CMB lensing and future polarization experiments

Kendrick Smith
Chicago, July 2009

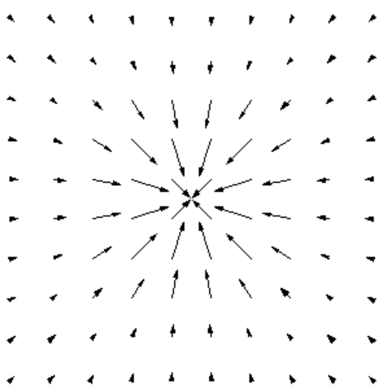
Main reference: K. Smith, A. Cooray, S. Das, O. Dore, D. Hanson, C. Hirata, M. Kaplinghat, B. Keating, M. LoVerde, N. Miller, G. Rocha, M. Shimon, O. Zahn (arxiv:0811.3916)

CMB lensing: introduction

CMB photons are deflected by gravitational potentials between last scattering and observer. This remaps the CMB while preserving surface brightness:

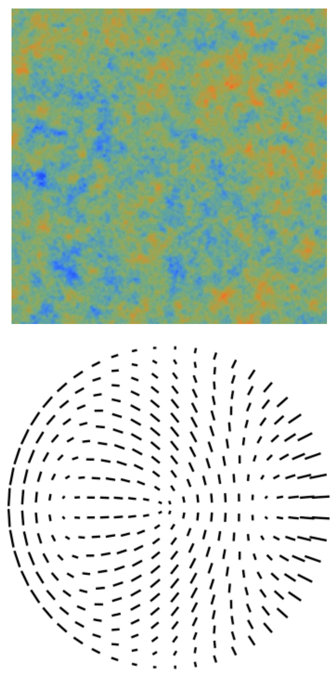
$$
\begin{aligned}
\Delta T(\mathbf{n})_{\text{lensed}} &= \Delta T(\mathbf{n} + \mathbf{d}(\mathbf{n}))_{\text{unlensed}} \\
(Q \pm iU)(\mathbf{n})_{\text{lensed}} &= (Q \pm iU)(\mathbf{n} + \mathbf{d}(\mathbf{n}))_{\text{unlensed}}
\end{aligned}
$$

where $\mathbf{d}(\hat{\mathbf{n}})$ is a vector field giving the deflection angle along line of sight



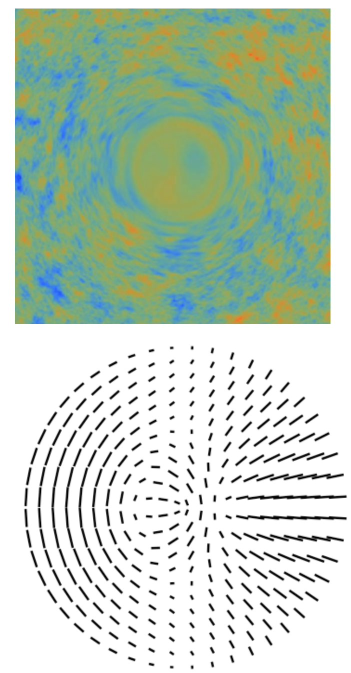
Deflection angles

+



Unlensed CMB

$\longrightarrow$



Wayne Hu

Lensed CMB

CMB lensing: E-mode power spectrum

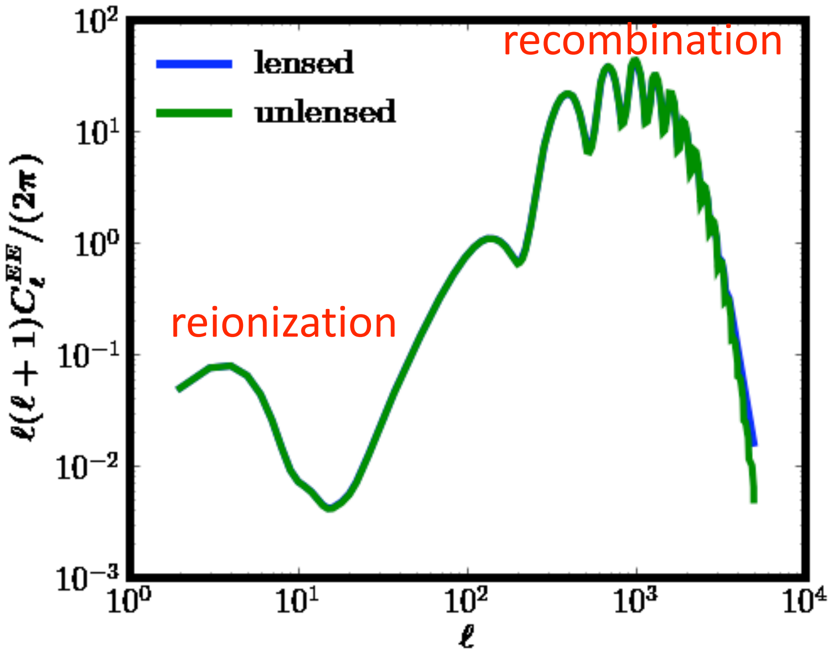
"Gradient-like" mode in polarization Π_{ab}

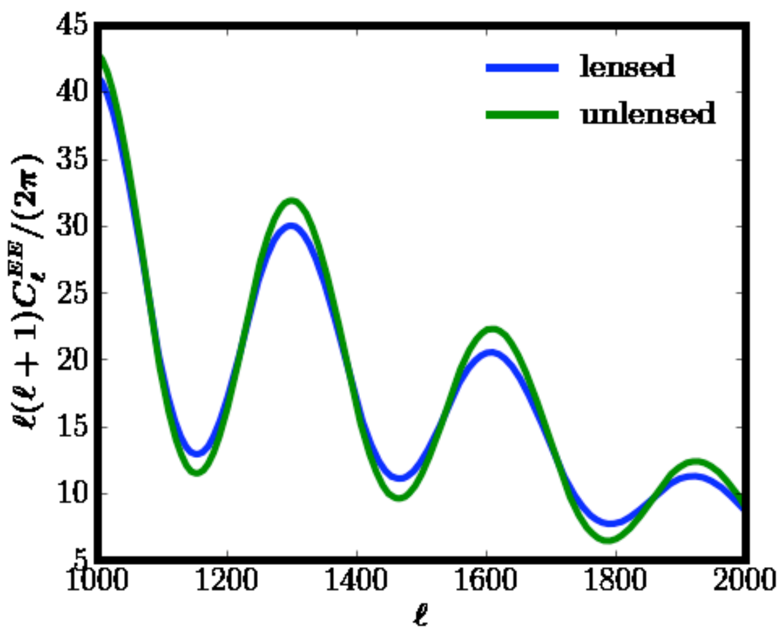
$$\Pi_{ab} = \left(\nabla_a \nabla_b - \frac{1}{2} g_{ab} \nabla^2 \right) \phi$$

Linear evolution + scalar sources -> E-modes

Lensing smooths the acoustic peaks and adds power in the damping tail (but is not a large effect in the E-mode spectrum)

peak: 40 (uK)^2





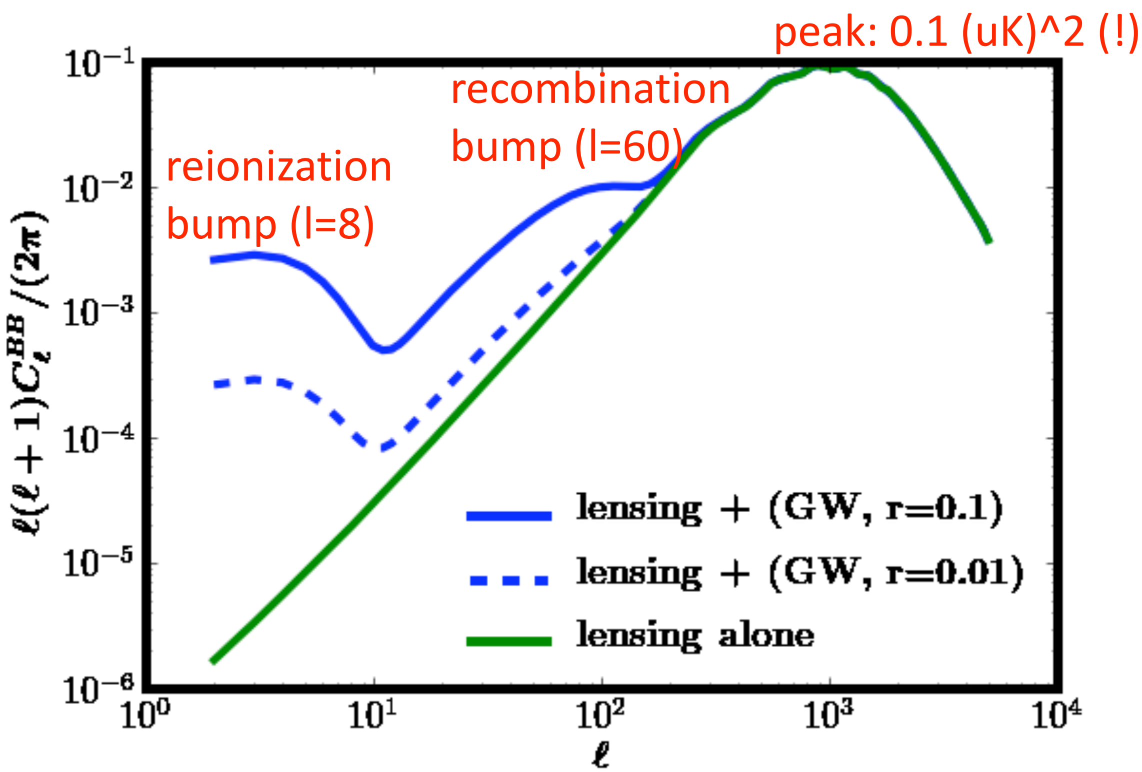
CMB lensing: B-mode power spectrum

"Curl-like" mode in polarization Π_{ab}

$$\Pi_{ab} = \frac{1}{2}\left(\epsilon_{ac}\nabla_b + \epsilon_{bc}\nabla_a\right)\nabla^c\phi$$

