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# Regularity properties of nonlocal minimal surfaces via limiting arguments ☆

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#### Abstract

We prove an improvement of flatness result for nonlocal minimal surfaces which is independent of the fractional parameter s when  $s \to 1^-$ .

As a consequence, we obtain that all the nonlocal minimal cones are flat and that all the nonlocal minimal surfaces are smooth when the dimension of the ambient space is less or equal than 7 and *s* is close to 1. © 2013 Elsevier Inc. All rights reserved.

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The purpose of this paper is to study some regularity properties of nonlocal minimal surfaces as they approach the classical minimal surfaces.

Let  $n \ge 2$  and  $s \in (0, 1)$ . Given two non-overlapping (measurable) subsets A and B of  $\mathbb{R}^n$ , we define

$$\mathcal{L}(A, B) := \int_{A} \int_{B} \frac{1}{|x - y|^{n + s}} \, dy \, dx$$

Given a bounded open set  $\Omega \subset \mathbb{R}^n$  and a set  $E \subseteq \mathbb{R}^n$ , we let

$$\begin{aligned} \mathcal{J}_{s}(E,\Omega) &:= \mathcal{L}\big(E \cap \Omega, (\mathbb{C}E) \cap \Omega\big) + \mathcal{L}\big(E \cap \Omega, (\mathbb{C}E) \cap (\mathbb{C}\Omega)\big) \\ &+ \mathcal{L}\big(E \cap (\mathbb{C}\Omega), (\mathbb{C}E) \cap \Omega\big). \end{aligned}$$

We say that *E* is *s*-minimal in  $\Omega$  if for any  $\widetilde{E} \subseteq \mathbb{R}^n$  for which  $\widetilde{E} \cap (\mathcal{C}\Omega) = E \cap (\mathcal{C}\Omega)$  one has that

$$\mathcal{J}_{s}(E,\Omega) \leqslant \mathcal{J}_{s}(\widetilde{E},\Omega).$$

That is, E is s-minimal if it minimizes the functional among<sup>1</sup> competitors which agree outside  $\Omega$ .

The functional  $\mathcal{J}_s$  has been recently introduced in [6] as a model for nonlocal minimal surfaces, and its relation with the classical minimal surfaces has been established in [8,2], both in the geometric sense and in the Gamma-convergence framework.

Besides their neat geometric motivation, such nonlocal minimal surfaces also arise as limit interfaces of nonlocal phase segregation problems, see [11,12].

The main difficulty in the framework we consider is, of course, the nonlocal aspect of the contributions in the functional. The counterpart of this difficulty, however, is given by the fact that the functional is well defined for every (measurable) set – in particular, there is no need to introduce Caccioppoli sets in this case. Nevertheless, in spite of the results of [6,8,2], several regularity issues for *s*-minimizers are still open.

$$E_{\mathcal{I}} := \left\{ x \in E \text{ s.t. } \exists r > 0 \text{ s.t. } \left| (\mathfrak{C}E) \cap B_r(x) \right| = 0 \right\} \text{ and }$$

$$E_{\mathcal{E}} := \{ x \in E \text{ s.t. } \exists r > 0 \text{ s.t. } |E \cap B_r(x)| = 0 \},\$$

we take the convention that  $E_{\mathcal{I}} \subseteq E$  and  $E \cap E_{\mathcal{E}} = \emptyset$ .

<sup>&</sup>lt;sup>1</sup> Following a standard convention in geometric measure theory, all the sets will be implicitly assumed to contain their measure theoretic interior and to lie outside their measure theoretic exterior – this is possible up to changing a set with a set of zero Lebesgue measure, which does not affect the functional  $\mathcal{J}_s$ . More explicitly, if we set

The purpose of this paper is to develop some regularity theory when *s* is close to 1 by a compactness argument, taking advantage of the regularity theory of the classical minimal surfaces. Our main result is the following improvement of flatness:

**Theorem 1.** Let  $s_o \in (0, 1)$ ,  $\alpha \in (0, 1)$  and  $s \in [s_o, 1)$ . Let *E* be *s*-minimal in  $B_1$ . There exists  $\varepsilon_b > 0$ , possibly depending on *n*,  $s_o$  and  $\alpha$ , but independent of *s*, such that if

$$\partial E \cap B_1 \subseteq \left\{ |x \cdot e_n| \leqslant \varepsilon_{\flat} \right\} \tag{0.1}$$

then  $\partial E$  is a  $C^{1,\alpha}$ -graph in the  $e_n$ -direction.

The crucial part of Theorem 1 is that its flatness threshold  $\varepsilon_b$  is independent of s as  $s \to 1^-$ : in fact, for a fixed s, an improvement of flatness whose threshold depends on s has been obtained in [6] (see Theorem 6.1 there). The techniques used to prove Theorem 1 (hence to obtain a threshold independently of s as  $s \to 1^-$ ) are a uniform measure estimate for the oscillation, and a Calderón–Zygmund iteration. Both these tools have somewhat a classical flavor, but they need to be appropriately, and deeply, modified here: in particular, some fine estimates performed in [7] turn out to be very useful here in order to obtain bounds that are independent of s, and the iteration is not straightforward, but it has to distinguish two cases according to the size of the cubes involved, and the technical difficulties arising in the course of the proof turn out to be quite challenging.

As a consequence of Theorem 1, we obtain several regularity and rigidity results for *s*-minimal surfaces, such as:

## **Theorem 2.** *Let* $n \leq 7$ .

There exists  $\epsilon_o > 0$  such that if  $s \in (1 - \epsilon_o, 1)$  then any s-minimal cone is a hyperplane.

## **Theorem 3.** *Let* $n \leq 7$ *.*

There exists  $\epsilon_o > 0$  such that if  $s \in (1 - \epsilon_o, 1)$  then any s-minimal set is locally a  $C^{1,\alpha}$ -hypersurface.

## **Theorem 4.** Let n = 8.

There exists  $\epsilon_o > 0$  such that if  $s \in (1 - \epsilon_o, 1)$  then any s-minimal set is locally  $C^{1,\alpha}$ , everywhere except, at most, at countably many isolated points.

**Theorem 5.** There exists  $\epsilon_o > 0$  such that if  $s \in (1 - \epsilon_o, 1)$  then any *s*-minimal set is locally  $C^{1,\alpha}$  outside a closed set  $\Sigma$ , with  $\mathcal{H}^d(\Sigma) = 0$  for any d > n - 8.

For other recent regularity results for nonlocal minimal surfaces see [3,13].

## 1. Notation

A point  $x \in \mathbb{R}^n$  will be often written in coordinates as  $x = (x', x_n) \in \mathbb{R}^{n-1} \times \mathbb{R}$ .

The complement of a set  $\Omega \subseteq \mathbb{R}^n$  will be denoted by  $\mathcal{C}\Omega := \mathbb{R}^n \setminus \Omega$ . For any  $P \in \mathbb{R}^n$  and  $\rho > 0$ , we define the cylinder

$$K_{\rho}(P) := \{ |x' - P'| < \rho \} \times \{ |x_n - P_n| < \rho \}.$$

We also set  $K_{\rho} := K_{\rho}(0)$ .

The (n-1)-dimensional cube of side *R* centered at  $x'_o \in \mathbb{R}^{n-1}$  will be denoted by  $Q_R(x_o)$ .

If  $\nu \in S^{n-1}$ , given  $x \in \mathbb{R}^n$ , we define its projection along  $\nu$ , that is  $\pi_{\nu} x := x - (x \cdot \nu)\nu$ .

Given a set  $E \subset \mathbb{R}^n$ , we denote by  $d_E(x)$  the signed distance of a point  $x \in \mathbb{R}^n$ ; we will take the sign convention that  $d_E(x) \ge 0$  if  $x \in \mathbb{C}E$ .

If  $\Sigma \subset \mathbb{R}^n$  is a  $C^2$ -portion of hypersurface, we define  $\mathcal{H}(P)$  to be the mean curvature of  $\Sigma$  at P (with the convention that  $\mathcal{H}$  equals the sum of all the principal curvatures).

The *k*-dimensional Lebesgue measure of a (measurable) set  $A \subseteq \mathbb{R}^k$  will be denoted by |A|.

We let  $\varpi$  be the (n-2)-dimensional Hausdorff measure of the boundary of the (n-1)-dimensional unit ball.

Often, we will denote by c, C a suitable positive constant, that we allow ourselves the latitude of renaming at each step of the computation.

## 2. Proof of Theorem 1

Now we start the proof of Theorem 1, which is based on several steps.

First, we need to approximate our *s*-minimal surface with a graph. As soon as *s* approaches 1, a flat *s*-minimal surface approaches a classical, smooth, minimal surface, and this will allow us to keep the Lipschitz norm of this approximating graph under control.

Then, we perform an estimate on the detachment of this graph from its tangent hyperplane: this bound (together with a suitable auxiliary function and an estimate relating the integral equation with the classical mean curvature equation in the limit) provides an Alexandrov–Bakelman–Pucci type theory that controls the oscillation of the graph in measure.

This may be repeated at finer and finer scales via dyadic decomposition, by possibly taking advantage of the closeness to the smooth minimal surface when the size of the cubes become too small. In this way, one obtains a pointwise control on the oscillation of the approximating graph (and so of the original *s*-minimal surface), leading to the proof of Theorem 1.

Below are the full details of the proof.

#### 2.1. Building a graph via the distance function

One of the difficulties of our framework is that the *s*-minimal surfaces we are dealing with are not necessarily graphs. To get around this problem, we follow an idea of [5] and we consider level sets of the distance function in an appropriate scaling (this may be seen as a sup-convolution technique).

For this, we recall the following classical geometric observation on the regularity of the level sets of the distance function:

## **Lemma 6.** Let $E \subset \mathbb{R}^n$ . Assume that

$$\{x_n \leqslant -\gamma\} \cap K_r \subseteq E \cap K_r \subseteq \{x_n \leqslant \gamma\} \cap K_r,\tag{2.1}$$

for some  $r > \gamma > 0$ .

Let  $\delta \in (0, r/4)$  and  $S^{\pm} := \{x \in \mathbb{R}^n \text{ s.t. } d_E(x) = \pm \delta\}.$ 

Then, there exist  $c \in (0, 1)$  and  $C \in (1, +\infty)$  such that if  $\gamma/\delta < c$  then  $S^{\pm} \cap K_{r-2\delta}$  is a Lipschitz graph in the nth direction with Lipschitz constant bounded by  $C\sqrt{\gamma/\delta}$ .

Furthermore,  $S^-$  (resp.,  $S^+$ ) may be touched at any point of  $K_{r-2\delta}$  by a tangent paraboloid from above (resp., below).

**Proof.** We focus on  $S^-$ , the case of  $S^+$  being analogous. We would like to show that for any  $x, z \in S^- \cap K_{r-2\delta}$ 

$$x_n - z_n \leqslant C \sqrt{\frac{\gamma}{\delta}} |x' - z'|, \tag{2.2}$$

from which the desired result follows by possibly exchanging the roles of x and z.

For this, we argue like this. For any  $x \in S^- \cap K_{r-2\delta}$ , the ball of radius  $\delta$  centered at x is tangent to  $\partial E$  at some point  $y(x) \in \partial E \cap K_r$ , and, conversely,

the ball of radius  $\delta$  centered at y(x) is tangent to  $\delta^-$  at x. (2.3)

Let  $e_n := (0, ..., 1)$ . Since  $x + \delta e_n \in B_{\delta}(x)$ , we have that  $x + \delta e_n$  must lie in the closure of *E*. Hence, by (2.1),

$$x_n + \delta \leqslant \gamma. \tag{2.4}$$

Similarly, since  $y(x) \in \partial E$ , we obtain from (2.1) that

$$y_n(x) \ge -\gamma. \tag{2.5}$$

By (2.4) and (2.5),

$$y_n(x) - x_n \ge \delta - 2\gamma. \tag{2.6}$$

In the same way, we see that

$$y_n(z) - z_n \ge \delta - 2\gamma. \tag{2.7}$$

Now, if  $|x' - z'| \ge \sqrt{\gamma \delta}$ , we use (2.1) and (2.6) to deduce that

$$\begin{aligned} x_n - z_n &\leq (x_n - y_n(x)) + |y_n(x)| + |y_n(z)| + |y_n(z) - z_n| \\ &\leq (2\gamma - \delta) + \gamma + \gamma + |y(z) - z| \\ &\leq (2\gamma - \delta) + \gamma + \gamma + \delta \\ &= 4\gamma \leq 4\sqrt{\frac{\gamma}{\delta}} |x' - z'|, \end{aligned}$$

which proves (2.2) in this case.

