Possible evidence for Planck-scale resonant particle production during inflation from the CMB power spectrum

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The power spectrum of the cosmic microwave background from both the Planck and WMAP data exhibits a slight dip for multipoles in the range of $l = 10$–30. We show that such a dip could be the result of the resonant creation of massive particles that couple to the inflaton field. For our best-fit models, the epoch of resonant particle creation reenters the horizon at a wave number of $k_* \sim 0.00011 \pm 0.0004$ (h Mpc^{-1}). The amplitude and location of this feature corresponds to the creation of a number of degenerate fermion species of mass $\sim(8$–$11)/\lambda^{3/2}\, m_{pl}$ during inflation where $\lambda \sim (1.0 \pm 0.5)N^{-2/5}$ is the coupling constant between the inflaton field and the created fermion species, while N is the number of degenerate species. Although the evidence is of marginal statistical significance, this could constitute new observational hints of unexplored physics beyond the Planck scale.

I. INTRODUCTION

The Planck satellite [1,2] has provided the highest resolution yet available in the determination of the power spectrum of the cosmic microwave background (CMB). Analysis of this power spectrum provides powerful constraints on the physics of the very early Universe [2].

The primordial power spectrum is believed to derive from quantum fluctuations generated during the inflationary epoch [3,4]. In this paper we discuss a peculiar feature visible in the observed power spectrum near multipoles $\ell = 10$–30. This is an interesting region in the CMB power spectrum because it corresponds to angular scales that are not yet in causal contact, so that the observed power spectrum is close to the true primordial power spectrum.

An illustration of the Planck observed power spectrum in this region is shown in Fig. 1. Although the error bars are large, there is a noticeable systematic deviation in the range $\ell = 10$–30 below the best fit based upon the standard ΛCDM cosmology with a power-law primordial power spectrum. There is also a well-known possible suppression of the quadrupole moment in the CMB (not shown). These same features are visible in the CMB power spectrum from the Wilkinson Microwave Anisotropy Probe (WMAP) [5], and hence, are likely a true feature in the CMB power spectrum, although it should be noted that in the Planck cosmological parameters paper [2] the deviation from a simple power law in the range $\ell = 10$–30 was deduced to be of weak statistical significance due to the large cosmic variance at low ℓ. In particular a range of models was considered, from the minimal case of a kinetic-energy-dominated phase preceding a short inflationary stage (with

just one extra parameter) to a model with a steplike feature in the potential and in the sound speed (with five extra parameters). These lead to an improved fit of up to $\Delta\chi^2 = 12$. However, it was deduced in that paper that neither the Bayesian evidence nor a frequentist simulation-based analysis showed any statistically significant preference over a simple power law.

Nevertheless, a number of mechanisms have been proposed [6] to deal with the suppression of the power spectrum on large scales and low multipoles. In addition to being an artifact of cosmic variance [2,7], large-scale power suppression could arise from changes in the effective inflation-generating potential [8], differing initial conditions at the beginning of inflation [9–17], the ISW effect [18], effects of spatial curvature [19], nontrivial topology [20], geometry [21,22], a violation of statistical anisotropies [23], effects of a cosmological-constant type of dark energy during inflation [24], the bounce due to a contracting phase prior to inflation [25,26], the production of primordial micro black holes [27], hemispherical anisotropy and non-Gaussianity [28,29], the scattering of the inflationary trajectory in multiple field inflation by a hidden feature in the isocurvature direction [30], brane symmetry breaking in string theory [31,32], quantum entanglement in the M theory landscape [33], or loop quantum cosmology [34], etc. Most of these works, however, were mainly concerned with the suppression of the lowest moments.

In the present work, however, we are concerned specifically with suppression of the power spectrum in the range $\ell = 10$–30. In spite of the weak statistical significance, several recent works [2,8,30–32] have deemed it worthwhile to consider the physical consequences of this

deviation, as it could point the way to new interesting physics at and above the Planck scale.

