Probing quantum gravity using precision primordial cosmology

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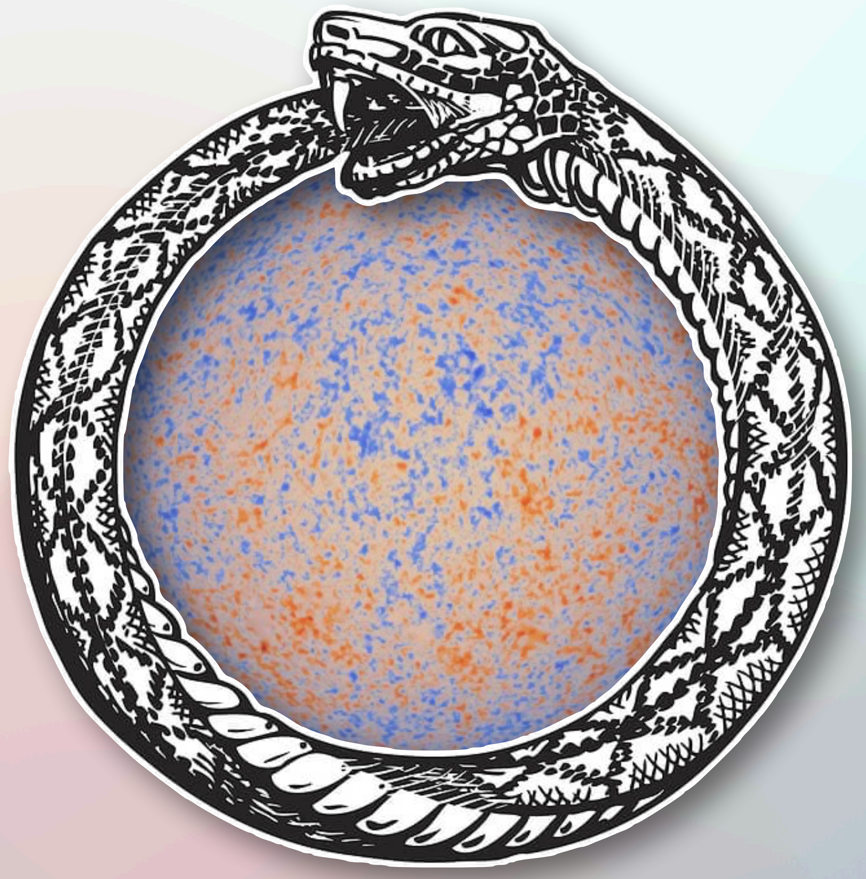
Based on work in collaboration with Eugenio Bianchi [arXiv: 2405.03157 and 2410.11812]



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An Effective Theory for semi-classical Gravity

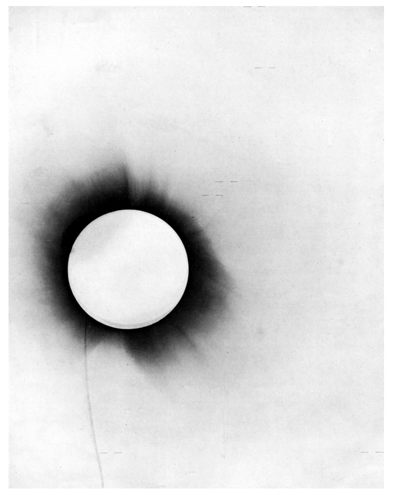
Classical gravity is well understood:

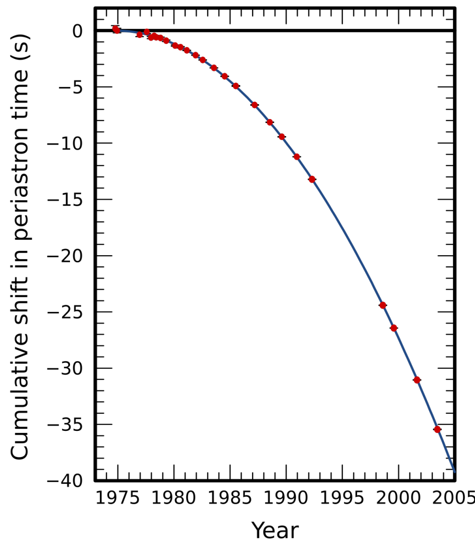
$$S[g_{\mu\nu}] = \frac{1}{16\pi G} \int \mathrm{d}^4x \, \sqrt{-g} \, \big(\underbrace{-2\Lambda}_{\text{const.}} + \underbrace{R}_{(\partial g)^2} \big)$$

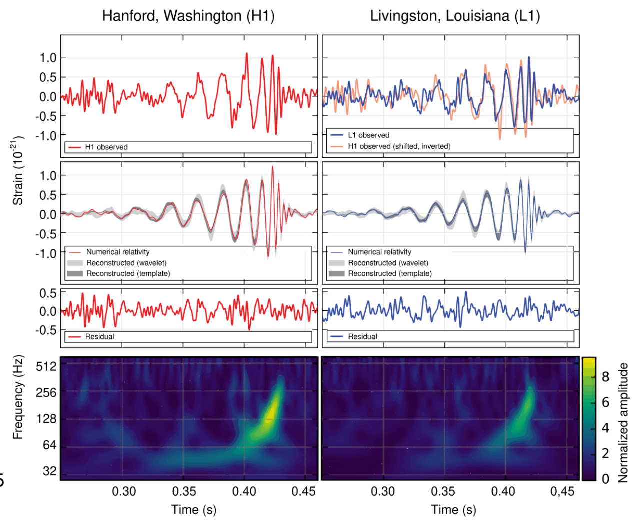
Lorentzian signature, 4 dimensional theory

GR

Accurately describe gravity
at large length scales







An Effective Theory for semi-classical Gravity

Quantum corrections to gravity can be organized as a derivative expansion within the framework of EFT:

