Cosmological Perturbations

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Most of the conventions and notations in [6, ch. 5] will be followed.

Suppose the metric can be expanded up to the linear order as

$$g = g^{(0)} + \epsilon g^{(1)} + O(\epsilon^2). \tag{1}$$

The background metric $g^{(0)}$ takes the Robertson–Walker form

$$g^{(0)}_{\mu\nu} \, \mathrm{d}x^\mu \, \mathrm{d}x^\nu = -N^2(t) \, \mathrm{d}t^2 + a^2(t) \, \mathrm{d}\Omega^2_{3\mathrm{F}}, \tag{2}$$

in which $\mathrm{d}\Omega^2_{3\mathrm{F}} = \mathrm{d}\chi^2 + \chi^2 \left(\mathrm{d}\theta^2 + \sin^2\theta \, \mathrm{d}\phi^2\right)$ is the dimensionless flat spatial metric. The linear perturbation can be decomposed into scalar, vector and tensor parts

$$g^{(1)}_{00} = -E, \tag{3}$$

$$g^{(1)}_{i0} = g^{(1)}_{i0} = F_{,i} + G_i, \tag{4}$$

$$g^{(1)}_{ij} = A\delta_{ij} + B_{,i,j} + C_{i,j} + C_{j,i} + D_{ij}. \tag{5}$$

Here one has some weird condition, where the contractions do not follow the one-up-one-down tradition

$$C_{i,i} = G_{i,i} = 0, \quad D_{ij,i} = 0, \quad D_{ii} = 0. \tag{6}$$

1 Metric perturbation under diffeomorphism

Consider a diffeomorphism generated by ξ^μ

$$x^\mu \to \overline{x}^\mu = x^\mu - \epsilon \xi^\mu. \tag{7}$$

The generator ξ^μ can in turn be decomposed into $\xi_0 = \zeta$, $\xi_i = \xi^{\mathrm{S}}_{,i} + \xi^{\mathrm{V}}_i$.

One has here again some weird condition, where the contractions do not follow the one-up-one-down tradition

$$\xi^{\mathrm{V}}_{i,i} = 0. \tag{8}$$

The Lie derivative of the metric $\mathbb{L}_\xi g$ is

$$\left(\mathbb{L}_\xi g\right)_{\mu\nu} = \xi^\lambda g_{\mu\nu,\lambda} + \xi^\lambda{}_{,\mu} g_{\lambda\nu} + \xi^\lambda{}_{,\nu} g_{\mu\lambda}. \tag{9}$$

In components and expansion, these are

$$\left(\mathbb{L}_\xi g\right)_{00} = 2\dot{\zeta} - 2\zeta\frac{\dot{N}}{N} + O(\epsilon), \tag{10}$$

$$\left(\mathbb{L}_\xi g\right)_{i0} = \left(\mathbb{L}_\xi g\right)_{0i} = \left(\zeta - 2\frac{\dot{a}}{a}\xi^{\mathrm{S}} + \dot{\xi}^{\mathrm{S}}\right)_{,i} + \left(-2\frac{\dot{a}}{a}\xi^{\mathrm{V}}_i + \dot{\xi}^{\mathrm{V}}_i\right) + O(\epsilon), \tag{11}$$

$$\left(\mathbb{L}_\xi g\right)_{ji} = \left(\mathbb{L}_\xi g\right)_{ij} = -\frac{2a\dot{a}}{N^2}\zeta\delta_{ij} + 2\xi^{\mathrm{S}}_{,i,j} + \xi^{\mathrm{V}}_{i,j} + \xi^{\mathrm{V}}_{j,i} + O(\epsilon). \tag{12}$$

2 Scalar perturbations

$$-N^2 - \epsilon E + O(\epsilon^2) \to -N^2 - \epsilon E + \epsilon\left(2\dot{\zeta} - 2\zeta\frac{\dot{N}}{N}\right) + O(\epsilon^2), \tag{13}$$

so one can write

$$\mathbb{L}_\xi E = -2\dot{\zeta} + 2\zeta\frac{\dot{N}}{N}. \tag{14}$$

Similarly one can read-off

$$\mathbb{L}_\xi F = \zeta - 2\frac{\dot{a}}{a}\xi^{\mathrm{S}} + \dot{\xi}^{\mathrm{S}}, \tag{15}$$

$$\mathbb{L}_\xi A = -\frac{2a\dot{a}}{N^2}\zeta, \tag{16}$$

$$\mathbb{L}_\xi B = 2\xi^{\mathrm{S}}. \tag{17}$$

The four scalar perturbations are generated by ζ and ξ^{S}, so that only two independent perturbations exists. It is clear that

$$\mathbb{L}_\xi\left(\frac{F}{a} - \frac{\mathbb{d}}{\mathbb{d}t}\frac{B}{2a}\right) = \frac{\zeta}{a}. \tag{18}$$

