ON THE $(1, p)$-POINCARÉ INEQUALITY

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ABSTRACT. We show that s-John domains support the $(1, p)$-Poincaré inequality for all finite $p > p_0$. We prove that the lower bound p_0 is sharp.

1. INTRODUCTION

A bounded domain D in $\mathbb{R}^n$, $n \geq 2$, supports a (q, p)-Poincaré inequality if there exists a finite constant c such that the inequality,

$$\left(\int_D |u(x) - u_D|^q dx\right)^{\frac{1}{q}} \leq c\left(\int_D |\nabla u(x)|^p dx\right)^{\frac{1}{p}},$$

holds for all $u \in W^{1,p}(D)$; here $1 \leq p < \infty$, $1 \leq q < \infty$, and u_D is the integral average of u. Poincaré inequalities are useful in analysis, especially in the theory of partial differential equations. They have been widely studied in the case $q \geq p$, see for example the book of Maz'ya and Poborchi [9]. Our focus on this question is different: we study the case $1 \leq q \leq p$. Clearly, by Hölder's inequality, if a domain supports the (p, p)-Poincaré inequality, then it supports the (q, p)-Poincaré inequality for every $1 \leq q \leq p$. The benefit is that the inequality with $q < p$ can be supported by more irregular domains than the inequality with $q = p$. We provide a sharp quantitative version of this statement for s-John domains. They form a large class of irregular domains including the widely used 1-John domains and domains that satisfy the quasihyperbolic boundary condition. Our result is given in terms of the upper Minkowski dimension which has been previously used with Poincaré inequalities on domains, for example in [1], [2].

In this paper we show that s-John domains support the $(1, p)$-Poincaré inequality for all finite $p > p_0 = \max\{1, p_1\}$ where

$$p_1 = \frac{s(n-1) - \lambda + 1}{n - \lambda + 1}$$

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depends on the upper Minkowski dimension λ of the domains boundary, Theorem 4.2. We prove that the lower bound p_0 is sharp in the critical case $p_0 > 1$, Remark 5.37. Our result is a generalization of the result of Smith and Stegenga [10] where the (p, p)-Poincaré inequality was studied.

We formulate and prove a decomposition theorem for a (q, p)-Poincaré inequality, $1 \le q < p < \infty$, Theorem 3.2 which we use when we prove our main theorem Theorem 4.2. We formulate and prove several lemmata in Section 4 in order to obtain sharp upper bounds for the requirements in Theorem 3.2. In order to show the sharpness of our result we introduce the s-version of a 1-John domain, Definition 5.9, using the concept of an s-apartment. Given a 1-John domain and its Whitney decomposition the rough idea is to plant an s-apartment into each Whitney cube. The upper Minkowski dimension of the boundary of a 1-John domain is inherited by the s-version, Proposition 5.11, and the s-version is an s-John domain, Proposition 5.16. With the s-version of an explicitly constructed 1-John domain we are able to show that the lower bound p_0 is sharp.

2. Notation

Let D and G be bounded domains in $\mathbb{R}^n$, $n \ge 2$, and let $1 \le q \le p < \infty$. An open n-dimensional ball centered at x and with radius $r > 0$ is denoted by $B^n(x, r)$. We let Q be a cube in $\mathbb{R}^n$, whose sides are parallel to the coordinate axes with x_Q the center and $\ell(Q)$ the side-length. By tQ, $t > 0$, we mean the cube that is centered at the same point x_Q but whose side-length is $t\ell(Q)$. The Lebesgue measure of a measurable set E in $\mathbb{R}^n$ is written as $|E|$.

We say that D is a (q, p)-*Poincaré domain* if it supports the (q, p)-Poincaré inequality: there is a finite positive constant $\kappa_{q,p}(D)$ such that

$$\left(\fint_D |u - u_D|^q dy\right)^{\frac{1}{q}} \le \kappa_{q,p}(D)\left(\fint_D |\nabla u|^p dy\right)^{\frac{1}{p}} \tag{2.1}$$

for all $u \in W^{1,p}(D)$; where

$$u_D := \fint_D u(x)dx = \frac{1}{|D|}\int_D u(x)dx$$

is the integral average of function u over D, and the constant $\kappa_{q,p}(D)$ depends only on n, p, q and D. By Hölder's inequality D is a (q, p)-Poincaré domain whenever D is a (p, p)-Poincaré domain and furthermore $\kappa_{q,p}(D) \le \kappa_{p,p}(D)$. The inequality (2.1) is often written in the form

$$\left(\int_D |u - u_D|^q dy\right)^{\frac{1}{q}} \le \kappa_{q,p}(D)|D|^{\frac{1}{q}-\frac{1}{p}}\left(\int_D |\nabla u|^p dy\right)^{\frac{1}{p}}$$

and $\kappa_{q,p}(D)|D|^{\frac{1}{q}-\frac{1}{p}}$ is called a (q, p)-Poincaré constant.

2.2. *Remark.* We frequently use the well-known fact

$$\kappa_{q,p}(Q) \leq \kappa_{p,p}(Q) \leq c(n)|Q|^{\frac{1}{n}}$$

for a cube Q, [3, p. 157].

By $\mathcal{W}_D$ we denote a Whitney decomposition of the domain D. This is a family of those closed dyadic cubes Q in the Whitney decomposition of $\mathbb{R}^n \setminus \partial D$ for which $Q \subset D$. However, we modify the standard construction, cf. [11, p. 167], such that $\mathcal{W}_D$ consists of cubes Q for which $\frac{9}{8}\operatorname{diam}(Q) \leq 1$ and

$$\kappa_{q,p}(\operatorname{int} \tfrac{9}{8}Q) \leq c(n)|\tfrac{9}{8}Q|^{\frac{1}{n}} \leq 1. \tag{2.3}$$

If the domain D is clear from the context we write simply $\mathcal{W}$ for $\mathcal{W}_D$. For every $k \in \mathbb{N}$, we write

$$\mathcal{W}_k := \{Q \in \mathcal{W}_D \,:\, \ell(Q) = 2^{-k}\}$$

and by $\sharp\mathcal{W}_k$ we denote the number of cubes in this family. Note that $\mathcal{W}_D = \bigcup_{k=0}^{\infty} \mathcal{W}_k$.

Let E in R^n be a non-empty bounded set. By $\mathcal{H}^\lambda(E)$ we mean the λ-dimensional Hausdorff measure of E. The Hausdorff dimension of E is written as $\dim_{\mathcal{H}}(E)$. The upper Minkowski dimension of E is

$$\dim_{\mathcal{M}}(E) := \sup\{d \geq 0 \,:\, \limsup_{r\to 0+} \mathcal{M}_d(E, r) = \infty\},$$

where

$$\mathcal{M}_d(E, r) := \frac{|E + B^n(0, r)|}{r^{n-d}} := \frac{|\cup_{x\in E} B^n(x, r)|}{r^{n-d}}, \quad r > 0,$$

is the d-dimensional Minkowski precontent.

3. Poincaré decomposition

The following Poincaré decomposition is from [4] which, in turn, is based on [5]. A collection $C(D) = \{D_0, D_1, \ldots, D_k\}$ of bounded domains in $\mathbb{R}^n$ with $D_k = D$ is said to be a *chain* from D_0 to D whenever $D_i \cap D_j \neq \emptyset$ if and only if $|i - j| \leq 1$. The length of a chain $C(D)$ is denoted by $\ell(C(D)) = k$.

Let Π be a collection of bounded (q, p)-Poincaré domains. Let us fix constants $N \geq 1$ and $c_1 > 0$. We call Π a (q, p)-*Poincaré decomposition* of a domain G, if

(i) $G = \bigcup_{D\in\Pi} D$;
(ii) $\sum_{D\in\Pi} \chi_D(x) \leq N\chi_G(x)$ for all $x \in \mathbb{R}^n$, where χ_G is the characteristic function of G; and
(iii) there is a domain $D_0 \in \Pi$ such that for each $D \in \Pi$ there exists a chain $C(D) = \{D_0, D_1, \ldots, D_{\ell(C(D))-1}, D\}$ of domains in Π with

$$\max\{|D_i|, |D_{i-1}|\} \leq c_1|D_i \cap D_{i-1}| \tag{3.1}$$

for $i = 1, \ldots, \ell(C(D))$.

For each D in Π we fix a chain $C(D)$ satisfying (3.1) and call this the *Poincaré chain* from D_0 to D. For a fixed $A \in \Pi$ we write

$$A(\Pi) := \{D \in \Pi : A \in C(D)\}.$$

Various Poincaré decompositions and their analogues are available in the literature. The Whitney cubes are used for example in [5, 6]. The optimal (q, p)-Poincaré inequalities for certain "Rooms and Passages"-domains are obtained in [4] by using a Poincaré decomposition arising from the special geometry of the underlying domain.

We prove a slight modification of [4, Theorem 2.4] and [5, Theorem 4.4]. For the sake of completeness we present the proof.

3.2. **Theorem.** *Let $1 \le q < p < \infty$. Let G be a bounded domain in $\mathbb{R}^n$ and let Π be a (q, p)-Poincaré decomposition of G. If $\kappa_{q,p}(D) \le 1$ for every $D \in \Pi$ and there are positive and finite constants c and $\varkappa$ such that*

$$\sum_{D \in \Pi} \kappa_{q,p}(D)^{\frac{pq}{p-q}-\varkappa} |D| \le c, \tag{3.3}$$

and for every $A \in \Pi$

$$\sum_{D \in A(\Pi)} \ell(C(D))^{q-1} |D| \le c\kappa_{q,p}(A)^{-\varkappa\frac{p-q}{p}} |A|, \tag{3.4}$$

then the domain G is a (q, p)-Poincaré domain.

