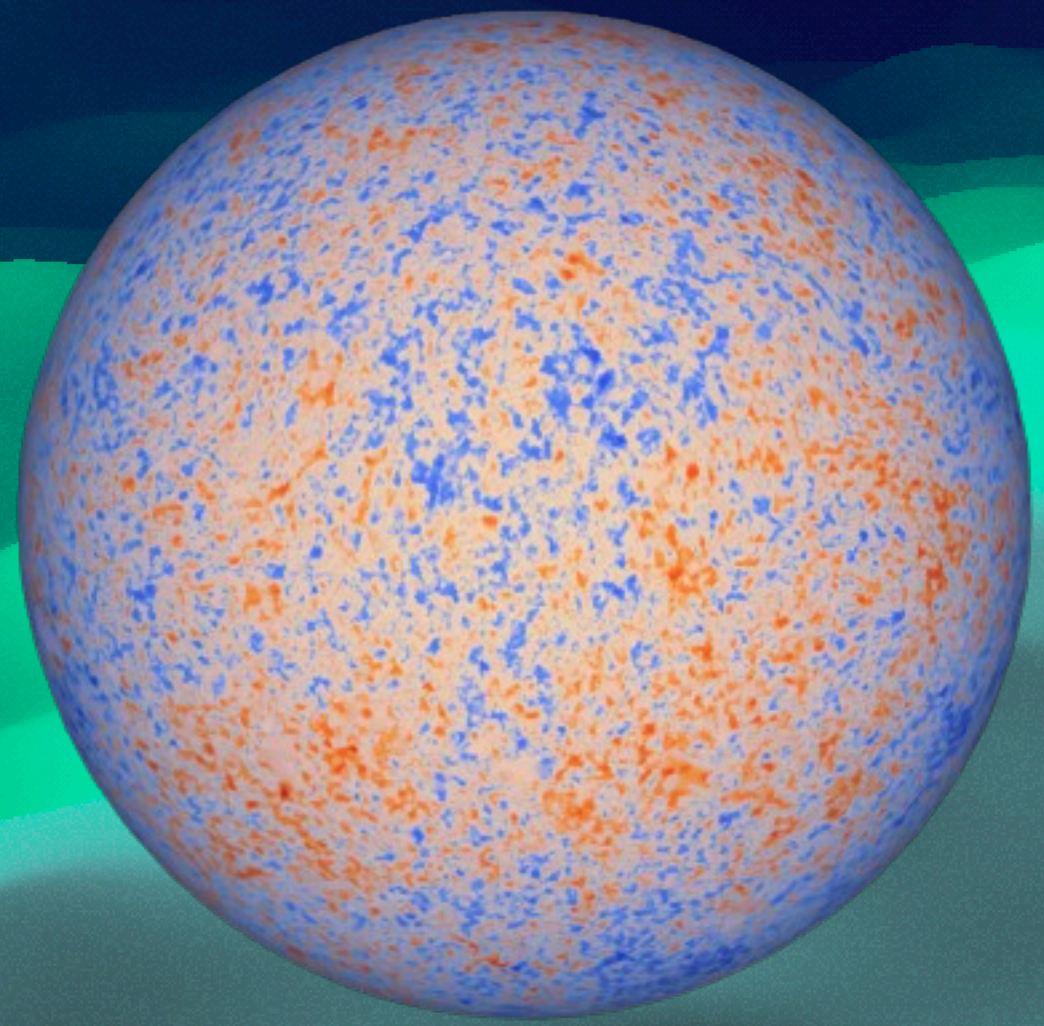
Precision cosmology as a probe of quantum gravity

Mauricio Gamonal
Physics PhD student at Penn State

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



Loops' 24 Conference - Florida Atlantic University, Fort Lauderdale, FL — May 7, 2024

THE BIG PICTURE

[MG PhD Thesis '26?]

Loop Quantum Cosmology

[Agullo, Ashtekar & Nelson '12]
[Fernandez-Mendez, Mena & Olmedo '12]

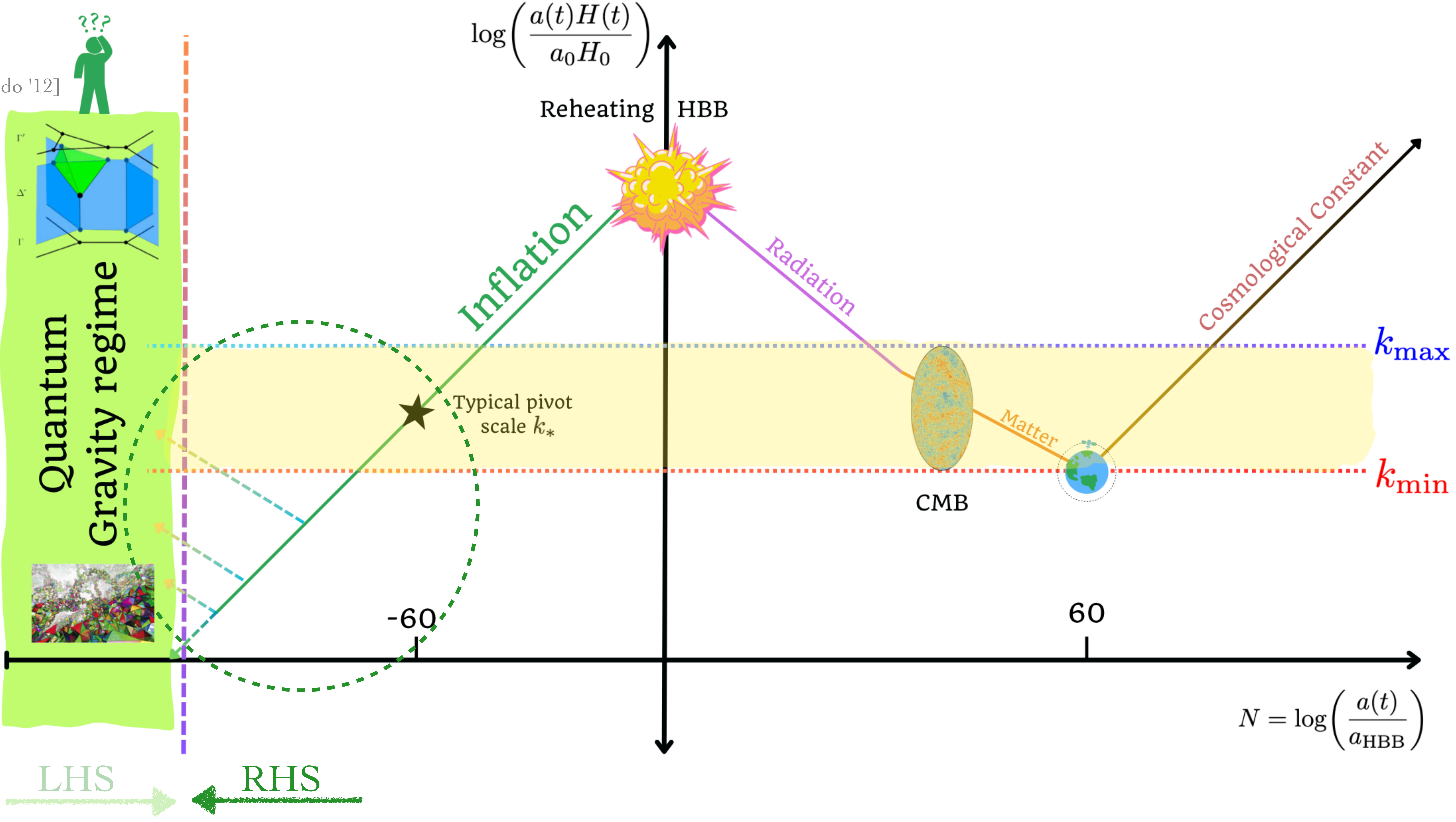
Spinfoam Cosmology

[Bianchi, Rovelli & Vidotto '10]