One can verify that

$$\mathbb{L}_\xi\left\{\frac{E}{2N} + \frac{\mathbb{d}}{\mathbb{d}t}\left[\frac{a}{N}\left(\frac{F}{a} - \frac{\mathbb{d}}{\mathbb{d}t}\frac{B}{2a}\right)\right]\right\} = 0, \tag{19}$$

$$\mathbb{L}_\xi\left\{\frac{A}{2} + \frac{a^2\dot{a}}{N^2}\left(\frac{F}{a} - \frac{\mathbb{d}}{\mathbb{d}t}\frac{B}{2a}\right)\right\} = 0. \tag{20}$$

3 Vector perturbations

4 Tensor perturbations

5 Scalar field perturbation under diffeomorphism

6 Perturbation in Arnowitt–Deser–Misner Hamiltonian formalism

The Hamiltonian action for General Relativity in terms of Arnowitt–Deser–Misner variables is [3, ch.4.2.2]

$$S = \int \mathbb{d}t\, \mathbb{d}x^3 \Big\{ \mathfrak{p}^{ij}\dot{h}_{ij} + \mathfrak{P}\dot{N} + \mathfrak{P}^i\dot{N}_i - N\mathfrak{H}^\perp - N_i\mathfrak{H}^i \\ - \mathfrak{P}V - \mathfrak{P}^i V_i \Big\} + \text{ boundary terms} \tag{21}$$

where

$$\mathfrak{H}^\perp = 2\varkappa\, \mathfrak{G}_{ijkl}\mathfrak{p}^{ij}\mathfrak{p}^{kl} - \frac{\sqrt{\mathfrak{h}}}{2\varkappa}R[h] \equiv 2\varkappa\, \mathfrak{F}^{ijkl}h_{ij}h_{kl} - \frac{\sqrt{\mathfrak{h}}}{2\varkappa}R[h], \tag{22}$$

$$\mathfrak{H}^i = -2\mathfrak{p}^{ij}{}_{|j} \tag{23}$$

are the secondary constraints,

$$\mathfrak{G}_{ijkl} := \frac{1}{2\mathfrak{h}^{1/2}}\big(h_{ik}h_{lj} + h_{il}h_{kj} - h_{ij}h_{kl}\big) \equiv -\frac{\delta\big(\mathfrak{h}^{-1/2}h_{ij}\big)}{\delta h^{kl}}, \tag{24}$$

$$\mathfrak{G}^{ijkl} := \frac{\mathfrak{h}^{1/2}}{2}\big(h^{ik}h^{lj} + h^{il}h^{kj} - 2h^{ij}h^{kl}\big) \equiv -\mathfrak{h}^{-1/2}\frac{\delta\big(\mathfrak{h}h^{ij}\big)}{\delta h_{kl}} \tag{25}$$

$$\mathfrak{F}^{ijkl} := \frac{1}{2\mathfrak{h}^{1/2}}\big(\mathfrak{p}^{ik}\mathfrak{p}^{jl} + \mathfrak{p}^{il}\mathfrak{p}^{kj} - \mathfrak{p}^{ij}\mathfrak{p}^{kl}\big) \tag{26}$$

are convenient notations. In eq. (21), V and V_i are velocities of N and N_i and play the role of Lagrange multipliers. Technical details about the boundary terms can be found in [5, ch. 4.2] and the references therein. Note that $\{N, N_i, h_{ij}; \mathfrak{P}, \mathfrak{P}^i, \mathfrak{p}^{ij}\}$ are not the unique choice of canonical variables for General Relativity in Hamiltonian formalism; instead, they are a special parametrisation of the phase space. One can also choose the components of the original four-metric and their conjugate momenta $\{g_{\mu\nu}; \mathfrak{p}^{\mu\nu}\}$ as canonical variables, as Dirac has done in [2]. The two approaches are different in some subtle aspects; see [4] for a comparison.

