Purely virtual particles in primordial cosmology and quantum gravity

Damiano Anselmi

NICPB, Tallinn, University of Pisa, INFN

This talk is about the prediction

$$\frac{(n_s - 1)^2}{3} \leqslant r \leqslant 3(n_s - 1)^2$$

for the tensor-to-scalar ratio, how it comes from high-energy physics and why it is basically unique

- D. A., E. Bianchi and M. Piva, Predictions of quantum gravity in inflationary cosmology: effects of the Weyl-squared term, J. High Energy Phys. 07 (2020) 211 and arXiv:2005.10293 [hep-th]

This talk is about the prediction

$$\frac{(n_s-1)^2}{3} \leqslant r \leqslant 3(n_s-1)^2$$

for the tensor-to-scalar ratio, how it comes from high-energy physics and why it is basically unique

- D. A., E. Bianchi and M. Piva, Predictions of quantum gravity in inflationary cosmology: effects of the Weyl-squared term, J. High Energy Phys. 07 (2020) 211 and arXiv:2005.10293 [hep-th]

And other connections between perturbative quantum field theory and primordial cosmology, such as the possibility of viewing inflation as a renormalization-group flow

- D.A., Cosmic inflation as a renormalization-group flow: the running of power spectra in quantum gravity, J. Cosmol. Astropart. Phys. 01 (2021) 048 and arXiv: 2007.15023 [hep-th]
- D.A, High-order corrections to inflationary perturbation spectra in quantum gravity, J. Cosmol. Astropart. Phys. 02 (2021) 029 and arXiv: 2010.04739 [hep-th]

Purely virtual particles, or fake particles, or ``fakeons", are “non particles”, or particles that have no classical limit. That is to say, they cannot be obtained by quantizing something classical, because their nature is purely quantum.

Purely virtual particles, or fake particles, or ``fakeons", are “non particles”, or particles that have no classical limit. That is to say, they cannot be obtained by quantizing something classical, because their nature is purely quantum.

Based on a new diagrammatics,

- D. A., Diagrammar of physical and fake particles and spectral optical theorem, J. High Energy Phys. 11 (2021) 030 and arXiv:2109.06889 [hep-th]

Purely virtual particles, or fake particles, or ``fakeons", are “non particles”, or particles that have no classical limit. That is to say, they cannot be obtained by quantizing something classical, because their nature is purely quantum.

Based on a new diagrammatics,

- D. A., Diagrammar of physical and fake particles and spectral optical theorem, J. High Energy Phys. 11 (2021) 030 and arXiv:2109.06889 [hep-th]

they allow us, among the other things, to formulate a consistent (i.e., local, unitary and renormalizable within perturbation theory) theory of quantum gravity

- D. A., On the quantum field theory of the gravitational interactions, J. High Energy Phys. 06 (2017) 086 and arXiv:1704.07728 [hep-th]

Purely virtual particles, or fake particles, or ``fakeons", are “non particles”, or particles that have no classical limit. That is to say, they cannot be obtained by quantizing something classical, because their nature is purely quantum.

Based on a new diagrammatics,

- D. A., Diagrammar of physical and fake particles and spectral optical theorem, J. High Energy Phys. 11 (2021) 030 and arXiv:2109.06889 [hep-th]

they allow us, among the other things, to formulate a consistent (i.e., local, unitary and renormalizable within perturbation theory) theory of quantum gravity

- D. A., On the quantum field theory of the gravitational interactions, J. High Energy Phys. 06 (2017) 086 and arXiv:1704.07728 [hep-th]

which is experimentally testable due to its sharp prediction ($0.4 \leq 1000r \leq 3$) of the tensor-to-scalar ratio r in inflationary cosmology

- D. A., E. Bianchi and M. Piva, Predictions of quantum gravity in inflationary cosmology: effects of the Weyl-squared term, J. High Energy Phys. 07 (2020) 211 and arXiv:2005.10293 [hep-th]

They can also be used to search for new physics beyond the standard model, by evading common constraints in collider phenomenology

- D. A., K. Kannike, C. Marzo, L. Marzola, A. Melis, K. Müürsepp, M. Piva and M. Raidal, Phenomenology of a fake inert doublet model, J. High Energy Phys. 10 (2021) 132 and arXiv:2104.02071 [hep-ph]

and offering new possibilities to solve discrepancies with data

- D. A., K. Kannike, C. Marzo, L. Marzola, A. Melis, K. Müürsepp, M. Piva and M. Raidal, A fake doublet solution to the muon anomalous magnetic moment, Phys. Rev. D 104 (2021) 035009 and arXiv:2104.03249 [hep-ph]

Their diagrammatics can be implemented in softwares like FeynCalc, FormCalc, LoopTools and Package-X and used to make predictions in phenomenology

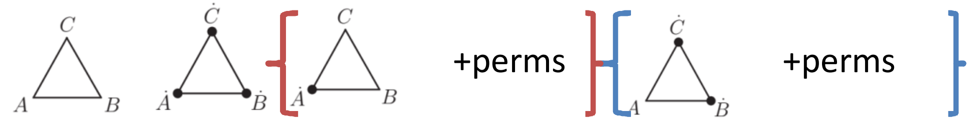
It is possible to describe inflation as a renormalization-group flow and calculate the power spectra to high orders in quantum gravity, in the presence of higher-derivative terms

- D.A., Cosmic inflation as a renormalization-group flow: the running of power spectra in quantum gravity, J. Cosmol. Astropart. Phys. 01 (2021) 048 and arXiv: 2007.15023 [hep-th]

- D.A, High-order corrections to inflationary perturbation spectra in quantum gravity, J. Cosmol. Astropart. Phys. 02 (2021) 029 and arXiv: 2010.04739 [hep-th]

Triangle diagram

$$\frac{i}{p^2 - m^2 + i\epsilon} = \mathcal{P}\frac{i}{p^2 - m^2} + \pi\delta(p^2 - m^2)$$



Th\G	T^s_{ABC}	$T^s_{\dot{\mathrm{A}}\dot{\mathrm{B}}\dot{\mathrm{C}}}$	$T^s_{\dot{\mathrm{A}}\mathrm{BC}}$	$T^s_{\mathrm{A}\dot{\mathrm{B}}\mathrm{C}}$	$T^s_{\mathrm{AB}\dot{\mathrm{C}}}$	$T^s_{\mathrm{A}\dot{\mathrm{B}}\dot{\mathrm{C}}}$	$T^s_{\dot{\mathrm{A}}\mathrm{B}\dot{\mathrm{C}}}$	$T^s_{\dot{\mathrm{A}}\dot{\mathrm{B}}\mathrm{C}}$
—	$-i\mathcal{P}_{\mathrm{ABC}}$	$i\mathcal{P}_{\mathrm{ABC}}$	0	0	0	0	0	0
Δ^{23}	$-\mathcal{Q}^{21}$	$-\mathcal{Q}^{21}$	0	0	0	0	0	$2\mathcal{Q}^{21}$
Δ^{12}	$-\mathcal{Q}^{13}$	$-\mathcal{Q}^{13}$	0	0	0	0	$2\mathcal{Q}^{13}$	0
Δ^{31}	$-\mathcal{Q}^{32}$	$-\mathcal{Q}^{32}$	0	0	0	$2\mathcal{Q}^{32}$	0	0
Δ^{32}	$-\mathcal{Q}^{31}$	$-\mathcal{Q}^{31}$	0	0	$2\mathcal{Q}^{31}$	0	0	0
Δ^{21}	$-\mathcal{Q}^{23}$	$-\mathcal{Q}^{23}$	0	$2\mathcal{Q}^{23}$	0	0	0	0
Δ^{13}	$-\mathcal{Q}^{12}$	$-\mathcal{Q}^{12}$	$2\mathcal{Q}^{12}$	0	0	0	0	0
$\Delta^{12}\Delta^{13}$	i	$-i$	$-2i$	0	0	0	$2i$	0
$\Delta^{23}\Delta^{21}$	i	$-i$	0	$-2i$	0	0	0	$2i$
$\Delta^{31}\Delta^{32}$	i	$-i$	0	0	$-2i$	$2i$	0	0
$\Delta^{31}\Delta^{21}$	i	$-i$	0	$-2i$	0	$2i$	0	0
$\Delta^{12}\Delta^{32}$	i	$-i$	0	0	$-2i$	0	$2i$	0
$\Delta^{23}\Delta^{13}$	i	$-i$	$-2i$	0	0	0	0	$2i$

