NONDEGENERACY OF NONRADIAL NODAL SOLUTIONS TO YAMABE PROBLEM

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Abstract: We prove the existence of a sequence of nondegenerate, in the sense of Duyckaerts-Kenig-Merle [9], nodal nonradial solutions to the critical Yamabe problem

\[-\Delta Q = |Q|^\frac{4}{n-2} Q, \ Q \in D^{1,2}(\mathbb{R}^n).\]

This is the first example in the literature of nondegeneracy for nodal nonradial solutions of nonlinear elliptic equations and it is also the only nontrivial example for which the result of Duyckaerts-Kenig-Merle [9] applies.

1. Introduction

In this paper we consider the critical Yamabe problem

\[\begin{align*}
-\Delta u &= \frac{n(n-2)}{4} |u|^\frac{4}{n-2} u, \quad u \in D^{1,2}(\mathbb{R}^n) \\
\end{align*}\]

where \(n \geq 3\) and \(D^{1,2}(\mathbb{R}^n)\) is the completion of \(C_0^\infty(\mathbb{R}^n)\) under the norm \(\sqrt{\int_{\mathbb{R}^n} |\nabla u|^2}\).

If \(u > 0\) Problem (1.1) is the conformally invariant Yamabe problem. For sign-changing \(u\) Problem (1.1) corresponds to the steady state of the energy-critical focusing nonlinear wave equation

\[\begin{align*}
\partial^2_t u - \Delta u - |u|^\frac{4}{n-2} u &= 0, \quad (t, x) \in \mathbb{R} \times \mathbb{R}^n.
\end{align*}\]

These are classical problems that have attracted the attention of several researchers in order to understand the structure and properties of the solutions to Problems (1.1) and (1.2).

Denote the set of non-zero finite energy solutions to Problem (1.1) by

\[\Sigma := \left\{ Q \in D^{1,2}(\mathbb{R}^n) \setminus \{0\} : -\Delta Q = \frac{n(n-2)}{4} |Q|^\frac{4}{n-2} Q \right\}.
\]

This set has been completely characterized in the class of positive solutions to Problem (1.1) by the classical work of Caffarelli-Gidas-Spruck [5] (see also [2, 24, 31]): all positive solutions to (1.1) are radially symmetric around some point \(a \in \mathbb{R}^n\) and are of the form

\[W_{\lambda,a}(x) = \left(\frac{\lambda}{\lambda^2 + |x-a|^2}\right)^{\frac{n+2}{2}}, \quad \lambda > 0.
\]

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Much less is known in the sign-changing case. A direct application of Pohozaev’s identity gives that all sign-changing solutions to Problem (1.1) are non-radial. The existence of elements of \( \Sigma \) that are nonradial sign-changing, and with arbitrary large energy was first proved by Ding [6] using Ljusternik-Schnirelman category theory. Indeed, via stereographic projection to \( S^n \) Problem (1.1) becomes

\[
\Delta_{S^n} v + \frac{n(n-2)}{4} (|v|^{\frac{4}{n-2}} - v) = 0 \quad \text{in} \ S^n,
\]

(see for instance [30], [14]) and Ding showed the existence of infinitely many critical points to the associated energy functional within functions of the form

\[
v(x) = v(|x_1|, |x_2|), \quad x = (x_1, x_2) \in S^n \subset \mathbb{R}^{n+1} = \mathbb{R}^k \times \mathbb{R}^{n+1-k}, \quad k \geq 2,
\]

where compactness of critical Sobolev’s embedding holds, for any \( n \geq 3 \). No other qualitative properties are known for the corresponding solutions. Recently more explicit constructions of sign changing solutions to Problem (1.1) have been obtained by del Pino-Musso-Pacard-Pistoia [7, 8]. However so far only existence is available, and there are no rigidity results on these solutions.

The main purpose of this paper is to prove that these solutions are rigid, up to the transformations of the equation. In other words, these solutions are nondegenerate, in the sense of the definition introduced by Duyckaerts-Kenig-Merle in [9]. Following [9], we first find out all possible invariances of the equation (1.1). Equation (1.1) is invariant under the following four transformations:

(1) (translation): If \( Q \in \Sigma \) then \( Q(x + a) \in \Sigma, \forall a \in \mathbb{R}^n \);

(2) (dilation): If \( Q \in \Sigma \) then \( \lambda^{\frac{2}{n-2}} Q(\lambda x) \in \Sigma, \forall \lambda > 0 \);

(3) (orthogonal transformation): If \( Q \in \Sigma \) then \( Q(Px) \in \Sigma \) where \( P \in O_n \) and \( O_n \) is the classical orthogonal group;

(4) (Kelvin transformation): If \( Q \in \Sigma \) then \( |x|^{2-N} Q(\frac{x}{|x|}) \in \Sigma \).

If we denote by \( \mathcal{M} \) the group of isometries of \( D^{1,2}(\mathbb{R}^n) \) generated by the previous four transformations, a result of Duyckaerts-Kenig-Merle [Lemma 3.8,[9]] states that \( \mathcal{M} \) generates an \( N \)-parameter family of transformations in a neighborhood of the identity, where the dimension \( N \) is given by

\[
N = 2n + 1 + \frac{n(n-1)}{2}.
\]

In other words, if \( Q \in \Sigma \) we denote

\[
L_Q := -\Delta - \frac{n(n+2)}{4} |Q|^{\frac{4}{n-2}}
\]

the linearized operator around \( Q \). Define the null space of \( L_Q \)

\[
\mathcal{Z}_Q = \{ f \in D^{1,2}(\mathbb{R}^n) : L_Q f = 0 \}
\]
The elements in $Z_Q$ generated by the family of transformations $\mathcal{M}$ define the following vector space

\[(1.7) \quad \tilde{Z}_Q = \text{span} \left\{ \begin{array}{l}(2 - n)x_j Q + |x|^2 \partial_{x_j} Q - 2 x_j x \cdot \nabla Q, \quad \partial_{x_j} Q, \quad 1 \leq j \leq n, \\
(x_j \partial_{x_k} - x_k \partial_{x_j}) Q, \quad 1 \leq j < k \leq n, \quad \frac{n-2}{2} Q + x \cdot Q \end{array} \right\}.\]

Observe that the dimension of $\tilde{Z}_Q$ is at most $N$, but in principle it could be strictly less than $N$. For example in the case of the positive solutions $Q = W$, it turns out that the dimension of $\tilde{Z}_Q$ is $n+1$ as a consequence of being $Q$ radially symmetric. Indeed, it is known that

\[(1.8) \quad \tilde{Z}_W = \left\{ \begin{array}{l} \frac{n-2}{2} W + x \cdot \nabla W, \quad \partial_{x_j} W, \quad 1 \leq j \leq n \end{array} \right\}.\]

Duyckaerts-Kenig-Merle [9] introduced the following definition of nondegeneracy for a solution of Problem (1.1): $Q \in \Sigma$ is said to be \textit{nondegenerate} if

\[(1.9) \quad Z_Q = \tilde{Z}_Q.\]

So far the only nondegeneracy example of $Q \in \Sigma$ is the positive solution $W$. The proof of this fact relies heavily on the radial symmetry of $W$ and it is straightforward: In fact since $Q = W$ is radially symmetric (around some point) one can decompose the linearized operator into Fourier modes, getting (1.9) as consequence of a simple ode analysis. See also [27]. In the case of nodal (nonradial) solutions this strategy no longer works out. In fact, as far as the authors know, there are no results in the literature on nondegeneracy of nodal nonradial solutions for nonlinear elliptic equations in the whole space. For positive radial solutions there have been many results. We refer to Frank-Lenzmann [12], Frank-Lenzmann-Silvestre [13], Kwong [21] and the references therein.

The knowledge of nondegeneracy is a crucial ingredient to show the soliton resolution for a solution to the energy-critical wave equation (1.2) with the compactness property obtained by Kenig and Merle in [16, 17]. If the dimension $n$ is 3, 4 or 5, and under the above nondegeneracy assumption, they prove that any non zero such solution is a sum of stationary solutions and solitary waves that are Lorentz transforms of the former. See also Duyckaerts, Kenig and Merle [10, 11]. Nondegeneracy also plays a vital role in the study of Type II blow-up solutions of (1.2). We refer to Krieger, Schlag and Tataru [20], Rodnianski and Sterbenz [26] and the references therein.

The main result of this paper can be stated as follows:

\textbf{Main Result:} There exists a sequence of nodal solutions to (1.1), with arbitrary large energy, such that they are nondegenerate in the sense of (1.9).

Now let us be more precise.

Let

\[(1.10) \quad f(t) = \gamma |t|^{p-1} t, \quad \text{for} \quad t \in \mathbb{R}, \quad \text{and} \quad p = \frac{n+2}{n-2}.\]
The constant $\gamma > 0$ is chosen for normalization purposes to be

$$\gamma = \frac{n(n - 2)}{4}.$$ 

In [7], del Pino, Musso, Pacard and Pistoia showed that Problem

(1.11) \[ \Delta u + f(u) = 0 \quad \text{in} \quad \mathbb{R}^n, \]

admits a sequence of entire non radial sign changing solutions with finite energy.

To give a first description of these solutions, let us introduce some notations. Fix an integer $k$. For any integer $l = 1, \ldots, k$, we define angles $\theta_l$ and vectors $n_l, t_l$ by

(1.12) \[ \theta_l = \frac{2\pi}{k}(l - 1), \quad n_l = (\cos \theta_l, \sin \theta_l, 0), \quad t_l = (-\sin \theta_l, \cos \theta_l, 0). \]

Here $0$ stands for the zero vector in $\mathbb{R}^{n-2}$. Notice that $\theta_1 = 0, n_1 = (1, 0, 0)$, and $t_1 = (0, 1, 0)$.

In [7] it was proved that there exists $k_0$ such that for all integer $k > k_0$ there exists a solution $u_k$ to (1.11) that can be described as follows

(1.13) \[ u_k(x) = U_*(x) + \tilde{\varphi}(x) \]

where

(1.14) \[ U_*(x) = U(x) - \sum_{j=1}^{k} U_j(x), \]

while $\tilde{\varphi}$ is smaller than $U_*$. The functions $U$ and $U_j$ are positive solutions to (1.11), respectively defined as

(1.15) \[ U(x) = \left( \frac{2}{1 + |x|^2} \right)^{\frac{n+2}{2}}, \quad U_j(x) = \mu_k^{-\frac{n+2}{2}} U(\mu_k^{-1}(x - \xi_j)). \]

For any integer $k$ large, the parameters $\mu_k > 0$ and the $k$ points $\xi_l, l = 1, \ldots, k$ are given by

(1.16) \[ \left[ \sum_{l=1}^{k} \frac{1}{(1 - \cos \theta_l)^{\frac{n+2}{2}}} \right] \mu_k^{\frac{n+2}{2}} = \left( 1 + O(\frac{1}{k}) \right), \quad \text{for} \quad k \to \infty \]

in particular, as $k \to \infty$, we have

$$\mu_k \sim k^{-2} \quad \text{if} \quad n \geq 4, \quad \mu_k \sim k^{-2} \log k^{-2} \quad \text{if} \quad n = 3.$$ 

Furthermore

(1.17) \[ \xi_l = \sqrt{1 - \mu_k^2} (n_l, 0). \]

The functions $U$, $U_j$ and $U_*$ are invariant under rotation of angle $\frac{2\pi}{k}$ in the $x_1, x_2$ plane, namely

(1.18) \[ U(e^{\frac{2\pi}{k}} \bar{x}, x') = U(\bar{x}, x'), \quad \bar{x} = (x_1, x_3), \quad x' = (x_3, \ldots, x_n). \]

They are even in the $x_j$-coordinates, for any $j = 2, \ldots, n$

(1.19) \[ U(x_1, \ldots, x_j, \ldots, x_n) = U(x_1, \ldots, -x_j, \ldots, x_n), \quad j = 2, \ldots, n \]
and they respect invariance under Kelvin’s transform:

\[ U(x) = |x|^{-n} U(|x|^{-2} x). \]

In (1.13) the function \( \tilde{\phi} \) is a small function when compared with \( U_* \). We will further describe the function \( u \), and in particular the function \( \tilde{\phi} \) in Section 2. Let us just mention that \( \tilde{\phi} \) satisfies all the symmetry properties (1.18), (1.19) and (1.20).

Recall that Problem (1.11) is invariant under the four transformations mentioned before: translation, dilation, rotation and Kelvin transformation. These invariances will be reflected in the element of the kernel of the linear operator

\[ L(\varphi) := \Delta \varphi + f'(u_k)\varphi = \Delta \varphi + p|u_{k}|^{p-2} u \varphi \]

which is the linearized equation associated to (1.11) around \( u_k \).

From now on, for simplicity we will drop the label \( k \) in \( u_k \), so that \( u \) will denote the solution to Problem (1.11) described in (1.13).

Let us introduce the following set of functions

\[ z_{0}(x) = \frac{n-2}{2} u(x) + \nabla u(x) \cdot x, \]

\[ z_{\alpha}(x) = \frac{\partial}{\partial x_{\alpha}} u(x), \quad \text{for} \quad \alpha = 1, \ldots, n, \]

and

\[ z_{n+1}(x) = -x_2 \frac{\partial}{\partial x_1} u(x) + x_1 \frac{\partial}{\partial x_2} u(x) \]

where \( u \) is the solution to (1.11) described in (1.13). Observe that \( z_{n+1} \) is given by

\[ z_{n+1}(x) = \frac{\partial}{\partial \theta}[u(R_\theta x)]_{\theta=0} \]

where \( R_\theta \) is the rotation in the \( x_1, x_2 \) plane of angle \( \theta \). Furthermore,

\[ z_{n+2}(x) = -2x_1 z_{0}(x) - |x|^2 z_1(x), \quad z_{n+3}(x) = -2x_2 z_{0}(x) - |x|^2 z_2(x) \]

for \( l = 3, \ldots, n \)

\[ z_{n+l+1}(x) = -x_l z_1(x) + x_1 z_l(x), \quad u_{2n+l-1}(x) = -x_l z_2(x) + x_2 z_l(x). \]

The functions defined in (1.25) are related to the invariance of Problem (1.11) under Kelvin transformation, while the functions defined in (1.26) are related to the invariance under rotation in the \( (x_1, x_l) \) plane and in the \( (x_2, x_l) \) plane respectively.

The invariance of Problem (1.11) under scaling, translation, rotation and Kelvin transformation gives that the set \( \tilde{Z}_0 \) (introduced in (1.7)) associated to the linear operator \( L \) introduced in (1.21) has dimension at least \( 3n \), since

\[ L(z_{\alpha}) = 0, \quad \alpha = 0, \ldots, 3n - 1. \]

We shall show that these functions are the only bounded elements of the kernel of the operator \( L \). In other words, the sign changing solutions (1.13) to Problem (1.11) constructed in [7] are non degenerate in the sense of Duyckaerts-Kenig-Merle [9].
To state our result, we introduce the following function: For any positive integer $i$, we define
\[ P_i(x) = \sum_{l=1}^{\infty} \frac{\cos(lx)}{l^i} \quad \text{and} \quad Q_i(x) = \sum_{l=1}^{\infty} \frac{\sin(lx)}{l^i}. \]
Up to a normalization constant, when $n$ is even, $P_n$ and $Q_n$ are related to the Fourier series of the Bernoulli polynomial $B_n(x)$, and when $n$ is odd $P_n$ and $Q_n$ are related to the Fourier series of the Euler polynomial $E_n(x)$. We refer to [1] for further details.

We now define
\[ g(x) = \sum_{j=1}^{\infty} \frac{1 - \cos(jx)}{j^n}, \quad 0 \leq x \leq \pi \]
which can be rewritten as
\[ g(x) = P_n(0) - P_n(x). \]
Observe that
\[ g'(x) = Q_{n-1}(x), \quad g''(x) = P_{n-2}(x). \]

**Theorem 1.1.** Assume that
\[ g''(x) < \frac{n - 2 (g'(x))^2}{n - 1} \quad \forall x \in (0, \pi). \]
Then all bounded solutions to the equation
\[ L(\varphi) = 0 \]
are a linear combination of the functions $z_\alpha(x)$, for $\alpha = 0, \ldots, 3n - 1$.

When $n = 3$, condition (1.29) is satisfied. Indeed, in this case we observe that $g''(x) = -\ln(2 \sin \frac{x}{2})$. Thus, if we call $\rho(x) = g''(x)g(x) - \frac{1}{2} (g'(x))^2$, we get $\rho'(x) = g'''(x)g(x) = -\frac{1}{2} \cot(\frac{x}{2})g(x) < 0$. Since $\rho(0) = 0$, condition (1.29) is satisfied.

When $n = 4$, let us check the condition (1.29): let $x = 2\pi t, t \in (0, \frac{1}{2})$. Using the explicit formula for the Bernoulli polynomial $B_4$ we find that
\[ g(t) = t^2(1-t)^2 \]
and hence (1.29) is reduced to showing
\[ 12t^2 - 12t + 2 < \frac{8}{3} (1+t)^2, \quad t \in (0, \frac{1}{2}) \]
which is trivial to verify.

In general we believe that condition (1.29) should be true for any dimension $n \geq 4$. In fact, we have checked (1.29) numerically, up to dimension $n \leq 48$. Nevertheless, let us mention that even if (1.29) fails, our result is still valid for a subsequence $u_{k_j}$, $k_j \rightarrow +\infty$, of solutions (1.13) to Problem (1.11). Indeed, also in this case, our proof can still go through by choosing a subsequence $k_j \rightarrow +\infty$ in order to avoid the resonance.

We end this section with some remarks.
First: very few results are known on sign-changing solutions to the Yamabe problem. In the critical exponent case and \( n = 3 \) the topology of lower energy level sets was analyzed in Bahri-Chanillo [3] and Bahri-Xu [4]. For the construction of sign-changing bubbling solutions we refer to Hebey-Vaugon [15], Robert-Vetois [28, 29], Vaira [32] and the references therein. We believe that the non-degeneracy property established in Theorem 1.1 may be used to obtain new type of constructions for sign changing bubbling solutions.

Second: as far as we know the kernels due to the Kelvin transform (i.e. \(-2x_jz_0 + |x|^2z_j\)) were first used by Korevaar-Mazzeo-Pacard-Schoen [18] and Mazzeo-Pacard ([23]) in the construction of isolated singularities for Yamabe problem by using a gluing procedure. An interesting question is to determine if and how the non-degenerate sign-changing solutions can used in gluing methods.

Third: for the sign-changing solutions considered in this paper, the dimension of the kernel equals \( 3n \) which is strictly less than \( N = 2n + 1 + \frac{n(n-1)}{2} \). An open question is whether or not there are sign-changing solutions whose dimension of kernel equals \( N \).

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2. Description of the solutions

In this section we describe the solutions \( u_k \) in (1.13), recalling some properties that have already been established in [7], and adding some further properties that will be useful for later purpose.

In terms of the function \( \tilde{\phi} \) in the decomposition (1.13), equation (1.11) gets re-written as

\[
\Delta \tilde{\phi} + p \gamma |U^*|^p - 1 \tilde{\phi} + E + \gamma N(\tilde{\phi}) = 0
\]
where \( E \) is defined by

\[
E = \Delta U^* + f(U^*)
\]
and

\[
N(\phi) = |U^* + \phi|^{p-1}(U^* + \phi) - |U^*|^{p-1}U^* - p|U^*|^{p-1}\phi.
\]

One has a precise control of the size of the function \( E \) when measured for instance in the following norm. Let us fix a number \( q \), with \( \frac{n}{2} < q < n \), and consider the weighted \( L^q \) norm

\[
||h||_{L^q} = ||(1 + |y|)^{n+2-\frac{2n}{q}}h||_{L^q(\mathbb{R}^n)}.
\]

In [7] it is proved that there exist an integer \( k_0 \) and a positive constant \( C \) such that for all \( k \geq k_0 \) the following estimates hold true

\[
||E||_{L^q} \leq Ck^{1-\frac{q}{n}} \quad \text{if} \quad n \geq 4, \quad ||E||_{L^q} \leq \frac{C}{\log k} \quad \text{if} \quad n = 3.
\]
To be more precise, we have estimates for the $\| \cdot \|_\infty$-norm of the error term $E$ first in the exterior region $\bigcap_{j=1}^k \{ |y - \xi_j| > \frac{\eta}{q} \}$, and also in the interior regions $\{ |y - \xi_j| < \frac{\eta}{q} \}$, for any $j = 1, \ldots, k$. Here $\eta > 0$ is a positive and small constant, independent of $k$.

In the exterior region. We have

$$ \| (1 + |y|)^{n+2-\frac{2n}{q}} E(y) \|_{L^q(\bigcap_{j=1}^k \{ |y - \xi_j| > \frac{\eta}{q} \})} \leq C k^{1-\frac{\eta}{q}} $$

if $n \geq 4$, while

$$ \| (1 + |y|)^{n+2-\frac{2n}{q}} E(y) \|_{L^q(\bigcap_{j=1}^k \{ |y - \xi_j| > \frac{\eta}{q} \})} \leq \frac{C}{\log k} $$

if $n = 3$. 

In the interior regions. Now, let $|y - \xi_j| < \frac{\eta}{q}$ for some $j \in \{ 1, \ldots, k \}$. It is convenient to measure the error after a change of scale. Define

$$ \hat{E}_j(y) := \mu^{\frac{n-1}{2}} E(\xi_j + \mu y), \quad |y| < \frac{\eta}{\mu k}. $$

We have

$$ \| (1 + |y|)^{n+2-\frac{2n}{q}} \hat{E}_j(y) \|_{L^q(|y|<\frac{\eta}{q})} \leq C k^{-\frac{\eta}{q}} \quad \text{if} \quad n \geq 4 $$

and

$$ \| (1 + |y|)^{n+2-\frac{2n}{q}} \hat{E}_j(y) \|_{L^q(|y|<\frac{\eta}{q})} \leq \frac{C}{k \log k} \quad \text{if} \quad n = 3. $$

We refer the readers to [7].