Proof. Let D_0 be a fixed domain in Π. The Hölder's inequality yields

$$\left(\int_G |u(x) - u_G|^q \, dx\right)^{\frac{1}{q}} \le 2\left(\int_G |u(x) - u_{D_0}|^q dx\right)^{\frac{1}{q}}.$$

By the elementary inequalities

$$|a + b|^q \le 2^{q-1}(|a|^q + |b|^q), \qquad |a + b|^{\frac{1}{q}} \le |a|^{\frac{1}{q}} + |b|^{\frac{1}{q}},$$

with $1 \le q < \infty$, we obtain

$$\begin{aligned} \left(\int_G |u(x) - u_{D_0}|^q dx\right)^{\frac{1}{q}} &\le \left(\sum_{D \in \Pi} \int_D |u(x) - u_{D_0}|^q dx\right)^{\frac{1}{q}} \\ &\le c \underbrace{\left(\sum_{D \in \Pi} \int_D |u(x) - u_D|^q dx\right)^{\frac{1}{q}}}_{=:\, I} + c \underbrace{\left(\sum_{D \in \Pi} \int_D |u_D - u_{D_0}|^q dx\right)^{\frac{1}{q}}}_{=:\, II}. \end{aligned} \tag{3.5}$$

The term $\mathcal{I}$ in (3.5) is estimated by the (q,p)-Poincaré inequality in D and Hölder's inequality for sums with $\left(\frac{p}{q}, \frac{p}{p-q}\right)$

$$\begin{aligned}
\mathcal{I} &\leq \left(\sum_{D\in\Pi} \kappa_{q,p}(D)^q |D|^{1-\frac{q}{p}} \left(\int_D |\nabla u(x)|^p dx\right)^{\frac{q}{p}}\right)^{\frac{1}{q}} \\
&\leq \left(\sum_{D\in\Pi} (\kappa_{q,p}(D)^q |D|^{1-\frac{q}{p}})^{\frac{p}{p-q}}\right)^{\frac{p-q}{pq}} \left(\sum_{D\in\Pi} \int_D |\nabla u(x)|^p dx\right)^{\frac{1}{p}} \qquad (3.6)\\
&\leq c\left(\int_G |\nabla u(x)|^p dx\right)^{\frac{1}{p}},
\end{aligned}$$

where in the last inequality we used the estimate

$$\sum_{D\in\Pi} \kappa_{q,p}(D)^{\frac{pq}{p-q}} |D| \leq \sum_{D\in\Pi} |D| \leq N|G| < \infty,$$

which follows from the properties of the (q,p)-Poincaré decomposition Π and the boundedness of G.

We are left to handle the term $\mathcal{II}$ in (3.5). Let us connect every domain $D \in \Pi$ to the fixed domain D_0 by a Poincaré chain $C(D) = (D_0, D_1, \ldots, D_{k-1}, D)$. By the inequality

$$\left(\sum_{i=1}^{k} t_i\right)^q \leq k^{q-1} \sum_{i=1}^{k} t_i^q,$$

with $1 \leq q < \infty$, we obtain

$$\begin{aligned}
\mathcal{II} &\leq \left(\sum_{D\in\Pi} \int_D \ell(C(D))^{q-1} \sum_{i=1}^{\ell(C(D))} |u_{D_i} - u_{D_{i-1}}|^q dx\right)^{\frac{1}{q}} \\
&= \left(\sum_{D\in\Pi} \int_D \ell(C(D))^{q-1} \sum_{i=1}^{\ell(C(D))} \fint_{D_i\cap D_{i-1}} |u_{D_i} - u_{D_{i-1}}|^q dy dx\right)^{\frac{1}{q}} \\
&\leq \left(\sum_{D\in\Pi} |D|\, \ell(C(D))^{q-1} \sum_{i=1}^{\ell(C(D))} |D_i \cap D_{i-1}|^{-1} 2^{q-1} \left\{\int_{D_i} |u(y) - u_{D_i}|^q dy\right.\right. \\
&\quad \left.\left. + \int_{D_{i-1}} |u(y) - u_{D_{i-1}}|^q dy\right\}\right)^{\frac{1}{q}}.
\end{aligned}$$

By the (q,p)-Poincaré inequality and condition (3.1)

$$
\begin{aligned}
\mathcal{II} \le c\Bigg(\sum_{D\in\Pi} |D|\,\ell(C(D))^{q-1} \sum_{i=1}^{\ell(C(D))} |D_i \cap D_{i-1}|^{-1} \\
\cdot \Bigg\{ \kappa_{q,p}(D_i)^q\, |D_i|^{1-\frac{q}{p}} \bigg(\int_{D_i} |\nabla u(y)|^p\, dy \bigg)^{\frac{q}{p}} \\
+ \kappa_{q,p}(D_{i-1})^q |D_{i-1}|^{1-\frac{q}{p}} \bigg(\int_{D_{i-1}} |\nabla u(y)|^p\, dy \bigg)^{\frac{q}{p}} \Bigg\}\Bigg)^{\frac{1}{q}} \\
\le c \underbrace{\Bigg(\sum_{D\in\Pi} |D|\ell(C(D))^{q-1} \sum_{A\in C(D)} \kappa_{q,p}(A)^q |A|^{-\frac{q}{p}} \bigg(\int_A |\nabla u|^p\, dy \bigg)^{\frac{q}{p}} \Bigg)^{\frac{1}{q}}}_{=:\,\mathcal{III}} .
\end{aligned}
$$

Rearranging the double sum and using (3.4) we obtain

$$
\begin{aligned}
\mathcal{III} &\le \Bigg(\sum_{A\in\Pi} \sum_{D\in A(\Pi)} \ell(C(D))^{q-1} |D|\; \kappa_{q,p}(A)^q |A|^{-\frac{q}{p}} \bigg(\int_A |\nabla u|^p\, dy \bigg)^{\frac{q}{p}} \Bigg)^{\frac{1}{q}} \\
&\le c \Bigg(\sum_{A\in\Pi} \kappa_{q,p}(A)^{q-\varkappa\frac{p-q}{p}} |A|^{1-\frac{q}{p}} \bigg(\int_A |\nabla u|^p\, dy \bigg)^{\frac{q}{p}} \Bigg)^{\frac{1}{q}} .
\end{aligned}
$$

By Hölder's inequality with $\left(\frac{p}{q}, \frac{p}{p-q}\right)$ and by (3.3) this yields

$$
\begin{aligned}
\mathcal{III} &\le c \Bigg(\sum_{A\in\Pi} \Big(\kappa_{q,p}(A)^{q-\varkappa\frac{p-q}{p}} |A|^{1-\frac{q}{p}} \Big)^{\frac{p}{p-q}} \Bigg)^{\frac{p-q}{pq}} \Bigg(\sum_{A\in\Pi} \int_A |\nabla u(y)|^p\, dy \Bigg)^{\frac{1}{p}} \\
&\le c \bigg(\int_G |\nabla u|^p\, dy \bigg)^{\frac{1}{p}} .
\end{aligned}
$$

This completes the proof. □

3.7. *Remark.* Theorem 3.2 is a generalization of [5, Theorem 4.4], where Hurri showed that G is a (p,p)-Poincaré domains if condition (3.4) is replaced by

$$
\sum_{D\in A(\Pi)} \ell(C(D))^{p-1} |D| \le c\kappa_{p,p}(A)^{-p} |A| \tag{3.8}
$$

and condition (3.3) is omitted. Note that condition (3.4) gives condition (3.8) by a limiting process: If we choose $\varkappa = pq/(p-q)$, then condition (3.3) holds. Condition (3.4) is now

$$
\sum_{D\in A(\Pi)} \ell(C(D))^{q-1} |D| \le c\kappa_{q,p}(A)^{-q} |A|,
$$

which yields (3.8) as $q \to p$.

3.9. *Remark.* The two conditions (3.3) and (3.4) were used in the proof of Theorem 3.2 to establish the following estimate:

$$\sum_{A\in\Pi}\Big(\sum_{D\in A(\Pi)}\ell(C(D))^{q-1}|D|\,\kappa_{q,p}(A)^q|A|^{-\frac{q}{p}}\Big)^{\frac{p}{p-q}}<\infty. \tag{3.10}$$

An examination of the proof reveals that the two conditions above can be replaced with (3.10) in the formulation of Theorem 3.2. We will use this single condition later to obtain sharp estimates in s-John domains.

4. s-John domains

We prove that an s-John domain G in $\mathbb{R}^n$ is a $(1,p)$-Poincaré domain if $\dim_{\mathcal{M}}(\partial G)\le\lambda$, $p\in(1,\infty)$, and

$$p>\frac{s(n-1)-\lambda+1}{n-\lambda+1}.$$

The last inequality can be written as

$$s<\frac{n}{n-1}+(n-\lambda+1)\cdot\frac{p-1}{n-1}.$$

Note that $n-\lambda+1\ge 1$. Smith and Stegenga [10, Theorem 10] proved that an s-John domain G in $\mathbb{R}^n$ is a (p,p)-Poincaré domain if $1\le p<\infty$ and

$$s<\frac{n}{n-1}+\frac{p-1}{n-1}.$$

Our result turns out to be a sharp generalization of the result of Smith and Stegenga in terms of the parameters n, p, s, and λ. The sharpness is discussed later in Remark 5.37.

