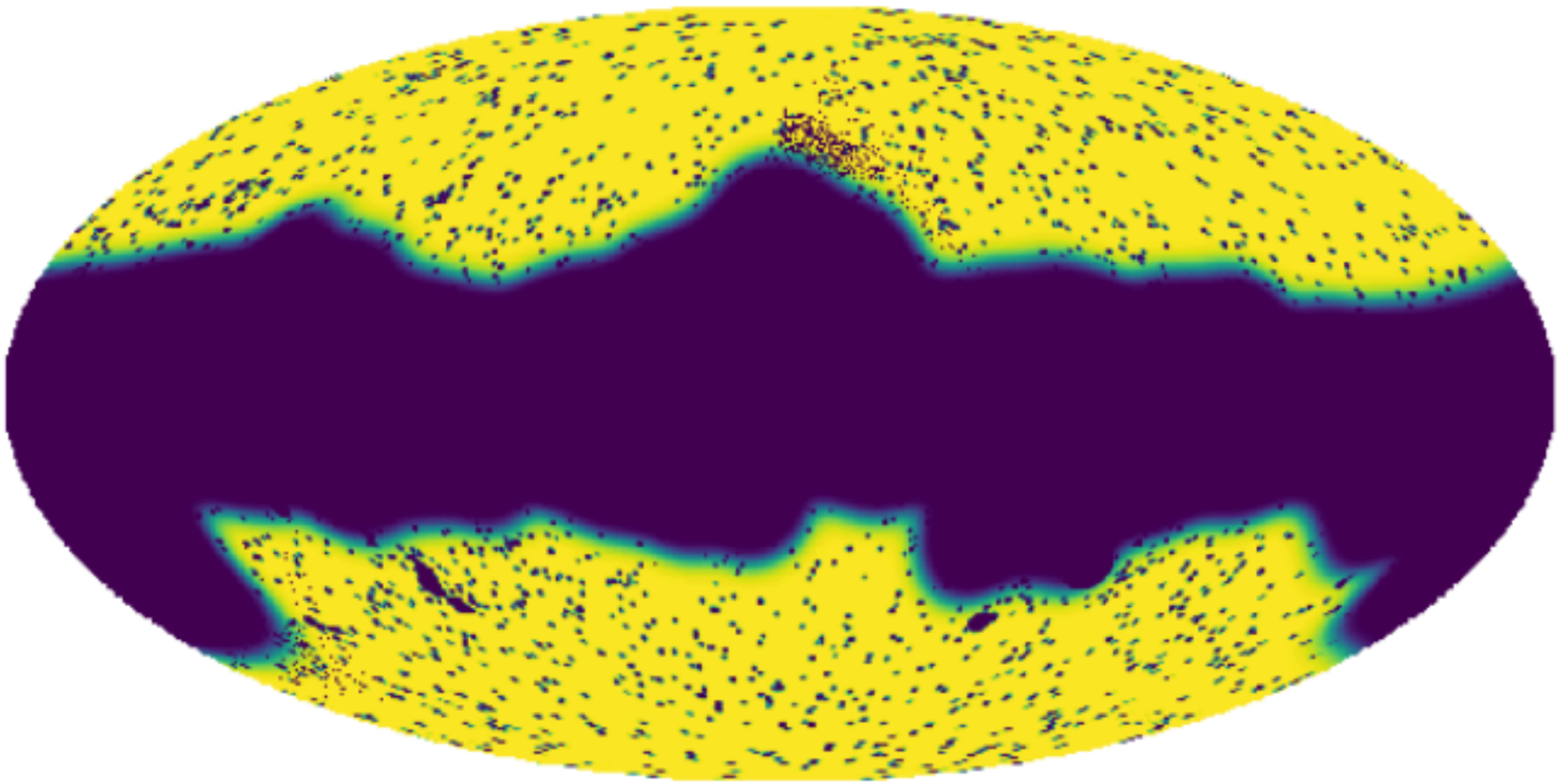
Are there any holes in the CMB likelihoods?



Cosmology from home 2020

Julien Carron , with G. Fabbian, A. Lewis, M. Lembo (in prep.)

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FNSNF
Fonds national suisse
Schweizerischer Nationalfonds
Fondo nazionale svizzero
Swiss National Science Foundation

Université de Genève

University of Sussex

erc
European Research Council

Context:

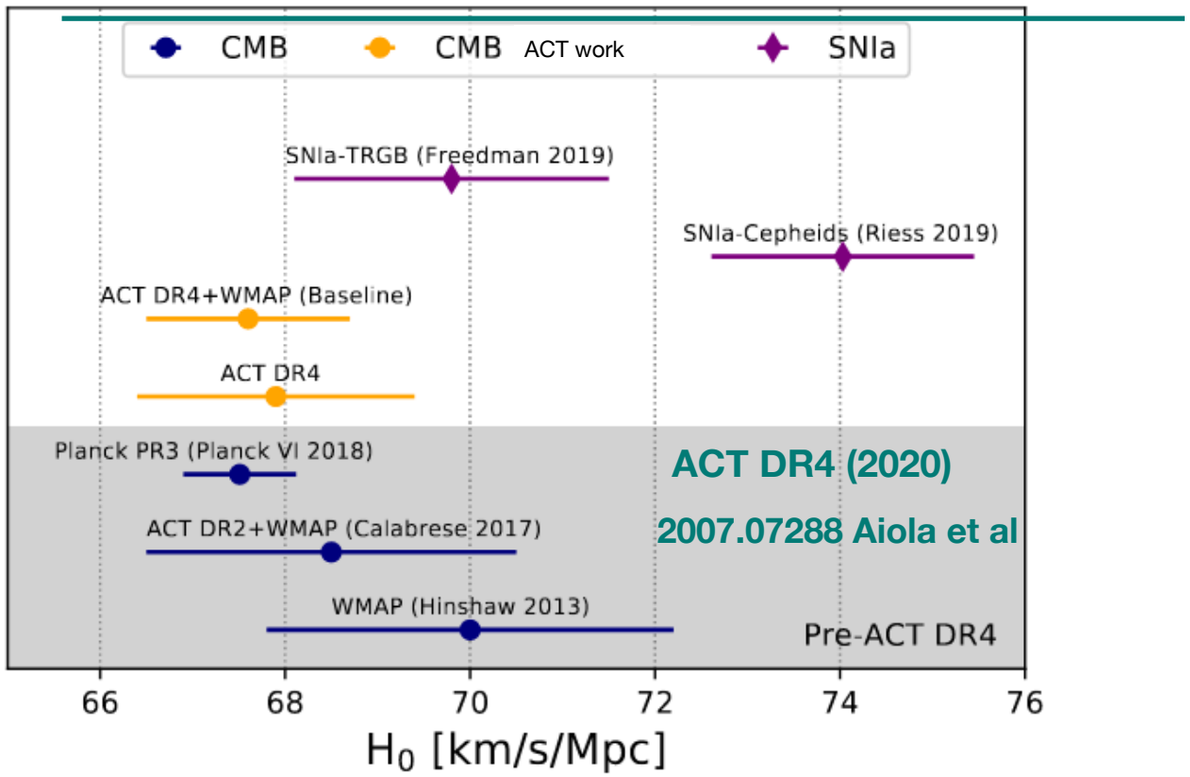
Lensing of the CMB

- Few degree coherent ~ 2 arcmin deflection of CMB photons on their path from last scattering surface to us by the large scale structures.
- Impacts in a very relevant manner the CMB spectra (peak smoothing, etc)
- Inference from CMB data routinely takes this into account

This work:

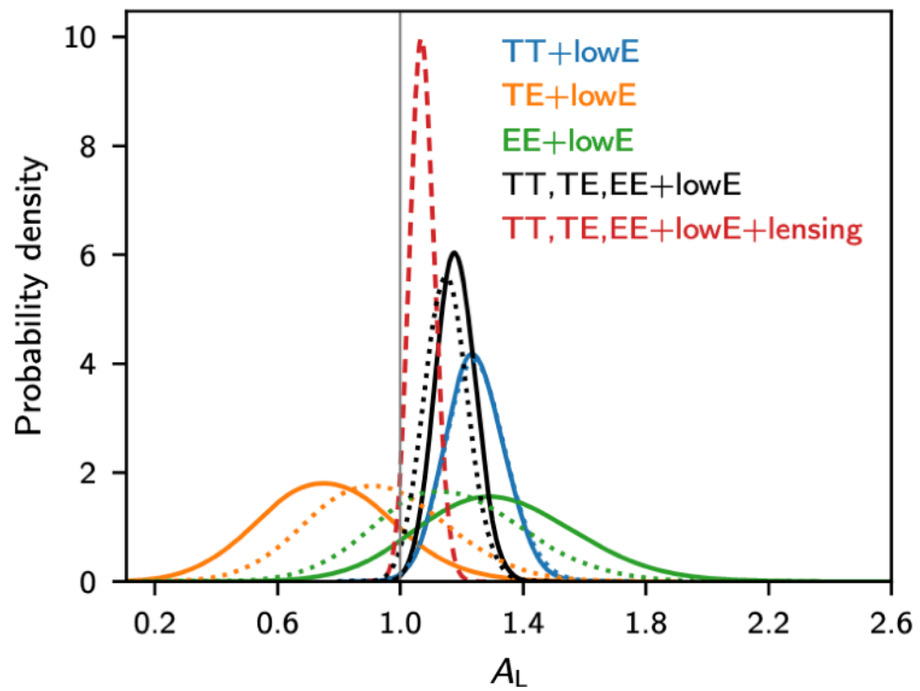
- Extragalactic sources in CMB data are correlated to large-scale structures (point sources (radio, IR…), clusters…) which lens the CMB
- Some sources will be masked prior analysis → **analysis mask can correlate to lensing**
- If (convergence) mass peaks are masked preferentially, we may be looking at a CMB which is different from the full-sky average. **Bias on CMB spectra?**

Motivations

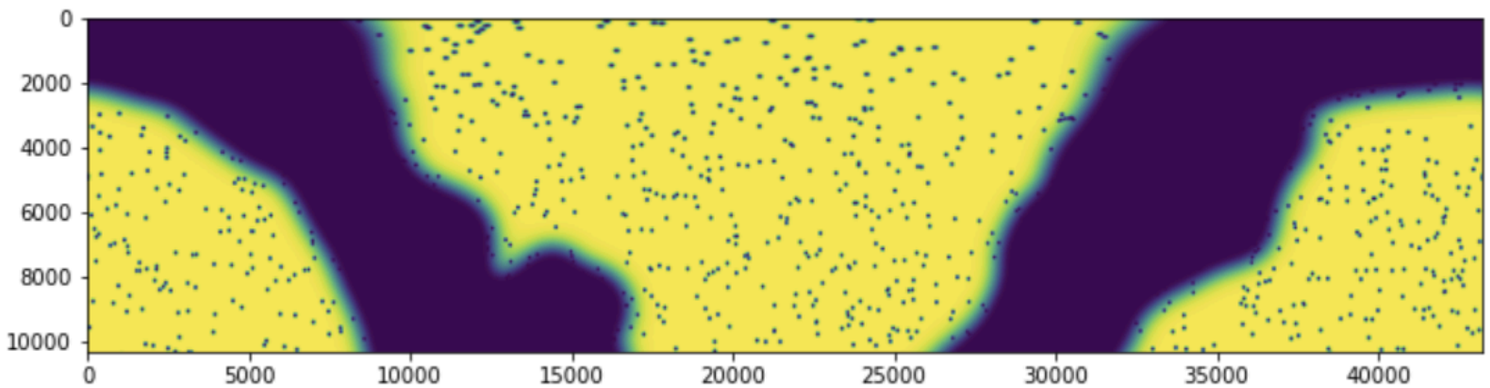


ACT DR4 (2020)

