Gravitational Waves

Gravitational waves provide an unobstructed view of the dynamics of the universe through cosmic history. Measurements of the CMB, including T, E, and B-modes, inform our understanding of both primordial gravitational waves and potentially sources that could be observed by direct measurements. This session will consider observables beyond the tensor-to-scalar ratio, and will explore the complementarity of these probes as well as opportunities to make more direct contact between these communities.

Host:
Note-taker: Sarah,....
Chat-monitor:

Tania: SGWB in Terrestrial Interferometers

Cosmological BG: primordial, possibly enhanced; also cosmic phase transitions, defects (cosmic strings)

- Some models enhance high frequency signal, 10^6 or more above slow-roll to be accessible by, say, Advanced LIGO.

Astrophysical BG: unresolved sources, compact binary coalescences for LVK

- Different statistical properties vs cosmological: non-continuous, non-Gaussian, non-isotropic (see estimate from binary neutron star, binary black hole mergers, in 2101.12130); although first pass analysis for simplicity assumes stationary, unpolarized, isotropic, and Gaussian
- Unresolved BG, so it decreases as detector sensitivity increases

Analysis: cross-correlate detectors (some loss of sensitivity due to detector separation and relative orientation) (two LIGO locations do best so far). Assume power law in frequency (a few choices, one for CBCs where it is known, others just to check for flat power spectrum or flat for cosmic strings, can also do broken power law. LVK has set upper limits: 2101.12130

Next pass: allow non-isotropic (arbitrary angular distribution). Simulation of expectations 1802.0646 for CBCs. Cosmic string simulations also exist: more isotropic results than for binary mergers.

Robert: LISA and GW cosmology across 29 decades in frequency

Strain amplitude (h) vs frequency plots are a nice way to look at inflationary signal that puts CMB + direct detection on the same figure. Also shows the very large gap in frequency space where we have no window.

Space-based direct detection is an old idea (1974), but finally two successful recent demonstrations of feasibility. LISA on track for mission adoption in 2024 (finalize design), launch mid 2030's. Interferometry done on the ground.

Pretty picture of sources: 1702.00786. Upshot: flood of signals right away...how do you remove all that to get to the stochastic background?

In Omega_GW, show "power-law" sensitivity curve. Those are the curves shown in the 29 decades in frequency figure in Lasky et al 2016.

Inflationary spectrum with a blue tilt? Well, can introduce new gauge fields in a few model varieties. Can get several other features in addition to the blue tilt (including chirality, tensor non-Gaussianity,). Examples from Thorne, Fujita, Hazumi, Katayama, Komatsu 2018 with blue-tilted, chiral, non-power law signal). Other examples Caldwell, Devulder 2018; Tishue, Caldwell 2021.

Daan: Beyond the Tensor to Scalar Ratio
The GW tilt: need CMB + direct detection, although, even then is it clear what you've measured (Kinney 2021)?
Higher order correlations: do we expect it? well , harder to get things like gamma-zeta-zeta than it is to get zeta-zeta-zeta (which you get by adding more fields). Non-squeezed correlators more likely but harder to constrain.

But, can we use cross-correlations to do better for tensor NG? Perhaps by cross-correlating with direct detection of GWs (e.g., gamma-gamma-zeta): ultra-ultra squeezed configs. Need running fnl (blue tilt). But, direct detection has low angular resolution, so...need BBO.

Challenges: other sources that look the same/similar either statistically or spectrally + sources that add variance. For CMB-bispectrum, for example, ISW-lensing, others see Hill 2018). Need de-lensing to remove some of the extra variance (Coulton et al 2019). Come particularly large identified sources that affect local, orthogonal bispectrum templates more than equilateral

Upshot: want to confirm if signal is inflationary, so in general look for statistics beyond the power spectrum. Need to think more about potential and issues for going after this via cross-correlations.

Even if no detection, can we still constrain consistency relation, spin-2 fields, etc via trispectra (Bordin et al 2016), but that brings new challenges.

