Title: Gravitational lensing of the CMB: Self-consistency tests and other implications

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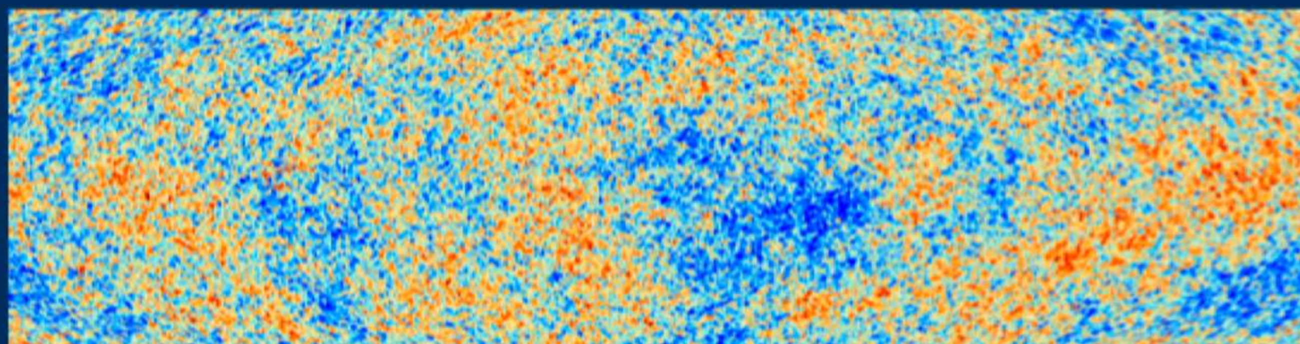
Abstract: <p>Cosmic microwave background (CMB) experiments, which currently provide some of the most powerful cosmological data sets, will become much more constraining in the near future. While these measurements promise to teach us more about the nature of dark energy, inflation and neutrino physics, increased precision will require special attention dedicated to the data analysis. In this talk I will focus on the gravitational lensing of the CMB and some of its implications. By introducing a novel analysis technique, applying it to the Planck satellite data and commenting on improvements which will be possible with a CMB Stage 4 experiment, I will first show how we can utilize CMB gravitational lensing to probe self-consistency of the CMB data sets. Then I will overview how gravitational lensing induces non-Gaussian covariances between the CMB data and how these covariances affect constraints on the cosmological parameters.</p>

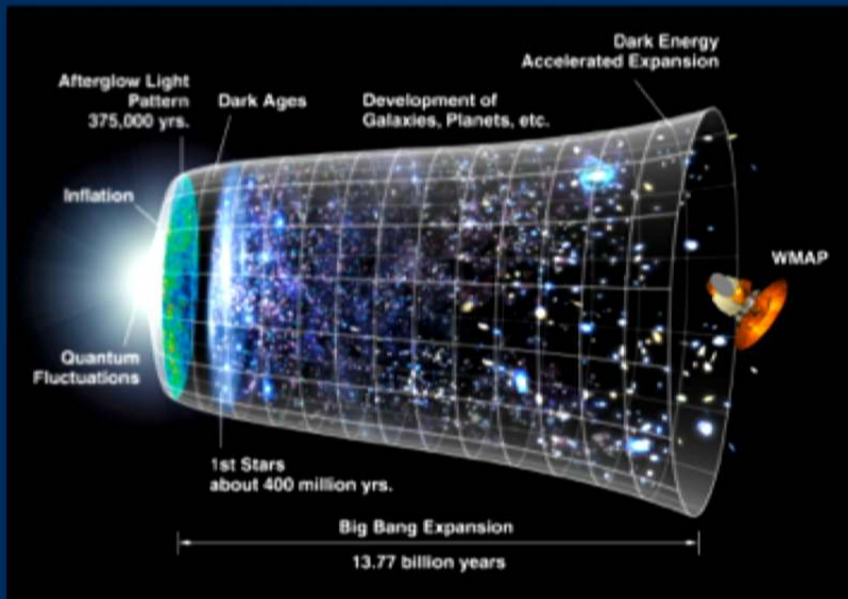
Gravitational lensing of the CMB: Self-consistency tests and other implications

