PROBING PRIMORDIAL FEATURES WITH SKA

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What it is:

- Based on General Relativity and on the assumption of homogeneity and isotropy of the space-time.
- Theory that the Universe as we know it began 13-14 billion years ago (latest estimate: 13.80±0.04 billion years).
- Initial state was a hot, dense, uniform soup of particles that filled space uniformly, and was expanding rapidly.

What it describes:

- How the early Universe expanded (according to Hubble’s law) and cooled.
- How the light chemical elements formed (produced by Big Bang Nucleosynthesis).
- How the Cosmic Microwave Background radiation and Large Scale cosmic Structures formed.
STANDARD BIG BANG MODEL

WHAT IT DOESN’T DESCRIBES:

● Why are the large scales of the Universe so uniform in all directions?

● Why was the early Universe so flat?
  (Flat does not mean two-dimensional but means Euclidean)

● Where did cosmological perturbations come from?
COSMIC INFLATION

WHAT IS IT:

- Inflation is a modification of the standard big bang theory, providing a very brief “prequel”.

- Inflation can explain the bang of the big bang in terms of gravitational repulsion.

- The repulsion drove it into exponential expansion. An initial patch large at least $10^{-28}$ centimeters exponentially expanded. Inflation lasted maybe $10^{-35}$ second, and at the end, the region destined to become the presently observed Universe was about the size of a marble.
COSMIC INFLATION

Solutions to the problems of the standard Big Bang model:

- Then inflation stretches a initial small uniform region to be large enough to include the visible Universe.

- Since inflation makes gravity become repulsive, the evolution of $\Omega_{tot}$ changes, too. $\Omega_{tot}$ is driven towards one, extremely rapidly.

- Inflation attributes these ripples to quantum fluctuations. These ripples are responsible for the anisotropies in the CMB and for the overdensity that we observe today in the LSS matter distribution.
Making the "galaxy seeds" with inflation

ultra-tiny quantum fluctuations become... large lumps seen in cosmic microwave background

Credits: Planck Collaboration

Credits: SDSS Collaboration
\[ P(k) = A_s \left( \frac{k}{k_*} \right)^{n_s - 1}, \quad n_s \simeq 1 \]
ANOMALIES IN THE CMB

[Planck 2015 results. XIII. Cosmological parameters]

low multipoles deficit feature at $\ell=20-30$
FROM 14 YEARS...

low multipoles deficit

feature at $\ell=20-30$

[WMAP Collaboration Peiris et al. (2003)]
A SMOOTH PRIMORDIAL POWER SPECTRUM?

Bottom-up:

- Reconstructing the shape of primordial power spectrum from the data.

Top-down:

- Fitting a specific physical features model or parameterized features spectrum to the data.

[Planck 2015 results. XX. Constraints on inflation]
SEARCH FOR PARAMETERIZED FEATURES

There are several theoretical motivations beyond violation of the slow-roll conditions: slow-roll parameters are not necessary small or slowly varying. The theoretical interest in models beyond the slow-roll approximation is corroborated by observations.

Planck 2015 results. XX. Constraints on inflation
MB, Finelli, Fedeli & Moscardini, JCAP 2016

Contaldi, Peloso, Kofman & Linde, JCAP 2003
Starobinsky, JETP 1992
Adams, Cresswell & Easther, PRD 2001
Flauger, Mc Allister, Pajer, Westphal & Xu, JCAP 2010
SEARCH FOR PARAMETERIZED FEATURES

- Inflationary models violating the slow-roll approximation predict features in the PPS which can provide better fit to the data or be constrained.

- Higher $\Delta \chi^2 \sim -12$ have been found with different parameterization.

  Miranda, Hu & Adshead, PRD 2012

  Planck 2015 results. XX. Constraints on inflation

  Hazra, Shafieloo, Smoot & Starobinsky, JCAP 2016
FEATURES IN THE MATTER POWER SPECTRUM
KINK IN THE INFLATON POTENTIAL

- Strong constraints from CMB mainly due to the oscillatory pattern

- Deviations $< 10\%$ at $k = 0.01 \, h/\text{Mpc}$ and $\sim 20\%$ at $k = 0.001 \, h/\text{Mpc}$

- Only $1\sigma$ constraints from future spectroscopic surveys, e.g. DESI and Euclid

[Starobinsky, JETP 1992]

[MB, Finelli, Fedeli & Moscardini, JCAP 2016]
KINK IN THE INFLATON POTENTIAL

[MB, Finelli, Maartens, Moscardini, 2017]
STEP IN THE INFLATON POTENTIAL

- Localized feature leads to bigger deviations from standard slow-roll predictions
- Deviations $\sim 40\%$ at $k = 0.003 \text{ h/Mpc}$
- Previous studies found that the combination of galaxy surveys and CMB data will not significantly improve constraints

[Dvorkin & Hu, PRD 2010]
STEP IN THE INFLATON POTENTIAL

[MB, Finelli, Maartens, Moscardini, 2017]
CONCLUSIONS

- *Planck* data are consistent with a smooth, power-law primordial spectrum as predicted by the simplest models of inflation; however, intriguing puzzles at $\ell < 40$ are present in the temperature power spectrum, not statistically preferred.
- Future LSS surveys, will be decisive to probe a possible primordial origin for these features.
- In order to test large scale features we need to have access to the largest scales (low resolution): large volume & high redshift (photometric, intensity mapping, radio continuum).
- SKA1 with the intensity mapping and continuum surveys will give the opportunity to distinguish between a simple power-law primordial power spectrum and primordial features thanks to the huge volume covered.
THANKS!
INFLATIONARY PREDICTIONS

