A Note Regarding Second-Order Γ-limits for the Cahn–Hilliard Functional

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Abstract

This note completely resolves the asymptotic development of order 2 by Γ-convergence of the mass-constrained Cahn–Hilliard functional, by showing that one of the critical assumptions of the authors’ previous work [10] is unnecessary.

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1 Introduction

In the recent paper [10] we have solved in most cases a long standing open problem, namely, the asymptotic development by Γ-convergence of order 2 of the Modica–Mortola or Cahn–Hilliard functional (see [8, 13, 17])

\[ F_\varepsilon(u) := \int_\Omega W(u) + \varepsilon^2|\nabla u|^2\,dx, \quad u \in H^1(\Omega), \]  

subject to the mass constraint

\[ \int_\Omega u\,dx = m. \]  

Here \( \Omega \subset \mathbb{R}^n, 2 \leq n \leq 7, \) is an open, connected, bounded set with

\[ \mathcal{L}^n(\Omega) = 1 \quad \text{and} \quad \partial \Omega \text{ is of class } C^{2,\alpha}, \quad \alpha \in (0,1], \]  

and the double-well potential \( W : \mathbb{R} \to [0,\infty) \) satisfies:

\[ W \text{ is of class } C^2(\mathbb{R}\setminus\{a,b\}) \text{ and has precisely two zeros at } a < b, \]  

\[ \lim_{s \to a} \frac{W''(s)}{|s-a|^{q-1}} = \lim_{s \to b} \frac{W''(s)}{|s-b|^{q-1}} := \ell > 0, \quad q \in (0,1], \]  

\[ W' \text{ has exactly 3 zeros at } a < c < b, \quad W''(c) < 0, \]  

\[ \liminf_{|s| \to \infty} |W'(s)| > 0. \]

We assume that the mass \( m \) in (1.2) satisfies

\[ a < m < b. \]
We recall that given a metric space $X$ and a family of functions $\mathcal{F}_\varepsilon : X \to \mathbb{R}$, $\varepsilon > 0$, an asymptotic development of order $k$
\[ \mathcal{F}_\varepsilon = \mathcal{F}^{(0)} + \varepsilon \mathcal{F}^{(1)} + \cdots + \varepsilon^k \mathcal{F}^{(k)} + o(\varepsilon^k) \]
holds if there exist functions $\mathcal{F}^{(i)} : X \to \mathbb{R}$, $i = 0, 1, \ldots, k$, such that the functions
\[ \mathcal{F}^{(i)}_\varepsilon := \frac{\mathcal{F}^{(i-1)}(u) - \inf_X \mathcal{F}^{(i-1)}}{\varepsilon} \]  
(1.9)
are well-defined and
\[ \mathcal{F}^{(i)}_\varepsilon \rightharpoonup_i \mathcal{F}^{(i)}, \]  
(1.10)
where $\mathcal{F}^{(0)}_\varepsilon := \mathcal{F}_\varepsilon$ and $\mathbb{R}$ is the extended real line (see [2]).

In our case $X := L^1(\Omega)$ and we define
\[ \mathcal{F}_\varepsilon(u) := \begin{cases} F_\varepsilon(u) & \text{if } u \in H^1(\Omega) \text{ and } (1.2) \text{ holds,} \\ \infty & \text{otherwise in } L^1(\Omega), \end{cases} \]  
(1.11)
where $F_\varepsilon$ is the functional in (1.1). It is well-known (see [3], [13], [17]) that, under appropriate assumptions on $\Omega$ and $W$, the $\Gamma$-limit $\mathcal{F}^{(1)}$ of order 1 (see (1.9) and (1.10)) of (1.11) is given by
\[ \mathcal{F}^{(1)}(u) := \begin{cases} 2c_W P\{(u = a); \Omega\} & \text{if } u \in BV(\Omega; \{a, b\}) \text{ and } (1.2) \text{ holds,} \\ \infty & \text{otherwise in } L^1(\Omega), \end{cases} \]  
(1.12)
where $P(\cdot; \Omega)$ is the perimeter in $\Omega$ (see [1, 5, 19]), $a, b$ are the wells of $W$, and
\[ c_W := \int_a^b W^{1/2}(s) \, ds. \]  
(1.13)
Hence, $u \in BV(\Omega; \{a, b\})$ is a minimizer of the functional $\mathcal{F}^{(1)}$ in (1.12) if and only if the set $\{u = a\}$ is a solution of the classical partition problem
\[ \mathcal{I}_\Omega(v) := \min\{P(E; \Omega) : E \subset \Omega, \mathcal{L}^n(E) = v\} \]  
(1.14)
at the value $v = v_m$, where (see (1.3))
\[ v_m := \frac{b - m}{b - a}. \]  
(1.15)
When $\Omega$ is bounded and of class $C^2$, minimizers $E$ of (1.14) exist, have constant generalized mean curvature $\kappa_E$, intersect the boundary of $\Omega$ orthogonally, and their singular set is empty if $n \leq 7$, and has dimension at most $n - 8$ if $n \geq 8$ (see [6, 7, 11, 18]). Here and in what follows we use the convention that $\kappa_E$ is the average of the principal curvatures taken with respect to the outward unit normal to $\partial E$.

Under the hypothesis that the isoperimetric function $v \mapsto \mathcal{I}_\Omega(v)$ satisfies the Taylor expansion
\[ \mathcal{I}_\Omega(v) = \mathcal{I}_\Omega(v_m) + \mathcal{I}_\Omega'(v_m)(v - v_m) + O(|v - v_m|^{1+\beta}) \]  
(1.16)
for all $v$ close to $v_m$ and for some $\beta \in (0, 1]$, in [10] we proved the following theorems (see also [4]).

**Theorem 1.1** ([10]). Assume that $\Omega, m, W$ satisfy hypotheses (1.3)-(1.8) with $q = 1$ and that (1.16) holds. Then
\[ \mathcal{F}^{(2)}(u) = \frac{2c^2_W(n - 1)^2}{W''(a)(b - a)^2} \kappa^2_u + 2(c_{sym} + c_W \tau_u)(n - 1)\kappa_u P\{(u = a); \Omega\} \]  
if $u \in BV(\Omega; \{a, b\})$ is a minimizer of the functional $\mathcal{F}^{(1)}$ in (1.11) and $\mathcal{F}^{(2)}(u) = \infty$ otherwise in $L^1(\Omega)$. 

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**Theorem 1.2** ([10]). Assume that $\Omega, m, W$ satisfy hypotheses (1.3)-(1.8) with $q \in (0, 1)$ and that (1.16) holds. Then

$$
\mathcal{F}^{(2)}(u) = 2(c_{\text{sym}} + c W_\tau)(n - 1)\kappa_u \mathcal{P}(\{u = a\}; \Omega)
$$

if $u \in BV(\Omega; \{a, b\})$ is a minimizer of the functional $\mathcal{F}^{(1)}$ and $\mathcal{F}^{(2)}(u) = \infty$ otherwise in $L^1(\Omega)$.