Non-scalar sources (e.g. GW background parameterized by tensor-to-scalar ratio r)
OR nonlinear evolution -> B-modes

Gravitational lensing is largest guaranteed B-mode (second-order effect)
Can think of lensing as converting primary E-mode to mixture of E and B

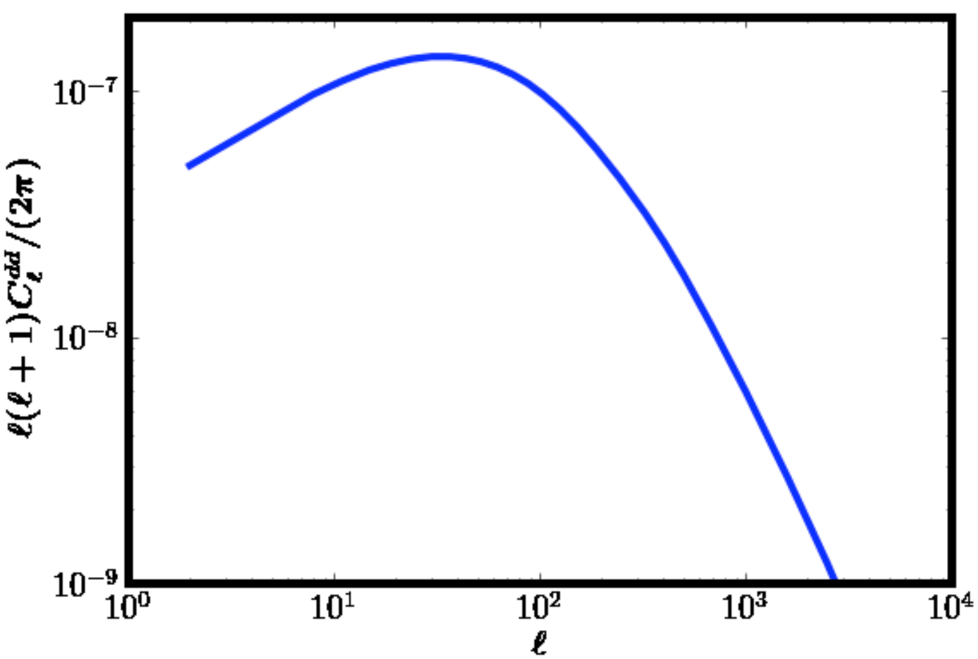


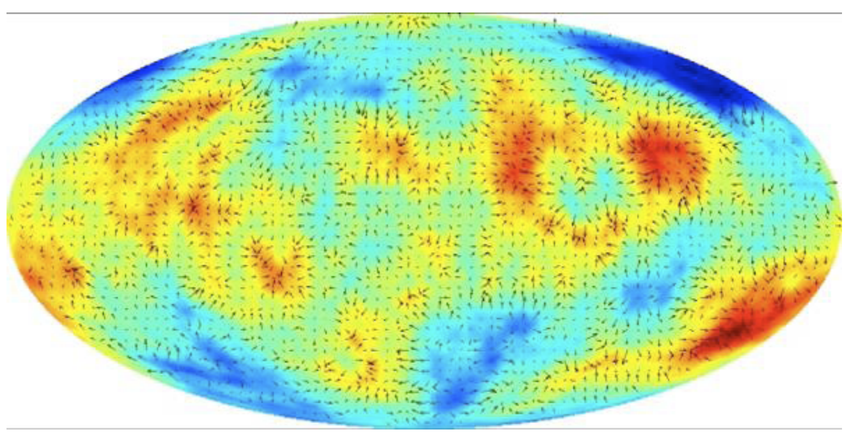
CMB lensing: deflection field

No curl component: $$d_a(\widehat{\mathbf{n}}) = -2\nabla_a \int_0^{\chi_*} d\chi \left(\frac{\chi_* - \chi}{\chi\chi_*}\right) \Psi(\chi\widehat{\mathbf{n}}, \eta_0 - \chi)$$

Radial kernel in line-of-sight integral is broadly peaked at z~2
Power spectrum broadly peaked at l~40, RMS of deflection field = 2.5 arcmin

"Degree-sized lenses carrying arcminute-sized deflections, sourced by LSS at z~2"





Antony Lewis

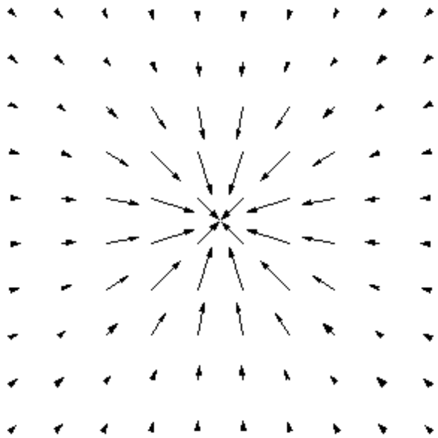
Outline

1. Lens reconstruction estimators
   A general framework for constructing higher-point statistics for lensing

2. Cosmological information from CMB lensing
   Neutrino mass, dark energy, spatial curvature

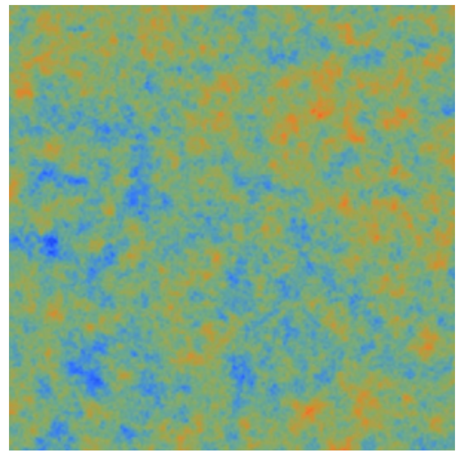
3. Gravitational lensing as a contaminant of the gravity wave B-mode
   Prospects for "delensing"

CMB lens reconstruction: idea



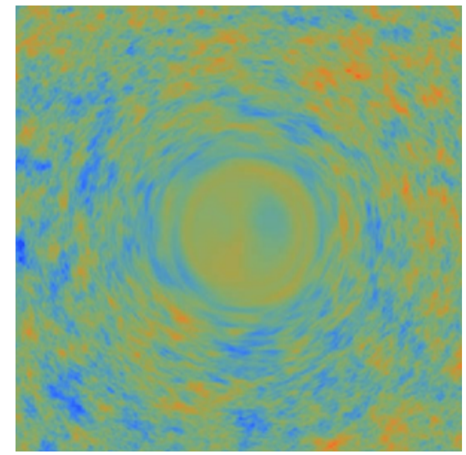
Deflection angles

+



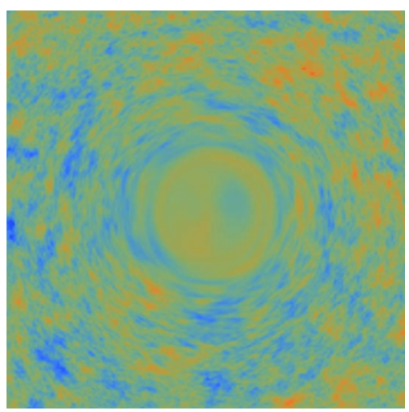
Unlensed CMB

$\longrightarrow$



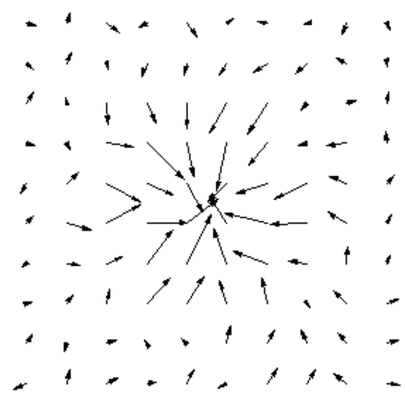
Lensed CMB

Idea: from observed CMB, reconstruct deflection angles (Hu 2001)



Lensed CMB

$\longrightarrow$



Reconstruction + noise

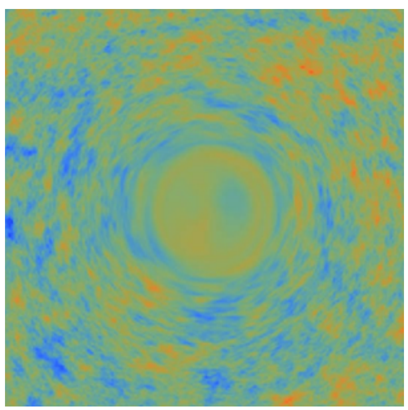
CMB lens reconstruction: quadratic estimator

Lensing potential weakly correlates Fourier modes with $\mathbf{l} \neq \mathbf{l}'$

$$\langle T(\mathbf{l}) T(\mathbf{l}')^* \rangle \propto [-\mathbf{l}' \cdot (\mathbf{l} - \mathbf{l}')] C_{\ell'}^{TT} \varphi(\mathbf{l} - \mathbf{l}')$$