Indeed, in the Planck cosmological analysis [2] the inflaton potential and the Hubble parameter evolution were reconstructed during the observable part of inflation by using a Taylor expansion of the inflaton potential or $H(\phi)$. When higher-order terms were allowed, both reconstructions found a change in the slope of the potential at the beginning of the observable range, thus better fitting the low-ℓ temperature deficit. As noted in that paper, however, these models were not significantly favored compared to lower-order parameterizations that lead to slow-roll evolution at all times.

In addition, in the Planck analysis three distinct methods to reconstruct the primordial power spectrum all independently found common patterns in the primordial power spectrum of curvature perturbations related to the dip at $\ell = 10$–30 in the temperature power spectrum.

Although it is of weak statistical significance, a number of works have proposed explanations of this particular dip anomaly as a possible hint of new physics. One way to explain the anomaly is by a phase transition in the inflation potential [8]. This is consistent with the abrupt changes in the slope of the inflation potential noted in the Planck reconstruction [2].

In Ref. [8] this feature was fit with a class of models dubbed first-order Wiggly Whipped inflation, whereby the field starts rolling from a steeper power-law potential and smoothly transitions to a flat power-law potential. This sharp feature in the inflaton potential produces a departure from the initial slow-roll phase, imprinting a large-scale suppression in the scalar primordial power spectrum. The best fits to the dip in such large-field models were found to have a transition from a faster roll to the slow-roll inflation at an inflaton field value of $\phi \approx 15 m_{pl}$.

As noted in that paper, however, in general this transition and any features in the large-field potential produce a suppression of scalar relative to tensor modes at small k. This, however, is not consistent with the latest Planck results [2] indicating a small tensor-to-scalar ratio. This fit also introduces wiggles in the primordial perturbation. Such wiggles in the matter power spectrum might also be used to constrain this possibility.

In [31,32] the suppression of low multipoles and the dip for $\ell = 10$–30 were simultaneously fit in a string-theory brane symmetry breaking mechanism. This mechanism splits boson and fermion excitations in string theory, leaving behind an exponential potential that is too steep for the inflaton to emerge from the initial singularity while descending it. As a result, the scalar field generically "bounces against an exponential wall." Just as in [8], this steep potential then introduces an infrared depression and a preinflationary break in the power spectrum of scalar perturbations, reproducing the observed feature.

In [30] the dip at $\ell = 10$–30 is explicitly related to the CMB cold spot with an angular radius of $\sim 10°$ noted in

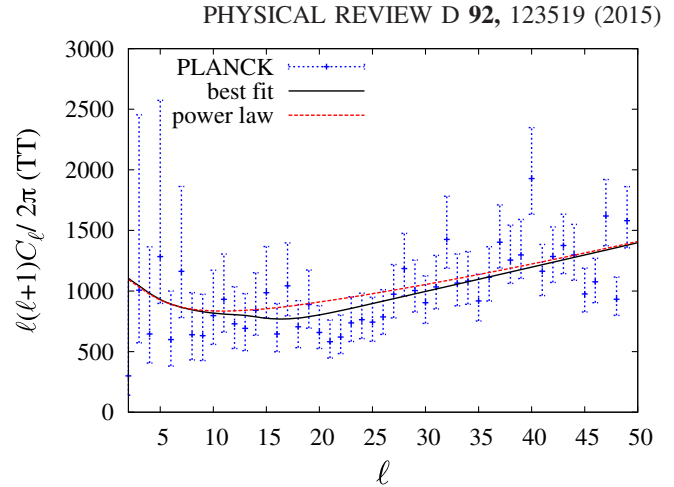FIG. 1 (color online).   CMB power spectrum in the range of $\ell = 3$–50. Points with error bars are from the Planck data release [1]. The dashed line shows the best standard ΛCDM fit to the Planck CMB power spectrum based upon a power-law primordial power spectrum. The solid line shows the best fit for a model with resonant particle creation during inflation.

both the Planck [1] and the WMAP [5] sky maps in the direction $(l, b) = (209°, -57°)$. In their scenario, this could be due to a scattering of a multiple-field inflationary trajectory off of a hidden feature in the isocurvature direction. The inflaton then loses some energy. If only a patch of the sky hits that feature due to stochastic fluctuations, then a cold spot in the sky and a corresponding dip in the temperature power spectrum ensues.