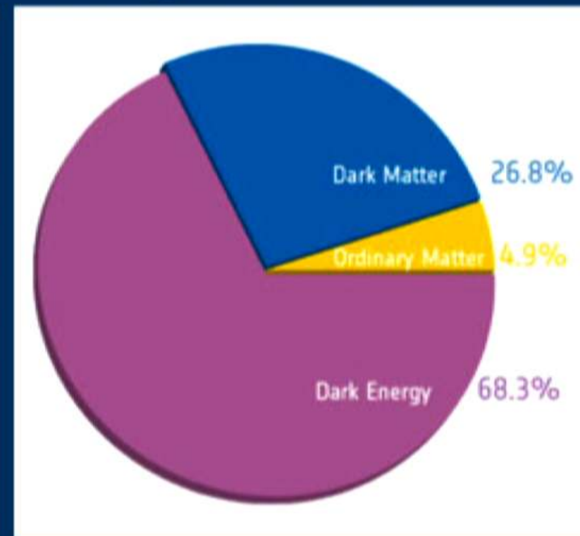


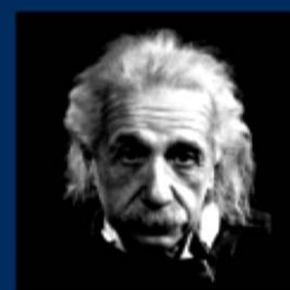
Pavel Motloch

with Wayne Hu, Aurélien Benoit-Lévy
1612.05637, 1709.03599, 1802.xxxxx

ΛCDM as standard cosmological model

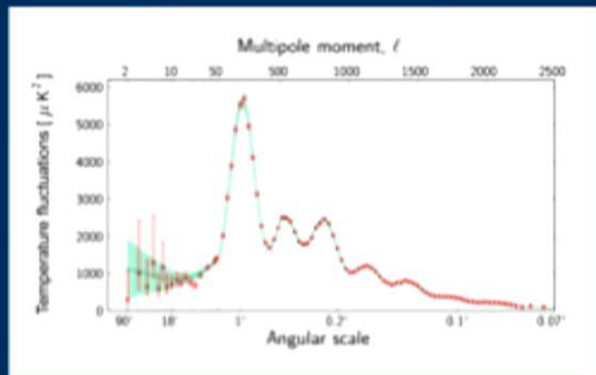




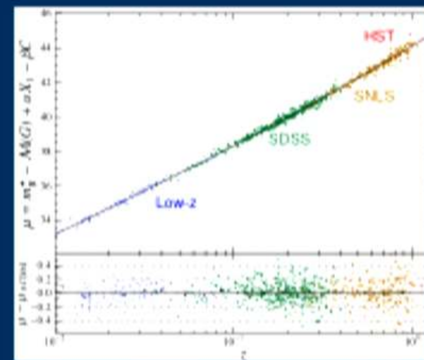


Fits data reasonably well

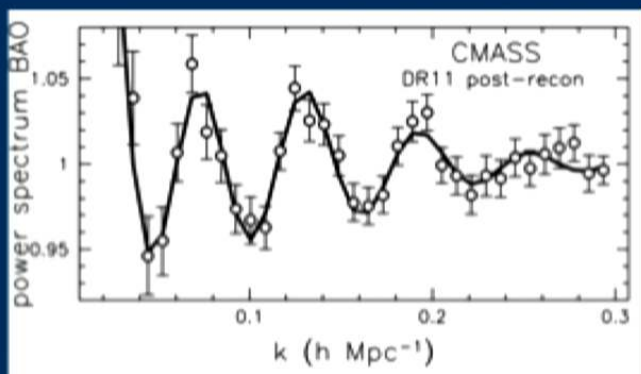
CMB
1303.5062



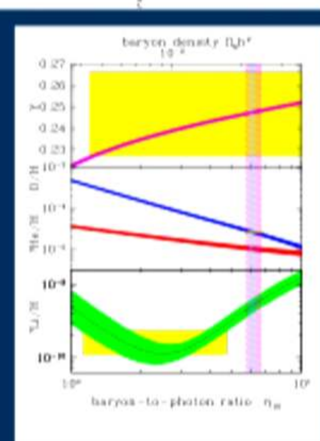
SN
1401.4064



BAO
1312.4877



BBN
1412.1408

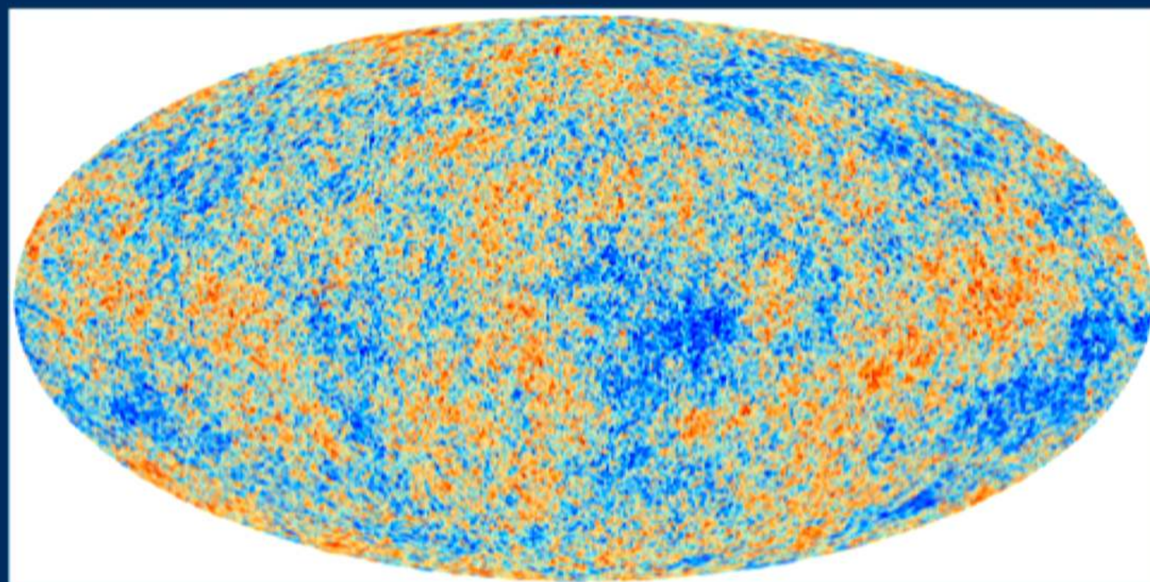


Some of the unsolved questions

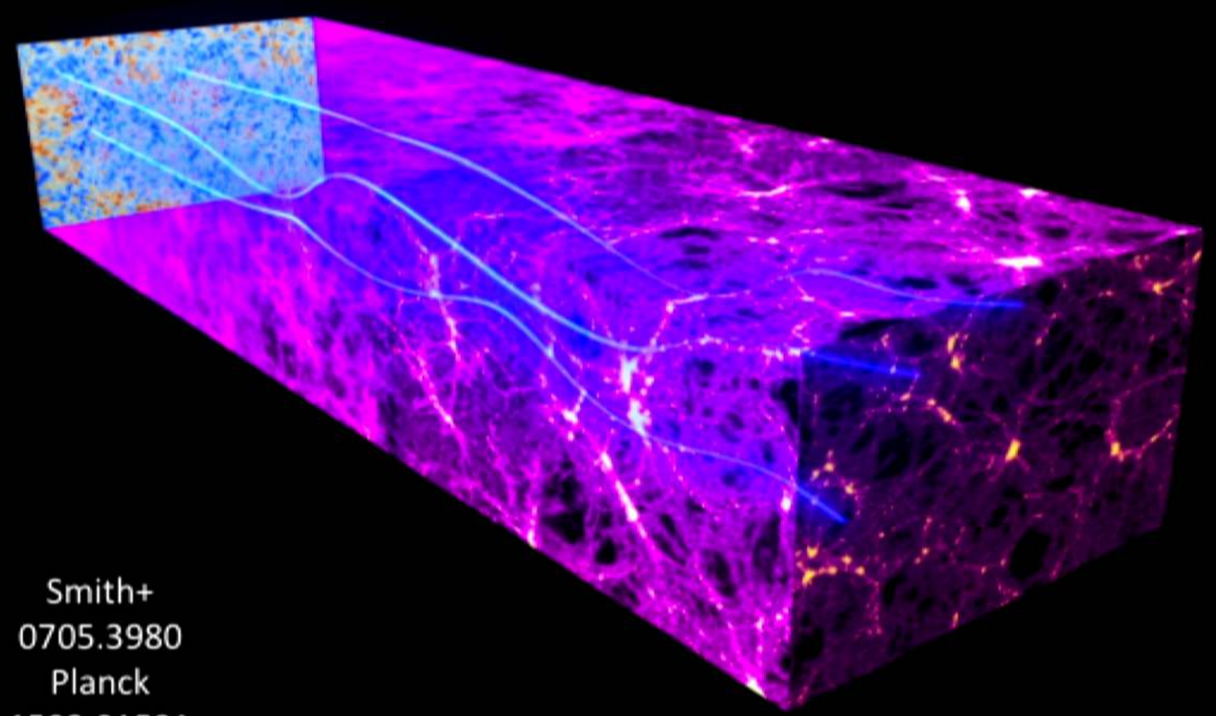
- What is dark energy? Dark matter?
- Is general relativity the correct theory?
- Inflation?
- Are the tensions (Hubble constant, …) real?

Cosmic Microwave Background

- Decoupling of photons from the plasma



Gravitational Lensing of CMB



Smith+
0705.3980
Planck
1502.01591

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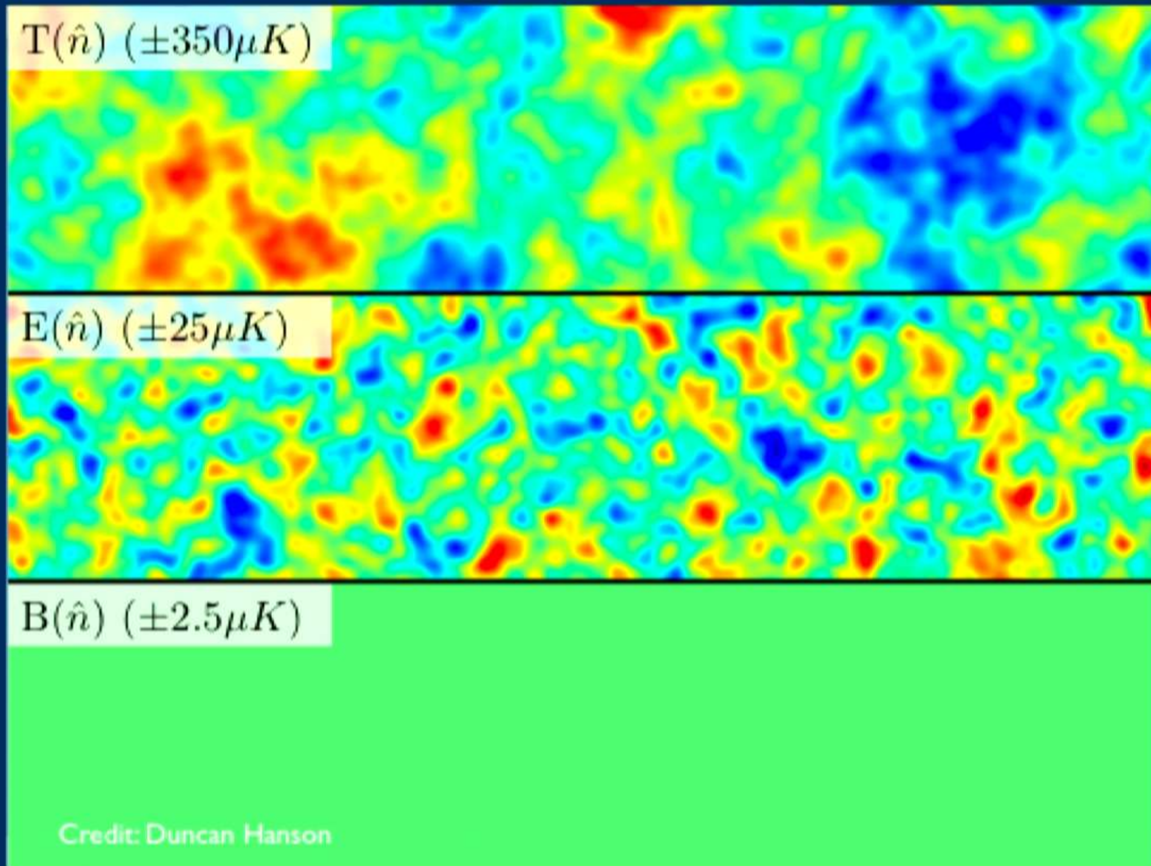
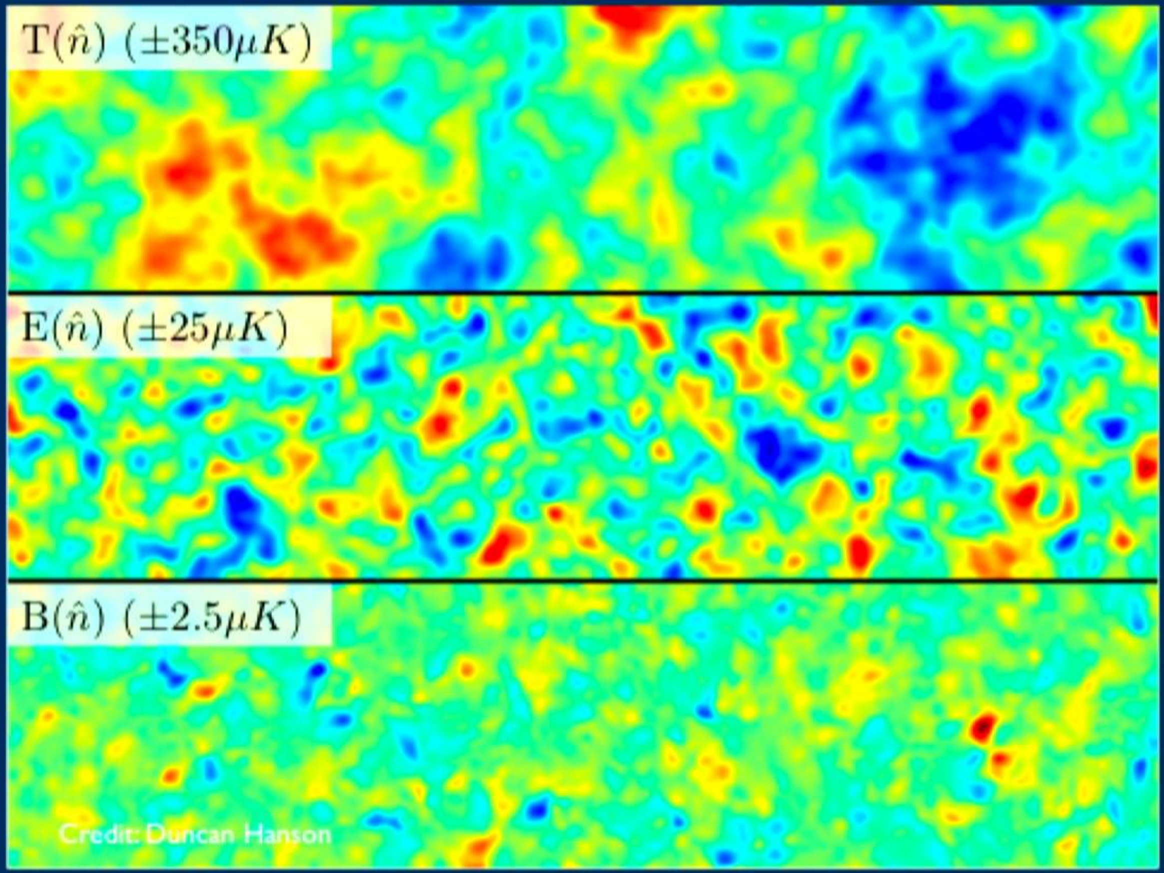
What lensing does

Unlensed



What lensing does



How to measure

- From power spectra
  - B modes
  - smoothing of the peaks

- From higher point statistics
  (lensing reconstruction)

Why we care

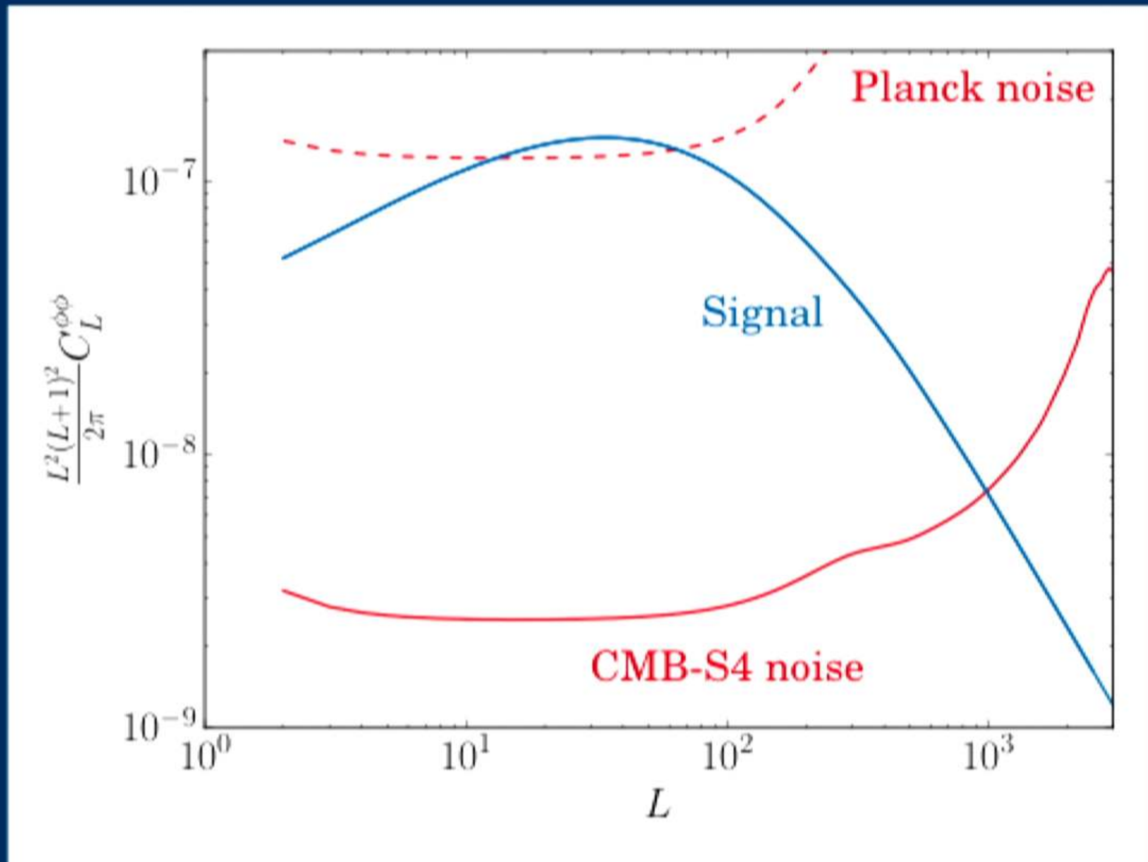
- Sensitive to low redshift physics
  - $\sum m_\nu$, dark energy
- Obscures primordial tensor modes
- Useful for cross-correlations

