CMB constraints on fundamental physics

Anthony Challinor

Institute of Astronomy
and
Department of Applied Mathematics and Theoretical Physics
University of Cambridge
a.d.challinor@ast.cam.ac.uk

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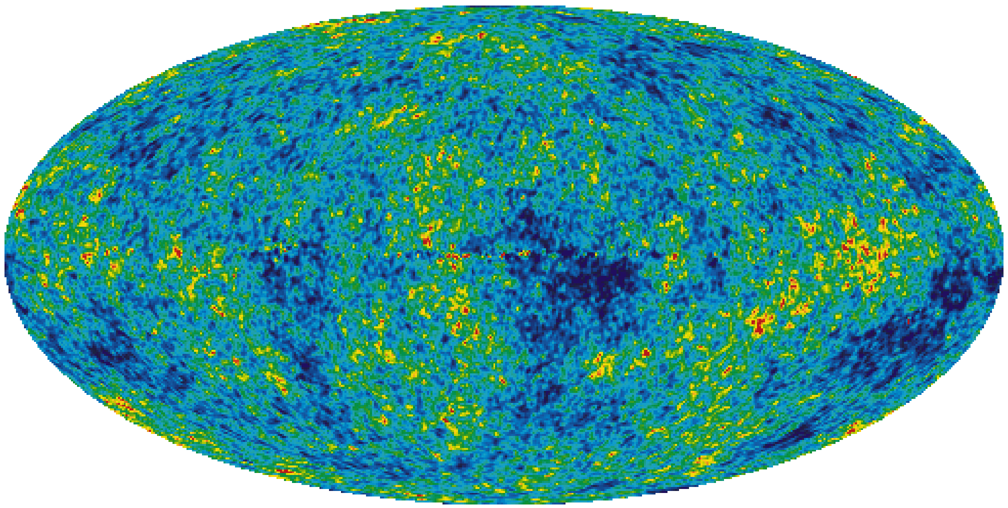
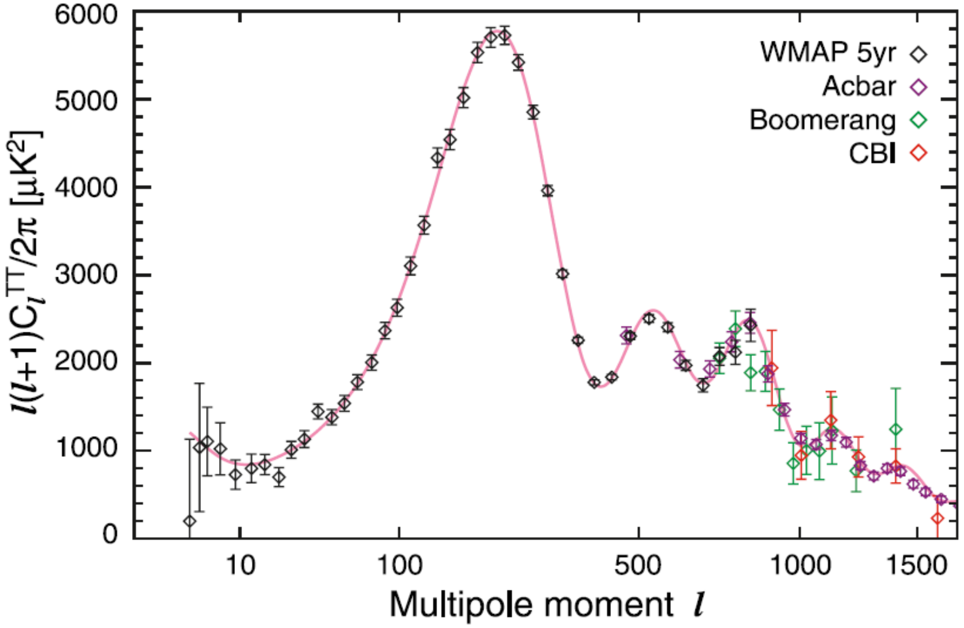
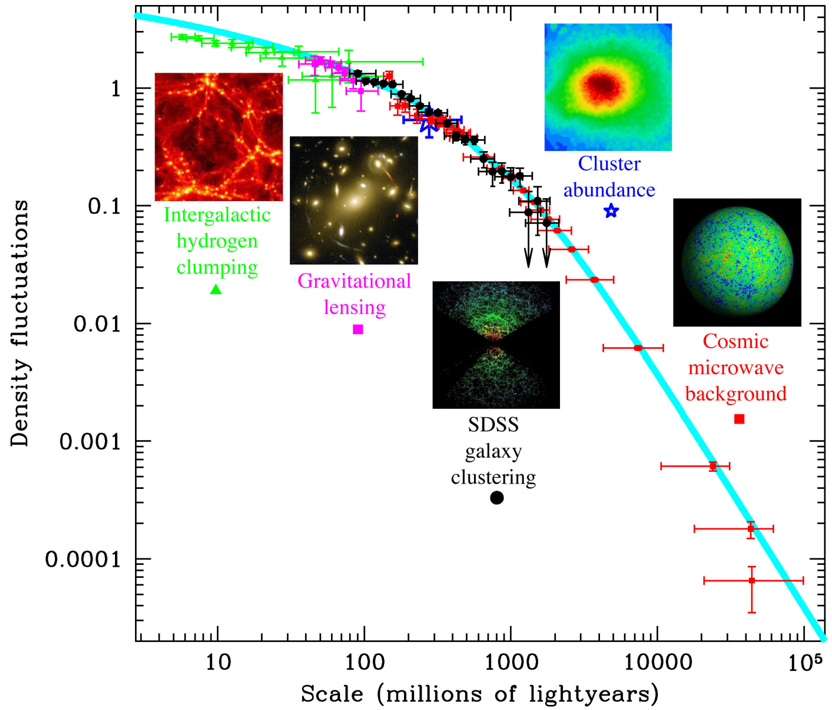
WHAT DO WE LEARN FROM CMB FLUCTUATIONS?





- Constraints on cosmological parameters ($\Omega_b h^2$, $\Omega_m h^2$, d_A etc.)
- Initial conditions and primordial fluctuations (inflation?)
  - Character (adiabatic, gw waves?), spectra and non-Gaussian statistics
- IGM and structure formation at high redshift (dark energy, m_ν etc.)

What scales are involved?



- CMB probes fluctuations on comoving scales $10\,\mathrm{Mpc} < k^{-1} < 10^4\,\mathrm{Mpc}$
- Primary CMB probes primordial fluctuation in shell of radius $d_A = 14000\,\mathrm{Mpc}$ and width $r_s(z_*) = 145\,\mathrm{Mpc} \rightarrow$ comoving volume $350\,\mathrm{Gpc}^3$
  - Upcoming galaxy surveys (e.g. DES) $\sim$ tens Gpc^3
  - Ideal, full-sky 21-cm survey of dark ages: $\sim 4 \times 10^3\,\mathrm{Gpc}^3$ down to scales $k^{-1} \sim 10^{-2}\,\mathrm{Mpc}$

CMB OBSERVABLES

- Power spectrum of $\Delta T = \sum_{lm} a_{lm} Y_{lm}(\hat{\boldsymbol{n}})$:

$$\langle a_{lm} a_{lm}^* \rangle = C_l \delta_{ll'} \delta_{mm'}$$

- Non-zero higher-order connected moments for non-Gaussian field; e.g. bispectrum

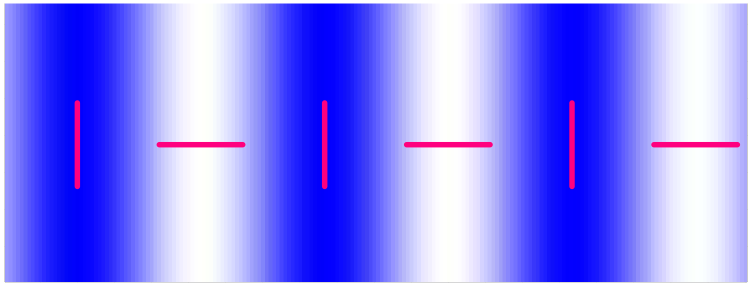
$$\langle a_{l_1 m_1} a_{l_2 m_2} a_{l_3 m_3} \rangle = B_{l_1 l_2 l_3} \begin{pmatrix} l_1 & l_2 & l_3 \\ m_1 & m_2 & m_3 \end{pmatrix}$$

- Decomposition of linear polarization into E and B modes:

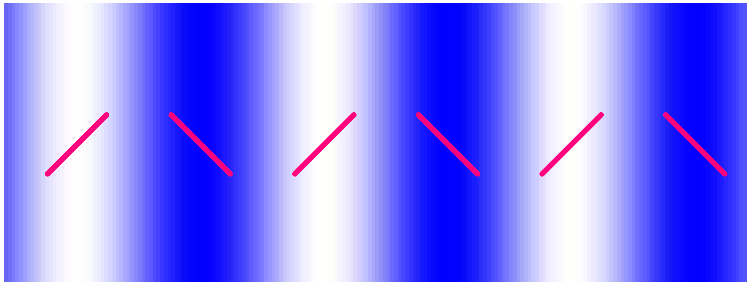
$$\mathcal{P}_{ab}(\hat{\boldsymbol{n}}) \equiv \frac{1}{2} \begin{pmatrix} Q & U \\ U & -Q \end{pmatrix} = \nabla_{\langle a} \nabla_{b \rangle} P_E + \epsilon^c{}_{(a} \nabla_{b)} \nabla_c P_B$$

  - Only C_l^E, C_l^B and C_l^{TE} non-zero if parity respected in mean
  - Linear scalar fluctuations produce only E-mode polarization

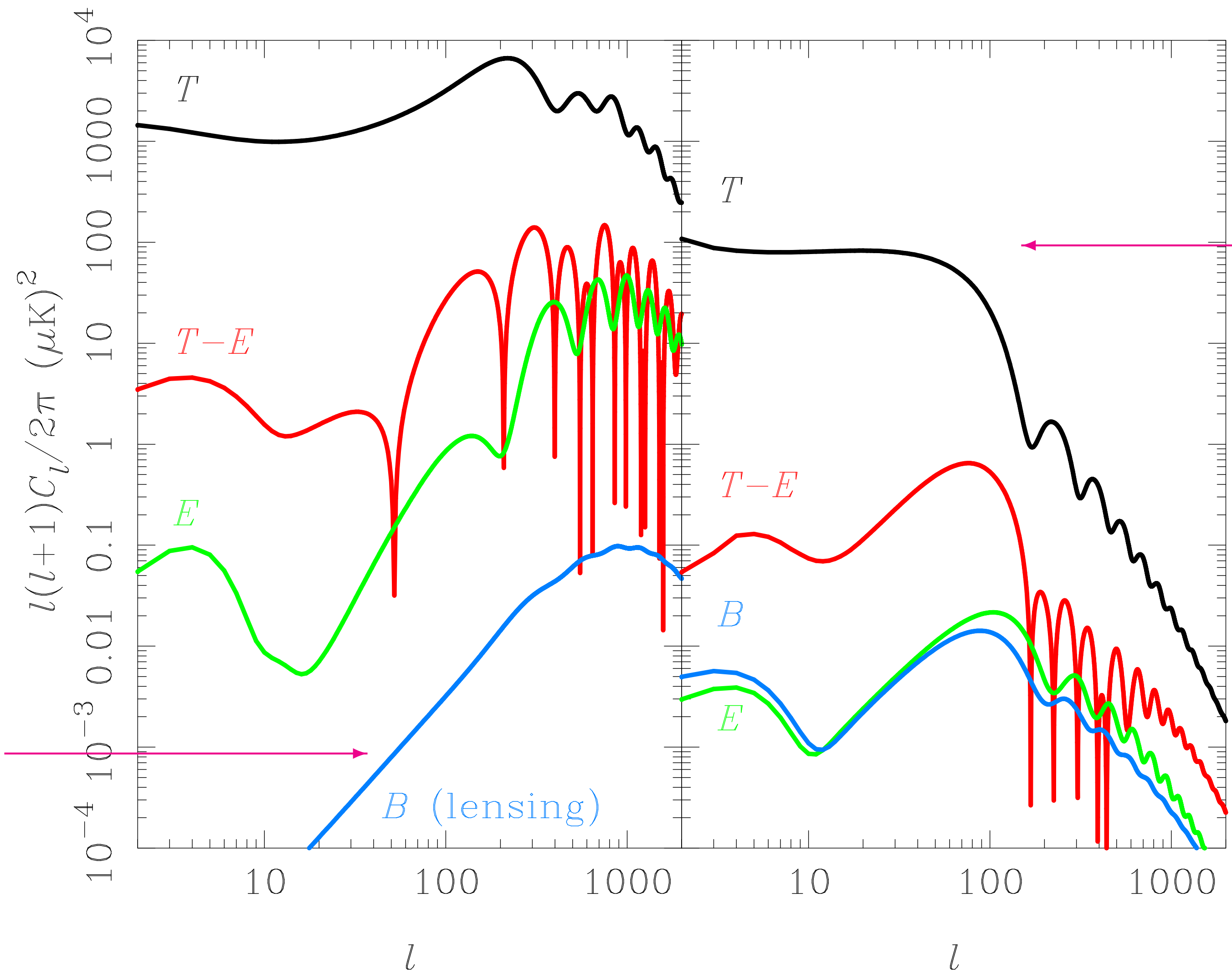
Pure E mode



Pure B mode



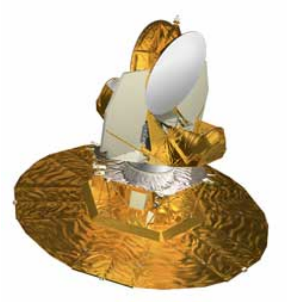
Theory power spectra ($r = 0.2$)