Gauge transformations in the Arnowitt–Deser–Misner canonical variables are generated by [1]

$$G = -\int \mathbb{d}^3x \Big\{ \Big[\xi_\perp\Big(\mathfrak{H}^\perp + N_{|i}\mathfrak{P}^i + \big(N\mathfrak{P}^i\big)_{|i} + \big(N_i\mathfrak{P}\big)^{|i}\Big) + \dot{\xi}_\perp\mathfrak{P}\Big] \\ + \Big[\xi_i\Big(\mathfrak{H}^i + N_j{}^{|i}\mathfrak{P}^j + \big(N_j\mathfrak{P}^i\big)^{|j} + N^{|i}\mathfrak{P}\Big) + \dot{\xi}_i\mathfrak{P}^i\Big]\Big\}. \tag{27}$$

Possible boundary terms have not been discussed so far. The infinitesimal gauge transformation of $\{N, N_i\}$ is

$$\delta N = [N, G]_{\mathrm{P}} = \xi_\perp{}^{|i} N_i - \dot{\xi}_\perp - \xi_i N^{|i}, \tag{28}$$

$$\delta N_i = -\xi_\perp N_{|i} + \xi_{\perp|i} N - \xi_j N_i{}^{|j} + \xi_i{}^{|j} N_j - \dot{\xi}_i, \tag{29}$$

which can be found in [4]. Transformations for g_{ij} and the momenta have to be worked out as

$$\delta\mathfrak{P} = -(\xi_\perp \mathfrak{P}^i)_{|i} - \xi_{\perp|i}\mathfrak{P}^i - (\xi_i \mathfrak{P})^{|i}, \tag{30}$$

$$\delta\mathfrak{P}^i = -\xi_{\perp|i}\mathfrak{P} - \left(\xi_j \mathfrak{P}^i\right)^{|j} - \xi_j{}^{|i}\mathfrak{P}^j, \tag{31}$$

where only the primary constraints are involved;

$$\begin{aligned}
\delta h_{ij} &= -\frac{\partial}{\partial \mathfrak{p}^{ij}}(\xi_\perp \mathfrak{H}^\perp + \xi_i \mathfrak{H}^i) \\
&= -\xi^\perp 4\varkappa \mathfrak{G}_{ijkl}\mathfrak{p}^{kl} - \xi_{i|j} - \xi_{j|i},
\end{aligned} \tag{32}$$

$$\begin{aligned}
\delta \mathfrak{p}^{ij} &= \frac{\partial}{\partial h_{ij}}(\xi_\perp \mathfrak{H}^\perp + \xi_i \mathfrak{H}^i) \\
&= 2\varkappa\,\xi_\perp \left(-\frac{1}{2}h^{ij}\mathfrak{F}^{klmn}h_{mn} + 2\mathfrak{F}^{ijkl}\right)h_{kl} \\
&\quad + \frac{1}{2\varkappa}\left(\sqrt{\mathfrak{h}}\,\xi_\perp G^{ij}[h] - \mathfrak{G}^{ijkl}(\xi_\perp)_{|k|l}\right) \\
&\quad + \left\{(\mathfrak{p}^{il}h^{kj} + \mathfrak{p}^{jl}h^{ki} - \mathfrak{p}^{ij}h^{kl})\xi_k\right\}_{|l},
\end{aligned} \tag{33}$$

where $G^{ij}[h] = R^{ij}[h] - h^{ij}R[h]/2$, and only the secondary constraints are involved. The results can be checked with [5, p. 4.2.7].

6.1 Expansion of the action with fluctuations

Some useful results

First variations

The first variation of the inverse metric h^{ij} reads

$$\delta h^{ij} = -h^{ik}h^{jl}\,\delta h_{kl} = -h^{i(k}h^{l)j}\,\delta h_{kl}. \tag{34}$$

The first variation of $\mathfrak{h} = \det h_{ij}$ reads

$$\delta\mathfrak{h} = \mathfrak{h}h^{ij}\,\delta h_{ij}. \tag{35}$$

The first variation of $\Gamma^i{}_{jk}$ can be obtained in normal coordinates, which reads

$$\delta\Gamma^i{}_{jk} = \frac{1}{2}h^{il}\left\{-\left(\delta h_{jk}\right)_{|l} + (\delta h_{kl})_{|j} + \left(\delta h_{lj}\right)_{|k}\right\} \tag{36}$$

$$= \frac{1}{2}\left\{-h^{il}\delta^m{}_j\delta^n{}_k + h^{in}\delta^l{}_j\delta^m{}_k + h^{im}\delta^n{}_j\delta^l{}_k\right\}(\delta h_{mn})_{|l}. \tag{37}$$

