Features of heavy physics in the CMB

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- $\delta T/T_{rad}$ is the intrinsic photon gas temperature variation (adiabatic / isocurvature).

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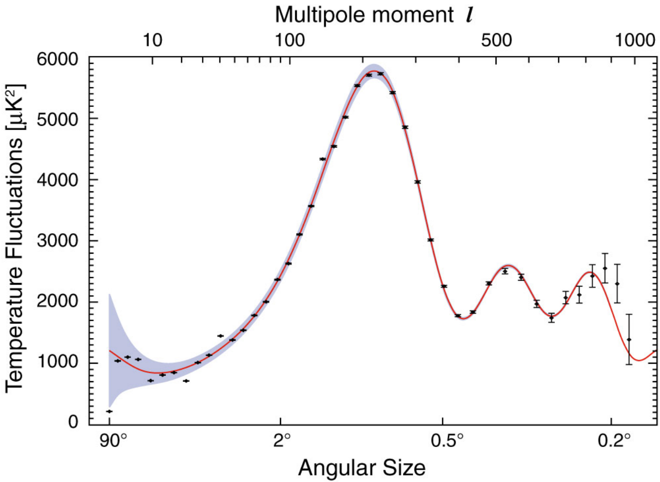
- It is a combination of an input seed spectrum + knowledge of physics since last scattering that we fit to the data, which allows us to infer cosmological parameters.

The cosmic ultrasound

Courtesy WMAP collaboration:



What *exactly* is the CMB telling us?

Although the simplest models of single field inflation remain compatible with current CMB experiments, a direct reconstruction of the primordial power spectrum is still limited by degeneracies in our priors and our systematics:

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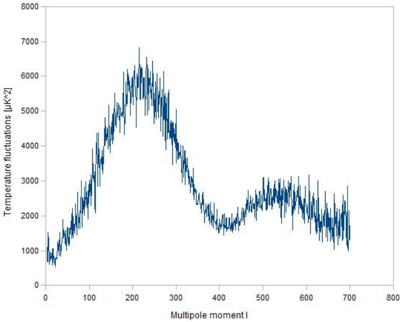

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Although an almost scale invariant spectrum ‘predicts’ what is ‘observed’ in the CMB, could it be that some very interesting physics has been glossed over in this approach?

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- Is a scale invariant spectrum even generic in a *realistic* model of inflation?
- Be wary of data black box– hidden assumptions of theorists creep in to the analysis. Hunt and Sarkar (arXiv:0706.2443): WMAP data can be better fit with a 'bump' in the spectrum with $h = 0.44$ and $\Omega_M = 1$ (better χ^2 arises from the data 'glitches').

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- The quality of data available to us is due to vastly improve in the coming years (PLANCK, CMBPol)– we may be able to more accurately constrain (or even detect!) non-trivial non-gaussianities in the CMB (and thus test models containing comsic strings, stringy inflation, alternatives to inflation).

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- With negligible self interactions (consistent with Gaussian statistics)
- Whose fluctuations were initially in the Bunch-Davies vacuum state.

Outline

In this talk, we wish to discuss inflation in the setting where it is an effective light direction in a multi-dimensional field space (representative of inflation realized in string theory), where we see that:

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- If representative of inflation in string theory, gives us information of the local geometry of field space: information about the particular string compactification.
- More generally, non-trivial information about some of the higher dimensional operators in the low effective field theory– information of the parent theory.

The collaboration

This work has been in done in a long standing collaboration with Ana Achúcarro, Jinn-Ouk Gong, Sjoerd Hardeman and Gonzalo A. Palma

- arXiv:1005.3848
- arXiv:1010.3693
- arXiv:11xx.xxxx

Inflation– an empirical probe of the highest energies?

Inflation is the putative quasi exponential expansion of spacetime at some early epoch which sets up the initial conditions for the hot big bang– homogeneous*, isotropic*, flat, thermalized initial conditions absent of dangerous topological relics.

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- and $\ddot{\phi} \ll 3H\dot{\phi} \rightarrow \eta := M_{pl}^2 V''/V \ll 1$

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Provided the 'slow roll' conditions can be met, inflation lasts for *sufficiently long* to give us a viable starting point for big bang cosmology.