In the present work, however, rather than addressing the implications for the inflation-generating potential, we consider the possibility that new trans-Planckian physics occurs near the end of the inflation epoch corresponding to the resonant creation [35,36] of Planck-scale particles that couple to the inflaton field. Our best fit is shown by the solid line in Fig. 1, which we describe in detail in the following sections.

This interpretation has the intriguing aspect that, if correct, an opportunity emerges to use the CMB to probe properties of new particle species that existed at and above the Planck scale ($m_{pl} \sim 10^{19}$ GeV). That is the goal of the present work.

Indeed, string theory compactification schemes generically postulate the existence of massive particles at or above the Planck scale from the Kaluza-Klein states, winding modes, string excitations, etc. Moreover, the coupling of the inflaton to other particle species near the end of inflation is not only natural, but probably required. This is because the energy density in the inflaton must be converted to entropy in light or heavy particle species at the end of inflation as a means to reheat the Universe. Hence, the existence of Planck-scale mass particles that couple to the inflaton near the end of inflation is a scenario that is both natural and even required. This provides a possible opportunity to uncover new physics in the trans-Planckian regime.

In our previous study [36] a similar analysis was made of a possible bump in the CMB in the range of very high multipoles. At that time there appeared to be an excess power in the CMB power spectrum for multipoles in the range $\ell = 2000$–3500 in the combined (CBI [37–39], ACBAR [40], BIMA [41], and VSA [42]) data, contrary to the expectation from the WMAP results [43]. Since that time, however, better high-resolution data have eliminated the apparent excess.

The present analysis, however, is significantly different from that previous work. In place of a bump we now seek to fit a dip in the power spectrum. This is achieved by use of a different Lagrangian. Also, the feature we fit here is at low multipoles and therefore much more likely to be a part of the primordial spectrum. Moreover, the deduced particle properties are very different than that of the previous study and even of opposite-sign coupling. Hence, here we present new results on possible resonant fermion particle production during inflation.

II. RESONANT PARTICLE PRODUCTION DURING INFLATION

The details of the resonant particle creation paradigm during inflation have been explained in Refs. [35,36]. Indeed, the idea was originally introduced [44] as a means for reheating after inflation. Since [35], subsequent work [45–48] has elaborated on the basic scheme into a model with coupling between two scalar fields. Here, we summarize essential features of the canonical single-fermion field coupled to the inflaton as a means to clarify the possible physics of the $\ell = 10$–30 dip.

In this minimal extension from the basic picture, the inflaton ϕ is postulated to couple to particles whose mass is of order the inflaton field value. These particles are then resonantly produced as the field obtains a critical value during inflation. If even a small fraction of the inflaton field is affected in this way, it can produce an observable feature in the primordial power spectrum. In particular, there can be either an excess in the power spectrum as noted in [35,36], or a dip in the power spectrum as described in this paper. Such a dip offers important new clues to the trans-Planckian physics of the early Universe.

We note that particle creation corresponding to an imaginary part of the effective action of quantum fields has been considered in [49]. In that case the same creation should occur at the present time. Thus, compatibility with the diffuse γ-ray background can be used to rule out the possibility of measurable effects from this type of trans-Planckian particle creation in the CMB anisotropy. However, the effect of interest here is a perturbation in the simple scalar field due to direct coupling to Planck-mass particles at energies for which the inflation potential is comparable to the particle mass and which cannot occur at the present time. The present scenario, therefore, is not constrained by the diffuse gamma-ray background.

