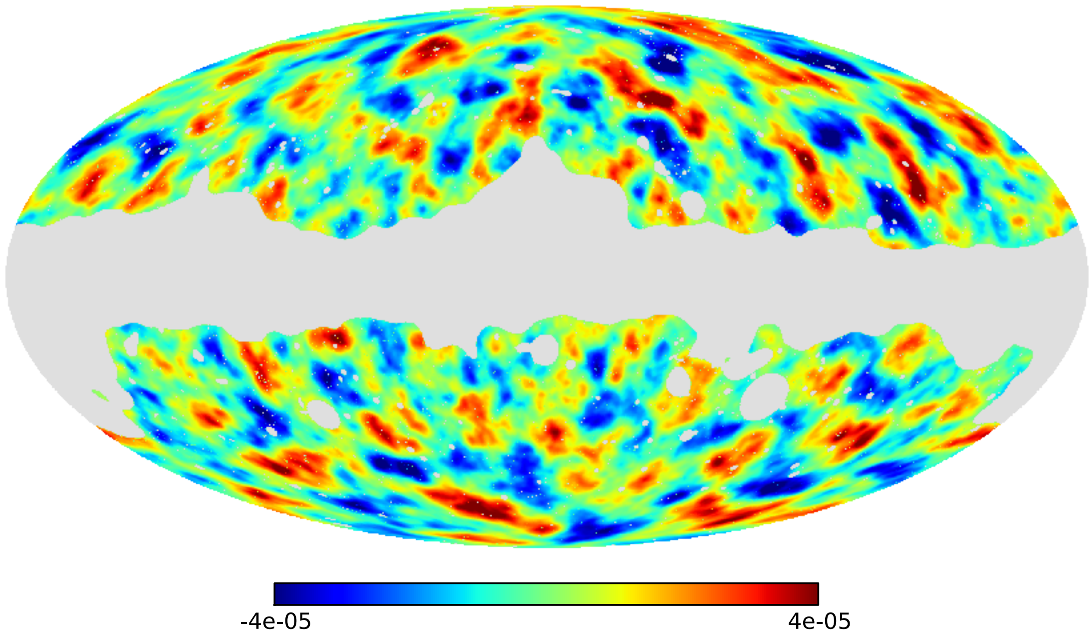
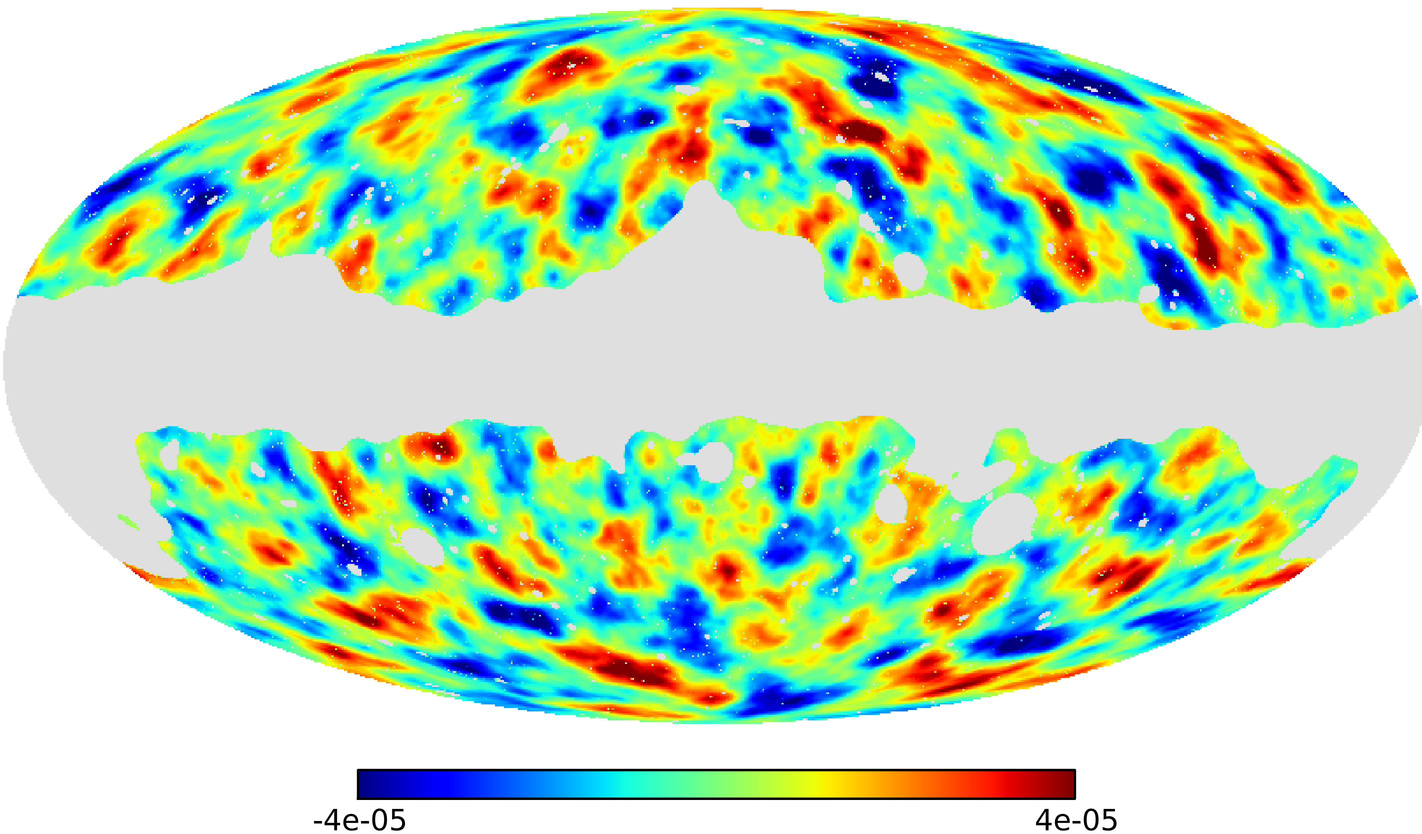
CMB lensing and delensing

Anthony Challinor and Olivier Doré



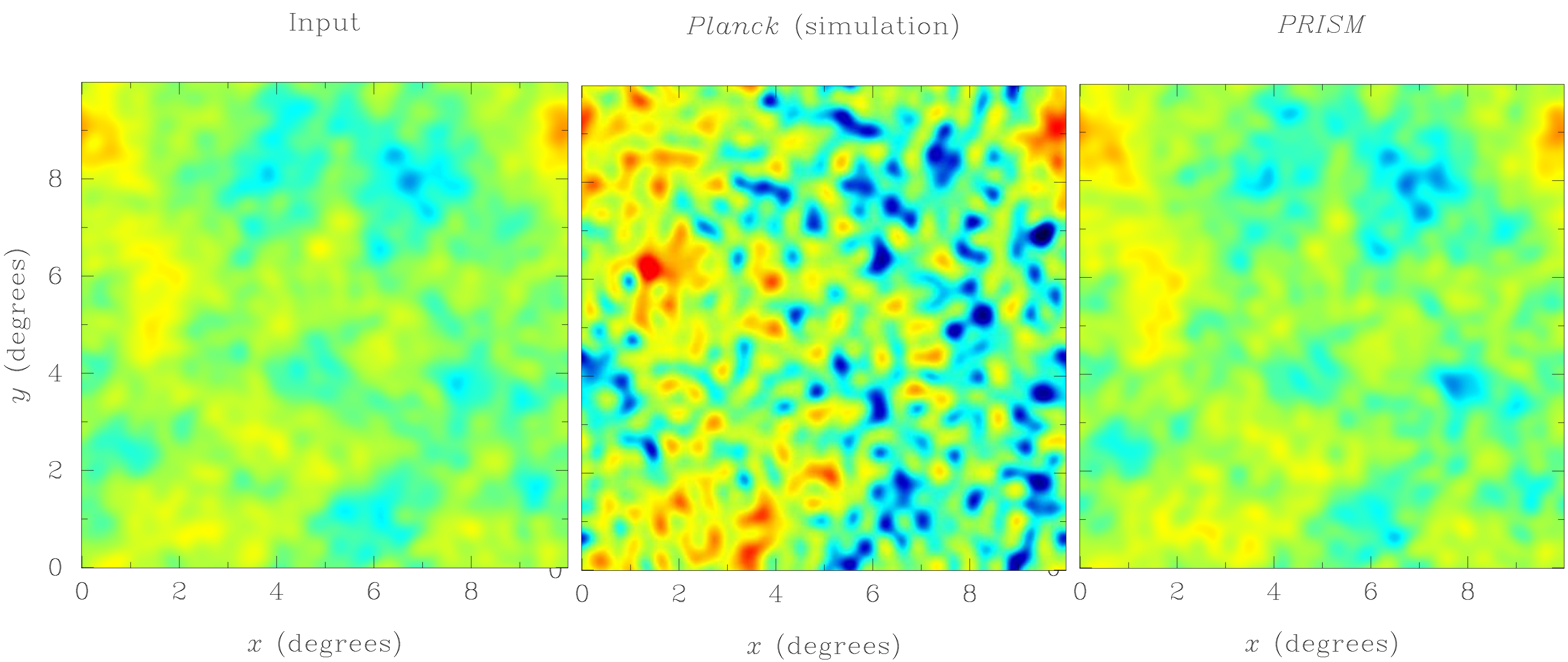
Current state of the art



Planck Collaboration 2016

4,000 resolved modes
S/N = 40 (power spectrum)

