Quantum Gravity and Precision Cosmology

From effective dynamics to primordial observables

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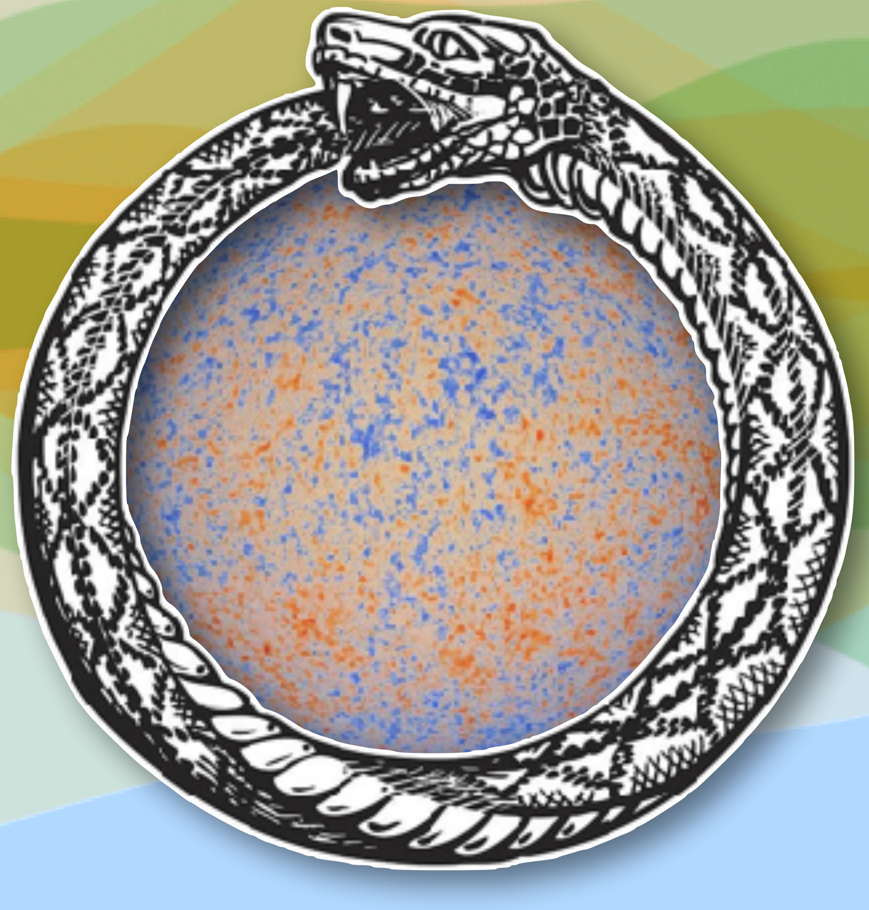

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IGC
PennState Eberly College of Science
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WOST Exploring Quantum Without SpaceTime
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What is my dissertation about?

How the things we know about…

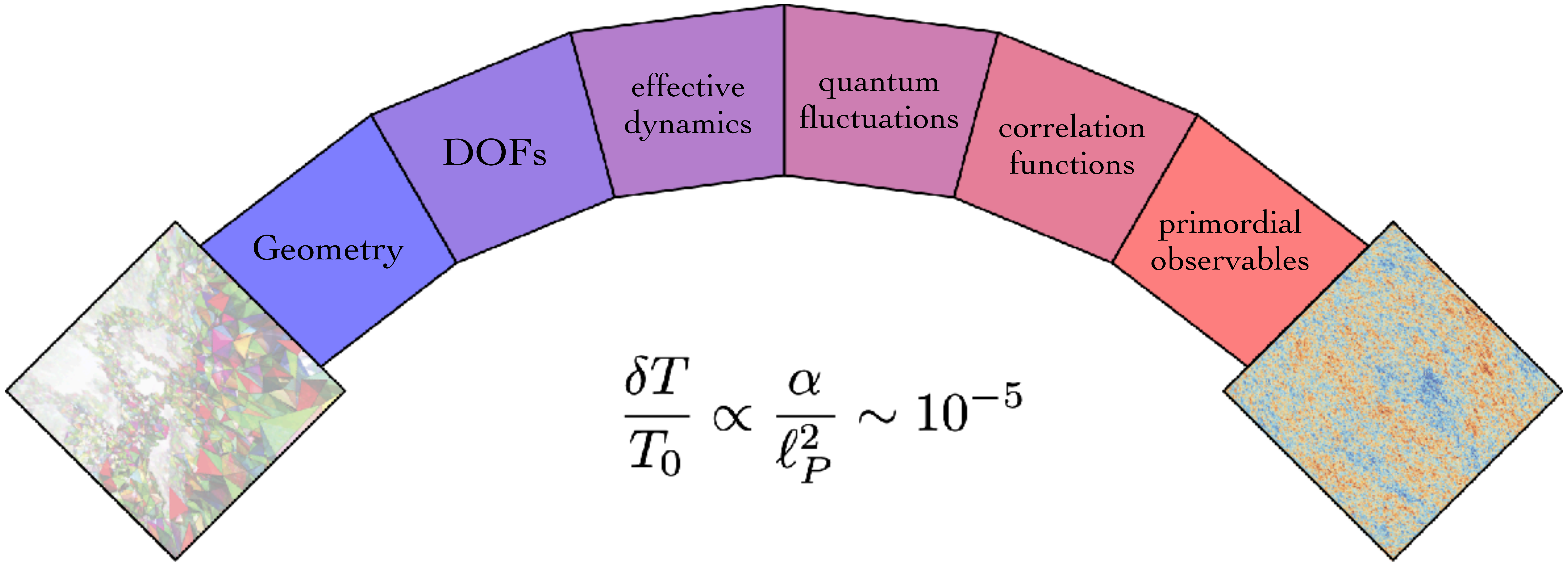
… which can be tested against…

Quantum Gravity and Precision Cosmology

From effective dynamics to primordial observables

…can guide the construction of …

…that provide specific predictions of…

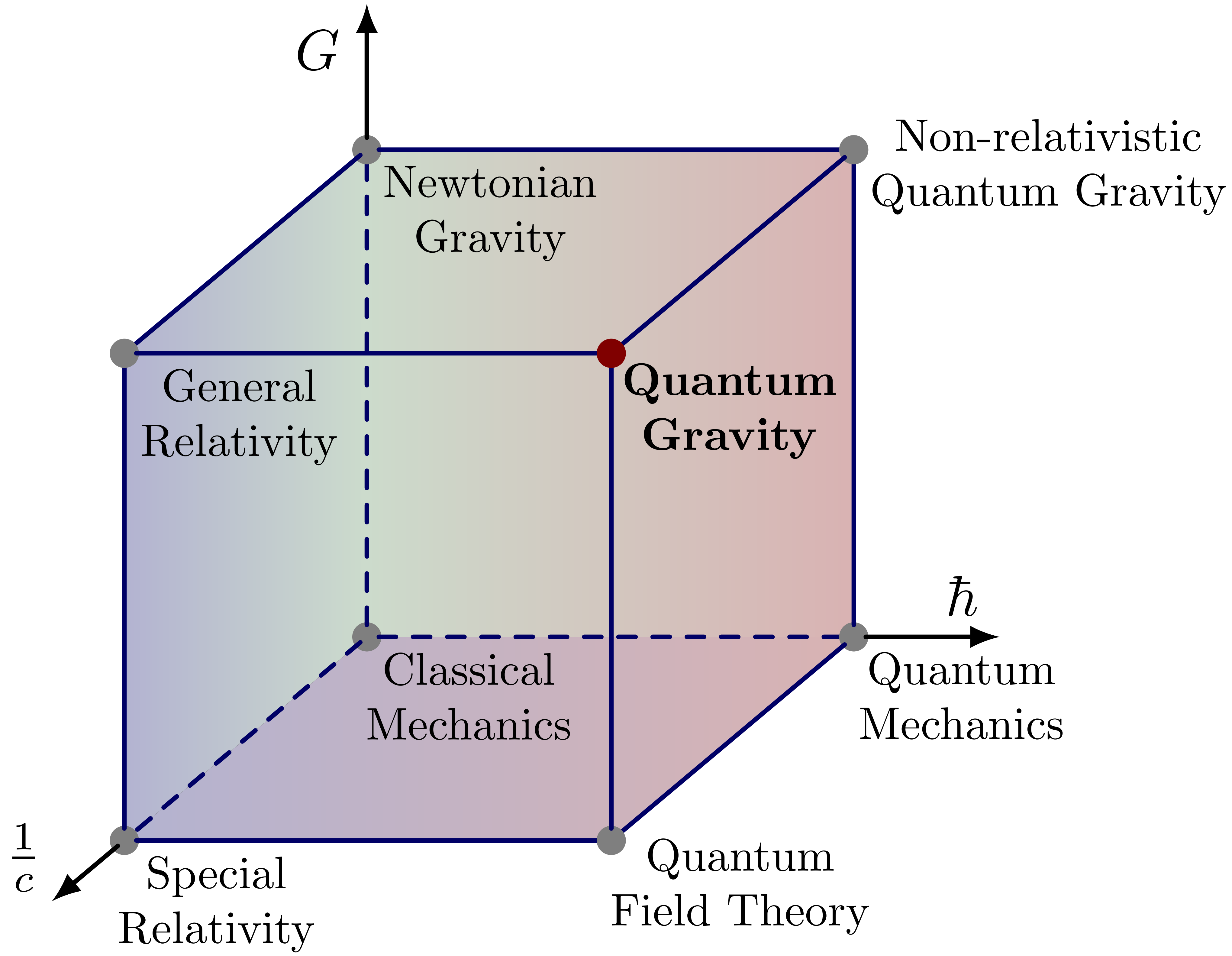


$$\frac{\delta T}{T_0} \propto \frac{\alpha}{\ell_P^2} \sim 10^{-5}$$

We know a few things…

Fundamental physical constants

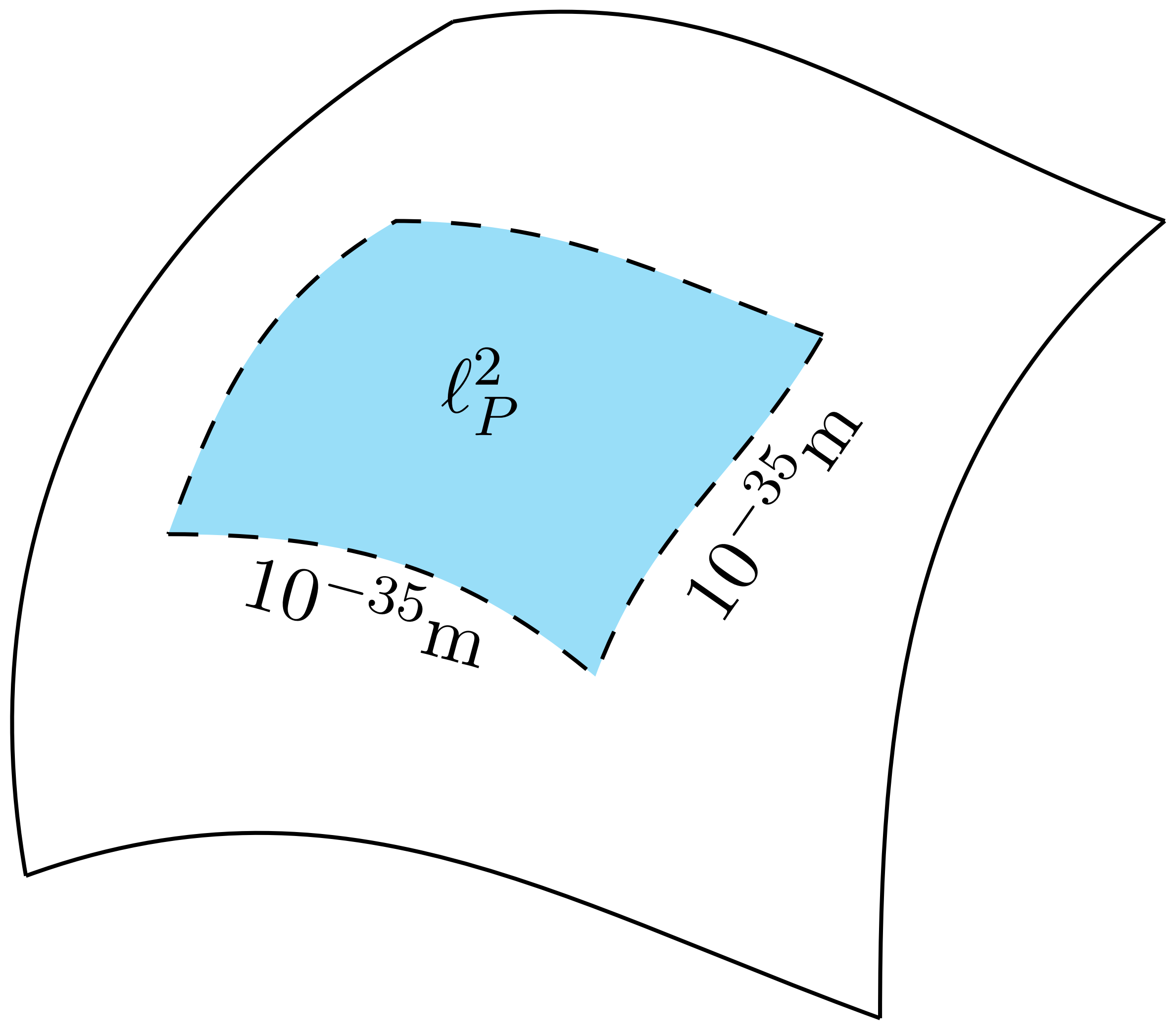
The measured fundamental constants $(c, G, \hbar)$ organizes theoretical frameworks according to the Bronstein cube.



[Bronstein 1933]

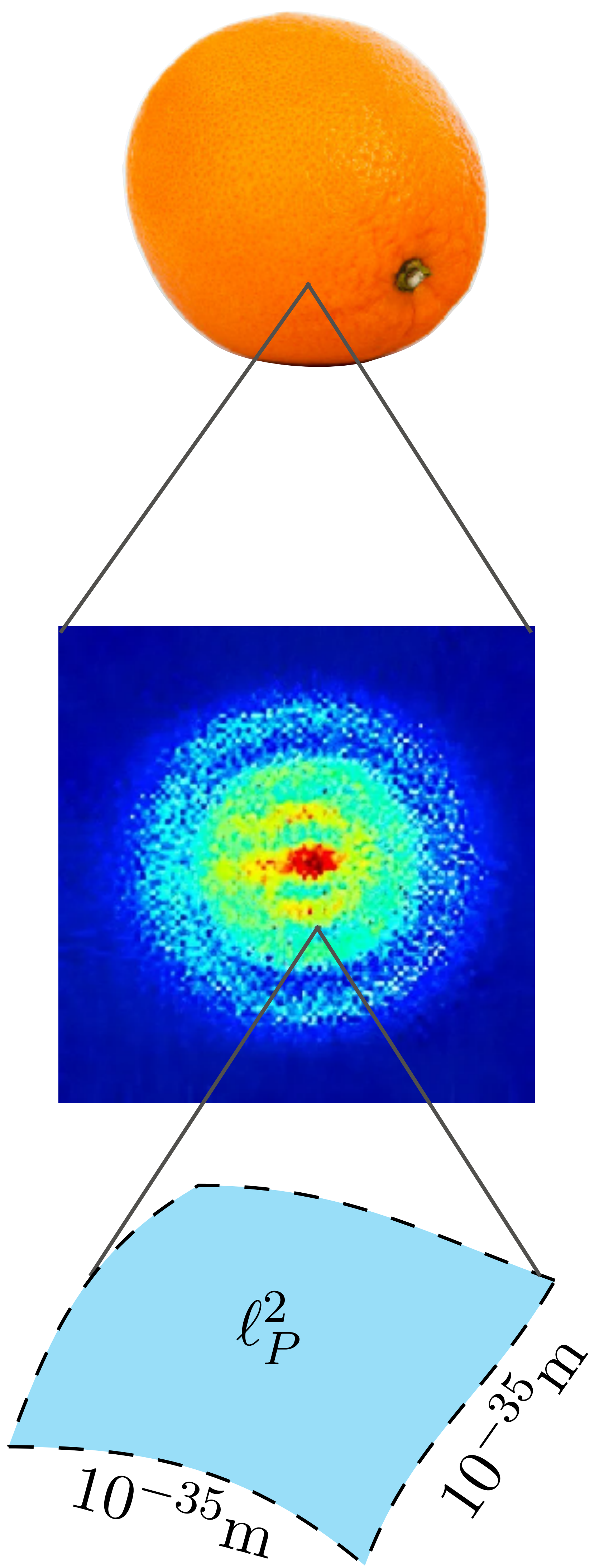
There is a characteristic scale

The presence of c, G and $\hbar$ defines a scale where quantum gravity cannot be neglected. The relevant quantity is the **Planck area:**



$$\ell_P^2 = \frac{G\hbar}{c^3} \sim 10^{-70}\,\mathrm{m}^2$$

To put things into perspective:



this orange
($A \sim 10^{-2}\,\mathrm{m}^2$)

an atom
($A \sim 10^{-20}\,\mathrm{m}^2$)

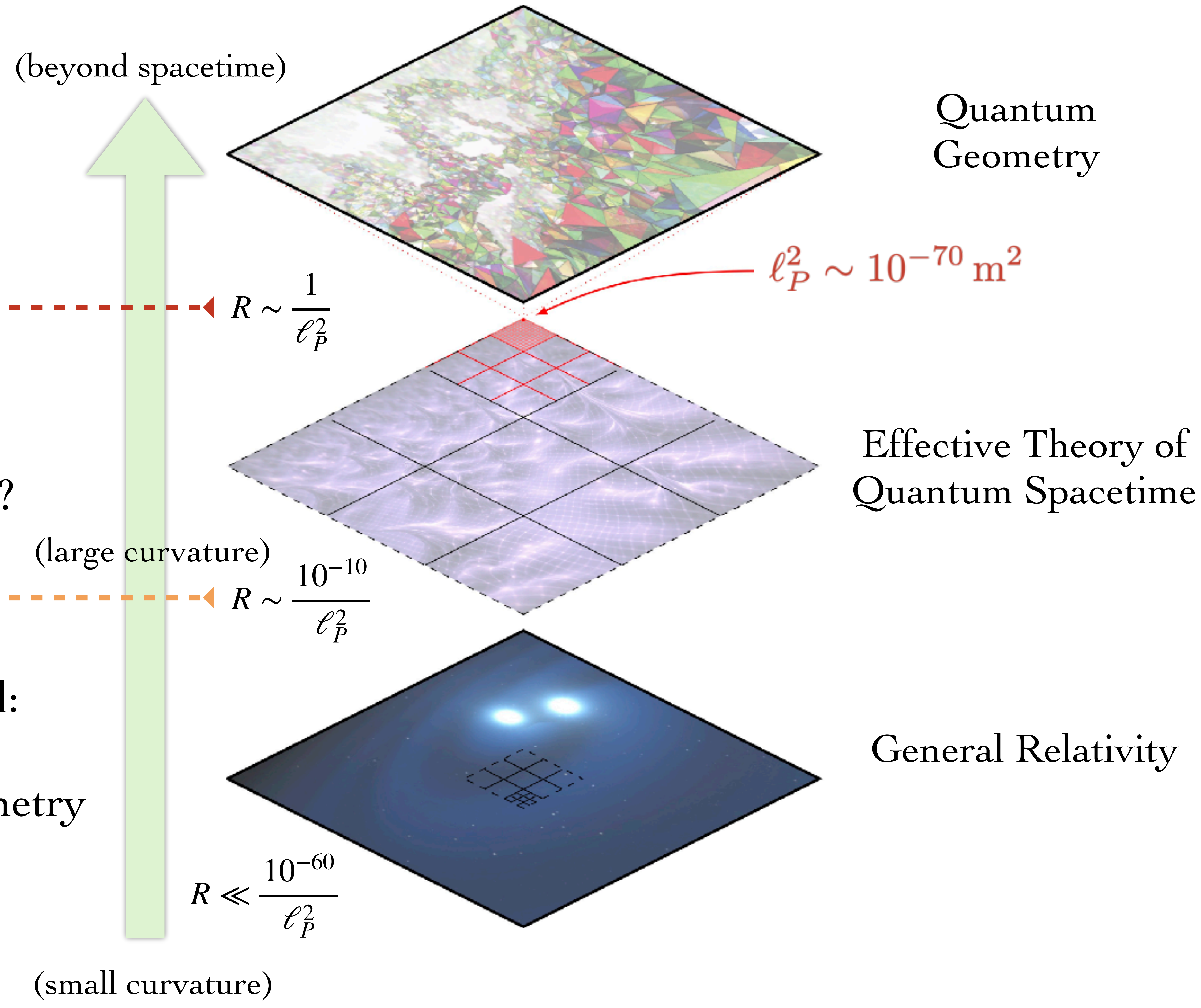
the Planck area
($A \sim 10^{-70}\,\mathrm{m}^2$)

We know a few things…

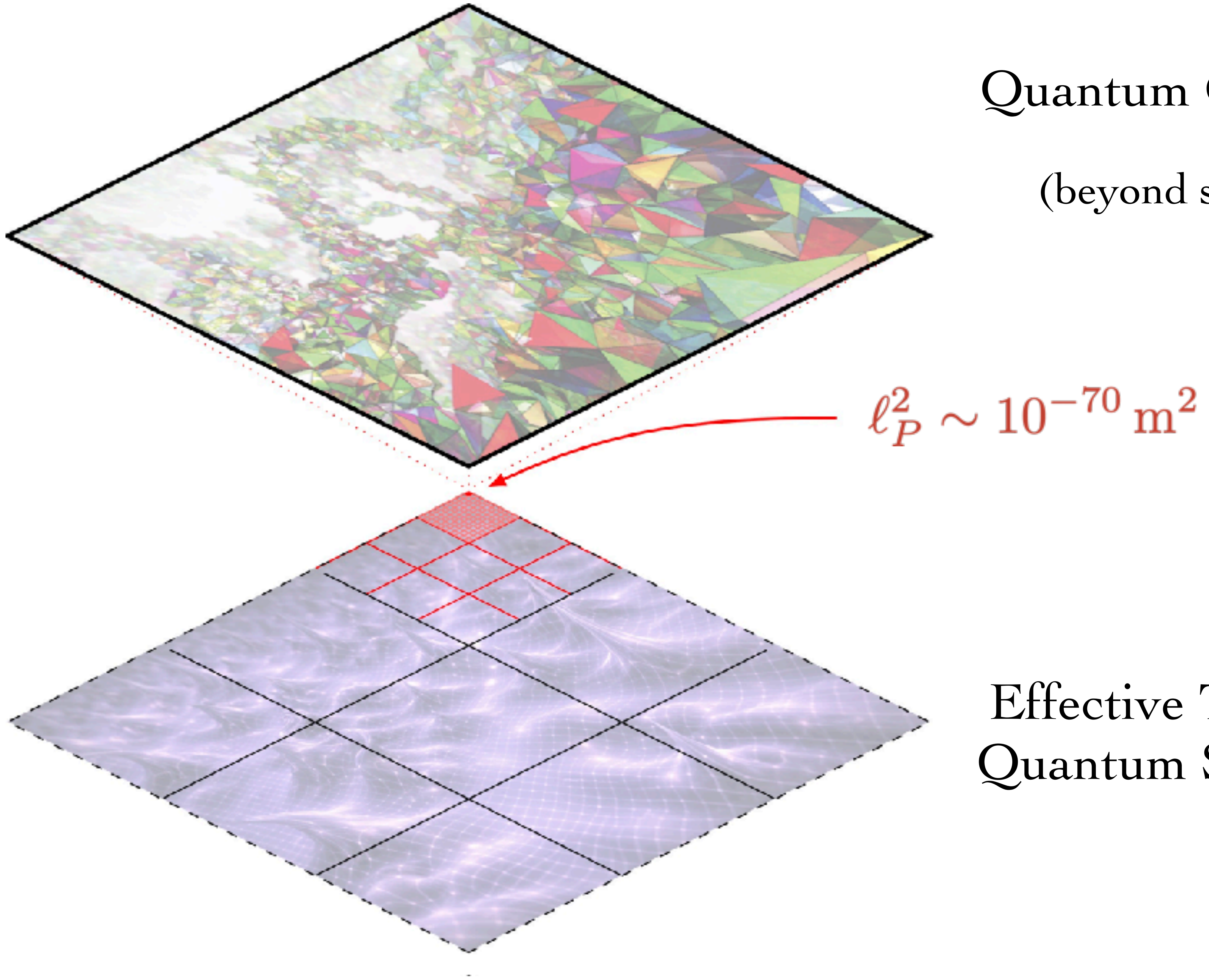
Spacetime must be abandoned by more fundamental structures

Intermediate regime:
- very large curvature, but still not Planckian
- different dynamics, new degrees of freedom?