Here $\kappa_u$ is the constant mean curvature of the set $\{u = a\}$,

$$
c_{\text{sym}} := \int_\mathbb{R} W(z(t)) t \, dt,
$$

where $z$ is the solution to the Cauchy problem

$$
\begin{aligned}
  z'(t) &= \sqrt{W(z(t))} & \text{for } t \in \mathbb{R}, \\
  z(0) &= c, & z(t) \in [a, b],
\end{aligned}
$$

with $c$ being the central zero of $W'$ (see (1.6)), and $\tau_u \in \mathbb{R}$ is a constant such that

$$
P(\{u = a\}; \Omega) \int_\mathbb{R} z(t - \tau_u) - \text{sgn}_{a,b}(t) \, dt = \frac{2c_W(n - 1)}{W''(a)(b - a)} \kappa_u
$$

if $q = 1$ in (1.5) and

$$
\int_\mathbb{R} z(t - \tau_u) - \text{sgn}_{a,b}(t) \, dt = 0
$$

if $q \in (0, 1)$ in (1.5), where

$$
\text{sgn}_{a,b}(t) := \begin{cases} 
  a & \text{if } t \leq 0, \\
  b & \text{if } t > 0.
\end{cases}
$$

The assumption (1.16) is known to hold at a.e. $v_m$, or, equivalently, for a.e. mass $m \in (a, b)$, since $\mathcal{I}_\Omega$ is semi-concave [15]. However, in the case that the isoperimetric function is differentiable at $v_m$ the mean curvature of the interface of minimizers is completely determined since (see Chapter 17 in[11])

$$
\mathcal{I}_\Omega'(v_m) = (n - 1)\kappa_E
$$

for every minimizer $E$ of (1.14) with $v = v_m$. Hence Theorems (1.1) and (1.2) do not provide a selection criteria for minimizers. Indeed, the case of two global minimizers of the partition problem (1.14) with different mean curvatures is excluded by (1.16).

The purpose of this note is to remove the assumption that $\mathcal{I}_\Omega$ is regular at $v_m$. Specifically, the theorem that we prove is the following:

**Theorem 1.3.** Theorems (1.1) and (1.2) continue to hold without assuming (1.16).

The lim sup portion of this theorem was already established in [10], see Remark 5.5 in the same. Thus this work focuses on proving the $\Gamma$-lim inf inequality.

Besides its intrinsic interest, Theorem 1.3 has important applications in the study of the speed of motion of the mass-preserving Allen–Cahn equation

$$
\begin{aligned}
  \partial_t u_\varepsilon &= \varepsilon^2 \Delta u_\varepsilon - W'(u_\varepsilon) + \varepsilon \lambda_\varepsilon & \text{in } \Omega \times [0, \infty), \\
  \frac{\partial u_\varepsilon}{\partial \nu} &= 0 & \text{on } \partial \Omega \times [0, \infty), \\
  u_\varepsilon &= u_{0,\varepsilon} & \text{on } \Omega \times \{0\}
\end{aligned}
$$

(1.19)
and of the Cahn–Hilliard equation

\[
\begin{cases}
\partial_t u_\varepsilon = -\Delta(\varepsilon^2 \Delta u_\varepsilon - W'(u_\varepsilon)) & \text{in } \Omega \times (0, \infty), \\
\frac{\partial u_\varepsilon}{\partial \nu} = \frac{\partial}{\partial \nu}(\varepsilon^2 \Delta u_\varepsilon - W'(u_\varepsilon)) = 0 & \text{on } \partial \Omega \times [0, \infty), \\
u_\varepsilon = u_{0,\varepsilon} & \text{on } \Omega \times \{0\}
\end{cases}
\]

(1.20)
in dimension \(n \geq 2\).

In what follows we say that a measurable set \(E_0 \subset \Omega\) is a volume–constrained local perimeter minimizer of \(P(\cdot; \Omega)\) if there exists \(\rho > 0\) such that

\[P(E_0; \Omega) = \inf \{ P(E; \Omega) : E \subset \Omega \text{ Borel}, L^n(E_0) = L^n(E), L^n(E_0 \ominus E) < \rho \},\]

where \(\ominus\) denotes the symmetric difference of sets. We define

\[u_{E_0} := a \chi_{E_0} + b \chi_{\Omega \setminus E_0}.\]

(1.21)

The following theorem improves upon Theorem 1.4 in [15]. In particular, the assumption that the local minimizer \(E_0\) has positive second variation (see Theorem 1.9 in [15]) is no longer needed.

**Theorem 1.4.** Assume that \(\Omega, m, W\) satisfy hypotheses (1.3)-(1.8) with \(q = 1\), and let \(E_0\) be a volume–constrained local perimeter minimizer with \(L^n(E_0) = v_m\). Assume that \(u_{0,\varepsilon} \in L^\infty(\Omega)\) satisfy

\[\int_\Omega u_{0,\varepsilon} \, dx = m, \quad u_{0,\varepsilon} \to u_{E_0} \text{ in } L^2(\Omega) \text{ as } \varepsilon \to 0^+\]

and

\[F_\varepsilon(u_{0,\varepsilon}) \leq \varepsilon F^{(1)}(u_{E_0}) + C \varepsilon^2\]

for some \(C > 0\). Let \(u_\varepsilon\) be a solution to (1.19). Then, for any \(M > 0\),

\[
\sup_{0 \leq t \leq M \varepsilon^{-1}} \| u_\varepsilon(t) - u_{E_0} \|_{L^1(\Omega)} \to 0 \text{ as } \varepsilon \to 0^+.
\]

The following theorem improves upon Theorem 1.4 in [15].

**Theorem 1.5.** Assume that \(\Omega, m, W\) satisfy hypotheses (1.3)-(1.8) with \(q = 1\) and that there exists a constant \(C_1 > 0\) so that

\[|W'(s)| \leq C_1 |s|^p + C_1,\]

where \(p = \frac{n}{n-2}\) for \(n \geq 3\), and \(p > 0\) for \(n = 1, 2\). Let \(E_0\) be a volume–constrained global perimeter minimizer with \(L^n(E_0) = v_m\). Assume that \(u_{0,\varepsilon} \in L^2(\Omega)\) satisfy

\[\int_\Omega u_{0,\varepsilon} \, dx = m, \quad u_{0,\varepsilon} \to u_{E_0} \text{ in } (H^1(\Omega))' \text{ as } \varepsilon \to 0^+\]

and

\[F_\varepsilon(u_{0,\varepsilon}) \leq F_0(u_{E_0}) \varepsilon + C \varepsilon^2\]

for some \(C > 0\). Let \(u_\varepsilon\) be a solution to (1.20). Then, for any \(M > 0\),

\[
\sup_{0 \leq t \leq M \varepsilon^{-1}} \| u_\varepsilon(t) - u_{E_0} \|_{(H^1(\Omega))'} \to 0 \text{ as } \varepsilon \to 0^+.
\]
2 Localized Isoperimetric Function

One of the central ideas in [10] was the development and use of a generalized Pólya–Szegő inequality to reduce the second-order $\Gamma$-lim inf of (1.1) to a one-dimensional problem. This generalized Pólya–Szegő inequality relied on comparing the perimeter of the level sets of arbitrary functions with values of $I_\Omega$. On the one hand, this approach is simple and very general. On the other hand, it is clearly not sharp in our setting because the minimizers of (1.14) may be widely separated in $L^1$, while the transition layers we are considering are known to converge in $L^1$. Hence, the isoperimetric function may be too pessimistic in estimating the perimeter of the level sets of transition layers.

In light of this, following [15], we use instead a localized version of the isoperimetric function. Specifically, given a set $E_0$, and some $\delta > 0$, we define the local isoperimetric function of parameter $\delta$ about the set $E_0$ to be

$$I^{E_0, \delta}_\Omega(v) := \inf \{ P(E, \Omega) : E \subset \Omega \text{ Borel, } L^n(E) = v, \alpha(E_0, E) \leq \delta \}, \quad (2.1)$$

where

$$\alpha(E_1, E_2) := \min \{ L^n(E_1 \setminus E_2), L^n(E_2 \setminus E_1) \} \quad (2.2)$$

for any Borel sets $E_1, E_2 \subset \Omega$.

The following proposition, which connects the definition of $I^{E_0, \delta}_\Omega$ with $L^1$ convergence, can be found in [15]. We present its proof for the convenience of the reader.

