Deviations from QCD, strings, inflation, and extra dimensions …in the CMB and big bang nucleosynthesis

Grant Mathews - UND

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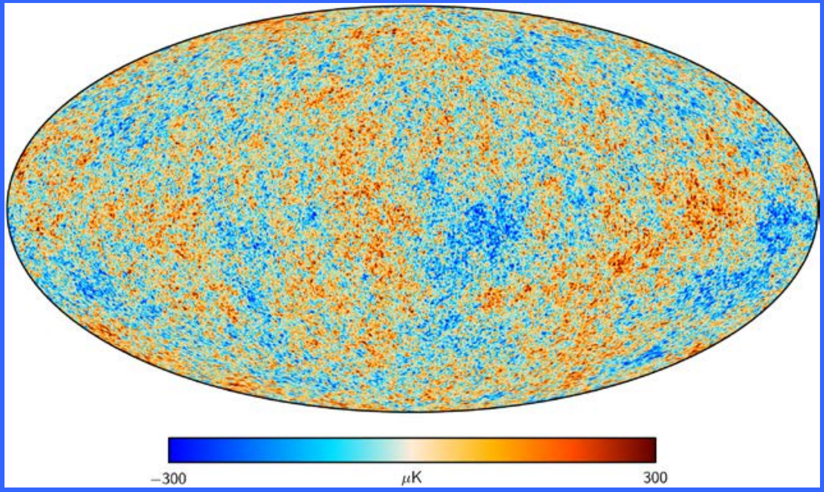
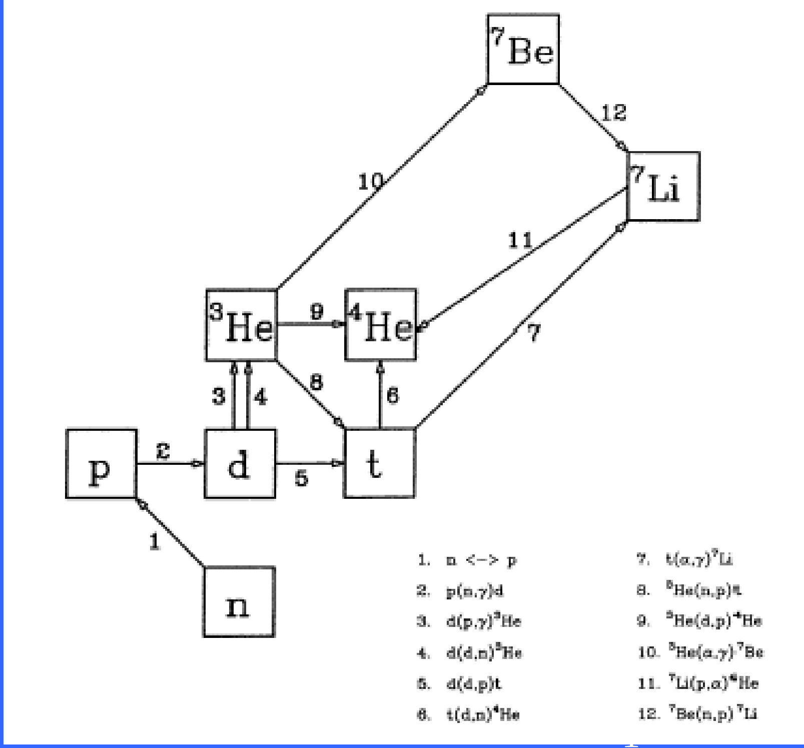
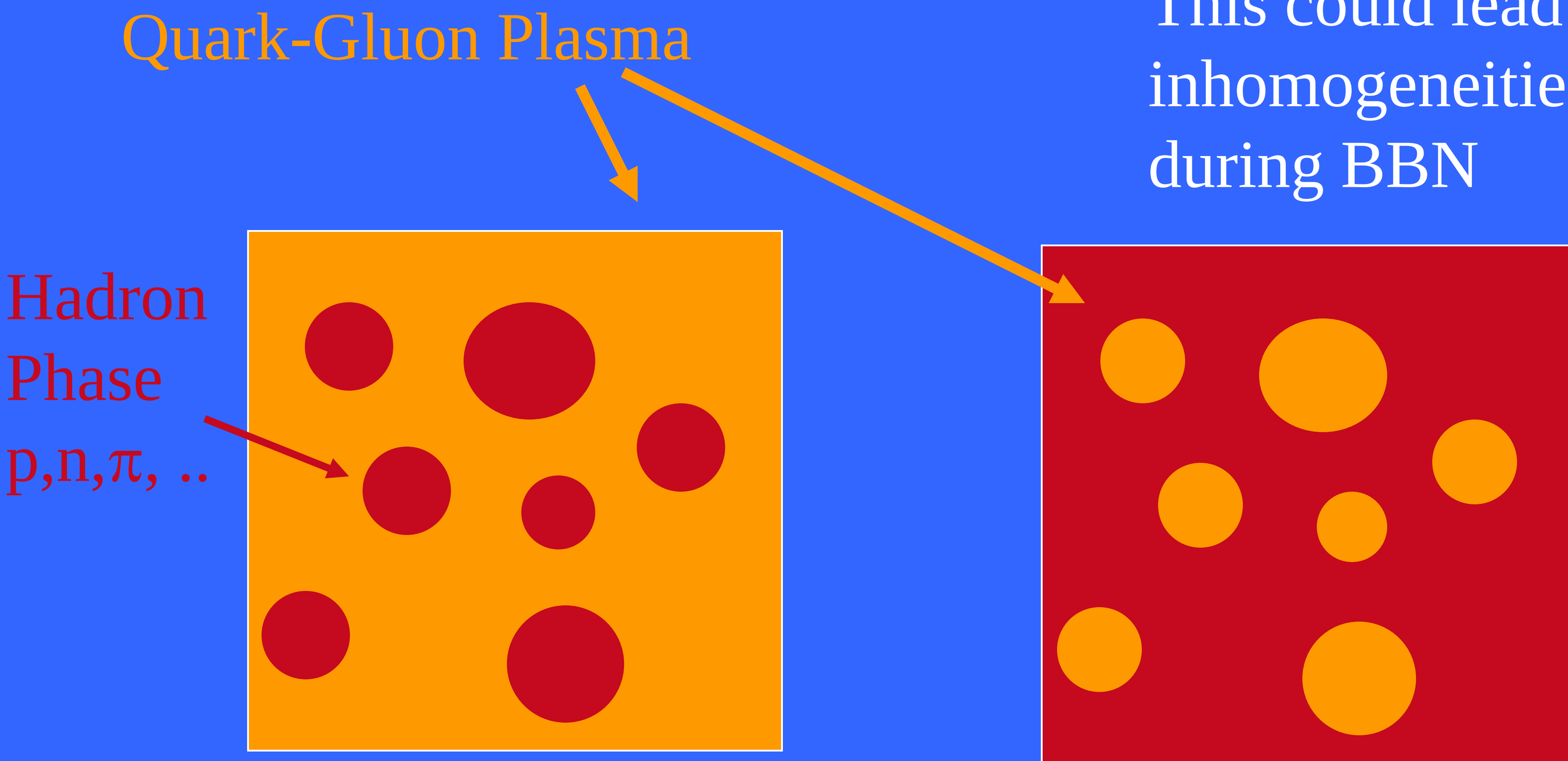




Big Bang Nucleosynthesis and the Cosmic Quarks-Hadron Phase Transiton

This could lead to inhomogeneities during BBN



THE QUARK-HADRON PHASE TRANSITION AND PRIMORDIAL NUCLEOSYNTHESIS

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ABSTRACT

An examination and a brief review are made of the effects of quark-hadron transition induced fluctuations on big bang nucleosynthesis. It is shown that cosmologically critical densities in baryons are difficult to reconcile with observation, but the traditional baryon density constraints from homogenous calculations might be loosened by as much as 50%, to 0.3 of critical density, and the limit on the number of neutrino flavors remains about $N_\nu \lesssim 4$. To achieve baryon densities $\gtrsim 0.3$ of critical density would require initial density contrasts $R \gg 10^3$, whereas the simplest models for the transition seem to restrict R to $\lesssim 10^2$.

Subject headings: elementary particles — nucleosynthesis

The possibility that effects due to the confinement of quarks in the early universe could create significant changes (Applegate, Hogan, and Scherrer 1987; Alcock, Fuller, and Mathews 1987) in the standard homogeneous big bang nucleosynthesis results (Yang *et al.* 1984; Boesgaard and Steigman 1985) has received a great deal of recent attention. In the standard homogeneous-isotropic big bang nucleosynthesis calcu-

abundances, particularly ^{7}Li and ^{4}He. The persistence of t nucleosynthesis conclusions despite the addition of new initi conditions with several additional parameters shows t robustness of big bang nucleosynthesis.