Formally: can define estimator $\widehat{\varphi}(\mathbf{l})$ which is **quadratic** in CMB temperature:

$$\widehat{\varphi}(\mathbf{l}) \propto \int \frac{d^2 \mathbf{l}_1}{(2\pi)^2} [(\mathbf{l} \cdot \mathbf{l}_1) C_{l_1} + (\mathbf{l} \cdot \mathbf{l}_2) C_{l_2}] \frac{T(\mathbf{l}_1) T(\mathbf{l}_2)}{C_{l_1}^{\mathrm{tot}} C_{l_2}^{\mathrm{tot}}} \qquad (\mathbf{l}_2 = \mathbf{l} - \mathbf{l}_1)$$



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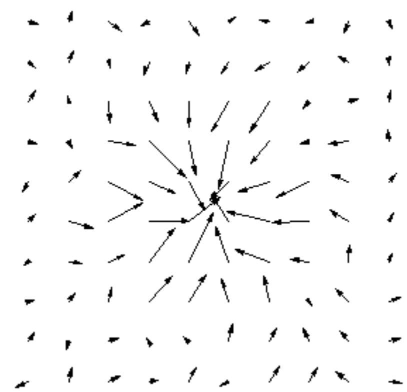


Lensed CMB

Reconstruction + noise

Intuitively: use hot and cold spots of CMB as local probes of lensing potential (analagous to cosmic shear: galaxy ellipticities are used as probes)

CMB lens reconstruction: higher-point statistics

Lens reconstruction naturally leads to higher-point statistics

e.g. take CMB temperature $T(\mathbf{n})$

$\longrightarrow \widehat{\varphi}(\mathbf{l})$ (apply quadratic estimator)

$\longrightarrow \widehat{C}_\ell^{\varphi\varphi}$ (take power spectrum)

defines 4-point estimator in the CMB

Or: take CMB temperature $T(\mathbf{n})$, galaxy counts $g(\mathbf{n})$

$\longrightarrow \widehat{\varphi}(\mathbf{l})$ (apply quadratic estimator)

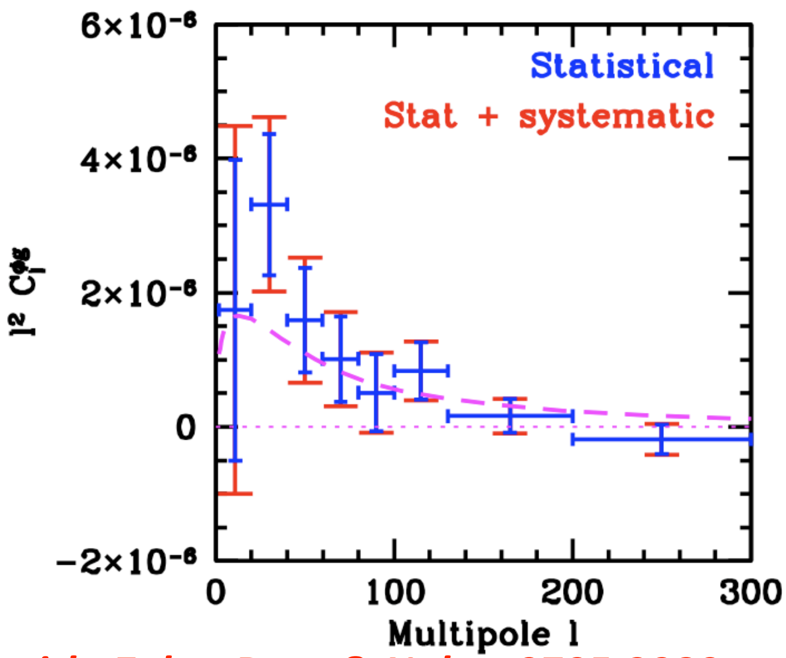
$\longrightarrow \widehat{C}_\ell^{\varphi g}$ (take cross power spectrum)

Defines (2+1)-point estimator in the (CMB,galaxy) fields

Can think of the lensing signal formally as a contribution to the 3-point or 4-point function, but lens reconstruction is more intuitive

CMB lens reconstruction: WMAP-NVSS analysis

		Beam			Galactic			Point source + SZ			
$(\ell_{\min}, \ell_{\max})$	Statistical	Asymmetry	Uncertainty	Total	Dust	Free-free	Total	Unresolved	Resolved	Total	Stat + systematic
(2, 20)	17.4 ± 22.4	± 0.9	± 0.3	± 1.2	± 0.4	± 1.4	± 3.6	± 10.9	± 0.5	± 11.4	17.4 ± 27.4
(20, 40)	33.2 ± 10.5	± 0.2	± 0.1	± 0.3	± 0.2	± 0.5	± 1.4	± 4.9	± 1.0	± 5.9	33.2 ± 13.0
(40, 60)	15.9 ± 7.8	± 0.1	± 0.1	± 0.2	± 0.2	± 0.3	± 1.0	± 2.8	± 1.5	± 4.3	15.9 ± 9.3
(60, 80)	10.1 ± 6.3	± 0.1	± 0.1	± 0.2	± 0.1	± 0.3	± 0.8	± 2.0	± 0.3	± 2.3	10.1 ± 7.0
(80, 100)	5.1 ± 5.8	± 0.1	± 0.1	± 0.2	± 0.1	± 0.3	± 0.8	± 1.1	± 0.2	± 1.3	5.1 ± 6.0
(100, 130)	8.3 ± 4.3	± 0.1	< 0.1	± 0.2	± 0.1	± 0.2	± 0.6	± 0.6	± 0.2	± 0.8	8.3 ± 4.4
(130, 200)	1.6 ± 2.5	< 0.1	< 0.1	± 0.1	± 0.1	± 0.1	± 0.4	± 0.3	± 0.1	± 0.4	1.6 ± 2.6
(200, 300)	-1.9 ± 2.2	< 0.1	< 0.1	± 0.1	± 0.1	± 0.1	± 0.4	± 0.3	± 0.1	± 0.4	-1.9 ± 2.3



Detection significance: fit in one large bandpower, in multiple of fiducial model

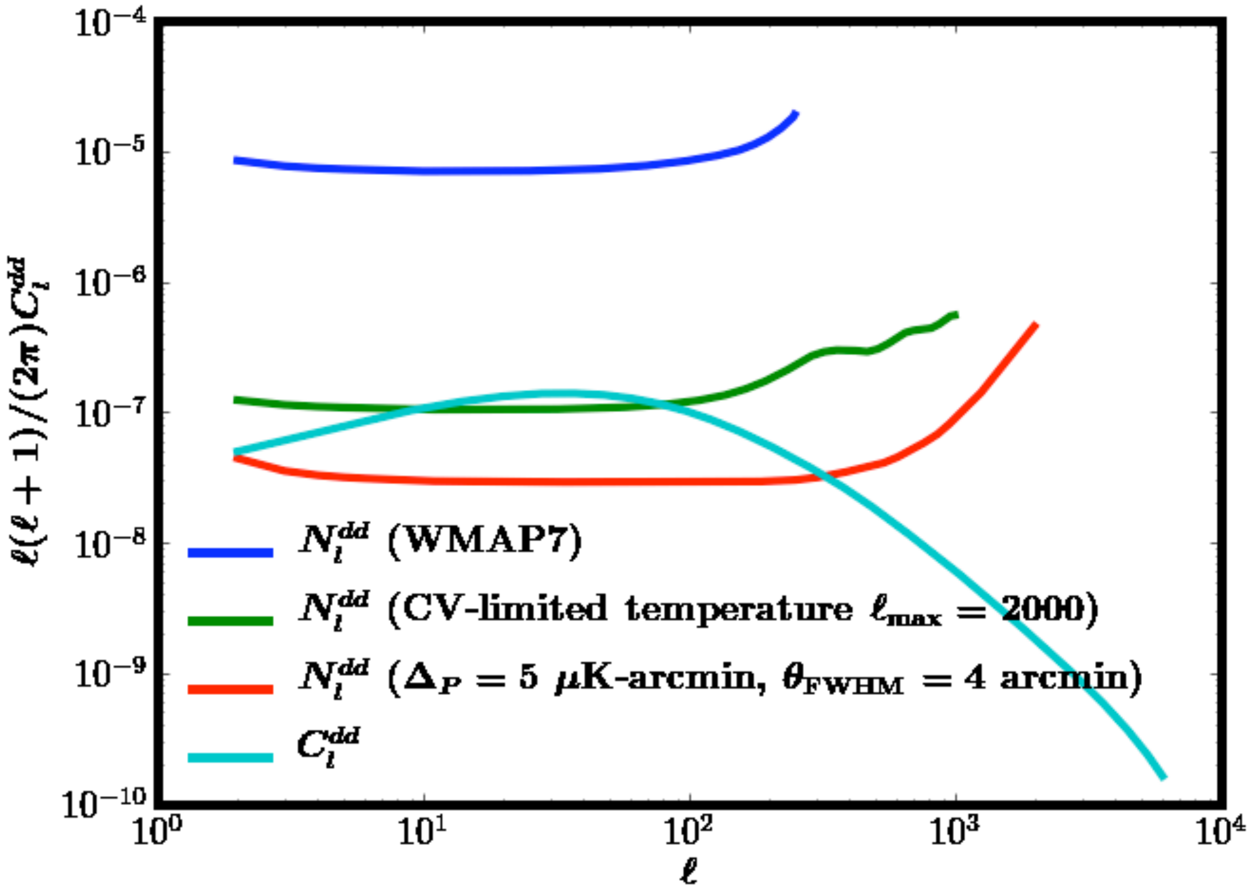
Result: 1.15 +/- 0.34, i.e. a 3.4 sigma detection, in agreement with the expected level

