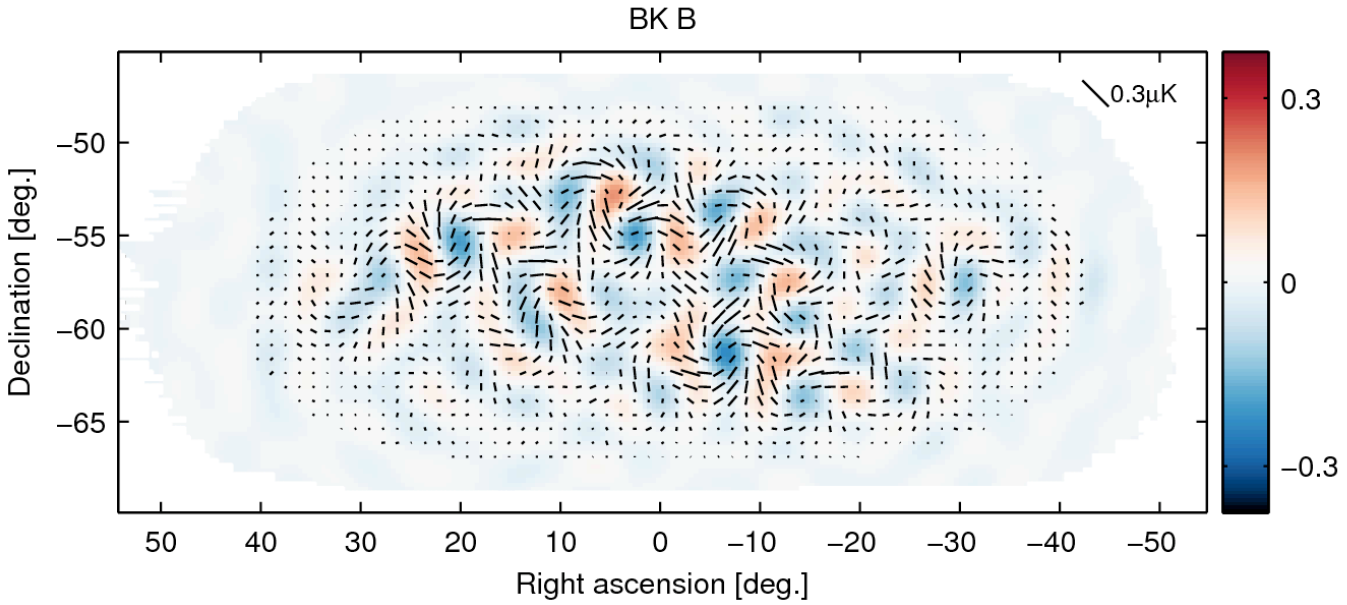
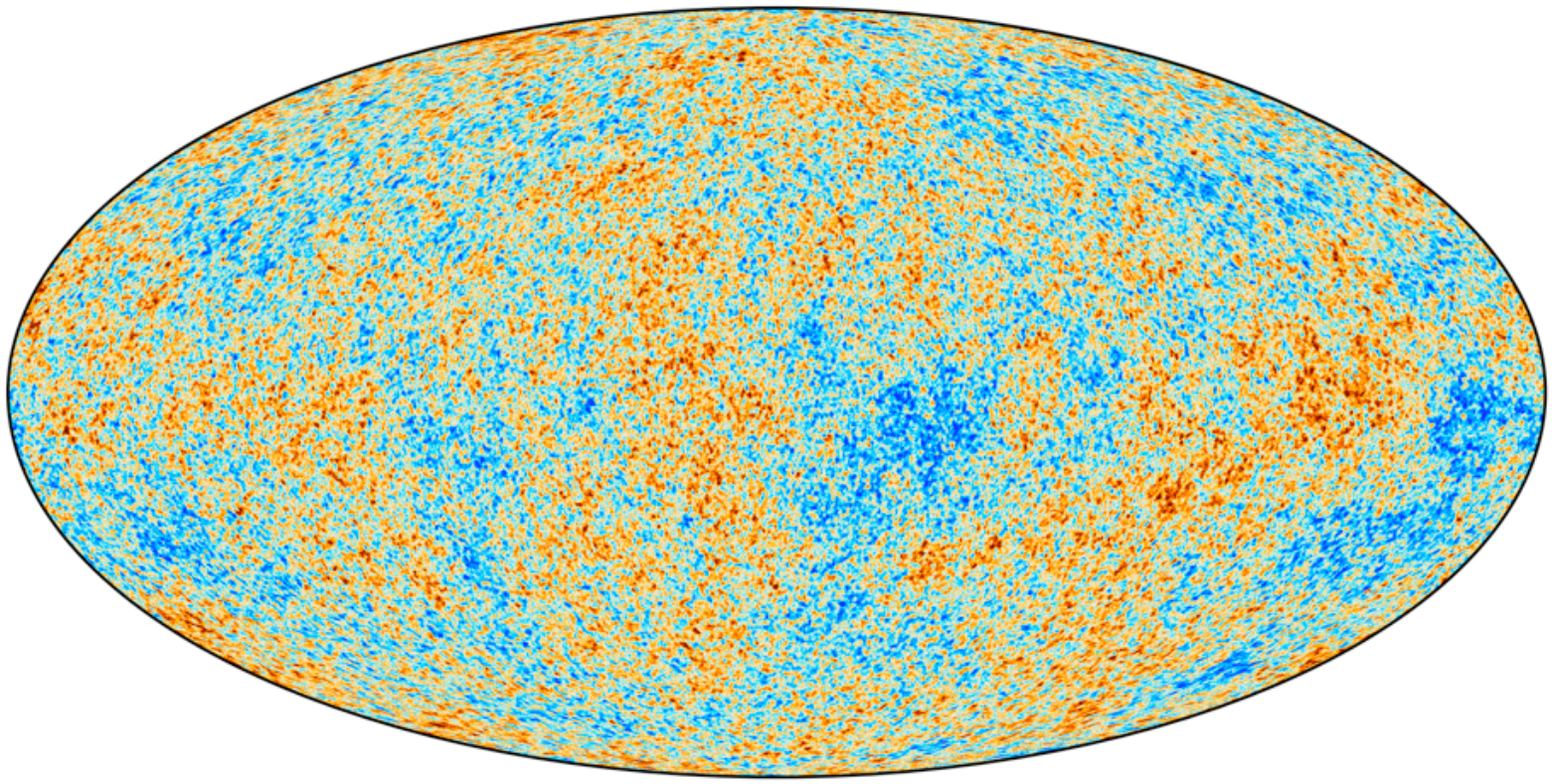
CMB *B*-mode science

Anthony Challinor



KICC/IoA/DAMTP
University of Cambridge

Planck ΔT



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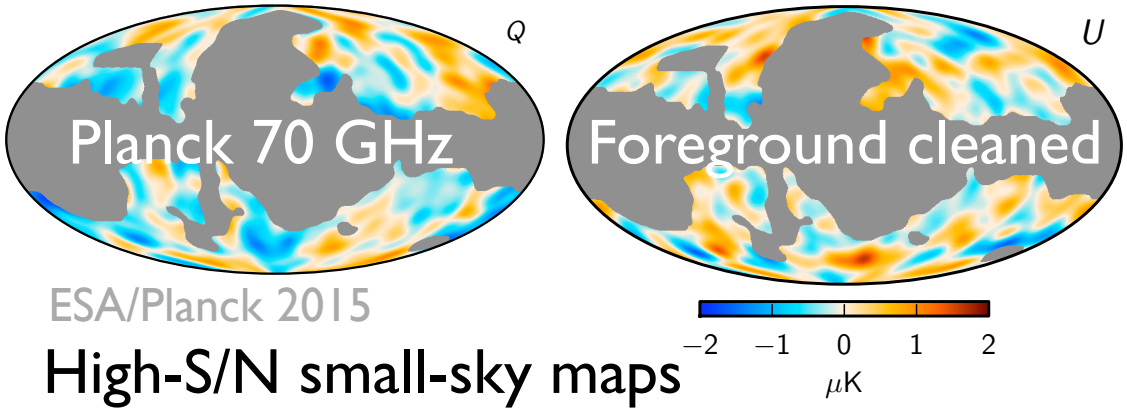
- Information in CMB ΔT close to exhausted with Planck

