



Some canonical metrics *via* Aubin’s local deformations

Giovanni Catino^a, Davide Dameno^b, Paolo Mastrolia^{b,*}

^a *Dipartimento di Matematica, Politecnico di Milano, Piazza Leonardo da Vinci 32, 20133, Milano, Italy*

^b *Dipartimento di Matematica, Università degli Studi di Milano, via Saldini 50, 20133, Milano, Italy*



ARTICLE INFO

Article history:

Received 20 December 2023

Available online 31 October 2024

MSC:

53C25

53B21

53C21

Keywords:

Canonical metrics

Weyl tensor

Cotton tensor

Bach tensor

Aubin’s metric deformation

ABSTRACT

English: In this paper, using special metric deformations introduced by Aubin, we construct Riemannian metrics satisfying non-vanishing conditions concerning the Weyl tensor, on every compact manifold. In particular, in dimension four, we show that there are no topological obstructions for the existence of metrics with non-vanishing Bach tensor.

© 2024 The Author(s). Published by Elsevier Masson SAS. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

R É S U M É

French : Dans cet article, en utilisant des déformations métriques spéciales introduites par Aubin, nous construisons des métriques Riemanniennes satisfaisant des conditions de non-annulation concernant le tenseur de Weyl, sur toute variété compacte. En particulier, en dimension quatre, nous montrons qu’il n’y a pas d’obstructions topologiques à l’existence de métriques avec un tenseur de Bach non nul.

© 2024 The Author(s). Published by Elsevier Masson SAS. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Let (M, g) be a Riemannian manifold of dimension $n \geq 3$. It is well-known that its Riemann curvature tensor, Riem_g , admits the decomposition

$$\text{Riem}_g = W_g + \frac{1}{n-2} \text{Ric}_g \otimes g - \frac{S_g}{2(n-1)(n-2)} g \otimes g,$$

where W_g , Ric_g , S_g are the Weyl tensor, the Ricci tensor and the scalar curvature of (M, g) , respectively, and \otimes denotes the Kulkarni-Nomizu product.

* Corresponding author.

E-mail addresses: giovanni.catino@polimi.it (G. Catino), davide.dameno@unimi.it (D. Dameno), paolo.mastrolia@unimi.it (P. Mastrolia).

If we require that the curvature of (M, g) satisfies certain conditions, several obstructions to the validity of these properties may occur: indeed, the topology of M may not allow the existence of such metrics. Famous examples of this relation between curvature and topology are given, for instance, by metrics with positive scalar curvature ([12], [13], [16], [18]) or by locally conformally flat metrics, which, for $n \geq 4$, are the ones with vanishing Weyl tensor ([4], [7], [14], [15]).

On the contrary, there are curvature conditions which can be realized on every Riemannian manifold (and we say that they are “non-obstructed”): for instance, Aubin ([3]) showed that, if M is closed and $n \geq 3$, there always exists a Riemannian metric g such that $S_g \equiv -1$; he also proved that, if M is compact and $n \geq 4$, there always exists a Riemannian metric g such that the Weyl tensor W_g nowhere vanishes ([2], [3]). The first author generalized these results showing that, given a Riemannian manifold (M, g) , for every $t \in \mathbb{R}$, there exists a Riemannian metric \tilde{g} such that the *scalar-Weyl curvature* $S_{\tilde{g}} + t|W_{\tilde{g}}|_{\tilde{g}} \equiv -1$ on M ([8]); on the other hand, the first and the third authors, together with D. D. Monticelli and F. Punzo, used Aubin’s result concerning the Weyl tensor to show the existence of *weak harmonic-Weyl* metrics on every closed Riemannian four-manifold ([10]). More precisely, these metrics arise as minimizers of the functional

$$g \longmapsto \mathfrak{D}(g) := \text{Vol}_g(M)^{\frac{1}{2}} \int_M |\delta_g W_g|_g^2 dV_g$$

in the conformal class with non-vanishing Weyl tensor constructed by Aubin.

Our main task in this paper is to investigate other curvature conditions which can be imposed without any topological obstruction: in particular, we focus on some properties involving geometric tensors related to W_g on compact manifolds of dimension $n \geq 4$.

First, for the sake of completeness, we provide a detailed proof of Aubin’s result (see Theorem 3.1). Then, we focus on the case $n = 4$: it is well-known that, on an oriented four-dimensional Riemannian manifold (M, g) , the Hodge operator \star induces a splitting of the bundle of 2-forms into two subbundles $\Lambda = \Lambda_+ \oplus \Lambda_-$, where Λ_{\pm} is the eigenspace of \star corresponding to the eigenvalue ± 1 . This leads to a decomposition of the Weyl tensor into a *self-dual* and an *anti-self-dual* part; namely,

$$W_g = W_g^+ + W_g^-.$$

Exploiting Aubin’s deformation method, we are able to prove the following

Theorem 1.1. *Let M be a compact smooth manifold, with $\dim M = 4$. Then, there exists a Riemannian metric \bar{g} such that*

$$|W_{\bar{g}}^+|_{\bar{g}}^2 \equiv 1 \quad \text{on } M.$$

The same result holds for the anti-self-dual component $W_{\bar{g}}^-$.

As a consequence, using the metric g_0 constructed in Theorem 1.1 and following the same strategy as in [10], it is immediate to prove the

Corollary 1.2. *On every smooth, closed four-manifold M , there exists a Riemannian metric g_0 such that, in its conformal class $[g_0]$, there exist weak half harmonic Weyl metrics, i.e. minimizers of the quadratic curvature functional*

$$g \longmapsto \mathfrak{D}^{\pm}(g) := \text{Vol}_g(M)^{\frac{1}{2}} \int_M |\delta_g W_g^{\pm}|_g^2 dV_g.$$

(see also Remark 4 in [10]).

Moreover, we generalize this statement, showing a “mixed-type” condition:

Theorem 1.3. *Let (M, g) be a compact Riemannian manifold, with $\dim M = 4$. Then, for every $t \in \mathbb{R}$, there exists a Riemannian metric \bar{g}_t such that*

$$|W_{\bar{g}_t}^+ + t W_{\bar{g}_t}^-|^2 \equiv 1 \quad \text{on } M.$$

In the subsequent sections, we focus on two other relevant geometric tensors: the *Cotton tensor* and the *Bach tensor*, which we denote as C_g and B_g , respectively (see Subsection 2.1 for the definitions and the main properties of these tensors).

First, we obtain a “non-obstructed” condition for C_g on a compact Riemannian manifold of dimension $n \geq 4$:

Theorem 1.4. *Let M be a compact smooth manifold of dimension $n \geq 4$. Then, there exists a metric \tilde{g} such that the Cotton tensor $C_{\tilde{g}}$ of (M, \tilde{g}) vanishes only at finitely many points $p_1, \dots, p_k \in M$.*

Remark 1.5. We point out that Aubin’s method in the proof of Theorem 1.4 does not lead to a sharp conclusion: indeed, one can prove the existence of left-invariant, non-Einstein metrics on the standard sphere whose Cotton tensor nowhere vanishes for every $n \geq 3$. Moreover, if $n = 3$, the method used in the proof does not work, due to the lack of independent equations in the case $p \in B_{r/2} \setminus \{p_0\}$.

The final section of the paper is dedicated to the tensor B_g , which has many applications, for instance, in General Relativity ([5]). This tensor is especially relevant when $n = 4$: indeed, in this case B_g is also divergence-free and conformally covariant, i.e., given a conformal change $\tilde{g} = e^{2u}g$ of g , the Bach tensor transforms as

$$e^{4u} \tilde{B}_{ij} = B_{ij},$$

which, in global notation, means

$$e^{2u} B_{\tilde{g}} = B_g$$

When $B_g \equiv 0$, we say that (M, g) is *Bach-flat*: these metrics are critical points of the *Weyl functional*

$$g \longmapsto \mathcal{W}(g) := \int_M |W_g|_g^2 dV_g,$$

which is a conformally invariant functional, playing an important role in the study of Einstein four-manifolds: indeed, Bach-flatness is a necessary condition for a metric g to be *conformally Einstein* (i.e., there exists a metric \tilde{g} in the conformal class $[g]$ such that (M, \tilde{g}) is an Einstein manifold). We point out that, in general, this condition is not sufficient (see [1]): however, Derdziński [11] showed that Bach-flatness is a sufficient condition for positive definite Kähler four-manifolds and recently LeBrun ([17]) classified Bach-flat compact Kähler complex surfaces.

Although the existence of topological obstructions for Bach-flat metrics on Riemannian four-manifolds is an open problem, in this paper we provide an answer to the “opposite” question, i.e. if the topology of the manifold plays a role in the existence of metrics with nowhere vanishing Bach tensor. More precisely, we exploit Aubin’s construction in the four-dimensional case to obtain the following:

Theorem 1.6. *Let M be a compact smooth manifold with $\dim M = 4$. Then, there exists a Riemannian metric \bar{g} such that*

$$|B_{\bar{g}}|_{\bar{g}}^2 \equiv 1 \quad \text{on } M.$$

Acknowledgments. The authors would like to thank Professor A. Derdziński for the useful observations appearing in Remark 1.5. All authors are members of the Gruppo Nazionale per le Strutture Algebriche, Geometriche e loro Applicazioni (GNSAGA) of INdAM (Istituto Nazionale di Alta Matematica) and have been partially supported by *2022 PRIN Project: Differential-geometric aspects of manifolds via Global Analysis (code 20225J97H5)*.

2. Aubin's deformation

2.1. Preliminaries

The (1, 3)-Riemann curvature tensor of a smooth Riemannian manifold (M^n, g) is defined by

$$R(X, Y)Z = \nabla_X \nabla_Y Z - \nabla_Y \nabla_X Z - \nabla_{[X, Y]} Z.$$

Throughout the article, the Einstein convention of summing over the repeated indices will be adopted. In a local coordinate system the components of the (1, 3)-Riemann curvature tensor are given by $R_{ijk}^l \frac{\partial}{\partial x^l} = R\left(\frac{\partial}{\partial x^j}, \frac{\partial}{\partial x^k}\right) \frac{\partial}{\partial x^i}$ and we denote by Riem_g its (0, 4) version with components by $R_{ijkl} = g_{im} R_{jkl}^m$. The Ricci tensor is obtained by the contraction $R_{ik} = g^{jl} R_{ijkl}$ and $S = g^{ik} R_{ik}$ will denote the scalar curvature (g^{ij} are the coefficient of the inverse of the metric g). As recalled in the Introduction, the *Weyl tensor* W_g is defined by the decomposition formula, in dimension $n \geq 3$,

$$\begin{aligned} W_{ijkl} = R_{ijkl} - \frac{1}{n-2} (R_{ik}g_{jl} - R_{il}g_{jk} + R_{jl}g_{ik} - R_{jk}g_{il}) \\ + \frac{S}{(n-1)(n-2)} (g_{ik}g_{jl} - g_{il}g_{jk}). \end{aligned} \quad (2.1)$$

The Weyl tensor shares the algebraic symmetries of the curvature tensor. Moreover, as it can be easily seen by the formula above, all of its contractions with the metric are zero, i.e. W is totally trace-free. In dimension three, W is identically zero on every Riemannian manifold, whereas, when $n \geq 4$, the vanishing of the Weyl tensor is a relevant condition, since it is equivalent to the local conformal flatness of (M^n, g) . We also recall that in dimension $n = 3$, local conformal flatness is equivalent to the vanishing of the *Cotton tensor* C_g , whose local components are

$$C_{ijk} = R_{ij,k} - R_{ik,j} - \frac{1}{2(n-1)} (S_k g_{ij} - S_j g_{ik}) = A_{ij,k} - A_{ik,j}; \quad (2.2)$$

here $R_{ij,k} = \nabla_k R_{ij}$ and $S_k = \nabla_k S$ denote, respectively, the components of the covariant derivative of the Ricci tensor and of the differential of the scalar curvature, and $A_{ij,k}$ denote the components of the covariant derivative of the *Schouten tensor*

$$A_g = \text{Ric}_g - \frac{S_g}{2(n-1)} g;$$

hence, the Cotton tensor represents the obstruction for A_g to be a Codazzi tensor (i.e., $(\nabla_X A)Y = (\nabla_Y A)X$ for every pair of vector fields X, Y). By direct computation, we can see that C_g satisfies the symmetries

$$C_{ijk} = -C_{ikj}, \quad C_{ijk} + C_{jki} + C_{kij} = 0, \tag{2.3}$$

moreover it is totally trace-free,

$$g^{ij}C_{ijk} = g^{ik}C_{ijk} = g^{jk}C_{ijk} = 0, \tag{2.4}$$

by its skew-symmetry and Schur lemma. We also recall that, for $n \geq 4$, the Cotton tensor can be defined as one of the possible divergences of the Weyl tensor:

$$C_{ijk} = \left(\frac{n-2}{n-3}\right)W_{tikj,t} = -\left(\frac{n-2}{n-3}\right)W_{tijk,t} = -\frac{n-2}{n-3}(\delta W)_{ijk}. \tag{2.5}$$

A computation shows that the two definitions coincide (see e.g. [9]).

