

# Oscillations in the inflaton potential: Exact numerical analysis and comparison with the recent and forthcoming CMB datasets

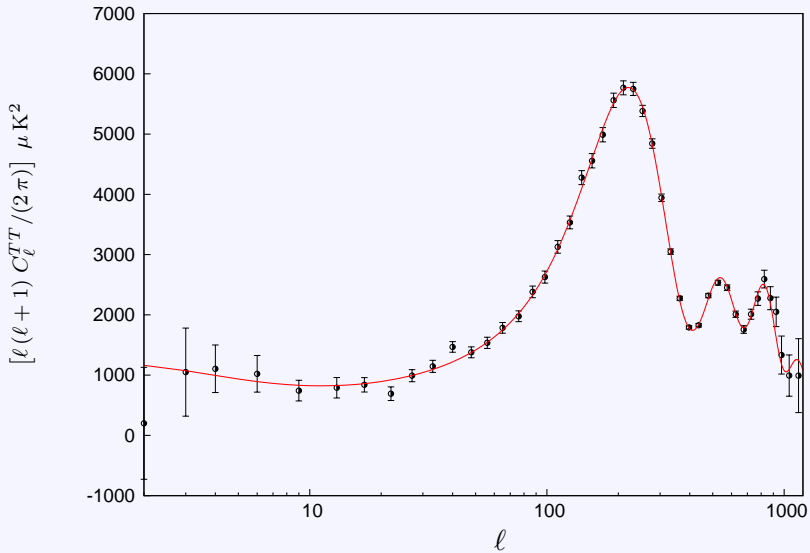
Dhiraj Kumar Hazra

Harish-Chandra Research Institute, Allahabad, India

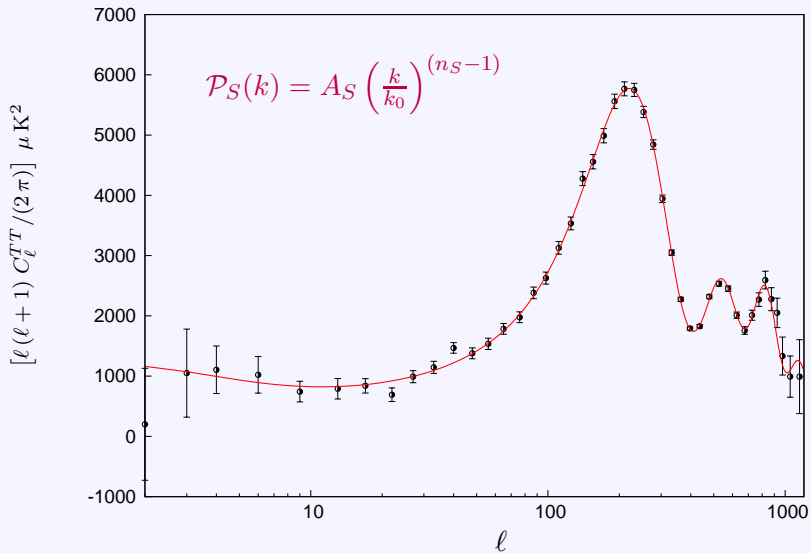
with M. Aich, L. Sriramkumar and T. Souradeep,  
*arXiv:1106.2798v1 [astro-ph.CO]*