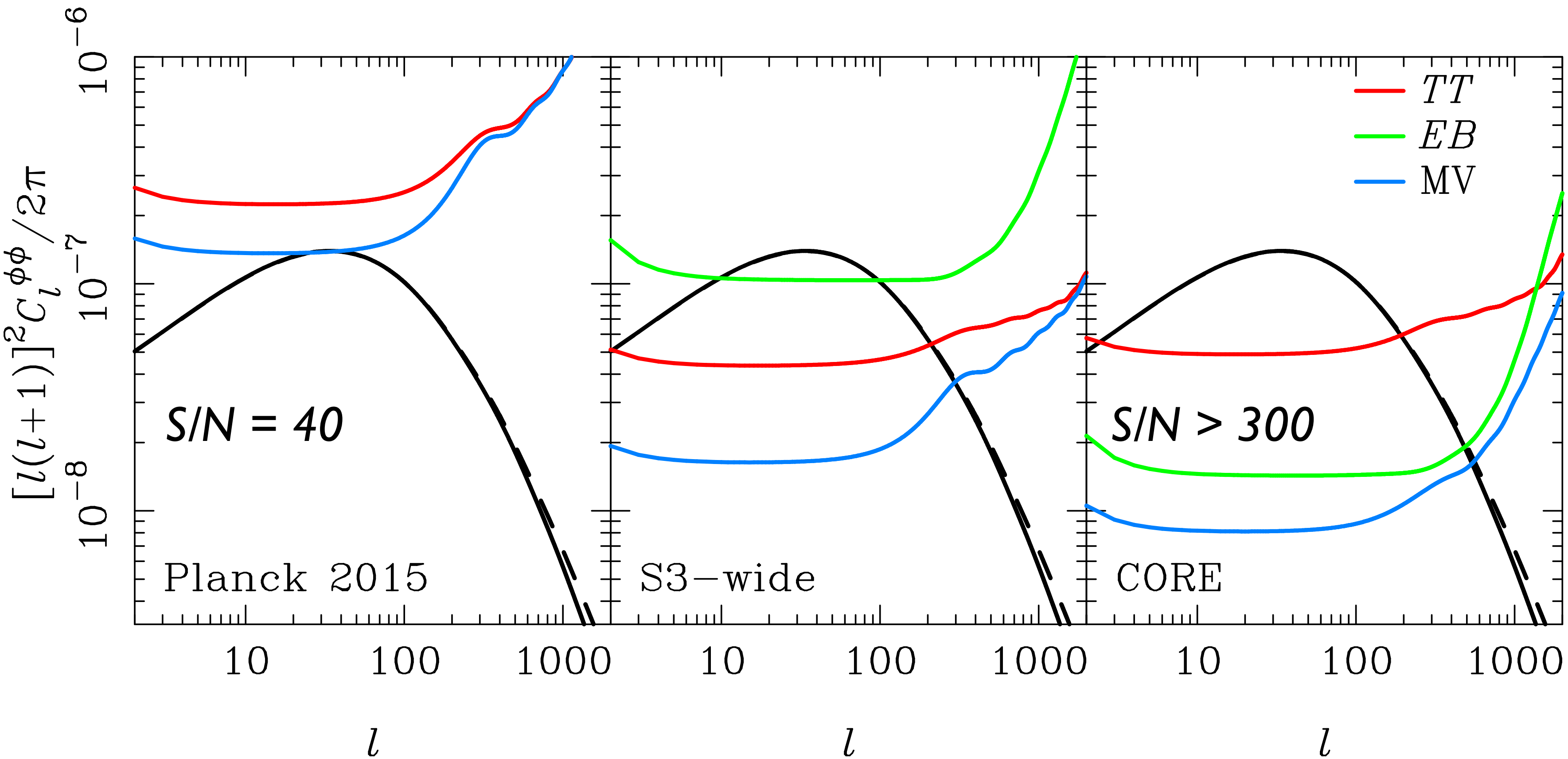
Where we want to be …



>10^5 resolved modes

S/N > 300 (power spectrum)

TT→EB dominance in future



- *EB* particularly helpful for pol. noise < 5 μK arcmin
  - *Polarization reconstructions less susceptible to extragalactic contamintion (e.g., tSZ) but more so to Galactic foregrounds*

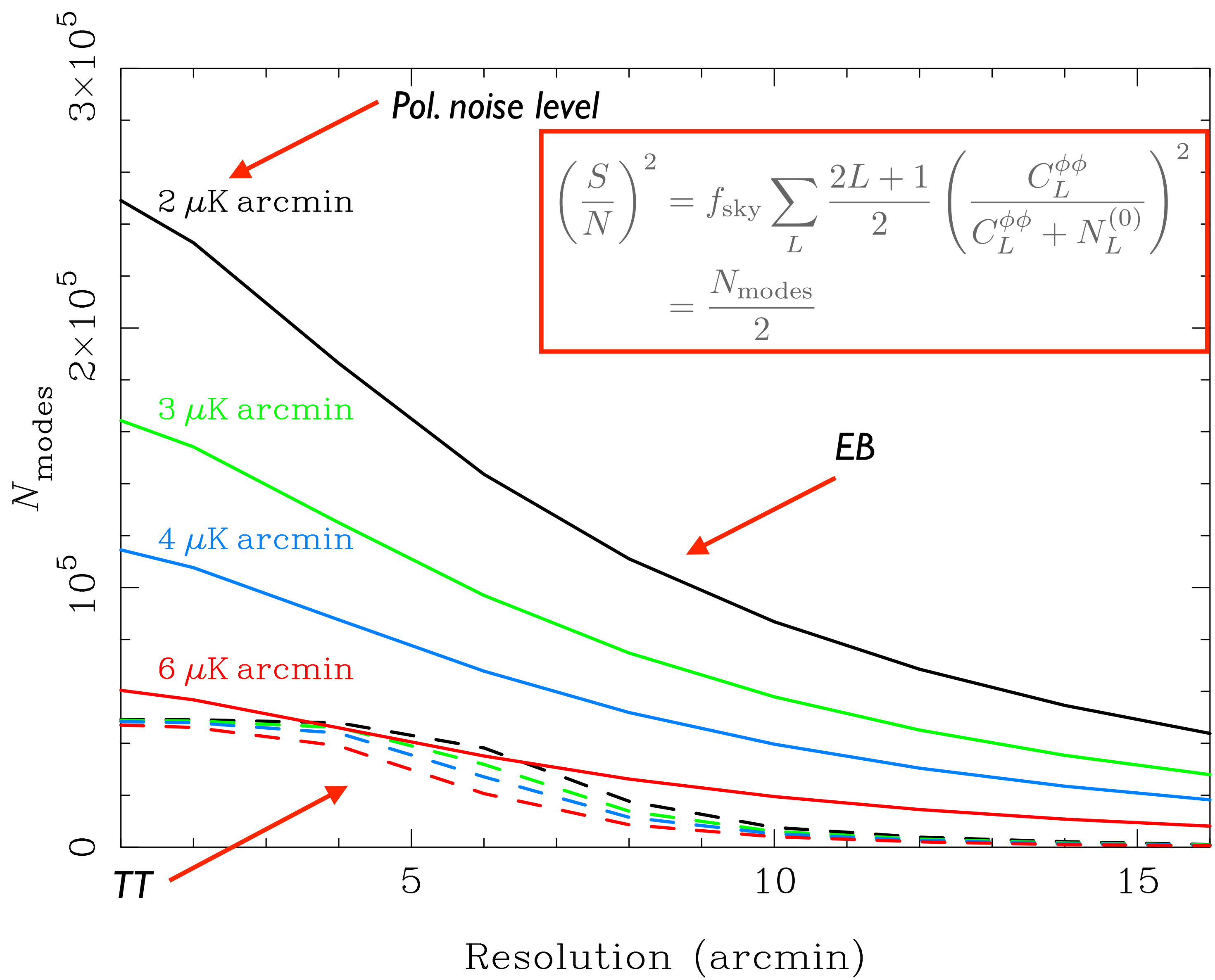
Goals for CMB lensing/delensing

- 4-pt φxφ (neutrino mass etc.)
- 3-pt φxLSS (growth of structure, dark energy, mitigation of systematics/self-calibration)
- Delensing (improve inflation constraints + N_{eff} etc.)
- Halo lensing (cluster mass calibration at high redshift)

Issues addressed in this session

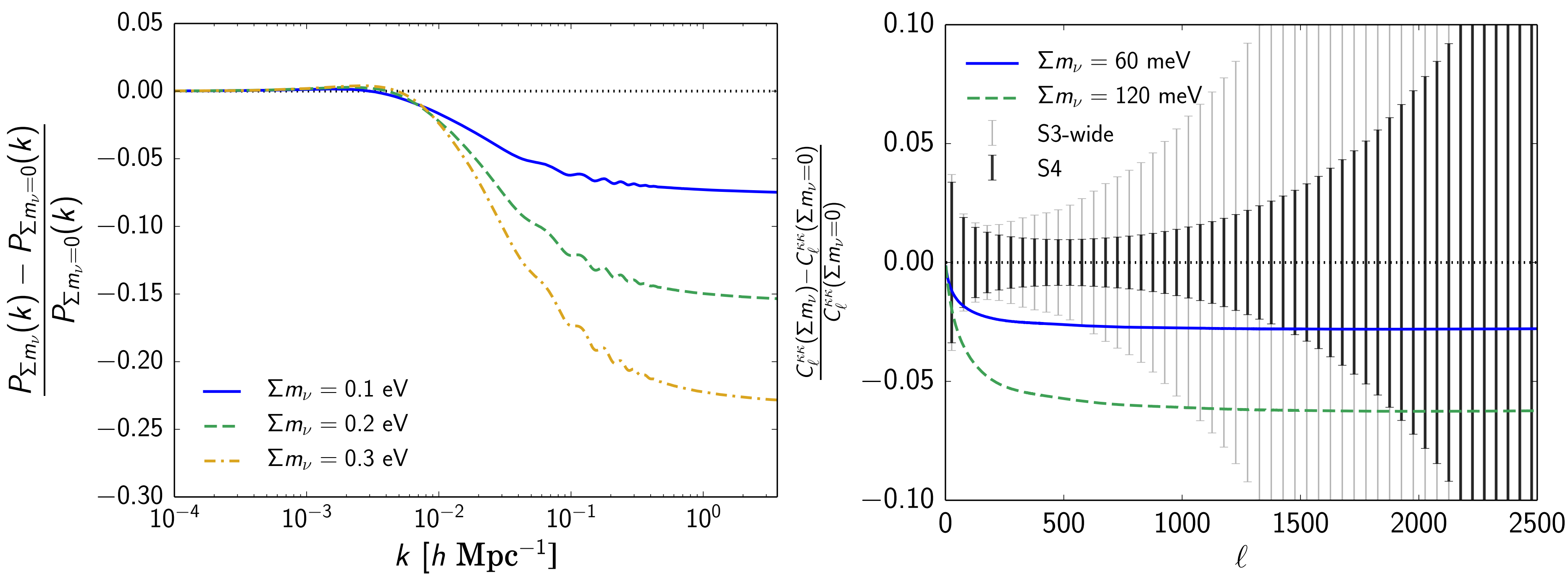
- How do we achieve these goals?
- Survey requirements (resolution, sensitivity, frequency coverage, sky coverage)
- Space or ground?
- An ultimate diffuse lensing mission?