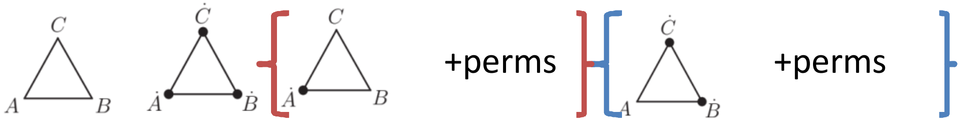
$$\frac{i}{x + i\epsilon} = \mathcal{P}\frac{i}{x} + \pi\delta(x)$$

$$\mathcal{P}^{ab} = \mathcal{P}\frac{1}{e_a - e_b - \omega_a - \omega_b},$$

$$\mathcal{Q}^{ab} = \mathcal{P}^{ab} - \mathcal{P}\frac{1}{e_a - e_b - \omega_a + \omega_b}$$

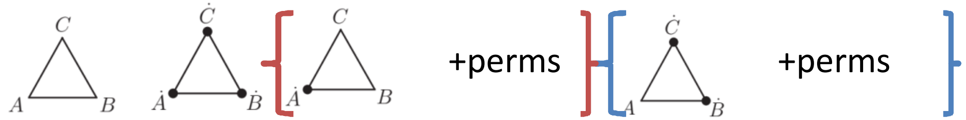
$$\Delta^{ab} = \pi\delta(e_a - e_b - \omega_a - \omega_b)$$

Triangle diagram with a fakeon in leg 1 (AB)



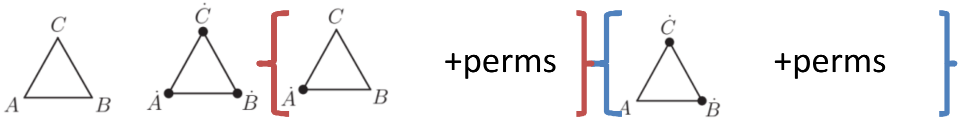
Th\G	T^s_{ABC}	$T^s_{\dot{\mathrm{A}}\dot{\mathrm{B}}\dot{\mathrm{C}}}$	$T^s_{\dot{\mathrm{A}}\mathrm{BC}}$	$T^s_{\mathrm{A}\dot{\mathrm{B}}\mathrm{C}}$	$T^s_{\mathrm{AB}\dot{\mathrm{C}}}$	$T^s_{\mathrm{A}\dot{\mathrm{B}}\dot{\mathrm{C}}}$	$T^s_{\dot{\mathrm{A}}\mathrm{B}\dot{\mathrm{C}}}$	$T^s_{\dot{\mathrm{A}}\dot{\mathrm{B}}\mathrm{C}}$
—	$-i\mathcal{P}_{\mathrm{ABC}}$	$i\mathcal{P}_{\mathrm{ABC}}$	0	0	0	0	0	0
Δ^{23}	$-\mathcal{Q}^{21}$	$-\mathcal{Q}^{21}$	0	0	0	0	0	$2\mathcal{Q}^{21}$
Δ^{12}	$-\mathcal{Q}^{13}$	$-\mathcal{Q}^{13}$	0	0	0	0	$2\mathcal{Q}^{13}$	0
Δ^{31}	$-\mathcal{Q}^{32}$	$-\mathcal{Q}^{32}$	0	0	0	$2\mathcal{Q}^{32}$	0	0
Δ^{32}	$-\mathcal{Q}^{31}$	$-\mathcal{Q}^{31}$	0	0	$2\mathcal{Q}^{31}$	0	0	0
Δ^{21}	$-\mathcal{Q}^{23}$	$-\mathcal{Q}^{23}$	0	$2\mathcal{Q}^{23}$	0	0	0	0
Δ^{13}	$-\mathcal{Q}^{12}$	$-\mathcal{Q}^{12}$	$2\mathcal{Q}^{12}$	0	0	0	0	0
$\Delta^{12}\Delta^{13}$	i	$-i$	$-2i$	0	0	0	$2i$	0
$\Delta^{23}\Delta^{21}$	i	$-i$	0	$-2i$	0	0	0	$2i$
$\Delta^{31}\Delta^{32}$	i	$-i$	0	0	$-2i$	$2i$	0	0
$\Delta^{31}\Delta^{21}$	i	$-i$	0	$-2i$	0	$2i$	0	0
$\Delta^{12}\Delta^{32}$	i	$-i$	0	0	$-2i$	0	$2i$	0
$\Delta^{23}\Delta^{13}$	i	$-i$	$-2i$	0	0	0	0	$2i$

Triangle diagram with a fakeon in leg 1 (AB)



Th\G	T^s_{ABC}	$T^s_{\dot{\mathrm{A}}\dot{\mathrm{B}}\dot{\mathrm{C}}}$	$T^s_{\dot{\mathrm{A}}\mathrm{BC}}$	$T^s_{\mathrm{A}\dot{\mathrm{B}}\mathrm{C}}$	$T^s_{\mathrm{AB}\dot{\mathrm{C}}}$	$T^s_{\dot{\mathrm{A}}\dot{\mathrm{B}}\mathrm{C}}$	$T^s_{\mathrm{A}\dot{\mathrm{B}}\dot{\mathrm{C}}}$	$T^s_{\dot{\mathrm{A}}\mathrm{B}\dot{\mathrm{C}}}$
—	$-i\mathcal{P}_{\mathrm{ABC}}$	$i\mathcal{P}_{\mathrm{ABC}}$	0	0	0	0	0	0
Δ^{23}	$-\mathcal{Q}^{21}$	$-\mathcal{Q}^{21}$	0	0	0	0	0	$2\mathcal{Q}^{21}$
Δ^{12}	$-\mathcal{Q}^{13}$	$-\mathcal{Q}^{13}$	0	0	0	0	$2\mathcal{Q}^{13}$	0
Δ^{31}	$-\mathcal{Q}^{32}$	$-\mathcal{Q}^{32}$	0	0	0	$2\mathcal{Q}^{32}$	0	0
Δ^{32}	$-\mathcal{Q}^{31}$	$-\mathcal{Q}^{31}$	0	0	$2\mathcal{Q}^{31}$	0	0	0
Δ^{21}	$-\mathcal{Q}^{23}$	$-\mathcal{Q}^{23}$	0	$2\mathcal{Q}^{23}$	0	0	0	0
Δ^{13}	$-\mathcal{Q}^{12}$	$-\mathcal{Q}^{12}$	$2\mathcal{Q}^{12}$	0	0	0	0	0
$\Delta^{12}\Delta^{13}$	i	$-i$	$-2i$	0	0	0	$2i$	0
$\Delta^{23}\Delta^{21}$	i	$-i$	0	$-2i$	0	0	0	$2i$
$\Delta^{31}\Delta^{32}$	i	$-i$	0	0	$-2i$	$2i$	0	0
$\Delta^{31}\Delta^{21}$	i	$-i$	0	$-2i$	0	$2i$	0	0
$\Delta^{12}\Delta^{32}$	i	$-i$	0	0	$-2i$	0	$2i$	0
$\Delta^{23}\Delta^{13}$	i	$-i$	$-2i$	0	0	0	0	$2i$