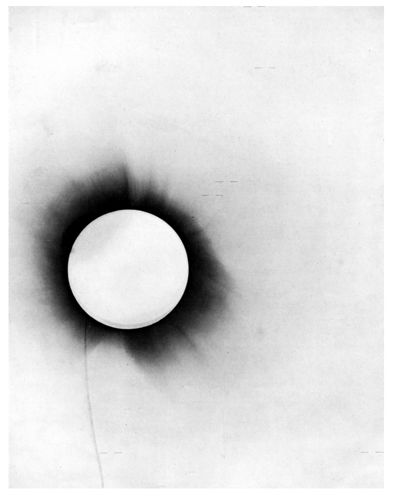
[Stelle '78, Starobinsky '79, Weinberg '08, Anselmi et al. '20]

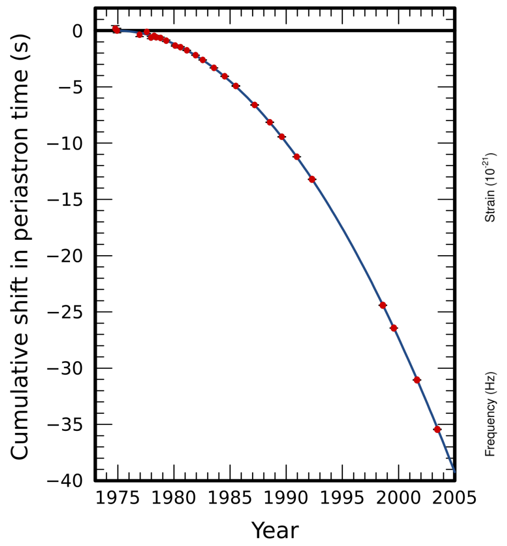
$$S[g_{\mu\nu}] = \frac{1}{16\pi G}\int d^4x\,\sqrt{-g}\,\Big(\underbrace{-2\Lambda}_{\text{const.}} + \underbrace{R}_{(\partial g)^2} + \underbrace{\alpha\,R^2}_{(\partial g)^4} + \underbrace{\beta\,W_{\mu\nu\rho\sigma}W^{\mu\nu\rho\sigma}}_{(\partial g)^4} + \cdots\Big)$$

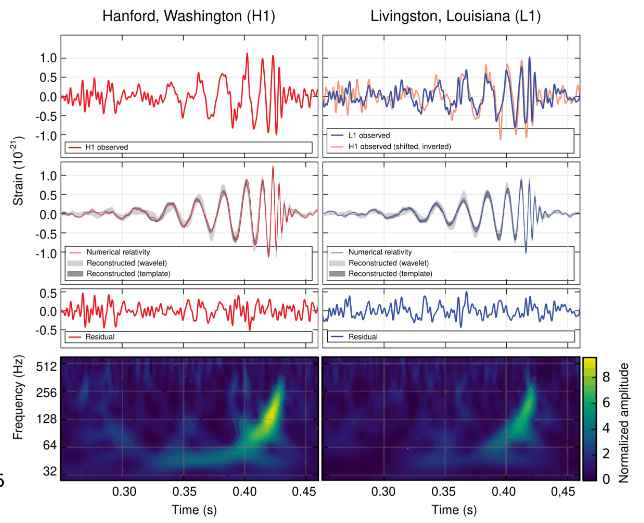
Lorentzian signature, 4 dimensional theory

GR

Accurately describe gravity at large length scales





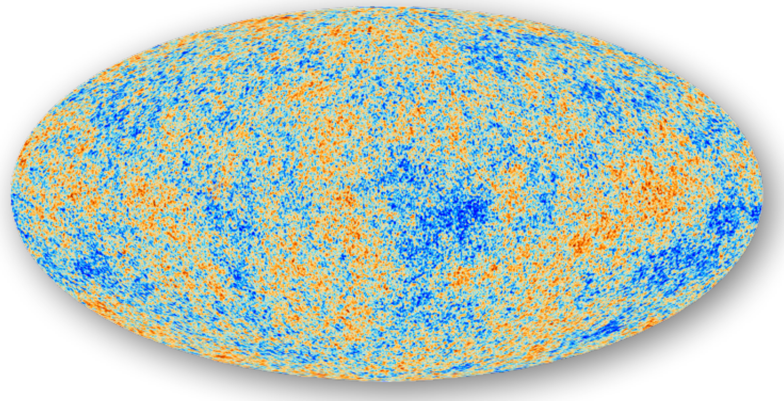


Our contribution

A gravitational EFT for Inflation

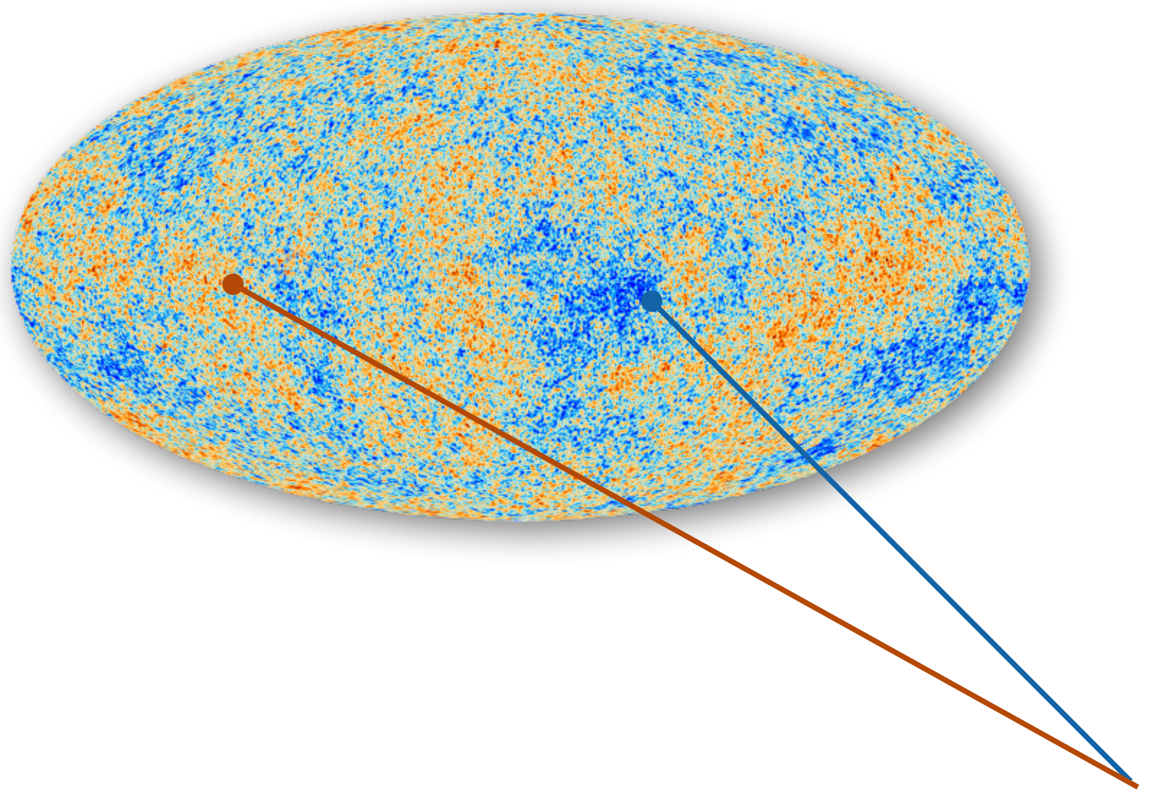
[Bianchi & **Gamonal** '25]

