Robustness of the pairwise kinematic Sunyaev-Zel'dovich power spectrum shape as a cosmological gravity probe

2001.08608, ApJ accepted

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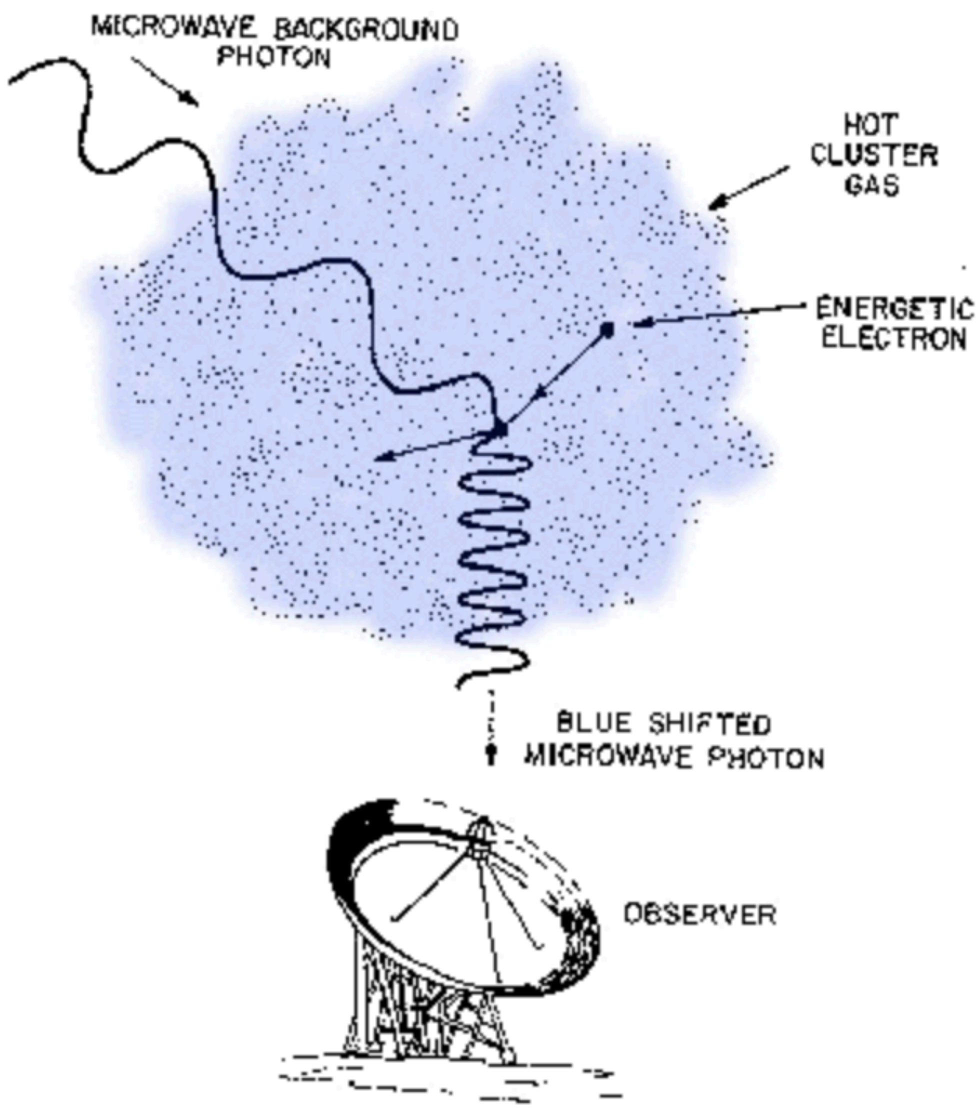
Kinematic Sunyaev-Zel'dovich effect



$$\delta T_{\rm kSZ}(\hat{n}) = -T_0 \int dl \sigma_{\rm T} n_{\rm e} \left(\frac{\vec{v}_{\rm e} \cdot \hat{n}}{c} \right)$$

$$\delta T_i \simeq \left(-T_0 \frac{\tau_i}{c} \right) \vec{v}_i \cdot \hat{n}_i,$$

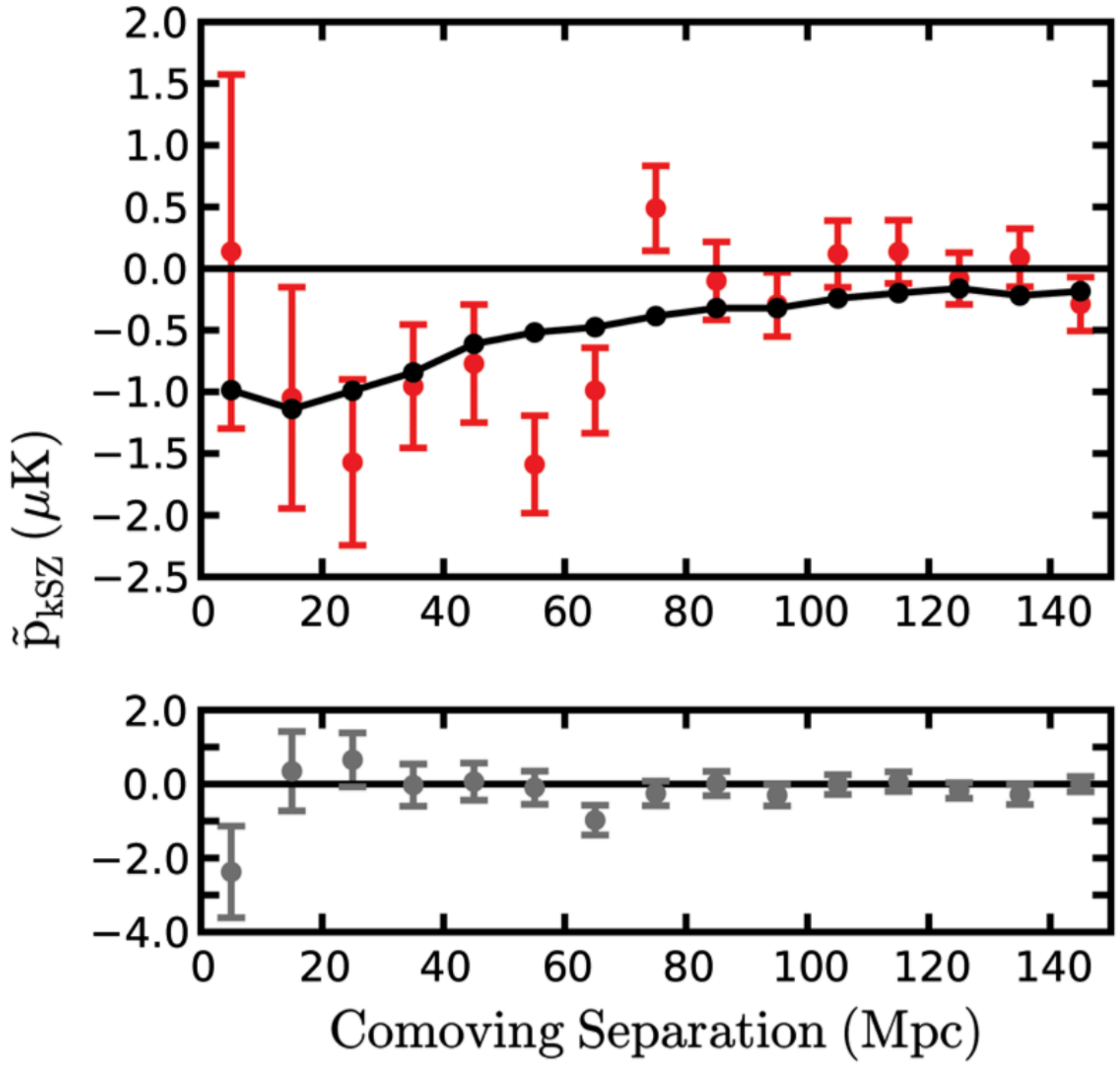
Optical depth

Peculiar velocity

$$\tau_{{\rm T},i} = \int dl \sigma_{\rm T} n_{e,i}$$

Sunyaev R. A., Zel'dovich Y. B., 1970, Ap&SS, 7, 3

kSZ effect measurement



$$\tilde{p}_{\rm kSZ}(r) = -\frac{\sum_{i<j}[(T_i - \mathcal{T}(z_i)) - (T_j - \mathcal{T}(z_j))]c_{ij}}{\sum_{i<j} c_{ij}^2}$$

