CMB, Gravitational Waves and String Theory Dynamics

**Brief** overview plus work with Dodelson, Dong, Green, Flauger, Horn, Kofman, Linde, Maloney, McAllister, Mirbabayi, Senatore, Torroba, Westphal, Wrase, Zaldarriaga, ...

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Data rich:

- \( \Lambda \) discovered '98 \( \Rightarrow \) Theory behind exp't
- CMB prime time \( \leftarrow \) \( N_s \)
  - PBK discovered \( \langle S_S \rangle \)
  - Other phenomenological opportunities
  - Other phenomenological opportunities
- LIGO, EHT
- DM / LHC

\( \Rightarrow \) horizon physics
UV Sensitivity of Inflation

1. Terms of order

\[
\frac{V \cdot (\alpha - \alpha_0)^2}{M_p^2}
\] (dimension 6)

in the effective action can ruin inflation

2. \( \frac{\Delta \Omega}{M_p} = r \frac{N_e}{\sqrt{8}} \) (Lyth)

GUT-scale inflation (with observable tensor modes) \( \iff \Delta \Omega > M_p \)

3. General Single-field inflation involves higher derivative terms which affect solution & perturbations

4. \( g^2 \alpha^2 \chi^2 \) couplings \( \iff \) temporarily light fields/strings affect evolution.

\( \text{cf Non-Gaussianity} \)
Heavy fields affect results as well:

\(5a\) they adjust in response to inflationary potential energy.

QFT toy model

\[
V(\phi_L, \phi_H) = g^2 \phi_L^2 \phi_H^2 + m^2 (\phi_H - \phi_0)^2
\]

\[
\frac{\partial V}{\partial \phi_H} = 0 \Rightarrow V = \frac{g^2 \phi_L^2}{g^2 \phi_L^2 + m^2} m^2 \phi_0^2
\]

\(\phi_H^2\) term subdominant

flatter: energetically favorable.
(5b) Time-dependent masses (from coupling to inflaton) can affect perturbations even if minimal mass $\mu \gg H$

Mirbabayi, Senatore, ES; Flauger, bi/spectrum templates

$$\left[ g^2 (\phi - \phi_n)^2 + \mu^2 \right] X_n^2$$

$$\Rightarrow \langle \Pi_x \rangle \sim \left( g \phi \right)^{3/2} e^{\frac{\pi \mu^2}{g \phi}}$$

Sources $\langle gg \rangle$, $\langle ggg \rangle$, $\langle gggg \rangle$, ...

$\langle \mathcal{M}, L, S, E, s, \ldots \rangle$

(...
$$\Delta \phi_k = \int d\mathbf{r}' \mathcal{G}_k(\mathbf{r}, \mathbf{r}'; a(\mathbf{r}'); J(\mathbf{r}'))$$

Source: Green's fn

determined by squeezed state of produced particles

$$\langle \delta \phi \delta \phi \rangle \sim \frac{S^2_{\text{vac}}}{S^2_{\text{prod}}} \frac{g^2 \tilde{\eta}_x}{H^3} \lesssim \frac{\hbar (k_n \eta_n)^2}{(-k_n \eta_n)^2}$$

$$\sim \frac{S^3_{\text{production}}}{(S^2_{\text{vac}})^3 \mathcal{L}^2} \frac{g^2 \sum (k \eta_n)^{-3} \hbar (k \eta_n)^3}{\sum (k \eta_n)^{-3} \hbar (k \eta_n)^2}$$
\[ <\bar{S} S> \propto \frac{\tilde{J}^2}{J_{\text{vac}}} \frac{g^2 \bar{\eta}_{x}}{H^3} \leq \frac{\hat{h}(k_{\eta}, \Pi_{\eta})}{\left(-k_{\eta} \Pi_{\eta}\right)} \]

\[ \sim \]

\[ \eta_x \propto e^{-\frac{\Pi_{\eta}^2}{2\tilde{g}}} \]

detectable/constrainable for

\[ \frac{<\bar{S} S>}{J_{\text{vac}}^2} \propto 10^{-2} \eta^3 \]

\[ \Rightarrow \text{sensitive to } \mu > \sqrt{g\phi} \gg H \]

This dynamics is (another) source of oscillatory N-spectra in e.g. axion monodromy...
Variety of inflationary mechanisms in string theory

Many contributors (Baumann/McAllister book)

$V(\phi)$ flat, $\Delta \phi \leq M_p$

- Accidental
  - 10% cancellation

KKLMMT, Roulette, LARGE Fibre

$V(\phi)$ flat, $\Delta \phi > M_p$

Self-interactions slowing $\phi$

$V(\phi)$ steep (e.g., DBI)

Trapped

Monodromy

$L_1$ Impact parameter

N-axis Alignment Gauge fields, ...