Triangle diagram with a fakeon in leg 1 (AB)



Th\G	T^s_{ABC}	$T^s_{\dot{\mathrm{A}}\dot{\mathrm{B}}\dot{\mathrm{C}}}$	$T^s_{\dot{\mathrm{A}}\mathrm{BC}}$	$T^s_{\mathrm{A}\dot{\mathrm{B}}\mathrm{C}}$	$T^s_{\mathrm{AB}\dot{\mathrm{C}}}$	$T^s_{\mathrm{A}\dot{\mathrm{B}}\dot{\mathrm{C}}}$	$T^s_{\dot{\mathrm{A}}\mathrm{B}\dot{\mathrm{C}}}$	$T^s_{\dot{\mathrm{A}}\dot{\mathrm{B}}\mathrm{C}}$
—	$-i\mathcal{P}_{\mathrm{ABC}}$	$i\mathcal{P}_{\mathrm{ABC}}$	0	0	0	0	0	0
Δ^{23}	$-\mathcal{Q}^{21}$	$-\mathcal{Q}^{21}$	0	0	0	0	0	$2\mathcal{Q}^{21}$
Δ^{12}	$-\mathcal{Q}^{13}$	$-\mathcal{Q}^{13}$	0	0	0	0	$2\mathcal{Q}^{13}$	0
Δ^{31}	$-\mathcal{Q}^{32}$	$-\mathcal{Q}^{32}$	0	0	0	$2\mathcal{Q}^{32}$	0	0
Δ^{32}	$-\mathcal{Q}^{31}$	$-\mathcal{Q}^{31}$	0	0	$2\mathcal{Q}^{31}$	0	0	0
Δ^{21}	$-\mathcal{Q}^{23}$	$-\mathcal{Q}^{23}$	0	$2\mathcal{Q}^{23}$	0	0	0	0
Δ^{13}	$-\mathcal{Q}^{12}$	$-\mathcal{Q}^{12}$	$2\mathcal{Q}^{12}$	0	0	0	0	0
$\Delta^{12}\Delta^{13}$	i	$-i$	$-2i$	0	0	0	$2i$	0
$\Delta^{23}\Delta^{21}$	i	$-i$	0	$-2i$	0	0	0	$2i$
$\Delta^{31}\Delta^{32}$	i	$-i$	0	0	$-2i$	$2i$	0	0
$\Delta^{31}\Delta^{21}$	i	$-i$	0	$-2i$	0	$2i$	0	0
$\Delta^{12}\Delta^{32}$	i	$-i$	0	0	$-2i$	0	$2i$	0
$\Delta^{23}\Delta^{13}$	i	$-i$	$-2i$	0	0	0	0	$2i$

Th\G	T^s_{AfBC}	$T^s_{\dot{\mathrm{A}}\mathrm{f}\dot{\mathrm{B}}\dot{\mathrm{C}}}$	$T^s_{\mathrm{AfB}\dot{\mathrm{C}}}$	$T^s_{\dot{\mathrm{A}}\mathrm{f}\dot{\mathrm{B}}\mathrm{C}}$
—	$-i\mathcal{P}_{\mathrm{ABC}}$	$i\mathcal{P}_{\mathrm{ABC}}$	0	0
Δ^{23}	$-\mathcal{Q}^{21}$	$-\mathcal{Q}^{21}$	0	$2\mathcal{Q}^{21}$
Δ^{32}	$-\mathcal{Q}^{31}$	$-\mathcal{Q}^{31}$	$2\mathcal{Q}^{31}$	0

Quantum gravity

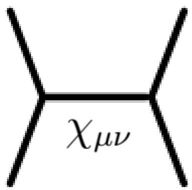
$$S_{\mathrm{QG}}(g) = -\frac{M_{\mathrm{Pl}}^2}{16\pi}\int \mathrm{d}^4x\sqrt{-g}\left(R + \frac{1}{2m_\chi^2}C_{\mu\nu\rho\sigma}C^{\mu\nu\rho\sigma} - \frac{R^2}{6m_\phi^2}\right)$$

Quantum gravity

$$S_{\mathrm{QG}}(g) = -\frac{M_{\mathrm{Pl}}^2}{16\pi} \int \mathrm{d}^4 x \sqrt{-g} \left(R + \frac{1}{2m_\chi^2} C_{\mu\nu\rho\sigma} C^{\mu\nu\rho\sigma} - \frac{R^2}{6m_\phi^2} \right)$$

It contains a triplet made of:

The graviton
The inflaton (spin 0, mass m_ϕ)
The "purely virtual particle" (or "fake particle" or "fakeon") (spin 2, mass m_χ)

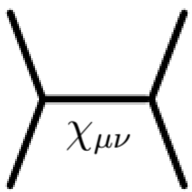


Quantum gravity

$$S_{\mathrm{QG}}(g) = -\frac{M_{\mathrm{Pl}}^2}{16\pi}\int \mathrm{d}^4x\sqrt{-g}\left(R + \frac{1}{2m_\chi^2}C_{\mu\nu\rho\sigma}C^{\mu\nu\rho\sigma} - \frac{R^2}{6m_\phi^2}\right)$$

It contains a triplet made of:

The graviton
The inflaton (spin 0, mass m_ϕ)
The “purely virtual particle” (or “fake particle” or “fakeon”) (spin 2, mass m_χ)



This is NOT the true classical action in the fakeon approach, because it is unprojected

True classical action: collection of tree diagrams with no external fakeon legs, where the purely virtual mediator is treated in a suitable way (to be truly virtual)

Primordial cosmology

With a field redefinition, switch to

$$S_{\mathrm{QG}} = -\frac{1}{16\pi G}\int \mathrm{d}^4x\sqrt{-g}\left(R + \frac{1}{2m_\chi^2}C_{\mu\nu\rho\sigma}C^{\mu\nu\rho\sigma}\right) + \frac{1}{2}\int \mathrm{d}^4x\sqrt{-g}\left(D_\mu\phi D^\mu\phi - 2V(\phi)\right),$$

Primordial cosmology

With a field redefinition, switch to

$$S_{\mathrm{QG}} = -\frac{1}{16\pi G}\int \mathrm{d}^4x\sqrt{-g}\left(R + \frac{1}{2m_\chi^2}C_{\mu\nu\rho\sigma}C^{\mu\nu\rho\sigma}\right) + \frac{1}{2}\int \mathrm{d}^4x\sqrt{-g}\left(D_\mu\phi D^\mu\phi - 2V(\phi)\right),$$

$$V(\phi) = \frac{3m_\phi^2}{32\pi G}\left(1 - \mathrm{e}^{\phi\sqrt{16\pi G/3}}\right)^2$$