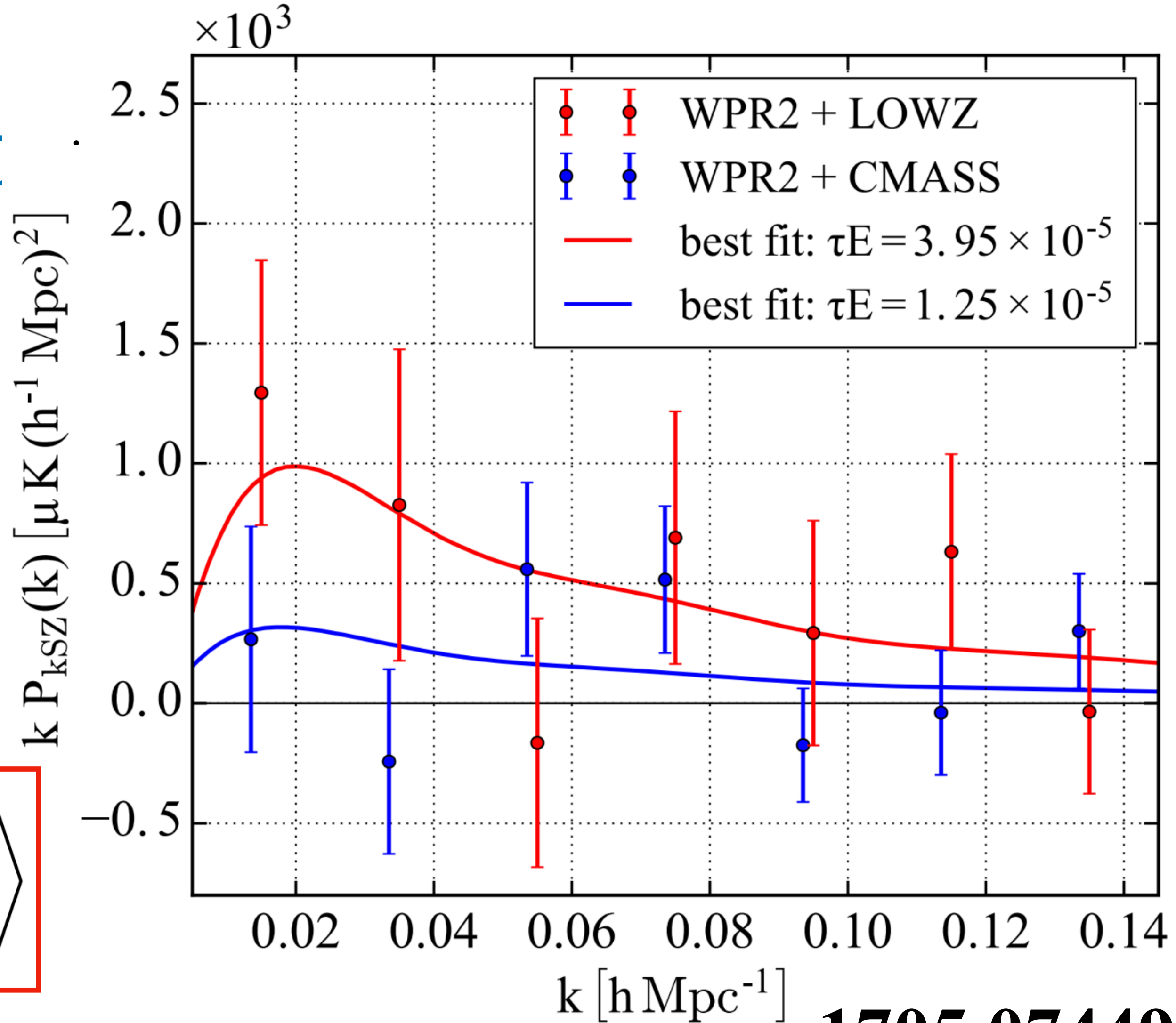
$$c_{ij} \equiv \hat{\mathbf{r}}_{ij} \cdot \frac{\hat{\mathbf{r}}_i + \hat{\mathbf{r}}_j}{2} = \frac{(r_i - r_j)(1 + \cos\theta)}{2\sqrt{r_i^2 + r_j^2 - 2r_i r_j \cos\theta}},$$

Hand et al., PRL 109, 041101 (2012)

kSZ effect measurement

$$\tilde{p}_{\mathrm{kSZ}}(r) = -\frac{\sum_{i<j}[(T_i - \mathcal{T}(z_i)) - (T_j - \mathcal{T}(z_j))]c_{ij}}{\sum_{i<j} c_{ij}^2}$$

$$\boxed{P_{\mathrm{kSZ}}(\boldsymbol{k}) = \left\langle -\frac{V}{N^2}\sum_{i,j}\left[\delta T_{\mathrm{kSZ}}^{(\mathrm{AP})}(\hat{n}_i) - \delta T_{\mathrm{kSZ}}^{(\mathrm{AP})}(\hat{n}_j)\right] \mathrm{e}^{-i\boldsymbol{k}\cdot\boldsymbol{s}_{ij}} \right\rangle}$$



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FWHM (arcmin)	Noise (μK arcmin)	Galaxy	Redshift	V $[(h^{-1}\,\mathrm{Gpc})^3]$	$\bar{n}_g$ $[(h^{-1}\,\mathrm{Mpc})^{-3}]$	b_g	M_{halo} $(h^{-1}\,M_\odot)$	S/N (FWHM = 1, 1.5, 2.0, 3.0 arcmin)
CMB-S4 + BOSS								
1–3	2	LRG	0.3 ($0.15 < z < 0.43$)	2.0	3.0×10^{-4}	2.0	5.2×10^{13}	(13, 12, 12, 12)
1–3	2	LRG	0.5 ($0.43 < z < 0.70$)	4.0	3.0×10^{-4}	2.0	2.6×10^{13}	(46, 43, 39, 32)
CMB-S4 + DESI								
1–3	2	LRG	0.8 ($0.65 < z < 0.95$)	13.5	2.8×10^{-4}	2.5	5.0×10^{13}	(105, 98, 90, 75)
1–3	2	ELG	1.1 ($0.95 < z < 1.25$)	18.7	4.7×10^{-4}	1.4	4.0×10^{12}	(92, 69, 52, 28)
CMB-S4 + PFS								
1–3	2	ELG	0.9 ($0.6 < z < 1.2$)	2.3	4.9×10^{-4}	1.3	4.0×10^{12}	(34, 27, 21, 12)
1–3	2	ELG	1.5 ($1.2 < z < 2.0$)	4.9	4.7×10^{-4}	1.7	5.0×10^{12}	(54, 39, 30, 16)