2007.07288 Aiola et al

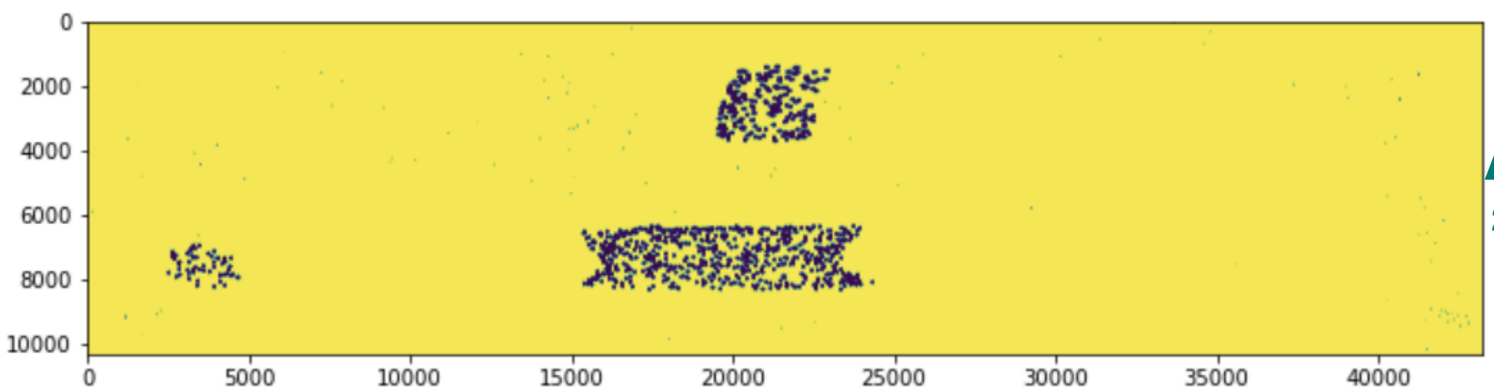


Planck collaboration 1807.06209



Planck 2018 mask

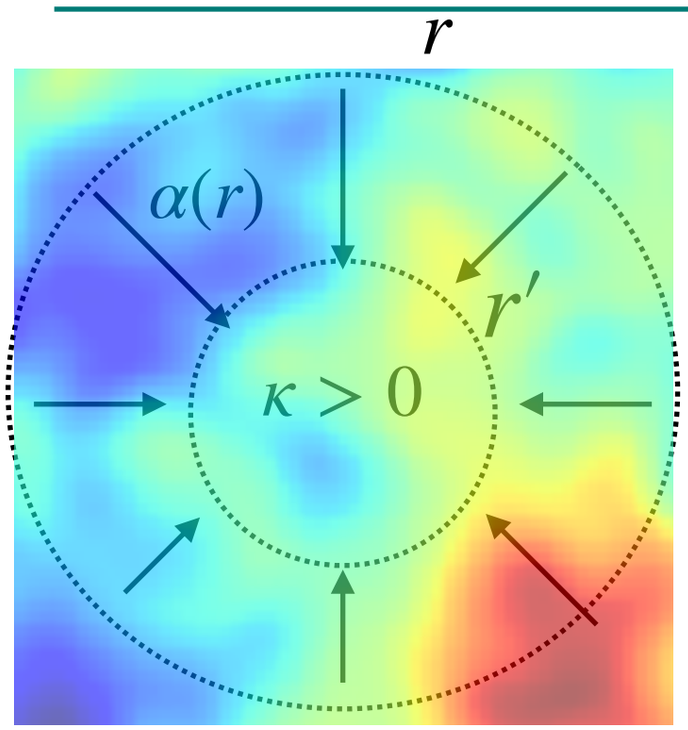
Planck collaboration 1807.06209



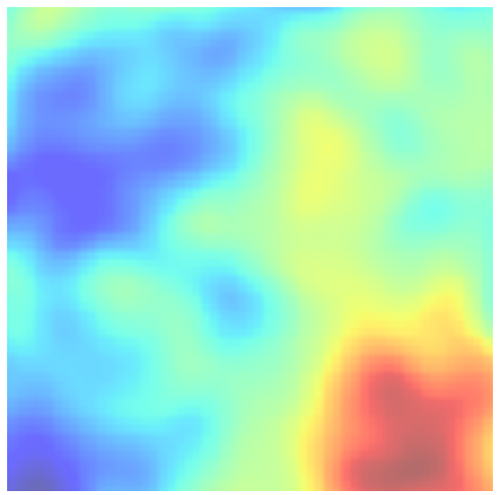
ACT DR4 point sources

2007.07288 Aiola et al

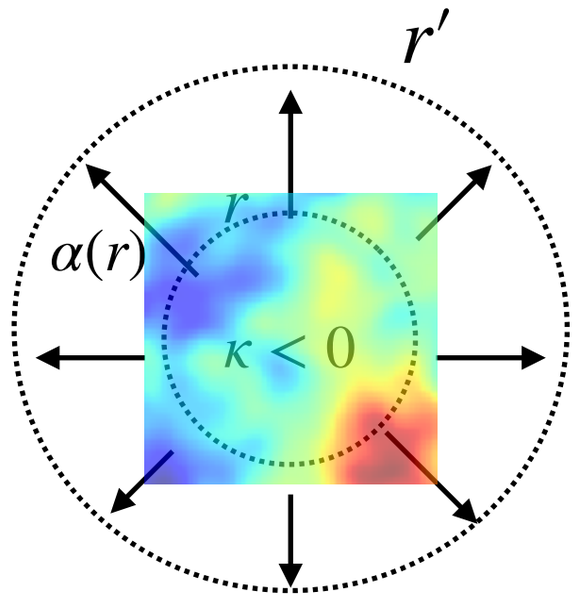
CMB demagnification from masking real space



$$T^{\rm obs}(r) = T^{\rm unl}(r' = r + \alpha(r))$$



unlensed patch



on κ peak,
$\xi^{TT,\rm obs}(r) = \xi^{TT}(r' < r)$
magnified CMB

on κ trough,
$\xi^{TT,\rm obs}(r) = \xi^{TT}(r' > r)$
demagnified CMB

Preferentially masked → observed reduction in correlation function on (almost) all scales