Classical GR describes gravity extremely well:
- general covariance
- gravity as a manifestation of spacetime geometry



Focus of this presentation



Quantum Geometry

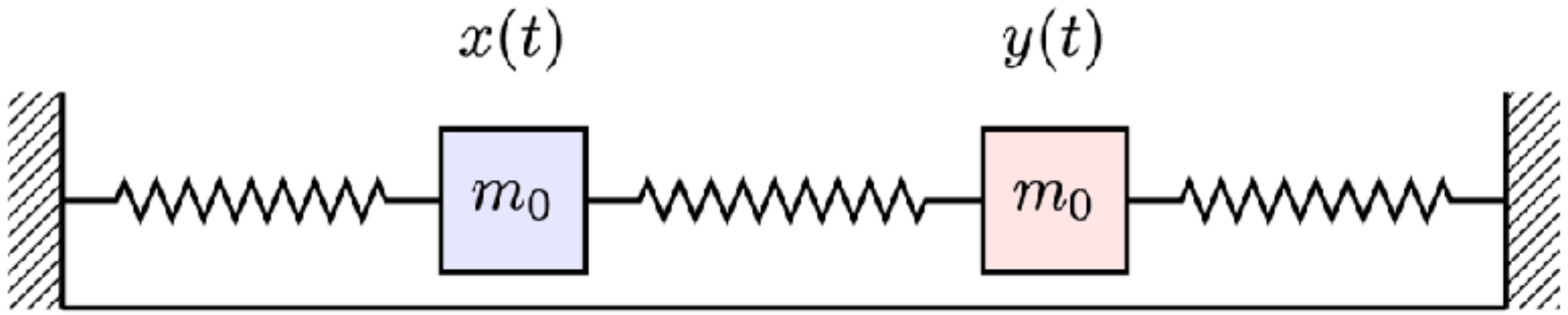
(beyond spacetime)

Effective Theory of Quantum Spacetime

Causal spinfoam vertex for 4d Lorentzian quantum gravity	(Bianchi, Chen, **MG,** '25a)
Toller matrices and the Feynman ***iε*** **in spinfoams**	(Bianchi, Chen, **MG,** '25b)
Precision predictions of Starobinsky inflation with self-consistent Weyl-squared corrections	(Bianchi & **MG,** PRD '25b)
Squeezed vacua and primordial features in effective theories of inflation at N2LO	(Bianchi & **MG,** PRD '25a)
Primordial power spectrum at N3LO in effective theories of inflation	(Bianchi & **MG,** PRD '24)

The effective approach

Let us consider an illustrative example. A classical physical system composed by two linearly coupled oscillators:



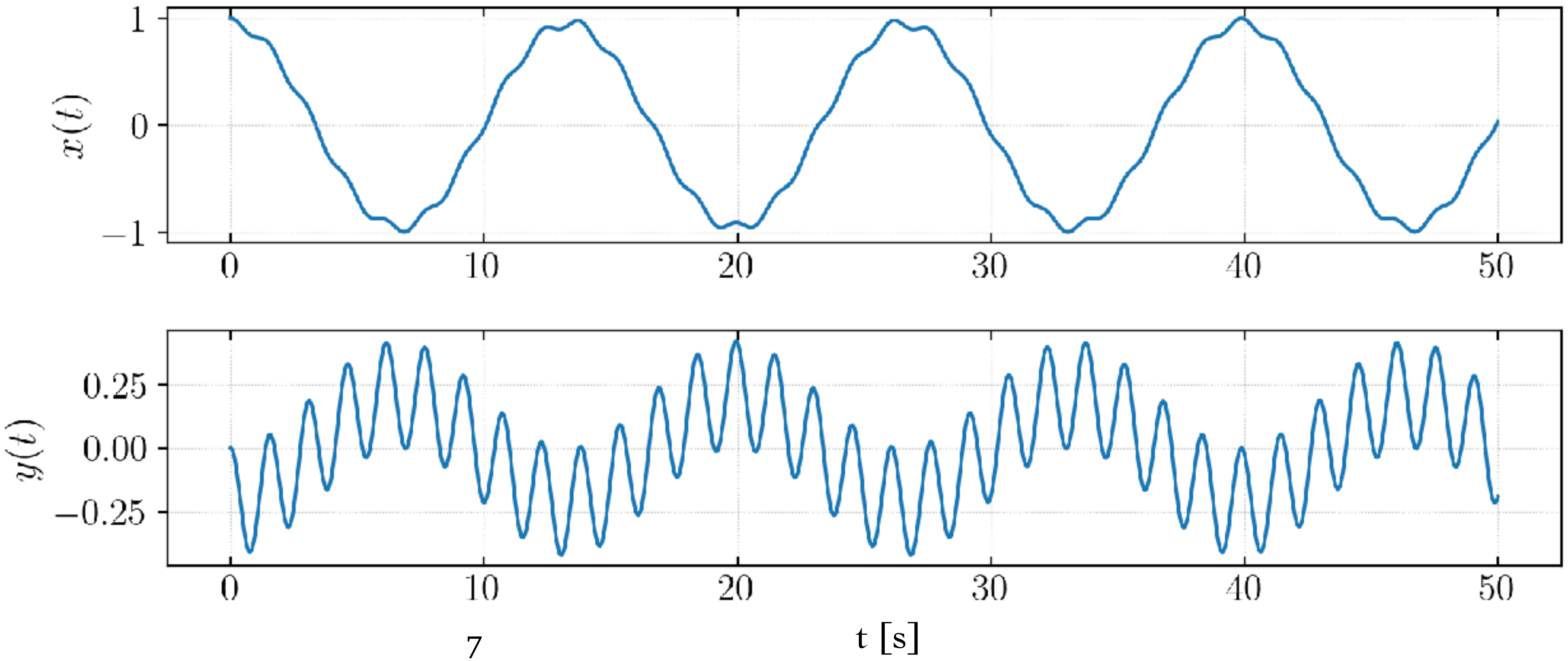
Action of the full theory: $S[x, y] = \int \mathrm{d}t \; m_0 \left[\frac{1}{2}\dot{x}(t)^2 - \frac{1}{2}\omega_0^2\, x(t)^2 + \frac{1}{2}\dot{y}(t)^2 - \frac{1}{2}\Omega_0^2\, y(t)^2 + g\, x(t)\, y(t)\right]$

Suppose there is separation of scales:

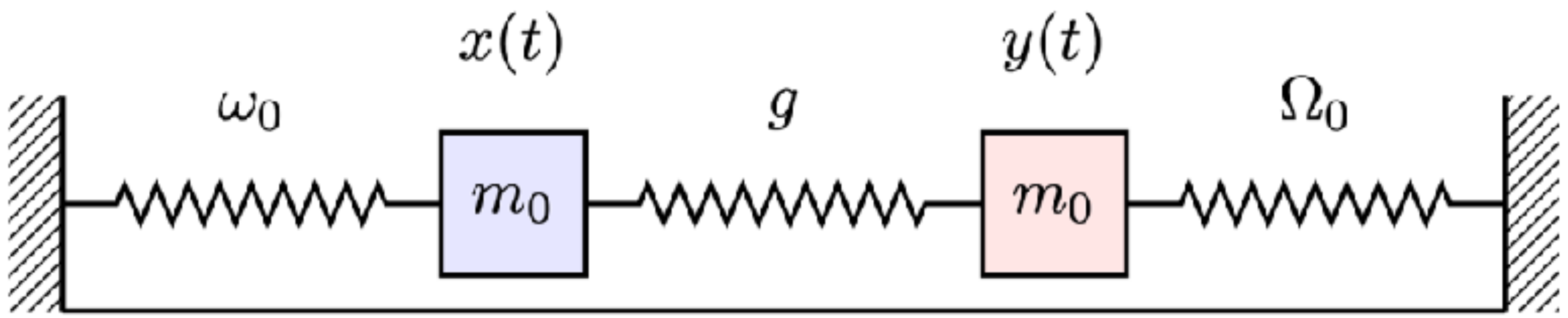
$$\Omega_0 \gg \omega_0$$

We can solve the coupled system numerically:

$$(\partial_t^2 + \omega_0^2)\, x(t) - g\, y(t) = 0$$
$$(\partial_t^2 + \Omega_0^2)\, y(t) - g\, x(t) = 0$$



The effective approach



Suppose we only can want to focus on the dynamics of $x(t)$:

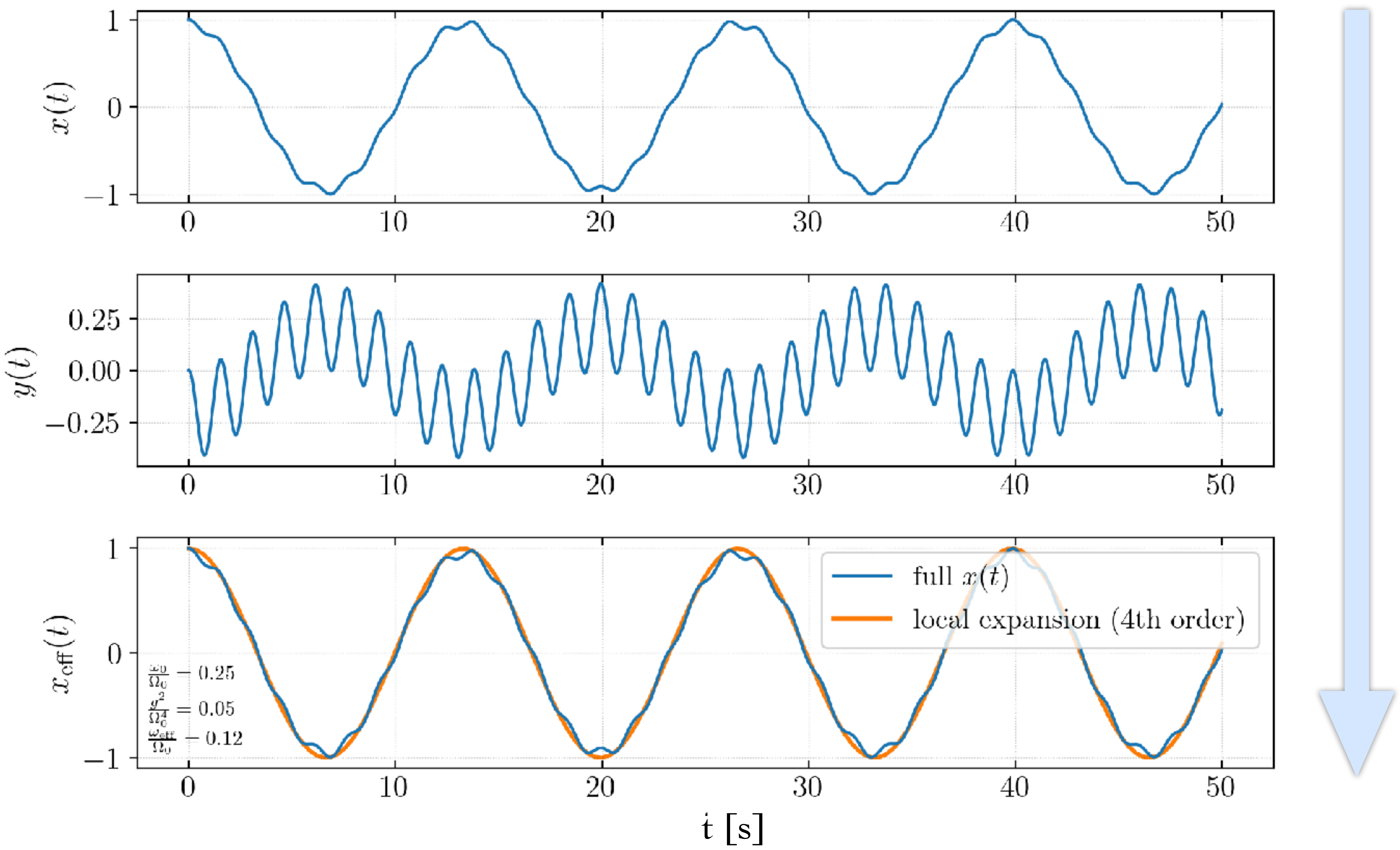
$$S[x] = \int \mathrm{d}t \; m_0 \left[\tfrac{1}{2}\dot{x}^2 - \tfrac{1}{2}\omega_0^2 x^2\right] + \frac{m_0\, g^2}{2} \int \mathrm{d}t \int \mathrm{d}t' \; x(t)\, G(t-t')\, x(t')$$

A useful effective description is typically encoded in a local derivative expansion:

$$S_{\mathrm{eff}}[x] = \int \mathrm{d}t\, m_0 \left[\frac{1}{2}\dot{x}^2 - \frac{1}{2}\omega_{\mathrm{eff}}^2 x^2 - \frac{\beta_{\mathrm{eff}}}{2}\ddot{x}^2 + \mathcal{O}\!\left(\frac{g^4}{\Omega_0^8}\right)\right]$$

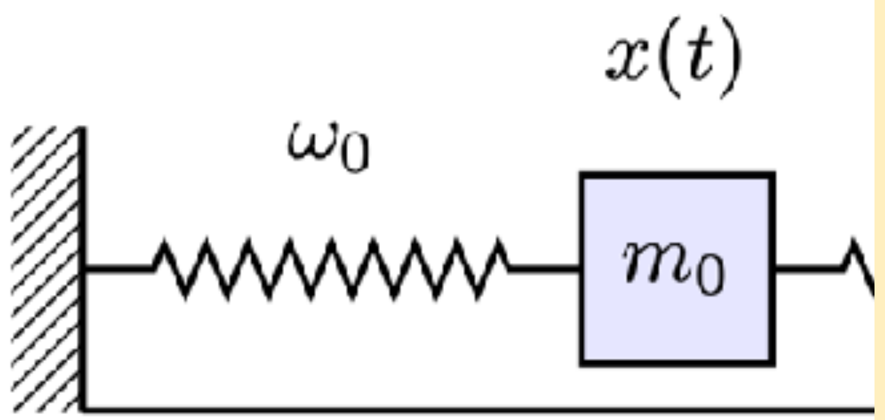
with

$$\omega_{\mathrm{eff}}^2 = \omega_0^2 - \frac{g^2}{\Omega_0^2} \qquad \beta_{\mathrm{eff}} = \frac{g^2}{\Omega_0^6}$$



This gives a top-down effective approach

The effective approach



In the absence of the full theory, we can use symmetries and an organizing principle to guide the construction of the effective action:

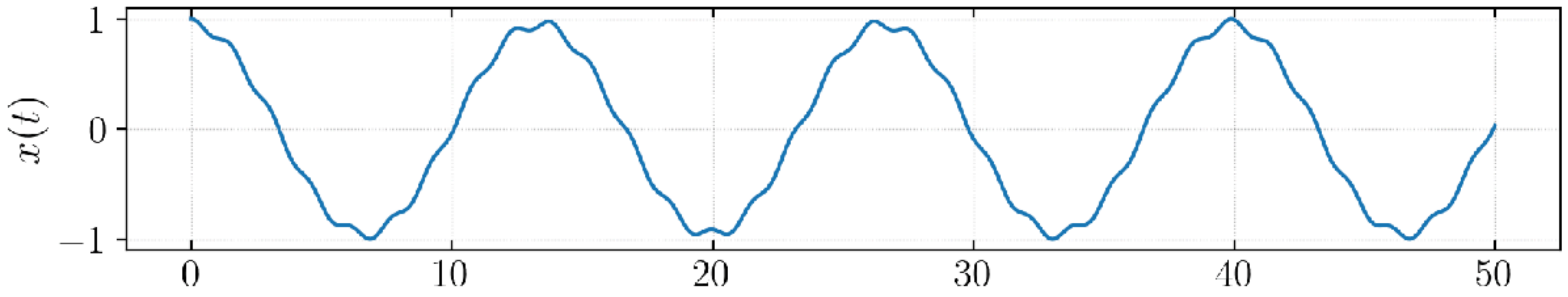
$$S_{\text{eff}}[x] = \int \mathrm{d}t\, m \left[\frac{1}{2}\dot{x}^2 - \frac{1}{2}\omega^2 x^2 - \frac{1}{2}\beta\, \ddot{x}^2 + \dots \right]$$

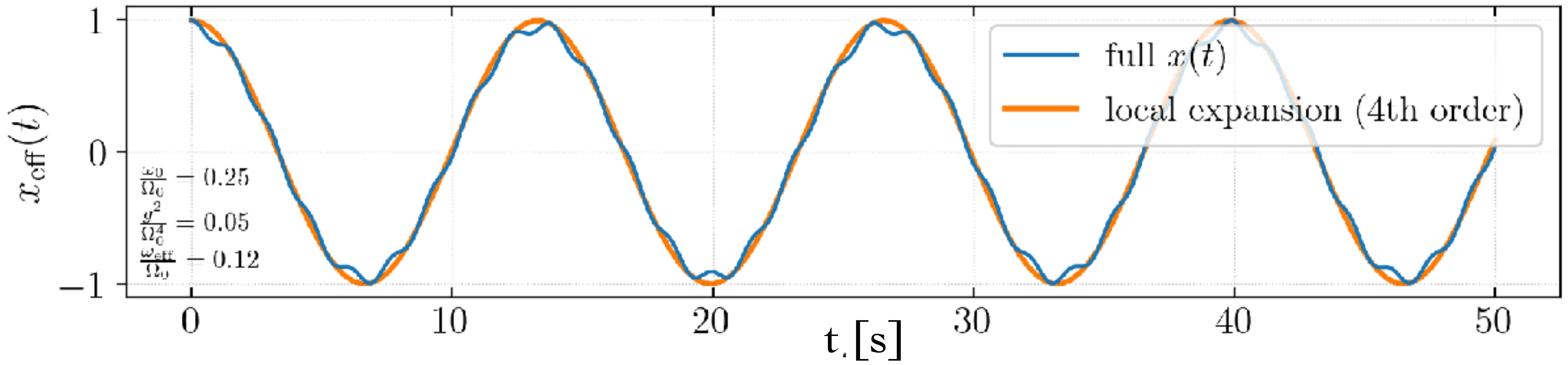
The coupling constants (m, ω, β) must be measured experimentally.

Sometimes, the solutions are problematic:

$$\ddot{x}(t) + \omega^2\, x(t) + \beta\, \dddot{x}(t) = 0$$

(e.g., runaway solutions)





This is a bottom-up effective approach

Our first goal is to construct a self-consistent implementation for gravity

The Effective Theory of Quantum Spacetime

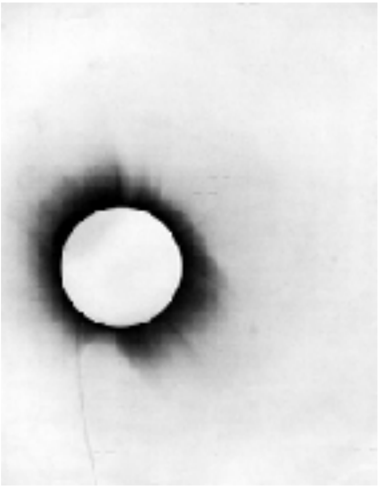
Symmetries (general covariance) + organizing principle (derivative expansion) + DOFs (2 tensors + 1 scalar):

[Stelle '78, Starobinsky '79, Donoghue '94, Burgess '03, Weinberg '08, Anselmi et al. '20]

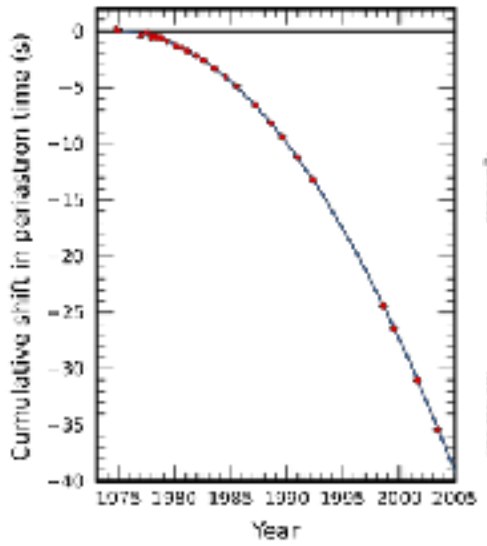
$$S[g_{\mu\nu}] = \frac{1}{16\pi G}\int \mathrm{d}^4x\,\sqrt{-g}\,\Big(\underbrace{-2\Lambda}_{\text{const.}} + \underbrace{R}_{(\partial g)^2} + \underbrace{\alpha\,R^2}_{(\partial g)^4} - \underbrace{\beta\,W_{\mu\nu\rho\sigma}W^{\mu\nu\rho\sigma}}_{(\partial g)^4} + \cdots\Big)$$

General Relativity
(dof: 2 tensor modes)

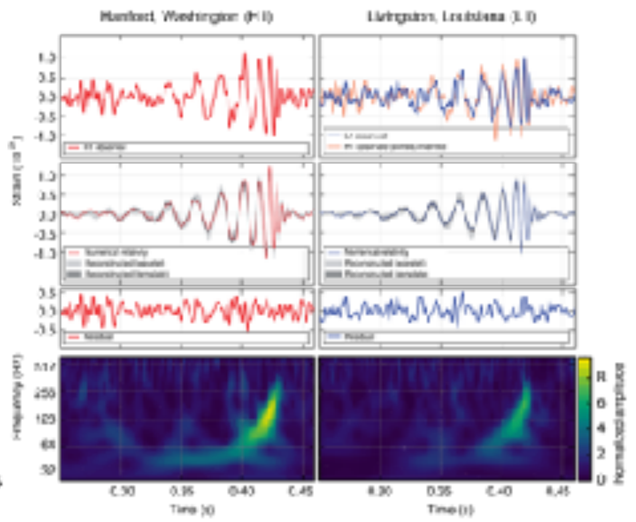
Accurately describe gravity at large length scales/late times



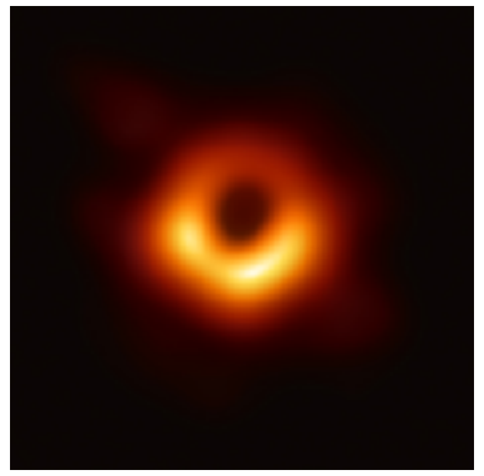
[Eddington 1919]



[Hulse & Taylor '75]



[LIGO '16]



[EHT '19]