4.1. **Definition.** Let $s\ge 1$. A bounded domain G in $\mathbb{R}^n$, $n\ge 2$, is an *s-John domain* if there exists a point x_0 in G and a constant $c>0$ such that every point x in G can be joined to x_0 by a rectifiable path $\gamma:[0,l]\to G$ parametrized by its arc length for which $\gamma(0)=x$, $\gamma(l)=x_0$, $l\le c$, and

$$\operatorname{dist}(\gamma(t),\partial G)\ge t^s/c\qquad\text{for } t\in[0,l].$$

The point x_0 is called an *s-John center* of G.

The following is our main theorem, concerning the $(1,p)$-Poincaré inequality on s-John domains.

4.2. **Theorem.** *Let $s>1$, $1<p<\infty$, and $\lambda\in[n-1,n]$. Let G be an s-John domain in $\mathbb{R}^n$ such that $\dim_{\mathcal{M}}(\partial G)\le\lambda$. If*

$$p>\frac{s(n-1)-\lambda+1}{n-\lambda+1}, \tag{4.3}$$

then G is a $(1,p)$-Poincaré domain.

First we prove certain lemmata. The actual proof of this theorem is presented at the end of this section.

We begin with the following reductions: The case $\lambda = n$ in Theorem 4.2 follows from Theorem 10 in [10]. Hence we can assume that $\lambda < n$. Choose $\lambda' \in (\lambda, n)$ such that (4.3) is true if λ is replaced by λ'. Then $\dim_{\mathcal{M}}(\partial G) < \lambda'$ and hence we may assume that $\dim_{\mathcal{M}}(\partial G)$ is strictly less than $\lambda \in [n-1, n)$. This assumption is later used with the aid of the following lemma.

4.4. **Lemma.** *Let K in $\mathbb{R}^n$ be a compact set such that*

$$\dim_{\mathcal{M}}(K) < \lambda, \qquad \textit{where } \lambda \in [n-1, n).$$

There is a positive constant c as follows: Assume that $\{B_1, B_2, \ldots, B_N\}$ is a family of N disjoint balls in $\mathbb{R}^n$, each of which is centered in K and whose radius is $r \in (0,1]$. Then $N \le cr^{-\lambda}$.

Proof. By definition, we have

$$\inf_{a>0} \left\{ \sup_{r\in(0,a)} \frac{|K + B^n(0,r)|}{r^{n-\lambda}} \right\} = \limsup_{r\to 0+} \mathcal{M}_\lambda(K, r) < \infty.$$

In particular, there is $a \in (0,1)$ such that

$$\sup_{r\in(0,a)} \frac{|K + B^n(0,r)|}{r^{n-\lambda}} = C < \infty. \tag{4.5}$$

We consider a family $\{B_1, \ldots, B_N\}$ of disjoint balls in $\mathbb{R}^n$, each of which is centered in K and whose radius is $r \in (0,1]$. We separate two cases **I** and **II**:

I: $r \in [a, 1]$. In this case we have

$$\begin{aligned} N &\le c_n \sum_{i=1}^N \frac{|B_i|}{r^n} \le c_n a^{-n} \sum_{i=1}^N |B_i| = c_n a^{-n} \left| \bigcup_{i=1}^N B_i \right| \\ &\le c_n a^{-n} |K + B^n(0,r)| \le c_n a^{-n} |K + B^n(0,1)| = c_1 \le c_1 r^{-\lambda}. \end{aligned}$$

II: $r \in (0,a)$. The estimate (4.5) yields

$$\begin{aligned} N &\le c_n r^{-n} \sum_{i=1}^N |B_i| \le c_n r^{-n} |K + B^n(0,r)| = c_n r^{-\lambda} \frac{|K + B^n(0,r)|}{r^{n-\lambda}} \\ &\le c_n C r^{-\lambda} = c_2 r^{-\lambda}. \end{aligned}$$

Combining the cases **I** and **II** the required estimate holds true with a constant $c = \max\{c_1, c_2\}$. □

For the proof of Theorem 4.2 we fix a Whitney decomposition $\mathcal{W} = \mathcal{W}_G$ satisfying (2.3).

We write

$$\frac{9}{8}\mathcal{W} := \left\{ \operatorname{int} \frac{9}{8} Q \ : \ Q \in \mathcal{W} \right\}.$$

In order to equip this family with Poincaré chains, we fix $Q_0 \in \mathcal{W}$ and state that the s-John center of G is x_{Q_0}. We wish to join Q_0 to every cube R in $\mathcal{W}$. It is convenient first to connect x_R to x_{Q_0} by an s-John path γ_R that joins a sequence of midpoints of intersecting Whitney cubes to each other. Indeed, such a path will yield a Poincaré chain with nice properties. The following construction is essentially from [10, p. 86]. Other constructions are used in [5, 6].

Fix a rectifiable path γ that is parametrized by its arc length and joins the points x_R and x_{Q_0} as in Definition 4.1. Assume that x_{Q_0} lies in one of the cubes intersecting R. Then join x_R to x_{Q_0} by an arc that is contained in $R \cup Q_0$ and whose length is comparable to $\ell(R)$. Otherwise there is $r > 0$ such that $\gamma(r)$ lies in the boundary of a cube $P \in \mathcal{W}$ that intersects R and $\gamma(t)$ belongs to a cube that is not intersecting R whenever $t \in (r, \ell(\gamma)]$. Now we connect the midpoint of x_R to the midpoint of x_P by an arc whose length is comparable to $\ell(R)$ and that is contained in $R \cup P$. Then we iterate the steps above but with R replaced by P. This procedure is repeated until we reach x_{Q_0}. Finally we collect the arcs in the order that they were constructed, and arc length parametrize them by a path γ_R. It is straightforward to verify that

$$t^s \leq c \operatorname{dist}(\gamma_R(t), \partial G) \qquad \text{if } t \in [0, \ell(\gamma_R)], \tag{4.6}$$

where $c > 0$ depends on the s-John constant of G and n.

We define $P(R)$, $R \in \mathcal{W}$, to be the union of those cubes in $\mathcal{W}$ whose midpoints lie in the trace of γ_R. If $Q \in \mathcal{W}$, we write

$$S(Q) := \bigcup \{R \in \mathcal{W} \,:\, Q \subset P(R)\}.$$

This is the *shadow* of Q. Let $D \in \frac{9}{8}\mathcal{W}$. Then $D = \operatorname{int} \frac{9}{8}Q$ for some $Q \in \mathcal{W}$, and we define $\mathcal{C}(D)$ to be the Poincaré chain

$$\left\{ \operatorname{int} \frac{9}{8} R \,:\, R \in \mathcal{W} \text{ and } R \subset P(Q) \right\}$$

that is ordered by reversing the order as γ_R hits the midpoints of these cubes. The cube $D_0 := \operatorname{int} \frac{9}{8}Q_0$ is the first and $\operatorname{int} \frac{9}{8}Q$ is the last.

It follows from the construction above that the family $\frac{9}{8}\mathcal{W}$ equipped with these Poincaré chains is a $(1,p)$-Poincaré decomposition of G.

For $j, k \in \mathbb{N}$ and $\sigma \geq 1$, we define

$$\mathcal{W}_{j,k,\sigma} := \{Q \in \mathcal{W}_j \,:\, 2^{-(j-k)n} \leq |S(Q)| \leq \sigma \cdot 2^{-(j-k-1)n}\}.$$

The following lemma gives crucial estimates for the cardinality of such a family of cubes.

4.7. **Lemma.** *Let $s > 1$ and G be an s-John domain in $\mathbb{R}^n$ such that $\dim_{\mathcal{M}}(\partial G) < \lambda$, where $\lambda \in [n-1, n)$. Then there is $\sigma \geq 1$ such that*

$$\mathcal{W}_j = \bigcup_{k=0}^{[j-j/s]} \mathcal{W}_{j,k,\sigma} \qquad \textit{for every } j \in \mathbb{N}. \tag{4.8}$$

Furthermore, if $k \in \{0, 1, \ldots, [j - j/s]\}$*, we have*

$$\sharp \mathcal{W}_{j,k,\sigma} \leq c 2^{-kn} 2^{j(n+1+(\lambda-n-1)/s)}. \tag{4.9}$$

The positive constant c *depends on* s*,* n*,* ∂G*, and the* s*-John constant of the domain* G*.*

Proof. Let us fix $j \in \mathbb{N}$ and begin with a covering argument. The $5r$-covering theorem, see e.g. [8, p. 23], implies that there is a finite family

$$\mathcal{F} \subset \{B^n(x, 2^{-j/s}) : x \in \partial G\}$$

of disjoint balls such that

$$\partial G \subset \bigcup_{B \in \mathcal{F}} 5B. \tag{4.10}$$

We claim that, if $Q \in \mathcal{W}_j$, then there exists $B \in \mathcal{F}$ such that $Q \subset c_1 B$. Here c_1 is a constant depending on n only. To verify this, let $y \in \partial G$ be a closest point in ∂G to the midpoint x_Q of Q. Using the covering property (4.10) yields a point x in ∂G such that $B^n(x, 2^{-j/s}) \in \mathcal{F}$ and $y \in B^n(x, 5 \cdot 2^{-j/s})$. Now, if $z \in Q$, we have

$$|z - x| \leq |z - x_Q| + |x_Q - y| + |y - x| \leq c2^{-j} + c2^{-j} + 5 \cdot 2^{-j/s} < c_1 2^{-j/s}.$$

It follows that $Q \subset B^n(x, c_1 2^{-j/s}) = c_1 B^n(x, 2^{-j/s})$ as required.

