Finding Cosmic Inflation

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Well, haven’t we found it yet?

- Single-field slow-roll inflation looks remarkably good:
  - Super-horizon fluctuation
  - Adiabaticity
  - Gaussianity
  - $n_s < 1$

- What more do we want? **Gravitational waves**. Why?
  - Because the “extraordinary claim requires extraordinary evidence”
Theoretical energy density

Spectrum of GW today

GW entered the horizon during the radiation era

GW entered the horizon during the matter era

no ν free-streaming, $g_*$=const.
Theoretical energy density

Spectrum of GW today

Wavelength of GW

~ Billions of light years!!!
You might not have noticed, but this conference has been very unique and remarkable.
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You might not have noticed, but this conference has been very unique and remarkable, Gauge-fielders! Thanks for comments on the first part of my talk and remarkable...
Are GWs from vacuum fluctuation in spacetime, or from sources?

\[ \Box h_{ij} = -16\pi G \pi_{ij} \]

- **Homogeneous solution**: “GWs from vacuum fluctuation”
- **Inhomogeneous solution**: “GWs from sources”

- Contribution from scalars is too small
- U(1) fields can produce detectable tensors, but not without difficulty
- SU(2) fields can do it too!
A New Paradigm

• We must not assume that detection of gravitational waves (GWs) from inflation immediately implies that GWs are from the vacuum fluctuation in tensor metric perturbation.

• The homogeneous solution is related to the energy scale (or the inflaton field excursion; “Lyth bound”) during inflation, but the inhomogeneous solution is not.

• Detection of B-mode polarisation ≠ Quantum Gravity.
One does not simply read off H from r

From Matteo Fasiello
Important Message to Experimentalists

\[ \Box h_{ij} = -16\pi G \pi_{ij} \]

- Do not write proposals saying that detection of the B-mode polarisation is a signature of “quantum gravity”!

- Only the homogeneous solution corresponds to the vacuum tensor metric perturbation. **There is no a priori reason to neglect an inhomogeneous solution!**

- Contrary, we have several examples in which detectable B-modes are generated by sources [U(1) and SU(2)]
Experimental Strategy

Commonly Assumed So Far

1. Detect B-mode polarisation in multiple frequencies, to make sure that it is the B-mode of the CMB

2. Check for scale invariance: Consistent with a scale invariant spectrum?
   - Yes => Announce discovery of the vacuum fluctuation in spacetime
   - No => WTF?
New Experimental Strategy: New Standard!

1. Detect B-mode polarisation in multiple frequencies, to make sure that it is the B-mode of the CMB

2. Consistent with a scale invariant spectrum?

3. Parity violating correlations (TB and EB) consistent with zero?

4. Consistent with Gaussianity?

• If, and **ONLY IF** Yes to **all** ⇒ Announce discovery of the vacuum fluctuation in spacetime
If not, you may have just discovered new physics during inflation!

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3. Parity violating correlations (TB and EB) consistent with zero?

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• If, and **ONLY IF** Yes to all => Announce discovery of the vacuum fluctuation in spacetime
New Experimental Strategy:

1. Detect B-mode polarisation in multiple frequencies, to make sure that it is the B-mode of the CMB consistent with a scale invariant spectrum?
2. Parity violating correlations (TB and EB) consistent with zero?
3. Consistent with Gaussianity?

- If, and ONLY IF Yes to all => Announce discovery of the vacuum fluctuation in spacetime

If not, you may have just discovered new physics during inflation!

You would not have to worry about super-Planckian field excursion. Easier integration with fundamental physics?
Further Remarks

• “Guys, you are complicating things too much!”

• **No.** These sources (e.g., gauge fields) should be ubiquitous in a high-energy universe. They have every right to produce GWs if they are around

• Sourced GWs with $r \gg 0.001$ can be phenomenologically more attractive than the vacuum GW from the large-field inflation [requiring super-Planckian field excursion]. Better radiative stability, etc

• Rich[er] phenomenology: Better integration with the Standard Model; reheating; baryon synthesis via leptogenesis, etc. **Testable using many more probes!**
Example Set Up

\[ \mathcal{L} = \mathcal{L}_{GR} + \mathcal{L}_\phi + \mathcal{L}_\chi - \frac{1}{4} F_{\mu\nu}^a F^{a\mu\nu} + \frac{\lambda}{4f} F_{\mu\nu}^a \tilde{F}^{a\mu\nu} \]

- \( \phi \): inflaton field \( \Rightarrow \) To reproduce the scalar perturbation

- \( \chi \): pseudo-scalar "axion" field. Spectator field (i.e., negligible energy density compared to the inflaton)

- Field strength of an SU(2) field \( A^a_\nu \):

\[ F_{\mu\nu}^a \equiv \partial_\mu A^a_\nu - \partial_\nu A^a_\mu - g \epsilon^{abc} A^b_\mu A^c_\nu \]
Scenario

- The SU(2) field contains tensor, vector, and scalar components

- The tensor components are amplified strongly by a coupling to the axion field in some parameter space

  - But, **only one helicity is amplified** => GW is **chiral** (well-known result)

- **GWs sourced by this mechanism are strongly non-Gaussian!** Agrawal, Fujita & EK, arXiv:1707.03023
Example Tensor Spectra

- Sourced tensor spectrum can be close to scale invariant, but can also be bumpy
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Sourced tensor spectrum can be close to scale invariant, but can also be bumpy.
Parity-violating Spectra

- Angle mis-calibration can be distinguished easily!