- It also provides us with the initial seed structure of gravitational perturbations– a scale invariant spectrum of *adiabatic* co-moving curvature perturbations $\mathcal{P}_{\mathcal{R}}(k) := k^3\langle|\mathcal{R}(k)|^2\rangle = (2\pi)^3\frac{H^2}{\dot{\phi}_0^2}k^3\langle|\delta\phi(k)|^2\rangle \sim k^{n_s-1}$

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- This begs the question: what exactly is the inflaton?

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To say that there is effectively one light scalar direction at such potentially high energies, with negligible interactions with other light directions if they exist (to ensure adiabaticity) is a strong statement. Furthermore:

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- To maintain slow roll at the quantum corrected level, we require that the *effective potential* satisfy the slow roll conditions.
- Requiring at least 60 e-folds of inflation, results in the tuning problem: $g \ll 48\pi^2\frac{H^2}{m^2}$

Non decoupling of heavy physics?

So it is the parameters of the effective inflaton action that we require to satisfy the slow roll requirements. It seems that heavy physics can only manifest as irrelevant (Planck suppressed) operators.

- However heavy physics does not always decouple so cleanly from low energy physics. There are certain situations in which the conditions underlying the decoupling theorem (Appelquist, Carrazone) may not be met:

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- When there is an induced time dependence in the heavy sector through the dynamics of inflation such that the adiabatic approximation is violated

Non decoupling of heavy directions?

Consider a typical 4-d low energy effective action resulting describing a particular string compactification, or the scalar sector of some supergravity theory:

- $S = \int \sqrt{-g}\,d^4x \left[\frac{M_{\rm Pl}^2}{2}R - \frac{1}{2}\gamma_{ab}g^{\mu\nu}\partial_\mu\phi^a\partial_\nu\phi^b - V(\phi)\right]$

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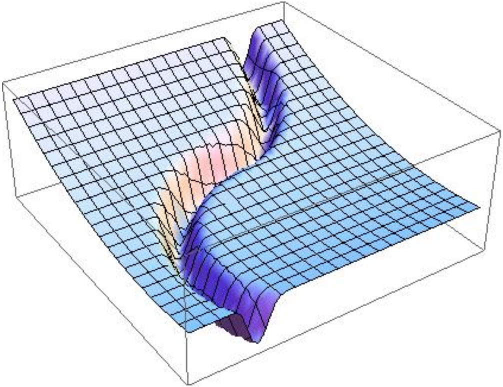
- And the associated Riemann tensor: $\mathbb{R}^a{}_{bcd} = \partial_c\Gamma^a_{bd} - \partial_d\Gamma^a_{bc} + \Gamma^a_{ce}\Gamma^e_{db} - \Gamma^a_{de}\Gamma^e_{cb}$
- The equations of motion are given by $\Box\phi^a + \Gamma^a_{bc}g^{\mu\nu}\partial_\mu\phi^b\partial_\nu\phi^c = \partial V/\partial\phi^a$
- We note that we can associate an energy scale associated with the curvature of $\mathcal{M}$: $\mathbb{R} \sim \Lambda_{\mathcal{M}}^{-2}$.
- In many concrete settings such as modular sector of string compactifications: $\Lambda_{\mathcal{M}} \sim M_{string}$

Non decoupling of heavy directions?

The inflaton trajectory is then determined by the forcing of the steepest descent directions of V on the span of geodesics of γ_{ab} .

- If the inflaton traverses a sharp enough bend in field space (without interrupting slow-roll), one can imagine exciting the heavy directions



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- Results in a modified speed of sound $c_s^2 = e^{-\beta}$ for the propagation of the curvature perturbations.

Bends in field space

In an FRW geometry $(ds^2 = -dt^2 + a^2(t)dx^i dx^i)$, the equations of motion for the inflaton become:

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- With the generalization of the slow roll parameters: $\epsilon \equiv -\frac{\dot{H}}{H^2} = \frac{\dot{\phi}_0^2}{2M_{\rm Pl}^2 H^2}$ and $\eta^a \equiv -\frac{1}{H\dot{\phi}_0}\frac{D\dot{\phi}_0^a}{dt}$

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- Which we can rewrite as $|\eta_\perp| = \sqrt{2\epsilon}\frac{M_{\rm Pl}}{\kappa}$

Perturbations

We now consider perturbations around a background solution $\phi^a(\tau, x) = \phi_0^a(\tau) + \delta\phi^a(\tau, x)$, with a perturbed line element $ds^2 = a^2(\tau)[-d\tau^2(1 + 2\psi(\tau, x)) + (1 - 2\psi(\tau, x))dx^i dx^i]$.