Confronting particle-cosmology with Planck and LHC, IUCAA, Pune

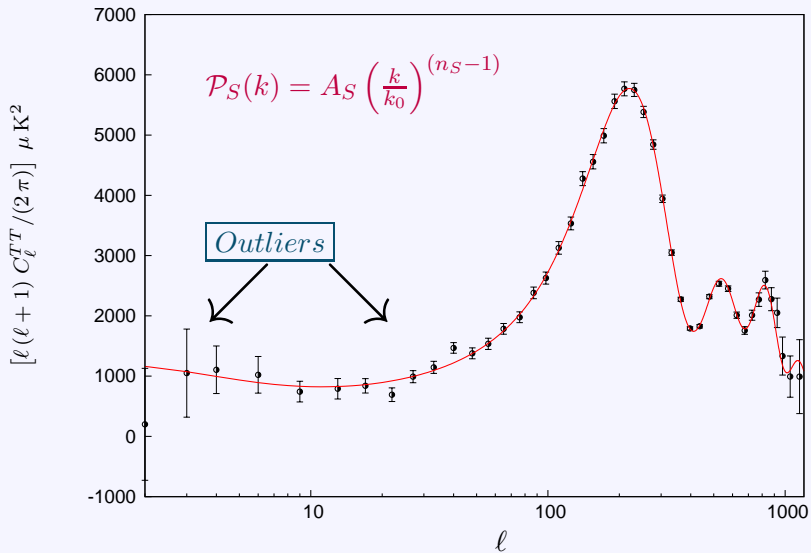
# Angular power spectrum from the WMAP 7-year data



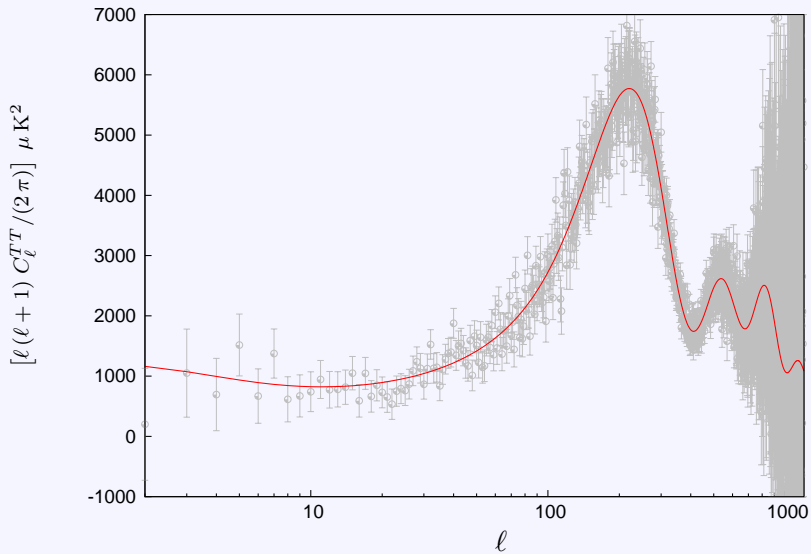
# Angular power spectrum from the WMAP 7-year data



# Angular power spectrum from the WMAP 7-year data



# Angular power spectrum from the WMAP 7-year data



# WMAP-7 year data: Points to note

## Features

- Theoretical primordial power spectrum predicted by inflation along with the  $\Lambda$ CDM model matches the CMB data very well
- There exists some **outliers in the data indicating features**
- Features can possibly be divided in two categories, **local** and **non-local**
- In this work we will study the non-local features of the angular power spectrum
- Features might indicate certain non-trivial inflationary dynamics

## Indication

This may lead to certain deviation from the conventional slow roll inflation

## WMAP-7 year data + ACT data: Points to note

### Tensors

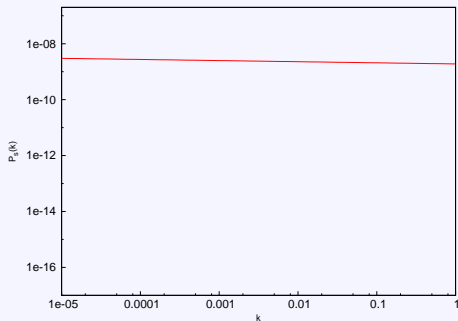
- Till now the tensor contribution from inflation is undetermined
- The tensor to scalar ratio  $r < 0.3$  from WMAP-7
- Atacama Cosmology Telescope (ACT) probes as small scales data as  $\ell \sim 10000$
- The joint constraint on  $r$  from WMAP-7 and ACT is  $< 0.24$