- ✳ DOFs: 2 tensor modes + 1 massive scalar (R^2)
- ✳ W^2 correction treated effectively via reduction of order for $\delta = |\beta/\alpha| \ll 1$
- ✳ Natural gravitational mechanism for observed signatures in the CMB (c.f. Starobinsky inflation)
- ✳ Sensible predictions depend at most on two parameters: α and β. **Theory is testable!**



CMB Temperature anisotropies

$$T(\hat{\mathbf{n}}) = T_0 + \delta T(\hat{\mathbf{n}})$$

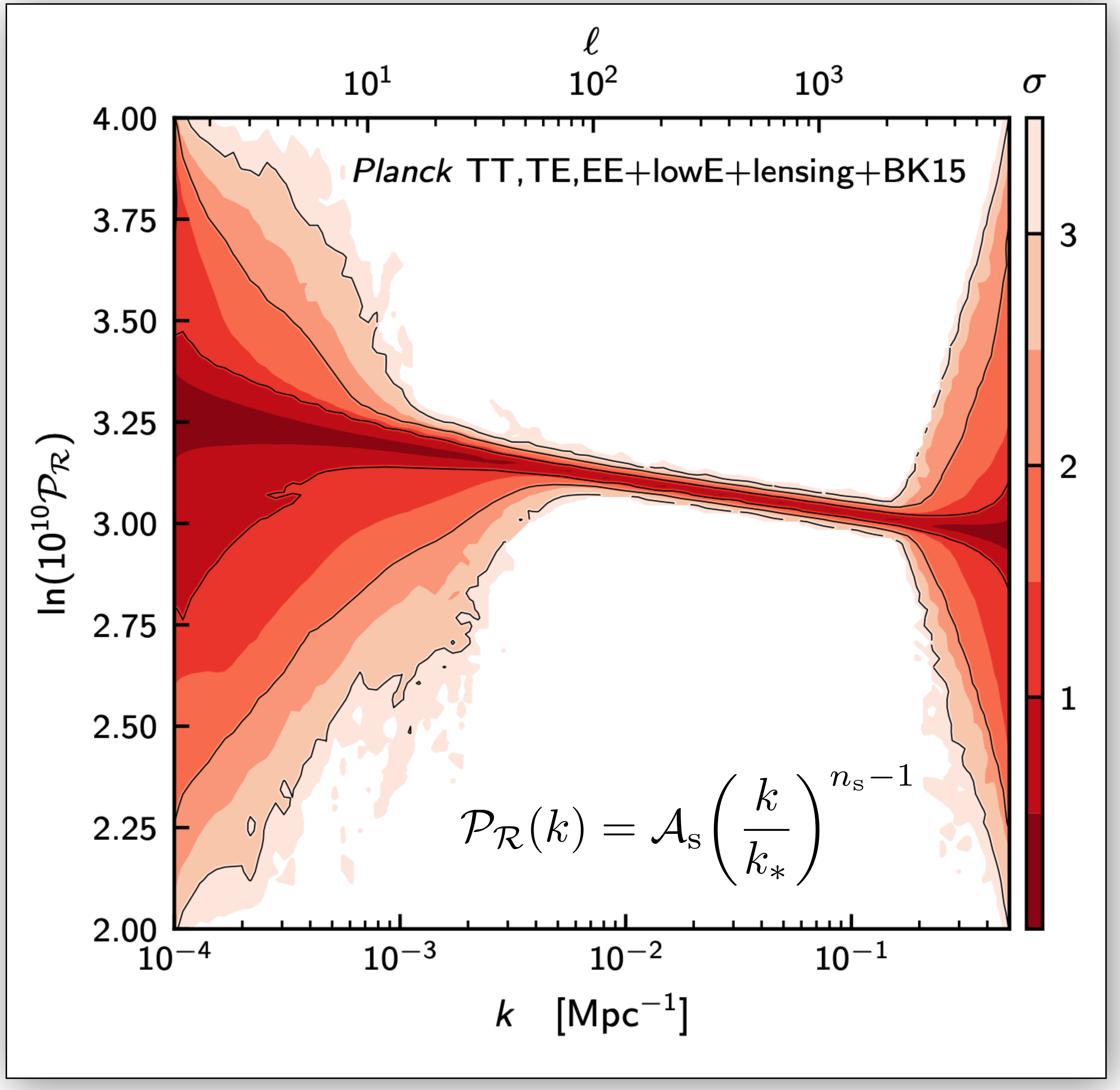


$$\left\langle \frac{\delta T(\hat{\mathbf{n}})}{T_0} \frac{\delta T(\hat{\mathbf{n}}')}{T_0} \right\rangle \propto \Theta(k) \times \mathcal{P}_{\mathcal{R}}(k)$$