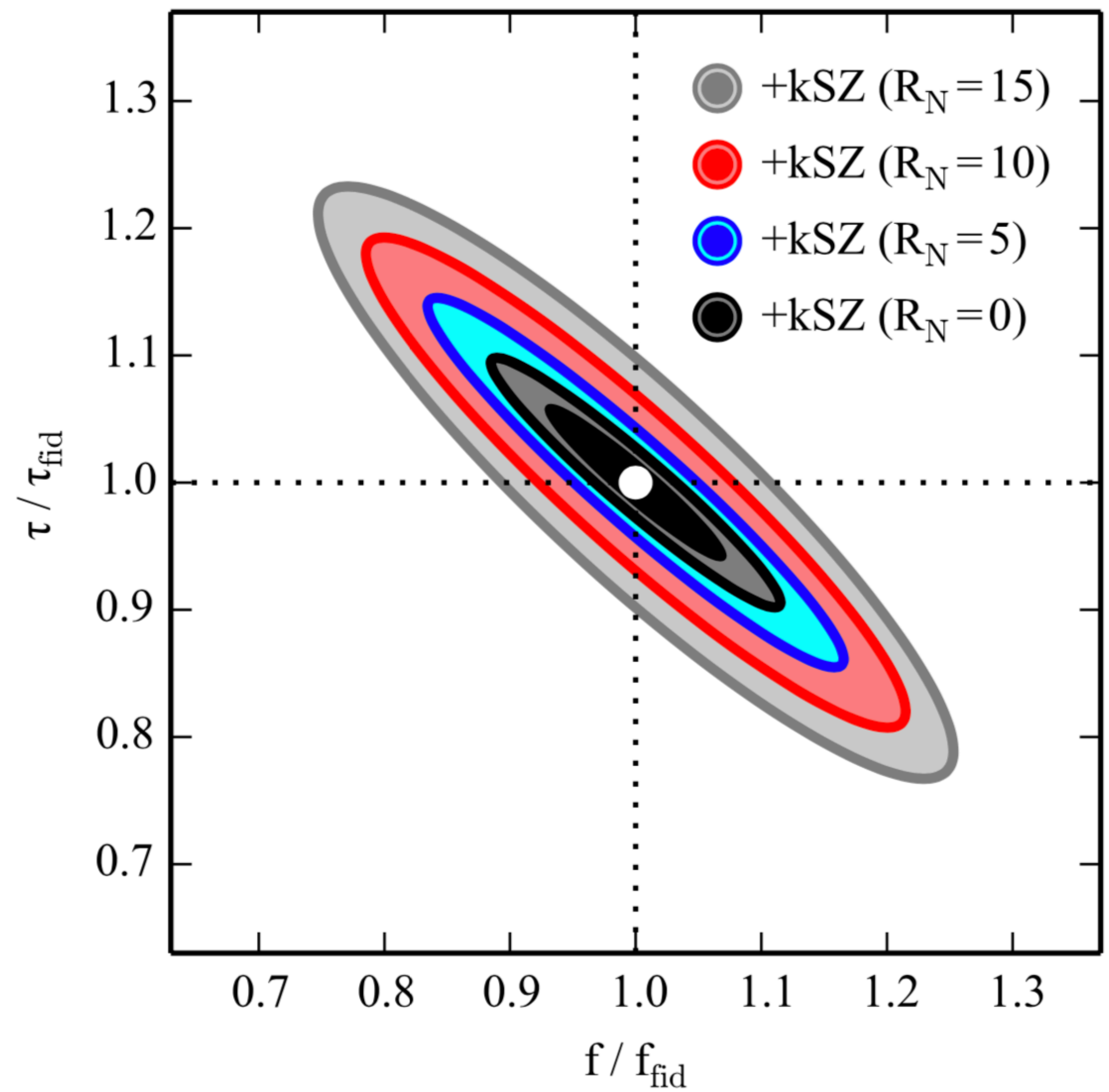
$\tau_T - f$ degeneracy

τ_T– amplitude degeneracy

$$P_{\rm kSZ}(\mathbf{k}) \simeq \left(\frac{T_0 \tau_{\rm T}}{c}\right) P_{\rm pv}(\mathbf{k}) \qquad \tau_{{\rm T},i} = \int dl \sigma_{\rm T} n_{e,i}$$

in linear theory:

$$P_{{\rm kSZ},\ell=1}(k) = 2iaH \left(\frac{T_0\tau_{\rm T}}{c}\right)\left(fb + \frac{3}{5}f^2\right)\frac{P_{\rm lin}(k)}{k}$$
$$P_{{\rm kSZ},\ell=3}(k) = 2iaH \left(\frac{T_0\tau_{\rm T}}{c}\right)\left(\frac{2}{5}f^2\right)\frac{P_{\rm lin}(k)}{k}.$$



→ **$\tau_T - f$ degeneracy**

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$\tau_T - f$ degeneracy breaking

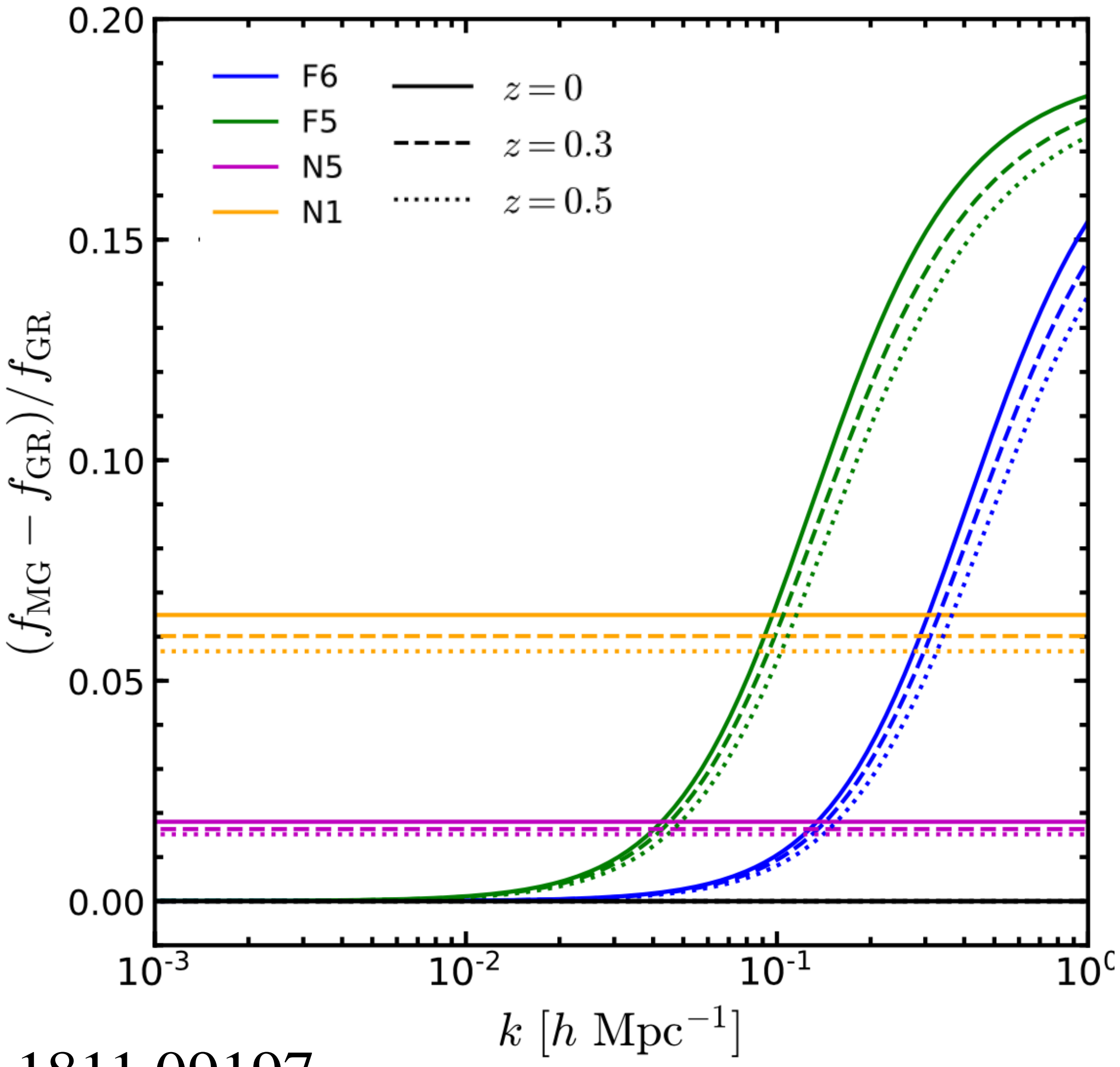
in linear theory:

1. Nonlinear evolution

2. Scale dependent f

$$P_{\mathrm{kSZ},\ell=1}(k) = 2iaH\left(\frac{T_0\tau_{\mathrm{T}}}{c}\right)\left(fb+\frac{3}{5}f^2\right)\frac{P_{\mathrm{lin}}(k)}{k}$$

$$P_{\mathrm{kSZ},\ell=3}(k) = 2iaH\left(\frac{T_0\tau_{\mathrm{T}}}{c}\right)\left(\frac{2}{5}f^2\right)\frac{P_{\mathrm{lin}}(k)}{k}.$$