Systematic errors were found to be small

Smith, Zahn, Dore & Nolta, 0705.3980

(see also Hirata et al 2008)

CMB lens reconstruction: future prospects



We are entering an era where high-resolution CMB experiments will "contain" lensing experiments

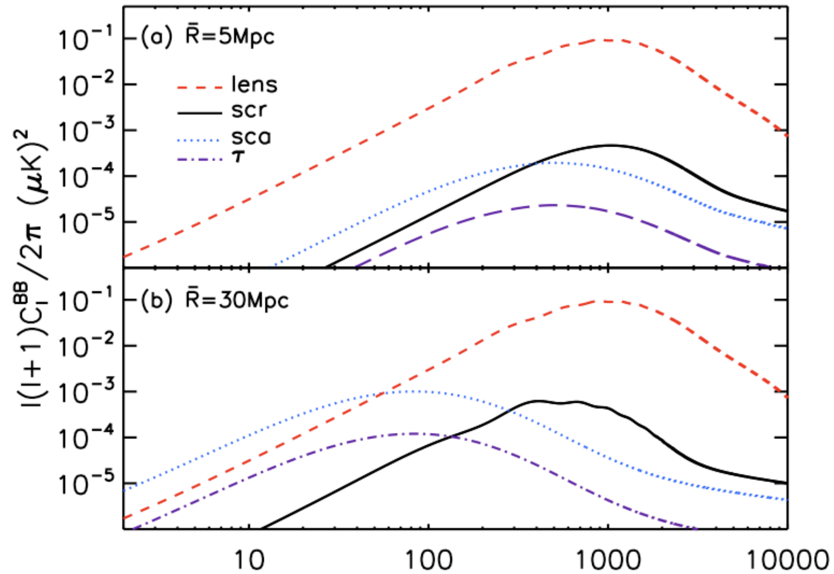
Polarization is ultimately more sensitive than temperature (because of B-mode)

Beyond the lensing B-mode: patchy reionization

Reionization bubbles generate B-modes:

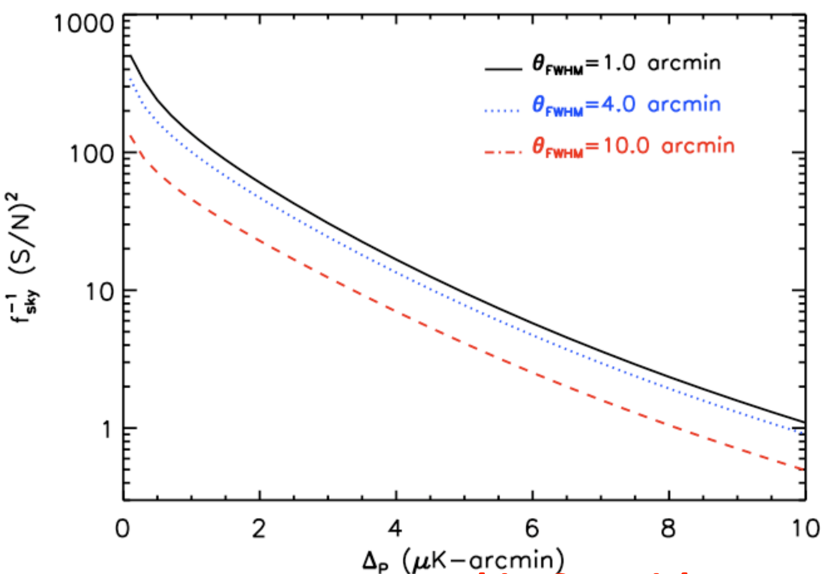
Via scattering (dominates on large scales)

Via screening (larger effect on small scales)



Dvorkin, Hu & Smith 0902.4413

Can construct quadratic estimator to reconstruct bubbles (analogous to lens reconstruction, with deflection field $d_a(\mathbf{n})$ replaced by optical depth $\Delta\tau(\mathbf{n})$)



Dvorkin & Smith, 0812.1566

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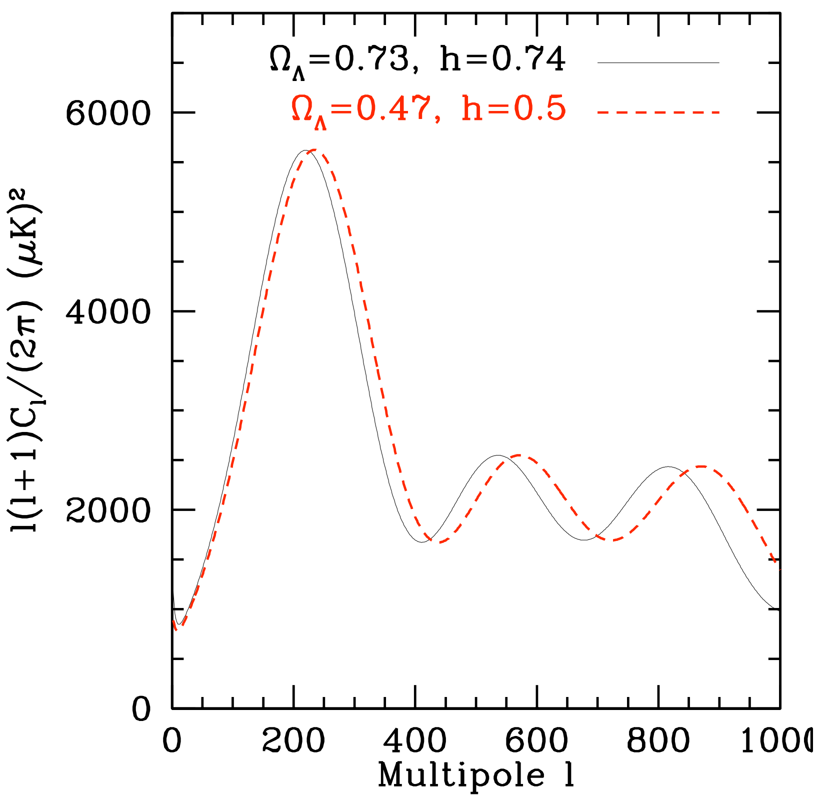
Angular diameter distance degeneracy in unlensed CMB

Consider the WMAP six-parameter space: $\{\Omega_b h^2, \Omega_m h^2, A_s, \tau, n_s, \Omega_\Lambda\}$

First 5 parameters are well-constrained through shape of power spectrum

Constraint on Ω_Λ comes entirely through angular peak scale:

$$\ell_a = \pi \frac{D_*}{s_*} \quad \begin{array}{l} \longleftarrow \text{ angular diameter distance to recombination} \\ \longleftarrow \text{ distance sound can travel before recombination} \end{array}$$



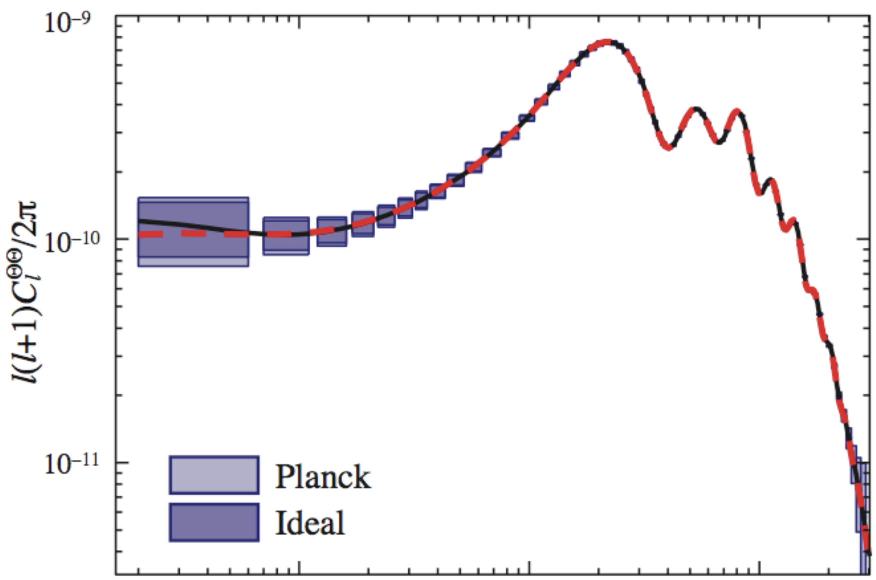
Suppose that N "late universe" parameters $(\Omega_K, m_\nu, w, w_a, \ldots)$ are added.

