

Contents

1	Scientific, Technical, and Management Section	2
1.1	Science Objectives	2
1.1.1	The Inflationary Gravity Wave Background	2
1.1.2	Neutrinos and Light Relics	3
1.2	The Challenges: Foregrounds, systematics	3
1.3	Current and Forthcoming Efforts and the CMB Probe	3
1.4	State of Technologies	3
1.5	Mission Study, and Management Plan	3
2	Curriculum Vitae	7
3	Summary of Work Effort	16
4	Current and Pending Support	16
5	Letters of Support	30
6	Budget Details - Narrative	34
6.1	Team, and Work Effort	34
6.1.1	Funded Team Members	34
6.1.2	Non-Funded Team Members	34
6.2	Costing Principles	34
6.3	University of Minnesota Budget	34
6.3.1	Direct Labor	34
6.3.2	Supplies	34
6.3.3	Travel	34
6.3.4	Other Direct Costs	34
6.3.5	Facilities and Administrative Costs	34
7	Budget Sheets	35

1 Scientific, Technical, and Management Section

0.5 pg. executive summary goes here: the sky is sunny

1.1 Science Objectives

5 pages for all science goals including the (temporary) two sections below.

1.1.1 The Inflationary Gravity Wave Background

The verbiage below is taken from another proposal. Here we need to explain what are the science objectives of the CMBProbe, how the science objectives relate to the current state of knowledge, and to NASA's goals

The paradigm of inflation [1–5] makes several predictions that are consistent with all current astrophysical measurements [6–9]. A robust prediction of inflation is the existence of a stochastic background of gravitational radiation with an amplitude depending on the mechanism driving the accelerated expansion [10–14]. In most scenarios, this ‘inflationary gravity wave background’ (IGB) is predicted to have a spatial power spectrum whose amplitude is proportional to the energy scale of inflation $V^{1/4}$ via $V^{1/4} = 3.7 \times 10^{16} r^{1/4}$ GeV, where V is the inflaton potential and r is the ratio of the temperature quadrupoles produced by gravity waves and by density perturbations. There are theoretical reasons $V^{1/4}$ may be close to the Grand Unification scale of 10^{16} GeV, suggesting detectable r values between ~ 0.001 and ~ 0.1 . In addition to determining the energy scale of inflation, measurements of the IGB probe the scalar field potential at or above the Planck scale, which is particularly relevant for inflation models motivated by string theory [15]. Measurements of the IGB thus probe fundamental physics at the highest possible energy scales.

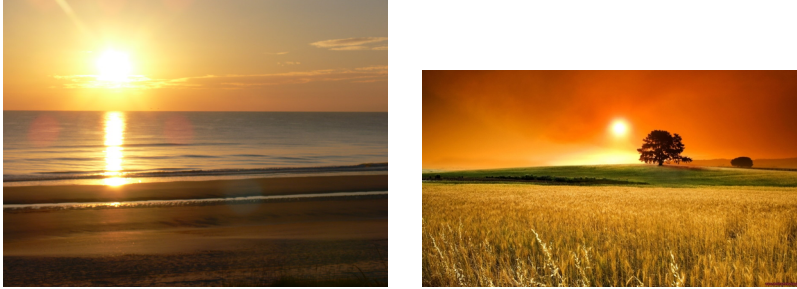


Figure 1: Sample Figure of Sunny Skies

The most promising way to search for the IGB is through its signature on the CMB polarization [16, 17]. Primordial energy density perturbations produce only a curl-free, or ‘E-mode’, pattern of polarization. Gravity waves also produce a curl, or ‘B-mode’, pattern of polarization that density perturbations cannot produce [18, 19]. The amplitude of the B mode is related to the energy scale of inflation by $V^{1/4} = 2 \times 10^{16} (B_{peak}/0.1 \mu\text{K})^{1/2}$ GeV, where B_{peak} is the amplitude of the power spectrum of the B mode in μK at $\ell = 80$; see Fig. 1. In its recent report New Worlds New Horizons (NWNH), the decadal survey committee strongly endorsed sub-orbital searches for the B-mode signal from inflation saying that “The convincing detection of B-mode polarization in the CMB produced in the epoch of reionization would represent a watershed discovery.” [20]