So, we may focus on the case in which

$$\left|x'-z'\right| \leqslant \sqrt{\gamma\delta}.\tag{2.8}$$

Then, from (2.7),

$$\delta^{2} = |y(z) - z|^{2} = |y'(z) - z'|^{2} + |y_{n}(z) - z_{n}|^{2} \ge |y'(z) - z'|^{2} + (\delta - 2\gamma)^{2},$$

which gives

$$\left|y'(z) - z'\right| \leqslant 2\sqrt{\gamma\delta}.\tag{2.9}$$

Hence

$$|x'-y'(z)| \leq |x'-z'| + |z'-y'(z)| \leq 3\sqrt{\gamma\delta},$$

due to (2.8) and (2.9), and so, in particular,

$$\left|x'-y'(z)\right| \leqslant \frac{\delta}{100}.\tag{2.10}$$

So, we can define

$$p := \left(x', y_n(z) - \sqrt{\delta^2 - \left|y'(z) - x'\right|^2}\right).$$
(2.11)

We observe that

$$p \in \partial B_{\delta}(y(z)). \tag{2.12}$$

Also, from (2.6) and (2.1),

$$y_n(z) - x_n \ge y_n(z) - y_n(x) + \delta - 2\gamma \ge \delta - 4\gamma > 0.$$

Therefore, by (2.10), we have that x must be below  $B_{\delta}(y(z))$ , hence (2.12) implies that

$$x_n \leqslant p_n. \tag{2.13}$$

Now, we define  $P := (p - y(z))/\delta$  and  $Z := (z - y(z))/\delta$ . We observe that  $P, Z \in \partial B_1$ , due to (2.12). Also,  $P_n, Z_n \leq 0$ , due to (2.7) and (2.11). Moreover,  $|P'| + |Z'| \leq 1/50$  thanks to (2.9), (2.10) and (2.11). As a consequence

$$|P_n-Z_n|\leqslant 100 |P'-Z'|^2.$$

By scaling back, this gives that

$$|p_n - z_n| \leq \frac{100}{\delta} |p' - z'|^2 = \frac{100}{\delta} |x' - z'|^2 \leq 100 \sqrt{\frac{\gamma}{\delta}} |x' - z'|,$$

where (2.8) was used once again. From this and (2.13), we infer that

$$x_n - z_n \leqslant p_n - z_n \leqslant 100 \sqrt{\frac{\gamma}{\delta}} |x' - z'|,$$

which gives (2.2) in this case too.

Then, the desired Lipschitz property is a consequence of (2.2), and the existence of a tangent paraboloid follows from (2.3) (and, by (2.6), the touching occurs from above in this case).

We point out that the Lipschitz bound  $C\sqrt{\gamma/\delta}$  in Lemma 6 is optimal, as the example in Fig. 1 shows.

A global version of Lemma 6 is given by the following result:

**Corollary 7.** Let  $E_{\star} \subseteq \mathbb{R}^n$ . Suppose that  $\partial E_{\star} \cap K_2$  is a  $C^{1,\alpha}$ -graph in the nth direction, for some  $\alpha > 0$ , and let  $M_{\star}$  be its  $C^{1,\alpha}$ -norm.

Then, there exists  $c_{\star} \in (0, 1)$ , possibly depending on  $M_{\star}$ , such that the following holds.



Fig. 1. Optimality of the Lipschitz constant  $\sqrt{\gamma/\delta} = \gamma/\sqrt{\delta\gamma}$  in Lemma 6.

Let  $\gamma, \delta \in (0, 1/4)$ ,  $E \subseteq \mathbb{R}^n$  and suppose that

 $E \cap K_2$  lies in a  $\gamma$ -neighborhood of  $E_{\star}$ .

(2.14)

Let  $\mathbb{S}^{\pm} := \{x \in \mathbb{R}^n \text{ s.t. } d_E(x) = \pm \delta\}.$ 

Then,  $S^{\pm} \cap K_1$  is a Lipschitz graph in the nth direction, provided that  $\gamma/\delta < c_{\star}$ ,  $\delta < c_{\star}\gamma^{1/(1+\alpha)}$  and  $\gamma < c_{\star}$ .

More precisely, there exists a constant C > 1 for which  $S^{\pm} \cap K_1$  is a Lipschitz graph in the nth direction and the Lipschitz norm of  $S^{\pm} \cap K_1$  is controlled by  $C\sqrt{\gamma/\delta} + M_o$ , where  $M_o$  is the Lipschitz norm of  $\partial E_{\star} \cap K_2$ .

Furthermore,  $S^-$  (resp.,  $S^+$ ) may be touched at any point of  $K_{1-2\delta}$  by a tangent paraboloid from above (resp., below). Finally, for any  $|x'| \leq 1/2$ ,

$$u^{+}(x') - u^{-}(x') \leq 2(2 + M_o)(\gamma + \delta).$$
 (2.15)

**Proof.** Since  $\partial E_{\star} \cap K_2$  is  $C^{1,\alpha}$ , it separates with power  $(1 + \alpha)$  from its tangent hyperplane, with multiplicative constant  $M_{\star}$ . Then, we take  $r := (\gamma/M_{\star})^{1/(1+\alpha)}$  and we cover  $\partial E_{\star} \cap K_2$  with cylinders  $K_r$ , centered at points of  $\partial E_{\star}$  and rotated parallel to the tangent plane of  $\partial E_{\star}$ .

By construction, in each of these cylinders,  $\partial E_{\star}$  separates no more than  $M_{\star}r^{1+\alpha} = \gamma$  from its tangent hyperplane, and so *E* is  $2\gamma$ -close to such hyperplane. Therefore, Lemma 6 applies (with  $\gamma$  there replaced by  $2\gamma$ ). Consequently, in each of these cylinders,  $S^{\pm}$  is a Lipschitz graph with respect to the normal direction  $\nu$  of  $\partial E_{\star}$  (and its Lipschitz norm is bounded by  $C\sqrt{\gamma/\delta}$  with respect to  $\nu$ ).

This proves the first part of Corollary 7. It remains to prove (2.15). For this, we fix  $|\bar{x}'| \leq 1/2$ and we set  $P^{\pm} := (\bar{x}', u^{\pm}(\bar{x}')) \in S^{\pm}$ . Then, we take  $Q^{\pm} \in \partial E$  that realizes the distance, i.e.  $|P^{\pm} - Q^{\pm}| = \delta$ . By (2.14), we find points  $R^{\pm} \in \partial E_{\star}$  such that  $|R^{\pm} - Q^{\pm}| \leq \gamma$ . Notice that

$$|(R^{\pm})' - (P^{\pm})'| \leq |(R^{\pm})' - (Q^{\pm})'| + |(Q^{\pm})' - (P^{\pm})| \leq \gamma + \delta.$$

Therefore, since  $(P^+)' = (P^-)' = u(\bar{x})$ ,

$$|(R^+)' - (R^-)'| \leq |(R^+)' - (P^+)'| + |(P^-)' - (R^-)'| \leq 2(\gamma + \delta).$$

So, since  $\partial E_{\star}$  is a Lipschitz graph,

$$|R_n^+ - R_n^-| \leq M_o |(R^+)' - (R^-)'| \leq 2M_o(\gamma + \delta).$$

In particular,

$$|R^+ - R^-| \leq 2(1 + M_o)(\gamma + \delta)$$

and so

$$|P^{+} - P^{-}| \leq |P^{+} - Q^{+}| + |Q^{+} - R^{+}| + |R^{+} - R^{-}| + |R^{-} - Q^{-}| + |Q^{-} - P^{-}| \leq 2(1 + M_{o})(\gamma + \delta) + 2\gamma + 2\delta,$$

which gives (2.15).

## 2.2. Detachment from the tangent hyperplane

Next result is one of the cornerstones of our procedure since it manages to reconstruct a geometry similar to the one obtained in Lemma 8.1 of [7]. In spite of its technical flavor, it basically states under which conditions we can say that a function separates from a tangent hyperplane quadratically in a ring, independently of s as  $s \to 1^-$ .

**Lemma 8.** Fix  $\overline{C} \ge 1$ . Let  $\varepsilon$ , R > 0 and  $\overline{x}' \in \mathbb{R}^{n-1}$ . Let  $u : \mathbb{R}^{n-1} \to \mathbb{R}$  be a Lipschitz function, with

$$\left|\nabla u(x')\right| \leqslant \overline{C} \tag{2.16}$$

*a.e.*  $|x' - \bar{x}'| \leq R$  and let  $\bar{x}_n := u(\bar{x}')$ ,  $\bar{x} := (\bar{x}', \bar{x}_n)$  and  $E := \{x_n < u(x')\}$ . Assume that

$$(1-s)\int_{B_R(\bar{x})} \frac{\chi_E(y) - \chi_{CE}(y)}{|\bar{x}-y|^{n+s}} dy \leqslant \frac{\varepsilon}{R^s}.$$
(2.17)

Suppose that there exists  $\mathcal{P} \in C^{1,1}(\mathbb{R}^{n-1})$  such that

$$\left|\nabla \mathcal{P}(x')\right| + R\left|D^2 \mathcal{P}(x')\right| \leqslant \varepsilon \tag{2.18}$$

a.e.  $|x' - \bar{x}'| \leq R$ ,

$$\mathcal{P}(\bar{x}') = u(\bar{x}') \quad and \quad \mathcal{P}(x') \leq u(x') \quad in |x' - \bar{x}'| \leq R.$$
(2.19)

Then, there exists a constant  $C \ge 1$ , only depending on n and  $\overline{C}$ , such that<sup>2</sup> the following result holds, as long as  $\varepsilon \in (0, 1/C)$ . There exists an (n - 1)-dimensional ring  $S_r := \{|x' - \overline{x}'| \in \mathbb{C}\}$ 

<sup>&</sup>lt;sup>2</sup> The reader may compare (2.20) here and (8.1) in [7]. Notice that such an estimate, roughly speaking, says that u separates quadratically from its tangent hyperplane in a ring, up to a set with small density – and the constants are independent of s.

From this, a general geometric argument implies a uniform quadratic detachment in a whole ball with smaller radius (see (8.2) and (8.3) in [7]) and consequently a linear bound on the image of the subdifferential of the convex envelope (see (8.4) in [7]), and this is the necessary ingredient for the Alexandrov–Bakelman–Pucci theory to work (see Sections 8, 9 and 10 in [7]). In our framework, u will be the level set of the distance from an s-minimal surface: we will add to it the auxiliary function of Section 2.4 and consider the touching point of the convex envelope. These points, by construction are touched from below by a hyperplane, so u is touched from below by a smooth function, which motivates the setting of Lemma 8.