CMB physics
(photons & matter)

Primordial curvature
fluctuations

Current constraints



(Planck Collaboration, 2018)

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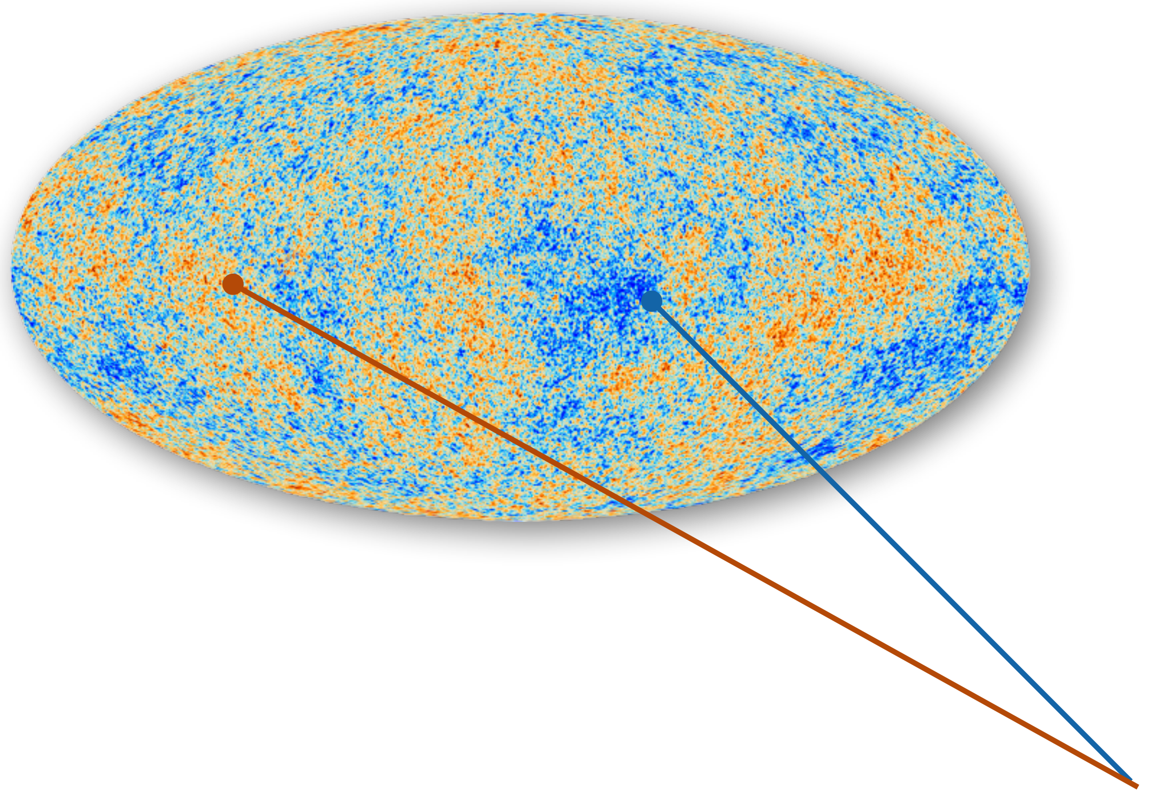
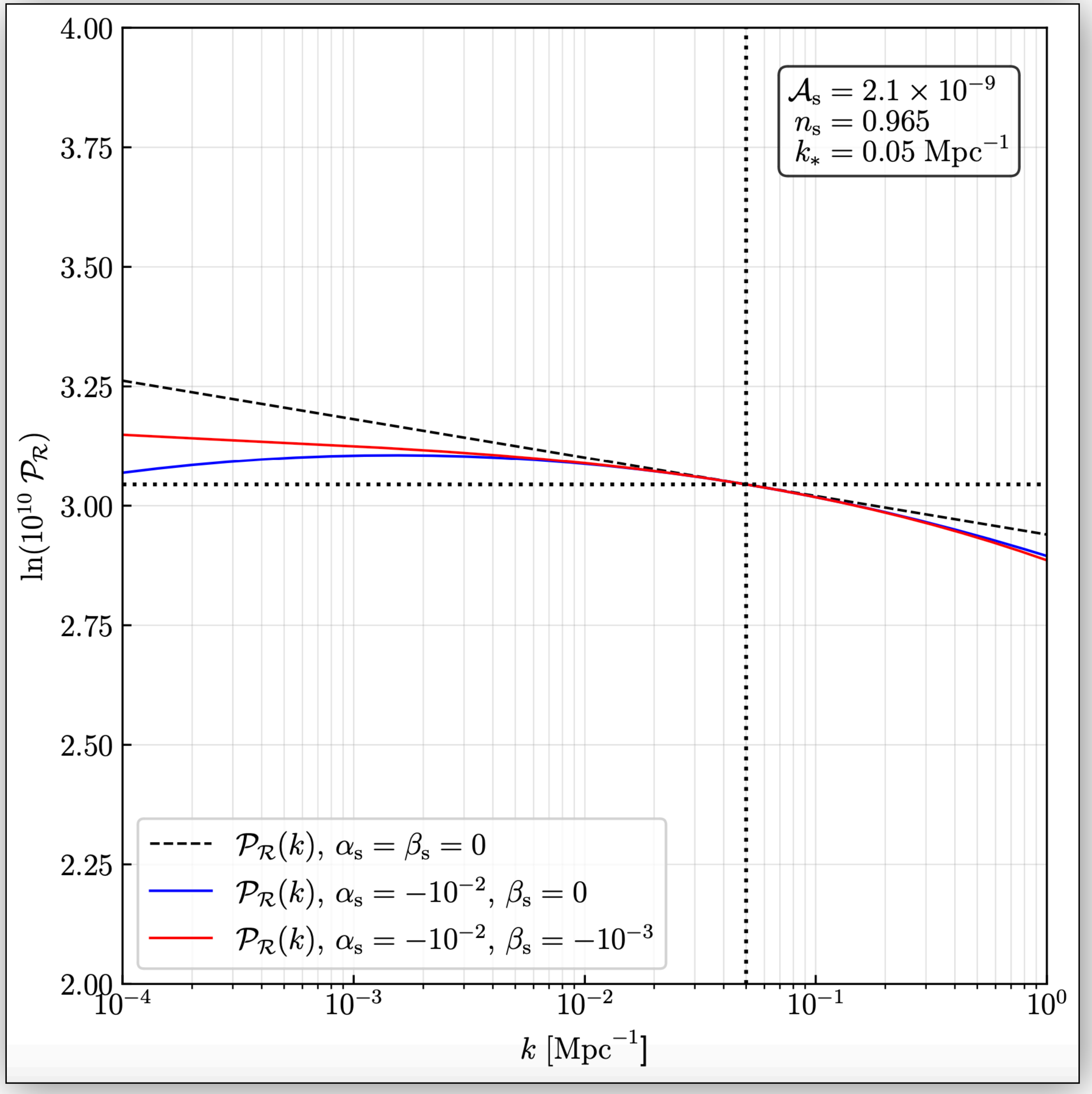