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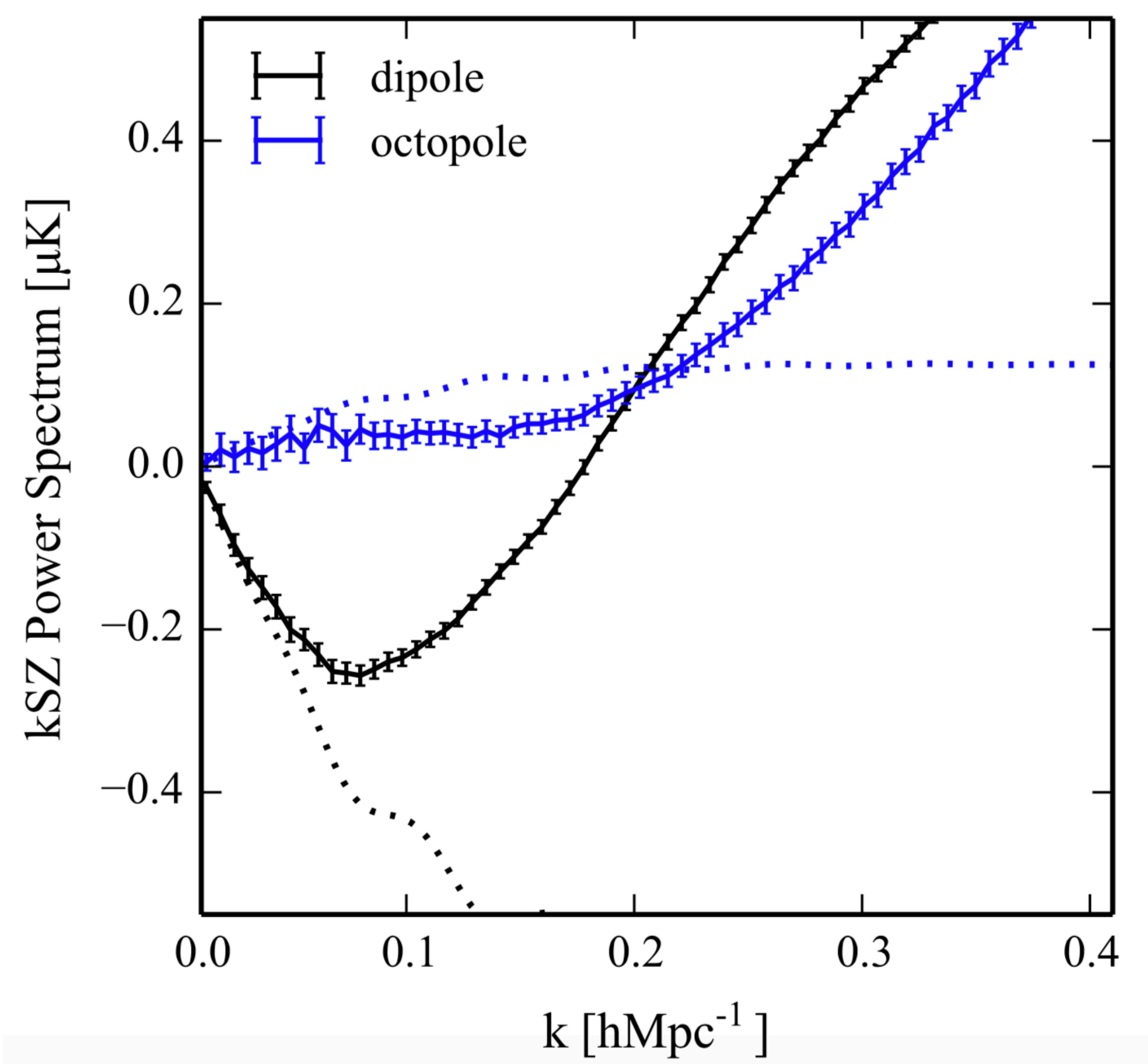

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A little explanations for the MG galaxy catalogs:

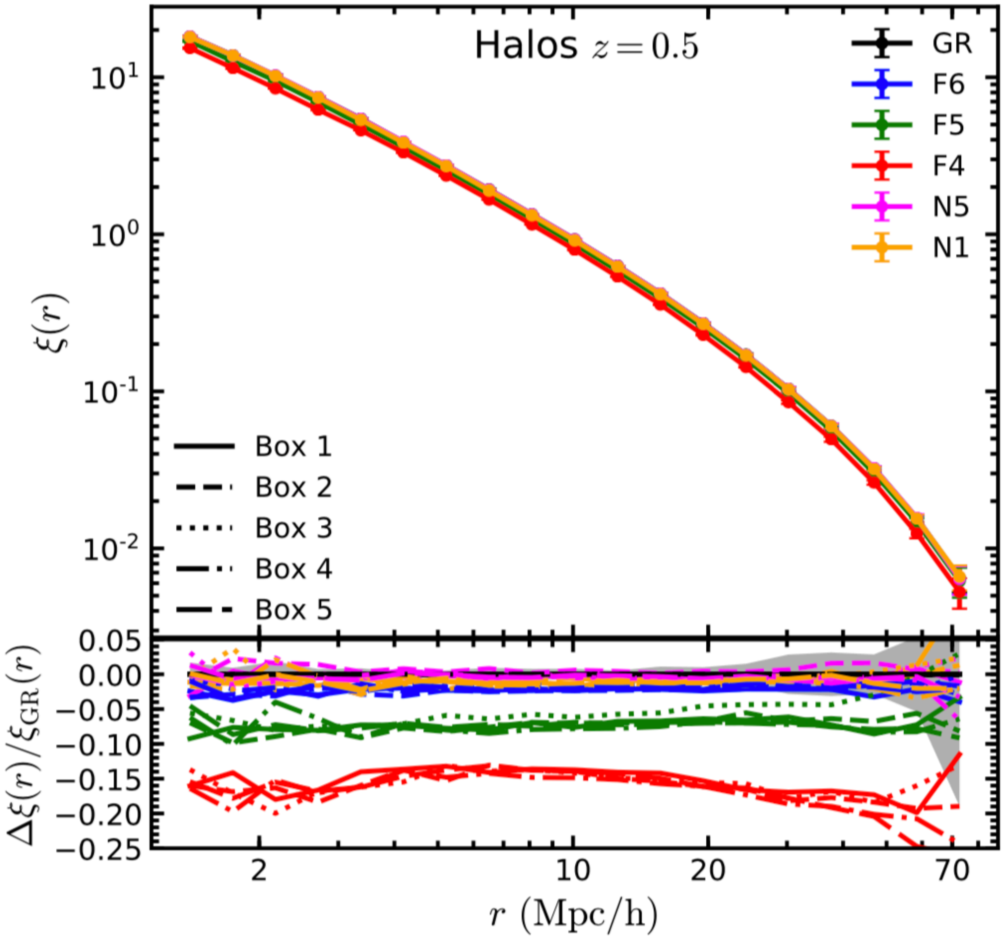
From Baojiu Li

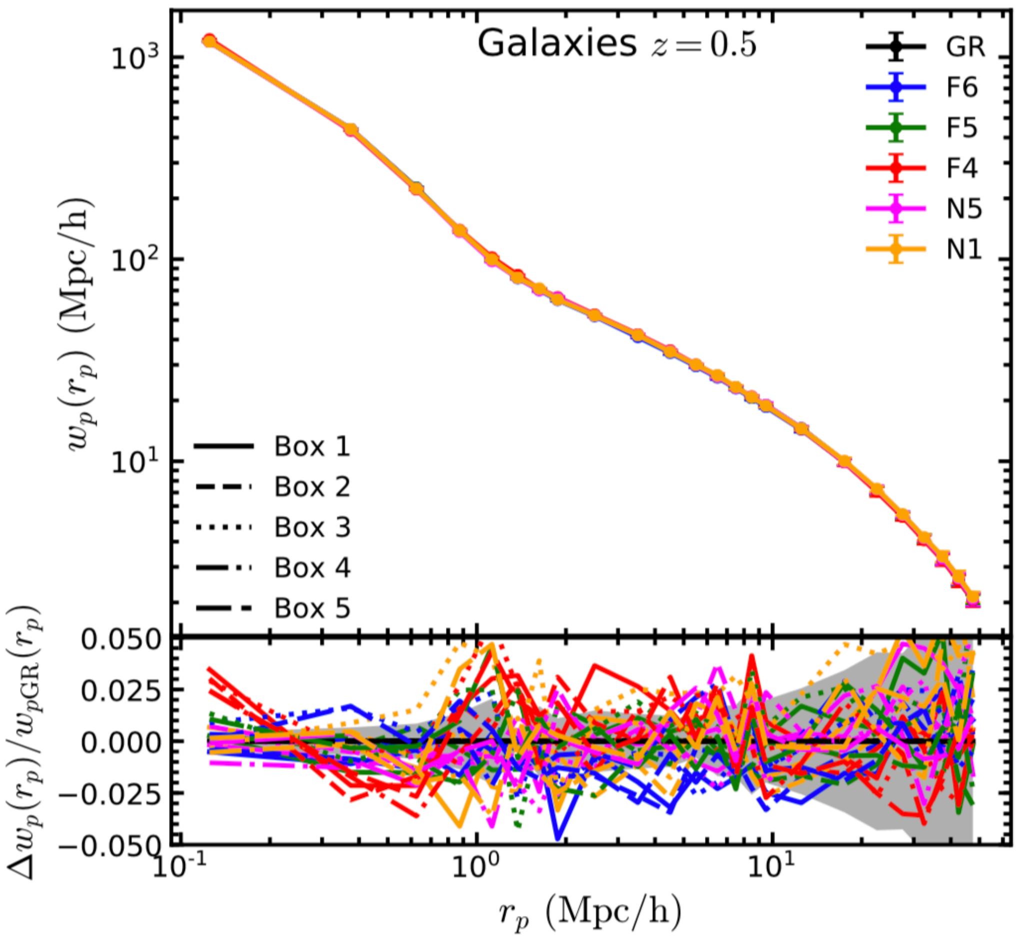
f(R) and normal branch DGP: F4>F5>F6; N1>N5

