin et al. 2006)



Motivation

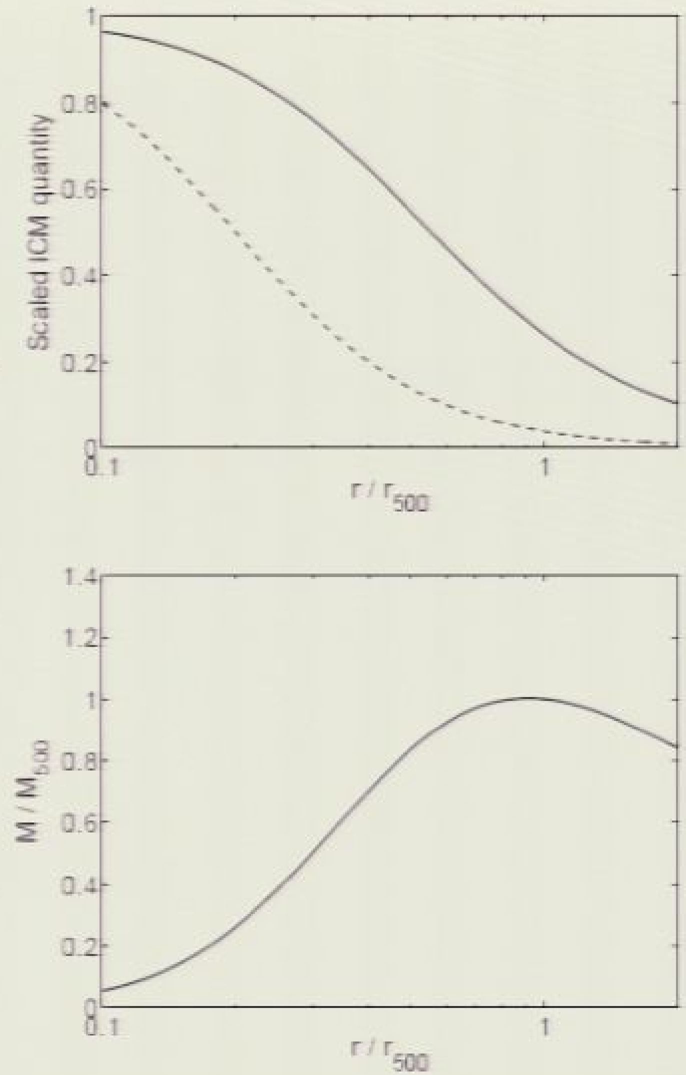
- Could try keeping beta-model description of the density and introduce a parameterisation for the temperature profile
- However there is scope for potentially non-physical mass profiles under our assumption of Hydrostatic equilibrium
- For example we could choose a beta-like parameterisation of the temperature:

$$T = T_0 \left(1 + \left(\frac{r}{r_T}\right)^2\right)^{-\delta}$$

Hallman et al. 2007

Motivation

- Combinations of density and temperature parameters within the scope of this model can produce non-physical results when deriving the total mass profile
- For example the plots to left show that the enclosed total mass can decline for strongly declining temperature profiles at the outskirts
- We want to choose a model where the physical constraints are hard-programmed from the beginning



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Our choice of analytical model

Model chosen on simple physically-motivated assumptions:

(1) Dark Matter Halo described by the standard NFW prescription (Navarro et al. 1997)

$$M(<r) = 4\pi\delta_c\rho_{\rm crit}r_s^3\left[\ln\left(\frac{r_s+r}{r_s}\right)-\left(\frac{r}{r_s+r}\right)\right]$$

$$r_s = \frac{r_{200}}{c_{200}} \qquad \delta_c = \frac{200}{3}\frac{c_{200}^3}{[\ln(1+c_{200})-c_{200}/(1+c_{200})]}$$

FIT FOR: concentration and r200

(So automatically encodes mass behaviour)

Our choice of analytical model

(2) Entropy observable parameterised by floor at small radii and a power-law at large radii (e.g. Tozzi & Norman 2001, Ponman et al. 2003, Zhang et al. 2006, 2007, 2008)

$$S = \frac{T}{n_{\mathrm{e}}^{2/3}} \qquad S(r) = S_0 \left(1 + \left(\frac{r}{r_{\mathrm{core}}}\right)^2\right)^{\alpha}$$

FIT FOR: r_core, alpha

S0 constrained by SZ/X-ray data constraints on T0 and n0

Our choice of analytical model

(3) Assume Hydrostatic Equilibrium holds for all scales in order to relate quantities and return total mass

$$P(r) = \left[P_0^{2/5} - \frac{2}{5} G \mu m_{\rm p} \int_0^r \frac{M \mathrm{d}r}{S^{3/5} r^2} \right]^{5/2}$$

Solve numerically – Integrate out from centre to large radii

The total mass M is equal to the sum of the Dark Matter (NFW) and Baryonic (Integrated gas density within radius r) components in this model.

Our choice of analytical model

SUMMARY:

- Joint Fit to CBI2-SZ and X-ray surface brightness
- Parameterise Dark Matter and Entropy
- Free parameters are n0, T0, rcore, entropy power law (alpha), c200, r200 (for Dark Matter)
- Note: Can also fit for position if required

Analysis Pipeline – Bayesian Inference

$$L = \frac{1}{(2\pi)^N \sqrt{|\mathbf{C}|}} \exp\left(-\frac{(\mathbf{d}-\mathbf{m})^t \mathbf{C}^{-1} (\mathbf{d}-\mathbf{m})}{2}\right) \qquad \Pr(d|M_j) = \int \Pr(d|\boldsymbol{\theta}, M_j)\Pr(d|M_j)\mathrm{d}\boldsymbol{\theta}$$

- Model constrained by SZ and X-ray surface brightness
- Invoke Bayes' Theorem: we compare to data by likelihood calculation and maximise the Posterior
- Use reasonable priors for the relevant parameters

SZ likelihood

- d = gridded visibilities (as mentioned in Jon's Talk)
- m = estimate of gridded visibilities
- C = C_noise + C_cmb + C_sources + (C_residual)
- C is non-diagonal for SZ due principally to correlation between CMB components

Analysis Pipeline – Bayesian Inference

X-ray likelihood

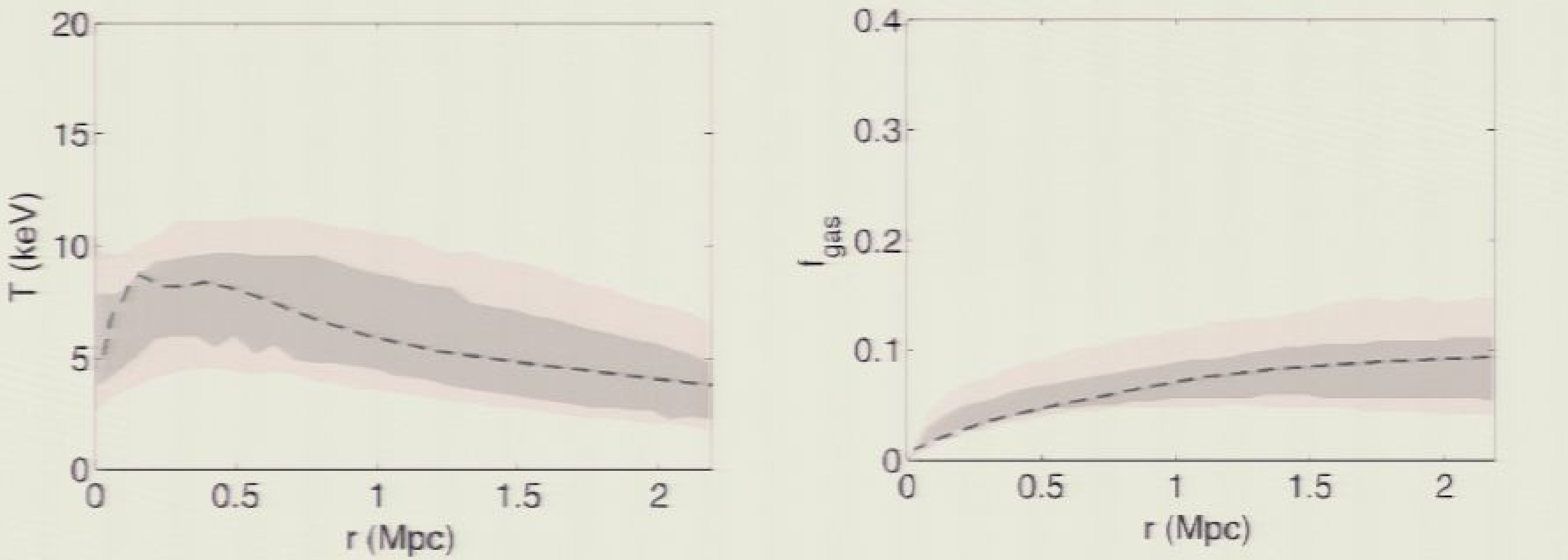
- At the moment fitting to published radial-binned X-ray counts – essentially gaussian after radial binning of maps
- Errors are un-correlated and so likelihood collapses to chi-square calculation

Implementation

- Total likelihood product of X-ray and SZ components
- We estimate the posterior distribution by sampling using Bayesys (MCMC Engine, John Skilling)
- This method allows us to marginalize over combinations of parameters to produce posterior distributions for constrained cluster properties
- We also calculate the evidence for a model to a given data set and hence can perform a comparative qualitative analysis for various models

Derived parameter profiles

- Each sample from Bayesys defines a set of cluster profiles (e.g. temperature, density, mass, fgas ….)
- After posterior exploration one can obtain average profiles with 1,2,3-sigma ranges



Test model based on simulated observations

Simulations from Kay et al. 2004

- N-Body/Hydro-dynamical simulations
- Assumed simple lambda CDM cosmology (0.3/0.7, h = 0.7)
- Performed using version 2 of the GADGET code (Springer, Yoshida & White 2001)
- We select the feedback gas model used in this work, where the cluster gas was allowed to loose energy by radiative cooling
- The approach is phenomenological and a fraction of the cooled gas is allowed to form stars, while the rest will be re-heated due to the star formation
- They find that their Feedback models correctly reproduce the observed Lx-Tx relation and also re-produces the observed excess entropy in the cores of the clusters

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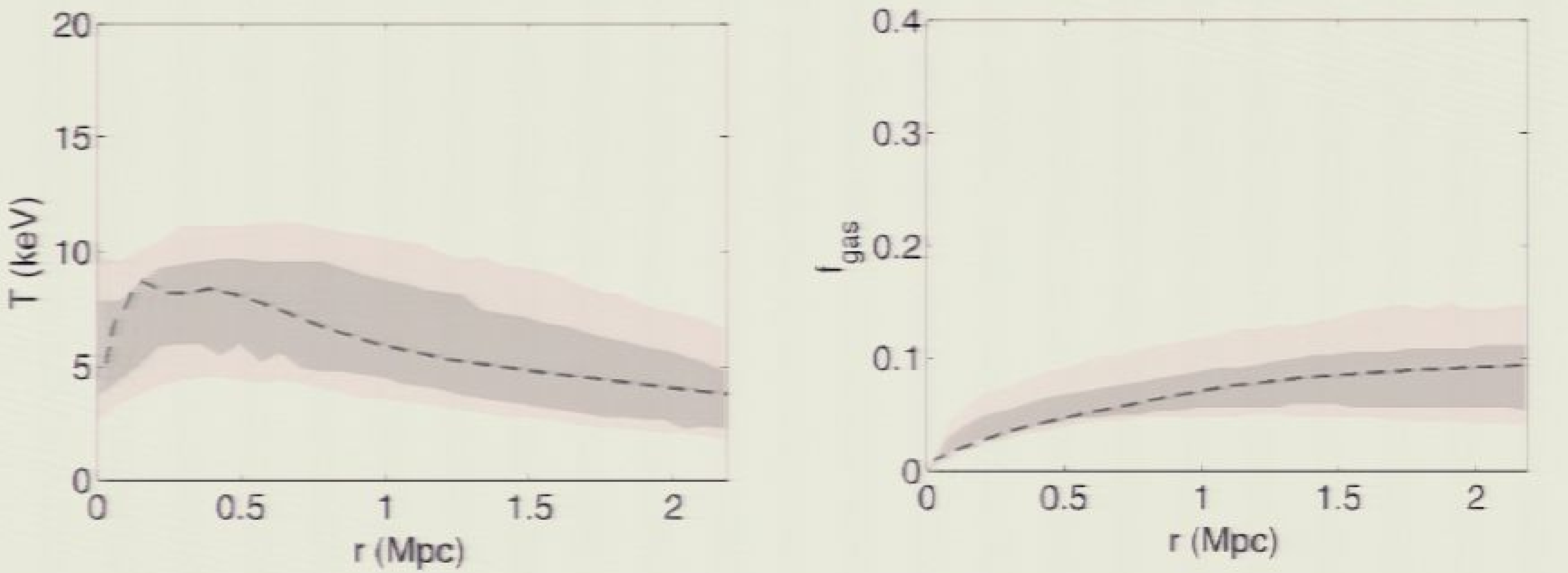

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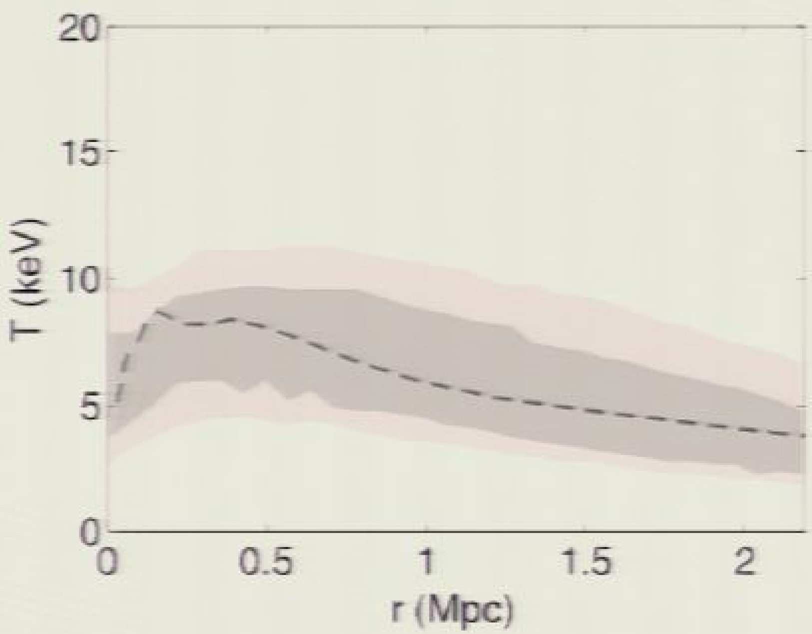