The function $\tilde{\phi}$ in (1.13) can be further decomposed. Let us introduce some cut-off functions $\zeta_j$ to be defined as follows. Let $\zeta(s)$ be a smooth function such that $\zeta(s) = 1$ for $s < 1$ and $\zeta(s) = 0$ for $s > 2$. We also let $\zeta^- = \zeta(2s)$. Then we set

$$ \zeta_j(y) = \begin{cases} 
\zeta(k \eta^{-1} |y|^2 (y - \xi_j)) & \text{if } |y| > 1, \\
\zeta(k \eta^{-1} |y| - \xi_j) & \text{if } |y| \leq 1,
\end{cases} $$

in such a way that

$$ \zeta_j(y) = \zeta_j(y/|y|^2). $$

The function $\tilde{\phi}$ has the form

$$ (2.5) \quad \tilde{\phi} = \sum_{j=1}^k \phi_j + \psi. $$

In the decomposition (2.5) the functions $\phi_j$, for $j > 1$, are defined in terms of $\tilde{\phi}_1$

$$ (2.6) \quad \phi_j(y, y') = \tilde{\phi}_1(e^{2x_j} y, y'), \quad j = 1, \ldots, k - 1. $$

Each function $\phi_j$, $j = 1, \ldots, k$, is constructed to be a solution in the whole $\mathbb{R}^n$ to the problem

$$ (2.7) \quad \Delta \phi_j + p y |U_i|^{p-1} \xi_j \phi_j + \zeta_j \phi_j = f(y, U_i |U_i|^{p-1} \psi + E + y N(\phi_j + \Sigma_{i \neq j} \phi_i + \psi) = 0, $$
while $\psi$ solves in $\mathbb{R}^n$
\[\Delta \psi + p y U^{p-1} \psi + \{ p y (|U|^{p-1} - U^{p-1})(1 - \Sigma_{j=1}^{k} \zeta_j) + p y U^{p-1} \Sigma_{j=1}^{k} \zeta_j \} \psi \]
(2.8) \[+ p y |U|^{|p-1| \sum_j (1 - \zeta_j) \tilde{\phi}_j + (1 - \Sigma_{j=1}^{k} \zeta_j) (E + y N(\Sigma_{j=1}^{k} \tilde{\phi}_j + \psi)) = 0.\]

Define now $\phi_1(y) = \mu^{\frac{n-2}{2}} \tilde{\phi}_1(\mu y + \xi_1)$. Then $\phi_1$ solves the equation
\[\Delta \phi_1 + f'(U)\phi_1 + \chi_1(\xi_1 + \mu y) \mu^{\frac{n-2}{2}} E(\xi_1 + \mu y) \]
(2.9) \[+ \gamma \mu^{\frac{n-2}{2}} N(\phi_1)(\xi_1 + \mu y) = 0 \quad \text{in} \quad \mathbb{R}^n\]
where
\[N(\phi_1) = p(|U|^{p-1} \xi_1 - U^{p-1}) + \xi_1[p|U|^{p-1}\psi(\phi_1) \]
(2.10) \[+ N(\tilde{\phi}_1 + \sum_{j=1}^{k} \tilde{\phi}_j + \Psi(\phi_1))\]

In [7] it is shown that the following estimate on the function $\psi$ holds true:
(2.11) \[\|\psi\|_{n-2} \leq C k^{1-\frac{n}{\gamma}} \quad \text{if} \quad n \geq 4, \quad \|\psi\|_{n-2} \leq \frac{C}{\log k} \quad \text{if} \quad n = 3,\]
where
(2.12) \[\|\phi\|_{n-2} := \| (1 + |y|^{n-2}) \phi \|_{L^{\infty}(\mathbb{R}^n)}.\]

On the other hand, if we rescale and translate the function $\tilde{\phi}_1$
(2.13) \[\phi_1(y) = \mu^{\frac{n-2}{2}} \tilde{\phi}_1(\xi_1 + \mu y)\]
we have the validity of the following estimate for $\phi_1$
(2.14) \[\|\phi_1\|_{n-2} \leq C k^{\frac{n-2}{\gamma}} \quad \text{if} \quad n \geq 4, \quad \|\phi_1\|_{n-2} \leq \frac{C}{k \log k} \quad \text{if} \quad n = 3.\]

Furthermore, we have
(2.15) \[\|N(\phi_1)\|_{\infty} \leq C k^{\frac{2n}{\gamma}} \quad \text{if} \quad n \geq 4, \quad \|N(\phi_1)\|_{\infty} \leq C (k \log k)^{-2} \quad \text{if} \quad n = 3,\]
see (2.10). Let us now define the following functions
(2.16) \[\pi_\alpha(y) = \frac{\partial}{\partial y_\alpha} \tilde{\phi}(y), \quad \text{for} \quad \alpha = 1, \ldots, n;\]
\[\pi_0(y) = \frac{n-2}{2} \tilde{\phi}(y) + \nabla \tilde{\phi}(y) \cdot y.\]

In the above formula $\tilde{\phi}$ is the function defined in (1.13) and described in (2.5). Observe that the function $\pi_0$ is even in each of its variables, namely
\[\pi_0(y_1, \ldots, y_j, \ldots, y_n) = \pi_0(y_1, \ldots, -y_j, \ldots, y_n) \quad \forall j = 1, \ldots, n,\]
while $\pi_\alpha$, for $\alpha = 1, \ldots, n$ is odd in the $y_\alpha$ variable, while it is even in all the other variables. Furthermore, all functions $\pi_\alpha$ are invariant under rotation of $\frac{2\pi}{k}$ in the first two coordinates, namely they satisfy (1.18). The functions $\pi_\alpha$ can be further described, as follows.
Proposition 2.1. The functions $\pi_\alpha$ can be decomposed into

\begin{equation}
\pi_\alpha(y) = \sum_{j=1}^{k} \tilde{\pi}_{\alpha,j}(y) + \hat{\pi}_\alpha(y)
\end{equation}

where

\[ \tilde{\pi}_{\alpha,j}(y) = \tilde{\pi}_{\alpha,1}(e^{2\pi i j/y}, y'). \]

Furthermore, there exists a positive constant $C$ so that

\[ \|\tilde{\pi}_0\|_{n-2} \leq Ck^{1-\frac{2}{q}}, \quad \|\tilde{\pi}_j\|_{n-1} \leq Ck^{1-\frac{2}{q}}, \quad j = 1, \ldots, k, \]

if $n \geq 4$, and

\[ \|\tilde{\pi}_0\|_{n-2} \leq \frac{C}{\log k}, \quad \|\tilde{\pi}_j\|_{n-1} \leq \frac{C}{\log k}, \quad j = 1, \ldots, k, \]

if $n = 3$. Furthermore, if we denote $\pi_{\alpha,1}(y) = \mu^{\frac{2\pi}{n}} \tilde{\pi}_{\alpha,1}(\xi_1 + \mu y)$, then

\[ \|\pi_{0,1}\|_{n-2} \leq Ck^{\frac{-2}{q}}, \quad \|\pi_{\alpha,1}\|_{n-1} \leq Ck^{\frac{-2}{q}}, \quad \alpha = 1, \ldots, n \]

if $n \geq 4$, and

\[ \|\pi_{0,1}\|_{n-2} \leq \frac{C}{k \log k}, \quad \|\pi_{\alpha,1}\|_{n-1} \leq \frac{C}{k \log k}, \quad \alpha = 1, \ldots, 3 \]

if $n = 3$.

The proof of this result can be obtained using similar arguments as the ones used in [7]. We leave the details to the reader.

3. Scheme of the proof

Let $\varphi$ be a bounded function satisfying $L(\varphi) = 0$, where $L$ is the linear operator defined in (1.21). We write our function $\varphi$ as

\begin{equation}
\varphi(x) = \sum_{\alpha=0}^{3n-1} a_{\alpha} z_{\alpha}(x) + \tilde{\varphi}(x)
\end{equation}

where the functions $z_{\alpha}(x)$ are defined in (1.22), (1.23), (1.24) (1.25), (1.26) respectively, while the constants $a_{\alpha}$ are chosen so that

\begin{equation}
\int u^{p-1} z_{\alpha} \tilde{\varphi} = 0, \quad \alpha = 0, \ldots, 3n - 1.
\end{equation}

Observe that $L(\tilde{\varphi}) = 0$. Our aim is to show that, if $\tilde{\varphi}$ is bounded, then $\tilde{\varphi} \equiv 0$.

For this purpose, recall that

\[ u(x) = U(x) - \sum_{j=1}^{k} U_j(x) + \tilde{\varphi}(x), \quad \text{with} \quad U(x) = \left( \frac{2}{1 + |x|^2} \right)^{\frac{n+2}{2}} \]

and

\[ U_j(x) = \mu_k^{\frac{n+2}{2}} U(\mu_k^{-1}(x - \xi_j)). \]
We introduce the following functions

\[ Z_0(x) = \frac{n-2}{2} U(x) + \nabla U(x) \cdot x, \]

and

\[ Z_\alpha(x) = \frac{\partial}{\partial x_\alpha} U(x), \quad \text{for} \quad \alpha = 1, \ldots, n. \]

Moreover, for any \( l = 1, \ldots, k \), we define

\[ Z_{l0}(x) = \frac{n-2}{2} U_l(x) + \nabla U_l(x) \cdot (x - \xi_l). \]

Observe that, as a consequence of (1.22) and (1.23), we have that

\[ z_0(x) = Z_0(x) - \sum_{l=1}^k \left[ Z_{l0}(x) + \sqrt{1-\mu^2} \cos \theta_l \frac{\partial}{\partial x_1} U_l(x) \\
+ \sqrt{1-\mu^2} \sin \theta_l \frac{\partial}{\partial x_2} U_l(x) \right] + \pi_0(x), \]

where \( \pi_0 \) is defined in (2.16). Define, for \( l = 1, \ldots, k \),

\[ Z_{l1}(x) = \sqrt{1-\mu^2} \left[ \cos \theta_l \frac{\partial}{\partial x_1} U_l(x) + \sin \theta_l \frac{\partial}{\partial x_2} U_l(x) \right] \]

\[ Z_{l2}(x) = \sqrt{1-\mu^2} \left[ -\sin \theta_l \frac{\partial}{\partial x_1} U_l(x) + \cos \theta_l \frac{\partial}{\partial x_2} U_l(x) \right] \]

where \( \theta_l = \frac{\pi}{k} (l-1) \). Furthermore, for any \( l = 1, \ldots, k \),

\[ Z_{l\alpha}(x) = \frac{\partial}{\partial x_\alpha} U_l(x), \quad \text{for} \quad \alpha = 3, \ldots, n. \]

Thus, we can write

\[ z_0(x) = Z_0(x) - \sum_{l=1}^k \left[ Z_{l0}(x) + Z_{l1}(x) \right] + \pi_0(x), \]

\[ z_1(x) = Z_1(x) - \sum_{l=1}^k \frac{\partial}{\partial x_1} U_l(x) + \pi_1(x) \]

\[ = Z_1(x) - \sum_{l=1}^k \frac{[\cos \theta_l Z_{l1}(x) - \sin \theta_l Z_{l2}(x)]}{\sqrt{1-\mu^2}} + \pi_1(x) \]

\[ z_2(x) = Z_2(x) - \sum_{l=1}^k \frac{\partial}{\partial x_2} U_l(x) + \pi_2(x) \]

\[ = Z_2(x) - \sum_{l=1}^k \frac{[\sin \theta_l Z_{l1}(x) + \cos \theta_l Z_{l2}(x)]}{\sqrt{1-\mu^2}} + \pi_2(x) \]
and, for $\alpha = 3, \ldots, n$,

$$z_\alpha(x) = Z_\alpha(x) - \sum_{l=1}^{k} Z_{\alpha,l} + \pi_\alpha(x)$$

Furthermore

$$z_{n+1}(x) = \sum_{l=1}^{k} Z_2(x) + x_2\pi_1(x) - x_1\pi_2(x)$$

$$z_{n+2}(x) = \sum_{l=1}^{k} \sqrt{1 - \mu^2} \cos \theta_l Z_0(x) - \sum_{l=1}^{k} \sqrt{1 - \mu^2} \cos \theta_l Z_1(x) - 2x_1\pi_0(x) + |x|^2\pi_1(x)$$

$$z_{n+3}(x) = \sum_{l=1}^{k} \sqrt{1 - \mu^2} \sin \theta_l Z_0(x) - \sum_{l=1}^{k} \sqrt{1 - \mu^2} \sin \theta_l Z_1(x) - 2x_2\pi_0(x) + |x|^2\pi_2(x)$$

and, for $\alpha = 3, \ldots, n$,

$$z_{n+\alpha+1}(x) = \sqrt{1 - \mu^2} \sum_{l=1}^{k} \cos \theta_l Z_{\alpha,l}(x) + x_1\pi_\alpha(x)$$

$$z_{2n+\alpha-1}(x) = \sqrt{1 - \mu^2} \sum_{l=1}^{k} \sin \theta_l Z_{\alpha,l}(x) + x_2\pi_\alpha(x)$$

Let

$$Z_{\alpha 0}(x) = Z_\alpha(x) + \pi_\alpha(x), \quad \alpha = 0, \ldots, n,$$

and introduce the $(k + 1)$-dimensional vector functions

$$\Pi_\alpha(x) = \begin{bmatrix} Z_{\alpha,0}(x) \\ Z_{\alpha,1}(x) \\ Z_{\alpha,2}(x) \\ \vdots \\ Z_{\alpha,k}(x) \end{bmatrix} \quad \text{for} \quad \alpha = 0, 1, \ldots, n.$$

For a given real vector $\vec{c} = \begin{bmatrix} c_0 \\ c_1 \\ c_2 \\ \vdots \\ c_k \end{bmatrix} \in \mathbb{R}^{k+1}$, we write

$$\vec{c} \cdot \Pi_\alpha(x) = \sum_{l=0}^{k} c_l Z_{\alpha,l}(x).$$
With this in mind, we write our function $\tilde{\varphi}$ as
\begin{equation}
\tilde{\varphi}(x) = \sum_{\alpha=0}^{n} c_\alpha \cdot \Pi_\alpha(x) + \varphi^\perp(x)
\end{equation}
where $c_\alpha = \begin{bmatrix} c_{\alpha0} \\ c_{\alpha1} \\ \vdots \\ c_{\alpha k} \end{bmatrix}$, $\alpha = 0, 1, \ldots, n$, are $(n+1)$ vectors in $\mathbb{R}^{k+1}$ defined so that
\begin{equation}
\int U_l^{p-1}(x)Z_\alpha(x)\varphi^\perp(x) \, dx = 0, \quad \text{for all } l = 0, 1, \ldots, k, \quad \alpha = 0, \ldots, n.
\end{equation}
Observe that
\begin{equation}
c_\alpha = 0 \quad \text{for all } \alpha \quad \text{and} \quad \varphi^\perp \equiv 0 \implies \tilde{\varphi} \equiv 0.
\end{equation}
Hence, our purpose is to show that all vector $c_\alpha$ are zero vectors and that $\varphi^\perp \equiv 0$.

This will be consequence of the following three facts.

**Fact 1.** The orthogonality conditions (3.2) take the form
\begin{equation}
\sum_{\alpha=0}^{n} c_\alpha \cdot \int \Pi_\alpha u^p z_\beta^{\perp} = -\int \varphi^\perp u^p z_\beta^{\perp}
\end{equation}
for $\beta = 0, \ldots, 3n-1$. Equation (3.21) is a system of $(n+2)$ linear equations in the $(n+1) \times (k+1)$ variables $c_\alpha$.

Let us introduce the following three vectors in $\mathbb{R}^k$
\begin{equation}
\mathbf{1}_k = \begin{bmatrix} 1 \\ 1 \\ \vdots \\ 1 \end{bmatrix}, \quad \cos = \begin{bmatrix} 1 \\ \cos \theta_2 \\ \vdots \\ \cos \theta_{k-1} \end{bmatrix}, \quad \sin = \begin{bmatrix} 0 \\ \sin \theta_2 \\ \vdots \\ \sin \theta_{k-1} \end{bmatrix}.
\end{equation}
Let us write
\begin{equation}
c_\alpha = \begin{bmatrix} c_{\alpha0} \\ c_\alpha \end{bmatrix}, \quad \text{with } c_{\alpha0} \in \mathbb{R}, \ c_\alpha \in \mathbb{R}^k, \ \alpha = 0, 1, \ldots, n,
\end{equation}
and
\begin{equation}
\tilde{c} = \begin{bmatrix} \tilde{c}_0 \\ \vdots \\ \tilde{c}_n \end{bmatrix} \in \mathbb{R}^{n(k+1)}, \quad \hat{c} = \begin{bmatrix} c_{0,0} \\ \vdots \\ c_{n,0} \end{bmatrix} \in \mathbb{R}^{n+1}
\end{equation}
We have the validity of the following

**Proposition 3.1.** The system (3.21) reduces to the following $3n$ linear conditions of the vectors $c_\alpha$:
\begin{equation}
0 \cdot \mathbf{1}_k + c_1 \cdot \mathbf{0} = t_0 + \Theta^1_k \mathcal{L}_0(\tilde{c}) + \Theta^2_k \mathcal{L}_0(\hat{c}),
\end{equation}
\begin{equation}
c_1 \cdot \mathbf{1}_k + c_2 \cdot \mathbf{0} = t_1 + \Theta^1_k \mathcal{L}_1(\tilde{c}) + \Theta^2_k \mathcal{L}_1(\hat{c}),
\end{equation}
\[(3.25)\]
\[
c_1 \begin{bmatrix} 0 \\ -\sin \end{bmatrix} + c_2 \begin{bmatrix} 1 \\ -\cos \end{bmatrix} = t_2 + \Theta_1^k \mathcal{L}_2(\hat{c}) + \Theta_2^k \hat{\mathcal{L}}_2(\hat{c}),
\]

for \(\alpha = 3, \ldots, n\)

\[(3.26)\]
\[
c_\alpha \begin{bmatrix} 1 \\ -1_k \end{bmatrix} = t_{\alpha + 1} + \Theta_1^k \mathcal{L}_{\alpha + 1}(\hat{c}) + \Theta_2^k \hat{\mathcal{L}}_{\alpha + 1}(\hat{c}),
\]

\[(3.27)\]
\[
c_2 \begin{bmatrix} 0 \\ 1_k \end{bmatrix} = t_{n + 1} + \Theta_1^k \mathcal{L}_{n + 1}(\hat{c}) + \Theta_2^k \hat{\mathcal{L}}_{n + 1}(\hat{c}),
\]

\[(3.28)\]
\[
c_0 \begin{bmatrix} 0 \\ \cos \end{bmatrix} - c_1 \begin{bmatrix} 0 \\ \cos \end{bmatrix} = t_{n + 2} + \Theta_1^k \mathcal{L}_{n + 2}(\hat{c}) + \Theta_2^k \hat{\mathcal{L}}_{n + 2}(\hat{c}),
\]

\[(3.29)\]
\[
c_0 \begin{bmatrix} 0 \\ \sin \end{bmatrix} - c_1 \begin{bmatrix} 0 \\ \sin \end{bmatrix} = t_{n + 3} + \Theta_1^k \mathcal{L}_{n + 3}(\hat{c}) + \Theta_2^k \hat{\mathcal{L}}_{n + 3}(\hat{c}),
\]

for \(\alpha = 3, \ldots, n\),

\[(3.30)\]
\[
c_\alpha \begin{bmatrix} 0 \\ \cos \end{bmatrix} = t_{n + \alpha + 1} + \Theta_1^k \mathcal{L}_{n + \alpha + 1}(\hat{c}) + \Theta_2^k \hat{\mathcal{L}}_{n + \alpha + 1}(\hat{c}),
\]

\[(3.31)\]
\[
c_\alpha \begin{bmatrix} 0 \\ \sin \end{bmatrix} = t_{2n + \alpha - 1} + \Theta_1^k \mathcal{L}_{2n + \alpha - 1}(\hat{c}) + \Theta_2^k \hat{\mathcal{L}}_{2n + \alpha - 1}(\hat{c}),
\]

In the above expansions, \(\begin{bmatrix} t_0 \\ t_1 \\ \vdots \\ t_n \end{bmatrix}\) is a fixed vector with

\[
\| \begin{bmatrix} t_0 \\ t_1 \\ \vdots \\ t_n \end{bmatrix} \| \leq C \| \varphi^1 \|_*,
\]

and \(\mathcal{L}_j : \mathbb{R}^{k(n + 1)} \to \mathbb{R}^{3n}, \hat{\mathcal{L}}_j : \mathbb{R}^n \to \mathbb{R}^{3n}\) are linear functions, whose coefficients are constants uniformly bounded as \(k \to \infty\). The number \(q\), with \(\frac{n}{2} < q < n\), is the one already fixed in (2.3). Furthermore, \(\Theta_1^k\) and \(\Theta_2^k\) denote quantities which can be described respectively as

\[
\Theta_1^k = k^{-\frac{q}{2}} O(1), \quad \Theta_1^k = (k \log k)^{-1} O(1), \quad \text{if} \quad n = 3,
\]

and

\[
\Theta_1^k = k^{1-\frac{q}{2}} O(1), \quad \Theta_1^k = (\log k)^{-1} O(1), \quad \text{if} \quad n = 3,
\]

where \(O(1)\) stands for a quantity which is uniformly bounded as \(k \to \infty\).

We shall prove (3.23)–(3.31) in Section 8.
Fact 2. Since $L(\tilde{\varphi}) = 0$, we have that
\begin{equation}
\sum_{a=0}^{n} c_{a} \cdot L(\Pi_{a}(x)) = \sum_{a=0}^{n} \sum_{l=0}^{k} c_{al} L(Z_{a,l}) = -L(\varphi^{\perp})
\end{equation}
Let $\varphi^{\perp} = \varphi^{\perp}_{0} + \sum_{l=1}^{k} \varphi^{\perp}_{l}$ where
\begin{equation}
-L(\varphi^{\perp}_{0}) = \sum_{a=0}^{n} c_{a0} L(Z_{a,0})
\end{equation}
and for any $l = 1, \ldots, k$
\begin{equation}
-L(\varphi^{\perp}_{l}) = \sum_{a=0}^{n} c_{al} L(Z_{a,l}).
\end{equation}
Furthermore, let
\begin{equation}
\tilde{\varphi}^{\perp}_{l}(y) = \mu^{2} \varphi^{\perp}_{l}(\mu y + \xi l),
\end{equation}
and define
\begin{equation}
||\varphi^{\perp}||_{r} = ||\varphi^{\perp}||_{n-2} + \sum_{l=1}^{k} ||\tilde{\varphi}^{\perp}_{l}||_{n-2}
\end{equation}
where the $|| \cdot ||_{n-2}$ is defined in (2.12). A first consequence of (3.32) is that there exists a positive constant $C$ such that
\begin{equation}
||\varphi^{\perp}||_{r} \leq C \mu^{1/2} \sum_{a=0}^{n} ||c_{a}||
\end{equation}
for all $k$ large. We postpone the proof of (3.34) to Section 9.

Fact 3. Let us now multiply (3.32) against $Z_{\beta l}$, for $\beta = 0, \ldots, n$ and $l = 0, 1, \ldots, k$.

After integrating in $\mathbb{R}^{n}$ we get a linear system of $(n+1) \times (k+1)$ equations in the $(n+1) \times (k+1)$ constants $e_{a,j}$ of the form
\begin{equation}
M \begin{bmatrix} c_{0} \\ c_{1} \\ \vdots \\ c_{n} \end{bmatrix} = - \begin{bmatrix} r_{0} \\ r_{1} \\ \vdots \\ r_{n} \end{bmatrix}, \quad \text{with} \quad r_{a} = \begin{bmatrix} \int_{\mathbb{R}^{n}} L(\varphi^{\perp}) Z_{a,0} \\ \int_{\mathbb{R}^{n}} L(\varphi^{\perp}) Z_{a,1} \\ \vdots \\ \int_{\mathbb{R}^{n}} L(\varphi^{\perp}) Z_{a,k} \end{bmatrix}
\end{equation}
Observe first that relation (3.9) together with the fact that $L(z_{a}) = 0$ for all $a = 0, \ldots, n$, allow us to say that the vectors $r_{a}$ have the form
\begin{equation}
\text{row}_{1}(r_{0}) = \sum_{l=2}^{k+1} \left[ \text{row}_{1}(r_{0}) + \text{row}_{1}(r_{1}) \right]
\end{equation}
\begin{equation}
\text{row}_{1}(r_{1}) = \frac{1}{\sqrt{1 - \mu^{2}}} \sum_{l=2}^{k+1} \left[ \cos \theta_{l} \text{row}_{1}(r_{1}) - \sin \theta_{l} \text{row}_{1}(r_{2}) \right],
\end{equation}
\[ \text{row}_1(\mathbf{r}_2) = \frac{1}{\sqrt{1 - \mu^2}} \sum_{l=2}^{k+1} [\sin \theta_l \text{row}_l(\mathbf{r}_1) + \cos \theta_l \text{row}_l(\mathbf{r}_2)] \]

\[ \text{row}_1(\mathbf{r}_\alpha) = \sum_{l=2}^{k+1} \text{row}_l(\mathbf{r}_\alpha) \quad \text{for all} \quad \alpha = 3, \ldots, n. \]

Here with \text{row}_l we denote the \( l \)-th row.

