

THE EQUALITY CASE OF THE PENROSE INEQUALITY FOR ASYMPTOTICALLY FLAT GRAPHS

LAN-HSUAN HUANG AND DAMIN WU

ABSTRACT. We prove the equality case of the Penrose inequality in all dimensions for asymptotically flat hypersurfaces. It was recently proven by G. Lam that the Penrose inequality holds for asymptotically flat graphical hypersurfaces in Euclidean space with non-negative scalar curvature and with a minimal boundary. Our main theorem states that if the equality holds, then the hypersurface is a Schwarzschild solution. As part of our proof, we show that asymptotically flat graphical hypersurfaces with a minimal boundary and non-negative scalar curvature must be mean convex, using the argument that we developed in our paper, *Hypersurfaces with non-negative scalar curvature* (J. Differential Geom., vol. 95 (2013), pp. 249–278). This enables us to obtain the ellipticity for the linearized scalar curvature operator and to establish the strong maximum principles for the scalar curvature equation.

1. INTRODUCTION

The Penrose inequality in general relativity states that the ADM mass of an asymptotically flat manifold is at least the mass of the black holes that it contains, if the energy density is non-negative everywhere. A particularly important special case of the physical statement is called the Riemannian Penrose inequality.

The Riemannian Penrose Inequality Conjecture. *Let (M^n, g) , $n \geq 3$, be an asymptotically flat n -dimensional smooth manifold with a strictly outer-minimizing smooth minimal boundary which is compact (not necessarily connected) of total $(n - 1)$ -volume A . Suppose M has non-negative scalar curvature and ADM mass m . Then*

$$m \geq \frac{1}{2} \left(\frac{A}{\omega_{n-1}} \right)^{\frac{n-2}{n-1}},$$

where ω_{n-1} is the volume of the unit $(n - 1)$ -sphere in Euclidean space. Moreover, the equality holds if and only if (M, g) is isometric to the region of a Schwarzschild metric outside its minimal hypersurface.

G. Huisken and T. Ilmanen proved the conjecture in dimension three for a connected minimal boundary [17]. H. Bray used a different approach and proved the conjecture in dimension three for any number of components of the minimal boundary [2]. In dimensions less than 8, the inequality was proved by H. Bray and D. Lee, with the extra spin assumption for the equality case [5]. In the case that (M, g) is conformally flat, H. Bray and K. Iga derived new properties of superharmonic functions in \mathbb{R}^n and proved the Penrose inequality with a suboptimal constant for

Received by the editors May 11, 2012.

2010 *Mathematics Subject Classification.* Primary 53C24; Secondary 83C99.

The first author acknowledges NSF grant DMS-1005560 and DMS-1301645 for partial support.

$n = 3$ [4]; F. Schwartz obtained a lower bound of the ADM mass in terms of the Euclidean volume of the region enclosed by the minimal boundary [25]; and J. Jau-regui proved a Penrose-like inequality [18]. For the Penrose inequality (with the sharp constant) in dimensions higher than 8, the only result that we know, other than the spherically symmetric case, is the result of G. Lam [19] (cf. [8]), where he proved the Penrose *inequality* for graphical asymptotically flat hypersurfaces. (Note some related work regarding the Penrose inequality for asymptotically hyperbolic graphs in [7, 9].)

Theorem 1 ([19]). *Let $\Omega \subset \mathbb{R}^n, n \geq 3$, be open and bounded. Assume that either each connected component of Ω is star-shaped or $\partial\Omega$ is outer-minimizing^{1,2}.*

Let $f \in C^2(\mathbb{R}^n \setminus \bar{\Omega}) \cap C^0(\mathbb{R}^n \setminus \Omega)$ be asymptotically flat. We assume that the graph of f has non-negative scalar curvature. Suppose each connected component of $\partial\Omega$ is the level set of f with $|Df(x)| \rightarrow \infty$ as $x \rightarrow \partial\Omega$, and each component of $\partial\Omega$ has positive (Euclidean) mean curvature in the hyperplane. Then,

$$m \geq \frac{1}{2} \left(\frac{|\partial\Omega|}{\omega_{n-1}} \right)^{\frac{n-2}{n-1}},$$

where $|\partial\Omega|$ is the $(n-1)$ -total volume of $\partial\Omega$.

The proof is simple and elegant, which we include in Section 5. However, the equality case was not discussed in [19], and the techniques there seem far from sufficient to handle the equality case. Our main result in this article proves the equality case in all dimensions $n \geq 3$. It may be particularly interesting because there was no rigidity result for the Penrose inequality, other than the spherically symmetric case, known to hold in dimensions $n \geq 8$.

Theorem 2. *Under the conditions of Theorem 1, suppose the graph of f is C^{n+1} up to boundary, and*

$$(1.1) \quad \max_{|x|=r} f(x) \leq \min_{|x|=r} f(x) + C \quad \text{for } n = 3 \text{ or } 4$$

for all r sufficiently large. If the equality holds, i.e.,

$$m = \frac{1}{2} \left(\frac{|\partial\Omega|}{\omega_{n-1}} \right)^{\frac{n-2}{n-1}},$$

then the graph of f is identical to the region of the Schwarzschild solution of mass m outside its minimal $(n-1)$ -hypersurface.

Remark 1.1. In dimensions less than 8, the above theorem is implied by more general results in [2, 5, 17] because hypersurfaces in Euclidean space are spin. Our proof is different and works for all dimensions. The additional assumption (1.1) for $n = 3$ or 4 ensures that the oscillation of f at infinity is under control. We actually conjecture a stronger statement that an n -dimensional asymptotically flat hypersurface with zero scalar curvature has the following expansion at infinity:

$$(1.2) \quad f(x) = \begin{cases} C_0 \sqrt{|x|} + C_1 + o(1) & \text{if } n = 3, \\ C_0 \ln |x| + C_1 + o(1) & \text{if } n = 4, \end{cases}$$

¹In [19], each connected component of Ω was assumed convex, but the proof can be generalized to our setting.

²The boundary $\partial\Omega$ is called outer-minimizing if whenever Ω' is a domain with $\Omega \subset \Omega'$, then $|\partial\Omega| \leq |\partial\Omega'|$.

for some constants C_0, C_1 . This conjecture should compare with the celebrated work of R. Schoen on the uniqueness of catenoids [24], in which a preliminary result says that complete minimal hypersurfaces have specific asymptotics at infinity, up to lower order terms. In general, hypersurfaces with zero scalar curvature are more difficult to analyze than minimal hypersurfaces, because the scalar curvature equation of the graphing function is fully non-linear. Assuming the strict ellipticity and certain asymptotic behavior of the hypersurfaces at infinity (in all dimensions, which is, in particular, stronger than (1.2) in the low dimensions), J. Hounie and M. Leite proved the uniqueness of embedded scalar-flat hypersurfaces with two ends [14].

Our proof of Theorem 2 relies on a key observation that an asymptotically flat graphical hypersurface with a minimal boundary and with non-negative scalar curvature must be mean convex. It is inspired by our earlier work [15], in which we proved that *closed* or *complete* asymptotically flat hypersurfaces with non-negative scalar curvature must be mean convex.

Theorem 3. *Let Ω be an open and bounded subset (not necessarily connected) in \mathbb{R}^n . Let $f \in C^{n+1}(\mathbb{R}^n \setminus \bar{\Omega}) \cap C^0(\mathbb{R}^n \setminus \Omega)$ be asymptotically flat and let the graph of f be C^{n+1} up to boundary. Suppose each connected component of $\partial\Omega$ is the level set of f with $|Df(x)| \rightarrow \infty$ as $x \rightarrow \partial\Omega$. If the scalar curvature of the graph of f is non-negative, then its mean curvature H has a sign, i.e., either $H \geq 0$ or $H \leq 0$ everywhere.*

The mean convexity enables us to derive the maximum principles for the scalar curvature equation and to compare the graph of f with the Schwarzschild graph. The proof of Theorem 2 is more delicate in the case $n = 3$ or 4 , because the graphing function of the Schwarzschild solution tends to infinity as $|x| \rightarrow \infty$, and it is subtle to compare two unbounded graphs. To control the asymptotical behavior of f , we use its asymptotic flatness and develop a global strong maximum principle (Theorem 4.6) in the region where $|x|$ is sufficiently large. The maximum principles for the scalar curvature equation are established in Section 4.

