Inflation with Superstrings?

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arXiv:1701.00577

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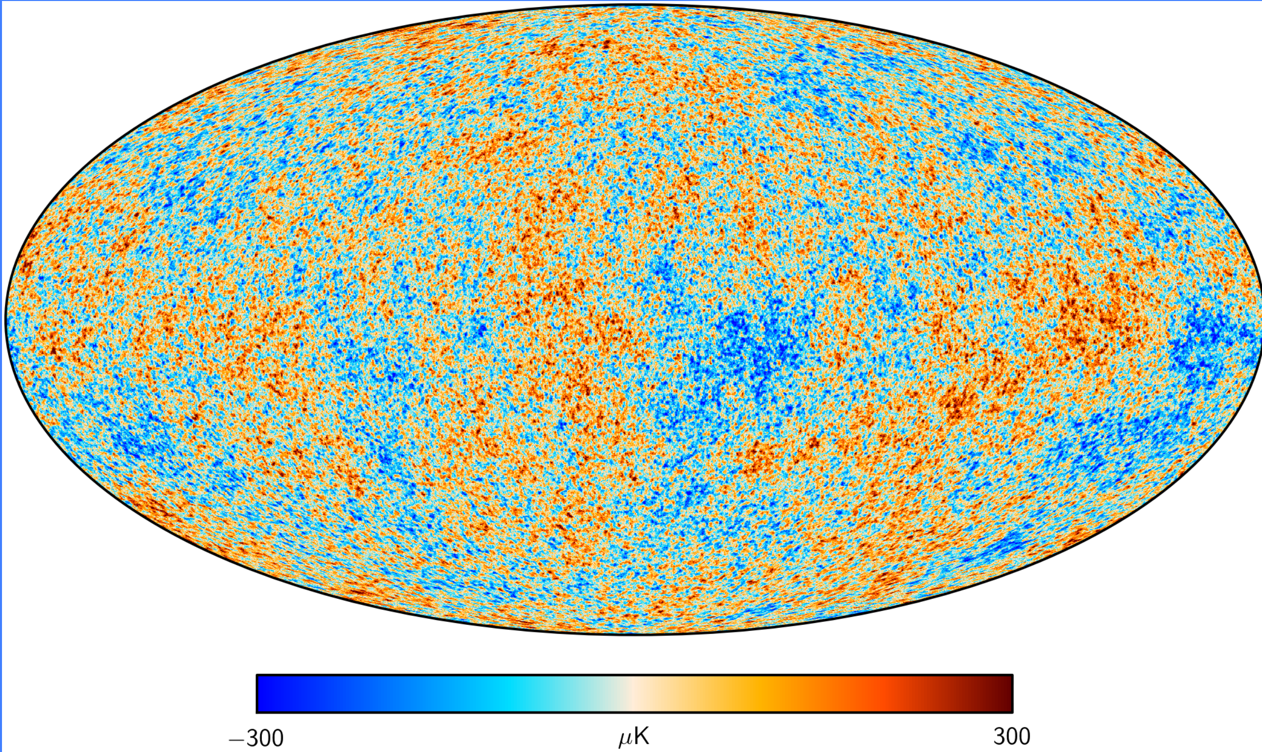
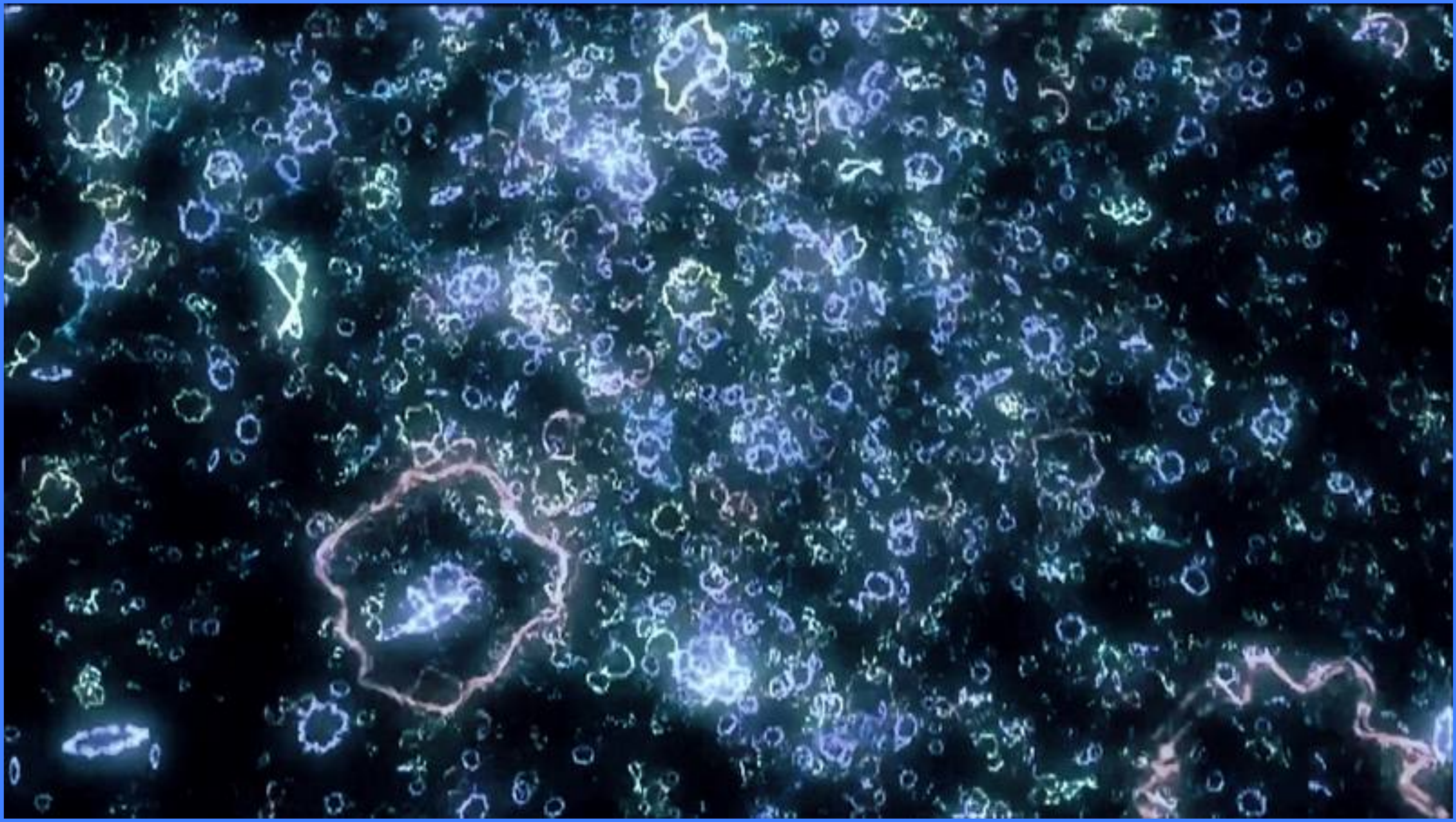
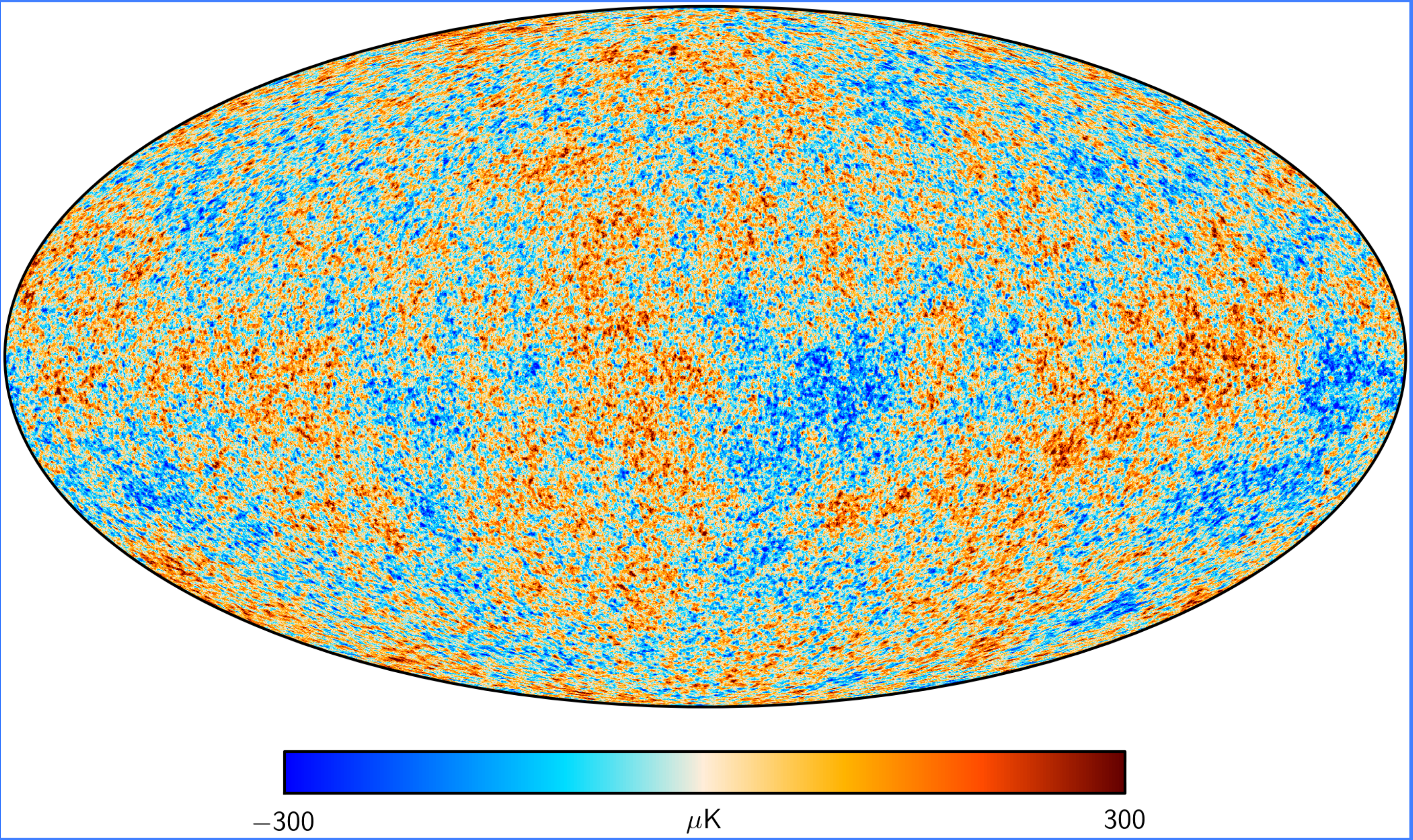