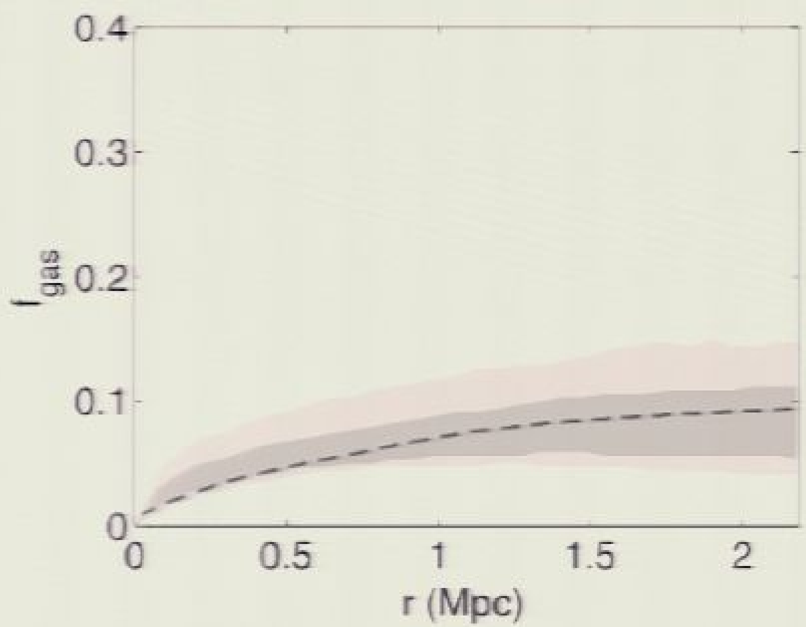

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Test model based on simulated observations

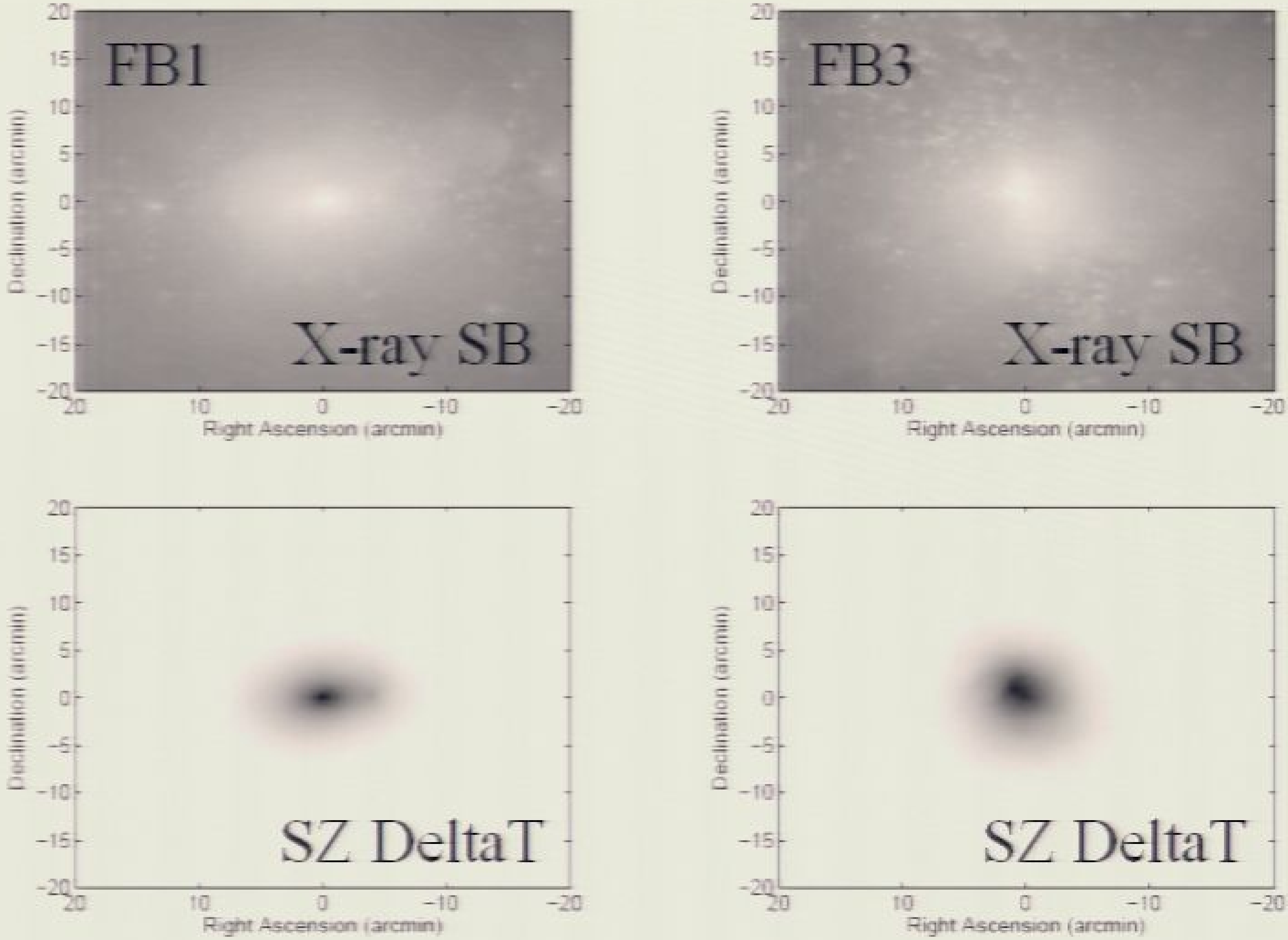
- From the sample of 15 simulated clusters we selected 2 moderately massive clusters that would be typical of the lower mass/temperature limit observable by CBI2
- These two cluster have similar global properties (Total Mass, Y, fgas), but with differing recent histories

  FB1 = Relaxed, Cool Core

  FB3 = Recent merger (z~0.4), Non-cool Core
- Hence we investigate if our model can correctly reproduce profiles for these two different clusters from CBI2 and X-ray observations

	Y (10^{-4} Mpc^2)	M_{total} (10^{14} M_{solar})	f_{gas}
FB1	0.973	1.17	0.101
FB3	0.873	1.06	0.101

Simulated Observables



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Simulated Observables

X-ray surface brightness

$$N_{\rm cts} = 5\left(\frac{S{\rm x}\Delta\Omega}{\rm erg\,s^{-1}\,cm^{-2}}\right) \times 10^{12}\,{\rm cts}$$

- We take the simulated X-ray surface brightness maps (in brightness units) and convert to counts per pixel based on a typical generic X-ray instrument (such as the EPIC camera on XMM-Newton)
- Note that these X-ray maps were simulated using a Raymond-Smith plasma model and in the 0.5-2 keV band
- Use a typical integration time of 10ks and a neutral hydrogen column density of 10^{20} cm^{-2}
- Apply poisson statistics to the counts map and bin radially to reproduce a mock data set typical of the published X-ray data available to us
- Note that we also bin the data such that the number of counts per bin is greater than 100 for all but the very centre of the cluster, allowing us to approximate the X-ray error bars to gaussian

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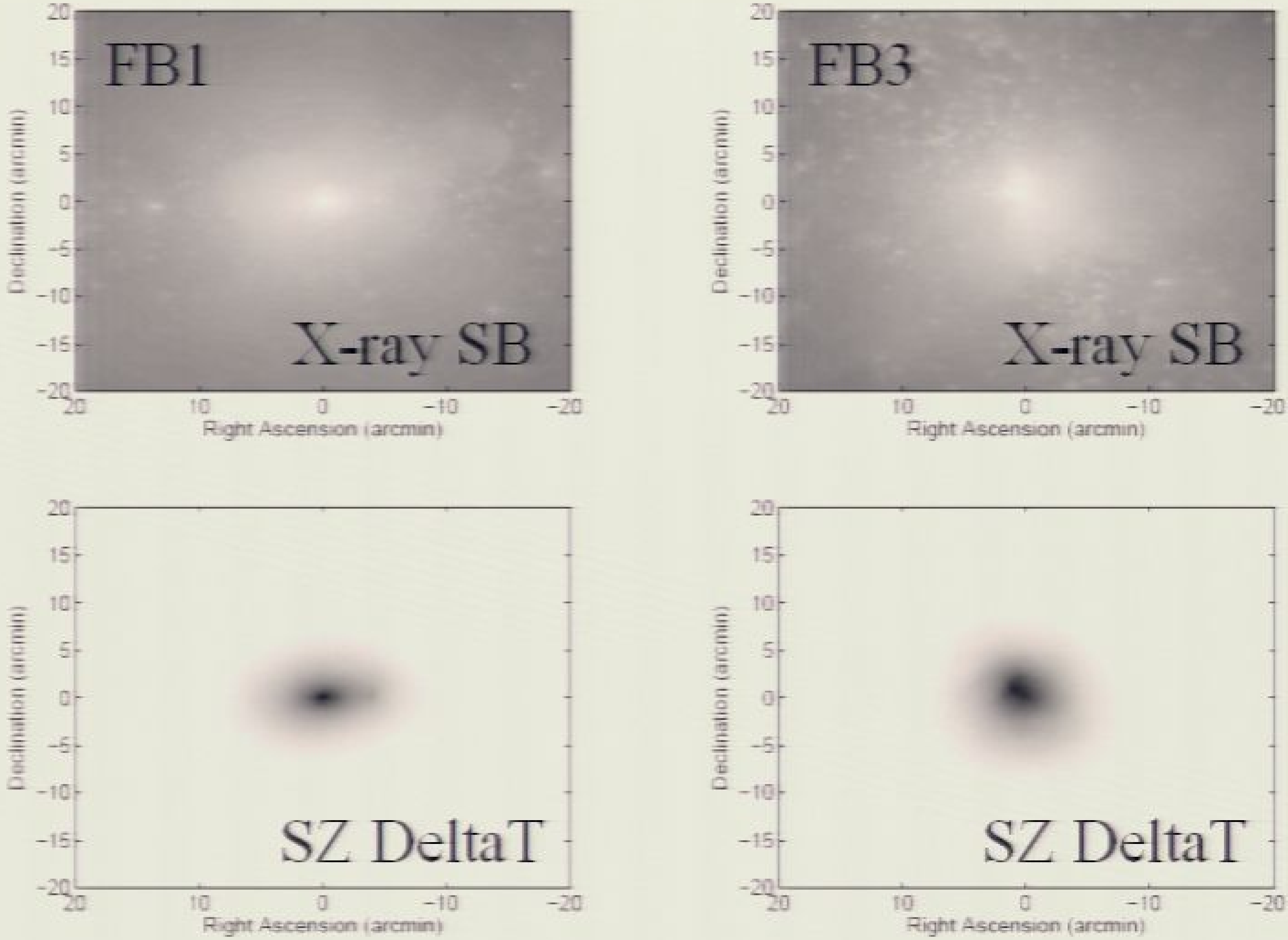

29th April 2009 Perimeter Institute James Allison

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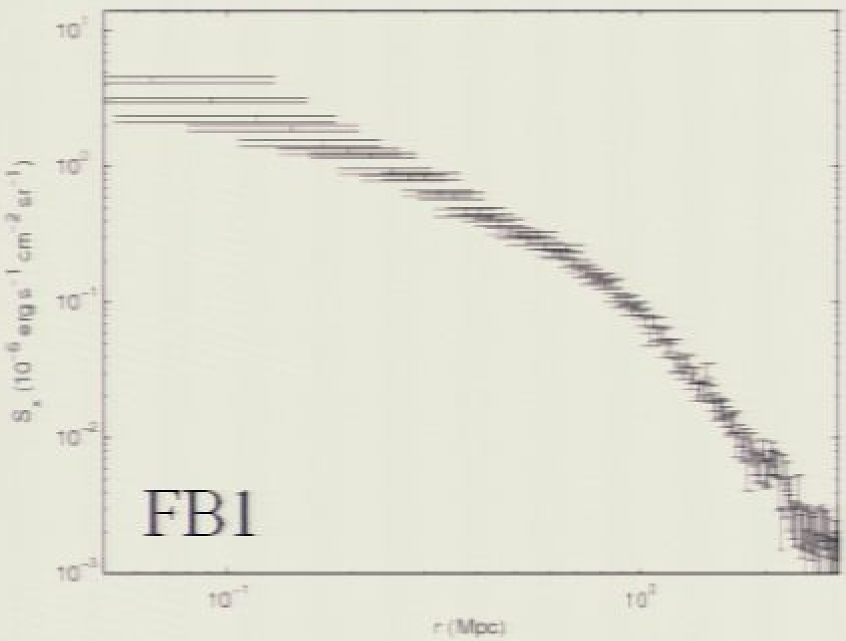
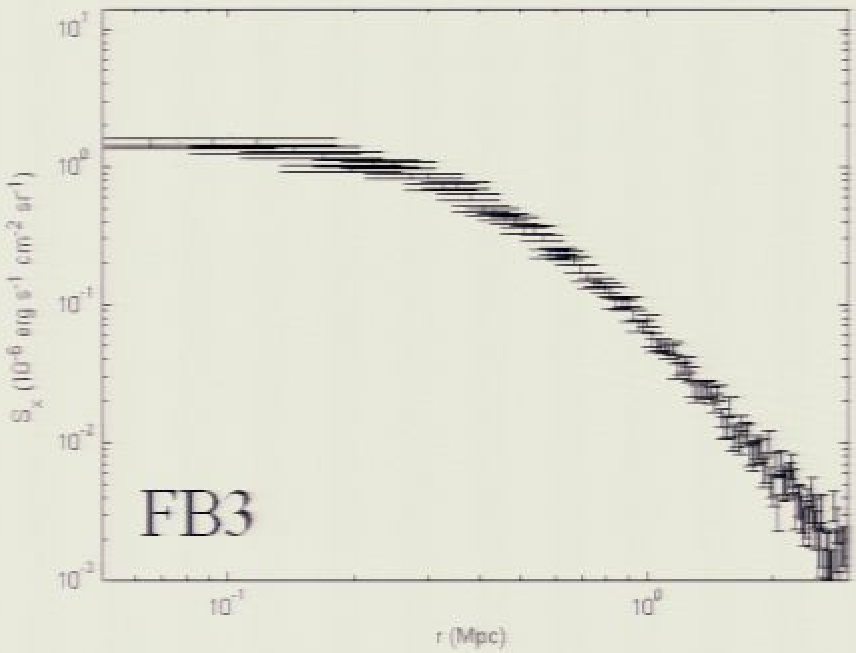