The *Bach tensor* B_g of (M, g) is defined, in components, as

$$B_{ij} := \frac{1}{n-2}(g^{ks}C_{jik,s} + g^{ks}g^{lt}R_{kl}W_{isjt}). \tag{2.6}$$

It is immediate to show that B_g is a traceless tensor; moreover, since $(n-3)W_{jkil,lk} = (n-2)C_{ijk,k}$, exploiting the second covariant derivative commutation formulas, it can be shown that B_g is symmetric (see, for instance, [9, Lemma 2.8]). Also, recall that, if $n = 4$, the Bach tensor acquires two additional features: it is divergence-free and conformally covariant.

2.2. Aubin’s local deformations

Let us introduce the following deformation of the metric g :

$$\tilde{g} = g + d\phi \otimes d\phi, \tag{2.7}$$

where $\phi \in C^\infty(M)$. We denote the Weyl tensor of (M, \tilde{g}) as $W_{\tilde{g}}$. If U is a local chart of M and x_1, \dots, x_n are local coordinates on U , the local components of the $(0, 4)$ -version of $W_{\tilde{g}}$, \tilde{W}_{ijkl} , are given by the following expression (see also [9], Chapter 2):

$$\begin{aligned} \tilde{W}_{ijkl} &= W_{ijkl} + \frac{1}{w}(\phi_{ik}\phi_{jt} - \phi_{it}\phi_{jk}) + \\ &+ \frac{1}{n-2}(R_{ik}\phi_j\phi_t - R_{it}\phi_j\phi_k + R_{jt}\phi_i\phi_k - R_{jk}\phi_i\phi_t) \\ &+ \frac{S}{(n-1)(n-2)}(g_{ik}\phi_j\phi_t - g_{it}\phi_j\phi_k + g_{jt}\phi_i\phi_k - g_{jk}\phi_i\phi_t) + \\ &+ \frac{\phi^p\phi^q}{w(n-2)}[R_{ipkq}(g_{jt} + \phi_j\phi_t) - R_{iptq}(g_{jk} + \phi_j\phi_k) + R_{jptq}(g_{ik} + \phi_i\phi_k) - R_{jpkq}(g_{it} - \phi_i\phi_t)] + \\ &- \frac{2R_{pq}\phi^p\phi^q}{w(n-1)(n-2)}[g_{ik}g_{jt} - g_{it}g_{jk} + g_{ik}\phi_j\phi_t - g_{it}\phi_j\phi_k + g_{jt}\phi_i\phi_k - g_{jk}\phi_i\phi_t] + \\ &- \frac{1}{w(n-2)}\{[(\Delta\phi)\phi_{ik} - \phi_{ip}\phi_k^p](g_{jt} + \phi_j\phi_t) - [(\Delta\phi)\phi_{it} - \phi_{ip}\phi_t^p](g_{jk} + \phi_j\phi_k)\} + \\ &- \frac{1}{w(n-2)}\{[(\Delta\phi)\phi_{jt} - \phi_{jp}\phi_t^p](g_{ik} + \phi_i\phi_k) - [(\Delta\phi)\phi_{jk} - \phi_{jp}\phi_k^p](g_{it} + \phi_i\phi_t)\} + \\ &+ \frac{1}{w(n-1)(n-2)}\left[(\Delta\phi)^2 - |\text{Hess}(\phi)|^2\right][g_{ik}g_{jt} - g_{it}g_{jk} + g_{ik}\phi_j\phi_t - g_{it}\phi_j\phi_k + g_{jt}\phi_i\phi_k - g_{jk}\phi_i\phi_t] + \end{aligned} \tag{2.8}$$

$$\begin{aligned}
& + \frac{\phi^p \phi^q}{w^2(n-2)} [(\phi_{ik} \phi_{pq} - \phi_{ip} \phi_{kq})(g_{jt} + \phi_j \phi_t) - (\phi_{it} \phi_{pq} - \phi_{ip} \phi_{tq})(g_{jk} + \phi_j \phi_k)] + \\
& + \frac{\phi^p \phi^q}{w^2(n-2)} [(\phi_{jt} \phi_{pq} - \phi_{jp} \phi_{tq})(g_{ik} + \phi_i \phi_k) - (\phi_{jk} \phi_{pq} - \phi_{jp} \phi_{kq})(g_{it} + \phi_i \phi_t)] + \\
& - \frac{2}{w^2(n-1)(n-2)} [(\Delta \phi) \phi^p \phi^q \phi_{pq} - \phi^p \phi_{pq} \phi^{qr} \phi_r] (g_{ik} g_{jt} - g_{it} g_{jk}) + \\
& - \frac{2}{w^2(n-1)(n-2)} [(\Delta \phi) \phi^p \phi^q \phi_{pq} - \phi^p \phi_{pq} \phi^{qr} \phi_r] (g_{ik} \phi_j \phi_t - g_{it} \phi_j \phi_k + g_{jt} \phi_i \phi_k - g_{jk} \phi_i \phi_t),
\end{aligned}$$

where $w = 1 + |\nabla \phi|^2$ and

$$\begin{aligned}
\phi_i &= \partial_i \phi = \frac{\partial \phi}{\partial x_i}, \\
\phi^i &= g^{ip} \phi_p, \\
\phi_{ij} &= \partial_i \partial_j \phi - \Gamma_{ij}^p \phi_p, \\
\phi_j^i &= g^{ip} \phi_{pj} = \partial_j \phi^i + \phi^p \Gamma_{pj}^i, \\
\phi^{ij} &= g^{ip} \phi_p^j.
\end{aligned}$$

3. A detailed proof of Aubin's result

In this section we give a complete proof of Aubin's result (see [2] and [3]), i.e. we prove the following

Theorem 3.1 (Aubin ([2], [3])). *On every smooth manifold of dimension at least 4 there exists a Riemannian metric g whose Weyl tensor nowhere identically vanishes.*

Proof. We divide the proof in two steps.

Step 1: the local deformation

Let g any Riemannian metric on M and consider the metric \tilde{g} given by (2.7). Let $p_0 \in M$ be such that W_g vanishes at p_0 and B_r an open ball of radius r and centered in p_0 . Moreover, let us consider normal coordinates x_1, \dots, x_n on B_r such that $p_0 = (0, \dots, 0)$. Thus, at p_0 we have

$$g_{ij} = g^{ij} = \delta_{ij}, \quad \phi_i = \phi^i, \quad \phi_{ij} = \partial_i \partial_j \phi = \phi_j^i = \phi^{ij}$$

From now on, we denote the local components of W_g ($W_{\tilde{g}}$, resp.) on B_r as W_{ijkl} (\widetilde{W}_{ijkl} , resp.).

We construct the function ϕ as follows: let $f \in C^\infty([0, +\infty))$ such that

$$\begin{cases} f(y) = 0, & \text{if } y \geq 1 \\ f'(y) > 0, f''(y) < 0, & \text{if } 0 \leq y < 1 \end{cases}.$$

For instance, we may choose

$$f(x) := \begin{cases} -e^{\left(\frac{b}{1-x}\right)} & \text{if } 0 \leq x < 1 \\ 0 & \text{if } x \geq 1 \end{cases}, \quad (3.1)$$

where $b > 0$ is sufficiently large. Now, let $\lambda, \alpha_1, \dots, \alpha_n$ be $n+1$ real numbers in the interval $[1, 2]$ and let

$$\phi = \frac{\lambda r^2}{2} f\left(\frac{\alpha_1 x_1^2 + \dots + \alpha_n x_n^2}{r^2}\right). \tag{3.2}$$

By definition, $\phi \in C^\infty(B_r)$ and

$$B_{\frac{r}{2}} \subset \text{supp } \phi \subset B_r.$$

Indeed, if x_1, \dots, x_n are such that $\alpha_1 x_1^2 + \dots + \alpha_n x_n^2 < r^2$, then, since $\alpha_i \geq 1$ for every i ,

$$\sum_{i=1}^n x_i^2 \leq \sum_{i=1}^n \alpha_i x_i^2 < r^2,$$

i.e. $p = (x_1, \dots, x_n) \in B_r$; on the other hand, if $p \in B_{\frac{r}{2}}$, then, since $\alpha_i \leq 2$ for every i ,

$$\sum_{i=1}^n \alpha_i x_i^2 \leq 2 \sum_{i=1}^n x_i^2 < \frac{r^2}{2},$$

thus $\alpha_1 x_1^2 + \dots + \alpha_n x_n^2 < r^2$ and $p \in \text{supp } \phi$.

The partial derivatives of ϕ satisfy

$$\phi_i = \lambda f' \cdot \alpha_i x_i = O(r), \tag{3.3}$$

as $r \rightarrow 0$. From now on, every $O(\cdot)$ will be regarded as $r \rightarrow 0$. Since we chose a system of normal coordinates, for small radii the second partial derivatives of ϕ satisfy

$$\phi_{ij} = \lambda \left(\alpha_i f' \delta_{ij} + 2 \frac{\alpha_i \alpha_j}{r^2} x_i x_j f'' \right) = O(1). \tag{3.4}$$

Now, let us consider equation (2.8): we can rewrite the expression as

$$\begin{aligned} \widetilde{W}_{ijkl} &= W_{ijkl} + \phi_{ik} \phi_{jl} - \phi_{il} \phi_{jk} + \\ &- \frac{1}{n-2} \Delta \phi (\phi_{ik} \delta_{jl} - \phi_{il} \delta_{jk} + \phi_{jl} \delta_{ik} - \phi_{jk} \delta_{il}) + \\ &+ \frac{1}{n-2} (\phi_{ip} \phi_{pk} \delta_{jl} - \phi_{ip} \phi_{pl} \delta_{jk} + \phi_{jp} \phi_{pl} \delta_{ik} - \phi_{jp} \phi_{pk} \delta_{il}) \\ &+ \frac{1}{(n-1)(n-2)} [(\Delta \phi)^2 - |\text{Hess}(\phi)|^2] (\delta_{ik} \delta_{jl} - \delta_{il} \delta_{jk}) + O(r^2). \end{aligned} \tag{3.5}$$

Thus, we informally distinguish a ‘‘principal part’’ and a ‘‘remainder’’ in the expression of the components \widetilde{W}_{ijkl} . We define

$$S := \overset{\circ}{\text{supp}} \phi = \left\{ p = (x_1, \dots, x_n) \in B_r : \sum_{i=1}^n \alpha_i x_i^2 < r^2 \right\}; \tag{3.6}$$

the key of the proof is to show that the principal parts of the components \widetilde{W}_{ijkl} cannot be simultaneously zero on S .

Now, let $i \neq j \neq k \neq l$; inserting (3.3) and (3.4) into (3.5), we obtain

$$\begin{aligned} \widetilde{W}_{ijij} &= W_{ijij} + \lambda^2 [a_{ij} (f')^2 + b_{ij} f' f''] + O(r^2); \\ \widetilde{W}_{ijik} &= W_{ijik} + \lambda^2 a_{ijk} f' f'' x_j x_k + O(r^2); \\ \widetilde{W}_{ijkl} &= W_{ijkl} + O(r^2), \end{aligned} \tag{3.7}$$

where

$$\begin{aligned}
 a_{ij} &= \frac{1}{n-2} \left[(n-4)\alpha_i\alpha_j - (\alpha_i + \alpha_j) \sum_{k \neq i,j} \alpha_k + \frac{2}{n-1} \sum_{k < l} \alpha_k\alpha_l \right]; \\
 b_{ij} &= \frac{2}{(n-2)r^2} \left[(n-4)(\alpha_i x_i^2 + \alpha_j x_j^2)\alpha_i\alpha_j - (\alpha_i^2 x_i^2 + \alpha_j^2 x_j^2) \sum_{k \neq i,j} \alpha_k + \right. \\
 &\quad \left. - (\alpha_i + \alpha_j) \sum_{k \neq i,j} \alpha_k^2 x_k^2 + \frac{2}{n-1} \sum_{k=1}^n \alpha_k \left(\sum_{l \neq k} \alpha_l^2 x_l^2 \right) \right]; \\
 a_{ijk} &= \frac{2\alpha_j\alpha_k}{(n-2)r^2} \left[(n-3)\alpha_i - \sum_{l \neq i,j,k} \alpha_l \right].
 \end{aligned} \tag{3.8}$$

Note that $a_{ij} \in \mathbb{R}$, $b_{ij} = b_{ij}(r, p)$ and $a_{ijk} = a_{ijk}(r)$, but a_{ij} , b_{ij} and $a_{ijk}x_jx_k$ are $O(1)$, for every i, j, k . It is important to note that there exist suitable choices for $\alpha_1, \dots, \alpha_n$ such that, for every $i \neq j \neq k$, a_{ij} and a_{ijk} nowhere vanish on S (observe that a_{ij} and a_{ijk} are scalars, while b_{ij} is a polynomial of degree 2 in the variables x_1, \dots, x_n for every $i \neq j \neq k$). For instance, we may define

$$\begin{cases}
 (\alpha_1, \dots, \alpha_n) = (2, 2, 1, 1, \dots, 1), & \text{if } n > 4; \\
 (\alpha_1, \alpha_2, \alpha_3, \alpha_4) = (1, \frac{5}{4}, \frac{3}{2}, 2), & \text{if } n = 4.
 \end{cases}$$

A direct inspection of (3.8) shows that, with this choice, $a_{ij}, a_{ijk} \neq 0$.