Next we fix $Q \in \mathcal{W}_j$ and any ball $B := B^n(x, 2^{-j/s})$ in $\mathcal{F}$ such that $Q \subset c_1 B$. We claim that

$$S(Q) \subset B^n(x, c_2 2^{-j/s}), \tag{4.11}$$

where $c_2 > c_1$ is a constant depending on s, n and the s-John constant of G. To show this, we let $R \in \mathcal{W}$ be a cube for which $Q \subset P(R)$. Consider the path γ_R which connects x_R to x_{Q_0} and satisfies (4.6). Because $Q \subset P(R)$, we find that $\gamma_R(t) = x_Q$ for some t. Using the properties of Whitney cubes and (4.6), we obtain

$$|x_R - x_Q|^s \leq t^s \leq c \operatorname{dist}(\gamma_R(t), \partial G) = c \operatorname{dist}(x_Q, \partial G) \leq c2^{-j}.$$

It follows that

$$\begin{aligned} \operatorname{diam}(R) &\leq c \operatorname{dist}(x_R, \partial G) \\ &\leq c|x_R - x_Q| + c \operatorname{dist}(x_Q, \partial G) \leq c2^{-j/s} + c2^{-j} \leq c2^{-j/s}. \end{aligned}$$

Hence, if $y \in R$, we have

$$\begin{aligned} |y - x| &\leq |y - x_R| + |x_R - x_Q| + |x_Q - x| \\ &\leq c2^{-j/s} + c2^{-j/s} + c_1 2^{-j/s} < c_2 2^{-j/s}. \end{aligned}$$

The inclusion (4.11) follows.

As a consequence of (4.11), we have

$$2^{-jn} = |Q| \leq |S(Q)| \leq \sigma \cdot 2^{-jn/s}$$

for a constant $\sigma \geq 1$ depending on s, n, and the s-John constant of G. In particular, we see that (4.8) is valid with this constant.

It remains to prove the estimate (4.9). In order to do this, we establish the following auxiliary estimate

$$\sharp\{Q\in\mathcal{W}_j\,:\,Q\subset P(R)\}\le c_3\,2^{j(1-1/s)}\qquad\text{if } R\in\mathcal{W}. \tag{4.12}$$

Here the constant c_3 depends on s, n, and the s-John constant of G. In order to see this, we fix $R\in\mathcal{W}$ and let γ_R be the path connecting x_R to x_{Q_0}. Let $Q_1,\dots,Q_M\in\mathcal{W}_j$ be cubes such that $Q_i\subset P(R)$ for every $i\in\{1,2,\dots,M\}$. We number these cubes in the same order as γ_R hits their midpoints. In particular, if $\gamma_R(t)=x_{Q_M}$, then $\gamma_R[0,t]$ joins the midpoints of M cubes whose side-length is 2^{-j}. Using (4.6), we obtain

$$(M-1)2^{-j}\le t\le c\,\operatorname{dist}(\gamma_R(t),\partial G)^{1/s}=c\,\operatorname{dist}(x_{Q_M},\partial G)^{1/s}\le c2^{-j/s}.$$

It follows that $M\le c_3\,2^{j(1-1/s)}$ as required in (4.12).

Then we fix $k\in\{0,1,\dots,[j-j/s]\}$ where $[j-j/s]$ is the integer part of $j-j/s$. Fix also $B:=B^n(x,2^{-j/s})\in\mathcal{F}$. First we estimate the number of cubes that are included in c_1B. Inclusion (4.11) yields

$$\begin{aligned}&\sharp\{Q\in\mathcal{W}_{j,k,\sigma}\,:\,Q\subset c_1B\}\\
&\le\sum_{\substack{Q\in\mathcal{W}_{j,k,\sigma}\\ Q\subset c_1B}}2^{(j-k)n}|S(Q)|\le 2^{(j-k)n}\sum_{Q\in\mathcal{W}_{j,k,\sigma}}|S(Q)\cap c_2B|\\
&\le 2^{(j-k)n}\sum_{Q\in\mathcal{W}_{j,k,\sigma}}\sum_{\substack{R\in\mathcal{W}\\ Q\subset P(R)}}|R\cap c_2B|=2^{(j-k)n}\sum_{R\in\mathcal{W}}\sum_{\substack{Q\in\mathcal{W}_{j,k,\sigma}\\ Q\subset P(R)}}|R\cap c_2B|.\end{aligned}$$

Now (4.12) shows that the last term above is bounded by

$$c_3\,2^{(j-k)n}2^{j(1-1/s)}|c_2B|\le c_4 2^{-kn}2^{j(n+1-1/s-n/s)}.$$

Here c_4 is a constant depending on s, n, and the s-John constant of G.

From the considerations above it follows that

$$\sharp\mathcal{W}_{j,k,\sigma}\le\sum_{B\in\mathcal{F}}\sharp\{Q\in\mathcal{W}_{j,k,\sigma}\,:\,Q\subset c_1B\}\le c_4\sum_{B\in\mathcal{F}}2^{-kn}2^{j(n+1-1/s-n/s)}. \tag{4.13}$$

Recall that $\mathcal{F}$ is a family of disjoint balls, each of which is centered in ∂G and whose radius is $2^{-j/s}\in(0,1]$. Therefore Lemma 4.4 yields $\sharp\mathcal{F}\le c2^{j\lambda/s}$. Combining this estimate with (4.13) allows us to conclude that

$$\sharp\mathcal{W}_{j,k,\sigma}\le c2^{j\lambda/s}2^{-kn}2^{j(n+1-1/s-n/s)}.$$

Simplifying the exponents gives us (4.9). □

Proof of Theorem 4.2. By using both Remark 2.2 and (2.3), we obtain $\kappa_{1,p}(D)\le c(n)|D|^{\frac{1}{n}}\le 1$ for every $D\in\frac{9}{8}\mathcal{W}$. Hence, according to Remark 3.9, it suffices to verify the finiteness of

$$\Sigma:=\sum_{A\in\frac{9}{8}\mathcal{W}}\Bigg(\sum_{D\in A(\frac{9}{8}\mathcal{W})}|D|\,|A|^{1/n-1/p}\Bigg)^{p/(p-1)}.$$

From the definitions and the estimate $|\frac{9}{8}Q| \le c_n|Q|$ it follows that

$$\Sigma \le c \sum_{Q\in\mathcal{W}} (|S(Q)|\,|Q|^{1/n-1/p})^{p/(p-1)}.$$

By using (4.8) from Lemma 4.7, we can write

$$\Sigma \le c \sum_{j=0}^{\infty} \sum_{k=0}^{[j-j/s]} \sum_{Q\in\mathcal{W}_{j,k,\sigma}} (|S(Q)|\,|Q|^{1/n-1/p})^{p/(p-1)}.$$

Then, by using the definition of $\mathcal{W}_{j,k,\sigma}$ and (4.9) from Lemma 4.7, we obtain the estimate

$$\begin{aligned}\Sigma &\le c \sum_{j=0}^{\infty} \sum_{k=0}^{[j-j/s]} 2^{-kn} 2^{j(n+1+(\lambda-n-1)/s)} \cdot (2^{-(j-k)n} \cdot 2^{-jn(1/n-1/p)})^{p/(p-1)} \\ &= c \sum_{j=0}^{\infty} \sum_{k=0}^{[j-j/s]} 2^{kn(p/(p-1)-1)} 2^{j(n+1+(\lambda-n-1)/s-np/(p-1)-p/(p-1)+n/(p-1))}.\end{aligned}$$

We fix j and k as in the summation above. Then

$$kn\Big(\frac{p}{p-1}-1\Big) \le n(j-j/s)\Big(\frac{p}{p-1}-1\Big) = \frac{jn(1-1/s)}{p-1}.$$

Using also the trivial estimate $[j-j/s] \le j$, we find that

$$\begin{aligned}\Sigma &\le c \sum_{j=0}^{\infty} j \cdot 2^{j(n(1-1/s)/(p-1)+n+1+(\lambda-n-1)/s-np/(p-1)-p/(p-1)+n/(p-1))} \\ &\le c \sum_{j=0}^{\infty} j \cdot 2^{j(ns-s+\lambda p-\lambda-np-p+1)/s(p-1)}.\end{aligned}$$

By (4.3), we see that the last series converges. □

5. FAILURE OF A $(1,p)$-POINCARÉ INEQUALITY

Theorem 4.2 states that an s-John domain G in $\mathbb{R}^n$ with $s>1$ is a $(1,p)$-Poincaré domain if $\dim_{\mathcal{M}}(\partial G) \le \lambda \in [n-1,n)$, $p\in(1,\infty)$, and

$$p > \frac{s(n-1)-\lambda+1}{n-\lambda+1}. \tag{5.1}$$

We show that this result is sharp by constructing an s-John domain G_s in $\mathbb{R}^n$ such that $\dim_{\mathcal{M}}(\partial G_s) = \lambda$ and G_s is not a $(1,p)$-Poincaré domain if (5.1) fails. Hence Theorem 4.2 is a sharp generalization of the result of Smith and Stegenga, [10, Theorem 10].

The construction is based on modifying a given 1-John domain G such that the resulting domain G_s, known as the s-version of G, is an s-John domain containing multiple copies of rooms and s-passages at every size-scale 2^{-j}. The number of these copies at each scale depends on the upper Minkowski dimension of ∂G or, more precisely, on the number of Whitney cubes at each scale. The modification also preserves the upper Minkowski dimension so that $\dim_{\mathcal{M}}(\partial G) = \dim_{\mathcal{M}}(\partial G_s)$.

