Searching for the WHIM with gravitational lensing.

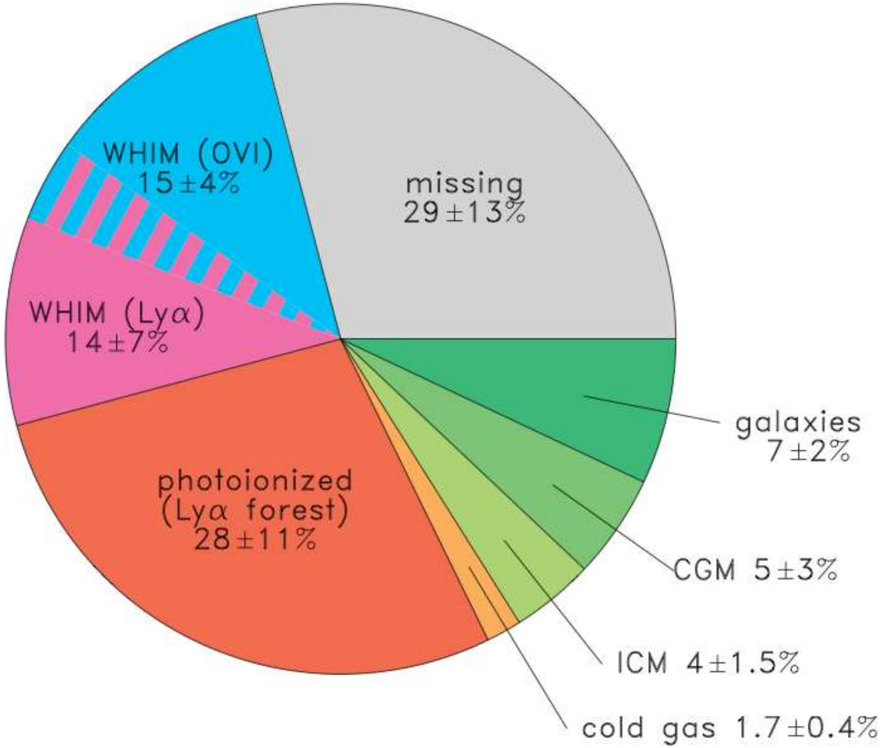
Fernando Atrio-Barandela.
Departamento de Física Fundamental.
Universidad de Salamanca.
eml: atrio@usal.es

In collaboration with:
J.P. Mücket, AIP (Postdam)

The Baryon Budget.

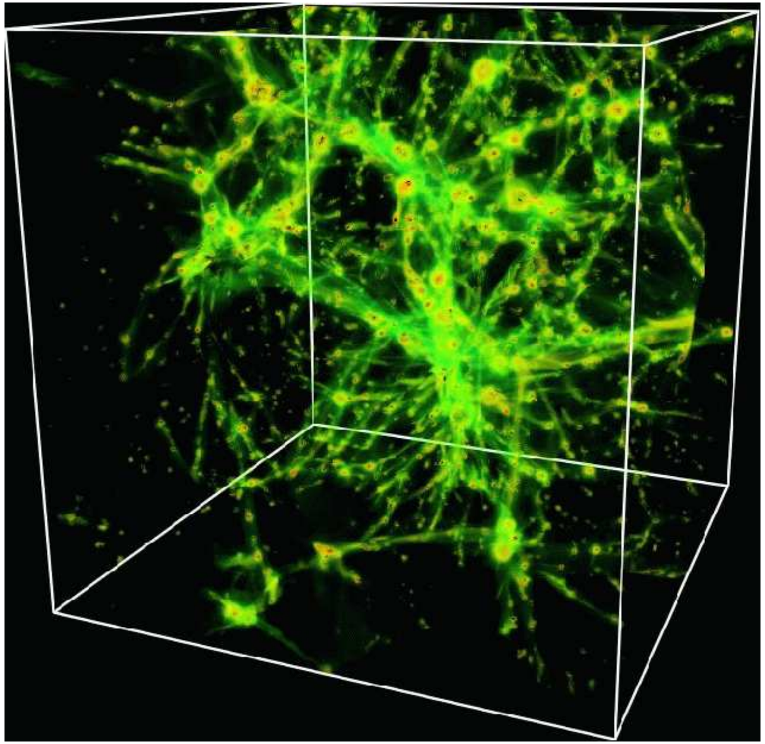
INFERRED FROM	$100\Omega_b$ $(h = 0.7)$
CMB anisotropy	4.5 ± 0.3
Observed at $z > 2$	
Ly-α forest	> 3.5
Observed at $z < 2$	
Stars	0.26 ± 0.08
HI+HeI+H_2	0.080 ± 0.016
X-ray gas in clusters	0.21 ± 0.06
Ly-α forest	1.34 ± 0.23
Warm + Warm-Hot O_{VI}	$0.6^{+0.4}_{-0.3}$
MISSING BARYONS	$2.1^{+0.5}_{-0.4}$