![Graph showing spectral analysis with TB and EB components, indicating mis-calibration effects.](image)
Signal-to-noise [LiteBIRD]

\[ k_p = 0.005 \text{ [Mpc]}^{-1} \]

\[ k_p = 7 \times 10^{-5} \text{ [Mpc]}^{-1} \]

\[ r^*_s \]

\[ \sigma \text{ [width of the tensor power spectrum]} \]

- \( S/N \sim \) a couple for the peak \( r^*_s \) of 0.07. It’s something!
Not just CMB!

[also Caldwell's and Sorbo's talks]
Large bispectrum in GW from SU(2) fields

\[
B_R^R R^R_R(k, k, k) \approx \frac{25}{\Omega_A}
\]

\[
\langle \hat{h}_R(k_1) \hat{h}_R(k_2) \hat{h}_R(k_3) \rangle = (2\pi)^3 \delta \left( \sum_{i=1}^{3} k_i \right) B_R^R R^R_R(k_1, k_2, k_3)
\]

- \( \Omega_A << 1 \) is the energy density fraction of the gauge field
- \( B_R/P_R^2 \) is of order unity for the vacuum contribution [Maldacena (2003); Maldacena & Pimentel (2011)]
- Gaussianity offers a powerful test of whether the detected GW comes from the vacuum or sources
NG generated at the tree level

\[ L_3^{(i)} = c^{(i)} \left[ \epsilon^{abc} t_{ai} t_{bj} \left( \partial_i t_{cj} - \frac{m_Q^2 + 1}{3m_Q \tau} \epsilon^{ijk} t_{ck} \right) \right] \]

\[ c^{(i)} = g = m_Q^2 H / \sqrt{\epsilon_B} M_{Pl} \sim 10^{-2} \]

\[ \epsilon_B \equiv \frac{g^2 Q^4}{H^2 M_{Pl}^2} \approx \frac{2 \Omega_A}{1 + m_Q^{-2}} \ll 1 \]

[m_Q \sim a few]

• This diagram generates second-order equation of motion for GW
NG generated at the tree level

\[ L_3^{(i)} = c^{(i)} \left[ \epsilon^{abc} t_{ai} t_{bj} \left( \partial_i t_{cj} - \frac{m_Q^2 + 1}{3m_Q \tau} \epsilon^{ijk} t_{ck} \right) \right. \]

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- This diagram generates second-order equation of motion for GW

\[ \psi \] [GW]

\[ t \] [tensor SU(2)]

\[ \delta A^a_i = t_{ai} + \cdots \]

\[ \text{BISPECTRUM} \]

\[ \langle \hat{\psi}_1(\tau, k_1) \hat{\psi}_1(\tau, k_2) \hat{\psi}_2(\tau, k_3) \rangle + \text{perm.} \]
This shape is similar to, but not exactly the same as, what was used by the Planck team to look for tensor bispectrum.
Current Limit on Tensor NG

- The Planck team reported a limit on the tensor bispectrum in the following form:

\[ f_{\text{tens}}^{\text{NL}} \equiv \frac{B_{h}^{++} (k, k, k)}{F_{\text{equil.}}^{\text{scalar}} (k, k, k)} \]

- The denominator is the \textbf{scalar} equilateral bispectrum template, giving \( F_{\text{scalar}}^{\text{equil.}} (k, k, k) = (18/5)P_{\text{scalar}}^2 (k) \)

- The current 68\%CL constraint is \( f_{\text{NL}}^{\text{tens}} = 400 \pm 1500 \)
SU(2), confronted

• The SU(2) model of DFF predicts:

\[ f_{\text{tens}}^{\text{NL}} \approx \frac{125}{18\sqrt{2}} \frac{r^2}{\epsilon_B} \approx 2.5 \frac{r^2}{\Omega_A} \]

• The current 68%CL constraint is \[ f_{\text{tens}}^{\text{NL}} = 400 \pm 1500 \]

• This is already constraining!
LiteBIRD would nail it!

- RFG + LiteBIRD noise, 0% delens, $f_{\text{sky}} = 0.5$
- Noiseless, 100% delens, $f_{\text{sky}} = 1$ ($\Delta_{\text{NL}}^{\text{tens}} = 100r^{3/2}$)

Err[$f_{\text{NL}}^{\text{tens}}$] = a few!