Before the modification procedure can take place, we need to find suitable 1-John domains in $\mathbb{R}^n$. Such domains G with

$$\dim_{\mathcal{M}}(\partial G) = \lambda \in [n-1, n)$$

are constructed in the proof of the following proposition.

5.2. **Proposition.** *Let $n \geq 2$ and $\lambda \in [n-1, n)$. There is a 1-John domain G in $\mathbb{R}^n$ such that $\dim_{\mathcal{M}}(\partial G) = \lambda$ and*

$$\limsup_{k\to\infty} 2^{-\lambda k} \cdot \sharp \mathcal{W}_k > 0. \tag{5.3}$$

Here $\sharp\mathcal{W}_k$ denotes the number of those cubes in $\mathcal{W}_G$ whose side-lengths are 2^{-k}.

Proof. We describe the construction in the case $n = 2$. The general case is similar.

Let us denote $Q := [-1,1] \times [-1,1] \subset \mathbb{R}^2$, $\kappa \in (0,1)$, and $r(\kappa) := (1-\kappa)/2 \in (0, 1/2)$. Let us write

$$z_1 := (\kappa + r(\kappa), \kappa + r(\kappa)),$$

and let z_2, z_3, z_4 stand for the corresponding symmetric points in the three remaining quadrants in any order. Let S_1, S_2, S_3, S_4 be similitudes that are defined by $S_i(x) := r(\kappa)x + z_i$, $i = 1,2,3,4$. Reasoning as in [8, pp. 66–67], we see that there is a non-empty compact set K in Q for which

$$K = S_1(K) \cup S_2(K) \cup S_3(K) \cup S_4(K). \tag{5.4}$$

The similitudes S_1, S_2, S_3, S_4 satisfy an open set condition [8, p. 67]. Hence, we can use both Corollary 5.8 and Theorem 4.14 in [8] to see that

$$\dim_{\mathcal{M}}(K) = \dim_{\mathcal{H}}(K) = -\frac{\log 4}{\log r(\kappa)}.$$

Notice that $-\log 4/\log r(\kappa)$ reaches all the values in $(0,2)$ if we let κ vary between $(0,1)$. In particular, there exists $\kappa = \kappa(\lambda) \in (0,1)$ for which the upper Minkowski dimension of the corresponding compact set $K_\lambda := K$ is λ. We define G to be the open set

$$G := B^n(0,2) \setminus K_\lambda.$$

Since $\partial G = \partial B^n(0,2) \cup K_\lambda$, we see that $\dim_{\mathcal{M}}(\partial G) = \lambda$.

We omit the proof of the evident fact that G is a 1-John domain. This proof can be based on that the iterations

$$\bigcup_{i_1=1}^{4} \cdots \bigcup_{i_m=1}^{4} S_{i_1} \circ \cdots \circ S_{i_m}(Q) \tag{5.5}$$

will converge to K_λ in the Hausdorff metric.

The inequality (5.3) is not immediately clear, so let us verify it. For this purpose, we write

$$Q_0^1 := [-\kappa, \kappa] \times [-\kappa, \kappa] \subset Q,$$

where $\kappa = \kappa(\lambda)$ is defined above. For every $m \in \mathbb{N}$ we re-index the 4^m disjoint cubes

$$S_{i_1} \circ \cdots \circ S_{i_m}(Q_0^1)\,,\; i_1, i_2, \ldots, i_m \in \{1, 2, 3, 4\},$$

by labeling them as Q_m^i, $i = 1, \ldots, 4^m$, in some fixed order. From (5.4) it follows that $\operatorname{int} Q_0^1 \subset Q \setminus K_\lambda$. Because (5.5) converges to K_λ in the Hausdorff metric, we see that $Q_0^1 \cap K_\lambda$ contains the four corner points of Q_0^1. These facts and (5.4) imply that $\operatorname{int} Q_m^i \subset Q \setminus K_\lambda \subset G$ and the intersection $Q_m^i \cap K_\lambda \subset \partial G$ contains the four corner points of Q_m^i for every $m \in \mathbb{N}$ and $i = 1, 2, \ldots, 4^m$.

Let us fix $m \in \mathbb{N}$. The previous observations imply that there are 4^m cubes $R_1, R_2, \ldots, R_{4^m}$ in $\mathcal{W}_G$ that are determined by requiring that the midpoint of Q_m^i is in R_i. Using also the properties of Whitney cubes, we find a constant $N \in \mathbb{N}$ such that

$$2^{-N}\ell(R_i) < \ell(Q_m^i) = 2\kappa\Big(\frac{1-\kappa}{2}\Big)^m \le 2^N \ell(R_i), \quad i = 1, 2, \ldots, 4^m.$$

By the pigeonhole principle, there is an index $k(m) \in \mathbb{Z}$ for which we have $\sharp\mathcal{W}_{k(m)} \ge 4^m/2N$ and

$$2^{-N-k(m)} < 2\kappa\Big(\frac{1-\kappa}{2}\Big)^m \le 2^{N-k(m)}.$$

Solving m gives us the inequalities

$$\frac{k(m) - N + \log_2(2\kappa)}{\log_2(2/(1-\kappa))} \le m < \frac{k(m) + N + \log_2(2\kappa)}{\log_2(2/(1-\kappa))}. \tag{5.6}$$

By using the first inequality in (5.6) and the identity

$$\lambda = -\frac{\log 4}{\log r(\kappa)} = \frac{2}{\log_2(2/(1-\kappa))},$$

we obtain the estimate

$$\sharp\mathcal{W}_{k(m)} \ge 4^m/2N \ge \underbrace{(2N)^{-1} 4^{\frac{-N+\log_2(2\kappa)}{\log_2(2/(1-\kappa))}}}_{=:c_{N,\kappa}} \cdot 2^{\frac{2k(m)}{\log_2(2/(1-\kappa))}} = c_{N,\kappa} 2^{k(m)\lambda}. \tag{5.7}$$

The second inequality in (5.6) implies that $\lim_{m\to\infty} k(m) = \infty$. Hence, using also (5.7), we have

$$\sup\{\sharp\mathcal{W}_k \cdot 2^{-\lambda k} \;:\; k \ge k_0\} \ge c_{N,\kappa} > 0 \qquad \text{if } k_0 \in \mathbb{N}.$$

The inequality (5.3) follows by taking the limit as $k_0 \to \infty$. □

Let us fix $s > 1$ and let Q in $\mathbb{R}^n$ be a closed cube that is centered at $x = (x_1, \ldots, x_n)$, and whose side-length is $\ell(Q) = \ell \le 1$. That is,

$$Q := \prod_{i=1}^{n} [x_i - \ell/2, x_i + \ell/2].$$

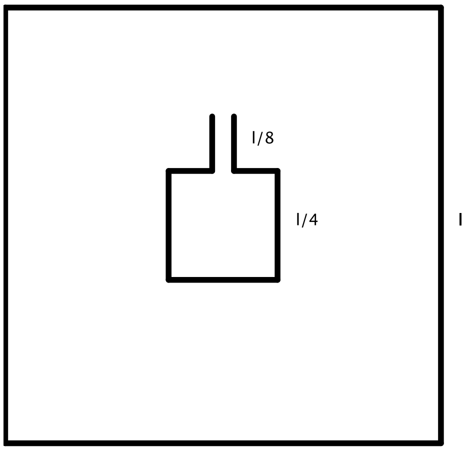

FIGURE 1. The s-apartment $A_s(Q)$.

The *room* in Q is the open cube

$$R(Q) := \operatorname{int}(\frac{1}{4}Q) = \prod_{i=1}^{n}(x_i - \ell/8, x_i + \ell/8)$$

whose center is x and side-length is $\ell/4$. The *s-passage* in Q is the open set

$$P_s(Q) := \Big(\prod_{i=1}^{n-1}(x_i - (\ell/8)^s, x_i + (\ell/8)^s)\Big) \times (x_n + \ell/8, x_n + \ell/4).$$

Note that $\ell/8 < 1$ and $s > 1$, so that we have $(\ell/8)^s < \ell/4$. Hence $P_s(Q) \subset \frac{1}{2}Q$. The *long s-passage* in Q is the open set

$$L_s(Q) := \Big(\prod_{i=1}^{n-1}(x_i - (\ell/8)^s, x_i + (\ell/8)^s)\Big) \times (x_n, x_n + \ell/2) \subset Q.$$

The *s-apartment* of Q is the set

$$A_s(Q) := L_s(Q) \cup Q \setminus (\partial R(Q) \cup \partial P_s(Q)) \subset Q, \tag{5.8}$$

see Figure 1.

5.9. **Definition.** If G in $\mathbb{R}^n$ is a 1-John domain and $s > 1$, then the *s-version of* G is the domain

$$G_s := Q_0 \cup \bigcup_{\substack{Q \in \mathcal{W}_G \\ Q \neq Q_0}} A_s(Q).$$

Recall that $\mathcal{W}_G$ is a Whitney decomposition of a bounded domain G, and Q_0 is the Whitney cube containing the 1-John center x_0 of G.

5.10. *Remark.* Since the s-apartment in $Q \in \mathcal{W}_G$ is a subset of Q, we have

$$G_s \subset \bigcup_{Q \in \mathcal{W}_G} Q = G.$$

The boundary of the s-version of G is given by

$$\partial G_s = \partial G \cup \bigcup_{\substack{Q\in\mathcal{W}_G\\ Q\neq Q_0}} \partial A_s(Q) \setminus \partial Q.$$

In particular, the countable stability of the Hausdorff dimension implies that $\dim_{\mathcal{H}}(\partial G_s) = \dim_{\mathcal{H}}(\partial G)$.