### Indication

As all the upper-bound quoted are at 95% CL

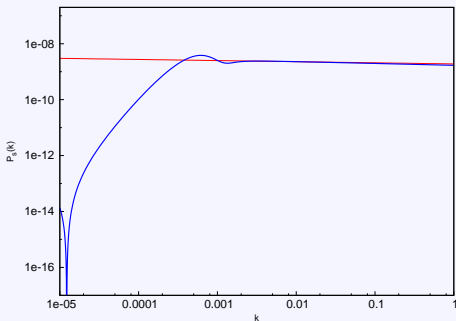
Models with lower tensor contributions are becoming important to study

# Fitting the **local** outliers



- Certain oscillatory features in the primordial scalar power spectrum are known to provide a better fit to the data

# Fitting the **local** outliers



- Certain oscillatory features in the primordial scalar power spectrum are known to provide a better fit to the data
- For example, **punctuated inflation**<sup>a</sup> is known to lead to a better fit to the outliers near  $\ell = 2$  and  $\ell = 22$  than the standard power law spectrum

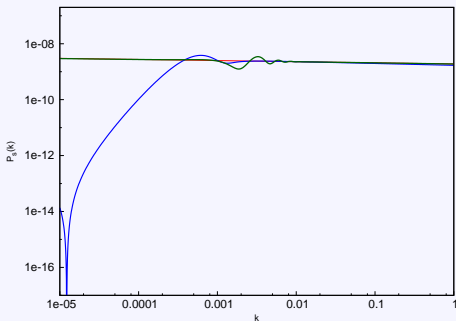
---

<sup>a</sup>Jain et. al.(2009)

## Potential for the PI

$$V(\phi) = \left(\frac{m^2}{2}\right) \phi^2 - \left(\frac{2\sqrt{\lambda} m}{3}\right) \phi^3 + \left(\frac{\lambda}{4}\right) \phi^4,$$

# Fitting the local outliers



- Certain oscillatory features in the primordial scalar power spectrum are known to provide a better fit to the data
- For example, **punctuated inflation**<sup>a</sup> is known to lead to a better fit to the outliers near  $\ell = 2$  and  $\ell = 22$  than the standard power law spectrum
- The oscillatory features can also be generated with the **introduction of a step**<sup>b</sup> in a potential which provides better fit to the CMB data near  $\ell = 22$  and  $\ell = 40$

<sup>a</sup>Jain et. al.(2009)

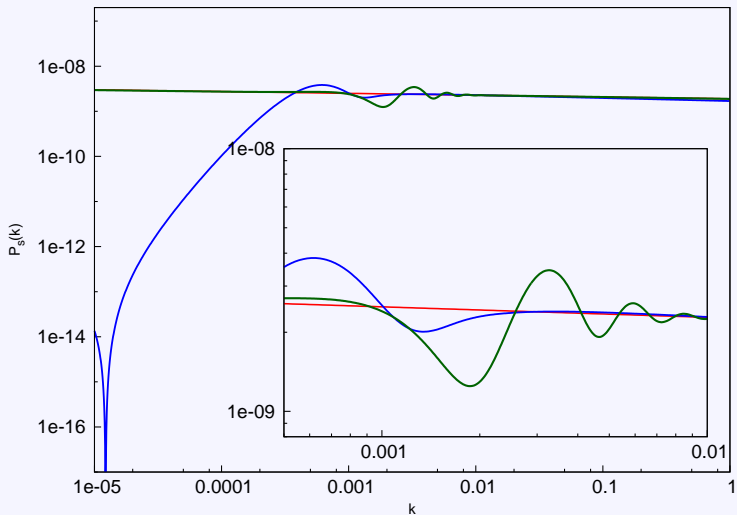
<sup>b</sup>Adams et. al.(2001); Covi et. al.(2006);  
Mortonson et. al.(2009); Hazra et. al.(2010)

Potential for the PI

$$V(\phi) = \left(\frac{m^2}{2}\right) \phi^2 - \left(\frac{2\sqrt{\lambda} m}{3}\right) \phi^3 + \left(\frac{\lambda}{4}\right) \phi^4, \tilde{V}(\phi) = V(\phi) \times \left[1 + \alpha \tanh\left(\frac{\phi - \phi_0}{\Delta\phi}\right)\right]$$

