Cosmology After Planck Workshop

September 23-25, 2013

Sponsored by:

340 West Hall

University of Michigan, Ann Arbor, Central Campus

Workshop Home

Participants

Registration

Accommodation

Inflationary cosmology has become an integral part of the standard model of the early Universe. Inflationary models and other signatures of the early-Universe physics have become stringently constrained by WMAP and Planck, as well as powerful new large-scale structure surveys. This workshop will discuss the theoretical, observational, and experimental aspects of inflation and primordial physics, interpreted broadly. We plan to gather 20-30 of the top experts in the field.

Mysteries of the Dark Universe Public Lecture - Monday, September 23, 2013

TIME: 7:00pm. Refreshments will be served prior to talk at 6:30pm.

VENUE: Edward Henry Kraus Building (Natural Science) #2140, 830 North University, Ann Arbor, MI 48109-1042 ( inertial Gravity, Maier, from fourfold structure, CC, and 19)
The Universe according to Planck
Planck Data

Angular size of acoustic scale determined to better than 0.1%

Seven acoustic peaks
Cosmological Parameters from Planck

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Planck (CMB+lensing)</th>
<th>Planck+WP+highL+BAO</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Best fit</td>
<td>68 % limits</td>
</tr>
<tr>
<td>( \Omega_b h^2 )</td>
<td>0.022242</td>
<td>0.02217 ± 0.00033</td>
</tr>
<tr>
<td>( \Omega_c h^2 )</td>
<td>0.11805</td>
<td>0.1186 ± 0.0031</td>
</tr>
<tr>
<td>100( \theta_{MC} )</td>
<td>1.04150</td>
<td>1.04141 ± 0.00067</td>
</tr>
<tr>
<td>( \tau )</td>
<td>0.0949</td>
<td>0.089 ± 0.032</td>
</tr>
<tr>
<td>( n_s )</td>
<td>0.9675</td>
<td>0.9635 ± 0.0094</td>
</tr>
<tr>
<td>( \ln(10^{10} A_s) )</td>
<td>3.098</td>
<td>3.085 ± 0.057</td>
</tr>
<tr>
<td>( \Omega_L )</td>
<td>0.6964</td>
<td>0.693 ± 0.019</td>
</tr>
<tr>
<td>( \sigma_8 )</td>
<td>0.8285</td>
<td>0.823 ± 0.018</td>
</tr>
<tr>
<td>( z_{rec} )</td>
<td>11.45</td>
<td>10.8^{+3.1}_{-2.5}</td>
</tr>
<tr>
<td>( H_0 )</td>
<td>68.14</td>
<td>67.9 ± 1.5</td>
</tr>
<tr>
<td>Age/Gyr</td>
<td>13.784</td>
<td>13.796 ± 0.058</td>
</tr>
<tr>
<td>100( \theta_s )</td>
<td>1.04164</td>
<td>1.04156 ± 0.00066</td>
</tr>
<tr>
<td>( r_{drag} )</td>
<td>147.74</td>
<td>147.70 ± 0.63</td>
</tr>
<tr>
<td>( r_{drag}/D_V(0.57) )</td>
<td>0.07207</td>
<td>0.0719 ± 0.0011</td>
</tr>
</tbody>
</table>
New Pie Picture: more dark matter

- WMAP: 4.7% baryons, 23% DM, 72% dark energy
- PLANCK: 4.9% baryons, 26% DM, 69% dark energy

For discussion: is the difference due to instrumental effects? Is it due to 217 X 217 spectra?
Effective Number of Neutrino Species

- In the Standard Model, $N_{\text{eff}} = 3.046$, due to non-instantaneous decoupling corrections (Mangano et al. 2005).

$$N_{\text{eff}} = 3.52^{+0.48}_{-0.45} \ (95\%; \text{Planck+WP+highL+}H_0+\text{BAO}).$$

Increasing the radiation density increases the expansion rate before recombination and reduces the age of the Universe at recombination.
Weird Anomalies of WMAP hold up

- Alignment between quadrupole and octopole moments (axis of evil)
- Asymmetry of power between two hemispheres
- The Cold Spot
- Deficit of power in low-l modes (below l=30)