Note that, for $n = 4$, $\alpha_i \neq \alpha_j$ if $i \neq j$. For $n > 4$, observe that a_{ij} and a_{ijk} can be seen as homogeneous polynomials in the n variables $\alpha_1, \dots, \alpha_n$, therefore, in particular, they are smooth functions of these variables: hence, since we found a n -tuple $(\alpha_1, \dots, \alpha_n)$ such that $a_{ij}, a_{ijk} \neq 0$, we know that there exist sufficiently small $\epsilon_1 \neq \dots \neq \epsilon_n$, with $\epsilon_i > 0$ for every i , such that $a_{ij}, a_{ijk} \neq 0$ for

$$(\alpha'_1, \dots, \alpha'_n) := (2 - \epsilon_1, 2 - \epsilon_2, 1 + \epsilon_3, 1 + \epsilon_4, \dots, 1 + \epsilon_n)$$

and $\alpha'_i \neq \alpha'_j$ for $i \neq j$. Therefore, without loss of generality, we may assume that $\alpha_i \neq \alpha_j$ whenever $i \neq j$.

Let us distinguish three cases.

Case 1 ($p = p_0$). By hypothesis, W_g vanishes at p and, since $p_0 = (0, \dots, 0)$ in our local coordinates, by (3.7) we obtain

$$\begin{aligned}
 \widetilde{W}_{ijij} &= \lambda^2 a_{ij} (f')^2 + O(r^2); \\
 \widetilde{W}_{ijik} &= O(r^2);
 \end{aligned}$$

since $a_{ij}, f', \lambda \neq 0$, we have that

$$|W_{\widetilde{g}}|_{\widetilde{g}}^2 \geq 2 \sum_{i < j} \widetilde{W}_{ijij}^2 = (\lambda f')^4 \sum_{i < j} (a_{ij})^2 > 0.$$

Case 2 ($p \in B_{r/2} \setminus \{p_0\}$). We want to show that the components of the Weyl tensor $W_{\widetilde{g}}$ cannot vanish simultaneously at p , if r is sufficiently small, i.e. $r < \bar{r} = \bar{r}(p_0, \|g\|_{C^k})$, for $k \geq 3$. Since p lies in the open ball of radius $r/2$ and centered in p_0 , by Taylor's Theorem we have that

$$|W_g| \leq C \cdot r + O(r^2).$$

Let us suppose $\widetilde{W}_{ijij} = \widetilde{W}_{ijik} = 0$ for every $i \neq j \neq k$. By (3.7), we can write

$$\begin{aligned} a_{ij}(f')^2 + b_{ij}f'f'' + O(r) &= 0; \\ a_{ijk}x_jx_k + O(r) &= 0. \end{aligned}$$

For a sufficiently small radius r , the previous equations imply

$$\begin{cases} a_{ij}(f')^2 + b_{ij}f'f'' = 0; & \text{(a)} \\ a_{ijk}x_jx_k = 0. & \text{(b)} \end{cases} \tag{3.9}$$

Note that we obtained an overdetermined system in the variables x_1, \dots, x_n : indeed, since $i \neq j \neq k$ and the coefficients a_{ijk} are symmetric with respect to the indices j and k , we have $n(n-1)/2$ independent equations of the form (3.9b) (observe that changing the index i in (3.9b) does not provide additional equations). Moreover, the polynomials $a_{ij}(f')^2 + b_{ij}f'f''$ are symmetric with respect to i and j and a straightforward computation shows that

$$\sum_{i \neq j} a_{ij} = \sum_{i \neq j} b_{ij} = 0, \text{ for every } j$$

(this can also be seen as a consequence of the fact that the Weyl tensor is traceless). Thus, we have

$$\frac{n(n-1)}{2} - n = \frac{n(n-3)}{2}$$

equations of the form (3.9a). Therefore, our system is made by

$$\frac{n(n-3)}{2} + \frac{n(n-1)}{2} = n(n-2)$$

independent equations, and $n(n-2) > n+1 > n$ for every $n \geq 4$.

Now, let us show that the system admits only the solution $x_1 = \dots = x_n = 0$, which will lead to a contradiction, since $p \neq p_0$. Since $a_{ijk} \neq 0$, we obtain that $x_jx_k = 0$ for every $j \neq k$. This implies that at least $n-1$ coordinates of p must be zero; since $p \neq p_0$, there is exactly one coordinate x_i which is non-zero.

Let us consider $j \neq t \neq s \neq i$ (note that this is possible since $n \geq 4$): by $\widetilde{W}_{ijij} = \widetilde{W}_{itit} = \widetilde{W}_{isis} = 0$ we obtain

$$\begin{aligned} 0 &= \frac{1}{n-2} \left[(n-4)\alpha_i\alpha_j - (\alpha_i + \alpha_j) \sum_{k \neq i,j} \alpha_k + \frac{2}{n-1} \sum_{k < l} \alpha_k\alpha_l \right] (f')^2 + \\ &+ \frac{2}{(n-2)r^2} \left[(n-4)\alpha_i^2\alpha_jx_i^2 - \alpha_i^2x_i^2 \sum_{k \neq i,j} \alpha_k + \frac{2}{n-1} \sum_{k=1}^n \alpha_k \left(\sum_{l \neq k} \alpha_l^2x_l^2 \right) \right] f'f''; \\ 0 &= \frac{1}{n-2} \left[(n-4)\alpha_i\alpha_t - (\alpha_i + \alpha_t) \sum_{k \neq i,t} \alpha_k + \frac{2}{n-1} \sum_{k < l} \alpha_k\alpha_l \right] (f')^2 + \\ &+ \frac{2}{(n-2)r^2} \left[(n-4)\alpha_i^2\alpha_tx_i^2 - \alpha_i^2x_i^2 \sum_{k \neq i,t} \alpha_k + \frac{2}{n-1} \sum_{k=1}^n \alpha_k \left(\sum_{l \neq k} \alpha_l^2x_l^2 \right) \right] f'f''; \end{aligned}$$

$$0 = \frac{1}{n-2} \left[(n-4)\alpha_i\alpha_s - (\alpha_i + \alpha_s) \sum_{k \neq i,s} \alpha_k + \frac{2}{n-1} \sum_{k < l} \alpha_k\alpha_l \right] (f')^2 +$$

$$+ \frac{2}{(n-2)r^2} \left[(n-4)\alpha_i^2\alpha_s x_i^2 - \alpha_i^2 x_i^2 \sum_{k \neq i,s} \alpha_k + \frac{2}{n-1} \sum_{k=1}^n \alpha_k \left(\sum_{l \neq k} \alpha_l^2 x_l^2 \right) \right] f' f'';$$

subtracting the second and the third equations from the first, since $\alpha_j \neq \alpha_t \neq \alpha_s$ and $f', f'' \neq 0$ on S , we get

$$0 = \left[(n-3)\alpha_i - \sum_{k \neq i,j,t} \alpha_k \right] f' + \frac{2}{r^2} (n-3)\alpha_i^2 x_i^2 f'',$$

$$0 = \left[(n-3)\alpha_i - \sum_{k \neq i,j,s} \alpha_k \right] f' + \frac{2}{r^2} (n-3)\alpha_i^2 x_i^2 f''.$$

It is immediate to observe that these two equations hold simultaneously if and only if

$$\sum_{k \neq i,j,t} \alpha_k = \sum_{k \neq i,j,s} \alpha_k \iff \alpha_s = \alpha_t,$$

which is impossible. Thus, not all the components of $W_{\tilde{g}}$ vanish at p .

Case 3 ($p \in S \setminus B_{\frac{r}{2}}$). Let us suppose again that $\tilde{W}_{ijij} = \tilde{W}_{ijik} = 0$ for every $i \neq j \neq k$. As in Case 2, for a sufficiently small r , the first two equations in (3.7) imply

$$\begin{cases} W_{ijij} + \lambda^2(a_{ij}(f')^2 + b_{ij}f'f'') = 0; & \text{(a)} \\ W_{ijik} + \lambda^2 a_{ijk} x_j x_k f' f'' = 0. & \text{(b)} \end{cases} \tag{3.10}$$

If $W_{ijij} = W_{ijik} = 0$ at p , we get a contradiction by the conclusions of Case 2. Thus, let us suppose that $|W_g|_g^2 > 0$ at p : for instance, let $W_{ijik} \neq 0$ for some i, j, k . The equation $\tilde{W}_{ijik} = 0$ allows us to compute λ :

$$\lambda^2 = -\frac{W_{ijik}}{a_{ijk} x_j x_k}.$$

This equation holds for every point whose coordinates are solutions of the system above; however, $\lambda \in [1, 2]$ appears as a free parameter in (3.2), therefore it is sufficient to choose $\lambda_1 \in [1, 2]$ such that $\lambda_1^2 \neq \lambda^2$ and repeat the argument of the proof to obtain a contradiction. Thus, $W_{ijik} = 0$. If, for instance, λ_1 is such that the equation

$$W_{i'j'i'k'} + \lambda_1^2 a_{i'j'k'} x_{j'} x_{k'} f' f'' = 0$$

holds for some $i' \neq j' \neq k'$, it is sufficient to choose $\lambda_2 \in [1, 2]$ such that $\lambda_2^2 \neq \lambda_1^2$ to get the same contradiction. Note that we can repeat the procedure for every equation of the system above.

Therefore, possibly choosing λ in (3.2) out of a finite set $\{\lambda_1, \dots, \lambda_k\}$, we can conclude that the system holds if and only if $W_{ijij} = W_{ijik} = 0$ at p : however, by the argument of Case 2, this leads to a contradiction.

Step 2: iteration of the process

In the first step, we proved that the Weyl tensor $W_{\tilde{g}}$ does not vanish on S . Now, let us call $g_0 = g, \phi^0 = \phi, S_0 = S, r_0 = r, \lambda_0 = \lambda$ and $g_1 = \tilde{g}$: given $p_0 \in M$ such that $|W_{g_0}|_{g_0}(p_0) = 0$, there exist a normal open

neighborhood U_0 and $\phi^0 \in C^\infty(M)$, defined as in (3.2) with r_0 and λ_0 , such that $S_0 = \text{supp}^\circ \phi^0 \subset U_0$ and W_{g_1} has non-vanishing square norm on S_0 , where $g_1 = g_0 + d\phi^0 \otimes d\phi^0$. Since M is compact by hypothesis, the set

$$Z := \left\{ p \in M : |W_{g_0}|_{g_0}(p) = 0 \right\}$$

is compact: indeed, Z is closed, since it is the zero locus of a continuous function on M . Therefore, there exists a finite open cover of Z of the form

$$\bigcup_{i=1}^N V_i := \bigcup_{i=1}^N (S_i \cap Z),$$

where S_i contains a point p_i where W_{g_0} vanishes and it is the interior of the support of a smooth function ϕ^i defined as in (3.2), with r_i small enough and λ_i such that Aubin’s local deformation can be performed as before. Moreover, observe that, if $p_j \in Z$, then, by construction, $p_j \notin V_k$ if $j \neq k$; we also note that Aubin’s deformation on S_i do not produce new zeroes of $|W_{g_0}|$ outside of Z , which means that, if $p' \notin Z$ before the deformation, then $p' \notin Z$ after deforming the metric as well.

The first step of the proof was to show that, around p_0 , the metric g_0 can be deformed in order to have $W_{g_1} \not\equiv 0$ on S_0 . Now, we perform the argument again: let p_1 such that $W_{g_0} \equiv 0$ at p_1 and let $V_1 \ni p_1$, with deformation function ϕ^1 , which has λ_1 and r_1 in its definition (recall that r_1 is chosen small enough so that Aubin’s method can be exploited).

If $V_0 \cap V_1 = \emptyset$, we can apply the deformation in S_1 in order to conclude that $W_{g_2} \not\equiv 0$ on S_1 , where $g_2 = g_0 + d\phi^1 \otimes d\phi^1$, and, hence, on V_1 . Therefore, let us suppose that $V_0 \cap V_1 \neq \emptyset$: if we consider a point $p \in V_1 \setminus V_0$, here $g_1 = g_0$, hence we Aubin’s argument on S_1 works as in the previous case. Let us suppose that there exists a point $q \in V_0 \cap V_1$ such that W_{g_2} vanishes identically at q : in this case, we have

$$g_2 = g_1 + d\phi^1 \otimes d\phi^1.$$

The expression for the components of W_{g_2} is given by (2.8), where $g_{ij} = (g_1)_{ij}$ and both the covariant derivatives of $\phi = \phi_1$ and the curvature quantities are referred to the metric g_1 .

Let us choose the indices i, j, k, t such that $W_{ijkt}^1 \neq 0$ at q (whose existence is guaranteed by the first deformation we performed). If we evaluate (2.8) at q , the left-hand side vanishes: hence, since $\alpha_1, \dots, \alpha_n$ and r_1 are fixed, if we multiply both sides by w^2 we obtain an equation of the form

$$0 = W_{ijkt}^1 + P_{ijkt}(\lambda_1), \tag{3.11}$$

where $W_{ijkt}^1 = W_{ijkt}^1(q)$ and $P_{ijkt}(\lambda) = \sum_{i=1}^M C_i(\lambda_1)^i$ is a non-trivial polynomial of degree M in λ_1 . Thus, (3.11) is a non-homogeneous polynomial equation in λ_1 with real coefficients, which means that the set of its roots is

$$L_1 = \{(\lambda_1)_1, \dots, (\lambda_1)_K\}, \quad K \leq M.$$

Note that, if $\lambda_1 = (\lambda_1)_{K'}$, for some $1 \leq K' \leq K$, since λ_1 is a real number, then every other point q' such that $|W_{g_2}|_{g_2}(q') = 0$ must satisfy (3.11) with $\lambda_1 = (\lambda_1)_{K'}$.