$$\left\langle \frac{\delta T(\hat{\mathbf{n}})}{T_0} \frac{\delta T(\hat{\mathbf{n}}')}{T_0} \right\rangle \propto \Theta(k) \times \mathcal{P}_{\mathcal{R}}(k)$$

Assuming a quasi-de Sitter background, in general we'll have deviations from a power-law:

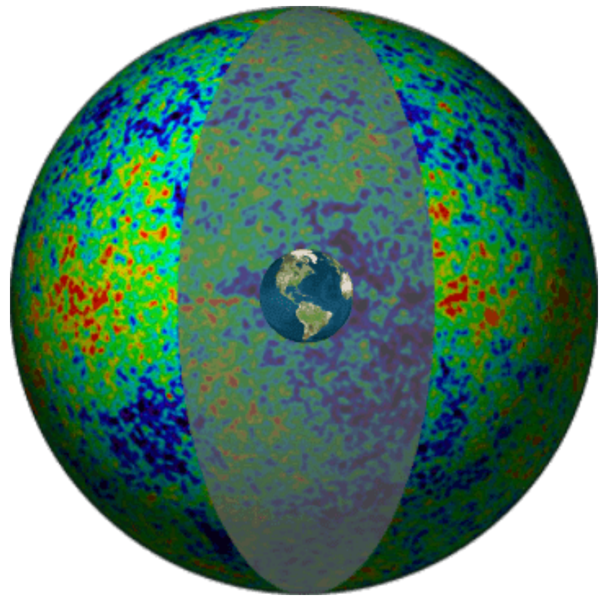
$$\ln(\mathcal{P}_{\mathcal{R}}(k)) = \ln(\mathcal{A}_s) + (n_s - 1)\ln(k/k_*) + \frac{\alpha_s}{2!}\ln(k/k_*)^2 + \frac{\beta_s}{3!}\ln(k/k_*)^2 + \cdots$$



Current CMB Measurements:

(Planck Collaboration, 2018)

$$n_s = 0.9649 \pm 0.0042$$
$$\ln\left(10^{10} \mathcal{A}_s\right) = 3.044 \pm 0.014$$
$$r = \frac{\mathcal{A}_t}{\mathcal{A}_s} < 0.056$$



$$n_s = 1 - \frac{2}{N_*} + \frac{c_1}{N_*^2} + \frac{c_2}{N_*^3} + \cdots \quad \leftrightarrow \quad \text{Fixes value for } N_* \approx 55$$

$$\mathcal{P}_{\text{curvature}}(k_*) = \frac{\ell_P^2 N_*^2}{18\pi\alpha}(1 + \cdots) \equiv \mathcal{A}_s \quad \leftrightarrow \quad \text{Fixes value for coupling } \alpha \approx 2.6 \times 10^{10}\,\ell_P^2$$