Linde $V(\phi) = \frac{m^2}{2} \phi^2$

$P_0 = 2$

$p < 2$

[drifting \(\sqrt{\nabla},\) oscillations]
I'll focus on Axion Monodromy, but other scenarios also interesting

- **KKLT / DBI** pioneered
  - careful assessment of Planck-suppressed contributions
  - illustrates range of inflation & Non-Gaussianity
  - Relativity on field space

- **Fibre, Roulette, ...**
  - Exponential potential $\leftrightarrow$ Starobinsky

- Multiple-field effects, connections to 'weak gravity conjecture' etc.
  - ...
Axions from gauge potentials

\[ S = \frac{1}{2\alpha'} \int d^Dx \sqrt{-G} e^{-2\phi} \left( R - \frac{D-10}{\alpha'} + 4(\partial \phi)^2 \right) + S_{\text{matter}}. \] (3.1)

\[ S_{\text{matter}} = \int d^Dx \sqrt{-G} \left\{ - \sum_{n_B} \tau_{n_B} \frac{\delta^{(D-1-n_B)}(x_\perp)}{\sqrt{G_\perp}} + \sum_{n_0} \tau_{n_0} \frac{\delta^{(D-1-n_0)}(x_\perp)}{\sqrt{G_\perp}} 
+ e^{-2\phi} |H_3|^2 + \sum_{p} |\tilde{F}_p|^2 + C.S. + h.d. \right\} \] (3.2)

\[ \int d^Dx \sqrt{-G} \sum_{g} \left| F_{g} - C A H + F_{\phi} \cdot B_{\perp} - \lambda_{\phi} \right|^2 \]

\[ \int \sum_{g} F_{\phi} = Q_{\phi} \]

Direct Dependence

\[ \text{fluxes} \]

\[ \text{axions} \ b = \int B \]

\[ + \text{e.g. instantons} \rightarrow \Lambda^4 \cos b(\phi) \]

\[ + \text{periodic particle /string production} \]
4d spacefilling flux / brane

$\Rightarrow$ large-field potential
$+ \Lambda^4(\phi_H) \cos \frac{\phi}{f}$

$\Rightarrow m_H^2$ oscillates

non-spacefilling defect,
new sectors reach minimal mass each period

$\Rightarrow$ particle production

highly model-dependent amplitude
Parameterized ignorance of quantum grav.

New degrees of freedom each $\Delta \Phi \sim M_p$

No continuous global symm. in QG

String Theory axions (and duals)

From ubiquitous Axion-Flux couplings

Discrete shift symm., $f << M_p$

[cf Chaotic Infl. (Linde), Natural Infl. (Freese et al)]
Small perturbations from $\Lambda$CDM allowed (tensors, features/oscillations, non-Gaussianity), but wildly dramatic effects highly constrained.
Major advance experimentally: direct bound competitive with indirect (TT) bound. Planck-BICEP/Keck reduced viable $n_s$-$r$ region by 29 percent. Primed for key range of $r$ down to Planck field range. Current (insignificant) bump centered at .05-.06, cf .04-.07 cluster axion monodromy models, tested soon...
Fig. 54. Marginalized joint 68 % and 95 % CL regions for $n_s$ and $r_{0.002}$ from Planck alone and in combination with its cross-correlation with BICEP2/Keck Array and/or BAO data compared with the theoretical predictions of selected inflationary models.

$V = \frac{1}{2} m^2 \phi^2$ 'strongly disfavoured'

$\uparrow$ contains exit, 2 parameters --> <ss>, $N_e$

Given that this minimal possibility is excluded, require additional parameter. *Expected from UV:
Heavy fields affect results: they adjust in response to inflationary potential energy.

- UV completion of gravity (e.g. string theory) can introduce $\phi_{\text{Heavy}}$ (e.g. 'moduli' scalar fields).
  - $V \propto \phi^n \rightarrow V \propto \phi^{p<n}$
  - In examples of axion monodromy
  - Other scenarios have lower additional structure
Moduli: Two basic structures

destabilization

\[ \hat{a}x - \hat{b}x^2 + \hat{c}x^4 \]

Need \( \hat{a}/\hat{b}^2 \) to stay within \( O(1) \) window for minimum

\[ \frac{2n}{n+n} \left( \frac{L_1}{L_2} \right)^2 + \left( \frac{L_1}{L_2} \right) (bQ^2) \]

\[ \Rightarrow V \propto b \frac{2n}{n+n} < 2 \]

\[ V \propto b \]

In specific models, find

\[ V \sim \hat{V}_1(x) \phi^{p_0} + V_0(x) \]

\[ = \mu^{4-p} \phi^p + \Lambda(\phi) \cos(b(\phi)) \]

With \( p < p_0 \); \( p = 3, 2, \frac{4}{3}, \frac{1}{2}, \frac{2}{3} \)
Fig. 54. Marginalized joint 68% and 95% CL regions for $n_s$ and $r_{0.002}$ from Planck alone and in combination with its cross-correlation with BICEP2/Keck Array and/or BAO data compared with the theoretical predictions of selected inflationary models.