(r/C, r), with  $r \in (0, R]$ , such that, for any M > 0 we have

$$\frac{|S_r \cap \{u(x') - \bar{x}_n - \nabla \mathcal{P}(\bar{x}') \cdot (x' - \bar{x}') > \frac{M\varepsilon r^2}{R}\}|}{|S_r|} \leqslant \frac{C}{M}.$$
(2.20)

**Proof.** We consider the normal vector of the graph of  $\mathcal{P}$  at  $\bar{x}'$ , to wit

$$\nu := \frac{(-\nabla \mathcal{P}(\bar{x}'), 1)}{\sqrt{|\nabla \mathcal{P}(\bar{x}')|^2 + 1}}.$$

Let also

$$P := \{x_n < \mathcal{P}(x')\},\$$

$$L := \{x_n < \nabla \mathcal{P}(\bar{x}') \cdot (x' - \bar{x}') + \bar{x}_n\} \text{ and }$$

$$A := \bar{x} + \{|x \cdot v| \leq \frac{4\varepsilon}{R} |\pi_v x|^2\}.$$

We recall that  $\pi_{\nu}$  is the projection along  $\nu$  (see Section 1) and we notice that A is just the translation and the rotation of the set

$$\left\{|x_n| \leqslant \frac{4\varepsilon}{R} \left|x'\right|^2\right\}$$

and so, for any  $\rho > r > 0$ ,

$$\int_{B_{\rho}(\bar{x})\setminus B_{r}(\bar{x})} \chi_{A}(y) \, dy \leqslant \int_{|y'|\leqslant \rho} \left[ \int_{|y_{n}|\leqslant (4\varepsilon/R)|y'|^{2}} dy_{n} \right] dy' \leqslant \frac{C\varepsilon\rho^{n+1}}{R}.$$
(2.21)

On the other hand, since L is a halfspace passing through  $\bar{x}$ , the following cancellations hold:

$$\int_{B_{\rho}(\bar{x})\setminus B_{r}(\bar{x})} \chi_{L}(y) - \chi_{\mathcal{C}L}(y) \, dy = 0 \quad \text{and} \quad \int_{B_{\rho}(\bar{x})\setminus B_{r}(\bar{x})} \frac{\chi_{L}(y) - \chi_{\mathcal{C}L}(y)}{|\bar{x} - y|^{n+s}} \, dy = 0.$$
(2.22)

Moreover, by (2.19), we have that  $P \subseteq E$ , thus

$$\chi_E \geqslant \chi_P \quad \text{and so} \quad \chi_{\mathbb{C}E} \leqslant \chi_{\mathbb{C}P}.$$
 (2.23)

Also, the quadratic detachment of  $\mathcal{P}$  from its tangent plane given by (2.18) implies that  $(L \setminus A) \cap B_R \subseteq P \cap B_R$  and  $(\mathcal{C}P) \cap B_R \subseteq ((\mathcal{C}L) \cup A) \cap B_R$ . Therefore, in  $B_R$ ,

$$\chi_L - \chi_A \leqslant \chi_{L\setminus A} \leqslant \chi_P \quad \text{and} \quad \chi_{\mathbb{C}P} \leqslant \chi_{(\mathbb{C}L)\cup A} \leqslant \chi_{\mathbb{C}L} + \chi_A. \tag{2.24}$$

So, from (2.23) and (2.24), we obtain that, in  $B_R$ ,

$$\chi_E - \chi_{CE} \geqslant \chi_P - \chi_{CP} \geqslant \chi_L - \chi_{CL} - 2\chi_A. \tag{2.25}$$

Now, for any  $m \in \mathbb{N}$ , let

$$r_m := \frac{R}{((2+\overline{C})n)^m},$$
  

$$R_m := B_{r_m}(\overline{x}) \setminus B_{r_{m+1}}(\overline{x}) \text{ and }$$
  

$$b_m := \int_{R_m} \frac{\chi_E(y) - \chi_{CE}(y)}{|\overline{x} - y|^{n+s}} dy.$$

Here above  $\overline{C}$  is the one fixed in the statement of Lemma 8. We claim that there exists  $m \in \mathbb{N}$  such that

$$b_m \leqslant \frac{C_o \varepsilon r_m^{1-s}}{R},\tag{2.26}$$

for a suitable constant  $C_o \ge 1$ . The proof is by contradiction: if not, we have

$$\int_{B_R(\bar{x})} \frac{\chi_E(y) - \chi_{CE}(y)}{|\bar{x} - y|^{n+s}} dy$$
$$= \sum_{m=0}^{+\infty} b_m \ge \frac{C_o \varepsilon}{R} \sum_{m=0}^{+\infty} r_m^{1-s} = \frac{C_o \varepsilon}{R^s} \sum_{m=0}^{+\infty} ((2 + \overline{C})n)^{-(1-s)m}$$
$$= \frac{C_o \varepsilon}{R^s} \cdot \frac{1}{1 - ((2 + \overline{C})n)^{-(1-s)}} \ge \frac{C_o \varepsilon}{R^s} \cdot \frac{1}{C(1-s)}$$

for some C > 0. This is in contradiction with (2.17) if  $C_o$  is large, and so (2.26) is established. From now on, *m* will be the one given by (2.26), and  $C_o$  will be simply *C* (and, as usual, we will take the freedom of renaming *C* line after line).

Now, we make use of (2.25), (2.22) and (2.21) to obtain that

$$\begin{split} &\int\limits_{R_m} \left(\chi_E(y) - \chi_{\mathbb{C}E}(y)\right) \left(\frac{1}{|\bar{x} - y|^{n+s}} - \frac{1}{r_m^{n+s}}\right) dy \\ &\geqslant \int\limits_{R_m} \left(\chi_L(y) - \chi_{\mathbb{C}L}(y) - 2\chi_A(y)\right) \left(\frac{1}{|\bar{x} - y|^{n+s}} - \frac{1}{r_m^{n+s}}\right) dy \\ &= \int\limits_{R_m} \left(-2\chi_A(y)\right) \left(\frac{1}{|\bar{x} - y|^{n+s}} - \frac{1}{r_m^{n+s}}\right) dy \\ &\geqslant -2\int\limits_{R_m} \frac{\chi_A(y)}{|\bar{x} - y|^{n+s}} dy \\ &\geqslant -\frac{C}{r_m^{n+s}} \int\limits_{R_m} \chi_A(y) dy \\ &\geqslant -\frac{C\varepsilon r_m^{1-s}}{R}. \end{split}$$

Combining this with (2.26), we conclude that

$$\frac{|E \cap R_m| - |(\mathcal{C}E) \cap R_m|}{r_m^{n+s}} = \int\limits_{R_m} \frac{\chi_E(y) - \chi_{\mathcal{C}E}(y)}{r_m^{n+s}} dy$$
$$= b_m - \int\limits_{R_m} \left(\chi_E(y) - \chi_{\mathcal{C}E}(y)\right) \left(\frac{1}{|\bar{x} - y|^{n+s}} - \frac{1}{r_m^{n+s}}\right)$$
$$\leqslant \frac{C\varepsilon r_m^{1-s}}{R}$$

that is

$$|E \cap R_m| - \left| (\mathcal{C}E) \cap R_m \right| \leqslant \frac{C \varepsilon r_m^{n+1}}{R}.$$
(2.27)

Now we prove that

$$\int_{\{r_{m+1} \leqslant |x'-\bar{x}'| \leqslant r_m/(\bar{C}\sqrt{n})\}} u(x') - \bar{x}_n - \nabla \mathcal{P}(\bar{x}') \cdot (x'-\bar{x}') \, dx' \leqslant \frac{C\varepsilon r_m^{n+1}}{R}.$$
(2.28)

To this scope, we observe that

$$K_{r_m/\sqrt{n}} \subseteq B_{r_m} \subseteq K_{r_m}$$

and  $r_{m+1} < r_m / (\overline{C}\sqrt{n})$ . Hence

$$S_m := \{ r_{m+1} < |x' - \bar{x}'| < r_m / \sqrt{n} \} \times \{ |x_n - \bar{x}_n| < r_m / \sqrt{n} \} \subseteq R_m.$$
(2.29)

Of course, no confusion should arise between  $S_m$  here and  $S_r$  in the statement of Lemma 8.

Let  $\alpha := \chi_E - \chi_L = \chi_{CL} - \chi_{CE}$ . We recall that

$$\alpha + \chi_A \geqslant 0 \quad \text{in } R_m, \tag{2.30}$$

due to (2.23) and (2.24).

Accordingly, by (2.21), (2.22), (2.29) and (2.30),

$$|E \cap R_{m}| - |(\mathbb{C}E) \cap R_{m}|$$

$$= \int_{R_{m}} \chi_{E}(y) - \chi_{\mathbb{C}E}(y) \, dy - 0$$

$$= \int_{R_{m}} \chi_{E}(y) - \chi_{\mathbb{C}E}(y) \, dy - \int_{R_{m}} \chi_{L}(y) - \chi_{\mathbb{C}L}(y) \, dy$$

$$= 2 \int_{R_{m}} \alpha(y) \, dy$$

$$= 2 \int_{R_{m}} \alpha(y) + \chi_{A}(y) \, dy - 2 \int_{R_{m}} \chi_{A}(y) \, dy$$

$$\geq 2 \int_{S_{m}} \alpha(y) + \chi_{A}(y) \, dy - \frac{\mathbb{C}\varepsilon r_{m}^{n+1}}{R}.$$
(2.31)

Now, we use (2.16) and (2.18) to see that, if  $|y' - \bar{x}'| < r_m / (\overline{C}\sqrt{n})$ , we have

$$\begin{aligned} \left| \nabla \mathcal{P}(\bar{x}') \cdot (y' - \bar{x}') \right| &\leq \left| y' - \bar{x}' \right| < r_m / \sqrt{n} \quad \text{and} \\ \left| u(y') - \bar{x}_n \right| &= \left| u(y') - u(\bar{x}') \right| \leq \overline{C} \left| y' - \bar{x}' \right| < r_m / \sqrt{n}. \end{aligned}$$

$$(2.32)$$

Hence, fixed y', with  $|y' - \bar{x}'| \in (r_{m+1}, r_m/(\overline{C}\sqrt{n}))$  we see that  $\alpha(y', y_n) = 1$  when  $(y', y_n)$  is trapped between *E* and *CL* (notice that it cannot exit *S<sub>m</sub>* from either the top or the bottom, by (2.32)), i.e., when

$$\bar{x}_n + \nabla \mathcal{P}(\bar{x}') \cdot (\bar{x}')(y' - \bar{x}') \leq y_n < u(y').$$

So, recalling (2.30) and integrating first in  $dy_n$ , we have that

$$\int_{S_m} \alpha(y) + \chi_A(y) \, dy \ge \int_{\{|y' - \bar{x}'| \in (r_{m+1}, r_m/(\overline{C}\sqrt{n}))\}} \left( u(y') - \bar{x}_n - \nabla \mathcal{P}(\bar{x}') \cdot (x' - \bar{x}') \right)^+ dy'.$$

This, (2.31) and (2.27) imply (2.28).

Then, (2.20) follows from (2.28) and the Chebyshev Inequality, taking  $r := r_m/(\overline{C}\sqrt{n})$ ,  $S_r := \{|x' - \overline{x'}| \in (r_{m+1}, r_m/(\overline{C}\sqrt{n}))\}$  and noticing that  $|S_r| \sim r_m^{n-1}$  (remember that  $S_r \subset \mathbb{R}^{n-1}$ ).  $\Box$ 

#### 2.3. The mean curvature as a limit equation

In this section, we show that the integral equation of *s*-minimal surfaces converges, in a somewhat uniform way, to the classical mean curvature equation as  $s \rightarrow 1^-$ , and we remark that the estimates improve as the surfaces get flatter and flatter (see [1] for a more detailed discussion on nonlocal curvatures). An estimate of this kind will be useful in the computation of the forthcoming Lemma 10.