Primordial cosmology

With a field redefinition, switch to

$$S_{\rm QG} = -\frac{1}{16\pi G}\int \mathrm{d}^4x\sqrt{-g}\left(R + \frac{1}{2m_\chi^2}C_{\mu\nu\rho\sigma}C^{\mu\nu\rho\sigma}\right) + \frac{1}{2}\int \mathrm{d}^4x\sqrt{-g}\left(D_\mu\phi D^\mu\phi - 2V(\phi)\right),$$

$$V(\phi) = \frac{3m_\phi^2}{32\pi G}\left(1 - \mathrm{e}^{\phi\sqrt{16\pi G/3}}\right)^2$$

Parametrizing the metric as $g_{\mu\nu} = \mathrm{diag}(1, -a^2, -a^2, -a^2)$

the Friedmann equations are not affected by C^2 and read

$$\frac{\ddot{a}}{a} - \frac{\dot{a}^2}{a^2} = -4\pi G\dot{\phi}^2, \qquad \frac{\dot{a}^2}{a^2} = \frac{4\pi G}{3}\left(\dot{\phi}^2 + 2V(\phi)\right), \qquad \ddot{\phi} + 3\frac{\dot{a}}{a}\dot{\phi} = -V'(\phi),$$

Then, parametrizing the fluctuactions as

$$g_{\mu\nu} = \mathrm{diag}(1, -a^2, -a^2, -a^2) - 2a^2 \left(u\delta^1_\mu \delta^1_\nu - u\delta^2_\mu \delta^2_\nu + v\delta^1_\mu \delta^2_\nu + v\delta^2_\mu \delta^1_\nu \right),$$
$$+2\mathrm{diag}(\Phi, a^2\Psi, a^2\Psi, a^2\Psi) - \delta^0_\mu \delta^i_\nu \partial_i B - \delta^i_\mu \delta^0_\nu \partial_i B$$

where $u = u(t, z)$ and $v = v(t, z)$

Then, parametrizing the fluctuactions as

$$g_{\mu\nu} = \mathrm{diag}(1, -a^2, -a^2, -a^2) - 2a^2 \left(u\delta^1_\mu \delta^1_\nu - u\delta^2_\mu \delta^2_\nu + v\delta^1_\mu \delta^2_\nu + v\delta^2_\mu \delta^1_\nu \right),$$
$$+2\mathrm{diag}(\Phi, a^2\Psi, a^2\Psi, a^2\Psi) - \delta^0_\mu \delta^i_\nu \partial_i B - \delta^i_\mu \delta^0_\nu \partial_i B$$

where $u = u(t,z)$ and $v = v(t,z)$

you can work out the spectra, tilts and tensor to scalar ratio *r*

$A_{\mathcal{R}}$	A_T	r	$n_{\mathcal{R}} - 1$	n_T
$\frac{m_\phi^2 N^2}{3\pi M_{\rm Pl}^2}$	$\frac{8m_\chi^2 m_\phi^2}{\pi(m_\phi^2+2m_\chi^2)M_{\rm Pl}^2}$	$\frac{24m_\chi^2}{N^2(m_\phi^2+2m_\chi^2)}$	$-\frac{2}{N}$	$-\frac{3m_\chi^2}{N^2(m_\phi^2+2m_\chi^2)}$

Then, parametrizing the fluctuactions as

$$g_{\mu\nu} = \mathrm{diag}(1, -a^2, -a^2, -a^2) - 2a^2\left(u\delta^1_\mu\delta^1_\nu - u\delta^2_\mu\delta^2_\nu + v\delta^1_\mu\delta^2_\nu + v\delta^2_\mu\delta^1_\nu\right),$$
$$+2\mathrm{diag}(\Phi, a^2\Psi, a^2\Psi, a^2\Psi) - \delta^0_\mu\delta^i_\nu\partial_i B - \delta^i_\mu\delta^0_\nu\partial_i B$$

where $u = u(t, z)$ and $v = v(t, z)$

you can work out the spectra, tilts and tensor to scalar ratio *r*

$A_{\mathcal{R}}$	A_T	r	$n_{\mathcal{R}} - 1$	n_T
$\frac{m_\phi^2 N^2}{3\pi M_{\mathrm{Pl}}^2}$	$\frac{8m_\chi^2 m_\phi^2}{\pi(m_\phi^2+2m_\chi^2)M_{\mathrm{Pl}}^2}$	$\frac{24m_\chi^2}{N^2(m_\phi^2+2m_\chi^2)}$	$-\frac{2}{N}$	$-\frac{3m_\chi^2}{N^2(m_\phi^2+2m_\chi^2)}$

$r \simeq -8n_T$ $\qquad n_{\mathcal{R}} = 0.9649 \pm 0.0042$

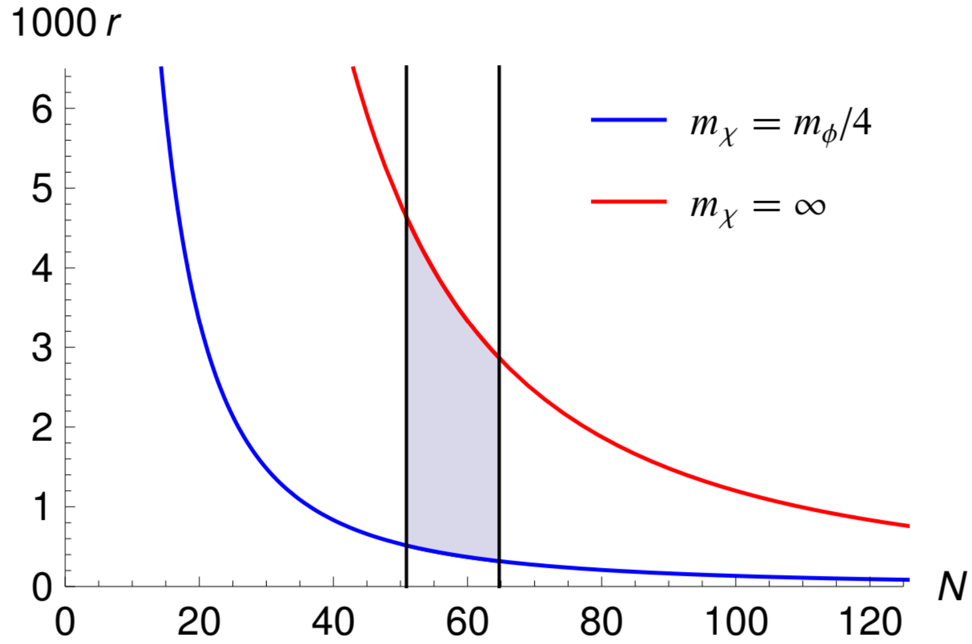
$$m_\phi = (2.99 \pm 0.37) \cdot 10^{13}\mathrm{GeV}$$