Traditional big bang nucleosynthesis had become one of t cornerstones of big bang cosmology because of its remarkab agreement with light-element abundance observations, spa

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The dynamics model and the k baryon number nucleosynthesis, a the universe whic the cooling due t temperature, and phase. We calcul baryon number c equilibrium is no small. In the extr we even find that of the primordial tuations in a uni constraints for a for an $\Omega = 1$ uni fract

Subj

I. INTRODUCTION

A transition from quark-gluon plasma to confined hadronic matter must have occurred at some point in the evolution of the early Universe. There may be a first-order phase transition at this epoch associated with either the color-confinement transition[1] or the chiral-symmetry-breaking transition.[2] Even a simple model of deconfined quark-gluon plasma with asymptotic freedom shows that if the Universe were ever at a temperature in excess of ~100 MeV then a color-deconfined plasma should be the most stable phase. For this reason alone, it is certainly of interest to explore whether there might be a relic signature of the quark-hadron transition in primordial light-element abundances or elsewhere. The purpose of this paper is to address these issues.

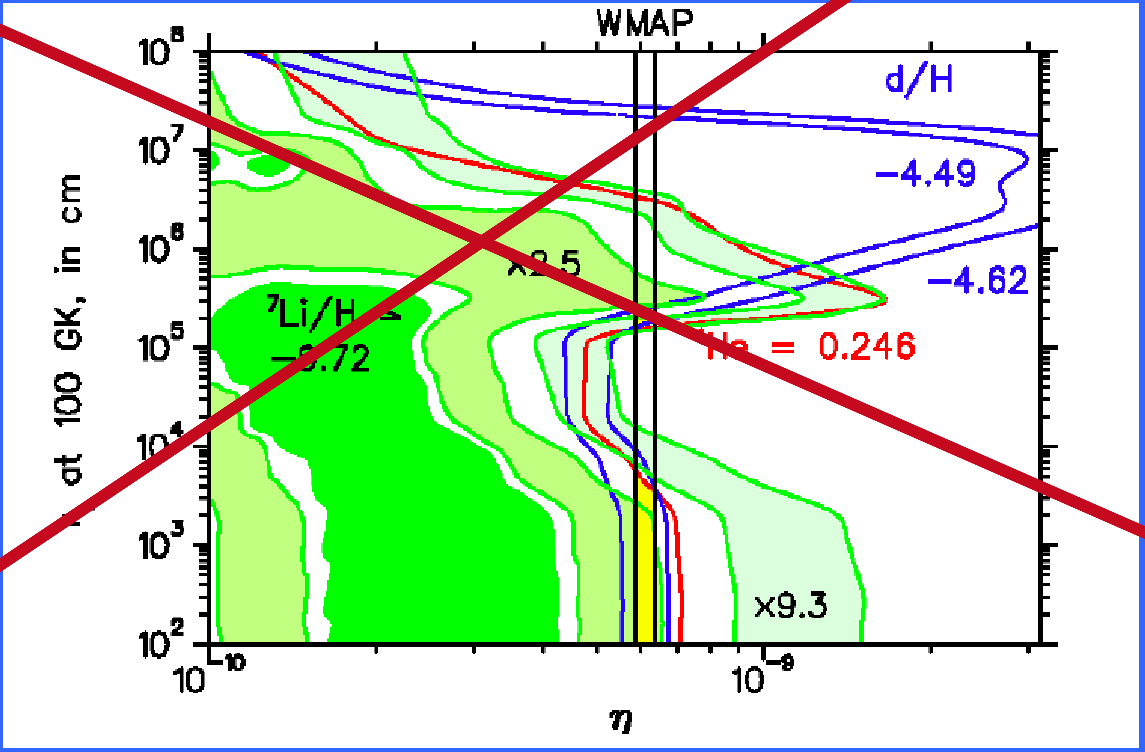
There have been several recent papers[3–5] based on the

that the nucleation rate does not become large until the temperature has dropped below the coexistence temperature.[8] In other words, supercooling occurs until the probability to nucleate bubbles of hadronic phase is high.

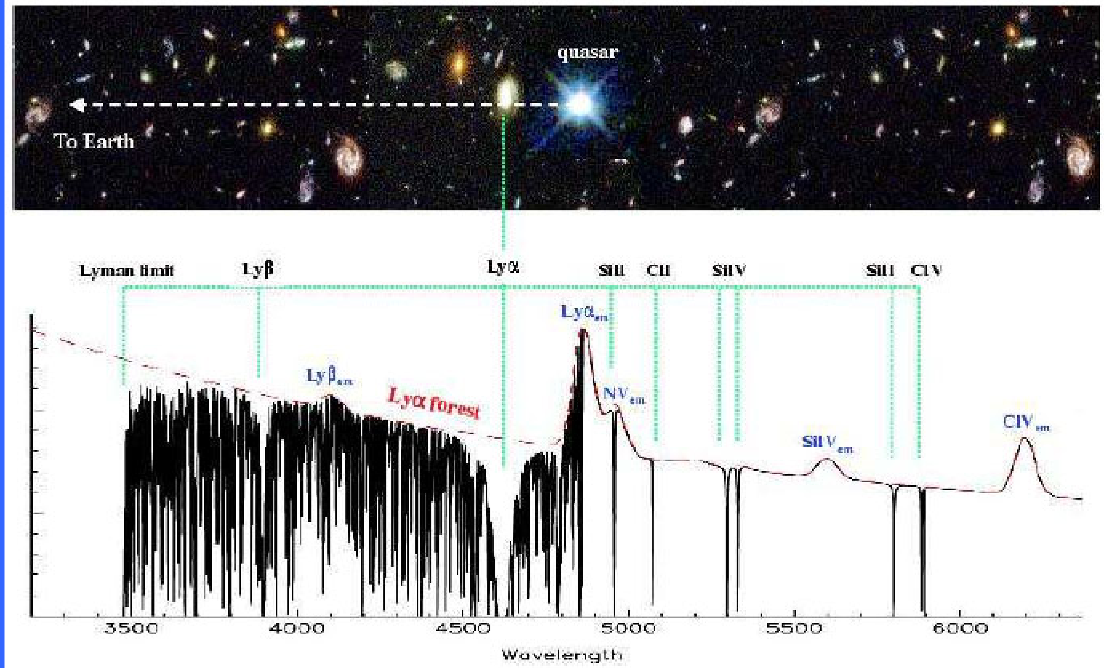
Once the first generation of nucleated bubbles of hadron phase appears, the release of latent heat from the QCD vacuum energy reheats the Universe to T_c, so that further nucleation of hadronic phase is inhibited. The quark-gluon plasma phase and the confined, hadronic phase now coexist in pressure equilibrium. As the Universe expands the temperature is held at T_c by the liberation of latent heat as the confined phase grows at the expense of the unconfined phase. This nearly isothermal evolution may continue until all of the Universe has been converted to confined phase. This scenario has been discussed in some detail by Kajantie and Kurki-Suonio.[9]

We will show that isothermal baryon density fluctuations could arise during this cosmic separation of phases

There is no evidence of the cosmic QCD transition in BBN

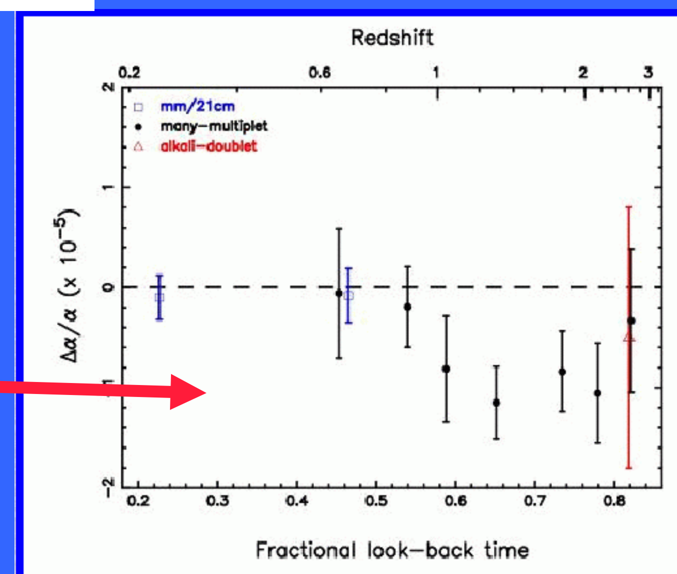


Lara, Kajino, Mathews, PRD (2006)



Another Deviation:

Webb et al, 1999,2011
Murphy et al. 2001, 2003
Kenekar et al. (2010)
Ewan et al. 2012
King et al. 2012



Time Varying electromagnetism?