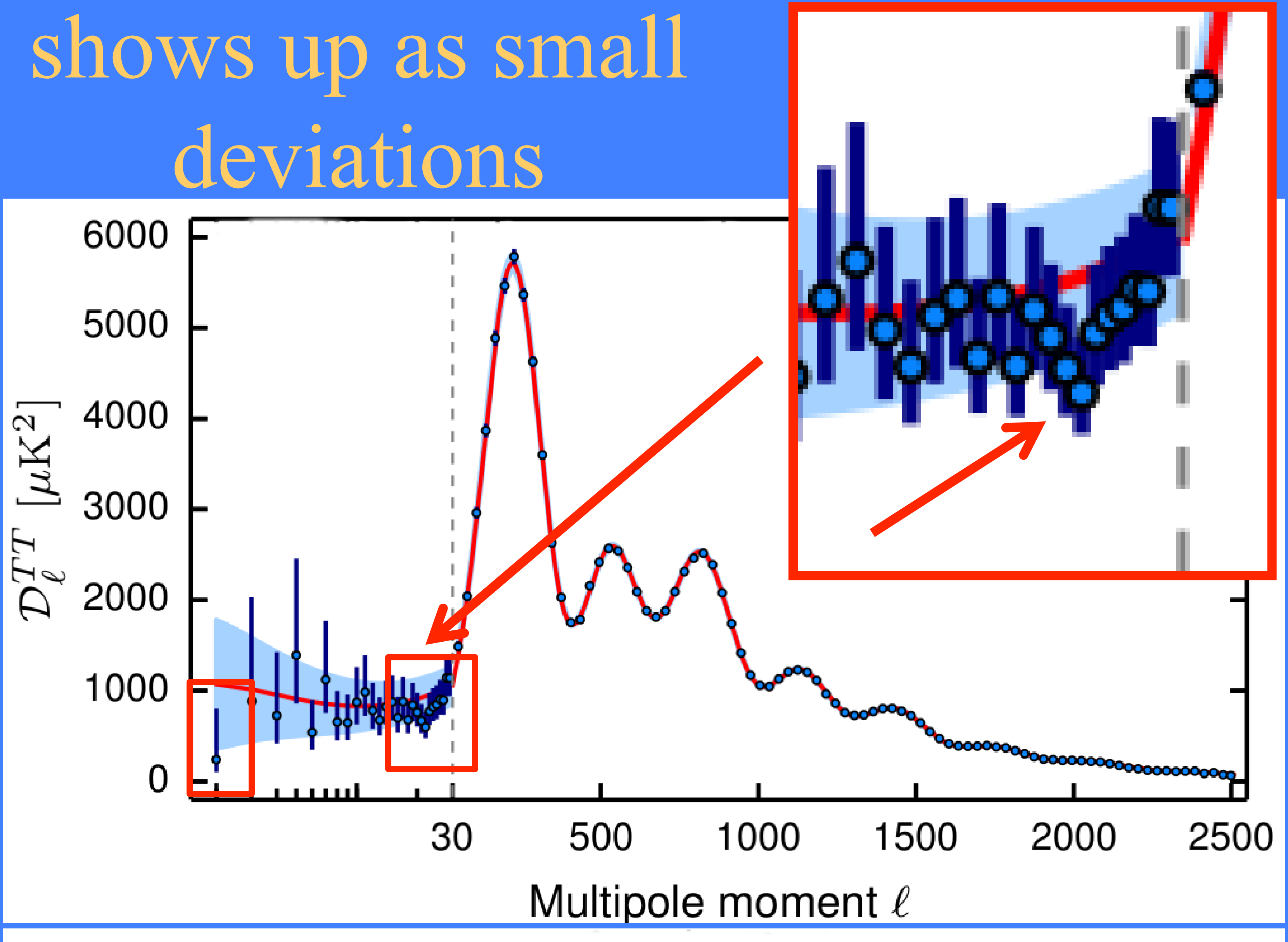
It is natural that the universe is born out of a landscape of superstrings