CMB demagnification from masking harmonic space

Effect of large fixed lens on CMB *(squeezed limit)*: 1608.01263 Lewis & Pratten

$$\ell^2 C_\ell^{TT,\mathrm{len}}\Big|_{\text{fixed }\kappa} = \ell^2 C_\ell^{TT} + \kappa \frac{d\ell^2 C_\ell^{TT}}{d\ln\ell} + \frac{1}{2}\kappa^2\left(\frac{d\ell^2 C_\ell^{TT}}{d\ln\ell} + \frac{d^2\ell^2 C_\ell^{TT}}{d\ln\ell^2}\right) + \dots$$

Local scale shifts (used for map-level lensing reconstruction), vanishes averaged over the full sky

Usual peak smoothing

but $\langle\kappa\rangle \neq 0$ and negative over unmasked area if mask traces κ peaks

- Bias on CMB spectra
- Linear in lensing
- More small scale power
- Less large scale power
- Oscillations

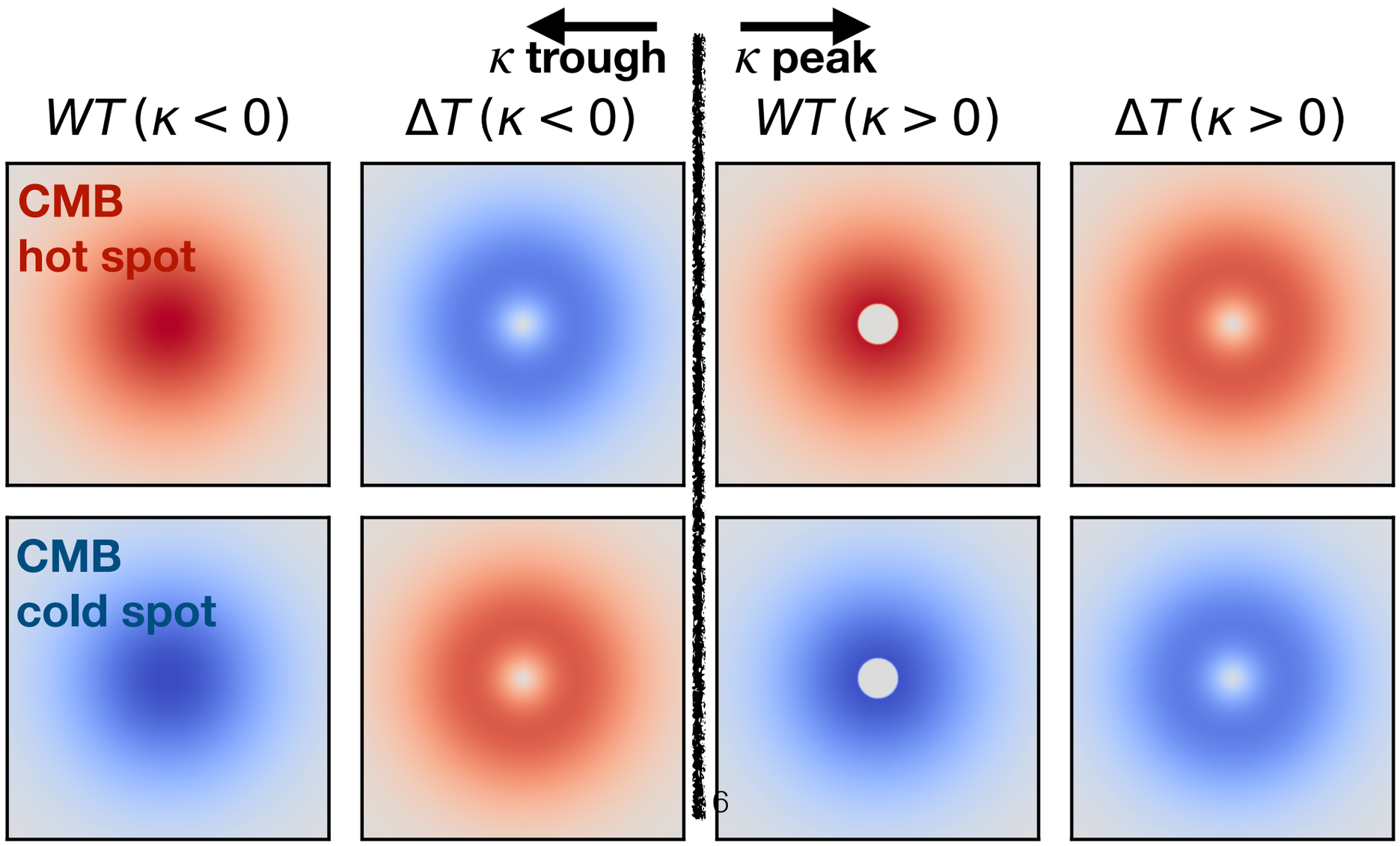
Derivation

- Say mask $W(x)$ is function of local value of ‘foreground’ field $f(x)$, correlated to κ
- Calculation perturbative in $C_\ell^{f\,\kappa}$ accurate for all spectra

Correction linear in lensing:

lensing signal ΔT

$$2 < (WT)(x) \cdot (W\,\alpha_i \nabla^i T)(y) > = 2 < (WT)(W\Delta T) > (x-y)$$



Derivation

- Say mask $W(x)$ is function of local value of ‘foreground’ field $f(x)$, correlated to κ
- Calculation perturbative in $C_\ell^{f\kappa}$ accurate for all spectra

Correction linear in lensing:

$$\left\langle (WT)(x) \cdot (W\,\alpha_i \nabla^i T)(y) \right\rangle = \langle (WT)(W\Delta T)\rangle (x-y)$$

$$\Delta\tilde{\xi} \approx \partial_r \tilde{\xi}(r)\bar{\Delta}(r) \qquad \bar{\Delta}(r) \equiv \frac{\langle [\alpha_r(\boldsymbol{x}) - \alpha_r(\boldsymbol{x}')]W(\boldsymbol{x})W(\boldsymbol{x}')\rangle}{\langle W(\boldsymbol{x})W(\boldsymbol{x}')\rangle}$$

mean change of distance between r-separated points across unmasked area

($\bar{\Delta}(r)$ can be obtained in closed form for thresholds masks e.g.)