No tachyon condition

$$m_\chi > \frac{m_\phi}{4}$$

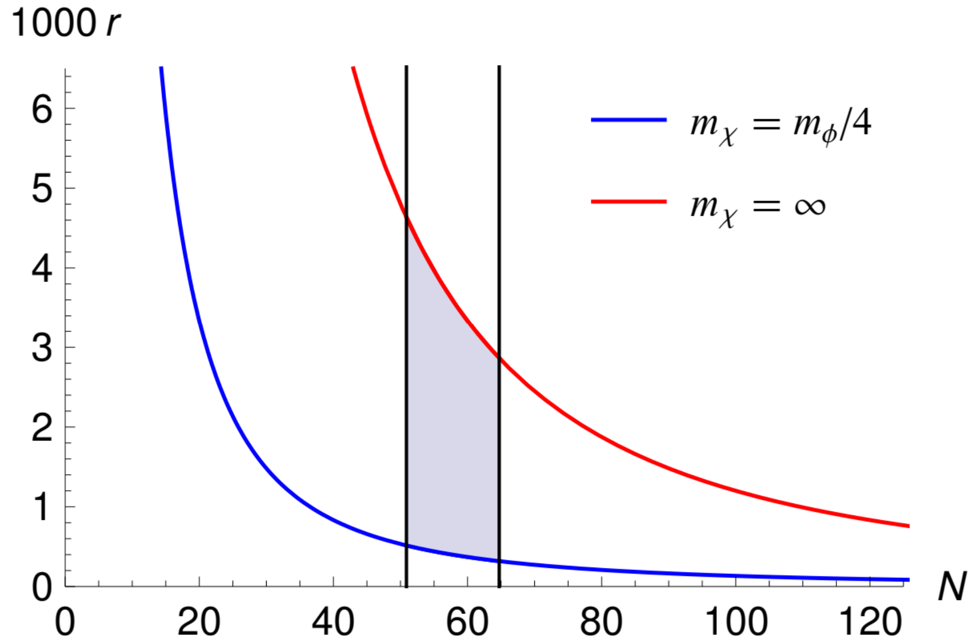
No tachyon condition

$$m_\chi > \frac{m_\phi}{4}$$



No tachyon condition

$$m_\chi > \frac{m_\phi}{4}$$



$$0.4 \lesssim 1000r \lesssim 3, \qquad -0.4 \lesssim 1000n_T \lesssim -0.05$$

The crucial novelty is the treatment of higher derivatives. Here is the procedure

The crucial novelty is the treatment of higher derivatives. Here is the procedure

-D.A., Quantum gravity, fakeons and microcausality, J. High Energy Phys. 11 (2018) 21 and arXiv: 1806.03605 [hep-th]

Consider the higher-derivative classical Lagrangian

$$\mathcal{L}_{\mathrm{HD}} = \frac{m}{2}(\dot{x}^2 - \tau^2\ddot{x}^2) - V \qquad V = \frac{m}{2}\omega^2 x^2 + \frac{\lambda}{4!}x^4$$

The crucial novelty is the treatment of higher derivatives. Here is the procedure

-D.A., Quantum gravity, fakeons and microcausality, J. High Energy Phys. 11 (2018) 21 and arXiv: 1806.03605 [hep-th]

Consider the higher-derivative classical Lagrangian

$$\mathcal{L}_{\mathrm{HD}} = \frac{m}{2}(\dot{x}^2 - \tau^2 \ddot{x}^2) - V \qquad V = \frac{m}{2}\omega^2 x^2 + \frac{\lambda}{4!}x^4$$

The equations of motion are

$$m\left(\frac{\mathrm{d}^2}{\mathrm{d}t^2} + \Omega^2\right)\left(\frac{\mathrm{d}^2}{\mathrm{d}t^2} + \tilde{\Omega}^2\right)x = -\frac{\tilde{\lambda}}{3!}x^3, \qquad \tilde{\lambda} = \frac{\lambda}{m}$$

where

$$\Omega = \frac{1}{\tau\sqrt{2}}\sqrt{1 - \sqrt{1 - 4\tau^2\omega^2}}, \qquad \tilde{\Omega} = \frac{1}{\tau\sqrt{2}}\sqrt{1 + \sqrt{1 - 4\tau^2\omega^2}},$$

The crucial novelty is the treatment of higher derivatives. Here is the procedure

-D.A., Quantum gravity, fakeons and microcausality, J. High Energy Phys. 11 (2018) 21 and arXiv: 1806.03605 [hep-th]

Consider the higher-derivative classical Lagrangian

$$\mathcal{L}_{\mathrm{HD}} = \frac{m}{2}(\dot{x}^2 - \tau^2 \ddot{x}^2) - V \qquad V = \frac{m}{2}\omega^2 x^2 + \frac{\lambda}{4!}x^4$$

The equations of motion are

$$m\left(\frac{\mathrm{d}^2}{\mathrm{d}t^2} + \Omega^2\right)\left(\frac{\mathrm{d}^2}{\mathrm{d}t^2} + \tilde{\Omega}^2\right)x = -\frac{\tilde{\lambda}}{3!}x^3, \qquad \tilde{\lambda} = \frac{\lambda}{m}$$

where

$$\Omega = \frac{1}{\tau\sqrt{2}}\sqrt{1-\sqrt{1-4\tau^2\omega^2}}, \qquad \tilde{\Omega} = \frac{1}{\tau\sqrt{2}}\sqrt{1+\sqrt{1-4\tau^2\omega^2}},$$

We want to project the higher-derivatives away

NOTE THE NO-TACHYON CONDITION

$$\omega > \frac{1}{2\tau}$$

Now that we have understood that THERE IS a condition, we proceed with the simpler case $\omega = 0$, where formulas can be more easily visualized

$$\frac{\mathrm{d}^2}{\mathrm{d}t^2}\left(1+\tau^2\frac{\mathrm{d}^2}{\mathrm{d}t^2}\right)x = -\frac{\tilde{\lambda}}{3!}x^3, \qquad \tilde{\lambda} = \frac{\lambda}{m}$$

Now that we have understood that THERE IS a condition, we proceed with the simpler case $\omega = 0$, where formulas can be more easily visualized

$$\frac{\mathrm{d}^2}{\mathrm{d}t^2}\left(1+\tau^2\frac{\mathrm{d}^2}{\mathrm{d}t^2}\right)x = -\frac{\tilde{\lambda}}{3!}x^3, \qquad \tilde{\lambda} = \frac{\lambda}{m}$$

$$\ddot{x} = -\frac{\tilde{\lambda}x}{6}\left(x^2 - 6\tau^2\dot{x}^2\right) - \frac{\tilde{\lambda}^2\tau^2 x}{12}\left(x^4 - 48\tau^2x^2\dot{x}^2 + 372\tau^4\dot{x}^4\right)$$
$$-\frac{\tilde{\lambda}^3\tau^4 x}{6}\left(x^6 - 156\tau^2x^4\dot{x}^2 + 4572\tau^4x^2\dot{x}^4 - 31152\tau^6\dot{x}^6\right) + \mathcal{O}(\tilde{\lambda}^4)$$

Now that we have understood that THERE IS a condition, we proceed with the simpler case $\omega = 0$, where formulas can be more easily visualized

$$\frac{\mathrm{d}^2}{\mathrm{d}t^2}\left(1+\tau^2\frac{\mathrm{d}^2}{\mathrm{d}t^2}\right)x = -\frac{\tilde{\lambda}}{3!}x^3, \qquad \tilde{\lambda} = \frac{\lambda}{m}$$

$$\ddot{x} = -\frac{\tilde{\lambda}x}{6}\left(x^2 - 6\tau^2\dot{x}^2\right) - \frac{\tilde{\lambda}^2\tau^2 x}{12}\left(x^4 - 48\tau^2x^2\dot{x}^2 + 372\tau^4\dot{x}^4\right) - \frac{\tilde{\lambda}^3\tau^4 x}{6}\left(x^6 - 156\tau^2x^4\dot{x}^2 + 4572\tau^4x^2\dot{x}^4 - 31152\tau^6\dot{x}^6\right) + \mathcal{O}(\tilde{\lambda}^4)$$

$$\frac{\mathcal{L}}{m} = \frac{\dot{x}^2}{2} - \frac{\tilde{\lambda}x^2}{4!}\left(x^2 + 12\tau^2\dot{x}^2\right) + \frac{\tau^2\tilde{\lambda}^2x^2}{72}(x^4 - 54\tau^2x^2\dot{x}^2 + 372\tau^4\dot{x}^4) + \mathcal{O}(\tilde{\lambda}^3)$$