Sensitivity and resolution



Cosmology from φxφ

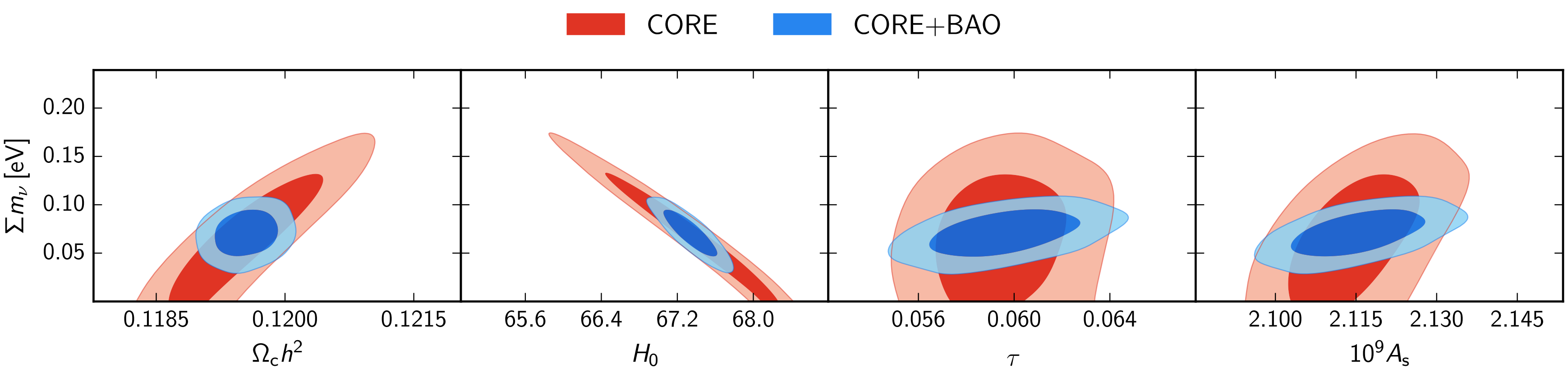
Neutrino masses



Allison+ 2015

- Complementary to optical weak lensing
  - *Higher-z, mostly linear regime, no intrinsic-alignment issues*
- Comparable precision on neutrino mass to e.g., Euclid lensing

Parameter degeneracies for m_ν



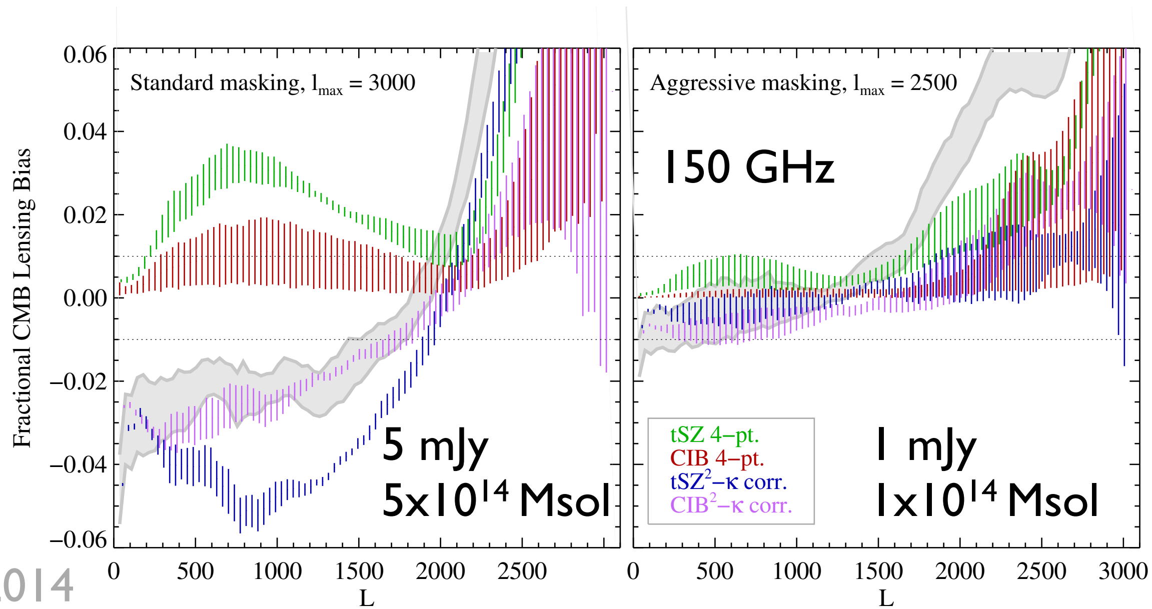
$$\sigma\left(\sum m_\nu\right) = 44\,\mathrm{meV} \qquad \mathit{CORE}$$
$$\sigma\left(\sum m_\nu\right) = 17\,\mathrm{meV} \qquad +\mathrm{BAO}$$

Constraint on τ important: degrades to 30 meV with Planck prior σ(τ) = 0.01

- Cosmic-variance-limited τ [σ(τ) = 0.002] becomes limiting for $N_{\mathrm{modes}} > 10^5$

Issue I: extragalactic foregrounds

- Issue in *T*-based reconstruction
- tSZ and CIB
  - tSZxtSZxφ *and* (tSZ)^4 *both important (van Engelen+ 2014)*
- Mitigation:
  - *Masking (loss of signal for tSZ)*
  - *Modelling (e.g., Planck for unclustered sources)*
  - *tSZ nulling (on gradient leg; Madhavacheril & Hill 2018)*



van Engelen+ 2014

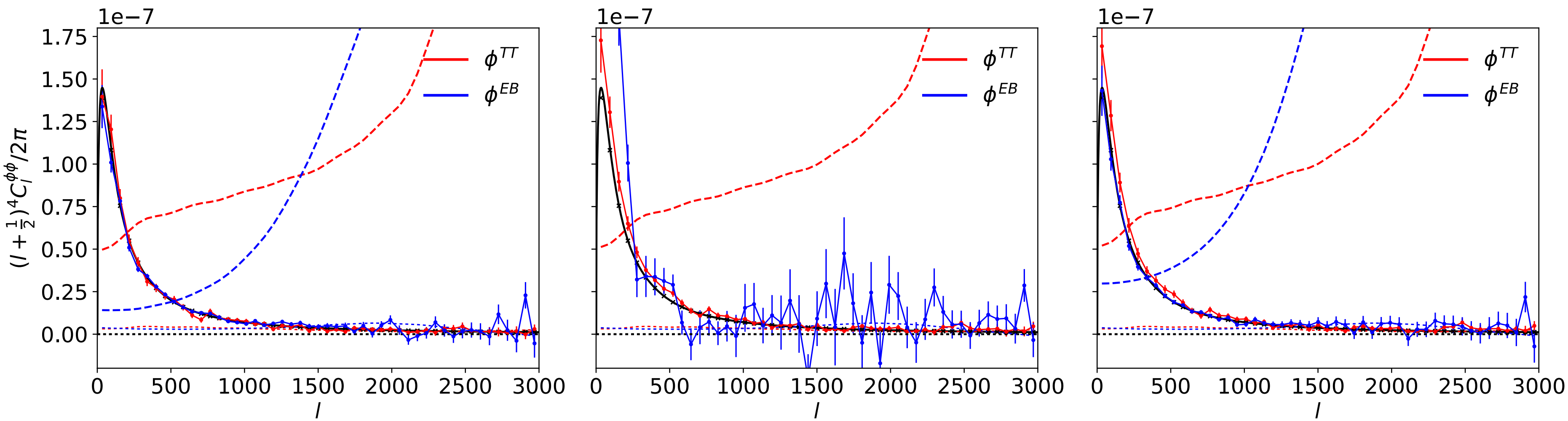
Issue 2: Galactic foregrounds

- Main issue for *EB* reconstruction

- Care (mainly) about 4-pt non-Gaussianity on intermediate and small scales
  - *Very limited empirical information on these scales*

- Mitigation:
  - *Multi-frequency cleaning*
  - *"Local" analysis with foreground power included in lensing filters to downweight contaminated modes*

Results on 150 GHz simulations



No dust | *Worst 600-deg^2 dust field* | *Dust inc. in lensing filters*

AC+CORE 2017

- Data-derived simulations (Planck FFP8) but do not capture small-scale NG from small-scale *B* field

Requirements for φxφ

- Mostly care about N_{modes} for power spectrum science
  - *Generally favours large sky coverage at fixed N_{det}*

- Neutrino mass requires precise τ measurement
  - *Low-l E-mode polarization from space (e.g., LiteBIRD)*
  - *Precision on mass (with BAO) saturates around N_{modes}~10^5*
  - *kSZ from patchy reionization (Ferraro & Smith 2018)*

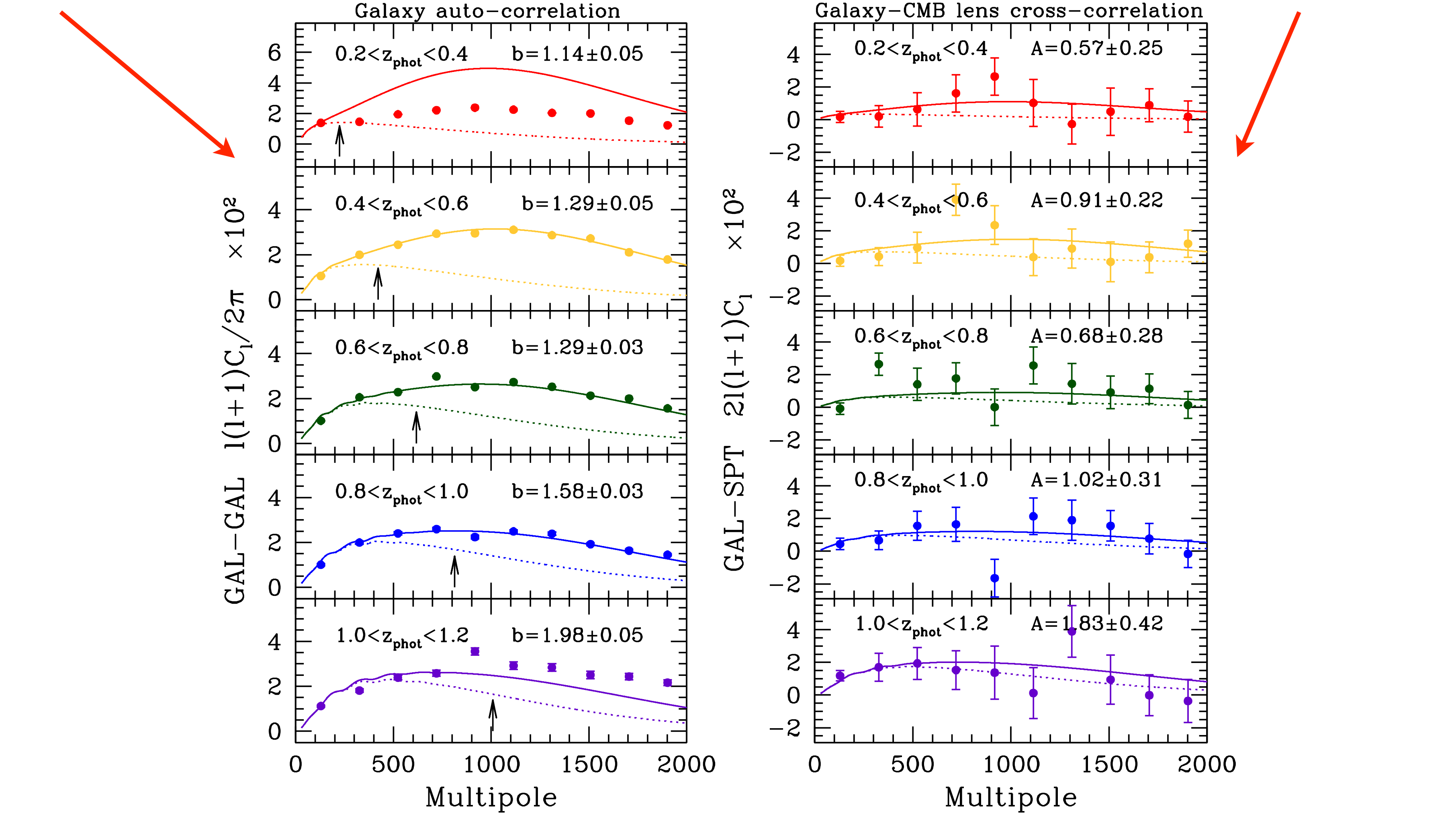
- Multi-frequency at high resolution prudent but less demanding than for low-*l* *B*-mode science
  - *Need for Galactic simulations properly capturing small-scale non-Gaussianity*