The Effective Theory of Quantum Spacetime

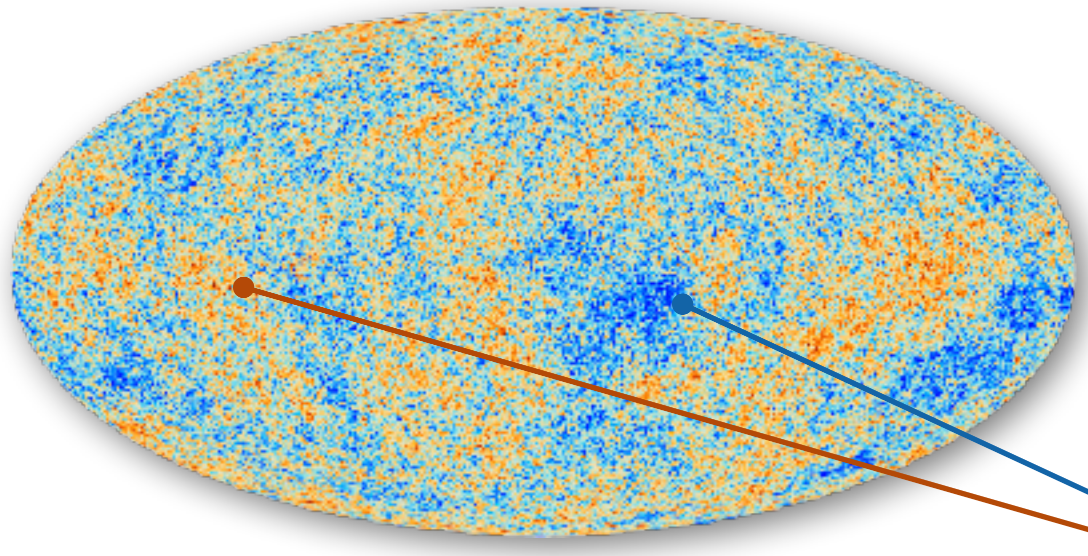
Needed for the description at short length scales/early times

[Bianchi & **MG**, PRD'25b]

- ✳ Most generally covariant theory up to fourth order. Not arbitrary, follows from organizational principle.
- ✳ Robust: Independent of UV completion.
- ✳ **What's new?** : W^2 correction treated self-consistently via reduction of order for $\beta/\alpha \ll 1$ → <u>Stable solutions!</u>

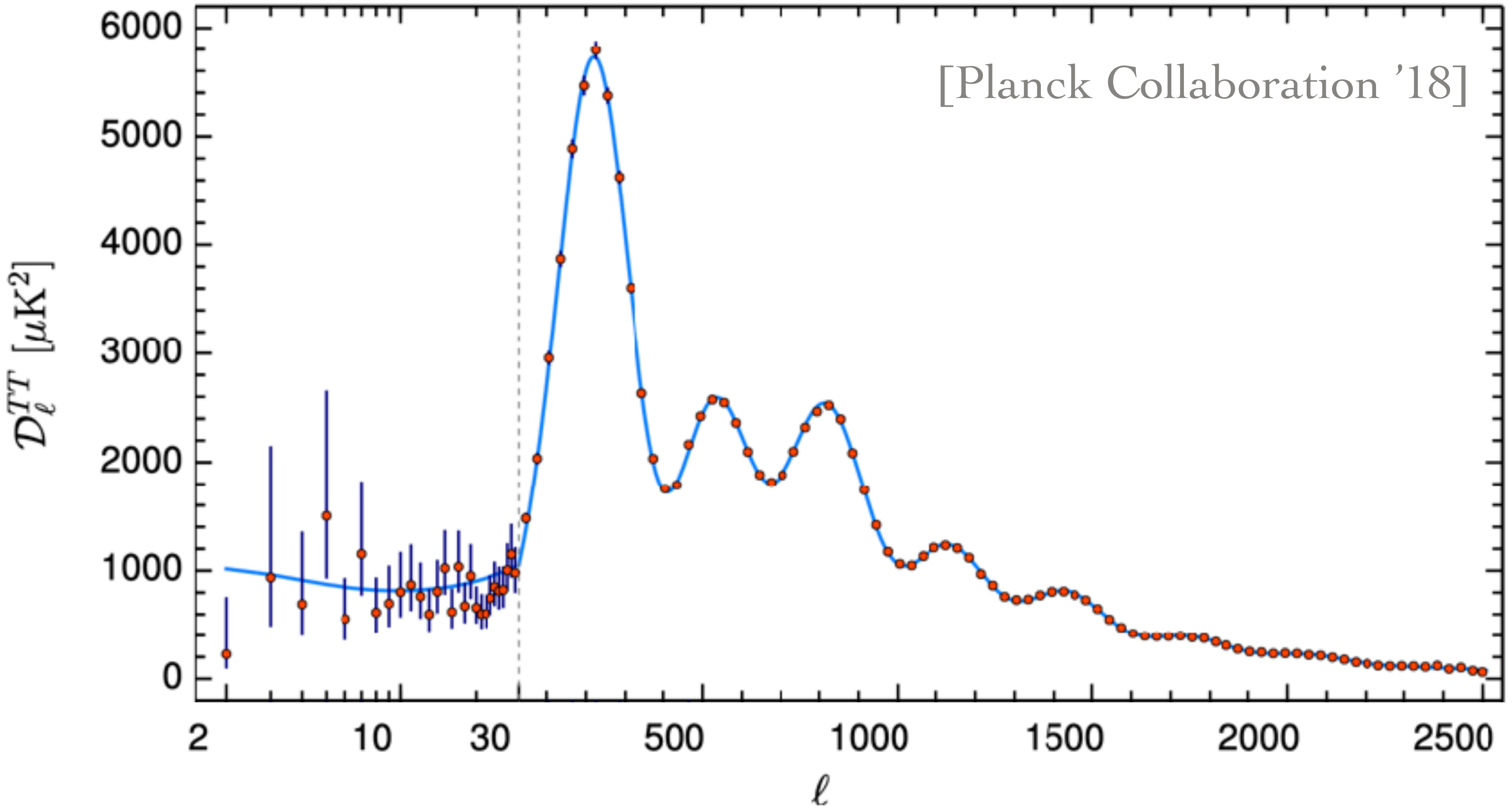
Something happened before the Hot Big Bang

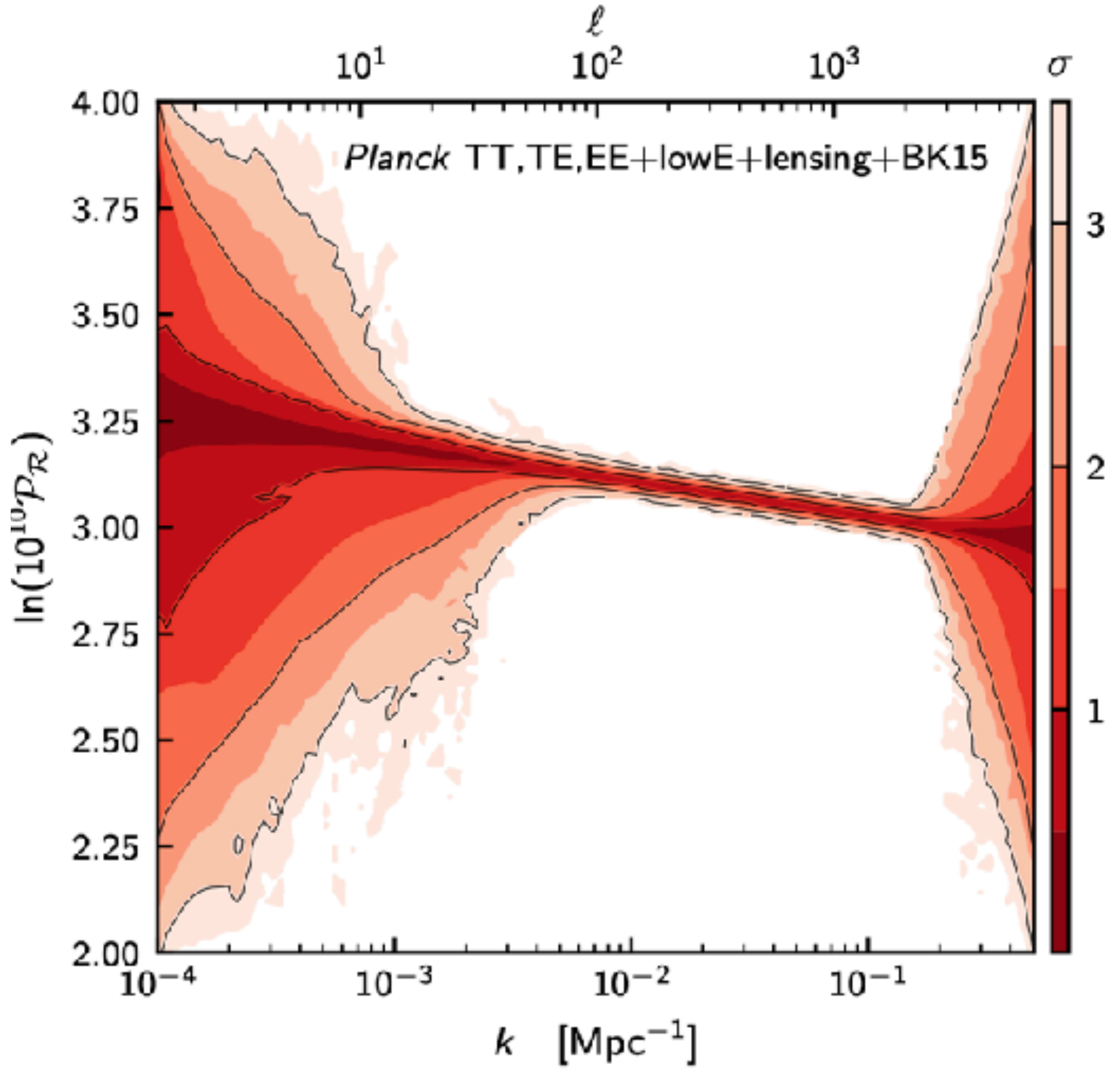
TT,TE,EE modes (Planck, ACT, SPT)
BB modes (BICEP/Keck, SO, LiteBird)



Precise observations of the temperature anisotropies of the cosmic microwave background suggests the existence of a primordial era:

$$\langle \delta T(\mathbf{n})\, \delta T(\mathbf{n}') \rangle \propto \underbrace{\mathcal{T}(k)}_{\text{transfer function}} \times \underbrace{\mathcal{P}_{\mathcal{R}}(k)}_{\text{primordial physics}}$$



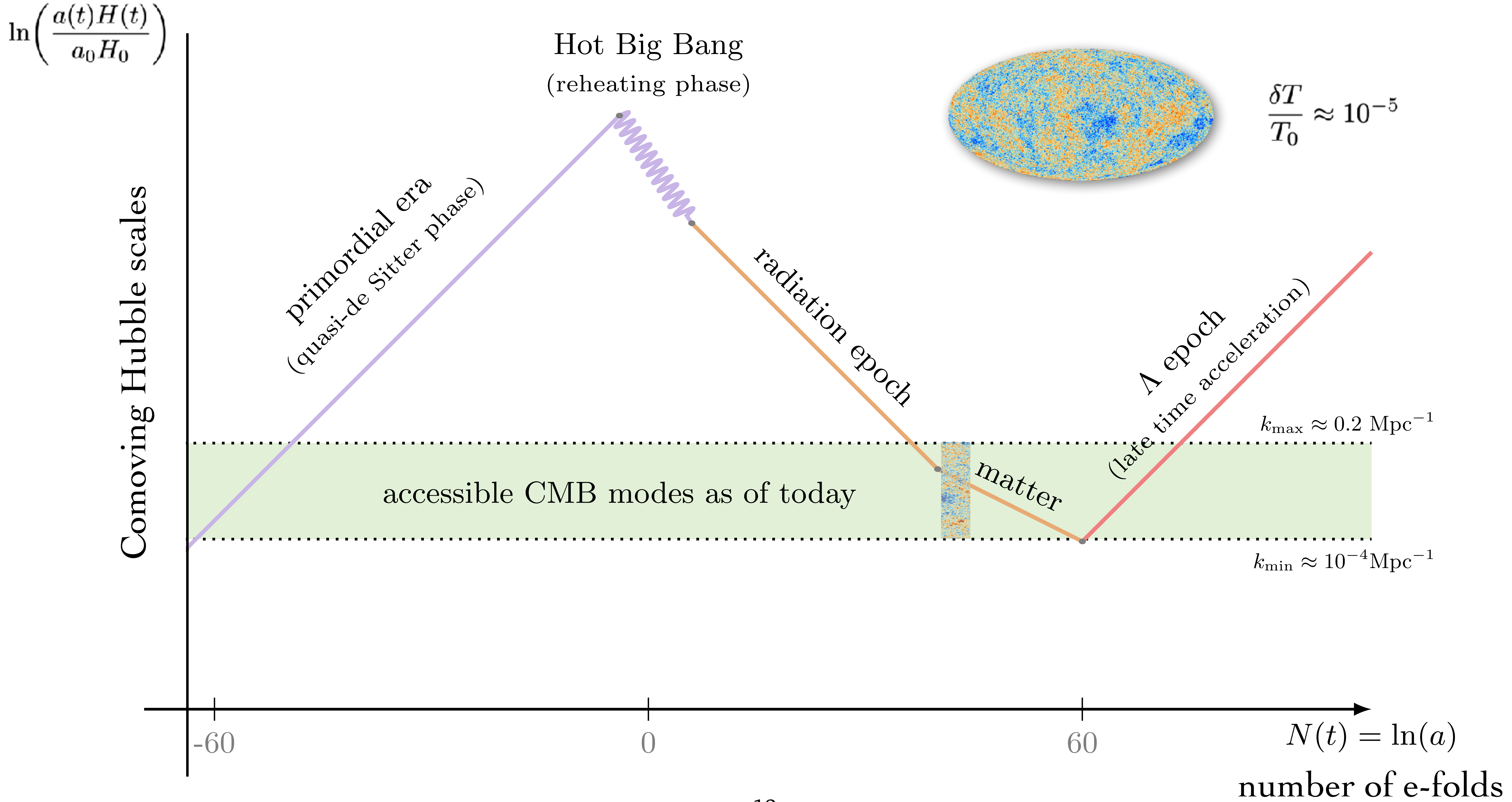


Primordial perturbations are consistent with being:

- small ($\sim 10^{-5}$)
- single adiabatic mode
- almost Gaussian
- nearly scale-invariant

Claim:
The underlying physical mechanism is rooted in the quantum nature of gravity.

The emergent picture of the primordial Universe



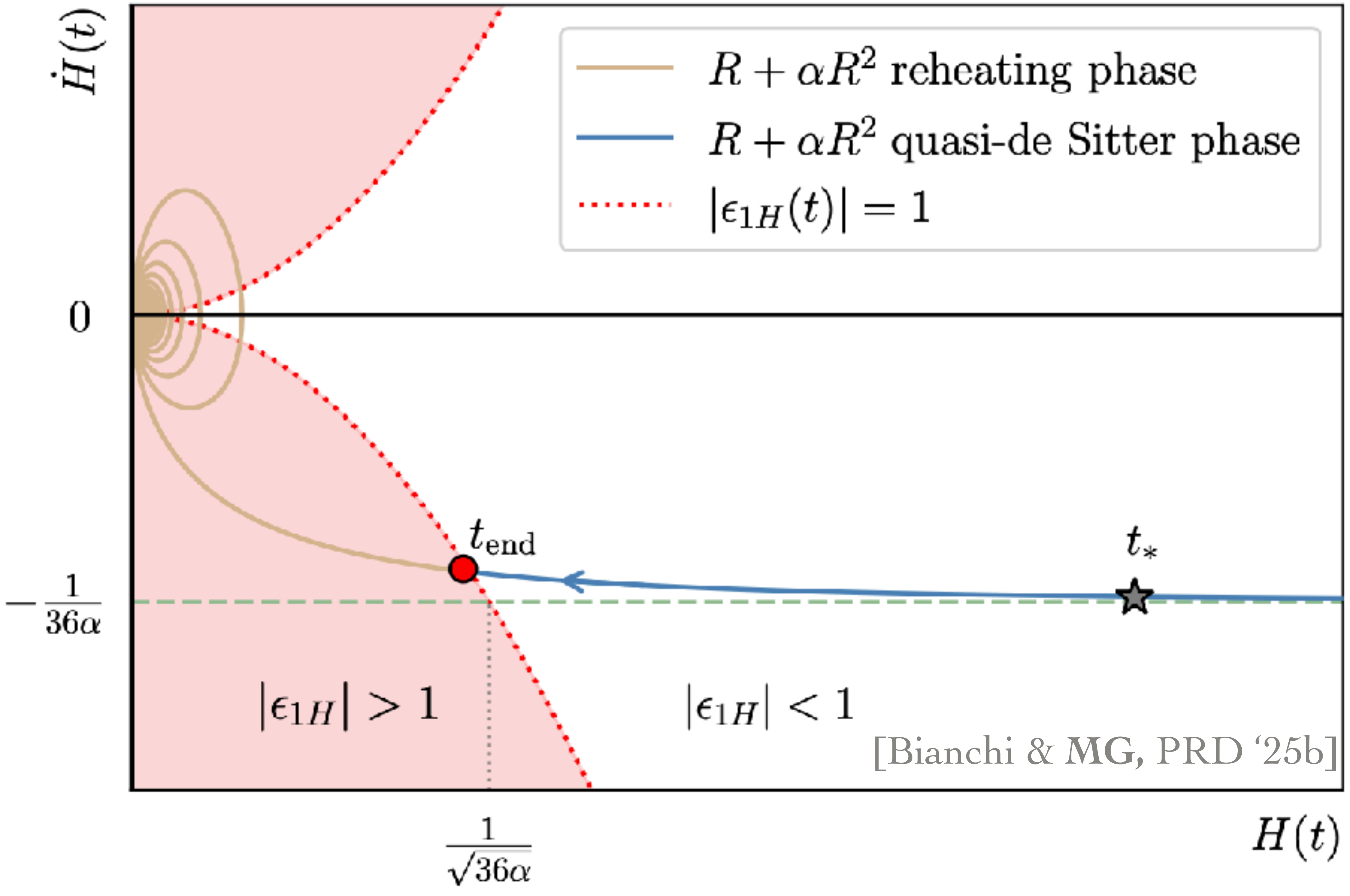
The background geometry

Higher curvature terms + homogeneity & isotropy (FLRW metric: $\bar{g}_{\mu\nu}\,\mathrm{d}x^\mu\,\mathrm{d}x^\nu = -\,\mathrm{d}t^2 + a(t)^2\delta_{ij}\,\mathrm{d}x^i\,\mathrm{d}x^j$)

$$G_{\mu\nu} + \Lambda\, g_{\mu\nu} + \alpha\, \mathcal{H}_{\mu\nu} - 4\,\beta \mathcal{B}_{\mu\nu} = 0$$

$$H(t) = \frac{\dot a}{a} \qquad \epsilon_{1H} = -\frac{\dot H}{H^2} \qquad \epsilon_{2H} = -\frac{\dot\epsilon_{1H}}{H\epsilon_{1H}}$$

$$H(t)^2 - 36\,\alpha\, H(t)^4\, \epsilon_{1H}(t)\left(1 - \tfrac{1}{2}\epsilon_{1H}(t) - \tfrac{1}{3}\epsilon_{2H}(t)\right) = 0$$



The effective geometry provide us with:

- Emergence of an accelerated expansion phase: ($\dot H \sim -\dfrac{1}{36\alpha}$: **quasi-de Sitter phase**)
- Natural transition to an oscillatory epoch ($H \sim \cos\left(\frac{t}{\sqrt{24\alpha}}\right)^2$: **reheating phase**)

[Starobinsky '80, Vilenkin '85]

Reduction of order

[Bianchi & **MG**, PRD '25b]

At the perturbative level, the W^2 term induces higher time-derivatives that need to be treated with care (Ψ: scalar/tensor)

$$g_{\mu\nu} = \bar{g}_{\mu\nu} + \delta g_{\mu\nu}[\Psi] \longrightarrow \mathcal{L}^{(2)}_{\Psi} \sim A(t)\dot{\Psi}^2 - B(t)(\partial_i \Psi)^2 + \beta\, C(t)\ddot{\Psi}^2$$

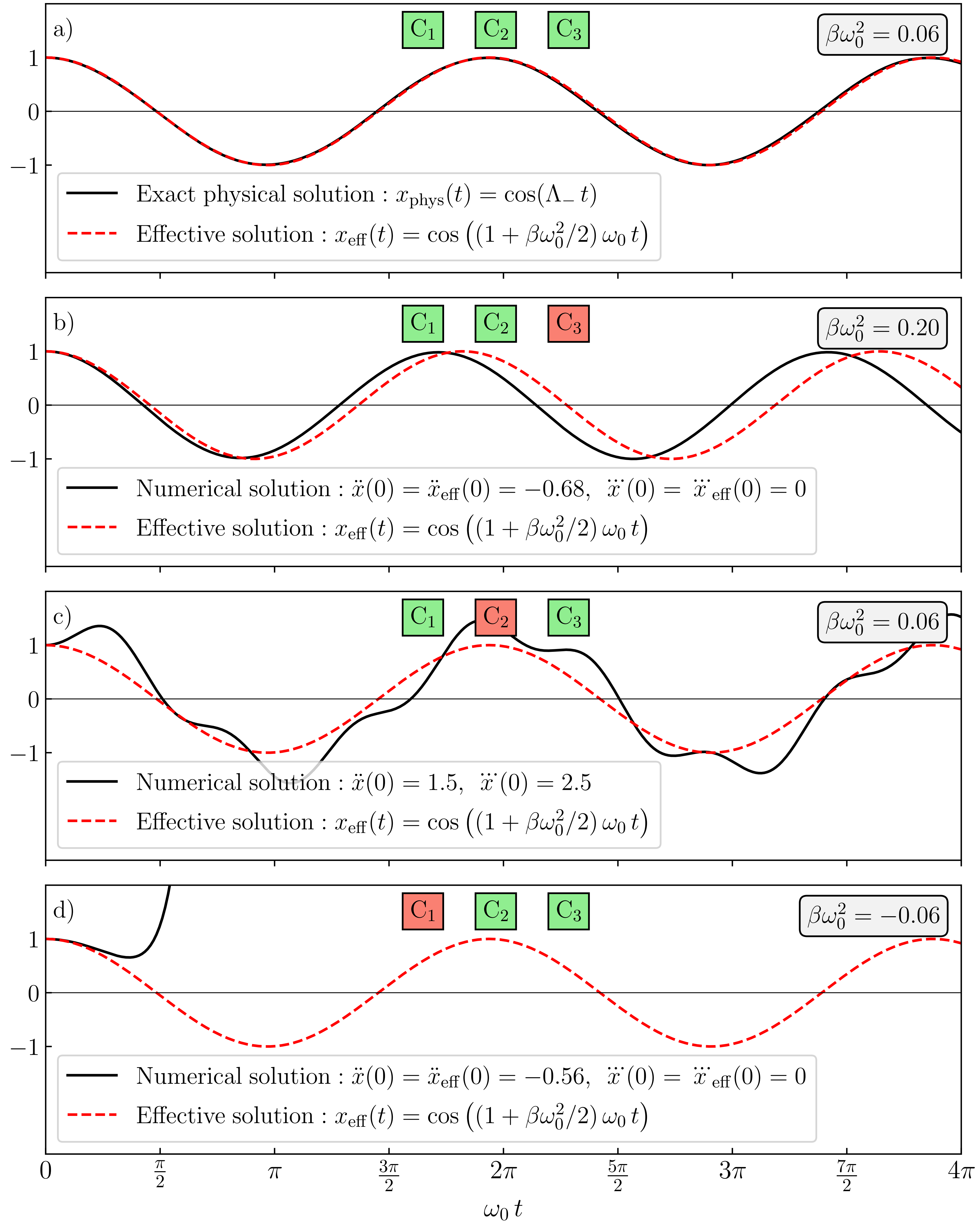
We use **reduction of order**, which is based on three conditions:

C_1 : Solutions of the effective theory must be stable (no runaways)
C_2 : Initial conditions restricted to solutions analytic in β
C_3 : Asymptotic expansion and regime of validity ($\beta/\alpha \ll 1$)

We derived a self-consistent quadratic action of scalar and tensor perturbations

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

$$c_s(t) = 1 + \frac{\beta}{6\,\alpha}\epsilon_{1\,H}(t)^2 + \mathcal{O}(\epsilon^2)$$
$$c_t(t) = 1 + \frac{\beta}{6\,\alpha} + \mathcal{O}(\epsilon)$$