**Proposition 2.1.** Let $\Omega \subset \mathbb{R}^n$ be an open set, $E_0 \subset \Omega$ be a Borel set and let $u_{E_0}$ be as in (1.21). Then

$$\alpha(E_0, \{ u \leq s \}) \leq \delta \quad (2.3)$$

for all $u \in L^1(\Omega)$ such that

$$||u - u_{E_0}||_{L^1} \leq (b - a)\delta, \quad (2.4)$$

and for every $s \in \mathbb{R}$, where the function $\alpha$ is given in (2.2).

**Proof.** Fix $\delta > 0$, and for $s \in \mathbb{R}$ define $F_s := \{ x \in \Omega : u(x) \leq s \}$. If $a < s < b$, then by (2.4),

$$(b - a)\delta \geq \int_{F_s \setminus E_0} |u - u_{E_0}| \, dx + \int_{E_0 \setminus F_s} |u - u_{E_0}| \, dx$$

$$\geq (b - s)L^n(F_s \setminus E_0) + (s - a)L^n(E_0 \setminus F_s) \geq (b - a)\alpha(E_0, F_s),$$

so that (2.3) is proved in this case. If $s \geq b$, again by (2.4),

$$(b - a)\delta \geq \int_{E_0 \setminus F_s} |u - u_{E_0}| \, dx \geq (s - a)L^n(E_0 \setminus F_s) \geq (b - a)\alpha(E_0, F_s).$$

The case $s \leq a$ is analogous. \hfill \Box

By construction, we know that $I^{E_0, \delta}_\Omega \geq I_\Omega$. Furthermore, by BV compactness and lower-semicontinuity, and the fact that $\alpha$ is continuous in $L^1$, we have that $I^{E_0, \delta}_\Omega$ is lower semi-continuous. The next proposition establishes a stronger type of regularity for $I^{E_0, \delta}_\Omega$.

**Proposition 2.2.** Assume that $\Omega$ satisfies (1.3) and let $E_0 \subset \Omega$ be a local volume-constrained perimeter minimizer, with $L^n(E_0) = v_m$. Then for $\delta$ small enough there exists a neighborhood $J_\delta$ of $v_m$ so that $I^{E_0, \delta}_\Omega$ is semi-concave on $J_\delta$.

Before proving this proposition, we state and prove a technical lemma. In what follows we say that an open set $U \subset \mathbb{R}^n$ has piecewise $C^2$ boundary if $\partial U$ can be written as the union of finitely many connected $(n - 1)$-dimensional manifolds with boundary of class $C^2$ up to the boundary, with pairwise disjoint relatively interiors.
Lemma 2.3. Let \( U = \Omega \setminus E_0 \) for some volume constrained perimeter minimizer \( E_0 \). Given \( \tau > 0 \), let

\[
U_\tau := \{ x \in U : d(x, \mathbb{R}^n \setminus U) > \tau \}.
\]  

Then there exist a \( A > 0 \) and \( C_1, C_2 > 0 \) so that for all \( \tau \) sufficiently small and all \( v \in (C_1 \tau, A) \),

\[
I_{U_\tau}(v) \geq C_2 v^{(n-1)/n}.
\]

Proof. We remark that the boundary of \( U \) will have piecewise \( C^2 \) with components that meet transversally. Furthermore the components of the boundary of \( U \) can be locally extended without intersecting \( U \).

Step 1: We begin by constructing a \( C^1 \) vector field \( T \) which points into the domain \( U \).

Let \( M_i, i = 1, \ldots, m \), be the finitely many connected \((n-1)\)-dimensional manifolds of class \( C^2 \) with boundary whose union gives \( \partial U \). Extend each \( M_i \) in such a way that \( M_i \) is a subset of the boundary of an open set \( V_i \) of class \( C^2 \) with \( V_i \cap U = \emptyset \). Set \( F_i = \partial V_i \). Next we extend the normal vector field \( \nu_{F_i} \) to a vector field \( T_i \in C^1(\mathbb{R}^n; \mathbb{R}^n) \). If \( M_i \) and \( M_j \) intersect transversally, then for \( x \in \partial M_i \cap \partial M_j \) we have \( T_i(x) \cdot T_j(x) = \nu_{F_i}(x) \cdot \nu_{F_j}(x) = 0 \) and thus by continuity we can find \( \rho > 0 \) such that \( |T_i(x) - T_j(x)| \leq \frac{1}{2m} \) for all \( x \) in a \( \rho \)-neighborhood (denoted by \( U_{i,j} \)) of \( \partial M_i \cap \partial M_j \). By taking \( \rho \) even smaller, if necessary, we can assume that the same \( \rho \) works for all \( i \) and \( j \) such that \( M_i \) and \( M_j \) intersect transversally. Next, set

\[
d_0 := \min_{i \neq j} d(M_i \setminus U_{i,j}, M_j \setminus U_{i,j}) > 0
\]

and let \( \rho := 1/2 \min(\rho, d_0) > 0 \).

We then choose smooth cutoff functions \( \varphi_i \) which are valued 1 on \( M_i \) and 0 at distance \( \rho/2 \) from the same sets and consider the vector field \( T := \sum_{i=1}^m \varphi_i T_i \). Note that \( T \in C^1(\mathbb{R}^n; \mathbb{R}^n) \), with \( \|T\|_{\infty} \leq C \) and \( \|\nabla T\|_{\infty} \leq C \) for some constant \( C > 0 \).

We claim that

\[
T(x) \cdot \nabla d_{V_i}(x) \geq 1/4
\]

for all points \( x \in U \) in a \( \rho_0 \)-neighborhood of \( F_i \), where \( d_{V_i} \) is the signed distance to the set \( V_i \) enclosed by \( F_i \). By Theorem 3 in [9] we have that \( d_{V_i} \) is a \( C^2 \) function in a neighborhood of \( F_i \).

Suppose \( x \in M_i \). Then \( T_i(x) = \nu_{F_i}(x) = \nabla d_{V_i}(x) \), and so

\[
T(x) \cdot \nabla d_{V_i}(x) = 1 + \sum_{j \neq i} \varphi_j(x) T_j(x) \cdot T_i(x).
\]  

If \( x \) is in a \( \rho \)-neighborhood of \( \partial M_i \cap \partial M_j \), then \( T_i(x) \cdot T_j(x) \geq -\frac{1}{2m} \) or \( \varphi_j(x) = 0 \). Thus, in both cases \( T(x) \cdot \nabla d_{V_i}(x) \geq \frac{1}{2} \). By continuity of \( T \) and \( \nabla d_{V_i} \), the inequality (2.7) implies that (2.6) holds in a neighborhood of \( M_i \).

Step 2: We consider the flow along \( T \), meaning that for \( x \in \mathbb{R}^n \) we take the initial value problem

\[
\begin{cases}
\frac{d\Psi(t)}{dt} = T(\Psi(t)), \\
\Psi(0) = x.
\end{cases}
\]

Since \( T \) is Lipschitz continuous, there exists a unique global solution \( \Psi \) defined for all \( t \in \mathbb{R} \). To highlight the dependence on \( x \) we write \( \Psi(\cdot, x) \) and we define \( \Psi_t(x) := \Psi(t, x) \). Let \( U^t := \Psi_t(U) \).

