CMB constraints on fundamental physics

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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, $m_{\nu}$ etc.)
**What scales are involved?**

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

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

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

- 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:

$$P_{ab}(\hat{n}) = \frac{1}{2} \begin{pmatrix} Q & U \\ U & -Q \end{pmatrix} = \nabla \langle a \nabla b \rangle P_E + \epsilon^c_{(a \nabla b)} \nabla c P_B$$

  - Only $C^E_l$, $C^B_l$ and $C^{TE}_l$ non-zero if parity respected in mean
  - Linear scalar fluctuations produce only $E$-mode polarization

Pure $E$ mode

Pure $B$ mode
THEORY POWER SPECTRA ($r = 0.2$)

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

Effects only on large scales since gravity waves damp inside horizon
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: $BB$

![Graph showing $l(l+1)C_l^{BB}/2\pi$ vs. $l$.]
• 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.)
• Inflation energy scale unknown: $r < 0.2$ from low-$l$ $\Delta T \Rightarrow E_{\text{inf}} < 2.2 \times 10^{16}$ 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

Komatsu et al. 2008
**IMPROVEMENTS WITH PLANCK?**

![Graphs showing improvements with Planck](image)

"Planck: the scientific programme" – Planck collaboration

- Marginalised error forecasts for
  \[
  \ln P_R(k) = \ln A_s + (n_s - 1) \ln(k/k_0) + \frac{1}{2} (dn_s/d\ln k) \ln^2(k/k_0) + \cdots:
  \]

  \[\Delta n_s = 0.0045 \quad \text{and} \quad \Delta (dn_s/d\ln k) = 0.005\]
SECONDARY SCATTERING

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

Mitigate by removing high-$l$ $\Delta T$ (polarization less affected) but $\sim 100\%$ hit in errors, or $C_l$ template marginalisation?

- Also theoretical uncertainty in recombination and beam uncertainties?

Zahn et al. 2005

<table>
<thead>
<tr>
<th>model</th>
<th>$\tau_{re}$</th>
<th>$\Omega_{\Lambda}$</th>
<th>$\omega_{dm}$</th>
<th>$\omega_{b}$</th>
<th>$n_s$</th>
<th>$A_s$</th>
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<tr>
<td>A</td>
<td>0.40</td>
<td>1.18</td>
<td>-1.10</td>
<td>1.71</td>
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<td>B</td>
<td>1.26</td>
<td>1.66</td>
<td>-1.54</td>
<td>2.40</td>
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<tr>
<td>C</td>
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<td>2.89</td>
<td>-2.69</td>
<td>4.20</td>
<td>5.62</td>
<td>1.58</td>
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</table>

TABLE 1
Bias in units of the statistical error ($B_l$) 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 $l = 4000$. 

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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?
Jaffe et al. (2005) find $3\sigma$ evidence for correlation between WMAP and Bianchi $\text{VII}_h$ template
- Only considers a subset of dynamical freedom in $\text{VII}_h$ 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 $\Delta T$ 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**
  \[
  \langle R(k_1)R(k_2)R(k_3) \rangle \propto \delta(k_1 + k_2 + k_3)F(k_1, k_2, k_3)
  \]

- **Local form peaks on squeezed triangles**
  \[
  F(k_1, k_2, k_3) \propto f_{NL} \left( \frac{P_R(k_1)P_R(k_2)}{k_1^3 k_2^3} + 1 \leftrightarrow 3 + 2 \leftrightarrow 3 \right)
  \]
  - Arises when non-Gaussianity created outside horizon (e.g. multi-field inflation, curvaton, fluctuating reheating):

    \[
    R(x) = R_G(x) - \frac{3}{5} f_{NL} \left( R_G^2(x) - \langle R_G^2(x) \rangle \right)
    \]

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

- **Non-local form peaks on equilateral triangles**
  - E.g. \( f \left[ (\nabla \phi)^2 \right] \) in DBI inflation
Large-scale $\Delta T/T = \mathcal{R}/5$
- Positive $f_{NL}$ skews $\mathcal{R}$ and $\Delta T$ negative

Fractional departure from Gaussianity very well measured: $\sim |f_{NL}|\sqrt{\mathcal{P}_R} < 10^{-3}$

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:
  \[ -9 < f_{NL}^{\text{local}} < 111 \quad \text{and} \quad -151 < f_{NL}^{\text{equilateral}} < 253 \quad (V + W \text{ and } KQ75) \]
  – 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 \( V - W \) maps
  – Corrections for point sources (small for local model)

• Analysis with Minkowski functionals: all consistent with Gaussianity
  \[ -178 < f_{NL}^{\text{local}} < 64 \quad (V + W \text{ and } KQ75) \]
  – Mild tension with bispectrum results for \( f_{NL}^{\text{local}} \)