Cosmology from φxLSS

Growth of structure

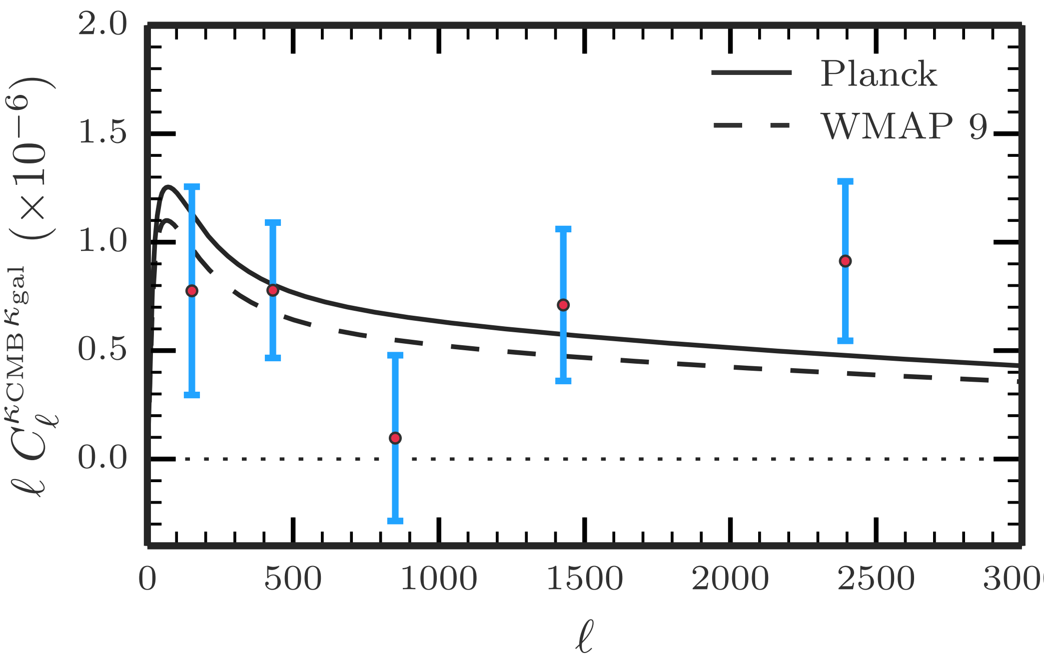
$\langle \Sigma\Sigma \rangle \propto b^2(z) D^2(z)$

$\langle \kappa_{\rm CMB}\Sigma \rangle \propto b(z) D^2(z)$

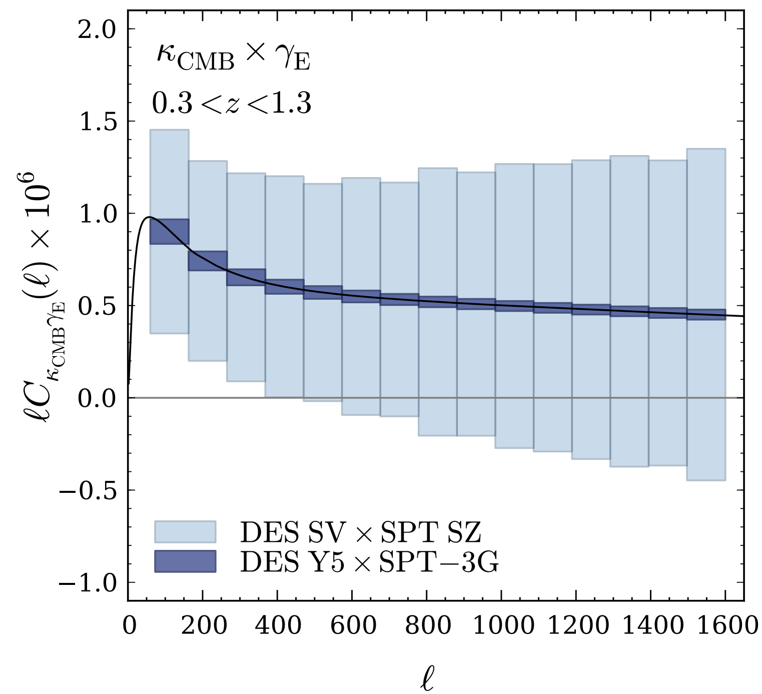


Giannantonio+ 2016

Galaxy lensing-CMB lensing



Hand+2013; see also Liu & Hill 2015



Kirk+ 2016

- Current detections around 3σ
- Will improve to >50σ with e.g., DES 5-yr x SPT-3G
- X-correlation more immune to additive systematic effects
- Full joint analysis can calibrate multiplicative bias effects in shape measurement and intrinsic alignments

Issue: extragalactic foregrounds

$$\langle\hat{\phi}(c+f,c+f)\times\mathrm{LSS}\rangle = \langle\hat{\phi}(c,c)\times\mathrm{LSS}\rangle + \langle\hat{\phi}(f,f)\times\mathrm{LSS}\rangle$$
$$= \langle\phi\times\mathrm{LSS}\rangle + \langle\hat{\phi}(f,f)\times\mathrm{LSS}\rangle$$

Desired x-correlation *Fg-fg-LSS bispectrum*

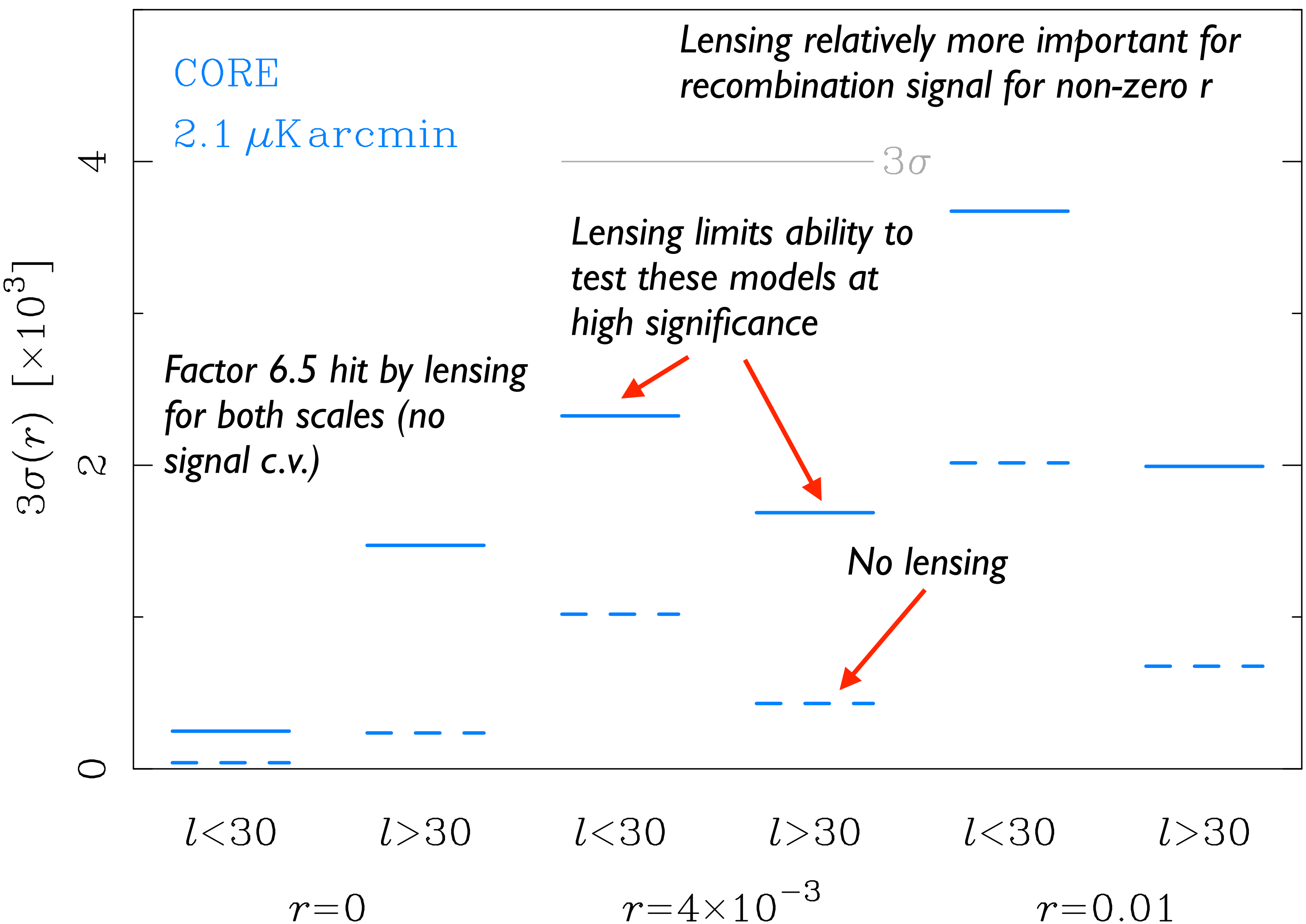
- tSZ and CIB are issues in *T*-based reconstruction
- Only, e.g., tSZxtSZxLSS now enters
- Mitigation:
  - *Masking*
  - *Modelling*
  - *tSZ nulling (on gradient leg; Madhavacheril & Hill 2018)*

Requirements for φxLSS

- Overlap with optical surveys
- Generally favours wide survey
- Galactic foregrounds less of an issue (no bias but can inflate errors)
- Extragalactic foregrounds in *TT* require cleaning/modelling/agressive masking
  - *Gradient-leg cleaning (e.g., with Planck)*

Delensing

Lensing and inflation constraints



AC+CORE Collaboration 2017

Delensing the CMB

- Remap CMB with Wiener-filtered tracer *I* of CMB lensing

$$\hat{\phi}_{\mathcal{W}} = \mathcal{W} * I$$

$$X^{\rm delens}(\hat{\mathbf{n}}) = X^{\rm obs}(\hat{\mathbf{n}} - \nabla\hat{\phi}_{\mathcal{W}})$$

$$\approx X^{\rm unlens}(\hat{\mathbf{n}} + \nabla(\underbrace{\phi - \hat{\phi}_{\mathcal{W}}}))) + {\rm noise}$$