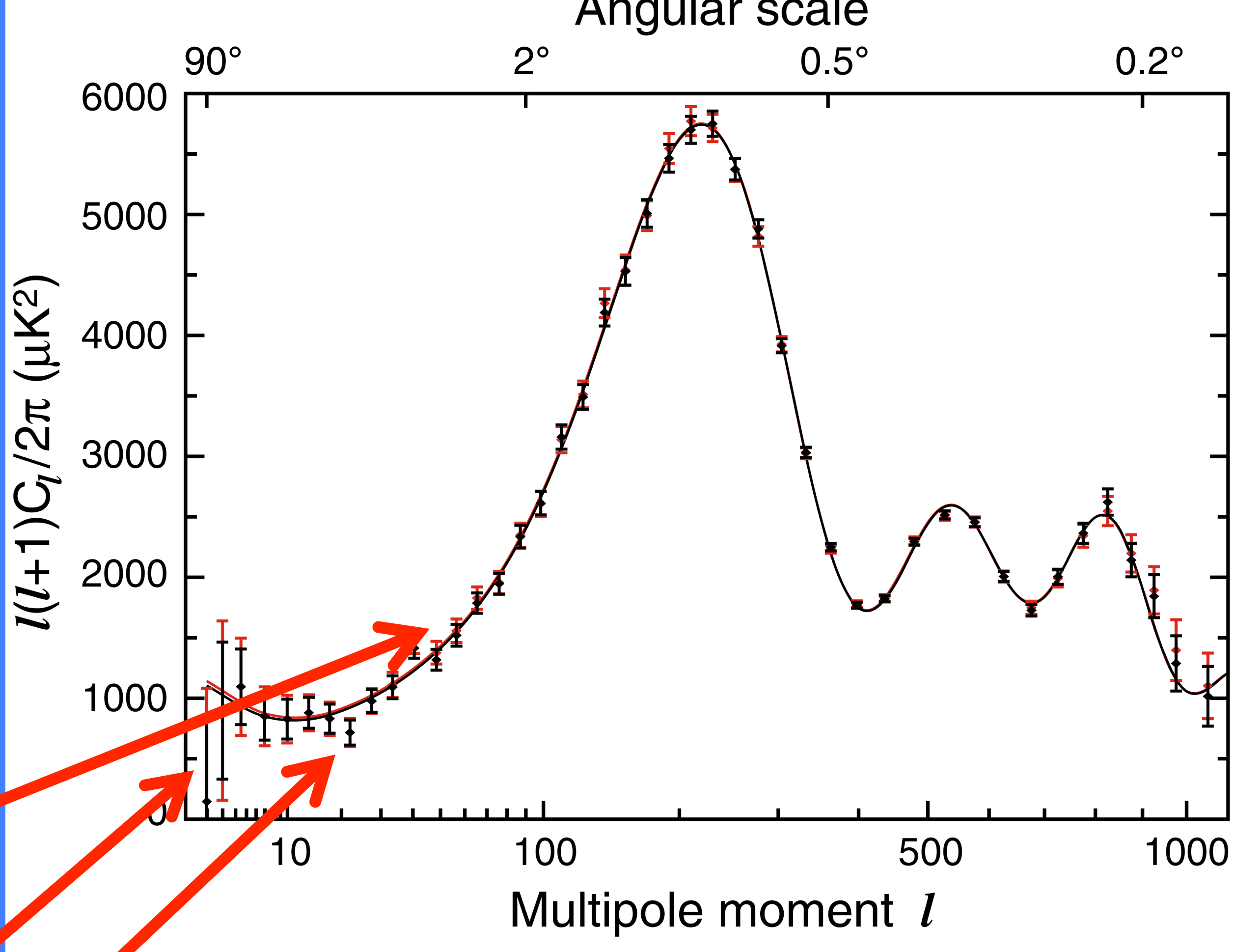
Is there new trans-Plankian physics imprinted on the Cosmic Microwave Background?