Now that we have understood that THERE IS a condition, we proceed with the simpler case $\omega = 0$, where formulas can be more easily visualized

$$\frac{\mathrm{d}^2}{\mathrm{d}t^2}\left(1+\tau^2\frac{\mathrm{d}^2}{\mathrm{d}t^2}\right)x = -\frac{\tilde{\lambda}}{3!}x^3, \qquad \tilde{\lambda} = \frac{\lambda}{m}$$

$$\ddot{x} = -\frac{\tilde{\lambda}x}{6}\left(x^2 - 6\tau^2\dot{x}^2\right) - \frac{\tilde{\lambda}^2\tau^2 x}{12}\left(x^4 - 48\tau^2x^2\dot{x}^2 + 372\tau^4\dot{x}^4\right)$$
$$-\frac{\tilde{\lambda}^3\tau^4 x}{6}\left(x^6 - 156\tau^2x^4\dot{x}^2 + 4572\tau^4x^2\dot{x}^4 - 31152\tau^6\dot{x}^6\right) + \mathcal{O}(\tilde{\lambda}^4)$$

$$\frac{\mathcal{L}}{m} = \frac{\dot{x}^2}{2} - \frac{\tilde{\lambda}x^2}{4!}\left(x^2 + 12\tau^2\dot{x}^2\right) + \frac{\tau^2\tilde{\lambda}^2x^2}{72}(x^4 - 54\tau^2x^2\dot{x}^2 + 372\tau^4\dot{x}^4) + \mathcal{O}(\tilde{\lambda}^3)$$

$$\frac{E}{m} = \frac{\dot{x}^2}{2} + \frac{\tilde{\lambda}x^2}{4!}\left(x^2 - 12\tau^2\dot{x}^2\right) - \frac{\tau^2\tilde{\lambda}^2x^2}{72}(x^4 + 54\tau^2x^2\dot{x}^2 - 1116\tau^4\dot{x}^4) + \mathcal{O}(\tilde{\lambda}^3).$$

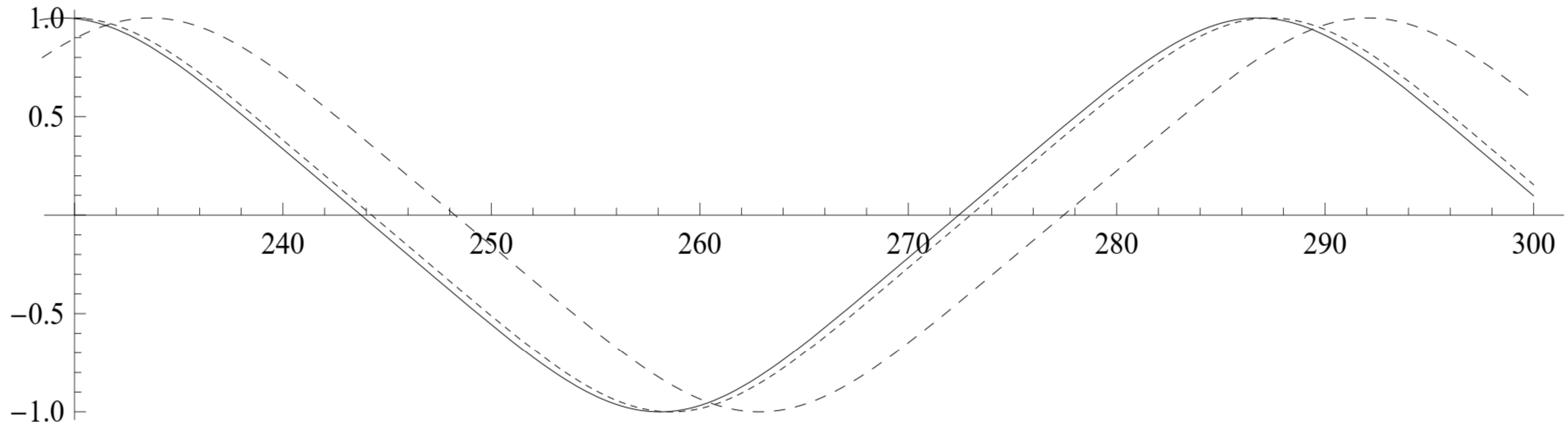


Figure 3: Solution $x(t)$ of the truncated equation (3.5) for $x(0) = 1$, $\dot{x}(0) = 0$, $m = \tau = 1$, $\lambda = 1/10$. The sparsely dashed line is $n = 1$. The densely dashed line is $n = 2$, while the continuous line is $n = 3$. The solution remains stable from $n = 3$ to $n = 10$.

Doing this in primordial cosmology, you find the no-tachyon condition

$$m_\chi > \frac{m_\phi}{4}$$

and then project the equations as explained and you find the spectra and r

Doing this in primordial cosmology, you find the no-tachyon condition

$$m_\chi > \frac{m_\phi}{4}$$

and then project the equations as explained and you find the spectra and r

To the leading order,

$$\frac{(n_s - 1)^2}{3} \leqslant r \leqslant 3(n_s - 1)^2$$

Doing this in primordial cosmology, you find the no-tachyon condition

$$m_\chi > \frac{m_\phi}{4}$$

and then project the equations as explained and you find the spectra and r

To the leading order,

$$\frac{(n_s - 1)^2}{3} \leqslant r \leqslant 3(n_s - 1)^2$$

It survives adding more scalar fields.

D. A.,Perturbation spectra and renormalization-group techniques in double-field inflation and quantum gravity cosmology, J. Cosmol. Astropart. Phys. 07 (2021) 037 and arXiv: 2105.05864 [hep-th]

Doing this in primordial cosmology, you find the no-tachyon condition

$$m_\chi > \frac{m_\phi}{4}$$

and then project the equations as explained and you find the spectra and r

To the leading order,

$$\frac{(n_s-1)^2}{3} \leqslant r \leqslant 3(n_s-1)^2$$

It survives adding more scalar fields.

D. A., Perturbation spectra and renormalization-group techniques in double-field inflation and quantum gravity cosmology, J. Cosmol. Astropart. Phys. 07 (2021) 037 and arXiv: 2105.05864 [hep-th]

The bound makes the theory predictive even before knowing the actual value of m_χ

Inflation as a “cosmic” RG flow

Quantum field theory Inflationary cosmology

Quantum field theory		Inflationary cosmology
RG flow	$\leftrightarrow$	slow roll

Quantum field theory		Inflationary cosmology
RG flow	$\leftrightarrow$	slow roll
couplings α, λ ...	$\leftrightarrow$	slow-roll parameters ϵ, δ ...

Quantum field theory		Inflationary cosmology
RG flow	$\leftrightarrow$	slow roll
couplings α, λ ...	$\leftrightarrow$	slow-roll parameters ϵ, δ ...
beta functions	$\leftrightarrow$	equations of $a(t)$, $H(t)$ ...