Cosmology from GFT

[Gielen, Oriti & Sindoni '13]

⋮



THE FRAMEWORK: A LARGE CLASS OF EFFECTIVE THEORIES OF INFLATION

Ingredients: Action Principle

1. A gravitational action (matter not required):

$$S = S[g_{\mu\nu}, \chi] \quad \text{with} \quad \begin{gathered} g_{\mu\nu}(\mathbf{x}, t) = \bar{g}_{\mu\nu}(t) + \delta g_{\mu\nu}(\mathbf{x}, t) \\ \chi(\mathbf{x}, t) = \bar{\chi}(t) + \delta\chi(\mathbf{x}, t) \end{gathered}$$

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2. Small perturbations (on a flat FLRW background):
   Ψ : Any dynamical SVT mode

$$\boxed{S^{(2)}_{\Psi}[\Psi] = \frac{1}{2}\int \mathrm{d}^4x \, \underbrace{Z_{\Psi}(t)}_{\text{Kinetic amplitude}} \, \underbrace{a(t)^3}_{\text{Scale factor}} \left(\dot{\Psi}^2 - \underbrace{\frac{c_{\Psi}(t)^2}{a(t)^2}}_{\text{Speed of sound}}(\partial_i\Psi)^2\right)}$$

c.f. single scalar field: $Z_{\mathrm{s}}(t) = \dfrac{\epsilon_{1H}(t)}{4\pi G}, \quad Z_{\mathrm{t}}(t) = \dfrac{1}{64\pi G}, \quad c_{\mathrm{t}}(t) = c_{\mathrm{s}}(t) = 1$

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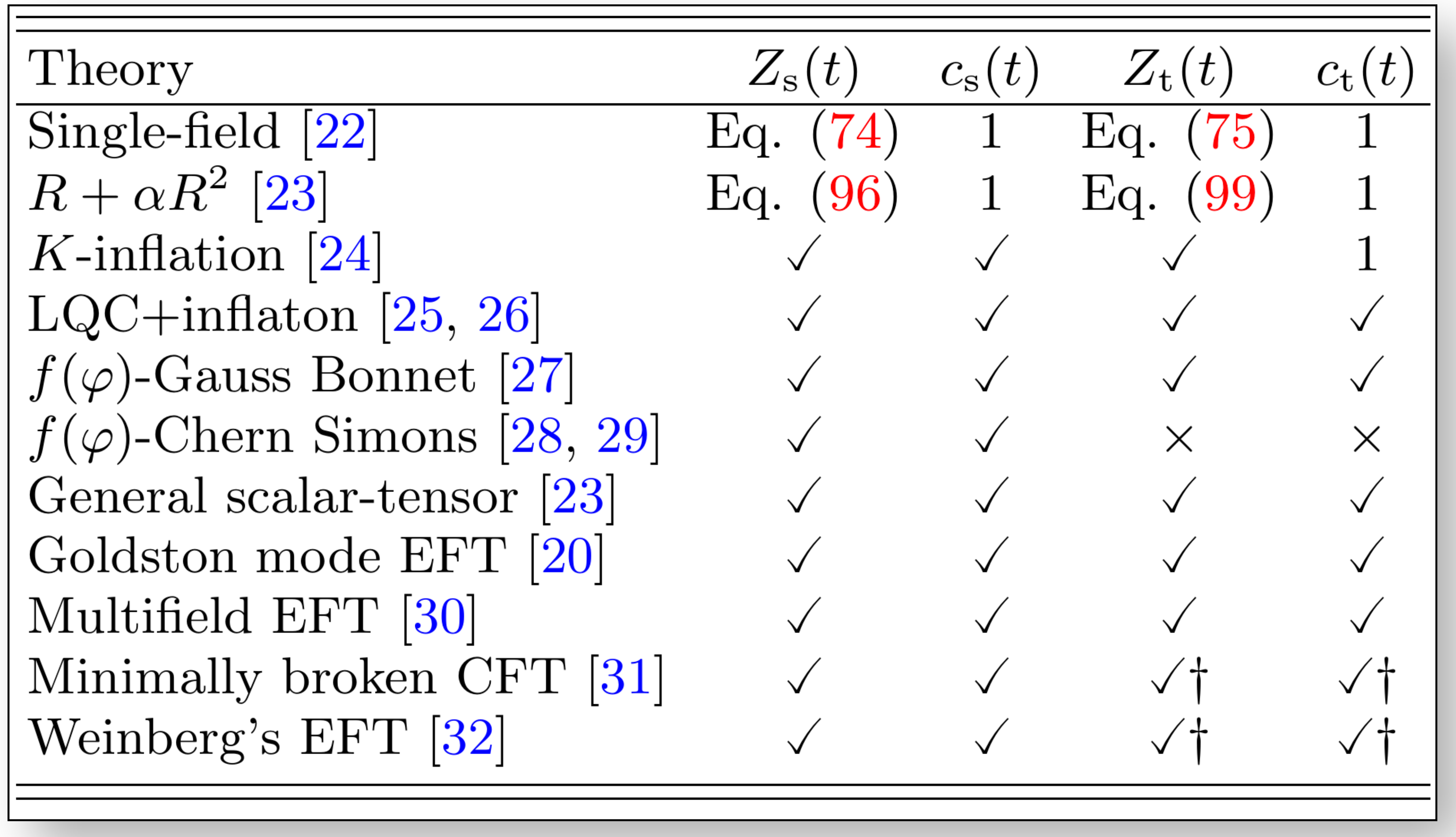