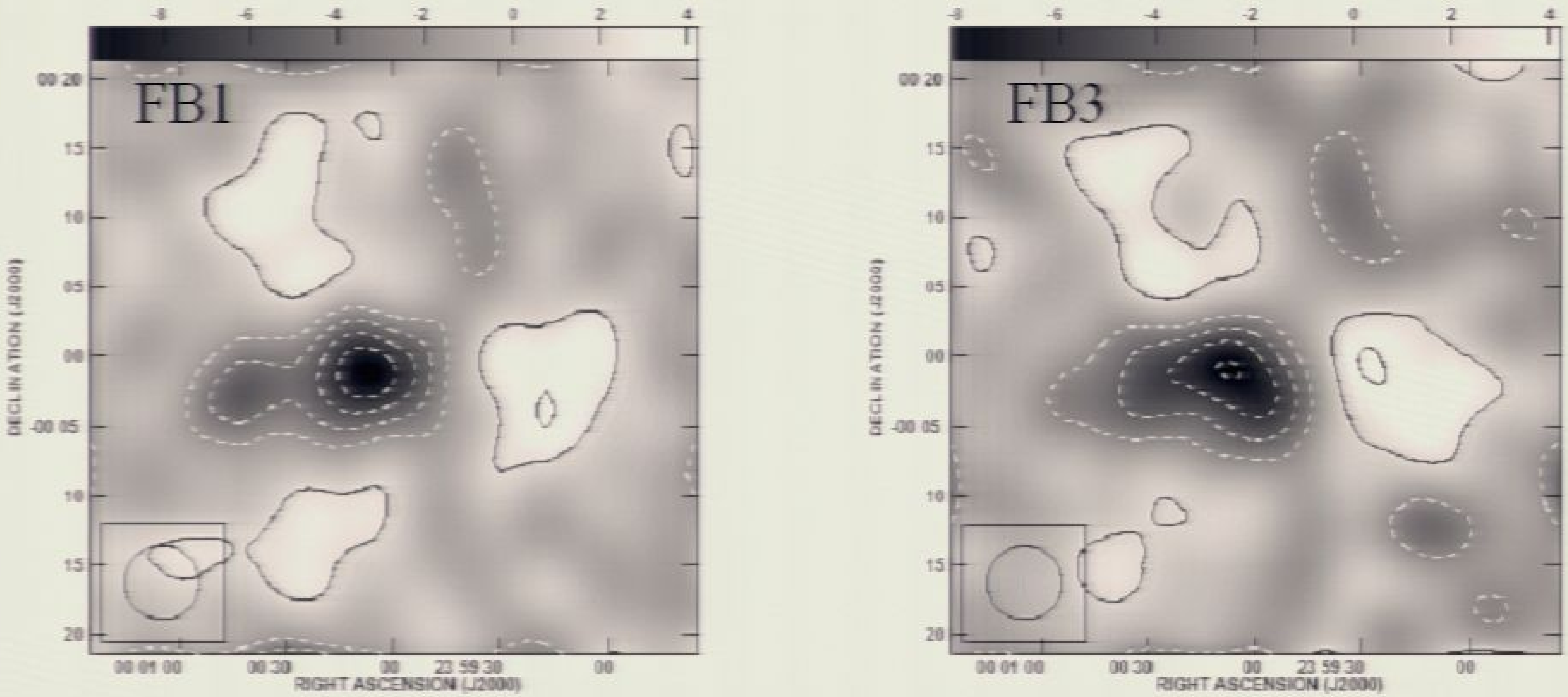
Simulated Observables

CBI2 SZ signal

$$\left(\frac{\mathrm{d}I}{\mathrm{d}T}\right)_{\mathrm{CMB}} = \frac{2k_{\mathrm{B}}\nu^2}{c^2} x^2 \mathrm{e}^x (\mathrm{e}^x - 1)^{-2}$$

- The SZ temperature maps are converted to sky brightness for each of the 10 CBI2 frequency channels using the above differential form of the Planck equation
- We also include the ratio of the frequency dependencies of the SZ temperature, assuming that the temperature map was produced at 31GHz
- Realisations of the CMB sky in each of the these channels are added to produce a representative sky map (we ignore point sources for the purposes of the simulated observations)
- The sky maps are then multiplied by the CBI2 primary beam and the consequent Fourier transform by a typical sampling from a 30hr set ob observations
- Gaussian noise is applied assuming typical system temperatures and atmosphere for CBI2 observations
- We also simulate the effect of differencing our data to remove the ground signal, essentially increasing the CMB primordial component by a factor of the square root of 3/2

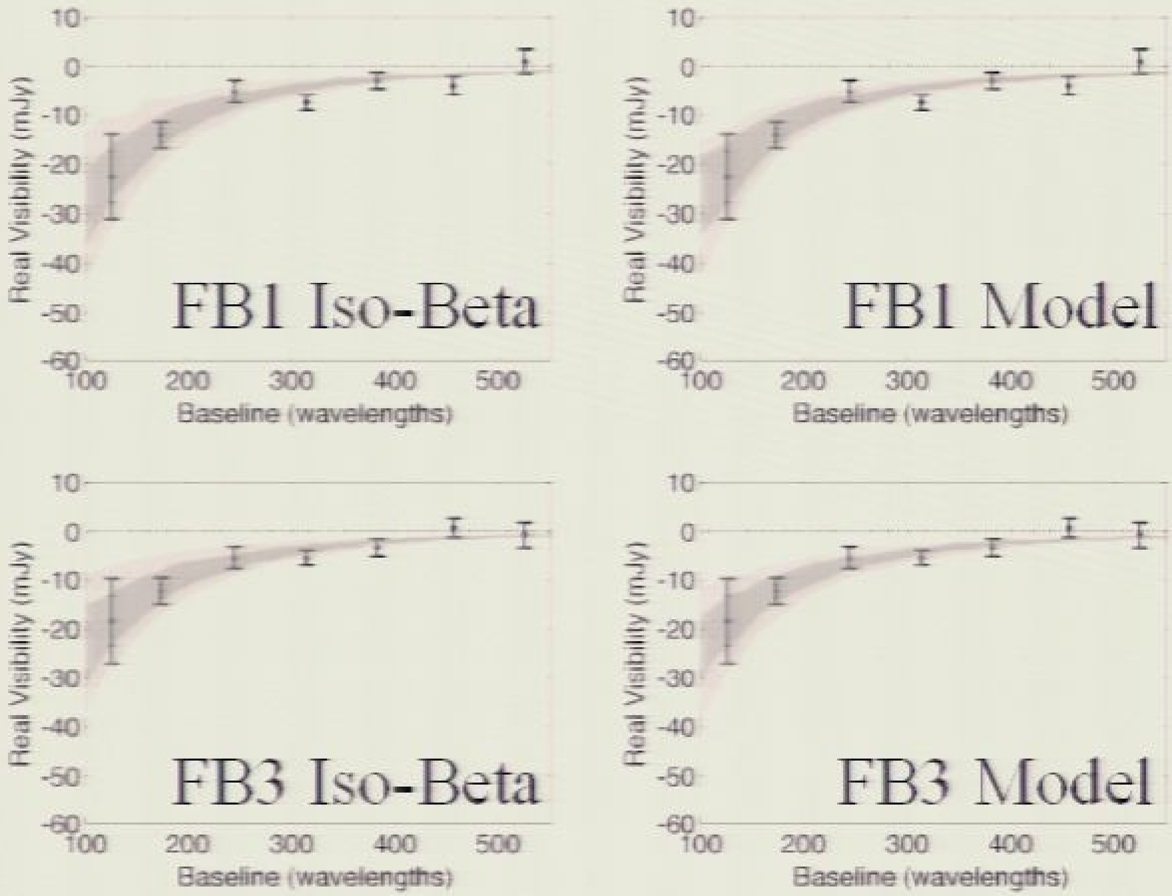
Simulated observables



(Contours = 2sigma noise on the map)

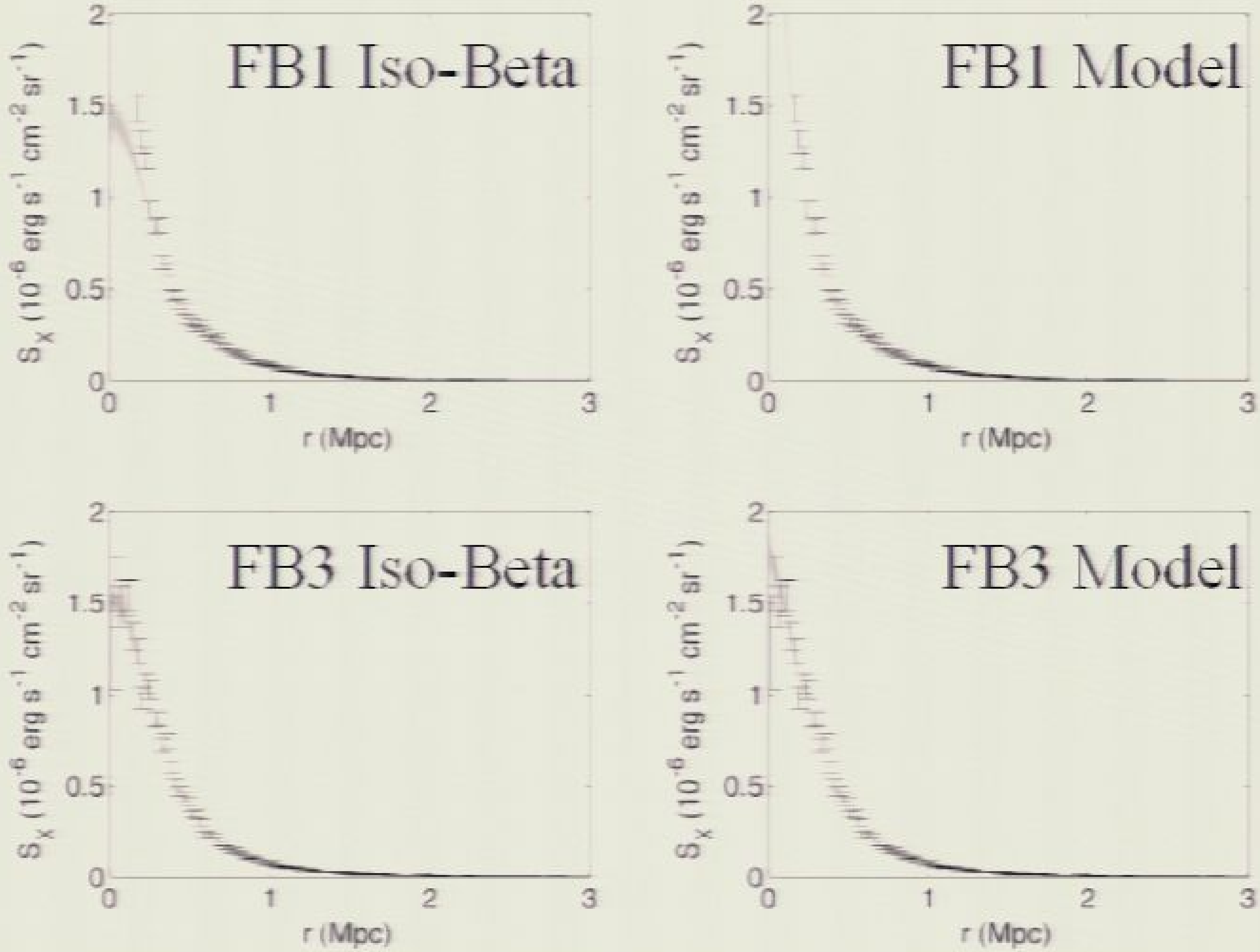
(Initial) Results of simulation tests

- Posterior for fit to gridded CBI2 visibilities



(Initial) Results of simulation tests

- Posterior for fit to radial X-ray surface brightness



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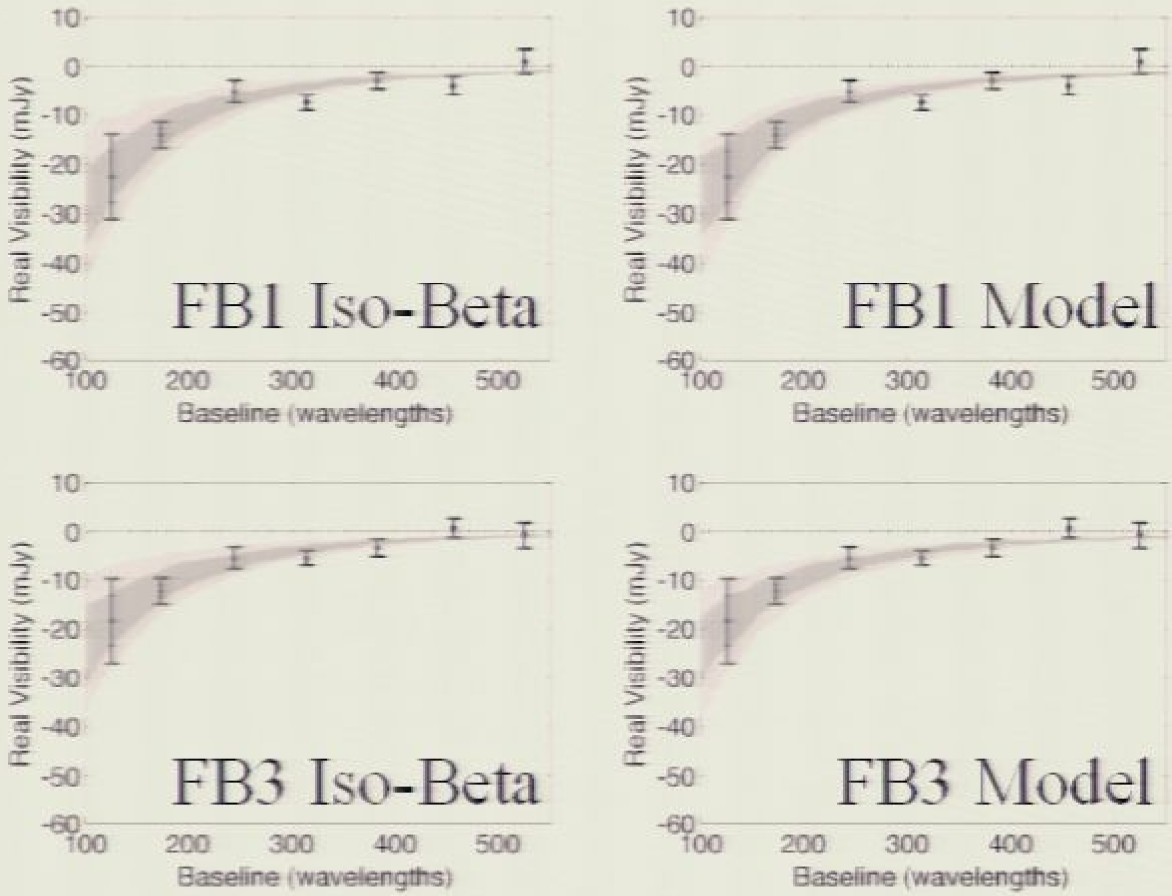