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- With $\zeta \equiv Z_{TN} = aH\eta_\perp$,
  $\Omega_{TT} = -a^2H^2\left(2 + 2\epsilon - 3\eta_{||} + \eta_{||}\xi_{||} - 4\epsilon\eta_{||} + 2\epsilon^2 - \eta_\perp^2\right)$,
  $\Omega_{NN} = -a^2H^2(2 - \epsilon) + a^2M^2$,
  $\Omega_{TN} = a^2H^2\eta_\perp(3 + \epsilon - 2\eta_{||} - \xi_\perp)$ and $\xi_\perp \equiv -\frac{\dot\eta_\perp}{H\eta_\perp}$.

Effective theory for the adiabatic mode

Given that $\Omega_{NN} \gg |\Omega_{TT}|$ and $\Omega_{NN} \gg |\Omega_{TN}|$ the field v^N is the heavier of the two. We noting that the above equations can be derived from the action:

- $$S = \int d\tau d^3x \, \frac{1}{2}\left[\left(\frac{dv^T}{d\tau}\right)^2 - \left(\nabla v^T\right)^2 - \left(\Omega_{TT} - \zeta^2\right)\left(v^T\right)^2\right] + \int d\tau d^3x \, \frac{1}{2}\left[\left(\frac{dv^N}{d\tau}\right)^2 - \left(\nabla v^N\right)^2 - \left(\Omega_{NN} - \zeta^2\right)\left(v^N\right)^2\right] - \int d\tau d^3x \, v^N \left(\Omega_{TN} - \frac{d\zeta}{d\tau} - 2\zeta\frac{d}{d\tau}\right) v^T$$

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$$S = \int \; d\tau d^3k \; \tfrac{1}{2}\left[\left(\frac{d\varphi}{d\tau}\right)^2 - \varphi \; e^{-\beta(\tau,k)}k^2\varphi - \varphi \; \Omega(\tau,k)\varphi\right]$$

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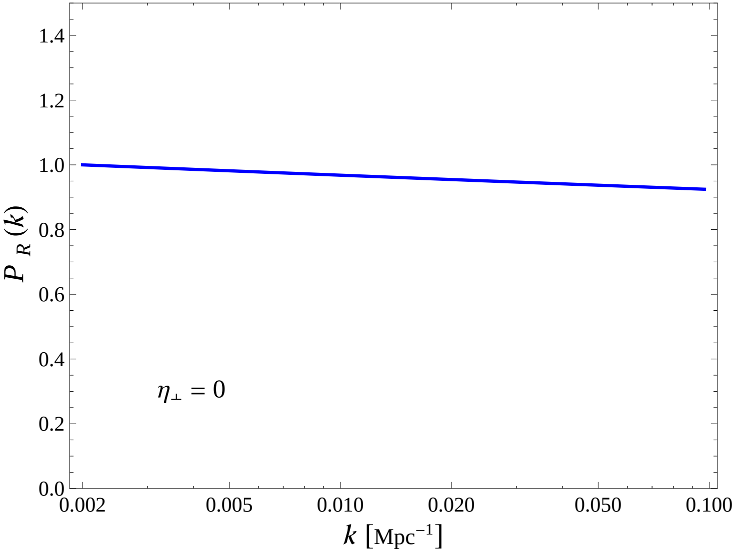
- with $\varphi \equiv e^{\beta/2} v^T$, and
$$e^{\beta(\tau,k^2)} \equiv 1 + 4\eta_\perp^2 \left(\frac{M^2}{H^2} - 2 + \epsilon - \eta_\perp^2 + \frac{k^2}{a^2H^2} \right)^{-1}$$

Numerics

We numerically evaluate the power spectrum from the full coupled equations, and from the effective theory. We evaluate the resulting power spectrum from a single sudden bend in field space preserving slow roll. We pick a fiducial background solution which renders the attractor values $\epsilon = 0.022, \eta_{||} = 0.034$ in the absence of any bending in field space. N.B. in what follows, we have COBE normalized at the pivot scale $k_* = 0.002 Mpc^{-1}$.