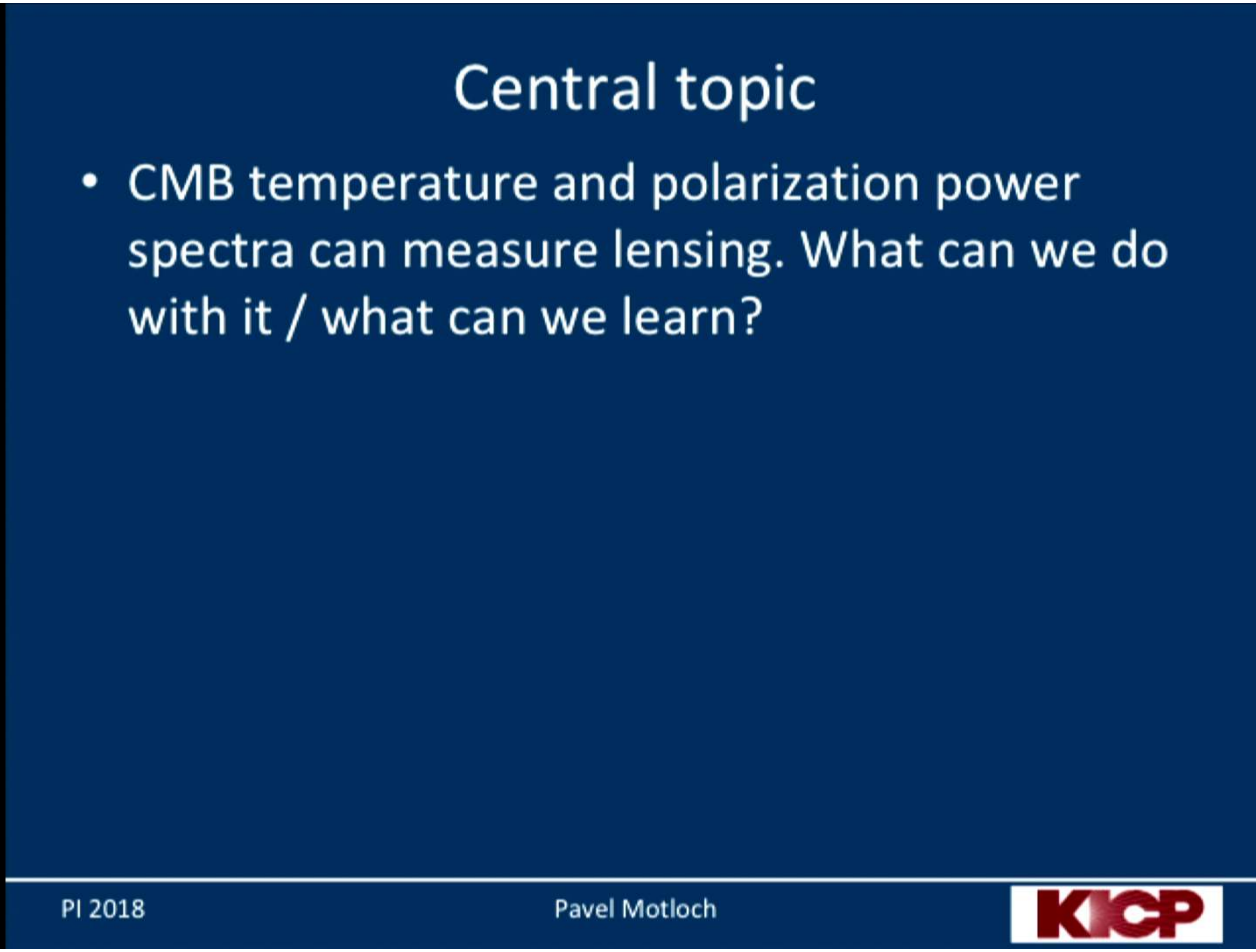
CMB Stage 4

- Active preparations
- Preliminary specs
  - 40% of the sky
  - 1 arcmin resolution
  - 1 uK-arcmin noise

➔ Great lensing measurements

Lensing reconstruction noise




Central topic
• CMB temperature and polarization power spectra can measure lensing. What can we do with it / what can we learn?
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PLANCK LENSING IS IN TENSION

Something about Planck lensing (?) is off

- Scaling parameter A_L

$$C_L^{\phi\phi} \rightarrow A_L C_L^{\phi\phi}$$

Planck
1502.01589

- From Planck data

$$A_L = 1.22 \pm 0.10$$

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Disadvantages of A_L

- Only changing the amplitude of $C_L^{\phi\phi}$, not shape (slope, …)
- Physical interpretation?
- How to compare with lensing reconstruction?