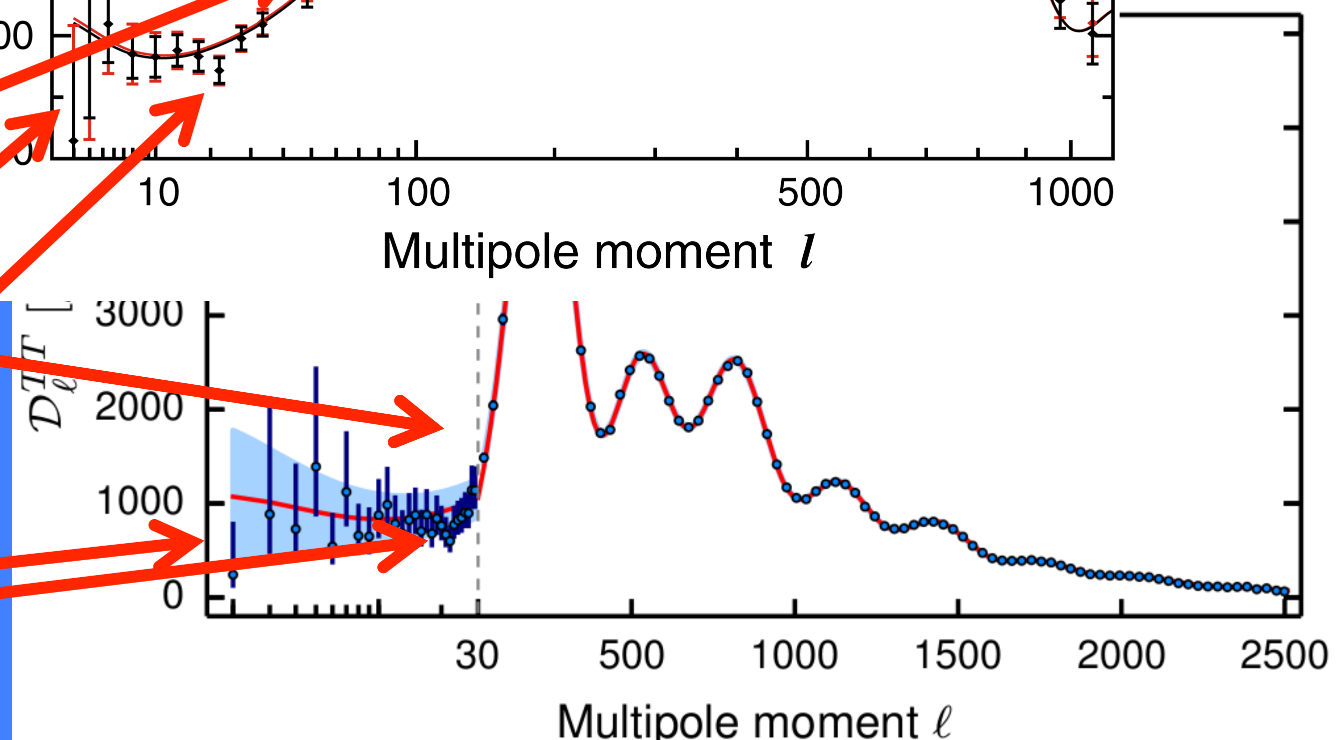
New physics always shows up as small deviations



WMAP 9yr

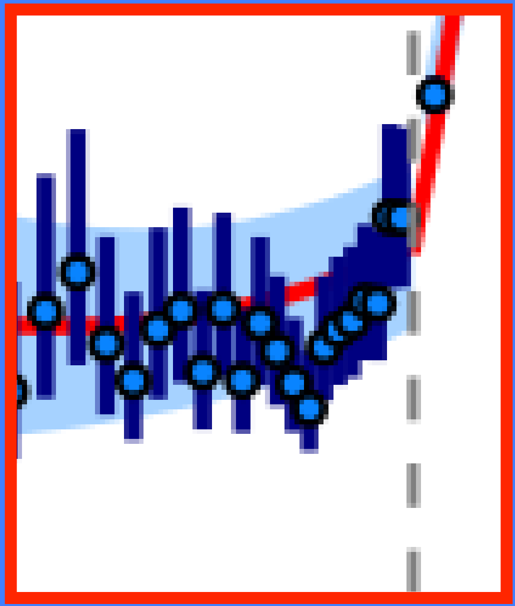


Angular scale
90°
2°
0.5°
0.2°
6000
5000
4000
3000
2000
1000
0
10
100
500
1000
$l(l+1)C_l/2\pi$ (μK^2)
Multipole moment l