Since the set of values of λ_1 such that W_{g_2} vanishes at q is finite, it is sufficient to choose $\lambda_1 = \bar{\lambda}_1$ in $[1, 2] \setminus L_1$ to get a contradiction: therefore, up to choose λ_1 outside of a finite set of values, we have that W_{g_2} does not vanish in $V_0 \cap V_1$, which implies that

$$|W_{g_2}|_{g_2} \neq 0 \text{ on } V_0 \cup V_1.$$

Since $\{V_0, \dots, V_N\}$ is a finite set, we have a finite number of non-empty intersections: hence, we can repeat the process finitely many times to conclude that there exists a metric \tilde{g} such that $W_{\tilde{g}} \not\equiv 0$ on M and this ends the proof. \square

Remark 3.2. If $|W_{\tilde{g}}|_{\tilde{g}} > 0$ for every point of M , then, operating the conformal change

$$\bar{g} := |W_{\tilde{g}}|_{\tilde{g}},$$

we obtain that the metric \bar{g} is such that its Weyl tensor $W_{\bar{g}}$ satisfies

$$|W_{\bar{g}}|_{\bar{g}}^2 \equiv 1 \text{ on } M.$$

4. Proof of Theorems 1.1 and 1.3

In this section we extend Aubin’s result in dimension four to the self-dual and anti-self dual components of the Weyl tensor in order to prove Theorem 1.1.

Proof of Theorem 1.1. First, note that, by Remark 3.2, it is sufficient to show that there exists a Riemannian metric whose self-dual Weyl tensor nowhere vanishes on M .

Similarly as we did in the proof of Theorem 3.1, let g any Riemannian metric on M and let again $p_0 \in M$ be such that $W^+(p_0) = 0$. We choose an open ball B_r centered at p_0 with normal coordinates x_1, x_2, x_3, x_4 such that $p_0 = (0, 0, 0, 0)$ and we define a function ϕ as in (3.2) in such a way that $B_{\frac{r}{2}} \subset \text{supp}\phi \subset B_r$. Let $S = \text{supp}\phi$ and \tilde{g} be the metric defined in (2.7).

By definition

$$W_{ijkl} = W_{ijkl}^+ + W_{ijkl}^-;$$

moreover, it is not hard to show that, for every $i, j, k, l = 1, \dots, 4$ such that $i \neq j$ and $k \neq l$, there exist indices k' and l' such that

$$W_{ijkl}^\pm = \pm W_{ijk'l'}^\pm.$$

The pair (k', l') is uniquely determined by the action of the Hodge star operator \star : indeed, it is well-known that the terms in which W decomposes are given by

$$W_{ijkl}^\pm = \frac{1}{2}[W_{ijkl} \pm (\star W)_{ijkl}]$$

(for a detailed discussion, see, for instance, [6,19]). This implies immediately that

$$W_{ijkl}^\pm = \frac{1}{2}(W_{ijkl} \pm W_{ijk'l'}).$$

Let us now focus on W_g^+ . By (3.7) and (3.8), for $i \neq j$ one can easily obtain

$$\begin{aligned} \widetilde{W}_{ijij}^+ &= \frac{1}{2}(\widetilde{W}_{ijij} + \widetilde{W}_{ij'j'}) = \\ &= \frac{1}{2}[W_{ijij} + W_{ij'j'} + \lambda^2(a_{ij}(f')^2 + b_{ij}f'f'') + O(r^2)] = \\ &= W_{ijij}^+ + \frac{\lambda^2}{2}(a_{ij}(f')^2 + b_{ij}f'f'') + O(r^2) \end{aligned} \tag{4.1}$$

(note that $(i', j') = (k, l)$ are such that $i \neq j \neq k \neq l$). Analogously, for $i \neq j \neq k$, we obtain

$$\begin{aligned} \widetilde{W}_{ijk}^+ &= \frac{1}{2}(\widetilde{W}_{ijik} + \widetilde{W}_{ij'i'k'}) = \\ &= \frac{1}{2}[W_{ijik} \pm W_{jijl} + \lambda^2(a_{ijk}x_jx_k \pm a_{jil}x_ix_l)f'f'' + O(r^2)] = \\ &= W_{ijk}^+ + \frac{\lambda^2}{2}(a_{ijk}x_jx_k \pm a_{jil}x_ix_l)f'f'' + O(r^2). \end{aligned} \tag{4.2}$$

Here, \pm appears in the equations since we may have $(i', k') = (l, j)$ or $(i', k') = (j, l)$.

Now, we are ready to prove the statement. Let us choose

$$(\alpha_1, \alpha_2, \alpha_3, \alpha_4) = \left(1, \frac{5}{4}, \frac{3}{2}, 2\right);$$

thus, an easy computation shows that

$$\begin{cases} a_{12} = \frac{5}{48} = a_{34} \\ a_{13} = -\frac{1}{48} = a_{24} \\ a_{14} = -\frac{1}{12} = a_{23} \end{cases} \quad \text{and} \quad \begin{cases} a_{123} = -\frac{15}{8r^2}, \quad a_{214} = -\frac{1}{2r^2} \\ a_{124} = -\frac{5}{4r^2}, \quad a_{213} = -\frac{9}{8r^2} \\ a_{134} = -\frac{3}{4r^2}, \quad a_{312} = -\frac{5}{8r^2} \end{cases}. \tag{4.3}$$

We recall that

$$\sum_{i \neq j} a_{ij} = 0 \text{ for every } j \text{ and } \sum_{i \neq j, k} a_{ijk} = 0 \text{ for every } j \neq k.$$

As before, we distinguish three cases.

Case 1 ($p = p_0$). As we did for Aubin's result, since $a_{ij} \neq 0$ for every $i \neq j$, by (4.1) and (3.8) we have

$$|W_g^+|_{\bar{g}}^2 \geq 2 \sum_{i < j} (\widetilde{W}_{ijij}^+)^2 = (\lambda f')^4 \sum_{i < j} (a_{ij})^2 > 0.$$

Case 2 ($p \in B_{r/2} \setminus \{p_0\}$). We can apply again Taylor's Theorem to conclude that

$$|W_g^+| \leq C \cdot r + o(r^2), \text{ as } r \rightarrow 0.$$

Let us suppose $\widetilde{W}_{ijij}^+ = \widetilde{W}_{ijik}^+ = 0$ for every $i \neq j \neq k$. By (4.2), letting $r \rightarrow 0$ we have

$$a_{ijk}x_jx_k \pm a_{jil}x_ix_l = 0.$$

More explicitly, we obtain the system

$$\begin{cases} a_{123}x_2x_3 + a_{214}x_1x_4 = 0 \\ a_{124}x_2x_4 - a_{213}x_1x_3 = 0 \\ a_{134}x_3x_4 + a_{312}x_1x_2 = 0 \end{cases} ;$$

by (4.3), the system becomes

$$\begin{cases} 4x_1x_4 = -15x_2x_3 \\ 9x_1x_3 = 10x_2x_4 \\ 5x_1x_2 = -6x_3x_4 \end{cases} .$$

If $x_i \neq 0$ for every $i = 1, 2, 3, 4$, a straightforward computation shows that the system does not admit any real solution: therefore, the components \widetilde{W}_{ijik}^+ cannot simultaneously vanish. Thus, without loss of generality, we may suppose $x_4 = 0$. This implies immediately that two out of the three remaining variables must be zero. Let us suppose that $x_2 = x_3 = x_4 = 0$ and $x_1 \neq 0$ (the other cases are analogous). By $\widetilde{W}_{ijij}^+ = 0$, for a sufficiently small r , (4.1) implies that

$$a_{ij}(f')^2 + b_{ij}f'f'' = 0.$$

However, since using (3.8) and (4.3) one has

$$a_{13}(f')^2 + b_{13}f'f'' = 0 \implies x_1^2 = \frac{r^2}{4} \cdot \frac{f'}{f''},$$

we get a contradiction, since, by definition of f , the ratio f'/f'' is negative on $B_{\frac{r}{2}}$.

Case 3 ($p \in S \setminus B_{\frac{r}{2}}$). As before, let us suppose that $\widetilde{W}_{ijij}^+ = \widetilde{W}_{ijik}^+ = 0$ for every $i \neq j \neq k$. As $r \rightarrow 0$, by (4.1) and (4.2) we obtain the system

$$\begin{cases} W_{ijij}^+ + \frac{\lambda^2}{2}(a_{ij}(f')^2 + b_{ij}f'f'') = 0 \\ W_{ijik}^+ + \frac{\lambda^2}{2}(a_{ijk}x_jx_k \pm a_{jil}x_ix_l)f'f'' = 0 \end{cases} .$$

As in the proof of Theorem 3.1, if we suppose that W^+ does not identically vanish at p , possibly choosing λ outside of a finite set of values, we obtain a contradiction: therefore, $W^+ = 0$ at p , which is impossible for the conclusions of Case 2.

Thus,

$$\left| W_{ij}^+ \right|_{\frac{r}{2}}^2 > 0$$

on S : since M is compact, we can repeat the argument presented in Step 2 of the proof of Theorem 3.1 to prove the claim.

Note that the proof is analogous if we consider W_{ij}^- . \square

Now, we prove the general condition defined in Theorem 1.3

Proof of Theorem 1.3. First, note that, if $t = 1$, there is nothing to show: indeed $W = W^+ + W^-$, therefore Aubin’s Theorem guarantees that the claim is true. If $t = 0$, we obtain Theorem 1.1.

Now, let us suppose $t = -1$. A straightforward computation shows that

$$\begin{aligned} W_{ijij}^+ - W_{ijij}^- &= W_{ijij'} \\ W_{ijik}^+ - W_{ijik}^- &= \pm W_{ijik'} \\ W_{ijkl}^+ - W_{ijkl}^- &= \pm W_{ijkl}; \end{aligned}$$

hence, we can apply again Theorem 3.1 to show the claim.

Therefore, let $t \neq -1, 0, 1$. We consider again the deformed metric \tilde{g}_t defined by (2.7), with ϕ as in (3.2). It is easy to obtain the system

$$\begin{cases} \widetilde{W}_{ijj}^+ + t\widetilde{W}_{ijj}^- = W_{ijj}^+ + tW_{ijj}^- + \frac{\lambda^2}{2}(1+t)[a_{ij}(f')^2 + b_{ij}f'f''] + O(r^2) & \text{(a)} \\ \widetilde{W}_{ijk}^+ + t\widetilde{W}_{ijk}^- = W_{ijk}^+ + tW_{ijk}^- + \frac{\lambda^2}{2}[(1+t)a_{ijk}x_jx_k \pm (1-t)a_{jil}x_ix_l]f'f'' + O(r^2) & \text{(b)} \\ \widetilde{W}_{ijkl}^+ + t\widetilde{W}_{ijkl}^- = W_{ijkl}^+ + tW_{ijkl}^- \pm \frac{\lambda^2}{2}(1-t)[a_{ij}(f')^2 + b_{ij}f'f''] + O(r^2) & \text{(c)} \end{cases} \quad (4.4)$$

where $i \neq j \neq k \neq l$. As we did for the proof of Aubin’s Theorem, let $p_0 \in M$ be a point such that $W_g^+ + tW_g^-|_{p_0} = 0$ and let B_r be an open ball of radius r and centered in p_0 ; moreover, let us define normal coordinates x_1, \dots, x_4 such that $p_0 = (0, 0, 0, 0)$ and let $p \in B_r$. We define ϕ and $S = \text{supp}\phi$ as usual; finally, we choose the coefficients $(\alpha_1, \dots, \alpha_4)$ such that $a_{ij}, a_{ijk} \neq 0$ for every i, j, k : note that the coefficients can be chosen in such a way that the numbers a_{ijk} have the same sign. By (4.3), it is easy to see that $\underline{\alpha} = (1, 5/4, 3/2, 2)$ is a suitable choice.

Case 1 ($p = p_0$). As usual, since $a_{ij} \neq 0$, we have that

$$\widetilde{W}_{ijj}^+ + t\widetilde{W}_{ijj}^- = \frac{\lambda^2}{2}(1+t)a_{ij}(f')^2 \neq 0, \quad \widetilde{W}_{ijkl}^+ + t\widetilde{W}_{ijkl}^- = \frac{\lambda^2}{2}(1-t)a_{ij}(f')^2 \neq 0$$

at p_0 ; therefore $W_{\tilde{g}_t}^+ + tW_{\tilde{g}_t}^- \neq 0$ at p_0 .