There is a better way

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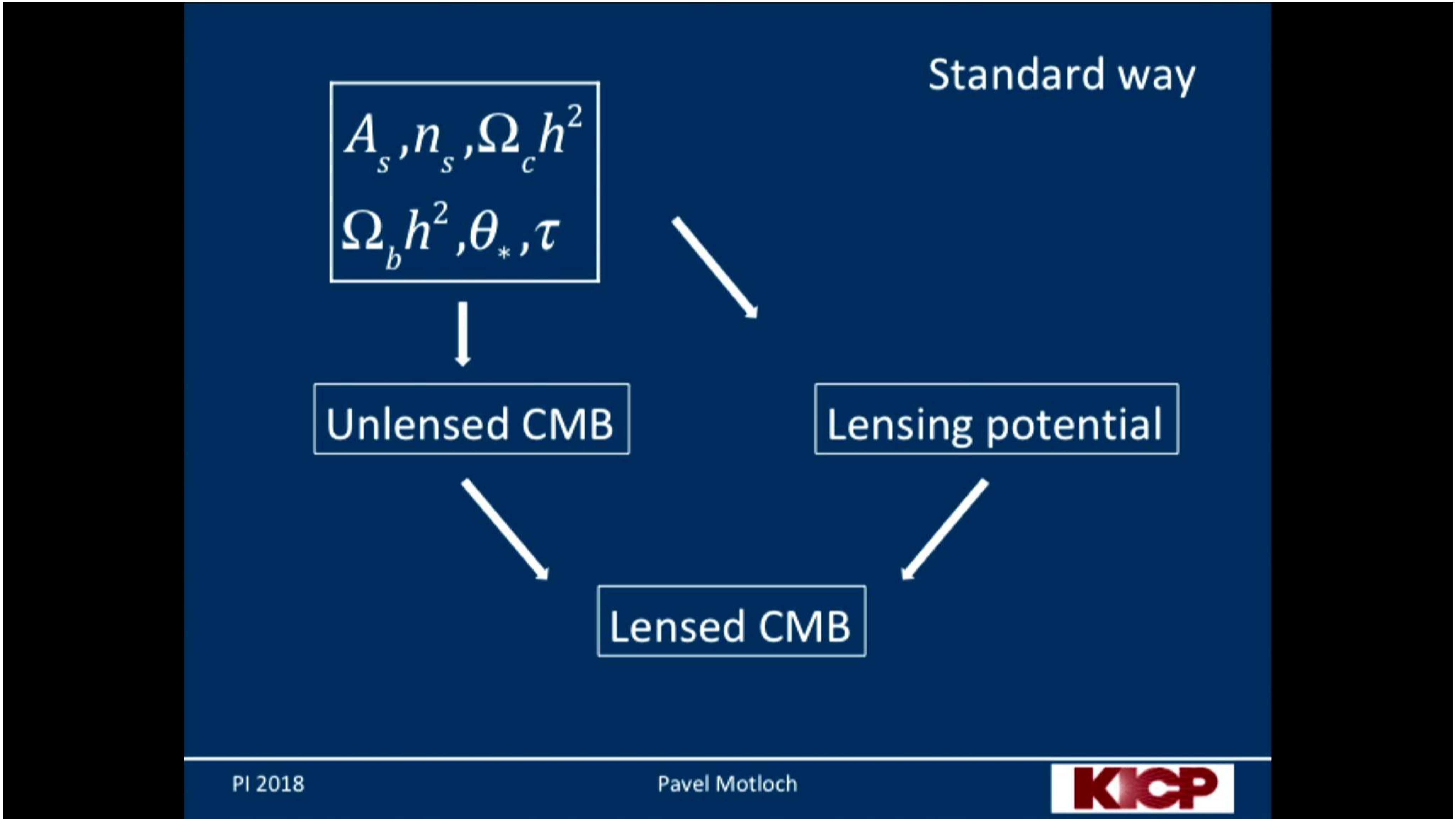
Standard way
$A_s, n_s, \Omega_c h^2$
$\Omega_b h^2, \theta_*, \tau$
Unlensed CMB
Lensing potential
Lensed CMB
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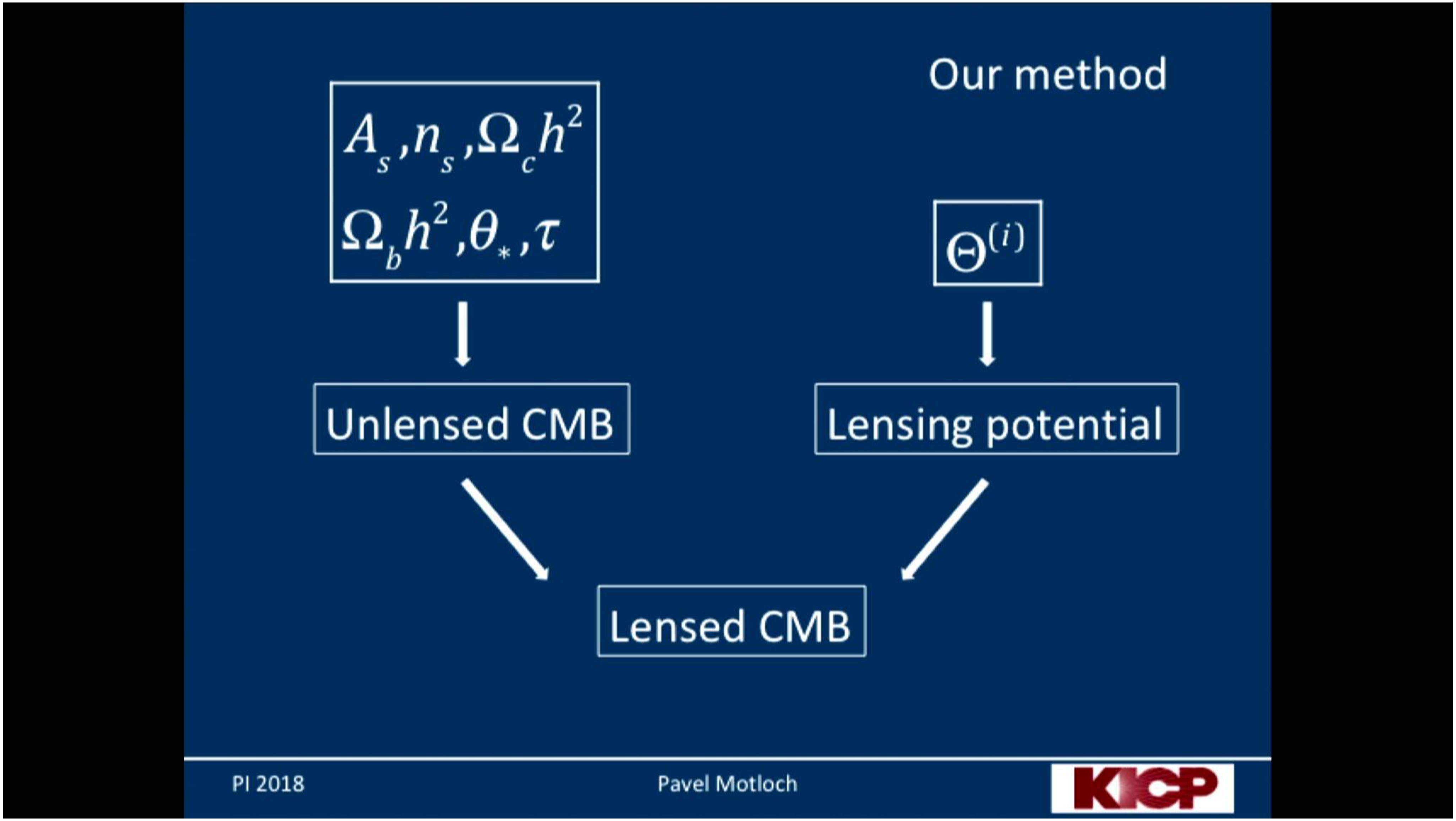
Our method
$A_s, n_s, \Omega_c h^2$
$\Omega_b h^2, \theta_*, \tau$
$\Theta^{(i)}$
Unlensed CMB
Lensing potential
Lensed CMB
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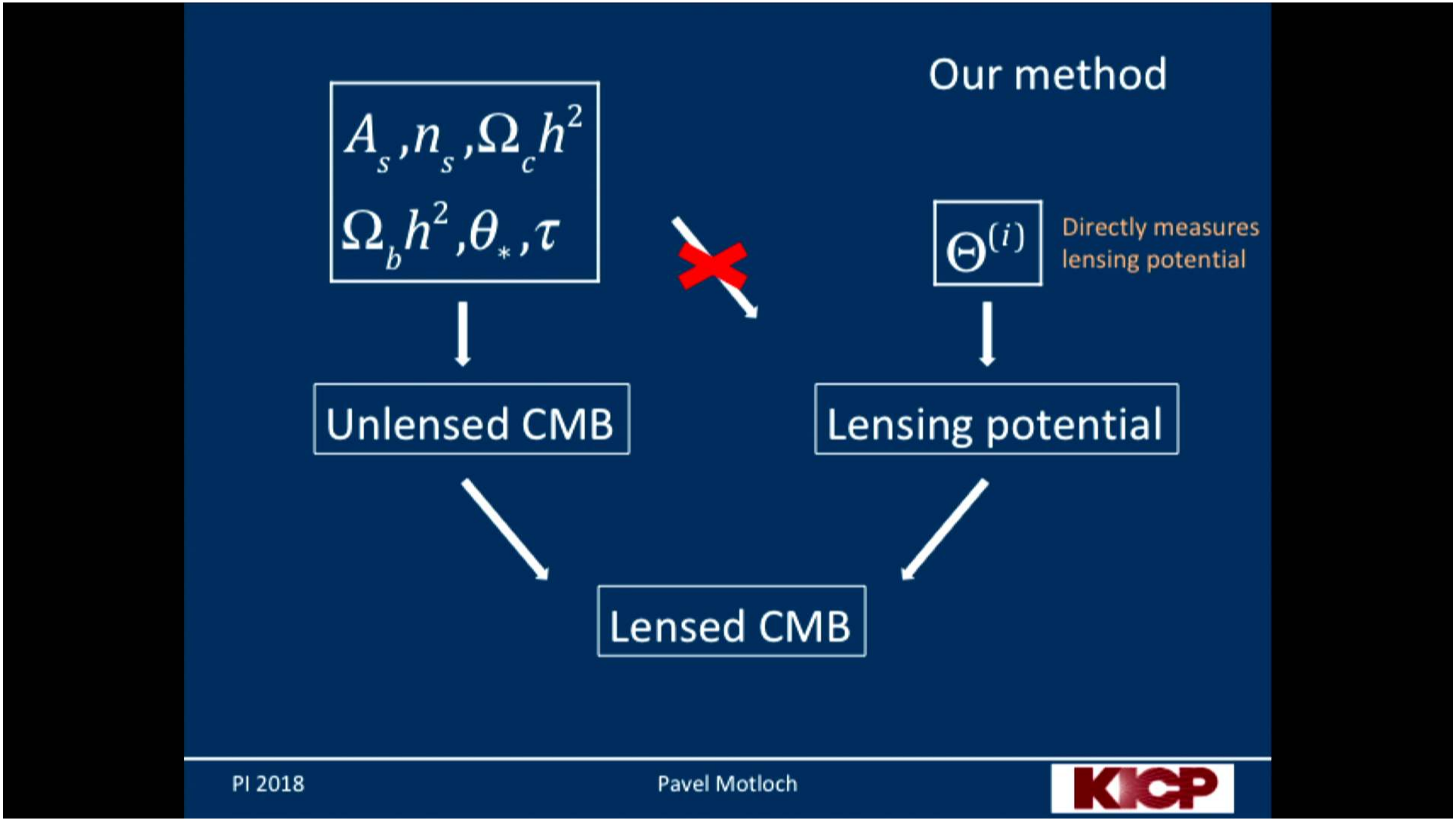
Our method
$A_s, n_s, \Omega_c h^2$
$\Omega_b h^2, \theta_*, \tau$
$\Theta^{(i)}$
Directly measures lensing potential
Unlensed CMB
Lensing potential
Lensed CMB
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Advantages

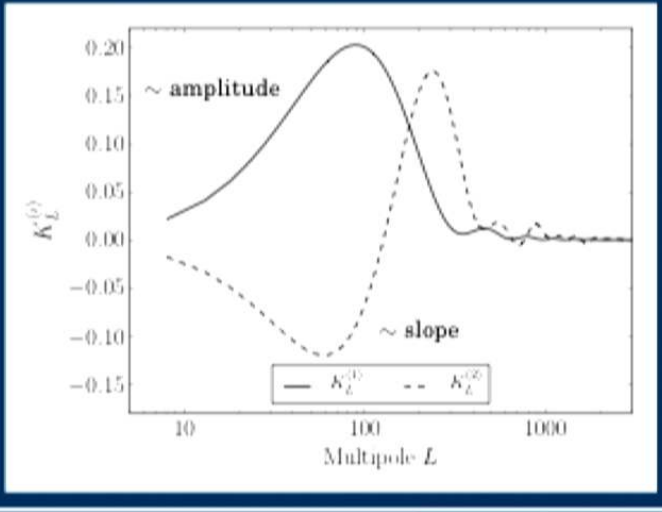
- Agnostic about the lensing potential
  - LCDM may not be correct..
- Easily beyond just changing amplitude
  (in this talk two d.o.f.)
- No strong correlation between $\Theta^{(i)}$ and LCDM parameters in CMB data ("independent")

Technicalities

- Lensing potential

$$C_L^{\phi\phi} = C_{L,\mathrm{fid}}^{\phi\phi} \exp\left(\sum_i K_L^{(i)} \Theta^{(i)} \right)$$

- Now: $\Theta^{(i)}$ are principal components of the measurement of $C_L^{\phi\phi}$ using Planck C_ℓ^{TT}



Alternative to A_L

- Run MCMC with 6+N parameters

- Compare
  - Direct measurement of $\Theta^{(i)}$
  - ΛCDM prediction from measured A_s, n_s, …

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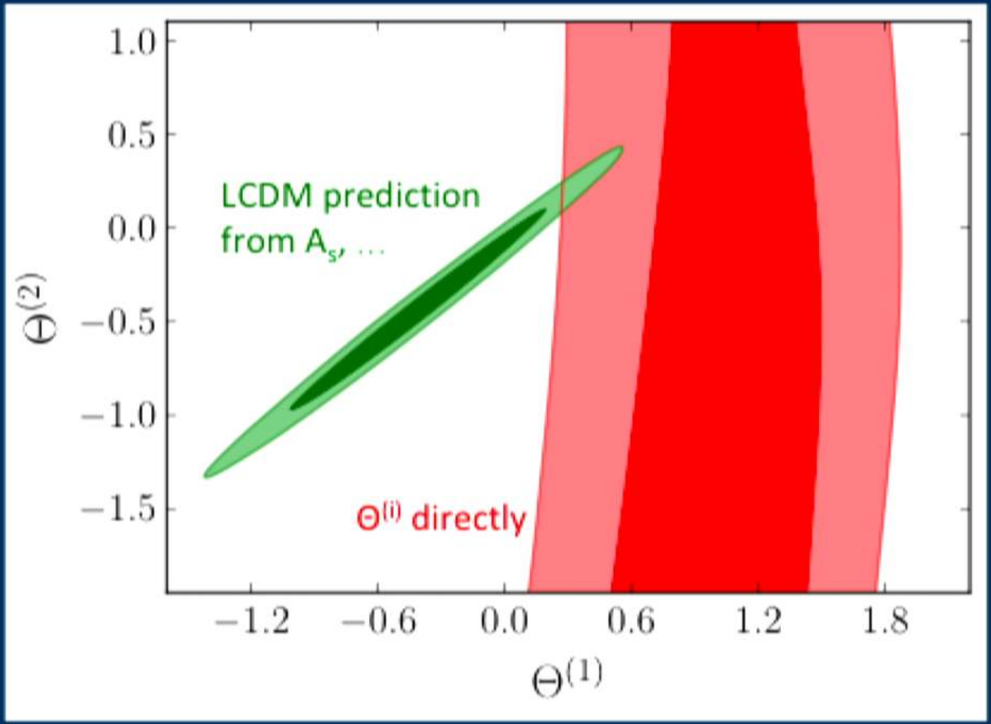
Tension in TT power spectrum