Theory	$Z_\mathrm{s}(t)$	$c_\mathrm{s}(t)$	$Z_\mathrm{t}(t)$	$c_\mathrm{t}(t)$
Single-field [22]	Eq. (74)	1	Eq. (75)	1
$R+\alpha R^2$ [23]	Eq. (96)	1	Eq. (99)	1
K-inflation [24]	✓	✓	✓	1
LQC+inflaton [25, 26]	✓	✓	✓	✓
$f(\varphi)$-Gauss Bonnet [27]	✓	✓	✓	✓
$f(\varphi)$-Chern Simons [28, 29]	✓	✓	×	×
General scalar-tensor [23]	✓	✓	✓	✓
Goldston mode EFT [20]	✓	✓	✓	✓
Multifield EFT [30]	✓	✓	✓	✓
Minimally broken CFT [31]	✓	✓	✓†	✓†
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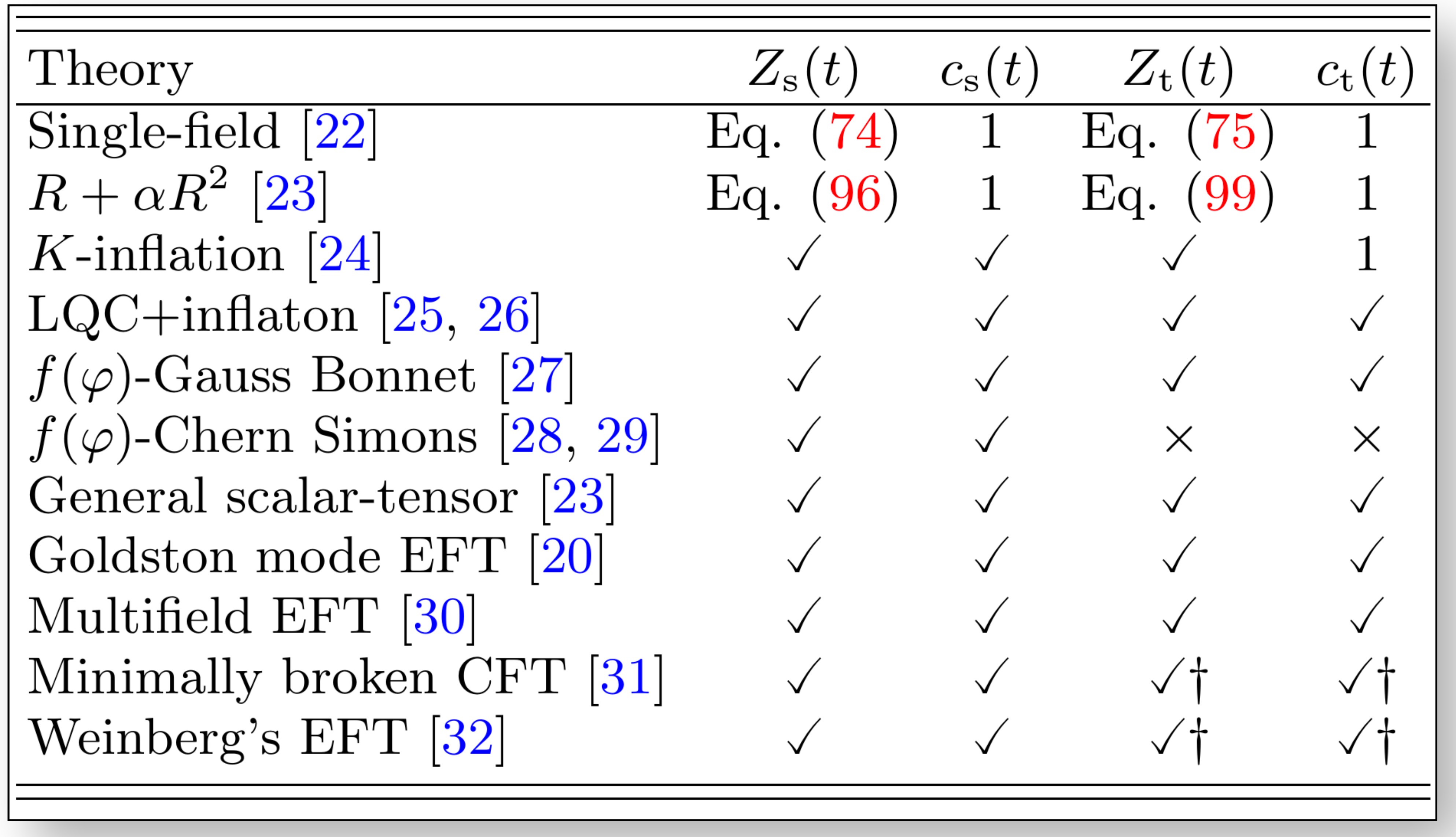

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Kinetic amplitude

Scale factor

Speed of sound

c.f. single scalar field: $Z_{\rm s}(t) = \dfrac{\epsilon_{1H}(t)}{4\pi G}, \quad Z_{\rm t}(t) = \dfrac{1}{64\pi G}, \quad c_{\rm t}(t) = c_{\rm s}(t) = 1$

$$\epsilon_{1Z}(t) \equiv -\frac{\dot{Z}_{\psi}(t)}{H(t) Z_{\psi}(t)}, \quad \epsilon_{2Z}(t) \equiv -\frac{\dot{\epsilon}_{1Z}(t)}{H(t)\epsilon_{1Z}(t)} \quad \cdots$$

$$\vdots$$

Accelerated expansion: $\epsilon_{1H}(t) < 1$

$$\ddot{a}(t) = \left(1 - \epsilon_{1H}(t)\right) a(t) H(t)^2 > 0$$

During inflationary epoch: $\epsilon_{n\rho *} \ll 1$

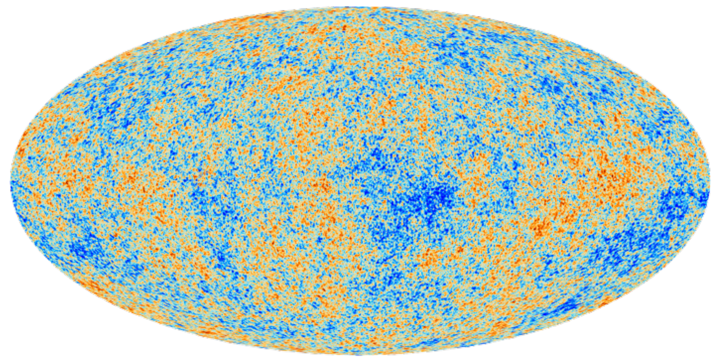
N3LO: $\mathcal{O}(\epsilon_*^3)$

THE FRAMEWORK: A LARGE CLASS OF EFFECTIVE THEORIES OF INFLATION

Methods: Green's function (a systematic expansion computable order-by-order)

[Gong & Stewart '01; Auclair & Ringeval '22; **Bianchi & Gamonal '24**]

Recall:



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

(Mukhanov-Sasaki+time reparametrization)

The framework: a large class of effective theories of inflation

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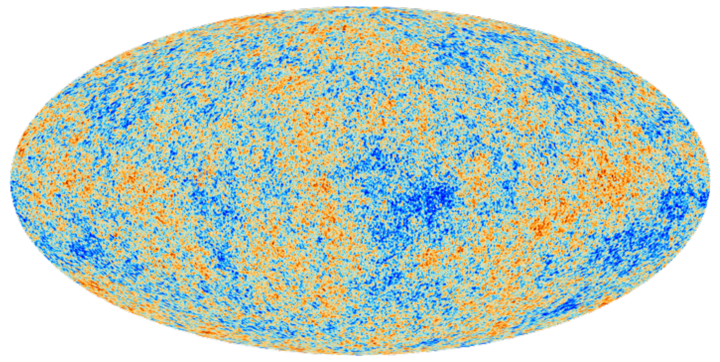