Residual lensing

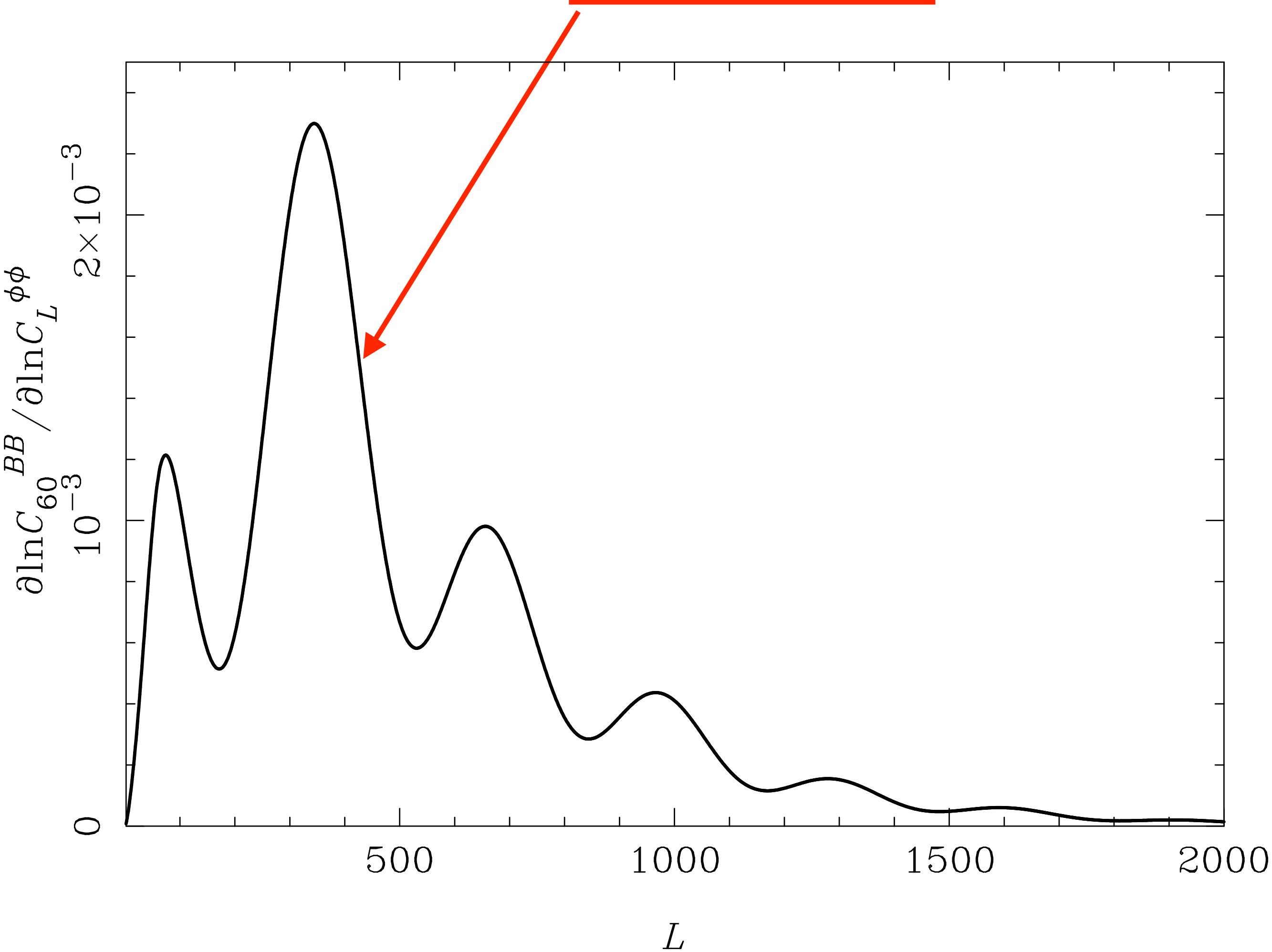
- Gradient approximation accurate for large-angle *B*-modes
- Residual lensing has power spectrum

$$C_l^{\phi\phi,\,{\rm delens}} = C_l^{\phi\phi}(1 - \rho_l^2)$$

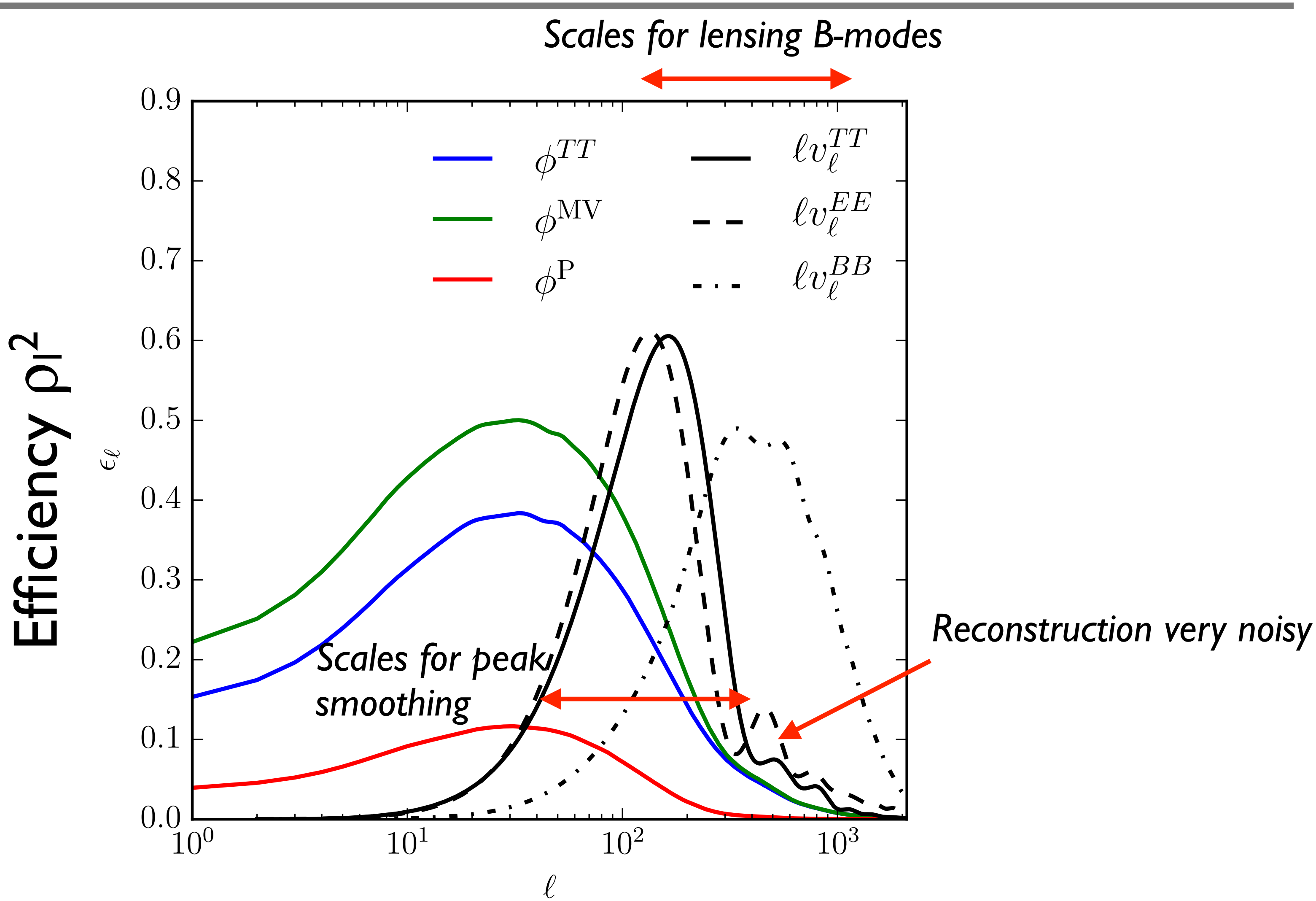
$$\rho_l^2 = \frac{\left(C_l^{I\phi}\right)^2}{C_l^{II,\,{\rm tot}} C_l^{\phi\phi}}$$

Scales for BB delensing

$$\frac{C_l^{BB,\mathrm{delens}}}{C_l^{BB,\mathrm{lens}}} \approx \sum_L \frac{\partial \ln C_l^{BB,\mathrm{lens}}}{\partial \ln C_L^{\phi\phi}} \left(1 - \rho_L^2\right)$$



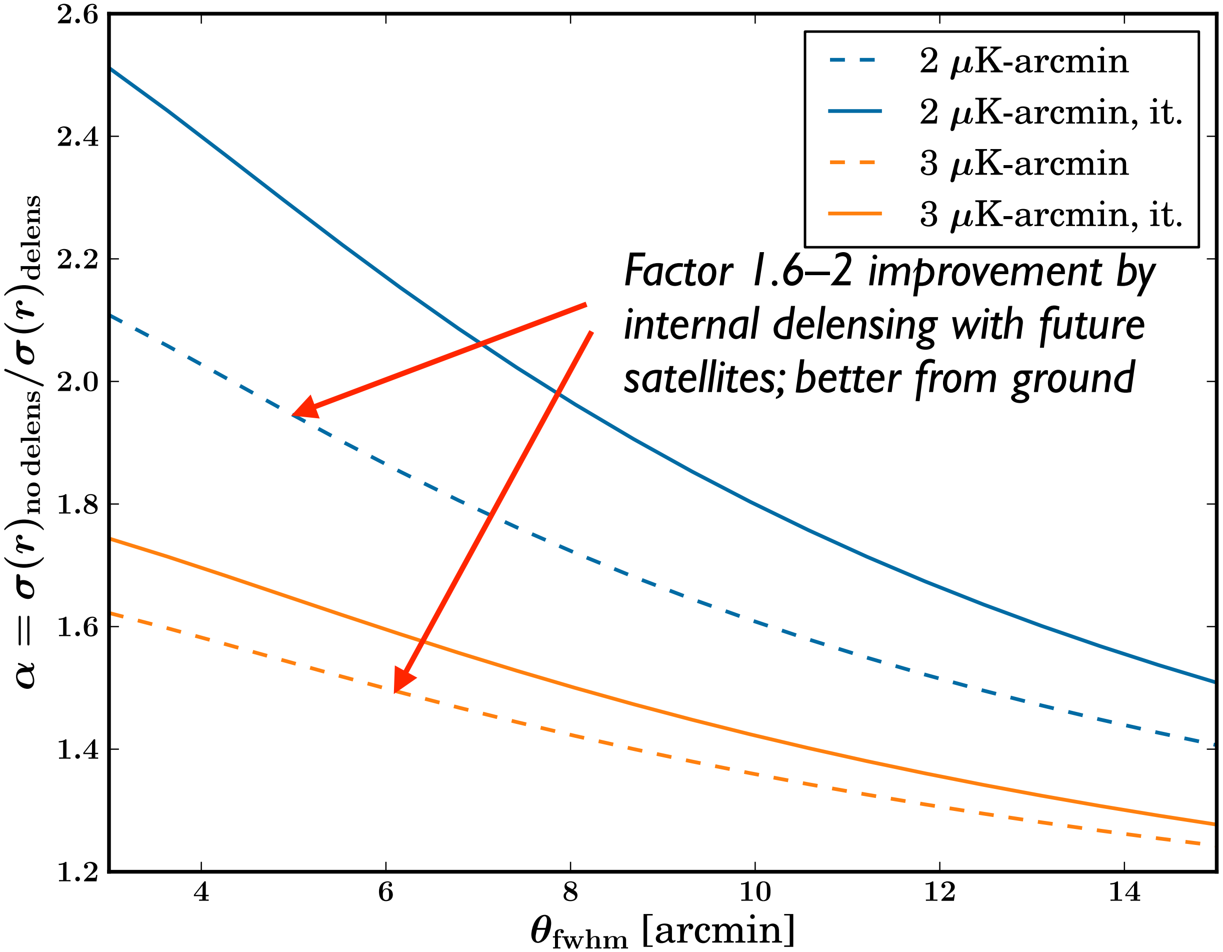
Internal delensing with Planck



Carron, Lewis & AC 2017

Improvements from internal delensing

Factor by which delensing improves σ(r) for *r*=0



AC+CORE Collaboration 2017

Bias from dependent recon. noise

- Consider *B*-mode template delensing with *XY* estimator:

$$B_{\mathrm{delens}} \sim B - \hat{E}_{\mathcal{W}}\hat{\phi}_{\mathcal{W}}(X,Y)$$