By construction \( \Psi_t \) satisfies

\[
(1 - Ct)|x - y| \leq |\Psi_t(x) - \Psi_t(y)| \leq (1 + Ct)|x - y|.
\]

This implies that for any set \( E \subset U^t \) of finite perimeter,

\[
(1 - Ct)^n \mathcal{L}^n(E) \leq \mathcal{L}^n(\Psi^{-1}_t(E)) \leq (1 + Ct)^n \mathcal{L}^n(E),
\]

\[
(1 - Ct)^{n-1} P(E; U^t) \leq P(\Psi^{-1}_t(E); U) \leq (1 + Ct)^{n-1} P(E; U^t).
\]
We claim that \( U_\tau \subset U^{c_3\tau} \), where \( c_3 := 1/\|T\|_\infty \). To see this, let \( y \in U_\tau \). For every \( t \in \mathbb{R} \) we have
\[
|\Psi_t(y) - y| \leq \|t\|T\|_\infty,
\]
and so
\[
d(\Psi_t(y), \mathbb{R}^n \setminus U) \geq d(y, \mathbb{R}^n \setminus U) - |\Psi_t(y) - y| > \tau - |t|\|T\|_\infty \geq 0
\]
provided \(|t| \leq \tau/\|T\|_\infty\). In turn, \( \Psi_t(y) \in U \) for \(|t| \leq \tau/\|T\|_\infty\). Define \( x_\tau := \Psi_{-c_3\tau}(y) \). and consider the function \( \Psi(\cdot, x_\tau) \). Since the system of differential equations is autonomous and solutions are unique, we have that \( \Psi_{c_3\tau}(x_\tau) = \Psi_{c_3\tau}(\Psi_{-c_3\tau}(y)) = y \), which shows that \( y \in U^{c_3\tau} = \Psi_{c_3\tau}(U) \).

Next, we claim that \( U^{c_3\tau} \subset U_{c_4\tau} \) for all \( \tau \) sufficiently small, and for some constant \( c_4 \). Let \( x \in U \) be in a \( \rho_0/2 \) neighborhood of \( \Omega \), where \( \rho_0 \) was given in Step 1. Since \( d_{V_i} \) is \( C^2 \), by the chain rule we may write
\[
d_{V_i}(\Psi_t(x)) = d_{V_i}(x) + \int_0^t \nabla d_{V_i}(\Psi_s(x)) \cdot T(\Psi_s(x)) \, ds
\]
where we have used (2.6), and where we have assumed that \( t < \frac{\rho_0}{2\|T\|_\infty} \). As this is true for all \( i \), and as \( d(x, \mathbb{R}^n \setminus U) = \min_i d_{V_i}(x) \) for \( x \in U \), we find that
\[
d(\Psi_t(x), \mathbb{R}^n \setminus U) \geq d(x, \mathbb{R}^n \setminus U) + t/4
\]
for \( x \) near \( \partial U \) and for \( t \) sufficiently small. This proves the claim for \( x \) close to the boundary, and for \( x \) far away from the boundary there is nothing to prove.

In summary, we know that \( U_\tau \subset U^{c_3\tau} \subset U_{c_4\tau} \), as along as \( \tau \) is sufficiently small, for \( c_3, c_4 \) independent of \( \tau \). These two inclusions, along with (2.8), imply that for any set \( E \) of finite perimeter we have that
\[
P(E; U_\tau) \geq P(E; U^{c_3\tau})
\]
and that \( \mathcal{L}^n(U_\tau \setminus U^{c_3\tau}) \leq c_5 \tau \), with \( c_5 > 0 \) independent of \( \tau \).

Finally, let \( E \subset U_\tau \) be a set of finite perimeter satisfying \( \mathcal{L}^n(E) > 2c_5\tau \). By (2.8), the previous inequalities, and the isoperimetric inequality (which applies as \( U \) must be Lipschitz) we have that
\[
P(E; U_\tau) \geq P(E; U^{c_3\tau})
\]
\[
\geq C P(\Psi_{c_3\tau}(E \cap U^{c_3\tau}); U)
\]
\[
\geq C \left( \mathcal{L}^n(\Psi_{c_3\tau}(E \cap U^{c_3\tau})) \right)^{\frac{n-1}{n}}
\]
\[
\geq C \left( \mathcal{L}^n(E \cap U^{c_3\tau}) \right)^{\frac{n-1}{n}}
\]
\[
\geq C \left( \mathcal{L}^n(E) - c_5 \tau \right)^{\frac{n-1}{n}} \geq C \mathcal{L}^n(E)^{\frac{n-1}{n}}.
\]
This completes the proof.

Now we prove Proposition 2.2.

**Proof of Proposition 2.2.** Let \( E_\delta \) be a minimizer of
\[
\min \{ P(E; \Omega) : E \subset \Omega \text{ Borel, } \mathcal{L}^n(E) = \hat{\nu}, \alpha(E_0, E) \leq \delta \},
\]
with \( \hat{\nu} \in J_\delta = (\nu_m - \delta/2, \nu_m + \delta/2) \). Since \( \partial E_0 \) is regular and intersects the boundary of \( \Omega \) orthogonally, we know that
\[
\mathcal{I}_{\Omega \cap E_0}(\nu) \geq C \nu^{\frac{1}{n-1}}, \quad \mathcal{I}_{\Omega \setminus E_0}(\nu) \geq C \nu^{\frac{1}{n-1}}
\]
(2.9)
for all \( v \) sufficiently small (see, e.g., Corollary 3 in Section 5.2.1 of [12]). We pick \( \delta \) small enough that (2.9) holds for \( v \in (0, 2\delta) \).

Next, we claim that we can construct a smooth function \( \phi_\delta \) defined on a neighborhood of \( \hat{v} \) so that
\[
\phi_\delta(\hat{v}) = \mathcal{E}_{\Omega}, \quad \phi_\delta(v) \geq \mathcal{E}_{\Omega}(v), \quad \phi_\delta'' \leq C, \tag{2.10}
\]
where \( C \) does not depend on \( \hat{v} \), but may depend on \( \delta \).

To prove this claim, we consider two different cases. First, suppose that \( \alpha(E_\delta, E_0) < \delta \). Then by (2.1), \( E_\delta \) is actually a volume-constrained local perimeter minimizer, and hence we can prove (2.10) by using a normal perturbation and the fact that \( \partial \Omega \) is smooth, see Lemma 4.3 in [15] for details.

Now suppose that \( \alpha(E_\delta, E_0) = \delta \). In view of (2.2) we may assume, without loss of generality, that \( \alpha(E_\delta, E_0) = \mathcal{L}^n(E_\delta \setminus E_0) \) (the opposite case is analogous). Hence, we may locally perturb \( E_\delta \) inside the set \( \Omega \setminus E_0 \) without increasing the value of \( \alpha(E_\delta, E_0) \). In particular, by (2.1), \( E_\delta \setminus E_0 \) is a local minimizer of the problem
\[
\min\{P(E; \Omega \setminus E_0) : E \subset \Omega \setminus E_0 \text{ Borel}, \mathcal{L}^n(E) = \mathcal{L}^n(E_\delta \setminus E_0)\}.
\]
Hence, by [6], \( \partial E_\delta \cap (\Omega \setminus E_0) \) is analytic.

We note that
\[
\delta - \mathcal{L}^n(E_\delta \setminus E_0) = \mathcal{L}^n(E_0 \setminus E_\delta) - \mathcal{L}^n(E_\delta \setminus E_0) = \mathcal{L}^n(E_0) - \mathcal{L}^n(E_\delta) = \rho_m - \hat{v} \in (-\delta/2, \delta/2).
\]
Hence, we know that \( \mathcal{L}^n(E_\delta \setminus E_0) \in [\delta, \frac{3\delta}{2}] \). Since \( E_0 \) is a local volume constrained perimeter minimizer by [6] and [7], its boundary is smooth inside \( \Omega \) and intersects \( \partial \Omega \) transversally. In particular, it may only have finitely many connected components, and hence by selecting \( \delta \) sufficiently small we may assume that \( \partial E_\delta \cap (\Omega \setminus E_0) \) is non-empty.