Then only one combination (corresponding to D_*) is constrained by the CMB

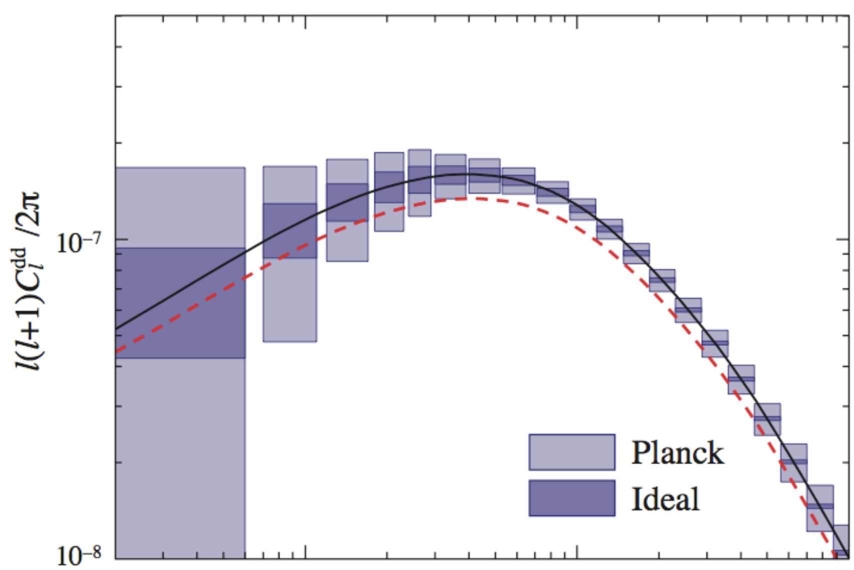
Generates N-fold "angular diameter distance degeneracy" in parameter space

CMB lensing breaks the angular diameter distance degeneracy

Example from Hu 2001: w=-1 and w=-2/3 models with same D_*



Unlensed temperature power spectrum



Deflection angle power spectrum

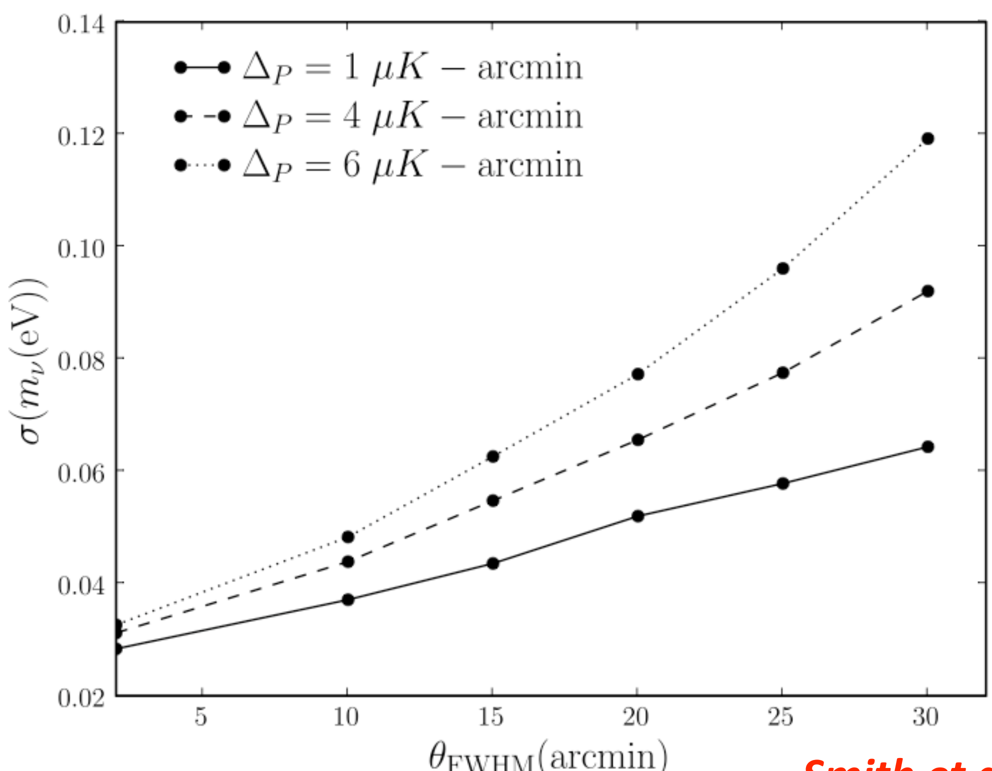
Neutrino mass

Neutrino oscillation experiments measure Δm_ν^2 between species

Current combined analysis of world data: $\Delta m_{31}^2 = (0.049 \text{ eV} \pm 0.0012)^2$

$$\Delta m_{21}^2 = (0.0087 \text{ eV} \pm 0.00013)^2$$

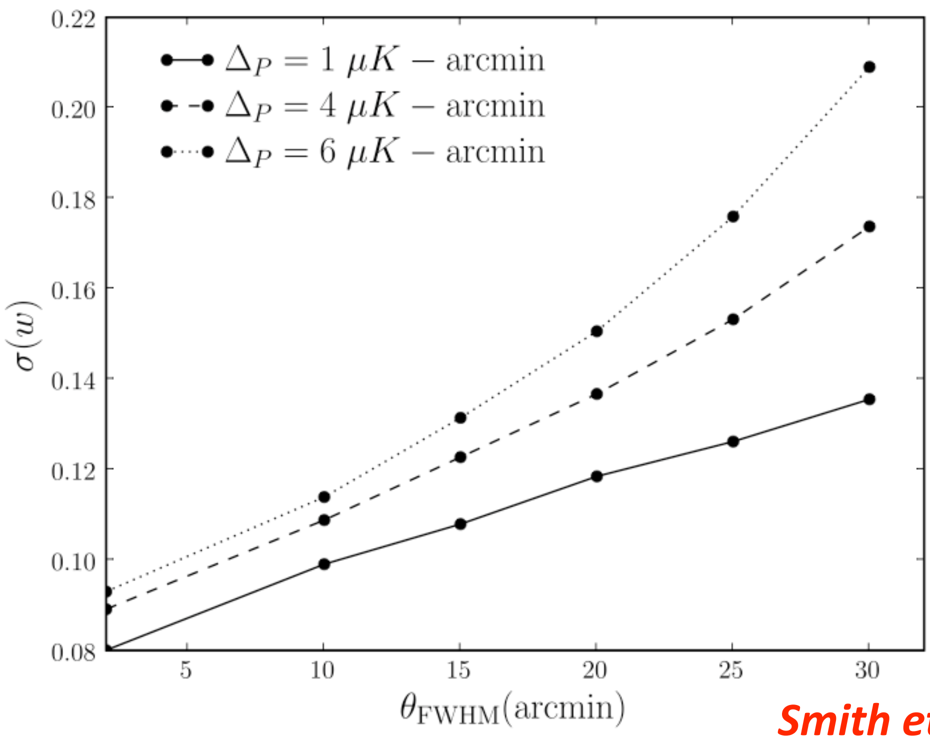
Cosmology is complementary: lensing potential is mainly sensitive to $\sum_\nu m_\nu$



Smith et al, 0811.3916

Dark energy

In many parameterizations (e.g. constant-w), CMB lensing constrains dark energy weakly because redshift kernel (peaked at z ~ 2) is poorly matched to redshifts where dark energy is important (z <~ 1)



Smith et al, 0811.3916

Early dark energy

Doran & Robbers parameterization (2006):

$$\Omega_\Lambda(a) = \frac{\Omega_\Lambda^0 - \Omega_\Lambda^e(1-a^{-3w_0})}{\Omega_\Lambda^0 + (1-\Omega_\Lambda^0)a^{3w_0}} + \Omega_\Lambda^e(1-a^{-3w_0})$$

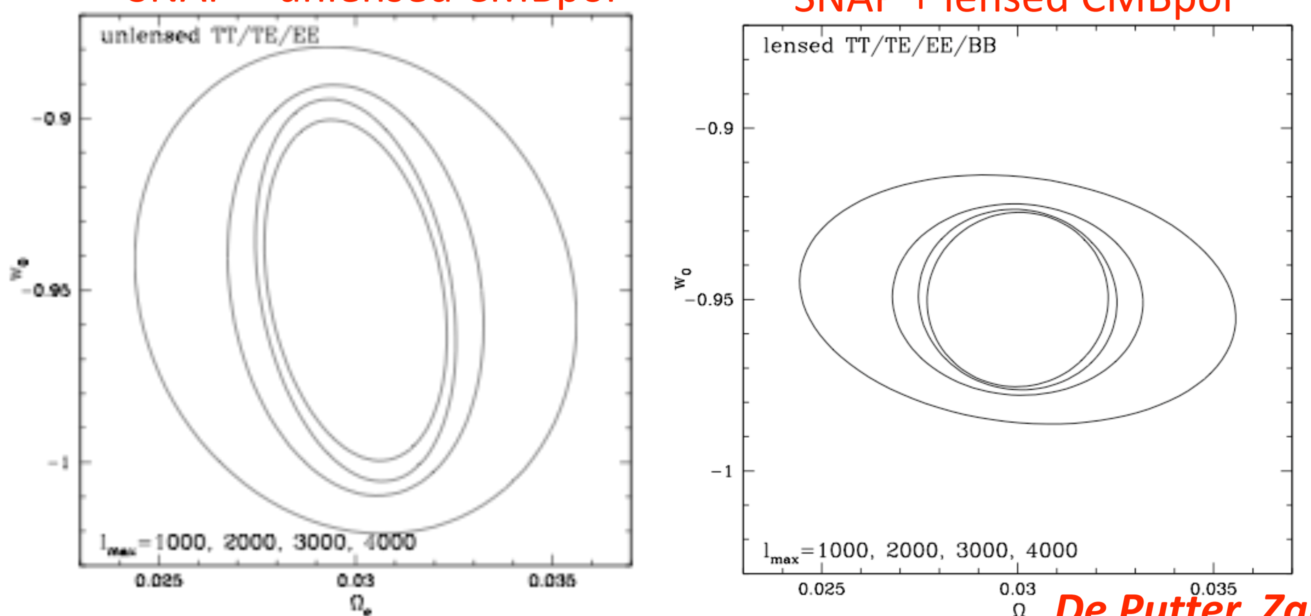
Tracker model:

As $z \to 0$ $\quad \Omega_\Lambda(z) \to \Omega_\Lambda^0$ and $w(z) \to w_0$

As $z \to \infty$ $\quad \Omega_\Lambda(z) \to \Omega_\Lambda^e$ and $w(z) \to 0$