← Less lensing More lensing →



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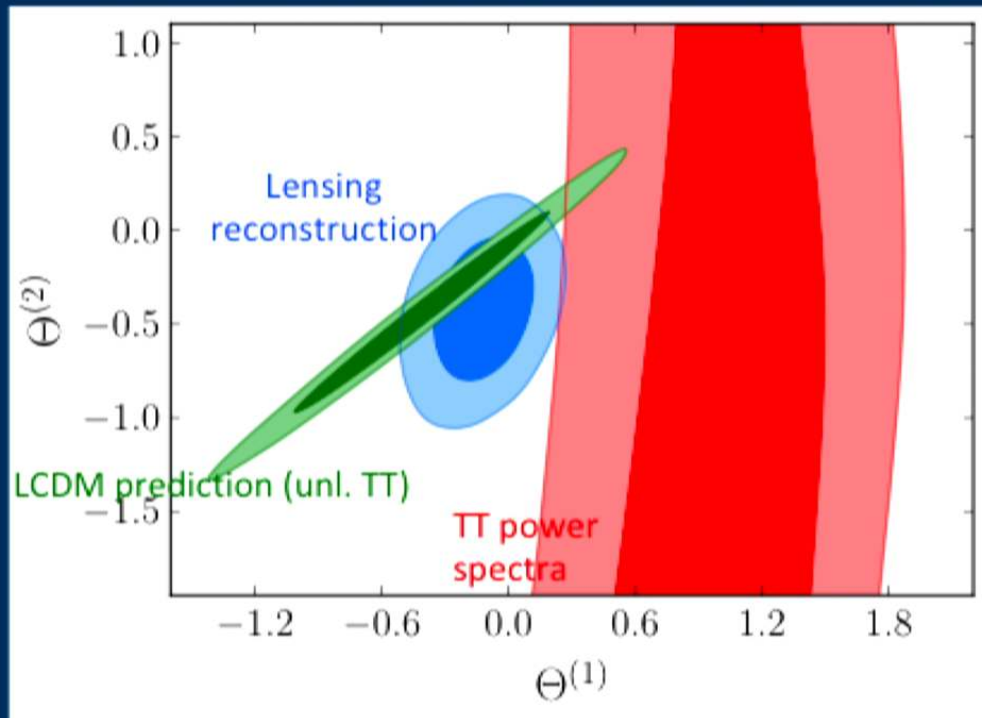
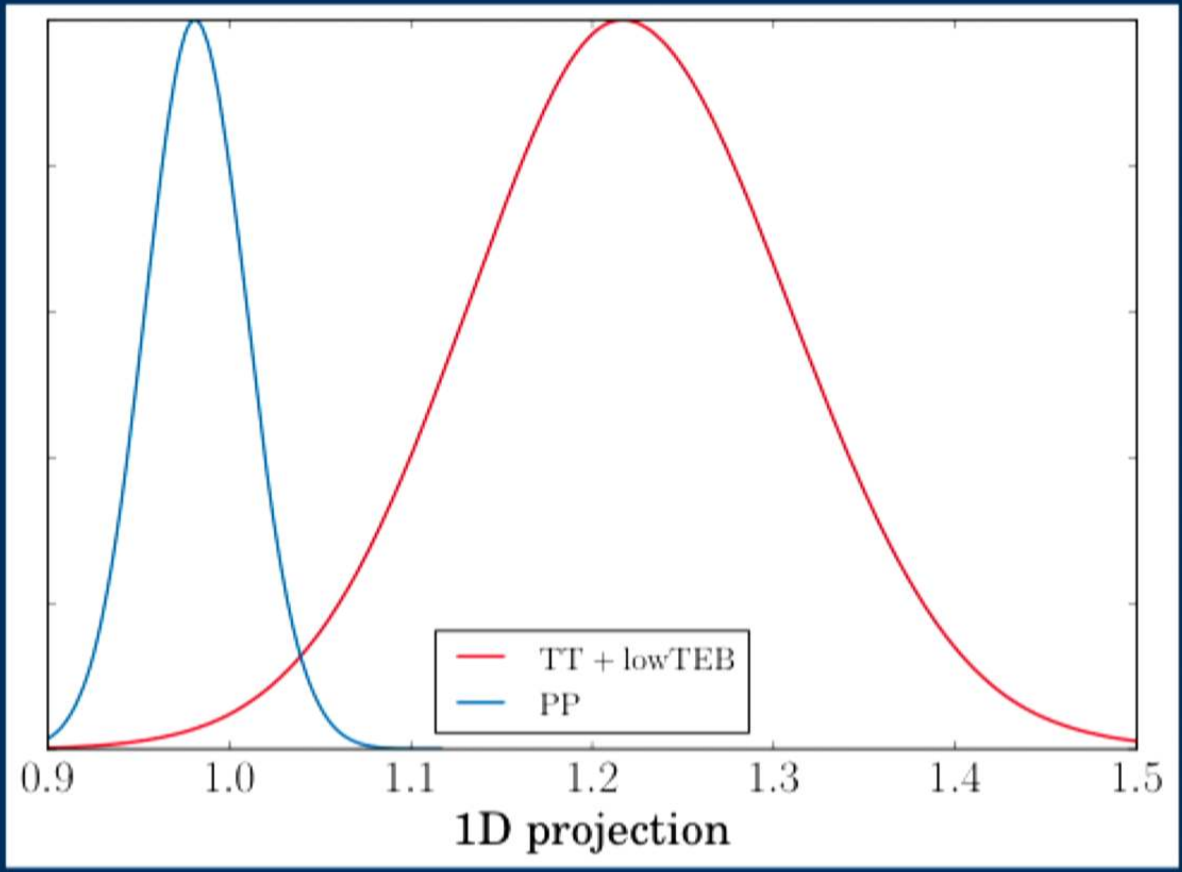
TT vs. lensing reconstruction



Lensing can not resolve the tensions

Significance (model independent)



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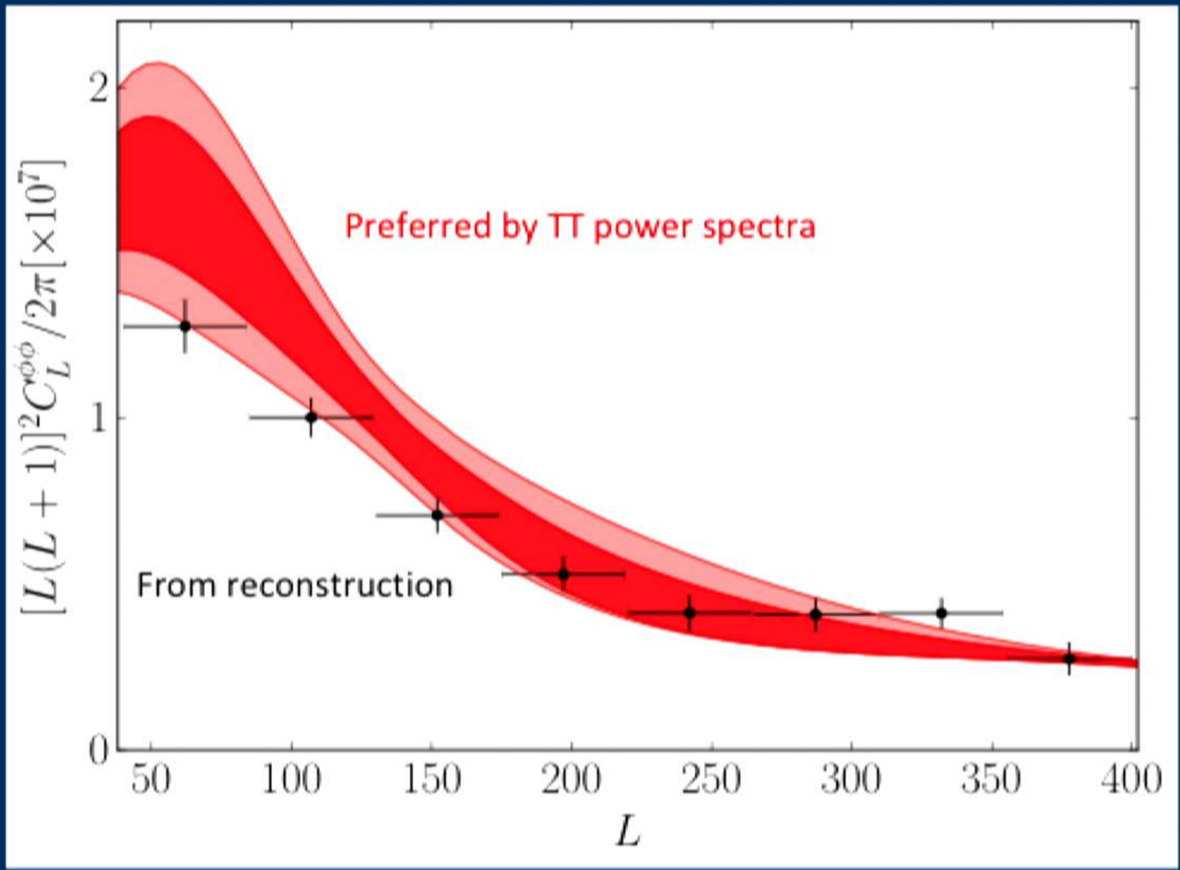
Results stable with respect to

- Adding small scale polarization (TE, EE)
- Changing $\Theta^{(2)}$ prior
- Assumptions about τ
- Allowing more $\Theta^{(i)}$
  (larger freedom for the lensing potential)