Next, let \( U := \Omega \setminus E_0 \). Let \( d \in C^\infty(\mathbb{R}^n \setminus \partial U) \) be a regularized distance function from \( \mathbb{R}^n \setminus U \), satisfying the properties
\[
C_1 \leq \frac{d(x)}{d(x, \mathbb{R}^n \setminus U)} \leq C_2 \quad \text{for } x \in U, \quad \|\nabla d\|_\infty \leq C, \tag{2.11}
\]
where \( d(x, \mathbb{R}^n \setminus U) \) is the signed distance function. Such a regularized distance function, as well as the aforementioned properties, is constructed in [16].

Let \( \phi_\tau : \mathbb{R} \to \mathbb{R}^+ \) be a smooth function satisfying \( \phi_\tau(s) = 0 \) for all \( s < \tau/2 \), \( \phi_\tau(s) = 1 \) for all \( s > \tau \), with \( \phi_\tau \) strictly increasing for \( \tau/2 < s < \tau \), and \( \|\phi_\tau''\|_\infty \leq \frac{C}{\tau} \) with \( \tau \) to be chosen. We define \( \Phi_\tau(x) := \phi_\tau(d(x)) \).

Let \( T \in C^\infty_0(U; \mathbb{R}^n) \) be an extension of the vector field \( \Phi_\tau \nu_{\partial E_\delta} \). Define a one parameter family of diffeomorphisms given by \( f_t(x) = x + t T(x) \), where \( t \) is sufficiently small. Note that \( f_t(x) = x \) for all \( x \in E_\delta \) and all \( t \) sufficiently small. Hence by (2.1) the sets \( f_t(E_\delta) \) satisfy \( P(f_t(E_\delta) ; \Omega) \geq \mathcal{T}_{\Omega}^{E_\delta}(\mathcal{L}^n(f_t(E_\delta))) \) since \( \alpha(E_\delta, E_0) = \mathcal{L}^n(E_0 \setminus E_\delta) \). Using the formulas in Chapter 17 of [11], there exists a function \( \phi_\hat{v} = P(f_{t(\hat{v})}(E_\delta); \Omega) \) such that for all \( v \) in a neighborhood of \( \hat{v} \):
\[
\phi_\hat{v}(\hat{v}) = \mathcal{T}_{\Omega}^{E_\delta}(\hat{v}), \quad \phi_\hat{v}(v) \geq \mathcal{T}_{\Omega}^{E_\delta}(v), \quad \phi_\hat{v}''(\hat{v}) = \frac{\int_{\partial E_\delta} |\nabla \Phi_\tau|^2 - \Phi_\tau^2 \|A_{E_\delta}\|^2 \, dH^{n-1}}{\left(\int_{\partial E_\delta} \Phi_\tau \, dH^{n-1}\right)^2},
\]
where \( \|A_{E_\delta}\| \) is the Frobenius norm of the second fundamental form of the boundary of \( E_\delta \), and where the mapping \( t(v) \to v \) is a smooth, increasing map with \( t(0) = 0 \). The second derivative formula can be proved as in [11], [18].
In order to prove (2.10) we thus only need to prove that
\[
\frac{\int_{\partial E_0} |\nabla_{\partial E_0} \Phi_\tau|^2 \, d\mathcal{H}^{n-1}}{\left(\int_{\partial E_0} \Phi_\tau \, d\mathcal{H}^{n-1}\right)^2} \leq C. 
\] (2.12)

To this end, using (2.11) and the fact that \(\|\phi_\tau'\|_\infty \leq \frac{C}{\tau}\) we have that
\[
\int_{\partial E_0} |\nabla_{\partial E_0} \Phi_\tau|^2 \, d\mathcal{H}^{n-1} \leq \frac{C}{\tau^2} P(E_0; \Omega) \leq \frac{C}{\tau^2}.
\] (2.13)

On the other hand, denoting the set \(\hat{U} := \{\Phi_\tau \geq 1\} = \{\hat{d} \geq \tau\}\), we have that
\[
\int_{\partial E_0} \Phi_\tau \, d\mathcal{H}^{n-1} \geq \int_{\partial E_0 \cap \hat{U}} \, d\mathcal{H}^{n-1} = P(\partial E_0; \hat{U}).
\] (2.14)

By (2.11) and the fact that \(U\) has Lipschitz boundary, we have that
\[
\mathcal{L}^n(U \setminus \hat{U}) \leq \mathcal{L}^n(\{x : 0 \leq d(x, \mathbb{R}^n \setminus U) \leq C_2 \tau\}) \leq C \tau.
\]

Using the notation (2.5) we also have, by (2.11), that \(U_{\tau/C_2} \subset \hat{U}\), and that \(\mathcal{L}^n(U \setminus U_{\tau/C_2}) \leq C_4 \tau\).

Hence using (1.14) and Lemma 2.3 we find that
\[
\mathcal{I}_0(v) \geq \inf_{\eta \leq C_4 \tau} \mathcal{I}_{U_{\tau/C_2}}(v - \eta) \geq C(v - C_4 \tau)^{(n-1)/n}
\]
as long as \(v - C_4 \tau \in (C \tau, A)\).

Again recalling that \(\mathcal{L}^n(E_0 \setminus E_0) \in [\delta, \frac{3\delta}{4}]\) we find that, for \(\delta\) sufficiently small and \(\tau = c\delta\) with sufficiently small \(c > 0\),
\[
P(E_0; \hat{U}) \geq C \delta^{(n-1)/n}.
\]

This inequality, together with (2.13) and (2.14), proves (2.12).

By then using an argument as in the proof of Lemma 2.7 in [18] (see also [15]) we find that \(\mathcal{I}_{\Omega}^{E_0, \delta}\) is semi-concave on \(J_\delta\), which is the desired conclusion. \(\square\)

As \(\mathcal{I}_{\Omega}^{E_0, \delta}\) is semi-concave, it has a left derivative \((\mathcal{I}_{\Omega}^{E_0, \delta})_-\)' and a right derivative \((\mathcal{I}_{\Omega}^{E_0, \delta})_+\)' at every point \(v\) in \(J_\delta\), with \((\mathcal{I}_{\Omega}^{E_0, \delta})_-(v) \geq (\mathcal{I}_{\Omega}^{E_0, \delta})_+(v)\). Furthermore, by considering a normal perturbation of \(E_0\), we have that \((n - 1)\kappa_{E_0} \in [(\mathcal{I}_{\Omega}^{E_0, \delta})_-'(v_0), (\mathcal{I}_{\Omega}^{E_0, \delta})_+'(v_0)]\). The following result gives a simple, yet important observation.

**Proposition 2.4.** Assume that \(\Omega\) satisfies (1.3) and let \(E_0 \subset \Omega\) be a volume-constrained local perimeter minimizer in \(\Omega\), with \(\mathcal{L}^n(E_0) = v_m\). Then as \(\delta \to 0\), \(\mathcal{I}_{\Omega}^{E_0, \delta}_-'(v_m) \to (n - 1)\kappa_{E_0}\) and \(\mathcal{I}_{\Omega}^{E_0, \delta}_+'(v_m) \to (n - 1)\kappa_{E_0}\), where \(\kappa_{E_0}\) is the mean curvature of \(E_0\).