Another route: can we constrain GWs using LSS? Hard but should we think more?

Intrinsic bispectrum (Coulton…): can do it (3-4 sigma), should do it.

Paolo: The path to precision measurements of the primordial SGWB spectrum

Synergy with LiteBIRD (~2028 timeline)
Post-LISA outlook for proposed space missions; ground is Einstein Telescope (~2035); PTA, eg SKA in 2040s
Forecasts for two cases: single field SR; spectator axion-SU(2) inflation (strong scale-dependence; chiral, non-Gaussian) found examples that peak in PTA or interferometer range while still detectable with CMB.

- Choose a filter function to maximise SNR of cross-correlation of detectors, carefully accounting for foregrounds (2101.02713)
- See binned sensitivity curves, look at constraining nT=-r/8….pretty tough

“road-map “ figure in conclusions is a useful one.

Clem: Measure non-standard tensors with BK-like SAT experiment?
BK18 maps about to be released; analysis does not assume anything about spectral shape for EE/BB/TB. Spectra are converted to r constraint assuming a template shape for the tensor spectrum: to constrain some other shape, need to make a new constraint curve.

- Could (and do) instead make a per ell bin analysis (shown in the figure), needs more foreground model parameters so less powerful.
- Reiterate that nt at desired level is out of reach
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- For EB spectrum, have to worry about calibration of absolute polarization angle of instrument. Miscalibration means TE and EE leak into TB and EB...but, can fit observed spectrum to template to see what is expected for data given miscalibration alpha. Still could see intrinsic TB/EB if it has a distinct spectral shape. (And, single polarization angle de-rotation may not be a good model: focal plane may need more complex de-rotation (consider detector pairs))
- Measure it directly? Use a source to check each detector in a pair; rotate whole telescope and check again (2012.05934). Data shows still not completely understood

What if there is spatially varying polarization rotation? (no detected: 1705.02523) Then have to worry about difference in behavior of different detectors

Take-aways: r analysis and forecasts assumes a template shape of tensor spectrum. Doing otherwise of course reduces constraining power. EB signal has some issues: should check degeneracy with leakage from mis-calibrated angle. Going forward need to do calibration on each detector.

Robert's plot:

