Zeesh Ahmed Lecture Questions

Questions marked in green were answered during the Q&A session. Original questions listed without correction for grammar/spelling. Where a slide number was given it is shown.

Q1-2 (merged) [slide 4]   Why do you remove the monopole and dipole?

The monopole of the CMB is 2.725K and is constant across the sky (therefore, monopole). Leaving it in the image simply offsets the colorbar by that number. Removing the monopole is like subtracting the mean value or DC value across the image. See for example: https://en.wikipedia.org/wiki/Cosmic_microwave_background#CMBR_monopole_anisotropy_(%E2%84%93_=_0)

The leading explanation for the CMB dipole (~3.3mK) is our motion relative to the CMB restframe causing velocity red shift and blue shift (Doppler effect). We remove the dipole because it is uninteresting for purposes of cosmology, but does give an estimate of Earth's velocity and the velocity of our local group of galaxies. See for example: https://en.wikipedia.org/wiki/Cosmic_microwave_background#CMBR_dipole_anisotropy_(%E2%84%93_=_1)

Q3   Why is the CMB linearly polarized ?

The CMB is linearly polarized because Thomson scattering of primordial photons off electrons at the time of last scattering (i.e. when the CMB starts free streaming) in the presence of quadrupolar temperature anisotropies of the matter (the electrons in this case) leads to net linear polarization of light. See Fig 1 and accompanying text of Wayne Hu's "CMB Polarization Primer" https://arxiv.org/pdf/astro-ph/9706147.pdf

Q4 [slide 5]   What is the physics behind the fact that D_l amplitude is peaked at l=250?

The anisotropies seen in CMB temperature are the result of acoustic oscillations in the primordial photon-baryon fluid. Hot spots indicate compressed fluid, and cold spots indicate rarified fluid. The CMB anisotropies as seen now are a snapshot of the cold/hot (rarefied/compressed) plasma as the photons decoupled; before decoupling you can imagine the fluid sloshing back and forth in time. The angular scale (l~250) of the CMB temperature peak in angular power spectrum corresponds to the mode which had exactly one oscillation resulting in an extremum of compressed or rarified state of that sized potential well at the time of decoupling, or correspondingly an extremum in temperature anistropy. This means that the scale that is able to reach extremum is highlighted in the power spectrum and the spatial anisotropy. This is significant, because together with its harmonics, it relates cleanly to the distance sound would have traveled in that medium and lets you decipher the composition of the medium. The size itself, ~ degree scale matches the expectation of the size of that characteristic mode if our universe is flat. If open or closed, the peak would be shifted to larger or smaller scales respectively. Follow this nice narrative with graphics for more detail: http://background.uchicago.edu/~whu/intermediate/gravity.html

Q5 [slide 8] at what distance does O(degree) ~ O(100s of Mpc) ?

Degree scale is about 150 Mpc comoving distance today.

Q6 [slide 11] Why does the experimental error increases with higher Multipoles ?

In this slide, I would argue that the error bars increase the lower in D_l the experiments try to reach, not with higher multipole. The sample variance on the measurement of an ell mode typically decreases with increasing multipole since there are more “m” modes to measure for every “l” mode. This means that with infinite integration, one should have smaller error bars on the higher ell modes!

I think what one’s eye catches is that the Planck satellite (dark blue markers) does a spectacular job in making high S/N measurements of whatever it can. However, it cuts off when its resolving power degrades. Ground-based CMB experiments are better able to measure higher ell modes than satellite missions because they can have a larger primary optic (e.g. 10m dish on SPT) than a space mission.

All the BB data are certainly instrument sensitivity limited, and this will improve with next-generation instruments.

Q7 [slide 11] Given that the lensing potential peaks at l < 150, then how come the lensing B-mode signal is peaked at larger l?

The gradient of the lensing potential determines the deflections of the CMB photons. Where the lensing potential spectrum peaks is a function of the matter power spectrum in 3D convolved with the source/lens plane locations, projected onto two dimensions. The B-mode power is created from the E-modes, so the lensing B-mode power follows the shape of the E-mode spectrum. If the lensing potential were a delta function in redshift instead of the shape determined by the matter power in 3D, then the B-mode power would be even closer to the E-mode power.