**Proof.** We will prove the result for the left derivative. For any fixed \(\delta\), pick a sequence of points \(v_k \uparrow v_0\) at which \(\mathcal{I}_{\Omega}^{E_0, \delta}\) is differentiable. This is possible as \(\mathcal{I}_{\Omega}^{E_0, \delta}\) is semi-concave. Also, as \(\mathcal{I}_{\Omega}^{E_0, \delta}\) is semi-concave we have that \((\mathcal{I}_{\Omega}^{E_0, \delta})_-'(v_k) \to (\mathcal{I}_{\Omega}^{E_0, \delta})_-'(v_0)\). Let \(E_{v_k}\) be a minimizer of
\[
\min\{P(E; \Omega) : E \subset \Omega \text{ Borel}, \mathcal{L}^n(E) = v_k, \alpha(E_0, E) \leq \delta\}.
\]

We claim that there exists a volume-constrained perimeter minimizer \(E_0^\delta\), satisfying \(\alpha(E_0^\delta, E_0) \leq \delta\), \(\mathcal{L}^n(E_0^\delta) = v_0\), and with mean curvature \(\kappa_{E_0}^\delta = (\mathcal{I}_{\Omega}^{E_0, \delta})_-'(v_0)\).

First, suppose that we can pick a subsequence of \(v_k\) (not relabeled), such that
\[
\min\{\mathcal{L}^n(E_{v_k} \setminus E_0), \mathcal{L}^n(E_0 \setminus E_{v_k})\} = \mathcal{L}^n(E_{v_k} \setminus E_0).
\]
Suppose furthermore that \( \liminf_{k \to \infty} L^n(E_0 \setminus E_{v_k}) \geq \delta. \)

Under these assumptions, and as long as \( \delta \) is small enough and \( v_k \) is close enough to \( v_0 \), we have that \( \partial E_{v_k} \cap E_0 \) is a non-empty set. Furthermore, taking local variations with support in \( E_0 \) will not increase the value of \( \alpha(E_{v_k}, E_0) \). Hence, the mean curvature of \( E_{v_k} \) inside the set \( E_0 \), which we will denote \( \kappa_{v_k}^* \), will satisfy (see Chapter 17 in [11])

\[
(n-1)\kappa_{v_k}^* = (T^{E_{v_k}, \delta}_{\Omega})(v_k).
\]

We remark that since \((T^{E_{v_k}, \delta}_{\Omega})(v_k) \to (T^{E_{v_k}, \delta}_{\Omega}) (v_0)\), we immediately have that \( \kappa_{v_k}^* \) is bounded.

By BV compactness, \( \chi_{E_{v_k}} \to \chi_{E_0} \) in \( L^1(\Omega) \), for some set \( E_0^\delta \) with finite perimeter. By lower semi-continuity of the perimeter, we have that \( P(E_0^\delta; \Omega) = T^{E_0, \delta}_{\Omega}(r_0) \leq P(E_0; \Omega) \). As \( E_0 \) is a local volume-constrained perimeter minimizer, for \( \delta \) small enough we have that \( E_0^\delta \) is a local volume-constrained perimeter minimizer as well. In particular, \( \partial E_0^\delta \) is a surface of constant mean curvature. Furthermore, by the assumption that \( \liminf_{k \to \infty} L^n(E_0 \setminus E_{v_k}) \geq \delta \) we know that \( \partial E_0^\delta \cap E_0 \) is a set with positive perimeter.

By using the uniform bound on the curvatures, along with elliptic regularity, we then have that \( E_{v_k} \to E_0^\delta \) in \( C^\infty \) in compact subsets of \( E_0 \) (see the proof of Theorem 1.9 in [15]). Hence the mean curvature \( \kappa_0^\delta \) of \( E_0^\delta \) satisfies \((n-1)\kappa_0^\delta = (T^{E_0, \delta}_{\Omega})(v_0)\).

The case where \( \liminf_{k \to \infty} L^n(E_0 \setminus E_{v_k}) < \delta \) is in fact simpler, because the \( \alpha \)-constraint will not be saturated and any local perturbation is permissible. On the other hand, if we cannot pick a subsequence of \( v_k \) satisfying \( \min\{L^n(E_{v_k} \setminus E_0), L^n(E_0 \setminus E_{v_k})\} = L^n(E_{v_k} \setminus E_0) \), then we must be able to pick a subsequence satisfying \( \min\{L^n(E_{v_k} \setminus E_0), L^n(E_0 \setminus E_{v_k})\} = L^n(E_0 \setminus E_{v_k}) \). We then conduct the same steps, but this time in \( \Omega \setminus E_0 \). This proves the claim.

Finally, we recall that \( \alpha(E_0^\delta, E_0) \leq \delta \). Hence we have that \( \chi_{E_{v_k}} \to \chi_{E_0} \) in \( L^1(\Omega) \) as \( \delta \to 0 \). By again using the same argument, \( E_0^\delta \) must in fact converge in \( C^\infty \) to \( E_0 \), and hence \( \kappa_0^\delta \to \kappa_{E_0} \), or in other words, \((T^{E_0, \delta}_{\Omega})(v_0) \to (n-1)\kappa_{E_0}\). This concludes the proof. \( \Box \)

### 3 Rearrangements and Weighted Problem

Let \( I = (A, B) \) for some \( A < B \) and consider a function \( \eta : I \to [0, \infty) \) which satisfies the following:

\[
\begin{align*}
\eta &\in C(I) \cap C^1((A, t_0)) \cap C^1([t_0, B)), \quad \eta > 0 \quad \text{in } I \quad (3.1) \\
d_1(t - A)^{a \over n} &\leq \eta(t) \leq d_2(t - A)^{b \over n} \quad \text{for } t \in (A, A + t^*), \quad (3.2) \\
d_3(B - t)^{a \over n} &\leq \eta(t) \leq d_4(B - t)^{b \over n} \quad \text{for } t \in (B - t^*, B), \quad (3.3) \\
|\eta'(t)| &\leq {d_5 \eta(t) \over \min\{B - t, t - A\}} \quad \text{for } t \in I \setminus \{t_0\}, \quad \eta'_-(t_0) \geq \eta'_+(t_0), \quad (3.4) \\
\int_A^{t_0} \eta \, dt &= v_m, \quad \int_I \eta \, dt = 1, \quad (3.5)
\end{align*}
\]

for some \( A < t_0 < B \) and for some constants \( d_1, \ldots, d_5 > 0 \) and \( t^* > 0 \).

Next, define the energy

\[
G_\varepsilon(v) := \int_I (W(v) + \varepsilon^2 |v'|^2) \eta \, dt \quad \text{if } v \in H^1(I) \text{ and } \int_I v \eta \, dt = m, \\
\text{otherwise.}
\]

Under the hypotheses (3.1)–(3.5), following the proof of Theorem 4.4 in [10], it can be shown that \( G_\varepsilon(1) = \varepsilon^{-1} G_\varepsilon \to G_0(1) \), where \( G_0(1) \) is given by

\[
G_0(1)(v) := \begin{cases} 
\frac{2\varepsilon^2}{b-a} |Dv| \eta(I) & \text{if } v \in BV(I) \text{ and } \int_I v \eta \, dt = m, \\
\infty & \text{otherwise},
\end{cases}
\]

for some \( 0 < a < b < \infty \).
with \( c_W \) the constant given in (1.13). In view of (1.15) and (3.5), it can also be shown as in Theorem 4.6 in [10] that \( v_0 = a \chi_{[A,t_0]} + b \chi_{[t_0,B]} \) is an isolated \( L^1 \)-local minimizer of \( G^{(1)}_0 \), and hence for some \( \delta \) sufficiently small we have that \( v_0 \) is the unique limit of minimizers \( v_\varepsilon \) of the functionals

\[
J_\varepsilon(v) := \begin{cases} G_\varepsilon(v) & \text{if } v \in H^1_0(I), \int_I v\eta \, dt = m \text{ and } \|v - v_0\|_{L^1} \leq \delta, \\
\infty & \text{otherwise.} \end{cases}
\]