Quantum field theory		Inflationary cosmology
RG flow	$\leftrightarrow$	slow roll
couplings α, λ ...	$\leftrightarrow$	slow-roll parameters ϵ, δ ...
beta functions	$\leftrightarrow$	equations of $a(t)$, $H(t)$ ...
sliding scale μ	$\leftrightarrow$	conformal time τ (or $\eta = -k\tau$)

Quantum field theory		Inflationary cosmology
RG flow	$\leftrightarrow$	slow roll
couplings α, λ ...	$\leftrightarrow$	slow-roll parameters ϵ, δ ...
beta functions	$\leftrightarrow$	equations of $a(t)$, $H(t)$ ...
sliding scale μ	$\leftrightarrow$	conformal time τ (or $\eta = -k\tau$)
correlation functions	$\leftrightarrow$	perturbation spectra

Quantum field theory		Inflationary cosmology
RG flow	$\leftrightarrow$	slow roll
couplings α, λ ...	$\leftrightarrow$	slow-roll parameters ϵ, δ ...
beta functions	$\leftrightarrow$	equations of $a(t)$, $H(t)$ ...
sliding scale μ	$\leftrightarrow$	conformal time τ (or $\eta = -k\tau$)
correlation functions	$\leftrightarrow$	perturbation spectra
Callan-Symanzik equation	$\leftrightarrow$	RG equation at superhorizon scales

Quantum field theory		Inflationary cosmology
RG flow	$\leftrightarrow$	slow roll
couplings α, λ ...	$\leftrightarrow$	slow-roll parameters ϵ, δ ...
beta functions	$\leftrightarrow$	equations of $a(t)$, $H(t)$ ...
sliding scale μ	$\leftrightarrow$	conformal time τ (or $\eta = -k\tau$)
correlation functions	$\leftrightarrow$	perturbation spectra
Callan-Symanzik equation	$\leftrightarrow$	RG equation at superhorizon scales
RG invariance	$\leftrightarrow$	conservation on superhorizon scales

Quantum field theory		Inflationary cosmology
RG flow	$\leftrightarrow$	slow roll
couplings α, λ ...	$\leftrightarrow$	slow-roll parameters ϵ, δ ...
beta functions	$\leftrightarrow$	equations of $a(t)$, $H(t)$ ...
sliding scale μ	$\leftrightarrow$	conformal time τ (or $\eta = -k\tau$)
correlation functions	$\leftrightarrow$	perturbation spectra
Callan-Symanzik equation	$\leftrightarrow$	RG equation at superhorizon scales
RG invariance	$\leftrightarrow$	conservation on superhorizon scales
asymptotic freedom	$\leftrightarrow$	de Sitter limit in the infinite past

Quantum field theory		Inflationary cosmology
RG flow	$\leftrightarrow$	slow roll
couplings α, λ ...	$\leftrightarrow$	slow-roll parameters ϵ, δ ...
beta functions	$\leftrightarrow$	equations of $a(t)$, $H(t)$ ...
sliding scale μ	$\leftrightarrow$	conformal time τ (or $\eta = -k\tau$)
correlation functions	$\leftrightarrow$	perturbation spectra
Callan-Symanzik equation	$\leftrightarrow$	RG equation at superhorizon scales
RG invariance	$\leftrightarrow$	conservation on superhorizon scales
asymptotic freedom	$\leftrightarrow$	de Sitter limit in the infinite past
subtraction scheme	$\leftrightarrow$	Einstein frame, Jordan frame, etc.

Quantum field theory		Inflationary cosmology
RG flow	$\leftrightarrow$	slow roll
couplings α, λ ...	$\leftrightarrow$	slow-roll parameters ϵ, δ ...
beta functions	$\leftrightarrow$	equations of $a(t)$, $H(t)$ ...
sliding scale μ	$\leftrightarrow$	conformal time τ (or $\eta = -k\tau$)
correlation functions	$\leftrightarrow$	perturbation spectra
Callan-Symanzik equation	$\leftrightarrow$	RG equation at superhorizon scales
RG invariance	$\leftrightarrow$	conservation on superhorizon scales
asymptotic freedom	$\leftrightarrow$	de Sitter limit in the infinite past
subtraction scheme	$\leftrightarrow$	Einstein frame, Jordan frame, etc.
dimensional transmutation	$\rightarrow$	τ drops out from the spectra, "replaced" by k
running coupling	$\rightarrow$	ok
resummation of leading logs	$\rightarrow$	ok
??	$\leftarrow$	potential $V(\phi)$
anomalous dimensions	$\rightarrow$	0

$$S=-\frac{1}{16\pi G}\int \mathrm{d}^4x\sqrt{-g}R+\frac{1}{2}\int \mathrm{d}^4x\sqrt{-g}\left(D_\mu\phi D^\mu\phi-2V(\phi)\right)$$

$$S=-\frac{1}{16\pi G}\int \mathrm{d}^4x\sqrt{-g}\left(R+\frac{1}{2m_\chi^2}C_{\mu\nu\rho\sigma}C^{\mu\nu\rho\sigma}\right)+\frac{1}{2}\int \mathrm{d}^4x\sqrt{-g}\left(D_\mu\phi D^\mu\phi-2V(\phi)\right)$$

For a classification of the allowed potentials, see

D. A., F. Fruzza and M. Piva, Renormalization-group techniques for single-field inflation in primordial cosmology and quantum gravity, Class. Quantum Grav. 38 (2021) 225011 and arXiv: 2103.01653 [hep-th]

Choose the metric $$g_{\mu\nu} = \mathrm{diag}(1, -a^2, -a^2, -a^2)$$

$$H = \dot{a}/a$$

$$\hat{\kappa} = \sqrt{16\pi G/3}$$

You obtain the equations

$$\dot{H} = -4\pi G\dot{\phi}^2, \qquad H^2 = \frac{4\pi G}{3}\left(\dot{\phi}^2 + 2V(\phi)\right), \qquad \ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0,$$

Choose the metric $g_{\mu\nu} = \mathrm{diag}(1, -a^2, -a^2, -a^2)$

$$H = \dot{a}/a$$

$$\hat{\kappa} = \sqrt{16\pi G/3}$$

You obtain the equations

$$\dot{H} = -4\pi G \dot{\phi}^2, \qquad H^2 = \frac{4\pi G}{3}\left(\dot{\phi}^2 + 2V(\phi)\right), \qquad \ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0,$$

Define the coupling $\alpha = \dfrac{\hat{\kappa}\dot{\phi}}{2H} = \sqrt{-\dfrac{\dot{H}}{3H^2}}$

Eliminating V and $\dot{\phi}$ by means of the first two equations of (2.4) and $\ddot{\phi}$ from the last equation, it is easy to show that α satisfies

$$\dot{\alpha} = m_\phi \sqrt{1-\alpha^2} - H(2+3\alpha)\left(1-\alpha^2\right).$$

$$\tau = -\int_t^{+\infty} \frac{\mathrm{d}t'}{a(t')},$$

Choose the metric $g_{\mu\nu} = \mathrm{diag}(1, -a^2, -a^2, -a^2)$

$$H = \dot{a}/a$$

$$\hat{\kappa} = \sqrt{16\pi G/3}$$

You obtain the equations

$$\dot{H} = -4\pi G \dot{\phi}^2, \qquad H^2 = \frac{4\pi G}{3}\left(\dot{\phi}^2 + 2V(\phi)\right), \qquad \ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0,$$

Define the coupling $\alpha = \frac{\hat{\kappa}\dot{\phi}}{2H} = \sqrt{-\frac{\dot{H}}{3H^2}}$