Note that in our earlier work [15], we proved the Positive Mass Theorem for hypersurfaces in Euclidean space in all dimensions, including the rigidity statement, which is a direct consequence of our proof of the positive mass inequality. However, the proof for the Penrose case requires a new argument which uses the *strict* ellipticity of the Schwarzschild solutions of $m > 0$.

In response to an interesting question raised by Christina Sormani and Dan Lee about the hypersurface which is a Schwarzschild solution outside a compact set, we have the following result.

Theorem 4. *There is no complete C^{n+1} hypersurface of one end with zero scalar curvature in \mathbb{R}^{n+1} which is identical to a Schwarzschild solution with $m > 0$ outside a compact set.³*

³Note that a Schwarzschild solution may not be uniquely embedded in Euclidean space as a hypersurface. Here, we say a hypersurface is identical to a Schwarzschild solution outside a compact set in the sense that the hypersurface is the graph of h outside a compact set of a hyperplane, where h is the radially symmetric function that gives a Schwarzschild solution in Proposition 2.6.

In other words, hyperplanes are the only complete one-ended scalar-flat C^{n+1} hypersurfaces in Euclidean space which are rotationally symmetric outside a compact set.

The above theorem is in contrast to a general result of J. Corvino [6], where he constructed the complete asymptotically flat manifold with zero scalar curvature which is a Schwarzschild metric outside a compact set, but not identical to a Schwarzschild solution.

After this article was written and distributed among a small mathematics community, we noticed a preprint by L. de Lima and F. Girão [10] that announced the rigidity theorem, using the uniqueness result of Hounie and Leite [14] and assuming ellipticity and certain expansions of the graph at infinity. Our theorem is different—the important part of our proof is to *derive* ellipticity and to apply the maximum principles. We believe that our arguments will have more future applications to hypersurfaces in space forms with the appropriate scalar curvature condition (see, for example, [7, 11]).

2. DEFINITIONS, NOTATION, AND PRELIMINARY RESULTS

Definition 2.1. Let Ω be a bounded subset in \mathbb{R}^n , $n \geq 3$. We say that $f \in C^2(\mathbb{R}^n \setminus \Omega)$ is asymptotically flat if the graph of f is a C^2 hypersurface up to boundary which satisfies the following conditions:

- (1) Either $\lim_{|x| \rightarrow \infty} f(x) = C$ for some bounded constant C or $\lim_{|x| \rightarrow \infty} f(x) = \infty$ (or $-\infty$).
- (2) $|Df(x)| = O(|x|^{-\frac{q}{2}})$ and $|D^2f(x)| = O(|x|^{-\frac{q}{2}-1})$, for some $q > \frac{n-2}{2}$, where $Df = (f_1, \dots, f_n)$, $D^2f = (f_{ij})$ and $f_i = \partial f / \partial x^i$, $f_{ij} = \partial^2 f / \partial x^i \partial x^j$.
- (3) The scalar curvature of the graph of f is integrable over the graph of f .

Remark 2.2. Under Condition (2), the induced metric of the graph of f has the asymptotics

$$g_{ij} = \delta_{ij} + f_i f_j = \delta_{ij} + O(|x|^{-q}).$$

The decay rate q is optimal in order for the ADM mass to be well defined, assuming Condition (3) (see [1]).

Remark 2.3. Condition (1) in Definition 2.1 is not needed in the proof of Theorem 1. Condition (1) is actually redundant for $n \geq 6$ because by Condition (2) and using the mean value theorem along the radial direction and along the spherical direction, we have

$$\lim_{|x| \rightarrow \infty} f(x) = C,$$

for some bounded constant C .

Definition 2.4 ([15, 19]). Let Ω be a bounded subset in \mathbb{R}^n , $n \geq 3$, and let $f \in C^2(\mathbb{R}^n \setminus \Omega)$. The mass of the graph of f is defined by

$$m = \frac{1}{2(n-1)\omega_{n-1}} \lim_{r \rightarrow \infty} \int_{S_r} \frac{1}{1 + |Df|^2} \sum_{i,j} (f_{ii}f_j - f_{ij}f_i) \frac{x^j}{|x|} d\sigma,$$

where $S_r = \{(x^1, \dots, x^n) : |x| = r\}$, and $d\sigma$ is the standard spherical volume measure of S_r .

Remark 2.5. The above definition of the mass is consistent with the classical definition of the ADM mass [15, Lemma 5.8]; cf. [19].

The spacelike n -dimensional Schwarzschild metric is a complete and conformally flat metric on $\mathbb{R}^n \setminus \{0\}$:

$$\left(\mathbb{R}^n \setminus \{0\}, \left(1 + \frac{m}{2|x|^{n-2}} \right)^{\frac{4}{n-2}} \delta \right),$$

where m is the ADM mass. If $m \geq 0$, the n -dimensional Schwarzschild solution can be isometrically embedded into Euclidean \mathbb{R}^{n+1} as a smooth hypersurface. We refer the reader to [3] for detailed discussions, especially for the $n = 3$ case. We are interested in the region of the Schwarzschild solution outside its minimal $(n - 1)$ -hypersurface, which is graphical as shown in the following proposition.

Proposition 2.6. *Denote by B_r the open ball in \mathbb{R}^n centered at the origin of radius r . The region of the Schwarzschild solution of mass $m > 0$ outside its minimal $(n - 1)$ -hypersurface can be represented as the graph of $h(x)$ over $\mathbb{R}^n \setminus B_{(2m)^{1/(n-2)}}$, where*

$$\begin{aligned} h(x) &= C_0 + \sqrt{8m(|x| - 2m)} && \text{if } n = 3, \\ h(x) &= C_0 + \sqrt{2m} \ln(|x| + \sqrt{|x|^2 - 2m}) && \text{if } n = 4, \\ h(x) &= C_0 + O(|x|^{2-\frac{n}{2}}) \quad \text{for } |x| \gg 1 && \text{if } n \geq 5, \end{aligned}$$

for some constant C_0 .

Proof. Let $h \in C^2(\mathbb{R}^n \setminus B_{r_0})$ for some $r_0 \geq 0$ be rotationally symmetric. With a minor abuse of notation, we will write $h(x) = h(r)$ where $r = |x|$. By direct computation, the scalar curvature R of the graph of h is given by

$$\frac{R}{2} = \frac{(n-1)h''h'}{r[1+(h')^2]^2} + \frac{\binom{n-1}{2}(h')^2}{r^2[1+(h')^2]},$$

where $h' = \frac{dh}{dr}$ and $h'' = \frac{d^2h}{dr^2}$. Set $y(r) = -\frac{1}{1+(h')^2}$. Then $-1 \leq y \leq 0$ and y solves

$$y' + \frac{n-2}{r}y + \frac{n-2}{r} = \frac{rR}{2(n-1)}.$$

If $R \equiv 0$, for some constant $C_1 \geq 0$, we have

$$y = C_1 r^{2-n} - 1.$$

Therefore, for $r > (C_1)^{1/(n-2)}$,

$$(h')^2 = \frac{1}{1 - C_1 r^{2-n}} - 1 = \frac{C_1 r^{2-n}}{1 - C_1 r^{2-n}} = \frac{C_1}{r^{n-2} - C_1}.$$