Linear polarization



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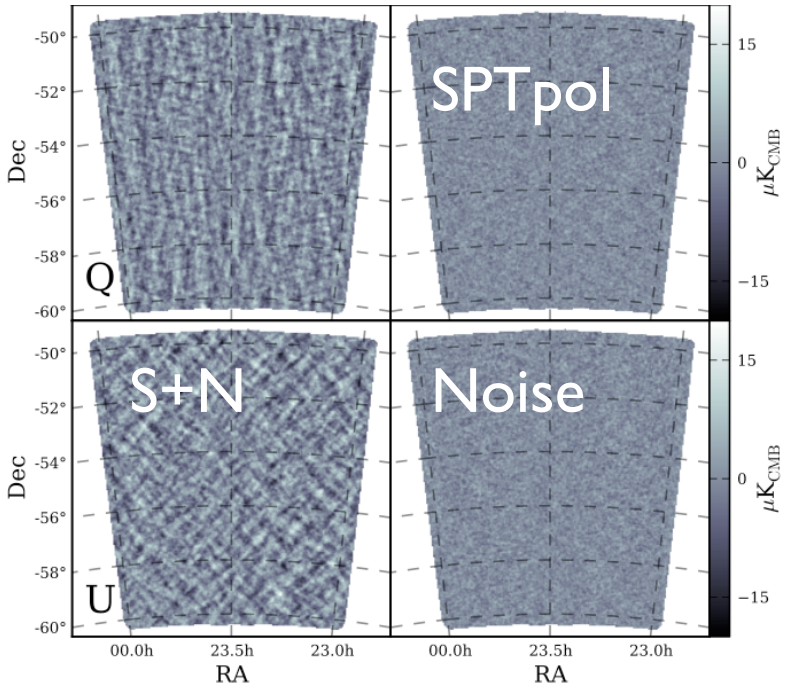
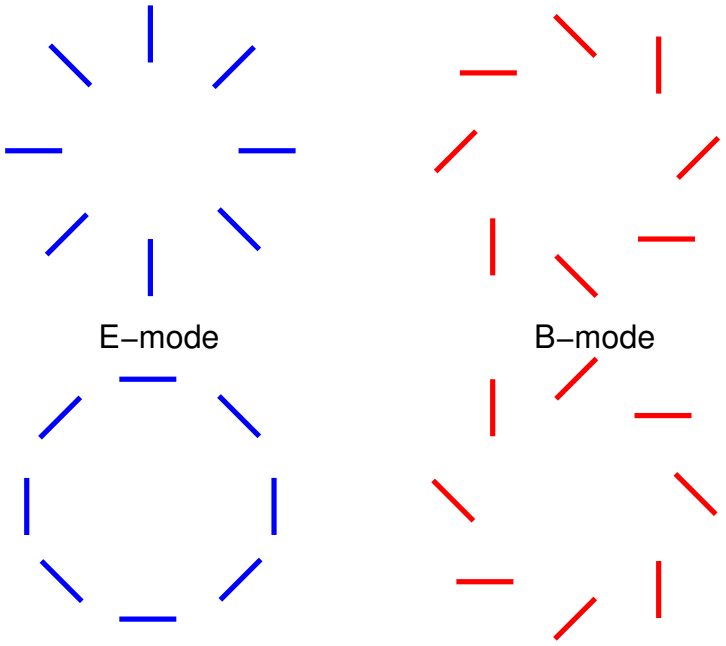
Low-S/N full-sky maps from Planck and WMAP

B-modes not generated by linear density perts

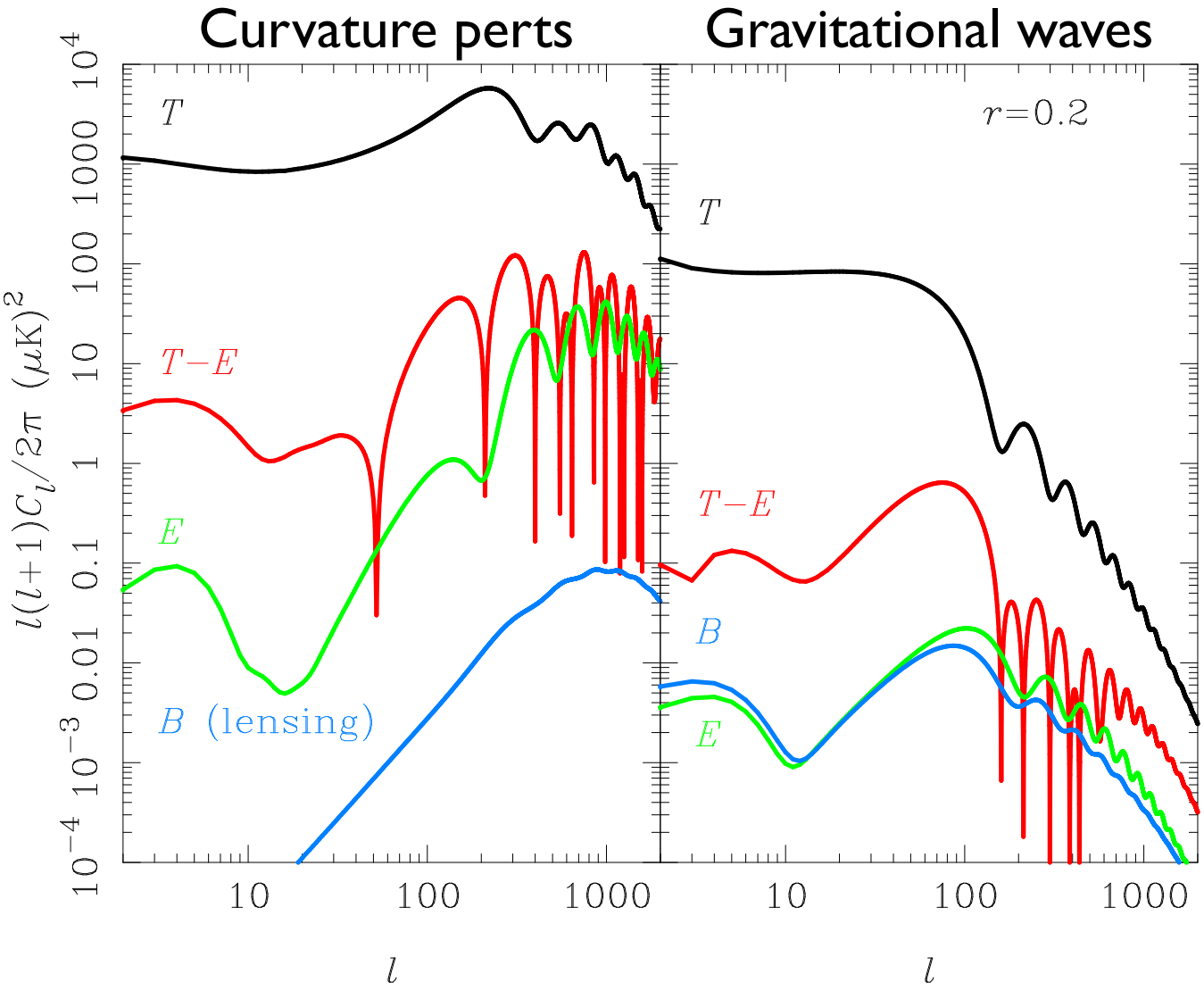
High-S/N small-sky maps





Crites+ 2015; also BICEP2/Keck, ACTPol, POLARBEAR

Polarization power spectra



CMB polarization science

- Reionization
- Large-angle anomalies
- *B*-modes and gravitational waves

} Degree-scale or larger

- Lensing reconstruction/delensing
- High-*l* *E*-modes:
  - *Parameters from the damping tail*
  - *Primordial non-Gaussianity*
- Cluster science:
  - *Transverse velocities*
  - *Lensing-calibrated masses*

} Few arcmin

Gravitational waves and inflation

- Strong evidence for inflation (flatness; adiabatic, almost Gaussian and scale-invariant primordial curvature perts)
- Also predicts quantum generation of primordial GWs

$$\mathcal{P}_{\rm t}(k) = \frac{d}{d\ln k}\langle h_{ij}h^{ij}\rangle = \frac{8}{M_{\rm Pl}^2}\left(\frac{H}{2\pi}\right)^2$$