The upper Minkowski dimension is lacking the countable stability property. Therefore we need the following computation to verify that the upper Minkowski dimension of the boundary is preserved.

5.11. **Proposition.** *Let G in $\mathbb{R}^n$ be a 1-John domain. Then* $\dim_{\mathcal{M}}(\partial G) = \dim_{\mathcal{M}}(\partial G_s)$ *for every* $s > 1$.

Proof. Because $\partial G \subset \partial G_s$, the upper Minkowski dimension of ∂G is bounded by the upper Minkowski dimension of ∂G_s. Fix $\lambda > \dim_{\mathcal{M}}(\partial G)$. It remains to show that

$$\limsup_{r\to 0+} \mathcal{M}_\lambda(\partial G_s, r) < \infty.$$

Let us fix $r \in (0,1)$ and an integer J such that $2^J < r^{-1} \le 2^{J+1}$. Remark 5.10 yields

$$|\partial G_s + B^n(0,r)| \le |\partial G + B^n(0,r)| + \Big| \bigcup_{Q\in\mathcal{W}_G} (\partial A_s(Q) \setminus \partial Q) + B^n(0,r)\Big|. \tag{5.12}$$

By using the properties of Whitney cubes, we have

$$\begin{aligned} &\Big| \bigcup_{\substack{Q\in\mathcal{W}_G\\ \ell(Q)<2^{-J}}} (\partial A_s(Q) \setminus \partial Q) + B^n(0,r)\Big| \\ &\le \Big| \bigcup_{\substack{Q\in\mathcal{W}_G\\ \ell(Q)<2^{-J}}} (Q + B^n(0,r))\Big| \le |\partial G + B^n(0,cr)|. \end{aligned} \tag{5.13}$$

Here the constant $c \ge 1$ is independent of r.

On the other hand, we have

$$\Big| \bigcup_{\substack{Q\in\mathcal{W}_G\\ \ell(Q)\ge 2^{-J}}} (\partial A_s(Q)\setminus\partial Q) + B^n(0,r)\Big| \le \sum_{j=0}^{J} \sum_{Q\in\mathcal{W}_j} |(\partial A_s(Q)\setminus\partial Q) + B^n(0,r)|. \tag{5.14}$$

We bound $\sharp\mathcal{W}_j$ by the number N_j of those cubes whose side-length is 2^{-j} and which belong to the Whitney decomposition of $\mathbb{R}^n \setminus \partial G$. Since $\dim_{\mathcal{M}}(\partial G) < \lambda$ and $|\partial G| = 0$, see [7, Corollary 6.4], we can use Theorem 3.12 in [7] to conclude that N_j is bounded by a constant multiple of $2^{j\lambda}$. Also, the Lebesgue measure of $(\partial A_s(Q) \setminus \partial Q) + B^n(0,r)$ is bounded by a constant multiple of $r \cdot \ell(Q)^{n-1}$ if $Q \in \mathcal{W}_j$ and $0 \le j \le J$. Combining the estimates above yields

$$\begin{aligned} &\sum_{j=0}^{J} \sum_{Q \in \mathcal{W}_j} |(\partial A_s(Q) \setminus \partial Q) + B^n(0,r)| \\ &\le cr \cdot \sum_{j=0}^{J} 2^{j(\lambda-n+1)} \le cr 2^{J(\lambda-n+1)} = cr^{n-\lambda}. \end{aligned} \tag{5.15}$$

In the penultimate step we used the estimate $\lambda > \dim_{\mathcal{M}}(\partial G) \ge n-1$.

By combining the estimates (5.12), (5.13), (5.14), and (5.15) above, we find that

$$\limsup_{r\to 0+} \mathcal{M}_\lambda(\partial G_s, r) \le \limsup_{r\to 0+} \frac{2\cdot|\partial G + B^n(0,cr)| + cr^{n-\lambda}}{r^{n-\lambda}} < \infty.$$

In the last step we used the estimate $\lambda > \dim_{\mathcal{M}}(\partial G)$. □

5.16. **Proposition.** *Let $s>1$ and let G be a 1-John domain in $\mathbb{R}^n$ with 1-John center x_0 in G. Then the s-version of G, denoted by G_s, is an s-John domain with s-John center x_0.*

Proof. Let x be a point in G_s and $\delta : [0,l] \to G$, $l \le c$, be a path parametrized by its arc length such that $\delta(0) = x$, $\delta(l) = x_0$, and

$$\operatorname{dist}(\delta(t), \partial G) \ge t/c \qquad \text{for } t \in [0,l]; \tag{5.17}$$

where the positive constant c is independent of x and $\delta(t) \ne x_0$ if $t < l$.

We will construct a path $\gamma : [0,l_1] \to G_s$ connecting x to x_0 as in the definition of s-John domains. The idea behind the construction is to follow the path δ if this is possible, and to modify it otherwise in a quantitatively controlled manner. Note that the modification may be required since ∂G is a proper subset of ∂G_s. To take care of the additional boundary points, we let $Q \in \mathcal{W}_G$, $Q \ne Q_0$, and define

$$E(Q) := \prod_{i=1}^{n} (x_i - 3\ell/8, x_i + 3\ell/8) \subset Q,$$

where $x = (x_1, \ldots, x_n)$ is the center of Q and $\ell = \ell(Q)$, see Figure 2. For later purposes it is convenient to define $E(Q_0) = \emptyset$.

The following estimates are used while constructing the path γ. Here $\kappa \in (0,1)$ is a constant that is independent of the Whitney cubes. First,

$$\operatorname{dist}(y, \partial G_s) \ge \kappa\, \ell(Q) \qquad \text{for } y \in Q \setminus E(Q) \text{ and } Q \in \mathcal{W}_G. \tag{5.18}$$

A useful property of Whitney cubes is the following:

$$\ell(Q) \ge \kappa \operatorname{dist}(y, \partial G) \qquad \text{for } y \in Q \text{ and } Q \in \mathcal{W}_G. \tag{5.19}$$

We also use the following observation: Let $Q \in \mathcal{W}_G$, $Q \ne Q_0$. Then we can join any pair of points $z \in \overline{E(Q)}$ and $\omega \in \partial Q$ by using a rectifiable path parametrized by its arc length $\pi : [0,\rho] \to Q \cap G_s$ such that

$$\ell(Q) \ge \kappa \rho \tag{5.20}$$

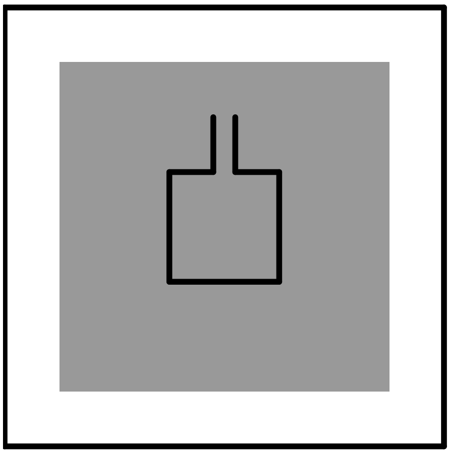

FIGURE 2. $E(Q)$.

and

$$\forall t \in [0,\rho] : \operatorname{dist}(\pi(t), \partial G_s) \geq \begin{cases} \kappa\, t^s, & \text{if } z \in E(Q); \\ \kappa\, \ell(Q), & \text{if } z \in \partial E(Q). \end{cases} \tag{5.21}$$

The construction of γ is based on an iterative algorithm. Hence, it is convenient to introduce the following invariant that allows us to keep track of the partial path that has already been constructed during the previous steps. We say that γ_r satisfies the (r,u)-*invariant* if $r \geq 0$, $u \in [0,l]$, and $\gamma_r : [0,r] \to G_s$ is a path parametrized by its arc length and satisfying the following conditions 1)–3):

1) $r \leq 8\kappa^{-1}u$;
2) $\gamma_r(0) = x$, $\gamma_r(r) = \delta(u)$;
3) $\operatorname{dist}(\gamma_r(t), \partial G_s) \geq \tau\, t^s$ if $t \in [0,r]$.

In 3) we have written

$$\tau = \min\{\kappa, 8^{-s}\kappa^{s+2}c^{-s}\} > 0.$$

Our goal is to construct $\gamma = \gamma_{l_1}$ which satisfies the (l_1,l)-invariant. Before the construction, let us introduce the following three steps that are used in the iterative process.

Step I: Let us assume that

$$\delta(0) = x \in E(Q) \qquad \text{for some } Q \in \mathcal{W}_G.$$

Recall that we have defined $E(Q_0) = \emptyset$ and therefore $Q \neq Q_0$. Since δ will reach $x_0 \in Q_0$, there is $u \in (0,l]$ such that $\delta(u) \in \partial Q$. Let us join $z = x \in E(Q)$ to $\omega = \delta(u) \in \partial Q$ by a path $\gamma_\sigma : [0,\sigma] \to Q \cap G_s$ satisfying (5.20) and (5.21) with $\rho = \sigma$. We claim that γ_σ satisfies the (σ,u)-invariant. First, it is a rectifiable path parametrized by its arc length whose trace lies in G_s. The other conditions:

1) By (5.20) we have $u \geq \operatorname{dist}(\partial Q, E(Q)) = \ell(Q)/8 \geq 8^{-1}\kappa\sigma$.
2) We have $\gamma_\sigma(0) = x$ and $\gamma_\sigma(\sigma) = \delta(u)$.