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$$w''(y) + \left[1 - \frac{2}{y^2}\right] w(y) = \frac{q(y)}{y^2} w(y)$$

$$q(x) \equiv q_1 + q_2 \ln(x) + q_3 \ln(x)^2$$

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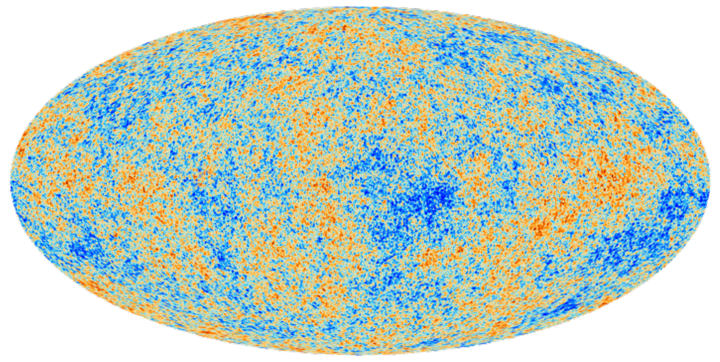

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$$\begin{cases} G(y,s) = \frac{\mathrm{i}}{2}\big(w_0(y)w_0^*(s) - w_0(s)w_0^*(y)\big)\,\Theta(s-y) \\ w_0(y) = \left(1 + \dfrac{\mathrm{i}}{y}\right)\mathrm{e}^{\mathrm{i}y} \end{cases}$$

[Bunch & Davies '78]

$$\boxed{w(y) = w_0(y) + \int_y^\infty \frac{q(y)}{s^2} w(s)\,G(y,s)\,\mathrm{d}s = w_0(y) + w_1(y) + w_2(y) + w_3(y) + \mathcal{O}(\epsilon^4)}$$

$$w_1(y) = g_1 \int_y^\infty \frac{G(y,s)}{s^2} w_0(s)\,\mathrm{d}s$$

$$w_2(y) = g_2 \int_y^\infty \frac{G(y,s)}{s^2}\ln(s) w_0(s)\,\mathrm{d}s + g_1 \int_y^\infty \frac{G(y,s)}{s^2} w_1(s)\,\mathrm{d}s$$

$$w_3(y) = g_3 \int_y^\infty \frac{G(y,s)}{s^2}\ln(s)^2 w_0(s)\,\mathrm{d}s + g_2 \int_y^\infty \frac{G(y,s)}{s^2}\ln(s) w_1(s)\,\mathrm{d}s + g_1 \int_y^\infty \frac{G(y,s)}{s^2} w_2(s)\,\mathrm{d}s$$

THE RESULTS: PRIMORDIAL POWER SPECTRUM AT N3LO

$$\mathcal{P}_0^{(\psi)}(k) = \frac{\hbar H_*^2}{4\pi^2 c_{\psi *}^3 Z_{\psi *}} \left[1 + p_{0*} + p_{1*} \ln\left(\frac{k}{k_*}\right) + p_{2*} \ln\left(\frac{k}{k_*}\right)^2 + p_{3*} \ln\left(\frac{k}{k_*}\right)^3 \right]$$

starts at: $\mathcal{O}(\epsilon_*)$ $\qquad$ $\mathcal{O}(\epsilon_*^2)$ $\qquad$ $\mathcal{O}(\epsilon_*^3)$

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starts at: $\mathcal{O}(\epsilon_*)$ $\mathcal{O}(\epsilon_*^2)$ $\mathcal{O}(\epsilon_*^3)$

Amplitude: $\mathcal{A}_* \equiv \mathcal{P}_0(k_*)$

Tilt: $\theta_* \equiv k \frac{\mathrm{d}}{\mathrm{d}k} \ln(\mathcal{P}_0(k)) \Big|_{k=k_*}$, $(n_\mathrm{s} \equiv 1 + \theta_\mathrm{s} \quad n_\mathrm{t} \equiv \theta_\mathrm{t})$

Running of the tilt: $\alpha_* \equiv k \frac{\mathrm{d}}{\mathrm{d}k} \left[k \frac{\mathrm{d}}{\mathrm{d}k} \ln(\mathcal{P}_0(k)) \right] \Big|_{k=k_*}$

Running of the running of the tilt: $\beta_* \equiv k \frac{\mathrm{d}}{\mathrm{d}k} \left\{ k \frac{\mathrm{d}}{\mathrm{d}k} \left[k \frac{\mathrm{d}}{\mathrm{d}k} \ln(\mathcal{P}_0(k)) \right] \right\} \Big|_{k=k_*}$