Then,

$$h(r) = \sqrt{C_1} \int \frac{1}{\sqrt{r^{n-2} - C_1}} dr.$$

Solving the integral, we have, for some constant C_0 ,

$$\begin{aligned} h(r) &= C_0 + \sqrt{4C_1(r - C_1)} && \text{if } n = 3, \\ h(r) &= C_0 + \sqrt{C_1} \ln(r + \sqrt{r^2 - C_1}) && \text{if } n = 4, \\ h(r) &= C_0 + O(r^{2-\frac{n}{2}}) \quad \text{for } r \gg 1 && \text{if } n \geq 5. \end{aligned}$$

By computing the mass directly, we have

$$m = \frac{1}{2(n-1)\omega_{n-1}} \lim_{r \rightarrow \infty} \int_{S_r} \frac{(n-1)(h')^2}{r(1+(h')^2)} d\sigma = \frac{C_1}{2}.$$

It is straightforward to check that if $m > 0$, $h'(r) \rightarrow \infty$ as $r \rightarrow (2m)^{1/(n-2)}$, and the graph of h over $\partial B_{(2m)^{1/(n-2)}}$ is the minimal $(n-1)$ -hypersurface in the graph of h . \square

Notation. For a hypersurface, we denote by A_{ij} the second fundamental form, by $A_j^i = \sum_k g^{ik} A_{kj}$ the shape operator where g^{ik} is the inverse of the induced metric, by H the mean curvature, and by R the scalar curvature. If the hypersurface is the graph of u , we compute A_{ij} with respect to the *upward* unit normal vector and we can write the above quantities as the functions of Du and D^2u . We may also suppress the arguments when the context is clear.

$$\begin{aligned} g^{ik}(Du) &= \left(\delta_{ik} - \frac{u_i u_k}{1 + |Du|^2} \right), \\ A_{ij}(Du, D^2u) &= \frac{u_{ij}}{\sqrt{1 + |Du|^2}}, \\ A_j^i(Du, D^2u) &= \sum_k \left(\delta_{ik} - \frac{u_i u_k}{1 + |Du|^2} \right) \frac{u_{kj}}{\sqrt{1 + |Du|^2}}, \\ H(Du, D^2u) &= \sum_{i,j} \left(\delta_{ij} - \frac{u_i u_j}{1 + |Du|^2} \right) \frac{u_{ij}}{\sqrt{1 + |Du|^2}}, \\ R(Du, D^2u) &= H^2(Du, D^2u) - \sum_{i,j} A_j^i(Du, D^2u) A_i^j(Du, D^2u). \end{aligned}$$

Proposition 2.7. *Let h be the graphing function of the Schwarzschild solution of $m > 0$ in Proposition 2.6. Then the matrix $(Hg^{ij} - \sum_k A_k^i g^{kj})$ of the graph of h is positive definite everywhere in $\mathbb{R}^n \setminus B_{(2m)^{1/(n-2)}}$.*

Proof. It suffices to show that $(H\delta_k^i - A_k^i)$ is positive definite, because $Hg^{ij} - \sum_k A_k^i g^{kj} = \sum_k (H\delta_k^i - A_k^i) g^{kj}$ and (g^{kj}) is positive definite. By rotating coordinates, we can assume that $A_k^i = \text{diag}(\lambda_1, \dots, \lambda_n)$ where λ_l are the principle curvatures. For the graph of a rotationally symmetric function $h(r)$, the principle curvatures are

$$\frac{h''}{(1+(h')^2)^{3/2}} \quad \text{and} \quad \frac{h'}{r\sqrt{1+(h')^2}} \quad \text{with multiplicity } (n-1).$$

Therefore, the principle curvatures of the Schwarzschild solution are

$$-\frac{n-2}{2}\sqrt{2mr}^{-\frac{n}{2}} \quad \text{and} \quad \sqrt{2mr}^{-\frac{n}{2}} \quad \text{with multiplicity } (n-1).$$

Hence, $(H\delta_k^i - A_k^i) \geq \frac{n-2}{2}\sqrt{2mr}^{-\frac{n}{2}} I$ where I is the $n \times n$ identity matrix, so it is positive definite everywhere in $\mathbb{R}^n \setminus B_{(2m)^{1/(n-2)}}$. \square

The following two propositions were proven in our earlier paper [15]. They play important roles to prove the mean convexity of the asymptotically flat graphs and to derive the ellipticity of the linearized scalar curvature operator.

Proposition 2.8 ([15, Proposition 2.1]). *Let $B = (b_{ij})$ be an $n \times n$ matrix with $n \geq 2$. Denote*

$$\begin{aligned}\sigma_1(B) &= \sum_{i=1}^n b_{ii}, & \sigma_1(B|k) &= \left(\sum_{i=1}^n b_{ii} \right) - b_{kk}, \\ \sigma_2(B) &= \sum_{1 \leq i < j \leq n} (b_{ii}b_{jj} - b_{ij}b_{ji}).\end{aligned}$$

For each $1 \leq k \leq n$, we have

$$\begin{aligned}\sigma_1(B)\sigma_1(B|k) &= \sigma_2(B) + \frac{n}{2(n-1)} (\sigma_1(B|k))^2 + \sum_{1 \leq i < j \leq n} b_{ij}b_{ji} \\ &\quad + \frac{1}{2(n-1)} \sum_{\substack{1 \leq i < j \leq n \\ i \neq k, j \neq k}} (b_{ii} - b_{jj})^2,\end{aligned}$$

where the last term is zero when $n = 2$. In particular, if B is real and $b_{ij}b_{ji} \geq 0$ for all $1 \leq i < j \leq n$, then

$$\sigma_1(B)\sigma_1(B|k) \geq \sigma_2(B) + \frac{n}{2(n-1)} (\sigma_1(B|k))^2$$

with equality if and only if b_{ii} are equal for all $i = 1, \dots, n$ and $i \neq k$, and $b_{ij}b_{ji} = 0$ for all $i, j = 1, \dots, n$ and $i \neq j$.

Notation. Let N be a (piece of) hypersurface in Euclidean space, and let μ be a unit normal vector field to N . The mean curvature of N defined by μ is given by

$$H_N = -\operatorname{div}_0 \mu,$$

where div_0 is the Euclidean divergence operator. (The n -dimensional sphere of radius r has mean curvature n/r with respect to the inward unit normal vector by this convention.) We denote by $\langle \cdot, \cdot \rangle$ the standard metric on Euclidean space. With a slight abuse of notation, we may view η as a vector in \mathbb{R}^n , as well as a vector in \mathbb{R}^{n+1} by letting the last component be zero.

Proposition 2.9 ([15, Theorem 2.2]). *Let M be a C^2 hypersurface in \mathbb{R}^{n+1} . Consider the height function $h : M \rightarrow \mathbb{R}$ given by $h(x^1, \dots, x^{n+1}) = x^{n+1}$. Let a be a regular value of h . Denote*

$$\Sigma = M \cap \{x^{n+1} = a\},$$

which is a C^2 hypersurface in $\{x^{n+1} = a\}$ and $|\nabla^M h| > 0$ at every point in Σ . Denote by ν and η the unit normal vector fields to $M \subset \mathbb{R}^{n+1}$ and $\Sigma \subset \{x^{n+1} = a\}$, respectively, and denote by H and H_Σ the mean curvatures of $M \subset \mathbb{R}^{n+1}$ and $\Sigma \subset \{x^{n+1} = a\}$ defined by ν and η , respectively. Let R be the induced scalar curvature of M . Then, at every point of Σ ,

$$\langle \nu, \eta \rangle H H_\Sigma \geq \frac{R}{2} + \frac{n}{2(n-1)} \langle \nu, \eta \rangle^2 H_\Sigma^2$$

with the equality at a point in Σ if and only if (M, Σ) satisfies the following two conditions at the point:

- (i) $\Sigma \subset \mathbb{R}^n$ is umbilic, with the principal curvature κ ;
- (ii) $M \subset \mathbb{R}^{n+1}$ has at most two distinct principal curvatures, and one of them is equal to $\langle \nu, \eta \rangle \kappa$, with multiplicity at least $n - 1$.

