Graviton correlations from inflation

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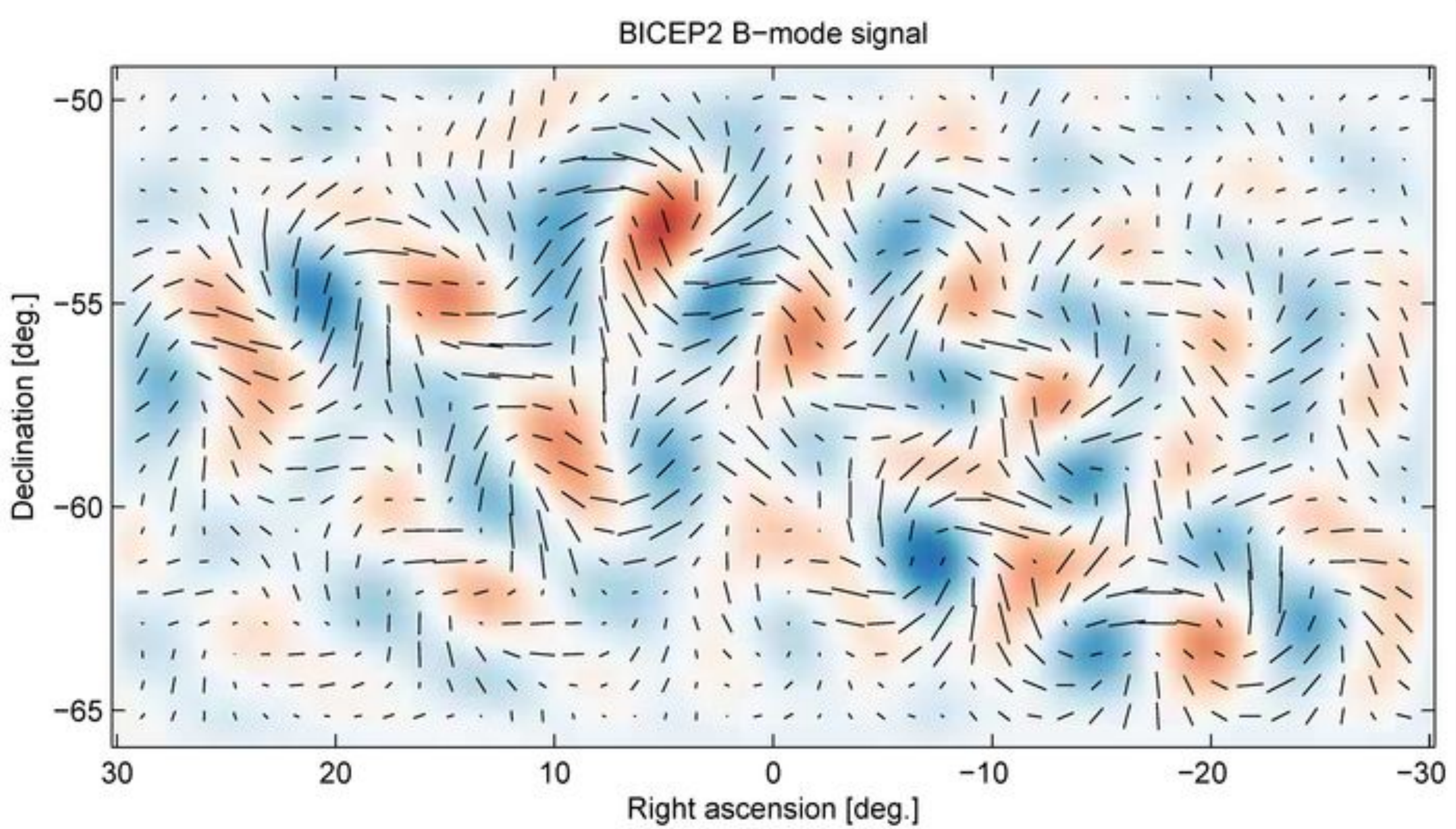
B-Mode polarization of the CMB: predicted to show gravitational waves from inflation



What is inflation?

A prolonged phase of accelerated expansion in the very early universe (a fraction of a second after the Big Bang), in approximately de Sitter spacetime:

$$a \sim e^{Ht}$$

Energy scale

$$1TeV \leq H \leq 10^{11}TeV$$

Gravitational Waves

Measurement of astrophysical GW

PRL **116,** 061102 (2016) PHYSICAL REVIEW LETTERS 12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.**
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 21 January 2016; published 11 February 2016)

PHYSICAL REVIEW LETTERS **125,** 101102 (2020)

Editors' Suggestion Featured in Physics

GW190521: A Binary Black Hole Merger with a Total Mass of 150 $M_{\odot}$

R. Abbott *et al.**
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 30 May 2020; revised 19 June 2020; accepted 9 July 2020; published 2 September 2020)

Gravitational waves in inflation

$$g_{\mu\nu}(\mathbf{x},t) = \bar{g}_{\mu\nu}(t) + h_{\mu\nu}(\mathbf{x},t)$$

Gauge transformation

$$x^\mu \to x^\mu + \epsilon^\mu(x)$$

get

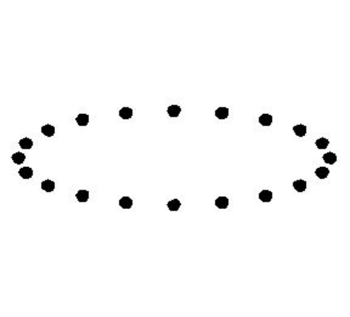
$$ds^2 = -dt^2 + a^2(\delta_{ij} + \gamma_{ij})dx^i dx^j$$