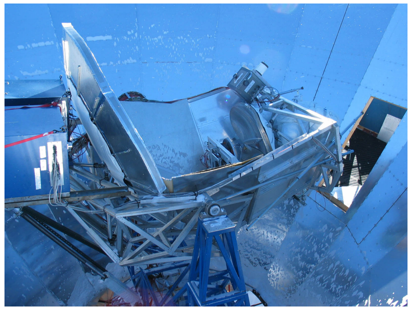


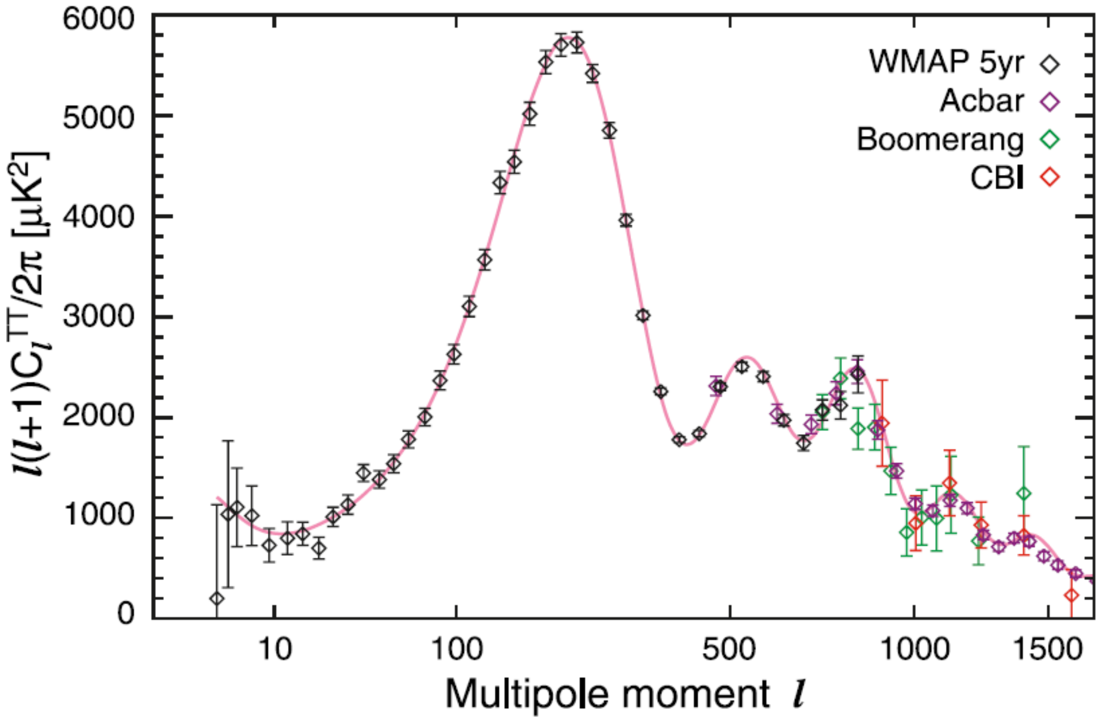
Effects only on large scales since gravity waves damp inside horizon

Lens-induced B modes ($\sqrt{C_l^B} \approx 1.3$ nK)

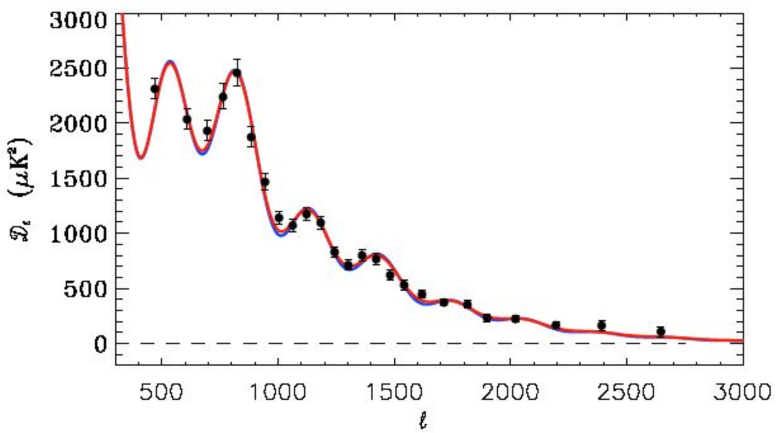
CURRENT C_l CONSTRAINTS: TT





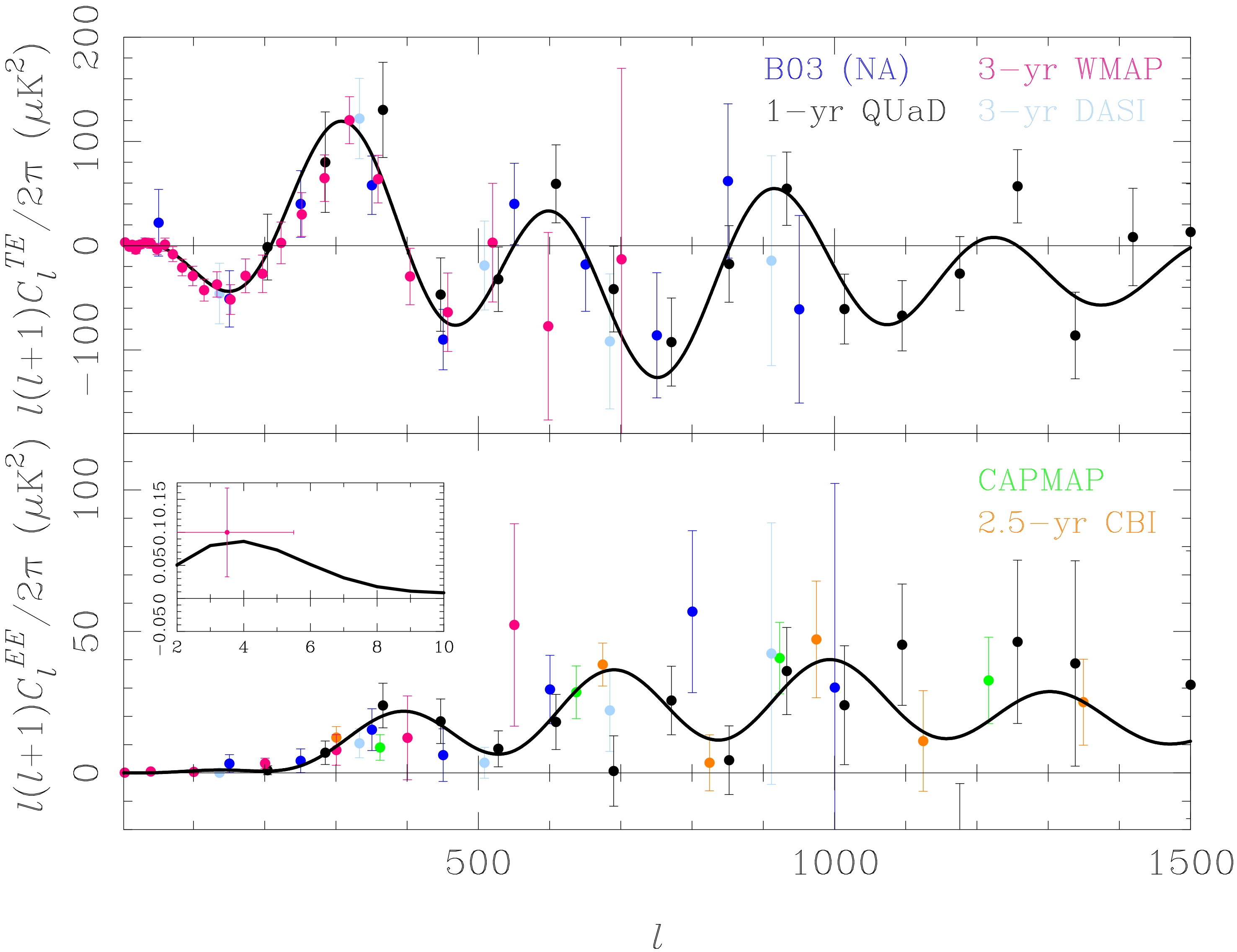


Nolta et al. 2008



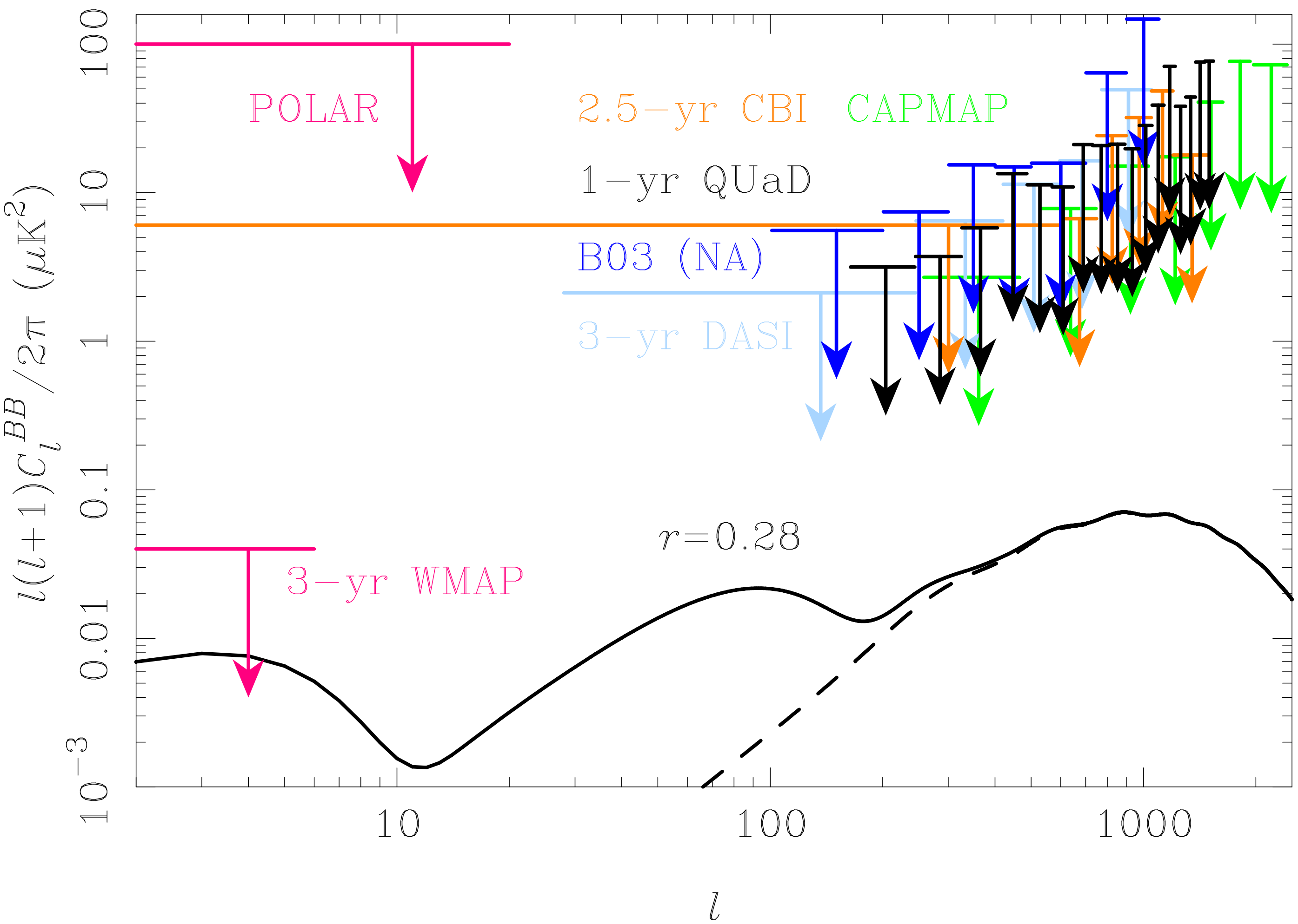
Reichardt et al. 2008

CURRENT C_l CONSTRAINTS: TE AND EE



- Large-angle E-modes $\Rightarrow \tau = 0.09 \pm 0.02$ (Dunkley et al. 2008)