Case 2 ($p \in B_{r/2} \setminus \{p_0\}$). For a sufficiently small radius r , we again have that

$$|W_g^+ + tW_g^-| \leq Cr + o(r^2), \text{ as } r \rightarrow 0.$$

Let us suppose that $\widetilde{W}_{ijk}^+ + t\widetilde{W}_{ijk}^- = 0$ at p : therefore, the subsystem consisting of the equations of the form (4.4b) becomes

$$\begin{cases} (1+t)a_{123}x_2x_3 + (1-t)a_{214}x_1x_4 = 0 \\ (1+t)a_{124}x_2x_4 - (1-t)a_{213}x_1x_3 = 0 \\ (1+t)a_{134}x_3x_4 + (1-t)a_{312}x_1x_2 = 0 \end{cases}$$

Let us suppose that $x_1, \dots, x_4 \neq 0$: hence, we have

$$\frac{1-t}{1+t} = \frac{a_{124}}{a_{213}} \cdot \frac{x_2x_4}{x_1x_3} = -\frac{a_{123}}{a_{214}} \cdot \frac{x_2x_3}{x_1x_4} \Rightarrow \frac{a_{124}}{a_{213}} \cdot \frac{x_4}{x_3} = -\frac{a_{123}}{a_{214}},$$

which is impossible, since, by hypothesis, the coefficients a_{ijk} all have the same sign. Thus, at least one coordinate x_i must vanish and, by the system above, this implies that there is just one coordinate of p different from zero. Without loss of generality, we may suppose that $x_1 \neq 0$. However, by choosing the coefficients $\alpha_1, \dots, \alpha_4$ in such a way that a_{ij} and the coefficient of x_1^2 in b_{ij} have opposite signs for some $i \neq j$, we get a contradiction, since $(f')^2$ and $f'f''$ have opposite signs on S : for instance, if $\underline{\alpha} = (1, 5/4, 3/2, 2)$, by (3.8) we have

$$a_{12} = \frac{5}{16} \quad \text{and} \quad b_{12} = -\frac{1}{3r^2}x_1^2.$$

Thus, the only solution of the system is $x_1 = \dots = x_4 = 0$, which is impossible, since $p \neq p_0$: hence, we conclude that $W_{\tilde{g}_t}^+ + tW_{\tilde{g}_t}^-$ does not identically vanish at p .

Case 3 ($p \in S \setminus B_{r/2}$). If we suppose that $W_{\tilde{g}_t}^+ + tW_{\tilde{g}_t}^-$ identically vanish at p , as $r \rightarrow 0$ the system consisting of the equations (4.4a), (4.4b) and (4.4c) becomes

$$\begin{cases} 0 &= W_{ijj}^+ + tW_{ijj}^- + \frac{\lambda^2}{2}(1+t)[a_{ij}(f')^2 + b_{ij}f'f''] \\ 0 &= W_{ijk}^+ + tW_{ijk}^- + \frac{\lambda^2}{2}[(1+t)a_{ijk}x_jx_k \pm (1-t)a_{jil}x_lx_i]f'f'' \\ 0 &= W_{ijkl}^+ + tW_{ijkl}^- \pm \frac{\lambda^2}{2}(1-t)[a_{ij}(f')^2 + b_{ij}f'f''] \end{cases}$$

However, if we suppose that $W_g^+ + tW_g^-$ does not identically vanish at p , as we did in the proofs of Theorem 3.1 and Theorem 1.1, by possibly choosing λ out of a finite set of values, we get a contradiction. Therefore, $W_g^+ + tW_g^-$ must vanish at p , which is impossible.

By the hypothesis of compactness on M , the claim is proven. \square

5. Proof of Theorem 1.4

In this section we prove Theorem 1.4. If we use again Aubin's deformation of g as described in (2.7), we can write the components of the Cotton tensor with respect to the deformed metric \tilde{g} as

$$\begin{aligned} \tilde{C}_{ijk} &= C_{ijk} - \frac{1}{w}[(\phi_k^t \phi^s + \phi_k^s \phi^t)R_{itjs} - (\phi_j^t \phi^s + \phi_j^s \phi^t)R_{itks}] + \\ &- \frac{\phi^p}{w} \phi_{ik} \left\{ R_{jip} - \frac{1}{w} [\phi^t \phi^s (R_{ptjs} + \phi_{jp} \phi_{ts} - \phi_{pt} \phi_{js}) - (\Delta \phi) \phi_{jp} + \phi_{pt} \phi_j^t] \right\} + \\ &+ \frac{\phi^p}{w} \phi_{ij} \left\{ R_{kjp} - \frac{1}{w} [\phi^t \phi^s (R_{ptks} + \phi_{kp} \phi_{ts} - \phi_{pt} \phi_{ks}) - (\Delta \phi) \phi_{kp} + \phi_{pt} \phi_k^t] \right\} + \\ &+ \frac{1}{w} [(\Delta \phi)_k \phi_{ij} - (\Delta \phi)_j \phi_{ik} + (\Delta \phi)^s R_{sijk} - \phi_i^t \phi^s R_{stjk} + \phi_k^t \phi_{itj} - \phi_j^t \phi_{itk} + \phi^t \phi^s (R_{itjs,k} - R_{itks,j})] + \\ &+ \frac{2\phi^p}{w^2} [\phi^t \phi^s (\phi_{kp} R_{itjs} - \phi_{jp} R_{itks}) + \phi_{jp} ((\Delta \phi) \phi_{ik} - \phi_{it} \phi_k^t) - \phi_{kp} ((\Delta \phi) \phi_{ij} - \phi_{it} \phi_j^t)] + \\ &- \frac{1}{w^2} \{ \phi^p [\phi_k^s (\phi_{ij} \phi_{sp} - \phi_{is} \phi_{jp}) - \phi_j^t (\phi_{ik} \phi_{pt} - \phi_{it} \phi_{kp})] \} + \\ &- \frac{1}{w^2} \{ \phi^p [\phi_k^s (\phi_{ij} \phi_{ps} - \phi_{ip} \phi_{js}) - \phi_j^t (\phi_{ik} \phi_{pt} - \phi_{ip} \phi_{kt})] \} + \\ &- \frac{1}{w^2} \{ \phi^s \phi^t (\phi^r (R_{rijk} \phi_{ts} - R_{rsjk} \phi_{it}) + \phi_{tsk} \phi_{ij} - \phi_{tsj} \phi_{ik} - \phi_{itk} \phi_{js} + \phi_{itj} \phi_{ks}) \} + \\ &- \frac{4\phi^p}{w^3} \phi^t \phi^s [\phi_{kp} (\phi_{ij} \phi_{ts} - \phi_{it} \phi_{js}) - \phi_{jp} (\phi_{ik} \phi_{ts} - \phi_{it} \phi_{ks})] + \\ &- \frac{1}{2w(n-1)} [\phi^p \phi^q R_{pq,k} + 2R_{pq} \phi^p \phi_k^q + 2(\Delta \phi)(\Delta \phi)_k - 2\phi^{pq} \phi_{pqk}] (g_{ij} + \phi_i \phi_j) + \\ &+ \frac{1}{2w(n-1)} [\phi^p \phi^q R_{pq,j} + 2R_{pq} \phi^p \phi_j^q + 2(\Delta \phi)(\Delta \phi)_j - 2\phi^{pq} \phi_{pqj}] (g_{ik} + \phi_i \phi_k) + \\ &- \frac{1}{2w^2(n-1)} \left\{ 2\phi^p \phi_{pk} \left[2R_{st} \phi^s \phi^t - (\Delta \phi)^2 + \phi_{st} \phi^{st} + \frac{4}{w} ((\Delta \phi) \phi^s \phi^t \phi_{st} - \phi^r \phi_{rs} \phi^{st} \phi_t) \right] + \right. \\ &+ (\Delta \phi)_k \phi^p \phi^q \phi_{pq} + (\Delta \phi) \phi^p \phi^q \phi_{pqk} + 2(\Delta \phi) \phi^p \phi_k^q \phi_{pq} - 2\phi^p \phi^q \phi_p^s \phi_{sqk} - 2\phi^p \phi_{pq} \phi^{qs} \phi_{sk} \left. \right\} (g_{ij} + \phi_i \phi_j) + \\ &+ \frac{1}{2w^2(n-1)} \left\{ 2\phi^p \phi_{pj} \left[2R_{st} \phi^s \phi^t - (\Delta \phi)^2 + \phi_{st} \phi^{st} + \frac{4}{w} ((\Delta \phi) \phi^s \phi^t \phi_{st} - \phi^r \phi_{rs} \phi^{st} \phi_t) \right] + \right. \\ &+ (\Delta \phi)_j \phi^p \phi^q \phi_{pq} + (\Delta \phi) \phi^p \phi^q \phi_{pqj} + 2(\Delta \phi) \phi^p \phi_j^q \phi_{pq} - 2\phi^p \phi^q \phi_p^s \phi_{sqj} - 2\phi^p \phi_{pq} \phi^{qs} \phi_{sj} \left. \right\} (g_{ik} + \phi_i \phi_k) + \\ &- \frac{2}{n-1} (S_k \phi_i \phi_j - S_j \phi_i \phi_k). \end{aligned} \tag{5.1}$$

Proof. Let g any Riemannian metric on M and consider the deformed metric \tilde{g} defined in (2.7), where ϕ is chosen as in (3.2), with $\alpha_1, \dots, \alpha_n \in [1, 2]$ and such that the derivatives of f satisfy the following inequalities

$$f' > 0, \quad f'' < 0, \quad f''' > 0 \quad \text{on } [0, 1]$$

(for instance, we can choose (3.1) with a sufficiently large b). Let us choose a point $p_0 \in M$ where the Cotton tensor C of (M, g) vanishes and let us consider again an open ball B_r with normal coordinates centered at p_0 ; we also define ϕ and $S = \text{supp}\phi$ as usual. Note that, in addition to (3.3) and (3.4), for a sufficiently small r we have

$$\phi_{ijk} = \frac{2\lambda}{r^2} \alpha_i \left[(\alpha_j x_i \delta_{jk} + \alpha_j x_j \delta_{ik} + \alpha_k x_k \delta_{ij}) f'' + \frac{2\alpha_j \alpha_k}{r^2} x_i x_j x_k f''' \right] = O\left(\frac{1}{r}\right). \tag{5.2}$$

By (3.4) and (5.2), we obtain

$$\Delta\phi = \lambda \left(f' \sum_{p=1}^n \alpha_p + \frac{2}{r^2} f'' \sum_{p=1}^n \alpha_p^2 x_p^2 \right) \tag{5.3}$$

$$(\Delta\phi)_k = \frac{2\lambda}{r^2} \left[\left(2\alpha_k^2 x_k + \alpha_k x_k \sum_{p=1}^n \alpha_p \right) f'' + \frac{2\alpha_k}{r^2} f''' \left(\sum_{p=1}^n \alpha_p^2 x_p^2 \right) x_k \right] \tag{5.4}$$

As we did for \tilde{W} in (3.5), for sufficiently small radii we can consider the principal part of the transformed Cotton tensor:

$$\begin{aligned} \tilde{C}_{ijk} &= C_{ijk} + (\Delta\phi)_k \phi_{ij} - (\Delta\phi)_j \phi_{ik} + \phi_{tk} \phi_{itj} - \phi_{tj} \phi_{itk} + \\ &\quad - \frac{1}{n-1} [((\Delta\phi)(\Delta\phi)_k - \phi_{pq} \phi_{pqk}) g_{ij} - ((\Delta\phi)(\Delta\phi)_j - \phi_{pq} \phi_{pqj}) g_{ik}] + O(r), \end{aligned} \tag{5.5}$$

where the expression $O(r)$ contains all the terms in (5.5) whose order is the same as r or higher. By inserting (5.2), (5.3) and (5.4) into (5.5), we obtain

$$\begin{aligned} \tilde{C}_{iji} &= C_{iji} + \lambda^2 \{ a_{ij} f' f'' + b_{ij} [f' f''' + (f'')^2] \} x_j + O(r^2) \\ \tilde{C}_{ijk} &= C_{ijk} + \lambda^2 a_{ijk} x_i x_j x_k [(f'')^2 + f' f'''] + O(r), \end{aligned} \tag{5.6}$$

where $i \neq j \neq k$ and

$$\begin{aligned} a_{ij} &= \frac{2\alpha_j}{r^2} \left[-4\alpha_i \alpha_j - \alpha_i \sum_{k \neq i, j} \alpha_k + \frac{2}{n-1} \left(\alpha_j \sum_{k \neq j} \alpha_k + \sum_{k < l} \alpha_k \alpha_l \right) \right]; \\ b_{ij} &= \frac{4\alpha_j}{r^4} \left[-\alpha_i \left(\alpha_i \alpha_j x_i^2 + \sum_{k \neq i} \alpha_k^2 x_k^2 \right) + \frac{1}{n-1} \sum_k \alpha_k \left(\sum_{l \neq k} \alpha_l^2 x_l^2 \right) \right]; \\ a_{ijk} &= \frac{4\alpha_i \alpha_j \alpha_k}{r^4} (\alpha_k - \alpha_j). \end{aligned} \tag{5.7}$$

Note that it is sufficient to choose $\alpha_1, \dots, \alpha_n$ such that $\alpha_i \neq \alpha_j$ for every $i \neq j$ to obtain $a_{ijk} \neq 0$ for every $i \neq j \neq k$.

It is immediate to observe that, by (5.6), the deformed cotton tensor $C_{\tilde{g}}$ vanishes at p_0 . Thus, we want to show that $C_{\tilde{g}}$ does not identically vanish on $S \setminus \{p_0\}$: by the compactness of M , we can repeat the finiteness

argument used to prove Theorem 3.1 in order to conclude that the Cotton tensor $C_{\tilde{g}}$ does not identically vanish on $M \setminus \{p_0 = p_0^1, \dots, p_0^k\} =: M \setminus \{p_1, \dots, p_k\}$.