3. PROOF OF THEOREM 3

Notation. Let M be a hypersurface in Euclidean space and let $\text{int}(M)$ be the set of interior points in M , i.e., $\text{int}(M) = M \setminus \partial M$. The set of interior geodesic points is given by

$$(3.1) \quad M_0 = \{p \in \text{int}(M) : (A_j^i) = 0 \text{ at } p\}.$$

A classical result of R. Sacksteder [23, Lemma 6] characterizes the set of geodesic points. While he proved the statement for complete hypersurfaces, the statement can be easily generalized to hypersurfaces with boundary; see also [15, Lemma 3.6] and [16, Lemma 4.5].

Lemma 3.1. *Let M be a C^{n+1} hypersurface in \mathbb{R}^{n+1} , and let M'_0 be a connected component of M_0 . Then M'_0 lies in a hyperplane which is tangent to M at every point in M'_0 .*

To prove Theorem 3, let us recall the following results in [15].

Lemma 3.2 ([15, Proposition 3.1]). *Let W be an open subset in \mathbb{R}^n , not necessarily bounded. Let $p \in \partial W$, and denote by $B(p)$ an open ball in \mathbb{R}^n centered at p . Suppose $f \in C^2(W \cap B(p)) \cap C^1(\overline{W} \cap B(p))$ satisfies*

$$\begin{aligned} H(Df, D^2f) &\geq 0 && \text{in } W \cap B(p), \\ f = c, |Df| &= 0 && \text{on } \partial W \cap B(p), \end{aligned}$$

for some constant c . Then either $f \equiv c$ in $W \cap B(p)$, or

$$\{x \in W \cap B(p) : f(x) > c\} \neq \emptyset.$$

Theorem 3.3 ([15, Theorem 3.9]). *Let W be a bounded open subset in \mathbb{R}^n and let N be an open neighborhood of ∂W . If $f \in C^{n+1}(\overline{W} \cap N)$, $f = c$, $|Df| = 0$, $|D^2f| = 0$ on ∂W , and the scalar curvature of the graph of f is non-negative, then $f \equiv c$ on $W \cap N$.*

Theorem 3.4. *Let $f \in C^{n+1}(\mathbb{R}^n \setminus \overline{\Omega}) \cap C^0(\mathbb{R}^n \setminus \Omega)$ and $|Df(x)| \rightarrow \infty$ as $x \rightarrow \partial\Omega$. Denote by M the graph of f . Suppose M is C^{n+1} up to boundary and has non-negative scalar curvature. Suppose that the mean curvature H of M changes signs. Let M_+ be a connected component of $\{p \in M : H \geq 0 \text{ at } p\}$ that contains a point of positive mean curvature. Then both M_+ and the boundary of each component of $M \setminus M_+$, except ∂M , must be unbounded.*

Proof. Note that M is homeomorphic to $\mathbb{R}^n \setminus \Omega$ given by the projection $\pi(x, f(x)) = x$. Let $\mathbb{R}^n \setminus \pi(M_+) = \bigsqcup_{\alpha} U_{\alpha}$ where each U_{α} is a connected component and $\Omega \subset U_{\alpha_0}$ for some α_0 . Because $\pi(M_+)$ is connected, each ∂U_{α} is connected [15, Proposition A.3]. We claim that U_{α} is unbounded for each $\alpha \neq \alpha_0$. Suppose to the contrary that U_{α} is bounded for some $\alpha \neq \alpha_0$. Denote $\pi^{-1}(\partial U_{\alpha}) = \Gamma$. By Lemma 3.1, $\Gamma \subset M_0$ lies in a hyperplane Π . Note that $\overline{\Gamma}$ does not intersect with ∂M because $|Df| = \infty$ on ∂M . Hence M can be represented as the graph of a C^{n+1} function u in an open neighborhood of Γ in Π , and u satisfies $u = 0, |Du| = 0, |D^2u| = 0$ on Γ . By Theorem 3.3, we have $u \equiv 0$ on $\pi^{-1}(U_{\alpha})$ and hence $\pi^{-1}(U_{\alpha}) \subset M_+$.

It contradicts. Similarly, one can show that U_{α_0} is unbounded and ∂U_{α_0} does not intersect $\partial\Omega$, unless $U_{\alpha_0} = \Omega$.

Furthermore, M_+ must be unbounded. Suppose not. Then the complement $\mathbb{R}^n \setminus \pi(M_+)$ has a unique unbounded connected component that contains infinity. Therefore, either $\mathbb{R}^n \setminus \pi(M_+) = \Omega \sqcup U$ where U is the unbounded connected component that contains infinity, or $\mathbb{R}^n \setminus \pi(M_+) = U_{\alpha_0}$ if U_{α_0} is unbounded. Hence we have either $\partial\pi(M_+) = \partial\Omega \sqcup \partial U$ or $\partial\pi(M_+) = \partial U_{\alpha_0}$. Applying Theorem 3.3 to $\pi(M_+)$ on either ∂U or ∂U_{α_0} , we have $H \equiv 0$ on M_+ which contradicts that M_+ contains a point of positive mean curvature. \square

Proof of Theorem 3. Suppose to the contrary that H changes signs. Let M_+ be a connected component of $\{p \in M : H \geq 0 \text{ at } p\}$ that contains a point of positive mean curvature. By Theorem 3.4, a component Γ of ∂M_+ is unbounded. By Lemma 3.1, Γ lies in a hyperplane Π and M is tangent to Π at Γ . By the assumption that f is asymptotically flat, the upward unit normal vector of M converges to ∂_{n+1} at infinity. Because M is tangent to the hyperplane Π at an unbounded set, we must have $\lim_{|x| \rightarrow \infty} f(x) = C$ for some bounded constant C and $\Pi = \{x^{n+1} = C\}$.

By Lemma 3.2, the level set $\{x : f(x) = C + \epsilon\}$ has non-empty intersection with $\{p \in \text{int}(M) : H > 0 \text{ at } p\}$ for all $\epsilon > 0$ sufficiently small. Let $\Sigma_{C+\epsilon}$ be a connected component of the level set which intersects $\{p \in \text{int}(M) : H > 0 \text{ at } p\}$. Note that $\Sigma_{C+\epsilon}$ is closed if $\epsilon \neq 0$, and that $H \geq 0$ at every point of $\Sigma_{C+\epsilon}$ because by Theorem 3.4 the mean curvature H can only change signs through an unbounded subset of M_0 , which must lie on $\{x^{n+1} = C\}$. By the Morse-Sard theorem, $\Sigma_{C+\epsilon}$ is a C^{n+1} submanifold with $|Df| > 0$ for almost every ϵ . Let $\eta = Df/|Df|$ be a unit normal vector of $\Sigma_{C+\epsilon}$ where $C + \epsilon$ is a regular value. For $\epsilon > 0$ sufficiently small, η points *inward* to the region enclosed by $\Sigma_{C+\epsilon}$ because f decreases to C at infinity. Let $H_{\Sigma_{C+\epsilon}}$ be the mean curvature with respect to η . By Proposition 2.9, $H_{\Sigma_{C+\epsilon}} \leq 0$ at every point of $\Sigma_{C+\epsilon}$, which contradicts compactness of $\Sigma_{C+\epsilon}$. \square

4. ELLIPTICITY AND MAXIMUM PRINCIPLES

In this section, we will derive various maximum principles for graphs with non-negative scalar curvature. The scalar curvature equation of the graphing function is fully non-linear. Its linearization, first introduced by [21], gives a second-order differential equation. The linearized equation may not be elliptic in general. It is known that if the scalar curvature is a *positive* constant, then the strict ellipticity trivially holds pointwise (see, for example, [22]). However, this is no longer true if the scalar curvature may vanish. An important step to establish our maximum principles is to explore the (strict) ellipticity of the linearized scalar curvature equation.