From Fukugita & Peebles (2004).



Shull et al arXiv:1112.2706

Hydrosimulations.



♠ Hydrodynamical simulations predict that a 'cosmic web' of $10^5 - 10^7$K should contain about half the baryons on the local Universe (Cen & Ostriker 1999, Davé et al 2001).

- Green $\delta > 10$
- Yellow $\delta > 100$
- Red $\delta > 1000$; sites of galaxy formation.

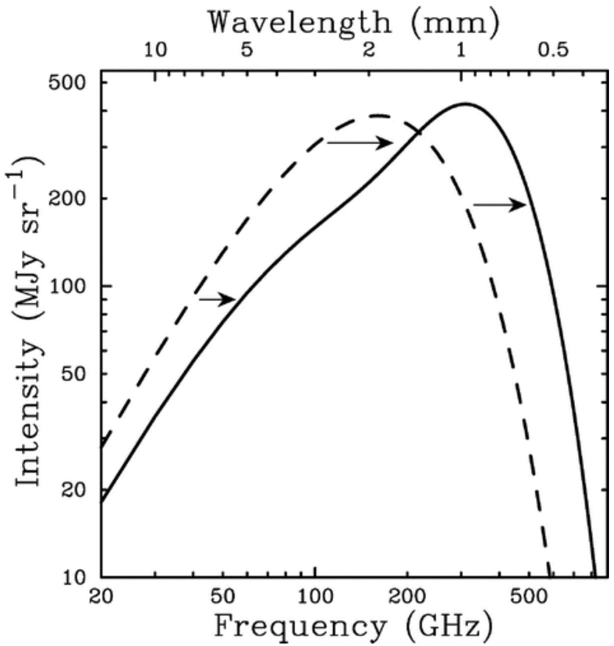
Tracing Baryons.

• Observers search for absorption lines to characterize the mass density, temperature and distribution of baryons:

Line	Phase	T/K	$\lambda(z=0)$/nm
Ly-Werner	Molecular gas	$10 - 10^2$	~ 100
21cm	Atomic gas	$10^2 - 10^3$	21cm
Lyα	Atomic+Ionized	$10^2 - 4 \times 10^4$	121.5
Hα	Ionized gas	$10^4 - 4 \times 10^4$	656
Ly limit	Ionized gas	$10^4 - 4 \times 10^4$	91.2
HeII	Ionized gas	$10^4 - 4 \times 10^4$	22.5
CIV	Ionized gas	$20,000 - 40,000$	155
OVI	Warm/Hot gas	$2 \times 10^4 - 10^6$	103
OVII,OVIII	Hot gas	$10^6 - 10^8$	2

Prochaska & Tumlison ArXiv:0805.4635

The Sunyaev-Zelovich effect.



SZ = CMB distortion.

- Thermal:

$$\left(\frac{\Delta T}{T_o}\right)_{TSZ}(\hat{s}) = G(\nu)\left(\frac{\sigma_T k_B}{m_e c^2}\right)\int n_e T_x ds$$

with $G(\nu) = x\coth(x/2) - 4, \quad x = h\nu/KT_{CMB}$.