Now, let $p \in S$ and let us consider $C_{\tilde{g}}$ at p .

Case 1 ($p \in B_{r/2} \setminus \{p_0\}$). As usual, we have that

$$|C_g| \leq D \cdot r + o(r^2), \text{ as } r \rightarrow 0;$$

if we suppose that $\tilde{C}_{iji} = \tilde{C}_{ijk} = 0$ for every $i \neq j \neq k$, we have that

$$\begin{cases} a_{ij}f'f'' + b_{ij}[f'f''' + (f'')^2]x_j & = 0 \\ a_{ijk}x_i x_j x_k [(f'')^2 + f'f'''] & = 0 \end{cases}$$

for a sufficiently small r . By the properties of f and our choice of $\alpha_1, \dots, \alpha_n$, we have that $x_i x_j x_k = 0$ for every $i \neq j \neq k$, which implies that at most two coordinates of p are not zero.

Therefore, let us suppose that $x_i, x_j \neq 0$. By hypothesis, $\tilde{C}_{iji} = \tilde{C}_{jij} = 0$: hence, by (5.6) and (5.7) we obtain the following equations

$$\begin{aligned} 0 &= \left[-4\alpha_i\alpha_j - \alpha_i \sum_{k \neq i,j} \alpha_k + \frac{2}{n-1} \left(\alpha_j \sum_{k \neq j} \alpha_k + \sum_{k < l} \alpha_k \alpha_l \right) \right] f'f'' + \\ &+ \frac{2}{r^2} \left[-\alpha_i(\alpha_i\alpha_j x_i^2 + \alpha_j^2 x_j^2) + \frac{1}{n-1} \sum_k \alpha_k \left(\sum_{l \neq k} \alpha_l^2 x_l^2 \right) \right] [(f'')^2 + f'f''']; \\ 0 &= \left[-4\alpha_i\alpha_j - \alpha_j \sum_{k \neq i,j} \alpha_k + \frac{2}{n-1} \left(\alpha_i \sum_{k \neq i} \alpha_k + \sum_{k < l} \alpha_k \alpha_l \right) \right] f'f'' + \\ &+ \frac{2}{r^2} \left[-\alpha_j(\alpha_i\alpha_j x_j^2 + \alpha_i^2 x_i^2) + \frac{1}{n-1} \sum_k \alpha_k \left(\sum_{l \neq k} \alpha_l^2 x_l^2 \right) \right] [(f'')^2 + f'f''']; \end{aligned}$$

subtracting the second equation from the first, it is easy to obtain

$$(\alpha_j - \alpha_i) \sum_{k \neq i,j} \alpha_k + \frac{2}{n-1} \left(\alpha_j \sum_{k \neq j} \alpha_k - \alpha_i \sum_{k \neq i} \alpha_k \right) = 0 \Leftrightarrow \frac{n-3}{n-1} (\alpha_j - \alpha_i) \sum_{k \neq i,j} \alpha_k = 0,$$

which is impossible, since $\alpha_i \neq \alpha_j$ by hypothesis. This implies that exactly one coordinate of p is different from zero (say, x_j). Since $n \geq 4$, if $i \neq t \neq j$, by $\tilde{C}_{iji} = \tilde{C}_{tjt} = 0$ we obtain

$$\begin{aligned} 0 &= \left[-4\alpha_i\alpha_j - \alpha_i \sum_{k \neq i,j} \alpha_k + \frac{2}{n-1} \left(\alpha_j \sum_{k \neq j} \alpha_k + \sum_{k < l} \alpha_k \alpha_l \right) \right] f'f'' + \\ &+ \frac{2}{r^2} \alpha_j^2 x_j^2 \left[-\alpha_i + \frac{1}{n-1} \sum_{k \neq j} \alpha_k \right] [(f'')^2 + f'f''']; \\ 0 &= \left[-4\alpha_t\alpha_j - \alpha_t \sum_{k \neq t,j} \alpha_k + \frac{2}{n-1} \left(\alpha_j \sum_{k \neq j} \alpha_k + \sum_{k < l} \alpha_k \alpha_l \right) \right] f'f'' + \end{aligned}$$

$$+ \frac{2}{r^2} \alpha_j^2 x_j^2 \left[-\alpha_t + \frac{1}{n-1} \sum_{k \neq j} \alpha_k \right] [(f'')^2 + f' f'''].$$

It is not hard to see that, for a suitable choice of $\alpha_1 \neq \dots \neq \alpha_n$, the coefficients of $[(f'')^2 + f' f''']$ in the equations do not vanish: this allows us to compute x_j^2 as

$$x_j^2 = \frac{r^2 \left[4\alpha_i \alpha_j + \alpha_i \sum_{k \neq i, j} \alpha_k - \frac{2}{n-1} \left(\alpha_j \sum_{k \neq j} \alpha_k + \sum_{k < l} \alpha_k \alpha_l \right) \right] f' f''}{2\alpha_j^2 \left[-\alpha_i + \frac{1}{n-1} \sum_{k \neq j} \alpha_k \right] [(f'')^2 + f' f''']}.$$

However, inserting this into the other equation, we obtain

$$\begin{aligned} & \left[4\alpha_t \alpha_j + \alpha_t \sum_{k \neq t, j} \alpha_k - \frac{2}{n-1} \left(\alpha_j \sum_{k \neq j} \alpha_k + \sum_{k < l} \alpha_k \alpha_l \right) \right] \left[-\alpha_i + \frac{1}{n-1} \sum_{k \neq j} \alpha_k \right] = \\ & = \left[4\alpha_i \alpha_j + \alpha_i \sum_{k \neq i, j} \alpha_k - \frac{2}{n-1} \left(\alpha_j \sum_{k \neq j} \alpha_k + \sum_{k < l} \alpha_k \alpha_l \right) \right] \left[-\alpha_t + \frac{1}{n-1} \sum_{k \neq j} \alpha_k \right], \end{aligned}$$

which implies

$$\begin{aligned} & \frac{4}{n-1} (\alpha_t - \alpha_i) \sum_{k \neq j} \alpha_k + \alpha_i \alpha_t (\alpha_t - \alpha_i) + \\ & + \frac{1}{n-1} (\alpha_t - \alpha_i) \left(\sum_{k \neq i, j, t} \alpha_k \right) \left(\sum_{l \neq j} \alpha_l \right) + \frac{2}{(n-1)^2} (\alpha_t - \alpha_i) \left(\alpha_j \sum_{k \neq j} \alpha_k + \sum_{k < l} \alpha_k \alpha_l \right) = 0 \end{aligned}$$

and this is clearly impossible. Since $p \neq p_0$, we have that the Cotton tensor $C_{\tilde{g}}$ cannot identically vanish at p .

Case 2 ($p \in S \setminus B_{r/2}$). As usual, let us suppose that $C_{\tilde{g}}$ identically vanishes at p . If C does not vanish at p , we can exploit the argument of Theorem 3.1 to conclude that, if we possibly choose λ out of a finite set of values, this is impossible. Therefore, $C \equiv 0$ at p , which is a contradiction, by the proof of Case 1; hence, $C_{\tilde{g}}$ does not vanish at p .

The hypothesis of compactness on M proves the claim. \square

6. Proof of Theorem 1.6

In this section, we focus on four-dimensional manifolds and we prove Theorem 1.6. If $n = 4$, the Bach tensor acquires two additional properties: it is conformally invariant and divergence-free (see [9], Section 1.4 and Section 2.2.2).

Proof. As we did in the proof of Theorem 3.1, let g any Riemannian metric on M and let $p_0 \in M$ such that B_g vanishes and let B_r an open ball of radius r and centered in p_0 . Let us choose normal coordinates x_1, \dots, x_4 such that $p_0 = (0, 0, 0, 0)$ and let us define the function ϕ as in (3.2) and $S = \text{supp}\phi$ as usual, with f defined as in (3.1). We know that $f \in C^\infty([0, +\infty))$: therefore, $\phi \in C^\infty(M)$ and it vanishes outside S . Moreover, for a sufficiently large b , the function f satisfies the following inequalities

$$f' > 0, \quad f'' < 0, \quad f''' > 0, \quad f^{IV} < 0 \quad \text{on } [0, 1).$$

By (5.2) and (5.3), we obtain the following additional expressions:

$$\begin{aligned} \phi_{ijkt} = & \frac{2}{r^2} \lambda \alpha_i \left\{ \frac{4}{r^4} \alpha_j \alpha_k \alpha_t x_i x_j x_k x_t f^{IV} + (\alpha_k \delta_{kt} \delta_{ij} + \alpha_j \delta_{jt} \delta_{ik} + \alpha_j \delta_{it} \delta_{jk}) f'' + \right. \\ & \left. + \frac{2}{r^2} [\alpha_j \alpha_k (\delta_{it} x_j x_k + \delta_{jt} x_i x_k + \delta_{kt} x_i x_j) + \alpha_t x_t (\delta_{ij} \alpha_k x_k + \delta_{ik} \alpha_j x_j + \delta_{jk} \alpha_i x_i)] f''' \right\}. \end{aligned} \quad (6.1)$$

$$\begin{aligned} (\Delta \phi)_{jk} = & \frac{2\lambda \alpha_j}{r^2} \left\{ \left(2\alpha_j + \sum_p \alpha_p \right) f'' \delta_{jk} + \right. \\ & \left. + \frac{2}{r^2} \left[\alpha_k \left(2\alpha_j + \sum_p \alpha_p \right) x_j x_k + 2\alpha_k^2 x_j x_k + \sum_p \alpha_p^2 x_p^2 \delta_{jk} \right] f''' + \frac{4\alpha_k}{r^4} \left(\sum_p \alpha_p^2 x_p^2 \right) x_j x_k f^{IV} \right\}. \end{aligned} \quad (6.2)$$

$$\begin{aligned} (\Delta \phi)_{kk} = & \frac{2\lambda}{r^2} \left[\left(2 \sum_p \alpha_p^2 + \left(\sum_q \alpha_q \right)^2 \right) f'' + \frac{4}{r^2} \left(2 \sum_p \alpha_p^3 x_p^2 + \sum_p \alpha_p \sum_q \alpha_q^2 x_q^2 \right) f''' + \right. \\ & \left. + \frac{4}{r^4} \left(\sum_p \alpha_p^2 x_p^2 \right)^2 f^{IV} \right]. \end{aligned} \quad (6.3)$$

Note that

$$\phi_{ijkt} = O\left(\frac{1}{r^2}\right)$$

as $r \rightarrow 0$. We consider the principal part of the transformed Bach tensor: by (5.1), (5.5) and the definition of the Bach tensor, we obtain

$$\begin{aligned} \tilde{B}_{ij} = & B_{ij} + (\Delta \phi)_{kk} \phi_{ij} + (\Delta \phi)_k \phi_{ijk} - (\Delta \phi)_{jk} \phi_{ik} - (\Delta \phi)_j \phi_{ikk} + \\ & + \phi_{tkk} \phi_{itj} + \phi_{tk} \phi_{itjk} - \phi_{tjk} \phi_{itk} - \phi_{tj} \phi_{itkk} + \\ & - \frac{1}{n-1} [((\Delta \phi)_k (\Delta \phi)_k + (\Delta \phi) (\Delta \phi)_{kk} - \phi_{pqk} \phi_{pqk} - \phi_{pq} \phi_{pqkk}) \delta_{ij} + \\ & - ((\Delta \phi)_i (\Delta \phi)_j + (\Delta \phi) (\Delta \phi)_{ji} - \phi_{pqi} \phi_{pqj} - \phi_{pq} \phi_{pqji})] + O(1), \end{aligned} \quad (6.4)$$

where $O(1)$ is the usual “remainder” term. Note that, as $r \rightarrow 0$, the terms given by $\tilde{R}_{kl} \tilde{W}_{ijkl}$ in the definition of the Bach tensor (2.6) do not appear in (6.4), since their order is lower than the order of $\tilde{C}_{ijk,k}$; however, as we did for the Cotton tensor, we make explicit the coefficients of B_g , since they do not depend on f (and, therefore, they do not *a priori* vanish as the argument of f goes to 1).