Quantity	Order	Expression	[Bianchi & Gamonal '24]
$\theta_*^{(\psi)}$	NLO :	$-2\epsilon_{1H*}+\epsilon_{1Z*}+3\epsilon_{1c*}$	
	N2LO :	$-2\epsilon_{1H*}^2+2(1+C)\epsilon_{1H*}\epsilon_{2H*}+\epsilon_{1Z*}(\epsilon_{1H*}-C\epsilon_{2Z*})+\epsilon_{1c*}(5\epsilon_{1H*}-3\epsilon_{1c*}-\epsilon_{1Z*})-(2+3C)\epsilon_{1c*}\epsilon_{2c*}$	
	N3LO :	$-2\epsilon_{1H*}^3+(14+6C-\pi^2)\epsilon_{1H*}^2\epsilon_{2H*}+\frac{1}{12}(-24-24C-12C^2+\pi^2)\epsilon_{1H*}\epsilon_{2H*}^2$	
		$+\frac{1}{12}(-24-24C-12C^2+\pi^2)\epsilon_{1H*}\epsilon_{2H*}\epsilon_{3H*}+\epsilon_{1H*}^2\epsilon_{1Z*}+\frac{1}{2}(-10-2C+\pi^2)\epsilon_{1H*}\epsilon_{1Z*}\epsilon_{2H*}$	
		$+\frac{1}{2}(-8-4C+\pi^2)\epsilon_{1H*}\epsilon_{1Z*}\epsilon_{2Z*}+\frac{1}{4}(8-\pi^2)\epsilon_{1Z*}^2\epsilon_{2Z*}+\frac{1}{24}(12C^2-\pi^2)\epsilon_{1Z*}\epsilon_{2Z*}^2$	
		$+\frac{1}{24}(12C^2-\pi^2)\epsilon_{1Z*}\epsilon_{2Z*}\epsilon_{3Z*}+3\epsilon_{1c*}^3-8\epsilon_{1c*}^2\epsilon_{1H*}+7\epsilon_{1c*}\epsilon_{1H*}^2+\epsilon_{1c*}^2\epsilon_{1Z*}-2\epsilon_{1c*}\epsilon_{1H*}\epsilon_{1Z*}$	
		$+\frac{1}{4}(100+36C-9\pi^2)\epsilon_{1c*}^2\epsilon_{2c*}+\frac{1}{2}(-36-16C+3\pi^2)\epsilon_{1c*}\epsilon_{1H*}\epsilon_{2c*}+\frac{1}{4}(28+4C-3\pi^2)\epsilon_{1c*}\epsilon_{1Z*}\epsilon_{2c*}$	
		$+\frac{1}{8}(16+16C+12C^2-\pi^2)\epsilon_{1c*}\epsilon_{2c*}^2+\frac{1}{2}(-38-14C+3\pi^2)\epsilon_{1c*}\epsilon_{1H*}\epsilon_{2H*}$	
		$+\frac{1}{4}(24+8C-3\pi^2)\epsilon_{1c*}\epsilon_{1Z*}\epsilon_{2Z*}+\frac{1}{8}(16+16C+12C^2-\pi^2)\epsilon_{1c*}\epsilon_{2c*}\epsilon_{3c*}$	
$\alpha_*^{(\psi)}$	N2LO :	$2\epsilon_{1H*}\epsilon_{2H*}-\epsilon_{1Z*}\epsilon_{2Z*}-3\epsilon_{1c*}\epsilon_{2c*}$	
	N3LO :	$+6\epsilon_{1H*}^2\epsilon_{2H*}-2(1+C)\epsilon_{1H*}\epsilon_{2H*}^2-2(1+C)\epsilon_{1H*}\epsilon_{2H*}\epsilon_{3H*}-\epsilon_{1H*}\epsilon_{2H*}\epsilon_{1Z*}-2\epsilon_{1H*}\epsilon_{1Z*}\epsilon_{2Z*}$	
		$+C\epsilon_{1Z*}\epsilon_{2Z*}^2+C\epsilon_{1Z*}\epsilon_{2Z*}\epsilon_{3Z*}+9\epsilon_{1c*}^2\epsilon_{2c*}-8\epsilon_{1c*}\epsilon_{1H*}\epsilon_{2c*}+\epsilon_{1c*}\epsilon_{1Z*}\epsilon_{2c*}+(2+3C)\epsilon_{1c*}\epsilon_{2c*}^2$	
		$-7\epsilon_{1c*}\epsilon_{1H*}\epsilon_{2H*}+2\epsilon_{1c*}\epsilon_{1Z*}\epsilon_{2Z*}+(2+3C)\epsilon_{1c*}\epsilon_{2c*}\epsilon_{3c*}$	
$\beta_*^{(\psi)}$	N3LO :	$-2\epsilon_{1H*}\epsilon_{2H*}(\epsilon_{2H*}+\epsilon_{3H*})+\epsilon_{1Z*}\epsilon_{2Z*}(\epsilon_{2Z*}+\epsilon_{3Z*})+3\epsilon_{1c*}\epsilon_{2c*}(\epsilon_{2c*}+\epsilon_{3c*})$	

THE IMPLEMENTATION: STAROBINSKY INFLATION IN THE GEOMETRIC FRAME

[Starobinsky '79-'80; Vilenkin '85]

Modified Friedmann equation:

$$\boxed{S[g_{\mu\nu}] = \frac{1}{16\pi G}\int \mathrm{d}^4x\,\sqrt{-g}\,(R + \alpha R^2)} \quad \longrightarrow \quad H(t)^2 + 6\alpha H(t)^4 \epsilon_{1H}(t)\Big(3\epsilon_{1H}(t) + 2\epsilon_{2H}(t) - 6\Big) = 0$$

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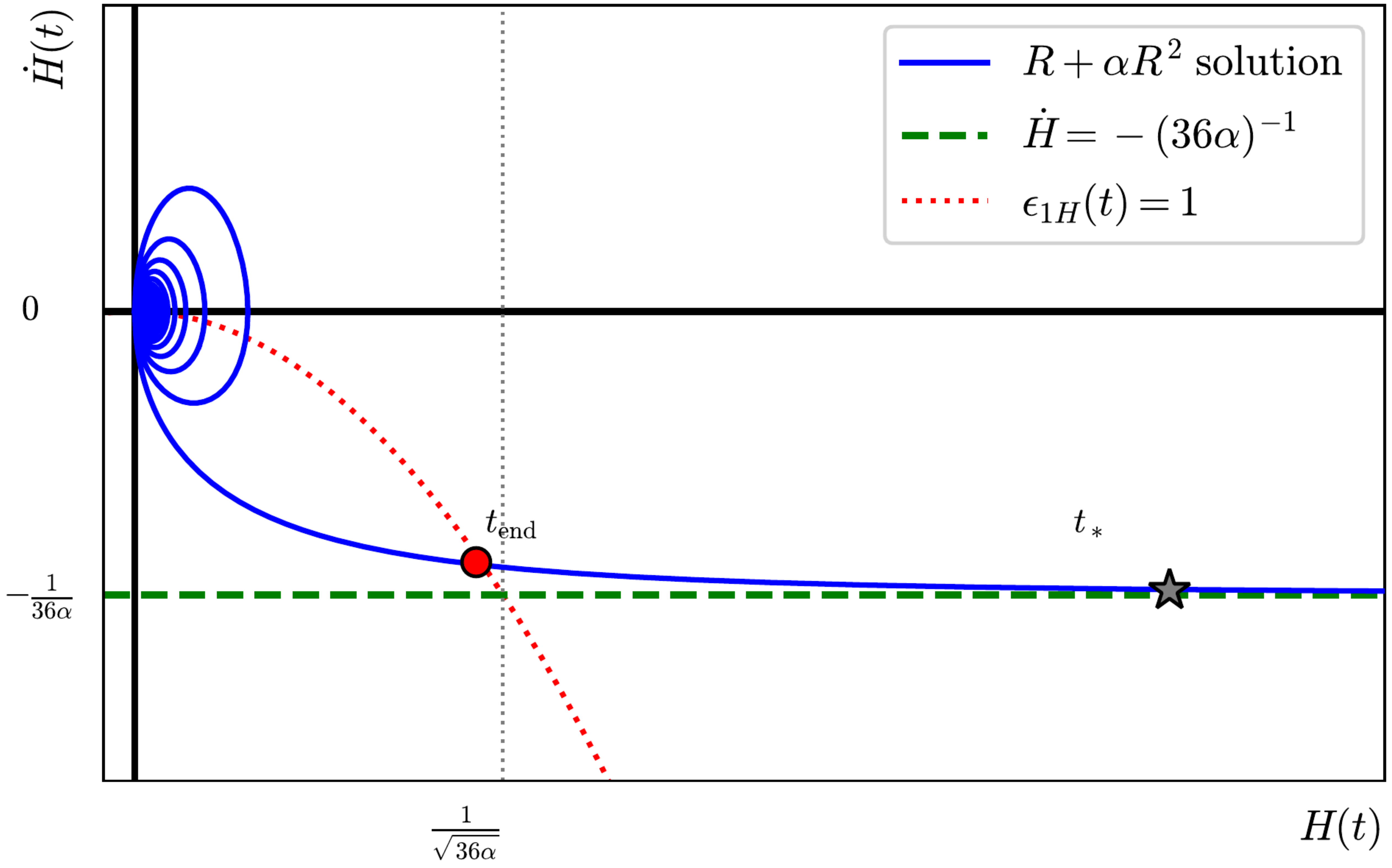