$$\alpha = e^2/(2\varepsilon_o hc)$$

$$(\Delta\alpha/\alpha) = (-3.1 \pm 1.2) \times 10^{-6}$$

The Caipirinha Paper

PRL, 92, 041102 (2004)

astro-ph/0309197, UMN–TH–2213/03, FTPI–MINN–03/24

The Chemical Evolution of Mg Isotopes vs. the Time Variation of the Fine Structure Constant

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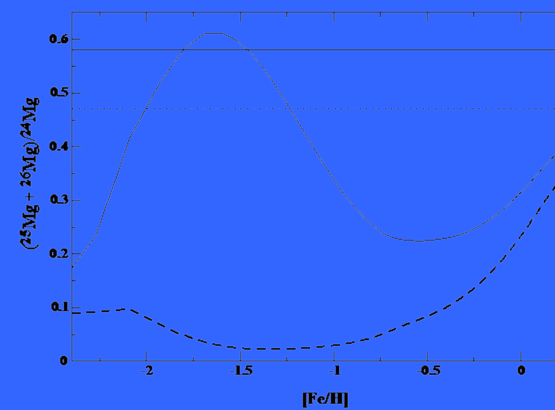
The many-multiplet method applied to high redshift quasar absorption spectra has indicated a possible time variation of the fine structure constant. Alternatively, a constant value of α is consistent with the observational analysis if a non-solar isotopic ratio of ^{24,25,26}Mg occurs at high redshift. In particular, a higher abundance of the heavier isotopes ^{25,26}Mg are required to explain the observed multiplet splitting. We show that the synthesis of ^{25,26}Mg at the base of the convective envelope in low-metallicity asymptotic giant branch stars, combined with a simple model of galactic chemical evolution, can produce the required isotopic ratios and is supported by recent observations of high abundances of the neutron-rich Mg isotopes in metal-poor globular-cluster stars. We conclude that the present data based on high redshift quasar absorption spectra may be providing interesting information on the nucleosynthetic history of such systems, rather than a time variation of fundamental constants.



$$\frac{d\sigma_i}{dt} = \int_{0.8}^{40} B(t-\tau(m))\Psi(m)X_i^{S}(t-\tau(m))dm$$
$$+ \int_{2.5}^{9.0} B(t-\tau(m))\Psi(m)X_i^{AGB}(t-\tau(m))dm$$
$$+ m_{CO}X_i^{Ia}R_{Ia} - B(t)\frac{\sigma_i}{\sigma_{gas}} + \dot{\sigma}_{i,gas},$$

Is there other evidence deviation of fundamental constants change with time?

Higgs <v>

$$\alpha = \frac{e^2}{\hbar c} \qquad \alpha_s(r) \sim \mathrm{const}/\ln\left(\frac{\Lambda_{QCD}\, r}{\hbar c}\right)$$

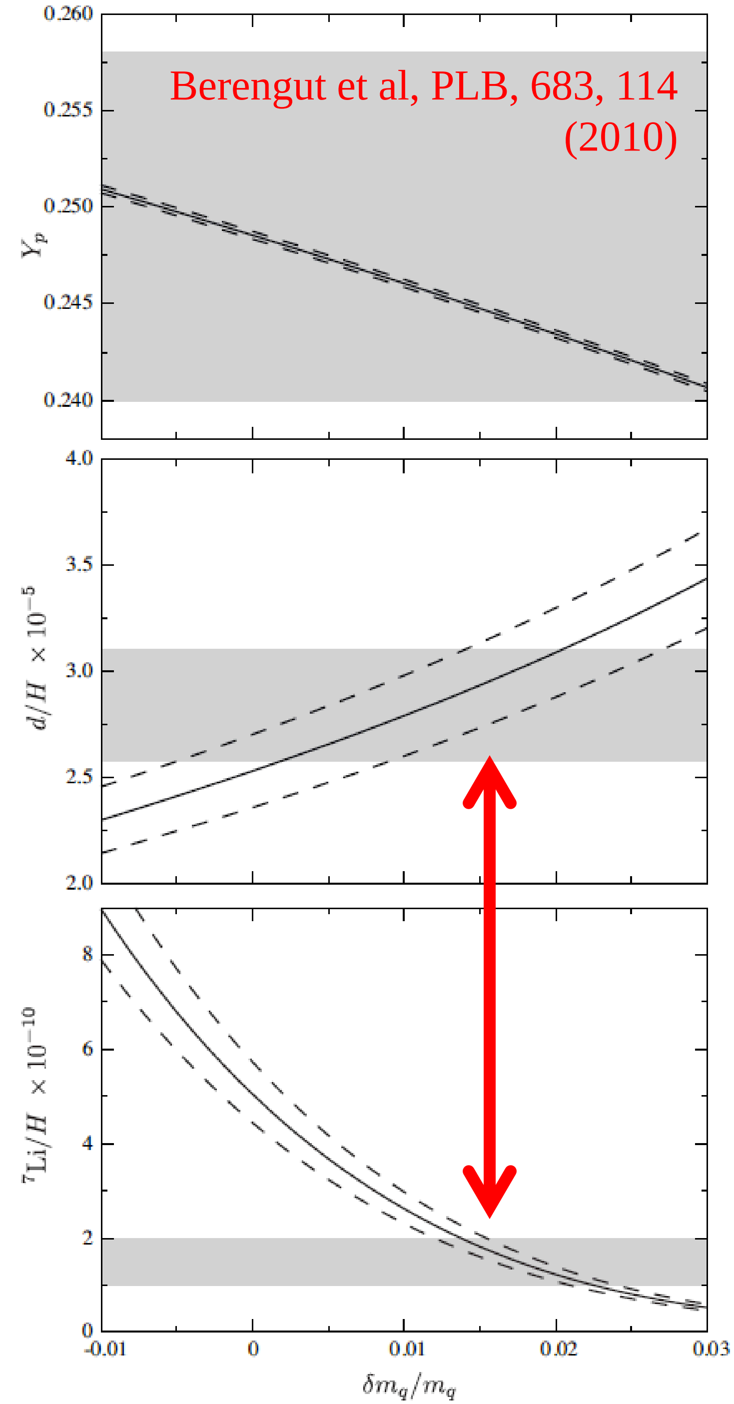
Changes in αs <v> affect mq and ΛQCD

$$\boxed{X_q = \frac{m_q}{\Lambda_{QCD}} \quad , \quad m_q \equiv (m_u + m_d)/2}$$

Limits to time varying quark masses

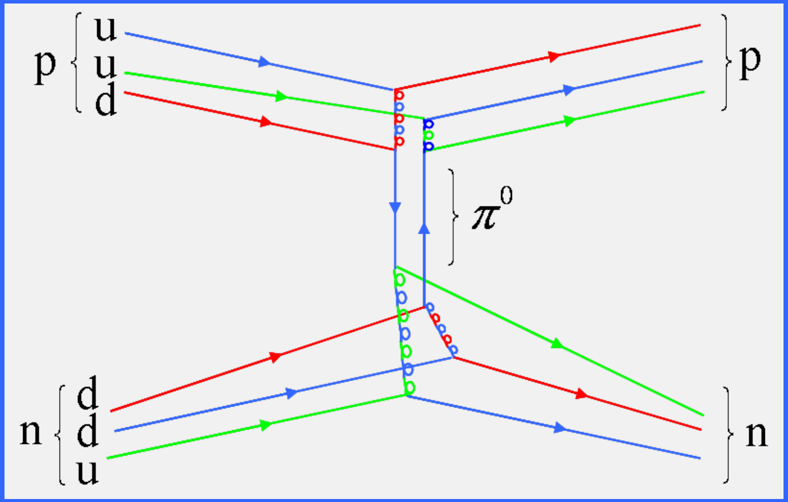
- BBN=> quark masses were heavier in the early universe?
- $\delta m_q/m_q = 0.016 \pm 0.005$?

M-K. Cheoun, T. Kajino, M. Kusakabe, G. J.M., PRD, 84, 043001 (2011).