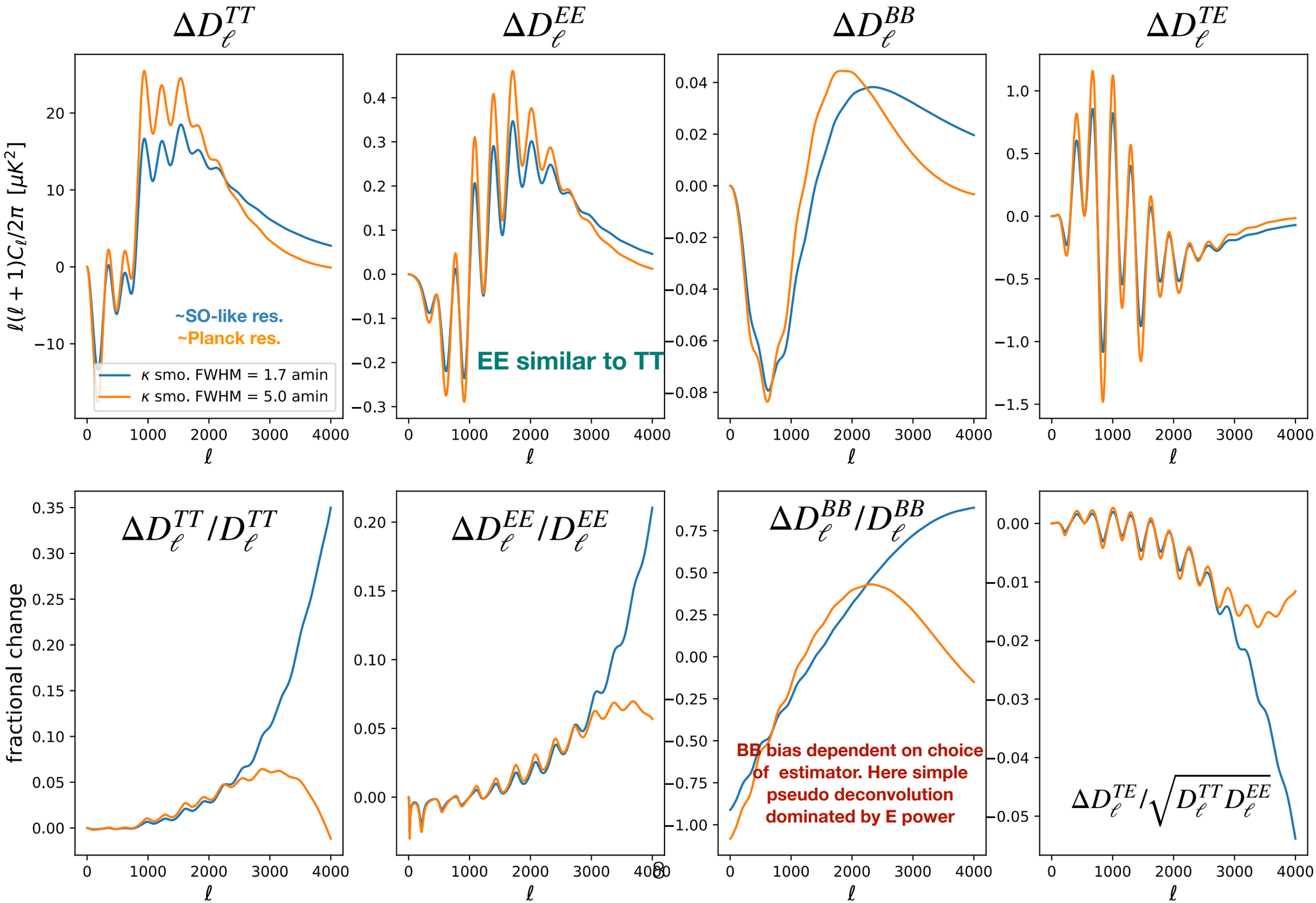
General result for masks related to Gaussian foreground: $$\Delta\tilde{\xi}(r) \approx -\frac{2\bar{f}(r)}{\sigma^2 + \xi_f(r)}\partial_r\tilde{\xi}(r)\xi^{f\alpha_r}(r)$$

Very smooth prefactor. Sets the amplitude

This sets the shape over most relevant scales. peaks at ~10 arcmin

Bias shape

For κ threshold mask, $f_{\rm masked} = 3\,\%$



Empirical determination

- **Exact results available only for very specific mask constructions**
- **But the bias can also estimated empirically from simulations:**

$$\Delta\tilde{\xi} \approx \partial_r \tilde{\xi}(r)\bar{\Delta}(r)$$

$$\bar{\Delta}(r) \equiv \frac{\langle[\alpha_r(\boldsymbol{x}) - \alpha_r(\boldsymbol{x}')]W(\boldsymbol{x})W(\boldsymbol{x}')\rangle}{\langle W(\boldsymbol{x})W(\boldsymbol{x}')\rangle}$$