B-mode signatures near the expected IGB peak at $\ell = 80$ have recently been detected by BICEP2 [21]. However, the combination of Planck data with those from the BICEP2 and Keck Array collaborations have demonstrated that the B-mode signal measured is entirely consistent with contributions from polarized emission of Galactic dust and the signal from the gravitational lensing of CMB photons by the large scale structure of the Universe (see Section ??) [?, 22, 23]. These data give an upper limit of $r < 0.09$ at 95% confidence level. Most importantly, the constraint is largely

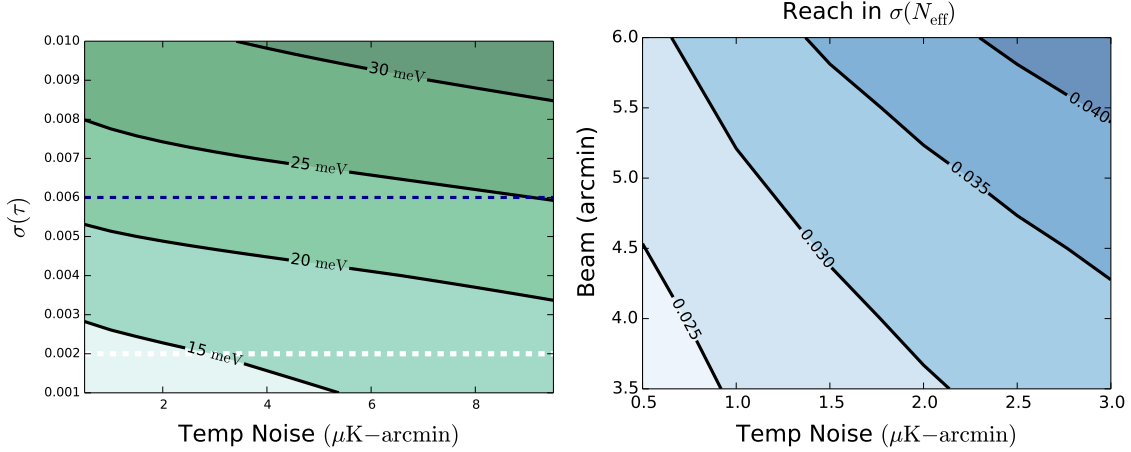


Figure 2: [Placeholders] *Left*: Neutrino mass constraints as a function of the prior on τ . *Right* Forecasts as a function of resolution in arc-min and temperature noise in $\mu\text{K-arcmin}$ assuming $f_{\text{sky}} = 0.7$.

limited by Planck’s noisy measurement of the dust properties in the 353 GHz band; a noiseless dust map could shrink the constraint by a factor of two [22]. Further progress — detections or improved limits — requires instruments with higher sensitivity at *both* the dust and CMB frequency bands so that this Galactic foreground can be properly identified and removed.

1.1.2 Neutrinos and Light Relics

Much of the information about our thermal history and the particle content of the universe is encoded in the T and E power spectra. A high-precision measurement these spectra over the full sky is expected to significantly improve our understanding of the post-inflationary universe. This is particularly true in E -mode polarization where far fewer modes have been measured at the level of cosmic variance.

1.2 The Challenges: Foregrounds, systematics

3 pages. Discuss the challenge of Foregrounds and Systematics.

1.3 Current and Forthcoming Efforts and the CMB Probe

2.5 pages. S3 experiments, forthcoming S4, Baselines CMB Probe options and their complementarity with S4.