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$$H(t)^2 + 6\alpha H(t)^4\epsilon_{1H}(t)\Big(3\epsilon_{1H}(t) + 2\epsilon_{2H}(t) - 6\Big) = 0$$

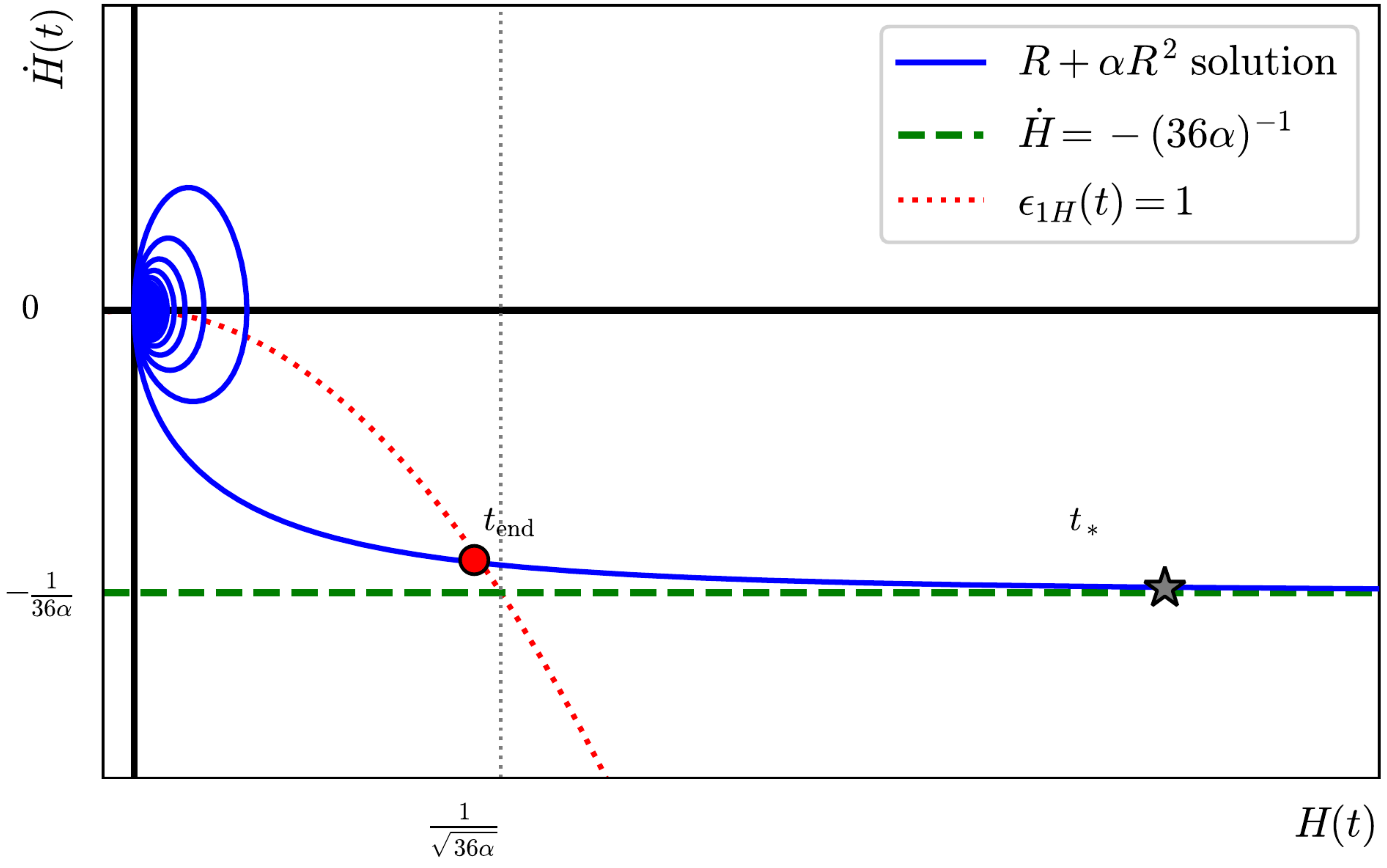
From quadratic action of cosmological perturbations ($c_s = c_t = 1$):

$$\boxed{Z_{\rm s}(t) = \frac{3\bar{\chi}(t)}{16\pi G_{\rm N}}\left(\frac{\epsilon_\chi(t)}{1+\frac{1}{2}\epsilon_\chi(t)}\right)^2,\; Z_{\rm t}(t) = \frac{\bar{\chi}(t)}{64\pi G_{\rm N}}}$$

with

$$\epsilon_\chi(t) = -\frac{\dot{\bar{\chi}}(t)}{H(t)\bar{\chi}}$$

$$\bar{\chi}(t) = 1 + 2\alpha\bar{R} = 1 - 12\alpha H(t)^2(\epsilon_{1H}(t) - 2)$$



THE IMPLEMENTATION: STAROBINSKY INFLATION IN THE GEOMETRIC FRAME

Amplitudes of the primordial power spectrum:

$$\mathcal{A}_{\mathrm{t}} = \frac{2G\hbar}{3\pi\alpha}(1+\cdots) \qquad \mathcal{A}_{\mathrm{s}} = \frac{G\hbar\, N_*^2}{18\pi\alpha}(1+\cdots)$$

[Bianchi & Gamonal '24]