- Kinematic:

$$\left(\frac{\Delta T}{T_o}\right)_{KSZ}(\hat{s}) = -(\vec{v}\cdot\hat{l}/c)\sigma_T \int n_e ds$$

For isothermal gas: $\frac{TSZ}{KSZ} \sim 40G(\nu)\frac{T_X}{10KeV}\frac{300km/s}{v_r}$

Searching for the WHIM signature with the SZ effect.

Earlier Results:

Atrio-Barandela & Mücket (2008) ApJ, 643, 1
Atrio-Barandela et al. (2008) ApJ 674, L81
Atrio-Barandela et al. (2009) ApJ, 700, 447
Génova-Santos et al. (2009) ApJ 700, 447
Suarez-Velásquez et al. (2013) ApJ, 769, 25

• **Fit the TSZ-KSZ contribution of WHIM to CMB data.** Génova-Santos et al (2013) MNRAS, 432, 2480

$$A_{WHIM} < 43\mu K^2 (95\%\ c.l.),\ \Omega_{WHIM} < 0.47\Omega_b$$

• **Cross correlation CMB anisotropies with tracers of the WHIM (maps of projected density of galaxies).** Génova-Santos et al (2015) ApJ, 806, 113

$$\langle TM \rangle < 0.17\mu K (95\%\ c.l.) \quad \Rightarrow \quad T_{WHIM} = [10^{4.5}, 10^{7.5}]K,\ \xi = [1, 100]$$

WHIM MODEL: Hypothesis.

WHIM: unbound diffuse gas within large scale structures with median overdensity around 10-30 (Davé et al 2001).

↓ ↓ ↓

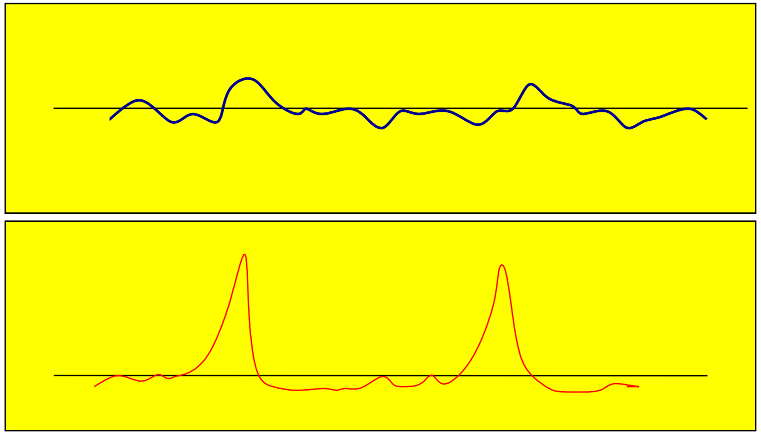
WHIM: continuous distribution of gas not bound in any specific objects.

References:

Atrio-Barandela & Mücket (2006) ApJ, 643, 1.

I. Suarez-Velásquez et al (2013) MNRAS, 431, 342

WHIM MODEL: The log-normal PDF.



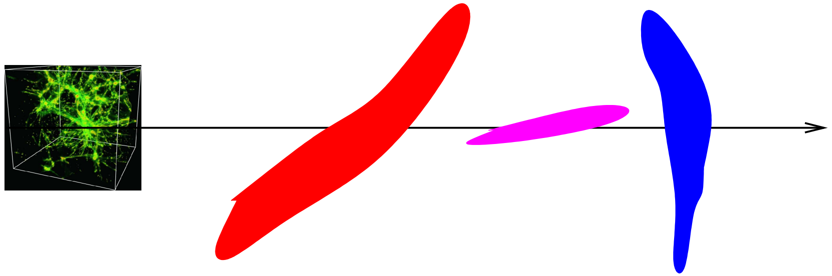
♠ (Coles & Jones 1991):

1. The linear density field δ is a Gaussian Random Field.
2. In the non-linear regime, velocities are still linear.
3. Continuity equation holds.