$\lvert f_{R0} \rvert$	Hu & Sawicki $f(R)$ parameter	0 (GR) 10^{-6} (F6), 10^{-5} (F5), 10^{-4} (F4)
$H_0 r_c$	nDGP parameter	5.0 (N5), 1.0 (N1)

$L_{\rm box}$	simulation box size	1024 h^{-1}Mpc
$N_{\rm p}$	simulation particle number	1024^3

z = 0.5





z = 0.8

$M_{\rm halo} > 10^{13} {\rm M}_\odot/h$

Pairwise kSZ power spectrum

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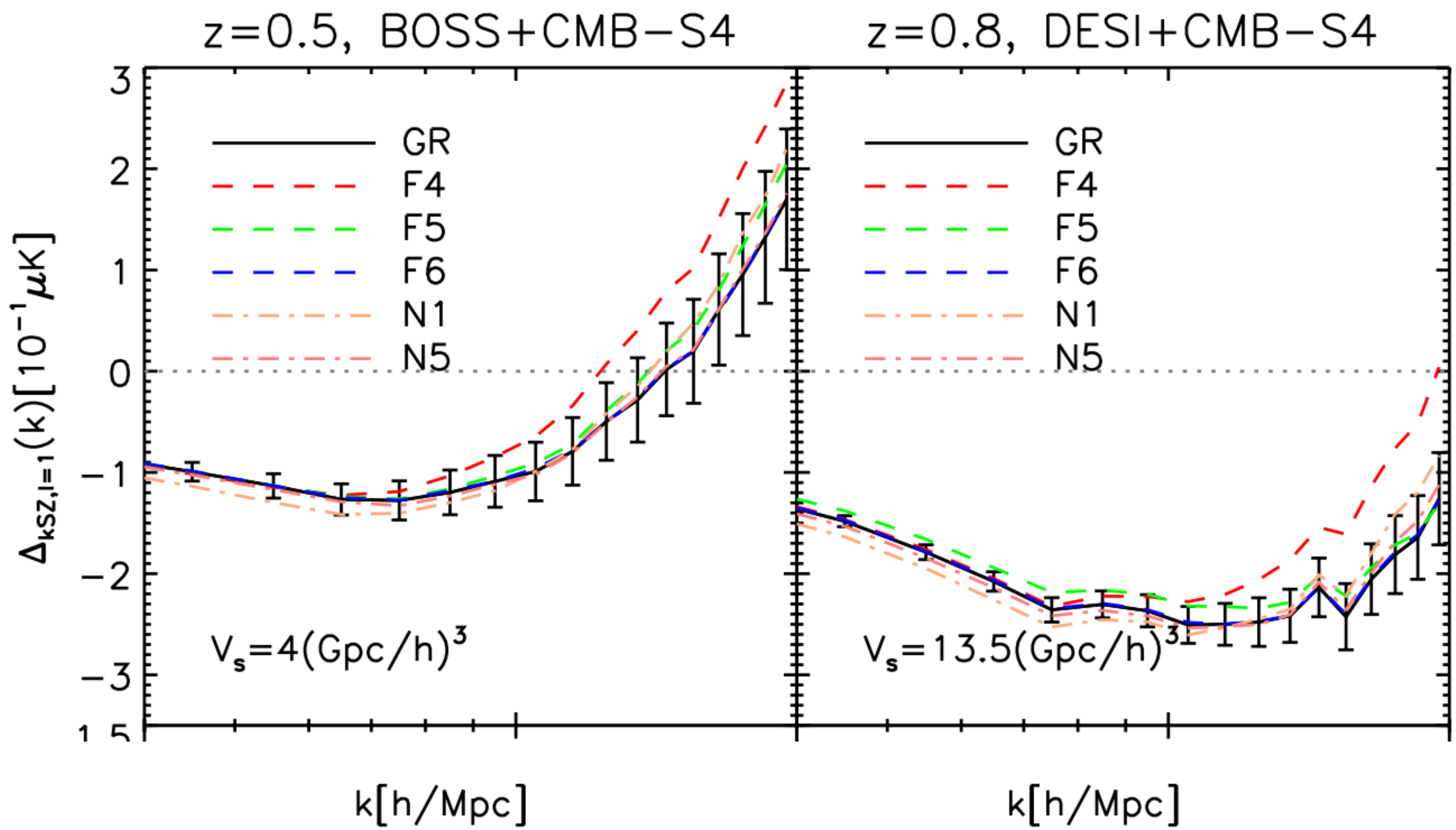


Three ingredients to be calculated:

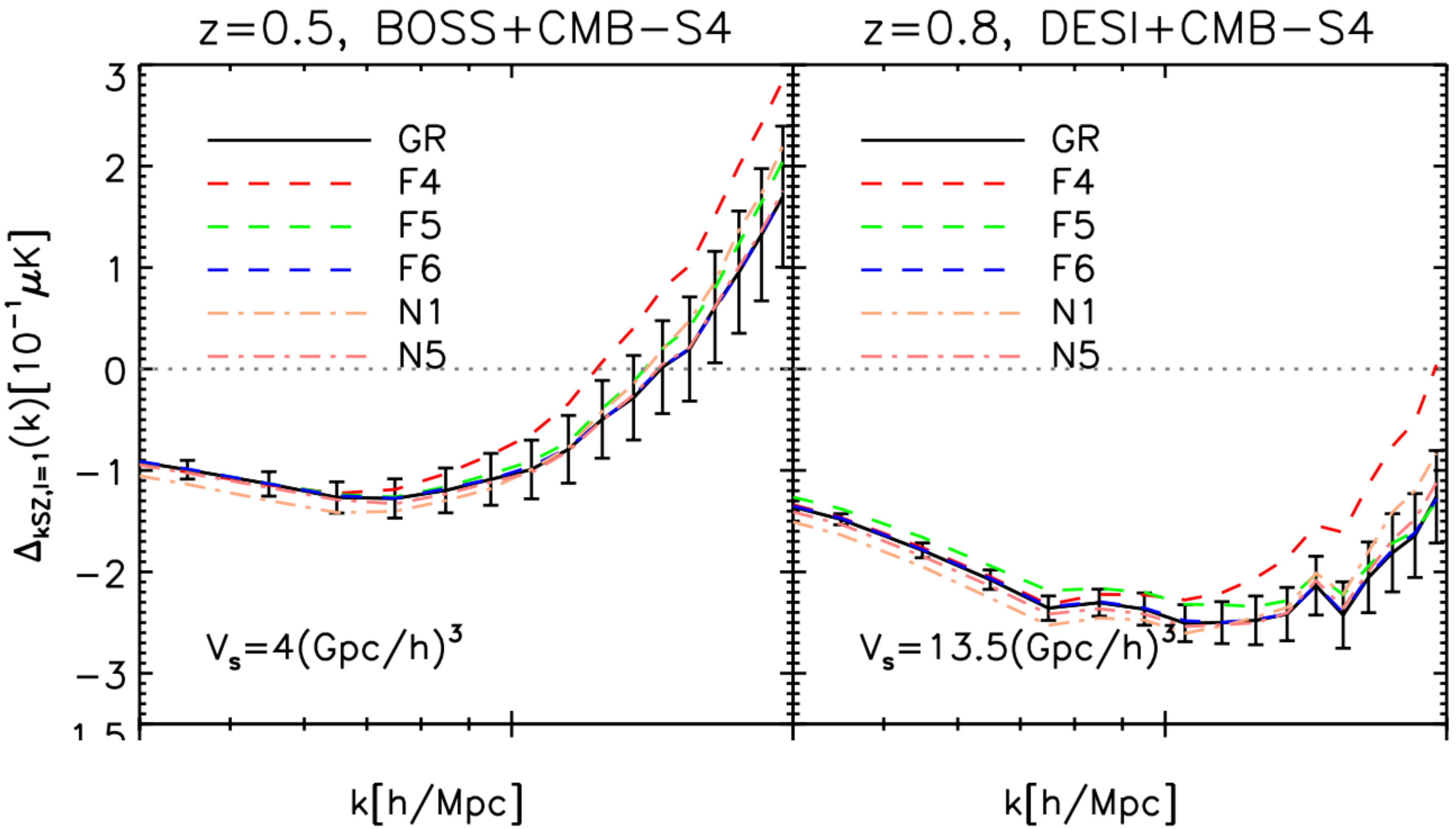
1. **Galaxy pairwise velocity power spectrum**
2. τ_T **of redshift** z
3. **Error estimation**