Potential for the step

# Fitting the local outliers



## Fitting the non-local outliers

Attempts have been made recently to fit the non-local features

- ① Superimposed Oscillations in the WMAP Data?<sup>1</sup>
- ② Chaotic model with sinusoidal modulation<sup>2</sup>

### Potential

$$V(\phi) = \frac{1}{2} m^2 \phi^2 \left[ 1 + \alpha \sin \left( \frac{\phi}{\beta} + \delta \right) \right]$$

- ③ The axion monodromy model<sup>3</sup>

### Potential

$$V(\phi) = \mu^3 \phi + \Lambda^4 \cos \left( \frac{\phi}{\gamma} + \delta \right) = \lambda \left[ \phi + \alpha \cos \left( \frac{\phi}{\beta} + \delta \right) \right]$$

---

<sup>1</sup>Martin et. al. 2003

<sup>2</sup>Pahud et. al. 2008

<sup>3</sup>Flauger et. al. 2009

# Fitting the non-local outliers: The slow roll parameters

- The following two parameters characterize slow roll inflation

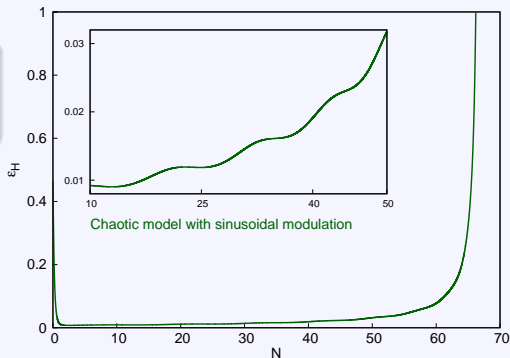
## Hubble slow roll parameters

$$\epsilon = -\dot{H}/H^2, \quad \eta = -\ddot{\phi}/H\dot{\phi}$$

If the inflaton is rolling slowly down a potential, then

$$(\epsilon, \eta) \ll 1$$

- These models have oscillations in the potential and so the slow roll parameters are also oscillatory



Which in turn leaves oscillations in the primordial power spectra

# Fitting the non-local outliers: The slow roll parameters

- The following two parameters characterize slow roll inflation

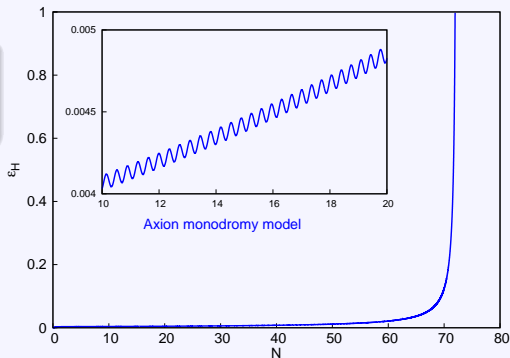
## Hubble slow roll parameters

$$\epsilon = -\dot{H}/H^2, \quad \eta = -\ddot{\phi}/H\dot{\phi}$$

If the inflaton is rolling slowly down a potential, then

$$(\epsilon, \eta) \ll 1$$

- These models have oscillations in the potential and so the slow roll parameters are also oscillatory



Which in turn leaves oscillations in the primordial power spectra

## The spectral tilt, tensor to scalar ratio

- The spectral tilt in the case of the chaotic model with sine modulation comes out to be  $n_s \simeq 0.96$
- Axion monodromy model produces a spectral tilt of  $n_s \simeq 0.97$
- The tensor to scalar ratio ( $r$ ) in the sine potential is  $\simeq 0.16$  over the scales of cosmological interest
- Monodromy model produce  $r \simeq 0.05 - 0.07$  over the same scales
- This model may perform better if the future CMB observations like PLANCK do not see a high tensor to scalar ratio
- We have evaluated the tensor modes for the two models exactly and used them to produce the angular power spectrum and included in our analysis