In the simplest slow-roll approximation [3,4], the generation of density perturbations of amplitude, $\delta_H(k)$, when crossing the Hubble radius is just

$$\delta_H(k) \approx \frac{H^2}{5\pi\dot\phi}, \qquad (1)$$

where H is the expansion rate and $\dot\phi$ is the rate of change of the inflaton field when the comoving wave number k crosses the Hubble radius during inflation. We caution, however, that resonant particle production could affect the inflaton field. In that case the conjugate momentum in the field $\dot\phi$ could be altered. This could cause either an increase or a diminution in $\delta_H(k)$ (the primordial power spectrum) for those wave numbers which exit the horizon during the resonant particle production epoch. In particular, when $\dot\phi$ is accelerated due to particle production, it may deviate from the slow-roll condition. In [35], however, this correction was analyzed and found to be $\ll 20\%$. Hence, for our purposes we can ignore this correction.

For the application here, we adopt a positive Yukawa coupling of strength λ between an inflaton field ϕ and a field ψ of N degenerate fermion species. This differs from [35,36], which adopted a negative Yukawa coupling. With our choice, the total Lagrangian density including the inflaton scalar field ϕ, the Dirac fermion field, and the Yukawa coupling term is then simply

$$\mathcal{L}_{\text{tot}} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi) + i\bar\psi\partial\psi - m\bar\psi\psi + N\lambda\phi\bar\psi\psi. \qquad (2)$$

For this Lagrangian, it is obvious that the fermions have an effective mass of

$$M(\phi) = m - N\lambda\phi. \qquad (3)$$

This vanishes for a critical value of the inflaton field, $\phi_* = m/N\lambda$. Resonant fermion production will then occur in a narrow range of the inflaton field amplitude around $\phi = \phi_*$.

Note that the vanishing of the effective mass term with a negative coupling term as in [35,36] requires a positive mass term in the associated free-particle Lagrangian. To achieve this a scenario was adopted in that paper whereby the inflaton ϕ controls the fermion mass ψ through the coupling

$$L_{\text{int}} = -\left[M_f - M_{pl}f\left(\frac{\phi}{M_{pl}}\right)\right]\bar\psi\psi, \qquad (4)$$

where M_f is the fermion mass. In that case, imposing $f \gg 1$ leads to a positive mass term and a cancellation of the effective mass is possible. Here, however, we consider the simpler case of $f \ll 1$ so that a simple free-particle Lagrangian is sufficient.

As in [35,36] we label the epoch at which particles are created by an asterisk. So, the cosmic scale factor is labeled a_* at the time t_* at which resonant particle production occurs. Considering a small interval around this epoch, one can treat $H = H_*$ as approximately constant (slow-roll inflation). The number density n of particles can be taken as zero before t_* and afterwards as $n = n_*[a_*/a(t)]^3$. The fermion vacuum expectation value can then be written

$$\langle \bar{\psi}\psi \rangle = n_*\Theta(t - t_*) \exp\left[-3H_*(t - t_*)\right], \qquad (5)$$

where Θ is a step function.

Then, following the derivation in [35,36], we have the following modified equation of motion for the scalar field coupled to ψ:

$$\ddot{\phi} + 3H\dot{\phi} = -V'(\phi) + N\lambda\langle\bar{\psi}\psi\rangle, \qquad (6)$$

where $V'(\phi) = dV/d\phi$. The solution to this differential equation after particle creation $(t > t_*)$ is then similar to that derived in Refs. [35,36] but with a sign change for the coupling term, i.e.,

$$\begin{aligned}
\dot{\phi}(t > t_*) = {} & \dot{\phi}_* \exp\left[-3H(t - t_*)\right] \\
& - \frac{V'(\phi)_*}{3H_*}\left[1 - \exp\left[-3H(t - t_*)\right]\right] \\
& + N\lambda n_*(t - t_*) \exp\left[-3H_*(t - t_*)\right].
\end{aligned} \qquad (7)$$

The physical interpretation here is that the rate of change of the scalar field rapidly increases due to the coupling to particles created at the resonance $\phi = \phi_*$.