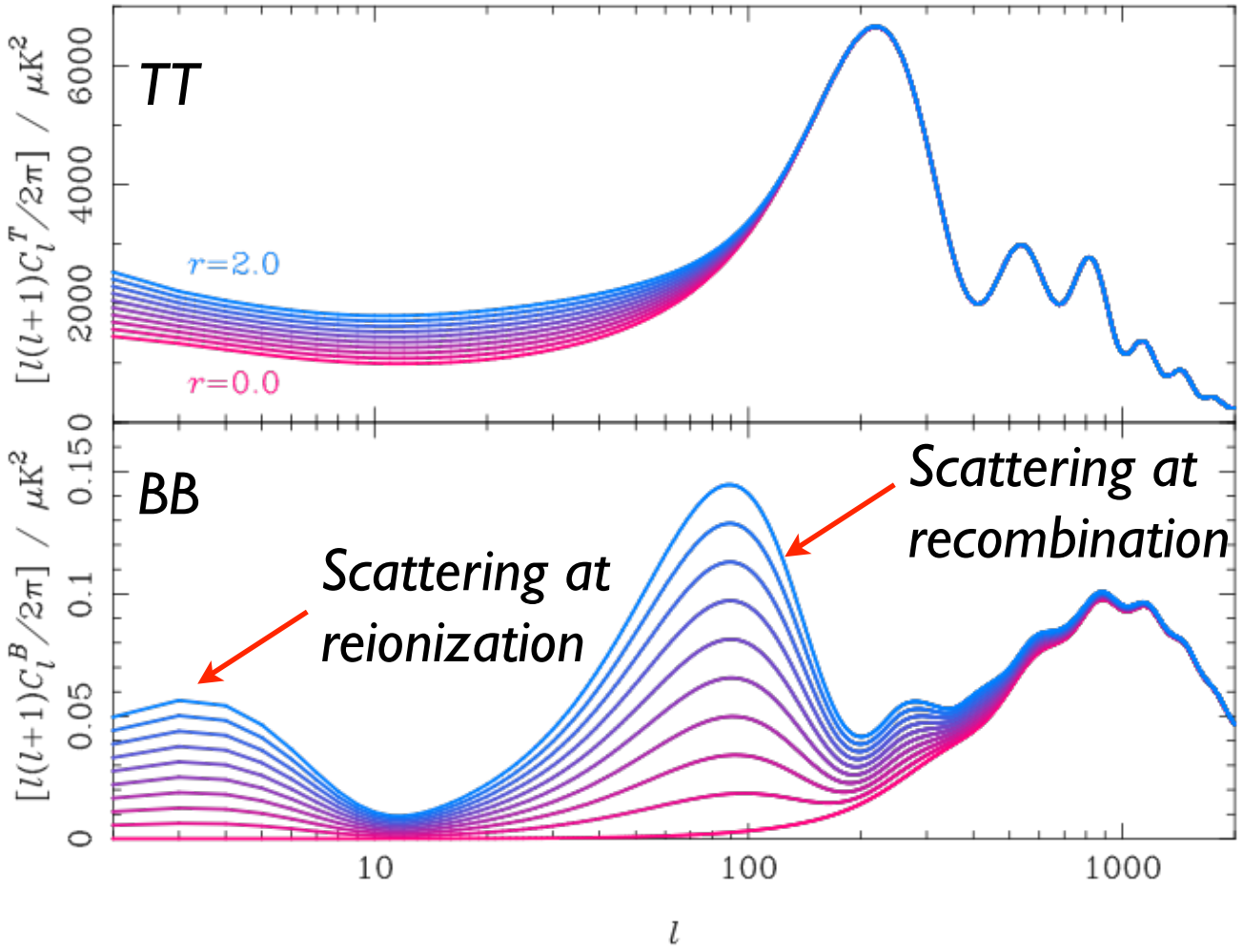
Depends only on energy scale

- Very generic; detectable if $E_{\rm inf} \sim 10^{16}$ GeV or greater
- Tensor-to-scalar ratio (relative importance of GWs)

$$r \equiv \mathcal{P}_{\rm t}/\mathcal{P}_{\rm s} = \frac{8}{M_{\rm Pl}^2}\frac{\dot\varphi^2}{H^2} = \frac{8}{M_{\rm Pl}^2}\left(\frac{d\varphi}{dN}\right)^2 \approx 8M_{\rm Pl}^2\left(\frac{V'}{V}\right)^2$$

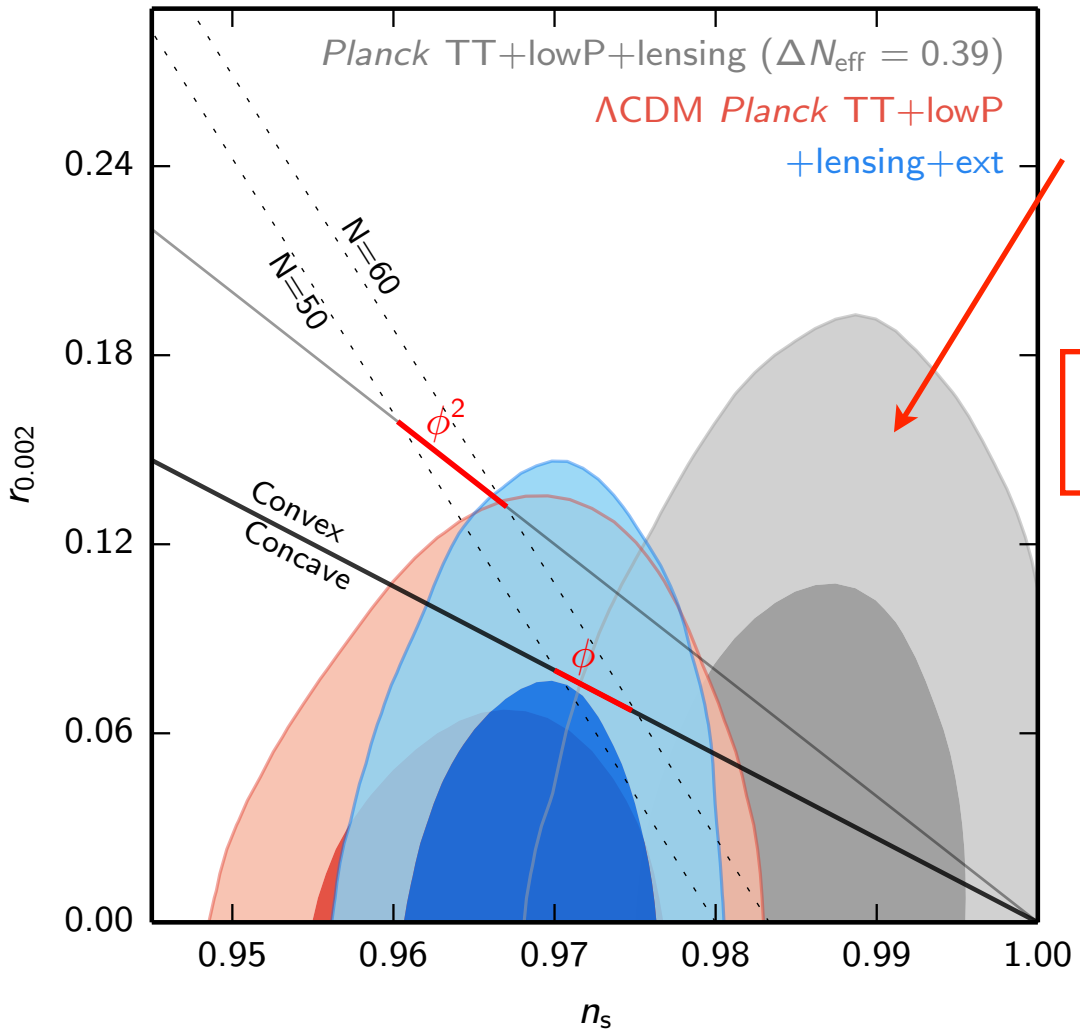
- *Lyth (1997) bound:* $\Delta\varphi/M_{\rm Pl} \geq \sqrt{r/8}\,\Delta N$

Gravitational waves in the CMB



- Confusion from curvature perts limits $\sigma(r) \approx 0.1$ from *TT*

Constraints on r and n_s from Planck



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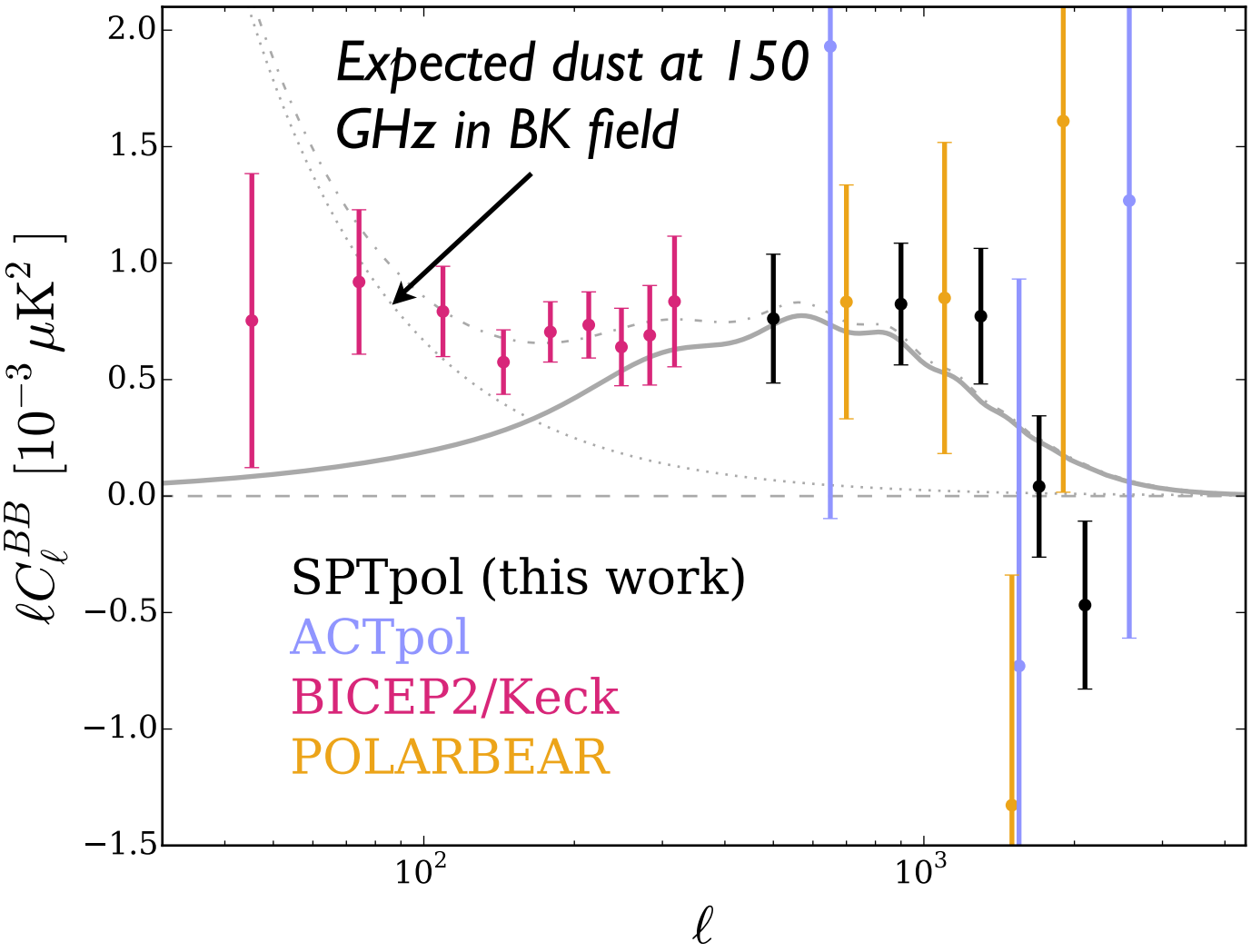
Constraints on GWs from ΔT are model-dependent