# Aims of the work

The aims of our work are threefold:

## Aims

- ① We want to see how each model perform against the CMB datasets both at large and small scales. **If the models perform better** than the standard power law primordial spectrum we want to examine where from the improvements come
- ② We have taken the tensor power spectrum into account to have a more realistic comparison
- ③ If the oscillations do give a better fit to the data than the standard case we would like to see **if the oscillations can be constrained** using the present datasets  
If not, then to forecast if the future datasets can, we have produced and used PLANCK mock data and have tested the models with the data

# Methodology and datasets

- For our analysis, we have made use of the following datasets:

## CMB Datasets

- ① WMAP-7
  - ② WMAP-7 + Atacama Cosmology Telescope 148 GHz spectrum
- We have calculated the **scalar and tensor power spectra for all the models numerically with high accuracy**
  - We have used publicly available **CAMB** and **CosmoMC** to compare our models with the data
  - We should mention that we have taken gravitational lensing and the SZ effect into account.

## Results: The $\chi_{eff}^2$ for the different models and datasets

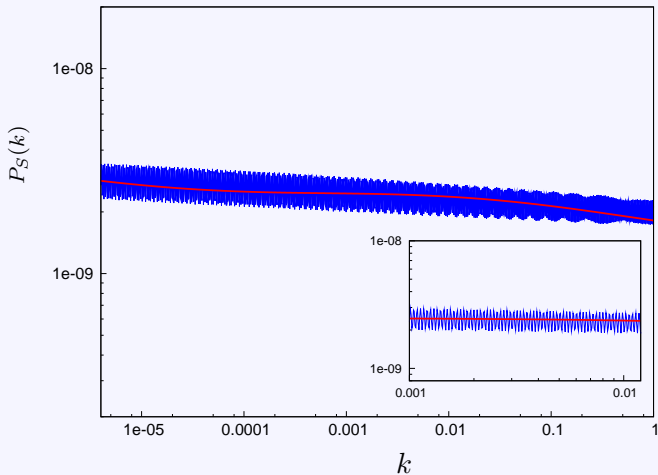
Datasets	WMAP-7	WMAP-7 + ACT
Power law case	7468.3	7500.4
Chaotic model with sine	7467.6 ( $\Delta\chi_{eff}^2 = 0.7$ )	7498.2 ( $\Delta\chi_{eff}^2 = 2.2$ )
Axion monodromy model	7462.1 ( $\Delta\chi_{eff}^2 = 6.2$ )	7495.2 ( $\Delta\chi_{eff}^2 = 5.2$ )

The chaotic model with the sinusoidal modulation provides a better fit of **0.7** over power law case

But the monodromy model provides a better fit of  $\simeq 6$  over the same. So the oscillations here indeed provide a reasonable better fit to the data

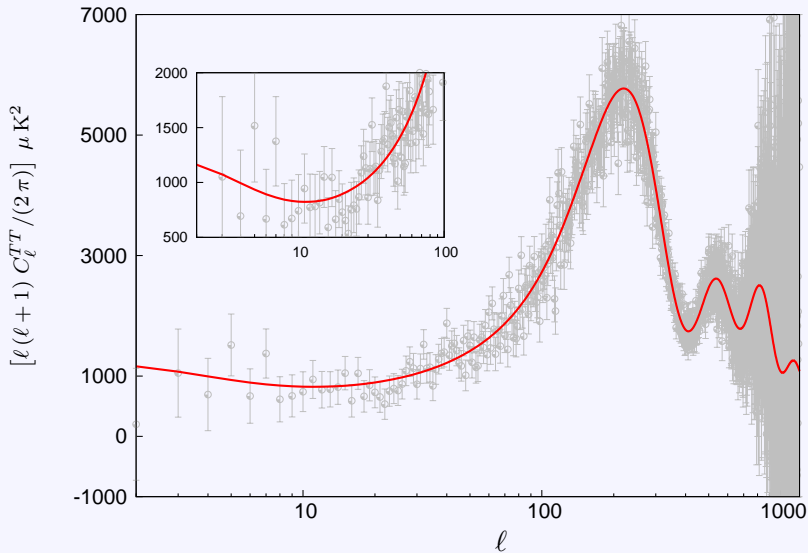
# Best fit primordial power spectra for all the models