Then, using Eq. (1) for the fluctuation as it exits the horizon, and constant $H \approx H_*$ in the slow-roll condition along with

$$d \ln a = H dt, \qquad (8)$$

one obtains the perturbation in the primordial power spectrum as it exits the horizon,

$$\delta_H = \frac{[\delta_H(a)]_{N\lambda=0}}{1 + \Theta(a - a_*)(N\lambda n_*/|\dot{\phi}_*|H_*)(a_*/a)^3 \ln(a/a_*)}. \qquad (9)$$

Here, it is clear that the power in the fluctuation of the inflaton field will diminish as the particles are resonantly created when the Universe grows to some critical scale factor a_*.

Using $k_*/k = a_*/a$, the perturbation spectrum Eq. (9) can then be reduced [36] to a simple two-parameter function,

$$\delta_H(k) = \frac{[\delta_H(a)]_{N\lambda=0}}{1 + \Theta(k - k_*)A(k_*/k)^3 \ln(k/k_*)}, \qquad (10)$$

where the amplitude A and characteristic wave number k_* $(k/k_* \geq 1)$ can be fit to the observed power spectrum from the relation

$$k_* = \frac{\ell_*}{r_{lss}}, \qquad (11)$$

where r_{lss} is the comoving distance to the last scattering surface, taken here to be 14 Gpc. The values of A and k_* determined from the CMB power spectrum relate to the inflaton coupling λ and fermion mass m, for a given inflation model via Eqs. (9) and (10),

$$A = |\dot{\phi}_*|^{-1}N\lambda n_*H_*^{-1}. \qquad (12)$$

The connection between resonant particle creation and the CMB temperature fluctuations is straightforward. As usual, temperature fluctuations are expanded in spherical harmonics, $\delta T/T = \sum_l \sum_m a_{lm}Y_{lm}(\theta, \phi)$ $(2 \leq l < \infty$ and $-l \leq m \leq l)$. The anisotropies are then described by the angular power spectrum, $C_l = \langle|a_{lm}|^2\rangle$, as a function of multipole number l. One then merely requires the conversion from perturbation spectrum $\delta_H(k)$ to angular power spectrum C_l. This is easily accomplished using the CAMB code [50]. When converting to the angular power spectrum, the amplitude of the narrow particle creation feature in $\delta_H(k)$ is spread over many values of ℓ. Hence, the particle creation feature looks like a broad dip in the power spectrum.

We have made a multidimensional Markov chain Monte Carlo analysis [51,52] of the CMB using the Planck data [1] and the COSMOMC code [52]. For simplicity and speed in the present study we only marginalized over parameters which do not alter the matter or CMB transfer functions. Hence, we only varied A and k_*, along with the six parameters, $\Omega_b h^2, \Omega_c h^2, \theta, \tau, n_s, A_s$. Here, Ω_b is the baryon content, Ω_c is the cold dark matter content, θ is the acoustic peak angular scale, τ is the optical depth, n_s is the power-law spectral index, and A_s is the normalization. As usual, both n_s and A_s are normalized at $k = 0.05$ Mpc^{-1}.

Figure 2 shows contours of likelihood for the resonant particle creation parameters, A and k_*. Adding this perturbation to the primordial power spectrum improves the total χ^2 for the fit from 9803 to 9798. One expects that the effect of interest here would only make a small change $(\Delta\chi^2 = 5)$ in the overall fit because it only affects a limited range of l values with large error bars. Nevertheless, from the likelihood contours we can deduce a mean value of $A = 1.7 \pm 1.5$ with a maximum likelihood value of $A = 1.5$, and a mean value of $k_* = 0.0011 \pm 0.0004$ h Mpc^{-1}.