The matrix \( M \) in (3.35) is a square matrix of dimension \([ (n+1) \times (k+1) ]^2 \). The entries of \( M \) are numbers of the form

\[ \int_{\mathbb{R}^n} L(Z_{\alpha l})Z_{\beta j} \, dy \]

for \( \alpha, \beta = 0, \ldots, n \) and \( l, j = 0, 1, \ldots, k \).

A first observation is that, if \( \alpha \) is any of the indices \( \{ 0, 1, 2 \} \), and \( \beta \) is any of the index in \( \{ 3, \ldots, n \} \), then by symmetry the above integrals are zero, namely

\[ \int_{\mathbb{R}^n} L(Z_{\alpha l})Z_{\beta j} \, dy = 0 \quad \text{for any} \quad l, j = 0, 1, \ldots, k. \]

This fact implies that the matrix \( M \) has the form

\[ M = \begin{bmatrix} M_1 & 0 \\ 0 & M_2 \end{bmatrix} \]

where \( M_1 \) is a square matrix of dimension \((3 \times (k+1))^2 \) and \( M_2 \) is a square matrix of dimension \([ (n-2) \times (k+1) ]^2 \).

Since

\[ \int_{\mathbb{R}^n} L(Z_{\alpha l})Z_{\beta j} \, dy = \int_{\mathbb{R}^n} L(Z_{\beta j})Z_{\alpha l} \, dy \]

for \( \alpha, \beta = 0, \ldots, n \) and \( l, j = 0, 1, \ldots, k \), we can write

\[ M_1 = \begin{bmatrix} \tilde{A} & \tilde{B} & \tilde{C} \\ \tilde{B}^T & \tilde{F} & \tilde{D} \\ \tilde{C}^T & \tilde{D}^T & \tilde{G} \end{bmatrix} \]

where \( \tilde{A}, \tilde{B}, \tilde{C}, \tilde{D}, \tilde{F} \) and \( \tilde{G} \) are square matrices of dimension \((k+1)^2 \), with \( \tilde{A}, \tilde{F} \) and \( \tilde{G} \) symmetric. More precisely,

\[ \tilde{A} = \left( \int L(Z_{0i})Z_{0j} \right)_{i,j=0,1,\ldots,k}, \quad \tilde{F} = \left( \int L(Z_{1i})Z_{1j} \right)_{i,j=0,1,\ldots,k}, \]

\[ \tilde{G} = \left( \int L(Z_{2i})Z_{2j} \right)_{i,j=0,1,\ldots,k}, \quad \tilde{B} = \left( \int L(Z_{0i})Z_{1j} \right)_{i,j=0,1,\ldots,k}, \]

and

\[ \tilde{C} = \left( \int L(Z_{0i})Z_{2j} \right)_{i,j=0,1,\ldots,k}, \quad \tilde{D} = \left( \int L(Z_{1i})Z_{2j} \right)_{i,j=0,1,\ldots,k}. \]

Furthermore, again by symmetry, since

\[ \int L(Z_{\alpha l})Z_{\beta j} \, dx = 0, \quad \text{if} \quad \alpha \neq \beta, \quad \alpha, \beta = 3, \ldots, n \]
the matrix $M_2$ has the form

$$M_2 = \begin{bmatrix}
\bar{H}_3 & 0 & 0 & 0 \\
0 & \bar{H}_4 & 0 & 0 \\
0 & 0 & \bar{H}_{n-1} & 0 \\
0 & 0 & 0 & \bar{H}_n \\
\end{bmatrix}$$

where $\bar{H}_j$ are square matrices of dimension $(k+1)^2$, and each of them is symmetric. The matrices $\bar{H}_\alpha$ are defined by

$$\bar{H}_\alpha = \left( \int L(Z_{\alpha i})Z_{\alpha j} \right)_{i,j=0,1,...,k}, \quad \alpha = 3, \ldots, n.$$  

Thus, given the form of the matrix $M$ as described in (3.40), (3.41) and (3.45), system (3.35) is equivalent to

$$M_1 \begin{bmatrix} c_0 \\ c_1 \\ c_2 \end{bmatrix} = \begin{bmatrix} r_0 \\ r_1 \\ r_2 \end{bmatrix}, \quad \bar{H}_\alpha c_\alpha = r_\alpha \quad \text{for} \quad \alpha = 3, \ldots, n,$$

where the vectors $r_\alpha$ are defined in (3.47).

Observe that system (3.47) impose $(n+1) \times (k+1)$ linear conditions on the $(n+1) \times (k+1)$ constants $c_{\alpha j}$. We shall show that $3n$ equations in (3.47) are linearly dependent. Thus in reality system (3.47) reduce to only $(n+1) \times (k+1) - 3n$ linearly independent conditions on the $(n+1) \times (k+1)$ constants $c_{\alpha j}$. We shall also show that system (3.47) is solvable. Indeed we have the validity of the following

**Proposition 3.2.** There exist $k_0$ and $C$ such that, for all $k > k_0$ System (3.47) is solvable. Furthermore, the solution has the form

$$c_\alpha = v_\alpha + s_1 \begin{bmatrix} 1 \\ -1_k \end{bmatrix} + s_2 \begin{bmatrix} 0 \\ 0 \end{bmatrix} + s_3 \begin{bmatrix} -1_k \cos \frac{1}{\sqrt{1-\mu^2}} \sin \frac{1}{\sqrt{1-\mu^2}} 0 0 0 0 \end{bmatrix},$$

$$c_\alpha = v_\alpha + s_1 \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} + s_5 \begin{bmatrix} 0 \\ 0 \end{bmatrix} + s_6 \begin{bmatrix} \cos \sin 0 0 0 0 \end{bmatrix}, \quad \alpha = 3, \ldots, n$$

and

$$c_\alpha = v_\alpha + s_{a1} \begin{bmatrix} 1 \\ -1_k \end{bmatrix} + s_{a2} \begin{bmatrix} 0 \\ \cos \sin 0 0 0 0 \end{bmatrix}, \quad \alpha = 3, \ldots, n$$

for any $s_1, \ldots, s_6, s_{a1}, s_{a2}, s_{a3} \in \mathbb{R}$, where the vectors $v_\alpha$ are fixed vectors with $\|v_\alpha\| \leq C\|\varphi^1\|$, $\alpha = 0, 1, \ldots, n$. 
Conditions (3.23)–(3.31) guarantees that the solution \( c_\alpha \) to (3.47) is indeed unique. Furthermore, we shall show that there exists a positive constant \( C \) such that

\[
\sum_{\alpha=0}^{n} \| c_\alpha \| \leq C \| \varphi^\perp \|.
\]

Here \( \| \cdot \| \) denotes the euclidean norm in \( \mathbb{R}^k \).

Estimates (3.48) combined with (3.34) gives that

\[
c_\alpha = 0 \quad \forall \alpha = 0, \ldots, n.
\]

Replacing equation (3.49) into (3.34) we finally get (3.20), namely

\[
c_\alpha = 0 \quad \text{for all} \quad \alpha \quad \text{and} \quad \varphi^\perp \equiv 0.
\]

**Scheme of the paper**: In Section 4 we discuss and simplify system (3.47). In Section 5 we establish an invertibility theory for solving (3.47). Section 6 is devoted to prove Proposition 3.2. In Section 7 we prove Theorem 1.1. Section 8 is devoted to the proof of Proposition 3.1, while Section 9 is devoted to the proof of (3.34). Section 10 is devoted to the detailed proofs of several computations.

4. **A first simplification of the system (3.47)**

Let us consider system (3.47) and let us fix \( \alpha \in \{3, \ldots, n\} \). Recall that the function \( z_\alpha \) defined in (1.23) satisfies \( L(z_\alpha) = 0 \). Hence, by (3.9), (3.18) and (3.46) we have that

\[
\text{row}_1(\bar{H}_\alpha) = \sum_{l=2}^{k+1} \text{row}_l(\bar{H}_\alpha).
\]

This implies that

\[
\begin{bmatrix}
1 \\
-1_k
\end{bmatrix} \in \text{kernel}(\bar{H}_\alpha)
\]

and thus that the system \( \bar{H}_\alpha c_\alpha = r_\alpha \) is solvable only if \( r_\alpha \cdot \begin{bmatrix}
1 \\
-1_k
\end{bmatrix} = 0 \). On the other hand, this last solvability condition is satisfied as consequence of (3.39). Thus \( \bar{H}_\alpha c_\alpha = r_\alpha \) is solvable.

Arguing similarly, we get that

\[
\text{row}_1(M_1) = \sum_{l=2}^{k+1} \text{row}_l(M_1) + \sum_{l=k+3}^{2k+2} \text{row}_l(M_1),
\]

\[
\text{row}_{k+2}(M_1) = \frac{1}{\sqrt{1 - \mu^2}} \left[ \sum_{l=1}^{k} \cos \theta_l \text{row}_{k+2+l}(M_1) - \sum_{l=1}^{k} \sin \theta_l \text{row}_{2k+3+l}(M_1) \right],
\]

and

\[
\text{row}_{2k+3}(M_1) = \frac{1}{\sqrt{1 - \mu^2}} \left[ \sum_{l=1}^{k} \sin \theta_l \text{row}_{k+2+l}(M_1) + \sum_{l=1}^{k} \cos \theta_l \text{row}_{2k+3+l}(M_1) \right].
\]
This implies that the vectors

\[
\begin{bmatrix}
1 \\
-1_k \\
0 \\
-1_k \\
0 \\
0
\end{bmatrix},
\begin{bmatrix}
0 \\
-1 / \sqrt{1-\mu^2} \cos \\
1 \\
0 \\
1 / \sqrt{1-\mu^2} \sin \\
-1 / \sqrt{1-\mu^2} \cos
\end{bmatrix},
\begin{bmatrix}
0 \\
-1 / \sqrt{1-\mu^2} \sin \\
0 \\
1 / \sqrt{1-\mu^2} \cos
\end{bmatrix}
\]

and thus that the system

\[
M_1 \begin{bmatrix}
c_0 \\
c_1 \\
c_2
\end{bmatrix} = \begin{bmatrix}
r_0 \\
r_1 \\
r_2
\end{bmatrix}
\]

is solvable only if

\[
\begin{bmatrix}
r_0 \\
r_1 \\
r_2
\end{bmatrix} \cdot \begin{bmatrix}
w_0 \\
w_1 \\
w_2
\end{bmatrix} = 0
\]

for \(j = 0, 1, 2\). On the other hand, this last solvability condition is satisfied as consequence of (3.36), (3.37) and (3.38).

We thus conclude that system (3.47) is solvable and the solution has the form

\[
(4.1) \begin{bmatrix}
c_0 \\
c_1 \\
c_2
\end{bmatrix} = \begin{bmatrix}
0 \\
\bar{c}_0 \\
0 \\
\bar{c}_1 \\
0 \\
\bar{c}_\alpha
\end{bmatrix} + t \begin{bmatrix}
w_0 \\
w_1 \\
w_2
\end{bmatrix}
\]

for all \(t, s, r \in \mathbb{R}\)

and, if \(\alpha = 3, \ldots, n\)

\[
(4.2) c_\alpha = \begin{bmatrix}
0 \\
\bar{c}_\alpha \\
0 \\
\bar{c}_1 \\
0 \\
\bar{c}_\alpha
\end{bmatrix} + t \begin{bmatrix}
1 \\
-1_k
\end{bmatrix} \quad \text{for all} \quad t \in \mathbb{R}
\]

In (4.1)-(4.2), \(\bar{c}_\alpha\) for \(\alpha = 0, \ldots, n\), are \((n + 1)\) vectors in \(\mathbb{R}^k\), respectively given by

\[
(4.3) \bar{c}_\alpha = \begin{bmatrix}
c_{\alpha 1} \\
c_{\alpha 2} \\
\vdots \\
c_{\alpha k}
\end{bmatrix}
\]

These vectors correspond to solutions of the systems

\[
(4.4) N \begin{bmatrix}
\bar{c}_0 \\
\bar{c}_1 \\
\bar{c}_2
\end{bmatrix} = \begin{bmatrix}
\bar{r}_0 \\
\bar{r}_1 \\
\bar{r}_2
\end{bmatrix}, \quad H_\alpha [\bar{c}_\alpha] = \bar{r}_\alpha \quad \text{for} \quad \alpha = 3, \ldots, n.
\]

In the above formula \(\bar{r}_\alpha\) for \(\alpha = 0, \ldots, n\), are \((n + 1)\) vectors in \(\mathbb{R}^k\), respectively given by

\[
\bar{r}_\alpha = \begin{bmatrix}
\int_{\mathbb{R}^k} L(\varphi^+) Z_{\alpha, 1} \\
\int_{\mathbb{R}^k} L(\varphi^+) Z_{\alpha, 2} \\
\vdots \\
\int_{\mathbb{R}^k} L(\varphi^+) Z_{\alpha, k}
\end{bmatrix}.
\]
In (4.4) the matrix $N$ is defined by

\begin{equation}
N := \begin{bmatrix}
A & B & C \\
B^T & F & D \\
C^T & D^T & G
\end{bmatrix}
\end{equation}

where $A$, $B$, $C$, $D$, $F$, $G$ are $k \times k$ matrices whose entrances are given respectively by

\begin{equation}
A = \left( \int L(Z_0)Z_0 \right)_{i,j=1,...,k}, \\
B = \left( \int L(Z_1)Z_1 \right)_{i,j=1,...,k}, \\
C = \left( \int L(Z_2)Z_2 \right)_{i,j=1,...,k}, \\
D = \left( \int L(Z_3)Z_3 \right)_{i,j=1,...,k}
\end{equation}

and

\begin{equation}
G = \left( \int L(Z_0)Z_1 \right)_{i,j=1,...,k}, \\
F = \left( \int L(Z_1)Z_2 \right)_{i,j=1,...,k}, \\
H_{\alpha} = \left( \int L(Z_\alpha)Z_\alpha \right)_{i,j=1,...,k}, \quad \alpha = 3, \ldots, n.
\end{equation}

Furthermore, in (4.4) the matrix $H_\alpha$ is defined by

The rest of this section is devoted to compute explicitly the entrances of the matrices $A$, $B$, $C$, $D$, $F$, $G$, $H_\alpha$ and their eigenvalues.

We start with the following observation: all matrices $A$, $B$, $C$, $D$, $F$, $G$ and $H_\alpha$ in (4.4) are circulant matrices of dimension $k \times k$. For properties of circulant matrices, we refer to [19].

A circulant matrix $X$ of dimension $k \times k$ has the form

\[
X = \begin{bmatrix}
x_0 & x_1 & \ldots & x_{k-2} & x_{k-1} \\
x_{k-1} & x_0 & x_1 & \ldots & x_{k-2} \\
\vdots & \vdots & \ddots & \ddots & \ddots \\
\vdots & \vdots & & \ddots & \ddots \\
x_1 & \ldots & \ldots & \ldots & x_0
\end{bmatrix},
\]

or equivalently, if $x_{ij}, i, j = 1, \ldots, k$ are the entrances of the matrix $X$, then

\[x_{ij} = x_{1,|i-j|+1}.
\]

In particular, in order to know a circulant matrix it is enough to know the entrances of its first row.

The eigenvalues of a circulant matrix $X$ are given by the explicit formula

\begin{equation}
\eta_m = \sum_{l=0}^{k-1} x_l e^{2\pi i \frac{m}{k}}, \quad m = 0, \ldots, k - 1
\end{equation}
and with corresponding normalized eigenvectors defined by

$$E_m = k^{-rac{1}{2}} \begin{bmatrix}
1 \\
e^{\frac{2\pi}{k} i} \\
\vdots \\
e^{\frac{2\pi}{k} i(k-1)}
\end{bmatrix} m = 0, \ldots, k - 1.$$  

Observe that any circulant matrix $X$ can be diagonalized

$$X = P D_X P^T$$

where $D_X$ is the diagonal matrix

$$D_X = \text{diag}(\eta_0, \eta_1, \ldots, \eta_{k-1})$$

and $P$ is the $k \times k$ invertible matrix defined by

$$P = \begin{bmatrix} E_0 & E_1 & \ldots & E_{k-1} \end{bmatrix}.$$

The matrices $A, B, C, D, F, G$ and $H_\alpha$ are circulant as a consequence of the invariance under rotation of an angle $\frac{2\pi}{k}$ in the $(x_1, x_2)$-plane of the functions $Z_{\alpha j}$. This is trivial in the case of $Z_{0 l}$ and $Z_{\alpha j}$ for all $\alpha = 3, \ldots, n$. On the other hand, if we denote by $R_j$ the rotation in the $(x_1, x_2)$ plane of angle $\frac{2\pi}{k} (j - 1)$, then we get

$$Z_{1,j}(x) = \nabla U_j(x) \cdot \xi_j = \mu^{-\frac{2\pi}{k}} \nabla U(R_j(y - \xi_1)) \cdot R_j \xi_1$$

$$= \mu^{-\frac{2\pi}{k}} R_j^{-1} U(R_j(y - \xi_1)) \cdot \xi_1, \quad x = R_j y.$$  

Thus, for instance

$$(F)_{jj} = \int L(Z_{1j})Z_{1j} = \int L(Z_{1j})Z_{11} = (F)_{11}, \quad j = 1, \ldots, k$$

and, after a rotation of an angle of $\frac{2\pi}{k} |h - j| + 1$,

$$(F)_{hj} = \int L(Z_{1h})Z_{1j} = \int L(Z_{1h})Z_{1(j-h+1)} = (F)_{1(h-j+1)}$$

In a similar way one can show that

$$Z_{2,j}(x) = \mu^{-\frac{2\pi}{k}} R_j^{-1} U(R_j(y - \xi_1)) \cdot \xi_1^\perp, \quad x = R_j y.$$  

With this in mind, it is straightforward to show that also the matrices $B, C, D$ and $G$ are circulant.

A second observation we want to make is that

$A, B, F, G, H_\alpha$ are symmetric

while

$C, D$ are anti-symmetric.
The fact that \( A, F, G \) and \( H_\alpha \) are symmetric follows directly from their definition. On the other hand, we have
\[
Z_1(x) = \mu^{-\frac{n-2}{2}} R_{2j}^{-1} \nabla U \left( \frac{R_{2j}(y - \xi_{k-j+1})}{\mu} \right) \cdot \xi_{k-j+1}, \quad x = R_{2j}y
\]
thus
\[
B_{1,j} = \int L(Z_{0,1})Z_{1,j} = \int L(Z_{0,1})Z_{1,k-j+2} = B_{1,k-j+2}.
\]
Furthermore,
\[
Z_2(x) = \mu^{-\frac{n-2}{2}} R_{2j}^{-1} \nabla U \left( \frac{R_{2j}(y - \xi_{k-j+1})}{\mu} \right) \cdot (-\xi_{k-j+1})^\perp, \quad x = R_{2j}y
\]
and thus
\[
C_{1,j} = \int L(Z_{0,1})Z_{2,j} = -\int L(Z_{0,1})Z_{2,k-j+2} = -C_{1,k-j+2},
\]
and
\[
D_{1,j} = \int L(Z_{1,1})Z_{2,j} = -\int L(Z_{1,1})Z_{2,k-j+2} = -D_{1,k-j+2},
\]
for \( j \geq 2 \). Combining this property with the property of being circulant, we get that \( B \) is symmetric, while \( C \) and \( D \) are anti-symmetric.

Let us now introduce the following positive number
\[
(4.14) \quad \Xi = \rho \gamma \left( \frac{n-2}{2} \right) \left( -\int y_1 U^{p-1} Z_1(y) \, dy \right).
\]
Next we describe the entrances of the matrices \( A, F, G, B, C, D \) and \( H_\alpha \), together with their eigenvalues. We refer the reader to Section 10 for the detailed proof of the following expansions. With \( O(1) \) we denotes a quantity which is uniformly bounded, as \( k \to \infty \).

**The matrix** \( A \). The matrix \( A = (A_{ij})_{i,j=1,...,k} \) defined by
\[
A_{ij} = \int_{\mathbb{R^n}} L(Z_0)Z_{0j}
\]
is symmetric. We have
\[
(4.15) \quad A_{11} = k^{n-2} \mu^{n-1} O(1)
\]
and for any integer \( l > 1 \),
\[
(4.16) \quad A_{ll} = \Xi \left[ -\frac{(n-2)}{2} \mu^{n-2} + \mu^{n-1} k^{n-2} O(1) \right],
\]
where \( O(1) \) is bounded as \( k \to \infty \).
Eigenvalues for $A$: A direct application of (4.10) gives that the eigenvalues of the matrix $A$ are given by

$$a_m = -\frac{n-2}{2} \Xi \mu^{n-2} \left[ \sum_{l=1}^{k} \frac{\cos(m \theta_l)}{(1-\cos \theta_l)^{\frac{n-2}{2}}} \right] \left(1 + O\left(\frac{1}{k}\right)\right)$$

(4.17)

for $m = 0, 1, \ldots, k-1$, where

$$\bar{a}_m = -\frac{n-2}{2} \frac{\Xi \mu^{n-2}}{(\sqrt{2\pi})^{n-2}} \left[ \sum_{l=1}^{k} \frac{\cos(m \theta_l)}{(1-\cos \theta_l)^{\frac{n-2}{2}}} \right] \left(1 + O\left(\frac{1}{k}\right)\right)$$

(4.18)

where $g$ is the function defined in (1.28).

The matrix $F$. The matrix $F = (F_{ij})_{i,j=1,\ldots,k}$ defined by

$$F_{ij} = \int_{\mathbb{R}^n} L(Z_{1i})Z_{1j}$$

is symmetric. We have

$$F_{11} = \Xi \left[ \sum_{l=1}^{k} \frac{\cos \theta_l}{(1-\cos \theta_l)^{\frac{n-2}{2}}} \right] \mu^{\frac{n+2}{2}} + O(\mu^2)$$

(4.19)

and, for any $l > 1$

$$F_{1l} = \Xi \left[ \sum_{l>1} \frac{\cos \theta_l}{(1-\cos \theta_l)^{\frac{n-2}{2}}} \right] \mu^{n-2} + O(\mu^n)$$

(4.20)

where $O(1)$ is bounded as $k \to 0$.

Eigenvalues for $F$. For any $m = 0, \ldots, k-1$, the eigenvalues of $F$ are

$$f_m = \Xi \bar{f}_m \mu^{n-2}.$$  

(4.21)

where

$$\bar{f}_m = \left[ \sum_{l=1}^{k} \frac{\cos \theta_l}{(1-\cos \theta_l)^{\frac{n-2}{2}}} \right] \mu^{\frac{n+2}{2}} + \sum_{l>1} \frac{\cos \theta_l}{(1-\cos \theta_l)^{\frac{n-2}{2}}} \cos m \theta_l \left(1 + O\left(\frac{1}{k}\right)\right).$$

(4.22)

The matrix $G$. The matrix $G = (G_{ij})_{i,j=1,\ldots,k}$ defined by

$$G_{ij} = \int_{\mathbb{R}^n} L(Z_{2i})Z_{2j}$$

is symmetric. We have

$$G_{11} = \Xi \left[ \sum_{l=1}^{k} \frac{\cos \theta_l + \frac{n}{2}}{(1-\cos \theta_l)^{\frac{n-2}{2}}} \right] \mu^{\frac{n+2}{2}} + \mu^n O(1)$$

(4.23)
and, for \( l > 1 \),
\[
G_{1l} = -\Xi \mu^{n-2} \left[ \frac{n-2}{2} \cos \theta_l + \frac{n}{2} \right] \mu^{n-2} + O(\mu^2).
\]
Again \( O(1) \) is bounded as \( k \to \infty \).