**Lemma 9.** Let  $s \in [1/10, 1)$ . Let  $\alpha \in (0, 1)$ . Let  $F \subset \mathbb{R}^n$ ,  $x_o \in \partial F$ , and suppose that  $\partial F \cap B_1(x_o)$  is a  $C^{2,\alpha}$ -graph in some direction, with  $C^{2,\alpha}$ -norm bounded by some M > 0. Then there exists  $C \ge 1$  only depending on  $\alpha$  and n such that

Then, there exists 
$$C \ge 1$$
, only depending on  $\alpha$  and n, such that

$$\left|\mathfrak{H}(x_o) - \frac{(n-1)(1-s)}{\varpi} \int\limits_{B_r} \frac{\chi_F(y) - \chi_{\mathcal{C}F}(y)}{|x_o - y|^{n+s}} \, dy \right| \leq \frac{CM(1-s)}{r},\tag{2.33}$$

where  $\mathcal{H}$  is the mean curvature (see Section 1) and

$$r := \min\left\{\frac{1}{n}, \frac{1}{2M}\right\}.$$
(2.34)

In particular, if  $M \in (0, 1]$ ,

$$\left| \mathcal{H}(x_o) - \frac{(n-1)(1-s)}{\varpi} \int\limits_{B_r} \frac{\chi_F(y) - \chi_{\mathbb{C}F}(y)}{|x_o - y|^{n+s}} \, dy \right| \leq CM(1-s).$$

$$(2.35)$$

**Proof.** Without loss of generality, up to a translation and a rotation, which leave our problem invariant, we may take  $x_o = 0$  and the tangent hyperplane of  $\partial F$  at 0 to be  $\{x_n = 0\}$ . In this way, we write  $\partial F$  as the graph  $x_n = g(x')$ , for  $|x'| \leq 1/\sqrt{n}$ , with  $\nabla g(0) = 0$  and  $\mathcal{H}(0) = \Delta g(0)$ . Up to a rotation of the horizontal coordinates, we also suppose that  $D^2g(0)$  is diagonal, with eigenvalues  $\lambda_1, \ldots, \lambda_{n-1}$ . In this way

$$g(y') = \frac{1}{2} \sum_{i=1}^{n-1} \lambda_i y_i^2 + h(y'),$$

and  $|h(y')| \leq M|y'|^{2+\alpha}$ . So, for any  $|y'| \leq r$ ,

$$\left|g(\mathbf{y}')\right| \leqslant Mr^2 \leqslant \frac{r}{2},\tag{2.36}$$

thanks to (2.34). We observe that, by rotational symmetry,

$$\int_{\{|y'|\leqslant r\}} y_j^2 |y'|^{-(n+s)} \, dy' = \int_{\{|y'|\leqslant r\}} y_1^2 |y'|^{-(n+s)} \, dy'$$

for any j = 1, ..., n - 1 and therefore, by summing up in j,

$$\frac{\varpi r^{1-s}}{1-s} = \int_{\{|y'| \le r\}} |y'|^{2-(n+s)} dy'$$
$$= (n-1) \int_{\{|y'| \le r\}} y_1^2 |y'|^{-(n+s)} dy' = (n-1) \int_{\{|y'| \le r\}} y_i^2 |y'|^{-(n+s)} dy'$$

for any  $i = 1, \ldots, n - 1$ . Therefore

$$\int_{\{|y'|\leqslant r\}} \sum_{i=1}^{n-1} \lambda_i y_i^2 |y'|^{-(n+s)} dy' = \frac{\varpi r^{1-s} \mathcal{H}(0)}{(n-1)(1-s)}.$$
(2.37)

Let now

$$G_{s}(\tau) := \int_{0}^{\tau} \frac{dt}{(1+t^{2})^{(n+s)/2}}.$$

We observe that  $G_s(0) = 0$ ,  $G'_s(0) = 1$  and  $|G''_s(\tau)| = (n+s)(1+\tau^2)^{-(n+s+2)/2} |\tau| \le (n+1)|\tau|$ . Therefore, a Taylor expansion gives

$$G_s(\tau) = \tau + \widetilde{G}_s(\tau),$$

with  $|\widetilde{G}_s(\tau)| \leq C |\tau|^3$ . Therefore, if we write

$$\tilde{g}(y') := \frac{g(y')}{|y'|} = \frac{1}{2|y'|} \sum_{i=1}^{n-1} \lambda_i y_i^2 + \tilde{h}(y')$$

with  $|\tilde{h}(y')| = |h(y')|/|y'| \leq M|y'|^{1+\alpha}$ , we have that

$$G_s(\tilde{g}(y')) = \tilde{g}(y') + \tilde{G}_s(\tilde{g}(y'))$$
  
=  $\frac{1}{2|y'|} \sum_{i=1}^{n-1} \lambda_i y_i^2 + \tilde{h}(y') + \tilde{G}_s(\tilde{g}(y'))$   
=  $\frac{1}{2|y'|} \sum_{i=1}^{n-1} \lambda_i y_i^2 + \ell(y'),$ 

with

$$|\ell(y')| \leq |\tilde{h}(y')| + C|\tilde{g}(y')|^3 \leq CM(|y'|^{1+\alpha} + |y'|^3) \leq CM|y'|^{1+\alpha}$$

for any  $|y'| \leq r$ . As a consequence of this and (2.37),

$$\int_{\{|y'| \le r\}} \frac{G_s(\tilde{g}(y'))}{|y'|^{n+s-1}} \, dy' = \frac{\varpi r^{1-s} \mathfrak{H}(0)}{2(n-1)(1-s)} + \varepsilon_1$$
(2.38)

with  $|\varepsilon_1| \leq CMr^{1+\alpha-s}/(1+\alpha-s) \leq CM$ . Now, since the map  $(0, +\infty) \ni t \mapsto 1 - e^{-t}$  is concave, we have that  $1 - e^{-t} \in [0, t]$ , hence

$$1 - r^{1-s} \in \left[0, (1-s)\log r^{-1}\right].$$

Accordingly, we may write (2.38) as

$$\int_{\{|y'|\leqslant r\}} \frac{G_s(\tilde{g}(y'))}{|y'|^{n+s-1}} \, dy' = \frac{\varpi \mathcal{H}(0)}{2(n-1)(1-s)} + \varepsilon_2 \tag{2.39}$$

with  $|\varepsilon_2| \leq CM(1 + \log r^{-1})$ .

Now, we recall (2.36), we integrate in the vertical coordinate and we substitute  $t := y_n/|y'|$  to obtain that

$$\begin{split} &\int_{K_r} \frac{\chi_F(y) - \chi_{CF}(y)}{|y|^{n+s}} dy \\ &= \int_{|y'|\leqslant r} \left[ \int_{-r}^{g(y')} \frac{dy_n}{(|y'|^2 + |y_n|^2)^{(n+s)/2}} - \int_{g(y')}^{r} \frac{dy_n}{(|y'|^2 + |y_n|^2)^{(n+s)/2}} \right] dy' \\ &= \int_{|y'|\leqslant r} \frac{1}{|y'|^{n+s}} \left[ \int_{-r}^{g(y')} \frac{dy_n}{(1 + (|y_n|/|y'|)^2)^{(n+s)/2}} - \int_{g(y')}^{r} \frac{dy_n}{(1 + (|y'|/|y_n|)^2)^{(n+s)/2}} \right] dy' \\ &= \int_{|y'|\leqslant r} \frac{1}{|y'|^{n+s-1}} \left[ \int_{-r/|y'|}^{\tilde{g}(y')} \frac{dt}{(1 + t^2)^{(n+s)/2}} - \int_{\tilde{g}(y')}^{r/|y'|} \frac{dt}{(1 + t^2)^{(n+s)/2}} \right] dy' \\ &= \int_{|y'|\leqslant r} \frac{1}{|y'|^{n+s-1}} \left[ G_s(\tilde{g}(y')) - G_s(-r/|y'|) - G_s(r/|y'|) + G_s(\tilde{g}(y')) \right] dy'. \end{split}$$

Therefore, since  $G_s$  is odd,

$$\int_{K_r} \frac{\chi_F(y) - \chi_{\mathcal{C}F}(y)}{|y|^{n+s}} \, dy = 2 \int_{|y'| \leqslant r} \frac{G_s(\tilde{g}(y'))}{|y'|^{n+s-1}} \, dy' = \frac{\varpi \mathcal{H}(0)}{(n-1)(1-s)} + \varepsilon_3 \tag{2.40}$$

with  $|\varepsilon_3| \leq CM(1 + \log r^{-1})$ , due to (2.39).

Now, we point out the following cancellation:

$$\left| \int\limits_{K_r \setminus B_r} \frac{\chi_F(y) - \chi_{\mathbb{C}F}(y)}{|y|^{n+s}} \, dy \right| \leq \int\limits_{(K_r \setminus K_{r/\sqrt{n}}) \cap \{|y_n| \leq M|y'|\}} \frac{1}{|y|^{n+s}} \, dy$$
$$\leq CM \int\limits_{r/\sqrt{n}}^r \rho^{-1-s} \, ds = \frac{CM(n^{s/2} - 1)}{sr^s} \leq \frac{CM}{r}.$$

Accordingly, we can write (2.40) as

$$\int_{B_r} \frac{\chi_F(y) - \chi_{\mathcal{C}F}(y)}{|y|^{n+s}} \, dy = \frac{\varpi \mathcal{H}(0)}{(n-1)(1-s)} + \varepsilon_4$$

with  $|\varepsilon_4| \leq CM(1 + \log r^{-1} + r^{-1}) \leq CMr^{-1}$ . This proves (2.33).

Then, (2.35) follows from (2.33) and (2.34), by observing that, if  $M \in (0, 1]$ , we have that r = 1/n so it does not depend on M.  $\Box$ 

## 2.4. Construction of an auxiliary function

The purpose of this section is to obtain a special function, which is positive in a large ball, and that satisfies the correct inequality with respect to the integral operator of (2.17) in a smaller ball. This is needed to apply an appropriate variation of the local Alexandrov–Bakelman–Pucci theory of [4,7], in order to localize the set in which the solution we are considering becomes positive. Indeed, the following function is the one that replaces the auxiliary functions in Lemma 4.1 of [4] and Corollary 9.3 of [7] for our framework (here, some technical complications also arise since the operator in (2.44) is both nonlocal and nonlinear in its dependence on the sets):

**Lemma 10.** Fix R > 0 and constants  $c_1, \ldots, c_5 > 0$ . Fix also  $c_0 \in (0, c_1)$ . There exists  $C \ge 1$  (possibly depending on  $c_0, \ldots, c_5 > 0$  but independent of R) such that, if  $1 - s, \varepsilon \in (0, 1/C]$ , the following results hold.

There exists  $\Phi \in C^{\infty}(\mathbb{R}^{n-1}, [-C \in R, C \in R])$  satisfying the following conditions:

$$\Phi(x') > \varepsilon R \quad if |x'| \ge (c_1 + c_2)R, \qquad \Phi(x') \le -4\varepsilon R \quad if |x'| \le c_1 R, \quad and$$
  
$$\sup_{\mathbb{R}^{n-1}} |\nabla \Phi| + R |D^2 \Phi| \le C\varepsilon. \tag{2.41}$$

Also, let L be an affine function with

$$|\nabla L| \leqslant \frac{1}{C},\tag{2.42}$$

set

$$\widetilde{\Phi} := L - \Phi \quad and \quad F := \left\{ x_n < \widetilde{\Phi}(x') \right\}.$$
(2.43)

Then

$$(1-s)\int_{B_{c_3R}(x)}\frac{\chi_F(y)-\chi_{CF}(y)}{|x-y|^{n+s}}\,dy \ge \frac{c_4\varepsilon}{R^s}$$
(2.44)

for any  $x \in \partial F \cap \{c_0 R < |x'| \le (c_1 + c_2 + c_5)R\}$ .

**Proof.** Up to replacing  $\Phi(x')$  with  $R\Phi(x'/R)$ , we may and do consider just the case R = 1. Then, the function we will construct is depicted in Fig. 2.