3) If $t \in [0,\sigma]$ we use (5.21) for $\mathrm{dist}(\gamma_\sigma(t), \partial G_s) \ge \kappa t^s \ge \tau t^s$.

Step II: Let us assume that γ_r satisfies the (r,u)-invariant and

$$\gamma_r(r) = \delta(u) \in \partial E(Q) \qquad \text{for some } Q \in \mathcal{W}_G.$$

There is a time $\bar{u} \in (u,l]$ such that $\delta(\bar{u}) \in \partial Q$. Join $z = \delta(u) \in \partial E(Q)$ to $\omega = \delta(\bar{u}) \in \partial Q$ by a path $\Pi : [0,\sigma] \to Q \cap G_s$ satisfying both (5.20) and (5.21) with $\rho = \sigma$. Then, we define

$$\gamma_{r+\sigma}(t) = \begin{cases} \gamma_r(t) & \text{for } t \in [0,r]; \\ \Pi(t-r) & \text{for } t \in [r, r+\sigma]. \end{cases}$$

We claim that $\gamma_{r+\sigma}$ satisfies the $(r+\sigma,\bar{u})$-invariant. It is an arc length parametrized path whose trace lies in G_s. The other conditions:

1) We have $\bar{u} - u \ge \mathrm{dist}(\partial Q, \partial E(Q)) = \ell(Q)/8$. Using also (5.20) yields

$$r + \sigma \le 8\kappa^{-1} u + \kappa^{-1}\ell(Q) \le 8\kappa^{-1}(u + \bar{u} - u) = 8\kappa^{-1}\bar{u}. \tag{5.22}$$

2) We have $\gamma_{r+\sigma}(0) = \gamma_r(0) = x$ and $\gamma_{r+\sigma}(r+\sigma) = \Pi(\sigma) = \delta(\bar{u})$.

3) If $t \in [0,r]$ we have $\mathrm{dist}(\gamma_{r+\sigma}(t), \partial G_s) = \mathrm{dist}(\gamma_r(t), \partial G_s) \ge \tau t^s$. If $t \in (r, r+\sigma]$, we use (5.21), (5.19), (5.17), and (5.22) for the estimate

$$\begin{aligned} \mathrm{dist}(\gamma_{r+\sigma}(t), \partial G_s) &= \mathrm{dist}(\Pi(t-r), \partial G_s) \\ &\ge \kappa\ell(Q) \ge \kappa^2\, \mathrm{dist}(\delta(\bar{u}), \partial G) \ge \kappa^2 c^{-1}\, \bar{u} \ge 8^{-1}\kappa^3 c^{-1} t. \end{aligned}$$

Note that again by (5.22), we have $0 < t \le 8\kappa^{-1}\bar{u} \le 8\kappa^{-1} l \le 8\kappa^{-1} c$. Since $1 - s \le 0$, we obtain

$$t = t^{1-s} t^s \ge (8\kappa^{-1}c)^{1-s} t^s = 8^{1-s}\kappa^{s-1}c^{1-s}t^s.$$

Hence, we have the estimate $\mathrm{dist}(\gamma_{r+\sigma}(t), \partial G_s) \ge (8^{-s}\kappa^{s+2}c^{-s})t^s \ge \tau t^s$.

Step III: Let us assume that γ_r satisfies the (r,u)-invariant and

$$\gamma_r(r) = \delta(u) \in Q \setminus \overline{E(Q)} \qquad \text{for some } Q \in \mathcal{W}_G.$$

By following δ from time u forwards, we will first arrive either at x_0 or $\partial E(Q)$ for some $Q_0 \ne Q \in \mathcal{W}_G$. Denote by $\bar{u} \in [u,l]$ this time of arrival, and define

$$\gamma_{r+\bar{u}-u}(t) = \begin{cases} \gamma_r(t) & \text{for } t \in [0,r], \\ \delta(t-r+u) & \text{for } t \in [r, r+\bar{u}-u]. \end{cases}$$

We claim that $\gamma_{r+\bar{u}-u}$ satisfies the $(r+\bar{u}-u,\bar{u})$-invariant. It is a path parametrized by its arc length and whose trace lies in G_s. The other properties:

1) Let $\varepsilon \in [0,\bar{u}-u]$. Since $8\kappa^{-1} > 1$, we have

$$r + \varepsilon \le 8\kappa^{-1}u + \varepsilon \le 8\kappa^{-1}(u+\varepsilon). \tag{5.23}$$

Setting $\varepsilon = \bar{u} - u$ yields $r + \bar{u} - u \le 8\kappa^{-1}\bar{u}$.

2) We have $\gamma_{r+\bar{u}-u}(0) = \gamma_r(0) = x$ and $\gamma_{r+\bar{u}-u}(r+\bar{u}-u) = \delta(\bar{u})$.

3) If $t \in [0, r]$ we have $\operatorname{dist}(\gamma_{r+\bar{u}-u}(t), \partial G_s) = \operatorname{dist}(\gamma_r(t), \partial G_s) \geq \tau t^s$. Assuming that $t \in [r, r + \bar{u} - u]$, we have

$$\operatorname{dist}(\gamma_{r+\bar{u}-u}(t), \partial G_s) = \operatorname{dist}(\delta(t - r + u), \partial G_s).$$

Let us fix $Q_t \in \mathcal{W}_G$ such that $\delta(t-r+u) \in Q_t \setminus E(Q_t)$. By using (5.18), (5.19), (5.17), and (5.23), we see that

$$\begin{aligned}\operatorname{dist}(\delta(t - r + u), \partial G_s) &\geq \kappa \ell(Q_t) \geq \kappa^2 \operatorname{dist}(\delta(t - r + u), \partial G)\\ &\geq \kappa^2 c^{-1} (u + t - r) \geq \kappa^2 c^{-1} (8\kappa^{-1})^{-1} (r + t - r) = 8^{-1} \kappa^3 c^{-1} t.\end{aligned}$$

Inequalities (5.23) yield

$$0 < t \leq r + \bar{u} - u \leq 8\kappa^{-1} \bar{u} \leq 8\kappa^{-1} l \leq 8\kappa^{-1} c.$$

Proceeding as in the end of Step II, we obtain the estimate

$$\operatorname{dist}(\gamma_{r+\bar{u}-u}(t), \partial G_s) \geq \tau t^s.$$

Having introduced these steps, we can now construct the path γ as follows. Let $x \in Q \in \mathcal{W}_G$. If $x \in E(Q)$, we apply Step I and obtain γ_σ satisfying the (σ, u)-invariant. Otherwise we write $\sigma = u = 0$ and define $\gamma_0(0) = x$. In any case, this procedure yields a path γ_σ which satisfies the (σ, u)-invariant and the condition $\gamma_\sigma(\sigma) \in Q \setminus E(Q)$ with $Q \in \mathcal{W}_G$. Assuming that $\gamma_\sigma(\sigma) \neq x_0$, we then proceed by invoking either Step II or Step III, depending on the situation. We keep on iterating these steps in alternating turns until, after a finite number of steps, we obtain a path γ_{l_1} satisfying the (l_1, l)-invariant as required. The process will end because every time we invoke Step II, we make at least

$$\min\{\ell(Q)/8 \,:\, Q \in \mathcal{W}_G \text{ and } \delta[0, l] \cap Q \neq \emptyset\} > 0$$

of progress along the path δ. This is seen by examining the proof of the condition 1) in Step II. □

We can now state one of the main result in this section.

5.24. **Theorem.** *Let G in $\mathbb{R}^n$ be a 1-John domain such that*

$$\dim_{\mathcal{M}}(\partial G) = \lambda \in [n - 1, n).$$

Then, for every $s > 1$, the s-version of G is an s-John domain with $\dim_{\mathcal{M}}(\partial G_s) = \lambda$ and it is not a (q, p)-Poincaré domain if $1 \leq q \leq p < \infty$ and

$$\frac{(p - q)(\lambda - n)}{pq} + \frac{(s - 1)(n - 1)}{p} > 1. \tag{5.25}$$

Proof. Let us assume that $s > 1$. The s-version of G is an s-John domain by Proposition 5.16. The upper Minkowski dimension of ∂G_s is λ by Proposition 5.11.

Let us then verify the claim concerning the (q, p)-Poincaré property. Choose $\lambda' \in (0, \lambda)$ so that (5.25) is true with λ replaced by λ'. Hence, by denoting λ' by λ, we may assume that the upper Minkowski dimension of ∂G is strictly greater than $\lambda \in (0, n)$. This fact is used as follows:

By both Theorem 3.12 and Lemma 6.5 in [7] we obtain the estimate

$$1 \le \limsup_{m\to\infty} 2^{-\lambda m} \cdot N_m \le c \limsup_{m\to\infty} 2^{-\lambda m} \cdot \Big(\sum_{M=m-2}^{m+2} \sharp \mathcal{W}_M \Big);$$

where N_m denotes the number of cubes in the Whitney decomposition of $\mathbb{R}^n \setminus \partial G$ whose side-length is 2^{-m} and c is a positive constant depending only on G and n. Choose $k_0 \in \mathbb{N}$ such that

$$\limsup_{m\to\infty} 2^{-\lambda(m+2-k_0)} \cdot \Big(\sum_{M=m-2}^{m+2} \sharp \mathcal{W}_M \Big) > 10.$$

Let $k \in \mathbb{N}$ and then choose $m := m(k) > \max\{k, k_0, -\log_2 \ell(Q_0)\} + 2$ and $j = j(k) \in \{m-2, \dots, m+2\}$ such that

$$\sharp \mathcal{W}_j \ge \Big(\sum_{M=m-2}^{m+2} \sharp \mathcal{W}_M \Big)/5 \ge 10 \cdot 2^{\lambda(m+2-k_0)}/5 \ge 2 \cdot 2^{\lambda(j-k_0)}. \tag{5.26}$$

Let us write $M_j := 2^{[\lambda(j-k_0)]}$, where $[\lambda(j-k_0)]$ means the integer-part of $\lambda(j-k_0) \ge 0$, and choose cubes

$$Q_j^1, \dots, Q_j^{2M_j} \in \mathcal{W}_j \setminus \{Q_0\}.$$

This can be done because of (5.26).