Inserting (3.4), (5.3), (5.2), (6.1) and (6.2) into (6.4), for a sufficiently small radius r we obtain the following expression for the Bach tensor:

$$\begin{aligned} \tilde{B}_{ij} = & B_{ij} + \frac{2\lambda^2}{3r^2} \left\{ \alpha_i \left[8 \sum_p \alpha_p^2 + 4 \sum_q \alpha_q \left(\sum_t \alpha_t - \alpha_i \right) - 8\alpha_i^2 \right] \right. \\ & \left. - \sum_p \alpha_p \left[\sum_q \alpha_q^2 + \left(\sum_t \alpha_t \right)^2 \right] + 2 \sum_p \alpha_p^3 \right\} f' f'' \delta_{ij} + \\ & + \frac{4\lambda^2}{3r^4} \left\{ 4 \sum_p \alpha_p^4 x_p^2 + \left(14\alpha_i - 3 \sum_p \alpha_p \right) \sum_q \alpha_q^3 x_q^2 + \right. \end{aligned} \quad (6.5)$$

$$\begin{aligned}
 &+ \sum_p \alpha_p^2 x_p^2 \left[\alpha_i \left(7 \sum_q \alpha_q - 6\alpha_i \right) + \sum_t \alpha_t^2 - 2 \left(\sum_r \alpha_r \right)^2 \right] \left[f' f''' + (f'')^2 \right] \delta_{ij} + \\
 &+ \frac{8\lambda^2}{3r^6} \sum_p \alpha_p^2 x_p^2 \left[\sum_q \alpha_q^3 x_q^2 + \sum_q \alpha_q^2 x_q^2 \left(3\alpha_i - \sum_t \alpha_t \right) \right] (f' f^{IV} + 3f'' f''') \delta_{ij} + \\
 &+ \frac{4\lambda^2 \alpha_i \alpha_j}{3r^4} x_i x_j \left[2 \sum_p \alpha_p^2 + \left(\sum_q \alpha_q \right)^2 - 2(\alpha_i^2 + \alpha_j^2 + 6\alpha_i \alpha_j) - (\alpha_i + \alpha_j) \sum_t \alpha_t \right] \left[f' f''' + (f'')^2 \right] + \\
 &+ \frac{8\lambda^2 \alpha_i \alpha_j}{3r^6} x_i x_j \left[2 \sum_p \alpha_p^3 x_p^2 - \left(3\alpha_i + 3\alpha_j - \sum_q \alpha_q \right) \sum_t \alpha_t^2 x_t^2 \right] (f' f^{IV} + 3f'' f''') + O(1).
 \end{aligned}$$

Let

$$A := f' f'', \quad B := f' f''' + (f'')^2, \quad C := f' f^{IV} + 3f'' f'''$$

and let us choose $(\alpha_1, \alpha_2, \alpha_3, \alpha_4) = (1, \frac{5}{4}, \frac{3}{2}, 2)$. For $i \neq j$, we obtain the following equations

$$\begin{aligned}
 \tilde{B}_{12} &= B_{12} + \frac{5\lambda^2}{3r^4} \left[\frac{2}{r^2} \left(x_1^2 + \frac{75}{32} x_2^2 + \frac{9}{2} x_3^2 + 12x_4^2 \right) C + \frac{141}{8} B \right] x_1 x_2 \\
 \tilde{B}_{13} &= B_{13} + \frac{2\lambda^2}{r^4} \left[\frac{2}{r^2} \left(\frac{1}{4} x_1^2 + \frac{75}{64} x_2^2 + \frac{45}{16} x_3^2 + 9x_4^2 \right) C + \frac{189}{16} B \right] x_1 x_3 \\
 \tilde{B}_{14} &= B_{14} + \frac{8\lambda^2}{3r^4} \left[-\frac{2}{r^2} \left(\frac{5}{4} x_1^2 + \frac{75}{64} x_2^2 + \frac{9}{16} x_3^2 - 3x_4^2 \right) C - \frac{9}{16} B \right] x_1 x_4 \\
 \tilde{B}_{23} &= B_{23} + \frac{5\lambda^2}{2r^4} \left[\frac{2}{r^2} \left(-\frac{1}{2} x_1^2 + \frac{9}{8} x_3^2 + 6x_4^2 \right) C + \frac{19}{4} B \right] x_2 x_3 \\
 \tilde{B}_{24} &= B_{24} + \frac{10\lambda^2}{3r^4} \left[-\frac{2}{r^2} \left(x_1^2 + \frac{75}{32} x_2^2 + \frac{9}{4} x_3^2 \right) C - \frac{73}{8} B \right] x_2 x_4 \\
 \tilde{B}_{34} &= B_{34} + \frac{4\lambda^2}{r^4} \left[-\frac{2}{r^2} \left(\frac{11}{4} x_1^2 + \frac{225}{64} x_2^2 + \frac{63}{16} x_3^2 + 3x_4^2 \right) C - \frac{287}{16} B \right] x_3 x_4;
 \end{aligned} \tag{6.6}$$

for $i = j$, we have the additional expressions

$$\begin{aligned}
 \tilde{B}_{11} &= B_{11} - \frac{323\lambda^2}{12r^2} A + \frac{\lambda^2}{3r^4} \left(\frac{7}{2} x_1^2 - \frac{4175}{32} x_2^2 - \frac{2727}{16} x_3^2 - 217x_4^2 \right) B + \\
 &+ \frac{8\lambda^2}{3r^6} \left[\left(x_1^2 + \frac{25}{16} x_2^2 + \frac{9}{4} x_3^2 + 4x_4^2 \right) \left(-\frac{7}{4} x_1^2 - \frac{75}{32} x_2^2 - \frac{45}{16} x_3^2 - 3x_4^2 \right) + \right. \\
 &+ \left. x_1^2 \left(\frac{7}{4} x_1^2 + \frac{225}{64} x_2^2 + \frac{99}{16} x_3^2 + 15x_4^2 \right) \right] C \\
 \tilde{B}_{22} &= B_{22} - \frac{41\lambda^2}{6r^2} A + \frac{\lambda^2}{r^4} \left(-\frac{97}{6} x_1^2 + \frac{75}{24} x_2^2 - 21x_3^2 + \frac{2}{3} x_4^2 \right) B + \\
 &+ \frac{\lambda^2}{3r^6} \left[\left(8x_1^2 + \frac{25}{2} x_2^2 + 18x_3^2 + 32x_4^2 \right) \left(-x_1^2 - \frac{75}{64} x_2^2 - \frac{9}{8} x_3^2 \right) + \right. \\
 &+ \left. x_2^2 \left(\frac{25}{8} x_1^2 + \frac{1875}{128} x_2^2 + \frac{1125}{32} x_3^2 + \frac{225}{2} x_4^2 \right) \right] C
 \end{aligned} \tag{6.7}$$

$$\begin{aligned} \tilde{B}_{33} &= B_{33} + \frac{53\lambda^2}{6r^2}A + \frac{\lambda^2}{r^4} \left(-\frac{43}{12}x_1^2 + \frac{25}{24}x_2^2 + \frac{39}{8}x_3^2 + \frac{209}{3}x_4^2 \right) B + \\ &\quad + \frac{2\lambda^2}{r^6} \left[\left(\frac{4}{3}x_1^2 + \frac{25}{12}x_2^2 + 3x_3^2 + \frac{16}{3}x_4^2 \right) \left(-\frac{1}{4}x_1^2 + \frac{9}{16}x_3^2 + 3x_4^2 \right) + \right. \\ &\quad \left. + x_3^2 \left(-\frac{15}{4}x_1^2 - \frac{225}{64}x_2^2 - \frac{27}{16}x_3^2 + 9x_4^2 \right) \right] C \\ \tilde{B}_{44} &= B_{44} + \frac{299\lambda^2}{12r^2}A + \frac{\lambda^2}{r^4} \left(\frac{223}{12}x_1^2 + \frac{3775}{96}x_2^2 + \frac{1167}{16}x_3^2 + 2x_4^2 \right) B + \\ &\quad + \frac{8\lambda^2}{3r^6} \left[\left(x_1^2 + \frac{25}{16}x_2^2 + \frac{9}{4}x_3^2 + 4x_4^2 \right) \left(\frac{5}{4}x_1^2 + \frac{75}{32}x_2^2 + \frac{63}{16}x_3^2 + 9x_4^2 \right) + \right. \\ &\quad \left. - x_4^2 \left(17x_1^2 + \frac{375}{16}x_2^2 + \frac{117}{4}x_3^2 + 36x_4^2 \right) \right] C \end{aligned}$$

Of course, the equations in (6.7) cannot be all independent, since the Bach tensor is trace-free.

As we did for Theorem 3.1, we consider three cases.

Case 1 ($p = p_0$). In our local coordinates, $p_0 = (0, 0, 0, 0)$; therefore, since $B_g \neq 0$ in p_0 and $A < 0$ on B_r , by (6.6) and (6.7) we obtain

$$|B_{\tilde{g}}|_{\tilde{g}}^2 = 2 \sum_{i=1}^4 \tilde{B}_{ii}^2 = CA^2 > 0,$$

where $C = \frac{105845\lambda^4}{36r^4}$.

Case 2 ($p \in B_{r/2} \setminus \{p_0\}$). In this case, we have again that

$$|B_g| \leq C \cdot r + o(r^2), \text{ as } r \rightarrow 0.$$

Thus, we may consider just the principal parts in the system defined by (6.6) and (6.7).

Let us suppose that $\tilde{B}_{ij} = 0$ for every i, j at $p = (x_1, x_2, x_3, x_4)$. We want to show that the only solution of the system is given by $x_i = 0$ for every i , which leads to a contradiction for the previous argument.

If we suppose that $x_i \neq 0$ for every i , we have that, for instance,

$$B = -\frac{16}{141r^2} \left(x_1^2 + \frac{75}{32}x_2^2 + \frac{9}{2}x_3^2 + 12x_4^2 \right) C$$

by the first equation in (6.6). Since $B > 0$ and $C < 0$ in B_r and $x_1, \dots, x_4 \neq 0$, inserting this into the other equations in (6.6), we obtain a system of five equations in the variables x_1, \dots, x_4 : a straightforward computation shows that this system admits only the trivial solution and, therefore, one of the variables x_1, \dots, x_4 must be zero.

Now, let us suppose that $x_i \neq 0$ for at least two indices i . If $x_i \neq 0$ for one index i , by (6.6) and (6.7) we obtain a system of 5 independent equations in x_j, x_k, x_l , where $j, k, l \neq i$: by an analogous argument, we can show that the system admits no solutions, which implies that at least two variables x_i and x_j must be zero. In this case, expressing B in terms of C as before, by (6.7) we can express A in terms of C as well and, therefore, obtain two independent equations in x_k, x_l ; however, by our choice of the coefficients $\alpha_1, \dots, \alpha_4$, the system is once again inconsistent.

Therefore, as in the proof of Theorem 3.1, we obtain that exactly one variable x_i is different from zero. Let us suppose that, for instance, $x_1 \neq 0$. By (6.7), we have that

$$\tilde{B}_{11} = -\frac{323\lambda^2}{12r^2}A + \frac{7\lambda^2}{6r^4}x_1^2B > 0,$$

since $A < 0$ and $B > 0$ on S . Thus, the system admits no solution. The other cases can be shown in an analogous way. Hence, we conclude that $|B_{\tilde{g}}|_{\tilde{g}}^2$ must be strictly positive at p .

We also point out that the same system was solved *via* technical computing through Wolfram Mathematica (see Appendix A for the code). Also note that the system in the Appendix is more general than the one we are considering in this proof: indeed, we showed that the system (6.6)+(6.7), with $B_{ij} = 0$, would admit no real solutions even if A, B and C were free real parameters satisfying $A, B, C \neq 0$.

Case 3 ($p \in S \setminus B_{r/2}$). In this case, we need to consider the components of the Bach tensor B_g in (6.6) and (6.7).

If $B_g \equiv 0$ at p , we can immediately conclude that $|B_{\tilde{g}}|_{\tilde{g}}^2 > 0$ at p , by the proof of Case 2. Thus, let us suppose that $\tilde{B}_{ij} = 0$ at p for every i, j and that $|B_g|_g^2 > 0$ at p . In particular, we may suppose that $B_{12} \neq 0$ at p . By the first equation in (6.6), we obtain that

$$\lambda^2 = -\frac{3r^4B_{12}}{5\left[\frac{2}{r^2}\left(x_1^2 + \frac{75}{32}x_2^2 + \frac{9}{2}x_3^2 + 12x_4^2\right)C + \frac{141}{8}B\right]x_1x_2}$$

at p . However, we may choose $\lambda_1 \in \mathbb{R}$ such that $\lambda_1^2 \neq \lambda^2$ in (3.2), since λ is a free parameter: if we repeat the argument of the proof with λ_1 instead of λ , we get a contradiction and, therefore, we conclude that $B_{12} = 0$ at p .

Now, if $B_{13} \neq 0$ at p , the second equation in (6.6) implies that

$$\lambda_1^2 = -\frac{r^4B_{13}}{2\left[\frac{2}{r^2}\left(\frac{1}{4}x_1^2 + \frac{75}{64}x_2^2 + \frac{45}{16}x_3^2 + 9x_4^2\right)C + \frac{189}{16}B\right]x_1x_3};$$

again, possibly choosing λ_2 such that $\lambda_2^2 \neq \lambda_1^2$, we obtain that $B_{13} = 0$ at p . Iterating this argument for every component B_{ij} , we conclude that, possibly choosing $\bar{\lambda}$ outside a finite set $\{\lambda, \dots, \lambda_k\}$, the components B_{ij} must all vanish at p . Therefore, we repeat the argument of Case 2 to conclude that

$$|B_{\tilde{g}}|_{\tilde{g}}^2 > 0 \text{ at } p.$$

Now, as in Step 2 of the proof of Theorem 3.1, since M is compact, we can deform the metric g on a finite cover of M : using the argument of Remark 3.2, the claim is proven. \square

Remark 6.1. Observe that, even if we did not obtain the full expression of the transformed Bach tensor, it can be easily seen that, once we fix a point $p \in S$, the quantity $\tilde{B}_{ij} - B_{ij}$, up to multiplying for a suitable power of w , is indeed a polynomial of finite degree in λ .