More explicitly, we take  $\Phi$  to be smooth, radial, radially increasing, satisfying (2.41) with R = 1, and in fact

$$\|\Phi\|_{C^{2,\alpha}(\mathbb{R}^{n-1})} \leqslant C(1+\mu_q)\varepsilon,$$

and such that

$$\Phi(x') = \varepsilon \left(\frac{c_0^q \mu_q}{c_1^q} - 4 - \frac{c_0^q \mu_q}{|x'|^q}\right)$$



Fig. 2. The auxiliary function  $\Phi$  (with R = 1).

if  $|x'| > c_0$ . Here, q > n - 3 is a fixed free parameter and  $\mu_q > 0$  will be chosen appropriately large<sup>3</sup> at the end of the proof. We observe that, if  $|x'| > c_0$ ,

$$\begin{aligned} |\partial_i \Phi| &\leq \varepsilon q \mu_q c_0^q |x'|^{-q-1}, \\ |\partial_{ij}^2 \Phi| &\leq \varepsilon q (q+3) \mu_q c_0^q |x'|^{-q-2} \quad \text{and} \\ -\Delta \widetilde{\Phi} &= \Delta \Phi = -\varepsilon q (q-n+3) \mu_q c_0^q |x'|^{-q-2} \end{aligned}$$

Accordingly, if  $|x'| > c_0$ ,

$$\begin{split} &\sqrt{1+|\nabla\widetilde{\Phi}|^2\in[1,2]} \quad \text{and} \\ &\Delta\widetilde{\Phi}-\left|\frac{(D^2\widetilde{\Phi}\nabla\widetilde{\Phi})\cdot\nabla\widetilde{\Phi}}{1+|\nabla\widetilde{\Phi}|^2}\right| \geqslant \frac{\varepsilon q\,(q+3-n)\mu_q}{4}c_0^q \left|x'\right|^{-q-2} \end{split}$$

<sup>3</sup> At the moment we only need that  $\mu_q$  is so large that

$$c_0^q \mu_q \left( \frac{1}{c_1^q} - \frac{1}{(c_1 + c_2)^q} \right) \ge 6.$$

In this way, if  $|x'| \ge c_1 + c_2$ , then

$$\Phi(x') \ge \varepsilon \left(\frac{c_0^q \mu_q}{c_1^q} - 4 - \frac{c_0^q \mu_q}{(c_1 + c_2)^q}\right) \ge 2\varepsilon$$

that gives (2.41).

as long as  $\varepsilon$  is small enough, thanks to (2.42). Hence, we estimate the mean curvature of  $\partial F$  at some point x with  $|x'| \in (c_0, c_1 + c_2 + c_5]$  as

$$\mathcal{H}(x) = \frac{1}{\sqrt{1 + |\nabla \widetilde{\varPhi}|^2}} \left( \Delta \widetilde{\varPhi} - \frac{(D^2 \widetilde{\varPhi} \nabla \widetilde{\varPhi}) \cdot \nabla \widetilde{\varPhi}}{1 + |\nabla \widetilde{\varPhi}|^2} \right) \geqslant \frac{\varepsilon \mu_q}{C}$$

Therefore, if  $x \in \partial F$ ,  $|x'| \in (c_0, c_1 + c_2 + c_5]$ , we have that

$$(1-s)\int\limits_{B_{c_3}(x)}\frac{\chi_F(y)-\chi_{CF}(y)}{|x-y|^{n+s}}\,dy \ge \frac{\varepsilon\mu_q}{C^2} - C(1+\mu_q)\varepsilon(1-s) \ge \frac{\varepsilon\mu_q}{C^3}$$

thanks to (2.35) in Lemma 9, as long as 1 - s and  $\varepsilon$  are small enough. This and a suitably large choice of  $\mu_q$  give (2.44) (namely, we take  $\mu_q/C^3 \ge c_4$ ).  $\Box$ 

## 2.5. Measure estimates for the oscillation

We obtain the following measure estimate. Such result may be seen as the counterpart, in our framework, of the measure estimate in Lemma 4.5 of [4] and Lemmata 8.6 and 10.1 of [7].

**Lemma 11.** Fix  $\overline{C} \ge 1$ . Let  $\kappa \in \mathbb{R}$  and R > 0. Let  $u : \mathbb{R}^{n-1} \to \mathbb{R}$  be a Lipschitz function, with

$$\left|\nabla u(x')\right| \leqslant \overline{C} \tag{2.45}$$

a.e.  $|x'| \leq 3R$ , and

$$u(x') \ge \kappa \quad \text{for any } |x'| \ge R.$$
 (2.46)

Let  $E := \{x_n < u(x')\}.$ 

Assume that, for any  $x \in \partial E \cap B_{4n}$ ,

$$(1-s)\int_{B_R(x)}\frac{\chi_E(y)-\chi_{CE}(y)}{|x-y|^{n+s}}\,dy\leqslant\frac{\varepsilon}{R^s}.$$
(2.47)

Then, if

$$\inf_{Q_{3R}} u \leqslant \kappa + \varepsilon R \tag{2.48}$$

we have that

$$\left| \{ u - \kappa \leqslant M \varepsilon R \} \cap Q_R \right| \ge \mu R^{n-1}, \tag{2.49}$$

for appropriate universal constants M > 1 and  $\mu \in (0, 1)$ , as long as 1 - s and  $\varepsilon \in (0, 1/C]$ , with  $C \ge 1$  suitably large.

Here, M,  $\mu$  and C only depend on n and  $\overline{C}$ .

**Proof.** Up to translation, we may suppose that  $\kappa = 0$ . Let  $\Phi$  be as in Lemma 10 (with  $c_0, \ldots, c_5$  to be conveniently chosen in what follows). Let  $v := u + \Phi$  and  $\Gamma : \mathbb{R}^{n-1} \to \mathbb{R}$  be the convex envelope of  $v^- := \min\{v, 0\}$  in  $B_{6\sqrt{nR}}$ , that is

$$\Gamma(x) := \begin{cases} \sup_{\Xi} \ell(x) & \text{if } |x'| < 6\sqrt{n}R, \\ 0 & \text{if } |x'| \ge 6\sqrt{n}R, \end{cases}$$

where  $\Xi$  above is a short-hand notation for all the affine functions  $\ell$  such that  $\ell(y') \leq v^-(y')$  for any  $|y'| < 6\sqrt{nR}$  (see pages 23–27 of [4] for the basic properties of the convex envelope). Let  $\mathcal{T}$  be the touching set between v and  $\Gamma$ , i.e.

$$\mathcal{T} := \left\{ x' \in \mathbb{R}^{n-1} \text{ s.t. } \Gamma\left(x'\right) = v(x') \right\}.$$

Let

$$m_o := -\inf_{Q_{3R}} v.$$

Notice that  $v \le u - 4\varepsilon R$  in  $Q_{3R}$ , due to (2.41) (for this we choose  $c_1 := 3\sqrt{n}/2$  in Lemma 10, so that  $Q_{3R} \subseteq \{|x'| \le c_1 R\}$ ; the other constants  $c_0, c_2, \ldots, c_5$  will be fixed in the sequel). Therefore, by (2.48),

$$\inf_{Q_{3R}} v \leqslant -2\varepsilon R,$$

so  $m_o \ge 2\varepsilon R$ .

We recall that all the hyperplanes with slope bounded by  $m_o/(CR)$  belong to  $\nabla \Gamma(B_{6\sqrt{nR}})$  (see page 24 of [4] and also (3.9) there), hence

$$\varepsilon^{n-1} \leqslant C\left(\frac{m_o}{R}\right)^{n-1} \leqslant C \left|\nabla\Gamma(\mathfrak{I})\right|.$$
 (2.50)

Now, for any  $\bar{x}' \in \mathcal{T}$ , we let

$$L(x') := v(\bar{x}') + \nabla \Gamma(\bar{x}') \cdot (x' - \bar{x}') \text{ and}$$
  
$$\mathcal{P} := L - \Phi.$$

~

We point out that v > 0 in  $\{|x'| \ge 3\sqrt{nR}\}$ , thanks to (2.41) and (2.46) (for this, we choose  $c_2 := 3\sqrt{n/2}$  in Lemma 10, so that  $c_1 + c_2 := 3\sqrt{n}$ ).

In particular, since  $\Gamma \leq 0$ , we see that  $\bar{x}' \in \mathfrak{T} \subseteq \{|x'| \leq 3\sqrt{n}R\}$ .

Also, from (2.41), we have

$$\left|D^{2}\mathcal{P}\right| = \left|D^{2}\Phi\right| \leqslant \frac{C\varepsilon}{R}.$$
(2.51)

Moreover, v is above  $\Gamma$  which is above L in  $B_{6\sqrt{n}R}$ , by convexity, therefore, for any  $e \in S^{n-1}$ 

$$0 \ge \Gamma(\bar{x}' + Re) \ge L(\bar{x}' + Re) = v(\bar{x}') + R\nabla\Gamma(\bar{x}') \cdot e \ge -C\varepsilon R + R\nabla\Gamma(\bar{x}') \cdot e$$

that is  $\nabla \Gamma(\bar{x}') \cdot e \leq C\varepsilon$ . So, since *e* is an arbitrary unit vector, we get that

$$|\nabla L| = \left|\nabla \Gamma\left(\bar{x}'\right)\right| \leqslant C\varepsilon,\tag{2.52}$$

and so, by (2.41),

$$|D\mathcal{P}| \leqslant C\varepsilon. \tag{2.53}$$

Now we observe that

$$\mathfrak{T} \subseteq Q_R. \tag{2.54}$$

The proof is by contradiction: if not,  $u + \Phi \ge L$  in  $\{|x'| \le 6\sqrt{n}R\}$ , with equality at some  $\bar{x}'$  with  $\bar{x}' \notin Q_R$ . In particular,  $|\bar{x}'| \ge R/2$ . Then, we can use Lemma 10, with *F* as in (2.43) (notice that (2.42) is satisfied here due to (2.52)). For this, we set  $\bar{x} := (\bar{x}', u(\bar{x}')) \in \partial F$ , and we

choose  $c_0 := 1/4$ ,  $c_4 := 2$  and  $c_5 := 100\sqrt{n}$  in Lemma 10. In this way since  $E \cap B_{6\sqrt{n}R} \supseteq F \cap B_{6\sqrt{n}R}$ , we deduce from (2.44) that

$$(1-s)\int\limits_{B_R(\bar{x})}\frac{\chi_E(y)-\chi_{\mathbb{C}E}(y)}{|x-y|^{n+s}}dy \ge (1-s)\int\limits_{B_R(\bar{x})}\frac{\chi_F(y)-\chi_{\mathbb{C}F}(y)}{|x-y|^{n+s}}dy \ge \frac{2\varepsilon}{R^s}$$

This is in contradiction with (2.47) and so it establishes (2.54).

Also, given  $\bar{x}' \in \mathcal{T}$ , we have that  $\mathcal{P}(\bar{x}') = v(\bar{x}') - \Phi(\bar{x}') = u(\bar{x}')$  and

 $\mathcal{P} \leqslant \Gamma - \Phi \leqslant v - \Phi = u.$ 

This, (2.45), (2.47), (2.51) and (2.53) say that the hypotheses of Lemma 8 are fulfilled (up to scaling  $\varepsilon$  to  $C\varepsilon$ ). As a consequence, by (2.20), for any *M* large enough,

$$\frac{|S^{(\bar{x}')} \cap \{u(x') - u(\bar{x}') - \nabla \mathcal{P}(\bar{x}') \cdot (x' - \bar{x}') > \frac{M\varepsilon r_{\bar{x}'}^2}{R}\}|}{|S^{(\bar{x}')}|} \leqslant \frac{C}{M}$$
(2.55)

for a suitable ring  $S^{(\bar{x}')} := \{ |x' - \bar{x}'| \in (r_{\bar{x}'}/C, r_{\bar{x}'}) \}$  and a suitable  $r_{\bar{x}'} \in (0, R]$ .