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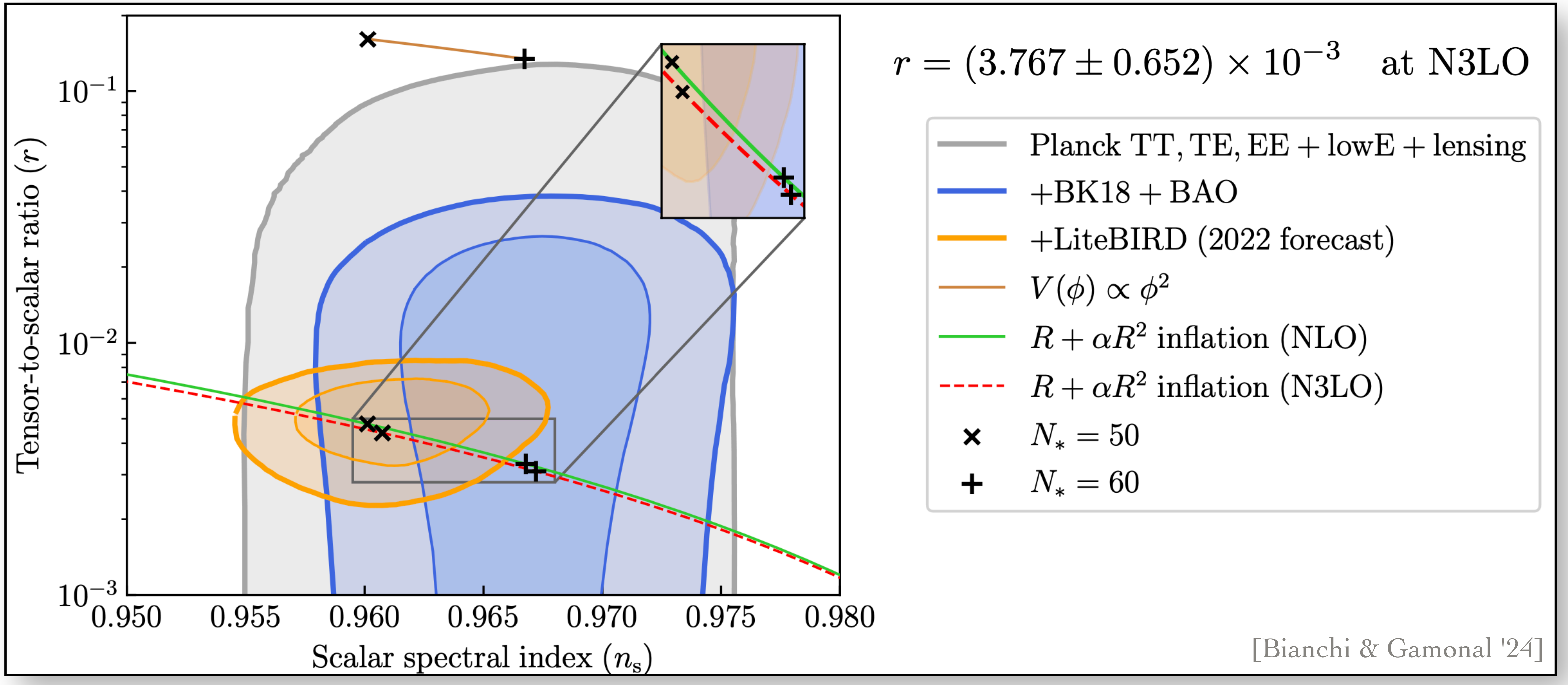
7% decrease in tensor-to-scalar ratio:

$$r \equiv \frac{\mathcal{A}_{\rm t}}{\mathcal{A}_{\rm s}} = \frac{12}{N_*^2} + \frac{2\ln(2N_*)}{N_*^3} - (2.36\ldots)\frac{24}{N_*^3} + \mathcal{O}(N_*^{-4})$$

$$= 1 + 2 - \ln(2) - \gamma_E - \left(-\frac{1}{2} + \frac{\ln(2)}{24} + \frac{\ln(3)}{12} - \frac{\ln(20)}{24} - \frac{19\tan^{-1}\left(\frac{1}{\sqrt{39}}\right)}{12\sqrt{39}} - \frac{19\cot^{-1}\left(\frac{3\sqrt{39}}{7}\right)}{12\sqrt{39}}\right)$$



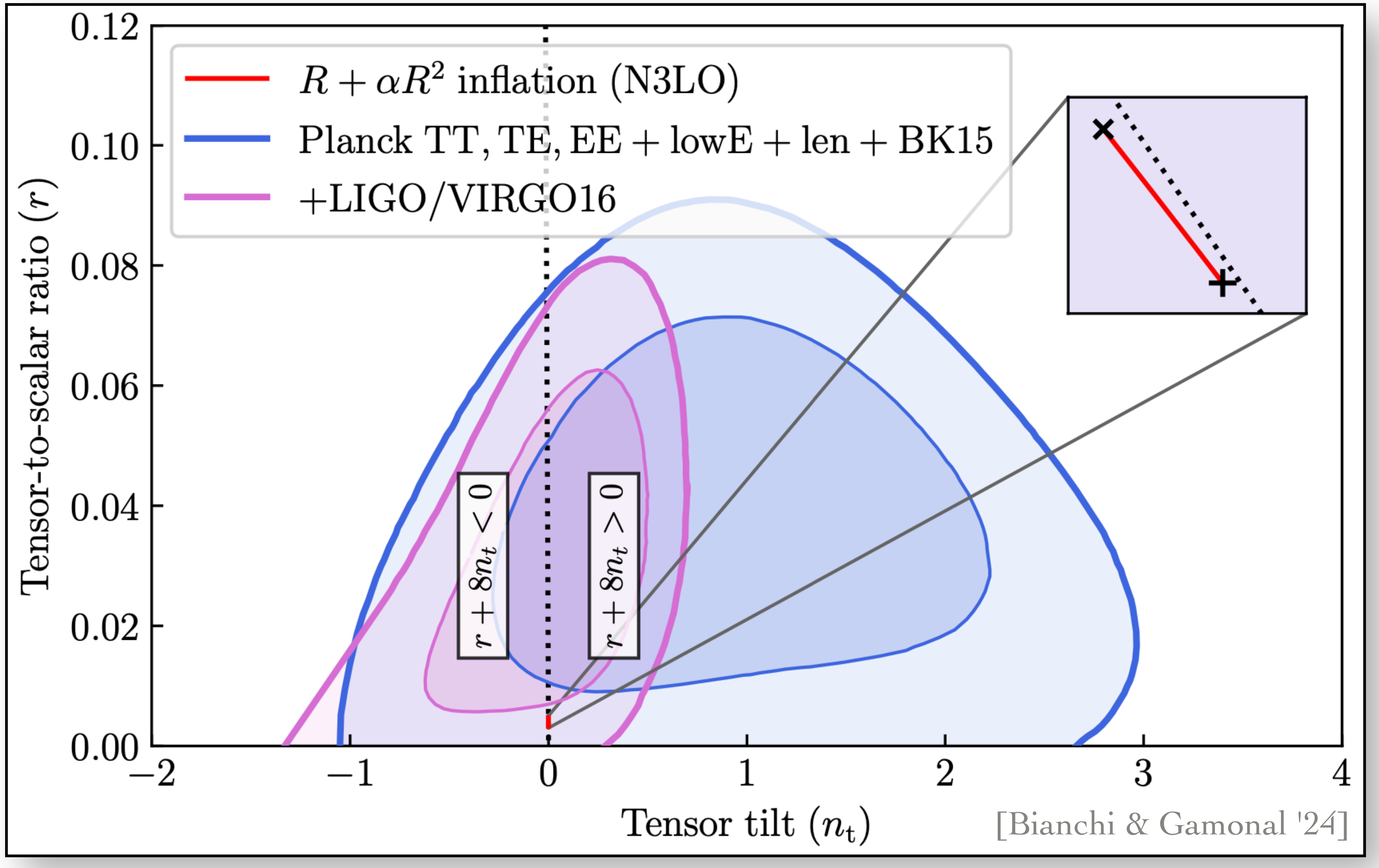
$$r = (3.767 \pm 0.652) \times 10^{-3} \quad \text{at N3LO}$$

[Bianchi & Gamonal '24]