The first variation of $R_{ij}[h]$ and $R^{ij}[h]$

$$\delta R_{ij}[h] = \left(\delta\Gamma^k{}_{ji}\right)_{|k} - \left(\delta\Gamma^k{}_{ki}\right)_{|j}, \tag{38}$$

$$\delta R^{ij}[h] = -2R^{k(i}h^{j)l}\,\delta h_{kl} + h^{k(i}\,\bar{\delta}u^{j)l}{}_{k|l}, \tag{39}$$

where

$$\bar{\delta}u^{ij}{}_k := h^{il}\,\delta\Gamma^j{}_{lk} - h^{ij}\,\delta\Gamma^l{}_{lk} \tag{40}$$

is related to the boundary terms. Equation (38) can be obtained in normal coordinates.

For the first variation of the constraints, one also needs

$$\bar{\delta}u^{ji}{}_j = \left(\delta h_{kl}\right)_{|j}\left(h^{i(k}h^{l)j} - h^{ij}h^{kl}\right) = \mathfrak{h}^{-1/2}\mathfrak{G}^{ijkl}\left(\delta h_{kl}\right)_{|j}; \tag{41}$$

therefore,

$$\sqrt{\mathfrak{h}}\,N\,\bar{\delta}u^{ji}{}_{j|i} = \delta h_{ij}\,\mathfrak{G}^{ijkl}N_{|k|l} + \left\{\mathfrak{G}^{ijkl}\left(N\left(\delta h_{kl}\right)_{|j} - N_{|j}\,\delta h_{kl}\right)\right\}_{|i}. \tag{42}$$

In the Hamiltonian constraint, the first variation of the 'kinetic term' $\mathfrak{G}_{ijkl}\mathfrak{p}^{ij}\mathfrak{p}^{kl} \equiv \mathfrak{F}^{ijkl}h_{ij}h_{kl}$ reads

$$\begin{aligned}&\delta\left(\mathfrak{G}_{ijkl}\mathfrak{p}^{ij}\mathfrak{p}^{kl}\right) \equiv \delta\left(\mathfrak{F}^{ijkl}h_{ij}h_{kl}\right)\\ &= \delta h_{ij}\left(-\frac{1}{2}h^{ij}\mathfrak{F}^{klmn}h_{mn} + 2\mathfrak{F}^{ijkl}\right)h_{kl} + \delta\mathfrak{p}^{ij}\,2\mathfrak{G}_{ijkl}\mathfrak{p}^{kl}.\end{aligned} \tag{43}$$

Equipped with eqs. (39) and (41), the first variation of the 'potential' $\sqrt{\mathfrak{h}}\,R[h]$ reads

$$\begin{aligned}\delta\left(\sqrt{\mathfrak{h}}R[h]\right) &= \sqrt{\mathfrak{h}}\left\{-G^{ij}[h]\,\delta h_{ij} + \bar{\delta}u^{ji}{}_{j|i}\right\}\\ &= -\sqrt{\mathfrak{h}}\,G^{ij}[h]\,\delta h_{ij} + \mathfrak{G}^{ijkl}\left(\delta h_{kl}\right)_{|j|i}.\end{aligned} \tag{44}$$

One can now write down the first variation of $N\mathfrak{H}^\perp$ with respect to $\left\{h_{ij}, \mathfrak{p}^{ij}\right\}$,

$$\begin{aligned}N\,\delta\mathfrak{H}^\perp = \delta h_{ij}&\left\{2\varkappa N\left(-\frac{1}{2}h^{ij}\mathfrak{F}^{klmn}h_{mn} + 2\mathfrak{F}^{ijkl}\right)h_{kl}\right.\\ &\left.+\frac{1}{2\varkappa}\left(\sqrt{\mathfrak{h}}\,NG^{ij}[h] - \mathfrak{G}^{ijkl}N_{|k|l}\right)\right\}\\ &+\delta\mathfrak{p}^{ij}\,4\varkappa\,N\mathfrak{G}_{ijkl}\mathfrak{p}^{kl}\\ &-\frac{1}{2\varkappa}\left\{\mathfrak{G}^{ijkl}\left(N\left(\delta h_{kl}\right)_{|j} - N_{|j}\,\delta h_{kl}\right)\right\}_{|i},\end{aligned} \tag{45}$$

where the terms in the last line will be pushed to the spatial boundary $\partial\Sigma$; the second term vanishes by $\delta h_{ij}\big|_{\partial\Sigma} = 0$, whereas the first one is cancelled by the boundary term.