$C^{\phi\phi}$ posterior



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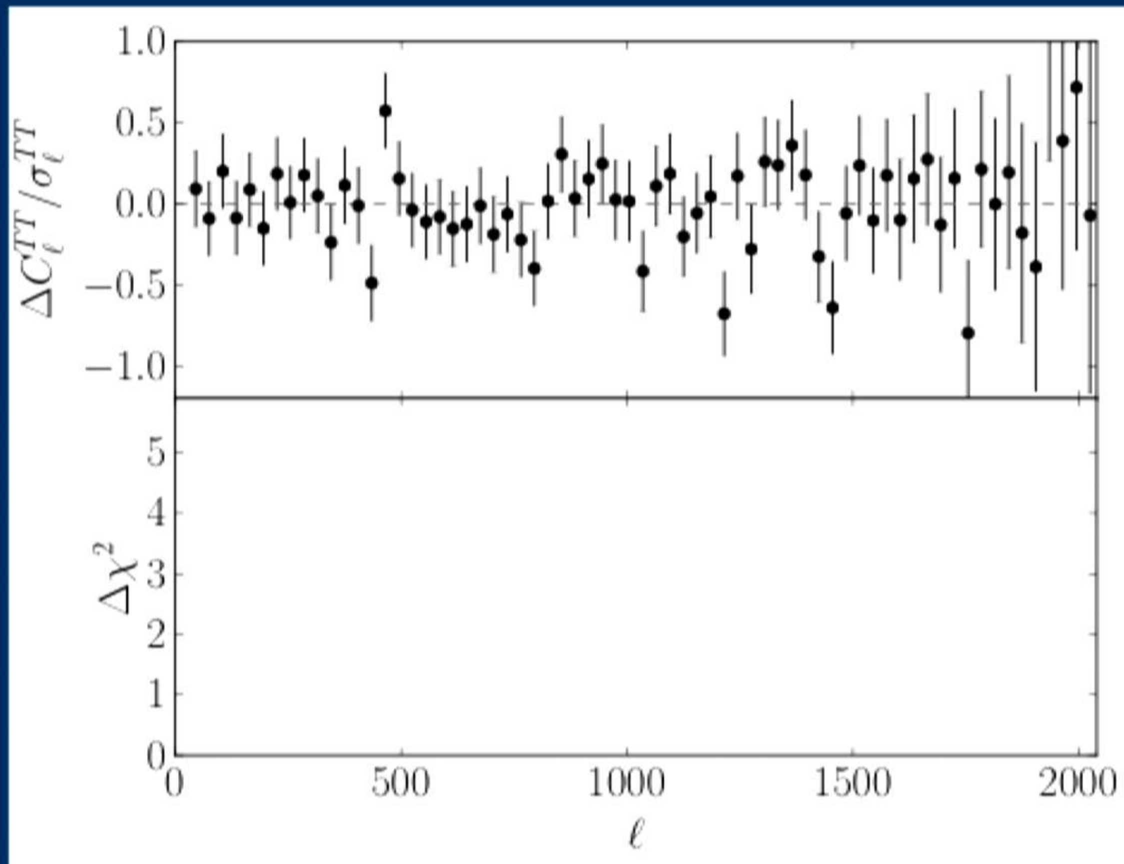
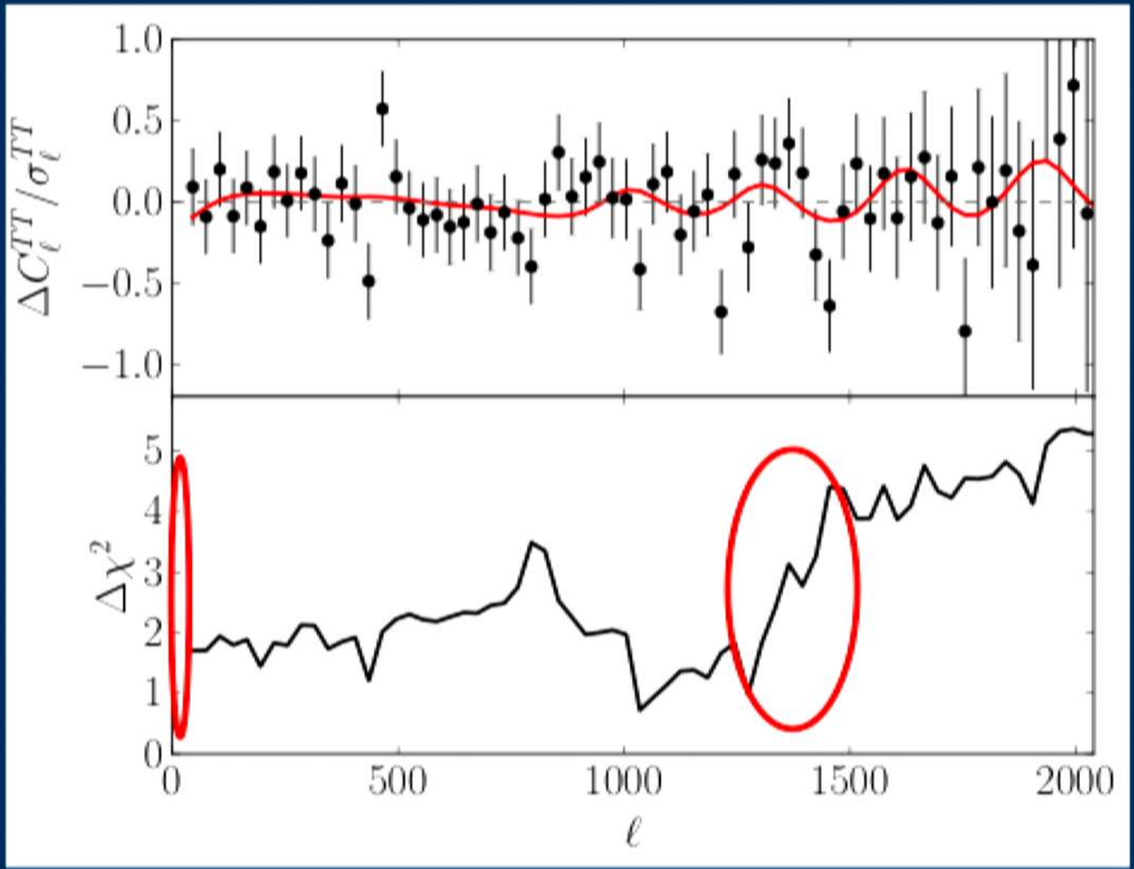
What about the data drives this?

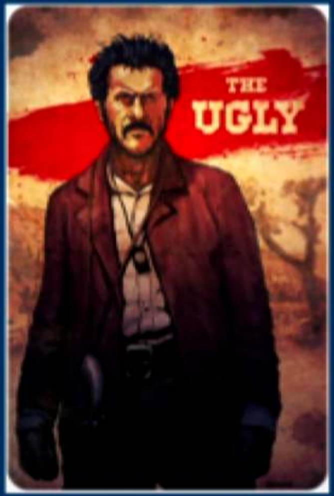


What about the data drives this?



What is it?

- Fluke?
- Planck foreground subtraction?
- Something else? Interesting physics?



LENSING CORRELATES DATA

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Lensing correlates data

- Unlensed CMB has uncorrelated multipoles, e.g.

$$\langle C_\ell^{\tilde{E}\tilde{E}} C_{\ell'}^{\tilde{E}\tilde{E}} \rangle = \delta_{\ell\ell'} \frac{2\left(C_\ell^{\tilde{E}\tilde{E}}\right)^2}{2\ell+1}$$

- With lensing this is no longer true: Amount of lensing is stochastic and changes T, E, B in a coherent manner

Analytical model for covariance

- Off-diagonal contributions, e.g.

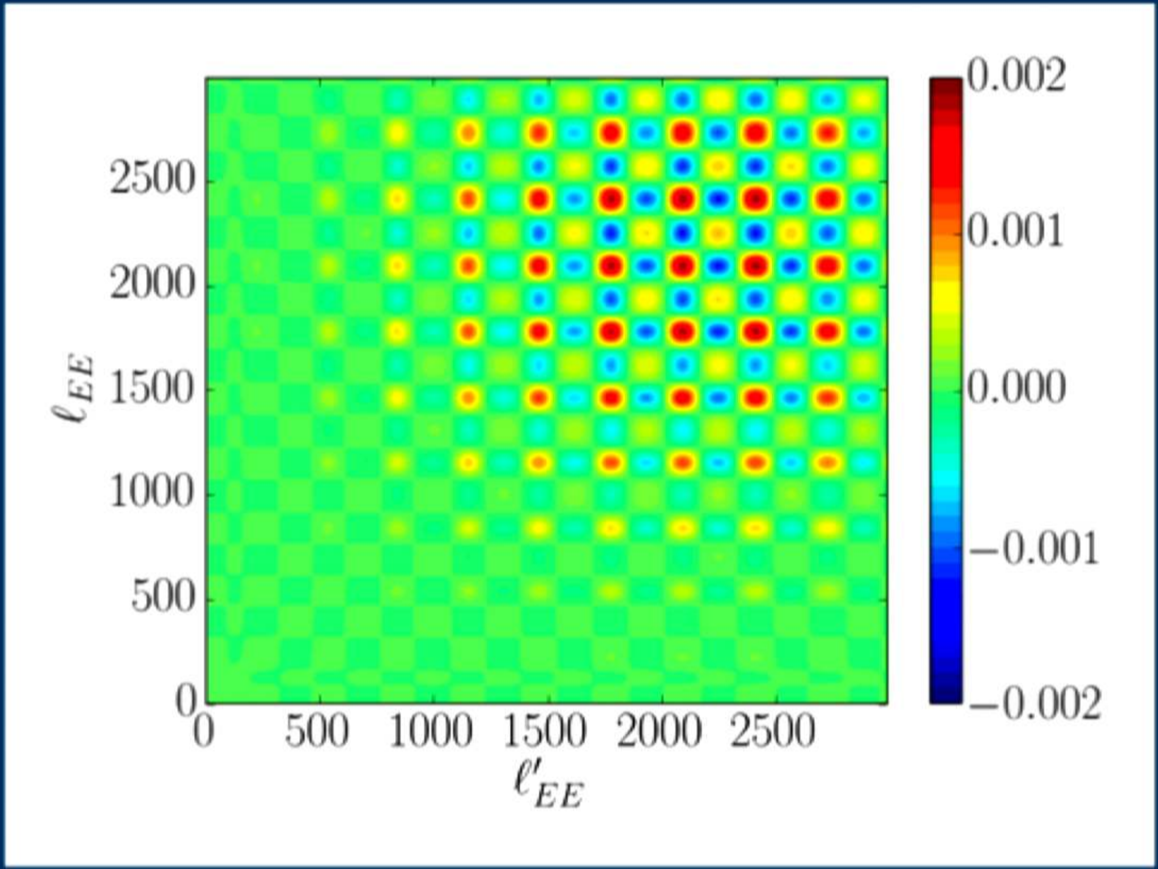
$$\langle C_\ell^{EE} C_{\ell'}^{EE} \rangle = \sum_L \frac{\partial C_\ell^{EE}}{\partial C_L^{\phi\phi}} \frac{2\left(C_L^{\phi\phi}\right)^2}{2L+1} \frac{\partial C_{\ell'}^{EE}}{\partial C_L^{\phi\phi}} \qquad \left(\ell \neq \ell'\right)$$

Uncertainty in lensing power at given scale

How sensitive to lensing the two variables are

Benoit-Lévy+ 1205.0474

Correlation matrix



Sources of uncertainty

- Instrumental noise, foregrounds, ...
- Cosmic variance of the unlensed CMB

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Sources of uncertainty

- Instrumental noise, foregrounds, …
- Cosmic variance of the unlensed CMB
- Cosmic variance of the gravitational lenses
  - New “noise”
  - Correlates C^{TT}, C^{TE}, C^{EE}, C^{BB}, $C^{\phi\phi}$

Effect on CMB-S4 measurements from TT, TE, EE, BB?