On the other hand, by (2.41),

$$-\Phi(x') + \Phi(\bar{x}') + \nabla\Phi(\bar{x}') \cdot (x' - \bar{x}') \ge -\frac{\varepsilon r_{\bar{x}'}^2}{R} \ge -\frac{M\varepsilon r_{\bar{x}'}^2}{2R}$$

if  $x' \in S^{(\bar{x}')}$ , as long as M is big enough. Consequently, using that v lies above  $\Gamma$  and that  $\bar{x}' \in \mathcal{T}$ , we have that

$$\begin{split} \Gamma(x') &- \Gamma(\bar{x}') - \nabla \Gamma(\bar{x}') \cdot (x' - \bar{x}') - \frac{M \varepsilon r_{\bar{x}'}^2}{2R} \\ &\leq \Gamma(x') - \Phi(x') - \Gamma(\bar{x}') + \Phi(\bar{x}') - (\nabla \Gamma(\bar{x}') - \nabla \Phi(\bar{x}')) \cdot (x' - \bar{x}') \\ &\leq \upsilon(x') - \Phi(x') - \upsilon(\bar{x}') + \Phi(\bar{x}') - (\nabla \Gamma(\bar{x}') - \nabla \Phi(\bar{x}')) \cdot (x' - \bar{x}') \\ &= u(x') - u(\bar{x}') - \nabla \mathcal{P}(\bar{x}') \cdot (x' - \bar{x}'). \end{split}$$

The latter estimate and (2.55) imply that

$$\frac{|S^{(\bar{x}')} \cap \{\Gamma(x') - \Gamma(\bar{x}') - \nabla \Gamma(\bar{x}') \cdot (x' - \bar{x}') > \frac{M\varepsilon r_{\bar{x}'}^2}{2R}\}|}{|S^{(\bar{x}')}|} \leqslant \frac{C}{M}$$

So, by taking M appropriately large and using Lemma 8.4 of [7] we deduce that

$$\Gamma(x') - \Gamma(\bar{x}') - \nabla \Gamma(\bar{x}') \cdot (x' - \bar{x}') \leqslant \frac{C \varepsilon r_{\bar{x}'}^2}{R}$$
(2.56)

for any  $|x' - \bar{x}'| < r_{\bar{x}'}/2$ .

In particular, for any  $|x' - \bar{x}'| < r_{\bar{x}'}/4$ , we set  $\rho := r_{\bar{x}'}/4$ , we plug the point  $x' + \rho e$  inside (2.56), we use the convexity of  $\Gamma$  twice and we obtain

$$\frac{C\varepsilon\rho^2}{R} \ge \Gamma(x'+\rho e) - \Gamma(\bar{x}') - \nabla\Gamma(\bar{x}') \cdot (x'+\rho e - \bar{x}') \\
\ge \Gamma(x') + \rho\nabla\Gamma(x') \cdot e - \Gamma(\bar{x}') - \nabla\Gamma(\bar{x}') \cdot (x'+\rho e - \bar{x}') \\
\ge \Gamma(\bar{x}') + \nabla\Gamma(\bar{x}') \cdot (x'-\bar{x}') + \rho\nabla\Gamma(x') \cdot e - \Gamma(\bar{x}') - \nabla\Gamma(\bar{x}') \cdot (x'+\rho e - \bar{x}') \\
= \rho(\nabla\Gamma(x') - \nabla\Gamma(\bar{x}')) \cdot e.$$

So, since e is an arbitrary unit vector, it follows that

$$\left|\nabla\Gamma(x')-\nabla\Gamma(\bar{x}')\right|\leqslant \frac{C\varepsilon r_{\bar{x}'}}{R}$$

for any  $|x' - \bar{x}'| < r_{\bar{x}'}/4$ , that is: the (n-1)-dimensional ball of radius  $r_{\bar{x}'}/4$  centered at  $\bar{x}'$  (which we now call  $B^{(\bar{x}')}$ ) is sent, via the map  $\nabla \Gamma$ , inside the (n-1)-dimensional ball of radius  $C\varepsilon r_{\bar{x}'}/R$  centered at  $\nabla \Gamma(\bar{x}')$  (we observe that the latter is a ball smaller by a scale factor  $C\varepsilon/R$ , and let us call  $\tilde{B}^{(\bar{x}')}$  such a ball).

Now we cover  $\mathfrak{T}$  with a countable, finite overlapping system of these balls, say  $\{B^{(j)}\}_{j\in\mathbb{N}}$ . By the previous observations, this covering induces a covering of  $\nabla\Gamma(\mathfrak{T})$  made of balls  $\{\widetilde{B}^{(j)}\}_{j\in\mathbb{N}}$ , with  $|\widetilde{B}^{(j)}| \leq C(\varepsilon/R)^{n-1}|B^{(j)}|$ . So, we obtain the measure estimate

$$\left|\nabla\Gamma(\mathfrak{I})\right| \leq \sum_{j \in \mathbb{N}} \left|\widetilde{B}^{(j)}\right| \leq C \left(\frac{\varepsilon}{R}\right)^{n-1} \sum_{j \in \mathbb{N}} \left|B^{(j)}\right|.$$
(2.57)

On the other hand, we observe that, if  $|x' - \bar{x}'| \leq r_{\bar{x}'}$ , then

$$u(x') \leq u(x') - \Gamma(x')$$
  

$$\leq u(x') - \Gamma(\bar{x}') - \nabla\Gamma(\bar{x}') \cdot (x' - \bar{x}')$$
  

$$= u(x') - u(\bar{x}') - \Phi(\bar{x}') - (\nabla \mathcal{P}(\bar{x}') + \nabla \Phi(\bar{x}')) \cdot (x' - \bar{x}')$$
  

$$\leq u(x') - u(\bar{x}') - \Phi(x') - \nabla \mathcal{P}(\bar{x}') \cdot (x' - \bar{x}') + \frac{C\varepsilon}{R} |x' - \bar{x}'|^2$$
  

$$\leq u(x') - u(\bar{x}') - \nabla \mathcal{P}(\bar{x}') \cdot (x' - \bar{x}') + C\varepsilon R$$

thanks to the convexity of  $\Gamma$  and (2.51). Therefore

$$S^{(\bar{x}')} \cap \left\{ u(x') - u(\bar{x}') - \nabla \mathcal{P}(\bar{x}') \cdot (x' - \bar{x}') \leqslant \frac{M \varepsilon r_{\bar{x}'}^2}{R} \right\}$$
  
$$\subseteq S^{(\bar{x}')} \cap \{ u(x') \leqslant C \varepsilon R \}$$
  
$$\subseteq B^{(\bar{x}')} \cap \{ u(x') \leqslant C \varepsilon R \}.$$
(2.58)

Also, by (2.55)

$$\left|S^{(\bar{x}')} \cap \left\{u(x') - u(\bar{x}') - \nabla \mathcal{P}(\bar{x}') \cdot (x' - \bar{x}') \leqslant \frac{M\varepsilon r_{\bar{x}'}^2}{R}\right\}\right|$$
$$\geqslant \left(1 - \frac{C}{M}\right) |S^{(\bar{x}')}| \geqslant \frac{|S^{(\bar{x}')}|}{2} \geqslant \frac{|B^{(\bar{x}')}|}{C}.$$

This and (2.58) give that

$$|B^{(\bar{x}')}| \leq C |B^{(\bar{x}')} \cap \{u(x') \leq C \varepsilon R\}|.$$

Gathering this estimate, (2.50) and (2.57), and using the finite overlapping property of  $\{B^{(j)}\}_{j \in \mathbb{N}}$ , we conclude that

$$\varepsilon^{n-1} \leq C \left| \nabla \Gamma(\mathfrak{T}) \right| \leq C \left( \frac{\varepsilon}{R} \right)^{n-1} \sum_{j \in \mathbb{N}} \left| B^{(j)} \right|$$
$$\leq C \left( \frac{\varepsilon}{R} \right)^{n-1} \sum_{j \in \mathbb{N}} \left| B^{(j)} \cap \{ u \leq C \varepsilon R \} \right|$$
$$\leq C \left( \frac{\varepsilon}{R} \right)^{n-1} \left| \bigcup_{j \in \mathbb{N}} B^{(j)} \cap \{ u \leq C \varepsilon R \} \right|.$$
(2.59)

Accordingly, (2.49) is a consequence of (2.59) and (2.54).

## 2.6. Uniform improvement of flatness

The cornerstone of the regularity theory of [6] is Lemma 6.9 there, to wit a Harnack Inequality, according to which *s*-minimal surfaces become more and more flat when we get closer and closer to any of their points. However, the estimates in Lemma 6.9 of [6] are all uniform when *s* is bounded away from both 0 and 1, but they do degenerate as  $s \rightarrow 1^-$  (see, in particular, the estimate on  $I_1$  on page 1129 of [6]), therefore such result cannot be applied directly in our framework.

For this scope, we provide the following result, which is a version of Lemma 6.9 of [6] with uniform estimates as  $s \to 1^-$ . In fact, the reader may compare Lemma 12 here below with Lemma 6.9 in [6]: the only difference is that the estimates here are uniform as  $s \to 1^-$ .

Our proof is completely different from the one in [6] and it is based on the uniformity of the results obtained in the preceding sections, together with a Calderón–Zygmund iteration, which needs to distinguish between two scales of the dyadic cubes.

**Lemma 12.** Fix  $s_o \in (0, 1)$  and  $\alpha \in (0, 1)$ . Then, there exist  $K \in \mathbb{N}$  and  $d \in (0, 1)$  which only depend on n,  $\alpha$  and  $s_o$ , for which the following result holds.

Let  $a := 2^{-K\alpha}$ . Let *E* be a set with *s*-minimal perimeter in  $B_{2^{K+1}}$ , with  $s \in [1/10, 1)$ . Assume that

$$\partial E \cap B_1 \subseteq \left\{ |x_n| \leqslant a \right\} \tag{2.60}$$

and, for any  $i \in \{0, ..., K\}$ ,

$$\partial E \cap B_{2^i} \subseteq \left\{ |x \cdot v_i| \leqslant a 2^{i(1+\alpha)} \right\}$$
(2.61)

for some  $v_i \in S^{n-1}$ . Then

either 
$$\partial E \cap B_d \subseteq \{x_n \leqslant a(1-d^2)\}$$
 or  $\partial E \cap B_d \subseteq \{x_n \geqslant a(-1+d^2)\}.$  (2.62)

**Proof.** The proof is not simple, but the naive idea is to argue by contradiction, supposing that there is a sequence of  $E_i$ 's that oscillate too much. Then one performs the following steps:

- By [8], one gets a sequence s<sub>j</sub> → 1<sup>-</sup> for which E<sub>j</sub> approaches a classical minimal surface E<sub>⋆</sub>;
- By (7), one shadows E<sub>j</sub> with level sets of distance functions u<sup>±</sup><sub>j</sub> from above and below, and the graphs of u<sup>±</sup><sub>j</sub> are close to ∂E<sub>\*</sub> as s<sub>j</sub> → 1<sup>-</sup>;

- Since (by contradiction) we assumed E<sub>j</sub> to oscillate too much, there are points of E<sub>j</sub> (and so of the graphs of u<sup>±</sup><sub>i</sub>) that stay very close to the bottom and the top of the cylinder of height a;
- Accordingly, from the fact that there is a point for which  $u_j^-$  is close to the bottom, we deduce that  $u_j^-$  is close to the bottom in a rather large set: for this, one needs to use a dyadic cube argument when the cubes are reasonably big, one can repeat Lemma 11, and when the cubes get too small one takes advantage of the regularity theory for the classical minimal surface  $E_{\star}$ ;
- Analogously, from the fact that there is a point for which  $u_j^+$  is close to the top, we deduce that  $u_j^+$  is close to the top in a rather large set;
- In particular, we find a point for which  $u_j^+$  is close to the top and  $u_j^-$  close to the bottom, that is  $u_j^+ u_j^-$  is of the order of a;
- This is in contradiction with (2.15) and so it completes the proof.