THE IMPLEMENTATION: STAROBINSKY INFLATION IN THE GEOMETRIC FRAME

Precise value for deviation from exact consistency condition:

$$r + 8n_{\mathrm{t}} = -\frac{48}{N_*^3} + \mathcal{O}\left(N_*^{-4}\right) = (-3.031 \pm 0.809) \times 10^{-4} \quad \text{for } N_* = 55 \pm 5 \quad \text{at N3LO}$$



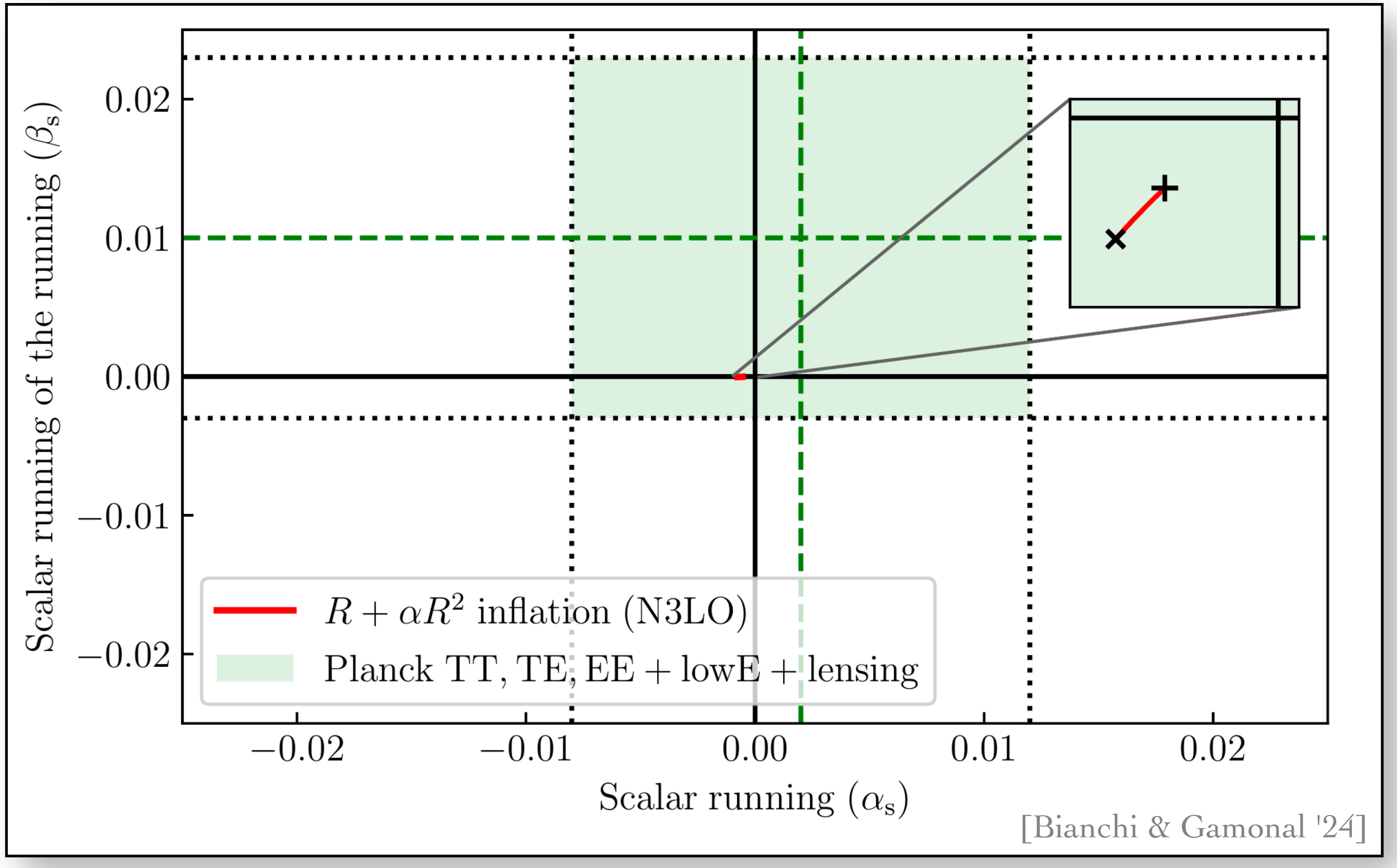
[Bianchi & Gamonal '24]

THE IMPLEMENTATION: STAROBINSKY INFLATION IN THE GEOMETRIC FRAME

Running and running-of-the-running for scalar modes:

$$\alpha_s = (-6.626 \pm 1.180) \times 10^{-4} \quad \text{at N3LO}$$
$$\beta_s = (-2.526 \pm 0.674) \times 10^{-5} \quad \text{at N3LO}$$

for $N_* = 55 \pm 5$



[Bianchi & Gamonal '24]

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- **Possible additional considerations (from RHS)**:

  1. Consider other vacuum choices: $\mathcal{A}_{\rm s} = \dfrac{G\hbar\, H_*^2}{\pi \epsilon_{1H*}} |\alpha_k - \beta_k|^2 \, (1 + \cdots)$

     [e.g. Danielsson '02; Broy '16]

  2. Consider closed cosmologies: $\mathcal{A}_{\rm s} = \dfrac{G\hbar\, H_*^2}{\pi(\epsilon_{1H*} + \frac{K}{\mathcal{H}})} (1 + \cdots)$

     [e.g. Bonga, Gupt & Yokomizo '16; Kiefer & Vardanyan '22]

  3. Consider parity-violating models: $v''(y) + \left(1 - \dfrac{2}{y^2} \pm \gamma\, \dfrac{\sigma}{y}\right) v(y) = 0$

     [e.g. Alexander & Yunes '09; Bianchi & Rincon-Ramirez'24]

Conclusions and Future work

- We computed the primordial power spectrum up to N3LO for the largest class of effective theories of inflation under minimal assumptions (flat FLRW & quasi-BD)

- **Possible additional considerations (from RHS):**

  1. Consider other vacuum choices: $\mathcal{A}_\mathrm{s} = \frac{G\hbar H_*^2}{\pi\epsilon_{1H*}}|\alpha_k - \beta_k|^2\,(1+\cdots)$

     [e.g. Danielsson '02; Broy '16]

  2. Consider closed cosmologies: $\mathcal{A}_\mathrm{s} = \frac{G\hbar H_*^2}{\pi(\epsilon_{1H*} + \frac{K}{\mathcal{H}})}(1+\cdots)$

     [e.g. Bonga, Gupt & Yokomizo '16; Kiefer & Vardanyan '22]

  3. Consider parity-violating models: $v''(y) + \left(1 - \frac{2}{y^2} \pm \gamma\,\frac{\sigma}{y}\right) v(y) = 0$

     [e.g. Alexander & Yunes '09; Bianchi & Rincon-Ramirez'24]

- **Long term goal (from LHS):** Explore the emergence of states from LQG/Spinfoams in Quantum Cosmology and build a bridge towards RHS and phenomenology.