Perturbative Quantum geometry and Power Spectrum

An important remark: spacetime geometry is quantized

$$g_{\mu\nu}[\Psi] = \bar{g}_{\mu\nu} + \delta g_{\mu\nu}[\Psi] \;\Rightarrow\; \begin{cases} \Psi = \mathcal{R} \to \hat{\mathcal{R}} & \text{primordial curvature} \\ \Psi = \gamma_\sigma \to \hat{\gamma}_\sigma & \text{primordial GWs} \end{cases}$$

A systematic Hubble-flow expansion allows us to introduce a quasi-Bunch-Davies vacuum state, $|\mathrm{qBD}\rangle$, such that

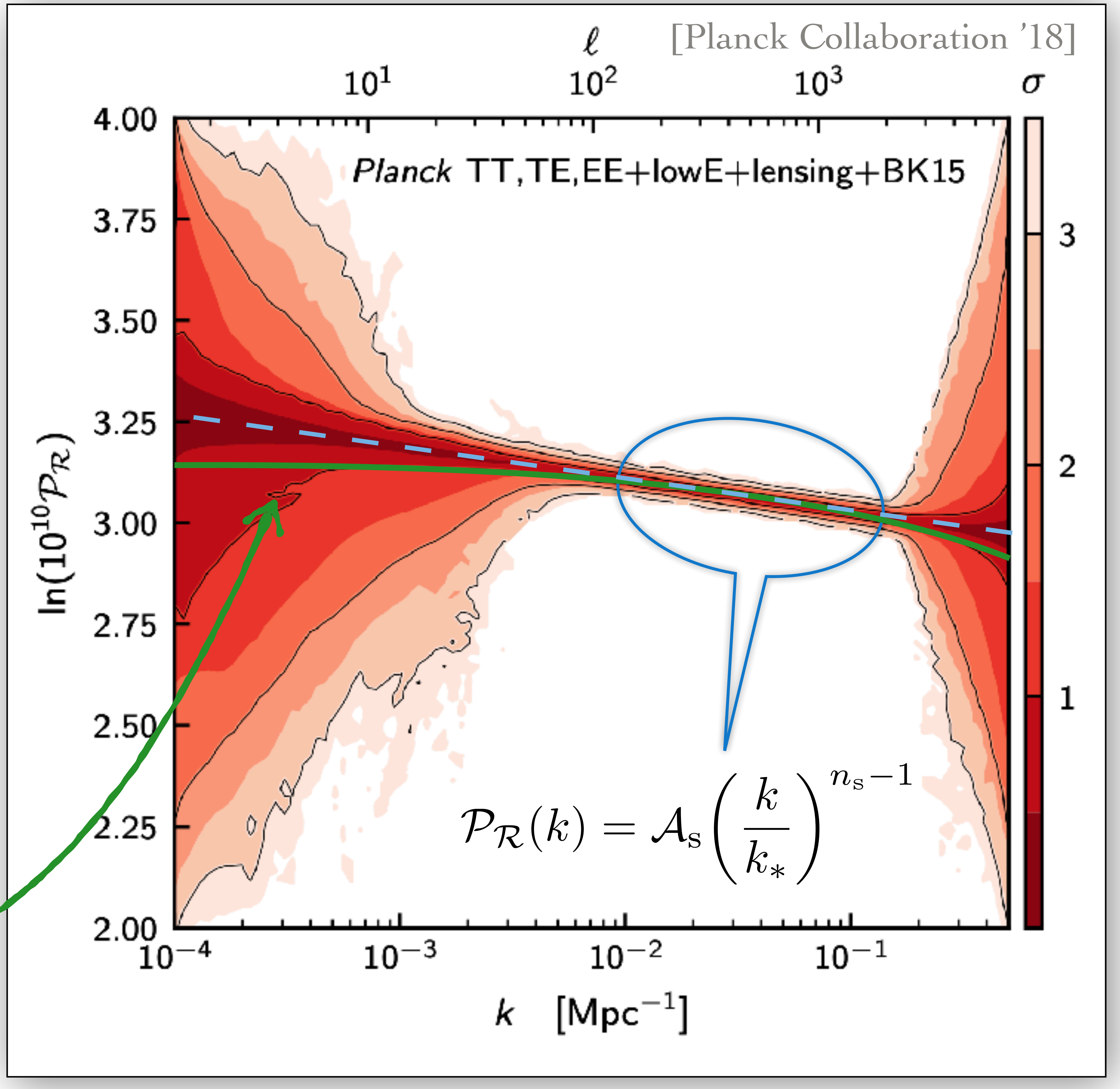
$$\langle \mathrm{qBD}|\, \hat{\Psi}(\mathbf{x},t)\, \hat{\Psi}(\mathbf{x}',t)\, |\mathrm{qBD}\rangle = \int \mathrm{d}(\log k)\, \mathcal{P}^{(\Psi)}_{\mathrm{qBD}}(k)\, \frac{\sin\!\big(k\,|\mathbf{x}-\mathbf{x}'|\big)}{k\,|\mathbf{x}-\mathbf{x}'|}$$

perturbative quantum geometry $\leftrightarrow$ CMB observations

$$\mathcal{P}^{(\mathrm{s})}_{\mathrm{qBD}}(k) = \mathcal{A}_\mathrm{s} \left(\frac{k}{k_*}\right)^{n_\mathrm{s}-1+\frac{1}{2!}\,\alpha_\mathrm{s}\,\ln(k/k_*)+\frac{1}{3!}\,\beta_\mathrm{s}\,\ln^2(k/k_*)+\cdots}$$

$$\mathcal{P}^{(\mathrm{t})}_{\mathrm{qBD}}(k) = \mathcal{A}_\mathrm{t} \left(\frac{k}{k_*}\right)^{n_\mathrm{t}+\frac{1}{2!}\,\alpha_\mathrm{t}\,\ln(k/k_*)+\frac{1}{3!}\,\beta_\mathrm{t}\,\ln^2(k/k_*)+\cdots}$$

(for exact de Sitter: $n_s = 1$, $\alpha_s = 0$, $\beta_s = 0$)



we developed a framework to compute corrections up to next-to-next-to-next-to leading order

[Bianchi & **MG**, PRD '24; PRD '25b]

Precision Predictions from $R + \alpha R^2 - \beta W^2$

Primordial amplitude of scalar and tensors

$$\mathcal{A}_s = \frac{2}{9\pi}\frac{\ell_P^2}{\alpha}\frac{1}{(n_s-1)^2}\left[1 - \frac{5}{12}(n_s-1)\right]$$

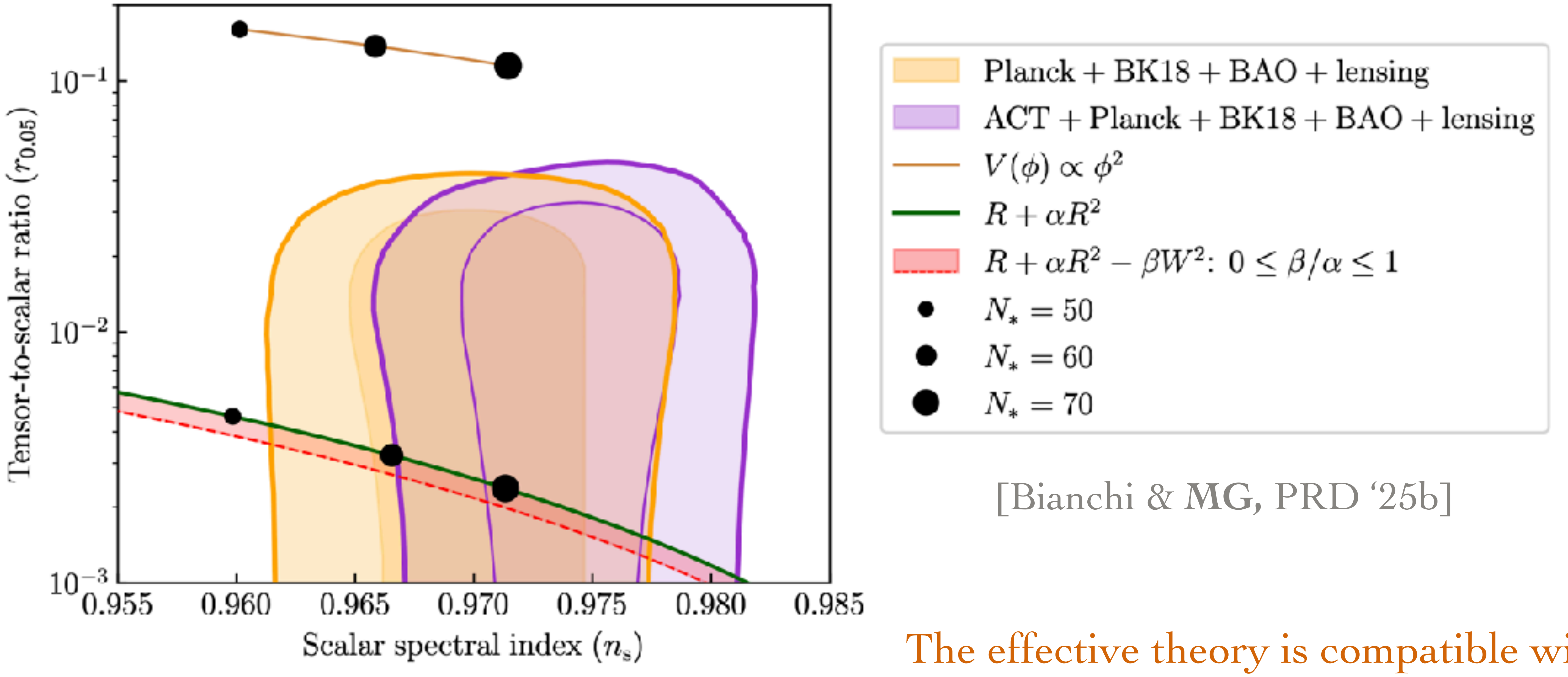
$$\mathcal{A}_t = \frac{2}{3\pi}\frac{\ell_P^2}{\alpha}\left[1-\frac{\beta}{6\alpha} + \frac{3}{4}\left(1-\frac{\beta}{3\alpha}\right)(n_s-1)\right]$$

Tensor-to-scalar ratio ($r \equiv \frac{\mathcal{A}_t}{\mathcal{A}_s}$), tensor tilt ($n_t$) and consistency relation:

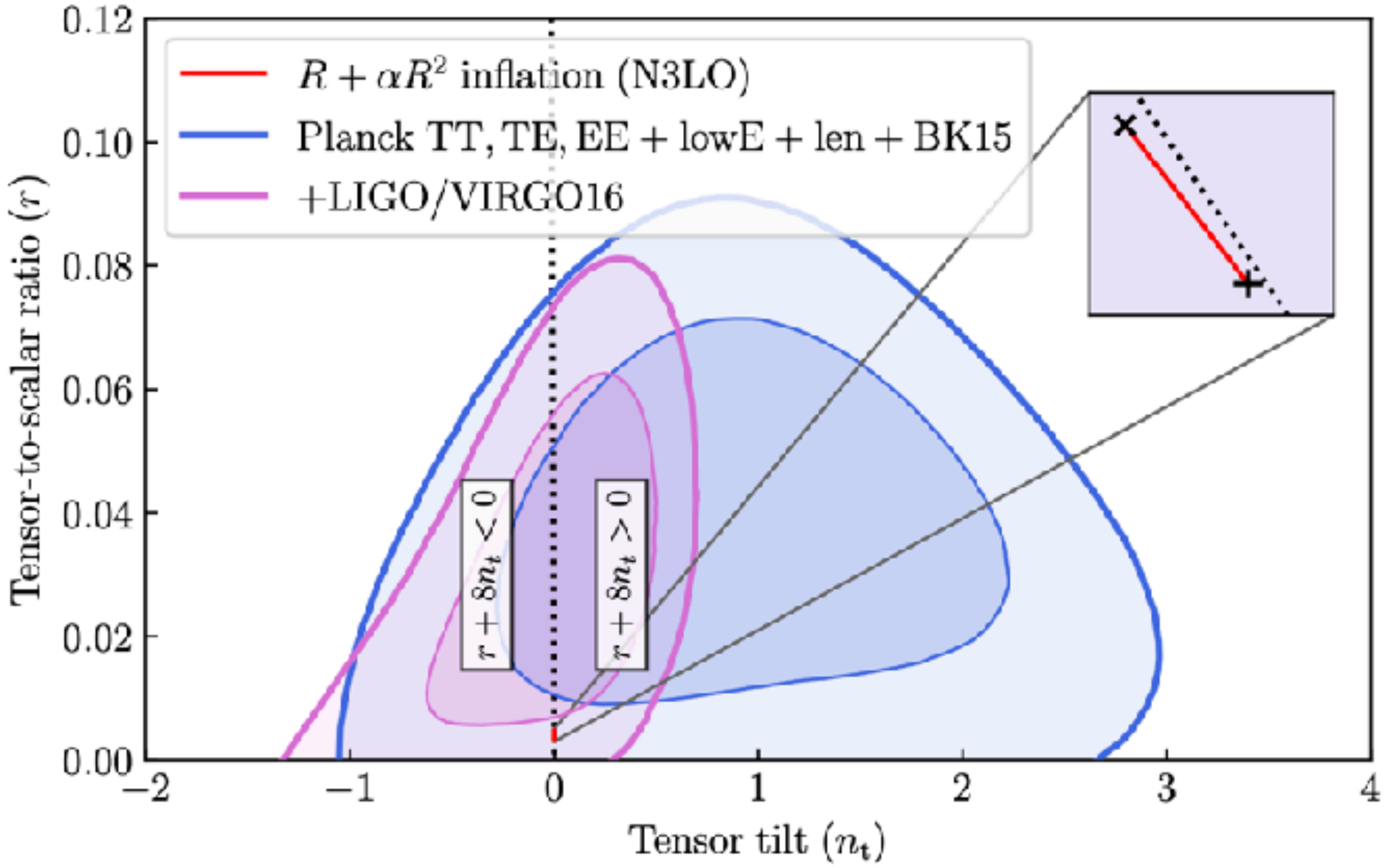
$$r = 3\left(1-\frac{\beta}{6\alpha}\right)(n_s-1)^2 + \frac{7}{2}\left(1-\frac{23\beta}{84\alpha}\right)(n_s-1)^3$$

$$n_t = -\frac{3}{8}\left(1-\frac{\beta}{6\alpha}\right)(n_s-1)^2 - \frac{1}{16}\left(1-\frac{11\beta}{12\alpha}\right)(n_s-1)^3$$

$$r + 8n_t = 3\left(1-\frac{\beta}{6\alpha}\right)(n_s-1)^3$$



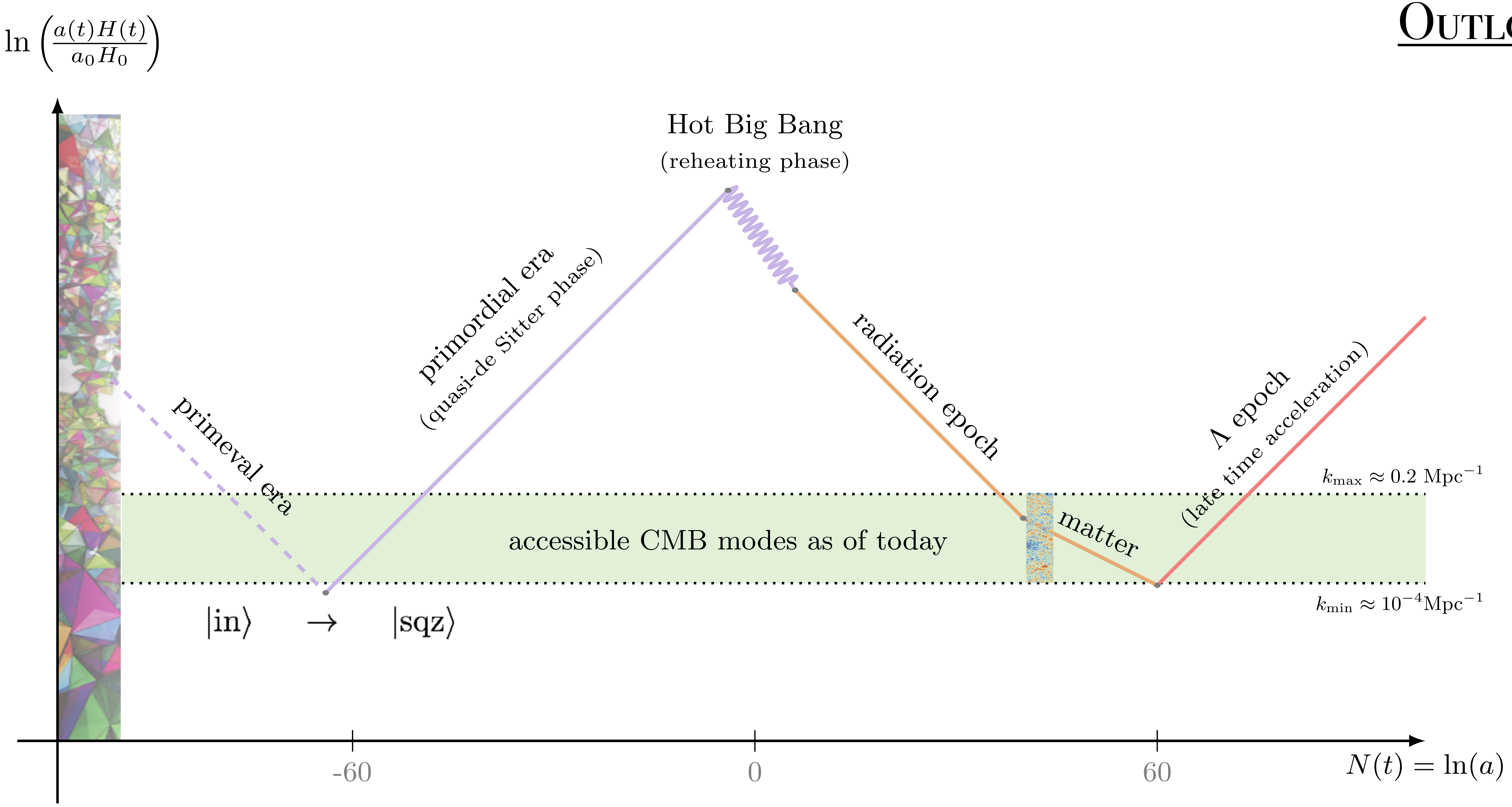
[Bianchi & **MG**, PRD ‘25b]



[Bianchi & **MG**, PRD ‘24]

The effective theory is compatible with current observations and can be further tested in the future

Outlook



$\ln\left(\frac{a(t)H(t)}{a_0 H_0}\right)$
Hot Big Bang
(reheating phase)
primordial era
(quasi-de Sitter phase)
primeval era
radiation epoch
Λ epoch
(late time acceleration)
matter
accessible CMB modes as of today
$k_{\max} \approx 0.2\ \mathrm{Mpc}^{-1}$
$k_{\min} \approx 10^{-4}\mathrm{Mpc}^{-1}$
$|\mathrm{in}\rangle \rightarrow |\mathrm{sqz}\rangle$
-60
0
60
$N(t) = \ln(a)$

Perspectives: A primeval era

If there was a pre-inflationary phase:

1. How to characterize the quantum state?

qBD can be a reference for a two-mode squeezed state:

$$\hat{a}(\mathbf{k})\,|\mathrm{qBD}\rangle = 0 \longrightarrow \hat{b}(\mathbf{k})\,|\mathrm{sqz}\rangle = 0$$

$$\text{for } \hat{b}(\mathbf{k}) = \alpha_k^*\,\hat{a}(\mathbf{k}) - \beta_k^*\,\hat{a}^\dagger(-\mathbf{k})\ ,\ |\alpha_k|^2 - |\beta_k|^2 = 1$$

2. What do α_k and β_k depend on?

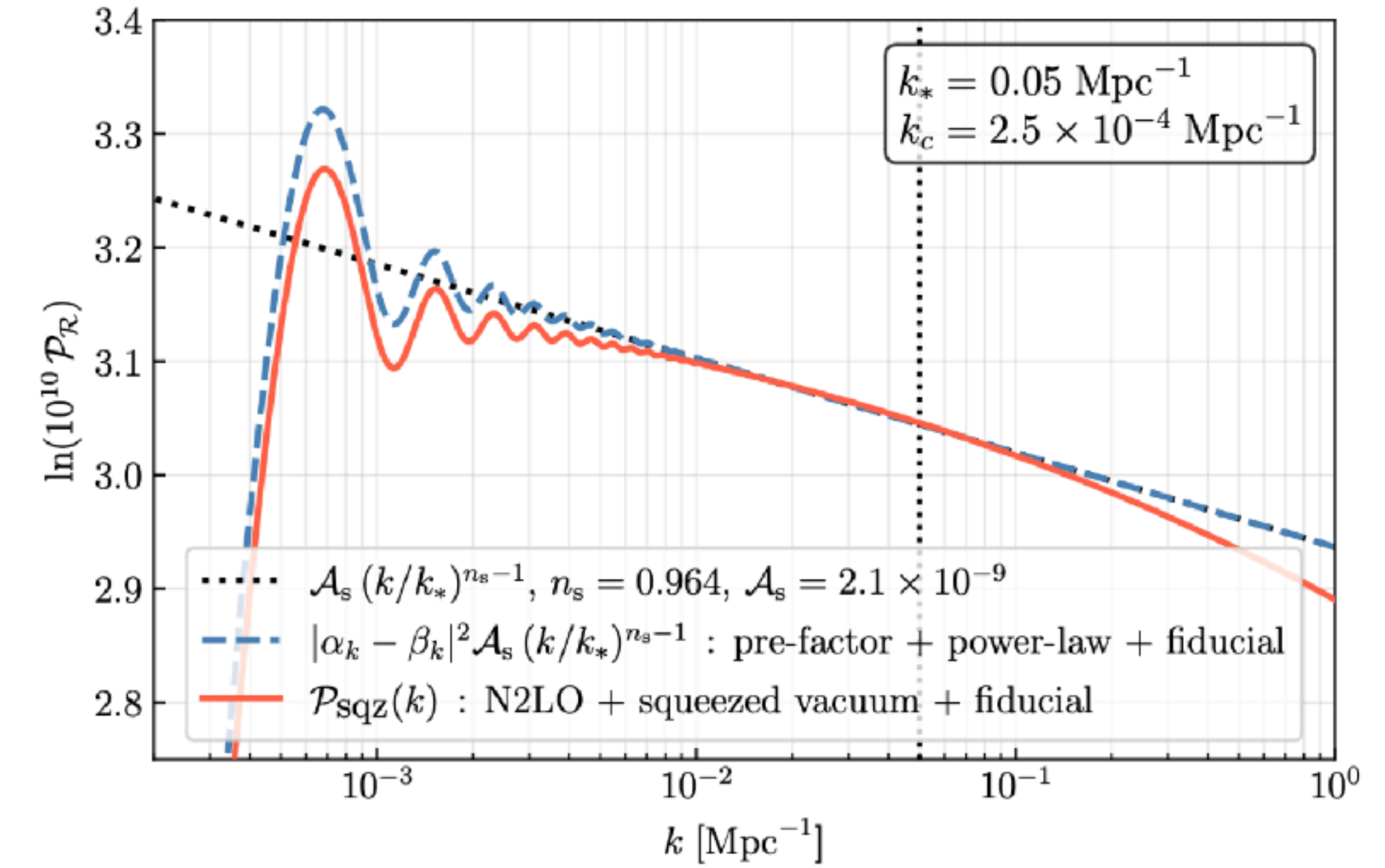
transition of the background geometry (induced by QG)