**Eigenvalues for \( G \).** The eigenvalues of \( G \) are given by
\[
g_m = -\Xi \mu^{n-2} \left[ \frac{n-2}{2} \cos \theta_l + \frac{n}{2} \right] \mu^{n-2} + O(\mu^2)
\]
\[
= \Xi \bar{g}_m \mu^{n-2} \left( 1 + O\left( \frac{1}{k} \right) \right),
\]
for \( m = 0, \ldots, k - 1 \) where
\[
\bar{g}_m = \frac{k^n}{(\sqrt{2\pi})^n} (n-1) g\left( \frac{2\pi}{k m} \right)
\]
see (1.28) for the definition of \( g \).

**The matrix \( B \).** The matrix \( B = (B_{ij})_{i,j=1,...,k} \) defined by
\[
B_{ij} = \int_{\mathbb{R}^n} L(Z_0_i) Z_2_j
\]
is symmetric. We have
\[
B_{11} = \mu^{n-1} k^{n-2} O(1)
\]
and, for any \( l > 1 \),
\[
B_{1l} = \Xi \mu^{n-2} \left[ \frac{n-2}{2} \cos \theta_l + \frac{n}{2} \right] \mu^{n-2} + \mu^{n-1} k^{n-2} O(1).
\]

**Eigenvalues for \( B \).** For any \( m = 0, \ldots, k - 1 \)
\[
b_m = \Xi \mu^{n-2} \left[ \frac{n-2}{2} \cos \theta_l + \frac{n}{2} \right] \mu^{n-2} + \mu^{n-1} k^{n-2} O(1).
\]
\[
= \Xi \bar{b}_m \mu^{n-2} \left( 1 + O\left( \frac{1}{k} \right) \right)
\]
with
\[
\bar{b}_m = \frac{n-2}{2} \frac{k^{n-2}}{(\sqrt{2\pi})^{n-2}} g''\left( \frac{2\pi}{k m} \right)
\]
see (1.28) for the definition of \( g \).

**The matrix \( C \).** The matrix \( C = (C_{ij})_{i,j=1,...,k} \) defined by
\[
C_{ij} = \int_{\mathbb{R}^n} L(Z_0_i) Z_3_j
\]
is anti symmetric. We have
\[
C_{11} = k^{n-2} \mu^{n-1} O(1)
\]
and, for $l > 1$,

\[
C_{1l} = \Xi \left[ \frac{n-2}{2} \sin \theta_l \left( 1 - \cos \theta_l \right)^{\frac{3}{2}} \right] \mu^{n-2} + k^{n-2} \mu^{n-1} O(1).
\]

**Eigenvalues for $C$.** For any $m = 0, \ldots, k - 1$

\[
c_m = \Xi i \mu^{n-2} \frac{n - 2}{2} \left[ \sum_{l > 1} \sin \theta_l \sin m \theta_l \left( 1 - \cos \theta_l \right)^{\frac{3}{2}} \right] \left( 1 + O\left( \frac{1}{k} \right) \right)
\]

\[
= \Xi i \bar{c}_m \mu^{n-2} \left( 1 + O\left( \frac{1}{k} \right) \right)
\]

where

\[
\bar{c}_m = \frac{n - 2}{2} \frac{\sqrt{2} k^{n-1}}{(\sqrt{2} \pi)^{n-1}} g' \left( \frac{2 \pi}{k} m \right)
\]

see (1.28) for the definition of $g$.

**The matrix $D$.** The matrix $D = (D_{ij})_{i,j=1,...,k}$

\[
D_{ij} = \int_{\mathbb{R}^n} L(Z_1 i) Z_{2j}
\]

is anti symmetric. We have

\[
D_{11} = k^{n-1} \mu^{n-1} O(1)
\]

and, for $l > 1$,

\[
D_{1l} = -\Xi \left[ \frac{n-2}{2} \sin \theta_l \left( 1 - \cos \theta_l \right)^{\frac{3}{2}} \right] \mu^{n-3} + k^{n-1} \mu^n O(1).
\]

**Eigenvalues for $D$.** For any $m = 0, \ldots, k - 1$

\[
d_m = i \Xi \mu^{n-2} \frac{n - 2}{2} \left[ \sum_{l > 1} \sin \theta_l \sin m \theta_l \left( 1 - \cos \theta_l \right)^{\frac{3}{2}} \right] \left( 1 + O\left( \frac{1}{k} \right) \right)
\]

\[
= -i \Xi \bar{d}_m \mu^{n-2} \left( 1 + O\left( \frac{1}{k} \right) \right)
\]

with

\[
\bar{d}_m = \frac{n - 2}{2} \frac{\sqrt{2} k^{n-1}}{(\sqrt{2} \pi)^{n-1}} g' \left( \frac{2 \pi}{k} m \right)
\]

see (1.28) for the definition of $g$.

**The matrix $H_\alpha$, for $\alpha = 3, \ldots, n$.** Fix $\alpha = 3$. The other dimensions can be treated in the same way. The matrix $H_3 = (H_{3,ij})_{i,j=1,...,k}$ defined by

\[
H_{3,ij} = \int_{\mathbb{R}^n} L(Z_3 i) Z_{3j}
\]
is symmetric. We have

\[ H_{3,11} = \Xi \mu^{\frac{n-2}{2}} \left[ \sum_{l=1}^{k} \frac{-\cos \theta_l}{(1 - \cos \theta_l)^2} \right] + O(\mu^2) \]

and, for \( l > 1 \),

\[ H_{3,1l} = \Xi \left[ \frac{1}{(1 - \cos \theta_l)^2} \right] \mu^{n-2} + O(\mu^2) \]

**Eigenvalues for \( H_3 \).** For any \( m = 0, \ldots, k - 1 \)

\[ h_{3,m} = \Xi \bar{h}_{3,m} \mu^{n-2} \]

where

\[ \bar{h}_{3,m} = \left[ \sum_{l=1}^{k} \frac{-\cos \theta_l + \cos m \theta_l}{(1 - \cos \theta_l)^2} \right] \left( 1 + O(\frac{1}{k}) \right) \]

5. **Solving a linear system.**

This section is devoted to solve system (4.4), namely

\[
N \begin{bmatrix} \bar{c}_0 \\ \bar{c}_1 \\ \bar{c}_2 \end{bmatrix} = \begin{bmatrix} \bar{s}_0 \\ \bar{s}_1 \\ \bar{s}_2 \end{bmatrix}, \quad H_{\alpha} [\bar{c}_\alpha] = \bar{s}_\alpha \quad \text{for} \quad \alpha = 3, \ldots, n.
\]

for a given right hand side \( \begin{bmatrix} \bar{s}_0 \\ \bar{s}_1 \\ \bar{s}_2 \end{bmatrix} \in \mathbb{R}^3 \), and \( \bar{s}_\alpha \in \mathbb{R}^k \), where \( N \) is the matrix defined in (4.5) and \( H_{\alpha} \) are the matrices defined in (4.9).

Let

\[ \Upsilon = \left( \frac{\sqrt{2} \pi}{py^{\frac{n-2}{2}}} \right) \]

where \( \Xi \) is defined in (4.14). We have the validity of the following

**Proposition 5.1.** Part a.

There exist \( k_0 \) and \( C > 0 \) such that, for all \( k > k_0 \), System

\[ (5.2) \]

is solvable if

\[ (5.3) \]

Furthermore, the solutions of System (5.2) has the form

\[ (5.4) \]
for all $t_1, t_2, t_3 \in \mathbb{R}$, and with
\[
\begin{bmatrix}
\tilde{w}_0 \\
\tilde{w}_1 \\
\tilde{w}_2
\end{bmatrix}
\] a fixed vector such that
\[
\begin{bmatrix}
\tilde{w}_0 \\
\tilde{w}_1 \\
\tilde{w}_2
\end{bmatrix}
\leq C \frac{k^n \mu^{n-2}}{k^n \mu^{n-2}} \begin{bmatrix}
\tilde{s}_0 \\
\tilde{s}_1 \\
\tilde{s}_2
\end{bmatrix}.
\]  

(5.5)

**Part b.** Let $\alpha = 3, \ldots, n$. There exist $k_0$ and $C$ such that, for any $k > k_0$, system
\[
H_\alpha [\tilde{c}_\alpha] = \tilde{s}_\alpha
\]
is solvable only if
\[
\tilde{s}_\alpha \cdot \cos = \tilde{s}_\alpha \cdot \sin = 0.
\]  
Furthermore, the solutions of System (5.6) has the form
\[
\tilde{c}_\alpha = \tilde{w}_\alpha + t_1 \cos + t_2 \sin
\]
for all $t_1, t_2 \in \mathbb{R}$, and with \[
\begin{bmatrix}
\tilde{w}_\alpha \\
\tilde{c}_\alpha
\end{bmatrix}
\] a fixed vector such that
\[
\begin{bmatrix}
\tilde{w}_\alpha \\
\tilde{c}_\alpha
\end{bmatrix}
\leq C \frac{k^n \mu^{n-2}}{k^n \mu^{n-2}} \begin{bmatrix}
\tilde{s}_\alpha
\end{bmatrix}.
\]  

(5.6)

(5.8)

(5.9)

Proof. Part a.

Define
\[
\mathcal{P} = \begin{bmatrix}
P & 0 & 0 \\
0 & P & 0 \\
0 & 0 & P
\end{bmatrix}
\]
where $P$ is defined in (4.13), a simple algebra gives that
\[
N = \mathcal{P}D\mathcal{P}^T
\]
where
\[
D = \begin{bmatrix}
D_A & D_B & D_C \\
D_B & D_F & D_D \\
D_C & D_D & D_G
\end{bmatrix}.
\]
Here $D_X$ denotes the diagonal matrix of dimension $k \times k$ whose entrances are given by the eigenvalues of $X$. For instance
\[
D_A = \text{diag} \left(a_0, a_1, \ldots, a_{k-1}\right)
\]
where $a_j$ are the eigenvalues of the matrix $A$, defined in (4.17). Using the change of variables
\[
\begin{bmatrix}
\tilde{y}_0 \\
\tilde{y}_1 \\
\tilde{y}_2
\end{bmatrix} = \mathcal{P}\begin{bmatrix}
\tilde{c}_0 \\
\tilde{c}_1 \\
\tilde{c}_2
\end{bmatrix}; \quad \begin{bmatrix}
\tilde{s}_0 \\
\tilde{s}_1 \\
\tilde{s}_2
\end{bmatrix} = \mathcal{P}\begin{bmatrix}
\tilde{h}_0 \\
\tilde{h}_1 \\
\tilde{h}_2
\end{bmatrix}
\]

(5.10)
We have the following cases being \( \ell \).

Let, for any \( m \), the determinant of the above matrix.

Furthermore, observe that

\[
\|\bar{y}_\alpha\| = \|\bar{\alpha}_\alpha\|, \quad \text{and} \quad \|\bar{z}_\alpha\| = \|\bar{\delta}_\alpha\|, \quad \alpha = 0, 1, 2.
\]

Let us now introduce the matrix

\[
D = \begin{bmatrix}
D_0 & 0 & \ldots & 0 \\
0 & D_1 & 0 & \ldots \\
\vdots & \ddots & \ddots & \ddots \\
0 & \ldots & 0 & D_{k-1}
\end{bmatrix}
\]

where for any \( m = 0, \ldots, k-1 \), \( D_m \) is the \( 3 \times 3 \) matrix given by

\[
D_m = \begin{bmatrix}
a_m & b_m & c_m \\
b_m & f_m & d_m \\
c_m & -d_m & g_m
\end{bmatrix} = \Xi \mu^{n-2} \begin{bmatrix}
a_m & \bar{b}_m & i\bar{c}_m \\
\bar{b}_m & \bar{f}_m & i\bar{d}_m \\
\bar{c}_m & -i\bar{d}_m & \bar{g}_m
\end{bmatrix}
\]

where \( a_m, b_m, c_m, f_m, g_m, d_m \) are the eigenvalues of the matrices \( A, B, C, F, G \) and \( D \) respectively. In the above formula we have used the computation for the eigenvalues \( a_m, b_m, c_m, d_m, f_m \) and \( g_m \) that we obtained in (4.17), (4.29), (4.33), (4.37), (4.21) and (4.25).

An easy argument implies that system (5.11) can be re written in the form

\[
D_m \begin{bmatrix}
\bar{y}_{0,m+1} \\
\bar{y}_{1,m+1} \\
\bar{y}_{2,m+1}
\end{bmatrix} = \begin{bmatrix}
h_{0,m+1} \\
h_{1,m+1} \\
h_{2,m+1}
\end{bmatrix} \quad m = 0, 1, \ldots, k-1.
\]

Taking into account that \( \bar{a}_m = -\bar{b}_m \) and \( \bar{c}_m = -\bar{d}_m \), a direct algebraic manipulation of the system gives that (5.14) reduces to the simplified system

\[
\begin{bmatrix}
-\bar{b}_m & 0 & i\bar{c}_m \\
0 & \bar{f}_m + \bar{b}_m & 0 \\
-i\bar{c}_m & 0 & \bar{g}_m
\end{bmatrix} \begin{bmatrix}
\bar{y}_{0,m+1} - \bar{y}_{1,m+1} \\
\bar{y}_{1,m+1} \\
\bar{y}_{2,m+1}
\end{bmatrix} = \frac{1}{\Xi \mu^{n-2}} \begin{bmatrix}
h_{0,m+1} + h_{0,m+1} \\
h_{1,m+1} \\
h_{2,m+1}
\end{bmatrix}.
\]

Let, for any \( m = 0, \ldots, k-1 \),

\[
\ell_m := -\left( \bar{b}_m + \bar{f}_m \right) \left[ \bar{g}_m \bar{b}_m + \bar{c}_m^2 \right],
\]

being \( \ell_m \) the determinant of the above matrix.

We have the following cases

\[
\begin{bmatrix}
\bar{y}_{0,m+1} \\
\bar{y}_{1,m+1} \\
\bar{y}_{2,m+1}
\end{bmatrix} = \begin{bmatrix}
h_{0,m+1} \\
h_{1,m+1} \\
h_{2,m+1}
\end{bmatrix}
\]

\[
\begin{bmatrix}
\bar{y}_{0,m+1} \\
\bar{y}_{1,m+1} \\
\bar{y}_{2,m+1}
\end{bmatrix} = \begin{bmatrix}
h_{0,m+1} \\
h_{1,m+1} \\
h_{2,m+1}
\end{bmatrix}
\]
Case 1. If \( m = 0 \), we have that \( \bar{g}_0 = \bar{\ell}_0 = 0 \) and so \( \ell_0 = 0 \). Furthermore,
\[
\bar{b}_0 = \frac{n - 2}{2} \frac{k^{n-2}}{(\sqrt{2\pi})^{n-2}} g''(0) \left( 1 + O\left(\frac{1}{k}\right) \right)
\]
and
\[
\bar{f}_0 + \bar{b}_0 = -\frac{k^{n-2}}{(\sqrt{2\pi})^{n-2}} g''(0) \left( 1 + O\left(\frac{1}{k}\right) \right).
\]
We conclude that System (5.15) for \( m = 0 \) is solvable if
\[
h_{21} = 0
\]
and there exists a positive constant \( C \), independent of \( k \), such that the solution has the form
\[
\begin{bmatrix}
y_{0,1} \\
y_{1,1} \\
y_{2,1}
\end{bmatrix} = \begin{bmatrix}
\hat{y}_{0,1} \\
\hat{y}_{1,1} \\
\hat{y}_{2,1}
\end{bmatrix} + t \begin{bmatrix}
0 \\
0 \\
1
\end{bmatrix}
\]
for any \( t \in \mathbb{R} \) and for a fixed vector \( \begin{bmatrix}
\hat{y}_{0,1} \\
\hat{y}_{1,1} \\
\hat{y}_{2,1}
\end{bmatrix} \) with
\[
\left\| \begin{bmatrix}
\hat{y}_{0,1} \\
\hat{y}_{1,1} \\
\hat{y}_{2,1}
\end{bmatrix} \right\| \leq \frac{C}{\mu^{n-2} k^{n-2}} \left\| \begin{bmatrix}
h_{0,1} \\
h_{1,1} \\
h_{2,1}
\end{bmatrix} \right\|.
\]

Case 2. If \( m = 1 \), we have that \( \bar{f}_1 + \bar{b}_1 = 0 \). By symmetry, for \( m = k - 1 \) we also have \( \bar{f}_{k-1} + \bar{b}_{k-1} = 0 \). Furthermore
\[
\bar{b}_1 = \bar{b}_{k-1} = \frac{n - 2}{2} \frac{k^{n-2}}{(\sqrt{2\pi})^{n-2}} g''(0) \left( 1 + O\left(\frac{1}{k}\right) \right),
\]
\[
\bar{g}_1 = \bar{g}_{k-1} = -(n - 1) \frac{k^{n-2}}{(\sqrt{2\pi})^{n-2}} g''(0) \left( 1 + O\left(\frac{1}{k}\right) \right),
\]
and
\[
\bar{c}_1 = -\bar{c}_{k-1} = (n - 2) \frac{k^{n-2}}{(\sqrt{2\pi})^{n-2}} g''(0) \left( 1 + O\left(\frac{1}{k}\right) \right).
\]
We conclude that System (5.15) for \( m = 1 \) is solvable if
\[
h_{02} + h_{12} = 0
\]
and there exists a positive constant \( C \), independent of \( k \), such that the solution has the form
\[
\begin{bmatrix}
y_{0,2} \\
y_{1,2} \\
y_{2,2}
\end{bmatrix} = \begin{bmatrix}
\hat{y}_{0,2} \\
\hat{y}_{1,2} \\
\hat{y}_{2,2}
\end{bmatrix} + t \begin{bmatrix}
1 \\
-1 \\
0
\end{bmatrix}
\]
for any \( t \in \mathbb{R} \) and for a fixed vector \[
\begin{bmatrix}
\hat{y}_{0,2} \\
\hat{y}_{1,2} \\
\hat{y}_{2,2}
\end{bmatrix}
\] with
\[
\| \begin{bmatrix}
\hat{y}_{0,2} \\
\hat{y}_{1,2} \\
\hat{y}_{2,2}
\end{bmatrix} \| \leq \frac{C}{\mu^{n-2k-2}} \| \begin{bmatrix}
h_{0,2} \\
h_{1,2} \\
h_{2,2}
\end{bmatrix} \|.
\]

On the other hand, when \( m = k - 1 \) System (5.15) is solvable if
\[ h_{0,k} + h_{1,k} = 0 \]
and there exists a positive constant \( C \), independent of \( k \), such that the solution has the form
\[
\begin{bmatrix}
y_{0,k} \\
y_{1,k} \\
y_{2,k}
\end{bmatrix} = \begin{bmatrix}
\hat{y}_{0,k} \\
\hat{y}_{1,k} \\
\hat{y}_{2,k}
\end{bmatrix} + t \begin{bmatrix}
-1 \\
-1 \\
0
\end{bmatrix}
\]
for any \( t \in \mathbb{R} \) and for a fixed vector \[
\begin{bmatrix}
\hat{y}_{0,k} \\
\hat{y}_{1,k} \\
\hat{y}_{2,k}
\end{bmatrix}
\] with
\[
\| \begin{bmatrix}
\hat{y}_{0,k} \\
\hat{y}_{1,k} \\
\hat{y}_{2,k}
\end{bmatrix} \| \leq \frac{C}{\mu^{n-2k-2}} \| \begin{bmatrix}
h_{0,k} \\
h_{1,k} \\
h_{2,k}
\end{bmatrix} \|.
\]

Case 3. Let now \( m \) be \( \neq 0, 1, k - 1 \). In this case we have
\[
\bar{b}_m = \frac{n - 2}{2} \frac{k^{n-2}}{(\sqrt{2\pi})^{n-2}} g''(\frac{2\pi}{k} m) \left(1 + O\left(\frac{1}{k}\right)\right),
\]
\[
\bar{f}_m + \bar{b}_m = \frac{k^n}{(\sqrt{2\pi})^n} g''(\frac{2\pi}{k} m) \left(1 + O\left(\frac{1}{k}\right)\right),
\]
\[
\bar{g}_m = -(n - 1) \frac{k^n}{(\sqrt{2\pi})^n} g'(\frac{2\pi}{k} m) \left(1 + O\left(\frac{1}{k}\right)\right),
\]
and
\[
\bar{c}_m = \frac{n - 2}{2} \frac{\sqrt{2} k^{n-1}}{(\sqrt{2\pi})^{n-1}} g'(\frac{2\pi}{k} m) \left(1 + O\left(\frac{1}{k}\right)\right).
\]
In particular
\[
\ell_m = -\frac{n - 2}{2} \frac{k^{3n-2}}{(\sqrt{2\pi})^{3n-2}} g''(\frac{2\pi}{m}) \times
\left[ -(n - 1) g(\frac{2\pi}{m}) g''(\frac{2\pi}{k} m) + (n - 2) (g'(\frac{2\pi}{m})^2) \left(1 + O\left(\frac{1}{k}\right)\right) \right]
\]
Thus under condition (1.29), we have that
\[ \ell_m < 0 \quad \forall m = 2, \ldots, k - 2. \]
Hence, for all \( m \neq 0, 1, k - 1 \), System (5.15) is uniquely solvable and there exists a positive constant \( C \), independent of \( k \), such that the solution \( \hat{y} \) satisfies

\[
\left\| \begin{bmatrix} \hat{y}_{0,1} \\ \hat{y}_{1,1} \\ \hat{y}_{2,1} \end{bmatrix} \right\| \leq \frac{C}{\mu^{n-2}k^n} \left\| \begin{bmatrix} h_{0,1} \\ h_{1,1} \\ h_{2,1} \end{bmatrix} \right\|.
\]

Going back to the original variables, and applying a fixed point argument for contraction mappings we get the validity of Part a of Proposition 5.1.

**Part b.** Fix \( \alpha = 3, \ldots, n \). We have

\[
H_\alpha = PD_\alpha P^T
\]

where \( P \) is defined in (4.13), and

\[
D_\alpha = \text{diag}(h_{\alpha,0}, h_{\alpha,1}, \ldots, h_{\alpha,k-1})
\]

where \( h_{\alpha,j} \) are the eigenvalues of the matrix \( H_\alpha \), defined in (4.41). Using the change of variables \( \tilde{y}_\alpha = P^T c_\alpha \) and \( \tilde{s}_\alpha = P^T h_\alpha \), we have to solve \( D_\alpha y_\alpha = h_\alpha \).