1. Galaxy pairwise velocity power spectrum

$$\boxed{(2\pi)^3\delta_{\rm D}(\mathbf{k}+\mathbf{k}')P_{\rm pv}(\mathbf{k}) = \langle p_{\rm s}(\mathbf{k})\delta_{\rm s}(\mathbf{k}') - \delta_{\rm s}(\mathbf{k})p_{\rm s}(\mathbf{k}')\rangle}$$

$$P_{\rm kSZ}(\mathbf{k}) \simeq \left(\frac{T_0\tau_{\rm T}}{c}\right)P_{\rm pv}(\mathbf{k})$$

$$\Delta_{{\rm kSZ},\ell}(k) = i^\ell \frac{k^3}{2\pi^2}P_{{\rm kSZ},\ell}(k),$$



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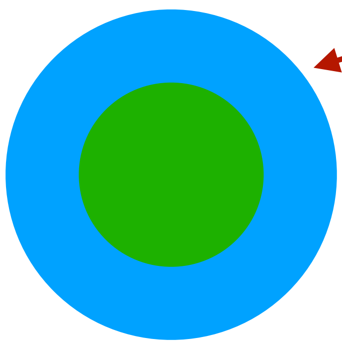
2. τ_T calculation

FT of AP filter

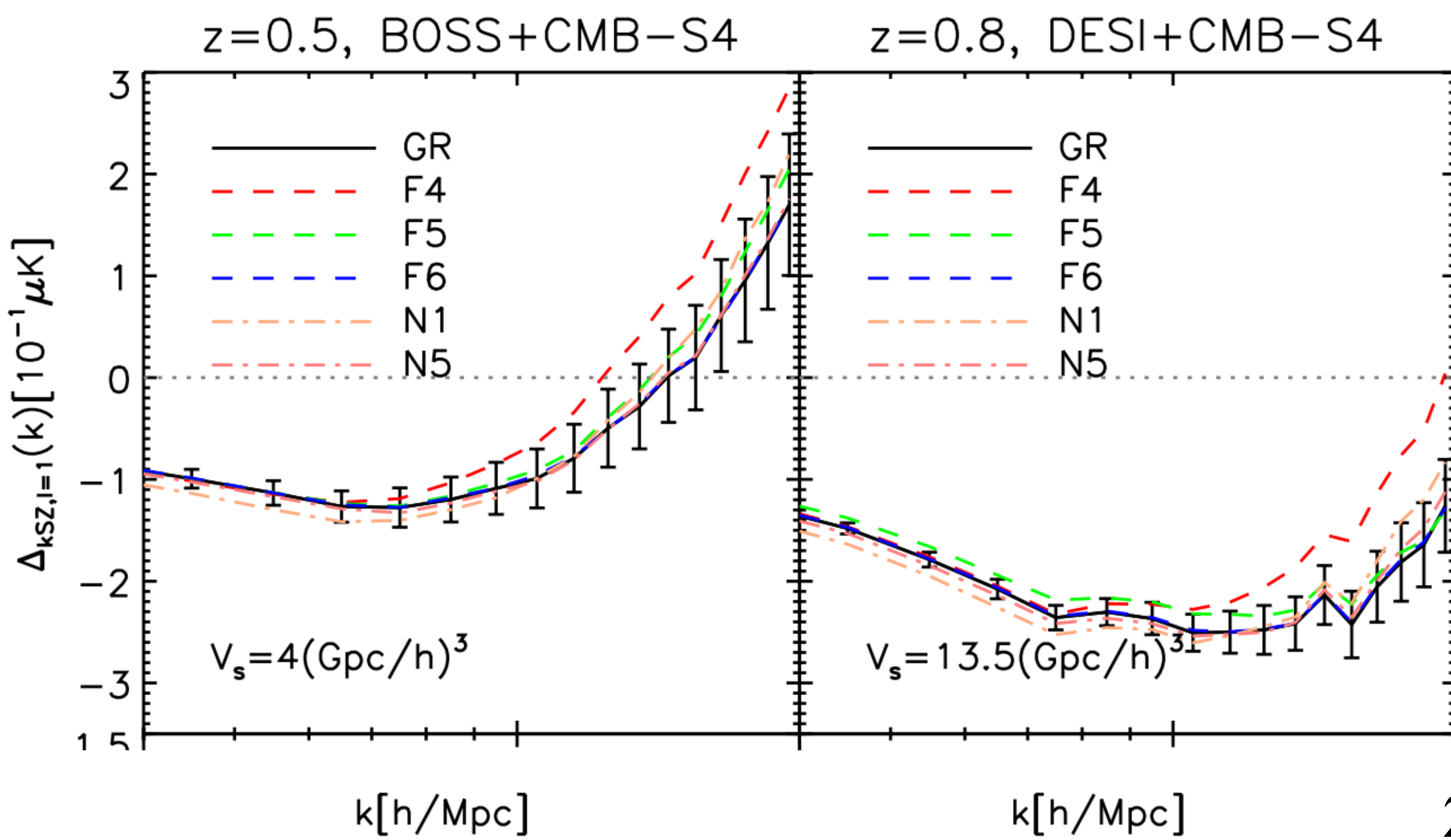
Gaussian gas density profile



$$\tau_T = \frac{\sigma_T f_{\rm gas} M_{\rm avg}}{\mu_{\rm e} m_{\rm p} D_{\rm A}^2(z_{\rm eff})} \int \frac{{\rm d}^2\ell}{(2\pi)^2} U(\ell\theta_{\rm c}) N(\ell) B(\ell)$$

Beam function

$\boxed{\tau_T = 4.5 \times 10^{-5}}$ $\boxed{6.0 \times 10^{-5}}$



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3. Error estimation

$$\mathrm{Cov}(P_{\mathrm{kSZ},\ell_1}(k), P_{\mathrm{kSZ},\ell_2}(k)) = \frac{1}{N_{\mathrm{mode}}(k)} \frac{2(2l_1+1)(2l_2+1)}{4\pi} \int d\varphi \int d\mu \mathcal{L}_{\ell_1}(\mu)\mathcal{L}_{\ell_2}(\mu)$$

Shot noise

$$\times \left(\frac{T_0 \tau_T}{c}\right)^2 \left[2\left(P_{\mathrm{s}}^{(1)(0)}(\mathbf{k})\right)^2 - 2\left(P_{\mathrm{s}}^{(1)(1)}(\mathbf{k}) + (1+R_{\mathrm{N}}^2)\frac{\sigma_{\mathrm{v}}^{(2)}}{\bar{n}}\right)\left(P_{\mathrm{s}}(\mathbf{k}) + \frac{1}{\bar{n}}\right)\right]. \quad \text{(A2)}$$

$$R_{\mathrm{N}}^2(\theta_{\mathrm{c}}) = \frac{\sigma_{\mathrm{N}}^2(\theta_{\mathrm{c}})}{\sigma_{\mathrm{kSZ}}^2(\theta_{\mathrm{c}})},$$

$$\sigma_{\mathrm{N}}^2(\sigma_{\mathrm{v}}) = \sum_{\ell}^{\ell_{\max}} \frac{2\ell+1}{4\pi} \langle C_\ell^{\mathrm{obs}} \rangle U(\ell\theta_{\mathrm{c}}) U(\ell\theta_{\mathrm{c}}).$$