1.4
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0.4
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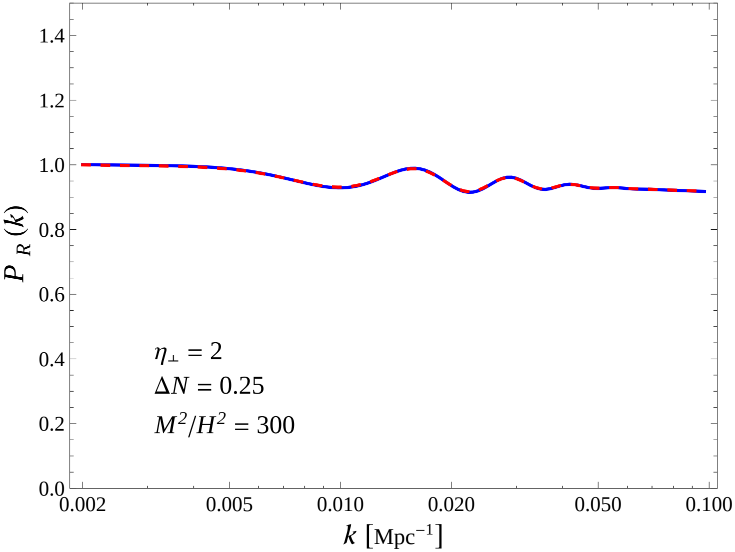
0.0
$P_R(k)$
$\eta_\perp = 0$
0.002
0.005
0.010
0.020
0.050
0.100
k [Mpc^{-1}]



1.4
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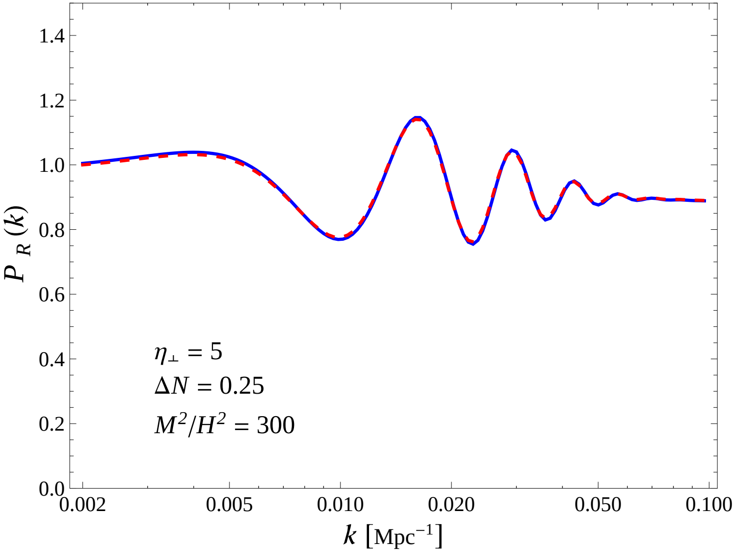
k [Mpc^{-1}]
$P_R(k)$
$\eta_\perp = 2$
$\Delta N = 0.25$
$M^2/H^2 = 300$



1.4
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0.100
$P_R(k)$
k [Mpc^{-1}]
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$\Delta N = 0.25$
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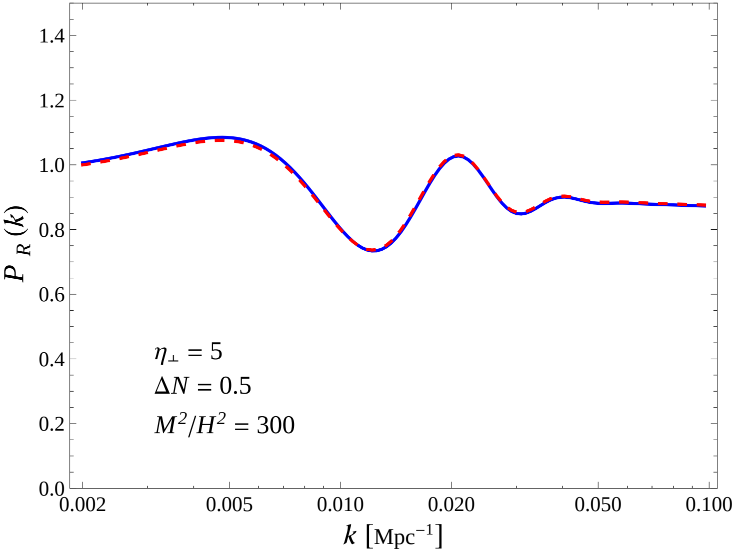