$\Longrightarrow$ THEN: the non-linear density field follows a log-normal PDF.

$$\xi = n_B(\vec{x}, z)/n_o(z); \qquad P(\xi) = \frac{1}{\xi\sqrt{2\pi}\sigma_B} \exp\left[-\frac{(\log(\xi) + \sigma_B^2/2)^2}{2\sigma_B^2}\right]$$

WHIM MODEL: Number density of filaments.



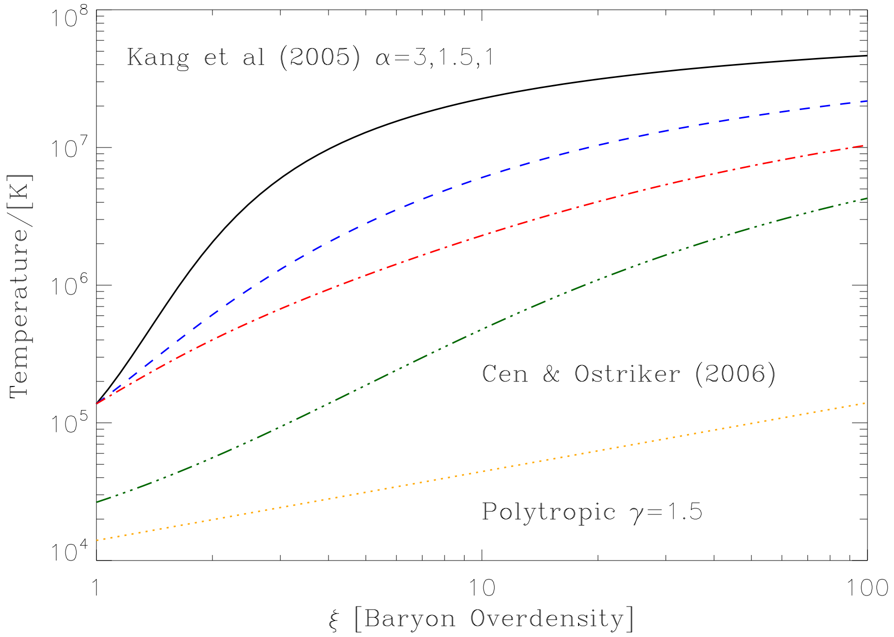
The statistical properties of filaments are described using a log-normal PDF:

$$n_B(\mathbf{x}, z) \quad = \quad n_0(z) \mathrm{e}^{\delta_B(\mathbf{x},z) - \sigma_B^2(z)/2}$$

(Fang et al 1993): The linear baryon density power spectrum is related to the matter power spectrum

$$\delta_B(k, z) = \frac{D_+(z)\delta_{\rm DM}(k)}{1 + L_0^2(z)k^2} \qquad\qquad L_0(z) \quad \equiv \quad \text{Baryon damping scale}$$

Equation of State.



- **Shock-heated gas $(z < 1)$** (Kang et al, 2005):