- All confirmed to 3 sigma
- Cosmological origin favored (consistency between different CMB maps)
WMAP cold spot (also in Planck)
SH initials in WMAP satellite data
Minimal inflation:

- 1) a single weakly-coupled neutral scalar field, the inflaton, drives the inflation and generates the curvature perturbation
- 2) with canonical kinetic term
- 3) slowly rolling down featureless potential
- 4) initially lying in a Bunch-Davies vacuum state

If any one of these conditions is violated, detectable amplitudes of nonGaussianity should have been seen.

\[
\langle \Phi(k_1)\Phi(k_2)\Phi(k_3) \rangle = (2\pi)^3 \delta^{(3)}(k_1 + k_2 + k_3) B_{\Phi}(k_1, k_2, k_3).
\]

\[
B_{\Phi}(k_1, k_2, k_3) = f_{NL} F(k_1, k_2, k_3).
\]
If primordial fluctuations are Gaussian distributed, then they are completely characterized by their two-point function, or equivalently by the power spectrum. All odd-point functions are zero.

If nonGaussian, there is additional info in the higher order correlation functions.

The lowest order statistic that can differentiate is the 3-point function, or bispectrum in Fourier space:

$$\langle \Phi(k_1)\Phi(k_2)\Phi(k_3) \rangle = (2\pi)^3 \delta^{(3)}(k_1 + k_2 + k_3)B_{\Phi}(k_1, k_2, k_3).$$

Here Phi is comoving curvature perturbation (density pert)
No primordial nonGaussianities in Planck

- Single field models: so small as to be undetectable
- Other models: three shapes (configurations of triangles formed by the three wavevectors)
- Any detection of nonGaussianity would have thrown out all single field models
- Data show no evidence of nonGaussianity, implying single field models work

\[
\begin{array}{ccc}
\text{Local} & \text{Equilateral} & \text{Orthogonal} \\
2.7 \pm 5.8 & -42 \pm 75 & -25 \pm 39 \\
\end{array}
\]

- Data bound the speed of sound \(c_s > 0.02\)
Models with NG: $f_{NL} \gg 1$

- **Local NG**: squeezed triangles, $k_1 \ll k_2 = k_3$, e.g. multifield models, curvaton

- **Equilateral NG**, $k_1 = k_2 = k_3$, e.g. non-canonical kinetic terms as in $k$-inflation or DBI inflation, models with general higher-derivative interactions of the inflaton field such as ghost inflation, and models arising from effective field theories

- **Folded NG**, e.g. single-field models with non-Bunch-Davies vacuum, and models with general higher derivative interactions.

- **Orthogonal NG**, e.g. non-canonical kinetic terms.

No evidence for any of these nonGaussianities in Planck. Disfavored: EKPYROTIC with exponential potential
Predictions of Single Field Models

- 1) no nonGaussianities
- 2) no running of spectral index of scalar perturbations

- Scalar modes
- Tensor modes

Both predictions proven true by Planck

“With these results, the paradigm of standard single-field inflation has survived its most stringent tests to date”
Four parameters from inflationary perturbations:

I. Scalar perturbations:
   - Amplitude: \( \frac{\delta \rho}{\rho} \bigg|_s \)
   - Spectral index: \( n_s \)

II. Tensor (gravitational wave) modes:
   - Amplitude: \( \frac{\delta \rho}{\rho} \bigg|_T \)
   - Spectral index: \( n_T \)

Expressed as:

\[
r \equiv \frac{P_T^{1/2}}{P_S^{1/2}}
\]

Inflationary consistency condition:

\[
r = -8n_T
\]

Plot in \( r \)-\( n \) plane (two parameters)
Inflation after Planck

Fig. 1. Marginalized joint 68% and 95% CL regions for $n_s$ and $r_{0.002}$ from Planck in combination with other data sets compared to the theoretical predictions of selected inflationary models.