Remark 6.2. As we recalled in the Introduction, when $\dim M = 4$, Bach-flatness is a necessary condition for (M, g) to be an Einstein manifold; therefore, an immediate consequence of Theorem 1.6 is that, given a smooth manifold M of dimension four, one can always choose a conformal class $[g]$ of Riemannian metrics which contains no Einstein metrics. In fact, we can say more: since we found a quadruple $\alpha_1, \dots, \alpha_4$ such that the system of equations (6.6)+(6.7) admits no solutions, there exists an open neighborhood $U_{\underline{\alpha}}$ of $\underline{\alpha} = (\alpha_1, \dots, \alpha_4)$ in $Q := [1, 2] \times [1, 2] \times [1, 2] \times [1, 2]$ such that, for every $\underline{\alpha}' \in U_{\underline{\alpha}}$, the system admits no solutions on M . Therefore, there exist infinitely-many conformal classes of Riemannian metrics on M which contain no Einstein metrics.

Although we did not prove it in this paper, we expect that, given any Riemannian metric g on M , the subset

$$Q' := \left\{ \alpha \in Q : |B_{g_\alpha}|_{g_\alpha}^2 \equiv 1, \text{ where } g_\alpha = g + d\phi_\alpha \otimes d\phi_\alpha \text{ and } \phi_\alpha \text{ is defined as in (3.2)} \right\}$$

is such that $Q \setminus Q'$ has Lebesgue measure zero in Q .

Appendix A. Solutions of the systems (6.6) and (6.7) in the homogeneous case

```
In[1]= B12 := (2 / r ^ 2 (x1 ^ 2 + 75 / 32 x2 ^ 2 + 9 / 2 x3 ^ 2 + 12 x4 ^ 2) C + 141 / 8 B) x1 * x2 ;
B13 := (2 / r ^ 2 * (1 / 4 x1 ^ 2 + 75 / 64 x2 ^ 2 + 45 / 16 x3 ^ 2 + 9 x4 ^ 2) C + 189 / 16 B) x1 * x3 ;
B14 := (-2 / r ^ 2 * (5 / 4 x1 ^ 2 + 75 / 64 x2 ^ 2 + 9 / 16 x3 ^ 2 - 3 x4 ^ 2) C - 9 / 16 B) x1 * x4 ;
B23 := (2 / r ^ 2 * (-1 / 2 x1 ^ 2 + 9 / 8 x3 ^ 2 + 6 x4 ^ 2) C + 19 / 4 B) x2 * x3 ;
B24 := (-2 / r ^ 2 (x1 ^ 2 + 75 / 32 x2 ^ 2 + 9 / 4 x3 ^ 2) C - 73 / 8 B) x2 * x4 ;
B34 := (-2 / r ^ 2 * (11 / 4 x1 ^ 2 + 225 / 64 x2 ^ 2 + 63 / 16 x3 ^ 2 + 3 x4 ^ 2) C - 287 / 16 B) x3 * x4 ;
B11 := -323 / 12 / r ^ 2 A + 1 / 3 / r ^ 4 * (7 / 2 x1 ^ 2 - 4175 / 32 x2 ^ 2 - 2727 / 16 x3 ^ 2 - 217 x4 ^ 2) B +
      8 / 3 / r ^ 6 ((x1 ^ 2 + 25 / 16 x2 ^ 2 + 9 / 4 x3 ^ 2 + 4 x4 ^ 2) (-7 / 4 x1 ^ 2 - 75 / 32 x2 ^ 2 - 45 / 16 x3 ^ 2 - 3 x4 ^ 2) +
      x1 ^ 2 (7 / 4 x1 ^ 2 + 225 / 64 x2 ^ 2 + 99 / 16 x3 ^ 2 + 15 x4 ^ 2)) C ;
B22 := -41 / 6 / r ^ 2 A + 1 / r ^ 4 * (-97 / 6 x1 ^ 2 + 75 / 24 x2 ^ 2 - 21 x3 ^ 2 + 2 / 3 x4 ^ 2) B +
      1 / 3 / r ^ 6 ((8 x1 ^ 2 + 25 / 2 x2 ^ 2 + 18 x3 ^ 2 + 32 x4 ^ 2) (-x1 ^ 2 - 75 / 64 x2 ^ 2 - 9 / 8 x3 ^ 2) +
      x2 ^ 2 (25 / 8 x1 ^ 2 + 1875 / 128 x2 ^ 2 + 1125 / 32 x3 ^ 2 + 225 / 2 x4 ^ 2)) C ;
B33 := 53 / 6 / r ^ 2 A + 1 / r ^ 4 * (-43 / 12 x1 ^ 2 + 25 / 24 x2 ^ 2 + 39 / 8 x3 ^ 2 + 209 / 3 x4 ^ 2) B +
      2 / r ^ 6 ((4 / 3 x1 ^ 2 + 25 / 12 x2 ^ 2 + 3 x3 ^ 2 + 16 / 3 x4 ^ 2) * (-1 / 4 x1 ^ 2 + 9 / 16 x3 ^ 2 + 3 x4 ^ 2) +
      x3 ^ 2 (-15 / 4 x1 ^ 2 - 225 / 64 x2 ^ 2 - 27 / 16 x3 ^ 2 + 9 x4 ^ 2)) C ;
```

```
In[9]= Solve[{B12 == 0, B13 == 0, B14 == 0, B23 == 0, B24 == 0, B34 == 0, B11 == 0, B22 == 0, B33 == 0},
{x1, x2, x3, x4, A, B, C}]
```

```
Out[9]= {{A -> 0, B -> 0, C -> 0}, {x2 -> 0, A -> 0, B -> 0, C -> 0}, {x1 -> 0, A -> 0, B -> 0, C -> 0}, {x3 -> 0, A -> 0, B -> 0, C -> 0},
{x4 -> 0, A -> 0, B -> 0, C -> 0}, {x1 -> 0, x2 -> 0, A -> 0, B -> 0, C -> 0}, {x1 -> 0, x3 -> 0, A -> 0, B -> 0, C -> 0},
{x1 -> 0, x3 -> -4 i x4 / sqrt(3), A -> 0, B -> 0, C -> 0}, {x1 -> 0, x2 -> -8 sqrt(2) x4 / 5, x3 -> -4 i x4 / sqrt(3), A -> 0, B -> 0},
{x1 -> 0, x2 -> 8 sqrt(2) x4 / 5, x3 -> -4 i x4 / sqrt(3), A -> 0, B -> 0}, {x1 -> 0, x3 -> 4 i x4 / sqrt(3), A -> 0, B -> 0, C -> 0},
{x1 -> 0, x2 -> -8 sqrt(2) x4 / 5, x3 -> 4 i x4 / sqrt(3), A -> 0, B -> 0}, {x1 -> 0, x2 -> 8 sqrt(2) x4 / 5, x3 -> 4 i x4 / sqrt(3), A -> 0, B -> 0},
{x1 -> 0, x2 -> 0, x3 -> 0, x4 -> 0, A -> 0}, {x2 -> 0, x3 -> 0, A -> 0, B -> 0, C -> 0},
{x2 -> 0, x3 -> -2 / 3 i sqrt(2) x1, A -> 0, B -> 0, C -> 0}, {x2 -> 0, x3 -> 2 / 3 i sqrt(2) x1, A -> 0, B -> 0, C -> 0},
{x2 -> 0, x4 -> 0, A -> 0, B -> 0, C -> 0}, {x1 -> 0, x4 -> 0, A -> 0, B -> 0, C -> 0},
{x1 -> 0, x2 -> 0, x3 -> 0, x4 -> 0, A -> 0}, {x3 -> 0, x4 -> 0, A -> 0, B -> 0, C -> 0},
{x3 -> -2 x1 / 3, x4 -> 0, A -> 0, B -> 0, C -> 0}, {x2 -> -4 / 5 i sqrt(2) x1, x3 -> -2 x1 / 3, x4 -> 0, A -> 0, B -> 0},
{x2 -> 4 / 5 i sqrt(2) x1, x3 -> -2 x1 / 3, x4 -> 0, A -> 0, B -> 0}, {x3 -> 2 x1 / 3, x4 -> 0, A -> 0, B -> 0, C -> 0},
{x2 -> -4 / 5 i sqrt(2) x1, x3 -> 2 x1 / 3, x4 -> 0, A -> 0, B -> 0}, {x2 -> 4 / 5 i sqrt(2) x1, x3 -> 2 x1 / 3, x4 -> 0, A -> 0, B -> 0},
{x2 -> 0, x3 -> -2 / 3 i sqrt(2) x1, x4 -> -x1 / 2, A -> 0, B -> 0}, {x2 -> 0, x3 -> 2 / 3 i sqrt(2) x1, x4 -> -x1 / 2, A -> 0, B -> 0},
{x2 -> 0, x3 -> -2 / 3 i sqrt(2) x1, x4 -> x1 / 2, A -> 0, B -> 0}, {x2 -> 0, x3 -> 2 / 3 i sqrt(2) x1, x4 -> x1 / 2, A -> 0, B -> 0},
{x1 -> 0, x2 -> 0, x3 -> 0, A -> 0, B -> 0, C -> 0}, {x1 -> 0, x2 -> 0, x4 -> 0, A -> 0, B -> 0, C -> 0},
{x1 -> 0, x2 -> 0, x4 -> 0, A -> 0, B -> 0, C -> 0}, {x1 -> 0, x3 -> 0, x4 -> 0, A -> 0, B -> 0, C -> 0},
{x1 -> 0, x2 -> 0, x3 -> 0, x4 -> 0, A -> 0, B -> 0}, {x1 -> 0, x2 -> 0, x4 -> 0, A -> 0, B -> 0, C -> 0},
{x1 -> 0, x3 -> 0, x4 -> 0, A -> 0, B -> 0, C -> 0}, {x1 -> 0, x2 -> 0, x3 -> 0, x4 -> 0, A -> 0, B -> 0},
{x2 -> 0, x3 -> 0, x4 -> 0, A -> 0, B -> 0, C -> 0}, {x2 -> 0, x3 -> 0, x4 -> 0, A -> 0, B -> 0, C -> 0}}
```


References

- [1] E. Abbena, S. Garbiero, S. Salamon, Bach-flat Lie groups in dimension 4, *C. R. Math. Acad. Sci. Paris* 351 (7–8) (2013) 303–306.
- [2] T. Aubin, Sur la courbure conforme des variétés riemanniennes, *C. R. Acad. Sci. Paris, Sér. A-B* 262 (1966) A391–A393.
- [3] T. Aubin, Métriques riemanniennes et courbure, *J. Differ. Geom.* 4 (1970) 383–424.
- [4] A. Avez, Characteristic classes and Weyl tensor: applications to general relativity, *Proc. Natl. Acad. Sci. USA* 66 (1970) 265–268.
- [5] R. Bach, Zur Weylschen Relativitätstheorie und der Weylschen Erweiterung des Krümmungstensorbegriffs, *Math. Z.* 9 (1–2) (1921) 110–135.
- [6] A.L. Besse, *Einstein Manifolds*, Classics in Mathematics, Springer-Verlag, Berlin, 2008. Reprint of the 1987 edition.
- [7] G. Carron, M. Herzlich, Conformally flat manifolds with nonnegative Ricci curvature, *Compos. Math.* 142 (3) (2006) 798–810.
- [8] G. Catino, Metrics of constant negative scalar-Weyl curvature, *Math. Res. Lett.* 30 (2) (2023) 319–340.
- [9] G. Catino, P. Mastrolia, *A Perspective on Canonical Riemannian Metrics*, Progress in Mathematics, vol. 336, Birkhäuser/Springer, Cham, 2020, ©2020.
- [10] G. Catino, P. Mastrolia, D.D. Monticelli, F. Punzo, Four-dimensional closed manifolds admit a weak harmonic Weyl metric, *Commun. Contemp. Math.* 25 (8) (2023) 2250047, 34.
- [11] A. Derdziński, Self-dual Kähler manifolds and Einstein manifolds of dimension four, *Compos. Math.* 49 (3) (1983) 405–433.
- [12] M. Gromov, H.B. Lawson Jr., The classification of simply connected manifolds of positive scalar curvature, *Ann. Math.* (2) 111 (3) (1980) 423–434.
- [13] M. Gromov, H.B. Lawson Jr., Positive scalar curvature and the Dirac operator on complete Riemannian manifolds, *Publ. Math. Inst. Hautes Études Sci.* 58 (1983) 83–196.
- [14] M.J. Gursky, Locally conformally flat four- and six-manifolds of positive scalar curvature and positive Euler characteristic, *Indiana Univ. Math. J.* 43 (3) (1994) 747–774.
- [15] N.H. Kuiper, On conformally-flat spaces in the large, *Ann. Math.* (2) 50 (1949) 916–924.
- [16] C. LeBrun, Kodaira dimension and the Yamabe problem, *Commun. Anal. Geom.* 7 (1) (1999) 133–156.
- [17] C. LeBrun, Bach-flat Kähler surfaces, *J. Geom. Anal.* 30 (3) (2020) 2491–2514.
- [18] R. Schoen, S.T. Yau, On the structure of manifolds with positive scalar curvature, *Manuscr. Math.* 28 (1–3) (1979) 159–183.
- [19] I.M. Singer, J.A. Thorpe, The curvature of 4-dimensional Einstein spaces, in: *Global Analysis (Papers in Honor of K. Kodaira)*, Univ. Tokyo Press, Tokyo, 1969, pp. 355–365.