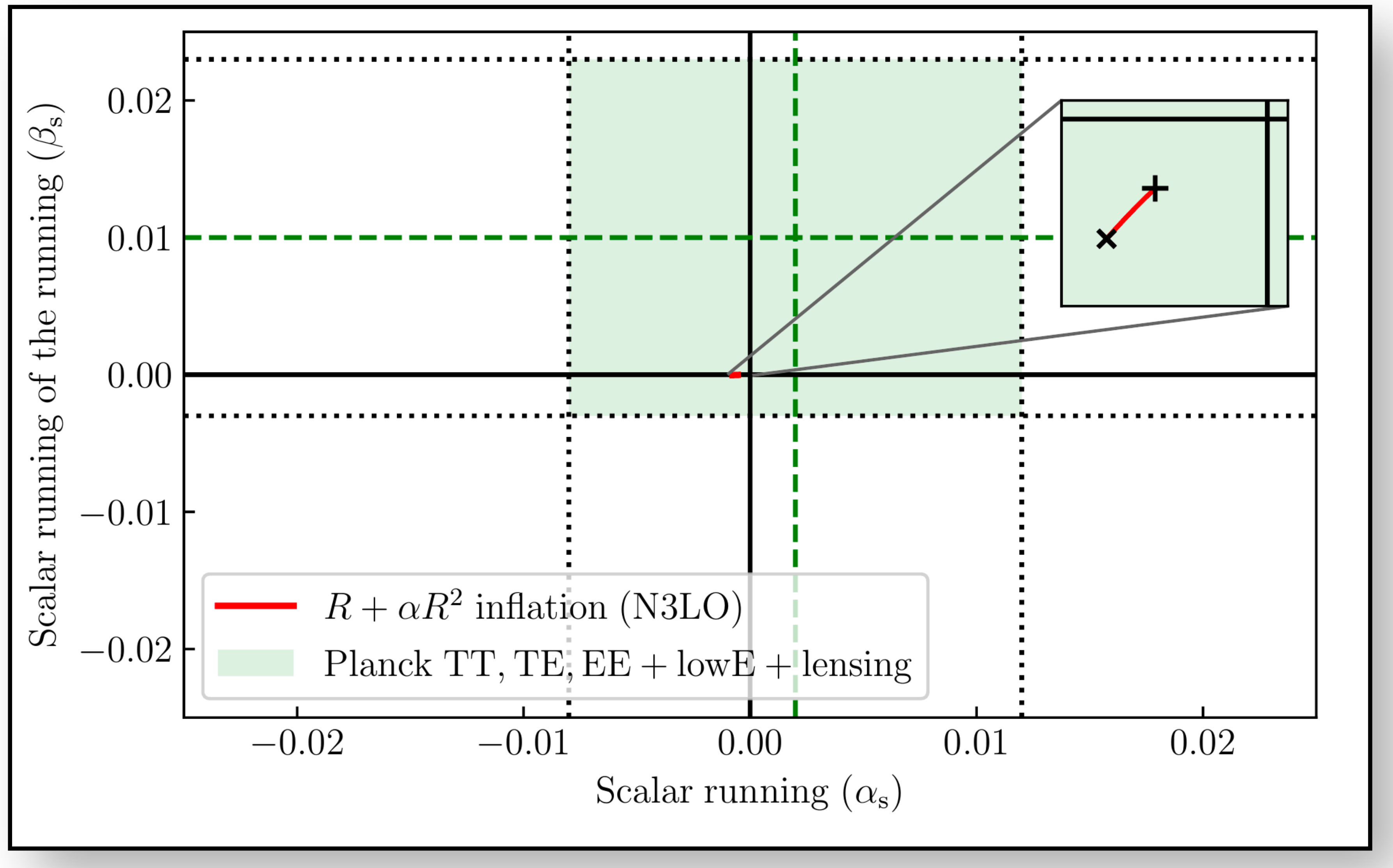
$$\mathcal{P}_{\text{tensor}}(k_*) = \frac{2\ell_P^2}{3\pi\alpha}\left(1 + \frac{\beta}{6\alpha} + \cdots\right) \equiv \mathcal{A}_t \quad \leftrightarrow \quad \text{Sets bound for coupling } \beta\text{: } -6 < \beta/\alpha < 0$$

Any further CMB measurement will put the theory to the test!

(e.g., Euclid, SPHEREx, S.O., DESI, Litebird, SKA)

$$\alpha_s = -\tfrac{1}{2}(n_s - 1)^2 + \tfrac{5}{48}(n_s - 1)^3 + \mathcal{O}\left((n_s - 1)^4\right)$$
$$\beta_s = -\frac{1}{2}(n_s - 1)^3 + \mathcal{O}\left((n_s - 1)^4\right)$$

[Bianchi & **MG**, PRD ’24]



Conclusions

Where are we now with our EFT approach?

We have measured α and set a bound on β. All further CMB measurements will test the rest of predictions of this theory

$$S[g_{\mu\nu}] = \frac{1}{16\pi G}\int \mathrm{d}^4x\,\sqrt{-g}\,\left(-2\Lambda + R + \alpha R^2 + \beta W_{\mu\nu\rho\sigma}W^{\mu\nu\rho\sigma}\right)$$

Cavendish balance

$G \approx 6.67 \times 10^{-11}\,\mathrm{m}^3\,\mathrm{kg}^{-1}\,\mathrm{s}^{-2}$

Accelerated expansion of the late Universe

$\Lambda \approx 1.1 \times 10^{-52}\,\mathrm{m}^{-2}$

Primordial perturbations

$\alpha \approx 7.1 \times 10^{-69}\,\mathrm{m}^2$

$-6 < \frac{\beta}{\alpha} < 0$

In this work we considered these assumptions:

- Metric perturbations around a quasi de Sitter background.
- Vacuum fluctuations of quantized metric perturbations around quasi Bunch-Davies.
- Effects from W^2 may be relevant only at scales much higher than the inflationary scale: $|\beta/\alpha| \ll 1$

Link to the papers and more +

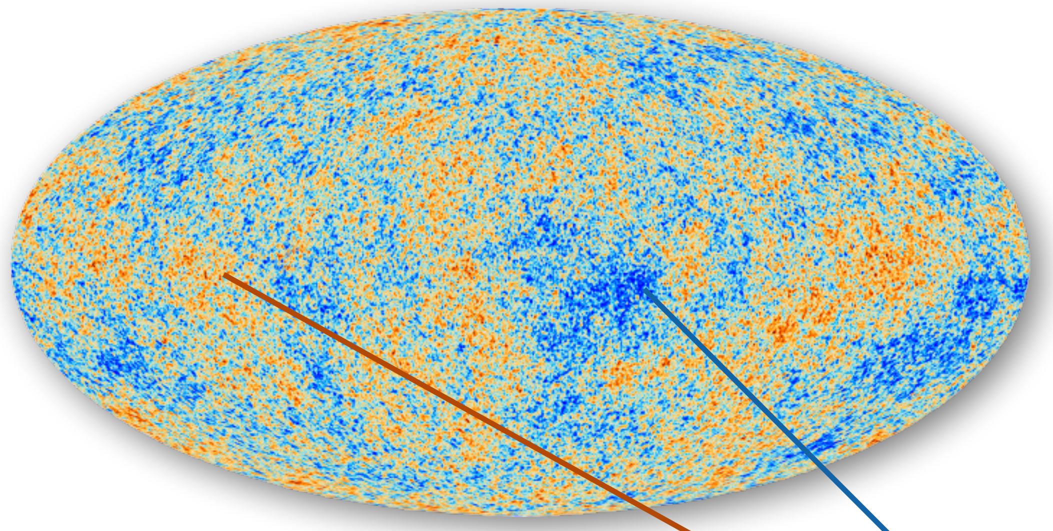
Backup: To study the CMB we developed this framework