CURRENT C_l CONSTRAINTS: BB

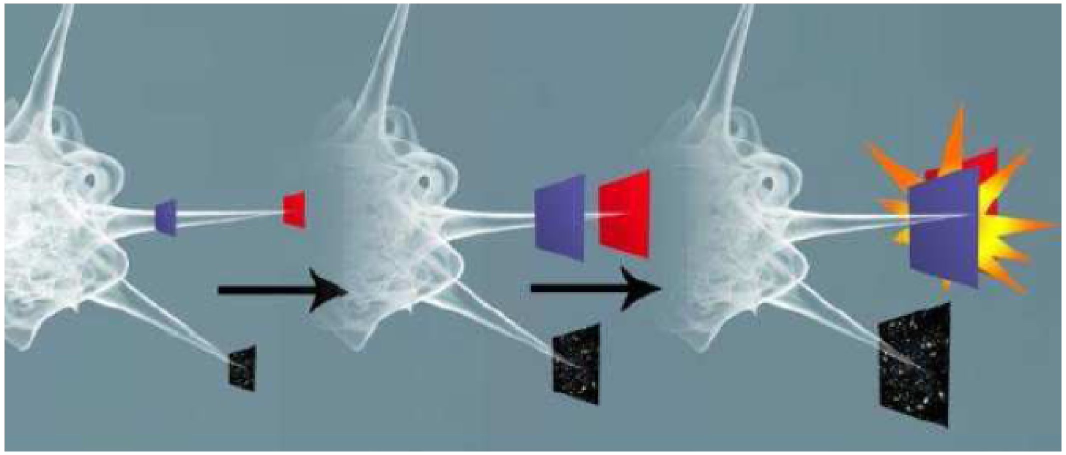


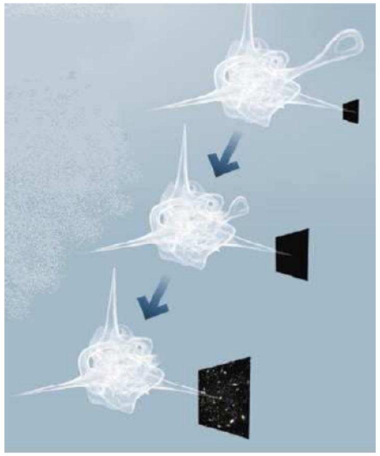
Minimal inflation vs. CMB

- Flat universe
  - $\Omega_K = -0.099^{+0.085}_{-0.100}$ from WMAP5 (weak H_0 prior and $w = -1$)
  - $-0.017 < \Omega_K < 0.0068$ from WMAP5+BAO ($w = -1$)
  - Similar for variable w with BAO *and* SN
- Nearly scale-invariant, almost power-law spectra
  - $n_s = 0.963 \pm 0.015$ from WMAP5, no running and $r = 0$ (little improvement from small-scale CMB)
  - Expect $dn_s/d\ln k \sim (n_s - 1)^2$: $dn_s/d\ln k = -0.037 \pm 0.028$ from WMAP5 with $r = 0$
- Adiabatic fluctuations confirmed at 10% level for general models (Bean et al. 2006)
- Gaussianity confirmed at 0.1% level
- Gravitational waves?
  - $r < 0.43$ (< 0.58 with n_s running) from WMAP5 alone
  - $r < 0.20$ from WMAP5+BAO+SN

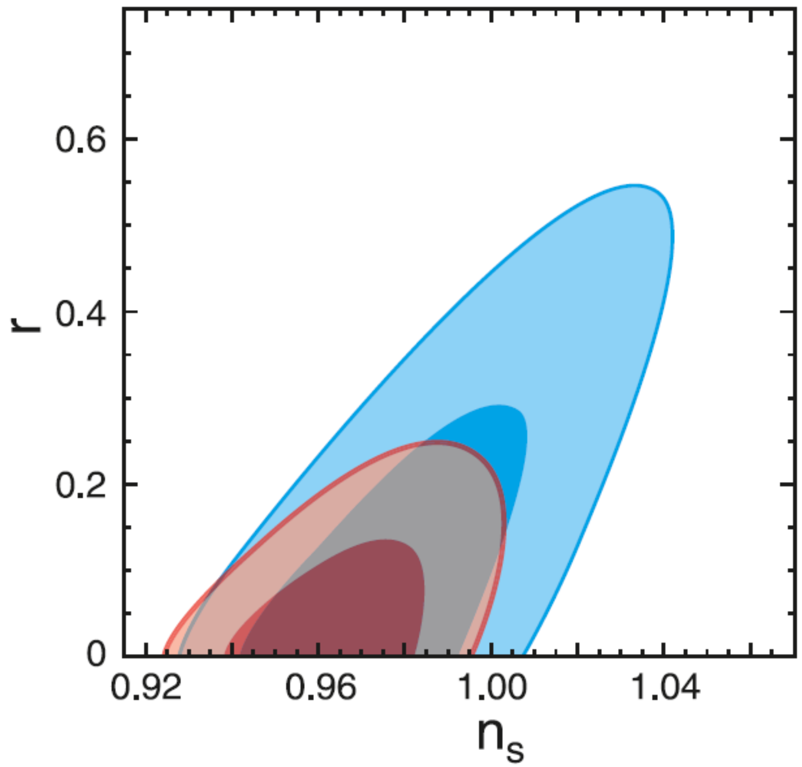
REALISING INFLATION IN FUNDAMENTAL THEORY

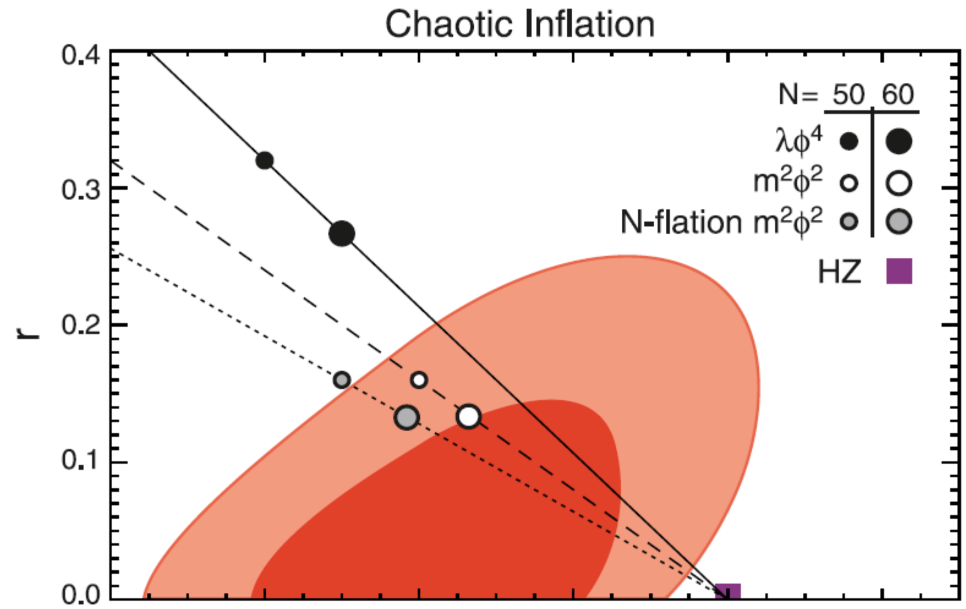
- Brane inflation from brane-antibrane annihilation (Dvali et al. 2001; Burgess et al. 2001) gives several stringy signatures
  - Cosmic (super-)strings (Sarangi & Tye 2002; Jones, Stoica & Tye 2002; Copeland, Myers & Polchinski 2004)
  - Isocurvature modes
  - Potentially large non-Gaussianity (Silverstein & Tong 2004)
  - No gravitational waves (Baumann & McAllister 2007; Kallosh & Linde 2007)
- Modular inflation from rolling of size and shape of extra dimensions (Blanco-Pillado 2004; Conlon & Quevedo 2006 etc.)





CONSTRAINTS ON PRIMORDIAL POWER SPECTRA

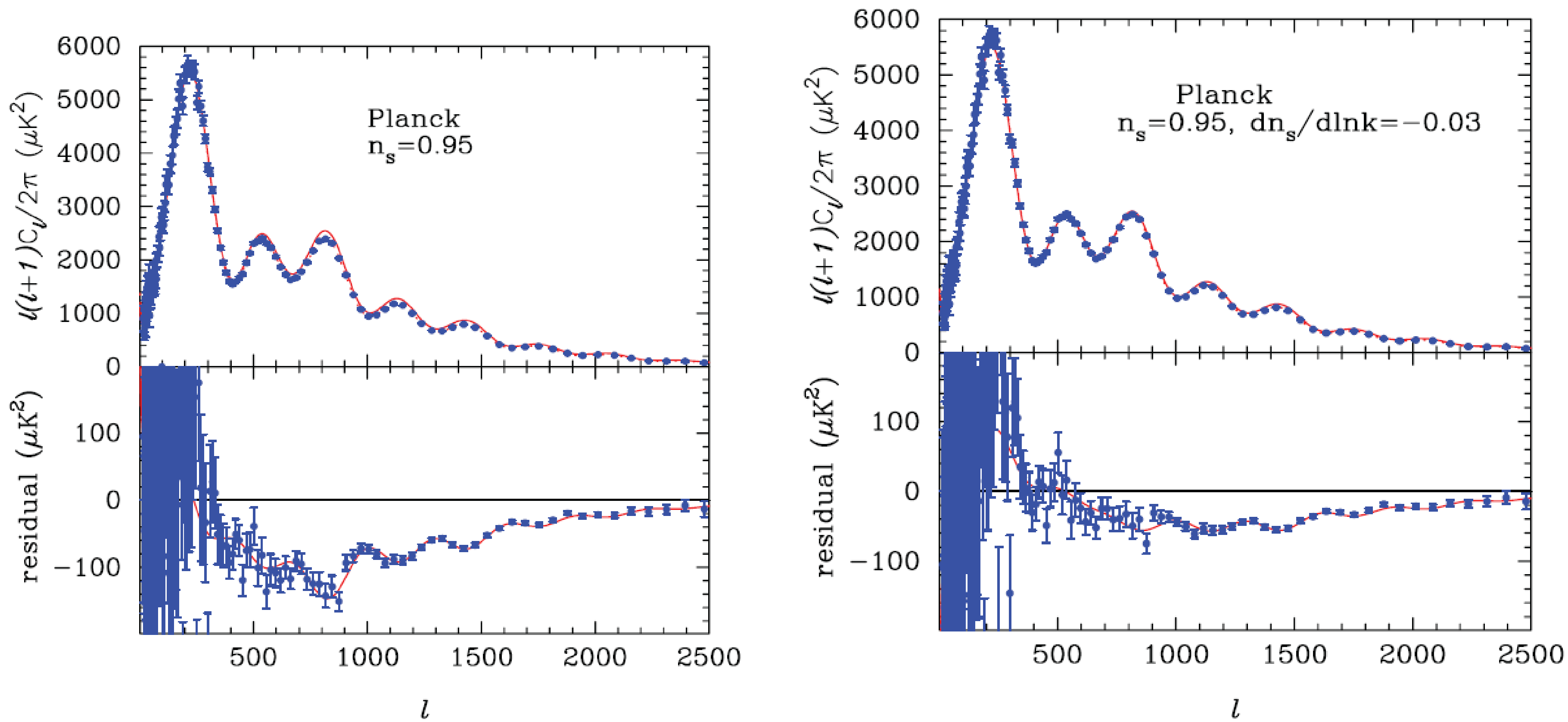




Komatsu et al. 2008

- Inflation energy scale unknown: $r < 0.2$ from low-l $\Delta T \Rightarrow E_{\rm inf} < 2.2 \times 10^{16}$ GeV
- Dynamics not yet classified (e.g. small-field, large-field or hybrid phenomenology)
- $n_s < 1$ with CMB+BAO+SN and $n_s = 0.963 \pm 0.015$ from WMAP5, no running and $r = 0$
  - n_s-$\Omega_b h^2$ degeneracy main one now affecting n_s
- $dn_s/d \ln k = -0.037 \pm 0.028$ from WMAP5 with $r = 0$
  - Some shifts ($\sim -0.5\sigma$) if allow running or small-scale CMB

IMPROVEMENTS WITH PLANCK?