- Compare constraints on unlensed parameters and on $\Theta^{(i)}$ (≈ model independent statements)

  CMB-S4 principal components

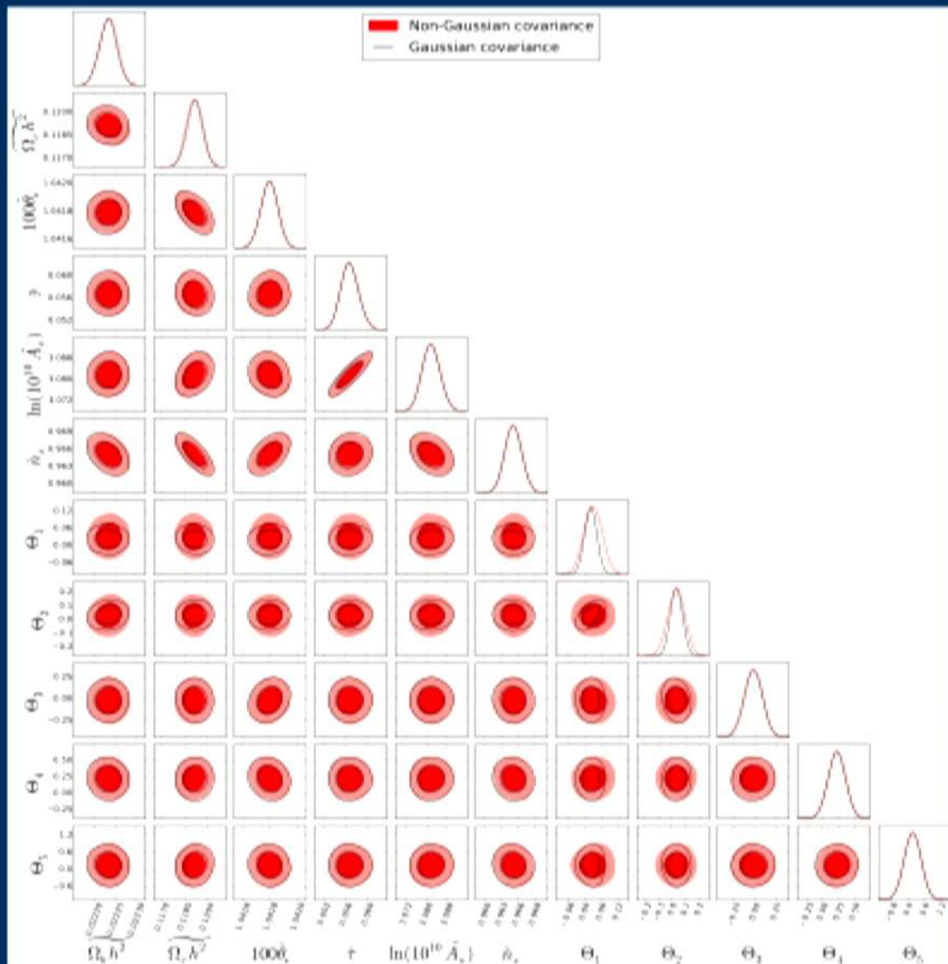
- To probe it, do:
  - Simulate CMB data
  - Run MCMC
  - Use likelihood with / without lensing covariance

Likelihood (full sky)

- Split largest and smallest scales, consider independent

- Largest scales ($\ell < 30$)
  - Wishart distributed, no lens sample noise

- Smaller scales
  - Normal distributed



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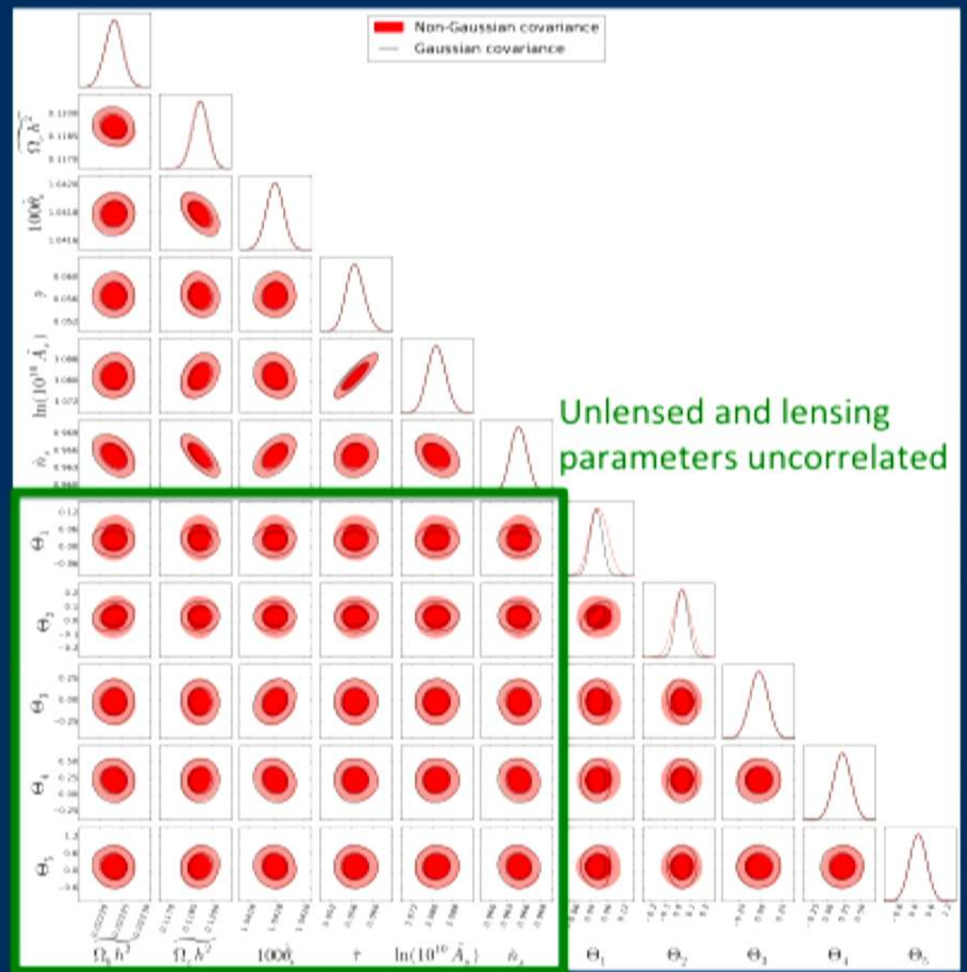

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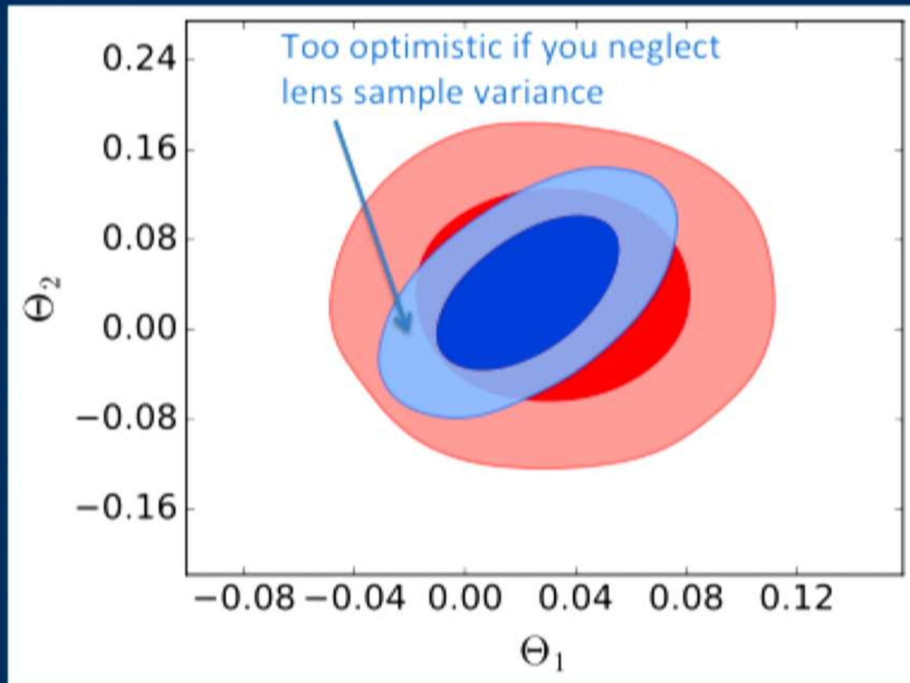
Only significant effects



Two best measured components of the lensing potential are affected

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Consequences

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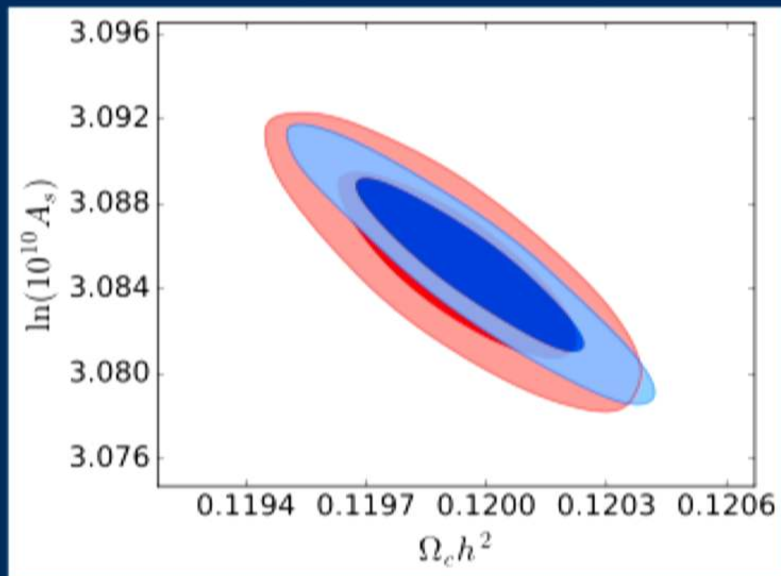
1) Constraints from TT, TE, EE, BB

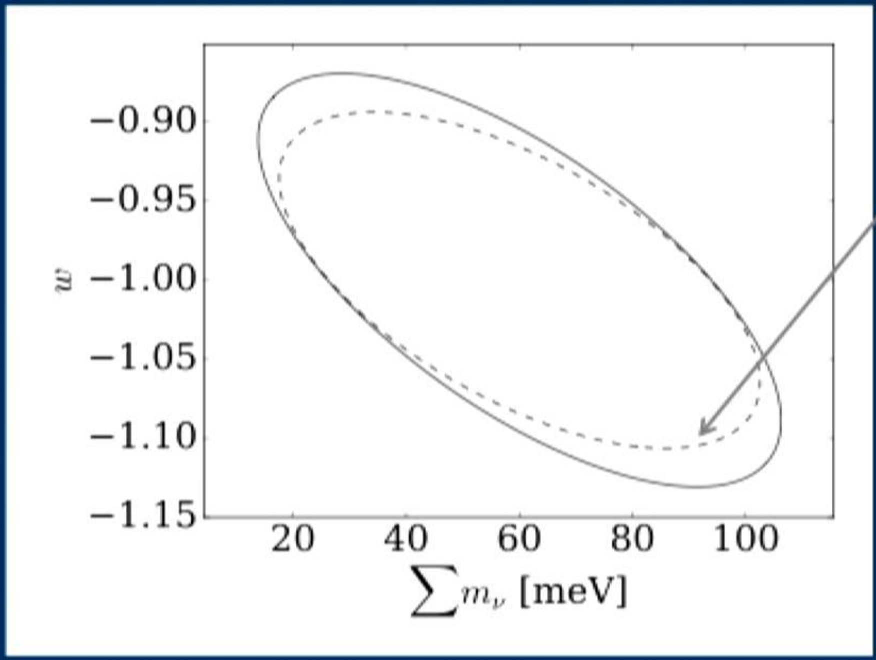
- Given a cosmological model, (some) parameter constraints weakened