The sine model, the axion monodromy model



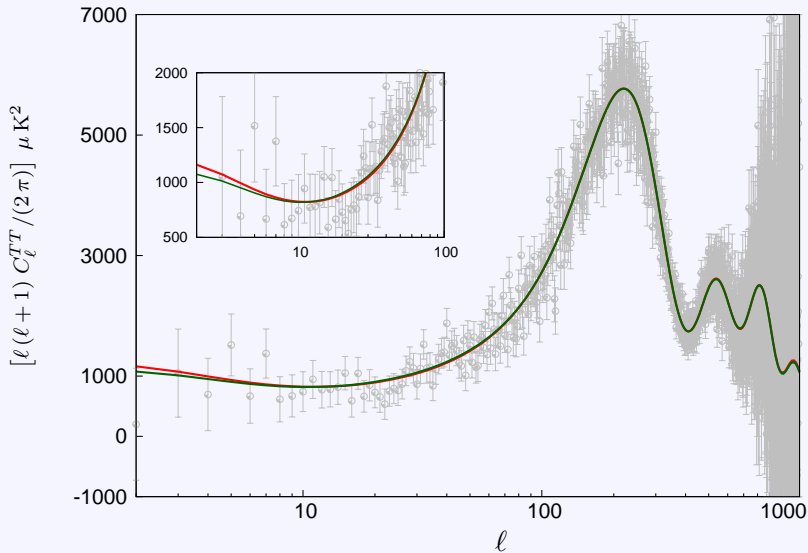
# The $C_\ell^{TT}$ for the best fit models

The power law



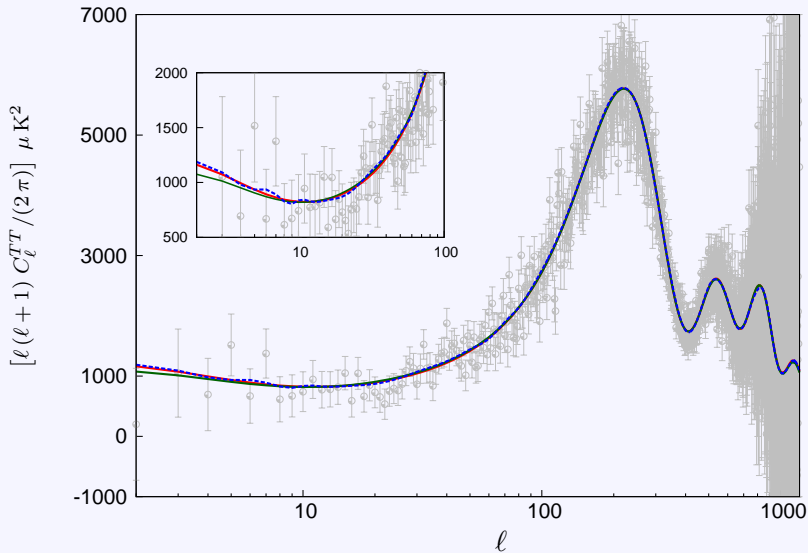
# The $C_\ell^{TT}$ for the best fit models

The power law, the chaotic model with sine modulation



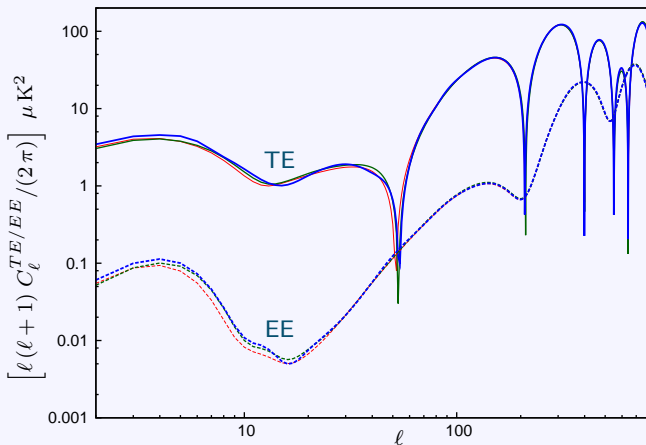
# The $C_\ell^{TT}$ for the best fit models