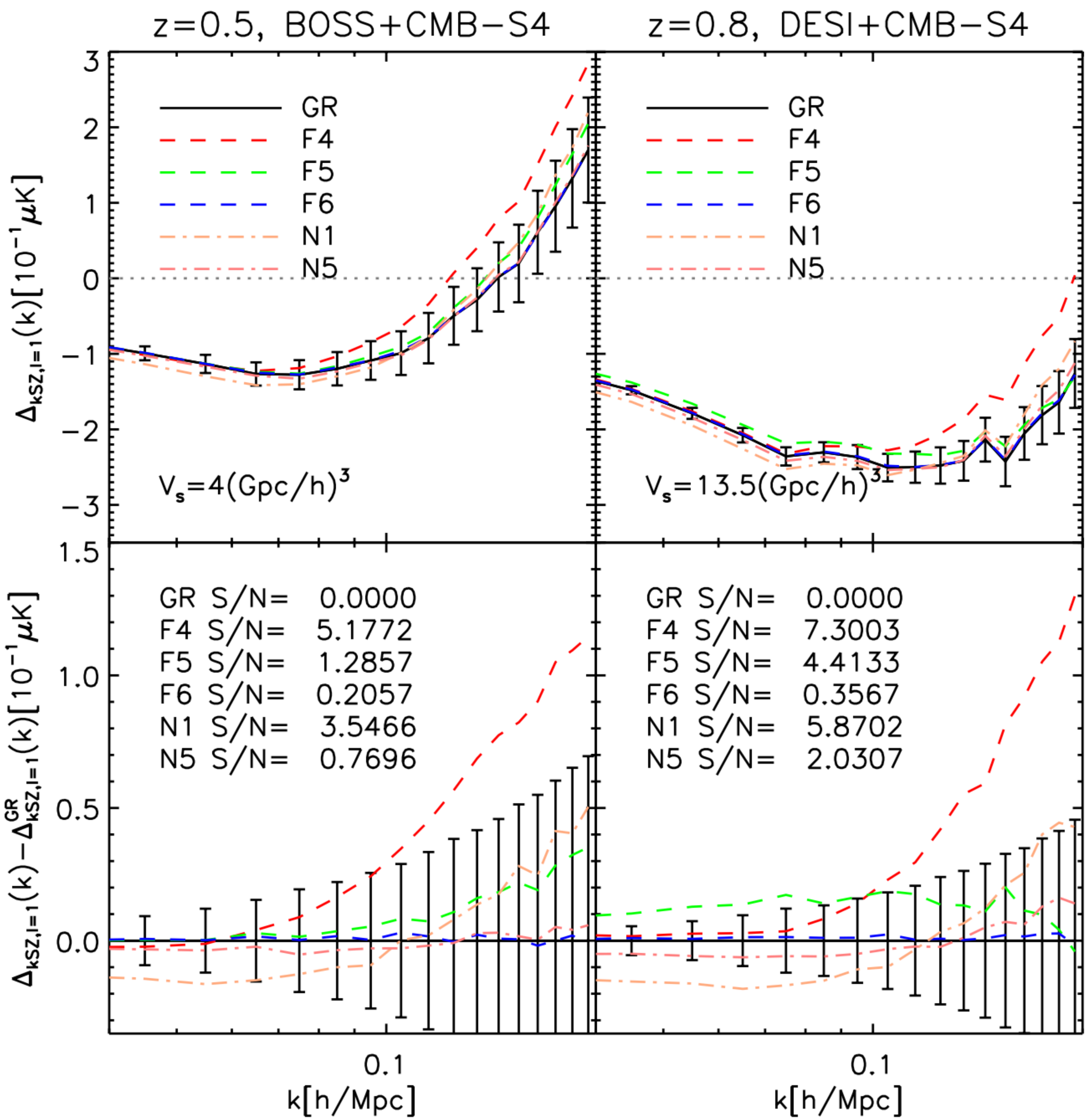
$$\sigma_{\mathrm{kSZ}}(\theta_{\mathrm{c}}) = \left(\frac{T_0 \tau(\theta_{\mathrm{c}})}{c}\right)\sigma_{\mathrm{v}}, \quad \sigma_{\mathrm{v}} = \sqrt{\sigma_{\mathrm{v}}^{(2)}},$$

$$\boxed{C_\ell^{\mathrm{obs}} = B_\ell^2 C_\ell^{\mathrm{the}} + N_\ell,}$$

Detector noise

FWHM [arcmin]	noise [μK-arcmin]	galaxy	redshift	V [$(h^{-1}\,\mathrm{Gpc})^3$]	$\bar{n}_{\mathrm{g}}$ [$(h^{-1}\,\mathrm{Mpc})^{-3}$]	M_{avg} [$h^{-1} M_\odot$]
CMB-S4 + BOSS						
1	2	LRG	0.5 $(0.43 < z < 0.70)$	4.0	3.2×10^{-4}	2.6×10^{13}
CMB-S4 + DESI						
1	2	LRG	0.8 $(0.65 < z < 0.95)$	13.5	2×10^{-4}	2.6×10^{13}

3. Error estimation



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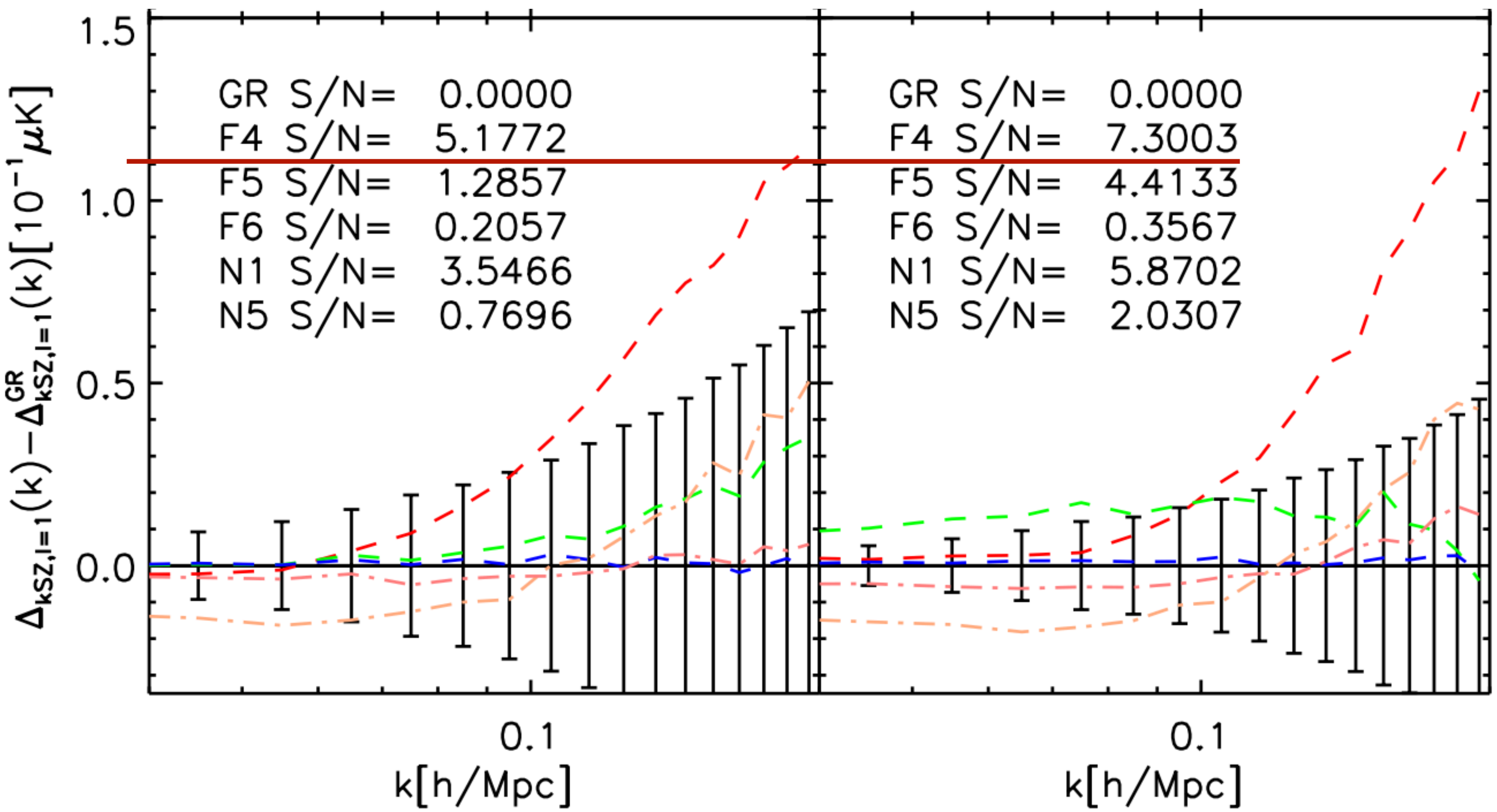
3. Error estimation

$$\frac{\mathrm{S}}{\mathrm{N}} = \sqrt{\chi^2} = \sqrt{\frac{\sum_i \left[\Delta_{\mathrm{kSZ},\ell=1}(k_i) - \Delta^{\mathrm{GR}}_{\mathrm{kSZ},\ell=1}(k_i)\right]^2}{\sigma^2_\Delta(k_i)}}.$$