SNAP + unlensed CMBpol

SNAP + lensed CMBpol



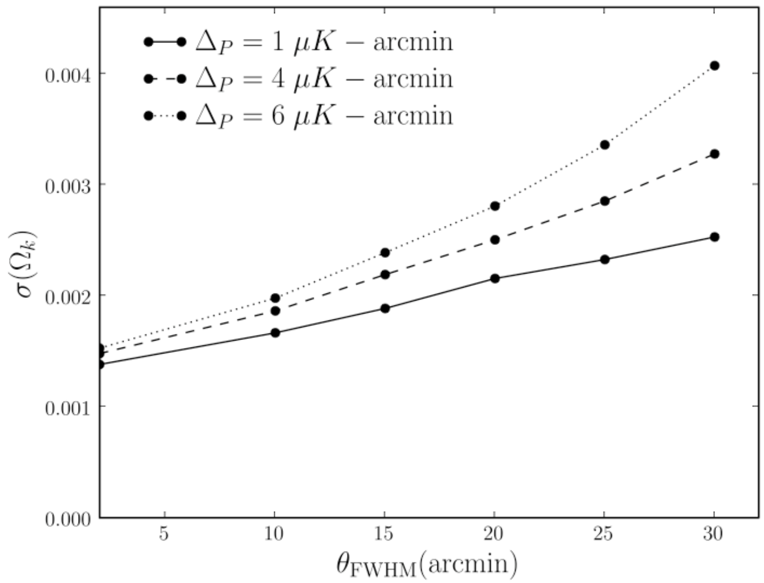
De Putter, Zahn & Linder (2009)

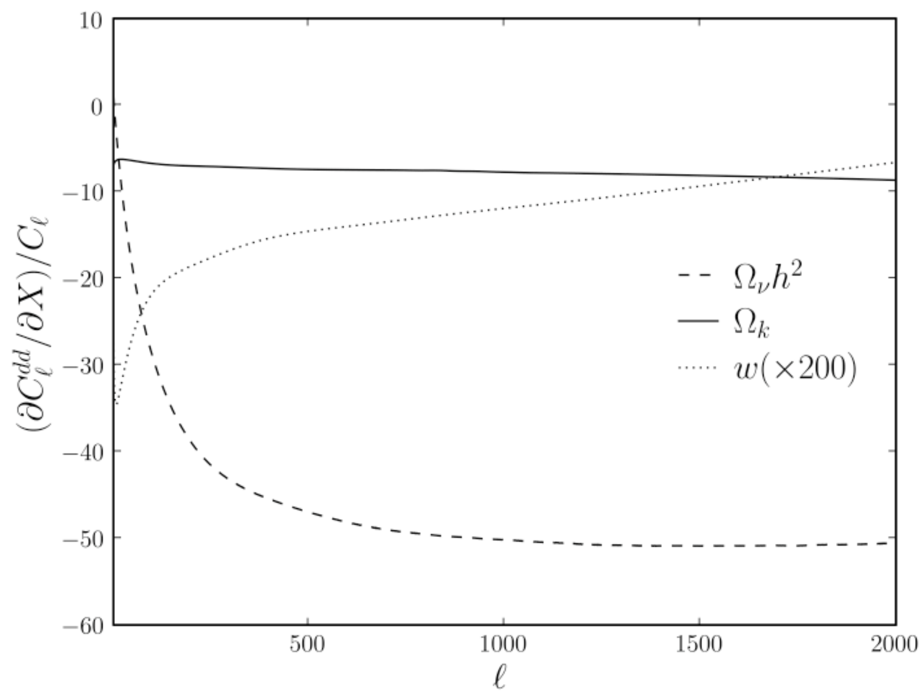
Curvature and joint constraints

CMB lensing can be used for constraining any parameter which would be "lost" in the angular diameter distance degeneracy in the unlensed CMB

Because full deflection power spectrum is measured, can constrain multiple parameters simultaneously

$$
\begin{array}{cc}
 & \begin{array}{ccc} \sum m_\nu & w & \Omega_K \end{array} \\
\begin{array}{c} \sum m_\nu \\ w \\ \Omega_K \end{array} & \begin{pmatrix} 1 & 0.34 & -0.82 \\ 0.34 & 1 & -0.63 \\ -0.82 & -0.63 & 1 \end{pmatrix}
\end{array}
$$





Smith et al, 0811.3916

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Gravity wave B-mode as a probe of inflation

Qualitative distinction between models with detectable r and undetectably small r e.g. in context of single-field inflation with canonical kinetic term,

$$S = \int d^4x \sqrt{-g} \left(\frac{M_{Pl}^2}{2} R - \frac{1}{2} (\partial\phi)^2 - V(\phi) \right)$$

models with detectable gravity waves are models in which:

energy scale of inflation is GUT-scale

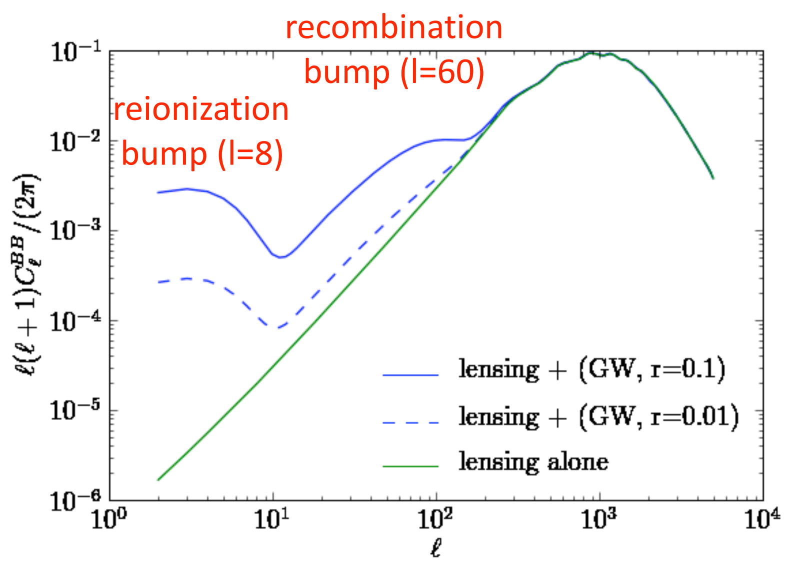
$$\rho^{1/4} = (3.35 \times 10^{16}\,\mathrm{GeV})(r^{1/4})$$

change in inflaton per e-folding is Planck scale

$$(d\phi)/(d\log a) = (0.354\, M_{\mathrm{Pl}})(r^{1/2})$$

time per e-folding is a few x 10^5 Planck times

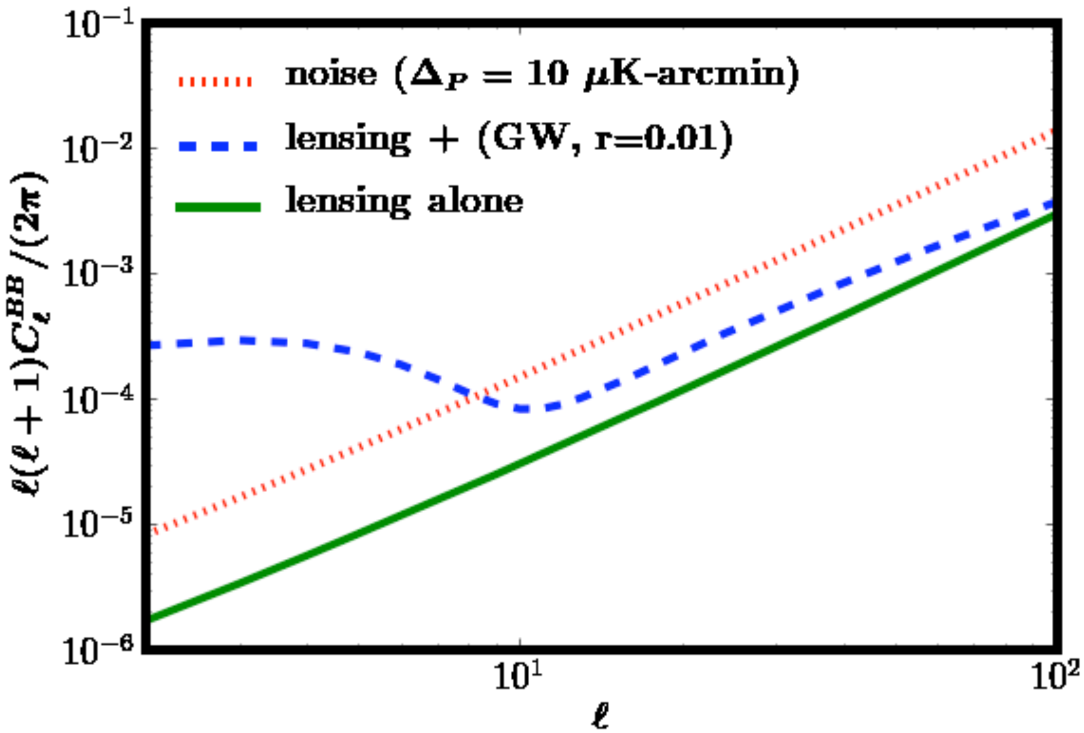
$$(dt)/(d\log a) = (9150\, M_{\mathrm{Pl}}^{-1})(r^{-1/2})$$



B-mode power spectra at low l

Lensing looks like white noise with amplitude $(\Delta_P)_{\text{lensing}} = 5.5\ \mu\text{K-arcmin}$