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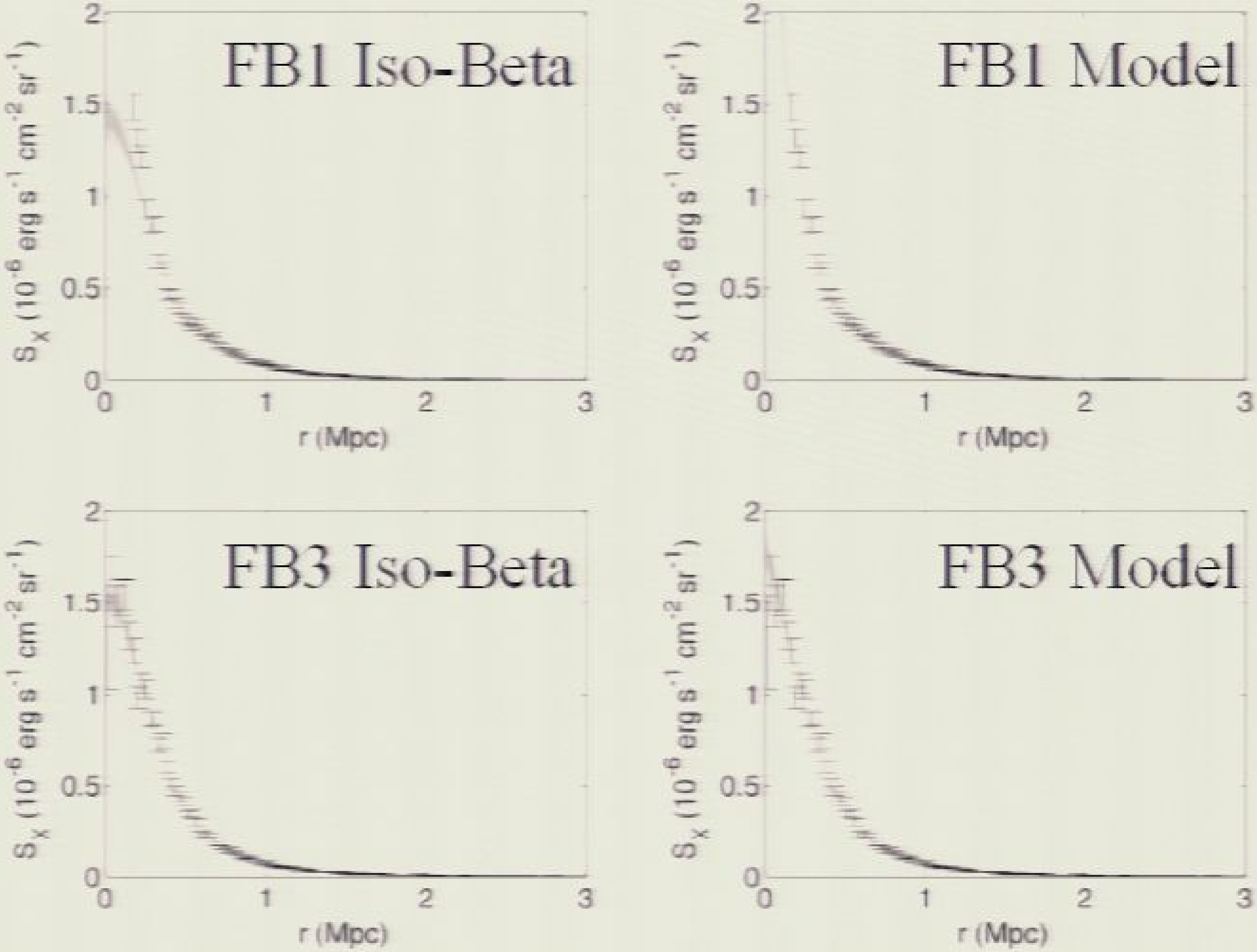

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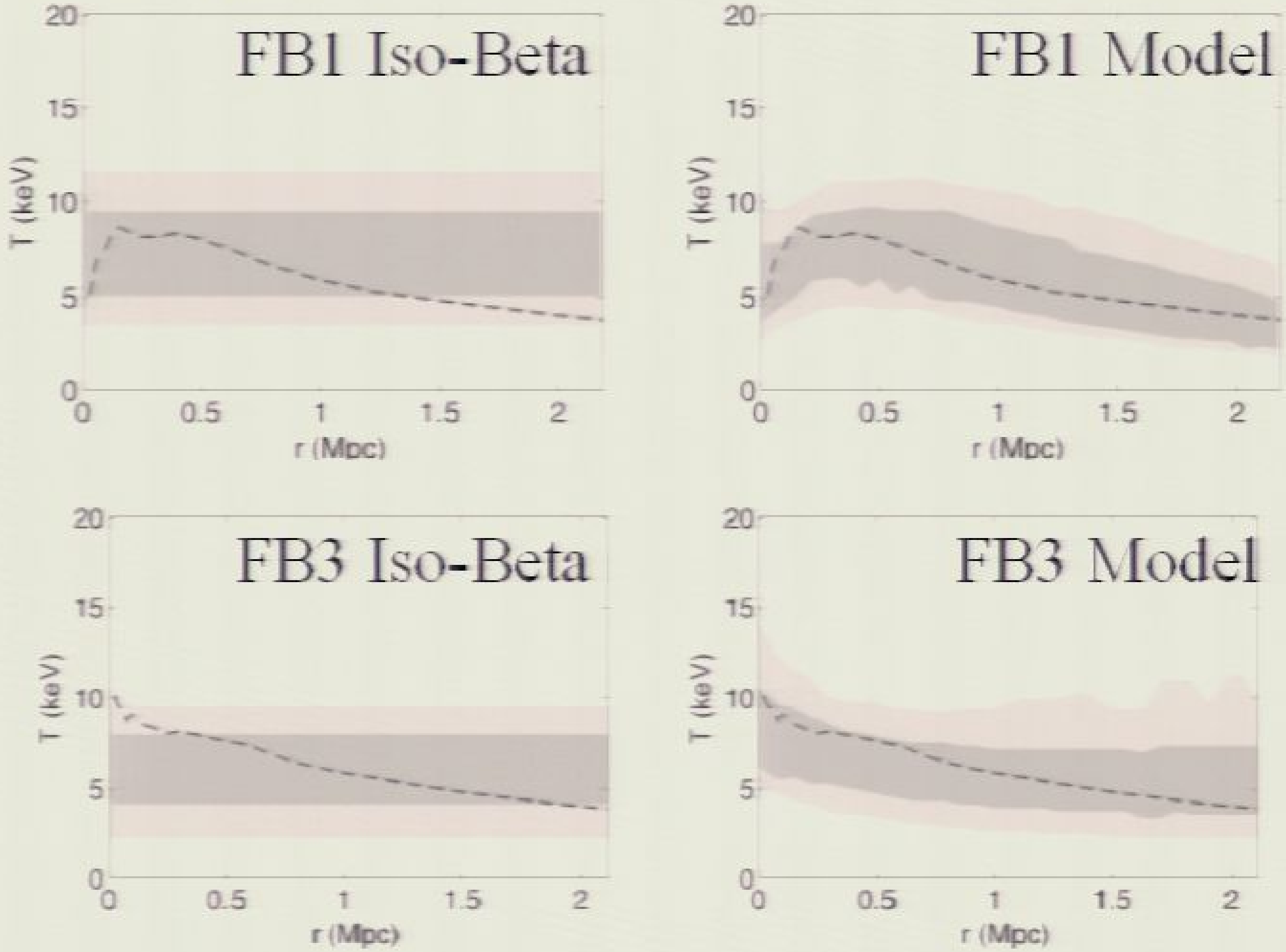

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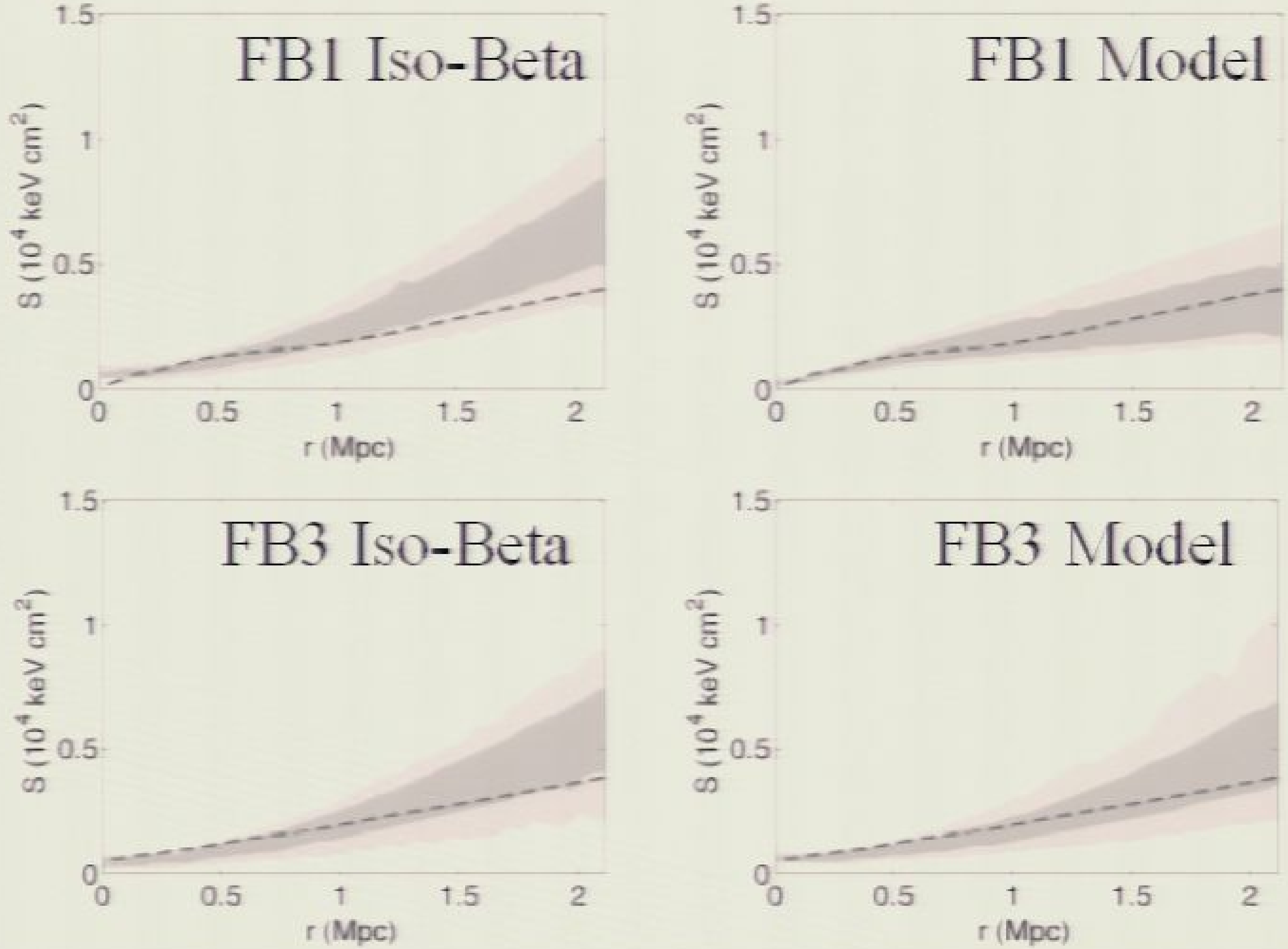