Recall that, for any \( m = 0, \ldots, k - 1 \)

\[
h_{\alpha,m} = \Xi \tilde{h}_{\alpha,m} \mu^{n-2}
\]

where

\[
\tilde{h}_{\alpha,m} = \left[ \sum_{l=1}^{k} \frac{-\cos \theta_l + \cos m \theta_l}{(1 - \cos \theta_l)^2} \right] \left( 1 + O\left( \frac{1}{k} \right) \right).
\]

If \( m = 1 \) or \( m = k - 1 \), we have that \( \sum_{l=1}^{k} \frac{-\cos \theta_l + \cos m \theta_l}{(1 - \cos \theta_l)^2} = 0 \), so the system is solvable only if \( h_{\alpha,2} = h_{\alpha,k-1} \). On the other hand we have

\[
h_{\alpha,0} = \Xi \mu^{n-2} \frac{k^{n-2}}{(\sqrt{2}\pi)^{n-2}} \left( 1 + O\left( \frac{1}{k} \right) \right)
\]

and for \( m = 2, \ldots, k - 2 \)

\[
h_{\alpha,m} = \Xi \mu^{n-2} \frac{k^n}{(\sqrt{2}\pi)^n} g\left( \frac{2\pi}{k} m \right) \left( 1 + O\left( \frac{1}{k} \right) \right)
\]

Going back to the original variables, we get the validity of Part b, and this concludes the proof of Proposition 5.1. \( \square \)
6. Proof of Proposition 3.2

A key ingredient to prove Proposition 3.2 is the estimates on the right hand sides of systems (4.4). We have

**Proposition 6.1.** There exists a positive constant $C$ such that, for any $\alpha = 0, 1, \ldots, n$,

\[
\|\bar{r}_\alpha\| \leq C \mu^{\frac{n-2}{2}} \|\varphi^\perp\|_*,
\]

for any $k$ sufficiently large.

**Proof.** We prove (6.1), only for $\alpha = 0$.

Recall that

\[
\bar{r}_0 = \begin{bmatrix}
\int_{\mathbb{R}^n} L(\varphi^\perp)Z_{01} \\
\vdots \\
\int_{\mathbb{R}^n} L(\varphi^\perp)Z_{0k}
\end{bmatrix}.
\]

Then estimate (6.1) will follows from

\[
\left| \int_{\mathbb{R}^n} L(\varphi^\perp)Z_{0j} \right| \leq C \mu^{\frac{n-2}{2}} \|\varphi\|_*,
\]

for any $j = 1, \ldots, k$. To prove (6.2), we fix $j = 1$ and we write

\[
\int_{\mathbb{R}^n} L(\varphi^\perp)Z_{01} \, dx = \int_{\mathbb{R}^n} L(Z_{01})\varphi^\perp
\]

\[
= \int_{\mathbb{R}^n \cup B(\xi_1, \eta_1/\sqrt{n})} L(Z_{01})\varphi^\perp + \sum_{j=1}^k \int_{B(\xi_j, \eta_1/\sqrt{n})} L(Z_{01})\varphi^\perp
\]

where $\eta$ and $\sigma$ are small positive numbers, independent of $k$.

We start to estimate

\[
\int_{B(\xi_1, \eta_1/\sqrt{n})} L(Z_{01})\varphi^\perp
\]

As we have already observed very close to $\xi_1$, $U_1(x) = O(\mu^{\frac{n-2}{2}})$ and so in $B(\xi_1, \eta_1/\sqrt{n})$ the function $U_1$ dominates globally the other terms, provided $\eta$ is chosen small enough. Thus, after the change of variable $x = \xi_1 + \mu y$,

\[
\left| \int_{B(\xi_1, \eta_1/\sqrt{n})} L(Z_{01})\varphi^\perp \right| \leq C \int_{B(0, \eta_1/\sqrt{n})} f''(U) \Upsilon(y)|Z_{01}(y)|\mu^{\frac{n-2}{2}} |\varphi^\perp(\xi_1 + \mu y)| \, dy
\]

\[
\leq C\|\varphi^\perp\|_* \int_{B(0, \eta_1/\sqrt{n})} f''(U) \Upsilon(y)|Z_{01}(y)| \, dy
\]

where

\[
\Upsilon(y) = \mu^{\frac{n-2}{2}} U(\xi_1 + \mu y) + \sum_{l \neq 1} U(y + \mu^{-1}(\xi_1 - \xi_l))
\]

A direct consequence of (10.2) is then that

\[
\left| \int_{B(\xi_1, \eta_1/\sqrt{n})} L(Z_{01})\varphi^\perp \right| \leq C \mu^{\frac{n-2}{2}} \|\varphi^\perp\|_*.
Let now \( j \neq 1 \) and consider \( \int_{B(\xi_j, \frac{\eta}{\sqrt{1-\mu^2}})} L(Z_{01})\varphi^+ \). In this case, after the change of variables \( x = \xi_j + \mu y \), we get
\[
\left| \int_{B(\xi_j, \frac{\eta}{\sqrt{1-\mu^2}})} L(Z_{01})\varphi^+ \right| 
\leq C \int_{B(0, \frac{\eta}{\sqrt{1-\mu^2}})} U^{p-1} Z_1(y + \mu^{-1}(\xi_1 - \xi_j)) [\mu^{-\frac{n-2}{2}}\varphi^+ (\xi_j + \mu y)] 
\leq C ||\varphi^+||_\alpha \left( \int_{\mathbb{R}^n} U^{p-1} \frac{1}{(1 + |y|^{n-2})} \right) \frac{\mu^{n-2}}{(1 - \cos \theta_j)^{\frac{n-2}{2}}}
\]
where we used (10.5). Thus we estimate
\[
\left| \sum_{j \neq 1} \int_{B(\xi_j, \frac{\eta}{\sqrt{1-\mu^2}})} L(Z_{01})\varphi^+ \right| \leq C \mu^{\frac{n-2}{2}} ||\varphi^+||_\alpha.
\]
Finally, in the exterior region \( \mathbb{R}^n \setminus \cup B(\xi_j, \frac{\eta}{\sqrt{1-\mu^2}}) \) we can estimate
\[
\left| \int_{\mathbb{R}^n \setminus \cup B(\xi_j, \frac{\eta}{\sqrt{1-\mu^2}})} L(Z_{01})\varphi^+ \right| \leq C ||\varphi^+||_\alpha \int_{\mathbb{R}^n \setminus \cup B(\xi_j, \frac{\eta}{\sqrt{1-\mu^2}})} U^{p-1} Z_1(y) dy 
\leq C \mu^{\frac{n-2}{2}} ||\varphi^+||_\alpha.
\]
Thus we have proven (6.1) for \( \alpha = 0 \). The other cases can be treated similarly. \( \square \)

We have now the tools for the

**Proof of Proposition 3.2.** System (3.47) is solvable only if the following orthogonality conditions are satisfied:

\[
(6.3) \quad \begin{bmatrix}
\tilde{r}_0 \\
\tilde{r}_1 \\
\tilde{r}_2
\end{bmatrix} \cdot \begin{bmatrix}
-1_k \\
0 \\
0
\end{bmatrix} = \begin{bmatrix}
\tilde{r}_0 \\
\tilde{r}_1 \\
\tilde{r}_2
\end{bmatrix} \cdot \begin{bmatrix}
0 \\
0 \\
1
\end{bmatrix} = \begin{bmatrix}
\tilde{r}_0 \\
\tilde{r}_1 \\
\tilde{r}_2
\end{bmatrix} \cdot \begin{bmatrix}
\cos \\
\sin \\
1
\end{bmatrix} = 0,
\]

\[
(6.4) \quad \begin{bmatrix}
\tilde{r}_0 \\
\tilde{r}_1 \\
\tilde{r}_2
\end{bmatrix} \cdot \begin{bmatrix}
0 \\
\cos \\
-\cos
\end{bmatrix} = \begin{bmatrix}
\tilde{r}_0 \\
\tilde{r}_1 \\
\tilde{r}_2
\end{bmatrix} \cdot \begin{bmatrix}
\sin \\
0 \\
0
\end{bmatrix} = 0
\]

and

\[
(6.5) \quad \tilde{r}_\alpha \cdot \begin{bmatrix}
-1_k \\
\cos \\
\sin
\end{bmatrix} = \tilde{r}_\alpha \cdot \begin{bmatrix}
0 \\
0 \\
0
\end{bmatrix} = 0 \quad \alpha = 3, \ldots, n
\]
We recall that $\bar{r}_\alpha = \begin{bmatrix} \int_{\mathbb{R}^n} L(\varphi^\perp) Z_{\alpha,1} \\ \vdots \\ \int_{\mathbb{R}^n} L(\varphi^\perp) Z_{\alpha,k} \end{bmatrix}$. As we already mentioned at the beginning of Section 4, the orthogonality conditions (6.3) are satisfied as consequence of (3.36), (3.37) and (3.38). Similarly, the first orthogonality condition in (6.5) is satisfied as consequence of (3.39).

Let us recall from (3.32) that

$$L(\varphi^\perp) = - \sum_{\alpha=0}^{n} \sum_{l=0}^{k} c_{\alpha l} L(Z_{\alpha,l}).$$

Thus the function $x \rightarrow L(\varphi^\perp)(x)$ is invariant under rotation of angle $\frac{2\pi}{k}$ in the $(x_1, x_2)$-plane. Thus

$$0 = \sum_{l=1}^{k} \int L(\varphi^\perp) Z_{2l}(x) \, dx = \bar{r}_2 \cdot 1_k$$

and, for all $\alpha = 3, \ldots, n$,

$$\sum_{l=1}^{k} \cos \theta_l \int L(\varphi^\perp) Z_{\alpha l}(x) \, dx = \left( \int L(\varphi^\perp) Z_{\alpha 1}(x) \, dx \right) \left( \sum_{l=1}^{k} \cos \theta_l \right) = 0,$$

thus $\bar{r}_\alpha \cdot \cos = 0$, and similarly

$$0 = \sum_{l=1}^{k} \sin \theta_l \int L(\varphi^\perp) Z_{\alpha l}(x) \, dx = \bar{r}_\alpha \cdot \sin$$

namely the first orthogonality condition in (6.4) and the remaining orthogonality conditions in (6.5) are satisfied. Let us check that also the last two orthogonality conditions in (6.4) are verified.

Observe that $L(\varphi^\perp)(x) = |x|^{-2-n} L(\varphi^\perp)(\frac{x}{|x|^2})$. The remaining orthogonality conditions in (6.4) are consequence of the following

**Lemma 6.1.** Let $h$ be a function in $\mathbb{R}^n$ such that $h(y) = |y|^{-n-2} h(\frac{y}{|y|^2})$. Then

$$\mu \int_{\mathbb{R}^n} \frac{\partial}{\partial \mu} \left( U_{\mu}(x - \xi_l) \right) h(y) \, dy = \xi_l \cdot \int_{\mathbb{R}^n} \nabla U_{\mu}(x - \xi_l) h(y) \, dy$$

We postpone the proof of the above Lemma to the end of this Section.

Combining the result of Proposition 5.1 and the a-priori estimates in Proposition 6.1, a direct application of a fixed point theorem for contraction mapping readily gives the proof of Proposition 3.2.

We conclude this section with
Proof of Lemma 6.1.

Proof of (6.6). Assume \( l = 1 \). Define

\[
I(t) = \int_{\mathbb{R}^n} \omega_\mu(y - t \xi_1) h(y) \, dy \quad \text{where} \quad \omega_\mu(y - t \xi_1) = \mu \frac{n-2}{n} U\left(\frac{y - t \xi_1}{\mu}\right).
\]

We have

\[
\frac{d}{dt} I(t) = -\int_{\mathbb{R}^n} \nabla \omega_\mu(y - t \xi_1) : \xi_1 h(y) \, dy,
\]

and

\[
\left(\frac{d}{dt} I(t)\right)_{t=1} = -\int_{\mathbb{R}^n} \nabla \omega_\mu(y - \xi_1) : \xi_1 h(y) \, dy.
\]

On the other hand, using the change of variables \( y = \frac{x}{|x|^2} \), we have

\[
I(t) = \int_{\mathbb{R}^n} \omega_\mu\left(\frac{x}{|x|^2} - t \xi_1\right) h\left(\frac{x}{|x|^2}\right) |x|^{2-n} \, dx = \int_{\mathbb{R}^n} \omega_\mu\left(\frac{x}{|x|^2} - t \xi_1\right) h(x) |x|^{2-n} \, dx = \int_{\mathbb{R}^n} \omega_\mu(x - \bar{p}) h(x) \, dx
\]

where

\[
\bar{\mu}(t) = \frac{\mu}{\mu^2 + t^2 |\xi_1|^2}, \quad \bar{p}(t) = \frac{t}{\mu^2 + t^2 |\xi_1|^2} \xi_1.
\]

Observe that \( \bar{\mu}(1) = \mu, \bar{p}(1) = \xi_1 \),

\[
\frac{d}{dt} \bar{\mu}(t) = \frac{-2\mu}{\mu^2 + t^2 |\xi_1|^2}, \quad \frac{d}{dt} \bar{p}(t) = \left[\frac{1}{\mu^2 + t^2 |\xi_1|^2} - \frac{2t^2 |\xi_1|^2}{\mu^2 + t^2 |\xi_1|^2}\right] \xi_1.
\]

Hence

\[
\frac{d}{dt} I(t) = \frac{d}{dt} \bar{\mu}(t) \int_{\mathbb{R}^n} \frac{\partial}{\partial \bar{\mu}} \omega_\mu(x - \bar{p}) h(x) \, dx - \frac{d}{dt} \bar{p}(t) \int_{\mathbb{R}^n} \nabla \omega_\mu(x - \bar{p}) h(x) \, dx.
\]

This gives

\[
\left(\frac{d}{dt} I(t)\right)_{t=1} = -2 \mu |\xi_1|^2 \int_{\mathbb{R}^n} \frac{\partial}{\partial \mu} \omega_\mu(x - \xi_1) h(x) \, dx - (1 - 2 |\xi_1|^2) \int_{\mathbb{R}^n} \nabla \omega_\mu(x - \xi_1) : \xi_1 h(x) \, dx.
\]

From (6.7) and (6.8) we conclude with the validity of (6.6).

If \( l > 1 \) in (6.6), the same arguments hold true. The thus conclude with the proof of the Lemma.
7. **Final Argument.**

Let 
\[
\begin{bmatrix}
\bar{c}_0 \\
\bar{c}_1 \\
\bar{c}_2 \\
\vdots \\
\bar{c}_n
\end{bmatrix}
\]
be the solution to (3.47) predicted by Proposition 3.2, given by

\[
\begin{bmatrix}
c_0 \\
c_1 \\
c_2 \\
\vdots \\
c_n
\end{bmatrix} = \begin{bmatrix}
v_0 \\
v_1 \\
v_2
\end{bmatrix} + s_1 \begin{bmatrix} 1 \\ -1_k \\ 0 \end{bmatrix} + s_2 \begin{bmatrix} 0 \\ 0 \\ -\frac{1}{\sqrt{1-\mu^2}} \cos \end{bmatrix} + s_3 \begin{bmatrix} 0 \\ 0 \\ -\frac{1}{\sqrt{1-\mu^2}} \sin \end{bmatrix}
\]

\[+ s_4 \begin{bmatrix} 0 \\ 0 \\ -\cos \end{bmatrix} + s_5 \begin{bmatrix} 0 \\ 0 \\ -\sin \end{bmatrix} + s_6 \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}\]

and

\[c_\alpha = v_\alpha + s_{\alpha 1} \begin{bmatrix} 1 \\ -1_k \end{bmatrix} + s_{\alpha 2} \begin{bmatrix} 0 \\ \cos \end{bmatrix} + s_{\alpha 3} \begin{bmatrix} 0 \\ \sin \end{bmatrix}, \quad \alpha = 3, \ldots, n\]

A direct computation shows that there exists a unique

\[(s^*_1, \ldots, s^*_6, s^*_3, 1, s^*_3, 2, s^*_3, 3, \ldots, s^*_n, 1, s^*_n, 2, s^*_n, 3) \in \mathbb{R}^{2n}\]

for which the above solution satisfies all the \(2n\) conditions of Proposition 3.1. Furthermore, one can see that

\[
\| (s^*_1, \ldots, s^*_6, s^*_3, 1, s^*_3, 2, s^*_3, 3, \ldots, s^*_n, 1, s^*_n, 2, s^*_n, 3) \| \leq C \sqrt{\| \varphi^+ \|}.
\]

Hence, there exists a unique solution to systems (4.4), satisfying estimates in Proposition 3.1. Furthermore, one has

\[
\|
\begin{bmatrix}
\bar{c}_0 \\
\bar{c}_1 \\
\bar{c}_2 \\
\vdots \\
\bar{c}_n
\end{bmatrix}
\|
\leq C \| \varphi^+ \|.
\]
for some positive constant $C$ independent of $k$. On the other hand, from (3.34) we conclude that

\[
\|\varphi^\perp\|_* \leq C \mu^{\frac{1}{2}} \|egin{bmatrix} \bar{c}_0 \\ \bar{c}_1 \\ \bar{c}_2 \\ \ldots \\ \bar{c}_n \end{bmatrix} \|
\]

where again $C$ denotes a positive constant, independent of $k$. Thus we conclude that

\[
c_{\alpha,j} = 0, \quad \text{for all} \quad \alpha = 0, 1, \ldots, n, \quad j = 0, \ldots, k.
\]

Plugging this information into (7.1), we conclude that $\varphi^\perp \equiv 0$ and this proves Theorem 1.1.

8. Proof of Proposition 3.1

We will give the proof of Proposition 3.1 when dimension $n \geq 4$. The estimates for dimension $n = 3$ can be obtained with similar arguments.

The key ingredient to prove Proposition 3.1 are the following estimates

\[
\int |u|^{p-1} Z_{\alpha,l} Z_0 = \int U^{p-1} Z_0^2 \, dy + O(\mu^{\frac{n+2}{2}}) \quad \text{if} \quad \alpha = 0, l = 0
\]

\[
= O(\mu^{\frac{n+2}{2}}) \quad \text{otherwise}
\]

(8.1)

\[
\int |u|^{p-1} Z_{\alpha,l} Z_0 = \int U^{p-1} Z_1^2 \, dy + O(\mu^{\frac{n+2}{2}}) \quad \text{if} \quad \alpha = \beta, l = 0
\]

\[
= O(\mu^{\frac{n+2}{2}}) \quad \text{otherwise}
\]

(8.2)

\[
\int |u|^{p-1} Z_{\alpha,l} Z_{0,j} = \int U^{p-1} Z_0^2 \, dy + O(\mu^{\frac{n+2}{2}}) \quad \text{if} \quad \alpha = 0, l = j
\]

\[
= O(\mu^{\frac{n+2}{2}}) \quad \text{otherwise}
\]

(8.3)

\[
\int |u|^{p-1} Z_{\alpha,l} Z_{\beta,j} = \int U^{p-1} Z_1^2 \, dy + O(\mu^{\frac{n+2}{2}}) \quad \text{if} \quad \alpha = \beta, l = j
\]

\[
= O(\mu^{\frac{n+2}{2}}) \quad \text{otherwise}
\]

(8.4)

We prove (8.3).

Let $\eta > 0$ be a small number, fixed independently from $k$. We write

\[
\int |u|^{p-1} Z_{\alpha,l} Z_0 = \int_{B(\xi, \frac{\eta}{2})} |u|^{p-1} Z_{\alpha,l} Z_0 \, dy + \int_{\mathbb{R}^n \setminus B(\xi, \frac{\eta}{2})} |u|^{p-1} Z_{\alpha,l} Z_0 \, dy
\]

\[
= i_1 + i_2.
\]
We claim that the main term is $i_1$. Performing the change of variable $x = \xi_l + \mu y$, we get

$$i_1 = \int_{B(0, \frac{\mu}{|\xi|})} |u|^{p-1}(\xi_l + \mu y)Z_\alpha(y)Z_0(y)dy$$

$$= \left( \int U^{p-1} Z_0^2 + O(\mu k) \right) \quad \text{if} \quad \alpha = 0$$

$$= 0 \quad \text{if} \quad \alpha \neq 0.$$

On the other hand, to estimate $i_2$, we write

$$i_2 = \int_{\mathbb{R}^n \setminus (\bigcup_{j=1}^k B(\xi_j, \frac{\mu}{|\xi|}))} |u|^{p-1}Z_{0,j} + \sum_{j \neq l} \int_{B(\xi_j, \frac{\mu}{|\xi|})} u^{p-1}Z_{a_l}Z_{0,j} = i_{21} + i_{22}$$

The first integral can be estimated as follows

$$|i_{21}| \leq C \int_{\mathbb{R}^n \setminus (\bigcup_{j=1}^k B(\xi_j, \frac{\mu}{|\xi|}))} \frac{\mu^{\frac{m+2}{2}}}{|x - \xi_j|^m (1 + |x|)^{m+2}} dx \leq C \mu^{\frac{n-2}{2}}$$

while the second integral can be estimated by

$$|i_{22}| \leq C \sum_{j \neq l} \int_{B(\xi_j, \frac{\mu}{|\xi|})} \frac{\mu^{\frac{m+2}{2}}}{|x - \xi_j|^m} |u|^{p-1}Z_{0,j} dx \leq C \mu^{\frac{n-2}{2}}$$

where again $C$ denotes an arbitrary positive constant, independent of $k$. This concludes the proof of (8.3). The proofs of (8.1), (8.2) and (8.4) are similar, and left to the reader.

Now we claim that

$$\int U^{p-1} Z_0^2 = \int U^{p-1} Z_j^2 = 2^{\frac{n-4}{2}} n (n-2)^2 \frac{\Gamma(\frac{n}{2})^2}{\Gamma(n+2)}.$$  

The proof of identity (8.5) is postponed to the end of this section.

Let us now consider (3.21) with $\beta = 0$, that is

$$\sum_{\alpha=0}^n \sum_{l=0}^k c_{\alpha l} \int Z_{a_l}u^{p-1}z_0 = -\int \varphi^+ u^{p-1}z_0.$$  

First we write $t_0 = -\frac{1}{\int U^{p-1} Z_0^2} \int \varphi^+ u^{p-1}z_0$. A straightforward computation gives that $|t_0| \leq C\|\varphi^+\|_\infty$, for a certain constant $C$ independent from $k$. Second, we observe
that, direct consequence of (8.1) – (8.4), of (3.9) and Proposition 2.1 is that
\[
\sum_{\alpha=0}^{n} \sum_{l=0}^{k} c_{\alpha l} \int Z_{\alpha l} u^{p-1} z_{0} = c_{00} \int U^{p-1} Z_{0}^{2} \]
\[
- \sum_{l=1}^{k} \left[ c_{0l} \int U^{p-1} Z_{0}^{2} - c_{1l} \int U^{p-1} Z_{1}^{2} \right] \]
\[
+ O(k^{-\frac{q}{2}}) \mathcal{L}(\left[ \begin{array}{c} \bar{c}_{0} \\
\bar{c}_{1} \\
\vdots \\
\bar{c}_{n} \end{array} \right]) + O(k^{1-\frac{q}{2}}) \hat{\mathcal{L}}(\left[ \begin{array}{c} c_{00} \\
c_{10} \\
\cdots \\
c_{n0} \end{array} \right])
\]
where \( \mathcal{L} \) and \( \hat{\mathcal{L}} \) are linear function, whose coefficients are uniformly bounded in \( k \), as \( k \to \infty \). Here we have used the fact that there exists a positive constant \( C \) independent of \( k \) such that
\[
\int |u|^{p-1} Z_{\alpha l} \pi_{0}(x) dx \leq C \| \hat{\pi}_{0} \|_{n-2}
\]
and
\[
\int |u|^{p-1} Z_{\alpha l} \pi_{0}(x) dx \leq C \| \hat{\pi}_{01} \|_{n-2},
\]
for a certain positive number \( a_{n} \) that depends only on \( n \). Using the formula
\[
\int_{0}^{\infty} \left( \frac{r}{1+r^{2}} \right)^{q} \frac{1}{r^{1+a}} dr = \frac{\Gamma(\frac{q+a}{2}) \Gamma(\frac{n}{2})}{2 \Gamma(q)}
\]
we get
\[
(8.6) \quad \int \frac{1}{(1+|x|^{2})^{n+2}} dx = \frac{\frac{q}{2}(\frac{q+1}{2}) \Gamma(\frac{n}{2})^{2}}{2 \Gamma(n+2)},
\]
and
\[
(8.7) \quad \int \frac{|x|^{2}}{(1+|x|^{2})^{n+2}} dx = \frac{\left(\frac{q}{2}\right)^{2} \Gamma\left(\frac{n}{2}\right)^{2}}{2 \Gamma(n+2)}.
\]
Replacing (8.6), (8.7) in \( \int U^{p-1}Z_1^2 \) and \( \int U^{p-1}Z_0^2 \) we obtain
\[
\int U^{p-1}Z_1^2 - \int U^{p-1}Z_0^2 = (n-2)^2 a_n \frac{\pi(\frac{q}{2})^2}{2\pi(n+2)} \times \left[ \frac{1}{2} - \frac{1}{4} \left( \frac{n}{2} + 1 \right) + \frac{n}{4} - \frac{1}{4} \left( \frac{n}{2} + 1 \right) \right] = 0,
\]
thus (8.5) is proven.