Effects of varying quark mass on Nuclear Physics/BBN

$$\delta m_q / m_q \equiv \delta X_q / X_q$$



$$\begin{aligned}
V_{\mathrm{NN}} &= V_{\mathrm{NN}}^{(0)} + V_{\mathrm{NN}}^{(2)} + V_{\mathrm{NN}}^{(4)} + \ldots, \\
V_{1\pi} &= V_{1\pi}^{(0)} + V_{1\pi}^{(2)} + V_{1\pi}^{(3)} + V_{1\pi}^{(4)} + \ldots, \\
V_{2\pi} &= V_{2\pi}^{(2)} + V_{2\pi}^{(3)} + V_{2\pi}^{(4)} + \ldots, \\
V_{3\pi} &= V_{3\pi}^{(4)} + \ldots.
\end{aligned}$$

$\Rightarrow$Changes in hadron masses

$\Rightarrow$ Changes pion exchange potentials

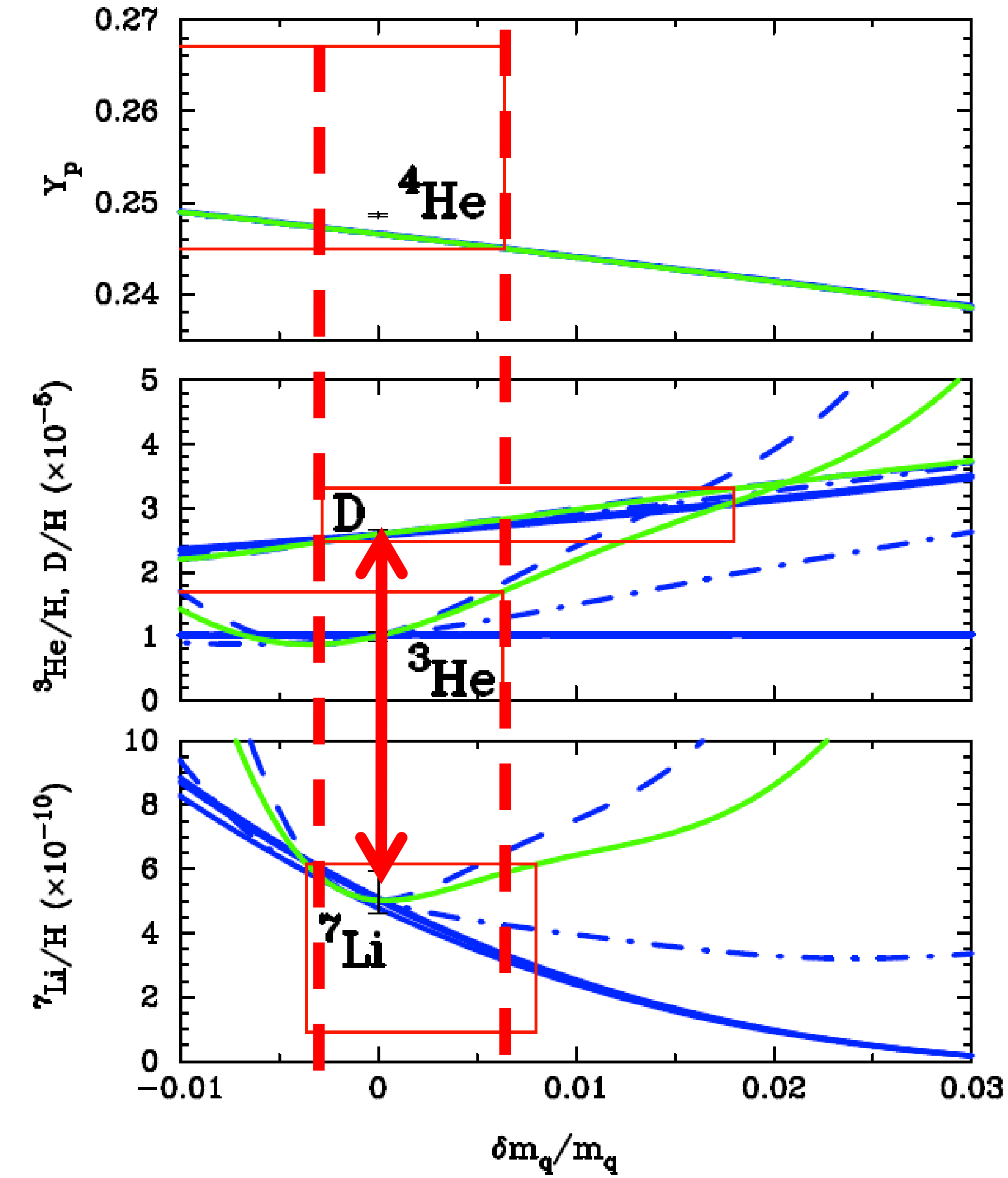
$\Rightarrow$Changes many-body Hamiltonian

$\Rightarrow$Changes Binding Energies/Q-values

$\Rightarrow$Changes in Reaction Rates

- Analysis:
- Cheoun, Kajino Kusakabe, G JM, PRD, 84, 043001 (2011).
- *$-0.005 < \delta mq/mq < 0.007$*

Consistent with no variation



Is there a deviation in BBN due to the existence of extra dimensions in BBN?

Randall & Sundrum (1999)

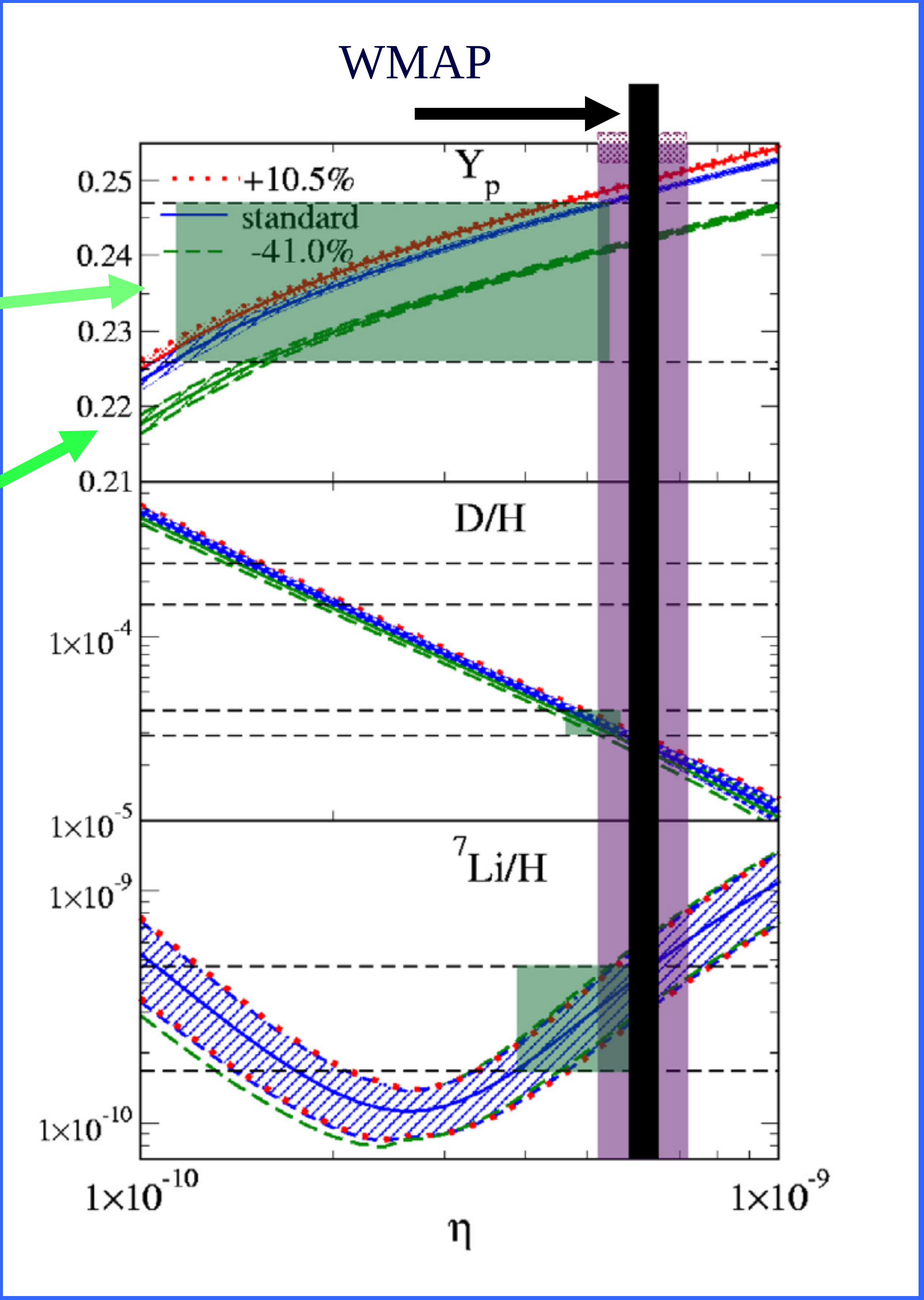
$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G_{\rm N}}{3}\rho - \frac{K}{a^2} + \frac{\Lambda_4}{3} + \frac{\kappa_5^4}{36}\rho^2 + \boxed{\frac{\mu}{a^4}}$$