Axion monodromy remains viable only because of the flattening effect. (Tested soon by $\mathcal{R}$)
Underlying periodicity
\( \rightarrow \) instanton-induced \( N^4 \cos \frac{\phi}{\xi} \)
\( \rightarrow \) particle/string production
\( \Rightarrow \) Needs inclusion

\[ g^2 \sum_n \chi_n^2 [(\phi - \phi_n)^2 + \mu_n^2] \]

Each event \( \Rightarrow \) \( \bar{\eta} \chi \phi \frac{3}{2} e^{-\mu_n^2} \)
\( (g \sim 1, \text{ loops } \sim \frac{1}{16\pi^2}) \)

* Work in slow roll regime, keeping track of discreteness of events \( \rightarrow \) oscillatory \( \frac{\log \theta}{\text{linear!}} \)

equilateral non-Gaussianity, consistent w/ power spectrum

In progress
Mirkabahy:
Senatore:
ES
Flauger
Planck searches motivate covering all bases

- $\Lambda$CDM Robust: $\chi^2_{\text{d.o.f.}} \sim 1.03-4$

- Useful searches for deviations require specific templates with limited parameters

- EFT of inflation contains arbitrary functions of time (and hence $k$)

$\Rightarrow$ Searches based on specific theories or additional symmetries
**Searches for features:**

**Planck**

Feature in the potential:

\[ V(\phi) = \frac{m^2}{2} \phi^2 \left( 1 + c \tanh \left( \frac{\phi - \phi_c}{d} \right) \right) \]

Non vacuum initial conditions/instanton effects in axion monodromy

\[ V(\phi) = \mu^3 \phi + \Lambda^4 \cos \left( \frac{\phi}{f} \right) \]

\[ \mathcal{P}_R^{\log}(k) = \mathcal{P}_R^0(k) \left[ 1 + A_{\log} \cos \left( \omega_{\log} \ln \left( \frac{k}{k_*} \right) + \varphi_{\log} \right) \right] \]

Linear oscillations as from Boundary EFT

\[ \mathcal{P}_R^{\text{lin}}(k) = \mathcal{P}_R^0(k) \left[ 1 + A_{\text{lin}} \left( \frac{k}{k_*} \right)^{n_{\text{lin}}} \cos \left( \omega_{\text{lin}} \frac{k}{k_*} + \varphi_{\text{lin}} \right) \right] \]

Just enough e-folds, i.e. inflation preceded by a kinetic stage

- No detection from existing searches
- Some outliers

A multipeak equilateral signal rose from 1.9\(\sigma\) (T-only) to 3.1\(\sigma\) (T+E) after adjusting for the ‘look elsewhere’ effect, while the flattened signal went from 2.4\(\sigma\) (T-only) to 3.2\(\sigma\) (T+E). These interesting results, reflecting those obtained for feature models, suggest the fit to any underlying NG signal might await alternative, but related, oscillatory models for a more compelling explanation. We note that the frequency range for this nascent resonant bispectrum analysis is still very limited (relative to the power spectrum analysis). It will remain a high priority to investigate resonance models for the final Planck data release, expanding the frequency domain and improving the differentiation between a variety of non-scaling models.
**Power + Bispectrum**

\[ \frac{\omega}{H} \text{ consistent with 1st-instanton effects} \]

Fig. 37. Constraints on the parameters of the analytic template, showing joint 68% and 95% CL. The dotted lines correspond to the frequencies showing the highest likelihood improvements (see text).

\[ \log(35) \approx 3.5 \]

Fig. 19. Generalized resonance models analysed at \( \ell_{\text{max}} = 2000 \) (\( E \)-modes \( \ell_{\text{max}} = 1500 \)) for the different Planck foreground separation methods, SIMCA (blue), S4SEM (red), KILC (green), Commander (yellow), together with the SSN average (black). The upper panels apply to the constant resonance model (Eq. 10), with \( T \)-only (left) and \( T+E \) (right), the middle panels give results for the equilateral resonance model (Eq. 13), and the lower panels for the flattened resonance model (Eq. 14). Both the equilateral and flattened resonance models produce broad peaks which are reinforced with polarization (middle and bottom right panels).