We start with the following

**Proposition 9.1.** Let
\[
L_0(\phi) = \Delta \phi + pyU^{p-1}\phi + a(y)\phi \quad \text{in} \quad \mathbb{R}^n.
\]
Assume that \( a \in L^\frac{2n}{n+2}(\mathbb{R}^n) \). Assume furthermore that \( h \) is a function in \( \mathbb{R}^n \) with \( \|h\|_{L^\frac{2n}{n+2}(\mathbb{R}^n)} \) bounded and such that \( |y|^{-n-2}h(|y|^{-2}y) = \pm h(y) \). Then there exists a positive constant \( C \) such that any solution \( \phi \) to
\[
(9.1) \quad L_0(\phi) = h
\]
satisfies
\[
\|\phi\|_{L^{n-2}} \leq C\|h\|_{\infty}.
\]

**Proof.** Since \( a \in L^\frac{2n}{n+2}(\mathbb{R}^n) \) and \( U^{p-1} = O(1 + |y|^\delta) \), the operator \( L_0 \) is a compact perturbation of the Laplace operator in the space \( D^{1,2}(\mathbb{R}^n) \). Thus standard argument gives that
\[
\|\nabla \phi\|_{L^2(\mathbb{R}^n)} + \|\phi\|_{L^\frac{2n}{n+2}(\mathbb{R}^n)} \leq C\|h\|_{L^\frac{2n}{n+2}(\mathbb{R}^n)},
\]
where the last inequality is a direct consequence of Holder inequality. Being \( \phi \) a weak solution to (9.1), local elliptic estimates yields
\[
\|D^2 \phi\|_{L^2(B_1)} + \|D \phi\|_{L^2(B_1)} + \|\phi\|_{L^\infty(B_1)} \leq C\|h\|_{L^\frac{2n}{n+2}(\mathbb{R}^n)}.
\]
Consider now the Kelvin’s transform of \( \phi \), \( \hat{\phi}(y) = |y|^{2-n}\phi(|y|^{-2}y) \). This function satisfies
\[
(9.2) \quad \Delta \hat{\phi} + pU^{p-1}\hat{\phi} + |y|^{-4}a(|y|^{-2}y)\hat{\phi} = \hat{h} \quad \text{in} \quad \mathbb{R}^n \setminus \{0\}
\]
where \( \hat{h}(y) = |y|^{-n-2}h(|y|^{-2}y) \). We observe that
\[
\|\hat{h}\|_{L^2(b<2)} = \|b^{n+2-\frac{2n}{n+2}} h\|_{L^2(b>\frac{1}{2})} \leq C\|h\|_{L^\frac{2n}{n+2}(\mathbb{R}^n)},
\]
\[
\| |y|^{-4} a(|y|^{-2}y)|\|_{L^2(b<2)} = \|a\|_{L^\frac{2n}{n+2}(b>\frac{1}{2})}
\]
and
\[
\|\nabla \hat{\phi}\|_{L^2(\mathbb{R}^n)} + \|\hat{\phi}\|_{L^\frac{2n}{n+2}(\mathbb{R}^n)} \leq C\|h\|_{L^\frac{2n}{n+2}(\mathbb{R}^n)}.
\]
Applying then elliptic estimates to (9.2), we get
\[
\|D^2 \hat{\phi}\|_{L^2(B_1)} + \|D \hat{\phi}\|_{L^2(B_1)} + \|\hat{\phi}\|_{L^\infty(B_1)} \leq CC\|h\|_{L^\frac{2n}{n+2}(\mathbb{R}^n)}.
\]
This concludes the proof of the proposition since \( \|\hat{\phi}\|_{L^\infty(B_1)} = \|\phi\|_{L^\infty(\mathbb{R}^n \setminus B_1)} \).
We have now the tools to give the

**Proof of (3.34).** We start with the estimate on \( \varphi^\perp_0 \). We write

\[
\varphi^\perp_0 = \sum_{a=0}^n c_a \varphi^\perp_{a0}
\]

where

\[
L(\varphi^\perp_{a0}) = -L(Z_{a0}).
\]

We write the above equation in the following way

\[
\Delta(\varphi^\perp_{a0}) + p\gamma U^{p-1}(\varphi^\perp_{a0}) + p(|u|^{p-1} - U^{p-1}) \varphi^\perp_{a0} = -L(Z_{a0}).
\]

Observe that

\[
|y|^{-n+2} L(Z_{a0})(|y|^{-2} y) = -L(Z_{a0})(y),
\]

while

\[
|y|^{-n+2} L(Z_{a0})(|y|^{-2} y) = L(Z_{a0})(y) \quad \alpha = 1, \ldots, n.
\]

We claim that \( a_0 \in L^{\frac{n}{2}}(\mathbb{R}^n) \),

\[
(9.3) \quad \|a_0\|_{L^{\frac{n}{2}}(\mathbb{R}^n)} \leq C k^\frac{n}{2}, \quad \text{and} \quad \|L(Z_{a0})\|_{L^{\frac{n}{2}}(\mathbb{R}^n)} \leq C \mu^{\frac{n-1}{2}},
\]

where we take into account that \( \|h\|_{C^0} \leq C \|h\|_{L^{\frac{n}{2}}(\mathbb{R}^n)} \). Let \( \eta > 0 \) be a fixed positive number, independent of \( k \). We split the integral all over \( \mathbb{R}^n \) into a first integral over \( \mathbb{R}^n \setminus \bigcup_{j=1}^k B(\xi_j, \frac{\eta}{k}) \) and a second integral over \( \bigcup_{j=1}^k B(\xi_j, \frac{\eta}{k}) \). We write then

\[
\|a_0\|_{L^{\frac{2}{n}}(\mathbb{R}^n)}^2 = \int_{\mathbb{R}^n \setminus \bigcup_{j=1}^k B(\xi_j, \frac{\eta}{k})} |a_0(y)|^2 \, dy + \sum_{j=1}^k \int_{B(\xi_j, \frac{\eta}{k})} |a_0(y)|^2 \, dy
\]

(9.4)

\[= i_1 + i_2.\]

In the region \( \mathbb{R}^n \setminus \bigcup_{j=1}^k B(\xi_j, \frac{\eta}{k}) \), we have that

\[
|a_0(y)| = p \|u|^{p-1} - U^{p-1} \| \leq C U^{p-2} \sum_{j=1}^k \frac{\mu^{\frac{n-1}{2}}}{|y - \xi_j|^{n-2}},
\]

for some positive convenient constant \( C \). Thus

\[
\int_{\mathbb{R}^n \setminus \bigcup_{j=1}^k B(\xi_j, \frac{\eta}{k})} |a_0(y)|^2 \, dy \leq C \mu^{\frac{n-1}{2}} \sum_{j=1}^k \int_{\mathbb{R}^n \setminus \bigcup_{j=1}^k B(\xi_j, \frac{\eta}{k})} U^{(p-2)\frac{n}{2}} \frac{1}{|y - \xi_j|^{(n-2)\frac{n}{2}}} \, dy
\]

\[\leq C k \mu^{\frac{n-1}{2}} \frac{2}{n} \int_0^1 \frac{\mu^{\frac{n-1}{2}}}{t^{n-2}} \, dt \leq C k \mu^{\frac{n-1}{2}} \frac{2}{n} \frac{1}{(n-2)}.\]

We conclude that

\[
(9.5) \quad \int_{\mathbb{R}^n \setminus \bigcup_{j=1}^k B(\xi_j, \frac{\eta}{k})} |a_0(y)|^2 \, dy \leq C \mu^{\frac{n-1}{2}}
\]

Let us now fix \( j \in \{1, \ldots, k\} \) and consider \( y \in B(\xi_j, \frac{\eta}{k}) \). In this region we have

\[
|a_0(y)| \leq C U_j^{p-1},
\]
for some proper positive constant $C$. Recalling that $U_j(y) = \mu^{-\frac{n+2}{2}} U(y-\xi_j)$, we easily get
\[
\int_{B(\xi_j, \frac{n}{2})} |a_0(y)|^\frac{2}{3} \, dy \leq C
\]
and thus
\[
(9.6) \quad \sum_{j=1}^{k} \int_{B(\xi_j, \frac{n}{2})} |a_0(y)|^\frac{2}{3} \, dy \leq Ck.
\]
We conclude then that $a_0 \in L^{\frac{n}{p}}(\mathbb{R}^n)$, and from (9.4), (9.5) and (9.6) we conclude the first estimate in (9.3).

We prove the second estimate in (9.3) for $\alpha = 0$. Analogous computations give the estimate for $\alpha$, $0$. We write
\[
(9.7) \quad \int_{\mathbb{R}^n} |L(Z_{00})|^{\frac{2n}{n+2}} \, dy = \int_{\mathbb{R}^n} \bigg( \bigg( \int_{B(\xi_j, \frac{n}{2})} |Z_{00}(y)|^{\frac{2n}{n+2}} \bigg)^{\frac{n+2}{2n}} \bigg)^{\frac{n+2}{n}}
\]
Since $L(Z_{00}) = p(|u|^{p-1} - U_p^{p-1}) Z_{00} = a_0(y) Z_{00}$, a direct application of Holder inequality gives
\[
|i_1| \leq C \left( \int_{\mathbb{R}^n} |a_0(y)|^\frac{2}{3} \right)^{\frac{4}{n+2}} \left( \int_{\mathbb{R}^n} |Z_{00}(y)|^{\frac{2n}{n+2}} \right)^{\frac{n+2}{n}}
\]
Taking into account that $\left( \int_{\mathbb{R}^n} |Z_{00}(y)|^{\frac{2n}{n+2}} \right)^{\frac{n+2}{n}} \leq \left( \int_{\mathbb{R}^n} |Z_{00}(y)|^{\frac{2n}{n+2}} \right)^{\frac{n+2}{n}}$ and the validity of (9.5), we get
\[
(9.8) \quad |i_1| \leq C \mu^\frac{n+2}{n+2}.
\]
Let us fix now $j \in \{1, \ldots, k\}$. Using now that
\[
\left| \int_{B(\xi_j, \frac{n}{2})} |L(Z_{00})|^{\frac{2n}{n+2}} \right| \leq C \left( \int_{B(\xi_j, \frac{n}{2})} |a_0(y)|^\frac{2}{3} \right)^{\frac{4}{n+2}} \left( \int_{B(\xi_j, \frac{n}{2})} |Z_{00}(y)|^{\frac{2n}{n+2}} \right)^{\frac{n+2}{n}}
\]
together with the fact that
\[
\int_{B(\xi_j, \frac{n}{2})} |Z_{00}(y)|^{\frac{2n}{n+2}} \leq C k^{-n},
\]
we conclude that
\[
(9.9) \quad |i_2| \leq C \mu^\frac{n+2}{n+2} \frac{n-1}{2}.
\]
From (9.7), (9.8) and (9.9) we conclude that
\[
||L(Z_{00})||_{L^{\frac{2n}{n+2}}(\mathbb{R}^n)} \leq C \mu^\frac{n-1}{n+2}
\]
thus completing the proof of (9.3).
Let us now fix \( l \in \{1, \ldots, k\} \). Say \( l = 1 \). We write
\[
\varphi_{l}^{\perp} = \sum_{a=0}^{n} c_{a_1\varphi_{l_1}}
\]
where
\[
L(\varphi_{l_1}^{\perp}) = -L(Z_{l_1}).
\]
After the change of variable \( \tilde{\varphi}_{l_1}^{\perp}(y) = \mu^{\frac{n-2}{2}} \varphi_{l_1}^{\perp}(\mu y + \xi_1) \), the above equation gets rewritten as
\[
\Delta(\tilde{\varphi}_{l_1}^{\perp}) + p U^{n-1}(\tilde{\varphi}_{l_1}^{\perp}) + p[(\mu - \frac{2}{n} |u|(\mu y + \xi_1))^{n-1} - U^{n-1}] \tilde{\varphi}_{l_1}^{\perp} = h(y) := a_1(y)
\]
where
\[
h(y) = -\mu^{\frac{n-2}{2}} L(Z_{l_1})(\mu y + \xi_1).
\]
We claim that \( a_1 \in L^2_\mu(\mathbb{R}^n) \).
\[
(9.10) \quad ||a_1||_{L^2_\mu(\mathbb{R}^n)} \leq C \mu, \quad ||h||_{L^{\frac{2n}{n+2}}(\mathbb{R}^n)} \leq C \mu.
\]
We leave the details to the reader. The proof of (3.34) follows by (9.3), (9.10) and a direct application of Proposition 9.1.

10. Appendix

In this section we perform the computations of the entrances of the matrices \( A, F, G, B, C, D \) and \( H_\alpha, \alpha = 3, \ldots, n \). The results of this section are valid for any dimension \( n \geq 3 \). We start with proving some usefull expansions and a formula.

Some usefull expansions.

Let \( \eta > 0 \) and \( \sigma > 0 \) be small and fixed numbers, independent of \( k \). Assume that \( y \in B(0, \frac{\eta}{\mu^{1/\sigma}}) \). We will provide usefull expansions of some functions in this region.

We start with the function, for \( y \in B(0, \frac{\eta}{\mu^{1/\sigma}}) \),
\[
(10.1) \quad \Upsilon(y) := \mu^{\frac{n-2}{2}} U(\xi_1 + \mu y) - \sum_{l>1} U(y + \mu^{-1}(\xi_1 - \xi_l)).
\]
We have the validity of the following expansion

\[
\begin{align*}
\Upsilon(y) &= -\frac{n-2}{2} \mu^2 \left[ y_1 - \mu^{\frac{n-2}{2}} \sum_{l=0}^{k} \frac{1}{(1 - \cos \theta_l)^{\frac{n-2}{2}}} (y_1 - \sin \theta_l \cdot y_1) \right] \times \\
&\quad (1 + \mu^2 O(|y|)) \\
&\quad + \frac{n-2}{4} \mu^{\frac{n-2}{2}} \left[ \sum_{l=0}^{k} \frac{1}{(1 - \cos \theta_l)^{\frac{n-2}{2}}} \times \\
&\quad \left( -1 - |y|^2 + \frac{n}{2} (1 - \cos \theta_l) y_1^2 + \frac{n}{2} (1 + \cos \theta_l) y_2^2 + n \sin \theta_l y_1 y_2 \right) \right] \times \\
&\quad (1 + \mu^2 O(|y|^2)) \\
\end{align*}
\]

(10.2) \[
+ \mu^{\frac{n-2}{2}} O(1 + |y|^3) + O(\mu^{\frac{n-2}{2}})
\]

for a fixed constant \(A\). Formula (10.2) is a direct application of the fact that

\[
\mu^{\frac{n-2}{2}} \left( \frac{2}{1 + |\xi_1|^2} \right)^{\frac{n-2}{2}} - \mu^{n-2} \sum_{l=1}^{k} \frac{1}{(1 - \cos \theta_l)^{\frac{n-2}{2}}} = O(\mu^{\frac{n-2}{2}})
\]

and of Taylor expansion applied separately to \(\mu^{\frac{n-2}{2}} U(\xi_1 + \mu y)\) and \(\sum_{l=1}^{k} U(y + \mu^{-1}(\xi_1 - \xi_l))\) in the considered region \(y \in B(0, \frac{\eta}{\mu^{k+\tau}})\). Indeed, we have

\[
\begin{align*}
U(\xi_1 + \mu y) &= \mu^{\frac{n-2}{2}} \left( \frac{2}{1 + |\xi_1|^2} \right)^{\frac{n-2}{2}} \left[ 1 - \frac{(n-2)}{2} y_1 \mu + \frac{n-2}{4} \left( \frac{n(y \cdot \xi_1)^2}{2} - |y|^2 \right) \mu^2 \right] \\
&\quad + \mu^3 O(|y|^3) \left( 1 + O(\mu^2) \right)
\end{align*}
\]

(10.3)

and

\[
\begin{align*}
U(y + \mu^{-1}(\xi_1 - \xi_l)) &= \frac{\mu^{n-2}}{(1 - \cos \theta_l)^{\frac{n-2}{2}}} \left[ 1 - \frac{(n-2)}{2} \frac{(\xi_1 - \xi_l) \cdot y}{(1 - \cos \theta_l)} \mu \right. \\
&\quad + \frac{n-2}{4} \frac{\mu^2}{(1 - \cos \theta_l)} \left( -1 - |y|^2 + n \frac{(\xi_1 - \xi_l) \cdot y}{|\xi_1 - \xi_l|^2} \right) \\
&\left. \right] + \mu^3 O(1 + |y|^3) \left( n \frac{y_1}{|\xi_1 - \xi_l|^3} \right).
\end{align*}
\]

(10.4)

Recall now the definition of the functions \(Z_\alpha\), \(\alpha = 0, \ldots, n\) in (3.3). In the region \(y \in B(0, \frac{\eta}{\mu^{k+\tau}})\), we need to describe the functions

\[
Z_\alpha(y + \mu^{-1}(\xi_1 - \xi_l)), \quad \alpha = 0, 1, \ldots, n.
\]
A direct application of Taylor expansion gives
\[
Z_0(y + \mu^{-1}(\xi_l - \xi_1)) = -\frac{n-2}{2} \frac{\mu^{n-2}}{(1 - \cos \theta_l)^{\frac{n}{2}}} \left[ 1 - (n - 2) \frac{(\xi_l - \xi_1) \cdot y}{|\xi_l - \xi_1|^2} \frac{\mu}{2} \right] + \frac{\mu^2}{|\xi_l - \xi_1|^2} O(1 + |y|^2),
\]
(10.5)

\[
Z_1(y + \mu^{-1}(\xi_l - \xi_1)) = -\frac{n-2}{2} \frac{\mu^n}{(1 - \cos \theta_l)^{\frac{n}{2}}} \left[ \mu^{-1}(\cos \theta_l - 1) + \left[ 1 - \frac{n}{2}(1 - \cos \theta_l) \right] y_1 \right]
\]
(10.6)

\[
Z_2(y + \mu^{-1}(\xi_l - \xi_1)) = -\frac{n-2}{2} \frac{\mu^n}{(1 - \cos \theta_l)^{\frac{n}{2}}} \left[ \mu^{-1} \sin \theta_l + \left[ 1 - \frac{n}{2}(1 + \cos \theta_l) \right] y_2 \right]
\]
(10.7)

and for \( \alpha = 3, \ldots, n \)
\[
Z_\alpha(y + \mu^{-1}(\xi_l - \xi_1)) = -\frac{n-2}{2} \frac{\mu^n}{(1 - \cos \theta_l)^{\frac{n}{2}}} y_\alpha \left[ 1 + \mu^2 O(1 + |y|) \right].
\]
(10.8)

We have now the tools to give the proofs of (4.15), (4.16), (4.19), (10.23), (4.23), (4.24), (4.27), (4.28), (4.31), (4.32), (4.35) and (4.36).

**Computation of** \( A_{11} \). Let \( \eta > 0 \) and \( \sigma > 0 \) be small and fixed numbers. We write
\[
A_{11} = \int_{\mathbb{R}^n} \left( f'(u) - f'(U_1) \right) Z_{01}^2
\]
\[
= \left[ \int_{B(\xi_1; \frac{n \eta}{4 \sigma})} + \int_{\mathbb{R}^n \setminus B(\xi_1; \frac{n \eta}{4 \sigma})} \right] \left( f'(u) - f'(U_1) \right) Z_{01}^2
\]
\[
= I_1 + I_2
\]

We claim that the main part of the above expansion is \( I_1 \). Note that very close to \( \xi_1, U_1(x) = O(\mu^{-\frac{n+2}{2}}) \). More in general, taking \( \eta \) small if necessary, we have that \( U_1 \) dominates globally the other terms. We thus have
\[ I_1 = \int_{B(\xi_j, \frac{n}{\mu^{2n-2}})} f''(U_j)(U(x) - \sum_{\lambda > 1} U_j(x) + \bar{\phi}(x)) Z_{01}^2(x) \, dx + O(k^{n-2} \mu^{-1}) \]  
\quad (x = \xi_j + \mu y) 

\[ = \int_{B(0, \frac{n}{\mu^{2n-2}})} f''(U) [T(y)] Z_{01}^2 \, dx \] 

\[ + \int_{B(0, \frac{n}{\mu^{2n-2}})} f''(U) \bigg[ \mu^{2n-2} \bar{\phi}(\mu y + \xi_j) \bigg] Z_{01}^2 \, dy + O(k^{n-2} \mu^{-1}) \]

\[ = \int_{B(0, \frac{n}{\mu^{2n-2}})} f''(U) [T(y)] Z_{01}^2 \] 

\[ + p(p-1) \gamma \int_{B(0, \frac{n}{\mu^{2n-2}})} U^{p-2} \phi_1(y) Z_{01}^2 \, dx + O(k^{n-2} \mu^{-1}) \]

where \( T(y) \) is defined in (10.1) and \( \phi_1(y) = \mu^{\frac{n-2}{2}} \bar{\phi}(\mu y + \xi_j) \). Using (1.16), expansion (10.3) and (10.4), we get

\[ I_1 = O(k^{n-2} \mu^{-1}). \]

On the other hand, we have that

\[ I_2 = O(k^{n-2} \mu^{-1}) \]

Indeed, we first write

\[ I_2 = \left[ \sum_{j=1} \int_{B(\xi_j, \frac{n}{\mu k^{2n-2}})} + \int_{\mathbb{R}^n \setminus \bigcup_{j=1} B(\xi_j, \frac{n}{\mu k^{2n-2}})} \right] (f''(u) - f''(U_1)) Z_{01}^2 \]

Fix now \( j > 1 \). In the ball \( B(\xi_j, \frac{n}{\mu k^{2n-2}}) \), \( u \sim U_j = O(\mu^{-\frac{n-2}{2}}) \) and \( U_j \) dominates all the other terms. Taking this into consideration, we have that

\[ \left| \int_{B(\xi_j, \frac{n}{\mu k^{2n-2}})} [f''(u) - f''(U_1)] Z_{01}^2 \right| \lessapprox \int_{B(\xi_j, \frac{n}{\mu k^{2n-2}})} f''(U_j) Z_{01}^2 \]

\[ \lessapprox C \int_{B(0, \frac{n}{\mu^{2n-2}})} \frac{1}{(1 + |y|^2)^2} Z_{01}^2(y + \mu^{-1}(\xi_j - \xi_1)) \, dy \]  

(using(10.5))

\[ \lessapprox C \frac{\mu^{2(n-2)}}{(1 - \cos \theta)^{n-2}} \int_{B(0, \frac{n}{\mu^{2n-2}})} \frac{1}{(1 + |y|^2)^2} \, dy \]

\[ \lessapprox C \frac{\mu^{2(n-2)}}{(1 - \cos \theta)^{n-2}} \frac{1}{(\mu k^{1+\gamma})^{n-4}} \]

where \( C \) is an appropriate positive constant independent of \( k \). Thus we conclude that

\[ \sum_{j > 1} \int_{B(\xi_j, \frac{n}{\mu k^{2n-2}})} [f''(u) - f''(U_1)] Z_{01}^2 \lessapprox C \mu^{n-1} k^{n-2}, \]
where again $C$ is an appropriate positive constant independent of $k$.