Of course, it is obvious that adding extra parameters should improve the goodness of fit. One should quantify the statistical significance of the improvement over a simple power-law primordial power spectrum. A $\Delta\chi^2 = 5$ in the fit corresponds to a 92% confidence level for two free
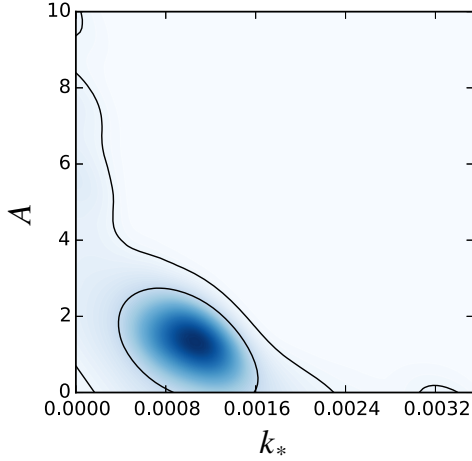
FIG. 2 (color online).   Constraints on parameters A and k_* from the MCMC analysis of the CMB power spectrum. Contours show 1σ and 2σ limits. The horizontal axis is in units of $(h\,\mathrm{Mpc}^{-1})$.

parameters, hence less than a 2σ confidence limit. To be more precise, the Bayesian information criterion (BIC) can be used to select whether one model is better than another by introducing a penalty term for the number of parameters in the model fit. Under the assumption that the model errors are independent and obey a normal distribution, the BIC can then be rewritten in terms of $\Delta\chi^2$ as BIC $\approx \Delta\chi^2 + df \cdot \ln n$ where df is the number of degrees of freedom in the test and n is the number of points in the observed data. For the 30 multipoles in the range of the fit, the introduction of 2 new free parameters then corresponds to a BIC $= 1.8$. Generally, BIC > 2 is considered positive evidence for an improvement in the fit. Hence, one must conclude that the evidence for this fit is statistically weak. Nevertheless, it is worthwhile to examine the possible physical meaning of the deduced parameters.

III. PHYSICAL PARAMETERS

The coefficient A can be related directly to the coupling constant λ using the approximation [35,53–55] for the particle production Bogoliubov coefficient

$$|\beta_k|^2 = \exp\left(\frac{-\pi k^2}{a_*^2 N\lambda|\dot\phi_*|}\right).$$ (13)

Then,

$$n_* = \frac{2}{\pi^2}\int_0^\infty dk_p\, k_p^2 |\beta_k|^2 = \frac{N\lambda^{3/2}}{2\pi^3}|\dot\phi_*|^{3/2}.$$ (14)

This gives

$$A = \frac{N\lambda^{5/2}}{2\pi^3}\frac{\sqrt{|\dot\phi_*|}}{H_*}$$ (15)

$$\approx \frac{N\lambda^{5/2}}{2\sqrt{5}\pi^{7/2}}\frac{1}{\sqrt{\delta_H(k_*)|_{\lambda=0}}},$$ (16)

where we have used the usual approximation for the primordial slow-roll inflationary spectrum [3,4]. This means that regardless of the exact nature of the inflationary scenario, for any fixed inflationary spectrum $\delta_H(k)|_{\lambda=0}$ without the backreaction, we have the particle production giving a dip of the form Eq. (10) with the parameter A expressed in terms of the coupling constant through Eq. (16). Given that the CMB normalization requires $\delta_H(k)|_{\lambda=0} \sim 10^{-5}$, we then have

$$A \sim 1.3 N\lambda^{5/2}.$$ (17)

Hence, for the maximum likelihood value of $A \sim 1.5$, we have

$$\lambda \approx \frac{(1.0 \pm 0.5)}{N^{2/5}}.$$ (18)

So, $\lambda \leq 1$ requires $N > 1$ as expected.