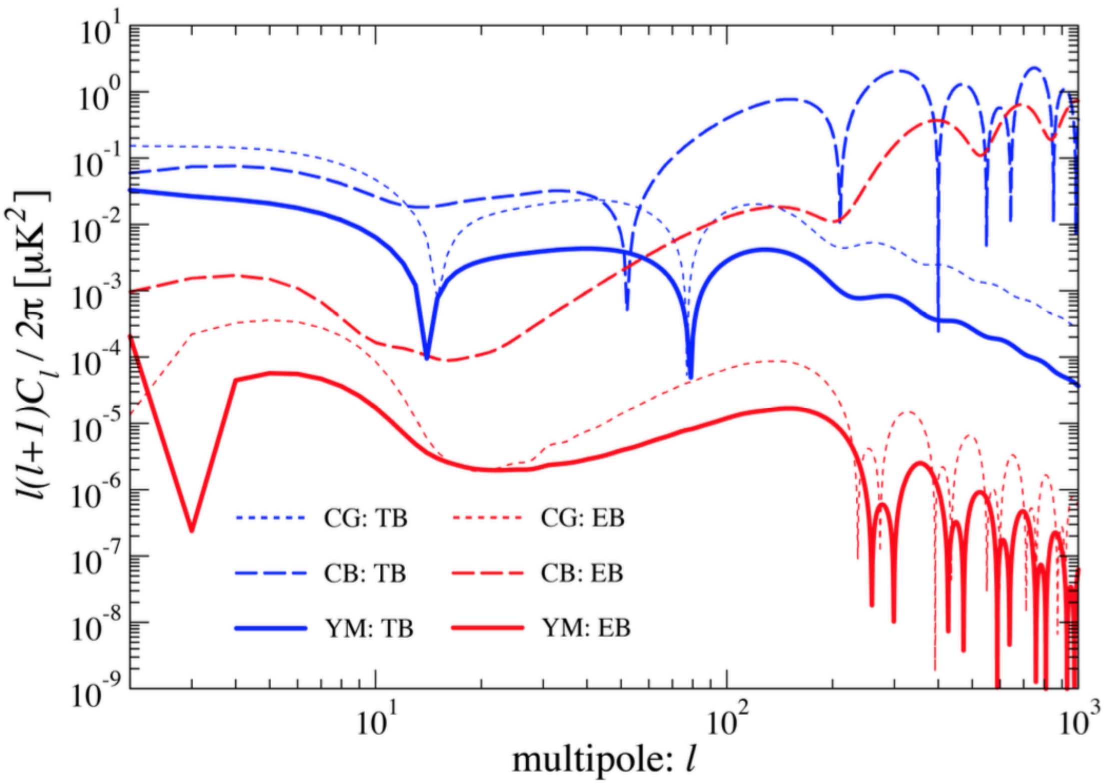


Fig. 10. The parity-violating cosmic polarization signals $\langle TB\rangle$ and $\langle EB\rangle$ from three different scenarios are shown. YM: the scenario based on the flavor-space locked gauge field presented in this article. CG: chiral gravity. CB: cosmic birefringence. We note that the YM and CG signals are similar. The CB signals strongly resemble the $\langle TE\rangle$ and $\langle EE\rangle$ power spectra shown in Fig. 9. For reference, the CB signal assumes a rotation angle $\Delta\theta = 1°$.

Raphael: Does EE power spectrum include foregrounds? Clem: Includes dust model as power law, but that just adds noise

- James C: In addition, Abitbol et al 2016 findings effectively showed that dust has a ~negligible impact on EB/TB minimization results (and thus delta-r) for a BICEP expt looking with BICEP-patch dust levels.

Toshiya: Measuring B-mode bispectrum with BICEP/Keck array

B-mode bispectrum: see review by Shiraishi 2019; BBB can even have larger S/N than BB (Agrawal et al 2018). Detection rules out standard minimal inflation models.

Planck tried, but since B-mode is noisy, used T and E bispectra to get sig(fnl, tensor)=1100. Expect BICEP can do better: simple forecast for BBB by Shiraishi looks pretty good...but it's hard to measure large-scale modes and that affects the constraint quite a bit. Can't fully recover L< about 30 (1% of sky) + galactic dust foreground on large scales which affects L< 150ish in 150 GHz. But 2018 has 110 GHZ channel, which is better….so, BK 15 was forecast to be worse than Planck, BK18 forecast to do much better (even parity bispectrum)

Another issue: lose some fraction of triangle configurations (see plot for scale-dependence) because of timestream filtering: estimate (via SNR from a realistic simulation) sig(fnl, tens)~ 600. Still some other things to check: lensing non-Gaussian covariance (for squeezed fnl), bias from foreground non-Gaussianity

Clem: CMB-S4 still has pretty small fsky,.
Raphael: comment on odd bispectrum? It's worse in the forecast...

Discussion/Follow-up questions:

1. For direct detection: what would be the ideal observatory to detect SGWB?
   Move to a bit higher frequency deci-hertz would help to avoid galactic binaries (then just have stellar mass CBs). Remove background by later detection via terrestrial detectors (ET), then go back to LISA signal and take them out of LISA. Paolo: we did a forecast to consider ground-based/space-based method like this, but still hard to reach the sensitivity you'd like (1919.09637, 2007.04241, 2101.02713)

2. What do we see as the set of final analysis products from CMB-S4 data to characterize results or constraints on GWs?

Maximally foreground-cleaned map; lensing cleaned spectra from it; r-constraint. Then, exotic models could use one of the first two. Bispectrum analysis: can we fill in any of those missing modes that were affecting fnl value Toshiya discussed. But, how to do it: change scan strategy - how?. Or, change the filtering (which is constructed to maximize autospectra), but maybe something different would be okay for BBB? Overlap between observations at two locations - maybe that helps fill in? Noise is different - how much does that matter?