Eliminating V and $\dot{\phi}$ by means of the first two equations of (2.4) and $\ddot{\phi}$ from the last equation, it is easy to show that α satisfies

$$\dot{\alpha} = m_\phi\sqrt{1-\alpha^2} - H(2+3\alpha)\left(1-\alpha^2\right).$$

$$\tau = -\int_t^{+\infty} \frac{\mathrm{d}t'}{a(t')},$$

$$\beta_\alpha = \frac{\mathrm{d}\alpha}{\mathrm{d}\ln|\tau|} = -2\alpha^2\left[1 + \frac{5}{6}\alpha + \frac{25}{9}\alpha^2 + \frac{383}{27}\alpha^3 + \frac{8155}{81}\alpha^4 + \frac{72206}{81}\alpha^5 + \frac{2367907}{243}\alpha^6 + \mathcal{O}(\alpha^7)\right]$$

de Sitter free

The spectra satisfy Callan-Symanzik equations at superhorizon scales:

$$\frac{\mathrm{d}\mathcal{P}}{\mathrm{d}\ln|\tau|} = \left(\frac{\partial}{\partial \ln|\tau|} + \beta_\alpha(\alpha)\frac{\partial}{\partial\alpha}\right)\mathcal{P} = 0.$$

The spectra satisfy Callan-Symanzik equations at superhorizon scales:

$$\frac{\mathrm{d}\mathcal{P}}{\mathrm{d}\ln|\tau|} = \left(\frac{\partial}{\partial \ln|\tau|} + \beta_\alpha(\alpha)\frac{\partial}{\partial\alpha}\right)\mathcal{P} = 0.$$

$$\mathcal{P} = \tilde{\mathcal{P}}(\alpha_k)$$

running coupling

$$\left(\frac{\partial}{\partial \ln k} + \beta_\alpha(\alpha_*)\frac{\partial}{\partial\alpha_*}\right)\mathcal{P}(k/k_*, \alpha_*) = 0.$$

$$\alpha = \frac{\alpha_k}{1 + 2\alpha_k \ln(-k\tau)}$$

The spectra satisfy Callan-Symanzik equations at superhorizon scales:

$$\frac{\mathrm{d}\mathcal{P}}{\mathrm{d}\ln|\tau|} = \left(\frac{\partial}{\partial \ln|\tau|} + \beta_\alpha(\alpha)\frac{\partial}{\partial\alpha}\right)\mathcal{P} = 0.$$

$$\mathcal{P} = \tilde{\mathcal{P}}(\alpha_k)$$

$$\left(\frac{\partial}{\partial \ln k} + \beta_\alpha(\alpha_*)\frac{\partial}{\partial\alpha_*}\right)\mathcal{P}(k/k_*, \alpha_*) = 0.$$

running coupling

$$\alpha = \frac{\alpha_k}{1 + 2\alpha_k \ln(-k\tau)}$$

Without Weyl squared:

$$\mathcal{P}_T(k) = \frac{4Gm_\phi^2}{\pi}\left[1 - 3\alpha_k + (47 - 24\gamma_M)\frac{\alpha_k^2}{4} - \left(\frac{307}{6} + 12\gamma_M^2 - 42\gamma_M - \pi^2\right)\alpha_k^3 + \mathcal{O}(\alpha_k^4)\right],$$

$$\mathcal{P}_{\mathcal{R}}(k) = \frac{Gm_\phi^2}{12\pi\alpha_k^2}\left[1 + (5 - 4\gamma_M)\alpha_k - \frac{67}{12}\alpha_k^2 + (12\gamma_M^2 - 40\gamma_M + 7\pi^2)\frac{\alpha_k^2}{3} + \mathcal{O}(\alpha_k^3)\right]$$

With Weyl squared

$$\mathcal{P}_T\,(k) = \frac{4m_\phi^2\zeta G}{\pi}\,\Bigg[1 - 3\zeta\alpha_k\left(1 + 2\alpha_k\gamma_M + 4\gamma_M^2\alpha_k^2 - \frac{\pi^2\alpha_k^2}{3}\right) + \frac{\zeta^2\alpha_k^2}{8}(94 + 11\xi)$$
$$+3\gamma_M\zeta^2\alpha_k^3(14 + \xi) - \frac{\zeta^3\alpha_k^3}{12}(614 + 191\xi + 23\xi^2) + \mathcal{O}(\alpha_k^4)\Bigg].$$

$$\mathcal{P}_{\mathcal{R}}(k) = \frac{Gm_\phi^2}{12\pi\alpha_k^2}\left[1 + (5 - 4\gamma_M)\alpha_k + \left(4\gamma_M^2 - \frac{40}{3}\gamma_M + \frac{7}{3}\pi^2 - \frac{67}{12} - \frac{\xi}{2}F_{\rm s}(\xi)\right)\alpha_k^2 + \mathcal{O}(\alpha_k^3)\right]$$

$$F_{\rm s}(\xi) = 1 + \frac{\xi}{4} + \frac{\xi^2}{8} + \frac{\xi^3}{8} + \frac{7\xi^4}{32} + \frac{19}{32}\xi^5 + \frac{295}{128}\xi^6 + \frac{1549}{128}\xi^7 + \frac{42271}{512}\xi^8 + \mathcal{O}(\xi^9)$$

$$\xi = \frac{m_\phi^2}{m_\chi^2}, \qquad \zeta = \left(1 + \frac{\xi}{2}\right)^{-1}, \qquad \tilde{\gamma}_M = \gamma_M - \frac{i\pi}{2}, \qquad \gamma_M = \gamma_E + \ln 2,$$

Conclusions

Purely virtual particles, or fake particles, or ``fakeons", based on a new diagrammatics, have a variety of applications

Conclusions

Purely virtual particles, or fake particles, or ``fakeons", based on a new diagrammatics, have a variety of applications

In phenomenology, they can be used to search for new physics beyond the standard model, by evading common constraints in collider physics and offering new possibilities to solve discrepancies with data. Their diagrammatics can be implemented in softwares to make hard calculations and work out predictions for potential new experiments

Conclusions

Purely virtual particles, or fake particles, or ``fakeons", based on a new diagrammatics, have a variety of applications

In phenomenology, they can be used to search for new physics beyond the standard model, by evading common constraints in collider physics and offering new possibilities to solve discrepancies with data. Their diagrammatics can be implemented in softwares to make hard calculations and work out predictions for potential new experiments

In cosmology, they lead to a sharp prediction ($0.4 \leq 1000r \leq 3$) of the tensor-to-scalar ratio r. This is a result of the theory of quantum gravity based on fakeons, which is unitary and renormalizable

Conclusions

Purely virtual particles, or fake particles, or ``fakeons", based on a new diagrammatics, have a variety of applications

In phenomenology, they can be used to search for new physics beyond the standard model, by evading common constraints in collider physics and offering new possibilities to solve discrepancies with data. Their diagrammatics can be implemented in softwares to make hard calculations and work out predictions for potential new experiments

In cosmology, they lead to a sharp prediction ($0.4 \leq 1000r \leq 3$) of the tensor-to-scalar ratio r. This is a result of the theory of quantum gravity based on fakeons, which is unitary and renormalizable

It is possible to study inflation as a renormalization-group flow, where the spectra play the roles of correlation functions and obey Callan-Symanzik equations in the super-horizon limit. The techniques imported from high-energy physics allow us to gain in understanding and compute high-order corrections more easily

Thanks!