Note that \( v_\varepsilon \) satisfies the Euler-Lagrange equation

\[
2\varepsilon^2 (v_\varepsilon')' - W'(v_\varepsilon) \eta = \varepsilon \lambda_\varepsilon \eta.
\]

Our goal is to prove the following theorem:

**Theorem 3.1.** Assume that \( W \) satisfies hypotheses (1.4)–(1.7) and that \( \eta \) satisfies (3.1)–(3.5). Let \( v_\varepsilon \) be a minimizer of \( G_\varepsilon \) with \( v_\varepsilon \to v_0 \) in \( L^1_\eta \) as \( \varepsilon \to 0^+ \). Then,

\[
\liminf_{\varepsilon \to 0^+} \frac{G^{(1)}_\varepsilon(v_\varepsilon) - 2c_W \eta_0(t_0)}{\varepsilon} \geq 2\eta_-'(t_0) \int_{-\infty}^{0} W^{1/2}(z(s - \tau_0)) z'(s - \tau_0) s \, ds + 2\eta_+'(t_0) \int_{0}^{\infty} W^{1/2}(z(s - \tau_0)) z'(s - \tau_0) s \, ds + \begin{cases} \frac{\lambda_0^2}{2W^{\prime\prime}(\theta)} \int_I \eta(t) \, dt & \text{if } q = 1, \\
0 & \text{if } q < 1, \end{cases} \tag{3.6}
\]

where \( c_{sym} \) is the constant given in (1.17),

\[
\lim_{j \to \infty} \lambda_{\varepsilon_j} = \lambda_0 = \begin{bmatrix} 2c_W\eta_+'(t_0) & 2c_W\eta_-'(t_0) \\ (b-a)\eta(t_0) & (b-a)\eta(t_0) \end{bmatrix} \tag{3.7}
\]

for some subsequence \( \varepsilon_j \to 0^+ \), and the number \( \tau_0 \) is given by

\[
\eta(t_0) \int_{\mathbb{R}} z(s - \tau_0) - s \text{gn}_{a,b}(s) \, ds = \frac{\lambda_0}{W^{\prime\prime}(a)} \int_I \eta(t) \, dt, \tag{3.8}
\]

with \( z \) the solution to (1.18).

**Proof.** By taking a subsequence (not relabeled), without loss of generality, we may assume that the \( \liminf \) on the left-hand side of (3.6) is actually a limit. Also, for simplicity we take \( t_0 = 0 \).

**Step 1.** We claim that (3.7) holds. This proof follows as in Theorem 4.9 in [10]. The only difference is that at the last part of the proof we can no longer use the fact that \( \eta \) is of class \( C^1 \) and we need to show that

\[
\lim_{\varepsilon \to 0^+} \int_I W^{1/2}(v_\varepsilon) |v_\varepsilon'| \eta \psi \, dt = c_W \psi(0) \eta_1,
\]

for some \( \eta_1 \in [\eta_+'(0), \eta_-'(0)] \). Following the proof cited above, we know that \( W^{1/2}(v_\varepsilon) |v_\varepsilon'| \eta_1 \overset{\ast}{\rightharpoonup} c_W \eta(0) \delta_0 \). Hence by picking an appropriate subsequence, we have, for some \( \theta \in [0,1] \),

\[
W^{1/2}(v_\varepsilon) |v_\varepsilon'| \eta_1 \overset{\ast}{\rightharpoonup} \theta c_W \eta(0) \delta_0, \\
W^{1/2}(v_\varepsilon) |v_\varepsilon'| \eta_1 \overset{\ast}{\rightharpoonup} (1 - \theta) c_W \eta(0) \delta_0.
\]

Hence,

\[
\lim_{\varepsilon \to 0^+} \int_I W^{1/2}(v_\varepsilon) |v_\varepsilon'| \eta \psi \, dt = c_W \psi(0)(\theta \eta_+'(0) + (1 - \theta) \eta_-'(0)),
\]

which is the desired conclusion.
Step 2. We claim that there exists a sequence of numbers \( \tau_\varepsilon \to \tau_0 \), where \( \tau_0 \) is given in (3.8), so that the functions \( w_\varepsilon(s) := v_\varepsilon(\varepsilon s) \), \( s \in (A\varepsilon^{-1}, B\varepsilon^{-1}) \), converge weakly to the profile \( w_0 := z(\cdot - \tau_0) \) in \( H^1((-l,l)) \) for any fixed \( l > 0 \), and satisfy

\[
w_\varepsilon(\tau_\varepsilon) = c_\varepsilon,
\]

where \( c_\varepsilon \) is the central zero of \( W' + \varepsilon \lambda_\varepsilon \).

This follows from the proofs of Lemmas 4.18 and 4.19 in [10] (see also [4]). We note that those proofs use significant machinery from that work, including detailed decay estimates, but do not require anything more than a Lipschitz estimate on \( \eta \) near \( 0 \) and (3.2), (3.3), and (3.4).

Step 3. We claim that (3.6) holds. Define \( \eta_\varepsilon(s) := \eta(s\varepsilon) \), \( s \in (A\varepsilon^{-1}, B\varepsilon^{-1}) \). After changing variables, and setting \( l_\varepsilon := C|\log \varepsilon| \), we obtain

\[
G^{(1)}_\varepsilon(v_\varepsilon) = \varepsilon^{-1} \int_{-l_\varepsilon}^{l_\varepsilon} (W^{1/2}(w_\varepsilon) - w_\varepsilon')^2 \eta_\varepsilon ds + 2\varepsilon^{-1} \int_{-l_\varepsilon}^{l_\varepsilon} W^{1/2}(w_\varepsilon)w_\varepsilon' (\eta_\varepsilon - \eta(0)) ds
\]

\[+ \varepsilon^{-1} \int_{[A\varepsilon^{-1}, B\varepsilon^{-1}] \setminus (-l_\varepsilon, l_\varepsilon)} (W(w_\varepsilon) + (w_\varepsilon')^2) \eta_\varepsilon ds + \varepsilon^{-1} 2\eta(0) \left( \int_{-l_\varepsilon}^{l_\varepsilon} W^{1/2}(w_\varepsilon)w_\varepsilon' ds - c_W \right)
\]

\[\geq 2\varepsilon^{-1} \int_{-l_\varepsilon}^{l_\varepsilon} W^{1/2}(w_\varepsilon)w_\varepsilon' (\eta_\varepsilon - \eta(0)) ds
\]

\[+ \varepsilon^{-1} \int_{[A\varepsilon^{-1}, B\varepsilon^{-1}] \setminus (-l_\varepsilon, l_\varepsilon)} W(w_\varepsilon)\eta_\varepsilon ds + \varepsilon^{-1} 2\eta(0) \left( \int_{-l_\varepsilon}^{l_\varepsilon} W^{1/2}(w_\varepsilon)w_\varepsilon' ds - c_W \right).
\]

The last term goes to zero, see 4.105 in [10]. Following the proof of 4.106 in [10], the second to last term satisfies

\[
\lim_{\varepsilon \to 0^+} \varepsilon^{-1} \int_{[A\varepsilon^{-1}, B\varepsilon^{-1}] \setminus (-l_\varepsilon, l_\varepsilon)} W(w_\varepsilon)\eta_\varepsilon ds = \begin{cases} \frac{\lambda_\varepsilon^2}{2W''(a)} \int_{l} \eta dt & \text{if } q = 1, \\ 0 & \text{if } q < 1. \end{cases}
\]

