Scientific objectives of space CMB probes?

(CMB target post FG-removal)

Nu's greater than 600 may not be useful for CMB analysis

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(hoped results) date

min(600, νmax) [GHz]

25 μνmin [GHz]

σν [μK,arcmin]

(CMB map)

FWHM [arcmin]

(tmin from ground is uncertain)

(lmin from ground is uncertain)

(fsky)

delensing factors

(actually usable fsky is debatable, and function of sensibility, nu coverage, etc.)

Scientific objectives of space CMB probes?

François R. Bouchet "Scientific Objectives of CMB space probes?"
TT, EE, BB – mid 2015 status

Only keeping points w. sufficiently small error bars, Fig. calabrese

\[ \tau = 0.055 \pm 0.009 \]

1 114 000 Modes measured with TT,

60 000 with TE

96 000 with EE

… and 10’s in BB

+ weak constraints with TB and EB
Planck 2015 TTT – 2001 modes

$f_{\text{local}}^{\text{NL}} = 0.8 \pm 5.0$
$f_{\text{equil}}^{\text{NL}} = -4 \pm 43$
$f_{\text{ortho}}^{\text{NL}} = -26 \pm 21$

$|f_{\text{NL}}^{\text{Loc}}| < 10^3$ (Maxima 2001), $10^2$ (WMAP7), $10$ (Planck15)

A hundred-fold improvement in 14 years
Planck for the first time measured the lensing power spectrum with higher accuracy than it is predicted by the base CDM model that fits the temperature data.
Summary: Basic $\Lambda$CDM fits

- CMB + LSS provide a consistent picture within LCDM. Content known with percent accuracy.
- Primordial fluctuations are, to a very good approximation:
  - Isotropic
  - Gaussian
  - Adiabatic (fluctuations in pressure $\alpha$ to the density)
  - Coherent (fluctuations start @same time, harm. osc)
  - Close to Scale invariant
  - but not exactly ($n_s \neq 1$ is excluded at more than 5$\sigma$)
- With minimal cosmological content,
  - Flat spatial geometry (is a very good approximation)
  - Matter is mostly dark (and cold)
  - “Dark energy” consistent with $\Lambda$ ($w=-1$)
  - Small fraction of baryon, consistent with BBN
- No gravitational waves (10 percent level)
- Large scale power, with TT versus TE anti-correlation ($5^{\circ} > \vartheta > 1^{\circ}$):
  - apparently a-causal physics, calling for a period of accelerated expansion
- I.e. all consistent within the generic inflationary framework, completing the standard model of cosmology (w. Hot Big Bang phase).
- “Anomalies" are present at tantalizing levels, but at large scales.
But what is the physics of inflation?

Why is the potential so flat?

Why did the field start here?

Where did this function come from?

Is there a completely different paradigm to explain the measurements?

And what are:
- Dark Matter
- Lambda/DE
- Neutrinos properties ...

How do we convert the field energy completely into particles?
CMB will continue uniquely helping!

- Planck has about exhausted (as promised back in 1996) the information content of the temperature anisotropies. But only a few per cent of the more tenuous CMB polarisation modes are known with $S/N > 1$.

- CMB polarisation is a unique source of still unknown cosmological information: globality (ensemble of parameters, some of which are quasi-inaccessible otherwise (e.g., $r$, $f_{\text{NL}}$), complementarity with temperature (an independent probe), with other probes of large scale structures (LSS) and particle physics experiments (e.g Neutrinos Phys.), nature (quasi-linearity).

- We now want to map as much of the sky as possible with exacting, but achievable, requirements of sensitivity and control of systematics, both instrumental and astrophysical in nature (to measure millions of CMB polarisation modes with $S/N > 1$), in synergy between ground, sub-orbital and space.

- The CMB polarisation requirements insures great ancillary science.

- Spectral distortion have not been revisited since FIRAS... Lots there too!
CMB-S4 « Roadmap »

- Ground-based is building on S2 & S3

- Complementary, but not dependant on balloons/satellites (to be demonstrated for very low r)

- US universities DOE, Natl. Labs, HEP comm.