Dark Radiation

K. Ichiki, M. Yahiro, T. Kajino, M. Orito, G. J. Mathews PRD 66, 043521 (2002)

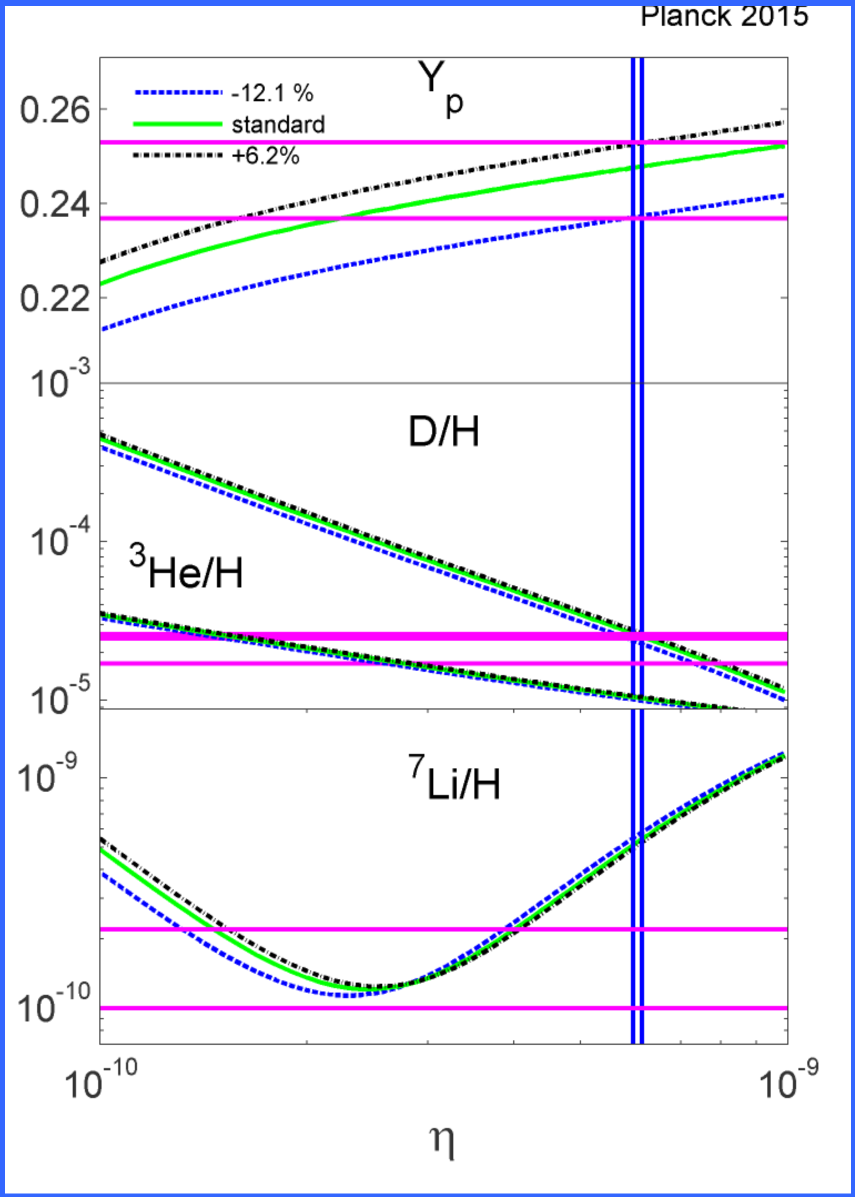
Standard BBN

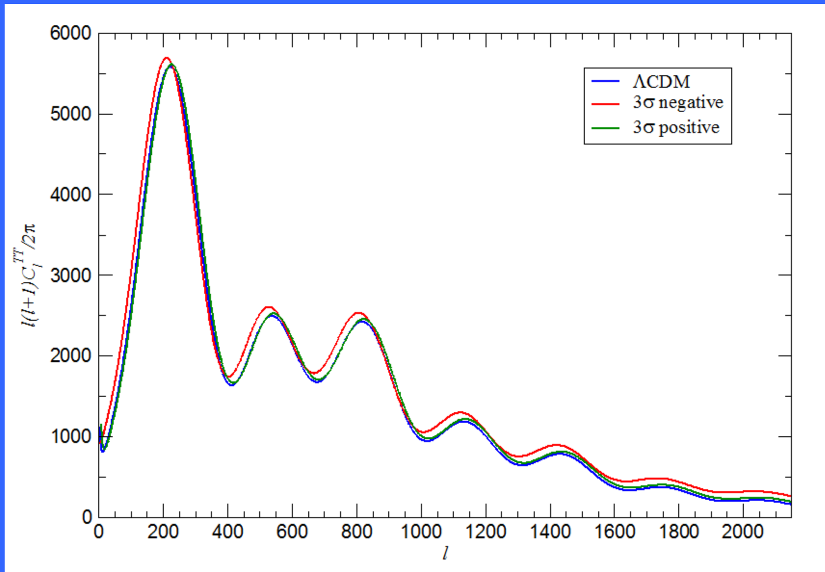
Dark Radiation decreases ^{4}He
Is constrained to be positive
by High Yp

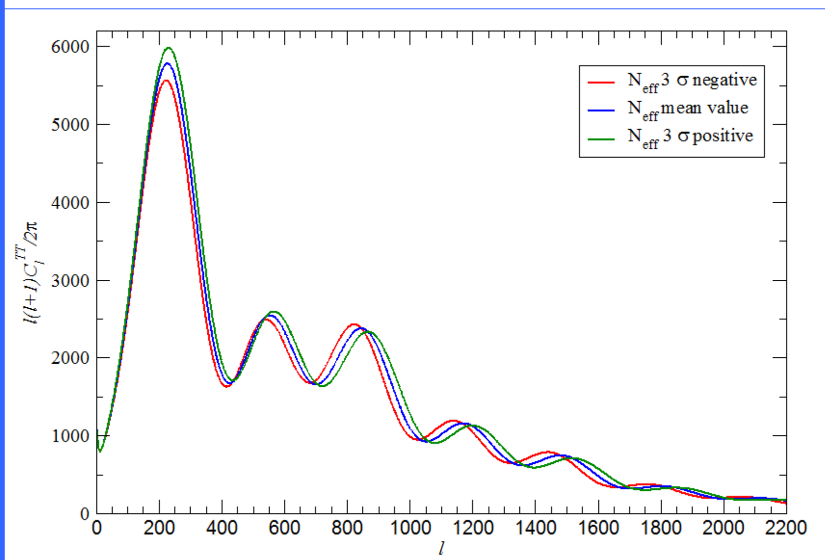


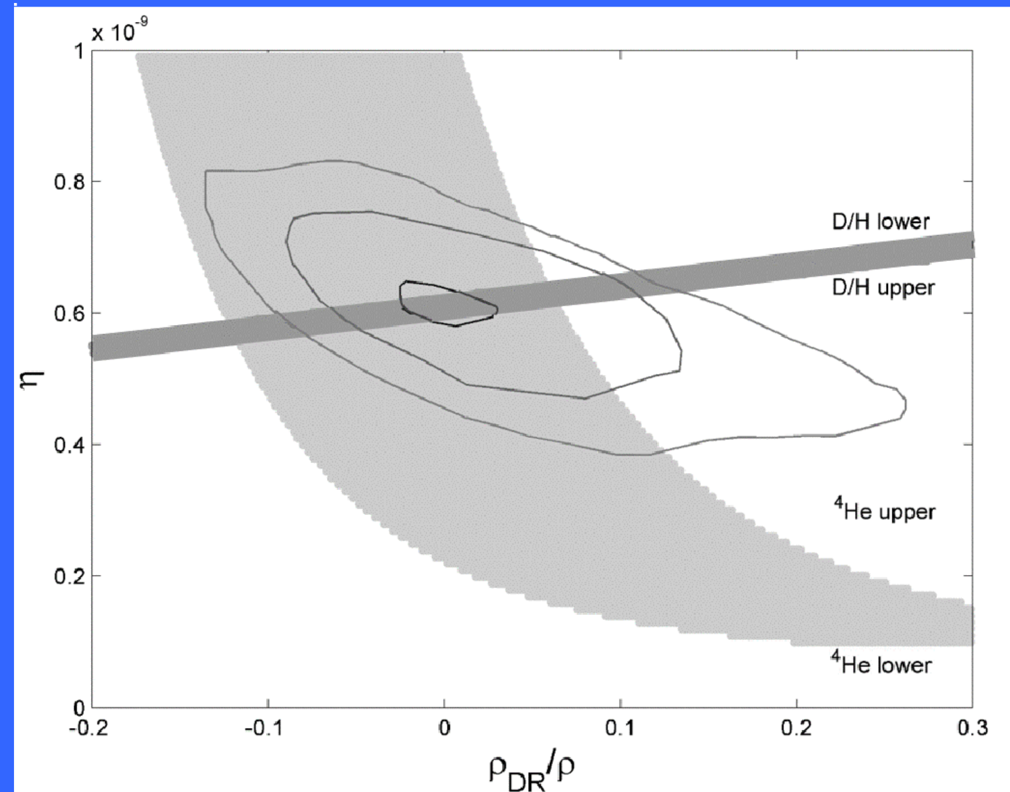
BBN and CMB Constraints on Dark Radiation in Brane-World Cosmology

Sasankan, Gangopadhyay, GJM, Kusakabe, PRD, 95, 083516 (2017)









-6.0% to $+6.2\%$ ($\Delta N_{x} = -0.19^{+0.56}_{-0.18}$

Constraints on Brane-World Inflation from the CMB Power Spectrum: Revisited

Is there another deviation giving insight into the existence of higher dimensions?