We remark that, in these arguments, there are two uncorrelated scales involved. One is the flatness of order one (which, in the course of the proof, will be dominated by a configuration of cylinders whose ratio between the height and the base is some  $\varepsilon^*$ ); the other is the one induced by the criticality ratio for the minimal surfaces flatness condition (which is some universal  $\varepsilon_o$ ). Of course, both these configurations are somewhat induced by the trapping of the surface in a strip of small size *a*. The interplay between these two scales is what allows us to choose the critical *s* in an independent way, and so to decouple the ratio of the scales involved. Finally, this implies also that as the flatness  $\varepsilon_b$  of (0.1) improves (while the classical minimal surfaces flatness  $\varepsilon_o$  is a fixed constant), we can apply the decrease of oscillation more and more times, so that in the vertical blow-up limit we get a Hölder graph, that is harmonic in viscosity sense (see [6]).

Below is the full detail discussion. The proof is by contradiction. If the claim were false, since the estimates of Lemma 6.9 of [6] are uniform when  $s \ge 1/10$  is bounded away from 1, it follows that there exist

$$s_i \to 1^-, \tag{2.63}$$

and a sequence  $E_j$  of  $s_j$ -minimal surfaces in  $B_{2^{K+1}}$  such that

$$\partial E_j \cap B_1 \subseteq \left\{ |x_n| \leqslant a \right\} \tag{2.64}$$

and, for any  $i \in \{0, ..., K\}$ ,

$$\partial E_j \cap B_{2^i} \subseteq \left\{ |x \cdot v_i| \leqslant a 2^{i(1+\alpha)} \right\}$$
(2.65)

for suitable  $v_i \in S^{n-1}$ , but

$$\partial E_j \cap B_d \cap \{x_n \ge a(1-d^2)\} \ne \emptyset$$
 and  $\partial E_j \cap B_d \subseteq \{x_n \le a(-1+d^2)\} \ne \emptyset$ . (2.66)

By (2.63) and Theorem 7 in [8], we have that  $\chi_{E_j}$  converges in  $L^1(B_{(9/7)2^K})$  to some  $E_{\star}$  (possibly up to subsequence). Therefore (see the remark after Corollary 17 in [8])  $E_j$  approaches  $E_{\star}$  uniformly in  $B_{(8/7)2^K}$  and then, by Theorem 6 in [8], we have that  $E_{\star}$  is a classical minimal surface in  $B_{2^K}$ .

We will define  $\gamma_j$  to be the distance between  $E_j$  and  $E_{\star}$  in  $B_{2^{\kappa}}$ : by construction

$$\lim_{j \to +\infty} \gamma_j = 0. \tag{2.67}$$

Let also

$$\delta_j := a \gamma_j^{1/(1+\alpha)},$$

and notice that

$$\lim_{j \to +\infty} \delta_j = 0. \tag{2.68}$$

Now, we observe that  $K\alpha > 4(1 + \alpha)$  if K is large enough, and so we can take  $K' \in \mathbb{N}$  such that

$$\frac{K\alpha}{2(1+\alpha)} - 1 < K' \leqslant \frac{K\alpha}{2(1+\alpha)}.$$
(2.69)

Now, we denote by  $\varepsilon_o$  the flattening constants of the classical minimal surfaces (see, e.g., [5] and references therein) according to which if a minimal surface is trapped in a cylinder whose ratio between the height and the base is below  $\varepsilon_o$ , then the minimal surface is a  $C^{1,\alpha}$ -graph in half the cylinder. By (2.65), (2.69) and the uniform convergence of  $E_j$ , we see that, for large K (possibly in dependence of  $\varepsilon_o$ ),

$$\begin{aligned} \partial E_{\star} \cap B_{2^{K'}} &\subseteq \left\{ |x \cdot \nu_{K'}| \leqslant 2^{-K\alpha} 2^{K'(1+\alpha)} \right\} \\ &\subseteq \left\{ |x \cdot \nu_{K'}| \leqslant 2^{-K\alpha/2} \right\} \subseteq \left\{ |x \cdot \nu_{K'}| \leqslant \varepsilon_o \right\} \end{aligned}$$

and so

$$\partial E_{\star} \cap B_{2K'-1}$$
 is a  $C^{1,\alpha}$ -graph. (2.70)

Now, we use Corollary 7 with  $\gamma := \gamma_i$  and  $\delta := \delta_i$ : for this, we define

$$S_j^{\pm} := \left\{ x \in \mathbb{R}^n \text{ s.t. } d_{E_j}(x) = \pm \delta_j \right\}$$
(2.71)

and we deduce from (2.70) and Corollary 7 that  $S_i^{\pm} \cap B_{2^{K'-2}}$  is

the graph of a uniformly Lipschitz function, say  $u_i^{\pm}$ . (2.72)

Also, from (2.15), (2.67) and (2.68), we have that

$$u_j^+(x') - u_j^-(x') \leqslant C\delta_j \tag{2.73}$$

for any  $|x'| \leq 1$ , as long as *j* is large enough.

Now we will concentrate on  $u_j^-$  (the case of  $u_j^+$  being specular): we set  $E_j^- := \{x_n < u^-(x')\}$ , so that  $\partial E_j^- = S_j^-$ . From (2.66) and the fact that  $S_j^-$  lies below  $E_j$ , we obtain that there exists  $\zeta' \in \mathbb{R}^{n-1}$  with

$$\left|\zeta'\right| \leqslant d \tag{2.74}$$

and

$$u_j^-(\zeta') \le a(-1+d^2).$$
 (2.75)

As usual in these types of proofs, the convenient d in our argument will be chosen later on, in dependence of the constants of the previous lemmata (see (2.82) below).

Now, we use the following notation: given any  $x \in S_j^-$ , let  $y(x) \in \partial E_j$  such that  $|y(x) - x| = \delta_j$ , and let v(x) := y(x) - x. Then

$$E_j^- + \nu(x) \subseteq \overline{E}. \tag{2.76}$$

Indeed, if  $p \in E_j^- + \nu(x)$ , we have that  $p - \nu(x) \in E_j^-$  and so  $\overline{B_{\delta_j}(p - \nu(x))} \subseteq \overline{E}_j$ . Then, since  $|\nu(x)| = \delta_j$ , we have  $p \in \overline{B_{\delta_j}(p - \nu(x))} \subseteq \overline{E}_j$ , proving (2.76).

Moreover  $\partial E$  has zero Lebesgue measure (see, e.g., Corollary 4.4(i) of [6]), thus we infer from (2.76) that, if  $x_o \in \partial E_i^-$ ,

$$\chi_{E_j^- + \nu(x_o)} \leqslant \chi_E \quad \text{and} \quad \chi_{\mathcal{C}(E_j^- + \nu(x_o))} \geqslant \chi_{\mathcal{C}E}.$$
 (2.77)

Therefore, using (2.77), the Euler–Lagrange equation satisfied by *E* (see Theorem 5.1 of [6]) and the change of variable  $z := x + v(x_o)$ , we obtain

$$\int_{\mathbb{R}^{n}} \frac{\chi_{E_{j}^{-}}(x) - \chi_{\mathcal{C}(E_{j}^{-})}(x)}{|x - x_{o}|^{n + s_{j}}} dx = \int_{\mathbb{R}^{n}} \frac{\chi_{E_{j}^{-} + \nu(x_{o})}(z) - \chi_{\mathcal{C}(E_{j}^{-} + \nu(x_{o}))}(z)}{|z - y(x_{o})|^{n + s_{j}}} dz$$

$$\leq \int_{\mathbb{R}^{n}} \frac{\chi_{E}(z) - \chi_{\mathcal{C}E}(z)}{|z - y(x_{o})|^{n + s_{j}}} dz \leq 0$$
(2.78)

for any  $x_o \in \partial E_j^- \cap B_C$ . On the other hand, by (2.65), we have that  $|x_o \cdot v_i| \leq Ca 2^{i(1+\alpha)}$ , and so

$$\partial E_j \cap B_{2^i}(x_o) \subseteq \partial E_j \cap B_{2^{i+C}}$$
$$\subseteq \left\{ |x \cdot v_i| \leqslant Ca2^{i(1+\alpha)} \right\} \subseteq \left\{ \left| (x - x_o) \cdot v_i \right| \leqslant Ca2^{i(1+\alpha)} \right\}$$

for any  $1 \leq i \leq K - C$ . Therefore, for *j* large,

$$\partial E_j^- \cap B_{2^i}(x_o) \subseteq \left\{ \left| (x - x_o) \cdot v_i \right| \leq Ca 2^{i(1+\alpha)} \right\}$$

for any  $1 \le i \le K - C$ . As a consequence, we obtain the following cancellation:

$$\begin{aligned} \left| \int_{\mathbb{C}B_{1}(x_{o})} \frac{\chi_{E_{j}^{-}}(x) - \chi_{\mathbb{C}(E_{j}^{-})}(x)}{|x - x_{o}|^{n + s_{j}}} dx \right| \\ &\leqslant \sum_{i=1}^{K-C} \left| \int_{B_{2^{i}}(x_{o}) \setminus B_{2^{i-1}}(x_{o})} \frac{\chi_{E_{j}^{-}}(x) - \chi_{\mathbb{C}(E_{j}^{-})}(x)}{|x - x_{o}|^{n + s_{j}}} dx \right| \\ &+ \left| \int_{\mathbb{C}B_{2^{K-C}}(x_{o})} \frac{\chi_{E_{j}^{-}}(x) - \chi_{\mathbb{C}(E_{j}^{-})}(x)}{|x - x_{o}|^{n + s_{j}}} dx \right| \\ &\leqslant C \left[ \sum_{i=1}^{K-C} \int_{B_{2^{i}}(x_{o}) \setminus B_{2^{i-1}}(x_{o})} \frac{1}{|x - x_{o}|^{n + s_{j}}} dx + \int_{\mathbb{C}B_{2^{K-C}}(x_{o})} \frac{1}{|x - x_{o}|^{n + s_{j}}} dx \right] \\ &\leqslant C \left[ \sum_{i=1}^{K-C} \int_{2^{i-1}}^{2^{i}} \frac{a2^{i(1+\alpha)}\rho^{n-2}}{\rho^{n + s_{j}}} d\rho + \int_{2^{K-C}}^{+\infty} \frac{\rho^{n-1}}{\rho^{n + s_{j}}} d\rho \right] \\ &\leqslant Ca \end{aligned}$$

$$(2.79)$$

provided that j is big enough (in particular,  $s_i$  is larger than  $\alpha$ ).

Therefore, by (2.78) and (2.79), for any  $x_o \in \partial E_i^- \cap B_C$ ,

$$\int_{B_1(x_o)} \frac{\chi_{E_j^-}(x) - \chi_{\mathcal{C}(E_j^-)}(x)}{|x - x_o|^{n + s_j}} dx \leqslant Ca.$$
(2.80)

With this, we are in position to obtain a finer bound in measure, often referred to with the name of " $L^{\beta}$ -estimate" (see, e.g., Lemma 4.6 of [4] and Lemma 9.2 of [7] for the corresponding results for fully nonlinear or fractional operators, the proof of which is based on related, but quite different, techniques). Such estimate will be based on a Calderón–Zygmund type dyadic cube decomposition. According to the different scales involved, we use either a repeated version of Lemma 11 or the vicinity of the classical minimal surface  $E_{\star}$  to deduce the necessary rigidity features.