[Bianchi & **Gamonal.** PRD '24]

CMB Temperature anisotropies

$$T(\hat{\mathbf{n}}) = T_0 + \delta T(\hat{\mathbf{n}})$$

[Planck Collaboration '18]



Angular correlation function
(ensemble average)

$$\left\langle \frac{\delta T(\hat{\mathbf{n}})}{T_0} \frac{\delta T(\hat{\mathbf{n}}')}{T_0} \right\rangle \propto \Theta(k) \times \mathcal{P}_{\mathcal{R}}(k)$$

CMB physics
(photons & matter)

Primordial curvature fluctuations

I. Quadratic action for generic SVT mode: $g_{\mu\nu} = \bar{g}_{\mu\nu} + \delta g_{\mu\nu}[\Psi]$

$$S^{(2)}_{\Psi}[\Psi] = \frac{1}{2} \int \mathrm{d}^4x \, Z_{\Psi}(t) \, a(t)^3 \left(\dot{\Psi}^2 - \frac{c_{\Psi}(t)^2}{a(t)^2} (\partial_i \Psi)^2 \right)$$

II. Arbitrary FLRW metric (<u>deviations from exact de Sitter</u>)

$$\epsilon_{1H}(t) \equiv -\frac{\dot{H}(t)}{H(t)^2}$$

III. Hubble-flow expansion (<u>deviations from vanilla inflation</u>)

$$\epsilon_{1Z}(t) \equiv -\frac{\dot{Z}_{\psi}(t)}{H(t) Z_{\psi}(t)} \qquad \epsilon_{1c}(t) \equiv -\frac{\dot{c}_{\psi}(t)}{H(t) c_{\psi}(t)}$$

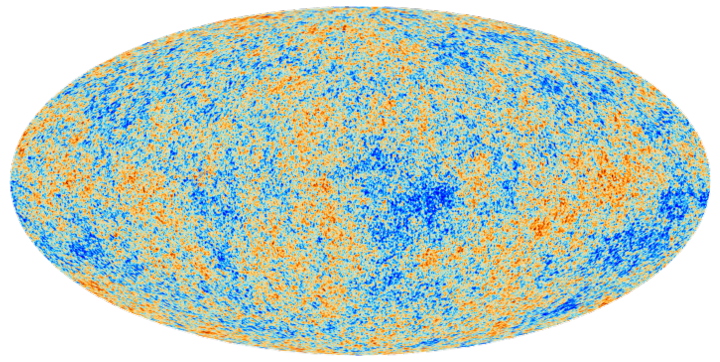
IV. Able to provide very precise predictions (next-to-next-to-next-to leading order)

$$\epsilon_{(n+1)\rho}(t) \equiv -\frac{\dot{\epsilon}_{n\rho}(t)}{H(t)\, \epsilon_{n\rho}(t)} \qquad \text{N3LO} = \mathcal{O}(\epsilon_*^3)$$

Backup: The Technique for the general case: Z_Ψ, c_Ψ arbitrary

How to find analytical expressions for two-point correlation functions?

(Mukhanov-Sasaki+time reparametrization)

Recall:  $\longleftrightarrow$ $\langle 0|\, \hat{\Psi}_f(t)\hat{\Psi}_f(t)\,|0\rangle = \int_0^\infty \frac{\mathrm{d}k}{k}\frac{k^3}{2\pi^2}\,|u(k,t)|^2\,\left|\tilde{f}(k)\right|^2 \longrightarrow \quad u(k,t(y)) \to \frac{y\,w(y)}{\sqrt{2\,k^3\,\mu(y)}}$

New time variable: $y = -k\tau = \frac{k\,\tilde{c}}{aH}$, expansion of $\epsilon_{1H}(t) \to \epsilon_{1H}(y) = \epsilon_{1Hk} + (\ldots) \times \log(y/y_k)$, and so on, around $y_k = 1$:

$$w''(y) + \left(1 - \frac{2}{y^2}\right)w(y) = \frac{g(y)}{y^2}\,w(y)\,, \qquad g(y) = g_{1k} + g_{2k}\ln(y) + g_{3k}\ln(y)^2 + \cdots$$

Leading order: $$w''(y) + \left(1 - \frac{2}{y^2}\right)w(y) = 0 \longrightarrow w(y) = \left(1 + \frac{i}{y}\right)e^{iy} \quad \text{(Bunch-Davies)}$$

NLO: $$w''(y) + \left(1 - \frac{2 + g_{1k}}{y^2}\right)w(y) = 0 \longrightarrow w(y) = \sqrt{\frac{\pi\,y}{2}}\,H_\nu^{(1)}(y)$$

N2LO: $$w''(y) + \left(1 - \frac{2 + g_{1k} + g_{2k}\ln(y)}{y^2}\right)w(y) = 0 \longrightarrow w(y) = ???$$

Backup: Beyond slow-roll inflation and quasi Bunch-Davies

Assuming a pre-inflationary epoch
(signatures of a Quantum Gravity era?)