On the other hand

$$\begin{align*}
\left| \int_{\mathbb{R}^n \setminus \bigcup_{j=1}^n B(\xi_j, \frac{n}{1+\sigma})} (f'(u) - f'(U_1))Z_{0l}^2 \right| &\leq C\mu^{-n+2} \int_{\mathbb{R}^n \setminus \bigcup_{j=1}^n B(\xi_j, \frac{n}{1+\sigma})} \frac{1}{(1 + |x|^2)^2} Z_{0l}^2 \frac{x - \xi_l}{\mu} \\
&\leq C\mu^{-n+2} \int_{\mathbb{R}^n \setminus \bigcup_{j=1}^n B(\xi_j, \frac{n}{1+\sigma})} \frac{1}{(1 + |x|^2)^2} \frac{1}{|x - \xi_l|^{2(n-2)}} \, dx \\
&\leq C\mu^{-n+2} k^{n-1}(1+\sigma)
\end{align*}$$

Thus we conclude that

$$\int_{\mathbb{R}^n \setminus \bigcup_{j=1}^n B(\xi_j, \frac{n}{1+\sigma})} (f'(u) - f'(U_1))Z_{0l}^2 \leq C\mu^{-n+2} k^{n-2}$$

Formulas (10.10) and (10.11) imply (10.9). Thus we get (4.15).

Computation of $A_{1l}$. Let $l > 1$ be fixed. Let again $\eta > 0$ and $\sigma > 0$ be small and fixed numbers. In this case we write

$$A_{1l} = \int_{\mathbb{R}^n} (f'(u) - f'(U_1))Z_{0l} \, Z_{0l} = \int_{B(\xi_l, \frac{n}{1+\sigma})} (f'(u) - f'(U_1))Z_{0l} \, Z_{0l} + \int_{\mathbb{R}^n \setminus B(\xi_l, \frac{n}{1+\sigma})} (f'(u) - f'(U_1))Z_{0l} \, Z_{0l} = I_1 + I_2$$

We start with the expansion of $I_1$. Using again the fact that in $B(\xi_l, \frac{n}{1+\sigma})$ the leading term in $u$ is $U_1$, which is of order $\mu^{-\frac{n+2}{2}}$, and dominates all the other terms in the definition of $u$, we get that

$$I_1 = \int_{B(\xi_l, \frac{n}{1+\sigma})} (f'(u) - f'(U_1))Z_{0l} \, Z_{0l} \, dx$$

$$= -py \int_{B(\xi_l, \frac{n}{1+\sigma})} \left[ \mu^{-\frac{n+2}{2}} U(\frac{x - \xi_l}{\mu}) \right]^{p-1} \mu^{-n+2} Z_0(\frac{x - \xi_l}{\mu}) Z_0(\frac{x - \xi_l}{\mu}) + R_1$$

$$= -py \int_{B(\xi_l, \frac{n}{1+\sigma})} U^{p-1}(y) Z_0(y) Z_0(y + \mu^{-1}(\xi_l - \xi_l)) \, dy + R_1$$

where $R_1 = I_1 - py \int_{B(\xi_l, \frac{n}{1+\sigma})} \left[ \mu^{-\frac{n+2}{2}} U(\frac{x - \xi_l}{\mu}) \right]^{p-1} \mu^{-n+2} Z_0(\frac{x - \xi_l}{\mu}) Z_0(\frac{x - \xi_l}{\mu})$. Now using the expansion (10.5), together with formula (10.13), we get, for any integer $l > 1$

$$I_1 = -py \frac{n-2}{2} \left( - \int_{\mathbb{R}^n} U^{p-1} \, Z_0(\frac{1}{1 - \cos \theta}) \frac{1}{(1 - \cos \theta)^{\frac{n+2}{2}}} \mu^{n-2} + O(\mu^{-1} k^{n-2}) \right)$$

Observe that

$$\int_{\mathbb{R}^n} U^{p-1} \, Z_0(\frac{1}{1 - \cos \theta}) \frac{1}{(1 - \cos \theta)^{\frac{n+2}{2}}} \mu^{n-2} + O(\mu^{-1} k^{n-2})$$

(10.12)

(10.13)
Indeed,
\[
\int_{\mathbb{R}^n} U^{p-1} Z_0 \, dy = \frac{n-2}{2} \int U^p + U^{p-1} \nabla U \cdot y \, dy
\]
(10.14)
\[
= \frac{n-2}{2} \int U^p + n \int U^{p-1} y_1 Z_1(y) \, dy
\]
On the other hand, we have
\[
p \int U^{p-1} y_1 Z_1(y) = - \int U^p
\]
We thus conclude (10.13) from (10.14). Replacing (10.13) in (10.12) we get
(10.15)
\[
I_1 = p \gamma \left( \frac{n-2}{2} \right) (- \int_{\mathbb{R}^n} U^{p-1} y_1 Z_1 \, dy) \left[ \frac{1}{(1 - \cos \theta_j) \frac{n}{2}} \right] \mu^{n-2} + O(\mu^{p-1} k^{n-2}).
\]
On the other hand, a direct computation gives that
(10.16)
\[
R_1 = O(\mu^{n-1} k^{n-2}).
\]
We now estimate the term \(I_2\). We write
\[
I_2 = \left[ \sum_{j \neq 1} \int_{B(\xi_j, \frac{\mu}{\sqrt{k} + \sigma})} + \int_{\mathbb{R}^n \setminus \bigcup_j B(\xi_j, \frac{\mu}{\sqrt{k} + \sigma})} \right] [f'(u) - f'(U_1)] Z_0 Z_0
\]
Fix now \(j \neq l\). In the ball \(B(\xi_j, \frac{\mu}{\sqrt{k} + \sigma})\), \(u \sim U_j = O(\mu^{-\frac{n-2}{2}})\) and \(U_j\) dominates all the other terms. Taking this into consideration, we have that
\[
\left| \int_{B(\xi_j, \frac{\mu}{\sqrt{k} + \sigma})} [f'(u) - f'(U_1)] Z_0 Z_0 \right| \leq \int_{B(\xi_j, \frac{\mu}{\sqrt{k} + \sigma})} f'(U_j) Z_0 Z_0
\]
(\text{using (10.5)})
\[
\leq C \int_{B(0, \frac{\mu}{\sqrt{k} + \sigma})} \frac{1}{(1 + |y|^2)^2} Z_0(y + \mu^{-1}(\xi_j - \xi_l)) Z_0(y + \mu^{-1}(\xi_j - \xi_l)) \, dy
\]
while
\[
\leq C \frac{\mu^{2(n-2)}}{(1 - \cos \theta_j) \frac{\mu}{2}} \text{ if } j \neq 1
\]
\[
\leq C \frac{\mu^{2(n-2)}}{(1 - \cos \theta_j) \frac{\mu}{2}} \text{ if } j = 1
\]
Thus we conclude that
\[
(10.17) \quad \left| \sum_{j \neq 1} \int_{B(\xi_j, \frac{\mu}{\sqrt{k} + \sigma})} [f'(u) - f'(U_1)] Z_0 Z_0 \right| \leq C \mu^{p-1} k^{n-2},
\]
where again \(C\) is an appropriate positive constant independent of \(k\).
On the other hand
\[
\left| \int_{\mathbb{R}^n \setminus \bigcup_{j \leq 1} B(\xi_j, \frac{n}{\mu + \sigma})} (f'(u) - f'(U_1)) Z_0 Z_1 \right|
\]
\[
\leq C \mu^{n+2} \int_{\mathbb{R}^n \setminus \bigcup_{j \leq 1} B(\xi_j, \frac{n}{\mu + \sigma})} \frac{1}{(1 + |x|^2)^2} Z_0 \frac{x - \xi_1}{\mu} Z_1 \frac{x - \xi_1}{\mu}
\]
\[
\leq C \mu^{n-2} \int_{\mathbb{R}^n \setminus \bigcup_{j \leq 1} B(\xi_j, \frac{n}{\mu + \sigma})} \frac{1}{(1 + |x|^2)^2} \frac{1}{|x - \xi_1|^{(n-2)}} dx
\]
Thus we conclude that
\[
(10.18) \quad \left| \int_{\mathbb{R}^n \setminus \bigcup_{j \leq 1} B(\xi_j, \frac{n}{\mu + \sigma})} (f'(u) - f'(U_1)) Z_0^2 \right| \leq C \mu^{n-1} k^{n-2}
\]

Summing up the information in (10.15), (10.16), (10.24) and (10.25), we conclude that the validity of (4.16).

**Computation of F_{11}.** Let \( \eta > 0 \) and \( \sigma > 0 \) be small and fixed numbers. We write
\[
F_{11} = \int_{\mathbb{R}^n} [f'(u) - f'(U_1)] Z_{11}^2 dx
\]
\[
= \left[ \int_{B(\xi_1, \frac{n}{\mu + \sigma})} + \int_{\mathbb{R}^n \setminus B(\xi_1, \frac{n}{\mu + \sigma})} \right] [f'(u) - f'(U_1)] Z_{11}^2 dx = I_1 + I_2
\]
We claim that the main part of the above expansion is \( I_1 \). In \( B(\xi_1, \frac{n}{\mu + \sigma}) \), the main part in \( u \) is given by \( U_1 \), which is of size \( \mu^{-\frac{\sigma}{2}} \) in this region, and which dominates all the other terms of \( u \). Thus we can perform a Taylor expansion of the function
\[
f'(u) - f'(U_1) = f''(U_1 + s(u - U_1))[u - U_1] \quad \text{for some} \quad 0 < s < 1,
\]
so we write
\[
I_1 = \int_{B(\xi_1, \frac{n}{\mu + \sigma})} f''(U_1) \left[ U(x) - \sum_{l \geq 1} U_l(x) + \tilde{\phi}(x) \right] Z_{11}^2 dx + R_1,
\]
Performing the change of variables \( x = \xi_1 + \mu y \), and recalling that \( Z_{11}(x) = \mu^{-\frac{\sigma}{2}} Z_1(\frac{x - \xi_1}{\mu})(1 + O(\mu^2)) \), we get
\[
I_1 - R_1 = \mu^{-2} \int_{B(0, \frac{n}{\mu + \sigma})} f''(U_1) \Upsilon(y) Z_1^2(y) dy
\]
\[
+ \mu^{-2} \int_{B(0, \frac{n}{\mu + \sigma})} f''(U_1) \mu^{\frac{n-2}{2}} \tilde{\phi}(\xi_1 + \mu y) Z_1^2(y) dy + O(\mu^5)
\]
where we recall that
\[
\Upsilon(y) = \left[ \mu^{\frac{n-2}{2}} U(\xi_1 + \mu y) - \sum_{l \geq 1} U(y + \mu^{-1}(\xi_1 - \xi_l)) \right].
Recall now that $\tilde{\phi}_1(y) = \mu^{1/2} \tilde{\phi}_1(\mu y + \xi_1)$ solves the equation
\[ \Delta \phi_1 + f'(U)\phi_1 + \chi_1(\xi_1 + \mu y)\mu^{1+2}E(\xi_1 + \mu y) + \gamma \mu^{1+2} N(\phi_1)(\xi_1 + \mu y) = 0 \quad \text{in} \quad \mathbb{R}^n \]

Hence we observe that
\[
p(p-1)\gamma \int_{\mathbb{R}^n} U^{p-2} \phi_1 Z_1^2 = p\gamma \int_{\mathbb{R}^n} \frac{\partial}{\partial y_1} (U^{p-1})\phi_1 Z_1
\]
\[
= -p\gamma \int_{\mathbb{R}^n} U^{p-1} \phi_1 (\partial_1 Z_1) - p\gamma \int_{\mathbb{R}^n} U^{p-1} (\partial_1 \phi_1) Z_1
\]
\[
= \int_{\mathbb{R}^n} \chi_1(\xi_1 + \mu y)\mu^{1+2}E(\xi_1 + \mu y)\partial_1 Z_1 dy + \gamma \mu^{1+2} \int_{\mathbb{R}^n} N(\phi_1)(\xi_1 + \mu y)\partial_1 Z_1
\]
\[
+ \int_{\mathbb{R}^n} \left[ \Delta \phi_1 (\partial_1 Z_1) + \Delta Z_1 (\partial_1 \phi_1) \right]
\]
\[
= \mu^{1+2} \int_{B(0, \frac{\eta}{\mu^{1+2}})} E(\xi_1 + \mu y)(\partial_1 Z_1) dy + \gamma \mu^{1+2} \int_{\mathbb{R}^n} N(\phi_1)(\xi_1 + \mu y)(\partial_1 Z_1) + O(\mu^{\frac{5}{2}})
\]

Taking this into account, we first observe that
\[
I_1 - R_1 = p\gamma \mu^{-2} \int_{B(0, \frac{\eta}{\mu^{1+2}})} \Upsilon(y) \partial_1 (U^{p-1} Z_1) dy + O(\mu^{\frac{5}{2}})
\]

On the other hand recall that
\[
R_1 = \int_{B(\xi_1, \frac{\eta}{\mu^{1+2}})} [f''(U_1 + s(u - U_1)) - f''(U_1)] \left[ U(x) - \sum_{l>1} U_l(x) + \tilde{\phi}(x) \right] Z_{11}^2 dx
\]

Thus we have
\[
|R_1| \leq C \int_{B(\xi_1, \frac{\eta}{\mu^{1+2}})} U_1^{p-2}(1 + sU_1^{-1}(u - U_1))^{\frac{p-2}{2}} - 1 \left[ U(x) - \sum_{l>1} U_l(x) + \tilde{\phi}(x) \right] Z_{11}^2 dx
\]
\[
\leq C \mu^{1+2} \int_{B(\xi_1, \frac{\eta}{\mu^{1+2}})} U_1^{p-2} \left[ U(x) - \sum_{l>1} U_l(x) + \tilde{\phi}(x) \right] Z_{11}^2 dx
\]

Arguing as before, we get that
\[
R_1 = \mu^{\frac{5}{2}} O(1)
\]
where $O(1)$ is bounded as $k \to 0$. Using the definition of $\mu$ and the expansions (10.3), (10.4) we conclude that

\[ I_1 = p \gamma \mu^{\frac{n+2}{2}} \left\{ n-2 \right\} \int_{\mathbb{R}^n} \left( \frac{n}{2} y_i^2 - |y|^2 \right) \partial_i (U^{p-1} Z_1) \]

\[- \mu^{n-2} \frac{2}{4} \sum_{j=1}^{\infty} \frac{1}{(1 - \cos \theta_j)^2} \int_{\mathbb{R}^n} \left[ -1 - |y|^2 + \frac{n}{2} (1 - \cos \theta_j)y_i^2 + \frac{n}{2} (1 + \cos \theta_j)y_j^2 \right] \partial_i (U^{p-1} Z_1) + O(\mu^n) \]

\[ = p \gamma \frac{n-2}{4} \frac{\mu^{n-2}}{2} \left( (n-2) + \mu \frac{n-2}{2} \sum_{j=1}^{\infty} \frac{\cos \theta_j - (n-2)}{(1 - \cos \theta_j)^2} \right) \int_{\mathbb{R}^n} \left( U^{p-1} Z_1 \right) + O(\mu^n) (10.19) \]

On the other hand, we have that

\[ (10.20) \quad I_2 = \mu^2 O(1) \]

where $O(1)$ is bounded as $k \to 0$. Indeed, we first write

\[ I_2 = \left[ \sum_{j=1}^{\infty} \int_{B(\xi_j, \frac{n}{4 \mu^{n-2}})} + \int_{\mathbb{R}^n \setminus \bigcup_{j=1}^{\infty} B(\xi_j, \frac{n}{4 \mu^{n-2}})} \right] (f'(u) - f'(U_1)) Z_{i1}^2 \]

Fix now $j > 1$. In the ball $B(\xi_j, \frac{n}{4 \mu^{n-2}})$, $u \sim U_j = O(\mu^{-\frac{n-2}{2}})$ and $U_j$ dominates all the other terms. Taking this into consideration, we have that

\[ \left| \int_{B(\xi_j, \frac{n}{4 \mu^{n-2}})} (f'(u) - f'(U_1)) Z_{i1}^2 \right| \leq \int_{B(\xi_j, \frac{n}{4 \mu^{n-2}})} f'(U_j) Z_{i1}^2 \]

\[ \leq C \mu^{-2} \int_{B(0, \frac{n}{4 \mu^{n-2}})} \frac{1}{(1 + |y|)^2} Z_i^2 (y + \mu^{-1}(\xi_j - \xi)) \, dy \]

(using (10.5))

\[ \leq C \frac{\mu^{2n-2}}{(1 - \cos \theta_j)^{n-2}} \int_{B(0, \frac{n}{4 \mu^{n-2}})} \frac{1}{(1 + |y|)^2} \, dy \]

\[ \leq C \frac{\mu^{2n-2}}{(1 - \cos \theta_j)^{n-2}} \mu^{1+\gamma} \]

where $C$ is an appropriate positive constant independent of $k$. Thus we conclude that

\[ (10.21) \quad \left| \sum_{j=1}^{\infty} \int_{B(\xi_j, \frac{n}{4 \mu^{n-2}})} (f'(u) - f'(U_1)) Z_{i1}^2 \right| \leq C \mu^2, \]

where again $C$ is an appropriate positive constant independent of $k$. 
On the other hand
\[
\left| \int_{\mathbb{R}^n \setminus \bigcup_{j=1}^k B(\xi_j, \frac{n}{\sqrt{\mu}})} (f'(u) - f'(U_1))Z_1^2 \right| \leq C\mu^{-\frac{n-2}{2}} \int_{\mathbb{R}^n \setminus \bigcup_{j=1}^k B(\xi_j, \frac{n}{\sqrt{\mu}})} \frac{1}{(1 + |x|^2)^2} \frac{1}{|x - \xi_1|^{2(n-1)}} \, dx
\]
\[
\leq C\mu^{-2}k^{n-2(1+\sigma)}
\]
Thus we conclude that
\[
(10.22) \quad \left| \int_{\mathbb{R}^n \setminus \bigcup_{j=1}^k B(\xi_j, \frac{n}{\sqrt{\mu}})} (f'(u) - f'(U_1))Z_1^2 \right| \leq C\mu^{\frac{n-2}{2}}
\]
\text{From (10.21) and (10.22) we get (10.20). From (10.19) and (10.20) we conclude (4.19).}

**Computation of F_{11}.** Let \( l > 1 \) be fixed. Let again \( \eta > 0 \) and \( \sigma > 0 \) be small and fixed numbers. In this case we write
\[
F_{11} = \int_{\mathbb{R}^n} (f'(u) - f'(U_1))Z_{11}Z_{11}
\]
\[
= \left[ \int_{B(\xi_1, \frac{n}{\sqrt{\mu}})} + \int_{\mathbb{R}^n \setminus B(\xi_1, \frac{n}{\sqrt{\mu}})} \right] (f'(u) - f'(U_1))Z_{11}Z_{11}
\]
\[
= I_1 + I_2
\]
We start with the expansion of \( I_1 \). Recall that
\[
Z_{11}(x) = \left[ \cos \theta \mu^{-\frac{n-2}{4}} Z_1(\frac{x - \xi_1}{\mu}) + \sin \theta \mu^{-\frac{n-1}{4}} Z_2(\frac{x - \xi_1}{\mu}) \right] (1 + O(\mu^2)).
\]
Using again the fact that in \( B(\xi_1, \frac{n}{\sqrt{\mu}}) \) the leading term in \( u \) is \( U_l \), which is of order \( \mu^{-\frac{n-2}{4}} \), and dominates all the other terms in the definition of \( u \), we get that
\[
I_1 = -p \cos \theta \int_{B(\xi_1, \frac{n}{\sqrt{\mu}})} [\mu^{-\frac{n-2}{4}} U(\frac{x - \xi_1}{\mu})]^{p-1} \mu^{-n} Z_1(\frac{x - \xi_1}{\mu}) Z_1(\frac{x - \xi_1}{\mu})
\]
\[
- p \sin \theta \int_{B(\xi_1, \frac{n}{\sqrt{\mu}})} [\mu^{-\frac{n-2}{4}} U(\frac{x - \xi_1}{\mu})]^{p-1} \mu^{-n} Z_1(\frac{x - \xi_1}{\mu}) Z_2(\frac{x - \xi_1}{\mu}) + R_1
\]
\[
(x = \mu y + \xi_1)
\]
\[
= -p \mu^{-\frac{n-2}{4}} \cos \theta \int_{B(0, \frac{n}{\sqrt{\mu}})} U^{p-1} Z_1 Z_1(y + \mu^{-1}(\xi_1 - \xi_1)) \, dy
\]
\[
- p \mu^{-\frac{n-2}{4}} \sin \theta \int_{B(0, \frac{n}{\sqrt{\mu}})} U^{p-1} Z_1 Z_2(y + \mu^{-1}(\xi_1 - \xi_1)) \, dy + R_1
\]
Now using the expansion (10.7) we get, for any $l > 1$

\[
I_1 - R_1 = p \gamma \frac{n - 2}{4} \Xi \cos \theta \left[ \frac{n - 2 - n \cos \theta}{(1 - \cos \theta)^2} \right] \mu^{n-2} - p \gamma \frac{n - 2}{4} \Xi \sin \theta \left[ \frac{n \sin \theta}{(1 - \cos \theta)^2} \right] \mu^{n-2} + O(\mu^2)
\]

\[
= p \gamma \frac{n - 2}{2} \Xi \left[ \frac{n - 2 \cos \theta - \frac{n}{2}}{(1 - \cos \theta)^2} \right] \mu^{n-2} + O(\mu^2)
\]

(10.23)

On the other hand we directly compute

\[ R_1 = \mu^2 O(1) \]

where $O(1)$ is bounded as $k \to 0$. We now estimate the term $I_2$. We write

\[
I_2 = \left[ \sum_{j \neq l} \int_{B(\xi_j, \eta k_1 + \sigma)} + \int_{\mathbb{R}^n \setminus \bigcup_j B(\xi_j, \eta k_1 + \sigma)} \right] (f'(u) - f'(U_1)) Z_{11} Z_{1l}
\]

