Planckian Features in the Cosmic Microwave Background

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Outline

Introduction and overview

- Observing *quantum gravity* (QG) effects is extremely difficult

$$M_{\mathrm{Pl}} \sim 10^{16}\ \mathrm{TeV}$$

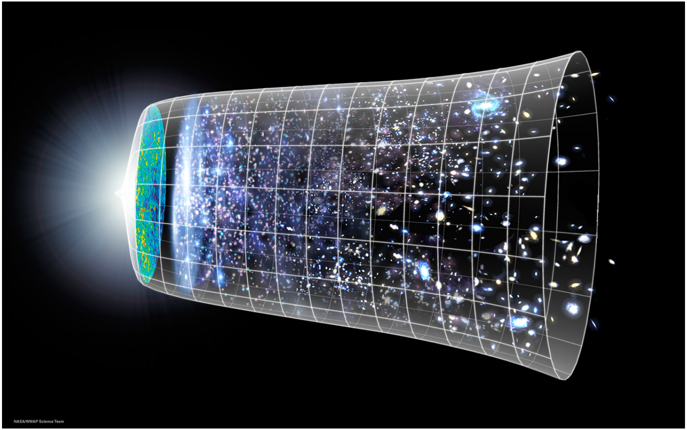
- Better prospects in the *Cosmic Microwave Background* (CMB)
  - relevant scales of CMB origin (inflation) much closer to M_{Pl}

- Today: study how (QG-motivated) *minimal length* manifested in primordial power spectrum

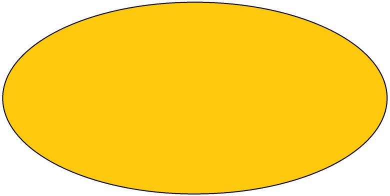
Plan for today

Outline

History of the Universe



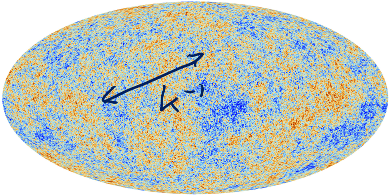
A coarse look at the CMB



~ 3 K

A finer look at the CMB

"F.T. of Temp. distro."



$\longrightarrow$ "Primordial Power Spectrum"

plasma phys...

$$\Delta^2_{\mathcal{R}}(k) = A_s \left(\frac{k}{k_P}\right)^{n_s - 1}$$

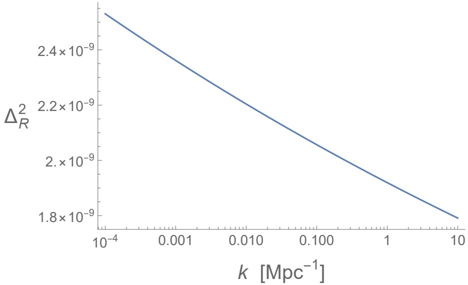
Primordial (scalar) power spectrum

$$\Delta^2_{\mathcal{R}}(k) = A_s \left(\frac{k}{k_P}\right)^{n_s - 1}$$

k_P : pivot scale, $0.05\ \mathrm{Mpc}^{-1}$

A_s : scalar fluctuation amplitude, $\sim 2.1 \times 10^{-9}$

n_s : scalar spectral tilt, ~ 0.97

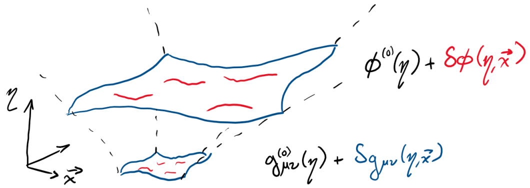


Inflation and the primordial power spectrum

Major success of *inflation* and *theory of cosmological perturbations*

- → predicts* this primordial power spectrum

- → literally, power spectrum of correlation function of quantized primordial scalar d.o.f.



$$\Delta^2_{\mathcal{R}}(k) = (\text{prefactors}) \cdot \mathrm{FT}\left[\langle 0|\hat{r}(\eta, 0)\hat{r}(\eta, \vec{x})|0\rangle\right]$$

$$= \left.\frac{H^2}{\pi \epsilon M_{\mathrm{Pl}}^2}\right|_{aH=k}$$

Planck and Hubble scales

$$\Delta^2_{\mathcal{R}}(k) = A_s \left(\frac{k}{k_P}\right)^{n_s - 1} = \left.\frac{H^2}{\pi \epsilon M_{\rm Pl}^2}\right|_{aH=k}$$

Size of QG effects controlled by $\left(H/M_{\rm Pl}\right)^{1.5}$

$$\left.\frac{H}{M_{Pl}}\right|_{aH=k} = \sqrt{\pi \epsilon A_s} \left(\frac{k}{k_P}\right)^{n_s-1} \sim 5\times 10^{-6}$$

$$k \in (10^{-4}, 10)\ \mathrm{Mpc}^{-1}$$

Outline

Minimum length

Idea: Any effective theory of quantum fields coupled to gravity should come with a notion of a *finite minimum length*, or *natural UV cutoff*

Intuition?