Purple swath is natural inflation model of Freese, Frieman, and Olinto 1990
Extensions to ΛCDM model
Early-Universe physics: ns, dn_s/dk and r

6σ departure from scale invariance

n_s = 0.9603 ± 0.0073

\[ \ell^2 D_{\ell} [mK^2] \]

Multipole moment \( \ell \)

\[ \frac{dn_s}{d \ln k} = -0.0134 \pm 0.0090 \]

\[ r < 0.11 \]

\[ V = (1.94 \times 10^{16} \text{ GeV})^4 \left( r_{0.02} / 0.12 \right) \]
Natural Inflation: Shift Symmetries

- Shift symmetries (e.g. axionic) protect flatness of inflaton potential
  \[ \Phi \rightarrow \Phi + \text{constant} \] (e.g. inflaton is Goldstone boson)
- Additional explicit breaking allows field to roll.
- This mechanism, known as natural inflation, was first proposed in
  Freese, Frieman, and Olinto 1990;
  Adams, Bond, Freese, Frieman and Olinto 1993
**Original Natural Inflation**

For QCD axion:

\[ f \sim 10^{12} \text{ GeV} \]
\[ \Lambda \sim 100 \text{ MeV} \]

For natural inflation:

\[ f \sim M_{\text{Pl}} \]
\[ \Lambda \sim M_{\text{GUT}} \]

- **Width \( f \):**
  Scale of spontaneous symmetry breaking of some global symmetry

- **Height \( \Lambda \):**
  Scale at which gauge group becomes strong

\[ V(\Phi) = \Lambda^4 [1 + \cos(\Phi/f)] \]
Shift Symmetries: Natural Inflation

- Non-perturbative axion: Freese et al., hep-ph/9207245
  \[ V(\phi) \propto \left[ 1 + \cos \left( \frac{\phi}{\mu} \right) \right] \]

- Chiral symmetry breaking: WHK, Mahanthappa, hep-ph/9503331
  \[ V(\phi) \propto \left[ m_{\psi}(\phi) \right]^2 \ln \left[ m_{\psi}(\phi) \right] \]

  \[ V(\phi) \propto \sin \left( \frac{\phi}{\mu} \right)^4 \ln \left[ \sin \left( \frac{\phi}{\mu} \right)^2 \right] \quad \text{(KM Model)} \]

  \[ V(\phi) \propto \phi^{2/3} \]
Slide from Will Kinney
A lesson from Planck

- Shift symmetries are a winning mechanism for generating the inflationary potential!

Shift symmetries were the point of natural inflation
Original model had cosine-shaped potential
Today many variants exist

Nice review by Pajer and Peloso
We eagerly await Planck polarization data

- To date: $r < 0.12$ (k=0.002Mpc^-1) at 95% C.L.

If cosine (original variant of natural inflation) is right, then $r > 0.02$ is predicted (given bounds on $n_s$)
Summary of Inflation after Planck:

• I. The predictions of inflation are right:
  (i) the universe has a critical density
  (ii) superhorizon fluctuations
  (iii) density perturbation spectrum nearly scale invariant
  (iv) Single rolling field models look good: Gaussian perturbations, not much running of spectral index

• II. Data differentiate between models
  • -- gravitational wave modes detectable in upcoming polarization experiments
  • -- WMAP and Planck rule out many models
    -- Natural Inflation (shift symmetries) is good fit to data
Provocative Point: Hints of NonGaussianity in data

- There is nonGaussianity in the Planck data at almost 4 sigma.
- It doesn’t correspond to familiar shapes or templates.
- i.e. not characterized well by fNL or from point sources
- Buried deep in the paper
- More work to be done
- Nature might surprise us!
Provocative Questions

- What is the target sensitivity that LSS/CMB surveys should be trying to reach in tests of inflation (e.g. \( r=0.001, f_{NL}=O(1), \text{curvature} = O(10^{-4}) \))? This is a very important question: it's easier for surveys to get funded provided there is a clear target from theory.

- Do we need a CMB *temperature* survey beyond Planck? For CMB polarization, do we need a space telescope, or is ground sufficient?

- Can LSS systematics be controlled sufficiently so that LSS reaches its full potential?
Large Scale Structure

- Provides complementary and/or competing info w/ CMB
- Different temporal (later) and spatial (smaller) scales
- LSS has more modes and in principle more info:
  CMB is 2D
  LSS is 3D
- Yet: can systematic errors be controlled?
- LSS has great potential: can it be tapped?
Provocative Questions II

- Can a convincing case be made that inflationary acceleration is somehow related to the present-day acceleration of the universe?
- One can fit any observational data with inflation theory - true or false
- From the theory side, should we be trying to get a "prior" for measured parameter distribution/values? Is this even possible?