Scalar spectral indices are given by

\[ \mathcal{P}_R(k) = A_s \left( \frac{k}{k_*} \right)^{n_s - 1 + \frac{1}{2} \frac{dn_s}{d \ln k} \ln(k/k_*) + \frac{1}{6} \frac{d^2 n_s}{d \ln k^2} (\ln(k/k_*))^2} \]

\[ \mathcal{P}_t(k) = r A_s \left( \frac{k}{k_*} \right)^{n_t + \frac{1}{2} \frac{dn_t}{d \ln k} \ln(k/k_*)} \]

Amplitude of perturbations are given by

\[ A_s \approx \frac{H^2}{8\pi^2 M_{pl}^3 \epsilon_1} \]

\[ r \equiv \frac{A_t}{A_s} \approx 16\epsilon_1 \]

The runnings are

\[ \frac{dn_s}{d \ln k} = \frac{d^2 \ln \mathcal{P}_R}{d(\ln k)^2} \approx \mathcal{O}(\epsilon^2) \]

\[ \frac{dn_t}{d \ln k} = \frac{d^2 \ln \mathcal{P}_t}{d(\ln k)^2} \approx \mathcal{O}(\epsilon^2) \]

Scalar spectral indices are given by

\[ n_s - 1 \equiv \frac{d \ln \mathcal{P}_R}{d \ln k}, \quad n_t \equiv \frac{d \ln \mathcal{P}_t}{d \ln k} \]

\[ n_s - 1 \approx -2\epsilon_1 - \epsilon_2, \quad n_t \approx -2\epsilon_1 \]
Inflationary models violating the slow-roll approximation predict features in the PPS which can provide better fit to the data or be constrained.

Higher $\Delta \chi^2 \sim -12$ have been found with different parameterization.

Miranda, Hu & Adshead, PRD 2012
Planck 2015 results. XX. Constraints on inflation
Hazra, Shafieloo, Smoot & Starobinsky, JCAP 2016
FEATURES AND CMB POLARIZATION

- Thanks to the sharpness of the CMB polarization transfer functions, future CMB polarization data will help in providing complementary information to further test if these deviations from a simple power-law spectrum are compatible with statistical fluctuations or are of primordial origin.

- Under the simplest set of assumptions for large-scale polarization in which we take the best-fit model for the temperature features polarization cosmic-variance limited measurements from a future all-sky experiment beyond Planck could potentially increase current significance to $|\Delta \chi^2| \sim 64$. 

[Mortonson, Dvorkin, Peiris & Hu, PRD 2009]
However, some of the polarization imprints of primordial features in the E-mode power spectrum could be confused with cosmic variance plus noise or could be degenerate with the physics of reionization beyond the simplest modelling of an average optical depth.

Allowing non-standard reionization histories with arbitrary changes the ionized fraction at $6<z<50$ can lower the significance up to a 30% [Mortonson, Dvorkin, Peiris & Hu, PRD 2009].
POWER SPECTRUM RECONSTRUCTION WITH CORE

[Exploring Cosmic Origins with CORE: Inflation, (Finelli et al.) 2017]
Axion monodromy inflation models predict a modification of the traditional featureless PPS via a multiplication of logarithmic oscillations:

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

CMB measures integrated angular correlations and suppressed sharp features.
SEARCH FOR PARAMETERIZED FEATURES

- Inflationary models violating the slow-roll approximation predict features in the PPS which can provide better fit to the data or be constrained.

Higher $\Delta \chi^2 \sim -12$ have been found with different parameterization.

<table>
<thead>
<tr>
<th>Model</th>
<th>Planck TT+lowP $\Delta \chi^2$</th>
<th>Planck TT+lowP $\Delta \chi^2$</th>
<th>$\ln B$</th>
<th>$\ln B$</th>
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<tbody>
<tr>
<td>Cutoff (+2)</td>
<td>$-3.4$</td>
<td>$-3.4$</td>
<td>$-1.4$</td>
<td>$-1.4$</td>
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<tr>
<td>Starobinsky (+2)</td>
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<td>$-4.9$</td>
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<td>Step (+3)</td>
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<td>$-7.3$</td>
<td>$-0.3$</td>
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<td>Logarithmic osc. (+3)</td>
<td>$-10.6$</td>
<td>$-10.1$</td>
<td>$-1.9$</td>
<td>$-1.5$</td>
</tr>
</tbody>
</table>

Miranda, Hu & Adshead, PRD 2012
Hazra, Shafieloo, Smoot & Starobinsky, JCAP 2016
OUTLINE

● Cosmic inflation

● *Planck* 2015 results
  ○ Constraints on slow-roll inflation
  ○ Constraints for parameterized features

● Slow-roll predictions

● Future CMB polarization measurements

● Probing primordial features with future LSS surveys
**AXION MONODROMY**

Axion monodromy inflation models predict a modification of the traditional featureless PPS via a multiplication of logarithmic oscillations:

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

CMB measures integrated angular correlations and suppressed sharp features.
ANOMALIES IN THE CMB

It is a feature of the CMB anisotropy pattern which is far from what expected in the standard ΛCDM scenario.

- power anomalies (lack of power at large angular scales, odd-even asymmetry)
- directional anomalies (hemispherical asymmetry, mirror symmetry, quadrupole-octupole alignment)
- local anomalies (cold spot)
- tension on some cosmological parameters, e.g. $H_0$ and $\sigma_8$, with some external dataset
FEATURES IN THE MATTER POWER SPECTRUM