- Power spectrum after delensing:

$$C^{BB}_{\mathrm{delens}} \sim \langle BB\rangle - 2\langle B\hat{E}_{\mathcal{W}}\hat{\phi}_{\mathcal{W}}(X,Y)\rangle + \langle \hat{E}_{\mathcal{W}}\hat{\phi}_{\mathcal{W}}(X,Y)\hat{E}_{\mathcal{W}}\hat{\phi}_{\mathcal{W}}(X,Y)\rangle$$

If reconstruction noise were independent of CMB, just gives usual

$$2\langle B\hat{E}_{\mathcal{W}}\phi_{\mathcal{W}}\rangle$$

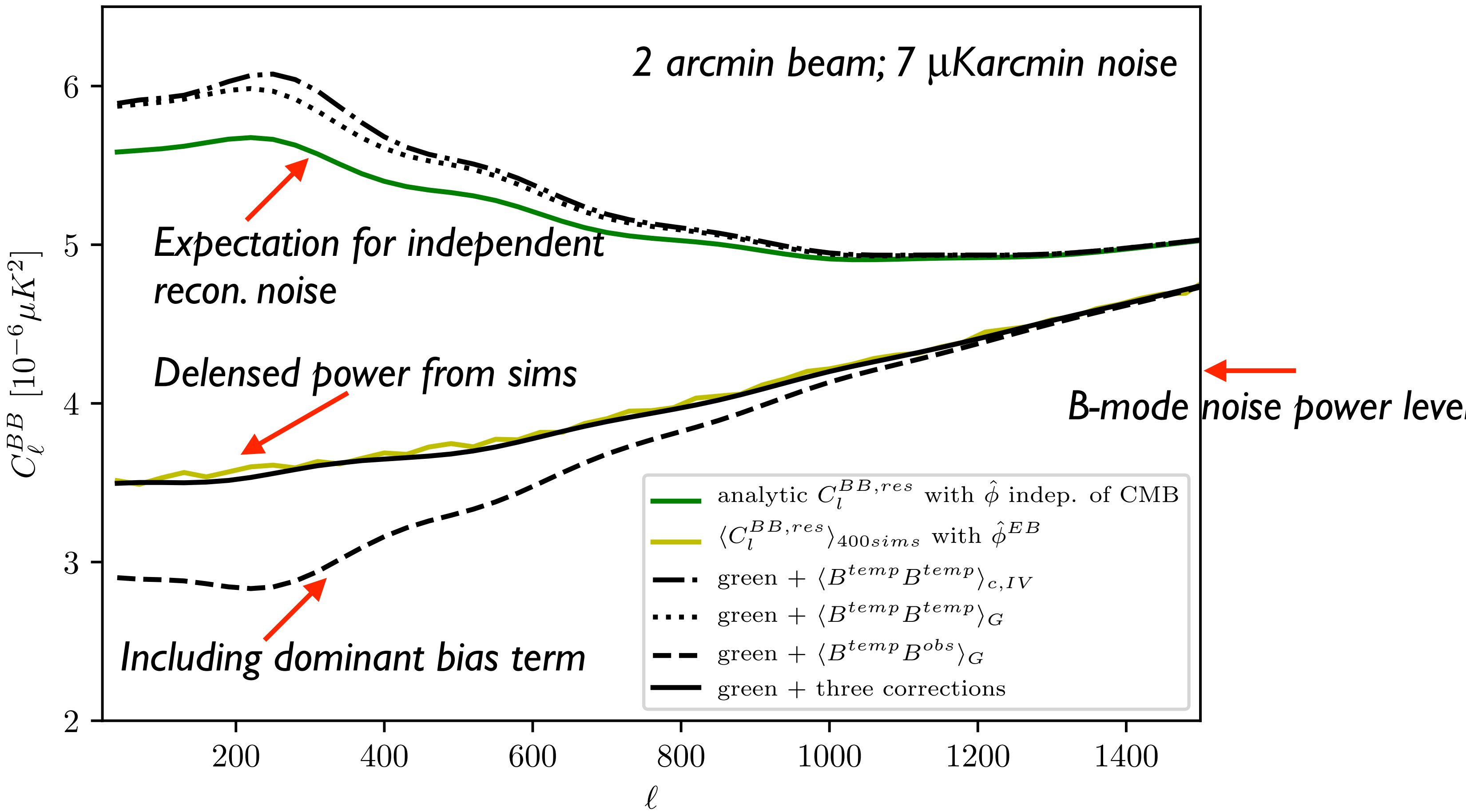
In practice, reconstruction dependent on CMB giving dominant bias

$$2B\hat{E}_{\mathcal{W}}\hat{\phi}_{\mathcal{W}}(X,Y) + 2B\hat{E}_{\mathcal{W}}\hat{\phi}_{\mathcal{W}}(X,Y)$$