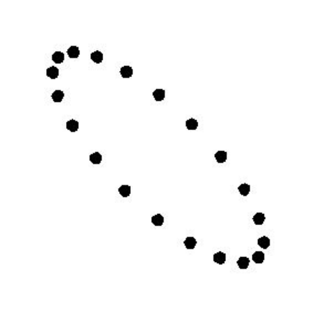
2 degrees of freedom only

Polarizations

s=+2,-2 gives the helicities (c.f. photons)

$$\gamma_{ij}(\mathbf{k}) = \sum_s \epsilon^s_{ij}(\mathbf{k})\gamma^s(\mathbf{k})$$





Quantum fluctuations

Quantization

$$\gamma^s(t,\mathbf{k}) = \frac{\sqrt{2}}{M_{pl}}\left(f_k(t)a^s_{\mathbf{k}} + f^*_k(t)(a^s_{-\mathbf{k}})^\dagger\right)$$

- a's are "like" ladder operators of QM harmonic oscillator (see QFT)
- f(t) mode functions: depend on spacetime

$$(f_k \propto 1/\sqrt{2E_k} = 1/\sqrt{2k} \text{ for massless field in Minkowski})$$

Correlators and Amplitudes

Correlators

$$\langle \gamma^{s_1}(\mathbf{k}_1)\ldots\gamma^{s_n}(\mathbf{k}_n)\rangle \equiv \langle 0|\gamma^{s_1}(\mathbf{k}_1)\ldots\gamma^{s_n}(\mathbf{k}_n)|0\rangle \equiv B_n$$

Cosmological correlators - main physical **observable**

These are equal-time correlators

Non-gaussianity: n>2
Juan Martin Maldacena. Non-Gaussian features of primordial fluctuations in single field inflationary models. JHEP, 05:013, 2003.

Can also have scalar field (eg the inflaton)

Amplitudes

In Cosmology, **in-in expectation values,** for (quantum) perturbations

- Early times: flat space, initial state
- Late-times: dS, same state
    - Perturbations evolve and interact
    - Not superposition of free states

$$A = \langle \alpha, in | \mathcal{L}_{int} | \alpha, in \rangle$$

Proportional to correlators -> Can recover correlators from amplitudes

What is the most generic graviton correlator?

Spinor Helicity Formalism

3-particle amplitudes

- 3 particle amplitudes
- Null vectors $P^\mu P_\mu = 0$
- Flat space
- **4-momentum conservation** $P_1^\mu + P_2^\mu + P_3^\mu = 0$
- "Square" $[ij]$ & "Angle" $\langle ij \rangle$ brackets between particles i, j

$$\langle ij \rangle [ij] = 2P_i \cdot P_j = (P_i + P_j)^2 = P_l^2 = 0$$

where i,j,l all distinct

Flat space non-perturbative result

If $h_1 + h_2 + h_3 \leq 0$

$$A(1^{h_1} 2^{h_2} 3^{h_3}) = \langle 12 \rangle^{h_3 - h_1 - h_2} \langle 23 \rangle^{h_1 - h_2 - h_3} \langle 31 \rangle^{h_2 - h_3 - h_1}$$

If $h_1 + h_2 + h_3 \geq 0$

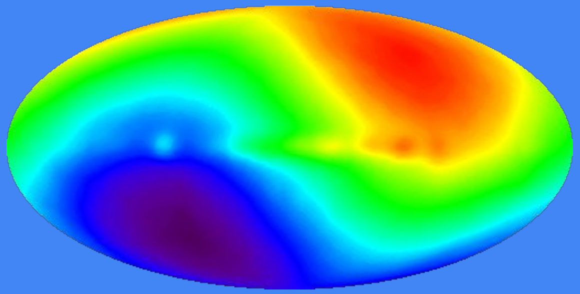
$$A(1^{h_1} 2^{h_2} 3^{h_3}) = [12]^{h_1 + h_2 - h_3} [23]^{h_2 + h_3 - h_1} [31]^{h_3 + h_1 - h_2}$$

Full dS result

- **On graviton non-Gaussianities during inflation**, Maldacena & Pimentel
- de Sitter (not flat) space, relevant for inflation
- $\langle \gamma\gamma\gamma \rangle$ correlators in terms of $\langle ij \rangle, [ij]$
- Assumes all symmetries of dS

Boost-Breaking Amplitudes

Cosmology breaks boosts



- *Approximately* de Sitter background → Lorentz invariance is broken
- Energy is not conserved:

$$\langle ij\rangle[ij] = (P_i + P_j)^2 = (E_T - E_k)^2 - \mathbf{p}_l^2 = k_T^2 - 2k_l k_T$$

where i,j,l all distinct and

$$E_T = \sum_{i=1}^{3} E_i = \sum_{i=1}^{3} k_i = k_T$$

- Can we **adapt the spinor-helicity formalism for broken boosts?**

Our recipe for flat boostless amplitudes

- First, Minkowski space

For the case $h_1 + h_2 + h_3 \geq 0$

$$A(1^{h_1} 2^{h_2} 3^{h_3}) = [12]^{h_3 - h_1 - h_2} [23]^{h_1 - h_2 - h_3} [31]^{h_2 - h_3 - h_1} \frac{f(k_1, k_2, k_3)}{k_1^{|h_1|} k_2^{|h_2|} k_3^{|h_3|}}$$

where f is a general polynomial (of appropriate degree)

Conclusion

1. We are making **predictions** for graviton correlators
2. B-mode polarization of the CMB will be **measured**

Opening doors to **test** perturbative **quantum gravity**

Wrap-up

- **Questions?**
- Feedback form: https://forms.gle/mQAEDXesvGT2gMaW8
- References and more resources at: mariaalegriagutierrez.wordpress.com/cosmo-talk-2

THANK YOU!