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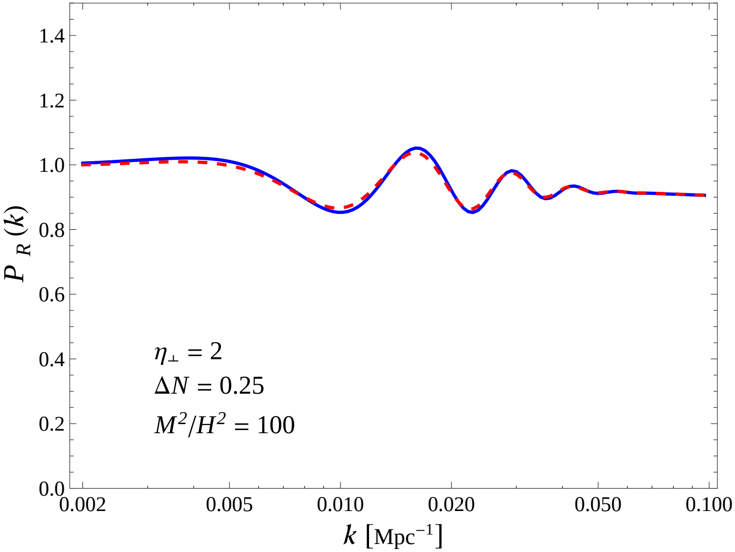

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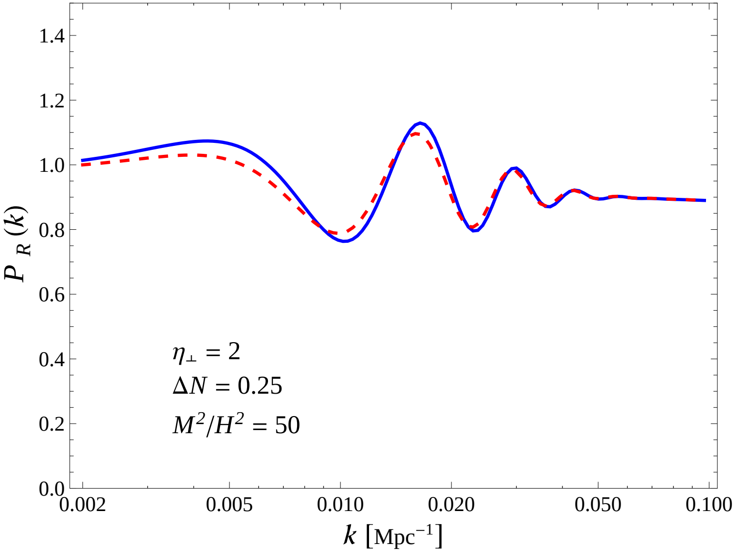
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A toy model

We now explore a concrete model that generates the requisite functional behaviour for $\eta_\perp$ and the slow roll parameters. Consider the two field model with the fields $\phi^1 = \chi, \phi^2 = \Psi$, and the sigma model metric:

- $\gamma_{ab} = \begin{pmatrix} 1 & \Gamma(\chi) \\ \Gamma(\chi) & 1 \end{pmatrix}$, with $\Gamma^2(\chi) < 1$