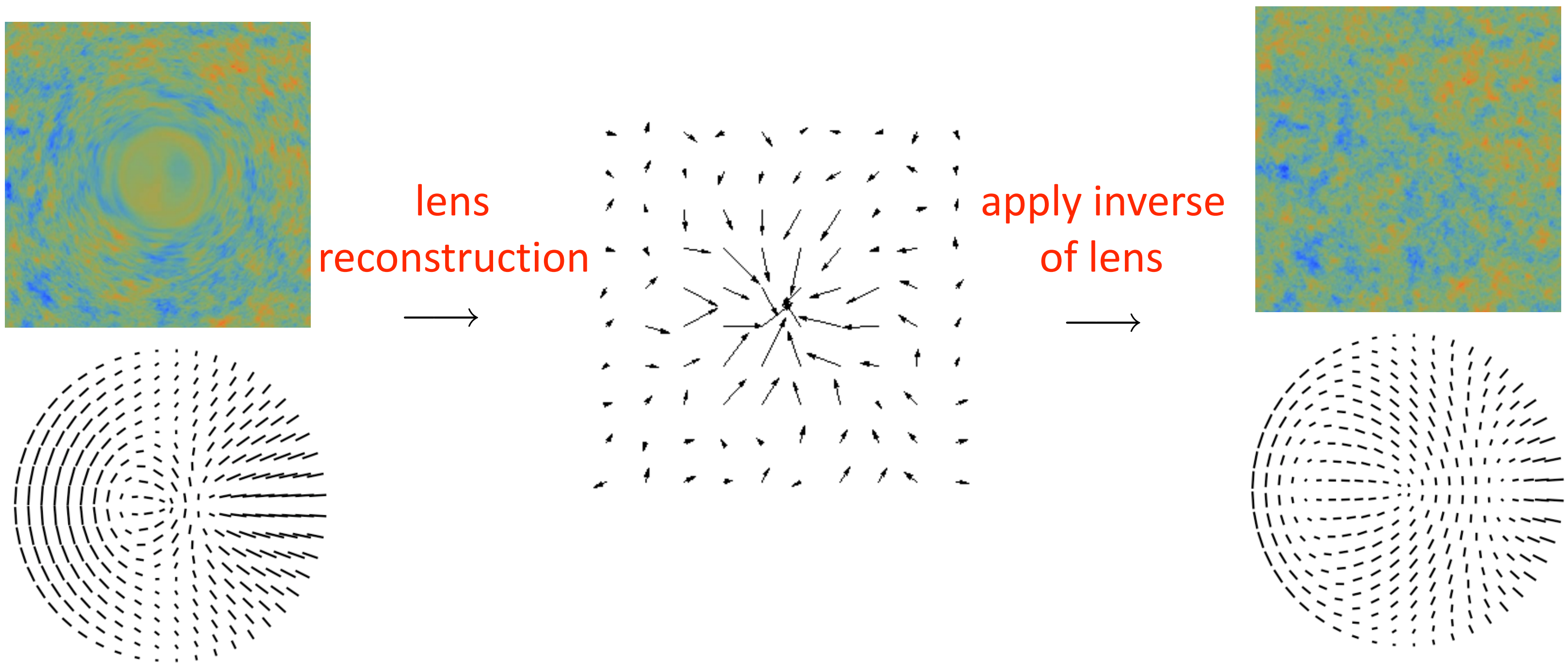
Combines with instrumental noise: $(\Delta_P)_{\text{effective}} = \sqrt{(\Delta_P)^2_{\text{instrumental}} + (\Delta_P)^2_{\text{lensing}}}$



Lensing becomes dominant source of error when instrumental noise <~ 5.5 uK-arcmin

Delensing: idea

Estimate unlensed CMB, by combining observed (lensed) CMB with statistical reconstruction of lens



Lensed CMB | Deflection angles | "Delensed" CMB

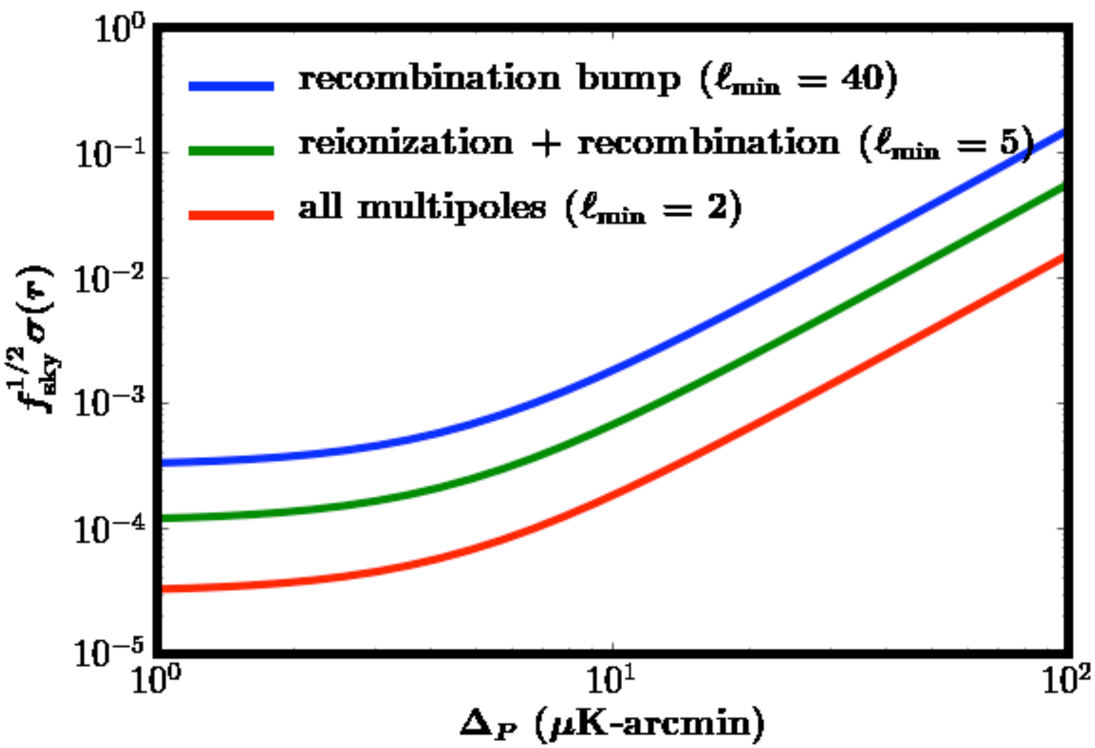
Delensed CMB has smaller lensed B-mode than original lensed CMB => improved $\sigma(r)$

Delensing uses B-mode observations on small scales to "clean" the large scales

Forecasts for "r" are very sensitive to assumptions about foregrounds

e.g. consider simple mode-counting forecast:

$$\frac{1}{\sigma(r)^2} = \frac{f_{\rm sky}}{2} \sum_\ell (2\ell+1) \left(\frac{(C_\ell^{BB})_{r=1}}{(C_\ell^{BB})_{\rm lensing} + N_\ell^{BB}} \right)^2$$



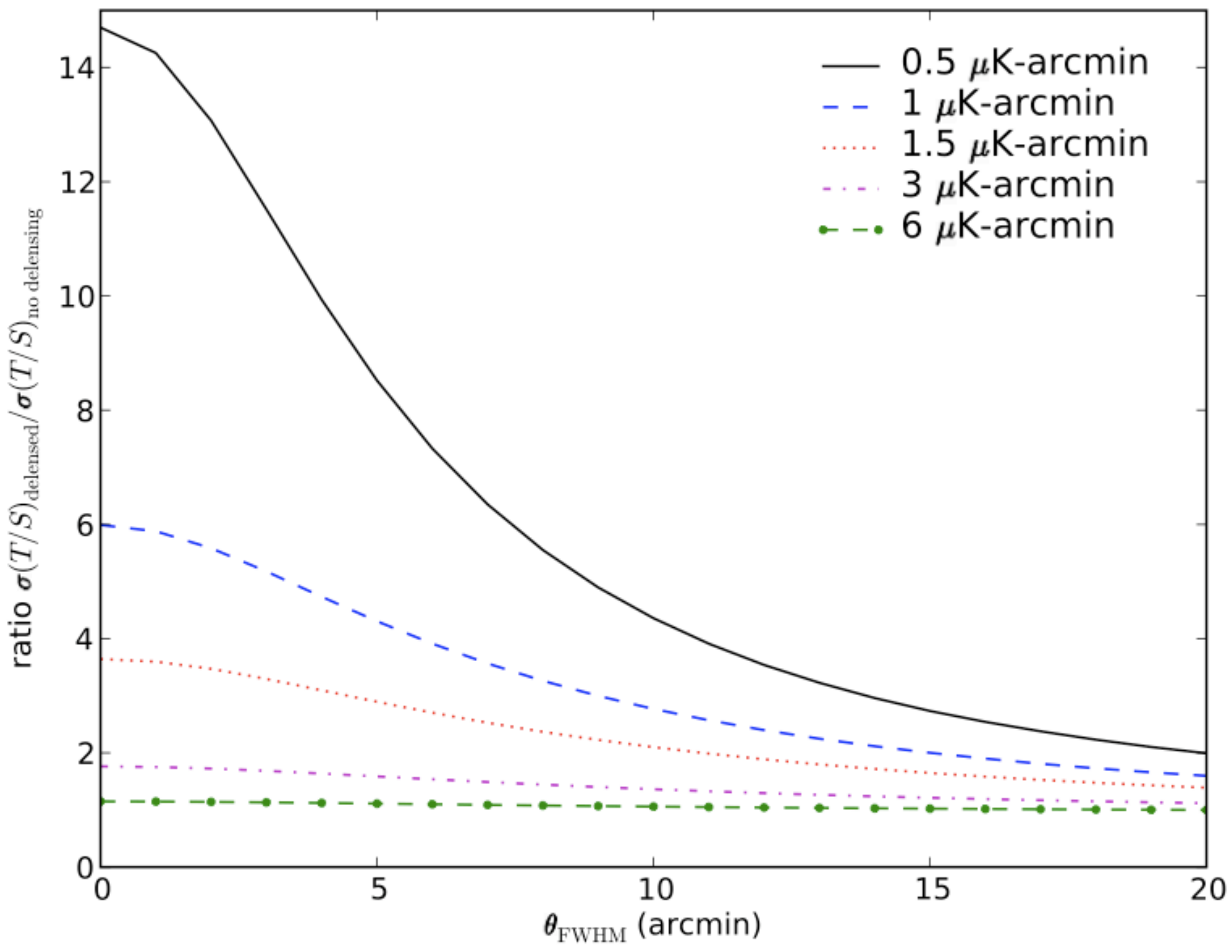
Reionization bump has 10 times the statistical weight of recombination bump