The power law, the chaotic model with sine modulation, the axion monodromy model



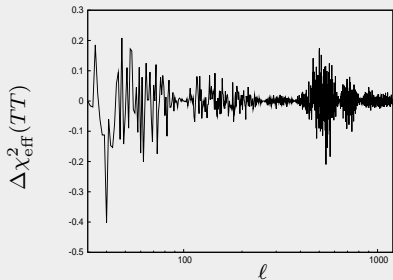
# The $C_\ell^{TE/EE}$ best fit curves: The difference

The power law, the chaotic model with sine modulation, the axion monodromy model

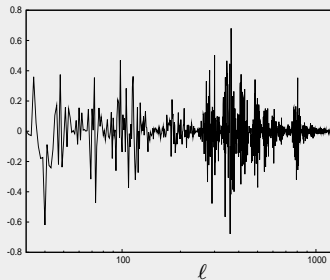


# Improvement in fit as a function of $\ell$ (WMAP-7): TT

Sine model



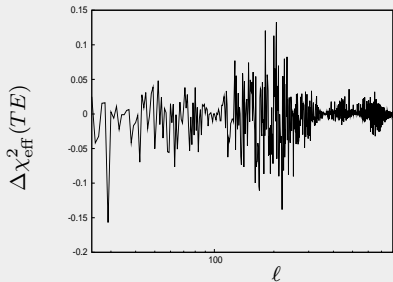
Monodromy model



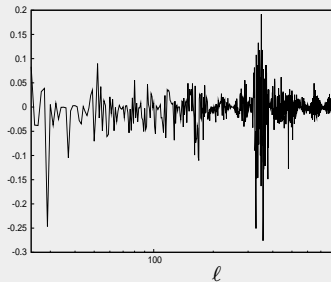
- The difference in the likelihood ( $\Delta\chi_{\text{eff}}^2(TT)$ ) for the sine model is not much both in the low as well as high  $\ell$ 's
- For the monodromy model,  
In the low  $\ell$  ( $\ell < 32$ ) the  $\Delta\chi_{\text{eff}}^2(TT) \simeq 3$   
In the high  $\ell$  ( $\ell > 32$ ) the  $\Delta\chi_{\text{eff}}^2(TT) \simeq 3$

# Improvement in fit as a function of $\ell$ (WMAP-7): TE

Sine model



Monodromy model



- For the sine model we get an overall improvement  $\Delta\chi_{\text{eff}}^2(TE) \simeq 1$
- In the case of monodromy model the improvement at high  $\ell$  ( $\ell > 24$ ) is nearly 3  
But if we consider the low  $\ell$  ( $\ell < 24$ ) then there is no overall improvement from the TE spectrum

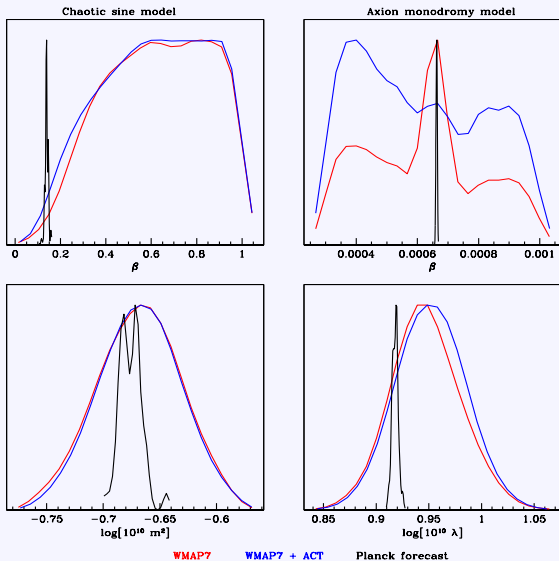
## Forecast for PLANCK

- It is expected that data from current missions such as Planck would be able to constrain the cosmological parameters better
- We have used **FuturCMB**<sup>1</sup> add on with the CosmoMC to arrive at constraints on parameters
- The CMB angular power spectrum generated from the best fit parameters of the models using the WMAP seven year data is treated as the fiducial power spectrum for generating the PLANCK mock data