Mayukh R. Gangopadhyay,[a] **G. J. Mathews**[a]

[a]Center for Astrophysics, Department of Physics,
University of Notre Dame, Notre Dame, IN 46556, USA

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G_{\mathrm{N}}}{3}\rho - \frac{K}{a^2} + \frac{\Lambda_4}{3} + \boxed{\frac{\kappa_5^4}{36}\rho^2} + \frac{\mu}{a^4}$$

$$H^2 = \frac{V(\phi)}{3}\left(1 + \frac{V(\phi)}{\rho_0}\right)$$

Modified Slow Roll Parameters

$$\epsilon = \frac{ln(H^2)' V'}{6H^2} \quad , \eta = \frac{V''}{3H^2} \quad .$$

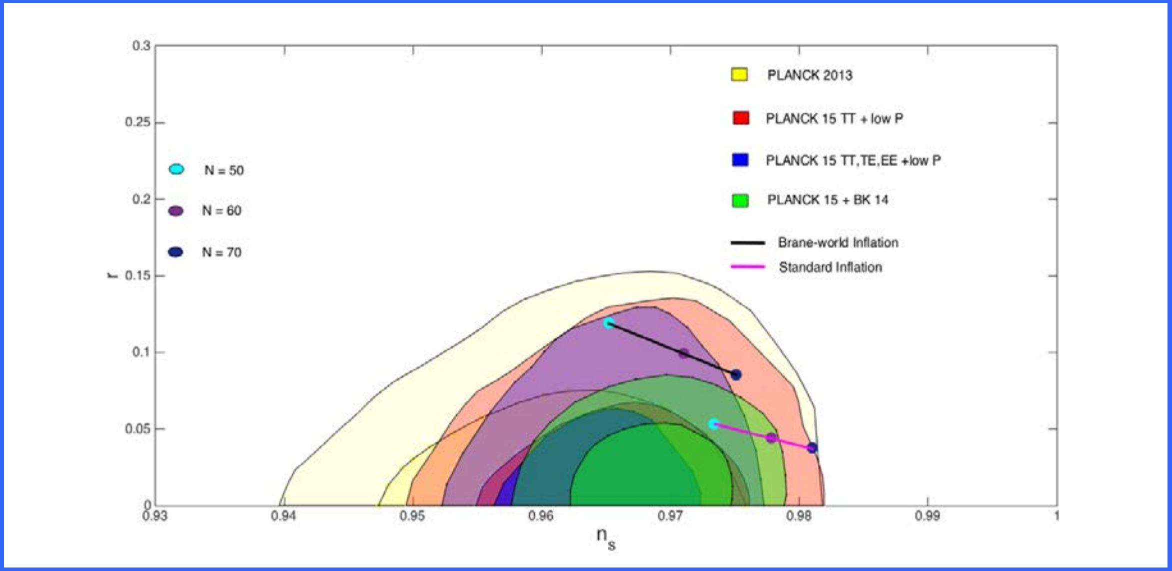
$$n_s = 1 - 6\epsilon + 2\eta \quad , \quad \alpha = \frac{V'}{3H^2}\left(6\epsilon' - 2\eta'\right)$$

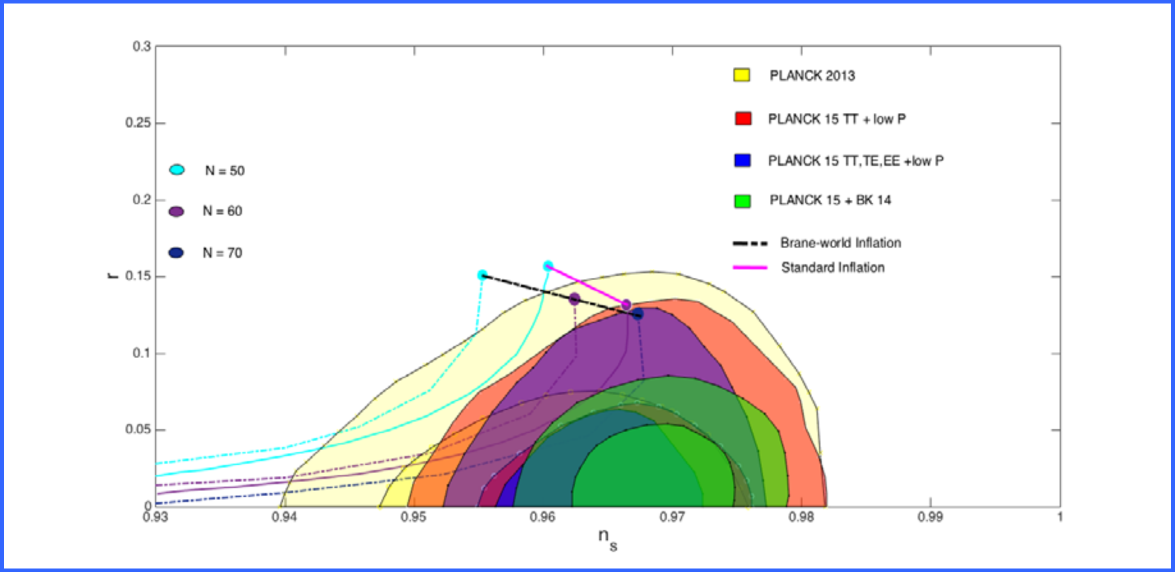
$$r \equiv P_T / P_s$$

$$P_T = 8\left(\frac{H}{2\pi}\right)^2 F(x_0)^2$$

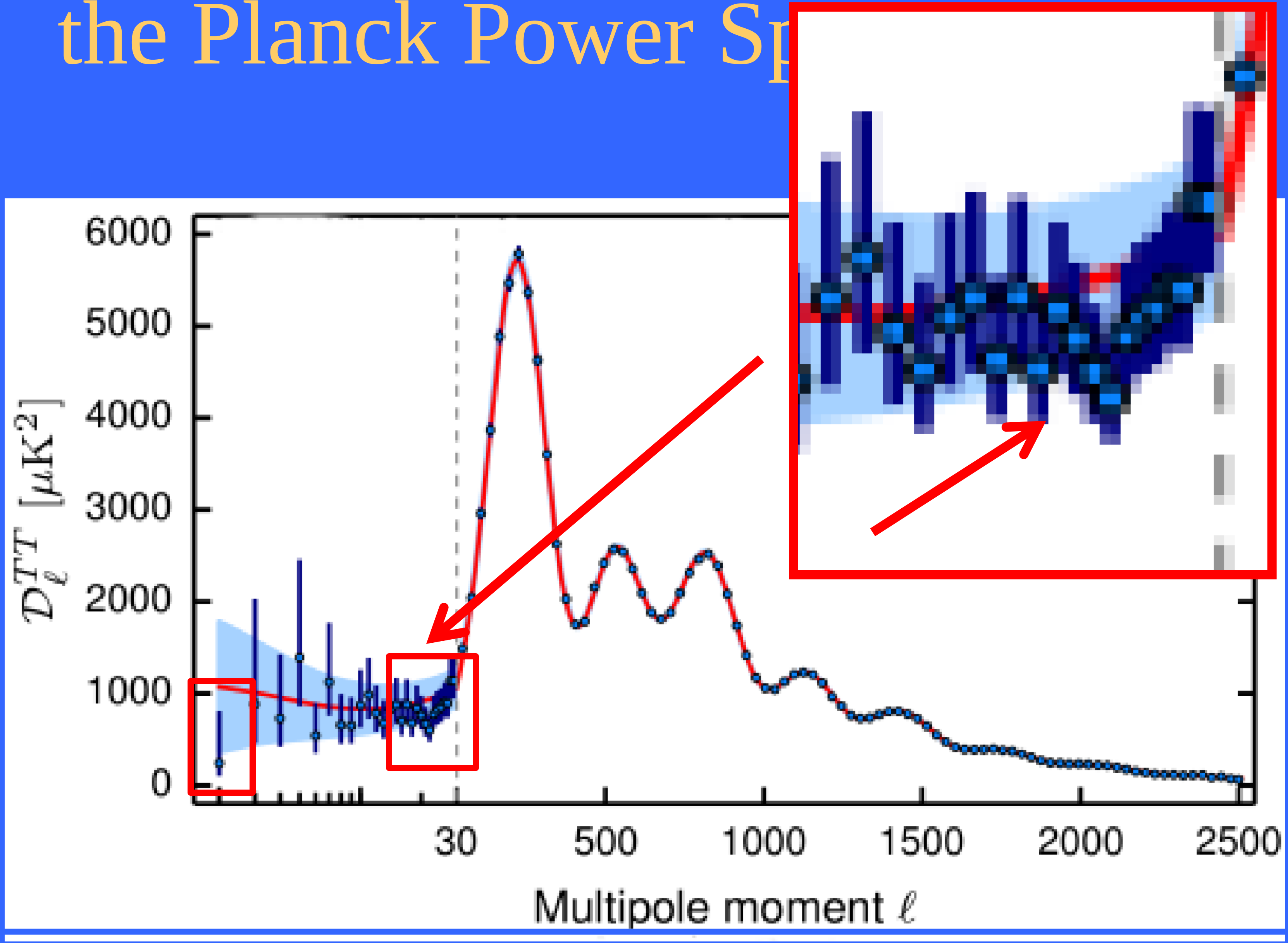
$$P_s = \frac{9}{4\pi^2}\frac{H^6}{V'^2}$$