$\mathcal{D}_\ell^{TT}$
3000
2000
1000
0
30
500
1000
1500
2000
2500
Multipole moment ℓ

Some possible explanations for dip at $\ell = 20$



- Cosmic Variance: Planck XX arXiv:1502.02114
- Modified inflation effective potential
  - Harza, et al. arXiv:1405.2012,
  - Kitazawa and Sagnotti 1411.6396v2,
  - Yang and Ma arXiv:1501.00282
- ….
- ….
- Planck-mass particles coupled to inflation
  - GJM, M. R. Gangopadhyay, K. Ichiki, and T. Kajino, Phys. Rev. D92, 123519 (2015). arXiv: 1504.06913

How does this work?

D. J. H. Chung, E. W. Kolb, A. Riotto, and I. I. Tkachev, Phys. Rev. D **62**, 043508 (2000).
G. J. Mathews, D. Chung, K. Ichiki, T. Kajino, and M. Orito, Phys. Rev. **D70**, 083505 (2004).

Mathews et al. PRD (2015)

- The total Lagrangian density is given as :

$$\mathcal{L}_{\rm tot} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi) + i\bar{\psi}\not{\partial}_\mu\psi - m\bar{\psi}\psi + N\lambda\phi\bar{\psi}\psi$$

- Then the fermion has the effective mass :

$$M(\phi) = m - N\lambda\phi$$

- This vanishes for a critical value of the inflaton field, $\phi_* = m/N\lambda$

When φ = φ*, resonant particle production occurs

$$n_* = \frac{2}{\pi^2}\int_0^\infty dk_p\, k_p^2\, |\beta_k|^2 = \frac{N\lambda^{3/2}}{2\pi^3}|\dot{\phi}_*|^{3/2}$$

$$|\beta_k|^2 = \exp\left(\frac{-\pi k^2}{a_*^2 N\lambda|\dot{\phi}_*|}\right)$$

$$\langle\bar{\psi}\psi\rangle = n_*\Theta(t-t_*)\exp\left[-3H_*(t-t_*)\right]$$

How does this affect inflation?

- Causes a jump in the evolution of the scalar field

$$
\begin{aligned}
\dot{\phi}(t > t_*) &= \dot{\phi}_* \exp\left[-3H(t - t_*)\right] \\
&- \frac{V'(\phi)_*}{3H_*}\left[1 - \exp\left[-3H(t - t_*)\right]\right] \\
&\boxed{+ \; N\lambda n_*(t - t_*) \exp\left[-3H_*(t - t_*)\right]}
\end{aligned}
$$

Alters the primordial power spectrum

$$\delta_H(a) = \frac{H^2}{5\pi\boxed{\dot{\phi}}}$$

$$C_l = \pi \int_0^\infty \frac{dk}{k} j_l^2\left(\frac{2k}{H_0}\right)\delta_H^2(k)$$

$$\delta_H = \frac{[\delta_H(a)]_{N\lambda=0}}{1 + \boxed{\Theta(a-a_*)(N\lambda n_*/|\dot{\phi}_*|H_*)(a_*/a)^3 \ln(a/a_*)}} \qquad (6)$$