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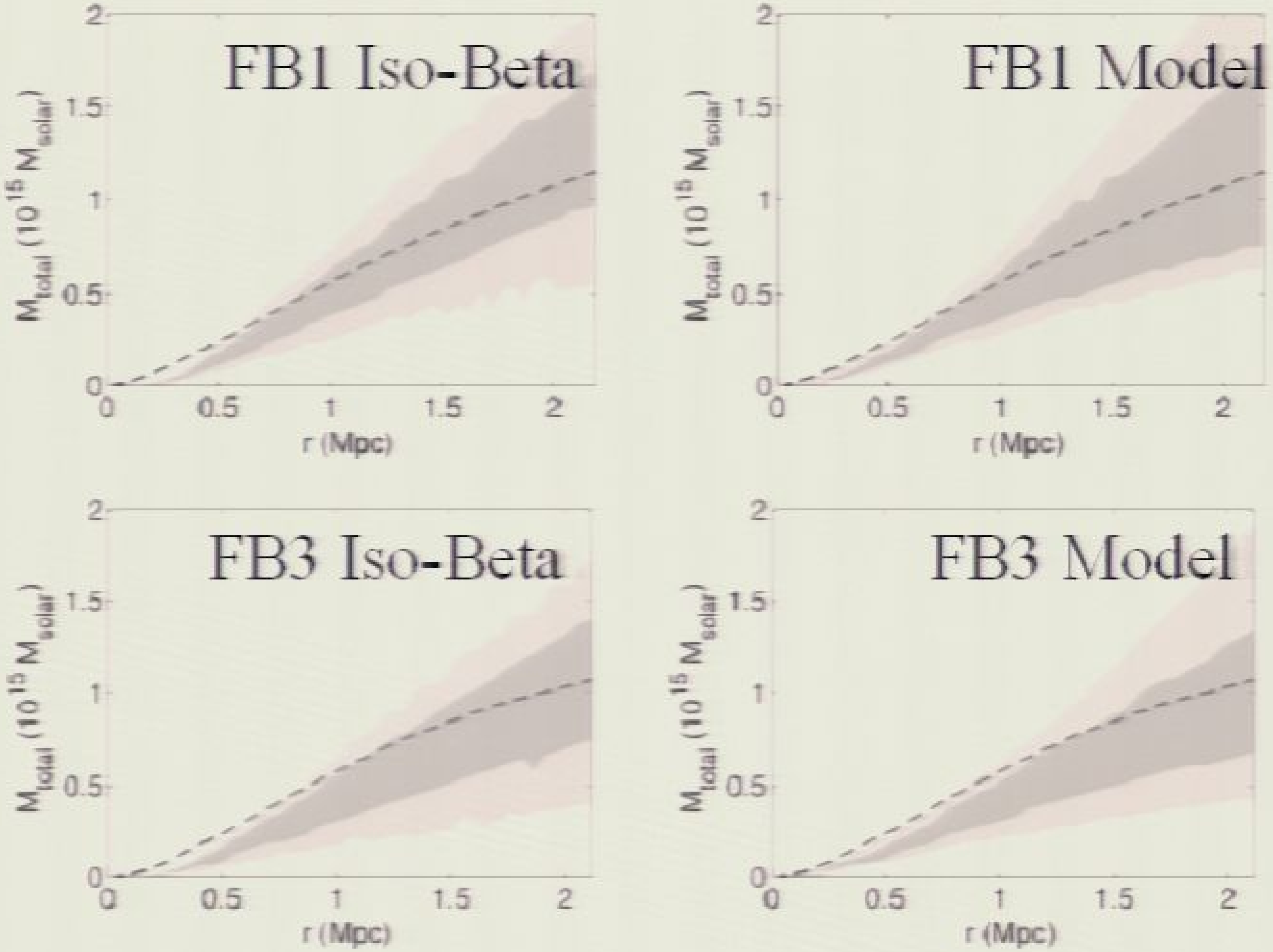

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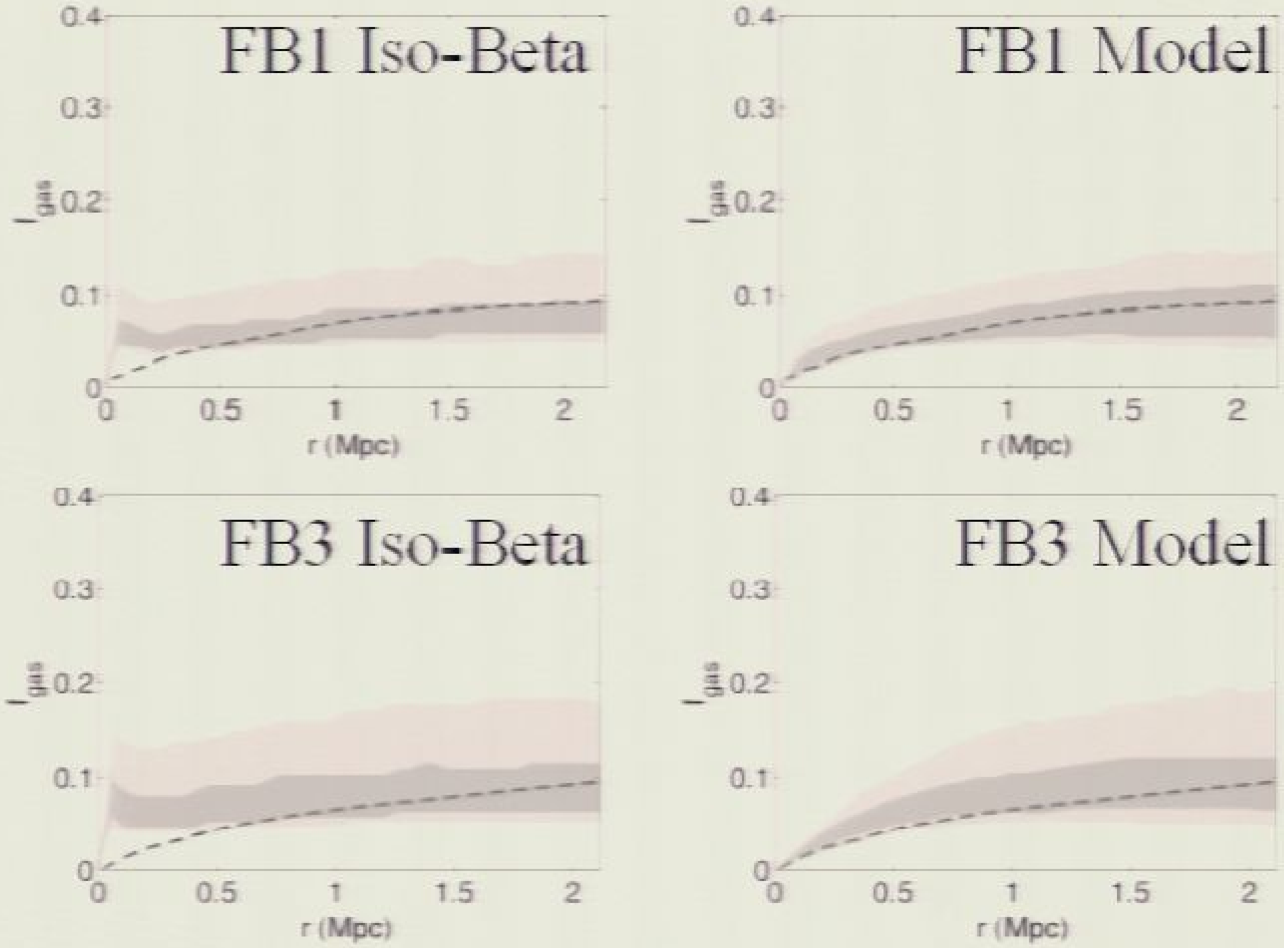

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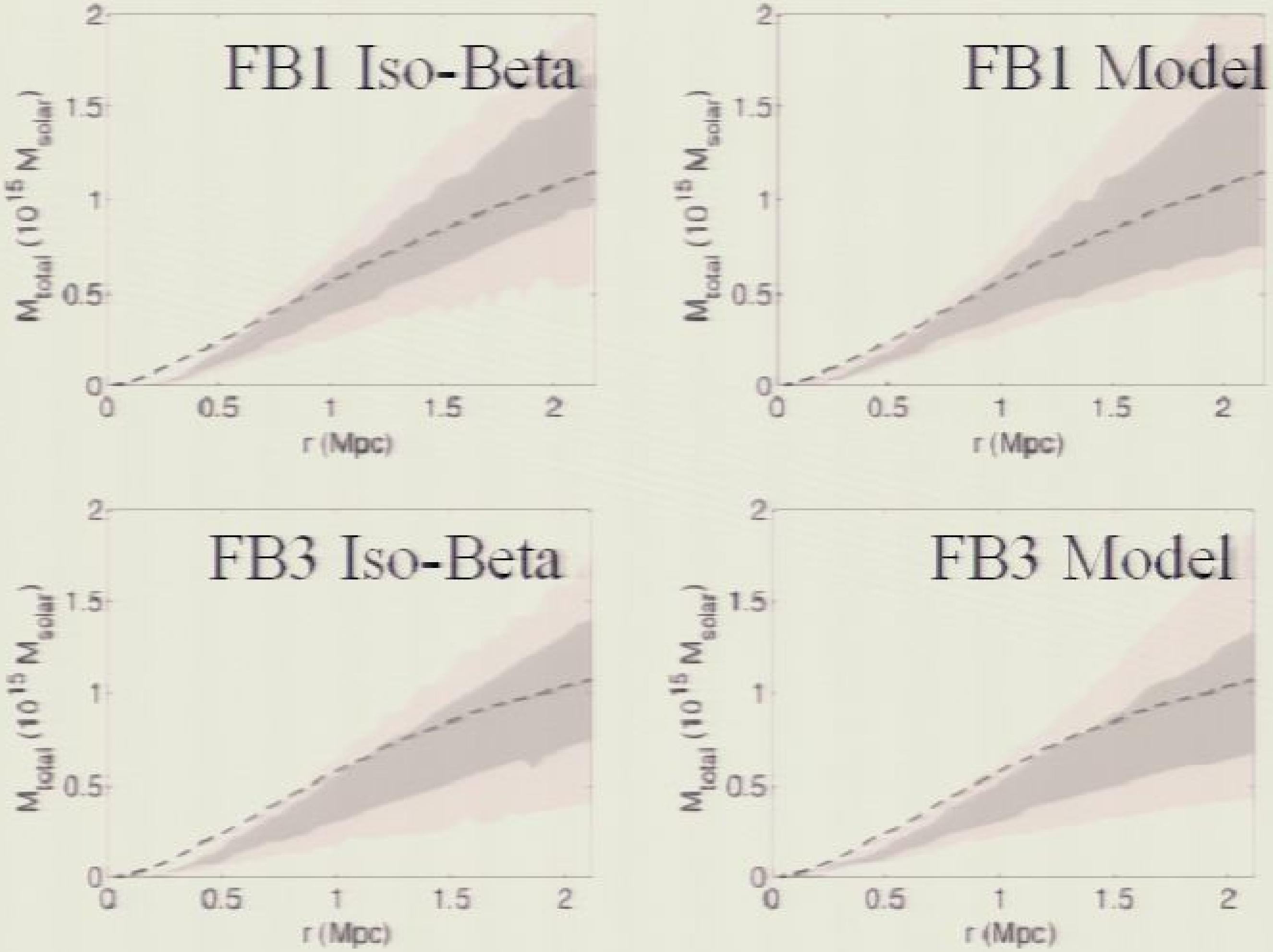

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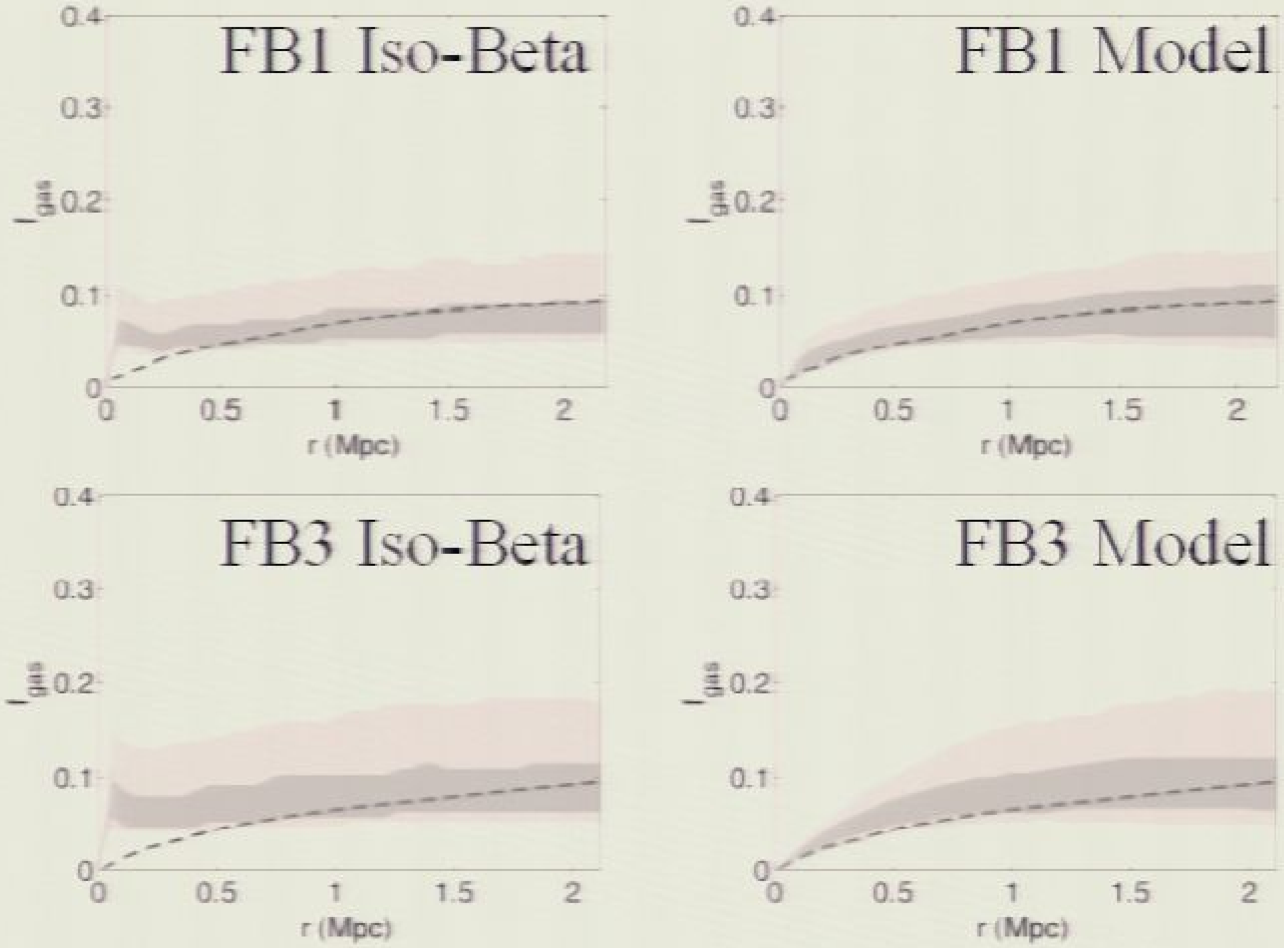