Brane-world inflation alters fit to the CMB

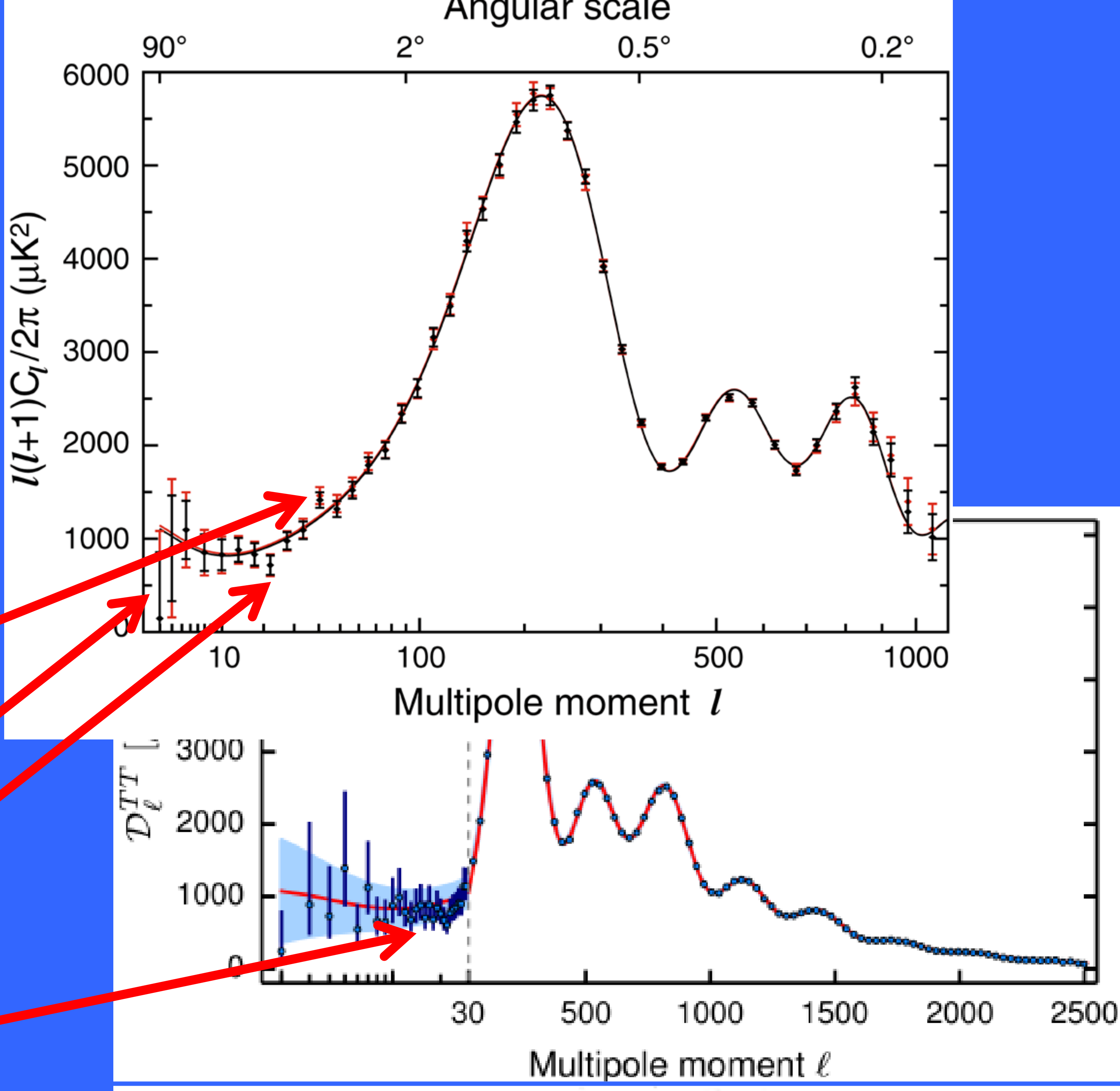




Is there evidence of deviation in the Planck Power Sp

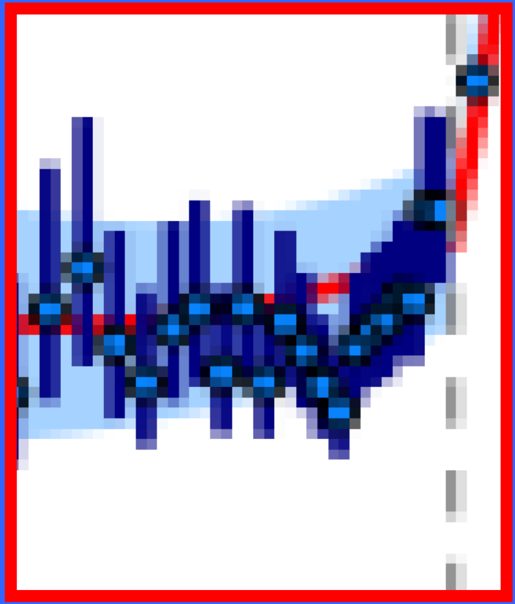


WMAP 9yr



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 dips at ℓ =10-30

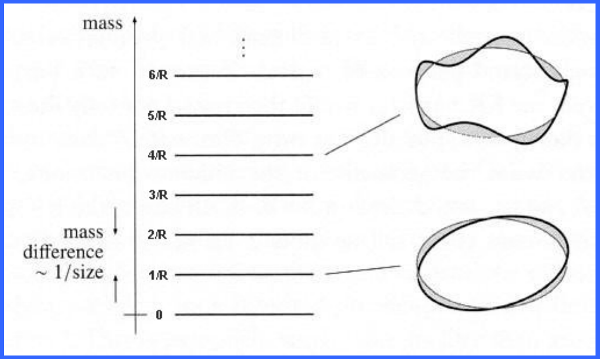


- Cosmic Variance: Planck XX arXiv:1502.02114
- Modified inflation effective potential
  - Harza, et al. arXiv:1405.2012,
  - Kitazawa and Sagnotti 1411.6396v2,
  - Yang and Ma arXiv:1501.00282
- Planck-mass particles coupled to inflation
  - GJM, Gangopadhya, Ichiki, Kajino arXiv: 1504.06913
- ….
- ….

Inflation occurs in a bath of string excitations

- Coupling such Trans-Planckian particles with the inflaton field is both natural and required to reheat the Universe

- $T = 0 \Rightarrow T \sim 10^{19}$ GeV



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).