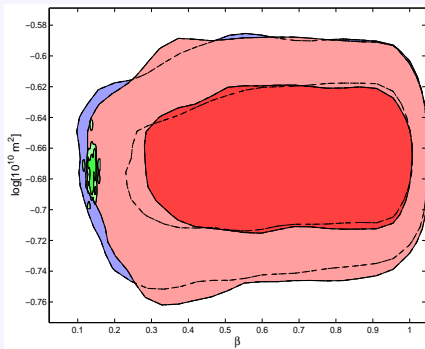
---

<sup>1</sup>Perotto et. al. (2006)

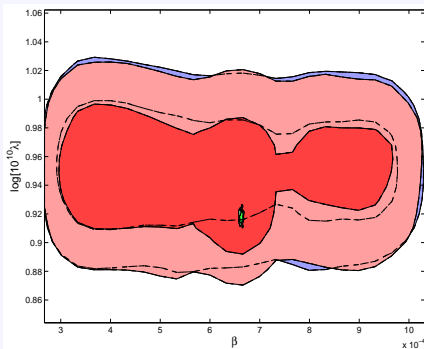
# One dimensional likelihood



# Two dimensional contours



Sine model



Axion monodromy model

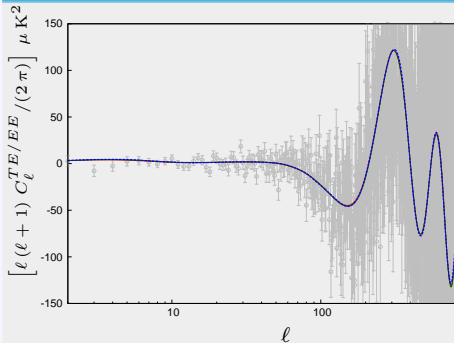
Constraints from **WMAP-7**, **WMAP-7+ ACT**, **PLANCK mock data**

## Summary

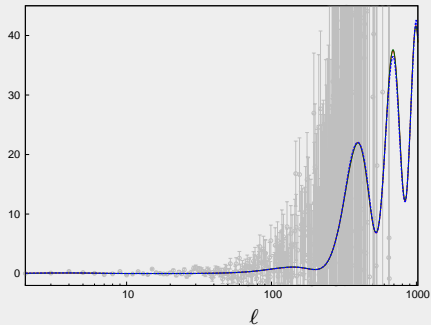
- In this work we have studied the effect of the oscillations in the inflaton potential
- The oscillation creates oscillations in the primordial power spectrum and thereby produces oscillations in the CMB angular power spectrum
- The oscillations fit the CMB data better than the power law primordial power spectrum
- The better fit comes from both the low  $\ell$  and the high  $\ell$  s
- The  $\Delta\chi_{\text{eff}}^2(TT)$  suggests that the monodromy model is in better agreement with the data
- The improvement from the Atacama Cosmology Telescope data tells us that the sine model is more favored in the small scales than the monodromy model
- While the current data is not able to constrain the frequency of the models well enough, our result suggests with the future PLANCK data it will be possible to constrain the frequency
- If PLANCK is unable to see a high tensor to scalar ratio  $r < 0.1$ , the sine model will be discarded along with all the large field models while the monodromy model will perform better than the conventional models

# Extra slides: The $C_\ell^{TE/EE}$ best fit curves with data

TE curves



EE curves



The power law, the chaotic model with sine modulation, the axion  
monodromy model