$$r_{0.002} < 0.10 \quad (95\%\mathrm{CL})$$

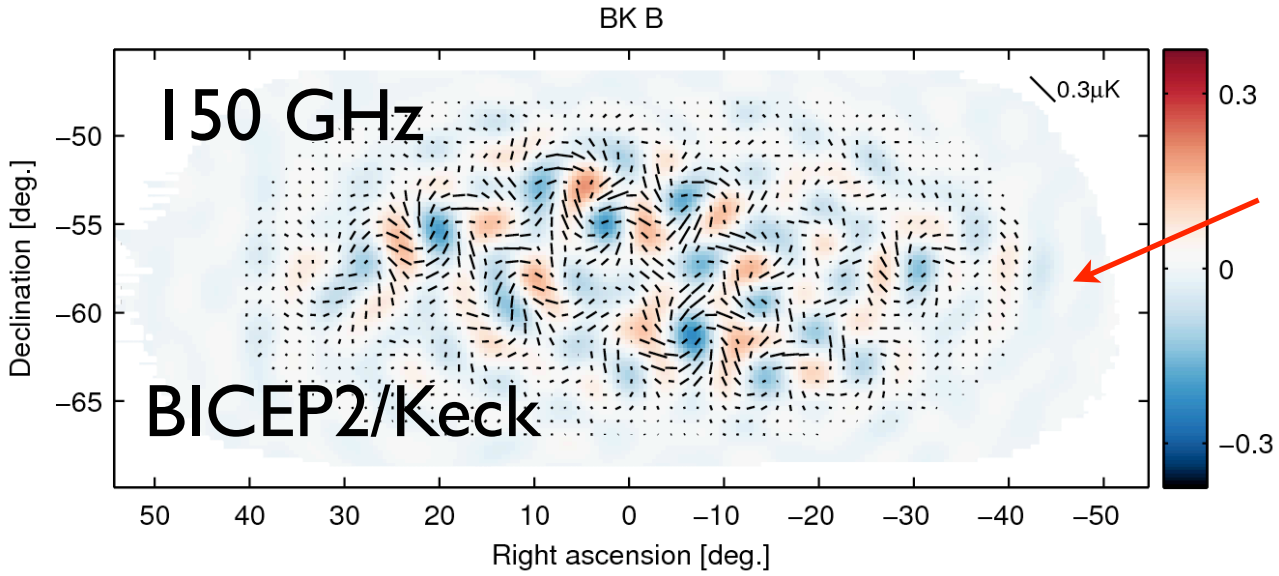
- Saturates information from ΔT
- To search further need *polarization B-modes*