$$\tilde{w}(y) = \alpha_k\, w(y) + \beta_k\, w(y)^*$$

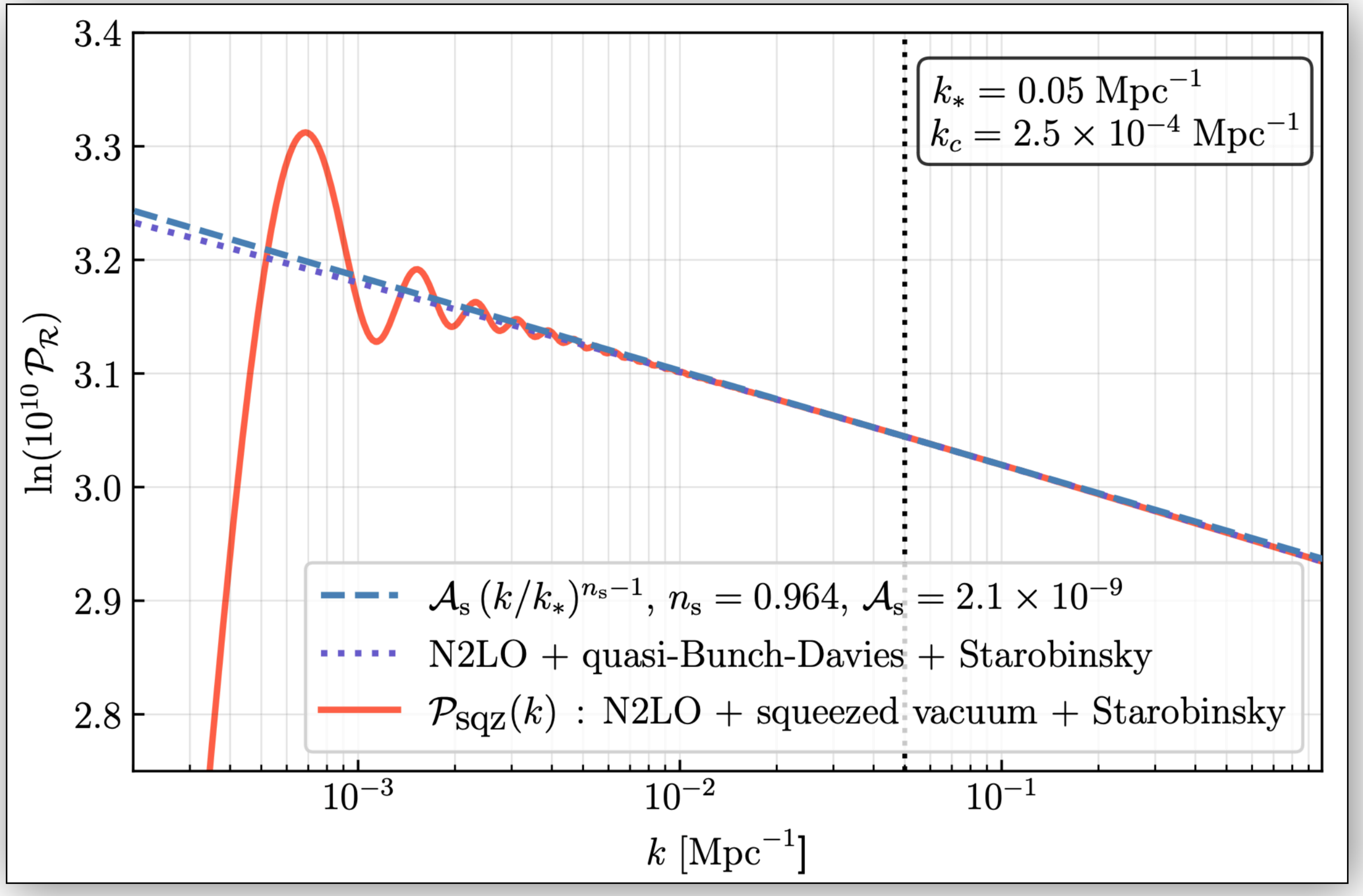
qBD becomes a reference for the new squeezed state:

$$|\text{sqz}\rangle = \frac{1}{\sqrt{\mathcal{N}}} \exp\!\left(-\int \frac{d^3\mathbf{k}}{(2\pi)^3} \frac{1}{2} \frac{\beta_k^*}{\alpha_k^*} \hat{a}^\dagger(\mathbf{k}) \hat{a}^\dagger(-\mathbf{k})\right) |\text{qBD}\rangle,$$

Squeezed vacua induce power suppression and modulations

$$\mathcal{P}_{\mathcal{R}}^{(\text{sqz})}(k) = |\alpha_k - e^{i\delta_k} \beta_k|^2 \mathcal{P}_{\mathcal{R}}^{(0)}(k)$$

[Bianchi & **Gamonal** '24; arXiv: 2410.11812]



Relevant for templates used to study primordial features

$$\mathcal{P}_{\mathcal{R}}^{(\text{phen})}(k) = \Big[1 - R_k \cos\left(\Xi_k + \delta\right)\Big] \left(\frac{k}{k_*}\right)^{n_s - 1} \mathcal{A}_s,$$

Backup: Pre-inflationary epoch and Squeezed vacua

Note that: $$\Upsilon(k) \equiv \frac{\mathcal{P}_{\rm sqz}(k)}{\mathcal{P}_{\rm qBD}(k)} = \lim_{y\to 0^+} \frac{|\alpha_k\, y\, w(y) + \beta_k\, y\, w^*(y)|^2}{|y\, w(y)|^2}$$
$$= \lim_{y\to 0^+} \left| \alpha_k + \beta_k \frac{w^*(y)}{w(y)} \right|^2$$

$$\Upsilon(k) = \left|\alpha_k - \beta_k\, \mathrm{e}^{\mathrm{i}\delta_k}\right|^2$$

Generic feature,
present at all orders

[Bianchi & MG, 2024b]

with $$\delta_k^{(\rm N2LO)} = -\frac{\pi}{3} g_{1k} + \frac{\pi}{27}\left(g_{1k}^2 + (9\,C - 3)\, g_{2k}\right) + \mathcal{O}(\epsilon^3)$$
$$= \frac{\pi}{2}(n_{\rm s} - 1) - \frac{\pi}{4}(n_{\rm s} - 1)^2 \ln\left(\frac{k}{k_*}\right) + \mathcal{O}(\rm N3LO)$$

Leading contributions for
curvature perturbations

The induced phase δ_k only contains information from the Hubble-flow parameters $\epsilon_{1Hk}, \epsilon_{1Zk}, \epsilon_{1ck}, \ldots$

Backup: Pre-inflationary phase and CMB anomalies

[Bianchi & **Gamonal** '25]

An epoch before standard inflation (e.g., a quantum gravity regime) could have a role in explaining/alleviating CMB anomalies, such as the large-scale power suppression.

$$\mathcal{D}_\ell = \frac{\ell(\ell+1)}{2\pi} C_\ell$$