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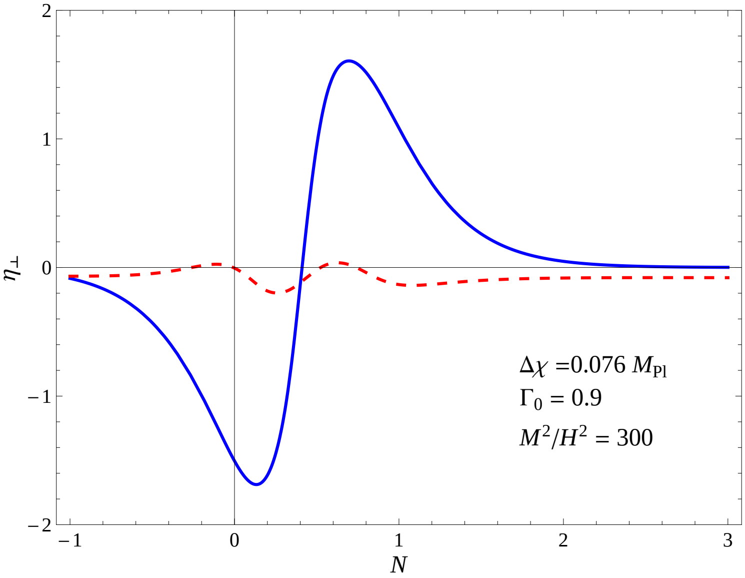
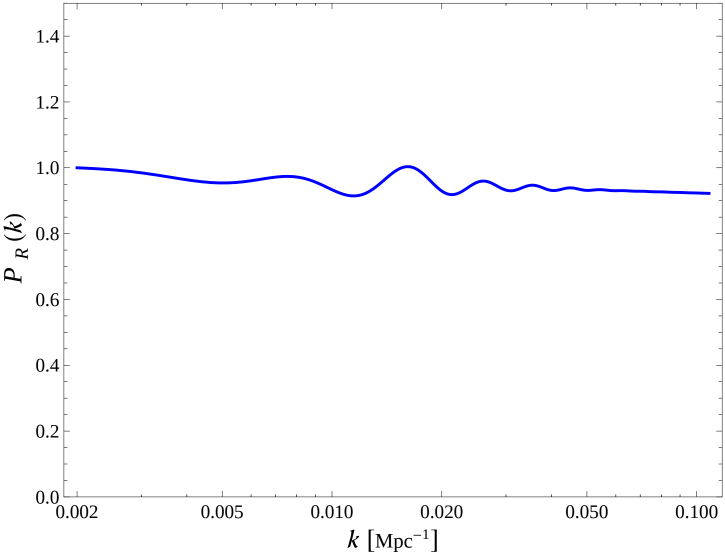


Solid line $= \eta_\perp$, dashed line $= 10 \times \eta_{||}$ as functions of e -fold number N



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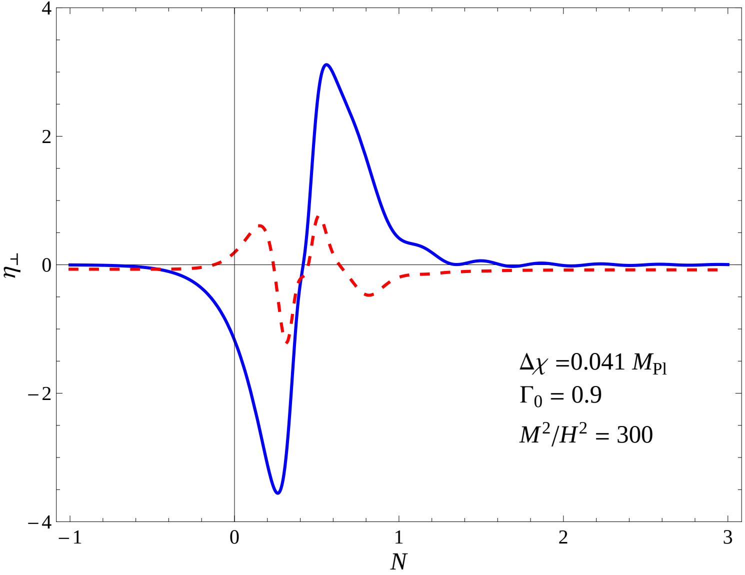

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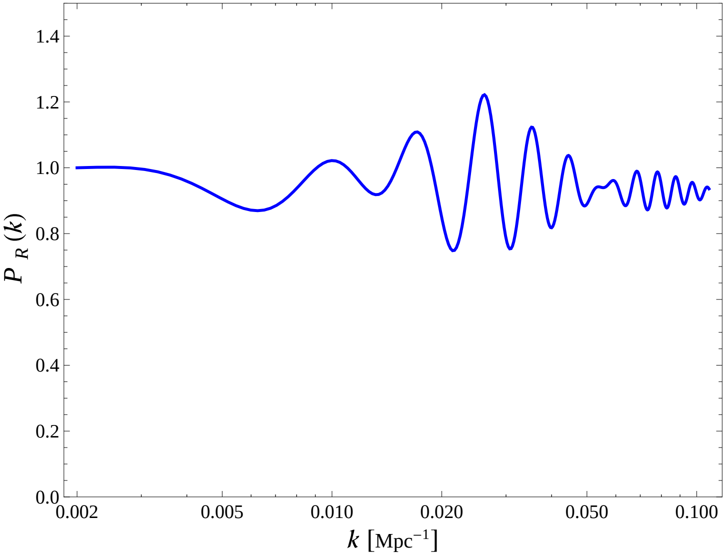
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0.050
0.100
$P_R(k)$
k [Mpc^{-1}]

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- Much more quality data to come!