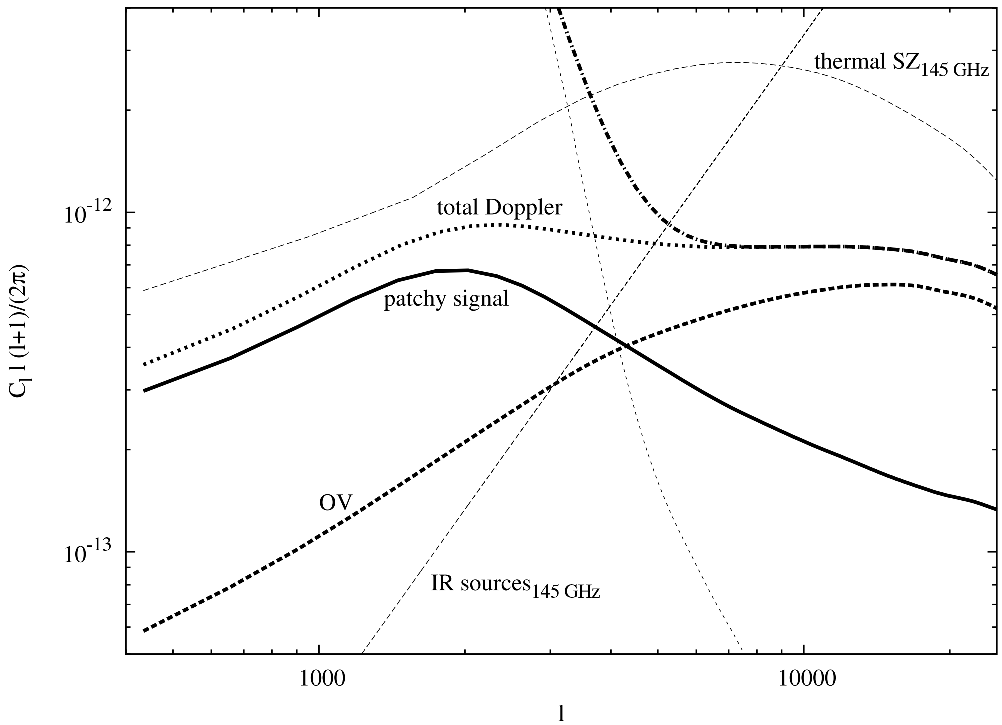
"Planck: the scientific programme" – Planck collaboration

- Marginalised error forecasts for
  $\ln \mathcal{P}_{\mathcal{R}}(k) = \ln A_s + (n_s - 1)\ln(k/k_0) + \frac{1}{2}(dn_s/d\ln k)\ln^2(k/k_0) + \cdots$:

$$\Delta n_s = 0.0045 \quad \text{and} \quad \Delta(dn_s/d\ln k) = 0.005$$

Secondary scattering

- Planck ΔT cosmic-variance limited to $l \sim 2500$ where secondaries becoming important:



model	τ_{ri}	Ω_Λ	ω_{dm}	ω_b	n_s	A_s
1σ	0.0035	0.010	0.0017	0.00018	0.0045	0.0050
A	0.40	1.18	-1.10	1.71	2.14	0.16
B	1.26	1.66	-1.54	2.40	3.05	0.78
C	2.25	2.89	-2.69	4.20	5.62	1.58

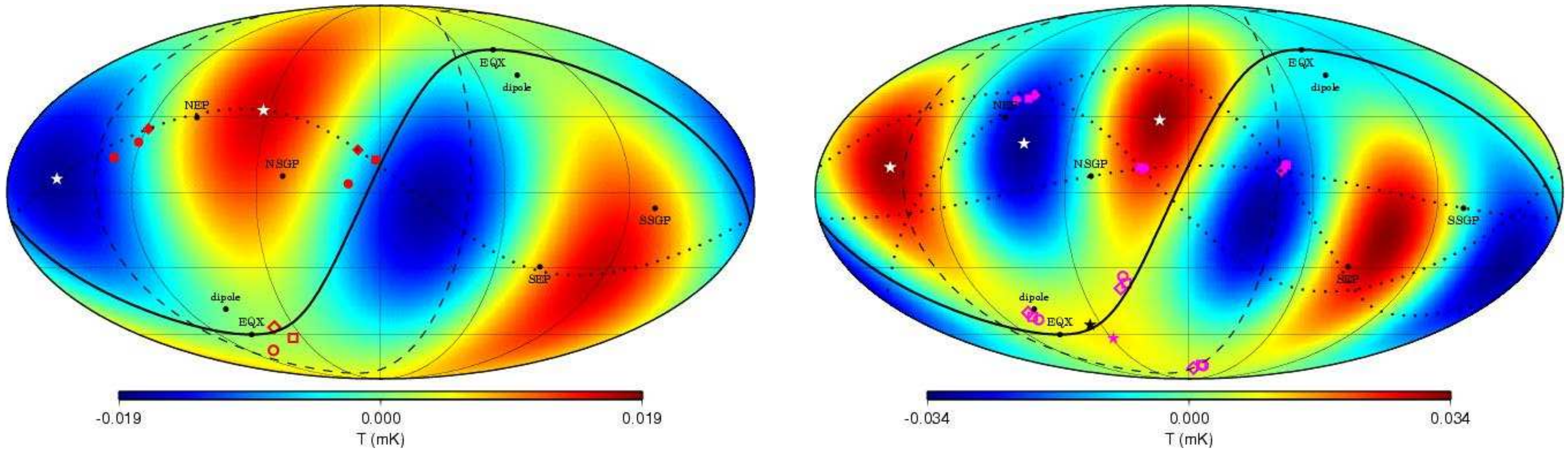
TABLE 1
Bias in units of the statistical error ($\mathcal{B}_i$) expected for cosmological parameter estimation with Planck, if temperature and polarization power spectra are used and the influences of kSZ/OV and patchy reionization are neglected in the power spectrum analysis. The maximum multipole in our analysis was $l = 4000$.

Zahn et al. 2005

- Mitigate by removing high-l ΔT (polarization less affected) but $\sim 100\%$ hit in errors, or C_l template marginalisation?
- Also theoretical uncertainty in recombination and beam uncertainties?

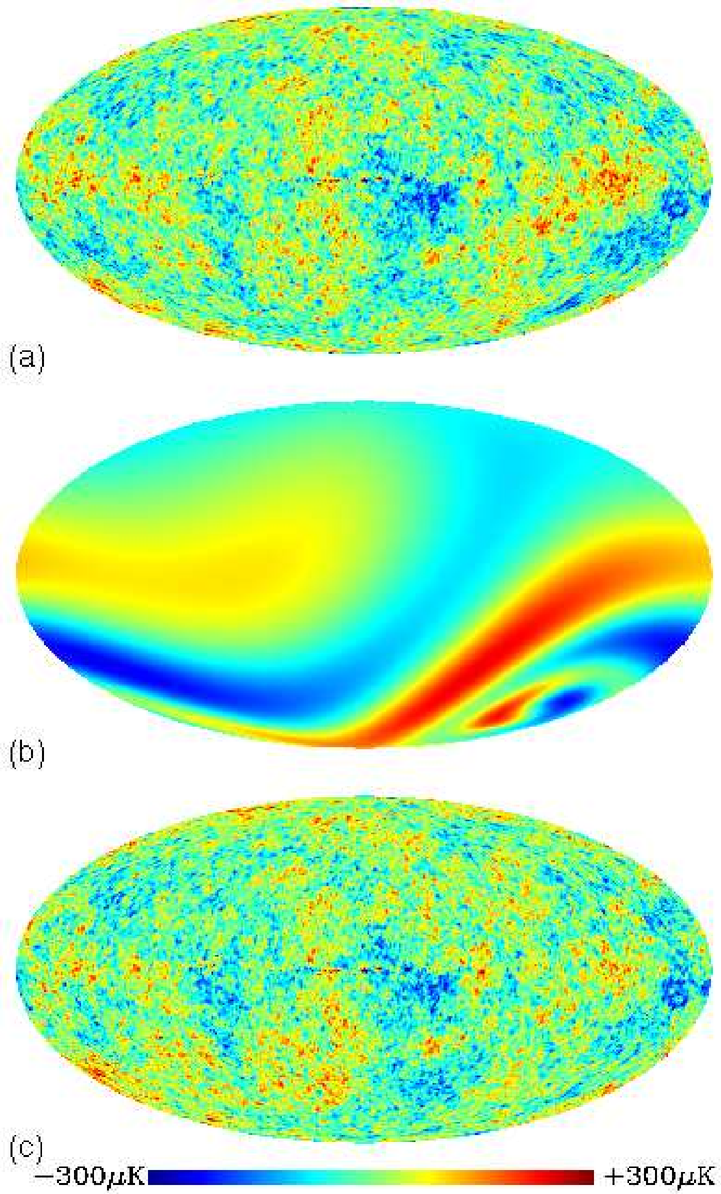
Testing statistical isotropy

- Several anomalous features in low-l temperature (Copi 2006 for review):
  - Low quadrupole
  - Quadrupole and octopole planar and aligned (perpendicular to ecliptic)
  - Power asymmetry between Northern and Southern hemispheres
  - Cold spot
- Fluke, cosmological (topology; solid dark energy; anisotropic generation of large-scale perturbations), local contamination (SZ; Rees-Sciama; Galactic), or instrumental?

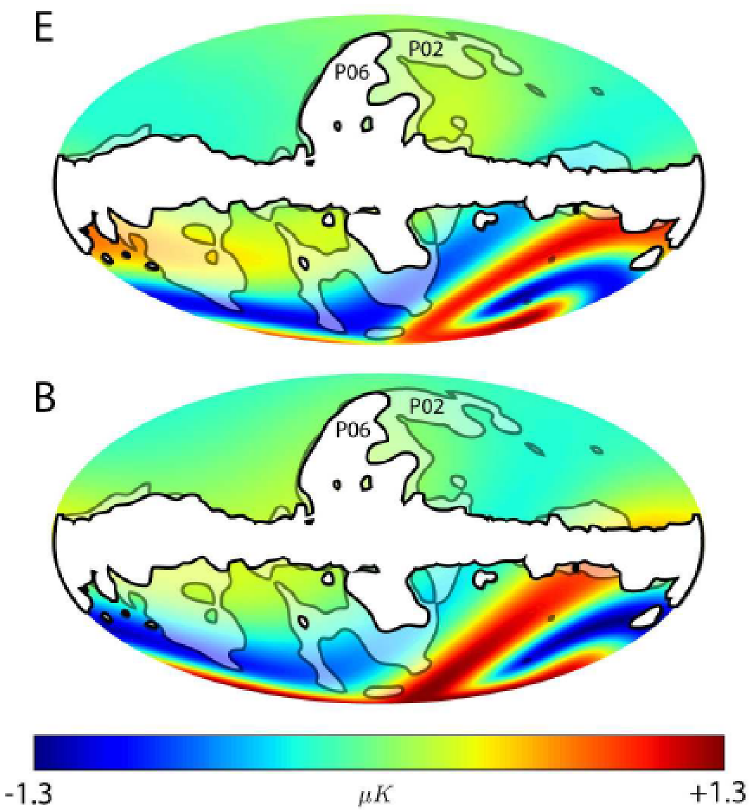


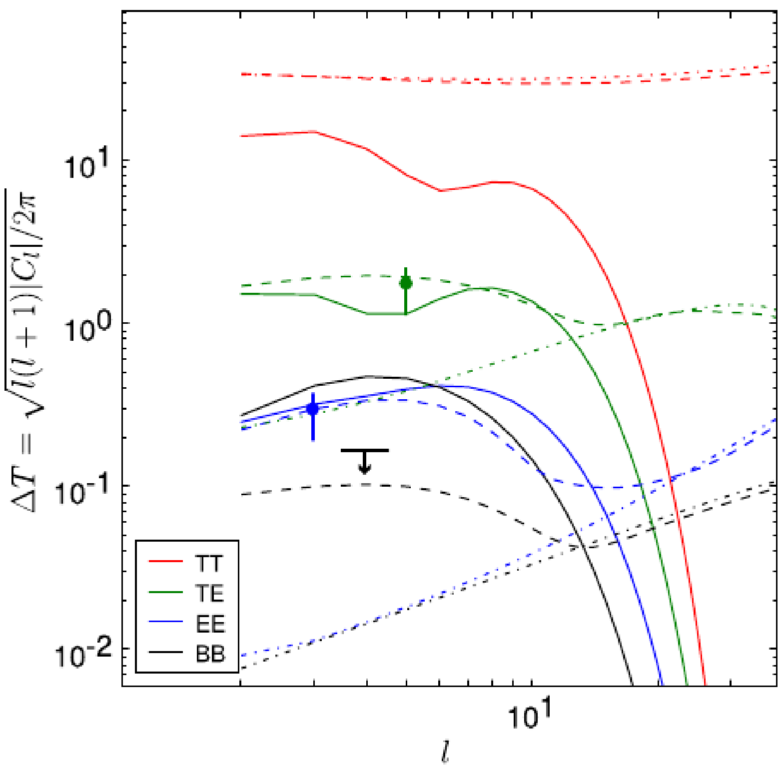
UNIVERSAL ROTATION AND SHEAR?

- Jaffe et al. (2005) find 3σ evidence for correlation between WMAP and Bianchi VII$_h$ template
  - Only considers a subset of dynamical freedom in VII$_h$ models
- Corrected map free of most “large-angle anomalies”
- Evidence for global rotation and anisotropy?
- Requires parameters in conflict with smaller-scale fluctuations



TESTABLE POLARIZATION PREDICTIONS*





- Rough power spectrum analysis: best-fit to ΔT over-produces B-modes
- Also E-B cross-power too high ($\chi^2/15 = 4.3$)
- More rigorous map-based comparison in progress (McEwen et al. in prep.) including additional dynamics degrees of freedom

*Pontzen & AC 2007

Primordial non-Gaussianity

- Bispectrum of primordial curvature perturbation

$$\langle \mathcal{R}(\boldsymbol{k}_1)\mathcal{R}(\boldsymbol{k}_2)\mathcal{R}(\boldsymbol{k}_3)\rangle \propto \delta(\boldsymbol{k}_1+\boldsymbol{k}_2+\boldsymbol{k}_3)F(k_1,k_2,k_3)$$

- Local form peaks on squeezed triangles

$$F(k_1,k_2,k_3) \propto f_{NL}\left(\frac{\mathcal{P}_\mathcal{R}(k_1)}{k_1^3}\frac{\mathcal{P}_\mathcal{R}(k_2)}{k_2^3} + 1 \leftrightarrow 3 + 2 \leftrightarrow 3\right)$$

  – Arises when non-Gaussianity created outside horizon (e.g. multi-field inflation, curvaton, fluctuating reheating):