- The total Lagrangian density is given as :

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

Fermions will be resonantly generated at some time t_* when the effective mass vanishes at φ_*

Slow-roll

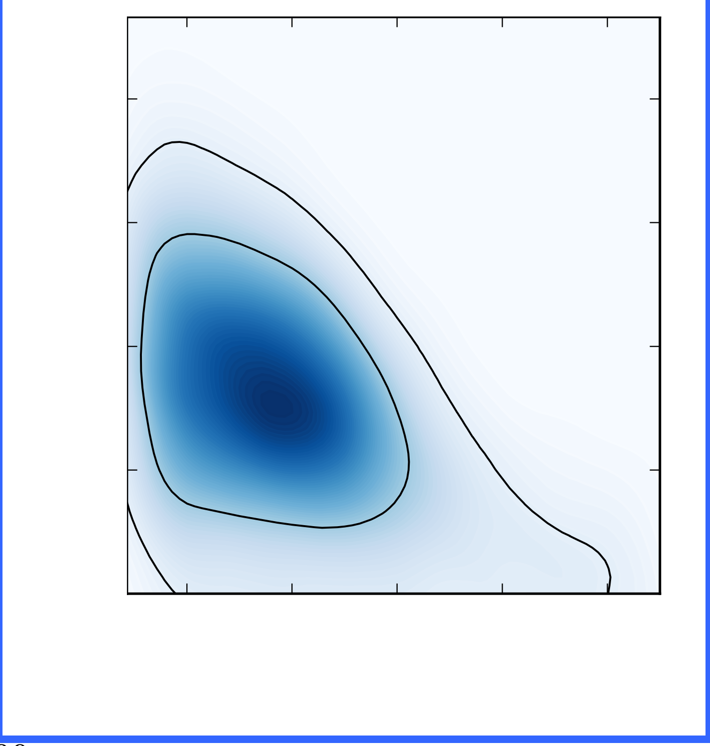
$$\dot{\phi} = \frac{-V'(\phi) + N\lambda\langle\bar{\psi}\psi\rangle}{3H}$$

Quantum fluctuations at horizon crossing

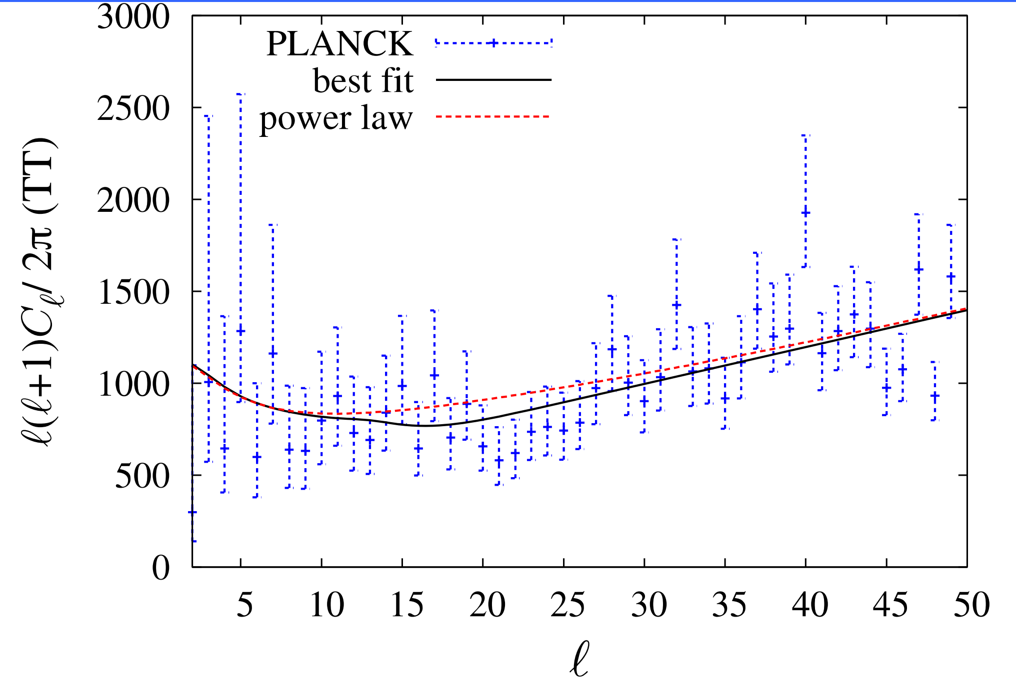
$$\delta_H(a) = \frac{H^2}{5\pi\boxed{\dot{\phi}}}$$

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

Causes Dip



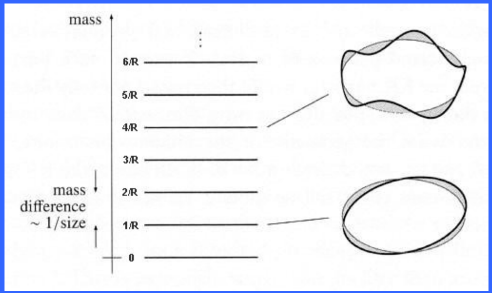
$\ell = 20$



PLANCK
best fit
power law
3000
2500
2000
1500
1000
500
0
5
10
15
20
25
30
35
40
45
50
$\ell(\ell+1)C_\ell / 2\pi$ (TT)
ℓ

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

- There should be similar resonant couplings corresponding to different numbers of oscillations on the string.



- Could this be the ℓ =2 suppression?

Resonant Superstring Excitations during Inflation

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

PRD, Submitted (2017 arXiv:1701.00577)

A simple example: Fermionic Open Strings

For open strings in the light cone gauge , the equations of motion imply ψ_1^l is right-moving, while ψ_2^i is left moving. At the endpoint one conventionally demands

$$\frac{1}{4}M^2 = N + \tilde{N} - 2 + \frac{m^2}{4R^2} + N^2R^2$$

$$\psi_1^l(\tau,\pi) = \pm\psi_2^l(\tau,\pi) \quad . \tag{13}$$

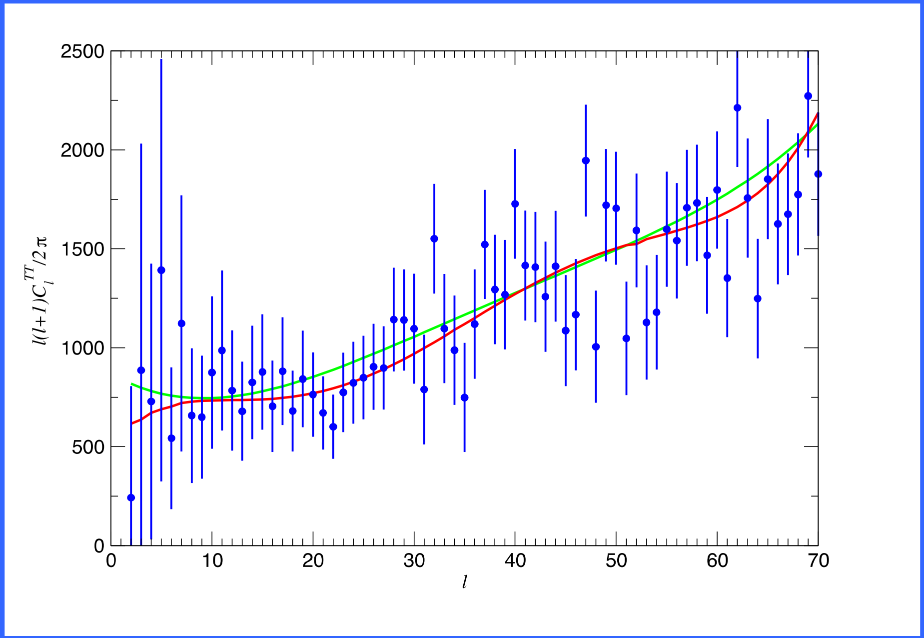
Key to the present work is that in the R sector, the mass spectrum has the simple form

$$\boxed{M = \sqrt{(n/\alpha')} \quad ,} \tag{14}$$

with n an integer eigenvalue of the number operator $N^\perp$

TT

EE



$$\ell = 2,\ A = 1.7,\ k_*(2) = 0.000148\ \mathrm{Mpc}^{-1}$$

$$\ell = 20,\ A = 2.0,\ k_*(20) = 0.00148\ \mathrm{Mpc}^{-1}$$

$$\ell = 60,\ A = 2.2,\ k_* = 0.004285\ \mathrm{Mpc}^{-1}$$

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

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

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

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

=>

$$\phi_* = \sqrt{2\alpha\mathcal{N}}$$

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

Can fix the number of oscillations on the string

$$\mathcal{N}_* = \mathcal{N} - \ln\left(k_*/k_H\right)$$

Then if we take $\mathcal{N} = 50$ ($\mathcal{N}_{eff} = 51.17$) we can write for the ratio of the quadrupole ($\ell^* = 2$) suppression resonance to the $\ell^* = 20$ resonance for open superstrings:

$$\frac{M^2(\ell^* = 2)}{M^2(\ell = 20)} = \frac{n+1}{n} = \frac{51.17 - .693}{51.17 - 3.00} \quad . \tag{20}$$

=> $n = 42$, *next resonance is at* $\ell^* = 60$

$$\frac{M^2(\ell^*)}{M^2(\ell = 20)} = \frac{n-1}{n} = \frac{51.17 - ln(\ell*)}{51.17 - 3.00} \quad . \tag{21}$$

Physical properties of the Superstring

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

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

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

Conclusions

- Happy Birthday Keith
- Press On