Direct measurements of BB

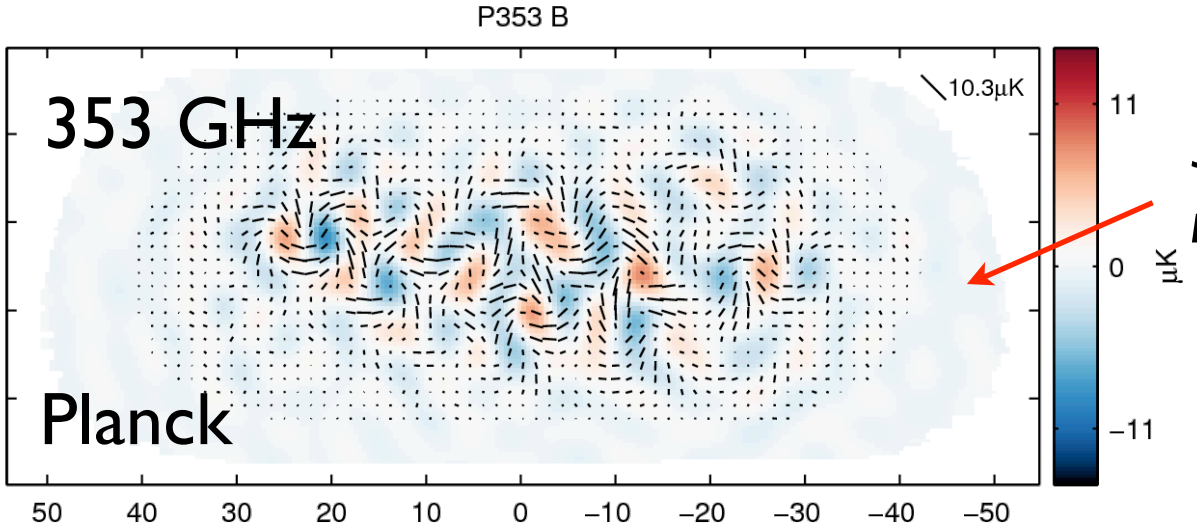


Keisler+2015

BK 150 GHz and Planck 353 GHz



3.4 μK-arcmin noise level

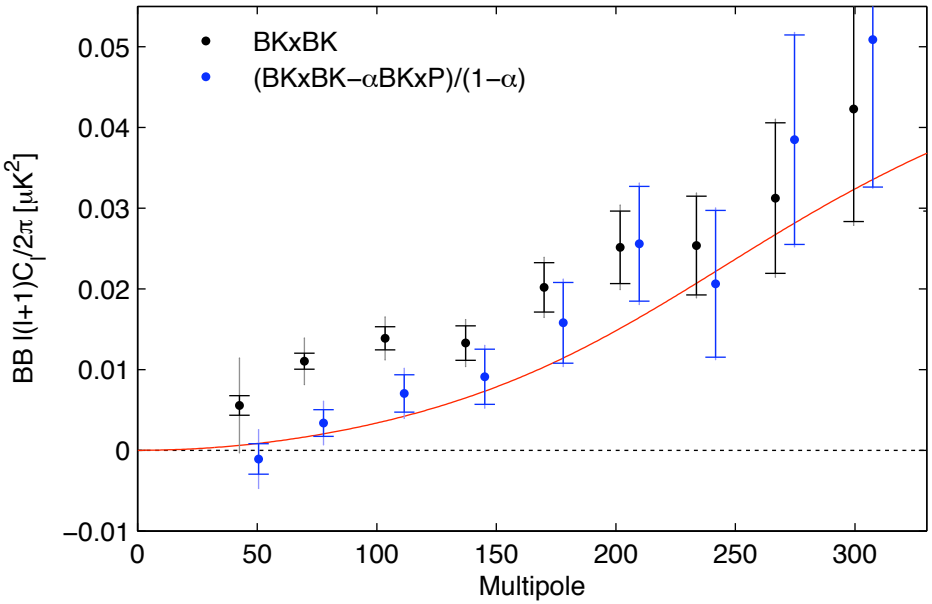


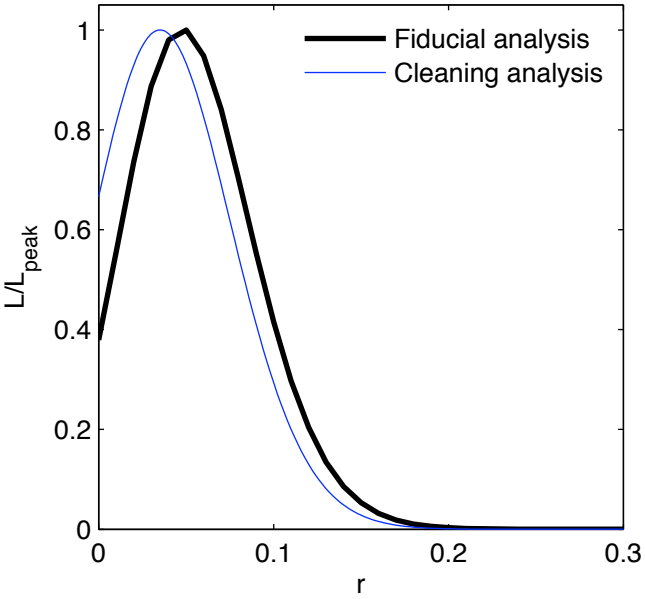
300 μK-arcmin noise level

Dust 20x brighter at 353 GHz

BICEP2/Keck + Planck Collaborations 2015

BK 150 GHz and Planck 353 GHz

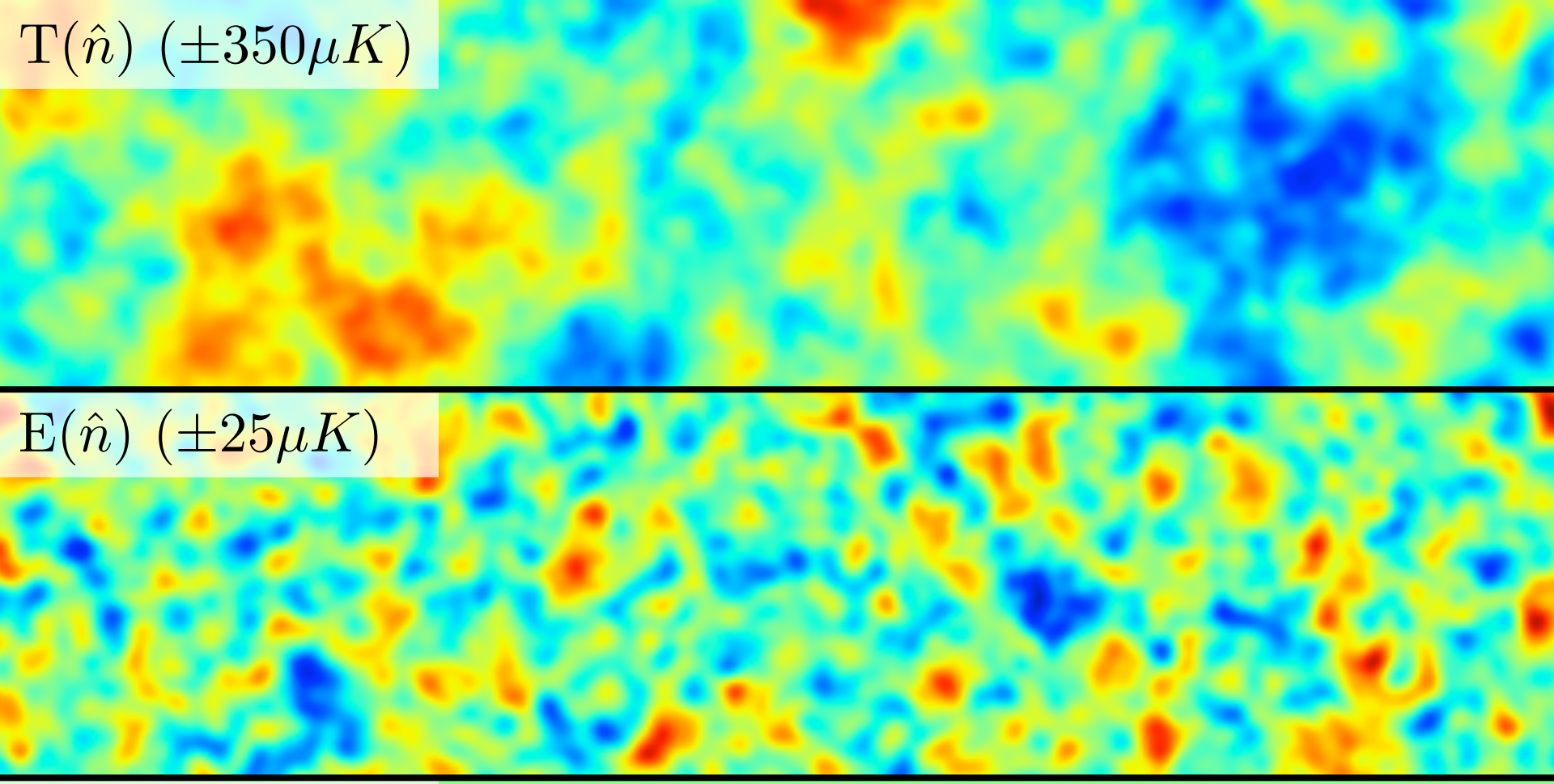




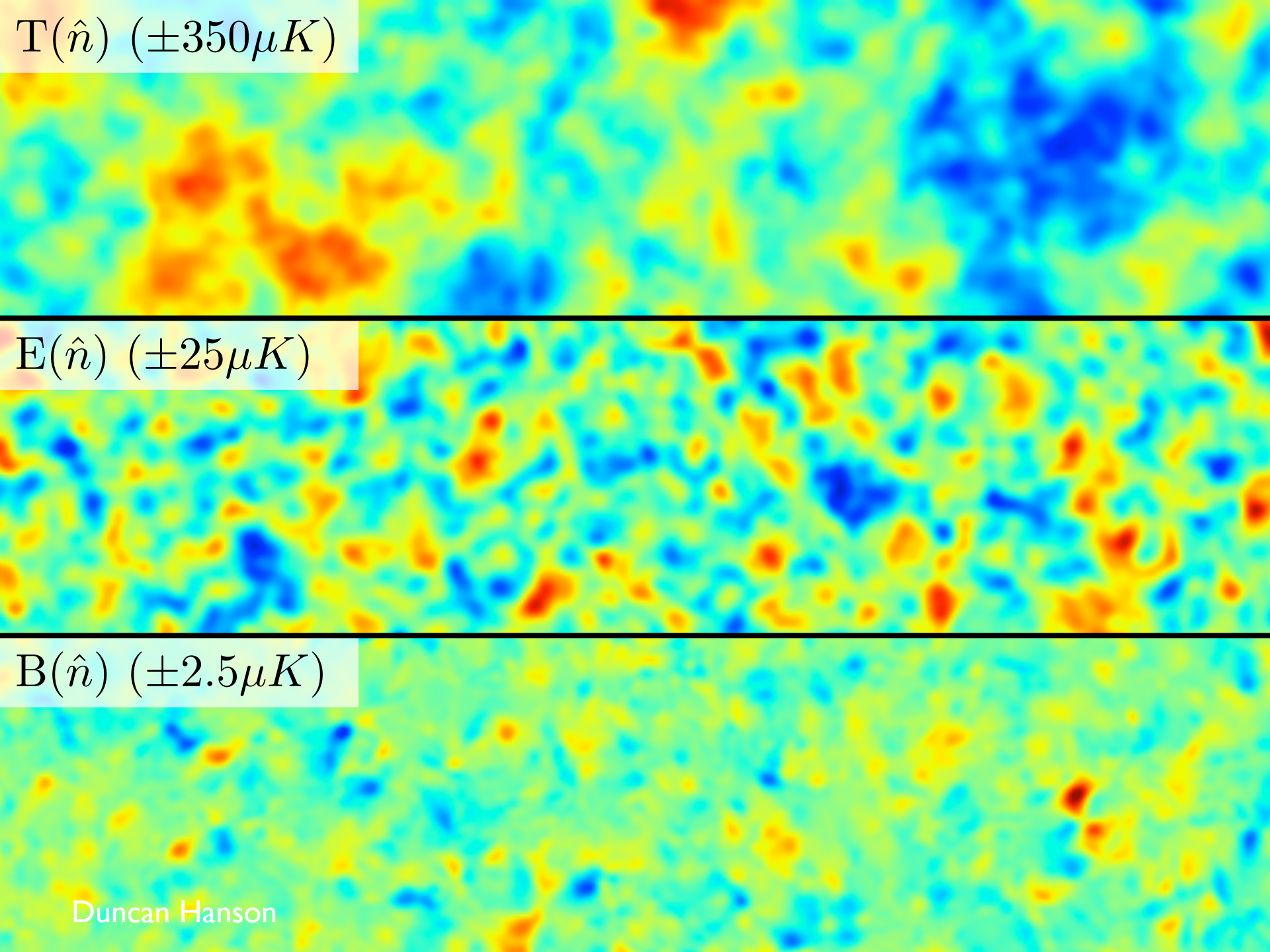
BICEP2/Keck + Planck Collaborations 2015