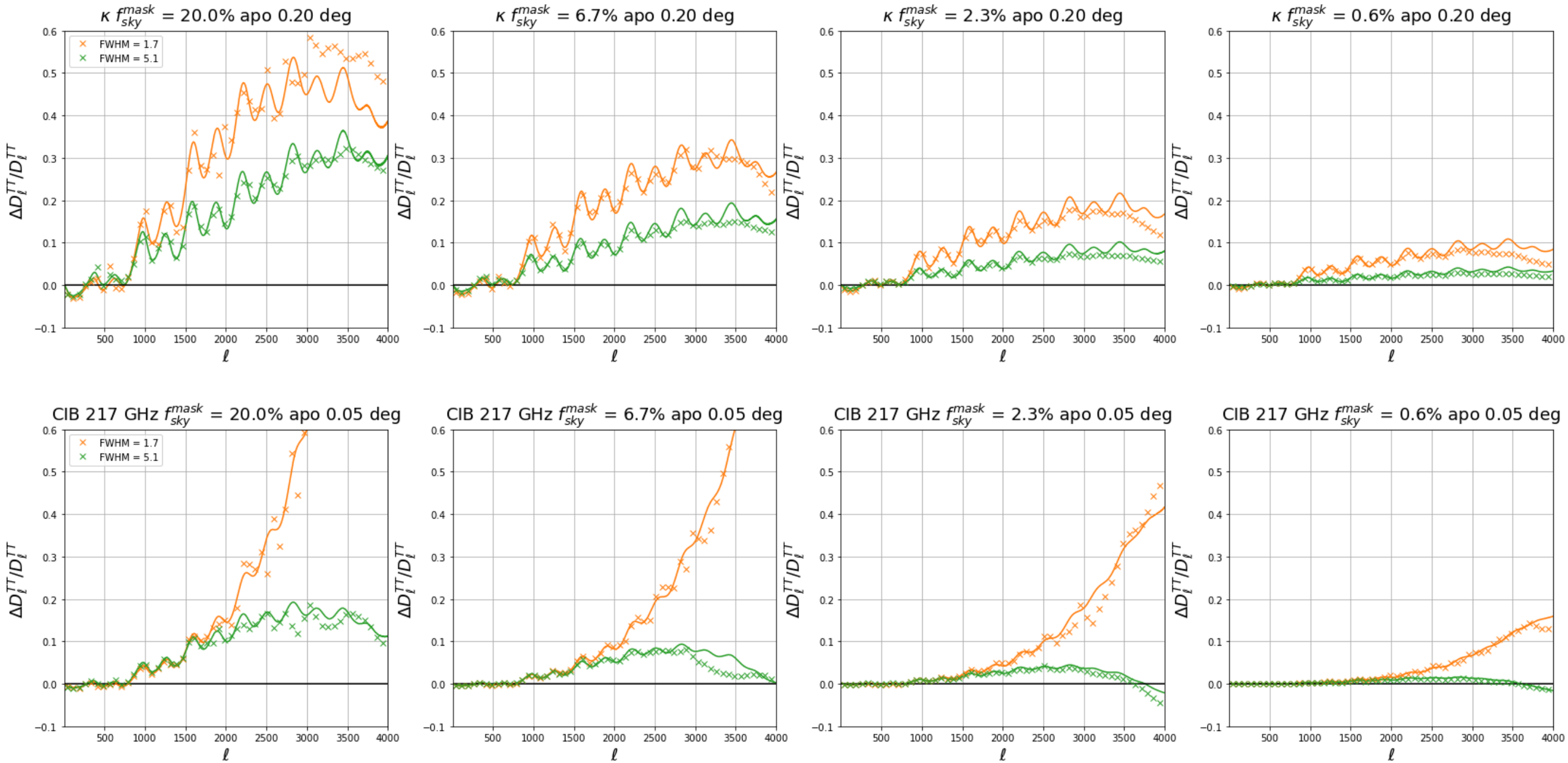
mean change of distance between r-separated points across unmasked area

Recipe:

- Build mask ($W_{\ell m} \cdot W^{\dagger}_{\ell m}$) spectrum
- Build spin-1 deflection ${}_1\alpha(\hat{n})$ and masked deflection ${}_1\alpha(\hat{n})W(\hat{n})$ from lensing map (e.g. with healpy…)
- Build deflection-mask cross-spectrum (($_1\alpha W)_{\ell m} \cdot W^{\dagger}_{\ell m}$)
- Transform both spectra to real space corr. fcts. to build $\bar{\Delta}(r)$.
- Feed $\bar{\Delta}(r)$ into analytic formula, you're done.

Tests on Websky simulations (Stein et al, 2001.08787)

Theory vs simulations on Websky simulations



biases in current data ?

Planck:

- Simulations suggest Planck point- source mask $f_{\rm sky} = 2\,\%$ could bias cosmological parameters by about 1σ if mask traces κ
- Assessing exactly the level of correlation from purely from theoretical considerations or simulation is difficult.

- Can perform empirical tests, e.g. :

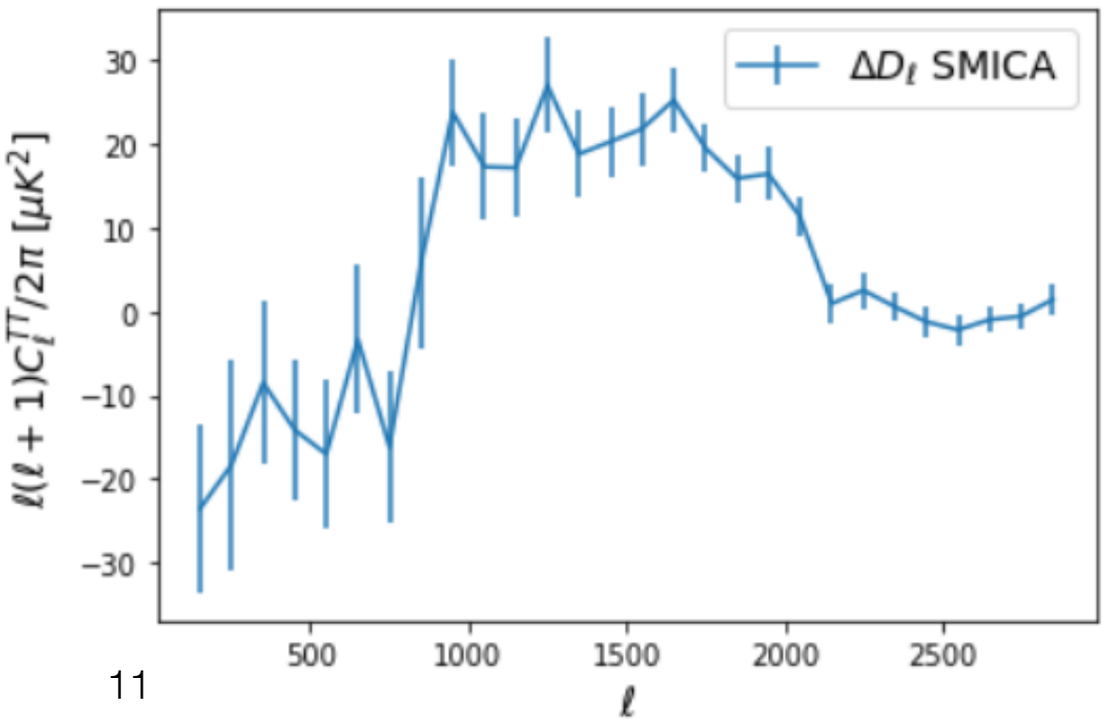
    - building bias prediction using the CIB and lensing maps as lensing tracer x Planck mask
    - or taking cross-spectra of Planck foreground cleaned SMICA with and without PS mask