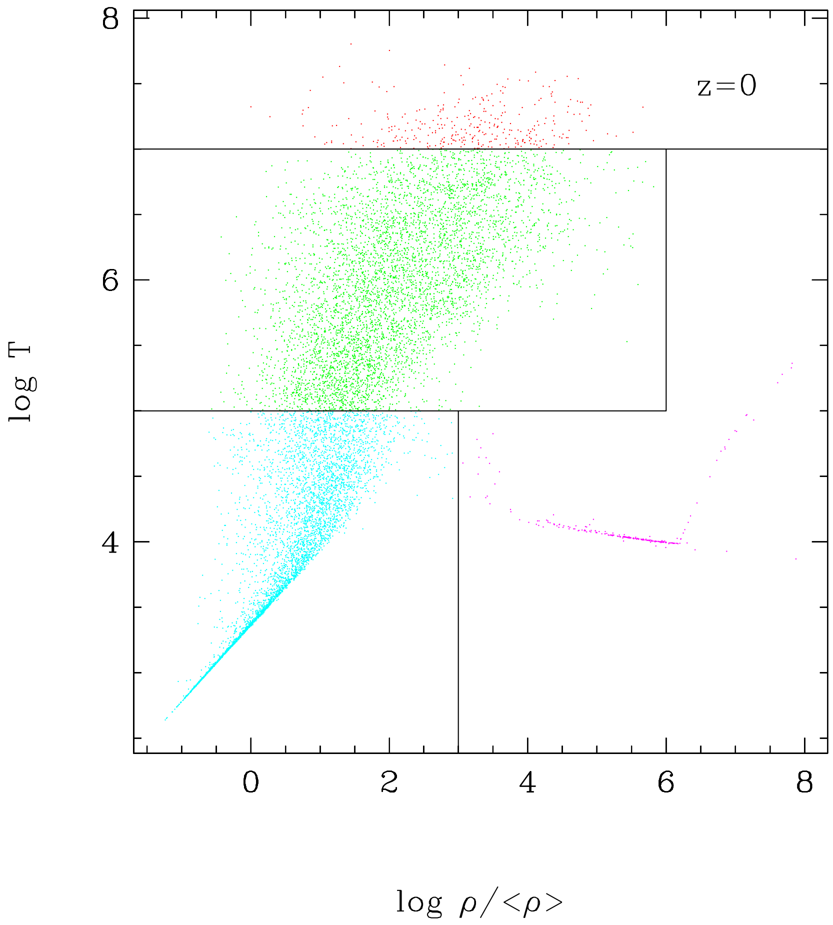
$$\log_{10}\left(\frac{T_e(\xi)}{10^8 K}\right) = -\frac{2}{\log_{10}(4+\xi^{\alpha+1/\xi})}$$

- **Shock-heated gas $(z < 1)$** (Cen & Ostriker, 2006):

$$\log_{10}\frac{T_e(\xi)}{10^8 K} = -\frac{2.5}{\log_{10}(4.0+\xi^{0.9})}$$

- **Polytropic Model:** $T(\hat{x}, z) = T_0(z)\xi^{(\gamma-1)}$

Average temperatures in shock-heated models: $\bar{T}_e = [20, 7, 3, 0.7] \times 10^6$K.



- The polytropic index is very uncertain: $\gamma = [1, 1.6]$. Fiducial Model: $\gamma = 1.5$.

$\leftarrow$ (Davé et al 2003) Temperature distribution of the different phases:

- Condensed: cold galactic gas.
- Hot: gas in clusters and large groups.
- Warm-Hot.
- Diffuse: Photoionized intergalactic gas that gives rise to Lyα absorption.

TSZ-Convergence Cross-Correlation: Baryon damping scales.

[Atrio-Barandela & Mücket (2017) ApJ, 845, 71; ArXiv:1707:03617]

- Shock heating scale $(z < 1)$:

$$L_0(z) = \frac{2\pi(1+z)c_s H_0^{-1}}{(\Omega_\Lambda + \Omega_m(1+z)^3)^{1/2} f(z) D_+(z)} \qquad L_0(0) = 1.7h^{-1}\mathrm{Mpc}$$

- Jeans scale $(z > 1)$:

$$L_0(z) = H_0^{-1}\left[\frac{2\gamma k_{\mathrm{B}} T_b(z)}{3\mu m_p \Omega_m (1+z)}\right]^{1/2} \qquad L_0(0) = 0.23h^{-1}\mathrm{Mpc}$$