Causes Dip

2 new parameters in fit to CMB

$$\boxed{k_*/k \;=\; a_*/a}$$

$$k_* = \frac{\ell_*}{r_{lss}}$$

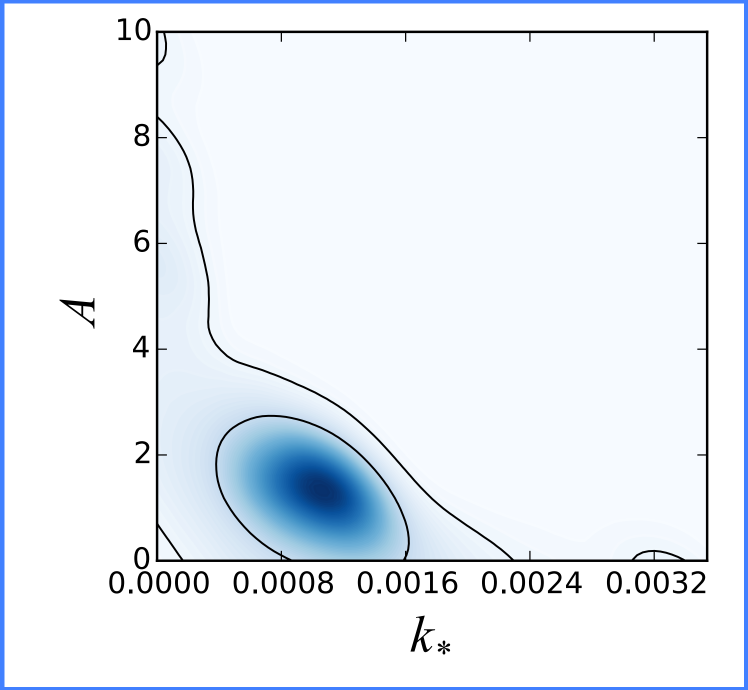
multipole

$$\boxed{A = |\dot{\phi}_*|^{-1} N\lambda n_* H_*^{-1}}$$

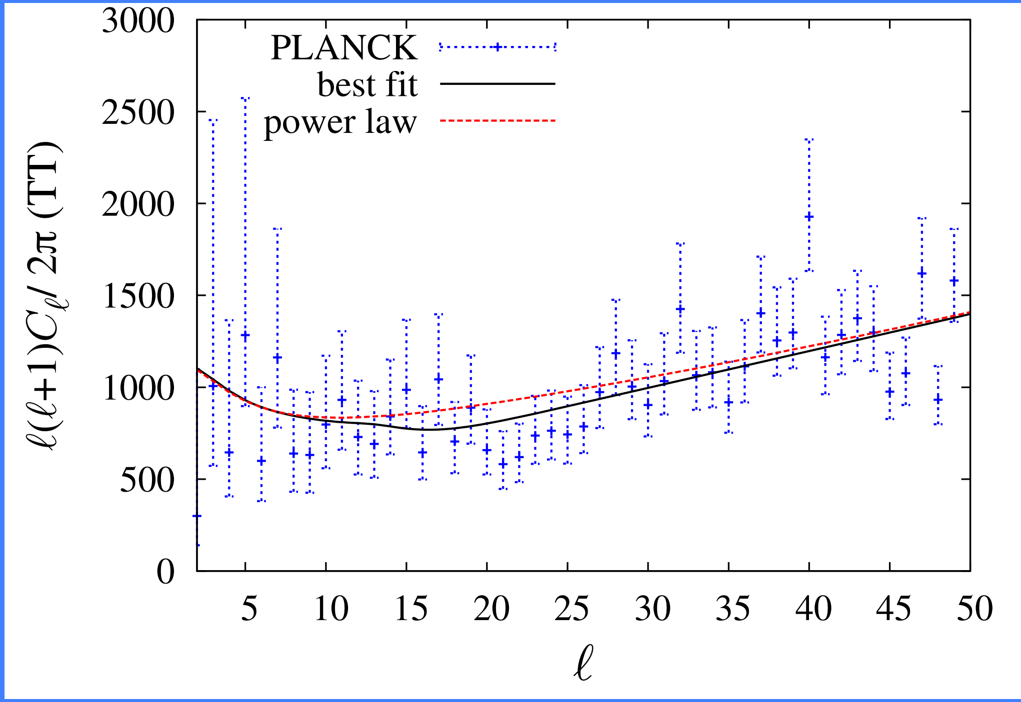
Amplitude

$$\delta_H(k) = \frac{[\delta_H(a)]_{N\lambda=0}}{1 + \Theta(k - k_*) A (k_*/k)^3 \ln{(k/k_*)}}$$

MCMC fit to CMB Power Spectrum



$\ell = 20$



Mathews et al. PRD (2015)

Amplitude, A, relates to the inflaton coupling λ and number N of degenerate Fermions

$$A = |\dot{\phi}_*|^{-1} N \lambda n_* H_*^{-1} \approx \frac{N\lambda^{5/2}}{2\sqrt{5}\pi^{7/2}} \frac{1}{\sqrt{\delta_H(k_*)|_{\lambda=0}}}$$

$$A \sim 1.3 N \lambda^{5/2}$$ COBE Normalization

$$\lambda \approx \frac{(1.0 \pm 0.5)}{N^{2/5}}$$

k_* relates to the fermion mass m for a given inflation model:

$$m = N\lambda\phi_* \Rightarrow \boxed{m \approx \phi_*/\lambda^{3/2}}$$

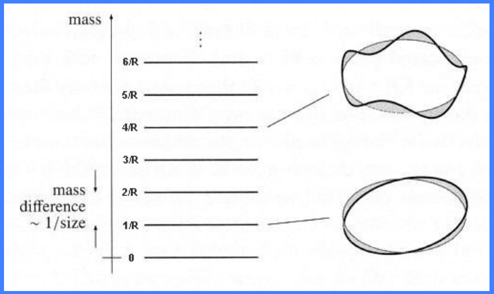
$$V(\phi) = \Lambda_\phi m_{pl}^4 \left(\frac{\phi}{m_{pl}}\right)^\alpha \qquad \phi_* = \sqrt{2\alpha\mathcal{N}_*}m_{pl}$$

$$m = N\lambda\sqrt{2\alpha}\sqrt{\mathcal{N} - \ln\left(k_*/k_H\right)}$$

$$\alpha = 2/3 \Rightarrow m \sim (8 - 11)\,\frac{m_{\rm pl}}{\lambda^{3/2}}$$

Suppose this particle is a Superstring: How could you know?

- There should be similar resonant couplings corresponding to different excitations of the same string.



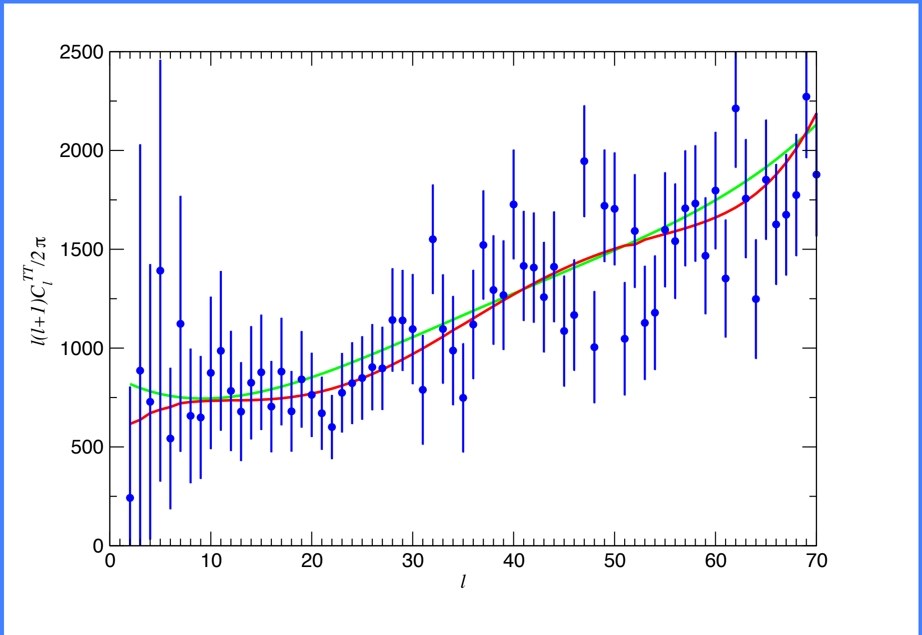
- Could this be the ℓ =2 suppression or more?