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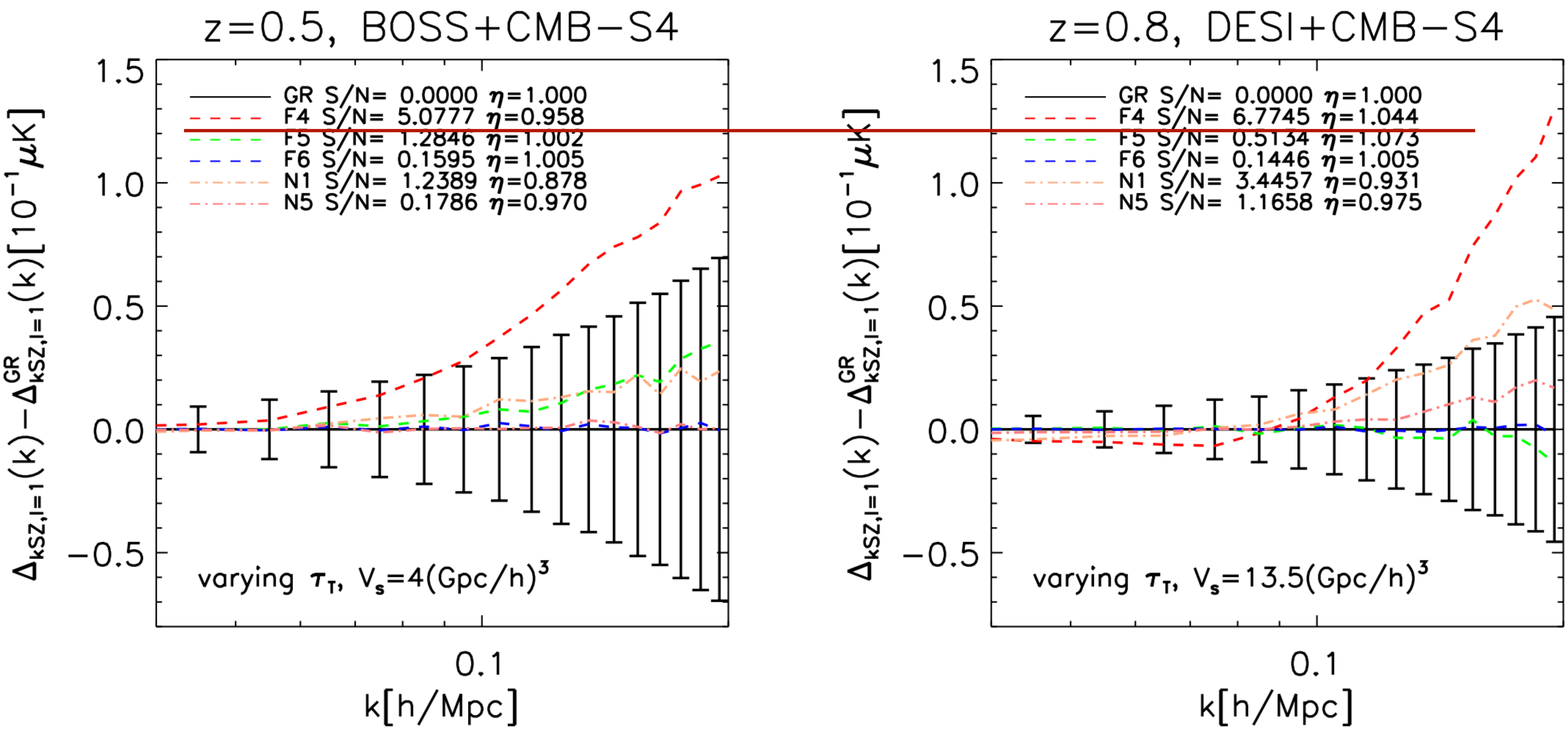
Varying τ_T

—— information only from the shape

$$\tau_T \to \eta\tau_T \quad \text{vary } \eta \text{ between } [0.5, 1.5]$$



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Discussions

- 1. Gas density profile more compact than Gaussian distribution
- 2. Matched filtering technique (Alonso et al. 2016)
- 3. Better pairwise kSZ PS model
- 4. Degeneracy of HOD/bias parameters.
- 5. τ_T not a constant
- 6. ……

1. Galaxy pairwise velocity power spectrum

Non-linear theory:

$$P_{\rm pv}(\mathbf{k}) = \left(i\frac{aHf}{\mathbf{k}\cdot\hat{n}}\right)\frac{\partial}{\partial f}P_{\rm s}(\mathbf{k})$$

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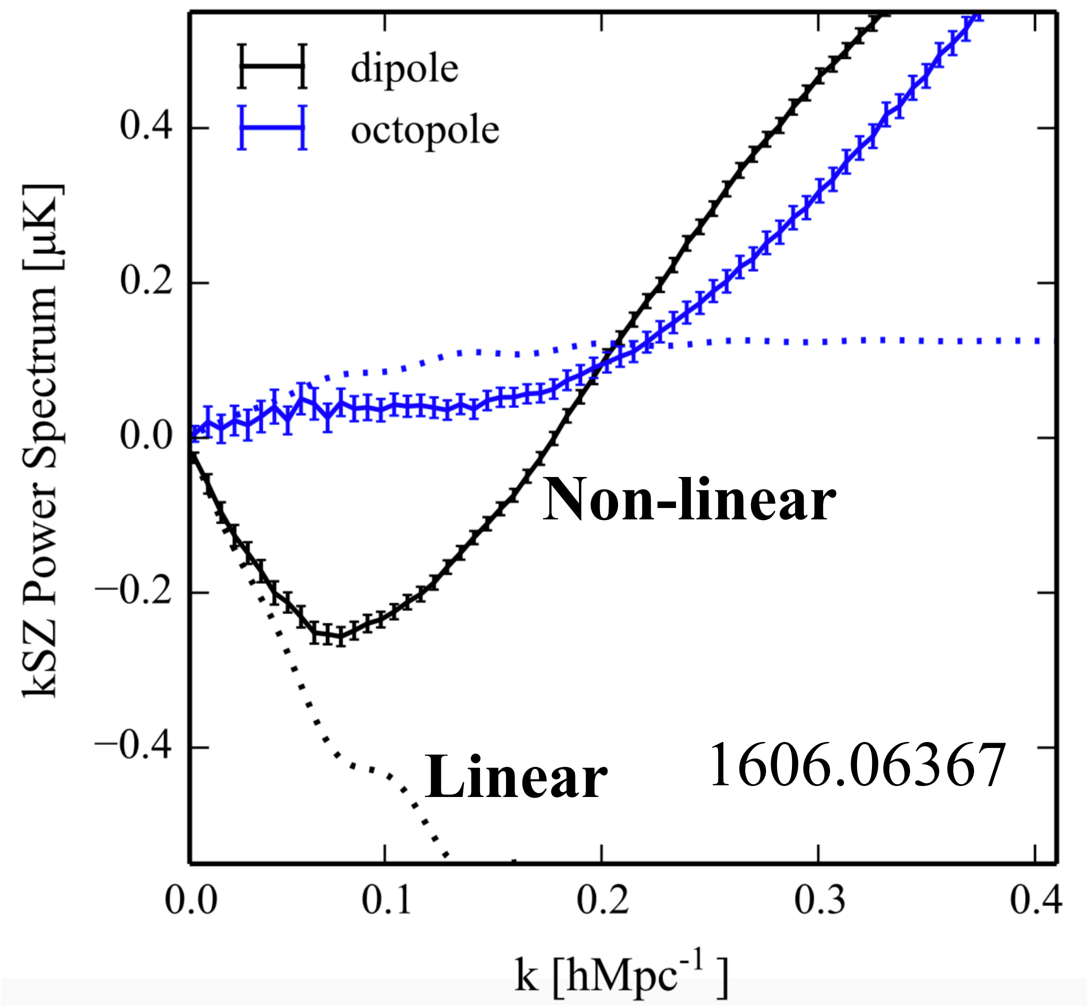
$$P_{\rm s}(k,\mu) = \underbrace{\left(b+f\mu^2\right)^2 P_{\rm lin}(k)}_{\text{Kaiser effect}}\,\underbrace{\exp(-k^2\mu^2\sigma_v^2/H^2)}_{\text{FoG effect}}\,.$$



$$\underbrace{\Delta_{\rm kSZ}(k,\mu) = \frac{k^3}{2\pi^2}\left(\frac{T_0\tau_{\rm T}}{c}\right)2iaHf\mu(b+f\mu^2)\frac{P_{\rm lin}(k)}{k}}_{\text{Linear theory}}$$

$$\times S(k,\mu)\exp(-k^2\mu^2\sigma_v^2/H^2)\,, \qquad (7)$$

$$\underbrace{S(k,\mu) = 1-(b/f+\mu^2)k^2\sigma_v^2/H^2\,.}_{\text{Shape kernel}} \qquad (8)$$

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