No biases seen ($\Delta D_\ell \simeq 1 \mu K^2$ consistent with expected cosmic variance)

(However we do see the bias signature on data with a designer mask:)

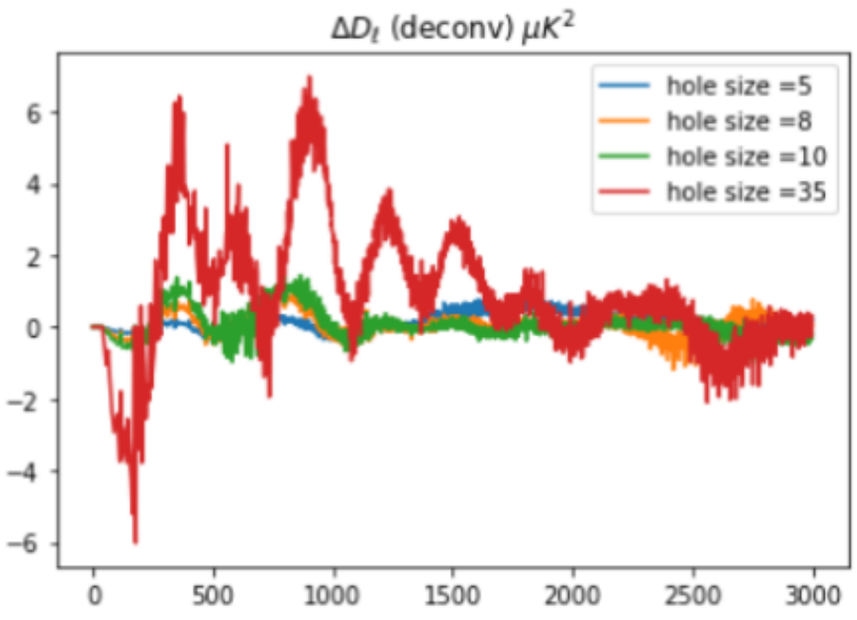
- Adding a $f_{\rm sky} = 5\,\%$ mask thresholding CIB map (GNILC) to the Planck mask

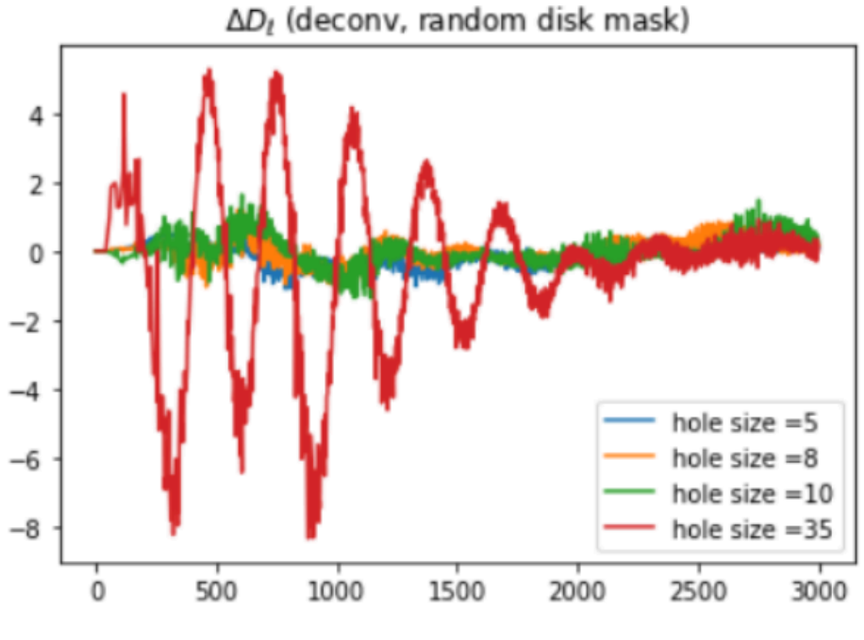
- looking at then spectrum difference in Planck SMICA data



biases in current data ?

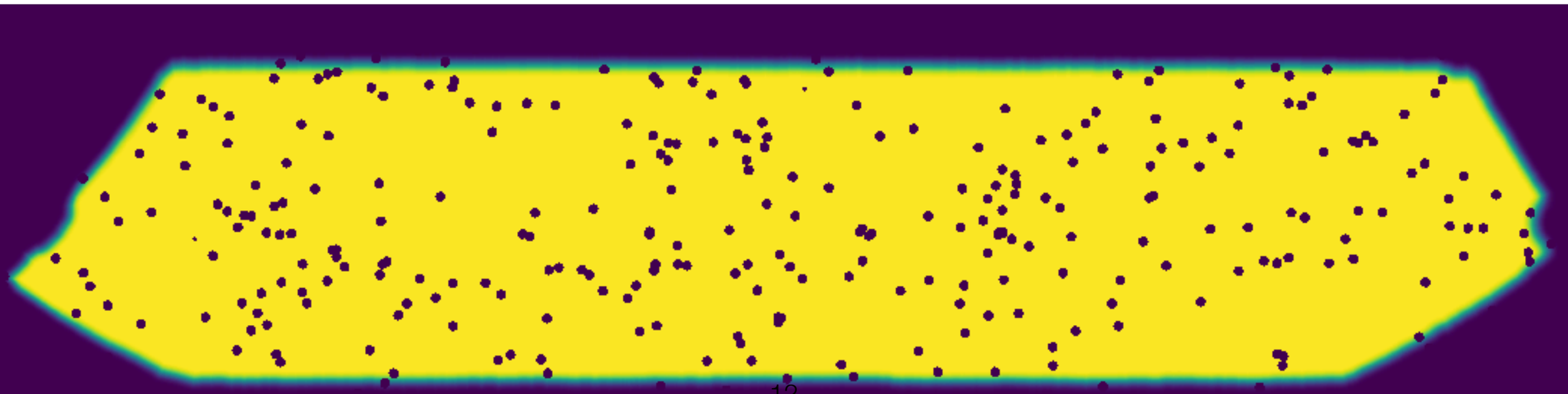
ACT:





ACT DR4 lensing x mask **No biases seen**

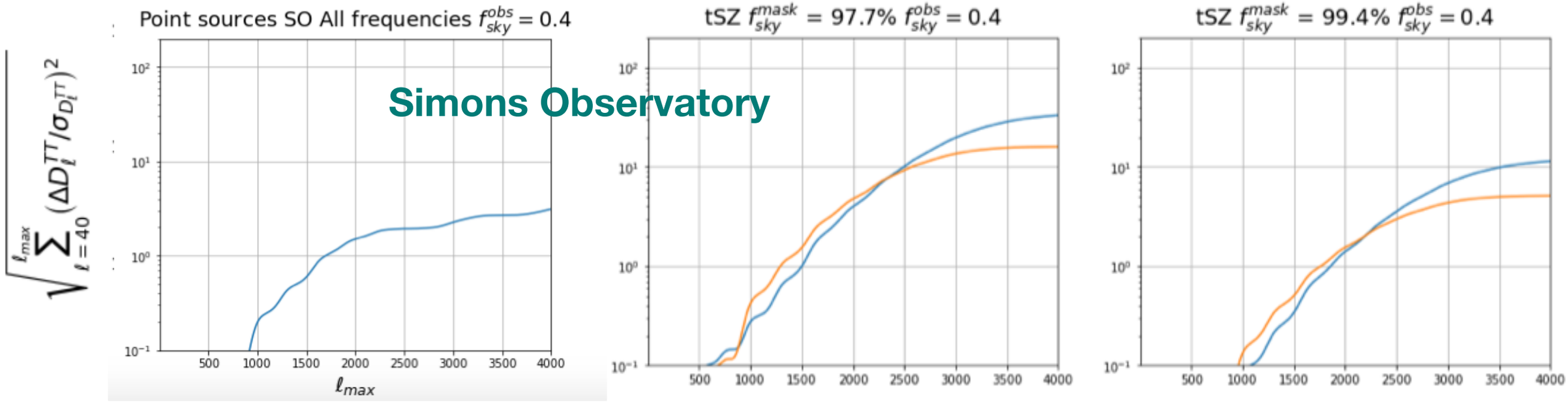
2007.07288 Aiola et al 2004.01139 Darwish et al



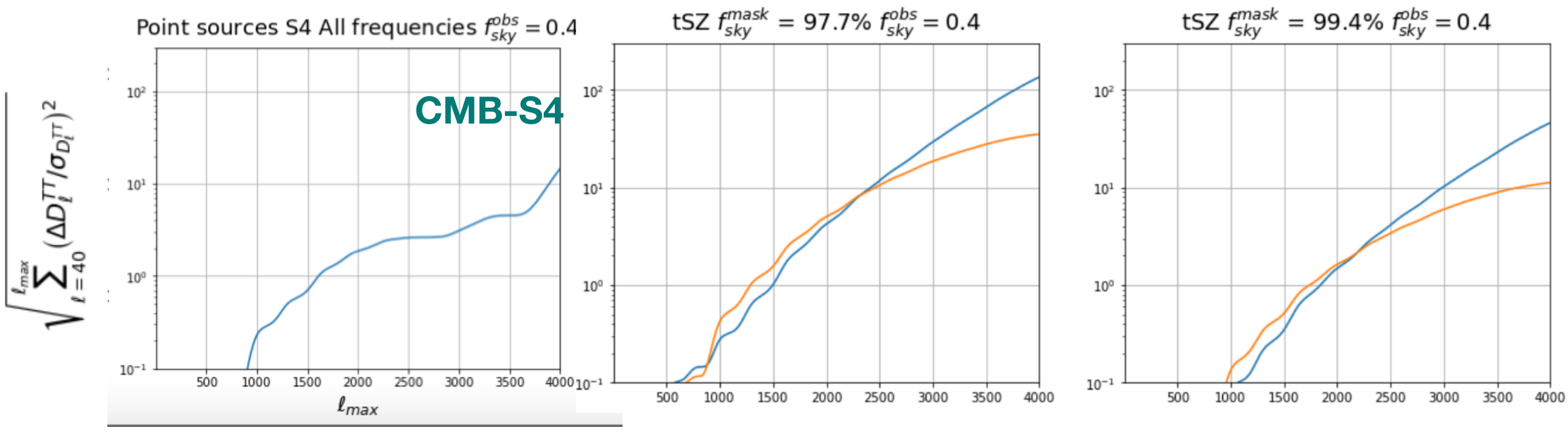
Forecasts

Preliminary

Simons Observatory



CMB-S4



Conclusions

- **CMB analysis masks correlated to LSS induces a bias on the CMB spectra, by introducing a signature linear in lensing absent on the full-sky**

- **This bias can be very large and lead to parameter biases if the mask traces the convergence peaks very well (shifts in CMB peak position, more small scale power….)**

- **For more realistic analysis masks (such a poisson sources), this bias appears negligible for current CMB data**

- **It might become sizeable for next-generation experiments**

- **Using cross-spectra, the bias can be estimated from simulations for any mask construction, or empirically on data**

- **Biases also for lensing reconstruction** **(see Lembo et al in prep)**

Thank you!