Lemma 4.1. *Let u be a C^2 function and let R be the scalar curvature of the graph of u . Then*

$$\frac{\partial R}{\partial u_{ij}}(Du, D^2u) = \frac{2}{\sqrt{1 + |Du|^2}} \left(Hg^{ij} - \sum_k A_k^i g^{kj} \right).$$

Proof. By the chain rule,

$$\begin{aligned}
\frac{\partial R}{\partial u_{ij}} &= \sum_{k,l} \frac{\partial R}{\partial A_l^k} \frac{\partial A_l^k}{\partial u_{ij}} \\
&= \sum_{k,l} \frac{\partial R}{\partial A_l^k} \frac{\partial}{\partial u_{ij}} \left(\sum_p g^{kp} A_{pl} \right) \\
&= \sum_k \frac{\partial R}{\partial A_k^i} \frac{g^{kj}}{\sqrt{1+|Du|^2}} \\
&= 2H \frac{g^{ij}}{\sqrt{1+|Du|^2}} - 2 \sum_k A_k^i \frac{g^{kj}}{\sqrt{1+|Du|^2}}. \quad \square
\end{aligned}$$

Proposition 4.2. *Let u be a C^2 function, and let R and H be the scalar curvature and mean curvature of the graph of u , respectively. If $R \geq 0$ and $H \geq 0$, then the matrix $(Hg^{ij} - \sum_k A_k^i g^{kj})$ is semi-positive definite.*

Proof. Because $Hg^{ij} - \sum_k A_k^i g^{kj} = \sum_k (H\delta_k^i - A_k^i)g^{kj}$ and (g^{kj}) is positive definite, it suffices to prove that $(H\delta_k^i - A_k^i)$ is semi-positive definite. By rotating the coordinates, we assume $(A_k^i) = \text{diag}(\lambda_1, \dots, \lambda_n)$. Then

$$(H\delta_k^i - A_k^i) = \text{diag}(\sigma_1(A|1), \dots, \sigma_1(A|n)).$$

By Proposition 2.8, because $H = \sigma_1(A) \geq 0$ and $R = 2\sigma_2(A) \geq 0$, we have $\sigma_1(A|k) \geq 0$ for all $k = 1, \dots, n$. \square

Theorem 4.3 (Strong maximum principle for the interior point). *Let Ω be a connected open subset in \mathbb{R}^n . Suppose $u, v \in C^2(\Omega)$, $u \geq v$ in Ω , and u, v satisfy*

$$\begin{aligned}
R(Du, D^2u) &= 0, & R(Dv, D^2v) &\geq 0, \\
H(Du, D^2u) &\geq 0, & \text{and } H(Dv, D^2v) &\geq 0 \quad \text{in } \Omega.
\end{aligned}$$

We assume that either u or v satisfies $(Hg^{ij} - \sum_k A_k^i g^{kj})$ being positive definite in Ω . If $u = v$ at some point in Ω , then $u \equiv v$ in Ω .

Proof. Let $R(p, \xi) \in C^1(\mathbb{R}^n \times \mathbb{R}^{n \times n})$ be the scalar curvature operator. Hence

$$\begin{aligned}
0 &\geq R(Du, D^2u) - R(Dv, D^2v) \\
&= R(Du, D^2u) - R(Du, D^2v) + R(Du, D^2v) - R(Dv, D^2v) \\
&= \sum_{i,j} a^{ij}(u_{ij} - v_{ij}) + \sum_i b^i(u_i - v_i),
\end{aligned}$$

where

$$b^i = \int_0^1 \frac{\partial R}{\partial p_i}(tDu + (1-t)Dv, D^2v) dt$$

and by Lemma 4.1

$$\begin{aligned} a^{ij} &= \int_0^1 \frac{\partial R}{\partial \xi_{ij}}(Du, tD^2u + (1-t)D^2v) dt \\ &= \frac{1}{\sqrt{1+|Du|^2}} \left((H(Du, D^2u)g^{ij}(Du) - \sum_k A_k^i(Du, D^2u)g^{kj}(Du)) \right. \\ &\quad \left. + (H(Du, D^2v)g^{ij}(Du) - \sum_k A_k^i(Du, D^2v)g^{kj}(Du)) \right). \end{aligned}$$

If $u = v$ at $p \in \Omega$, then $Du = Dv$ at p . Then, by the assumption and Proposition 4.2, (a^{ij}) is positive definite at p . By continuity, (a^{ij}) is positive definite in an open neighborhood Ω' of p in Ω . Then by the standard strong maximum principle, $u \equiv v$ in Ω' . Hence, the set $\{p \in \Omega : u(p) = v(p)\}$ is open and closed. Because Ω is connected, we prove that $u \equiv v$ in Ω . \square

Theorem 4.4 (Strong maximum principle for the boundary point). *Let Ω_1, Ω_2 be connected open sets in \mathbb{R}^n such that $\Omega_1 \subset \Omega_2$. Suppose $p \in \partial\Omega_1 \cap \partial\Omega_2 \neq \emptyset$ and $\partial\Omega_1, \partial\Omega_2$ are C^1 near p .*

Let $u \in C^2(\Omega_1) \cap C^0(\overline{\Omega_1}), v \in C^2(\Omega_2) \cap C^0(\overline{\Omega_2})$. Suppose the graphs of u, v are C^2 hypersurfaces up to boundary which satisfy

$$\begin{aligned} R(Du, D^2u) &= 0, \quad R(Dv, D^2v) \geq 0, \\ H(Du, D^2u) &\geq 0, \quad \text{and} \quad H(Dv, D^2v) \geq 0 \quad \text{in } \Omega_1. \end{aligned}$$

We also assume that either u or v satisfies $(Hg^{ij} - \sum_k A_k^i g^{kj})$ being positive definite in Ω_1 . If $u \geq v \geq 0$ in Ω_1 and $u|_{\partial\Omega_1 \cap B_r(p)} = v|_{\partial\Omega_2 \cap B_r(p)} = 0$ for some open ball centered at p of radius r with $|Du(x)| \rightarrow \infty$ and $|Dv(x)| \rightarrow \infty$ as $x \rightarrow p \in \partial\Omega_1 \cap \partial\Omega_2$, then $u \equiv v$ in Ω_1 .

Proof. Let Π be the vertical hyperplane in \mathbb{R}^{n+1} so that Π is tangent to $\partial\Omega_1 \times \{x^{n+1}\text{-axis}\}$ at $p \times \{x^{n+1}\text{-axis}\}$. The graphs of u, v near p can be locally represented as the graphs of some functions \tilde{u}, \tilde{v} over a subset of Π , say $\tilde{u}, \tilde{v} \in C^2(D \times [0, \epsilon])$ where $p \in \text{int}(D) \subset \{x^{n+1} = 0\}$ and $D \times [0, \epsilon] \subset \Pi$. Moreover, \tilde{u} and \tilde{v} satisfy $\tilde{u} \geq \tilde{v}$ in $D \times [0, \epsilon]$, $\tilde{u} = \tilde{v}$ and $\partial_{n+1}\tilde{u} = \partial_{n+1}\tilde{v} = 0$ at $p \in D \times \{0\}$, and

$$\begin{aligned} R(D\tilde{u}, D^2\tilde{u}) &= 0, \quad R(D\tilde{v}, D^2\tilde{v}) \geq 0, \\ H(D\tilde{u}, D^2\tilde{u}) &\geq 0, \quad \text{and} \quad H(D\tilde{v}, D^2\tilde{v}) \geq 0 \quad \text{in } D \times [0, \epsilon]. \end{aligned}$$

Either \tilde{u} or \tilde{v} has $(Hg^{ij} - \sum_k A_k^i g^{kj})$ being positive definite in $D \times [0, \epsilon]$. As analyzed in the proof of Theorem 4.3, $(\tilde{u} - \tilde{v})$ satisfies

$$0 \geq \sum_{i,j} a^{ij}(\tilde{u}_{ij} - \tilde{v}_{ij}) + \sum_i b^i(\tilde{u}_i - \tilde{v}_i),$$

where (a^{ij}) is positive definite in $D \times [0, \epsilon]$ with a possibly smaller ϵ . Then by the standard Hopf boundary point lemma, $\tilde{u} = \tilde{v}$ at some interior points of $D \times [0, \epsilon]$. Hence $u = v$ at some interior points in Ω_1 , and by Theorem 4.3, $u \equiv v$ everywhere in Ω_1 . \square

To prove Theorem 4, we need the following version of the strong maximum principle for the boundary point, where the domains of u and v are complement to each other. The proof is nearly identical to the proof of Theorem 4.4, so we omit it.