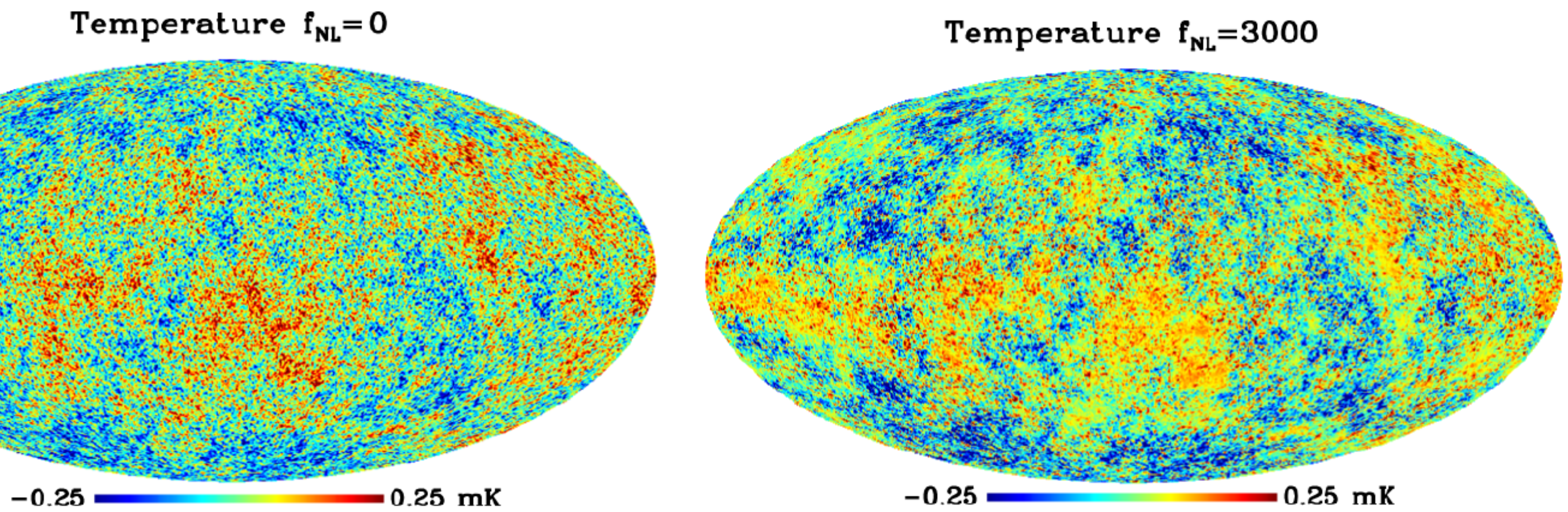
$$\mathcal{R}(\boldsymbol{x}) = \mathcal{R}_G(\boldsymbol{x}) - \tfrac{3}{5}f_{NL}\left(\mathcal{R}_G^2(\boldsymbol{x}) - \langle\mathcal{R}_G^2(\boldsymbol{x})\rangle\right)$$

  – Small in single-field inflation: $f_{NL} \sim n_s - 1$ in squeezed limit

- Non-local form peaks on equilateral triangles

  – E.g. $f[(\nabla\phi)^2]$ in DBI inflation

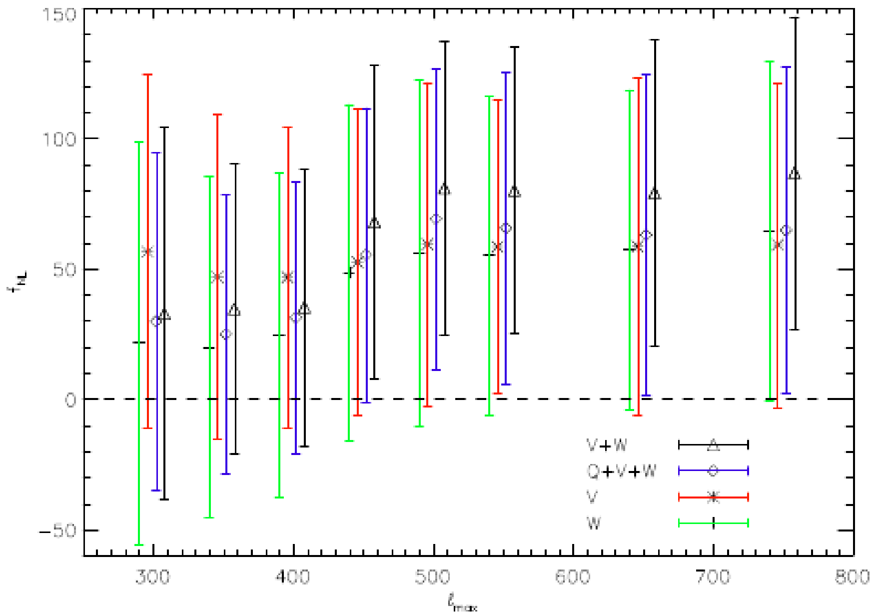
NON-GAUSSIANITY IN THE CMB



Liguori et al. (2007)

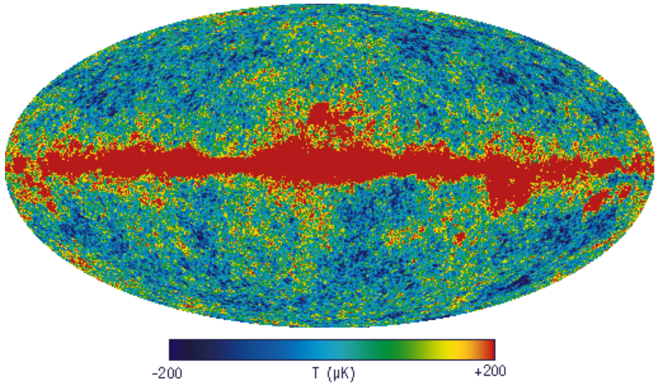
- Large-scale $\Delta T/T = \mathcal{R}/5$
  - Positive f_{NL} skews $\mathcal{R}$ and ΔT negative
- Fractional departure from Gaussianity very well measured: $\sim |f_{NL}|\sqrt{\mathcal{P}_\mathcal{R}} < 10^{-3}$
- Planck should achieve $\Delta f_{NL} = 5$

TROUBLE FOR SIMPLE INFLATION?

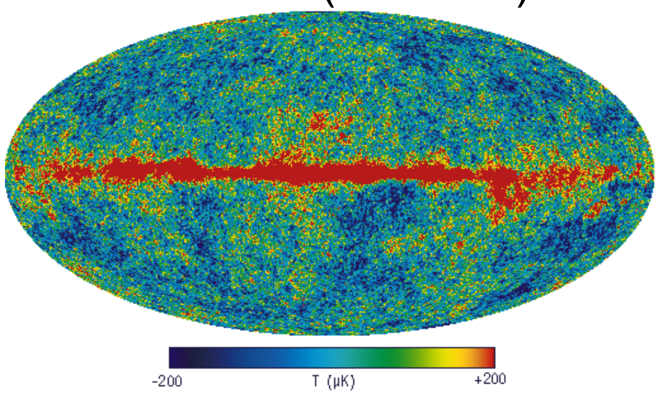


Yadav & Wandelt (2007)

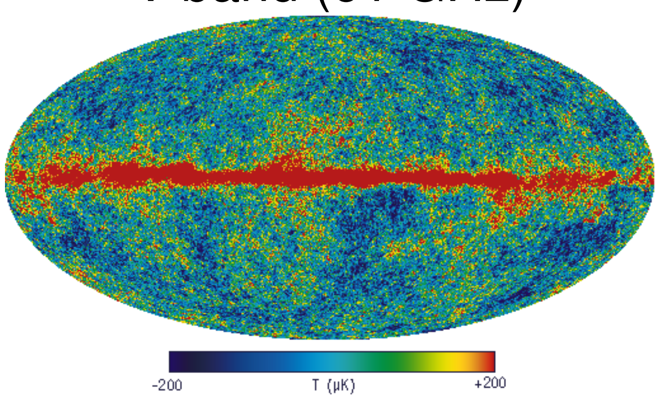
- Headline figure: $27 < f_{NL}^{\text{local}} < 147$
- Statistical issues:
  - Selects highest S/N result
  - Jump in S/N from adding triangles with little statistical weight



Q-band (41 GHz)



V-band (61 GHz)



W-band (94 GHz)

WMAP5 ANALYSES

- Komatsu (et al. 2008) bispectrum analysis:

$$-9 < f_{NL}^{\text{local}} < 111 \quad \text{and} \quad -151 < f_{NL}^{\text{equilateral}} < 253 \quad (\text{V}+\text{W and } KQ75)$$

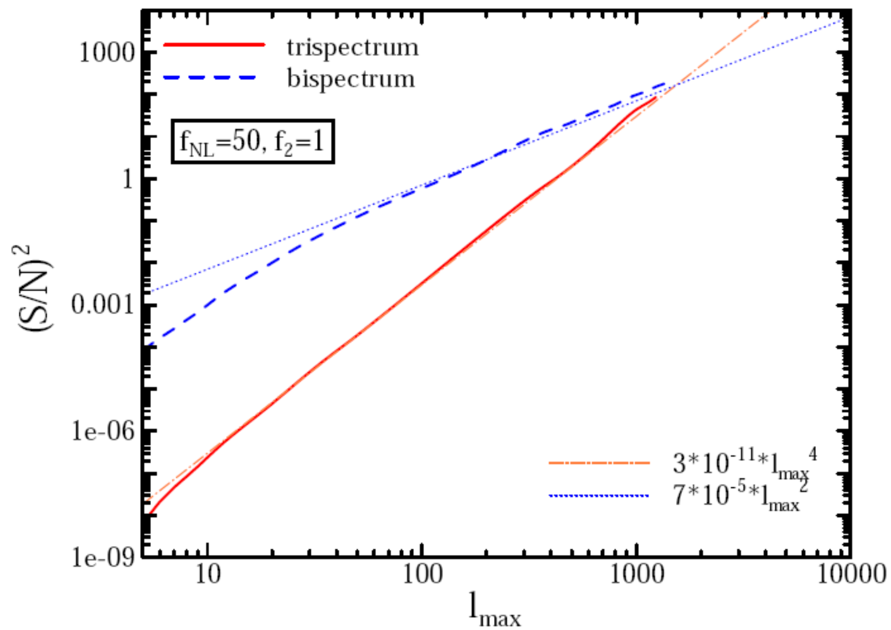
  - Map noise lower by 22%
  - New masks (e.g. $KQ75$ and $KQ75p$) that avoid potential upwards bias in f_{NL}
  - Null tests fine for $KQ75$ and foreground-cleaned $\text{V}-\text{W}$ maps
  - Corrections for point sources (small for local model)

- Analysis with Minkowski functionals: all consistent with Gaussianity

$$-178 < f_{NL}^{\text{local}} < 64 \quad (\text{V}+\text{W and } KQ75)$$

  - Mild tension with bispectrum results for f_{NL}^{local}

- Kendrick Smith et al. WMAP5 analysis (Perimeter meeting, March 2008)
  - Optimal-weighting in bispectrum estimator
  - Foreground template marginalisation
  - $f_{NL}^{\text{local}} = 21 \pm 22$



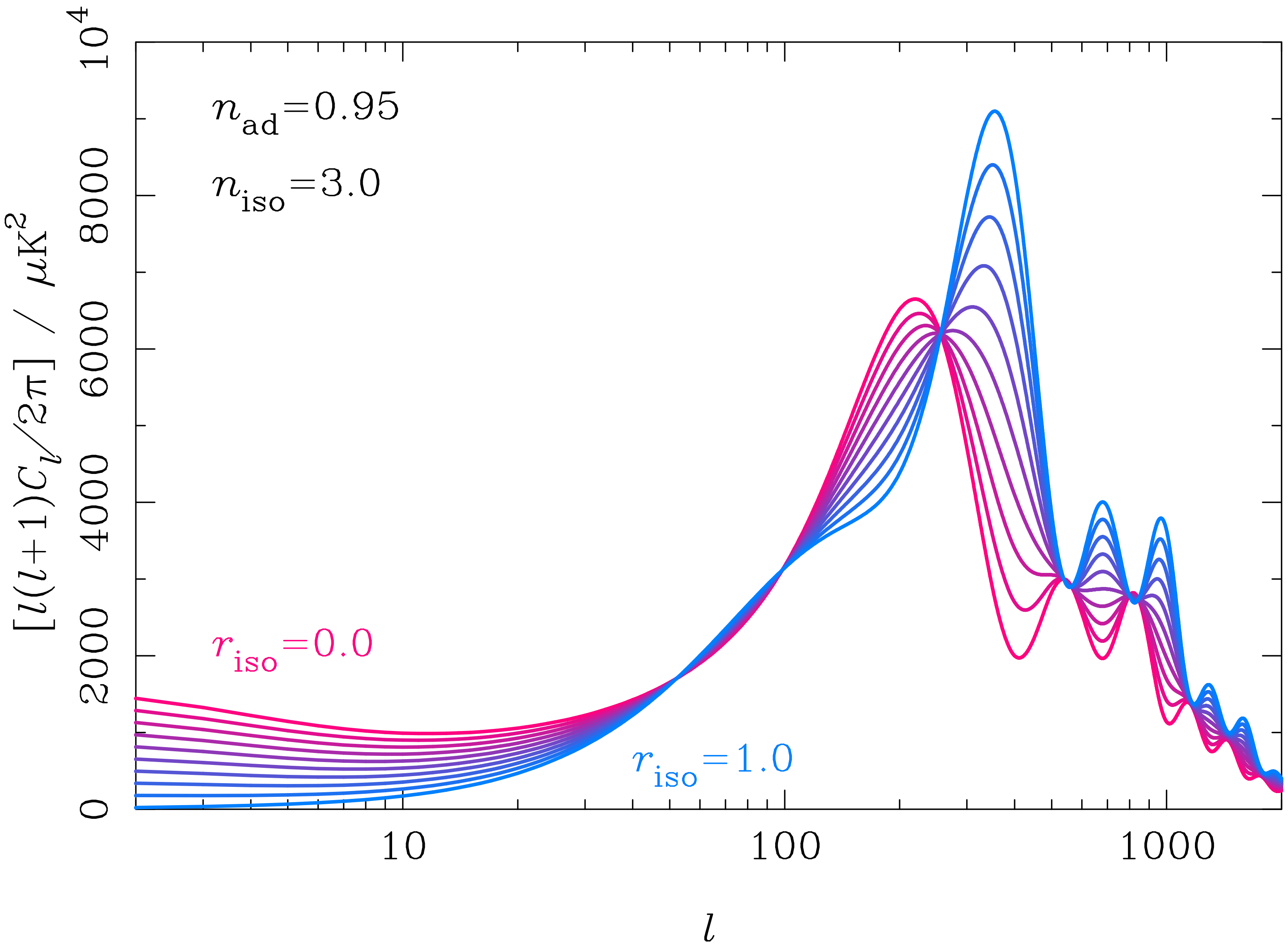
Kongo & Komatsu (2006)