Here are the details of such  $L^{\beta}$ -estimate. We take  $\mu \in (0, 1)$  and  $M \in (1, +\infty)$  as in Lemma 11, and we fix a large integer  $k_o$  such that

$$(1-\mu)^{k_o} \leqslant \frac{1}{4}.$$
 (2.81)

Then, we choose

$$d := \frac{1}{2M^{k_o}} \in (0, 1), \tag{2.82}$$

we set  $a_j := a + \delta_j + \gamma_j$ , and we claim that, for any  $k \in \mathbb{N}$ , with  $1 \leq k \leq k_o$ , we have that

$$\left|\left\{u_j^- + a_j \ge \frac{a_j M^{k-k_o}}{2}\right\} \cap Q_1\right| \le (1-\mu)^k \tag{2.83}$$

as long as *j* is large enough.

Indeed, when k = 1, (2.83) is a consequence of (2.49), by applying Lemma 11 here with  $\varepsilon := da_j$ ,  $\kappa := -a_j$  and R := 1 – for this recall (2.75), (2.80) and (2.82) in order to check (2.47) and (2.48), and consider the complement set in (2.49): such configuration is sketched in Fig. 3.

Then, we proceed by induction, by supposing that (2.83) holds for k - 1, and we prove it for  $k \le k_o$ . For simplicity, we just perform the step from k = 1 to k = 2 (the others are analogous). For this, we define

$$A := \left\{ u_j^- + a_j > \frac{a_j M^{2-k_o}}{2} \right\} \cap Q_1 \quad \text{and} \quad B := \left\{ u_j^- + a_j > \frac{a_j M^{1-k_o}}{2} \right\} \cap Q_1.$$

Notice that

$$A \subseteq B \subseteq Q_1 \tag{2.84}$$

and

$$|A| \leqslant \left| \left\{ u_j^- + a_j > \frac{a_j M^{1-k_o}}{2} \right\} \cap Q_1 \right| \leqslant 1 - \mu,$$

$$(2.85)$$

since we know that (2.83) holds when k = 1.

Now we take a dyadic cube decomposition of  $Q_1$ , with the notation that if Q is one of the cubes of the family, its predecessor is denoted by  $\tilde{Q}$ . We claim that

if 
$$|A \cap Q| > (1-\mu)|Q|$$
 then  $\tilde{Q} \subseteq B$ . (2.86)



Fig. 3. Proving (2.83) when k = 1.

Notice that if (2.86) holds, then, by Lemma 4.2 of [4] (applied here with  $\delta := 1 - \mu$ ) and the inductive assumption (that is, in this case, (2.83) with k = 1), we have that

$$\left| \left\{ u_j^- + a_j > \frac{a_j M^{2-k_o}}{2} \right\} \cap Q_1 \right| = |A|$$
  
$$\leq (1-\mu)|B| = (1-\mu) \left| \left\{ u_j^- + a_j > \frac{a_j M^{1-k_o}}{2} \right\} \cap Q_1 \right| \leq (1-\mu)^2.$$

This would complete the induction necessary for the proof of (2.83), hence we focus on the proof of (2.86).

For the proof of (2.86), we argue by contradiction, by supposing that

$$|A \cap Q| > (1 - \mu)|Q| \tag{2.87}$$

but there exists  $\xi' \in \widetilde{Q} \setminus B$ , i.e.

$$u_{j}^{-}(\xi') + a_{j} \leqslant \frac{a_{j}M^{1-k_{o}}}{2}.$$
(2.88)

We denote by  $\ell$  the width of Q (which is, say, centered at some  $x'_{\star} \in \mathbb{R}^{n-1}$ ). We need to distinguish two cases, according to the scale of the cube Q, namely, we distinguish whether or not  $a_j/\ell \leq \varepsilon^{\star}$ , using either Lemma 11 or the minimal surface rigidity (here  $\varepsilon^{\star}$  is a small quantity, say the minimum between the threshold for the classical minimal surface regularity  $\varepsilon_o$ , as introduced after (2.69), and the small constants given by Lemma 11: a precise requirement about this will be taken after (2.90)).

If

$$a_j/\ell \leqslant \varepsilon^\star, \tag{2.89}$$

we use Lemma 11. For this scope, given  $x_o \in \partial E_i^- \cap B_C$ , we notice that



Fig. 4. Proving the inductive step of (2.83) when  $a_i/\ell \leq \varepsilon^{\star}$ .

$$\left| \int_{B_1 \setminus B_{\ell}(x_o)} \frac{\chi_{E_j^-}(x) - \chi_{\mathcal{C}(E_j^-)}(x)}{|x - x_o|^{n + s_j}} dx \right|$$
  
= 
$$\left| \int_{(B_1 \setminus B_{\ell}(x_o)) \cap \{|x_n| \leqslant Ca_j\}} \frac{\chi_{E_j^-}(x) - \chi_{\mathcal{C}(E_j^-)}(x)}{|x - x_o|^{n + s_j}} dx \right|$$
  
$$\leqslant C \int_{(\mathcal{C}B_{\ell}(x_o)) \cap \{|x_n| \leqslant Ca_j\}} \frac{1}{|x' - x'_o|^{n + s_j}} dx \leqslant Ca_j \int_{\ell}^{+\infty} \frac{\rho^{n-2}}{\rho^{n+s}} d\rho \leqslant \frac{Ca_j}{\ell^{1+s}}.$$

As a consequence, recalling (2.80),

$$(1-s_j)\int_{B_{\ell}(x_o)}\frac{\chi_{E_j^-}(x)-\chi_{\mathcal{C}(E_j^-)}(x)}{|x-x_o|^{n+s_j}}dx \leqslant \frac{C(1-s_j)a_j}{\ell^{1+s}}.$$
(2.90)

With this, we are in position to apply Lemma 11 with  $\kappa := -a_j$ ,  $R := \ell$  and  $\varepsilon := a_j M^{1-k_o}/(2\ell) -$  notice indeed that (2.47) follows from (2.90), (2.48) follows from (2.88) and, recalling (2.89), we see that  $\varepsilon \leq \varepsilon^* M^{1-k_o}/2$  which is small if so is  $\varepsilon^*$ : this configuration is represented in Fig. 4.

So, we obtain from (2.49) that

$$|A \cap Q| = \left| \left\{ u_j^- + a_j > \frac{a_j M^{2-k_o}}{2} \right\} \cap Q \right|$$
$$= \left| \left\{ u_j^- - \kappa > M \varepsilon R \right\} \cap Q \right| \leqslant (1-\mu) |Q|$$

which is in contradiction with (2.87). This proves (2.86) if (2.89) holds true.

Now we deal with the case in which  $a_j/\ell \ge \varepsilon^*$ , and we fix  $\theta \in (0, 1)$  to be chosen suitably small in the sequel. We set  $p := a_j/(\theta^2 \varepsilon^*)$ . Notice that, for small  $\theta$ , we have that  $p > 10a_j/\varepsilon^* \ge 10\ell$ . Also, the ratio between  $a_j$  and p is below  $\theta^2 \varepsilon^*$ , hence a minimal surface that is trapped

inside  $\{|x'| \leq p\} \times \{|x_n| \leq 8a_j\}$  is the graph of a function  $\omega$ , with  $|\nabla \omega| \leq \theta^{3/2} \varepsilon^*$ . Accordingly,

the oscillation of  $\omega$  in  $\{|x_i'| \leq 6\ell\}$  is bounded by  $\theta \varepsilon^* \ell \leq \theta a_j$ . (2.91)

Keeping this in mind, we take *j* so large that  $\gamma_j$ , i.e. the distance between  $E_j$  and  $E_{\star}$  is less than  $\theta^2 \varepsilon^{\star} p/2$  (recall (2.67)). Also, for large *j*, we have that the graph of  $u_j^-$  is at distance  $\delta_j$  less than  $\theta^3 \varepsilon^{\star} p/2$  from  $E_j$ , and so less than  $\theta^3 \varepsilon^{\star} p$  from  $E_{\star}$  (recall (2.68) and (2.71)).

Accordingly,  $\partial E^* \cap \{|x_i'| \leq 6\ell\}$  is trapped in a slab of width  $4a_j + 2\theta^3 \varepsilon^* p < 8a_j$ , and, by (2.88), its boundary contains a point with vertical entry below  $(a_j M^{1-k_o}/2) + \theta^3 \varepsilon^* p$ . Then, by (2.91), the whole of  $\partial E^* \cap \{|x_i'| \leq 4\ell\}$  has vertical entry below

$$-a_j + (a_j M^{1-k_o}/2) + \theta^3 \varepsilon^* p + \theta a_j$$

Consequently, the graph of  $u^-$  on Q would stay below

$$-a_j + (a_j M^{1-k_o}/2) + \theta^3 \varepsilon^* p + \theta a_j + \theta^3 \varepsilon^* p$$
  
=  $-a_j + (a_j M^{1-k_o}/2) + 3\theta a_j < -a_j + (a_j M^{2-k_o}/2),$ 

as long as we choose  $\theta < M^{1-k_o}(M-1)/6$ . Hence,  $A \cap Q = \emptyset$ , which is in contradiction with (2.87). This ends the proof of (2.86), and therefore the one of (2.83).

As a consequence, by taking  $k := k_0$  in (2.83) and recalling (2.81), we obtain that

$$\left|\left\{u_j^- < -\frac{a_j}{2}\right\} \cap Q_1\right| \ge \frac{3}{4} \tag{2.92}$$

for large j. A mirror argument on  $u_i^+$  gives that

$$\left|\left\{u_j^+ > \frac{a_j}{2}\right\} \cap Q_1\right| \geqslant \frac{3}{4} \tag{2.93}$$

for large *j*. So, by (2.92) and (2.93), there must exist  $y'_j$  such that  $u_j^-(y'_j) \leq -a_j/2$  and  $u_j^+(y'_j) \geq a_j/2$ , hence

$$u_j^+(y_j') - u_j^-(y_j') \ge a_j \ge a/2.$$

This is in contradiction with (2.73), and so the proof of Lemma 12 is completed.  $\Box$ 

#### 2.7. Completion of the proof of Theorem 1

Thanks to Lemma 12, we have obtained a statement analogous to the one of Lemma 6.9 of [6], but with uniform estimates. Then, the argument from Lemma 6.10 to the end of Section 6 in [6] also yield the proof of Theorem 1 here.

## 3. Proof of Theorem 2

The proof is by contradiction. We suppose that there are  $s_k$ -minimal cones  $E_k$  that are not hyperplanes, with  $s_k \rightarrow 1^-$ . By dimensional reduction (see Theorem 10.3 of [6]), we may focus on the case in which  $E_k$  is singular at the origin.

From [8], up to subsequence, we have that  $E_k$  approaches locally uniformly a classical cone of minimal perimeter. Since  $n \leq 7$ , we have that such a cone is a halfspace, say  $\{x_n < 0\}$  (see,

e.g., Section 1.5.2 of [10]). So, for large k, we have that (0.1) holds true for  $E_k$ , namely

$$\partial E_k \cap B_1 \subseteq \{ |x \cdot e_n| \leq \varepsilon_{\flat} \}.$$

Therefore, by Theorem 1, we obtain that  $\partial E_k$  is smooth, i.e.  $E_k$  is a hyperplane, for infinitely many k's. This is a contradiction with our assumptions and it proves Theorem 2.

## 4. Proof of Theorem 3

Let *E* be *s*-minimal. We take the blow-up of *E* and we obtain a minimal cone E' (see Theorem 9.2 of [6]).

By Theorem 2, we know that E' is a hyperplane. Then,  $\partial E$  is  $C^{1,\alpha}$ , thanks to Theorem 9.4 in [6]. This ends the proof of Theorem 3.

## 5. Proof of Theorems 4 and 5

The proofs of Theorems 4 and 5 follow now verbatim the ones of Theorems 11.7 and 11.8 in [9] (the only difference is that the dimensional reduction is performed via Theorem 10.3 of [6], and the regularity needed in low dimension is assured here by Theorem 2).

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