Theorem 4.5. *Let Ω be an open subset in \mathbb{R}^n . Let $p \in \partial\Omega$ and consider the open ball $B_r(p)$ centered at p of radius r for some $r > 0$ small. Suppose $\partial\Omega \cap B_r(p)$ is C^1 . Let $u \in C^2(B_r(p) \setminus (\Omega \cap \overline{B_r(p)})) \cap C^0(B_r(p) \setminus (\Omega \cap B_r(p)))$, $v \in C^2(\Omega \cap B_r(p)) \cap C^0(\overline{\Omega \cap B_r(p)})$ and $u \geq 0, v \leq 0$. Suppose the graphs of u, v are C^2 hypersurfaces up to boundary which satisfy*

$$\begin{aligned} R(Du, D^2u) &= 0, & R(Dv, D^2v) &= 0, \\ H(Du, D^2u) &\geq 0, & \text{and } H(Dv, D^2v) &\geq 0. \end{aligned}$$

We also assume that the matrix $(Hg^{ij} - \sum_k A_k^i g^{kj})$ of u is positive definite. If $u|_{\partial\Omega \cap B_r(p)} = v|_{\partial\Omega \cap B_r(p)} = 0$, then $|Du(x)|$ and $|Dv(x)|$ cannot both tend to ∞ as $x \rightarrow p \in \partial\Omega$.

Theorem 4.6 (Global strong maximum principle). *Let Ω be a bounded subset (not necessarily connected) in \mathbb{R}^n , and let $v \in C^2(\mathbb{R}^n \setminus \Omega)$ be asymptotically flat. We assume that the graph of v satisfies $R = 0$ and $H \geq 0$ in $\mathbb{R}^n \setminus \Omega$. Let h be the Schwarzschild solution given by Proposition 2.6. Then there exists $r \gg 1$ so that, for any $r_2 > r_1 \geq r$,*

$$\begin{aligned} \max_{\overline{B_{r_2}} \setminus B_{r_1}} (h - v) &= \max_{S_{r_2} \cup S_{r_1}} (h - v), \\ \min_{\overline{B_{r_2}} \setminus B_{r_1}} (h - v) &= \min_{S_{r_2} \cup S_{r_1}} (h - v). \end{aligned}$$

If $(h - v)$ attains its maximum or minimum at an interior point in $B_{r_2} \setminus \overline{B_{r_1}}$, then $(h - v)$ must be a constant in $\overline{B_{r_2}} \setminus B_{r_1}$.

Proof. As computed in the proof of Theorem 4.3, we have

$$\begin{aligned} 0 &= R(Dh, D^2h) - R(Dv, D^2v) \\ &= \sum_{i,j} a^{ij} (h_{ij} - v_{ij}) + \sum_i b^i (h_i - v_i), \end{aligned}$$

where

$$\begin{aligned} a^{ij} &= \frac{1}{\sqrt{1 + |Dh|^2}} \sum_k \left(H(Dh, D^2h) \delta_k^i - A_k^i (Dh, D^2h) \right. \\ &\quad \left. + H(Dh, D^2v) \delta_k^i - A_k^i (Dh, D^2v) \right) g^{kj} (Dh). \end{aligned}$$

We shall prove that (a_{ij}) is positive definite in $\mathbb{R}^n \setminus B_r$ for $r \gg 1$. Then the lemma follows directly from the standard maximum principles. Because (g^{kj}) is positive definite, we can prove the positivity of (a^{ij}) by showing that the matrix

$$(4.1) \quad (H(Dh, D^2h) \delta_k^i - A_k^i (Dh, D^2h) + H(Dh, D^2v) \delta_k^i - A_k^i (Dh, D^2v))$$

is positive definite. By direct computation,

$$\begin{aligned} &H(Dh, D^2v) \delta_k^i - A_k^i (Dh, D^2v) \\ &= H(Dv, D^2v) \delta_k^i - A_k^i (Dv, D^2v) + O(|Dv|^2 |D^2v| + |Dh|^2 |D^2h|) \\ &= H(Dv, D^2v) \delta_k^i - A_k^i (Dv, D^2v) + o\left(r^{(-3n+2)/4}\right), \end{aligned}$$

where $r = |x|$ and we use the asymptotic flatness of h and v . By Proposition 4.2, $(H(Dv, D^2v)\delta_k^i - A_k^i(Dv, D^2v))$ is semi-positive definite. By Proposition 2.7,

$$(H(Dh, D^2h)\delta_k^i - A_k^i(Dh, D^2h)) \geq \frac{n-2}{2}\sqrt{2mr}^{-n/2}I.$$

The right-hand side above is positive enough to absorb the error term $o(r^{(-3n+2)/4})$ if $r \gg 1$. Hence (4.1) is positive definite. \square

5. PROOFS OF THEOREM 2 AND THEOREM 4

We need the following inequalities. Proposition 5.1 is a special case of the Alexandrov-Fenchel inequalities. The classical result was proven for a convex domain. It has been generalized to a star-shaped domain Ω with a mean-convex boundary [13] or a domain whose boundary is outer-minimizing by Huisken and by [12].

Proposition 5.1. *Let $\Omega \subset \mathbb{R}^n$ be star-shaped or outer-minimizing and let $\Sigma = \partial\Omega$ be mean convex. Denote by H_Σ the mean curvature of Σ with respect to the inward unit normal vector. Then*

$$\frac{1}{2(n-1)\omega_{n-1}} \int_\Sigma H_\Sigma d\sigma \geq \frac{1}{2} \left(\frac{|\Sigma|}{\omega_{n-1}} \right)^{\frac{n-2}{n-1}}$$

with equality if and only if Σ is an $(n-1)$ -sphere.

Proposition 5.2. *Let a_1, a_2, \dots, a_k be non-negative real numbers and $0 \leq \beta \leq 1$. Then*

$$\sum_{i=1}^k a_i^\beta \geq \left(\sum_{i=1}^k a_i \right)^\beta.$$

If $0 \leq \beta < 1$, the equality holds if and only if at most one of a_i is non-zero.