- For local model $\mathcal{R}(\boldsymbol{x}) = \mathcal{R}_G(\boldsymbol{x}) - \frac{3}{5} f_{NL} \left(\mathcal{R}_G^2(\boldsymbol{x}) - \langle \mathcal{R}_G^2(\boldsymbol{x}) \rangle \right) + f_2 \mathcal{R}_G^3(\boldsymbol{x}) + \cdots$

$$T(\boldsymbol{k}_1, \boldsymbol{k}_2, \boldsymbol{k}_3, \boldsymbol{k}_4) \propto \underbrace{\frac{1}{2} \left(\frac{6 f_{NL}}{5} \right)^2}_{\tau_{NL}} \left(\frac{\mathcal{P}_{\mathcal{R}}(k_1)}{k_1^3} \frac{\mathcal{P}_{\mathcal{R}}(k_2)}{k_2^3} \frac{\mathcal{P}_{\mathcal{R}}(k_{14})}{k_{14}^3} + \text{perms} \right) + O(f_2)$$

- No direct constraints on τ_{NL} yet but $|\tau_{NL}| < 10^8$ from rhombus configurations for COBE (Kunz et al. 2001)
  - $\Delta \tau_{NL} \sim 200$ from Planck $\Rightarrow \Delta f_{NL} \sim 50/f_{NL}$

Isocurvature modes in the CMB

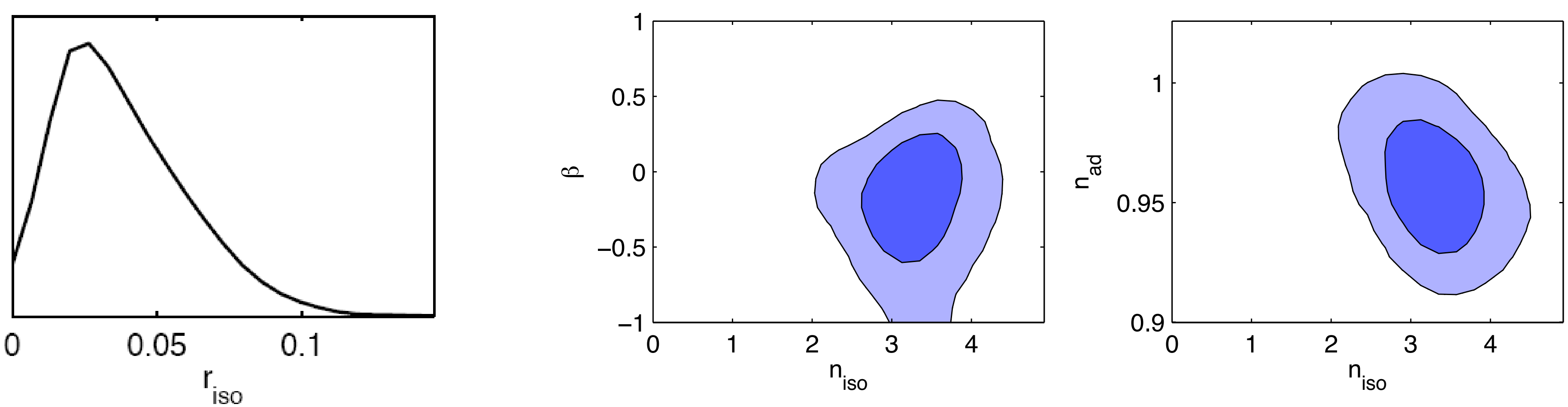


- Large-angle $\Delta T/T = \mathcal{R}/5 - 2\mathcal{S}/5 + \mathrm{ISW}$

Constraints on isocurvature modes

$$C_l = A(1-\alpha)C_l^{AA}(n_s) + A\alpha C_l^{II}(n_{\rm iso}) + 2A\beta\sqrt{\alpha(1-\alpha)}C_l^{AI}[(n_s+n_{\rm iso})/2]$$

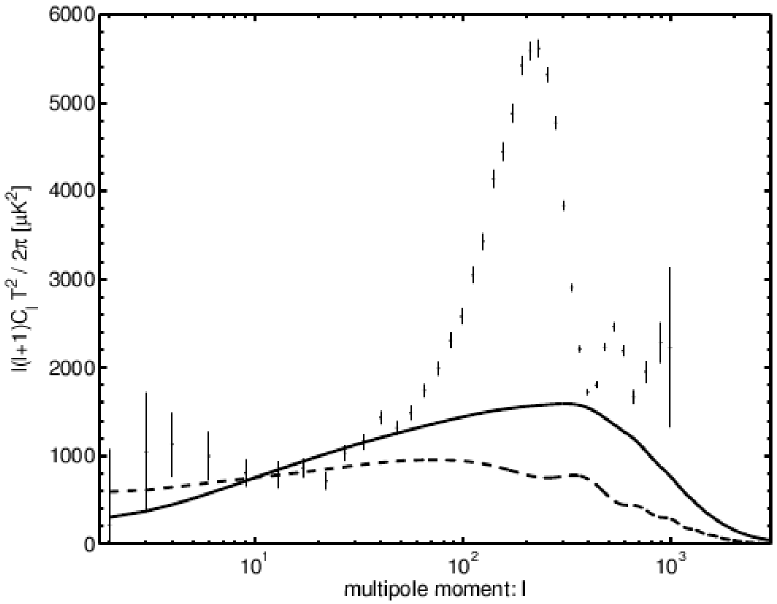
- WMAP5 constraints (Komatsu et al. 2008):
  - For $\beta = 0$ and $n_{\rm iso=1}$ (axion-type) $\alpha < 0.16$ (CMB) and $\alpha < 0.067$ (+ BAO and SN)
  - For $\beta = -1$ and $n_s = n_{\rm iso}$ (e.g. curvaton decaying to CDM) $\alpha < 0.011$ (CMB) and $\alpha < 0.0037$ (+ BAO and SN)



Sollom, AC & Hobson, in prep.

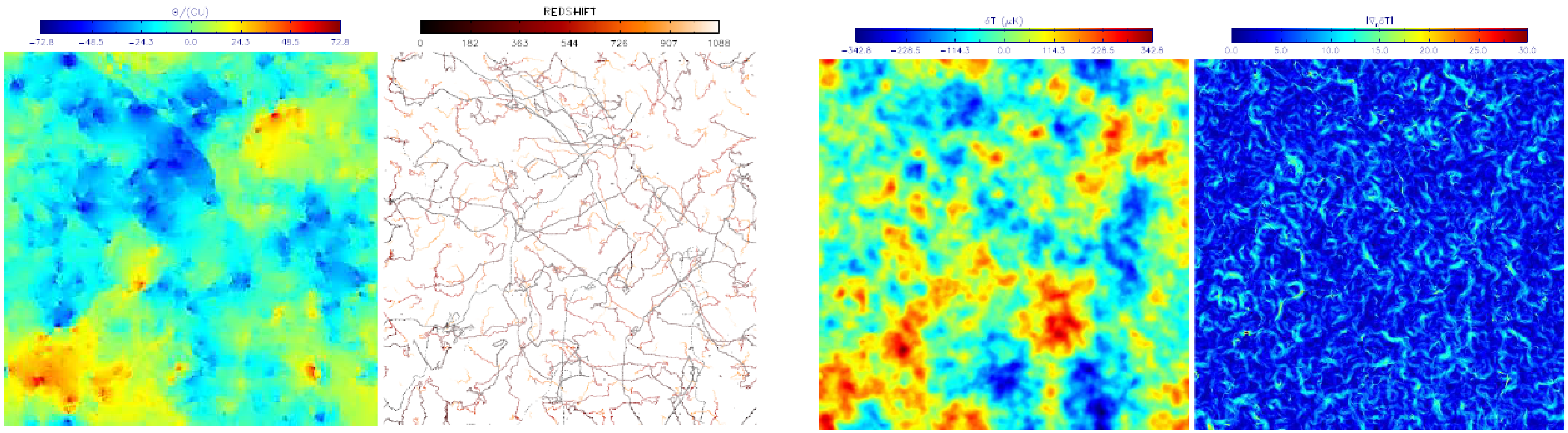
- For general correlations and spectral indices: $r_{\rm iso} < 10\%$ from WMAP3, ACBAR, SDSS, BBN and SNLS

CONSTRAINTS ON LOCAL COSMIC STRINGS



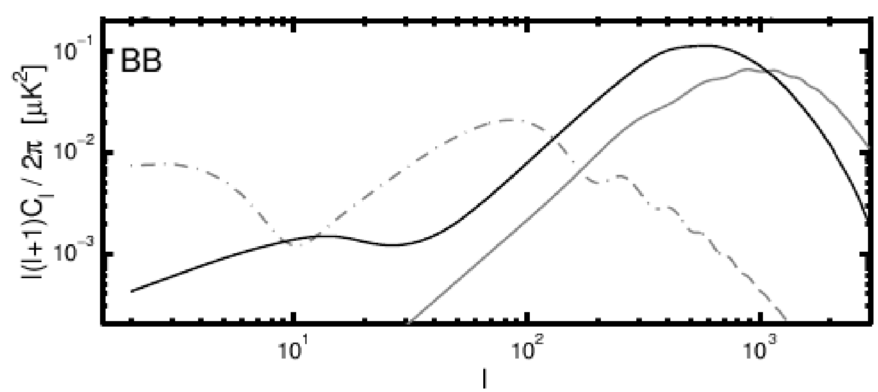
Bevis et al. 2007

- $< 10\%$ contribution (at 95%) to CMB temperature anisotropies
- Theoretical uncertainties in relation to $G\mu$:
  - $G\mu < 7 \times 10^{-7}$ from field-theory simulations (Bevis et al. 2007)
  - $G\mu < 2.7 \times 10^{-7}$ from approximations to Nambu-Goto (Pogosian et al 2006)
- Mindful of conclusion $n_s < 1$ in $r \approx 0$ models (e.g. Battye et al. 2008)



Fraisse et al. 2007

- At current upper limit, strings "eye-visible" in e.g. ACT maps (no sources, Gaussian secondaries!)