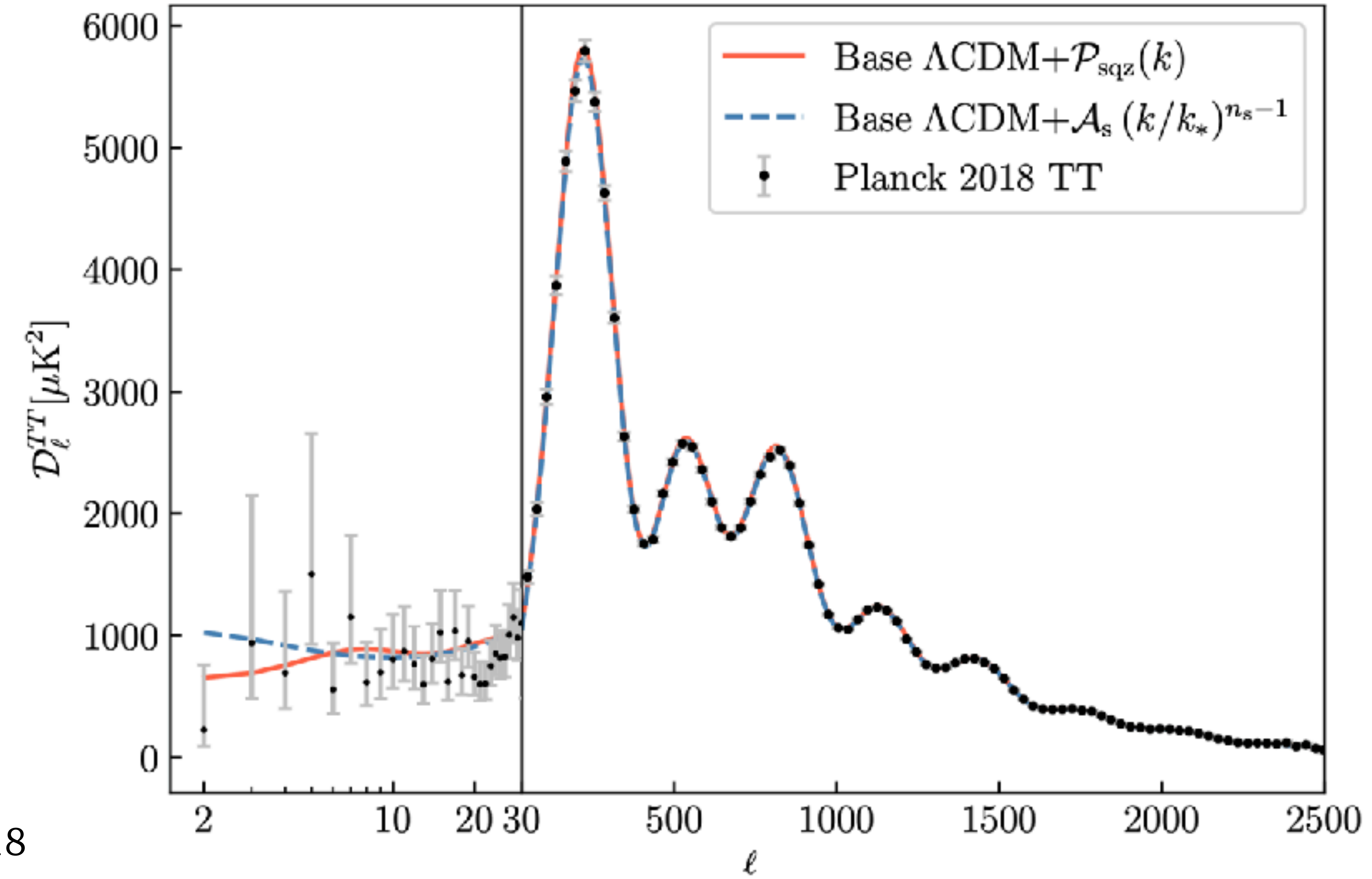
3. How is the power spectrum modified?

indications of a radiation → quasi-de Sitter transition:

$$\mathcal{P}_{\mathrm{sqz}}(k) \sim \left[1 - (k_c^2/k^2)\,\cos(2k/k_c + \delta_k)\right]\mathcal{P}_{\mathrm{qBD}}(k)$$

[Bianchi & **MG** '25a]





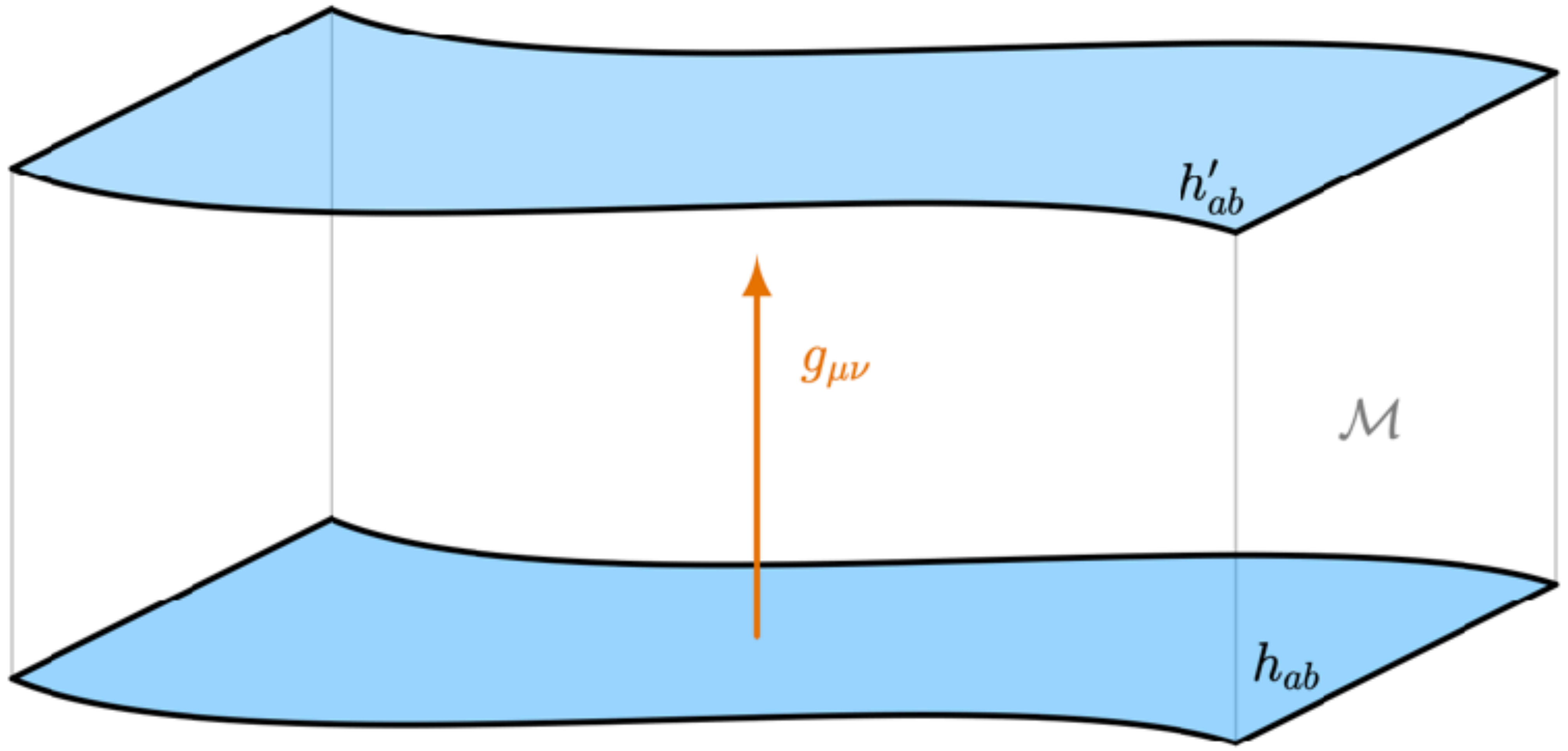
Perspectives: Full Lorentzian Quantum Gravity in 4D

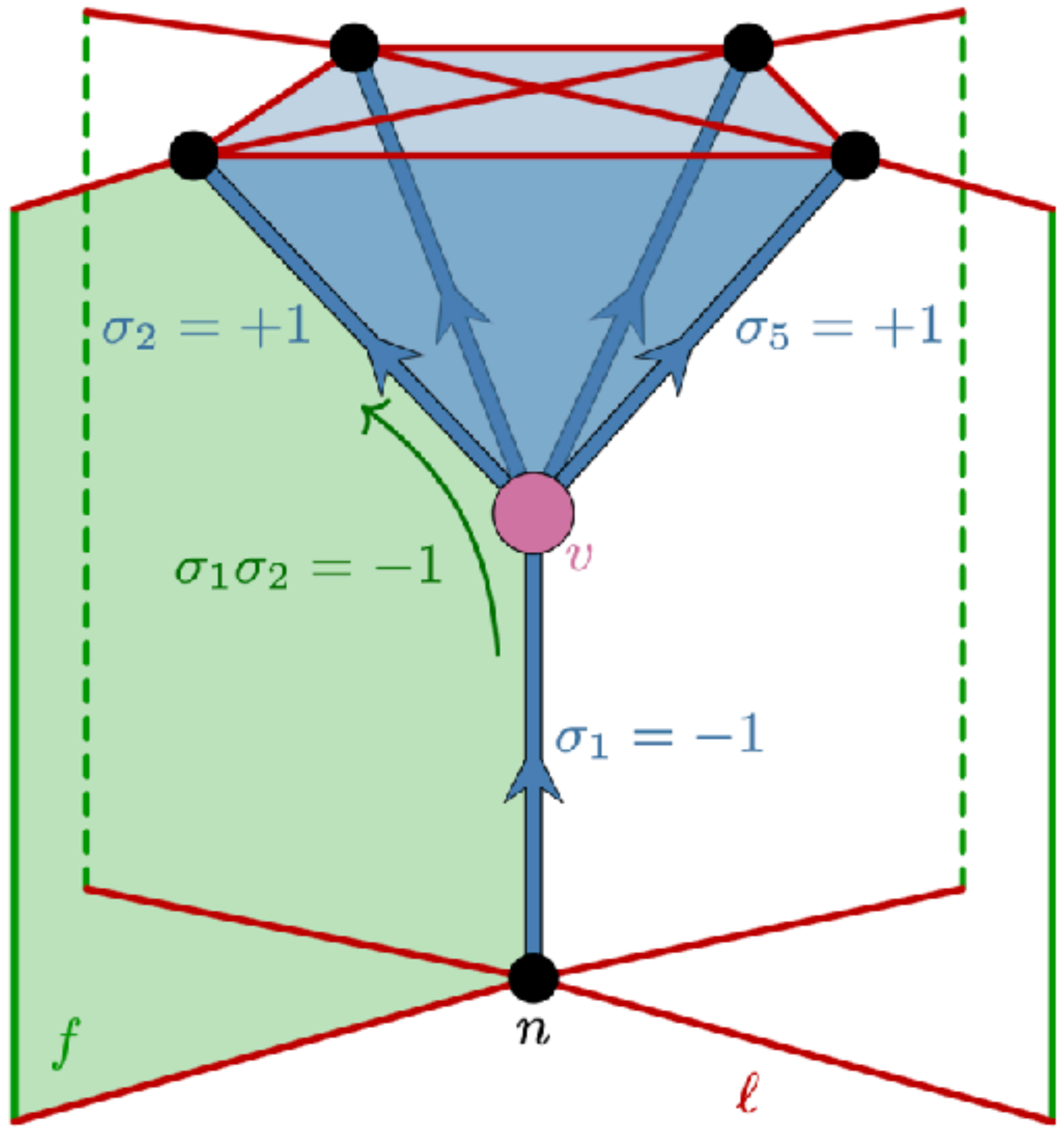
[Rovelli & Vidotto '14]
[Ashtekar & Bianchi '21]

Gravitational path integral

[Feynman '49; Wheeler '57, Misner '57]
[DeWitt '67; Hawking '80, Teitelboim '83]

$$\mathcal{W}[h_{ab} \to h'_{ab}] = \int_{h_{ab}}^{h'_{ab}} \mathcal{D}[g_{\mu\nu}]\, \mathrm{e}^{+\frac{\mathrm{i}}{\hbar} S_{\mathrm{EH}}[g_{\mu\nu}]}$$





Spinfoam path integral

$$\mathcal{W}[s \to s'] = \sum_{\Delta_*} \sum_{j_f, i_e, \sigma_e} \prod_f A_f \prod_e A_e \prod_v A_v$$

[Bianchi, Chen & **MG** '26]

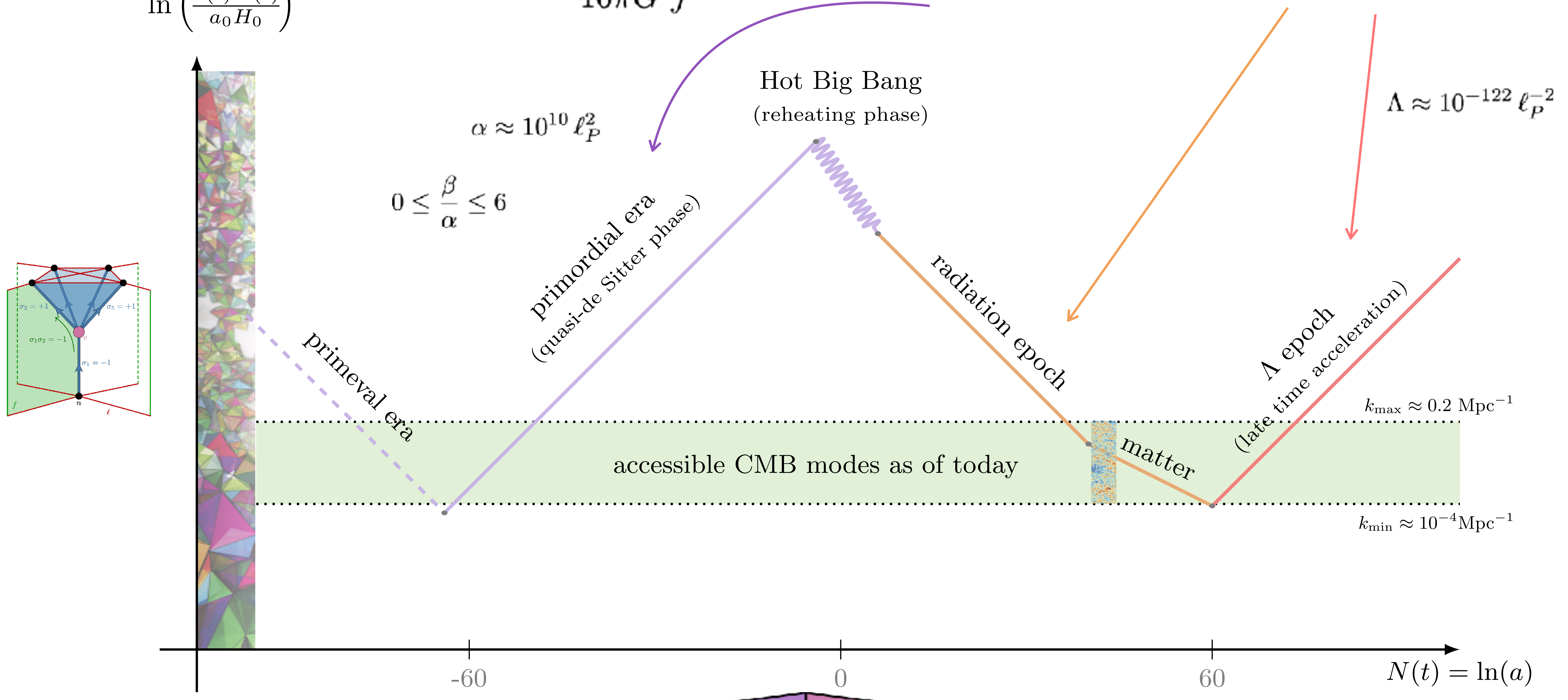
The Future

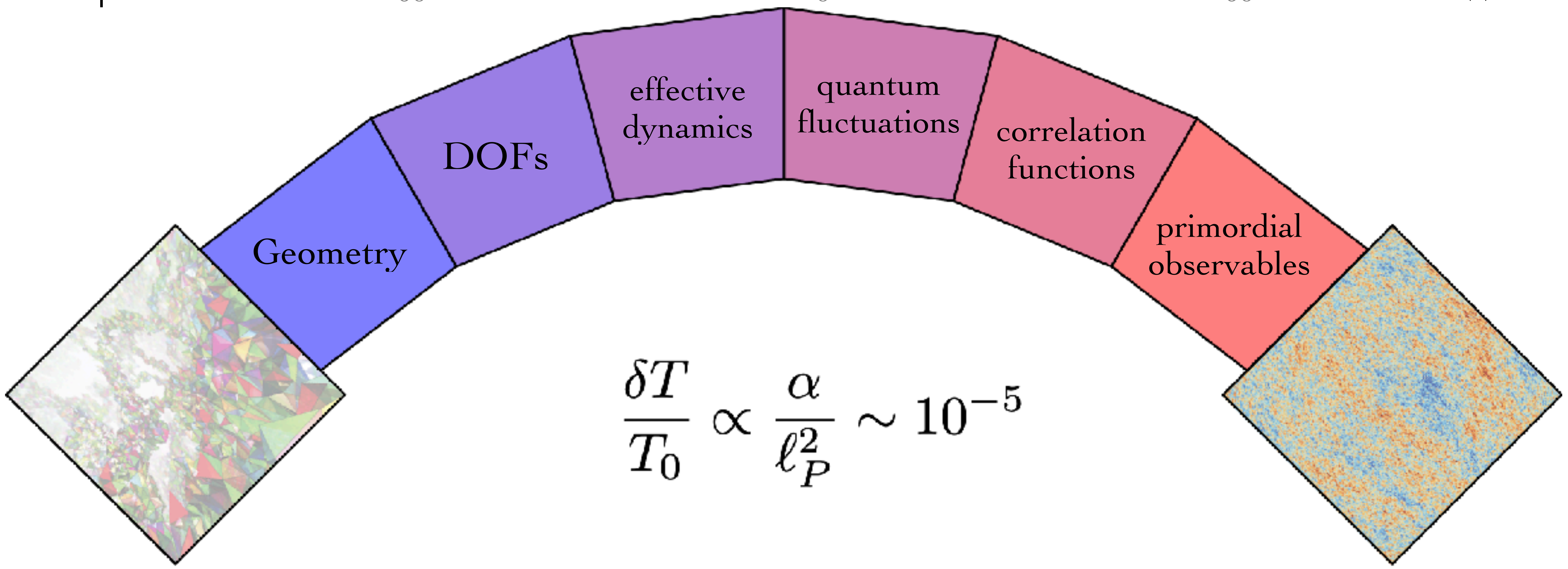
As some of you may know, I recently accepted an offer for a postdoctoral position to work with the group of Francesca Vidotto at the Instituto de Estructura de la Materia, in Madrid, Spain :)

WOST Exploring Quantum Without SpaceTime

Thanks!

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

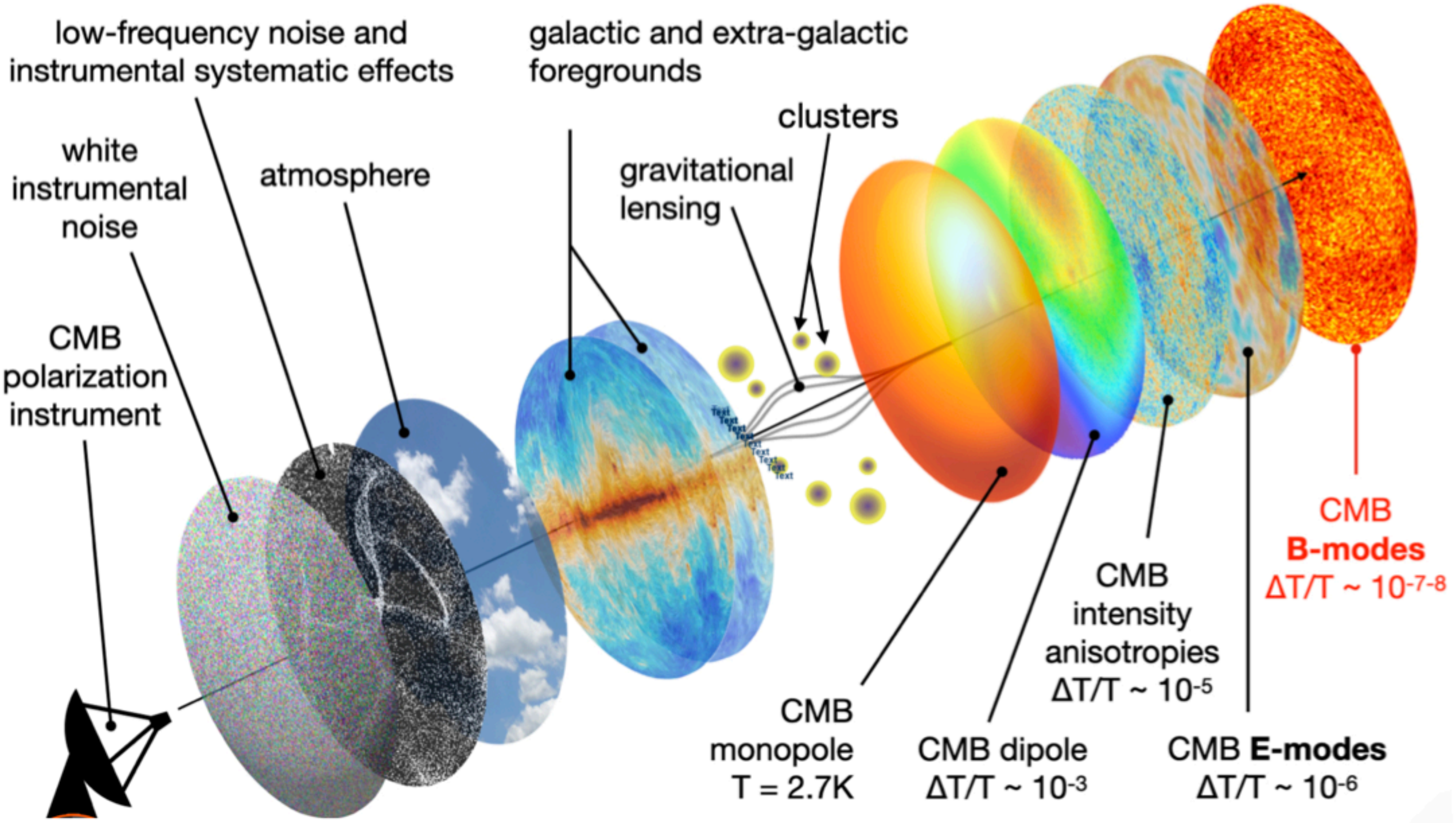




$$\frac{\delta T}{T_0} \propto \frac{\alpha}{\ell_P^2} \sim 10^{-5}$$

Quantum gravity encoded in dynamics and/or primordial quantum states

Signatures of these quantum effects can be observed in the sky, today



Credit: J. Errard

Metric perturbations

$$g_{\mu\nu}\mathrm{d}x^\mu\,\mathrm{d}x^\nu = -N^2\,\mathrm{d}t^2 + h_{ij}(N^i\,\mathrm{d}t + \mathrm{d}y^i)(N^j\,\mathrm{d}t + \mathrm{d}y^j)$$

$$h_{ij} = a(t)^2(\delta_{ij} + \delta h^{(s)}_{ij} + \delta h^{(t)}_{ij})$$

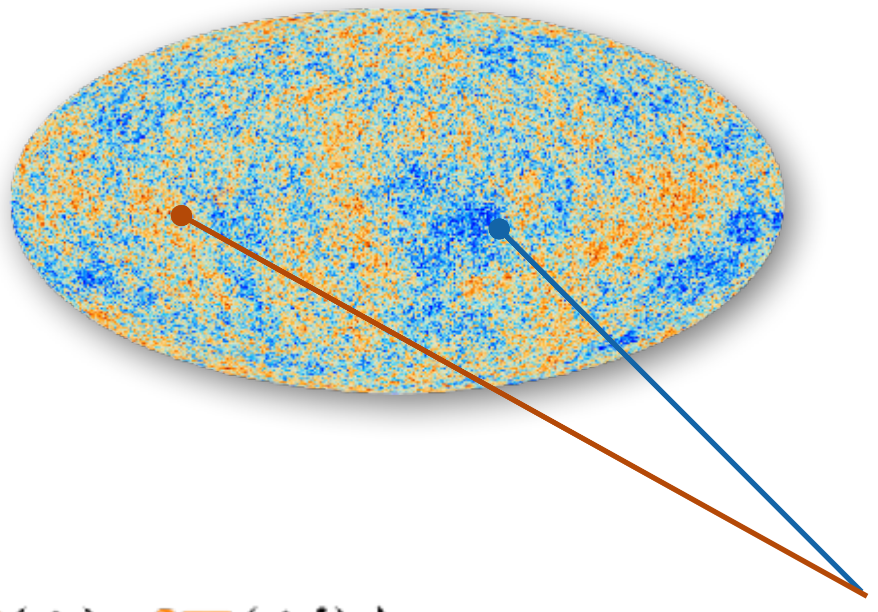
$$\delta h^{(s)}_{ij}(\mathbf{x},t) = -2\,\mathcal{R}(\mathbf{x},t)\,\delta_{ij}$$

$$\delta h^{(t)}_{ij}(\mathbf{x},t) = \sum_{\sigma=\pm} e^{\sigma}_{ij}(\mathbf{x})\,\gamma^\sigma(\mathbf{x},t)$$