$$r_{0.05} < 0.12 \quad (95\%\ \mathrm{CL})$$

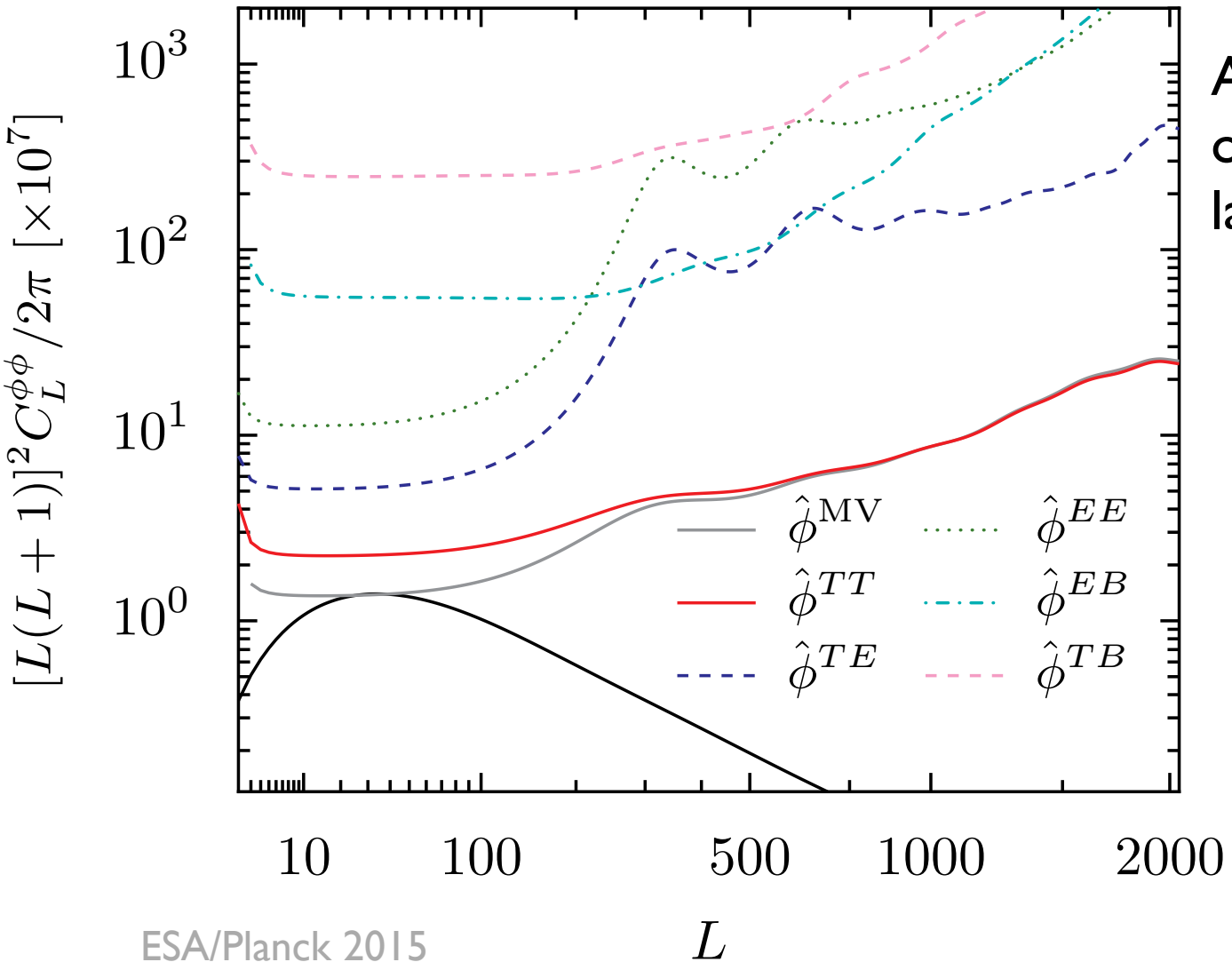
- *B*-modes now as constraining as *TT*
- Demonstrated power of multi-frequency dust cleaning



Duncan Hanson


$\mathrm{T}(\hat{n})\ (\pm 350 \mu K)$
$\mathrm{E}(\hat{n})\ (\pm 25 \mu K)$
$\mathrm{B}(\hat{n})\ (\pm 2.5 \mu K)$
Duncan Hanson

Planck reconstruction noise levels



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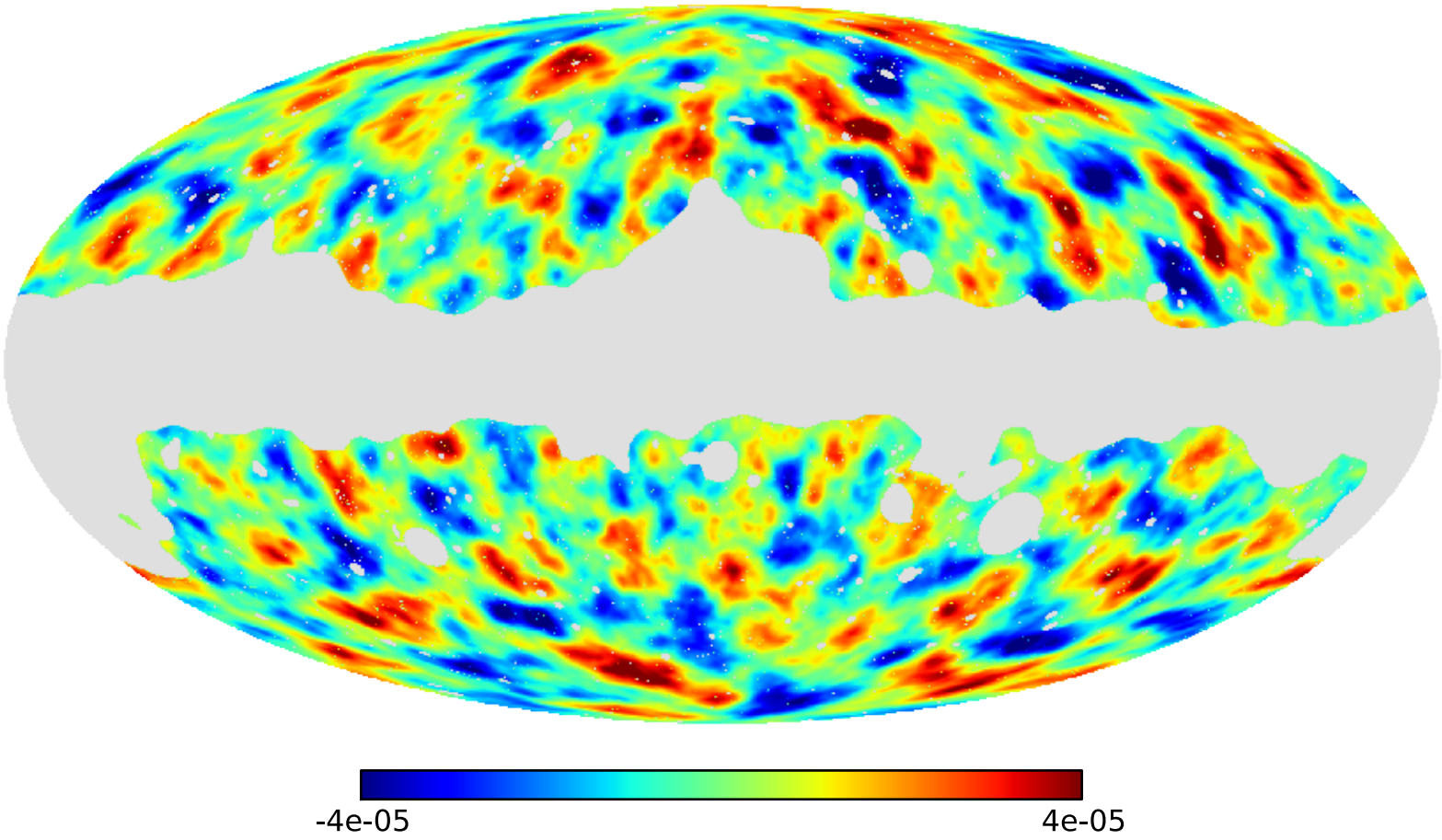
Almost white noise on $L(L+1)\varphi_{LM}$ on large scales

Planck 2015 minimum-variance



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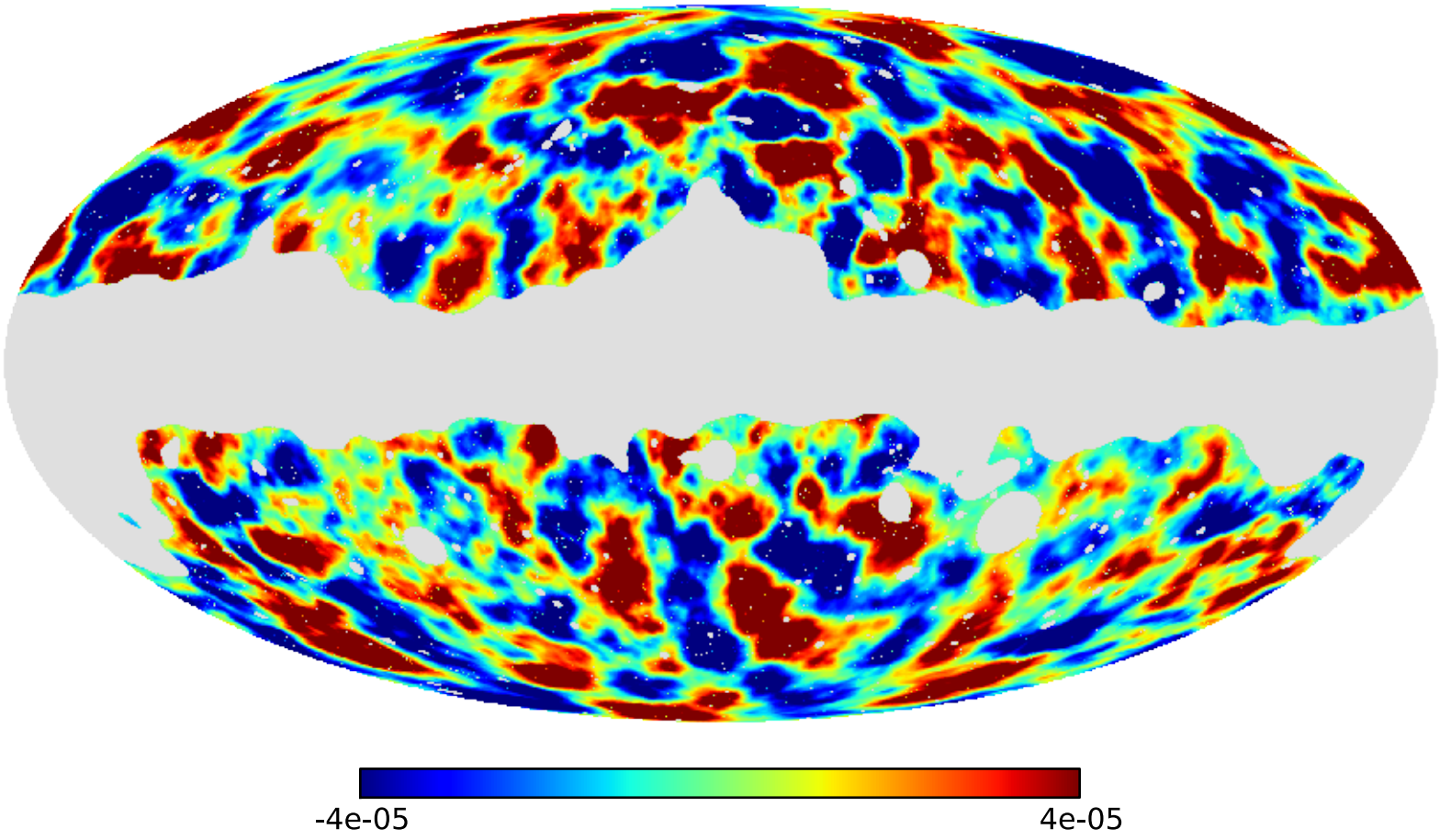
Planck 2015 EE+BB