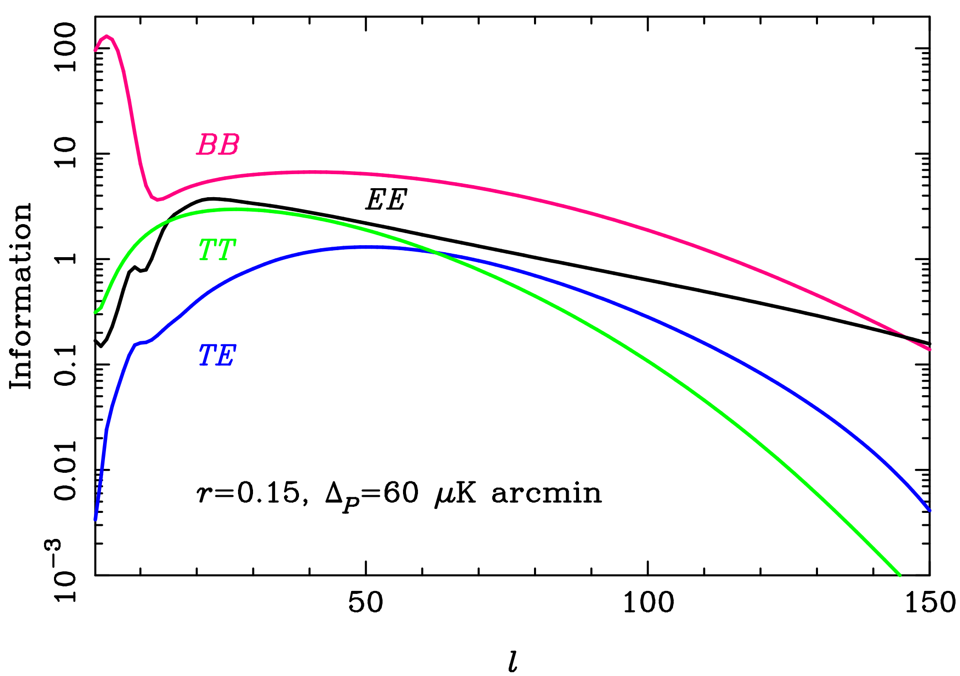
Bevis et al. 2007

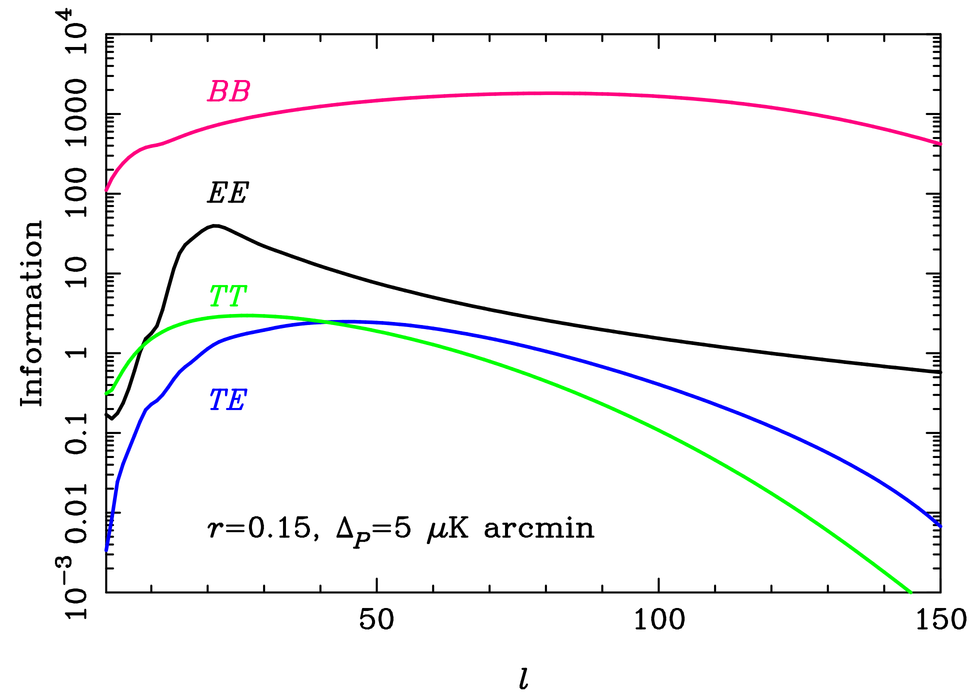
- Factor 6 improvement in $G\mu$ (to 1×10^{-7}) from upcoming sub-orbital B-mode obs

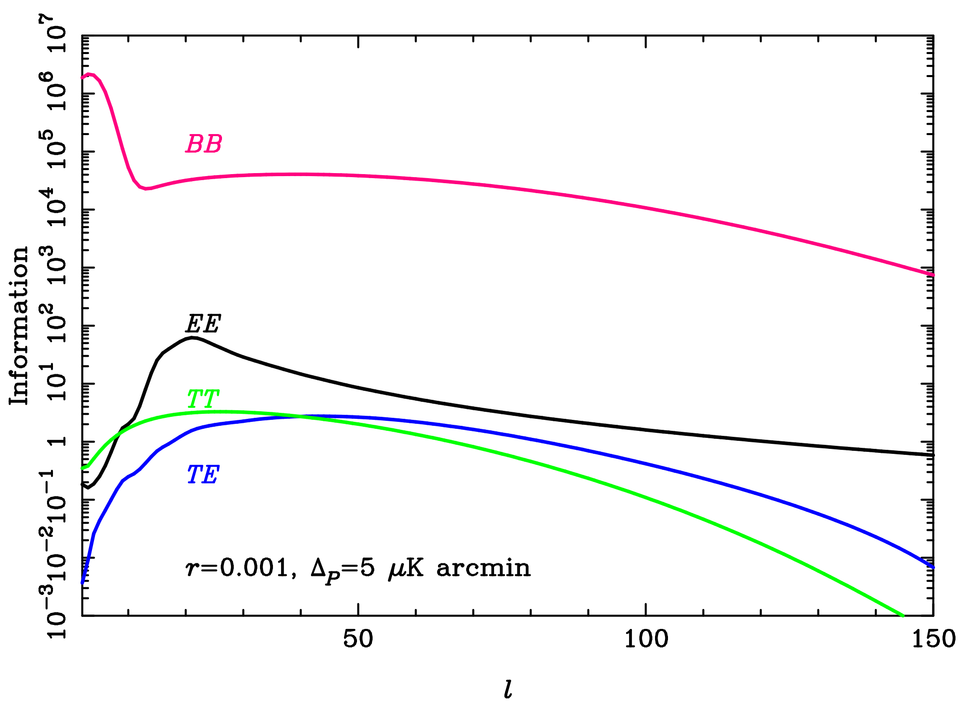
SEARCHING FOR GRAVITY WAVES IN B-MODE POLARIZATION

- Taking data:
  - BICEP/Robinson telescope (98 detectors; South Pole; 100, 150 GHz; 40 arcmin; $r \sim 0.1$)
- Undergoing integration:
  - Planck (56 pol. detectors; L2; 30–353 GHz; 5–33 arcmin; $r \sim 0.1$)
  - QUIET Phase I (110 receivers; Atacama; 40 & 90 GHz; 8 & 20 arcmin; $r \sim 0.05$)
- R&D/fabrication:
  - Clover (600 detectors; Atacama; 97, 150 & 220 GHz; 5–10 arcmin; $r \sim 0.02$)
  - EBEX (1320 detectors; LDB; 150, 220, 350 & 450 GHz; 2.7–8 arcmin; $r \sim 0.01$)
  - PolarBear (1200 detectors phase II; Atacama?; 90, 150 & 220 GHz; 3–7 arcmin; $r \sim 0.01$)
  - PAPPA (350 detectors phase III; LDB; 100, 200 & 300 GHz; 30 arcmin; $r \sim 0.01$)
  - SPIDER (2600 detectors; LDB; 96, 145, 225 & 275 GHz; 20–60 arcmin; $r < 0.01$)
  - QUIET Phase II (1000 receivers; Atacama; 40 & 90 GHz; 8 & 20 arcmin; $r \sim 0.01$)
- Design study?
  - EPIC (~ 2000? detectors; L2; 30–300 GHz)
  - B-Pol ($\sim 10^4$? detectors; L2; 30–300 GHz)

Gravity waves in the CMB: information content







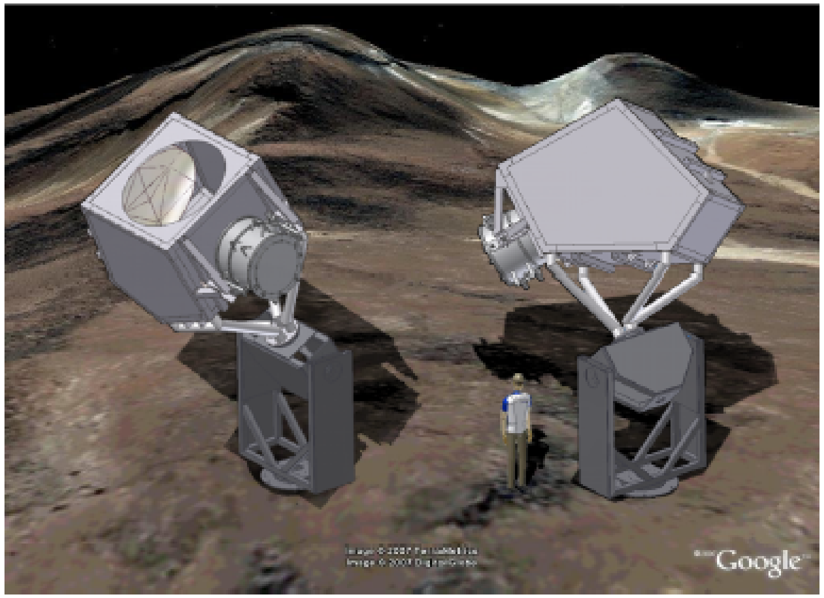
1-σ errors for $r = 0.15$ and $\Delta_P = 5\,\mu$Karcmin:

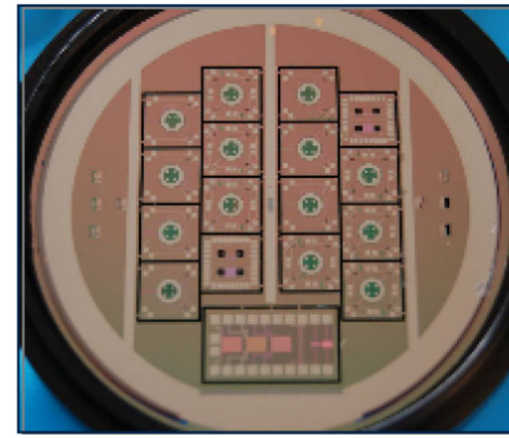
Spectra	Δr
TT	0.08
TE	0.12
EE	0.03
TT, EE & TE	0.02
BB	0.002

BASIC ISSUES FOR B-MODE POLARIMETRY

- Small signal – r.m.s. primordial B-mode $= 160\sqrt{r/0.2}\,\mathrm{nK}$ – requires many hundreds of background-limited detectors
- Instrumental and environmental systematic effects: informed design and build in redundancy and modulation
- Foreground contamination: target clean regions with multiple frequencies
- Data challenges: E and B separation for realistic surveys; few tens of TBs of data
- Confusion from non-linear effects: weak gravitational lensing important for $\Delta_P < 5\,\mu\mathrm{K\,arcmin}$