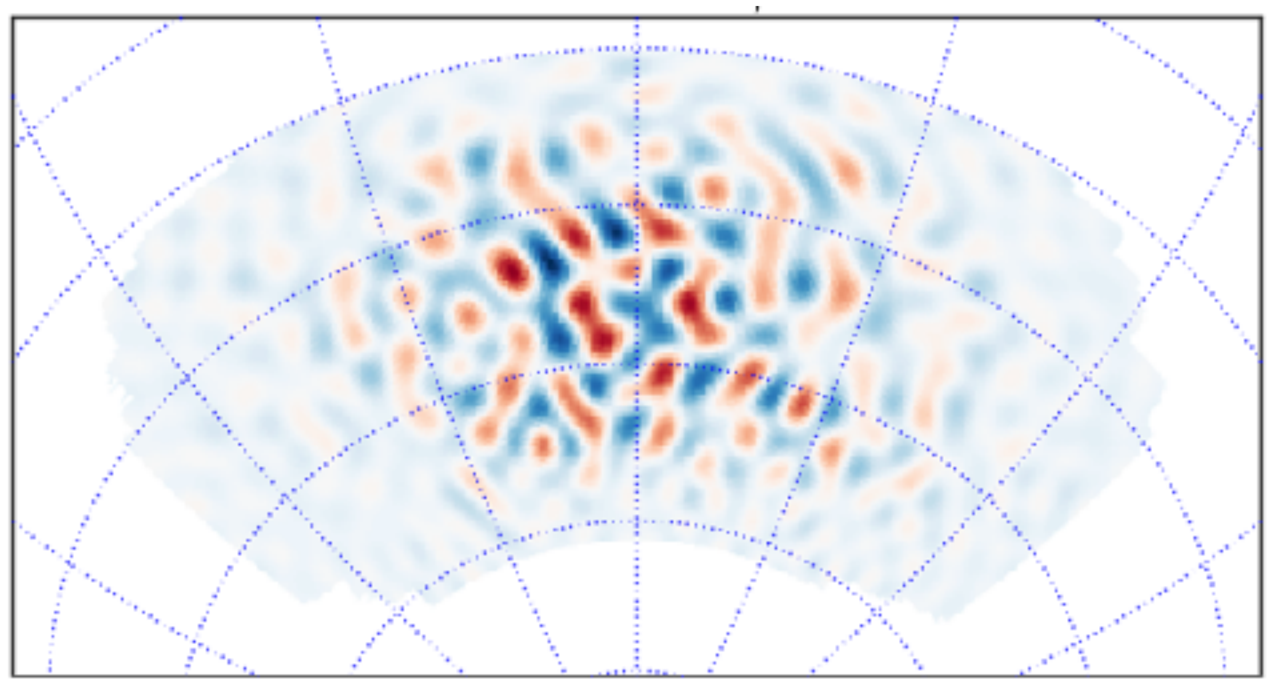
Primordial curvature perturbations: ${}^{(3)}R = \frac{4}{a(t)^2}\delta^{ij}\partial_i\partial_j\,\mathcal{R}$

Primordial gravitational waves

TT modes in CMB (Planck, ACT, SPT)



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



BB modes in CMB (BICEP/Keck, SO, Litebird)

Assuming a quasi-de Sitter background, in general vacuum fluctuations will induce deviations from a power-law:

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

(for exact de Sitter: $n_s = 1$, $\alpha_s = 0$, $\beta_s = 0$)

Hierarchy of quasi-de Sitter observables:

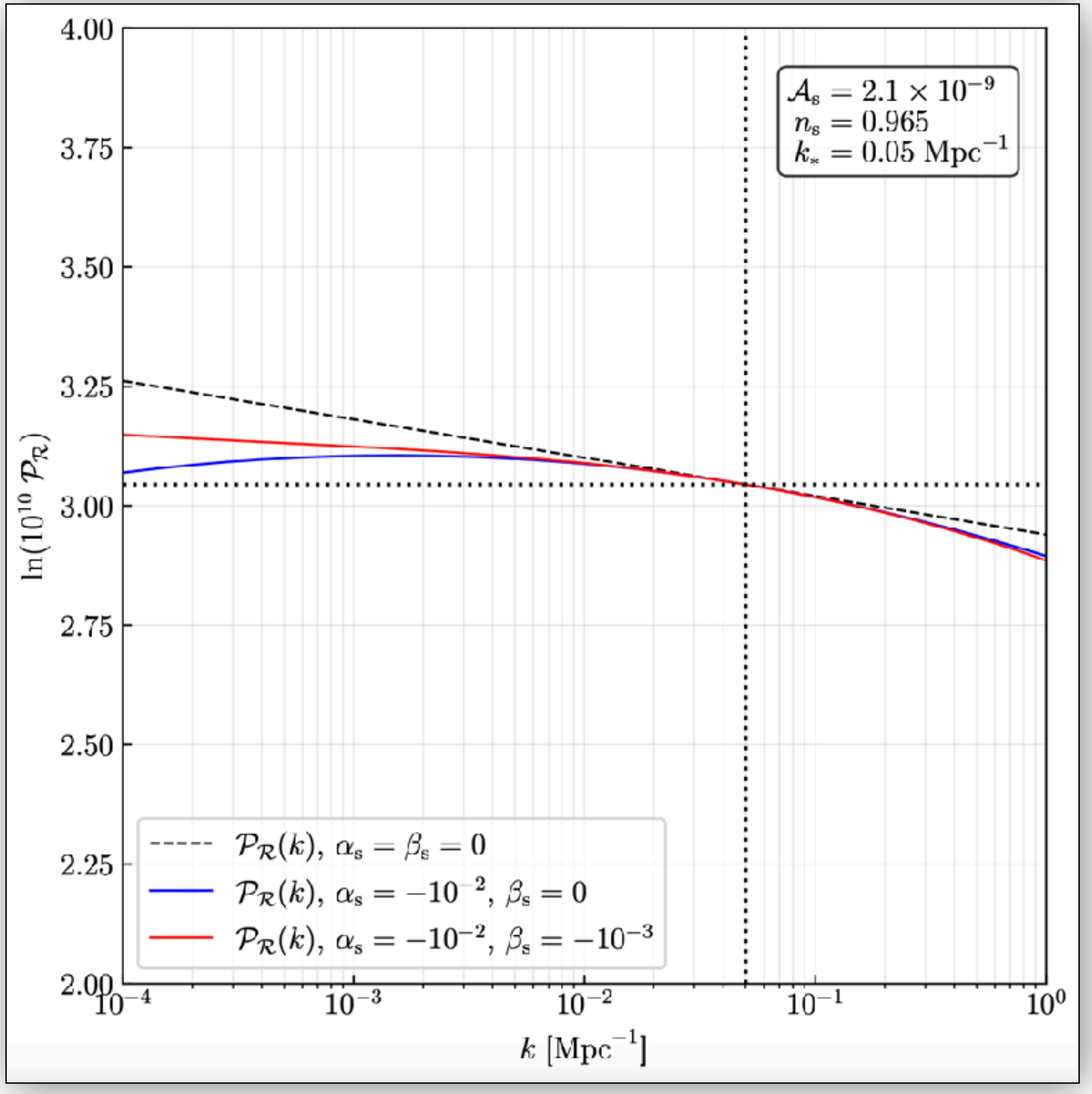
$$n_s = \frac{d\ln(\mathcal{P}_\mathcal{R})}{d\ln(k)} \quad \leftrightarrow \quad \text{“tilt”}$$

$$\alpha_s = \frac{d\ln(n_s)}{d\ln(k)} \quad \leftrightarrow \quad \text{“running of the tilt”}$$

$$\beta_s = \frac{d^2\ln(n_s)}{d\ln(k)^2} \quad \leftrightarrow \quad \text{“running of the running of the tilt”}$$

A consistent next-to-next-to-next-to leading order (N3LO) framework is required

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



Backup: Main ingredients of the N3LO framework

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

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

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

II. Arbitrary FLRW metric (systematic deviations from exact de Sitter)

$$\epsilon_{1H}(t) \equiv -\frac{\dot{H}(t)}{H(t)^2} \;\text{not constant} \qquad \leftrightarrow \qquad H_{\rm dS} = \sqrt{\frac{\Lambda}{3}}$$

III. Hubble-flow expansion (systematic deviations from vanilla inflation)

$$\epsilon_{1Z}(t) \equiv -\frac{\dot{Z}_\psi(t)}{H(t) Z_\psi(t)} \qquad \epsilon_{1c}(t) \equiv -\frac{\dot{c}_\psi(t)}{H(t) c_\psi(t)} \qquad \leftrightarrow \qquad \begin{array}{l} Z^{(\rm scalar)} = \frac{\epsilon_{1H}}{4\pi G} \;\rightarrow\; \epsilon_{1Z}^{(\rm scalar)} = \epsilon_{2H} \\ c = 1 \;\rightarrow\; \epsilon_{1c} = 0 \end{array}$$

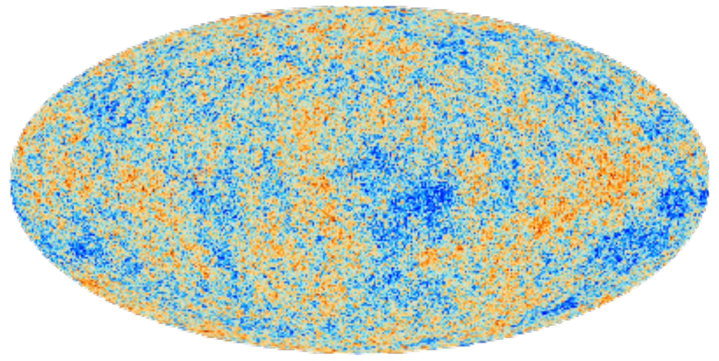
IV. Able to provide very precise predictions (next-to-next-to-next-to leading order)

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

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

New time variable: $y = -k\tau = \dfrac{k\,\tilde c}{aH}$, 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: $$w''(y) + \left(1 - \frac{2+g_{1k}+g_{2k}\ln(y)}{y^2}\right)w(y) = 0 \longrightarrow w(y) = w_0(y) + \int_y^\infty \frac{g(s)}{s^2}\,w(s)\,G(y,s)\,\mathrm{d}s$$

Scalar dof emerging from geometry

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

$$= \frac{1}{16\pi G}\int \mathrm{d}^4x\,\sqrt{-g}\left(\chi\,R - \frac{1}{4\alpha}(\chi-1)^2 - \beta W^2\right)$$

with $\chi = 1 + 2\,\alpha\,R$

Propagating **scalaron**: $\Box\chi(\mathbf{x},t) = \frac{1}{6\alpha}\chi(\mathbf{x},t)$

Only metric perturbations: $g_{\mu\nu} = \bar{g}_{\mu\nu} + \delta g_{\mu\nu}[\Psi]$

Dynamics of 2-point correlations encoded in quadratic action

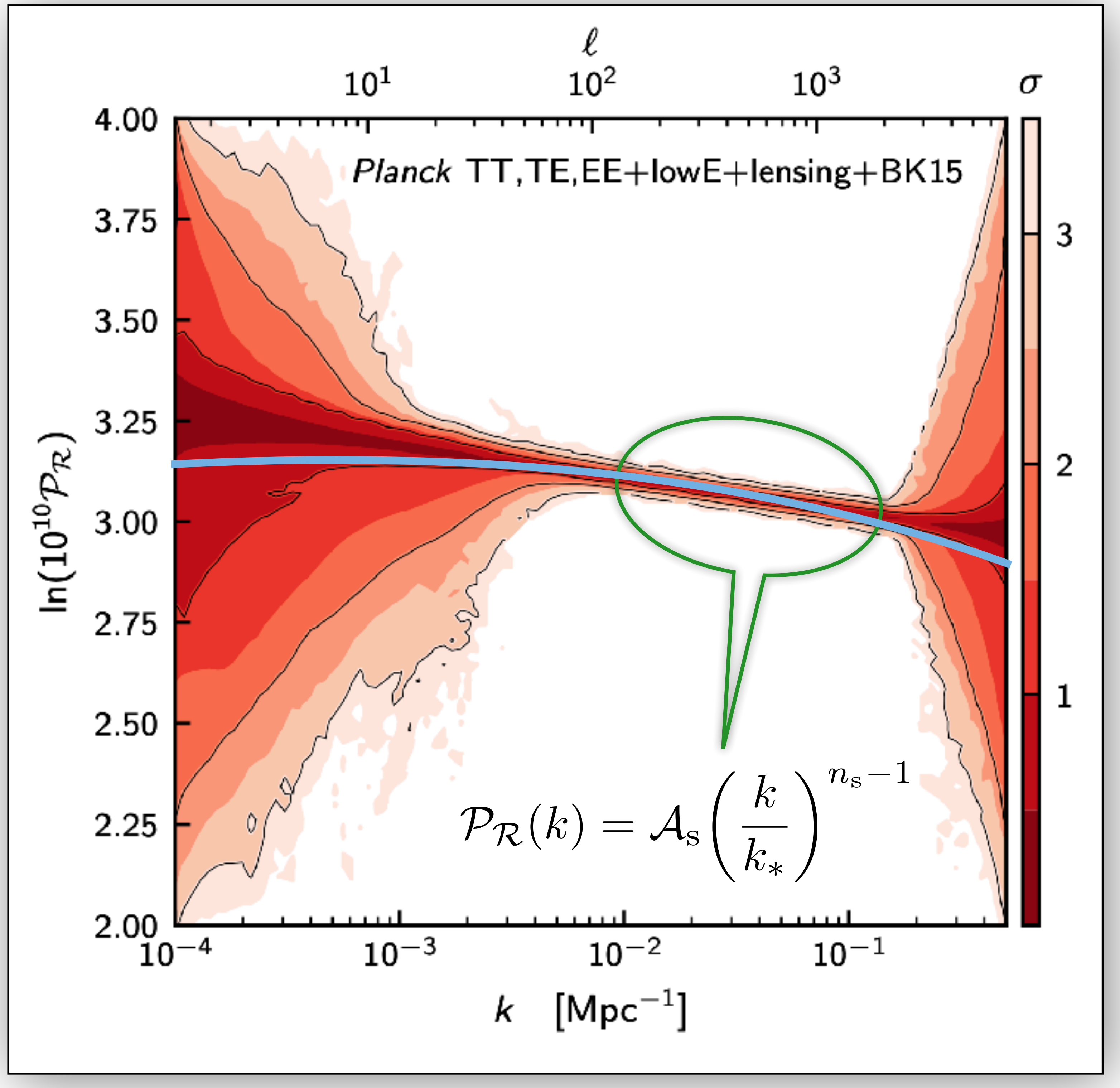
$$S^{(2)}_{\Psi}[\Psi] = \frac{1}{2}\int \mathrm{d}^4x\, Z_\Psi(t)\, a(t)^3\left(\dot{\Psi}^2 - \frac{c_\Psi(t)^2}{a(t)^2}(\partial_i\Psi)^2\right)$$

$$c_s(t) = 1 + \frac{\beta}{6\,\alpha}\epsilon_{1H}(t)^2 + \mathcal{O}(\epsilon^2)$$

$$c_t(t) = 1 + \frac{\beta}{6\,\alpha} + \mathcal{O}(\epsilon)$$

Current CMB constraints

(Planck Collaboration, 2018)



Assuming vacuum fluctuations (quasi-Bunch-Davies)

$$\ln(\mathcal{P}_\mathcal{R}(k)) = \ln(\mathcal{A}_s) + (n_s - 1)\ln\left(\frac{k}{k_*}\right)$$

$$+ \frac{1}{2!}\frac{\mathrm{d}\ln(n_s)}{\mathrm{d}\ln(k)}\ln(k/k_*)^2 + \frac{1}{3!}\frac{\mathrm{d}^2\ln(n_s)}{\mathrm{d}\ln(k)^2}\ln\left(\frac{k}{k_*}\right)^2 + \cdots$$

[Bianchi & **MG**, PRD '24]

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:

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

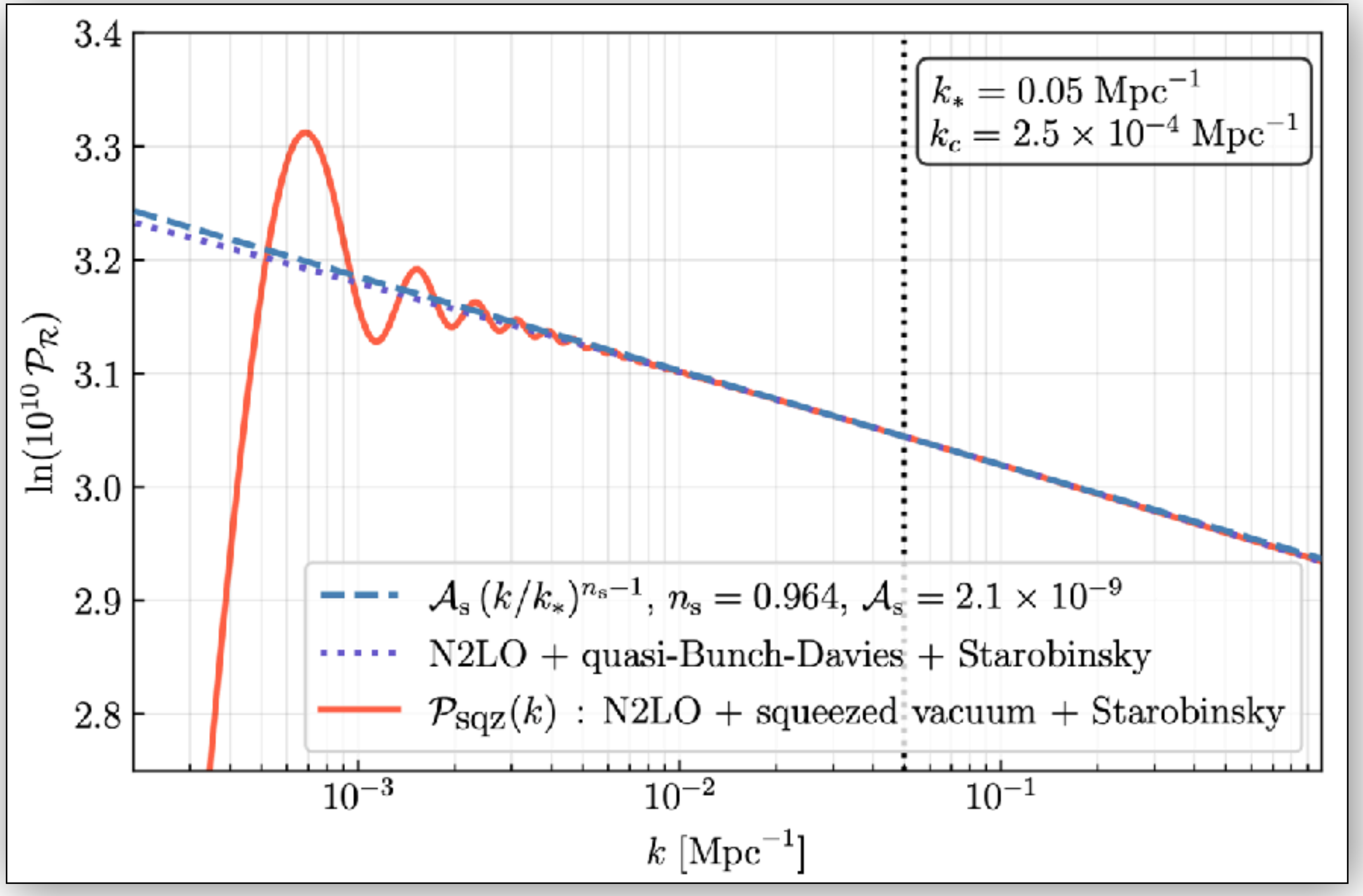
Squeezed vacua induce power suppression and modulations

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

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

Simple choice for Bogoliuvob coefficients illustrating a pre-inflationary phase (instant transition)

$$\alpha_k = 1 - \frac{k_c^2}{2k^2} - \mathrm{i}\,\frac{k_c}{k}, \quad \beta_k = -\frac{k_c^2}{2k^2}\, \mathrm{e}^{\,2\,\mathrm{i}k/k_c}.$$



Relevant for templates used to study primordial features

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

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: Templates

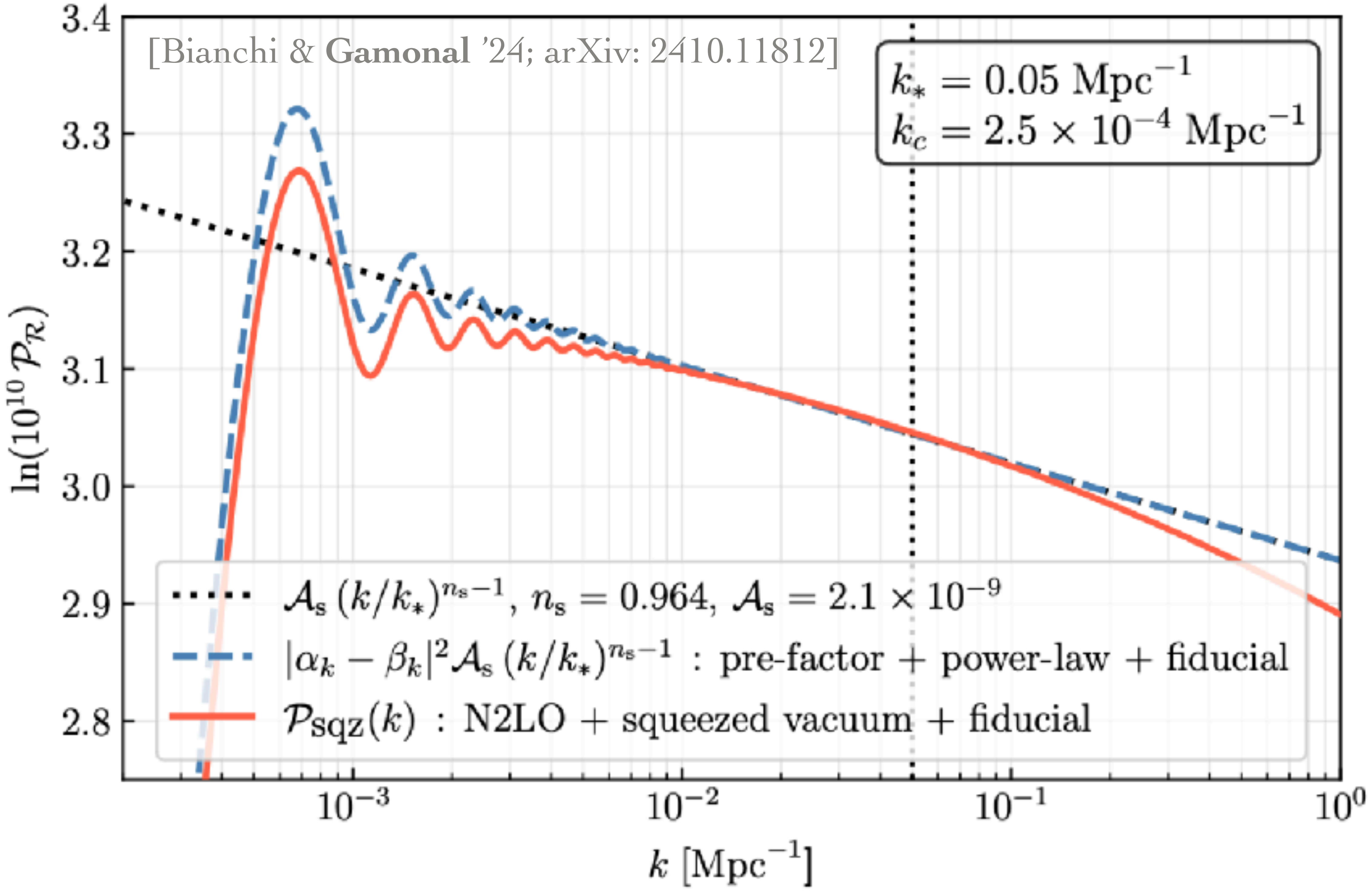
Why interesting?: Templates used to study primordial features (Euclid, ACT, LiteBIRD, +)