Quadrupole has the same statistical weight as all l > 2 modes combined

We will avoid quoting values for $\sigma(r)$, will instead quote foreground-independent quantities (e.g. ratio between two values of $\sigma(r)$ with same foreground assumptions)

Improvement in "r" due to delensing

For noise levels significantly better than 5 uK-arcmin, delensing with a few-arcmin beam allows one to "beat" the noise floor from lensing



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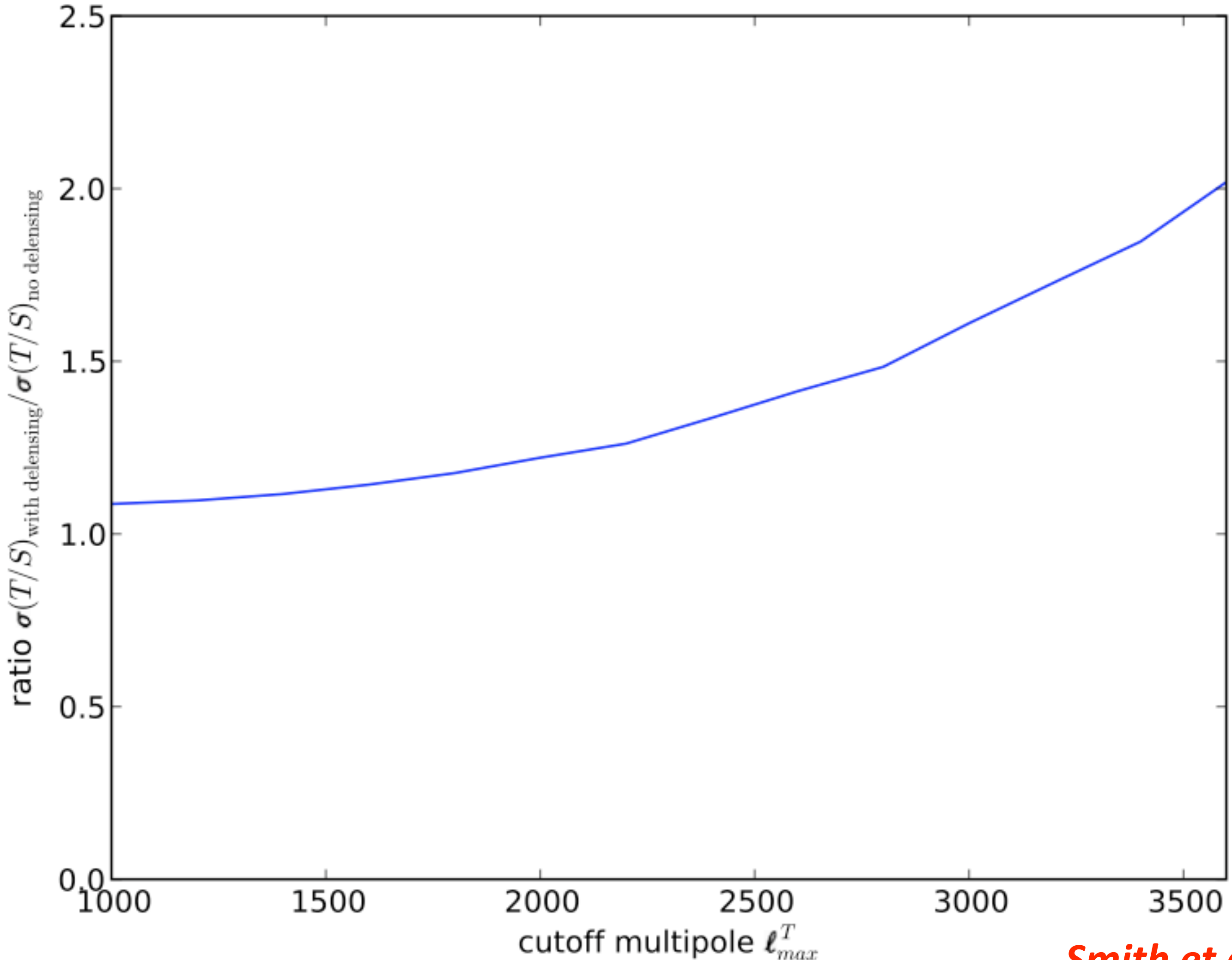
“No-go” result: cannot delens polarization using small-scale temperature

Assume (ideal temperature experiment up to lmax) + (ideal E-modes for all l)



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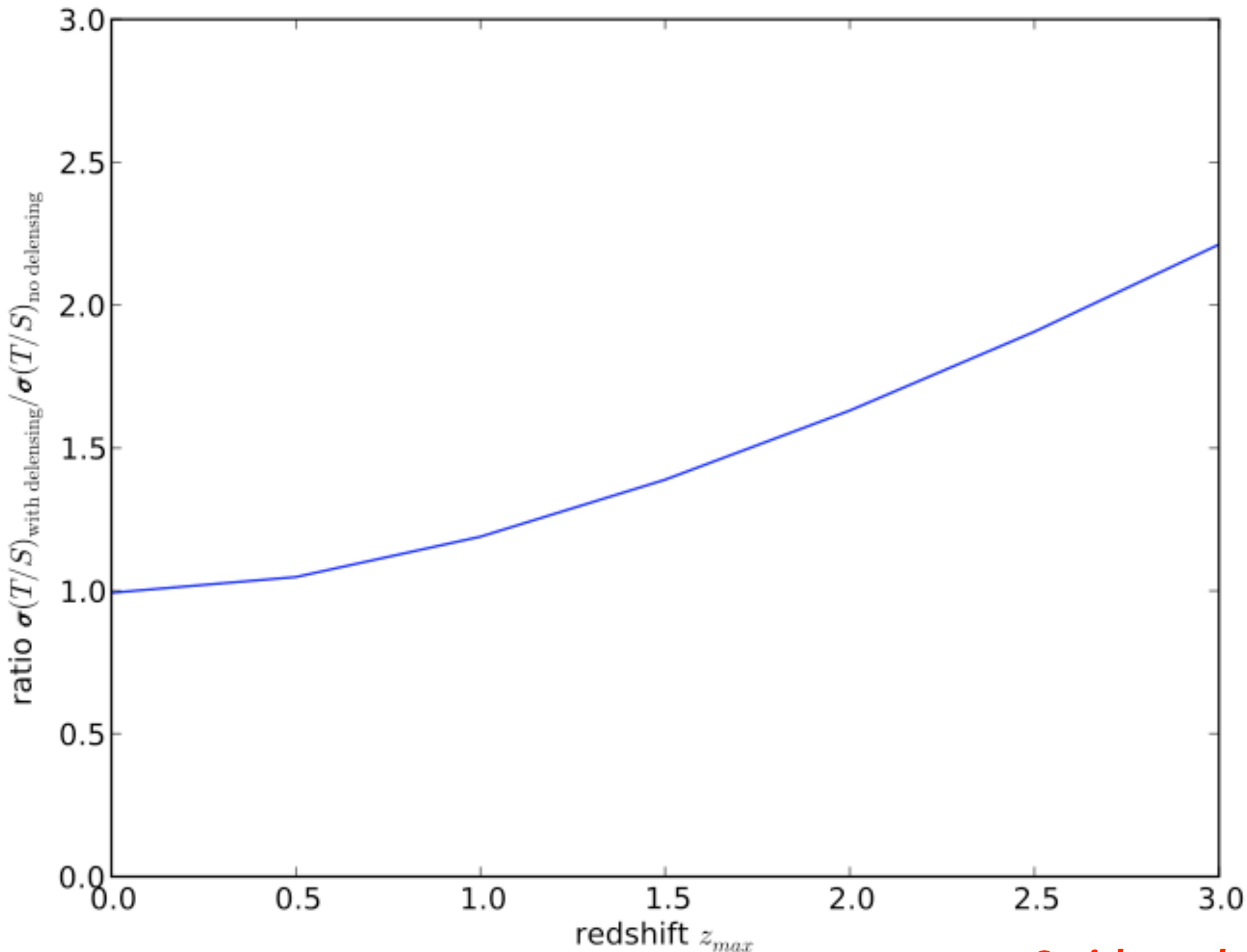
"No-go" result: cannot delens polarization using large-scale structure

Assume (ideal LSS survey out to redshift zmax) + (ideal E-modes for all l)



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Summary

Lensing can be extracted from the small-scale CMB using higher-point statistics

Breaks angular diameter distance degeneracy in unlensed CMB, maps gravitational potentials at high redshift on largest scales of universe

Polarization ultimately provides better S/N than temperature

Delensing the gravity wave B-mode: one scenario where small-scale polarization is required

Delensing allows one to beat the 5 uK-arcmin noise floor from lensing