Resonant Superstring Excitations during Inflation

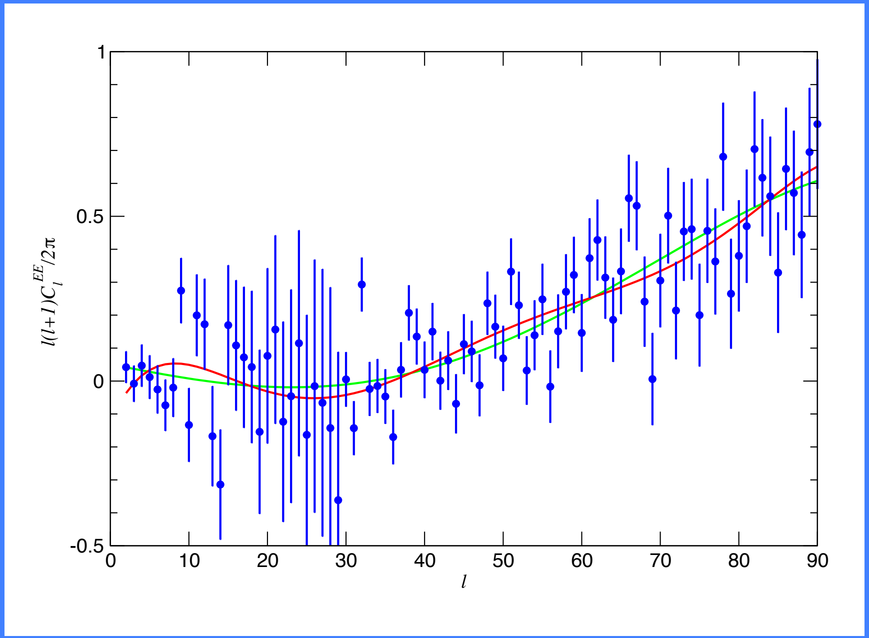
G. J. Mathews[1,2], M. R. Gangopadhyay[1], K. Ichiki[3], T. Kajino[2,4,5]

arXiv:1701.00577

TT



EE



$$\ell \approx 2,\ \ A = 1.7 \pm 1.5,\ \ k_*(n+1) = 0.0004 \pm 0.0003\ h\ \mathrm{Mpc}^{-1}$$

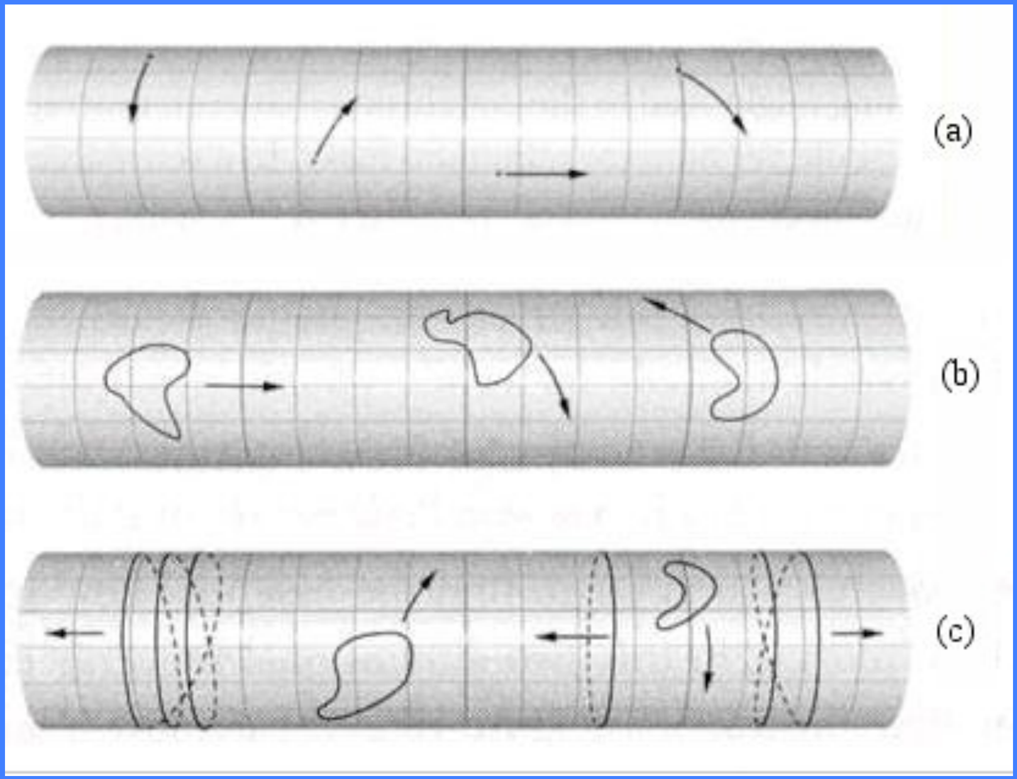
$$\ell \approx 20,\ \ A = 1.7 \pm 1.5,\ \ k_*(n) = 0.0015 \pm 0.0005\ h\ \mathrm{Mpc}^{-1}$$