- *r*-dependent bias if *X or Y*=*B* and overlapping scales

Carron, Lewis & AC 2017; see also Sehgal+ 2017; Teng+ 2011; Namikawa 2017

Modelling the bias

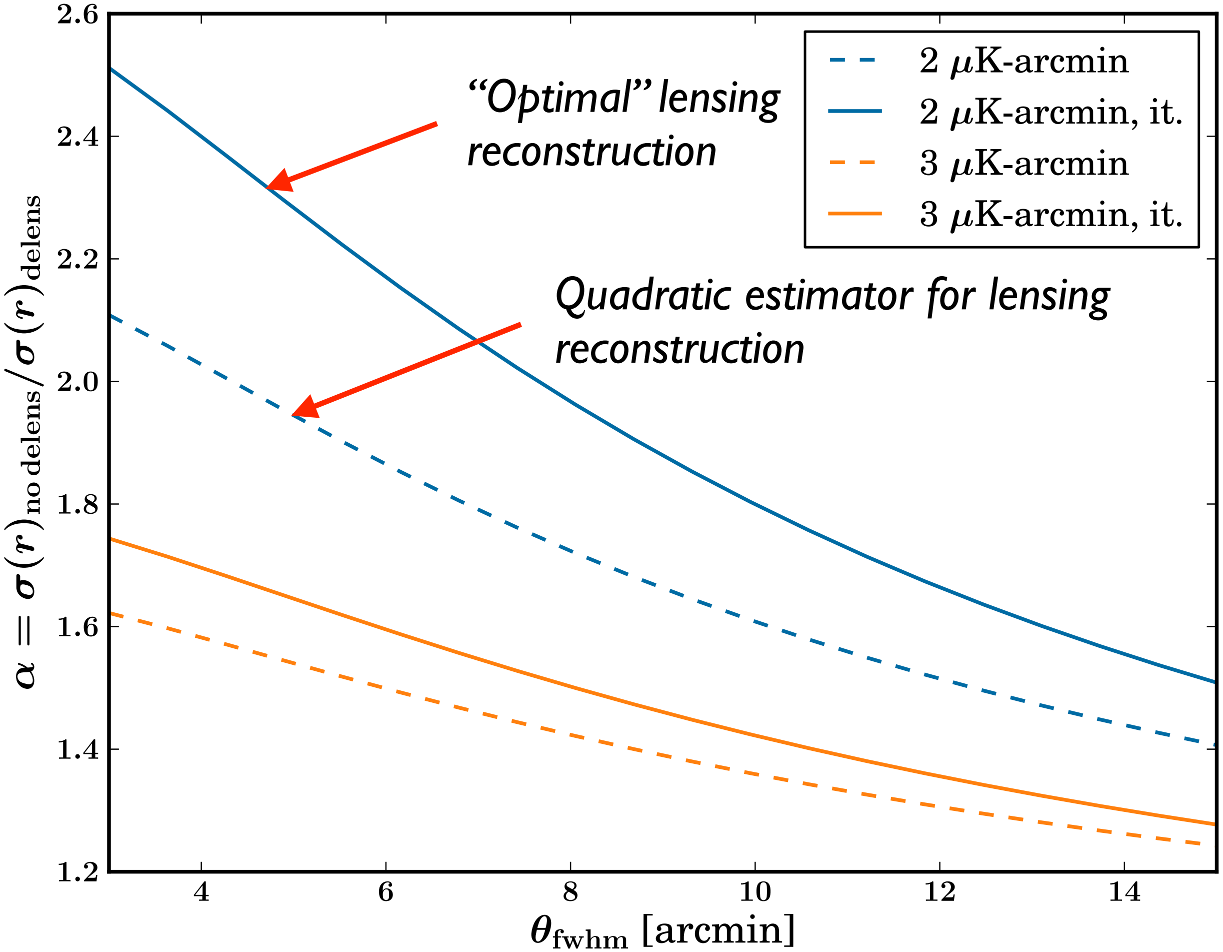


Baleato-Lizancos+AC in prep.; see also Namikawa 2017

- Non-trivial power spectrum covariance also

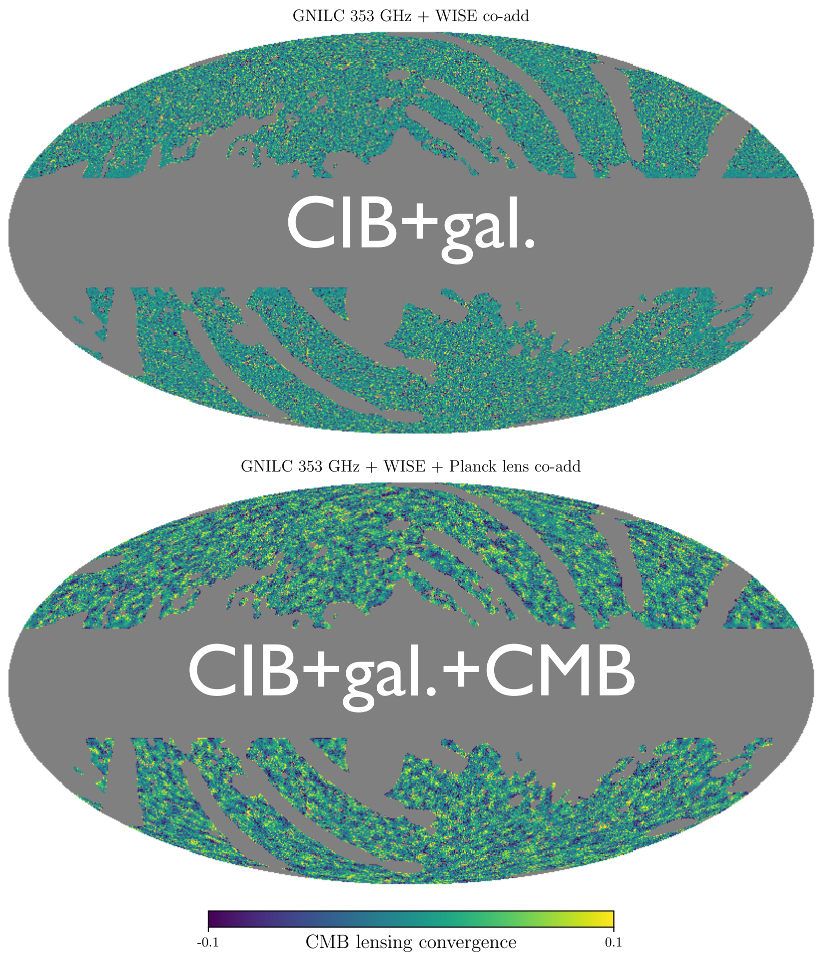
More optimal lens reconstruction

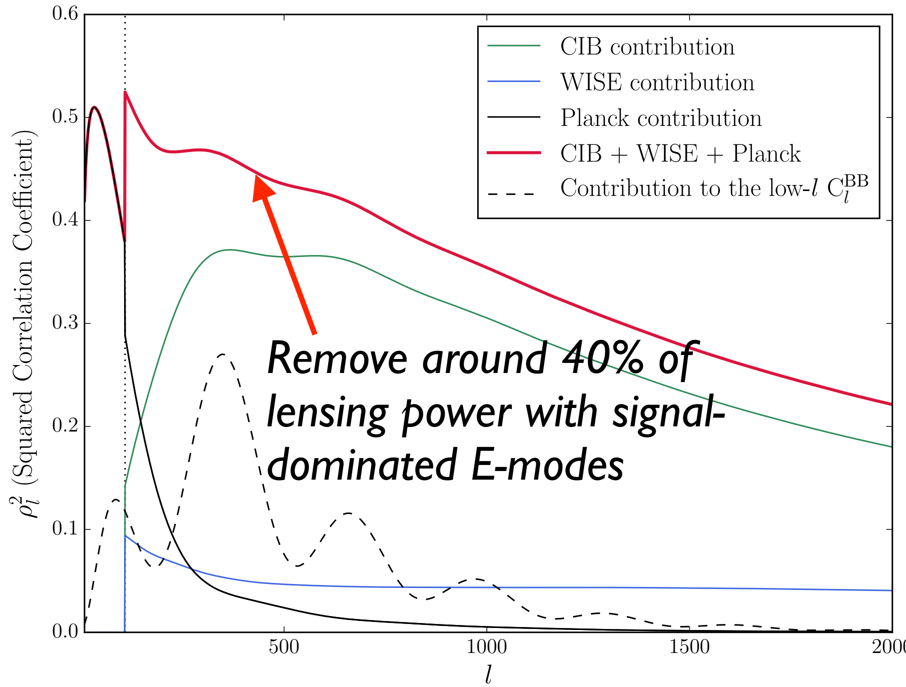
Factor by which delensing improves σ(*r*) for *r*=0



AC+CORE Collaboration 2017

External delensing





Byeonghee+ 2017

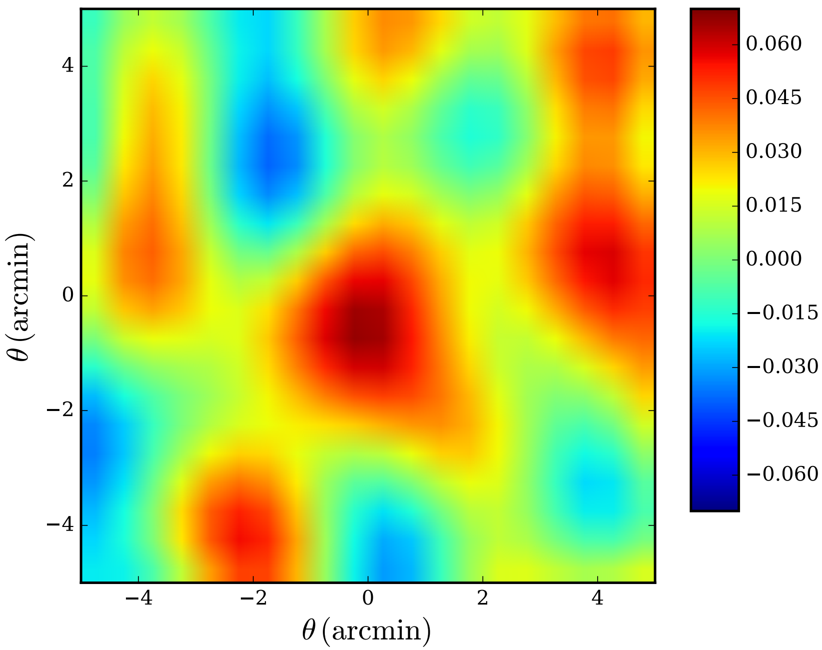
- Need high-z sources (CIB, LSST galaxies etc.)
- Residual power can be modelled from empirical spectra

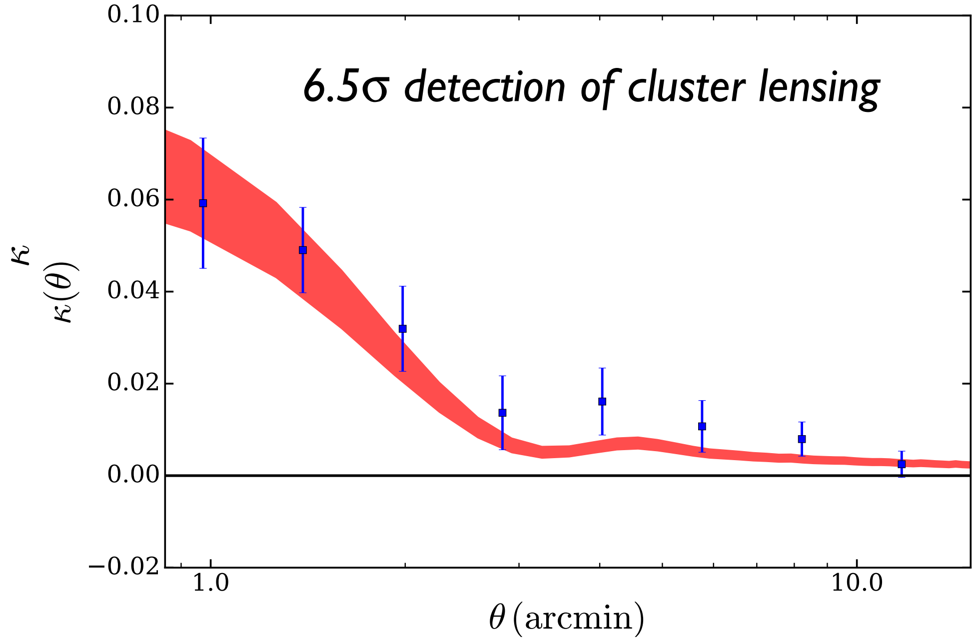
Requirements for BB delensing

- Overlap of high-resolution survey with degree-scale *B*-mode survey (e.g., CMB-S4)
- Sensitivity better than 5 μKarcmin
- Bias from non-Gaussian Galactic foregrounds not yet quantified
  - *Residual B-mode power involves up to 6-pt function*

Halo lensing

Halo lensing





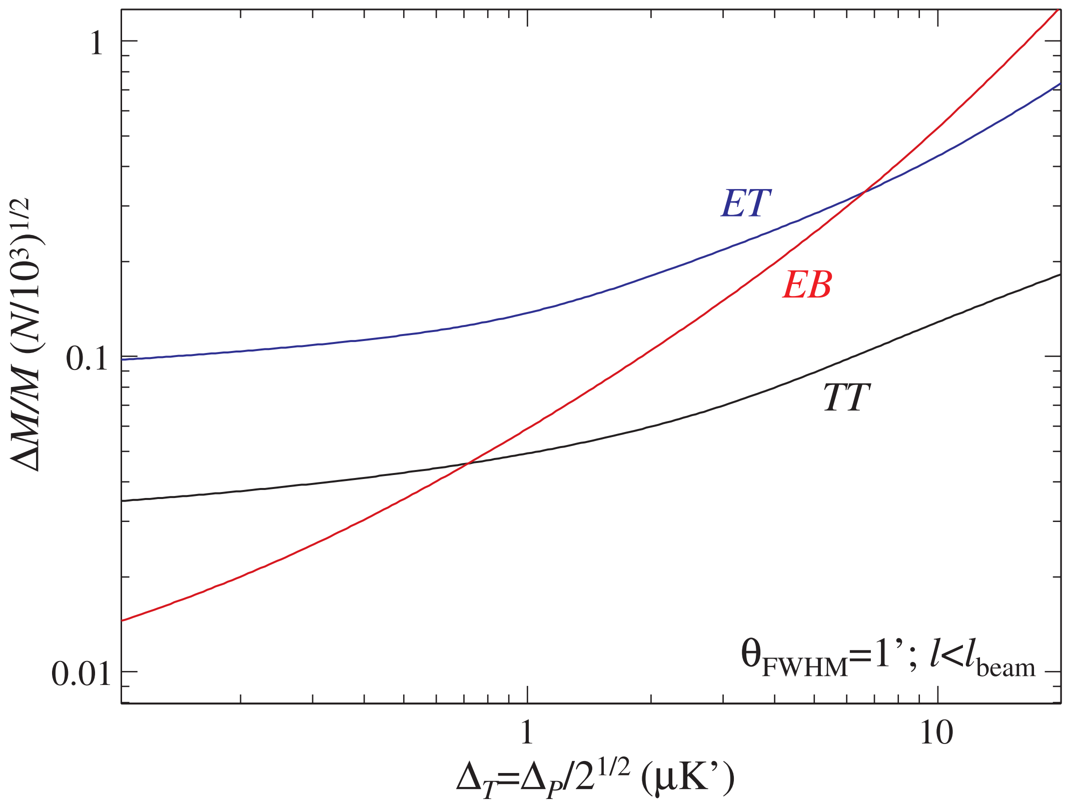
Baxter+ 2017

- Statistical mass calibration for large samples at high redshift

See also Baxter+ 2015; Planck Collaboration 2016; Madhavacheril+ 2015; Geach & Peacock 2017

Requirements for halo lensing

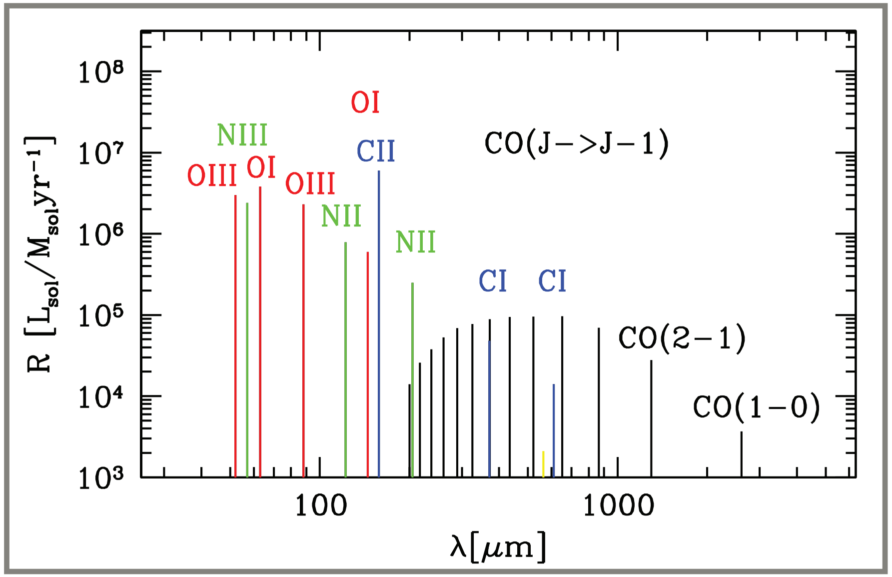
Fractional mass error on 1000 cluster stack