The fermion particle mass m can then be deduced from $m = N\lambda\phi_*$. From Eq. (18), then, we have $m \approx \phi_*/\lambda^{3/2}$. For this purpose, however, one must adopt a specific form for the inflaton potential to determine ϕ_* appropriate to the scale k_*. Here, we adopt a general monomial potential whereby

$$V(\phi) = \Lambda_\phi m_{pl}^4 \left(\frac{\phi}{m_{pl}}\right)^\alpha,$$ (19)

for which there is a simple analytic relation [3] between the value of ϕ_* and the number of e-folds $\mathcal{N}(k_*)$ between when k_* exits the horizon and the end of inflation, i.e.,

$$\mathcal{N}(k_*) = \frac{1}{m_{pl}^2}\int_{\phi_{\text{end}}}^{\phi_*}\frac{V(\phi)}{V'(\phi)}d\phi,$$ (20)

implies

$$\phi_* = \sqrt{2\alpha\mathcal{N}}\,m_{pl}.$$ (21)

For $k_* = 0.0011 \pm 0.0004\,h\,\mathrm{Mpc}^{-1}$, and $k_H = a_0 H_0 = (h/3000)\mathrm{Mpc}^{-1} \sim 0.0002$, we have $\mathcal{N} - \mathcal{N}_* = \ln(k_H/k_*) < 1$. Typically one expects $\mathcal{N}(k_*) \sim \mathcal{N} \sim 50$–$60$. We note, however, that one can have the number of e-folds as low as $\mathcal{N} \sim 25$ in the case of thermal inflation [3]. For standard inflation a monomial potential with $\alpha = 2$ would have $\phi_* \sim (14$–$15)m_{pl}$. However, the limits on the tensor-to-scalar ratio from the Planck analysis [2] rule out $\alpha = 2$ at the 95% confidence level. Monomial potentials are more consistent with $\alpha = 1$ [$\phi_* = (10 - 11)m_{pl}$], or even $\alpha = 2/3$ [$\phi_* = (8 - 9)m_{pl}$]. Hence, we have roughly the constraint
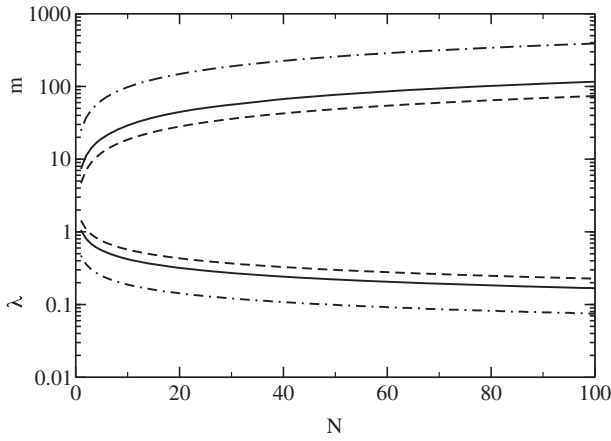
FIG. 3. Implied values of λ and m as a function of the number of degenerate species N for a $\phi^{2/3}$ inflaton effective potential experiencing 50 e-folds of inflation. Upper curves show the allowed mass. Lower curves are the coupling constant. Solid line is for the best-fit normalization $A = 1.5$. The dashed and dot-dashed lines show the uncertainties due to the upper and lower limits on A, respectively.

$$m \sim (8\text{–}11)\frac{m_{pl}}{\lambda^{3/2}}. \qquad (22)$$

So, one can deduce a family of possible properties of the resonantly produced particle (i.e., its mass and coupling strength) in terms of a single parameter, the degeneracy N. This is illustrated in Fig. 3, which shows allowed values and uncertainty in the coupling constant and particle mass as a function of the number of degenerate species for a $\phi^{2/3}$ inflaton effective potential experiencing 50 e-folds of inflation.

Indeed, it is natural [35] to have a large degeneracy (e.g., $N \sim 10\text{–}100$ in Fig. 3) among trans-Planckian massive particles. Supergravity and super-string theories generally contain a spectrum of particles with masses well in excess of the Planck mass. Moreover, the compact extra dimensions lead to a tower of nearly degenerate Kaluza-Klein states [56,57], and as noted above, reheating may require that some of these particles couple to the inflaton field near the end of inflation.

IV. MATTER POWER SPECTRUM

It is perhaps obvious that the matter power spectrum will be unaffected by the $\ell = 10\text{–}30$ anomaly since, as noted above, this range of multipoles is for the most part not yet in causal contact. Nevertheless, the largest multipoles affected by this dip are near the scale of the horizon at decoupling. For completeness, as in other studies [8], we hence examine the impact of this anomaly on the matter power spectrum.