Proof. Without loss of generality, we assume $k = 2$. We shall prove that $x^\beta + y^\beta \geq (x+y)^\beta$ if $0 \leq \beta \leq 1$ and $x, y \geq 0$. Fix β, x and define $w(y) = x^\beta + y^\beta - (x+y)^\beta$. Then $w(0) = 0$ and

$$w'(y) = \beta(y^{\beta-1} - (x+y)^{\beta-1}) \geq 0 \quad \text{for all } y \geq 0.$$

Hence $w(y) \geq 0$ for all $y \geq 0$ with $w(y) = 0$ if and only if $x = 0$, or $y = 0$, or $\beta = 1$. \square

Proof of Theorem 1 ([19]). The scalar curvature of the graph of f has a divergence form in terms of the derivatives of f [20] (see also [15, 19])

$$R = \sum_j \partial_j \sum_i \left(\frac{f_{ii}f_j - f_{ij}f_i}{1 + |Df|^2} \right).$$

Let Ω^ϵ be a bounded open set in \mathbb{R}^n that contains Ω with $\Omega^\epsilon \rightarrow \Omega$ as $\epsilon \rightarrow 0$, and let each connected component Σ_k^ϵ of $\partial\Omega^\epsilon$ be the level set of f . By applying the

divergence theorem over $\mathbb{R}^n \setminus \Omega^\epsilon$, we have

$$\begin{aligned}
& 2(n-1)\omega_{n-1}m \\
&= \lim_{r \rightarrow \infty} \int_{S_r} \frac{1}{1+|Df|^2} \sum_{i,j} (f_{ii}f_j - f_{ij}f_i) \frac{x^j}{|x|} d\sigma \\
&= \int_{\mathbb{R}^n \setminus \Omega^\epsilon} R dx - \sum_k \int_{\Sigma_k^\epsilon} \frac{1}{1+|Df|^2} \sum_{i,j} (f_{ii}f_j - f_{ij}f_i) \eta^j d\sigma \\
&= \int_{\mathbb{R}^n \setminus \Omega^\epsilon} R dx + \sum_k \int_{\Sigma_k^\epsilon} \frac{|Df|^2}{1+|Df|^2} H_{\Sigma_k^\epsilon} d\sigma,
\end{aligned}$$

where $H_{\Sigma_k^\epsilon}$ denotes the mean curvature of the level set Σ_k^ϵ with respect to the unit normal vector η pointing *inward* to the region enclosed by Σ_k^ϵ (cf. [15, Proof of Lemma 5.6]). Let ϵ tend to zero. Then each level set Σ_k^ϵ tends to the connected component Σ_k of $\partial\Omega$ and $|Df| \rightarrow \infty$. Therefore, we have

$$\begin{aligned}
m &= \frac{1}{2(n-1)\omega_{n-1}} \left(\int_{\mathbb{R}^n \setminus \Omega} R dx + \sum_k \int_{\Sigma_k} H_{\Sigma_k} d\sigma \right) \\
&\geq \sum_k \frac{1}{2(n-1)\omega_{n-1}} \int_{\Sigma_k} H_{\Sigma_k} d\sigma \\
&\geq \sum_k \frac{1}{2} \left(\frac{|\Sigma_k|}{\omega_{n-1}} \right)^{\frac{n-2}{n-1}} \quad (\text{by Proposition 5.1}) \\
&\geq \frac{1}{2} \left(\frac{|\partial\Omega|}{\omega_{n-1}} \right)^{\frac{n-2}{n-1}} \quad (\text{by Proposition 5.2}). \quad \square
\end{aligned}$$

Corollary 5.3. *Under the conditions of Theorem 1, if*

$$m = \frac{1}{2} \left(\frac{|\partial\Omega|}{\omega_{n-1}} \right)^{\frac{n-2}{n-1}},$$

then $R \equiv 0$ in $\mathbb{R}^n \setminus \Omega$, and $\partial\Omega$ is a sphere of radius $(2m)^{\frac{1}{n-2}}$.

The proof of Theorem 2 makes use of the maximum principles proven in Section 4. The case $n = 3$ or 4 is more subtle because the graphing function of the Schwarzschild solution tends to infinity as $|x| \rightarrow \infty$, and difficulty arises when comparing two unbounded graphs. In that case, instead of using the strong maximum principles Theorem 4.3 or Theorem 4.4 directly, we first control the growth at infinity, by the asymptotic flatness of the graph and Theorem 4.6.

Proof of Theorem 2. Suppose the equality of the Penrose inequality holds. By Corollary 5.3, the scalar curvature of the graph of f is identically zero everywhere and $\partial\Omega$ is a round sphere of radius $(2m)^{\frac{1}{n-2}}$. By translating f , we assume that $f = 0$ on $\partial\Omega$ and $\partial\Omega = S_{(2m)^{\frac{1}{n-2}}} \subset \{x^{n+1} = 0\}$. By Theorem 3, the mean curvature of the graph of f must have a sign. Suppose that $H \geq 0$ with respect to the upward unit normal. Then, we have either $\lim_{|x| \rightarrow \infty} f(x) = C$ for some positive constant C or $\lim_{|x| \rightarrow \infty} f(x) = +\infty$.

Let h be the function in Proposition 2.6 which gives the exterior region of the Schwarzschild solution of mass m outside its minimal boundary. By translating h ,

we assume that its minimal boundary is $S_{(2m)^{\frac{1}{n-2}}} \subset \{x^{n+1} = 0\}$. We consider two cases, depending on the dimension n .

Case 1: $n \geq 5$. In this case, $\lim_{|x| \rightarrow \infty} h(x) = C_0$ for some bounded constant C_0 .

If $\lim_{|x| \rightarrow \infty} f(x) = C \leq C_0$, we let $u_\lambda = h + \lambda$ for $\lambda \geq 0$. For λ sufficiently large, $u_\lambda > f$. We then continuously decrease λ , until $u_\lambda = f$ at $p \in \mathbb{R}^n \setminus B_{(2m)^{\frac{1}{n-2}}}$ for the first time. If p is an interior point, $u_\lambda \equiv f$ by Theorem 4.3. If p is a boundary point in $S_{(2m)^{\frac{1}{n-2}}}$, $u_\lambda \equiv f$ by Theorem 4.4. Hence, the graph of f is identical to the exterior region of the Schwarzschild solution of mass m outside its minimal boundary.

If $\lim_{|x| \rightarrow \infty} f(x) = C \geq C_0$ or $\lim_{|x| \rightarrow \infty} f(x) = +\infty$, we consider $v_\lambda = h - \lambda$ for $\lambda \geq 0$. Note that $f > v_\lambda$ for λ sufficiently large. We then continuously decrease λ until $f = v_\lambda$ for the first time. Then by either Theorem 4.3 or Theorem 4.4, we have $f \equiv h$ in $\mathbb{R}^n \setminus B_{(2m)^{\frac{1}{n-2}}}$.

Case 2: $n = 3$ or 4 . (In this case, $\lim_{|x| \rightarrow \infty} h(x) = \infty$.)

We claim that either $\max_{|x|=r} f(x) > h(r)$ or $\max_{|x|=r} f(x) \leq h(r)$ for all r sufficiently large. Suppose the first statement is false. Then there exists a sequence of positive numbers $\{r_k\}$ with $r_k \rightarrow \infty$ as $k \rightarrow \infty$ so that $\max_{|x|=r_k} f(x) \leq h(r_k)$. Then by Theorem 4.6, we have $\max_{|x|=r} f(x) \leq h(r)$ for all r sufficiently large. This proves the claim.

Suppose $\max_{|x|=r} f(x) > h(r)$ for all r sufficiently large. By the assumption $\min_{|x|=r} f + C \geq \max_{|x|=r} f(x)$ for r sufficiently large, we have for all $r \geq (2m)^{\frac{1}{n-2}}$

$$\min_{|x|=r} f(x) > h(r) - C',$$

for some constant $C' > 0$. Hence, $f(x) > h(x) - C'$ for all $x \in \mathbb{R}^n \setminus B_{(2m)^{\frac{1}{n-2}}}$. We then continuously decrease C' until $f(x) = h(x) - C'$ for the first time. Then either Theorem 4.3 or Theorem 4.4 implies $f(x) \equiv h(x)$, which leads to a contradiction. Hence, $\max_{|x|=r} f(x) \leq h(r)$ for all r sufficiently large. Let $v_\lambda = h + \lambda$ for $\lambda > 0$ sufficiently large. Then we continuously decrease λ . The graph of v_λ approaches the graph of f from above, until they touch for the first time. By either Theorem 4.3 or Theorem 4.4, we conclude that $f \equiv h$. \square

Proof of Theorem 4. Suppose to the contrary that there is a complete C^{n+1} hypersurface M of one end with zero scalar curvature in \mathbb{R}^{n+1} which is identical to the Schwarzschild solution h (given in Proposition 2.6) of $m > 0$ outside a compact set. We consider the graph of $h - \lambda$ for some constant $\lambda > 0$. For $\lambda \gg 1$, the graph of $h - \lambda$ has no intersection with M . Then we decrease λ until the graph of $h - \lambda$ approaches M from below and touches M at a point p for the first time.