- International is encouraged (S4 is not funded yet)

<table>
<thead>
<tr>
<th>Year</th>
<th>Stage</th>
<th>Sensitivity ($\mu K^2$)</th>
<th>$r_{\text{u,lim}}$</th>
<th>$\sigma(N_{\text{eff}})$</th>
<th>$\sigma(\Sigma m_\nu)$</th>
<th>D.E. F.O.M</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015</td>
<td>Stage 2</td>
<td>1000 detectors</td>
<td>$\geq 10^{-5}$</td>
<td>$r \leq 0.1$</td>
<td>0.14</td>
<td>0.15 eV</td>
</tr>
<tr>
<td>2016</td>
<td>Stage 3</td>
<td>10,000 detectors</td>
<td>$10^{-6}$</td>
<td>$r \leq 0.01$</td>
<td>0.06</td>
<td>0.06 eV</td>
</tr>
<tr>
<td>2020</td>
<td>Stage 4</td>
<td>CMB-S4</td>
<td>$\approx 10^{-8}$</td>
<td>$r \leq 0.001$</td>
<td>0.02</td>
<td>0.015 eV</td>
</tr>
</tbody>
</table>

From John Carlstrom@UMich

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Planned CMB space missions

Each with rather different trade-offs/synergies/objectives...

PIXIE, DARE, EPIC+? (NASA)
(BPOL, CORE, PRISM, CORE+) LiteCORE? (ESA-M2/M3/L2/M4/M5!)
LiteBird (JAXA) down selected to a list of 3, 6 June 2015. Passed last week in A1

LiteBIRD (JAXA)
30-60’ 2 uK/arcmin
+PhyA NASA
Launch 2025

PIXIE (NASA)
Next Prop 12/2016
Launch 2023

DARE (NASA)
Prop 12/2016

ESA/M5 (LiteCore?)
Prop ~10/2016
(AO 04/2016)
Launch 2026-30?

François R. Bouchet  "Scientific Objectives of CMB space probes?"
CERN, May 7th 2016
How do different CMB projects compare on parameter estimation within LCDM? What is the gain with more capable experiments/satellites, on $r (n_t)$, if $r$ is as « large » as $r=10^{-2}$? on $r (n_t)$, if $r\leq10^{-3}$ (when “delensing” becomes an important factor)? on standard LCDM parameters? on neutrinos physics? On checks of LCDM extensions and serendipitous discovery?

→ Might be useful to have an homogeneous comparison for various fiducial cases for space sats alone, various ground options, and their combinations

Here follows a potentially useful series of plots, in view of the M5 proposal to be submitted, from a simplistic analysis comparing PIXIE, LiteBird, LiteCORE120, CORE-M4 baseline, CORE-M4 extended, S3d, S3w, S4, looking only at the withdrawable information content in the CMB, i.e. specs are compressed to

- $\sigma_p$
- FWHM
- $F_{sky}$

without worrying about actual foreground taming capabilities. (but looking at biasing effect of unaccounted residuals easy to do, + ala JE)
Simplistic Sats summary

(CMB map)

(l_{min} from ground is uncertain)

(CMB target post FG-removal)

(Nu's greater than 600 may not be useful for CMB analysis)
(n_s, r) plane from sats alone

The Core extension is of course mostly useful for low \( r \) through delensing capability (nearly a factor of 2)

\( (r_{\text{fid}}=10^{-2}) \)  \( (r_{\text{fid}}=10^{-3}) \)  \( (r_{\text{fid}}=10^{-4}) \)

\( r_{\text{fid}} = 10^{-3} \)

\( r_{\text{fid}} = 10^{-4} \)

\( (r_{\text{fid}}=10^{-2}) \)

\( r_{\text{fid}} = 10^{-3} \)

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Sats by themselves

 François R. Bouchet "Scientific Objectives of CMB space probes?" CERN, May 7th 2016
Constraints on $n_t$ according to $r_{\text{fid}}$  