- 50% sky, no delensing, LiteBIRD noise, and residual foreground

CV limited

Preliminary
What is LiteBIRD?
Finding Cosmic Inflation

- No detection of polarisation from primordial GW yet

- Many ground-based and balloon-borne experiments are taking data now

The search continues!!
JAXA + possibly NASA

LiteBIRD 2025– [proposed]

Polarisation satellite dedicated to measure CMB polarisation from primordial GW, with a few thousand super-conducting detectors in space
JAXA + possibly NASA

LiteBIRD

2025- [proposed]

Target sensitivity: \( \sigma(r=0) = 0.001 \)
ESA

2025– [proposed]

JAXA
+ possibly NASA

LiteBIRD
2025– [proposed]

Down-selected by JAXA as one of the two missions competing for a launch in mid 2020’s
LiteBIRD working group

152 members, international and interdisciplinary (as of July 2017)

JAXA
T. Dotani
H. Fuke
H. Imada
I. Kawano
H. Matsuhara
K. Mitsuda
T. Nishibori
K. Nishijo
A. Noda
A. Okamoto
S. Sakai
Y. Sato
K. Shinozaki
H. Sugita
Y. Takei
H. Tomida
T. Wada
R. Yamamoto
N. Yamasaki
T. Yoshida

Osaka U.
M. Nakajima
K. Takano

Osaka Pref. U.
M. Inoue
K. Kimura
H. Ogawa
N. Okada

Okayama U.
T. Funaki
N. Hidehira
H. Ishino
A. Kibayashi
Y. Kida
K. Komatsu
S. Uozumi
Y. Yamada

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A. Kibayashi
Y. Kida
K. Komatsu
S. Uozumi
Y. Yamada

NIFS
S. Takada

Kavli IPMU
A. Ducout
T. Iida
D. Kaneko
N. Katayama
T. Matsumura
Y. Sakurai
H. Sugai
B. Thorne
S. Utsunomiya

KEK
M. Hazumi (PI)
M. Hasegawa
Y. Inoue
N. Kimura
K. Kohri
M. Maki
Y. Minami
T. Nagasaki
R. Nagata
H. Nishino
T. Okamura
N. Sato
J. Suzuki
T. Suzuki
S. Takakura
O. Tajima
T. Tomarai
M. Yoshida

SOKENDAI
Y. Akiba
Y. Inoue
H. Ishitsuka
Y. Segawa
S. Takatori
D. Tanabe
H. Watanabe

NAOJ
A. Dominjon
T. Hasebe
J. Inatani
K. Karatsu
S. Kashima
M. Nagai
T. Noguchi
Y. Sekimoto
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T. Shimizu
S. Shu
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APC Paris
R. Stompor

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G. Pisan

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N. Halverson

McGill U.
M. Dobbs

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E. Komatsu

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J. Hubmayr

UC San Diego
K. Arnold
T. Elleot
B. Keating
G. Rebeiz

Stanford U.
S. Cho
K. Irwin
S. Kernasovskiy
C.-L. Kuo
D. Li
T. Namikawa
K. L. Thompson

UC Berkeley / LBNL
D. Barron
J. Borrill
Y. Chinone
A. Cukierman
D. Curtis
T. de Haan
L. Hayes
J. Fisher
N. Goeckner-wald
C. Hill
O. Jeong
R. Keskitalo
T. Kisner
A. Kusaka
A. Lee (US PI)
E. Linder
D. Meilhan
E. Taylor
U. Seljak
B. Sherwin
A. Suzuki
P. Turin
B. Westbrook
M. Willer
N. Whitehorn
Observation Strategy

- **Launch vehicle:** JAXA H3
- **Observation location:** Second Lagrangian point (L2)
- **Scan strategy:** Spin and precession, full sky
- **Observation duration:** 3-years
- **Proposed launch date:** Mid 2020’s

*Slide courtesy Toki Suzuki (Berkeley)*
Polarized foregrounds
- Synchrotron radiation and thermal emission from inter-galactic dust
- Characterize and remove foregrounds

15 frequency bands between 40 GHz - 400 GHz
- Split between Low Frequency Telescope (LFT) and High Frequency Telescope (HFT)
  - LFT: 40 GHz – 235 GHz
  - HFT: 280 GHz – 400 GHz

Slide courtesy Toki Suzuki (Berkeley)
Instrument Overview

- Two telescopes
  - Crossed-Dragone (LFT) & on-axis refractor (HFT)
- Cryogenic rotating achromatic half-wave plate
  - Modulates polarization signal
- Stirling & Joule Thomson coolers
  - Provide cooling power above 2 Kelvin
- Sub-Kelvin Instrument
  - Detectors, readout electronics, and a sub-kelvin cooler
Summary

• Single-field slow-roll inflation looks very good in everything we have looked at in the scalar perturbation
  • Super-horizon, isotropic, adiabatic, Gaussian, and $n_s<1$
  • But we want more to find definitive evidence for inflation: primordial gravitational waves with the wavelength of billions of light years
Summary

• This conference has seen a new direction in the B-mode search: GWs from sources!

\[ h_{ij} = -16\pi G \pi_{ij} \]

• Experimental designs should pay attention to:
  
  • Non scale-invariance,
  
  • Parity-violating correlations, and
  
  • Non-Gaussianity

• LiteBIRD in an excellent position to not only find GWs but also to characterise them
Many thanks to the organisers!