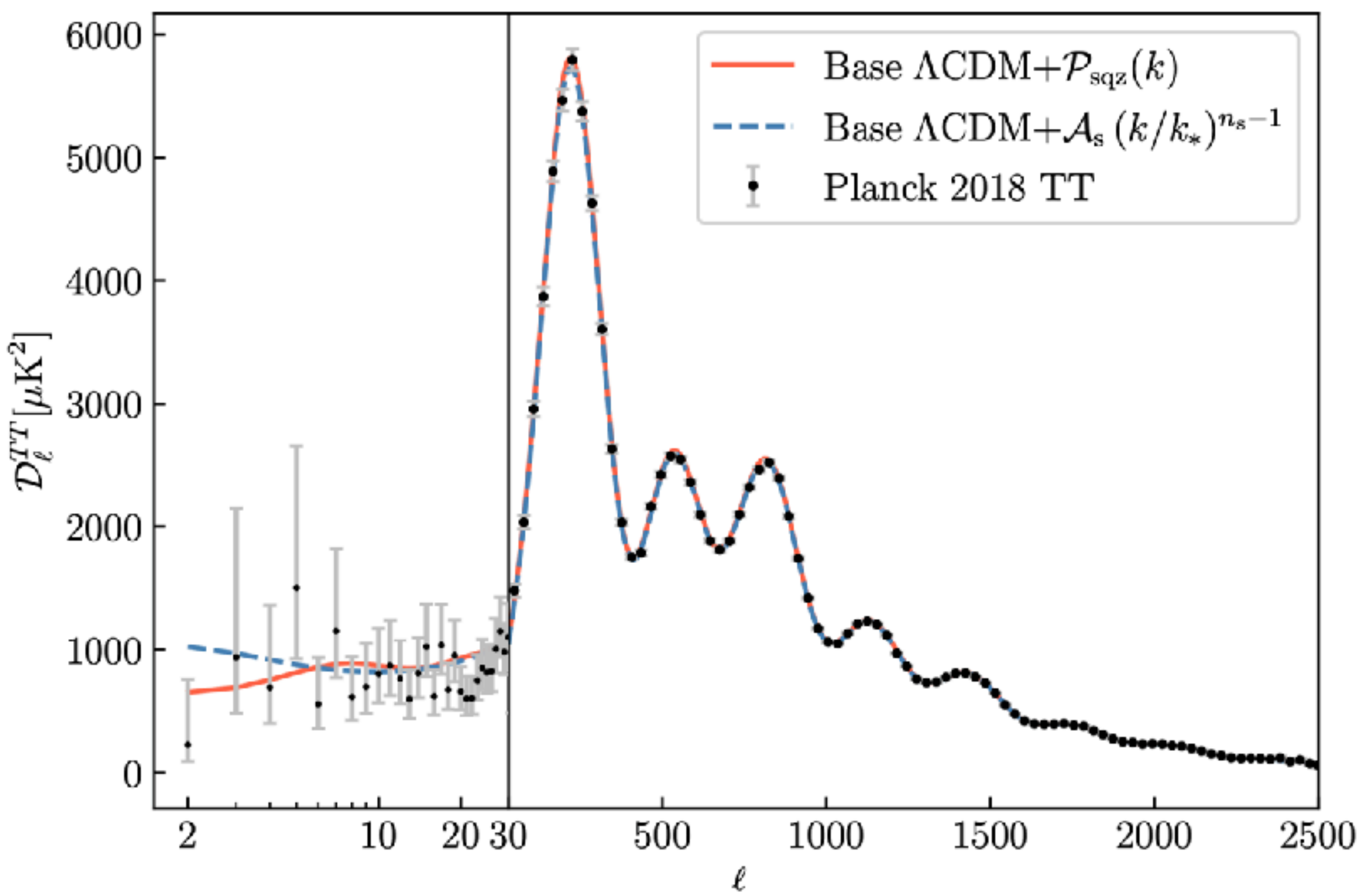
$$\mathcal{P}_{\mathcal{R}}^{(\mathrm{phen})}(k) = \left[1 - R_k \cos\left(\Xi_k + \delta\right)\right] \left(\frac{k}{k_*}\right)^{n_s - 1} \mathcal{A}_s$$

Example: simple choice for Bogoliuvob coefficients (e.g., instant transition Minkowski-dS at $\eta = \eta_c$)

$$\alpha_k = 1 - \frac{k_c^2}{2k^2} - \mathrm{i}\,\frac{k_c}{k}, \quad \beta_k = -\frac{k_c^2}{2k^2}\, \mathrm{e}^{2\,\mathrm{i}k/k_c}.$$

$$\mathcal{P}_{\mathrm{sqz}}(k) \sim \left[1 - (k_c^2/k^2)\, \cos(2k/k_c + \delta_k)\right] \mathcal{P}_{\mathrm{qBD}}(k)$$



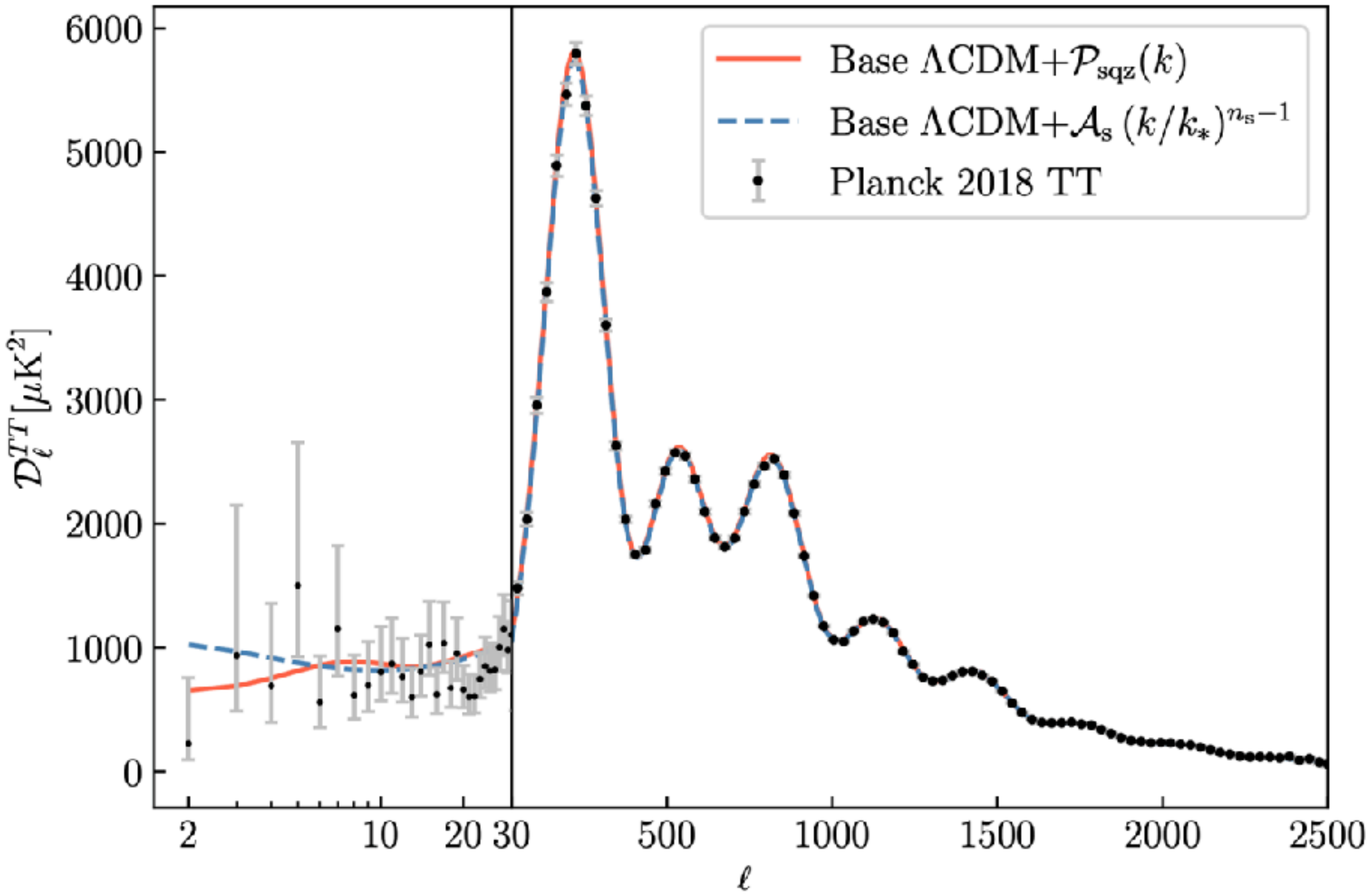


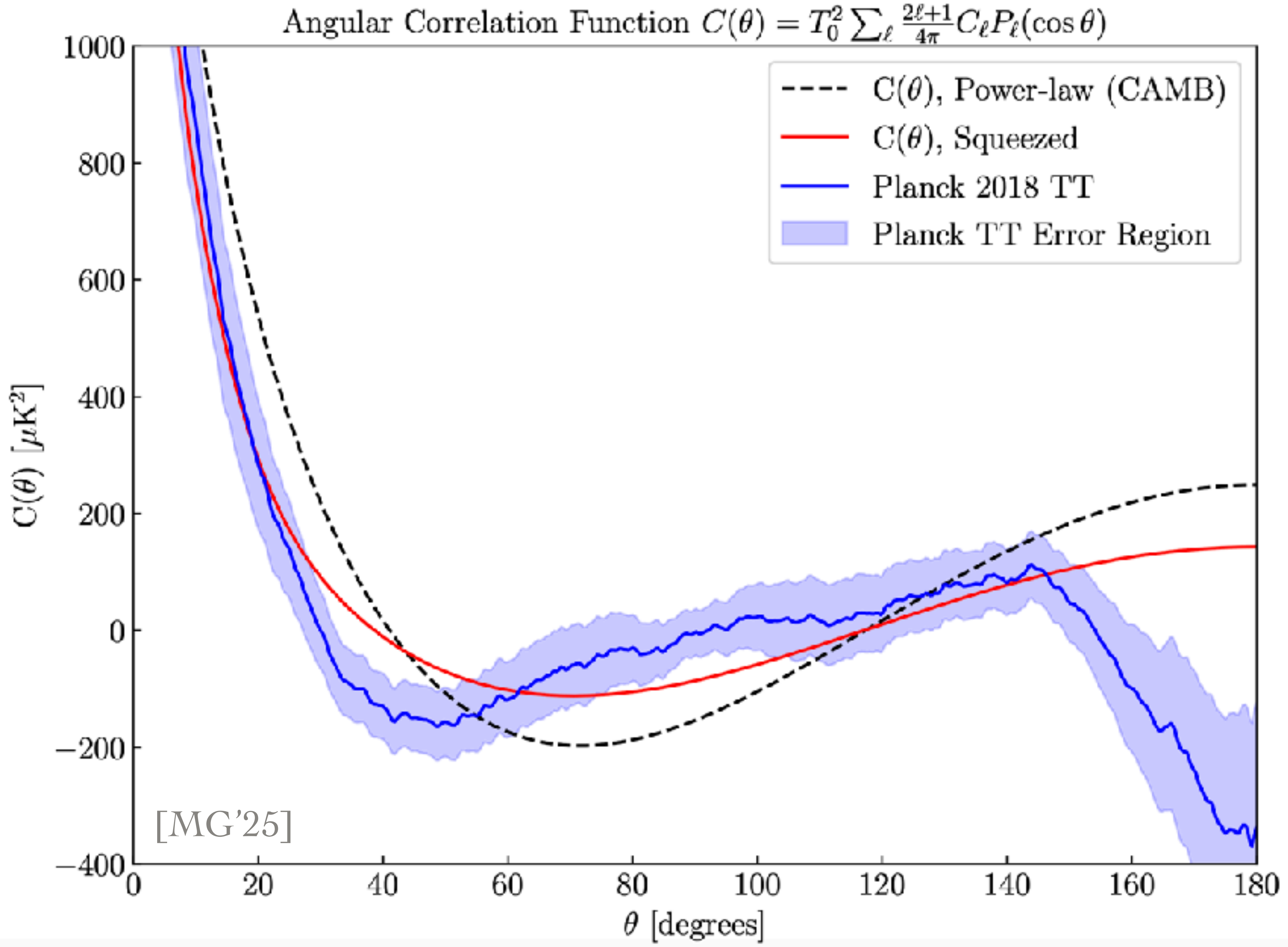
Backup: Pre-inflationary phase and CMB anomalies

[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.

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





LORENTZIAN EPRL VERTEX AMPLITUDE [Engle, Pereira, Rovelli, Livine '07]

The Lorentzian EPRL model provides a covariant formulation of loop quantum gravity in 4d, with a vertex amplitude built from Wigner D-matrices associated with each wedge (ab):

4d Lorentz invariance

γ–simple representation: $(\rho, k) \to (\gamma j_{ab}, j_{ab})$

$$\langle A_v^{(\mathrm{EPRL})} | \Psi_{j_{ab}, m_{ab}} \rangle = \int_{SL(2,\mathbb{C})} \prod_{a=2}^{5} \mathrm{d}g_a \prod_{ab} D^{(\gamma j_{ab}, j_{ab})}_{j_{ab}\, m_{ba}\, j_{ab}\, m_{ab}} (g_b^{-1} g_a)$$

boundary states

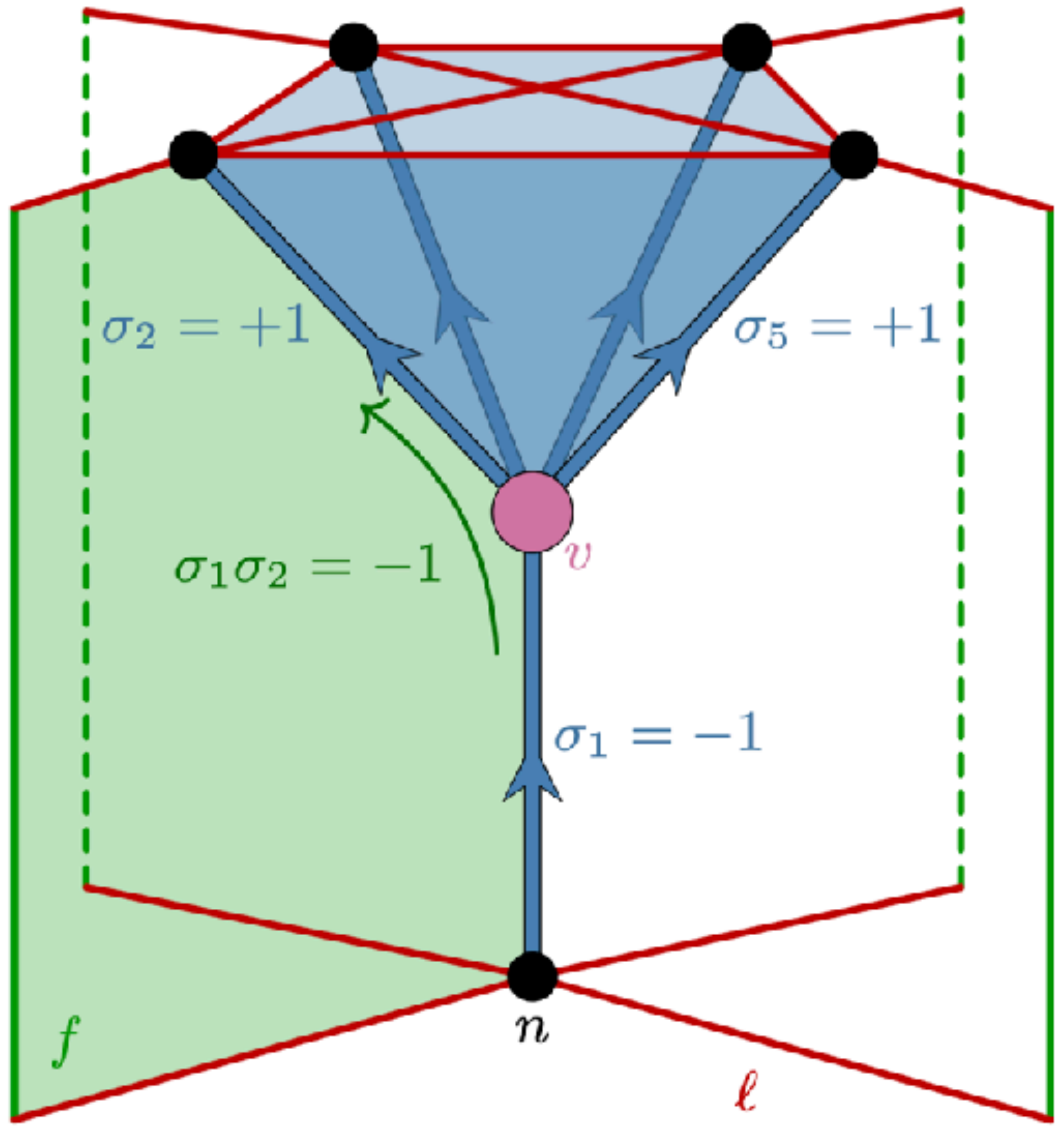
Wigner D-matrix: Unitary irreps of $SL(2,\mathbb{C})$ in principal series $(\rho, k) \in (\mathbb{R}, \mathbb{Z}/2)$

1. "EPRL model is **blind** to the bulk orientation structure" [Bianchi & Martin-Dussaud '21]
2. One would like to have an object that depends on the orientation. Our work: $T^{(+)} + T^{(-)} = D$

THE CAUSAL SPINFOAM VERTEX [Bianchi, Chen & Gamonal '26]

This new ingredient, the Toller T-matrix, allows us to define a vertex amplitude with fixed causal structure:

$$\langle A_v^{(\sigma_a\sigma_b)}|\Psi_{j_{ab},m_{ab}}\rangle = \int_{SL(2,\mathbb{C})} \prod_{a=2}^{5} \mathrm{d}g_a \prod_{ab} T^{(\sigma_a\sigma_b,\,\gamma j_{ab},j_{ab})}_{j_{ab}\,m_{ba}\,j_{ab}\,m_{ab}}(g_b^{-1}g_a)$$



To each wedge (ab) in a spinfoam vertex, we associate a Toller T-matrix with sign ± determined by the wedge orientation $\kappa_{ab} = \sigma_a\sigma_b$, induced by the orientations σ_a and σ_b of the two edges forming the wedge:

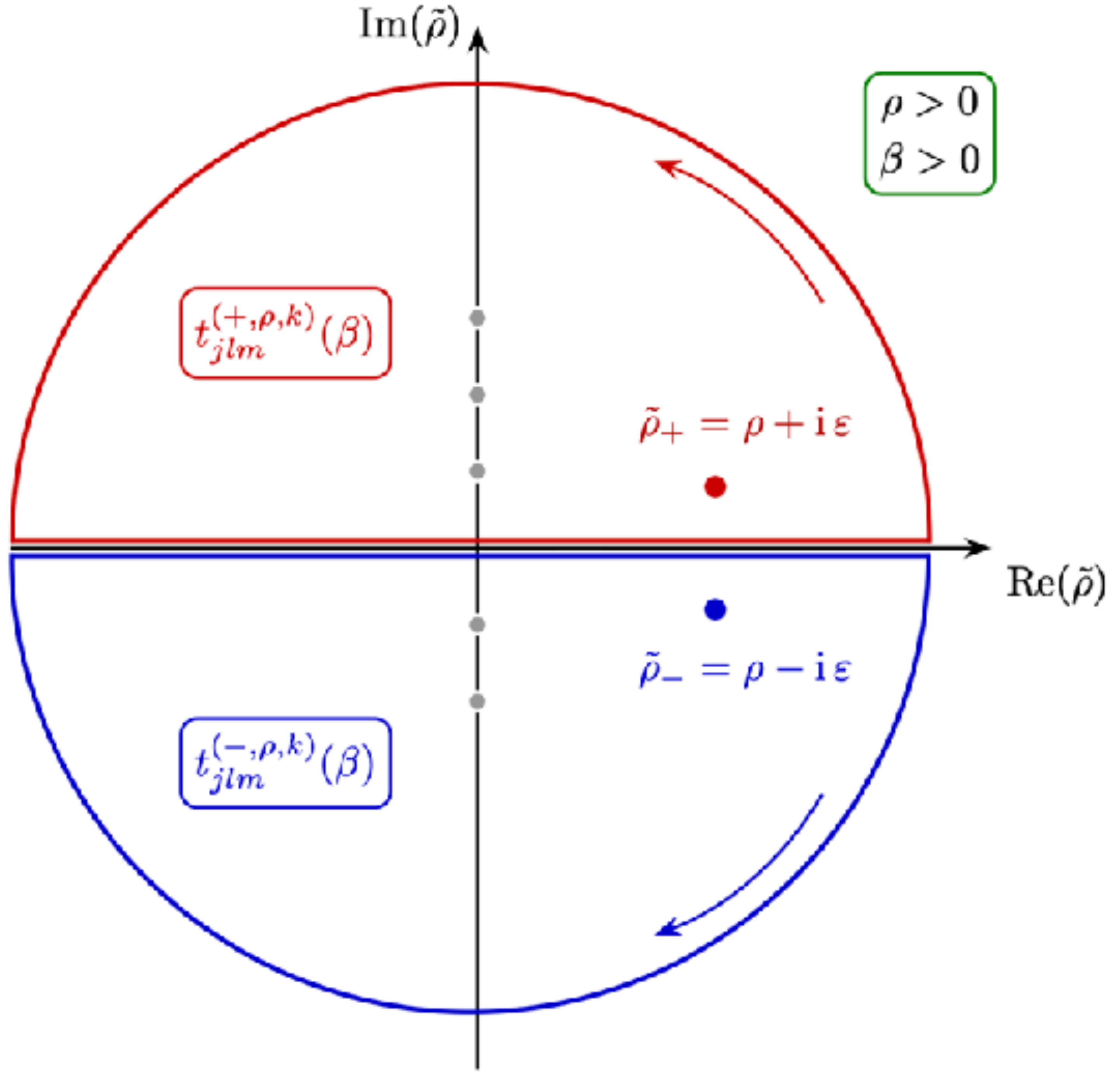
$$\sigma_a\,\sigma_b = \begin{cases} -1 & \text{for an anti-chronal wedge} \\ +1 & \text{for a co-chronal wedge} \end{cases}$$

<u>This is the building block for a spinfoam path integral with a sum over causal structures</u>

FEYNMAN $i\varepsilon$ REPRESENTATION OF THE TOLLER MATRICES [Bianchi, Chen & Gamonal '26]

We can encode the defining analytic properties of the Toller t-matrices via a Feynman $i\varepsilon$ prescription:

$$t_{jlm}^{(\pm,\rho,k)}(\beta) = \lim_{\varepsilon\to 0^+} \int_{-\infty}^{+\infty} \frac{d\tilde\rho}{2\pi i} \frac{\pm 1}{\tilde\rho - \rho \mp i\varepsilon} \left(\prod_{n=0}^{j+l} \frac{i\tilde\rho - (n-j)}{i\rho - (n-j)} \right) d_{jlm}^{(\tilde\rho,k)}(\beta)$$



Select a contour:
asymptotic properties

Analytic kernel:
Toller poles
(expressed later as Γ's)

Wigner d-matrix:
matching properties

$$\longleftrightarrow \quad T_{jm\,ln}^{(\pm,\rho,k)}(g) = \sum_{p=-\min(j,l)}^{\min(j,l)} D_{mp}^{(j)}(U_1)\, t_{jlp}^{(\pm,\rho,k)}(\beta)\, D_{pn}^{(l)}(U_2)$$

Regge geometry of a Lorentzian 4-simplex

[Regge '61; Sorkin '19; Asante, Dittrich, Padua-Argüelles '21]
[Minkowski 1897; Bianchi, Donà, Speziale '11; Wieland PhD '13]

A set of five 4-vectors N_a^I satisfying the closure condition $\sum_{a=1}^{5} N_a^I = 0$ uniquely determines the Regge geometry of a 4-simplex (cf. Minkowski theorem).