It is straightforward to determine the matter power spectrum. To convert the amplitude of the perturbation as each wave number k enters the horizon, $\delta_H(k)$, to the present-day power spectrum, $P(k)$, which describes the
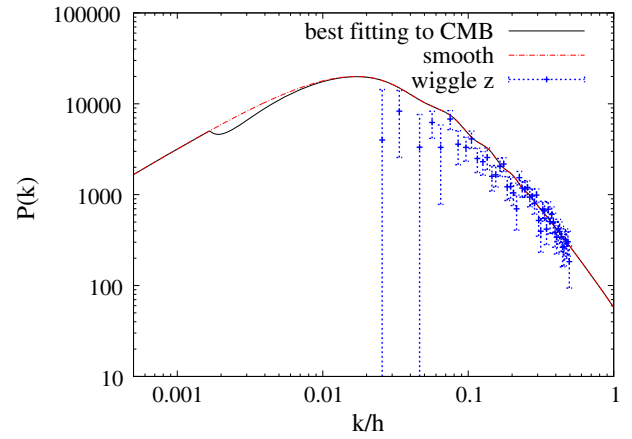

FIG. 4 (color online). Comparison of the observed galaxy cluster function from [60] with the spectrum implied from the fits to the matter power spectrum with (solid line) and without (dashed line) resonant particle creation during inflation as described in the text.

amplitude of the fluctuation at a fixed time, one utilizes the transfer function, $T(k)$ [58], which is easily computed using the CAMB code [50] for various sets of cosmological parameters (e.g., Ω, H_0, Λ, Ω_B). An adequate approximate expression for the structure power spectrum is then

$$\frac{k^3}{2\pi^2}P(k) = \left(\frac{k}{aH_0}\right)^4 T^2(k)\delta_H^2(k). \qquad (23)$$

This expression is only valid in the linear regime, which in comoving wave number is up to approximately $k \lesssim 0.2\, h\,\text{Mpc}^{-1}$ and therefore is adequate for our purposes. However, we also correct for the nonlinear evolution of the power spectrum [59].

Figure 4 shows the matter power spectrum from the WiggleZ Dark Energy Survey [60] compared to the computed maximum likelihood power spectrum with and without the perturbation due to the resonant particle creation. Unfortunately, the perturbation is on a scale too large to be probed by the observed matter power spectrum.

V. CONCLUSION

We have analyzed the $\ell = 10\text{–}30$ dip in the Planck CMB power spectrum in the context of a model for the creation of N nearly degenerate trans-Planckian massive fermions during inflation. The best fit to the CMB power spectrum implies an optimum feature at $k_* = 0.0011 \pm 0.0004 h\text{Mpc}^{-1}$ (wave number at the resonant frequency) and from Eq. (16) $A \approx 1.7 \pm 1.5$. For monomial inflation potentials consistent with the Planck tensor-to-scalar ratio, this feature would correspond to the resonant creation of nearly degenerate particles with $m \sim 8\text{–}11\, m_{pl}/\lambda^{3/2}$ and a Yukawa coupling constant λ between the fermion species and the inflaton field of $\lambda \approx (1.0 \pm 0.5)N^{-2/5}$ for N degenerate fermion species.

Obviously there is a need for more precise determinations of the CMB power spectrum for multipoles in the range of $\ell = 10$–30, although this may ultimately be limited by the cosmic variance.

Nevertheless, in spite of these caveats, we conclude that if the present analysis is correct, this may be one of the first hints at observational evidence of new particle physics at the Planck scale. Indeed, one expects a plethora of particles at the Planck scale, particularly in the context of string theory. Perhaps the presently observed CMB power spectrum contains the first suggestion that a subset of such particles may have coupled to the inflaton field, leaving a relic signature of their existence in the CMB primordial power spectrum.

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