Let $Q = Q_j^i$ for some i. To the s-apartment $A_s(Q)$ in Q, we associate the function $u_{A_s(Q)} \colon G_s \to \mathbb{R}$ which has linear decay along the n^{th} variable in $P_s(Q)$ and satisfies

$$u_{A_s(Q)}(x) = \begin{cases} \ell(Q)^{(\lambda-n)/q}, & \text{if } x \in R(Q); \\ 0, & \text{if } x \in G_s \setminus (R(Q) \cup P_s(Q)). \end{cases} \tag{5.27}$$

Its partial derivatives in $\mathcal{D}'(G_s)$ are given by

$$\nabla u_{A_s(Q)} = (0, \dots, 0, -8\ell(Q)^{(\lambda-n)/q-1} \chi_{P_s(Q)}) \tag{5.28}$$

pointwise almost everywhere.

Let us define

$$u_j := \sum_{i=1}^{M_j} u_{A_s(Q_j^i)} - \sum_{i=M_j+1}^{2M_j} u_{A_s(Q_j^i)} \in W^{1,p}(G_s). \tag{5.29}$$

Note that

$$(u_j)_{G_s} = \frac{1}{|G_s|} \int_{G_s} u_j = 0 \tag{5.30}$$

because the integrals of functions $u_{A_s(Q_j^i)}$ are independent of i. It is also important to realize that the supports of the functions $u_{A_s(Q_j^i)}$ are mutually disjoint as i varies.

Using (5.30) and (5.27), we obtain

$$A_j := \Big(\int_{G_s} |u_j - (u_j)_{G_s}|^q\Big)^{1/q} = \Big(\sum_{i=1}^{2M_j} \int_{G_s} |u_{A_s(Q_j^i)}|^q\Big)^{1/q} \tag{5.31}$$
$$\geq \Big(2\cdot 2^{\lambda(j-k_0)-1}\cdot 2^{-j(\lambda-n)}\cdot 4^{-n}\cdot 2^{-jn}\Big)^{1/q} = c_{n,q,\lambda,k_0};$$

where $c_{n,q,\lambda,k_0} > 0$ depends on the indicated parameters. On the other hand, by using (5.28), we obtain

$$B_j := \Big(\int_{G_s} |\nabla u_j|^p\Big)^{1/p}$$
$$= \Big(\sum_{i=1}^{2M_j} \int_{G_s} |\nabla u_{A_s(Q_j^i)}|^p\Big)^{1/p} \tag{5.32}$$
$$\leq \Big(2\cdot 2^{\lambda(j-k_0)}\cdot (8\cdot 2^{-j((\lambda-n)/q-1)})^p\cdot (2\cdot (2^{-j}/8)^s)^{n-1}\cdot 2^{-j}/8\Big)^{1/p}$$
$$= c_{n,s,p,\lambda,k_0} 2^{j(1-(p-q)(\lambda-n)/pq-(s-1)(n-1)/p)};$$

where $c_{n,s,p,\lambda,k_0} > 0$ depends on the indicated parameters.

By combining the estimates (5.31) and (5.32), we obtain

$$\frac{A_j}{B_j} \geq c_{n,s,p,q,\lambda,k_0} 2^{j(-1+(p-q)(\lambda-n)/pq+(s-1)(n-1)/p)}. \tag{5.33}$$

Recall that $j = j(k) \geq k$. Hence, by using both (5.33) and (5.25), we find that the sequence $(A_{j(k)}/B_{j(k)})_{k=1}^\infty$ tends to ∞ as $k \to \infty$. This allows us to conclude that G_s is not a (q,p)-Poincaré domain. □

Under further assumptions we can replace the inequality in (5.25) by the identity. This is the content of the following theorem which can be used to provide sharp counter-examples if $q < p$.

5.34. **Theorem.** *Let G be a 1-John domain in $\mathbb{R}^n$ such that*

$$\limsup_{k\to\infty} 2^{-\lambda k}\cdot \sharp\mathcal{W}_k > 0, \qquad \text{where } \lambda = \dim_{\mathcal{M}}(\partial G) \in [n-1, n).$$

Then, for every $s > 1$, the s-version of G is an s-John domain with $\dim_{\mathcal{M}}(\partial G_s) = \lambda$ and it is not a (q,p)-Poincaré domain if $1 \leq q < p < \infty$ and

$$\frac{(p-q)(\lambda-n)}{pq} + \frac{(s-1)(n-1)}{p} \geq 1. \tag{5.35}$$

Proof. According to Theorem 5.24 we only need to verify that G_s is not a (q,p)-Poincaré domain if the left-hand side of (5.35) is equal to one. To this end, we choose $k_0 \in \mathbb{N}$ such that

$$\limsup_{k\to\infty} 2^{-\lambda(k-k_0)}\cdot \sharp\mathcal{W}_k > 2.$$

This allows us to inductively choose indices $j(k)$, $k \in \mathbb{N}$, such that

$$\max\{k_0, -\log_2 \ell(Q_0)\} < j(1) < j(2) < \cdots$$

and $\sharp\mathcal{W}_{j(k)} \geq 2\cdot 2^{\lambda(j(k)-k_0)}$ for every $k\in\mathbb{N}$. For every $j=j(k)$ we proceed as in Theorem 5.24; we begin from (5.26) and continue until we reach (5.29). This yields functions $u_{j(k)}\in W^{1,p}(G_s)$. Then, for each $m\in\mathbb{N}$ we define

$$v_m = \sum_{k=1}^{m} u_{j(k)} \in W^{1,p}(G_s).$$

Estimating further as in the proof of Theorem 5.24, we have $(v_m)_{G_s}=0$ and

$$C_m := \Big(\int_{G_s} |v_m - (v_m)_{G_s}|^q\Big)^{1/q} = \Big(\sum_{k=1}^{m}\sum_{i=1}^{2M_{j(k)}}\int_{G_s} |u_{A_s(Q^i_{j(k)})}|^q\Big)^{1/q} \geq c_{n,q,\lambda,k_0} m^{1/q}.$$

Furthermore, by using (5.35), we have

$$D_m := \Big(\int_{G_s} |\nabla v_m|^p\Big)^{1/p} = \Big(\sum_{k=1}^{m}\sum_{i=1}^{2M_{j(k)}}\int_{G_s} |\nabla u_{A_s(Q^i_{j(k)})}|^p\Big)^{1/p} \leq c_{n,s,p,\lambda,k_0} m^{1/p}.$$

Concluding from above and using the assumption that $q<p$, we find that

$$\frac{C_m}{D_m} \geq c_{n,s,p,q,k_0,\lambda} m^{1/q-1/p} \xrightarrow{m\to\infty} \infty.$$

This shows that G_s is not a (q,p)-Poincaré domain. □

The following corollary collects all of the results in this section. It is a consequence of Proposition 5.2, Theorem 5.24, and Theorem 5.34.

5.36. **Corollary.** *Let $n\geq 2$, $s>1$, and $\lambda\in[n-1,n)$. There is an s-John domain G_s in $\mathbb{R}^n$ such that $\dim_{\mathcal{M}}(\partial G_s)=\lambda$ and G_s is not a (q,p)-Poincaré domain if either $1\leq q\leq p<\infty$ and (5.25) is true, or $1\leq q<p<\infty$ and (5.35) is true.*

We finish with a remark concerning the sharpness of our results.

5.37. *Remark.* (i) Let $n\geq 2$, $s>1$, $\lambda\in[n-1,n)$, and $p>1$ be such that

$$p \leq \frac{s(n-1)-\lambda+1}{n-\lambda+1}.$$

Applying Corollary 5.36 with $q=1<p$ yields an s-John domain G_s in $\mathbb{R}^n$ such that $\dim_{\mathcal{M}}(\partial G_s)=\lambda$ and G_s is not a $(1,p)$-Poincaré domain. This allows us to conclude that Theorem 4.2 is sharp for $\lambda<n$.

(ii) Let $n\geq 2$, $s>1$, and $p>1$ be such that

$$p<(s-1)(n-1).$$

Using Corollary 5.36 with parameter λ sufficiently close to n yields an s-John domain G_s in $\mathbb{R}^n$ such that G_s is not a $(1,p)$-Poincaré domain. Theorem 4.2 implies that s-John domains in $\mathbb{R}^n$ are $(1,p)$-Poincaré domains if $p>(s-1)(n-1)$. In fact, they are (p,p)-Poincaré domains. Hence, Theorem 4.2 is essentially sharp for $\lambda=n$.

(iii) The reasoning in (ii) above shows that Theorem 10 in [10] for the (p,p)-case is essentially sharp. This theorem states that s-John domains in $\mathbb{R}^n$ are (p,p)-Poincaré domains if $1 \leq p < \infty$ and $p > (s-1)(n-1)$.

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