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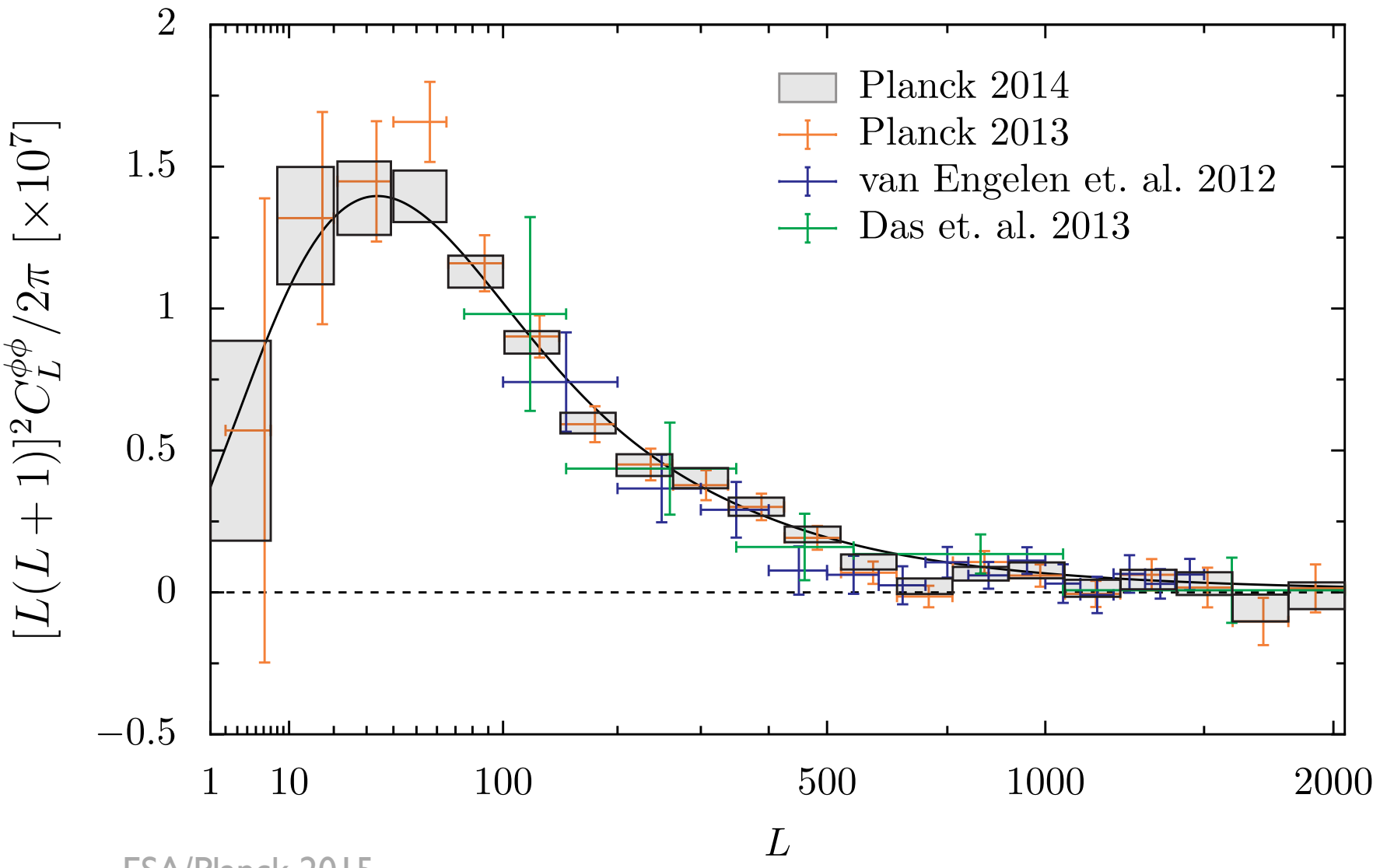
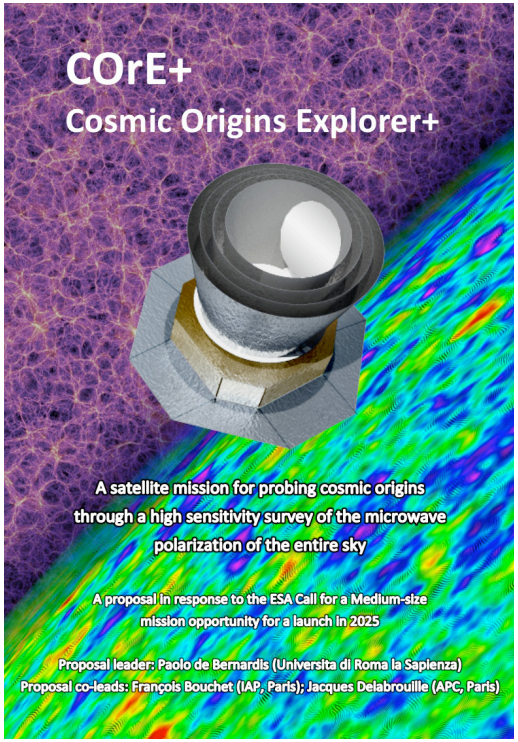
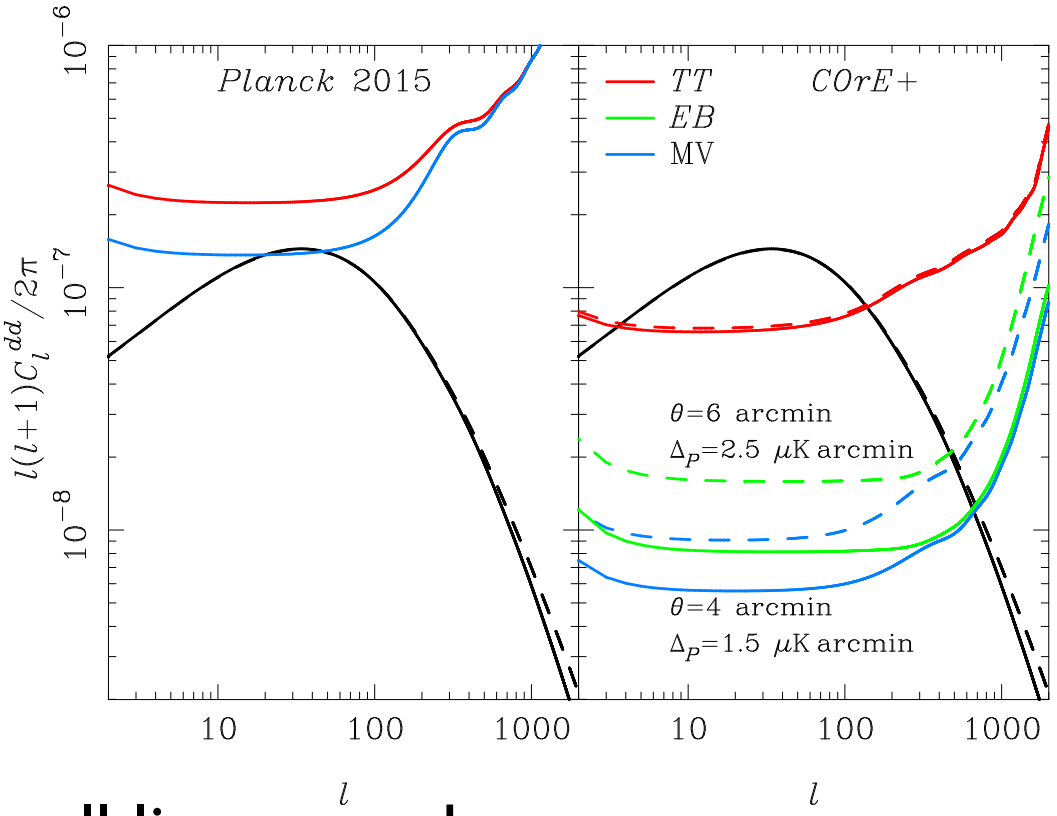
2015 MV power spectrum