Also, go after other fnls, not BBB.

Maybe we wait for a satellite, which would be well-motivated if we had a detection.

We want to be ready to convince ourselves we are not seeing foregrounds, if we seeing something. Bigger r could motivate shifting some detectors.

3. What can we be doing now to prepare? What needs to be forecasted? Should we suggest that the low-ell BB working group take on some of these tasks? Who can help?

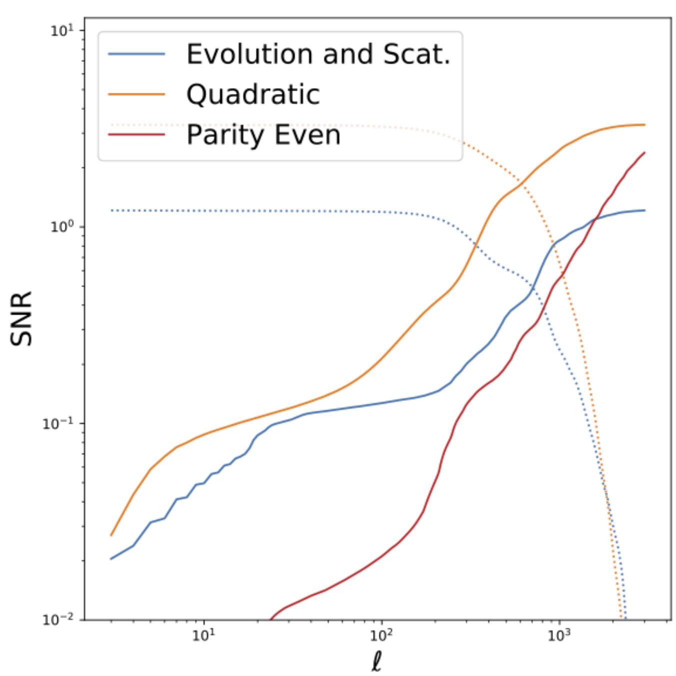
- Without a leading model for alternatives to simpler single field slow-roll type observations... what features we really expect...Regardless, we can go after particular features. Do we think the theory space is fully explored? How contrived are models that give big signals? Somewhat is the feeling. (Enrico Pajer paper upcoming limiting bispectra...)

4. Are there directions we should explore jointly with “messengers of the early universe group”? E.g., dark matter signatures gravitationally detected with LIGO/LISA, but with non-gravitational CMB signals…

- Topological defects

5. What figures/main points do we want to present in our report tomorrow? Are there ideal figures we don’t have but would like?

Intrinsic bispectrum: this is the bispectrum arising from Gaussian initial conditions due to the second order evolution and scattering. The parity-odd bispectrum, discussed in this recent work https://arxiv.org/pdf/2103.08614.pdf, is the BTT, BTE and BEE bispectra produced from this second-order evolution. There are several second order sources the SNR for S4 of the most interesting two are shown in the plot below (see the paper for more details). S4 should be the first experiment capable of measuring these. The evolution and scattering term, which is slightly beyond S4, is very interesting as it probes induced vector and gravitational waves at recombination.



Plenary discussion:
Some focus on how we ensure that it's a detection if we measure something with CMB-S4.

1. Would measuring the reionization bump from e.g. Litebird be useful? Yes! Important to measure n_t.
2. Aside from the exciting complementarity with direct detection probes, it is important to make sure that what we measure is the CMB, not other sources (foregrounds, systematics etc.).
3. It is not clear how one could translate from knowledge learned about foregrounds close to the galactic plane to the high-galactic latitudes that the deep patch, since these see through different numbers of clouds, for example. But it will be interesting to see if we could use the large field galactic observations and translate that to the deep patch.
4. Litebird is considering adding a 500GHz band. Would be interesting to forecast how useful adding this band would be for CMB-S4 r.
5. Science book second edition is coming up. This could be place to flesh out some of the ideas discussed in the parallel session.