<table>
<thead>
<tr>
<th>Model</th>
<th>Tensor power-spectrum</th>
<th>Tensor spectral index</th>
<th>Consistency relation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard infl.</td>
<td>$P_T = \frac{8}{M_{\text{pl}}^3} \left( \frac{H}{2\pi} \right)^2$</td>
<td>$n_T = -2 \epsilon$</td>
<td>red $r = -8n_T$</td>
</tr>
<tr>
<td>EFT inflation</td>
<td>$P_T = \frac{8}{c_T^2 M_{\text{pl}}^3} \left( \frac{H}{2\pi} \right)^2$</td>
<td>$n_T = -2 \epsilon + \frac{2 m_T^2}{3 H^2} (1 + \frac{3}{2} \epsilon)$</td>
<td>$r/b$ -</td>
</tr>
<tr>
<td>Gen. G-Infl.</td>
<td>$P_T = \frac{8}{M_{\text{pl}}^3} \gamma_T \frac{\eta}{H^2} \left( \frac{H}{2\pi} \right)^2$</td>
<td>$n_T = 3 - 2 \nu_T$</td>
<td>$r/b$ -</td>
</tr>
<tr>
<td>Pot.-driv. G-Infl.</td>
<td>$P_T = \frac{8}{M_{\text{pl}}^3} \left( \frac{H}{2\pi} \right)^2$</td>
<td>$n_T = -2 \epsilon$</td>
<td>$r/b$ $r \simeq \frac{32 \sqrt{6}}{9} n_T$</td>
</tr>
<tr>
<td>Extra background</td>
<td>$P_T = 8.6 \times 10^{-3} \frac{H^2}{M_{\text{pl}}^2} \left( \frac{H}{2\pi} \right)^2$</td>
<td>-</td>
<td>blue violation</td>
</tr>
<tr>
<td>Particle prod.</td>
<td>$P_T \simeq 3 \frac{H^4}{c_s^2 H_{\text{pl}}^4}$</td>
<td>$n_T \simeq 2 \left( \frac{2m_y^2}{3H^2} - 2 \epsilon \right) - \frac{18}{5} \frac{\delta n}{H_{\text{pl}}^2}$</td>
<td>$r/b$ violation</td>
</tr>
<tr>
<td>Spectator field</td>
<td>$P_T \simeq 3 \frac{H^4}{c_s^2 H_{\text{pl}}^4}$</td>
<td>$n_T \simeq 2 \left( \frac{2m_y^2}{3H^2} - 2 \epsilon \right) - \frac{18}{5} \frac{\delta n}{H_{\text{pl}}^2}$</td>
<td>$r/b$ violation</td>
</tr>
</tbody>
</table>

(di Valentino, FRB, in prep)
Sats, more fishing for deviations...

Isocurvature modes fraction

Generalised Dark Matter
(1/3, 1/3) for nu's:

PRELIMINARY
Sats vs S/H inflation model

Slow roll parameters for a Higgs inflation model with $r_{\text{fid}}=3.6 \times 10^{-3}$ ($n_s = 0.96$)

$$V(\phi) = M^4 \left(1 - e^{-\sqrt{2/3}\phi/M_{\text{Pl}}}\right)^2$$

\[
\begin{align*}
\epsilon_1 & = \frac{M_{\text{Pl}}^2}{2} \left(\frac{V_\phi}{V}\right)^2, \\
\epsilon_2 & = 2M_{\text{Pl}}^2 \left[\left(\frac{V_\phi}{V}\right)^2 - \frac{V_{\phi\phi}}{V} \right], \\
\epsilon_{3} & = 2M_{\text{Pl}}^4 \left[\frac{V_{\phi\phi\phi\phi}}{V^2} - 3 \frac{V_{\phi\phi}}{V} \left(\frac{V_\phi}{V}\right)^2 + 2 \left(\frac{V_\phi}{V}\right)^4\right]
\end{align*}
\]

$$x \equiv \phi/M_{\text{Pl}}.$$  

NB: This is computed for internal delensing)

(di Valentino, FRB, in prep)

François R. Bouchet "Scientific Objectives of CMB space probes?"  
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Sats + DESI: low-z dynamics

(di Valentino, FRB, in prep)
Sats+Desi: Neutrinos

\[ \sum m_{\nu} = 0.06\text{eV} \]

(dii Valentino, FRB, in prep)

PRELIMINARY
Ground \((w\ P.\tau \text{ prior})\) vs sats

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VERY PRELIMINARY
CHALLENGES

- **BEAMS**: in situ measurement of beams, esp. sidelobes ($\nu$ & polzn dependence, stability)
- **BANDPASSES**: in situ characterization, matching, polzn dependence, avoiding CO etc
- **GROUND PICKUP**: shielding, sufficient suppression of scan synchronous pickup, stability
- **I $\rightarrow$ Q/U LEAKAGE**: $\nu$ dependence, polarization dependence, stability, spatial dependence
- **SENSITIVITY**: low loading, high optical throughput
- **CALIBRATION**: stability, dynamic range, $\nu$ dependence, pointing jitter
- **POLARIZATION ANGLES**: in situ measurement, $\nu$ dependence
- **STRIPING**: minimize 1/f with fast modulation
Extract the most from this expensive data flow
- Low level codes not universal, i.e. code share only for high-level analyses
- Moore’s law on cpus unlikely to be enough (smaller final uncertainties tend to increase algorithmic complexity)
- Simulations will become more challenging (and so will be the size of the analysis groups?), but needed for precision science (and even more for accurate science).

Sharing the data efficiently?
- at TOI level? (e.g. to surround pixelization issues); data size
- X-correlations need a lot of detailed knowledge on both sides (e.g. Planck x Bicep/Keck)
- Flexible/efficient formats

Overall organisation… (we probably need large integrated teams with varied cultural backgrounds in scattered sites)

On all those, we gained much experience from Planck!
The journey continues!
And we have lots to do