ESA/Planck 2015

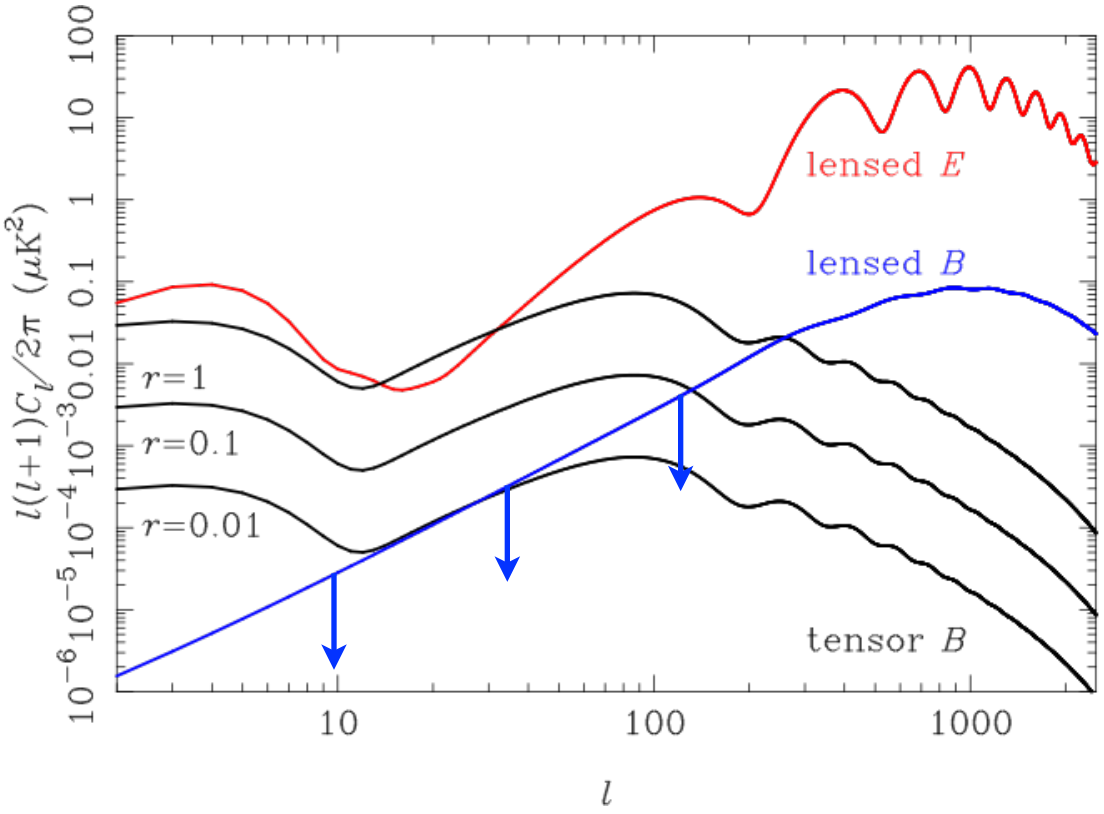
Future CMB lensing surveys





- S/N>1 possible for all linear modes
  - $\sigma(\Sigma m_\nu) \approx 30$ *meV and rather better with X-corrs (LV's talk)*
- Similar performance may be possible from ground (dust?): AdvACT, Stage-IV

Delensing degree-scale B-modes

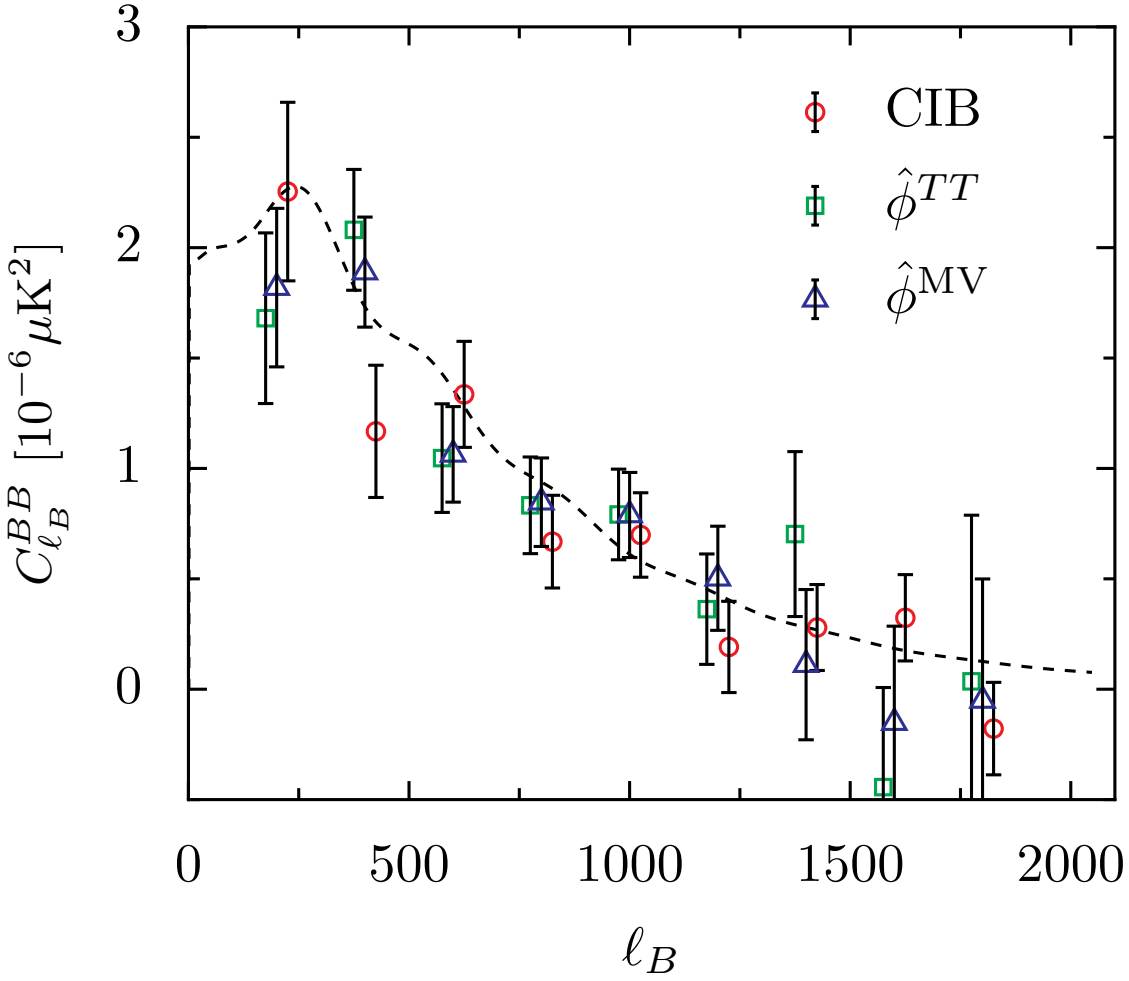


- Improve limits on amplitude of GWs
- Access primordial *B*-modes on smaller scales
  - *Tensor tilt*
  - *Oscillations*

- Large-angle lens-induced *B*-modes like 5 μK-arcmin white noise (c.f. 3 μK-arcmin in BICEP2/Keck before dust cleaning)
- Subtract lens-induced *B*-modes with estimate of φ: $B_{\rm delens} \sim B - E\varphi$
  - *Requires high-S/N E and φ (or proxy, e.g., CIB) on small scales*

Towards delensing: indirect BB

- "Correction" in $B_{\rm delens}$~B−$E\varphi$ correlated with B at expected level



$$C^{B\hat{B}} \sim B(E\hat{\phi})$$

See also Hanson+2013, Ade+2014, and van Engelen+2014

Challenges

- Sensitivity:

$$\Delta_P = 1\,\mu\mathrm{K\,arcmin}\sqrt{\frac{10^5}{N_\mathrm{d}}}\left(\frac{s_\mathrm{d}}{100\,\mu\mathrm{K}\sqrt{\mathrm{s}}}\right)\sqrt{\frac{1\,\mathrm{yr}}{t_\mathrm{obs}}}\sqrt{f_\mathrm{sky}}$$

- Galactic foregrounds (see PL's talk)
  - *Issue for GW detection everywhere at 150 GHz*
  - *Minimum at lower frequency but requires multi-component modeling and synchrotron is likely more complex*
  - *Issue for lensing science?*
- Systematic effects (see PL's talk)
  - *BICEP2/Keck demonstrated control to r~O(0.01) level with template projection*
  - *Characterisation of O(10^5) focal-plane elements?*

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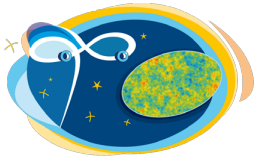

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a look back to the birth of Universe

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