1.4 State of Technologies

2 pages. Discuss the technologies, their TRL, and what will be studied

1.5 Mission Study, and Management Plan

1.5 pages; Describe what we want to do, who is doing what, what we are funding

References

- [1] A. H. Guth. Inflationary universe: A possible solution to the horizon and flatness problems. *Phys. Rev. D.*, 23:347–356, January 1981.
- [2] A. D. Linde. A New Inflationary Universe Scenario: A Possible Solution of the Horizon, Flatness, Homogeneity, Isotropy and Primordial Monopole Problems. *Phys. Lett.*, B108:389–393, 1982.
- [3] A. Albrecht and P. J. Steinhardt. Cosmology for grand unified theories with radiatively induced symmetry breaking. *Phys. Rev. Lett.*, 48:1220–1223, 1982.
- [4] K. Sato. First-order phase transition of a vacuum and the expansion of the Universe. *MNRAS*, 195:467–479, May 1981.
- [5] E. W. Kolb and M. S. Turner. *The Early Universe*. Addison-Wesley, Redwood City, CA, 2nd. edition, 1994.
- [6] D. N. Spergel, R. Bean, O. Doré, M. R. Nolta, C. L. Bennett, J. Dunkley, G. Hinshaw, N. Jarosik, E. Komatsu, L. Page, H. V. Peiris, L. Verde, M. Halpern, R. S. Hill, A. Kogut, M. Limon, S. S. Meyer, N. Odegard, G. S. Tucker, J. L. Weiland, E. Wollack, and E. L. Wright. Three-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Implications for Cosmology, June 2007.
- [7] M. Tegmark, D. Eisenstein, M. Strauss, D. Weinberg, M. Blanton, J. Frieman, M. Fukugita, J. Gunn, A. Hamilton, G. Knapp, R. Nichol, J. Ostriker, N. Padmanabhan, W. Percival, D. Schlegel, D. Schneider, R. Scoccimarro, U. Seljak, H. Seo, M. Swanson, A. Szalay, M. Vogeley, J. Yoo, I. Zehavi, K. Abazajian, S. Anderson, J. Annis, N. Bahcall, B. Bassett, A. Berlind, J. Brinkmann, T. Budavari, F. Castander, A. Connolly, I. Csabai, M. Doi, D. Finkbeiner, B. Gillespie, K. Glazebrook, G. Hennessy, D. Hogg, Z. Ivezic, B. Jain, D. Johnston, S. Kent, D. Lamb, B. Lee, H. Lin, J. Loveday, R. Lupton, J. Munn, K. Pan, C. Park, J. Peoples, J. Pier, A. Pope, M. Richmond, C. Rockosi, R. Scranton, R. Sheth, A. Stebbins, C. Stoughton, I. Szapudi, D. Tucker, D. Vanden Berk, B. Yanny, and D. York. Cosmological Constraints from the SDSS Luminous Red Galaxies. *Phys. Rev. D.*, 74:123507, 2006.
- [8] Planck Collaboration, P. A. R. Ade, N. Aghanim, M. Arnaud, M. Ashdown, J. Aumont, C. Baccigalupi, A. J. Banday, R. B. Barreiro, J. G. Bartlett, and et al. Planck 2015 results. XIII. Cosmological parameters. *ArXiv e-prints*, February 2015.
- [9] Planck Collaboration, P. A. R. Ade, N. Aghanim, M. Arnaud, F. Arroja, M. Ashdown, J. Aumont, C. Baccigalupi, M. Ballardini, A. J. Banday, and et al. Planck 2015. XX. Constraints on inflation. *ArXiv e-prints*, February 2015.
- [10] A. A. Starobinsky. Dynamic of Phase Transition in the New Inflationary Universe Scenario and Generation of Perturbationss. *Phys. Lett.*, B117:175–178, 1982.
- [11] A. A. Starobinskii. The Perturbation Spectrum Evolving from a Nonsingular Initially De-Sitter Cosmology and the Microwave Background Anisotropy. *Soviet Astronomy Letters*, 9:302–+, June 1983.