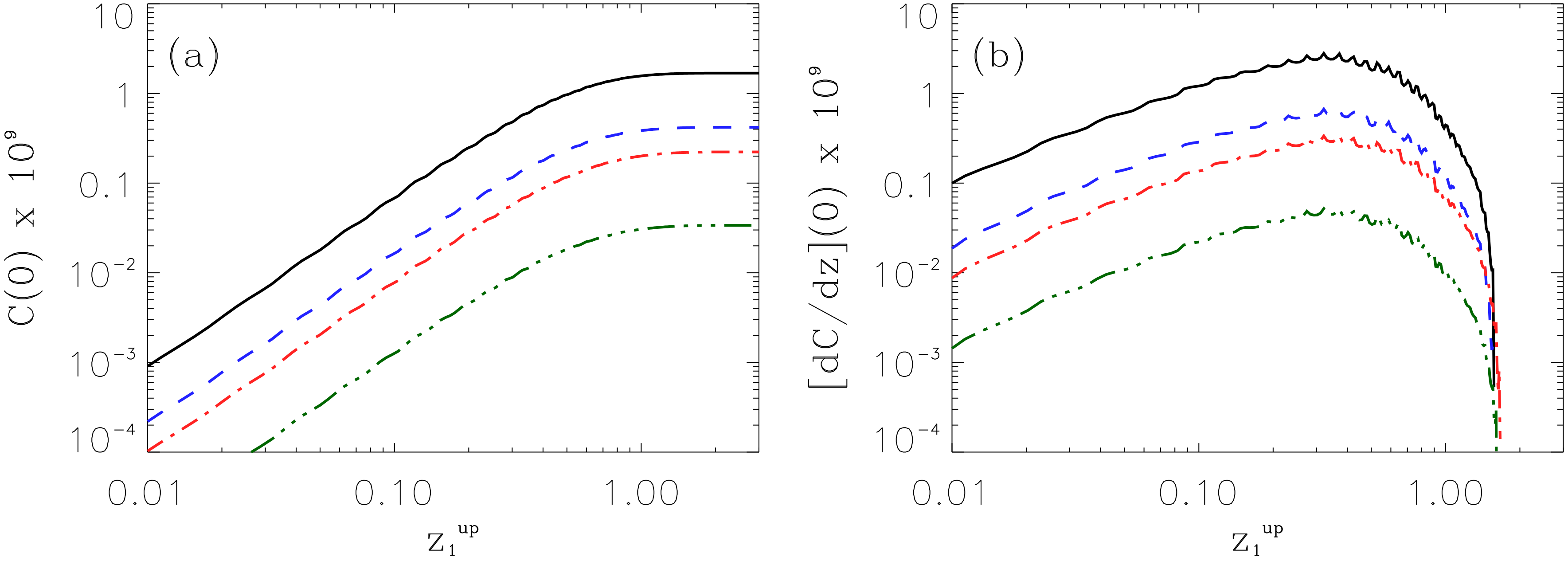
TSZ-Convergence Cross-Correlation: Formalism.

$$C(\theta) \equiv \langle \Delta Y_C(\hat{x}_1, z_1) \Delta\kappa_{eff}(\hat{x}_2, z_2)\rangle(\theta)$$
$$= \int_0^{z_1^{up}} dz_1 \int_0^{z_2^{up}} dz_2 \int_1^{100} d\xi \int_{-\infty}^{\infty} d\delta \Delta Y_C(\hat{x}_1, z_1) \Delta\kappa_{eff}(\hat{x}_2, z_2) F(\xi, \delta)$$