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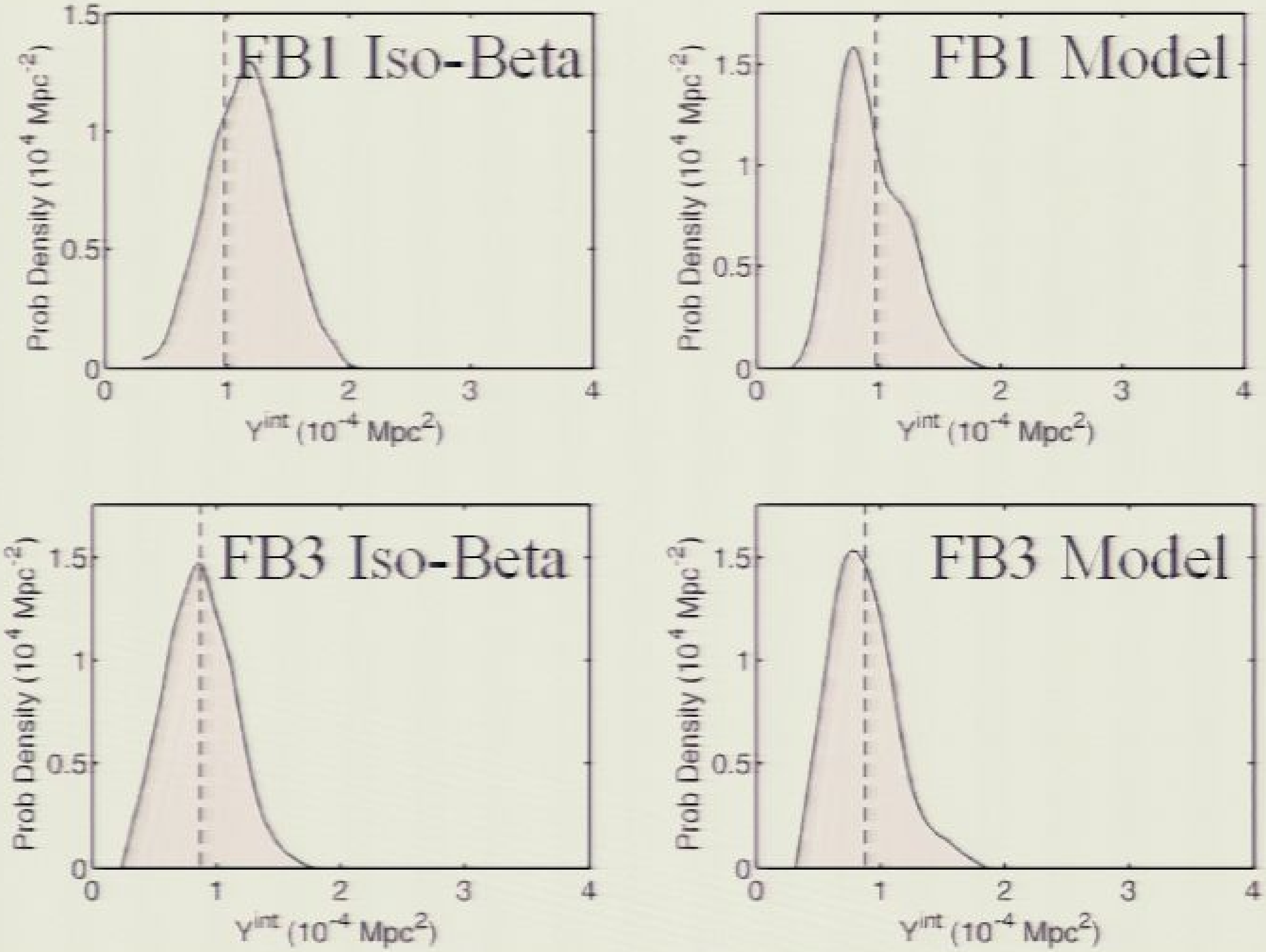
- Posterior for properties enclosed at simulated r200



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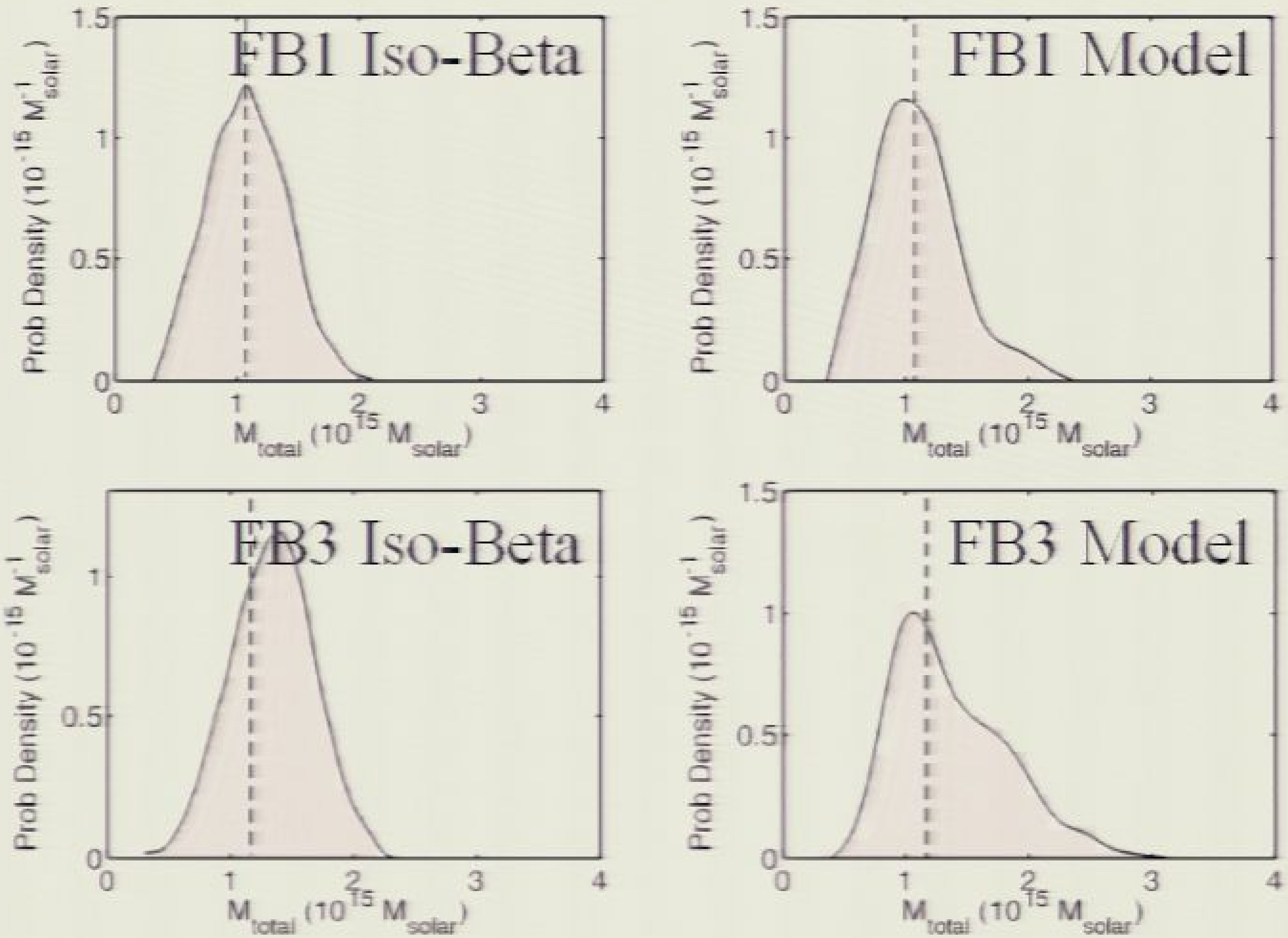

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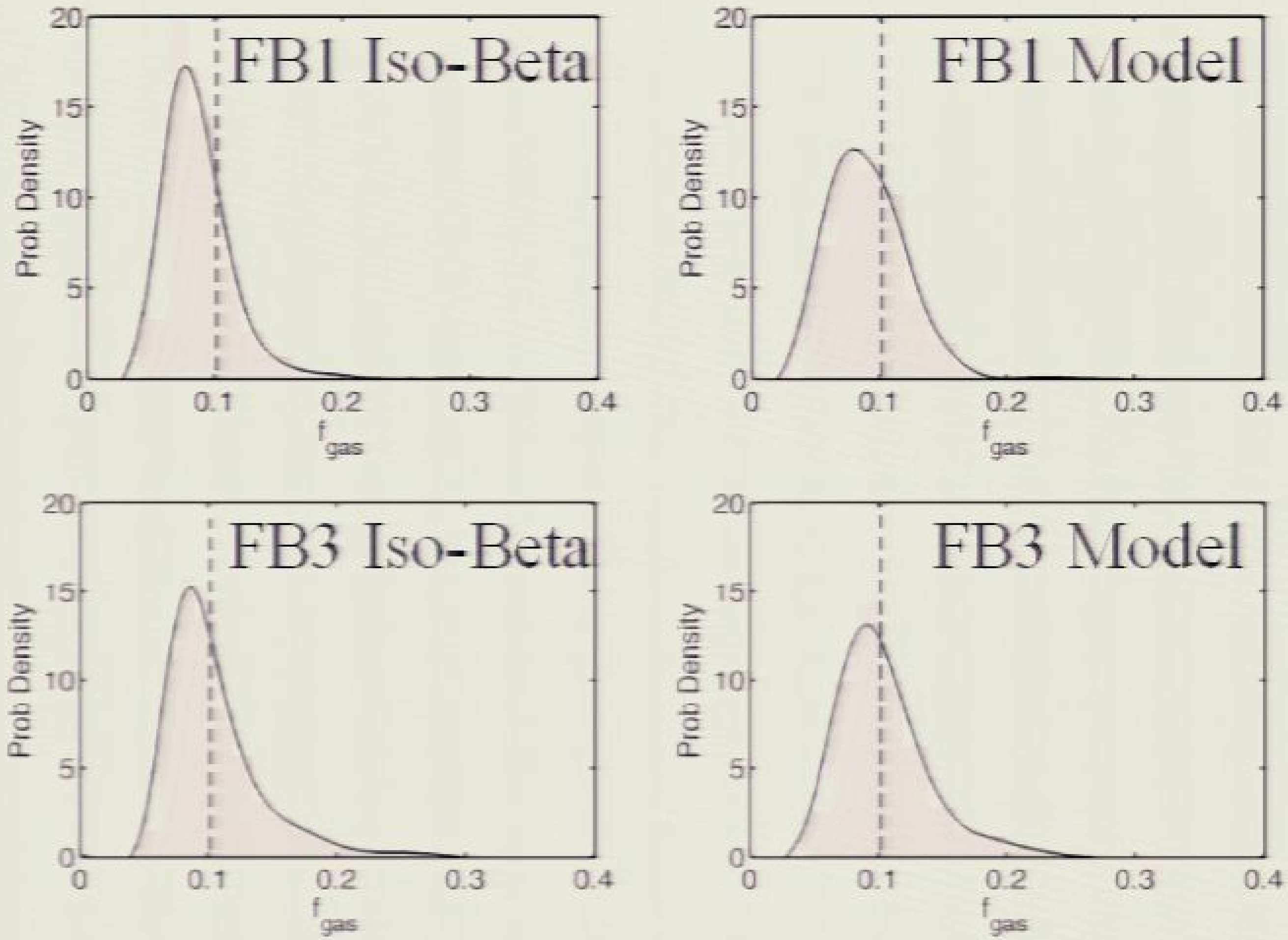
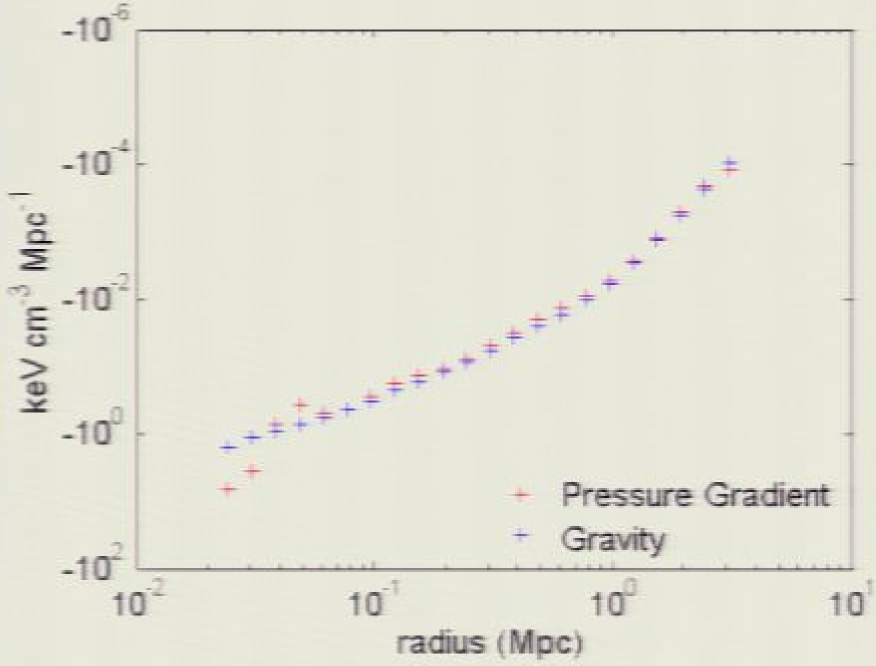
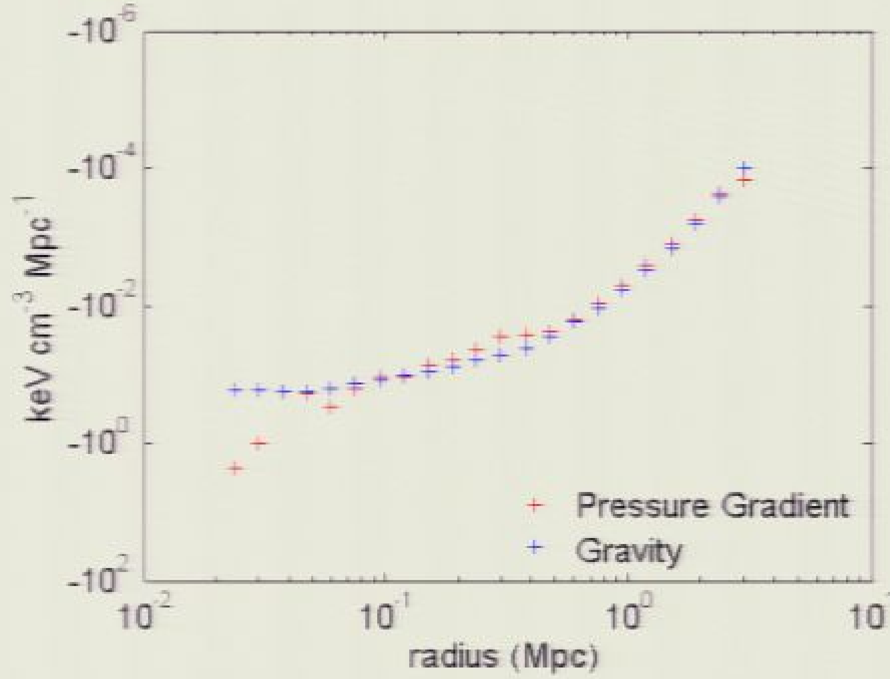


Unresolved Core Issues

- Clusters generally not in Hydrostatic Equilibrium in their cores
- Should we cut the X-ray data in the core and by how much?