Finally, the first variation of $N_i\mathfrak{H}^i$ with respect to $\{h_{ij}, \mathfrak{p}^{ij}\}$ is easier,

$$\begin{aligned}N_i\,\delta\mathfrak{H}^i &= \delta h_{ij}\,\{(\mathfrak{p}^{il}h^{kj} + \mathfrak{p}^{jl}h^{ki} - \mathfrak{p}^{ij}h^{kl})N_k\}_{|l} + \delta\mathfrak{p}^{ij}\,2N_{(i|j)}\\ &\quad - \big(-h^{il}\delta^m{}_j\delta^n{}_k + h^{in}\delta^l{}_j\delta^m{}_k + h^{im}\delta^n{}_j\delta^l{}_k\big)\big(N_i\mathfrak{p}^{jk}\,\delta h_{mn}\big)_{|l}\\ &\quad - 2\big(\delta\mathfrak{p}^{ij}\,N_j\big)_{|i},\end{aligned}\tag{46}$$

where the last two lines will be pushed to the spatial boundary and vanish by $\delta h_{ij}\big|_{\partial\Sigma} = 0 = \delta\mathfrak{p}^{ij}\big|_{\partial\Sigma}$.

Second variations

First variation of $\mathfrak{F}^{ijkl}h_{kl}$

$$\begin{aligned}\delta(\mathfrak{F}^{ijkl}h_{kl}) = \delta h_{kl}&\left(-\frac{1}{2}\mathfrak{F}^{ijmn}h^{kl}h_{mn} + \mathfrak{F}^{ijkl}\right)\\ &+ \delta\mathfrak{p}^{kl}\,(\delta^i{}_k\mathfrak{G}^j{}_{lmn} + \delta^i{}_m\mathfrak{G}^j{}_{nkl})\mathfrak{p}^{mn}.\end{aligned}\tag{47}$$

First variation of $\mathfrak{G}_{ijkl}\mathfrak{p}^{kl}$

$$\begin{aligned}\delta\big(\mathfrak{G}_{ijkl}\mathfrak{p}^{kl}\big) = \delta h_{kl}&\left(-\frac{1}{2}\mathfrak{G}_{ijmn}h^{kl} + \delta^k{}_i\mathfrak{G}^l{}_{jmn} + \delta^k{}_m\mathfrak{G}^l{}_{nij}\right)\mathfrak{p}^{mn}\\ &+ \delta p^{kl}\,\mathfrak{G}_{ijkl}.\end{aligned}\tag{48}$$

First variation of $\sqrt{\mathfrak{h}}\,G^{ij}[h]$

$$\begin{aligned}\delta\Big(\sqrt{\mathfrak{h}}\,G^{ij}[h]\Big) = \sqrt{\mathfrak{h}}\bigg\{&\delta h_{kl}\cdot\\ &\left(-\frac{1}{2}\right)(R^{ik}h^{lj} + R^{il}h^{kj} - R^{ij}h^{kl} + h^{ik}G^{lj} + h^{il}G^{kj} - h^{ij}G^{kl})\\ &+ \left(h^{il}\,\bar{\delta}u^{jk}{}_l - \frac{1}{2}h^{ij}\,\bar{\delta}u^{lk}{}_l\right)_{|k}\bigg\}.\end{aligned}\tag{49}$$

For the following calculation, one also needs

$$h^{k(i}\,\bar{\delta}u^{j)l}{}_{k|l} = \tag{50}$$

About $\bar{\delta}u^{ij}{}_k$, the identity

$$\sqrt{\mathfrak{h}}\,Nh^{k(i}\,\bar{\delta}u^{j)l}{}_{k|l} = \tag{51}$$

is also useful.