Q8 [slide 14] Am I correct in saying that the Neff able to be measured by the CMB is only be able to take into account the relativistic species that are active before recombination

Only relativistic species that were in thermal equilibrium with the primordial plasma and “freeze out” before recombination will contribute to N_eff.

Q9 [slide 17] why do primordial gravitational waves only interact with B-modes and not E-modes.

Primordial gravitational waves generate both E-modes and B-modes. But most of the rest of cosmology generates E-modes and not B-modes. Thus a measurement of an unambiguous degree-scale B-mode signal after removal of foregrounds and lensed B-modes is in most inflation models a measurement of primordial gravitational waves.

Q10 [slide 24] Why was there a factor of 2 in both the expressions for NEP_shot^2 and NEP_Bose^2?

The 2 in derivation of photon noise comes from converting 1 second of integration into unit bandwidth. However, it survives only in the shot noise term. The 2 in the Boise noise term was a typo on my slide and can be dropped. The Richards '94 paper cited on slide 78 has a quick derivation if you want to see how to obtain the result.

Q11 [slide 20+] What are the relative magnitudes of the various noise sources that are discussed?

This is captured on slide 45 as a cumulative noise in the NEP and NET columns by adding each component of the noise in the rows of the table. The sky and the instrument add the most noise. The CMB photon noise and the detector noise are typically comparable. Systematic effects can be larger than these contributions if not controlled carefully.

Q12 [slide 39] Where was the fabrication for the focal plane done?

The detector modules for the BICEP3 focal plane were built at the Jet Propulsion Laboratory and the California Institute of Technology, in collaboration with SLAC National Laboratory. The camera was assembled first at Stanford University, then dismantled to ship to South Pole. It was then rebuilt on site at the South Pole. This picture was taken inside the "Dark Sector Lab" at the Amundsen-Scott Research Station at the South Pole.

Q13 Why is NET letting us measure a depth if the assumption of measuring CMB is that we're measuring light back to the surface of last scattering, which seems like a fixed distance for the relic light to have traveled?

My use of the word depth, or map depth, is a colloquial term for map noise. Sorry for the confusion. If I referred to going "deeper" in the map, I just meant integrating longer, and thereby averaging down photon (CMB, atmosphere, instrument) and detector noise in the map while summing the anisotropy signal. We expect map depth or map noise to reduce (in units of uK-arcmin or nK-deg) with longer and longer integration. And for completeness, let me remind everyone that NET or noise-equivalent temperature (in units of uK-rt(s)) measures the “instantaneous” noise at the bolometer or detector time stream. When we build a map by scanning the sky with the camera’s detectors, then the noise “accumulated” in the map is called map noise or map depth. The conversion between the two is on slide 59.

Q14 What sorts of multimessenger events does CMS-s4 expect to be participate in?

The space of mm-wave transients is largely open discovery space but with potential impact in the study of gamma-ray bursts (GRBs), fast radio bursts (FRBs), and possibly gravitational wave sources etc, since CMB-S4 would survey most of the southern sky at high cadence. An interesting example is gamma-ray bursts (GRBs) with associated mm-wave afterglows spanning ~O(week). This is especially useful for so-called “orphan” afterglows where the prompt gamma-ray emission is lost because of gamma-ray instrument field-of-view limitations, misalignment of the jet with the Earth etc. See arXiv:1907.04473 for more details.

Q15 [slide 71+] What's the projected timeline for when CMB-S4 will be able to start taking data?

Currently, we expect CMB-S4 to start science operations in 2028.

Q16 what are the advantages to set up in the south pole.

As mentioned on slide 35, South Pole is a 10,000 ft high dry plateau with some of the lowest precipitable water vapor content in the atmosphere on all Earth, which makes for excellent observing in the microwave bands. Additionally, the South Pole sky rises and sets seasonally as opposed to diurnally. This makes the atmosphere very stable, i.e. no daily expansion, contraction of the atmosphere and limited turbulence. It additionally enables continuous integration on a field being observed by the telescope, i.e.a patch of sky well above the horizon is always above the horizon, daily as well as year-round.

Q17 So do CMB experiments measure the linearly polarized light, and the science comes from decomposing the polarization maps into E and B modes?

CMB experiments can measure simply just the intensity of the CMB radiation, or using polarization-sensitive detectors, measure the polarization intensity as well. These are then decomposed into T, E and B maps. The science comes from the statistical properties of these maps.