• Kendrick Smith et al. WMAP5 analysis (Perimeter meeting, March 2008)
  – Optimal-weighting in bispectrum estimator
  – Foreground template marginalisation
  – \( f_{NL}^{\text{local}} = 21 \pm 22 \)
For local model $\mathcal{R}(x) = \mathcal{R}_G(x) - \frac{3}{5} f_{NL} \left( \mathcal{R}_G^2(x) - \langle \mathcal{R}_G^2(x) \rangle \right) + f_2 \mathcal{R}_G^3(x) + \cdots$

$$T(k_1, k_2, k_3, k_4) \propto \frac{1}{2} \left( \frac{6 f_{NL}}{5} \right)^2 \left( \frac{\mathcal{P}_R(k_1) \mathcal{P}_R(k_2) \mathcal{P}_R(k_{14})}{k_1^3 k_2^3 k_{14}^3} + \text{perms} \right) + O(f_2)$$

No direct constraints on $\tau_{NL}$ yet but $|\tau_{NL}| < 10^8$ from rhombus configurations for COBE (Kunz et al. 2001)

- $\Delta \tau_{NL} \sim 200$ from Planck $\Rightarrow \Delta f_{NL} \sim 50/f_{NL}$
Large-angle $\Delta T/T = R/5 - 2S/5 + \text{ISW}$
CONSTRAINTS ON ISOCURVATURE MODES

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

- WMAP5 constraints (Komatsu et al. 2008):
  - For \( \beta = 0 \) and \( n_{iso} = 1 \) (axion-type) \( \alpha < 0.16 \) (CMB) and \( \alpha < 0.067 \) (+ BAO and SN)
  - For \( \beta = -1 \) and \( n_s = n_{iso} \) (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: \( r_{iso} < 10\% \) from WMAP3, ACBAR, SDSS, BBN and SNLS
• < 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)
FUTURE CONSTRAINTS?

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 $1 \times 10^{-7}$) 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 ($\sim 2000?$ 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 $\Delta P = 5 \mu K \text{arcmin}$:

<table>
<thead>
<tr>
<th>Spectra</th>
<th>$\Delta r$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$TT$</td>
<td>0.08</td>
</tr>
<tr>
<td>$TE$</td>
<td>0.12</td>
</tr>
<tr>
<td>$EE$</td>
<td>0.03</td>
</tr>
<tr>
<td>$TT$, $EE$, $TE$</td>
<td>0.02</td>
</tr>
<tr>
<td>$BB$</td>
<td>0.002</td>
</tr>
</tbody>
</table>
• Small signal – r.m.s. primordial $B$-mode $= 160\sqrt{r/0.2}$ 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 $\Delta_P < 5\, \mu\text{K arcmin}$
• Cardiff-Cambridge-Manchester-Oxford collaboration (+ NIST & UBC)
• Clean, highly-sensitive polarimetry (∼5 µK-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
Primary Science Goals

- 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
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 ($1–2\sigma$) of excess power cf. WMAP3 expectations
- Limited constraining power — perfect correlation gives only $S/N \sim 10$
\[ \langle E_\nu \rangle = 0.58 \text{ eV at last scattering} \]

- Sub-eV neutrinos only affect CMB through \( d_A \), late-time ISW and lensing
  - WMAP5 alone: \( \sum_\nu m_\nu < 1.3 \text{ eV for } w = -1; \sum_\nu m_\nu < 1.5 \text{ eV for } w \neq -1 \)
  - WMAP5+BAO+SN: \( \sum_\nu m_\nu < 0.61 \text{ eV for } w = -1; \sum_\nu m_\nu < 0.66 \text{ eV for } w \neq -1 \)

- Tighter constraints from e.g. CMB+Ly-\( \alpha \) \( (\sum_\nu m_\nu < 0.17 \text{ eV}; \text{Seljak et al. 2006}) \) but systematic issues
FUTURE CONSTRAINTS ON DARK SECTOR

- $\Delta m_\nu = 0.04 \text{ eV}$ and $\Delta w = 0.2$ from CMB alone with future ‘inflation probe’ (Kaplinghat et al. 2003)

- Planck may achieve $\Delta m_\nu \sim 0.15 \text{ eV}$ (Lesgourges et al. 2006)

- Comparable precision to galaxy clustering and 1-Mpc scale Ly-\(\alpha\) forest (but avoids issues of bias etc.)
Summary

- CMB cleanest probe of primordial fluctuations down to scales $k^{-1} \sim 10$ Mpc
  - $4 \times 10^6$ 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? – consensus 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)