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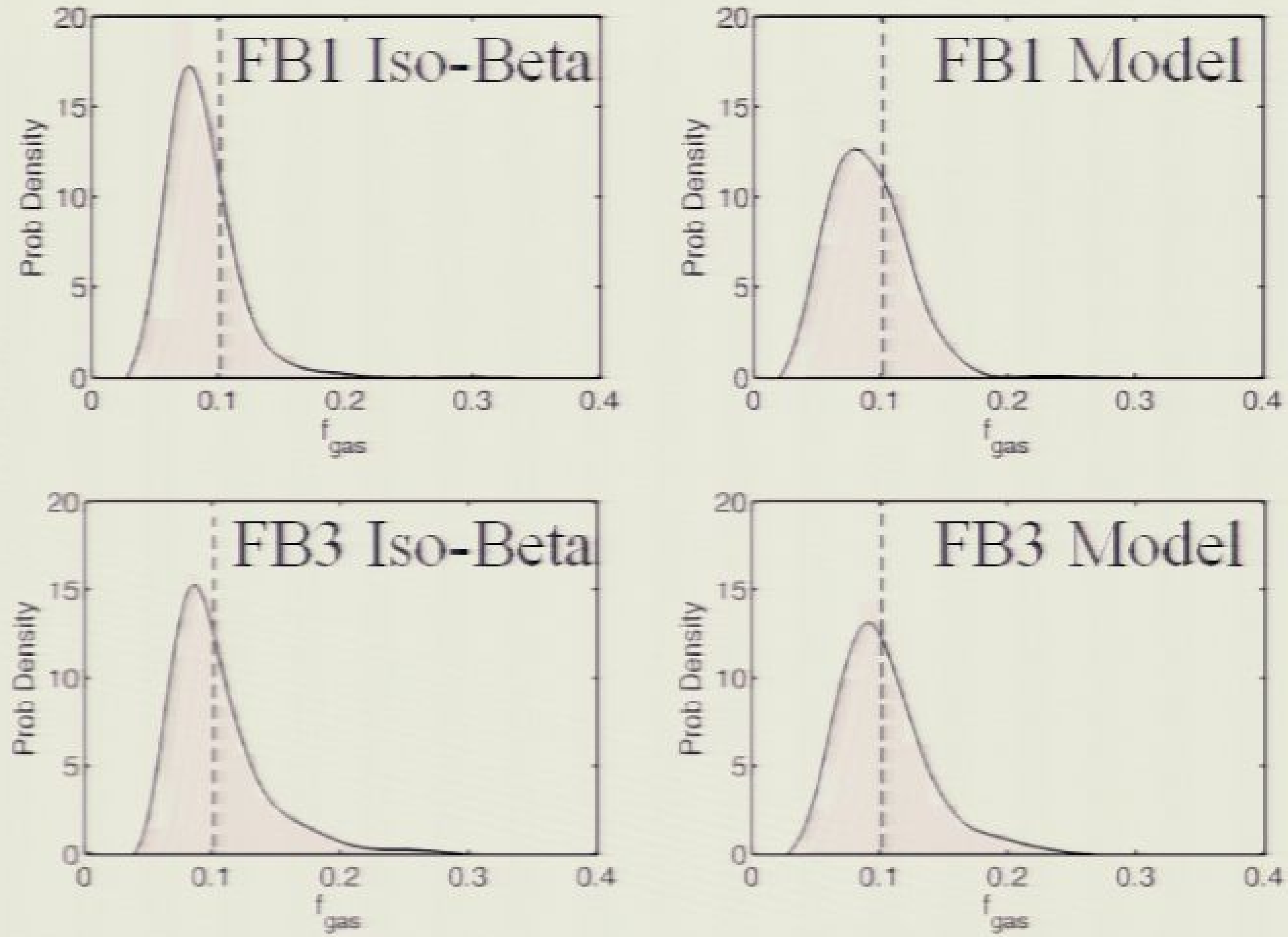

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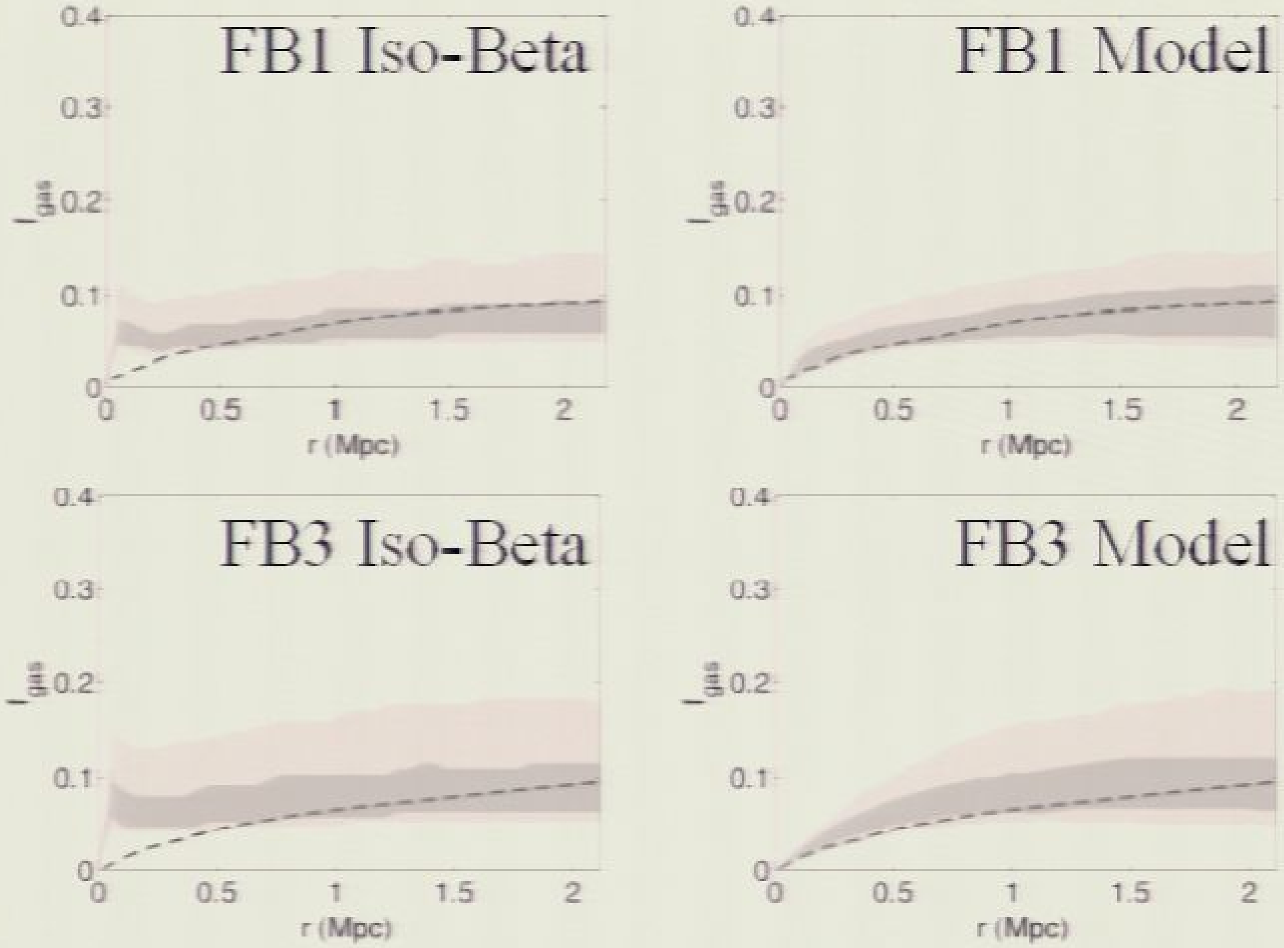

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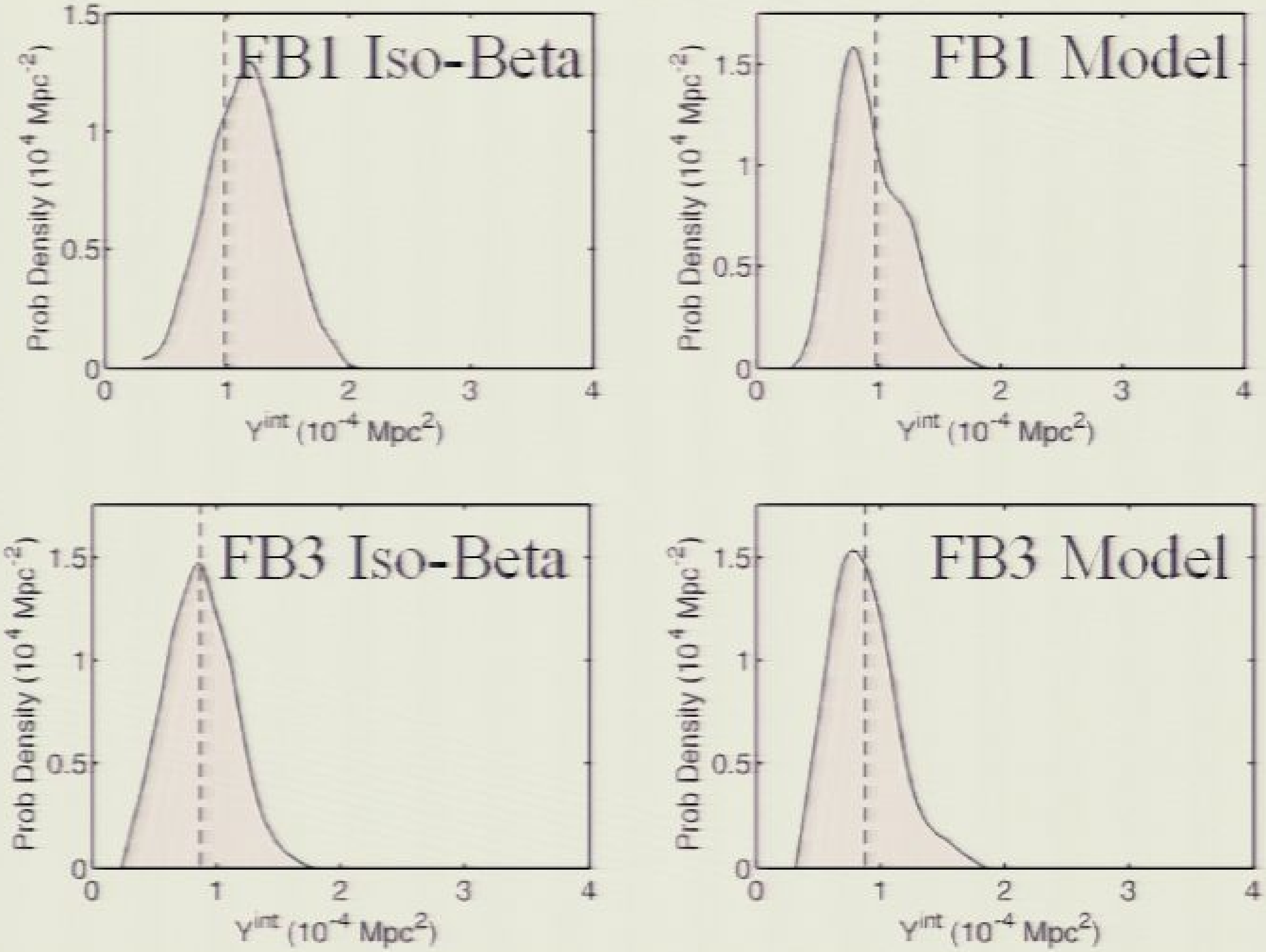