ΛCDM example

2) Adding lensing reconstruction

- Must avoid double counting information as measurements of $\Theta^{(1,2)}$ are comparably good



When neglecting cross correlation

Simple Lensing Approximation

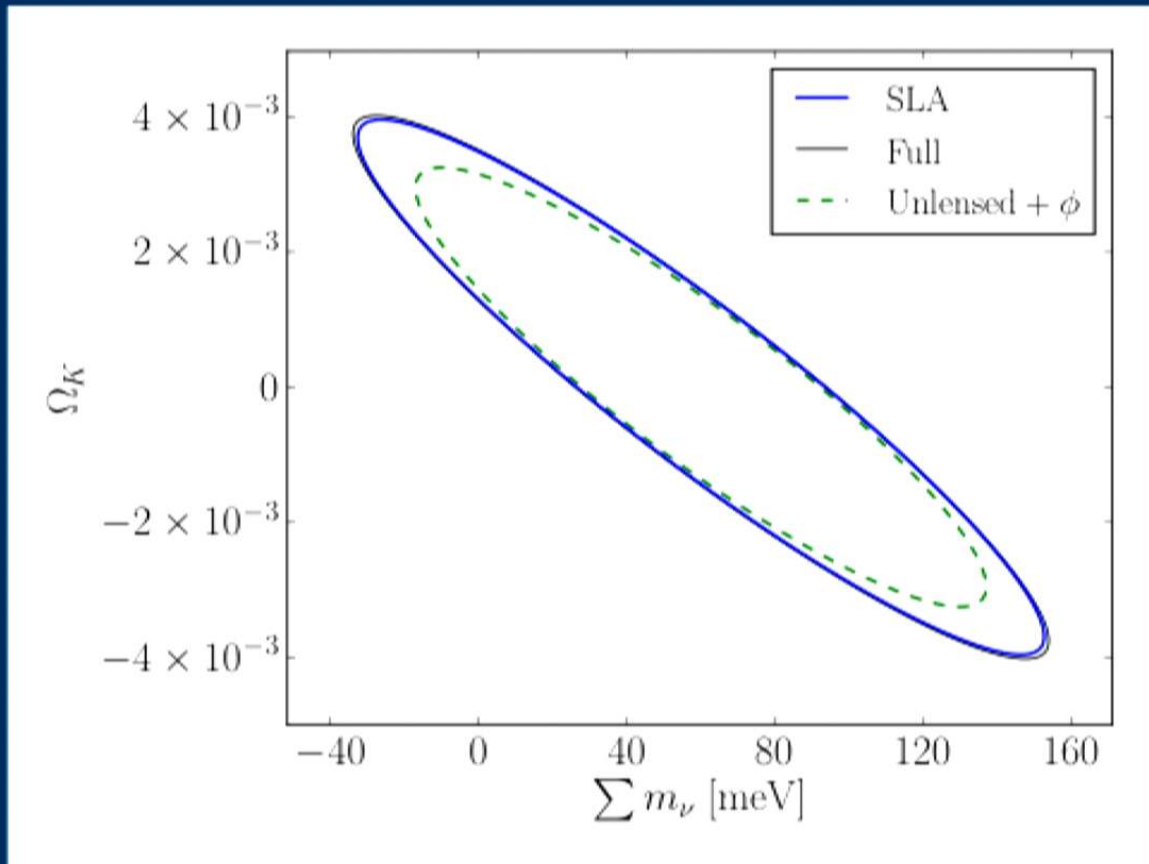
- How to combine TEB and reconstruction?

- Neglect lensing information in TEB completely by evaluating

$$\left.\frac{\partial C_\ell^{XY}}{\partial p_A}\right|_{C_L^{\phi\phi}=const.} \qquad XY = TT, TE, EE, BB$$

and use Gaussian covariance

Example



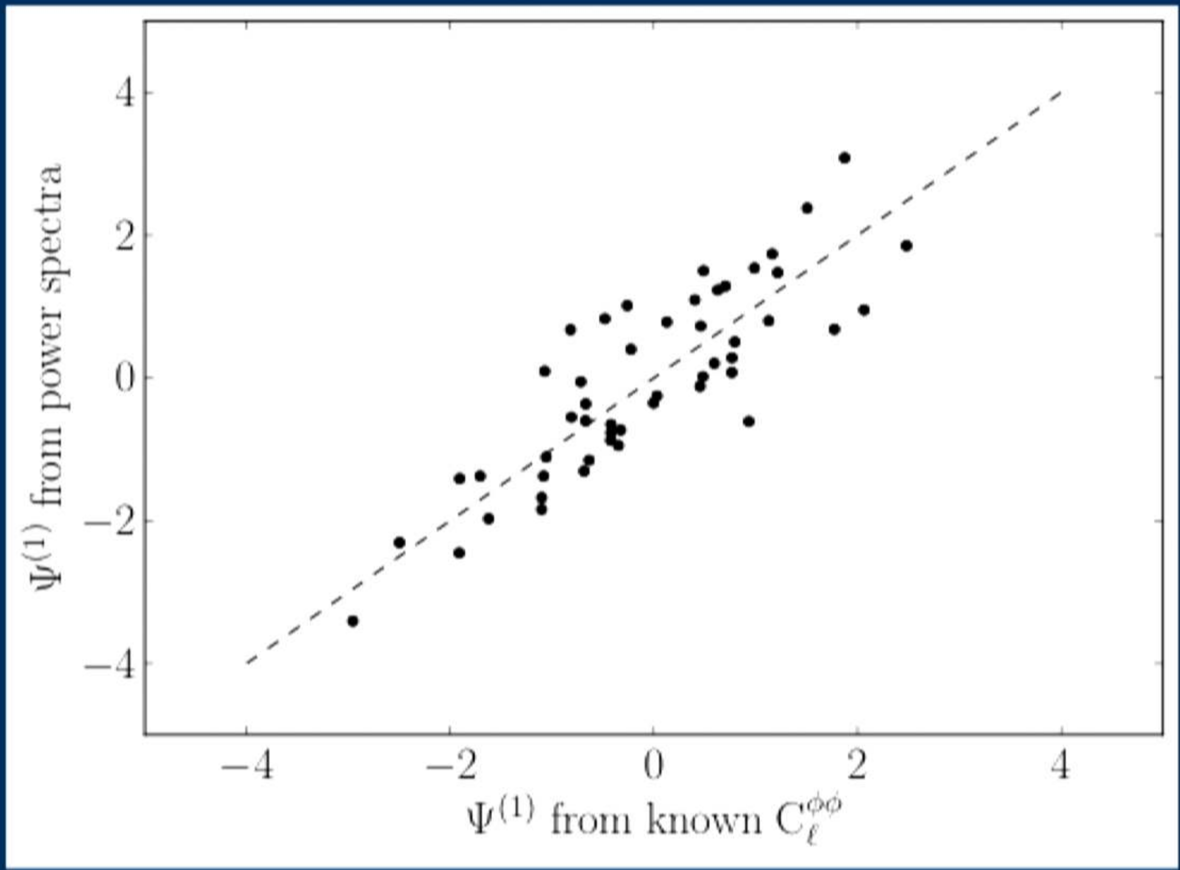
SLA
Full
Unlensed + ϕ
4×10^{-3}
2×10^{-3}
0
-2×10^{-3}
-4×10^{-3}
Ω_K
−40
0
40
80
120
160
$\sum m_\nu$ [meV]

3) Consistency check

- In CMB-S4 we can measure 1-2 modes of $C_\ell^{\phi\phi}$ with comparable precision in T,E,B power spectra and lensing reconstruction

- Both limited by cosmic variance of the lenses
  - Cancel out when comparing the two measurements! (cosmic variance cancellation)
  - Great consistency check before one attempts delensing

Two measurements correlated



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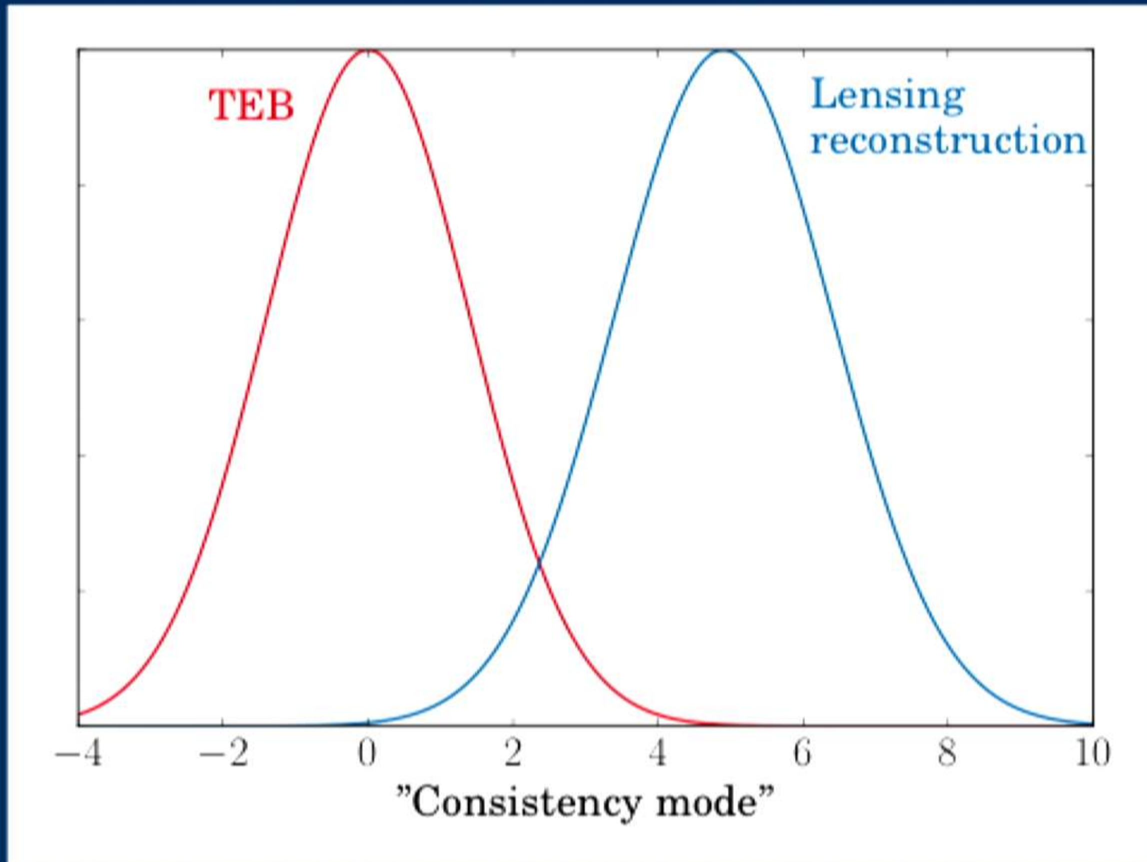
CMB-S4 toy example



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Take aways

- It is useful to split unlensed and lensing info from CMB T, E, B power spectra
- There is (about) 2.5σ tension in the Planck data and lensing does not look like the cause
- Lens sample variance has to be taken into account for future experiments
- Consistency checks great, even better in the future