- [12] V. A. Rubakov, M. V. Sazhin, and A. V. Veryaskin. Graviton creation in the inflationary universe and the grand unification scale. *Phys. Lett. B.*, 115:189–192, September 1982.
- [13] L. P. Grishchuk. Amplification of gravitational waves in an isotropic universe. *Sov. Phys. JETP*, 40:409–415, 1975.
- [14] L. F. Abbott and M. B. Wise. Constraints on generalized inflationary cosmologies. *Nuclear Physics B*, 244:541–548, October 1984.
- [15] K. N. Abazajian, K. Arnold, J. Austermann, B. A. Benson, C. Bischoff, J. Bock, J. R. Bond, J. Borrill, I. Buder, D. L. Burke, E. Calabrese, J. E. Carlstrom, C. S. Carvalho, C. L. Chang, H. C. Chiang, S. Church, A. Cooray, T. M. Crawford, B. P. Crill, K. S. Dawson, S. Das, M. J. Devlin, M. Dobbs, S. Dodelson, O. Doré, J. Dunkley, J. L. Feng, A. Fraisse, J. Gallicchio, S. B. Giddings, D. Green, N. W. Halverson, S. Hanany, D. Hanson, S. R. Hildebrandt, A. Hincks, R. Hlozek, G. Holder, W. L. Holzapfel, K. Honscheid, G. Horowitz, W. Hu, J. Hubmayr, K. Irwin, M. Jackson, W. C. Jones, R. Kallosh, M. Kamionkowski, B. Keating, R. Keisler, W. Kinney, L. Knox, E. Komatsu, J. Kovac, C.-L. Kuo, A. Kusaka, C. Lawrence, A. T. Lee, E. Leitch, A. Linde, E. Linder, P. Lubin, J. Maldacena, E. Martinec, J. McMahon, A. Miller, V. Mukhanov, L. Newburgh, M. D. Niemack, H. Nguyen, H. T. Nguyen, L. Page, C. Pryke, C. L. Reichardt, J. E. Ruhl, N. Sehgal, U. Seljak, L. Senatore, J. Sievers, E. Silverstein, A. Slosar, K. M. Smith, D. Spergel, S. T. Staggs, A. Stark, R. Stompor, A. G. Vieregg, G. Wang, S. Watson, E. J. Wollack, W. L. K. Wu, K. W. Yoon, O. Zahn, and M. Zaldarriaga. Inflation Physics from the Cosmic Microwave Background and Large Scale Structure. *ArXiv e-prints*, September 2013.
- [16] M. Kamionkowski, A. Kosowsky, and A. Stebbins. Statistics of Cosmic Microwave Background Polarization. *Phys. Rev. D.*, 55:7368–7388, June 1997.
- [17] U. Seljak and M. Zaldarriaga. Signature of Gravity Waves in the Polarization of the Microwave Background. *Phys. Rev. Lett.*, 78:2054–2057, March 1997. astro-ph/9609169.
- [18] M. Kamionkowski, A. Kosowsky, and A. Stebbins. A Probe of Primordial Gravity Waves and Vorticity. *Phys. Rev. Lett.*, 78:2058–2061, March 1997. astro-ph/9609132.
- [19] M. Zaldarriaga and U. Seljak. All-sky analysis of polarization in the microwave background. *Phys. Rev. D.*, 55:1830–1840, 1997.
- [20] Committee for a Decadal Survey of Astronomy and Astrophysics. *New Worlds, New Horizons in Astronomy and Astrophysics*. National Academy Press, 2010.
- [21] P. A. R. Ade, R. W. Aikin, D. Barkats, S. J. Benton, C. A. Bischoff, J. J. Bock, J. A. Brevik, I. Buder, E. Bullock, C. D. Dowell, L. Duband, J. P. Filippini, S. Fliescher, S. R. Golwala, M. Halpern, M. Hasselfield, S. R. Hildebrandt, G. C. Hilton, V. V. Hristov, K. D. Irwin, K. S. Karkare, J. P. Kaufman, B. G. Keating, S. A. Kernasovskiy, J. M. Kovac, C. L. Kuo, E. M. Leitch, M. Lueker, P. Mason, C. B. Netterfield, H. T. Nguyen, R. O’Brien, R. W. Ogburn, A. Orlando, C. Pryke, C. D. Reintsema, S. Richter, R. Schwarz, C. D. Sheehy, Z. K. Staniszewski, R. V. Sudiwala, G. P. Teply, J. E. Tolan, A. D. Turner, A. G. Vieregg, C. L. Wong, K. W. Yoon, and Bicep2 Collaboration. Detection of B-Mode Polarization at Degree Angular Scales by BICEP2. *Physical Review Letters*, 112(24):241101, June 2014.

- [22] BICEP2/Keck, Planck Collaborations, :, P. A. R. Ade, N. Aghanim, Z. Ahmed, R. W. Aikin, K. D. Alexander, M. Arnaud, J. Aumont, and et al. A Joint Analysis of BICEP2/Keck Array and Planck Data. *ArXiv e-prints*, February 2015.
- [23] Planck Collaboration, R. Adam, P. A. R. Ade, N. Aghanim, M. Arnaud, J. Aumont, C. Baccigalupi, A. J. Banday, R. B. Barreiro, J. G. Bartlett, and et al. Planck intermediate results. XXX. The angular power spectrum of polarized dust emission at intermediate and high Galactic latitudes. *ArXiv e-prints*, September 2014.

2 Curriculum Vitae

3 Summary of Work Effort

4 Current and Pending Support

5 Letters of Support

6 Budget Details - Narrative

6.1 Team, and Work Effort

6.1.1 Funded Team Members

6.1.2 Non-Funded Team Members

6.2 Costing Principles

- **Summer Salaries:**
 - **Workshop:**

6.3 University of Minnesota Budget

6.3.1 Direct Labor

6.3.2 Supplies

6.3.3 Travel

6.3.4 Other Direct Costs

Publications and Teleconferencing

Other Subcontracts

6.3.5 Facilities and Administrative Costs

7 Budget Sheets