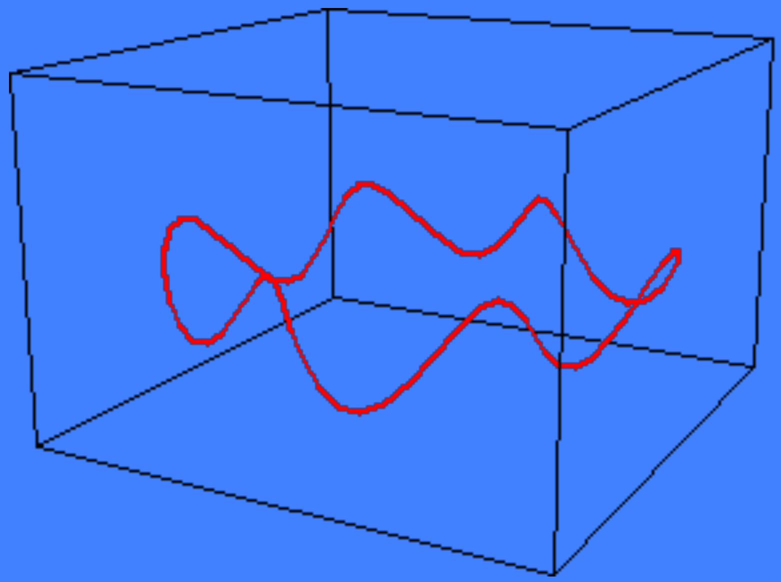
$$\ell \approx 60,\ \ A = 1.7 \pm 1.5,\ \ k_*(n-1) = 0.005 \pm 0.004\ h\ \mathrm{Mpc}^{-1}$$

MCMC fit to multiple dips in the CMB power spectrum

Gangopadhyay, Mathews, Ichiki, Kajino arXiv:1701.00577

Do these states look like Excitation modes of a superstring?





1. Momentum states in the compact dimension
2. Oscillations
3. Winding around the compact dimensions

A simple example:
D=26 Bosonic closed string with 1 dimension compacted in a circle of radius R

$$M^2 = \frac{n^2}{R^2} + \frac{w^2 R^2}{\alpha'^2} + \frac{2}{\alpha'}(N + \tilde{N} + 2)$$

Oscillations

Momentum States

Winding Potential Energy

$$N = \sum(\alpha^{\mu}_{-n}\alpha_{n\mu} + \alpha_{-n}\alpha_n)$$

$$\tilde{N} = \sum(-\tilde{\alpha}^{\mu}_{-n}\tilde{\alpha}_{n\mu} + \tilde{\alpha}_{-n}\tilde{\alpha}_n)$$

$$N - \tilde{N} + nw = 0$$

Special Cases:

$$M^2 \approx \left(\frac{N_{osc} + \xi}{\alpha'}\right) \quad , \quad \text{Case I.}$$

only oscillations

$$\xi \equiv \alpha' \left(\frac{n}{R}\right)^2 \quad .$$

$$M^2 \approx \left(\frac{n^2 + \xi}{R^2}\right) \quad , \quad \text{Case II.}$$

Only momentum or winding states

$$\xi = \frac{2R^2}{\alpha'}(N + \tilde{N} - 2)$$

Can fix the ratio of mass states

$$\frac{M^2(\ell^* = 2)}{M^2(\ell^* = 20)} \equiv \mathcal{R}_{+1} \approx \frac{\mathcal{N} - \ln\left(k_*(n+1)/k_H\right)}{\mathcal{N} - \ln\left(k_*(n)/k_H\right)}$$

$$\frac{M^2(\ell^*=2)}{M^2(\ell=20)} \equiv \mathcal{R}_{+1} = 1.024 \pm 0.050.$$

$$\frac{M^2(\ell^* = 20)}{M^2(\ell^* = 60)} \equiv \mathcal{R}_{-1} \approx \frac{\mathcal{N} - \ln\left(k_*(n)/k_H\right)}{\mathcal{N} - \ln\left(k_*(n-1)/k_H\right)}$$

$$\frac{M^2(\ell^*=20)}{M^2(\ell=60)} \equiv \mathcal{R}_{-1} = 1.024 \pm 0.030.$$

Case of simple oscillations

$$\frac{M^2(\ell^* = 2)}{M^2(\ell^* = 20)} \equiv \mathcal{R}_{+1} \approx \frac{\mathcal{N} - \ln\left(k_*(n+1)/k_H\right)}{\mathcal{N} - \ln\left(k_*(n)/k_H\right)}$$

$$\mathcal{R}_{+1} = \frac{(N_{osc}+1)}{N_{osc}}$$

$$N_{osc} = \frac{1}{\mathcal{R}_{+1} - 1}$$

=> $N_{osc} = 42^{+\infty}_{-28}$

Physical properties of the Superstring

$$\lambda \approx \frac{(1.0 \pm 0.5)}{N^{2/5}} \; .$$

Coupling Constant is Small because N is large

$$m \sim (8 - 11)\; \frac{m_{\rm pl}}{\lambda^{3/2}}$$

Very large

$$N_{osc} = 42^{+\infty}_{-28}$$

Very uncertain

Conclusions

- Marginal evidence of sequential dips in the CMB power spectrum
- These could be caused by resonant coupling to successive excitations of a superstring during inflation.
- The regular spacing and constant amplitude of the dips is consistent with mass eigenstates corresponding to successive oscillations or momentum states of a single closed superstring.
- Uncertainties are too large to make definitive conclusion