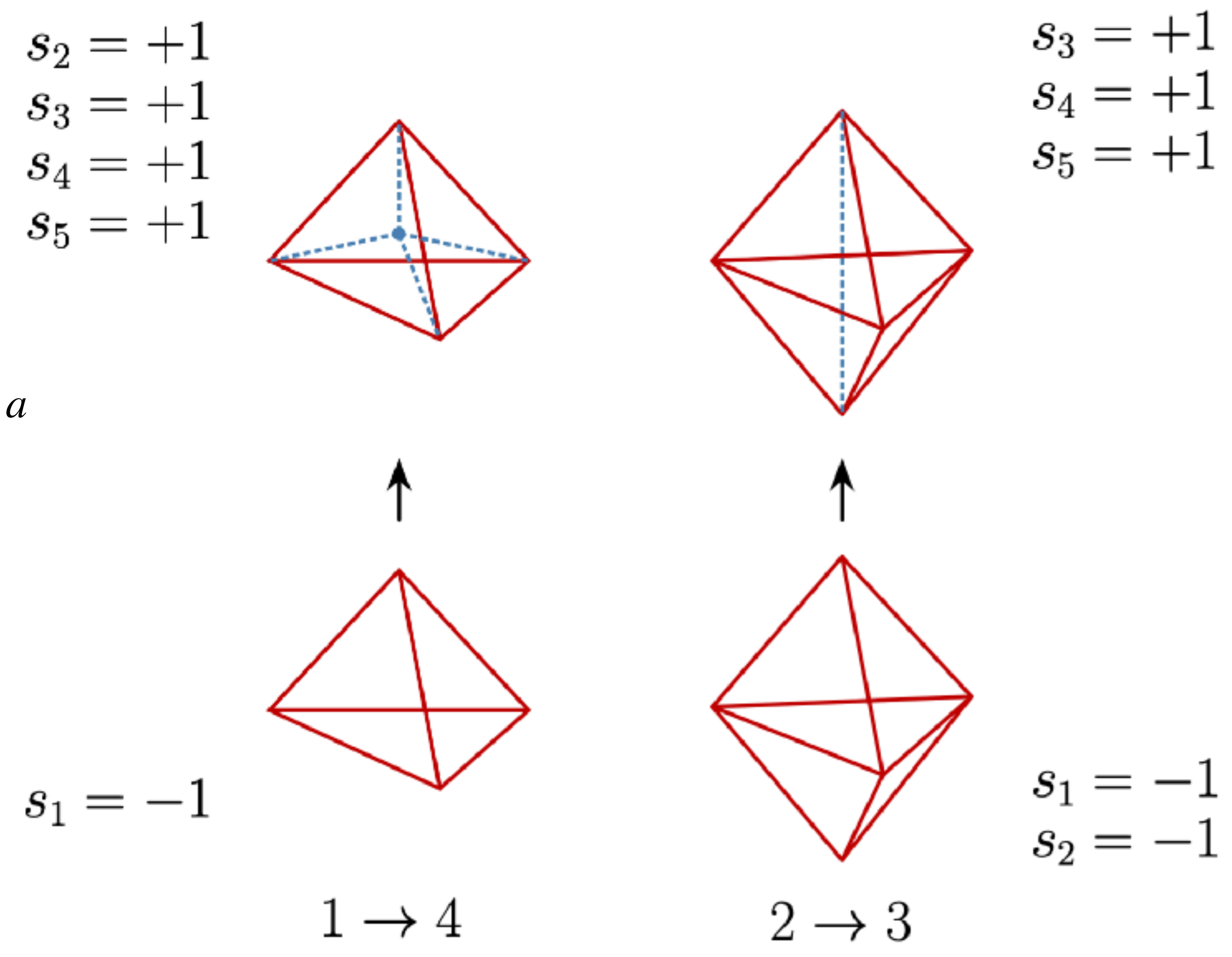
For spacelike boundary tetrahedra, we can write their corresponding timelike 4-normals as:

$$N_a^I = s_a \, V_a \, \hat{N}_a^I$$

Regge causal data (s_a)

$$s_a = \begin{cases} -1 & \text{for a past pointing 4-normal} \\ +1 & \text{for a future pointing 4-normal} \end{cases}$$

volume of the tetrahedron a (V_a)



The Regge action for the Lorentzian 4-simplex takes the form:

$$S_{\text{Regge}} = \sum_{ab} \frac{A_{ab}}{8\pi G} \, s_a s_b \, \beta_{ab}$$

$$s_a \, s_b = \begin{cases} -1 & \text{for anti-chronal tetrahedra} \\ +1 & \text{for co-chronal tetrahedra} \end{cases}$$

boost from tet(a) to tet(b)

$$\cosh(\beta_{ab}) = -\eta_{IJ} \hat{N}_a^I \hat{N}_b^J$$

Asymptotics and Causal Rigidity

[Engle '11; Engle, Vilensky, Zipfel '15]
[Bianchi & Martin-Dussaud '21]
[Bianchi, Chen & Gamonal '26]

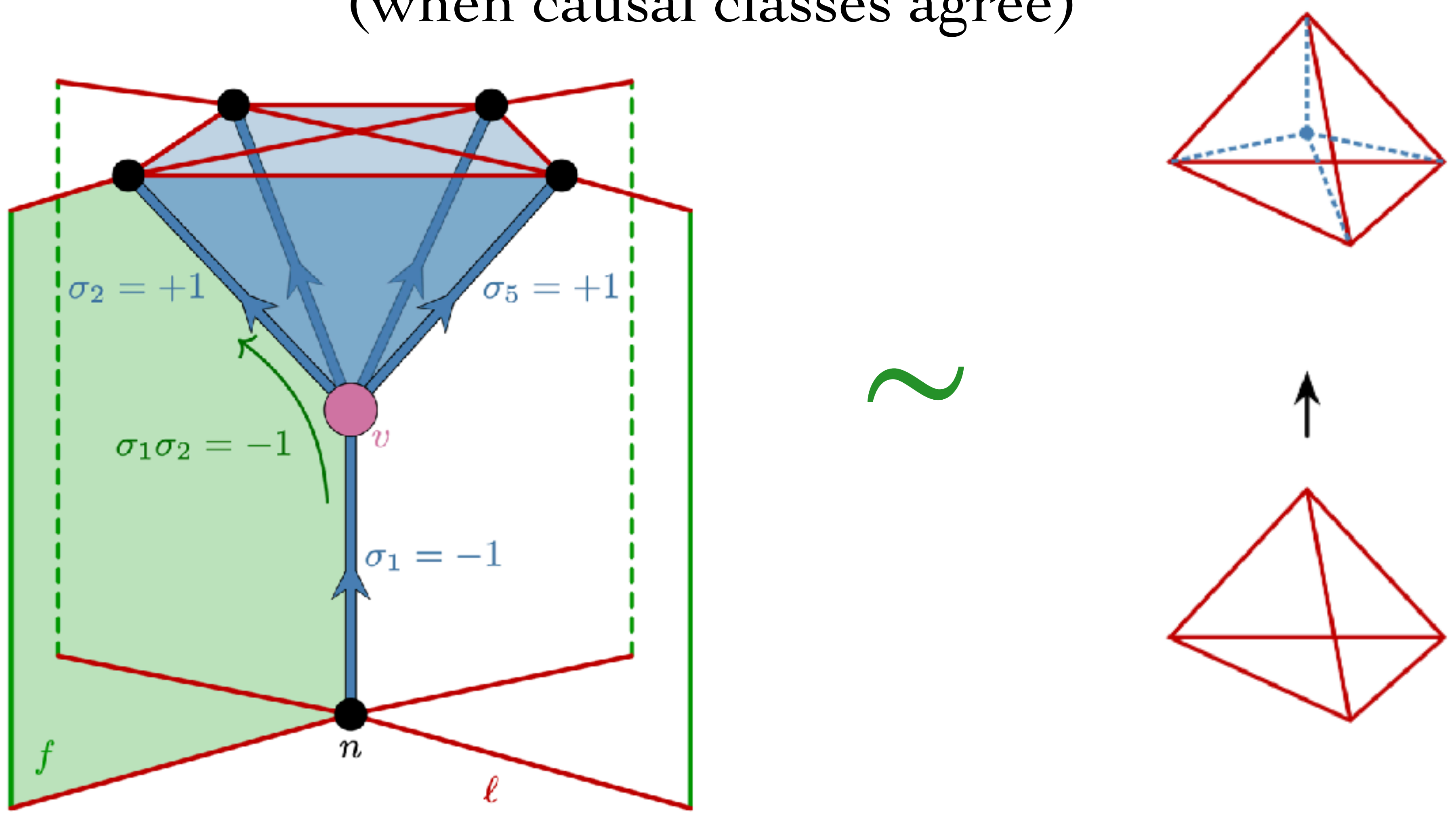
$$\sigma_a\,\sigma_b = \begin{cases} -1 & \text{for an anti-chronal wedge} \\ +1 & \text{for a co-chronal wedge} \end{cases}$$

$$s_a\,s_b = \begin{cases} -1 & \text{for anti-chronal tetrahedra} \\ +1 & \text{for co-chronal tetrahedra} \end{cases}$$

The Toller T-matrix inserts a step function $\theta(+\sigma_a\sigma_b\, s_a\, s_b)$ at the **exact** level.
On a semiclassical boundary state peaked on the geometry of a Lorentzian 4-simplex, the causal vertex, in the large-spin limit ($j_{ab} \to \lambda j_{ab}\,, \lambda \to \infty$), selects one saddle point and enforces a form of **causal rigidity**: if for all couples (ab) we have

$$\sigma_a\sigma_b = +s_a s_b$$

(when causal classes agree)

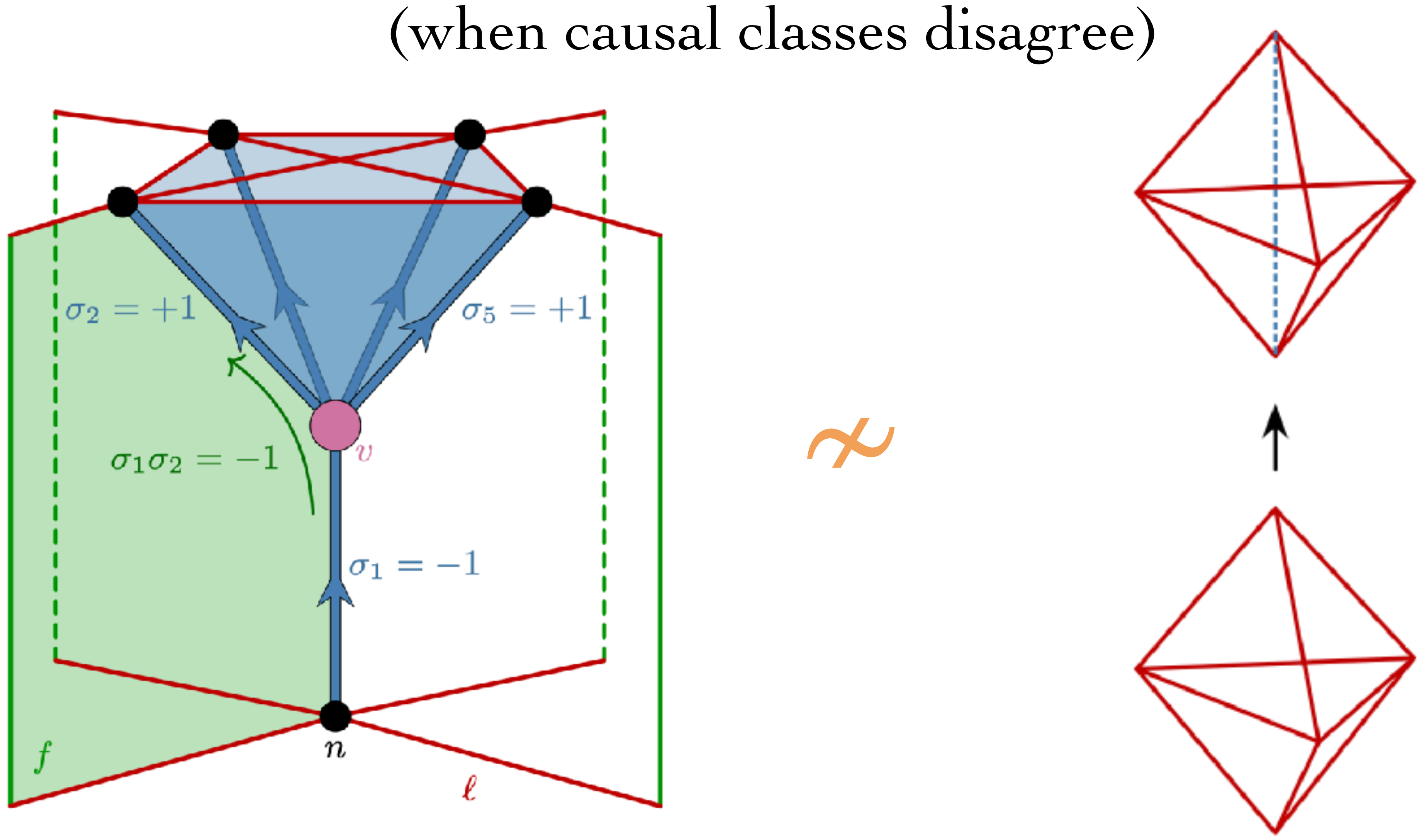


$1 \to 4$

$$\langle A_v^{(\sigma_a\sigma_b)} | \Psi_{\lambda j_{ab},\zeta_{ab}} \rangle = \frac{e^{i(\mu+\lambda\Upsilon)}}{2\,\lambda^{12}\,\mathcal{N}}\, e^{+i\lambda S_{\mathrm{Regge}}/\hbar} + \mathcal{O}(\lambda^{-13})$$

$$\sigma_a\sigma_b \neq +s_a s_b$$

(when causal classes disagree)



$2 \to 3$

$$\langle A_v^{(\sigma_a\sigma_b)} | \Psi_{\lambda j_{ab},\zeta_{ab}} \rangle = \mathcal{O}(\lambda^{-N})\,, \quad \forall N > 0$$

Perspectives

Possible Implications for phenomenology

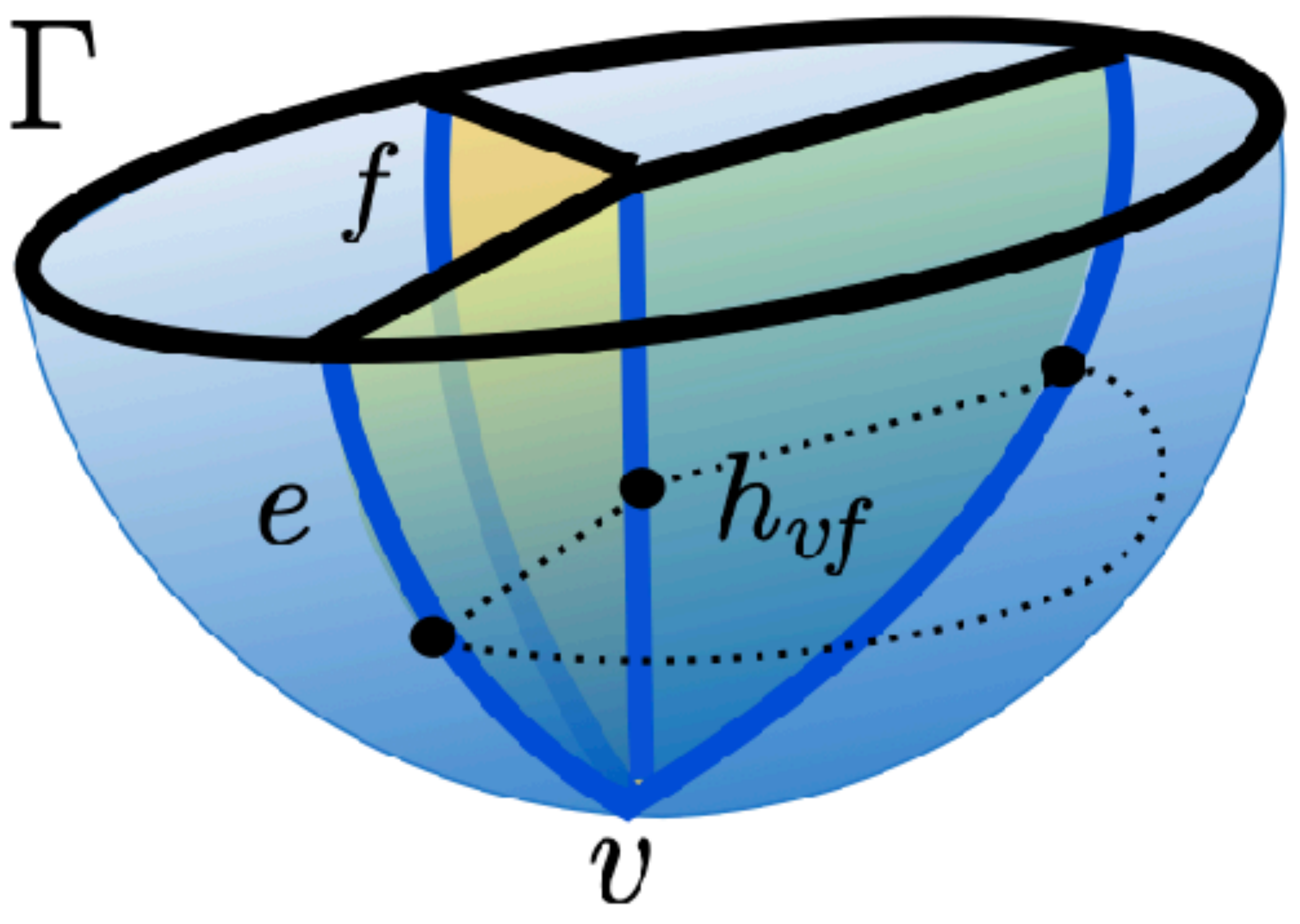
Finally, it would be interesting to investigate the effects of the causal spinfoam vertex on transition amplitudes of phenomenological relevance, in spinfoam cosmology

[Vidotto '10; Bianchi, Rovellli, Vidotto '10; Gozzini & Vidotto '19; +]

and in spinfoam black-to-white hole tunneling

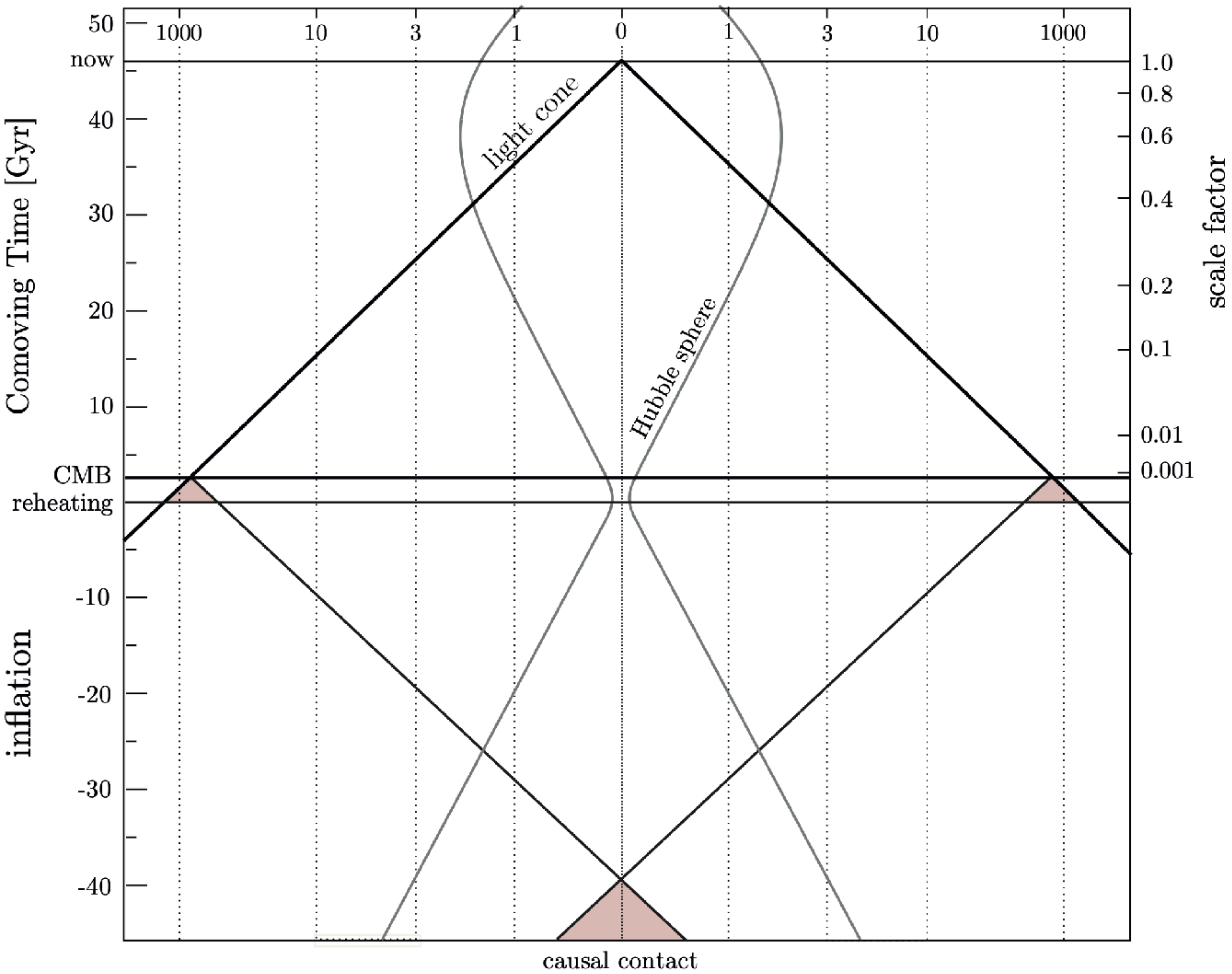
[Haggard & Rovelli '14; Christodoulou, Rovelli, Speziale, Vilensky '16; Donà, Haggard, Rovelli, Vidotto '24; Rovelli & Vidotto '24; +]

Spinfoam Hartle-Hawking state



[Vidotto LQG Summer School '24]

Comoving Time [Gyr]
50
now
40
30
20
10
CMB
0
1000
10
3
1
0
1
3
10
1000
light cone
Hubble sphere
1.0
0.8
0.6
0.4
0.2
0.1
0.01
0.001
scale factor
-40
-20
0
20
40
Comoving Distance [Glyr]



Comoving Time [Gyr]
50
now
40
30
20
10
CMB
reheating
-10
-20
-30
-40
inflation
1000
10
3
1
0
1
3
10
1000
1.0
0.8
0.6
0.4
0.2
0.1
0.01
0.001
scale factor
light cone
Hubble sphere
causal contact