Finally, by (3.1) the function \( \eta \) satisfies the following Taylor’s formula:

\[
\eta(t) = \eta(0) - t^- \eta'_-(0) + t^+ \eta'_+(0) + |t| R_1(t),
\]

where \( R_1(t) \to 0 \) as \( t \to 0 \). Hence, we find that

\[
2\varepsilon^{-1} \int_{-l_\varepsilon}^{l_\varepsilon} W^{1/2}(w_\varepsilon(s))w'_\varepsilon(s)(\eta_\varepsilon(s) - \eta(0)) ds = 2 \int_{-l_\varepsilon}^{l_\varepsilon} W^{1/2}(w_\varepsilon(s))w'_\varepsilon(s)(-\eta'_-(0)s^- + \eta'_+(0)s^+) ds
\]

\[+ 2 \int_{-l_\varepsilon}^{l_\varepsilon} W^{1/2}(w_\varepsilon(s))w'_\varepsilon(s)|s|R_1(\varepsilon s) ds.
\]

As in [10], we now break the integrals over \([-l_\varepsilon, -l], [-l, l], [l, l_\varepsilon]\) for any fixed \( l > 0 \). Since by Step 2, \( \{w_\varepsilon\} \) converges weakly to \( z(\cdot - \tau_0) \) in \( H^1((-l,l)) \), we can follow the computations after formula (4.106) in [10] using the exponential decay (see (4.95) and (4.96) in [10]) in \([-l_\varepsilon, -l] \) and \([l, l_\varepsilon]\) to obtain that

\[
\lim_{\varepsilon \to 0^+} 2 \int_{-l_\varepsilon}^{l_\varepsilon} W^{1/2}(w_\varepsilon(s))w'_\varepsilon(s)(-\eta'_-(0)s^- + \eta'_+(0)s^+) ds
\]

\[= 2\eta'_-(0) \int_{-\infty}^{0} W^{1/2}(z(s - \tau_0))z'(s - \tau_0)s ds + 2\eta'_+(0) \int_{0}^{\infty} W^{1/2}(z(s - \tau_0))z'(s - \tau_0)s ds.
\]
Similarly, using the facts that \( R_1(t) \to 0 \) as \( t \to 0 \) and \( \varepsilon|s| \leq \varepsilon l_\varepsilon \leq C\varepsilon \log \varepsilon \) for \( |s| \leq l_\varepsilon \), we can use Step 2 to show that
\[
\lim_{\varepsilon \to 0^+} 2 \int_{-l}^{l} W^{1/2}(w_\varepsilon(s))w_\varepsilon'(s)|s|R_1(\varepsilon s) \, ds = 0,
\]
while by Lemma 4.19 and (4.96) in [10],
\[
2 \int_{l}^{l_\varepsilon} W^{1/2}(w_\varepsilon(s))|w_\varepsilon'(s)||s|R_1(\varepsilon s) \, ds \leq 2\|R_1\|_{L^\infty(-l_\varepsilon, l_\varepsilon)}\|w_\varepsilon''\|_\infty \int_{l}^{l_\varepsilon} W^{1/2}(w_\varepsilon(s))|s| \, ds \to 0
\]
as \( \varepsilon \to 0^+ \). A similar estimate holds in \([-l_\varepsilon, -l]\). This concludes the proof of (3.6).

\[
\square
\]

4 Proof of the Main Results

Now we give a proof of Theorem 1.3.

Proof of Theorem 1.3. We only give the proof in the case \( q = 1 \) in (1.5), the case \( q < 1 \) being similar. Since \( \mathcal{I}_{\Omega} \leq \mathcal{I}_{\Omega}^{E_0, \delta} \) (see (1.14) and (2.1)), reasoning as in Proposition 3.1 in [10] we can construct a function \( \mathcal{I} \in C((0,1) \cap C^1((0, \varepsilon_m)] \cap C^1([\varepsilon_m, 0)) \) satisfying
\[
\mathcal{I}(v_m) = \mathcal{I}^{E_0, \delta}(v_m), \quad \mathcal{I}_{\pm}(v_m) = (\mathcal{I}^{E_0, \delta})_{\pm}(v_m), \quad \mathcal{I}(v) = C_0 v^\frac{n-1}{2} \text{ for } v \in (0, 0), \quad \mathcal{I}(v) = C_0 (1 - v)^\frac{n-1}{2} \text{ for } v \in (1 - r, 1)
\]
for some constant \( C_0 > 0 \) and some \( 0 < r < 1/2 \) small. Let \( \eta := \mathcal{I} \circ V_{\Omega} \), where \( V_{\Omega} \) satisfies
\[
\frac{d}{dt} V_{\Omega}(t) = \mathcal{I}(V_{\Omega}(t)), \quad V_{\Omega}(0) = v_m. \tag{4.2}
\]
As in the proof of Theorem 5.1 in [15] one can show that \( \eta \) satisfies all of the assumptions (3.1)–(3.5).

Let \( u_\varepsilon \) be a minimizer of \( \mathcal{F}_\varepsilon \) and let \( v_\varepsilon := f_w \) be the increasing function given in Remark 3.11 of [10]. Following the proof of Theorem 5.1 in [10] (see also [14] or [15] for more details), we have that
\[
\frac{\mathcal{F}_\varepsilon^{(1)}(u_\varepsilon) - \min \mathcal{F}_0}{\varepsilon} \geq \frac{G_\varepsilon^{(1)}(v_\varepsilon) - 2c_W \eta(t_0)}{\varepsilon},
\]
Hence, by Theorem 3.1, we have that
\[
\liminf_{\varepsilon \to 0^+} \frac{\mathcal{F}_\varepsilon^{(1)}(u_\varepsilon) - \min \mathcal{F}_0}{\varepsilon} \geq \frac{\lambda_0^2(\delta)}{2W''(a)} \int_{l}^{l_\varepsilon} \eta(t) \, dt + 2\eta'_-(t_0) \int_{-\infty}^{0} W_1/2(z(s - \tau_0(\delta)))z'(s - \tau_0(\delta))s \, ds
\]
\[
+ 2\eta'_+(t_0) \int_{0}^{\infty} W_1/2(z(s - \tau_0(\delta)))z'(s - \tau_0(\delta))s \, ds,
\]
where
\[
\lambda_0(\delta) \in \left[ \frac{2c_W \eta'_+(t_0)}{(b - a)\eta(t_0)} - \frac{2c_W \eta'_-(t_0)}{(b - a)\eta(t_0)} \right]. \tag{4.3}
\]
and \( \tau_0(\delta) \) is given by
\[
\eta(t_0) \int_{\mathbb{R}} z(s - \tau_0(\delta)) - sgn_{a,b}(s) \, ds = \frac{\lambda_0(\delta)}{W''(a)} \int_{l} \eta(t) \, dt. \tag{4.4}
\]
By Proposition 2.4, (4.1), and (4.2), we find that as $\delta \to 0$ the quantities $\eta_\delta'(t_0)$ and $\eta_\delta'(t_0)$ converge to the same value, namely, $(n - 1)\kappa_{E_0}$, and hence by (4.3) and (4.4) we have that $\lambda_0(\delta) \to \lambda_u$ and $\tau_0(\delta) \to \tau_u$ converge as well. Thus by taking $\delta \to 0$ we obtain

$$\liminf_{\varepsilon \to 0^+} \frac{\mathcal{F}(u_\varepsilon)}{\varepsilon} - \min \mathcal{F}_0 \geq \frac{2c_W^2(n - 1)^2}{W''(a)(b - a)^2} \kappa_u^2 + 2(c_{sym} + c_W \tau_u)(n - 1)\kappa_u P(\{u = a\}; \Omega),$$

which is the desired result.

The proofs of Theorems 1.4 and 1.5 now follow from Theorems 1.2 and 1.7 and Theorem 1.4 in [15], respectively, with the only change that we apply Theorem 1.3 of this paper in place of Theorem 1.1 in [10].

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Compliance with Ethical Standards

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