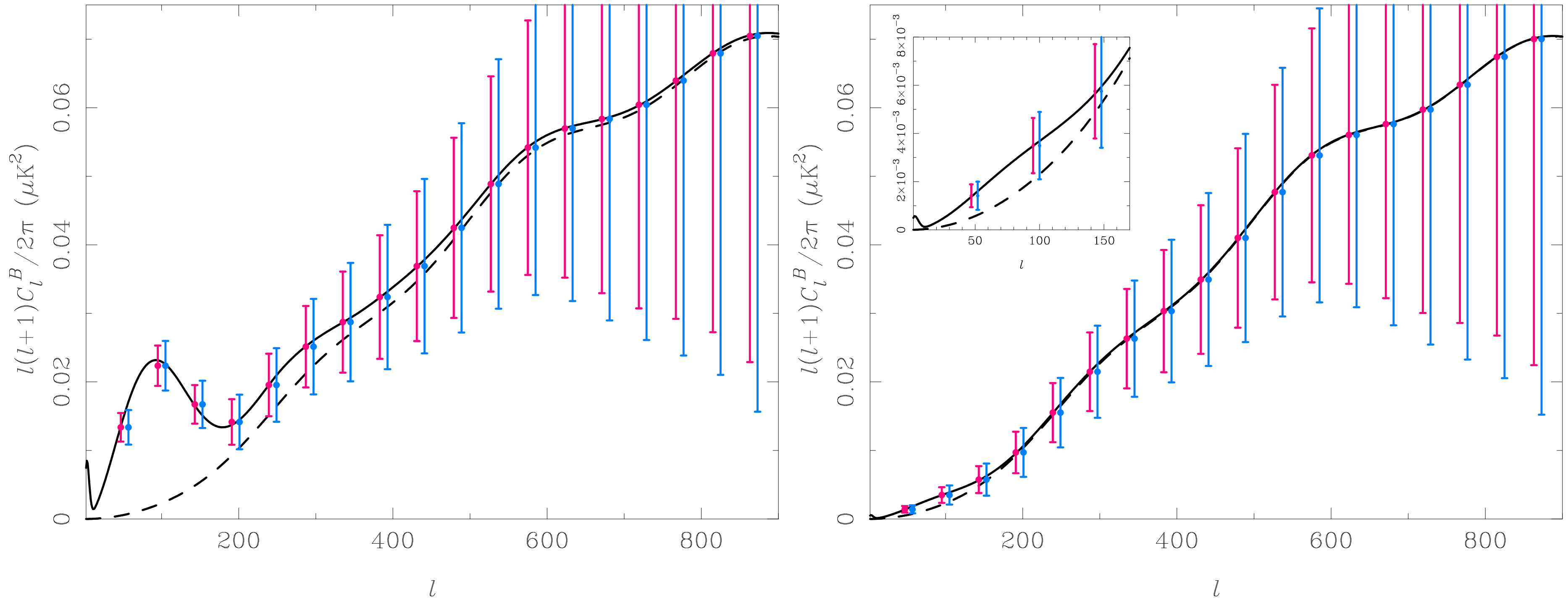
Clover summary



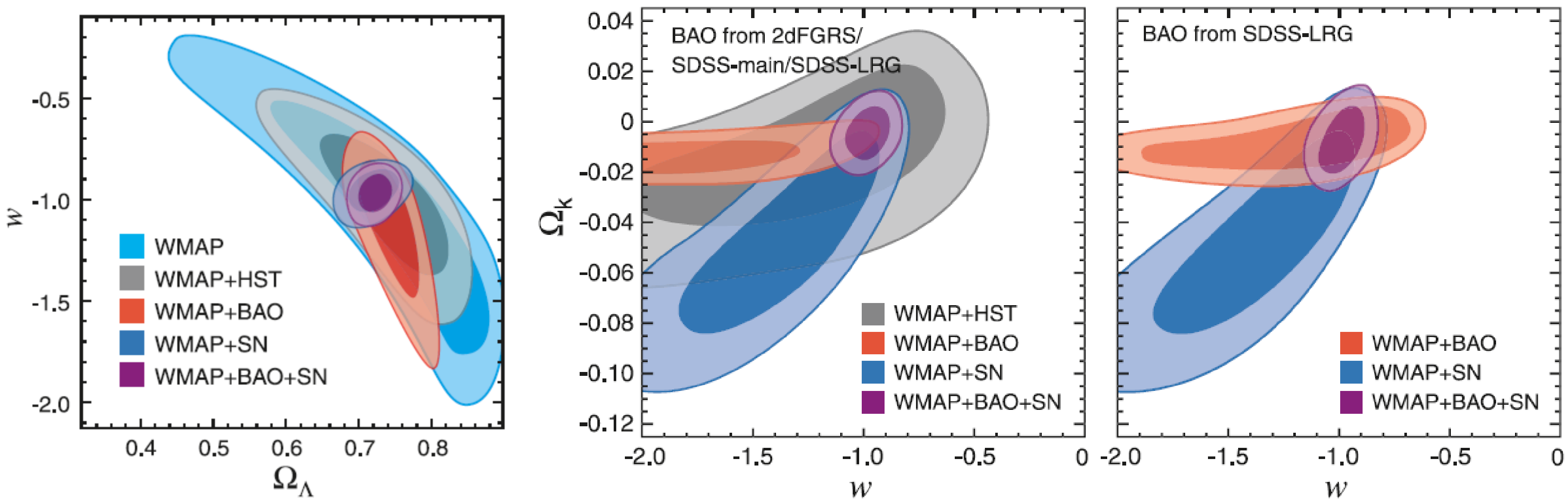


- Cardiff-Cambridge-Manchester-Oxford collaboration (+ NIST & UBC)
- Clean, highly-sensitive polarimetry ($\sim 5\,\mu$K-arcmin imaging at 97 GHz)
- 600 background-limited TES detectors
- Multiple levels of modulation (HWP, scanning and boresight rotation)
- Two instruments: one at 97 (7.5 arcmin); one with mixed focal plane at 150 and 225 GHz (5.5 arcmin)
- Two years observing from Atacama, Chile; commissioning from mid-2009

- Characterise B-mode polarization on scales $20 < l < 600$
- Sensitivity to detect gravity waves down to $r \sim 0.02$ (c.f. current 95% limit of 0.2)
  - Hence measure energy scale of inflation if $> 1.2 \times 10^{16}$ GeV
- Place tight constraints on dynamics of inflation

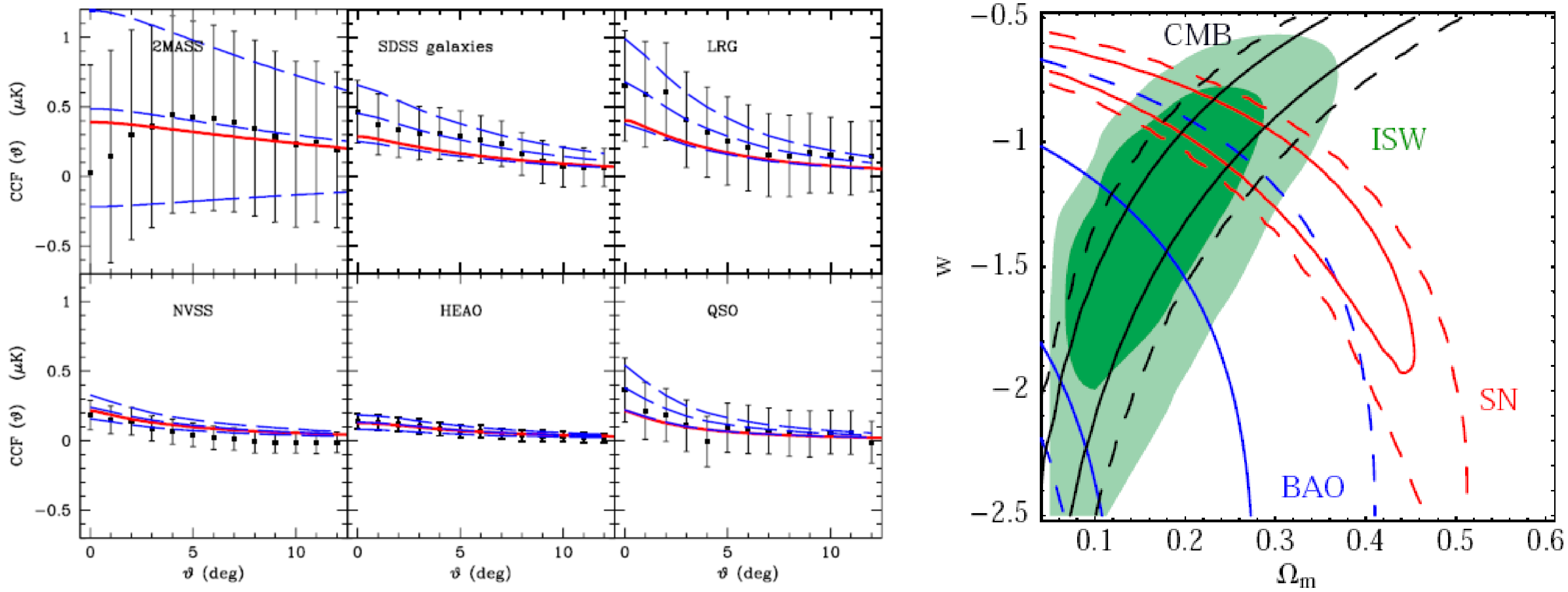


Dark energy and the CMB



Komatsu et al. 2008

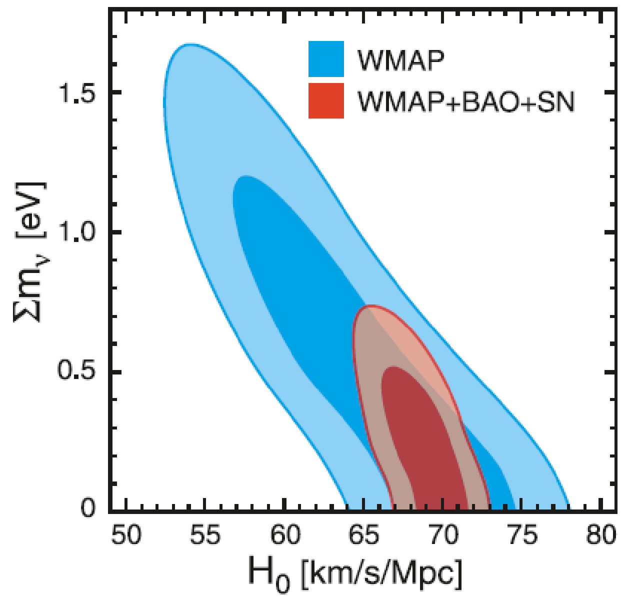
- Mainly affects CMB through $d_A(z_*)$
  - Break geometric degeneracy with external distance measures
  - $-1.098 < w < -0.841$ from WMAP5+SN(+BAO) in flat, constant-w models
  - $-1.11 < w < -0.86$ from WMAP5+SN+BAO in curved, constant-w models



Giannantonio et al. 2008

- Positive correlation with LSS tracers to $z \sim 1$
- Combined analyses give $\sim 4\sigma$ detection (Giannantonio et al. 2008; Ho et al. 2008)
  - Hints (1–2σ) of excess power cf. WMAP3 expectations
- Limited constraining power — perfect correlation gives only $S/N \sim 10$

NEUTRINO MASSES AND CMB

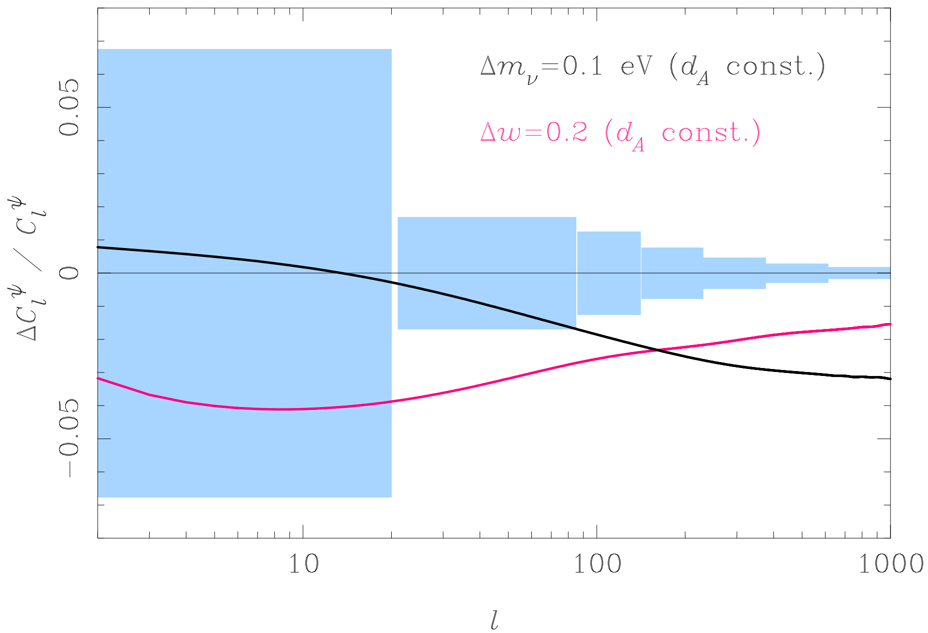


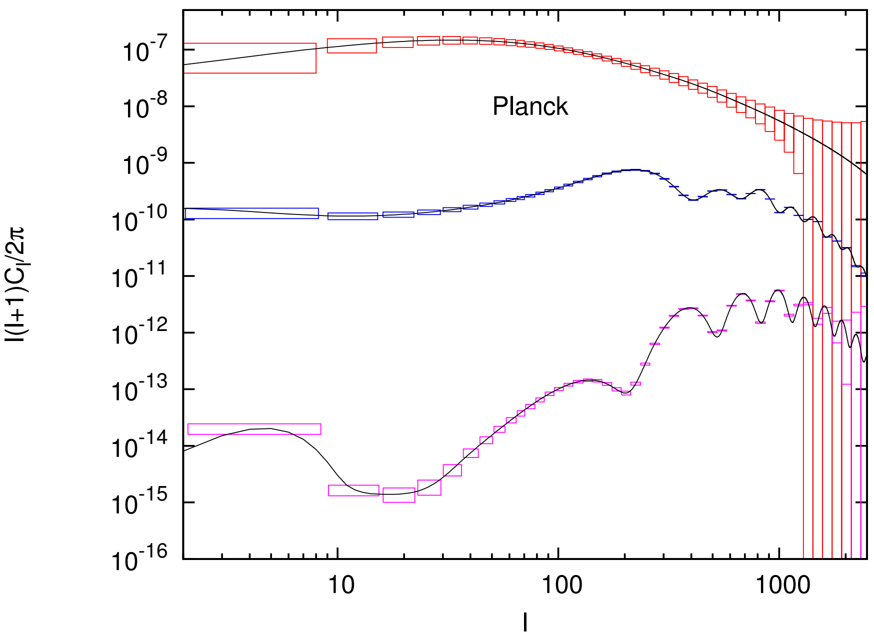
Komatsu et al. 2008

- $\langle E_\nu \rangle = 0.58\,\mathrm{eV}$ at last scattering
- Sub-eV neutrinos only affect CMB through d_A, late-time ISW and lensing
  - WMAP5 alone: $\sum_\nu m_\nu < 1.3\,\mathrm{eV}$ for $w = -1$; $\sum_\nu m_\nu < 1.5\,\mathrm{eV}$ for $w \neq -1$
  - WMAP5+BAO+SN: $\sum_\nu m_\nu < 0.61\,\mathrm{eV}$ for $w = -1$; $\sum_\nu m_\nu < 0.66\,\mathrm{eV}$ for $w \neq -1$
- Tighter constraints from e.g. CMB+Ly-α ($\sum_\nu m_\nu < 0.17\,\mathrm{eV}$; Seljak et al. 2006) but systematic issues

FUTURE CONSTRAINTS ON DARK SECTOR

- $\Delta m_\nu = 0.04\,\mathrm{eV}$ and $\Delta w = 0.2$ from CMB alone with future 'inflation probe' (Kaplinghat et al. 2003)
- Planck may achieve $\Delta m_\nu \sim 0.15\,\mathrm{eV}$ (Lesgourges et al. 2006)
- Comparable precision to galaxy clustering and 1-Mpc scale Ly-α forest (but avoids issues of bias etc.)





SUMMARY

- CMB cleanest probe of primordial fluctuations down to scales $k^{-1} \sim 10\,\mathrm{Mpc}$
  - 4×10^6 independent modes in total
- Simple inflation holding up well (flat universe with almost scale-invariant, adiabatic, almost Gaussian fluctuations) but some niggles:
  - Large-scale anisotropy? – many models testable in Planck polarization
  - Too large non-Gaussianity? – concensus not reached; awaits shape analysis with better data ($\Delta f_{NL} \sim 5$ from Planck) and higher moments
  - Large running? – further small-scale CMB and better modelling of e.g. Ly-α forest
- Theory guiding us to more exotic phenomenology testable with upcoming data
  - Cosmic (super-)strings
  - Isocurvature modes
  - Measurable non-Gaussianity
  - “No” inflationary gravitational waves (though see Silverstein & Westphal 2008)