**Not significant as it stands...**
New templates from repeated particle production:

peaked for \( \frac{k_i}{k_j} \sim \Theta(1) \), but oscillate in \( k \) or \( \frac{k_i}{k_j} \Rightarrow \frac{F_{\text{prod}} \cdot F_{\text{pure equilibrium}}}{\sqrt{F_{\text{prod}}^2 + F_{\text{pure}}^2}} \approx 1 \)

(a) sequence of events, \( J \sim \Theta(n-m) \)

Low input frequency, linear oscillations generated
(b) sinusoidal $\xi$

- oscillates in $x_{ij} = \frac{k_i}{k_j}$

- $(S/N)_{\text{production}}$ bispectrum can be $\gg (S/N)_{\text{resonant}}$
  
  \[
  \frac{(S/N)_{\text{prod. power spectrum}}}{(S/N)_{\text{oscillatory power}}} < \frac{(S/N)_{\text{resonant force}}}{(S/N)_{\text{oscillatory power}}}
  \]

$\Rightarrow$ relevant for joint analysis between power spectrum & bispectrum.
• It will be interesting to see if shapes (a) or (b) affect the statistical significance, survives/improves with polarization.

• Since even $m \gg H$ fields can have effect, null results can be useful:

  'Planck'-suppressed operators
Main Role So Far:

- String-theory mechanisms feed into more systematic EFT & data analysis
  - Planck field range $\iff r > 0.01$ \(\Rightarrow\) especially relevant for $r$
- NG at single-field level
- discrete shift symmetries $\cup$ features & oscillations
- dissipative processes
- exotic sources

$\Rightarrow$ Worthwhile to help make maximal use of precious data
(Yes, String Theory $<$ Science.)
More Direct String Theory Signatures?
--cosmic strings, bubbles, etc. (H. Tye et al...)

Alternatives to inflation that are more sensitive to strong curvature (singular) regimes?
--but black hole thermodynamics precludes some exotic sources for bounces

--Breakdown of EFT at horizons (ongoing work w/M. Dodelson): beyond-GR physics...

In the presence of horizons, the breakdown of effective field theory is not well estimated by

\[ \alpha' R \ll 1: \]

This may lead to new effects relevant for thought experiments and conceivably real ones.
\[ ds^2 = -2r_s \frac{1 - \frac{r}{r_s}}{r} \ dX^+ dX^- + r^2 d\Omega^2 \]

Outside: 
\[ E, m \text{ fixed} \]

Near Horizon: 
\[ X_h^+ = 2r_s \sqrt{E} \frac{E}{m} \]
\[ p^+_h = m \frac{dx^+}{dx^-} \bigg|_h = me \]

Near horizon
\[ S - 2p_{B,h}^+ p_{A,h}^- \sim e \frac{\Delta t}{2r_s} \]
\[ X_B^+ - X_A^+ \sim p_B^+ \sim e \frac{\Delta t}{2r_s} \]
Near horizon: huge energy, but separated along $X^+$.  

String Spreading  
- Susskind '94  
- Brown, Polchinski, Strassler, Tan '06

Light Cone gauge: $X^- = p^- y$,  
Constraint determines $X^+$ in terms of $X^-$

$$
\langle \Psi | (X^+ - x^+)^2 | \Psi \rangle = \sum_{n}^{n_{\text{max}}} \log \frac{n_{\text{max}}}{n_0} + O \left( \frac{1}{n_{\text{max}}} \right)
$$

$$
\langle \Psi | (X^+ - x^+)^2 | \Psi \rangle \approx \frac{1}{(p^-)^2} \sum n = \frac{n_{\text{max}}}{(p^-)^2}
$$

$n_{\text{max}} \leftrightarrow$ light cone time resolution + detector trajectory

$n_{\text{max}} \propto \frac{\Sigma}{-t}$ explicitly
Gathering S-matrix 'data'

C→2 peaks early by predicted longitudinal spreading scale!
Robust against parameter variations
Previous results: 4-5 points

Peak trajectories meet when traced back (in higher D)

Radiation comes from turn 8→3

(3) Explicit & simple string solutions for intermediate S-channel states ↔ pairs & quantitative agreement with peak b & T

(4) Use causality & limited spread to isolate longitudinal effects find e.g.

\[ x_1 = x \cos \theta, \]

\[ y \sin \theta, \]

\[ T \rightarrow T \text{ advanced (early interaction), } T < 0 \]
*Cosmo horizons: safe in early U given Bunch-Davies, safe in late U given that age of U of order 1/H. Any residual effect, e.g. constraints on more exotic scenarios?

*Black hole horizons:

The longitudinal-spreading induced interactions as derived above are similar in amplitude to quasinormal modes. These are expected to be seen in GW detectors (e.g. LIGO) in the ringdown signal from black hole or neutron star mergers. Could there be string theoretic physics beyond GR to be derived? (Interestingly, not a model building exercise -- just uses extent of fundamental strings, although so far restricted to weak coupling regime.)

Early days but fun questions...