$\delta x \searrow \;\Rightarrow\; \delta p \nearrow \;\rightarrow\; \delta R \nearrow \;\Rightarrow\; \delta x \nearrow$

Want a covariant notion of min length for scalar fields

(isolate min length effects from breaking diffeos)

Idea: Given $\{\mathcal{M}, \phi\}$, cut off $\operatorname{spec} \Box$

i.e. let $\{u_\lambda\}$ be an eigenfunction basis, $\Box u_\lambda = \lambda u_\lambda$

$$\phi(x) = \sum_\lambda \phi_\lambda u_\lambda(x) \;\mapsto\; \sum_{|\lambda| \le \Omega^2} \phi_\lambda u_\lambda(x)$$

Intuition:

$$\mathcal{M} = \mathbb{R}, \quad \Box = -\frac{d^2}{dx^2}, \quad u_\lambda(x) = e^{ikx} \; (\lambda = k^2)$$

Ω: limit on k
max. freq.

Remark: information-theoretic interpretation as cutoff on density of degrees of freedom in spacetime

How does one “implement” this?

A: Restrict domain of *path integration*

Example: Feynman propagator

$$iG_F(x,x') = \frac{\int \mathcal{D}\phi \; \phi(x)\phi(x') e^{iS[\phi]}}{\int \mathcal{D}\phi \; e^{iS[\phi]}} \mapsto \frac{\int_{B_{\mathcal{M}}(\Omega)} \mathcal{D}\phi \; \phi(x)\phi(x') e^{iS[\phi]}}{\int_{B_{\mathcal{M}}(\Omega)} \mathcal{D}\phi \; e^{iS[\phi]}}$$

Planck-scale cutoff: $\Omega \sim M_{\mathrm{Pl}}$

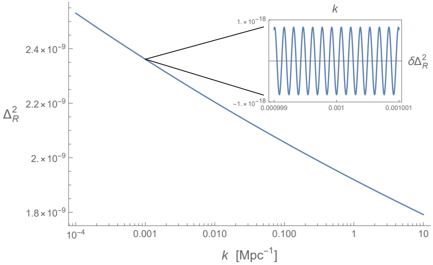
Outline

The last example was no accident

$$\Delta^2_{\mathcal{R}}(k) = 4\pi k^3 \left| G_F(\eta; k) \right|_{aH=k}$$

- $G_F \to G_F^{\Omega}$ results in small correction $\Delta^2_{\mathcal{R}} \to \Delta^2_{\mathcal{R}} + \delta\Delta^2_{\mathcal{R}}$
- So, what does $\delta\Delta^2_{\mathcal{R}}(k)$ look like?

Small superposed oscillations



- amplitude tracks $(H/\Omega)^{3/2}$, $\delta\Delta/\Delta \sim 10^{-9}$
- frequency is more robust
  - $\rightarrow$ approx. constant on log scale, ~ 30 "kHz" for $\Omega = M_{\mathrm{Pl}}$
- Free parameter: location of cutoff scale

$$\Omega = \frac{M_{\mathrm{Pl}}}{\mu} \qquad \text{(presumably } \mu \geq 1\text{)}$$

Observational prospects

→ relative amplitude is small (1 part in 10^9), but still closer to Planck scale than laboratory scales

→ but, we should be more ambitious

Templates...

- let $b_0(k)$ denote the predicted signal $\delta\Delta_{\mathcal{R}}(k)$
- for $10^{-4}\ \mathrm{Mpc}^{-1} < k < 10\ \mathrm{Mpc}^{-1}$, relative power in signal $\delta\Delta_{\mathcal{R}}(k)$ vs background $\Delta_{\mathcal{R}}(k)$:

$$\frac{|\langle b|\delta\Delta_{\mathcal{R}}^2\rangle|^2}{|\langle b|\Delta_{\mathcal{R}}^2\rangle|^2} \sim 10^{-4}$$

- i.e. win by matching to template instead of directly looking for oscillations
- measure more $k \to$ win more (about 1 order of magnitude per octave)

Outline

Summary

- The Planck scale is far away from laboratory scales, but not too far from the Hubble scale during inflation
- Motivates looking for Planckian features in the CMB
  - Here: covariant natural UV cutoff
- Prediction: small oscillations superposed on primordial power spectrum
  - Free parameter: cutoff scale Ω

What next?

$\rightarrow$ Talk with my observational colleagues, link up with Planck data

fwo Research Foundation Flanders Opening new horizons

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