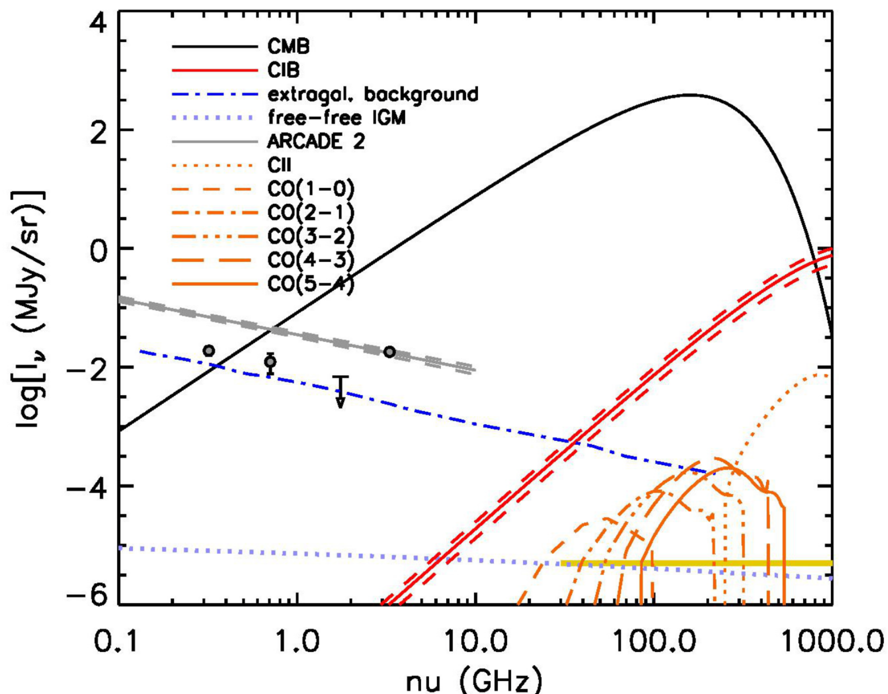
Hu+ 2007

- Arcmin resolution
- Rejection of tSZ and IR emission from cluster galaxies
- Large area

Ultimate diffuse lensing mission?



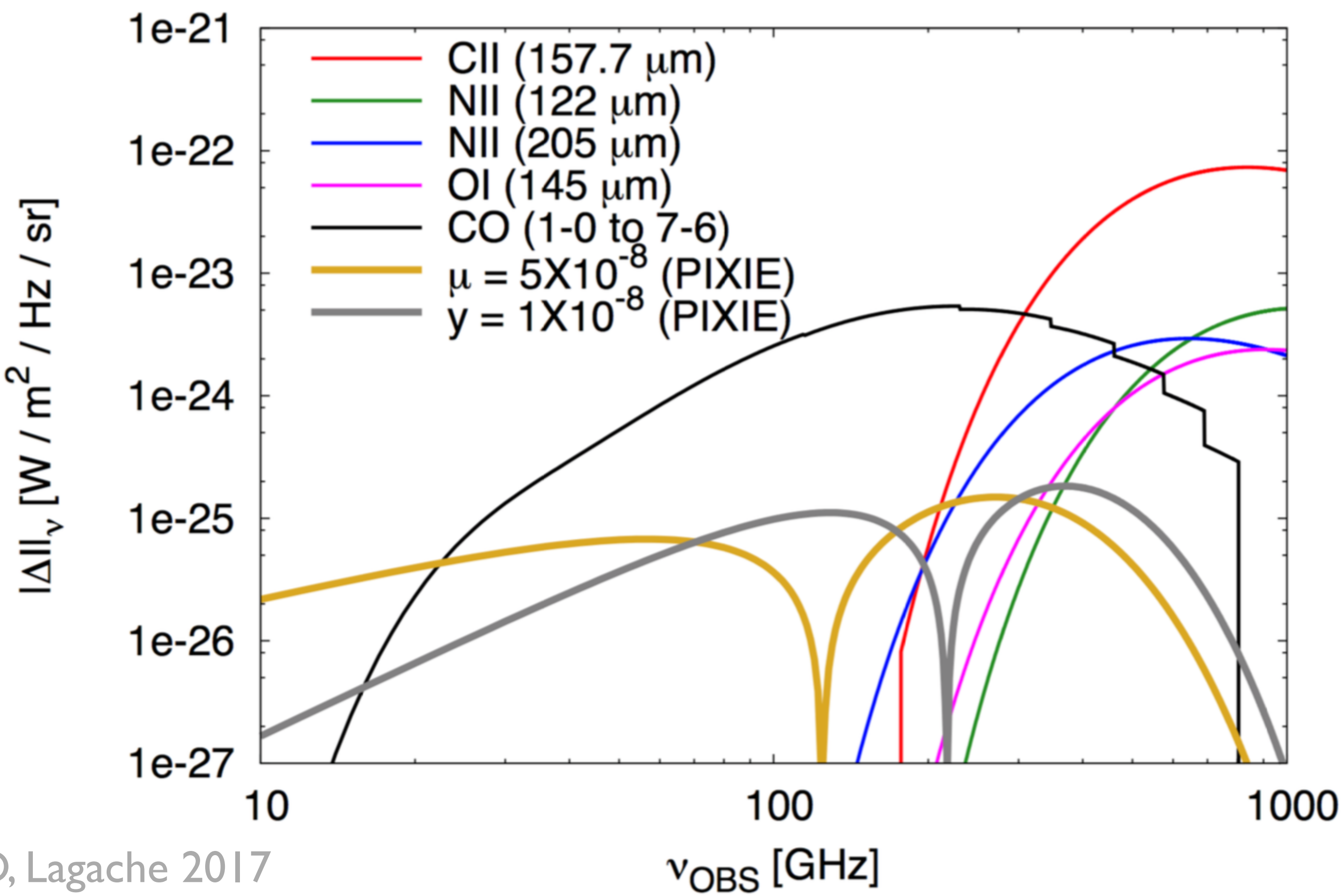
Visbal, Trac, Loeb 2011



de Zotti+2016

There is more to extra-galactic galaxies than CIB!

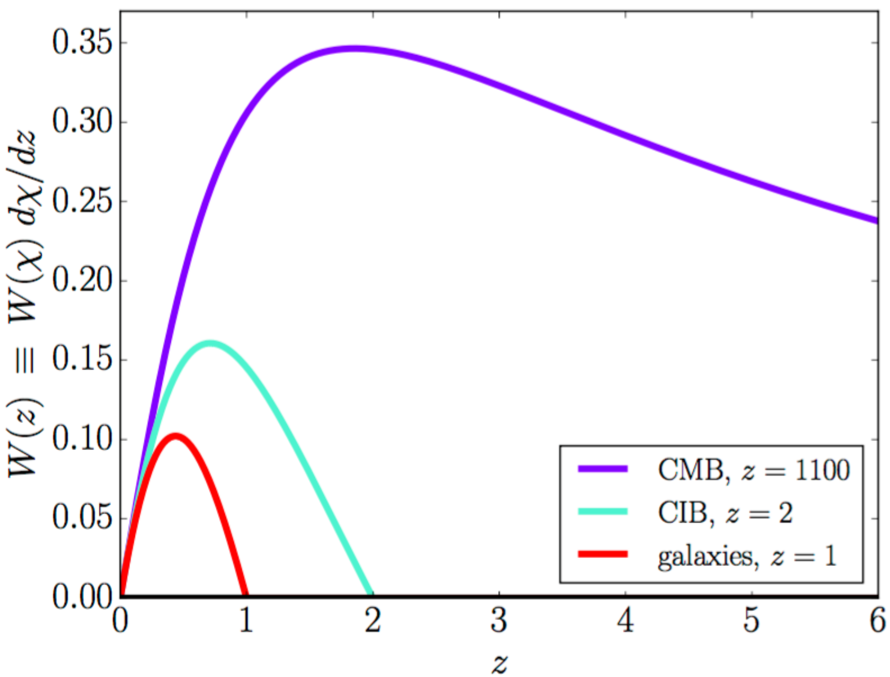
Ultimate diffuse lensing mission?

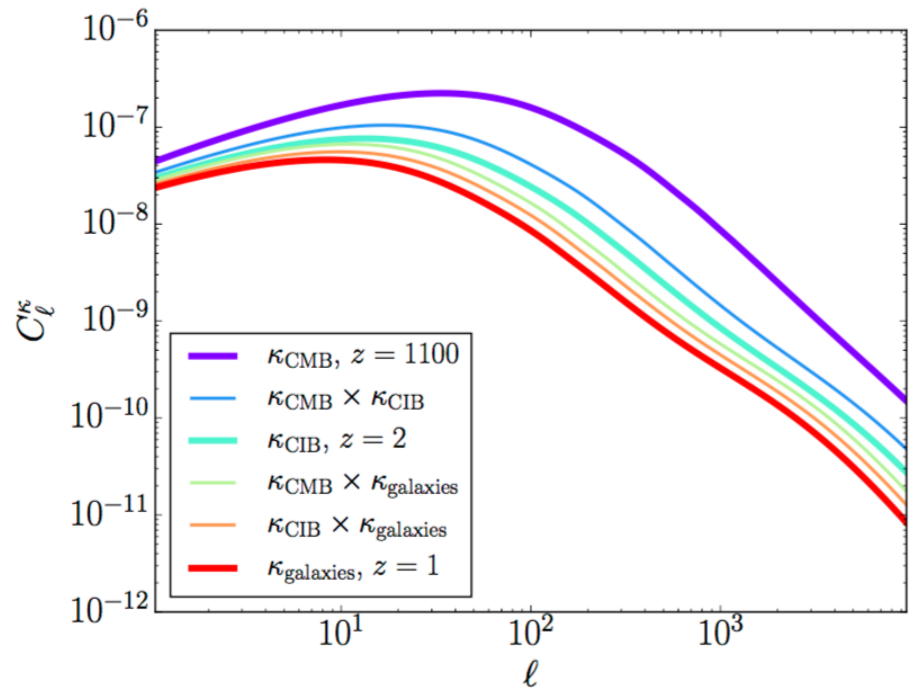


Serra, OD, Lagache 2017

Potentially a challenge to measure the primordial distortions

Ultimate diffuse lensing mission?





Schaan, Spergel, Ferraro 2018
Foreman+ 2018

- But an opportunity to perfectly delense and measure the growth of structures…
- We are at a KISS workshop after all!