Second variation of $N\mathfrak{H}^{\perp}$

$$
\begin{aligned}
&\delta^2(N\mathfrak{H}^{\perp}) \\
&= \delta h_{ij}\,\delta h_{kl}\Bigg\{2\varkappa\bigg[\frac{1}{4}(h^{ik}h^{lj}+h^{il}h^{kj}+h^{ij}h^{kl})\mathfrak{F}^{mnrs}h_{mn}h_{rs} \\
&\qquad\qquad - (h^{ij}\mathfrak{F}^{klmn}+\mathfrak{F}^{ijmn}h^{kl})h_{mn}+\mathfrak{F}^{ijkl}\bigg] \\
&\qquad - \frac{\sqrt{\mathfrak{h}}}{4\varkappa}(R^{ik}h^{lj}+R^{il}h^{kj}-R^{ij}h^{kl}+h^{ik}G^{lj}+h^{il}G^{kj}-h^{ij}G^{kl})\Bigg\} \\
&\quad + \delta h_{ij}\,\frac{\sqrt{\mathfrak{h}}}{2\varkappa}\left(h^{il}\,\bar{\delta}u^{jk}{}_{l}-\frac{1}{2}h^{ij}\,\bar{\delta}u^{lk}{}_{l}\right)_{|k} \\
&\quad + \delta h_{ij}\,\delta\mathfrak{p}^{kl}\,4\varkappa\{-h^{ij}\mathfrak{G}_{klmn}+2(\delta^{i}{}_{k}\mathfrak{G}^{j}{}_{lmn}+\delta^{i}{}_{m}\mathfrak{G}^{j}{}_{nkl})\}\mathfrak{p}^{mn} \\
&\quad + \delta p^{ij}\,\delta p^{kl}\,4\varkappa\mathfrak{G}_{ijkl} \\
&\quad - \delta h_{ij}\,\delta\left(\frac{\sqrt{\mathfrak{h}}}{2\varkappa}\,\bar{\delta}u^{lk}{}_{l|k}\right).
\end{aligned}
\tag{52}
$$

Second variation of $\Gamma^{i}{}_{jk}$

$$
\delta^2\Gamma^{i}{}_{jk} = -h^{im}\,\delta\Gamma^{l}{}_{jk}\,\delta h_{lm}. \tag{53}
$$

Second variation of $\mathfrak{H}^{i}$

$$
\delta^2(\mathfrak{H}^{i}) = -h^{im}p^{jk}\,\delta\Gamma^{l}{}_{jk}\,\delta h_{lm} + 2\,\delta\Gamma^{i}{}_{jk}\,\delta p^{jk}. \tag{54}
$$

Other second variations

Second variation of h^{ij}

$$
\delta^2 h^{ij} = (h^{im}h^{jl}h^{kn}+h^{ik}h^{jm}h^{ln})\,\delta h_{kl}\,\delta h_{mn} \tag{55}
$$

Second variation of $\mathfrak{h} = \det h_{ij}$

$$
\delta^2\mathfrak{h} = -\frac{1}{4}\mathfrak{h}(h^{ik}h^{jl}+h^{il}h^{kj}-h^{ij}h^{kl})\,\delta h_{ij}\,\delta h_{kl}. \tag{56}
$$

First variation of $\left(\delta h_{ij}\right)_{|k}$

$$
\delta\Big\{\left(\delta h_{ij}\right)_{|k}\Big\} = -2\delta\Gamma^{l}{}_{k(i}\,\delta h_{j)l}. \tag{57}
$$

In a general background, the second variations of the quantities are much more tedious.

In Robertson–Walker background,

References

[1] Leonardo Castellani. "Symmetries in constrained Hamiltonian systems". In: *Annals of Physics* 143.2 (Oct. 1982), pp. 357–371. DOI: 10.1016/0003-4916(82)90031-8.

[2] Paul A. M. Dirac. "The Theory of Gravitation in Hamiltonian Form". In: *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences* 246.1246 (Aug. 1958), pp. 333–343. DOI: 10.1098/rspa.1958.0142.

[3] Claus Kiefer. *Quantum Gravity*. 3rd ed. Oxford University Press, Apr. 2012. DOI: 10.1093/acprof:oso/9780199585205.001.0001.

[4] Natalia Kiriushcheva and Sergei Kuzmin. "The Hamiltonian formulation of General Relativity: myths and reality". In: *Central Eur.J.Phys.9:576-615,2011* 9.3 (Aug. 31, 2008). DOI: 10.2478/s11534-010-0072-2. arXiv: 0809.0097 [gr-qc].

[5] Eric Poisson. *A Relativist's Toolkit*. Cambridge University Press, 2004. DOI: 10.1017/cbo9780511606601.

[6] Steven Weinberg. *Cosmology*. Oxford University Press, 2008. ISBN: 9780198526827. URL: https://global.oup.com/academic/product/cosmology-9780198526827.