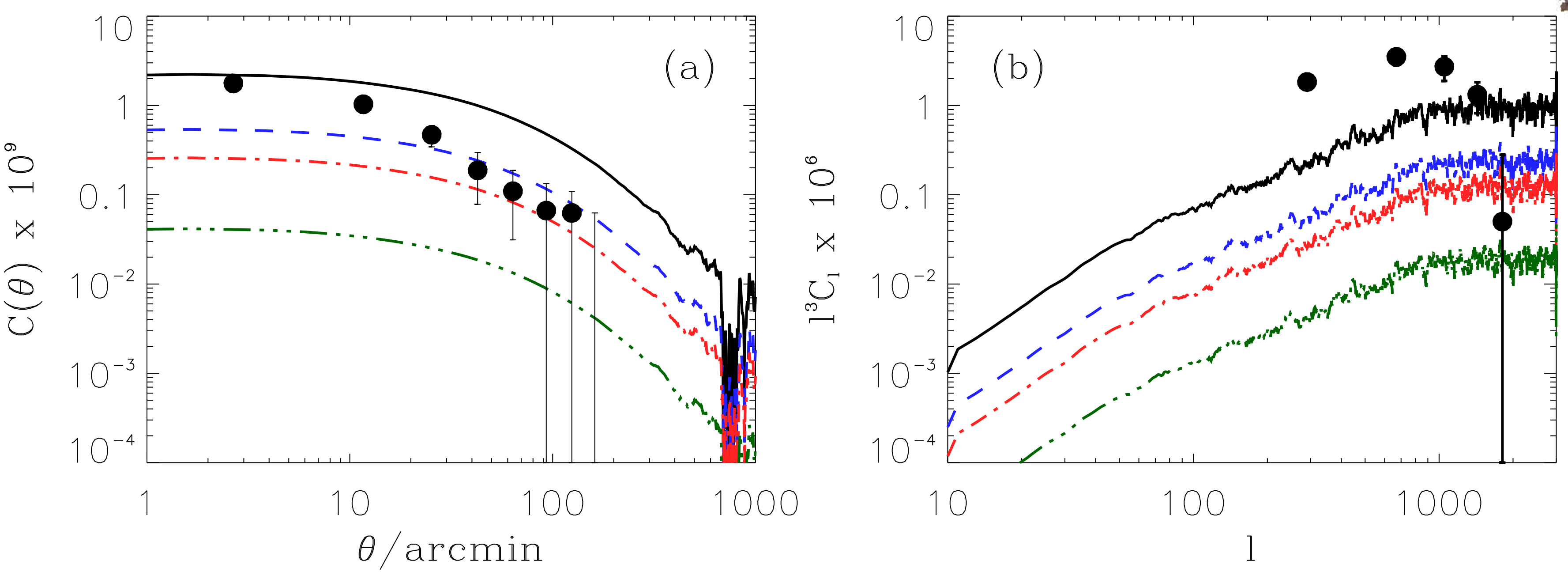
with $\cos\theta = \hat{x}_1 \cdot \hat{x}_2$ and

$$F(\xi, \delta) = \frac{1}{2\pi\xi\sigma_B\sigma_\delta(1-\rho_c)^{1/2}} \exp\left[\frac{1}{2(1-\rho_c^2)}\left(\frac{(\log\xi - \sigma_B^2/2)^2}{\sigma_B^2} - 2\rho_c\frac{(\log\xi-\sigma_B^2/2)(\delta-\mu_\delta)}{\sigma_B\sigma_\delta} + \frac{(\delta-\mu_\delta)^2}{\sigma_\delta^2}\right)\right]$$

with $\sigma_\delta^2 = (D_+^2(z)/2\pi^2) \int P_{\rm DM}(k) W^2_{\rm top-hat}(kR_{\rm cut}) k^2 dk.$



Contribution and differential contribution as a function of the upper limit of integration.



Cross-correlation and Power Spectrum for Kang et al (2005) $[\alpha = 3, 1.5, 1]$ and Cen & Ostriker (2006) temperature models, and measurements from Hojjati et al (2016).

TSZ-Convergence Cross-Correlation: Results/Conclusions.

• In the overdensity intervals $\xi = ([1-3.3], [3.3-10], [10-33], [33-100])$, **the fractional contribution to the cross-correlation would be:**

$$\langle \Delta\kappa \Delta Y_C \rangle(0) = (0.08, 0.45, 0.41, 0.06)$$

• In the interval $\theta = [40 - 120]$ arcmin:

- The Kang et al (2005) temperature model with $\alpha = 1.5$ reproduces the measured amplitude of the correlation. **The average temperature is bounded above: $\bar{T}_e \leq 7 \times 10^6$K.**

- The Cen & Ostriker (2006) model predicts an amplitude 10% of the measured correlation. **The average temperature of the IGM would be $\bar{T}_e \sim 10^6$K.**

• The shape of the predicted and measured power spectra are different. It could be used to distinguish cluster from WHIM contributions.