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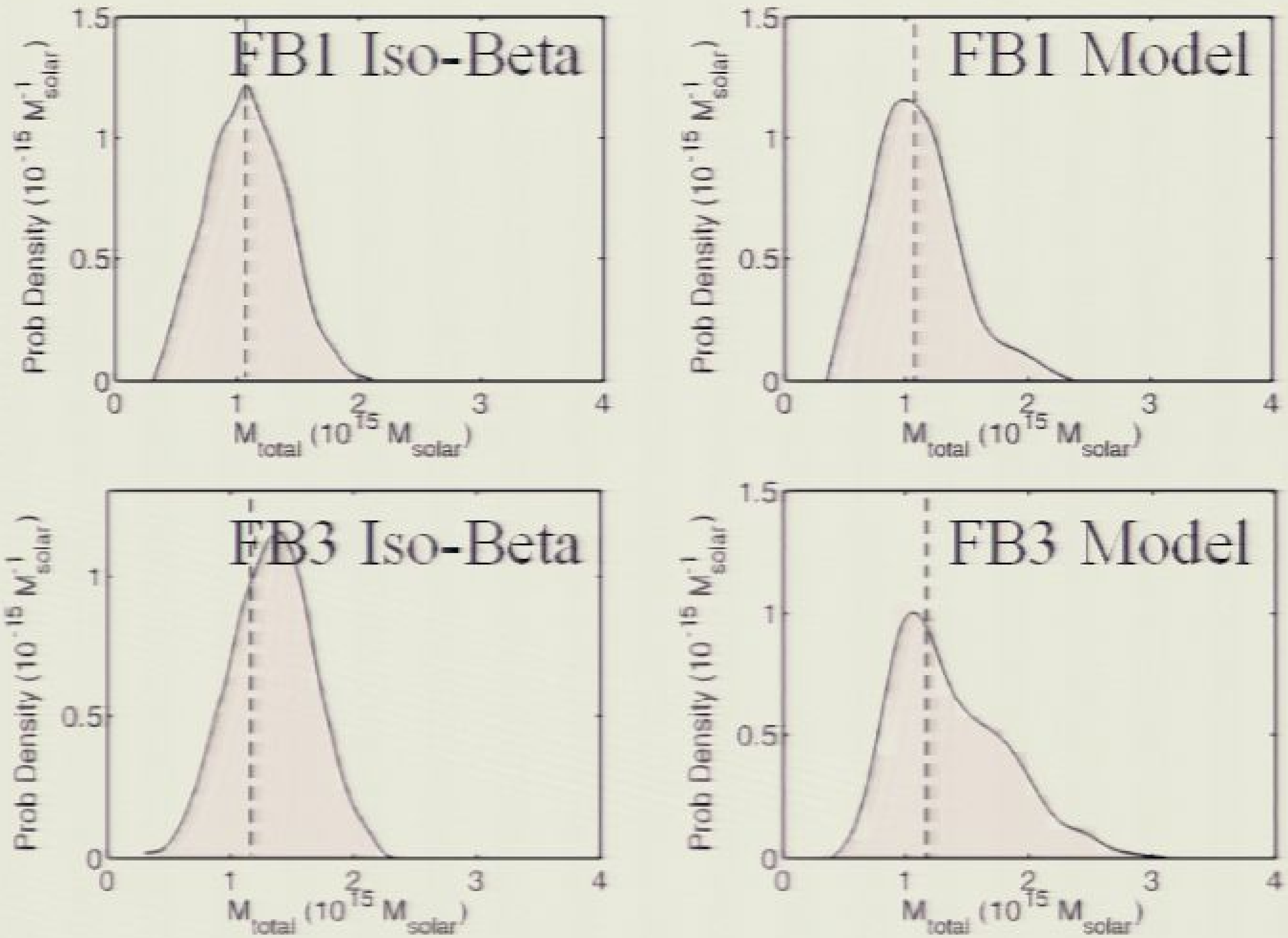

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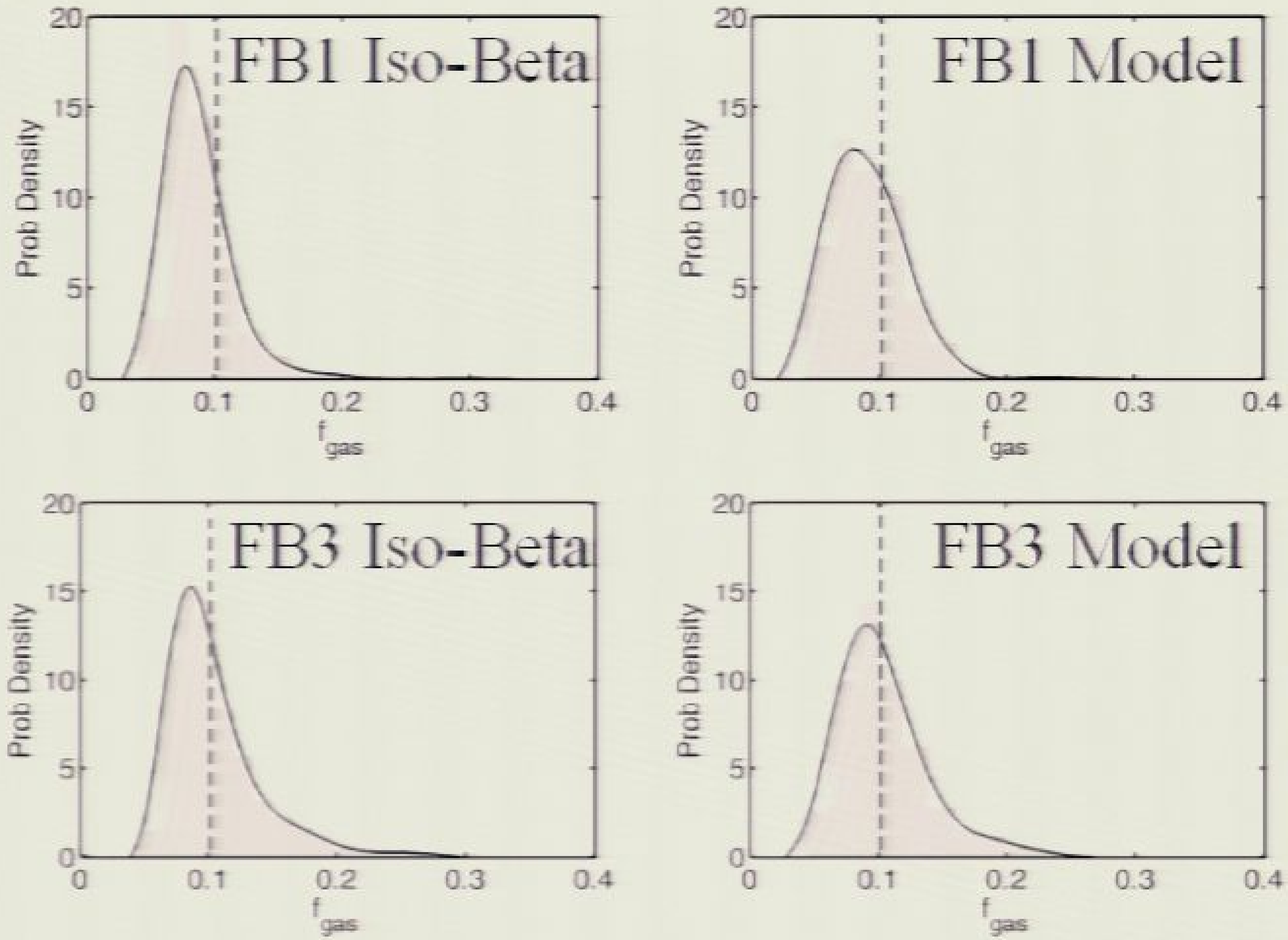

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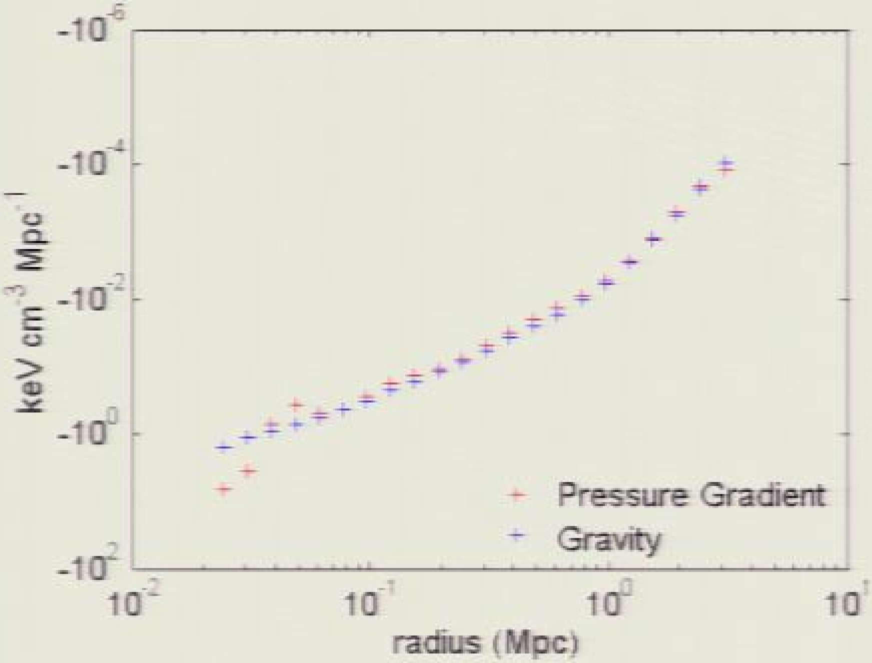

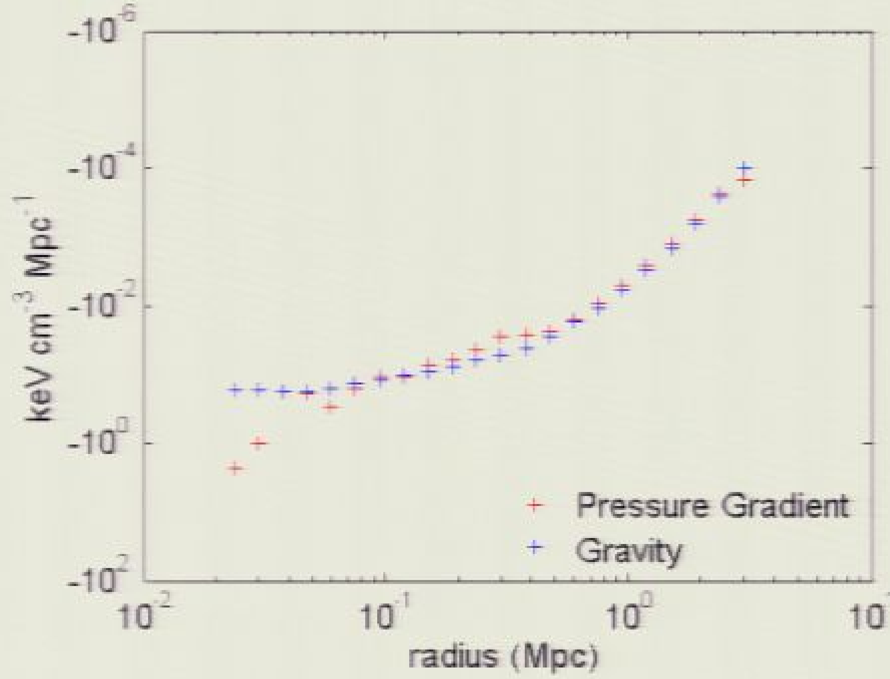

Summary

- CBI2 has observed a significant sample of known X-ray clusters
- We can probe the cluster gas on the largest scales (~virial radius)
- We have developed a simple analytical model based on know cluster physics with three principal components
- An NFW parameterisation of the Dark Matter component
- A simple gas entropy parameterisation based on a central isentropic floor and power law at large radii
- Assume Hydrostatic equilibrium holds
- Initial tests against realistic ICM simulations show that our model can reproduce simulated cluster profiles and global properties out to large radii
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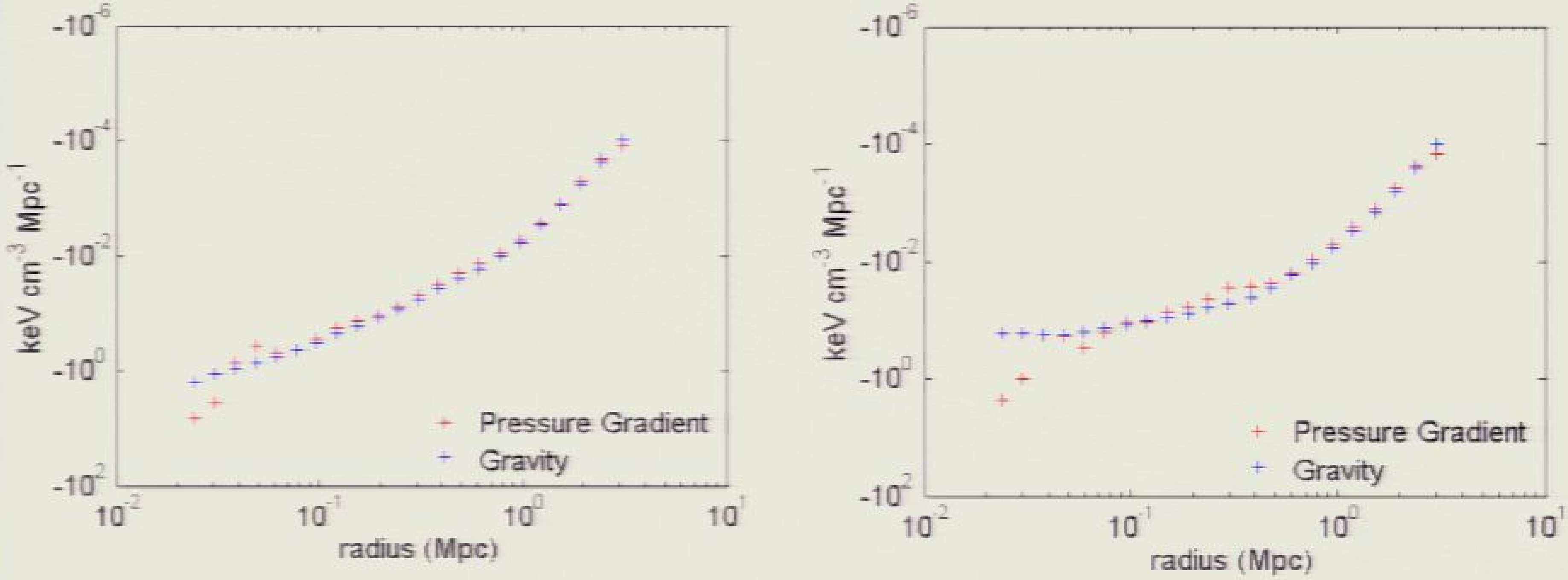

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Φxford Physics

Next Talk: Real CBI2 SZ Observations!