Note that by [15, Theorem 4] the mean curvature of M has a sign. Then by Proposition 2.9 and the fact that the level set of M passing through p is mean convex near p with respect to the inward unit normal, the mean curvature of M near p (with respect to the unit normal vector pointing away from the graph of h) is non-negative. Depending on whether p is either an interior point or a boundary point of the graph of $h - \lambda$, we apply either Theorem 4.3 or Theorem 4.4 to conclude that M is identical to the graph of h outside $B_{(2m)^{\frac{1}{n-2}}}$ over \mathbb{R}^n . Then notice that

M must be graphical in a neighborhood of $S_{(2m)\frac{1}{n-2}}$ in $B_{(2m)\frac{1}{n-2}}$, for otherwise p cannot be the first touch point. Applying Theorem 4.5 yields a contradiction. \square

ACKNOWLEDGEMENTS

The authors thank Hugh Bray and Romain Gicquaud for bringing the question about the equality case of the Penrose inequality to their attention and the referee for pointing out the relevant references. They also thank Dan Lee and Professor S. T. Yau for helpful discussions.

REFERENCES

- [1] Robert Bartnik, *The mass of an asymptotically flat manifold*, Comm. Pure Appl. Math. **39** (1986), no. 5, 661–693, DOI 10.1002/cpa.3160390505. MR849427 (88b:58144)
- [2] Hubert L. Bray, *Proof of the Riemannian Penrose inequality using the positive mass theorem*, J. Differential Geom. **59** (2001), no. 2, 177–267. MR1908823 (2004j:53046)
- [3] Hubert L. Bray, *On the positive mass, Penrose, and ZAS inequalities in general dimension*, Surveys in geometric analysis and relativity, Adv. Lect. Math. (ALM), vol. 20, Int. Press, Somerville, MA, 2011, pp. 1–27. MR2906919
- [4] Hubert L. Bray and Kevin Iga, *Superharmonic functions in \mathbf{R}^n and the Penrose inequality in general relativity*, Comm. Anal. Geom. **10** (2002), no. 5, 999–1016. MR1957660 (2003k:83066)
- [5] Hubert L. Bray and Dan A. Lee, *On the Riemannian Penrose inequality in dimensions less than eight*, Duke Math. J. **148** (2009), no. 1, 81–106, DOI 10.1215/00127094-2009-020. MR2515101 (2010f:53051)
- [6] Justin Corvino, *Scalar curvature deformation and a gluing construction for the Einstein constraint equations*, Comm. Math. Phys. **214** (2000), no. 1, 137–189, DOI 10.1007/PL00005533. MR1794269 (2002b:53050)
- [7] Mattias Dahl, Romain Gicquaud, and Anna Sakovich, *Penrose type inequalities for asymptotically hyperbolic graphs*, Ann. Henri Poincaré **14** (2013), no. 5, 1135–1168, DOI 10.1007/s00023-012-0218-4. MR3070749
- [8] Levi Lopes de Lima and Frederico Girão, *The ADM mass of asymptotically flat hypersurfaces*, arXiv:1108.5474v3 [math.DG].
- [9] Levi Lopes de Lima and Frederico Girão, *Positive mass and Penrose type inequalities for asymptotically hyperbolic hypersurfaces*, arXiv:1201.4991 [math.DG].
- [10] Levi Lopes de Lima and Frederico Girão, *A rigidity result for the graph case of the Penrose inequality*, arXiv:1205.1132 [math.DG].
- [11] Levi Lopes de Lima and Frederico Girão, *An Alexandrov-Fenchel-type inequality in hyperbolic space with an application to a Penrose inequality*, arXiv:1209.0438 [math.DG].
- [12] Alexandre Freire and Fernando Schwartz, *Mass-capacity inequalities for conformally flat manifolds with boundary*, Comm. Partial Differential Equations **39** (2014), no. 1, 98–119, DOI 10.1080/03605302.2013.851211. MR3169780
- [13] Pengfei Guan and Junfang Li, *The quermassintegral inequalities for k -convex starshaped domains*, Adv. Math. **221** (2009), no. 5, 1725–1732, DOI 10.1016/j.aim.2009.03.005. MR2522433 (2010i:52021)
- [14] Jorge Hounie and Maria Luiza Leite, *Two-ended hypersurfaces with zero scalar curvature*, Indiana Univ. Math. J. **48** (1999), no. 3, 867–882, DOI 10.1512/iumj.1999.48.1664. MR1736975 (2001b:53077)
- [15] Lan-Hsuan Huang and Damin Wu, *Hypersurfaces with nonnegative scalar curvature*, J. Differential Geom. **95** (2013), no. 2, 249–278. MR3128984
- [16] Lan-Hsuan Huang and Damin Wu, *Geometric inequalities and rigidity theorems on equatorial spheres*, arXiv:1104.0406 [math.DG].
- [17] Gerhard Huisken and Tom Ilmanen, *The inverse mean curvature flow and the Riemannian Penrose inequality*, J. Differential Geom. **59** (2001), no. 3, 353–437. MR1916951 (2003h:53091)
- [18] Jeffrey L. Jauregui, *Penrose-type inequalities with a Euclidean background*, arXiv:1108.4042v1 [math.DG].

- [19] Mau-Kwong George Lam, *The Graph Cases of the Riemannian Positive Mass and Penrose Inequalities in All Dimensions*, ProQuest LLC, Ann Arbor, MI, 2011. Thesis (Ph.D.)—Duke University. MR2873434
- [20] Robert C. Reilly, *On the Hessian of a function and the curvatures of its graph*, Michigan Math. J. **20** (1973), 373–383. MR0334045 (48 #12364)
- [21] Robert C. Reilly, *Variational properties of functions of the mean curvatures for hypersurfaces in space forms*, J. Differential Geometry **8** (1973), 465–477. MR0341351 (49 #6102)
- [22] Harold Rosenberg, *Hypersurfaces of constant curvature in space forms*, Bull. Sci. Math. **117** (1993), no. 2, 211–239. MR1216008 (94b:53097)
- [23] Richard Sacksteder, *On hypersurfaces with no negative sectional curvatures*, Amer. J. Math. **82** (1960), 609–630. MR0116292 (22 #7087)
- [24] Richard M. Schoen, *Uniqueness, symmetry, and embeddedness of minimal surfaces*, J. Differential Geom. **18** (1983), no. 4, 791–809 (1984). MR730928 (85f:53011)
- [25] Fernando Schwartz, *A volumetric Penrose inequality for conformally flat manifolds*, Ann. Henri Poincaré **12** (2011), no. 1, 67–76, DOI 10.1007/s00023-010-0070-3. MR2770090 (2012e:53059)

DEPARTMENT OF MATHEMATICS, UNIVERSITY OF CONNECTICUT, STORRS, CONNECTICUT 06269
E-mail address: lan-hsuan.huang@uconn.edu

DEPARTMENT OF MATHEMATICS, UNIVERSITY OF CONNECTICUT, STORRS, CONNECTICUT 06269
E-mail address: damin.wu@uconn.edu