Fix now $j \neq l$. In the ball $B(\xi_j, \eta k_1)$, $u \sim U_j = O(\mu^{-\frac{n-2}{2}})$ and $U_j$ dominates all the other terms. Taking this into consideration, we have that

\[
\left| \int_{B(\xi_j, \eta k_1/\sqrt{k})} [f'(u) - f'(U_1)] Z_{11} Z_{1l} \right| \leq \int_{B(\xi_j, \eta k_1/\sqrt{k})} f'(U_j) Z_{11} Z_{1l}
\]

\[
\leq C \mu^{n-2} \int_{B(0, \frac{\eta \sqrt{k}}{\sqrt{k}})} \frac{1}{(1 + |y|^2)^2} Z_1(y + \mu^{-1}(\xi_j - \xi_l)) Z_1(y + \mu^{-1}(\xi_j - \xi_l)) dy
\]

(10.7)

\[
\leq C \frac{\mu^{2n-2}}{(1 - \cos \theta_j)^n} \int_{B(0, \frac{\eta \sqrt{k}}{\sqrt{k}})} \frac{1}{(1 + |y|^2)^2} dy \quad \text{if} \quad j \neq 1
\]

while

\[
\leq C \frac{\mu^{2n-2}}{(1 - \cos \theta_j)^2} \quad \text{if} \quad j = 1
\]

Thus we conclude that

\[
(10.24) \quad \left| \sum_{j \neq l} \int_{B(\xi_j, \eta k_1/\sqrt{k})} [f'(u) - f'(U_1)] Z_{11} Z_{1l} \right| \leq C \mu^2,
\]

where again $C$ is an appropiate positive constant independent of $k$. 
Recall that
\[
Z_n \leq C \mu^{-n}
\]

Thus we conclude that
\[
|\int_{\mathbb{R}^n \setminus \bigcup_{j>1} B(\xi_j, \mu^{-n})} (f'(u) - f'(U_1))Z_{11}Z_{21}| \leq C \mu^{\frac{n}{2}}
\]

**Computation of \( G_{11} \).** Let \( \eta > 0 \) and \( \sigma > 0 \) be small and fixed numbers. We write
\[
G_{11} = \int_{\mathbb{R}^n} (f'(u) - f'(U_1))Z_{21}^2
\]
\[
= \left[ \int_{B(\xi_1, \frac{\sigma}{\mu^{1-n}})} + \int_{\mathbb{R}^n \setminus B(\xi_1, \frac{\sigma}{\mu^{1-n}})} \right] (f'(u) - f'(U_1))Z_{21}^2
\]
\[
= I_1 + I_2
\]

Recall that \( Z_{21}(x) = \mu^{-\frac{n}{2}}Z_2(\frac{x - \xi_1}{\mu}) \). We claim that the main part of the above expansion is \( I_1 \). Arguing as in the expansion of \( F_{11} \), in the set \( B(\xi_1, \frac{\sigma}{\mu^{1-n}}) \) we perform a Taylor expansion of the function \( f'(u) - f'(U_1) \) so that
\[
I_1 = \int_{B(\xi_1, \frac{\sigma}{\mu^{1-n}})} f''(U_1)[U(x) - \sum_{l=1}^{k} U_l(x) + \phi(x)]Z_{21}^2(x) \, dx + R_1
\]

changing variables \( x = \xi_1 + \mu y \)
\[
= \mu^{-2} \int_{B(0, \frac{\sigma}{\mu^{2-n}})} f''(U)Y(y)Z_2^2
\]
\[
+ \mu^{-2} \int_{B(0, \frac{\sigma}{\mu^{2-n}})} f''(U)\mu^{\frac{n}{2}}\phi(\mu y + \xi_1)Z_2^2 \, dx + R_1
\]
\[
= \mu^{-2} \int_{B(0, \frac{\sigma}{\mu^{2-n}})} f''(U)Y(y)Z_2^2
\]
\[
+ p(p-1)\mu^{-2} \int_{B(0, \frac{\sigma}{\mu^{2-n}})} U^{p-2}\phi_1(y)Z_2^2 \, dx + R_1
\]

where \( \phi_1(y) = \mu^{\frac{n}{2}}\phi(\mu y + \xi_1) \) and \( Y(y) = \left[ \mu^{\frac{n}{2}} U(\xi_1 + \mu y) - \sum_{l=1}^{k} U(y + \mu^{-1}(\xi_1 - \xi_l)) \right] \).
Using the equation satisfied by $\phi_1$ and by $Z_2$ in $\mathbb{R}^n$, we get
\[
p(p - 1)\gamma \int U^{p-2} \phi_1 Z_2^2 = p\gamma \int \frac{\partial}{\partial y_2} U^{p-1} \phi_1 Z_2
\]
\[= -p\gamma \int U^{p-1} \phi_2 \phi_1 Z_2 - p\gamma \int U^{p-1} \phi_1 \phi_2 Z_2
\]
\[= \int \zeta_1(\xi_1 + \mu y) \mu^{-\frac{2n}{p-2}} E(\xi_1 + \mu y) \phi_2 Z_2 + \gamma \mu^{-\frac{2n}{p-2}} \int N(\phi_1)(\xi_1 + \mu y) \phi_2 Z_2
\]
\[= p\gamma \int I_0(\mu y) U^{p-1} \left[ \mu^{n-2} U(\xi_1 + \mu y) - \sum_{l>1} U(y + \mu^{-1} (\xi_l - \xi_1)) \right] \phi_2 Z_2
\]
\[+ O(\mu^{\frac{2}{p}})
\]
Thus we conclude that
\[
I_1 = p\gamma \mu^{-2} \int I_0(y) \phi_2 \left( U^{p-1} Z_2 \right) dy + O(\mu^{\frac{2}{p}})
\]
Using the definition of $\mu$ in (1.16), we see that the first order term in expansions (10.3) and (10.4) gives a lower order contribution to $I_1$. Furthermore, by symmetry, also the second order term in the expansions (10.3) and (10.4) gives a small contribution. Thus, the third order term in the above mentioned expansions is the one that counts. We get indeed
\[
I_1 = p\gamma \frac{n - 2}{4} \mu^{\frac{n-2}{2}} \int \left[ \frac{n}{2} \gamma_l^2 - |\gamma|^2 \right] \partial_{y_2} \left( U^{p-1} Z_2 \right)
\]
\[= p\gamma \frac{n - 2}{4} \mu^{n-2} \sum_{l>1} \frac{1}{(1 - \cos \theta_l)^2} \int \left[ -1 - |\gamma|^2 \right]
\]
\[+ \frac{n}{2} (1 - \cos \theta_l) \mu^{-2} + \frac{n}{2} (1 + \cos \theta_l) \mu^{-2} \partial_{y_2} \left( U^{p-1} Z_2 \right) + O(\mu^{\frac{2}{p}})
\]
\[= -p\gamma \frac{n - 2}{4} \mu^{\frac{n-2}{2}} \left[ 2 + \mu^{n-2} \sum_{l>1} \frac{-2 + n(1 + \cos \theta_l)}{(1 - \cos \theta_l)^2} \right] \left( - \int \partial_{y_2} \left( U^{p-1} Z_2 \right) + O(\mu^{\frac{2}{p}}) \right)
\]
On the other hand, arguing as in the proof of estimate (10.20), we have that
\[
I_2 = \mu^{\frac{2}{p}} O(1)
\]
where $O(1)$ is bounded as $k \to \infty$. Thus we conclude (4.23).

**Computation of $G_{1l}$**. Let $l > 1$ be fixed. Arguing as in the computation of $F_{1l}$, we first observe that
\[
G_{1l} = \int B(\xi_l, \frac{1}{2}) \left[ f'(u) - f'(U_1) \right] Z_2^l Z_{2l} dy + O(\mu^{\frac{2}{p}})
\]
Recall that
\[
Z_{2l}(x) = \left[ -\sin \theta_l \mu^{-\frac{n}{2}} Z_l \left( \frac{x - \xi_l}{\mu} \right) + \cos \theta_l \mu^{-\frac{n}{2}} Z_2 \left( \frac{x - \xi_l}{\mu} \right) \right] \left( 1 + O(\mu^{\frac{2}{p}}) \right).
\]
In the ball $B(\xi_l, \frac{\eta}{\mu})$, we expand as before in Taylor, and we get

$$G_{11} = -p \gamma \cos \theta \int_{B(\xi_l, \frac{\eta}{\mu})} [\mu^{-\frac{n-2}{2}} U \left( \frac{x - \xi_l}{\mu} \right)]^{p-1} \mu^{-n} Z_2 \left( \frac{x - \xi_l}{\mu} \right) Z_2 \left( \frac{x - \xi_l}{\mu} \right)$$

$$+ p \gamma \sin \theta \int_{B(\xi_l, \frac{\eta}{\mu})} [\mu^{-\frac{n-2}{2}} U \left( \frac{x - \xi_l}{\mu} \right)]^{p-1} \mu^{-n} Z_2 \left( \frac{x - \xi_l}{\mu} \right) Z_1 \left( \frac{x - \xi_l}{\mu} \right)$$

$$+ O(\mu^2)$$

$$\quad (x = \mu y + \xi_l)$$

$$= -p \gamma \mu^{-2} \sin \theta \int_{B(0, \frac{\eta}{\mu})} U^{p-1} Z_2 Z_2(y + \mu^{-1}(\xi_l - \xi_1)) \ dy$$

$$+ p \gamma \mu^{-2} \cos \theta \int_{B(0, \frac{\eta}{\mu})} U^{p-1} Z_2 Z_1(y + \mu^{-1}(\xi_l - \xi_1)) \ dy + O(\mu^2).$$

Now using the expansion (10.7) we get, for any $l > 1$, the validity of (4.24).

**Computation of $B_{11}$.** Let $\eta > 0$ and $\sigma > 0$ be small and fixed numbers. We write

$$B_{11} = \int_{\mathbb{R}^n} (f'(u) - f'(U_1)) Z_0 Z_1$$

$$= \int_{\mathbb{R}^n, B(\xi_l, \frac{\eta}{\mu})} (f'(u) - f'(U_1)) Z_0 Z_1$$

$$= I_1 + I_2$$

We claim that the main part of the above expansion is $I_1$. We have

$$I_1 = \int_{B(\xi_l, \frac{\eta}{\mu})} f''(U_1)(U(x) - \sum_{l=1}^{k} U_l(x) + \tilde{\phi}(x)) Z_0 Z_1 \ dx + O(\mu^2)$$

$$\quad (x = \xi_l + \mu y)$$

$$= \mu^{-2} \int_{B(0, \frac{\eta}{\mu})} f''(U) \Upsilon(y) Z_0 Z_1 \ dy$$

$$+ \mu^{-2} \int_{B(0, \frac{\eta}{\mu})} f''(U) \left[ \mu^{-\frac{n-2}{2}} \tilde{\phi}(\mu y + \xi_l) \right] Z_0 Z_1 \ dx$$

$$+ O(\mu^2)$$

$$= \mu^{-2} \int_{B(0, \frac{\eta}{\mu})} f''(U) \left[ \mu^{-\frac{n-2}{2}} U(\xi_l + \mu y) - \sum_{l=1}^{k} U(y + \mu^{-1}(\xi_l - \xi_1)) \right] Z_0 Z_1 \ dy$$

$$+ p(p - 1) \gamma \mu^{-2} \left[ \int_{B(0, \frac{\eta}{\mu})} U^{p-2} \phi_1(y) Z_0 Z_1 \ dy \right] + O(\mu^2)$$

where $\phi_1(y) = \mu^{-\frac{n-2}{2}} \tilde{\phi} (\mu y + \xi_l)$. 


Using the equation satisfied by $\phi_1$ and by $Z_0, Z_1$ in $\mathbb{R}^n$, we have that

$$p(p - 1)\gamma \int U^{p-2}\phi_1 Z_0 Z_1 = p\gamma \int \frac{\partial}{\partial y_1} U^{p-1} \phi_1 Z_0$$

$$= -p\gamma \int U^{p-1} \phi_1 Z_0 - p\gamma \int U^{p-1} \phi_1 \partial_{y_1} Z_0$$

$$= p\gamma \int_{B(0, \frac{\mu}{\sqrt{\gamma}})} U^{p-1} \mathcal{T}(y) \partial_{y_1} (U^{p-1} Z_0)$$

where $\mathcal{T}(y) = \left[ \mu^\frac{n-2}{2} U(y + \mu y) - \sum_{|j| = 1}^k U(y + \mu^{-1}(\xi_j - \xi_1)) \right]$. Using expansions (10.3) and (10.4), and taking into account that $\partial_{y_1} (U^{p-1} Z_0) = (p-1)U^{p-1} Z_0 + U^{p-1} \partial_{y_2} Z_0$,

$$I_1 = p\gamma \mu^{-2} \int_{B(0, \frac{\mu}{\sqrt{\gamma}})} \mathcal{T}(y) \partial_{y_1} (U^{p-1} Z_0)$$

$$= p\gamma \frac{n-2}{2} \mu^\frac{n-4}{2} \int y_1 \partial_{y_2} (U^{p-1} Z_0) dy + O(\mu^2)$$

$$= \mu^{-3} \sum_{k>1} \frac{1}{(1 - \cos \theta_j)^\frac{n-2}{2}} \int y_1 \partial_{y_2} (U^{p-1} Z_0) + O(\mu^2).$$

On the other hand, arguing as in the expansion of $A_{11}$, one can easily prove that

$$I_2 = O(\mu^2).$$

Taking into account (10.13), we conclude (4.27).  

**Computation of $B_{1l}$**. Let $l > 1$ be fixed. We have

$$B_{1l} = \int_{B(\xi_j, \frac{\mu}{\sqrt{\gamma}})} \left[ \frac{f'(u) - f'(U_1)}{Z_0} Z_{1l} dx + O(\mu^2) \right]$$

$$= -p\gamma \cos \theta_i \int_{B(\xi_j, \frac{\mu}{\sqrt{\gamma}})} \left[ \mu^\frac{n-2}{2} U\left(\frac{x - \xi_i}{\mu}\right) \right]^{-1} \mu^{-n} Z_0 \left(\frac{x - \xi_1}{\mu}\right) Z_1 \left(\frac{x - \xi_i}{\mu}\right)$$

$$- p\gamma \sin \theta_i \int_{B(\xi_j, \frac{\mu}{\sqrt{\gamma}})} \left[ \mu^\frac{n-2}{2} U\left(\frac{x - \xi_i}{\mu}\right) \right]^{-1} \mu^{-n} Z_0 \left(\frac{x - \xi_1}{\mu}\right) Z_2 \left(\frac{x - \xi_i}{\mu}\right)$$

$$+ O(\mu^2)$$

$$+ O(\mu^{-1} \cos \theta_i)$$

$$= -p\gamma \mu^{-1} \cos \theta_i \int_{\overline{B(0, \frac{\mu}{\sqrt{\gamma}})}} U^{p-1} Z_1 Z_0 (y + \mu^{-1}(\xi_l - \xi_1)) dy$$

$$- p\gamma \mu^{-1} \sin \theta_i \int_{\overline{B(0, \frac{\mu}{\sqrt{\gamma}})}} U^{p-1} Z_2 Z_0 (y + \mu^{-1}(\xi_l - \xi_1)) dy + O(\mu^2).$$

Now using the expansion (10.5) we get, for any $l > 1$, (4.28).
**Computation of** $C_{11}$. Arguing as in the computation of $G_{11}$, we are led to

$$C_{11} = p\gamma\mu^{-1} \left[ \int_{B(0, \frac{\mu}{n^2})} \mathcal{T}(y) \partial_{y_2}(U^{p-1}Z_0) \, dy \right] (1 + O(\mu))$$

$$+ k^{n-2}\mu^{n-1}O(1)$$

$$= -p\gamma\mu^{k} \left( \sum_{l=1}^{k} \frac{\sin \theta_l}{(1 - \cos \theta_l)^2} \right) \int U^{p-1}Z_0 + k^{n-2}\mu^{n-1}O(1),$$

where

$$\mathcal{T}(y) = \left[ \mu^{\frac{n+2}{2}} U(\xi_1 + \mu y) - \sum_{l=1}^{k} U(y + \mu^{-1}(\xi_1 - \xi_l)) \right]$$

so that we conclude, by cancellation, the validity of (4.31).

**Computation of** $C_{1l}$. Let $l > 1$ be fixed. We have

$$C_{1l} = \int_{B(\xi, \frac{\mu}{n^2})} \left[ f'(u) - f'(U_1) \right] Z_0(z_2) \, dx + k^{n-2}\mu^{n-1}O(1)$$

$$= -p\gamma \cos \theta_l \int_{B(\xi, \frac{\mu}{n^2})} \left[ \mu^{\frac{n+2}{2}} U(\frac{x - \xi_1}{\mu}) \right]^{p-1} \mu^{-n+1}Z_0(\frac{x - \xi_1}{\mu})Z_2(\frac{x - \xi_l}{\mu}) \, dx$$

$$+ p\gamma \sin \theta_l \int_{B(\xi, \frac{\mu}{n^2})} \left[ \mu^{\frac{n+2}{2}} U(\frac{x - \xi_1}{\mu}) \right]^{p-1} \mu^{-n+1}Z_0(\frac{x - \xi_1}{\mu})Z_2(\frac{x - \xi_l}{\mu}) \, dx$$

$$+ k^{n-2}\mu^{n-1}O(1)$$

$$= -p\gamma \mu^{-1} \cos \theta_l \int_{B(0, \frac{\mu}{n^2})} U^{p-1}Z_2Z_0(y + \mu^{-1}(\xi_1 - \xi_l)) \, dy$$

$$+ p\gamma \mu^{-1} \sin \theta_l \int_{B(0, \frac{\mu}{n^2})} U^{p-1}Z_2Z_0(y + \mu^{-1}(\xi_1 - \xi_l)) \, dy + k^{n-2}\mu^{n-1}O(1).$$

Now using the expansion (10.5) we get, for any $l > 1$, (4.32).

**Computation of** $D_{11}$. Arguing as in the computation of $G_{11}$, we are led to

$$D_{11} = p\gamma\mu^{-2} \int \mathcal{T}(y) \partial_{y_1}(U^{p-1}Z_2) \, dy$$

$$+ k^{n-1}\mu^nO(1)$$

$$= p\gamma \frac{n-2}{4} m\mu^{n-2} \left( \sum_{l=1}^{k} \frac{\sin \theta_l}{(1 - \cos \theta_l)^2} \right) \int y_2 U^{p-1}Z_2 + k^{n-1}\mu^nO(1)$$

so that we conclude (4.35).
Computation of $D_{11}$. Let $l > 1$ be fixed. We have

$$D_{11} = \int_{B(\xi_1, \frac{\mu}{\sqrt{\mu}})} [f''(u) - f''(U_1)]Z_{11}Z_{21} \, dx + k^{n-1}\mu^n O(1)$$

$$= -py \cos \theta l \int_{B(\xi_1, \frac{\mu}{\sqrt{\mu}})} [\mu^{-\frac{n+1}{2}} U(\frac{x - \xi_1}{\mu})]^{p-1} \mu^{-n} Z_1(\frac{x - \xi_1}{\mu})Z_2(\frac{x - \xi_1}{\mu}) \, dx$$

$$+ py \sin \theta l \int_{B(\xi_1, \frac{\mu}{\sqrt{\mu}})} [\mu^{-\frac{n+1}{2}} U(\frac{x - \xi_1}{\mu})]^{p-1} \mu^{-n} Z_1(\frac{x - \xi_1}{\mu})Z_2(\frac{x - \xi_1}{\mu}) \, dx$$

$$+ k^{n-1}\mu^n O(1)$$

$(x = \mu y + \xi_1)$

$$= -py\mu^{-2} \cos \theta l \int_{B(0, \frac{\mu}{\sqrt{\mu}})} U^{p-1} Z_2 Z_1(y + \mu^{-1}(\xi_1 - \xi_1)) \, dy$$

$$+ py\mu^{-2} \sin \theta l \int_{B(0, \frac{\mu}{\sqrt{\mu}})} U^{p-1} Z_2 Z_2(y + \mu^{-1}(\xi_1 - \xi_1)) \, dy + k^{n-1}\mu^n O(1).$$

Now using the expansion (10.7) we get (4.36).

Computation of $H_{3,11}$. Let $\eta > 0$ and $\sigma > 0$ be small and fixed numbers. We write

$$H_{3,11} = \int_{\mathbb{R}^n} (f''(u) - f''(U_1))Z_{31}^2$$

$$= \int_{B(\xi_1, \frac{\eta}{\sqrt{\eta}})} (f''(u) - f''(U_1))Z_{31}^2 + \int_{\mathbb{R}^n \setminus B(\xi_1, \frac{\eta}{\sqrt{\eta}})} (f''(u) - f''(U_1))Z_{31}^2$$

$$= I_1 + I_2$$

Arguing as before one can show that

$$I_2 = O(\mu^2).$$

In $B(\xi_1, \frac{\eta}{\sqrt{\eta}})$ we can perform a Taylor expansion of the function $(f''(u) - f''(U_1))$ so that

$$I_1 = \int_{B(\xi_1, \frac{\eta}{\sqrt{\eta}})} f''(U_1)[U(x) - \sum_{i=1}^{k} U_i(x) + \tilde{\phi}(x)]Z_{31}^2(x) \, dx + O(\mu^2)$$

$(x = \xi_1 + \mu y)$

$$= \mu^{-2} \int_{B(0, \frac{\eta}{\sqrt{\eta}})} f''(U)\mathcal{Y}(y)Z_3^2$$

$$+ \mu^{-2} \int_{B(0, \frac{\eta}{\sqrt{\eta}})} f''(U)\mu^{-\frac{n-2}{2}} \tilde{\phi}(\mu y + \xi_1)Z_3^2 \, dx + O(\mu^2)$$

$$= \mu^{-2} \int_{B(0, \frac{\eta}{\sqrt{\eta}})} f''(U)\mathcal{Y}(y)Z_3^2$$

$$+ p(p-1)\gamma \mu^{-2} \int_{B(0, \frac{\eta}{\sqrt{\eta}})} U^{p-2}\tilde{\phi}(y)Z_3^2 \, dx + O(\mu^2)$$
where \( \phi_1(y) = \mu^{\frac{n+2}{2}} \phi(\mu y + \xi_1) \). Using the equation satisfied by \( \phi_1 \) and by \( z_2 \) in \( \mathbb{R}^n \), and arguing as in the previous steps, we get

\[
p(p-1)\gamma \int U^{p-2} \phi_1 Z_3^2 = p \gamma \int_{B(0, p^{\frac{2}{2p}})} U^{p-1} \mathcal{T}(y) \partial_{\gamma_3} Z_3
\]

where we recall that

\[
\mathcal{T}(y) = \left[ \mu^{\frac{n+2}{2}} U(\xi_1 + \mu y) - \sum_{l=1}^{k} U(y + \mu^{-1}(\xi_l - \xi)) \right].
\]

Thus we conclude (4.39).

Using the definition of \( \mu \) in (1.16), we see that the first order term in expansions (10.3) and (10.4) gives a lower order contribution to \( I_1 \). Furthermore, by symmetry, also the second order term in the expansions (10.3) and (10.4) gives a small contribution. Thus, the third order term in the above mentioned expansions is the one that counts. We get indeed

\[
I_1 = p \gamma \mu^{-2} \int_{B(0, p^{\frac{2}{2p}})} \mathcal{T}(y) \partial_{\gamma_3} \left( U^{p-1} Z_3 \right) dy + O(\mu^2).
\]

Thus we conclude (4.39).

**Computation of \( H_{3,1} \).** Let \( l > 1 \) be fixed. Arguing as before, we get

\[
H_{3,1} = \int_{B(\bar{\xi}, \bar{\xi})} \left[ f'(u) - f'(U_1) \right] Z_3 Z_3 + O(\mu^2)
\]

\[
= -p \gamma \int_{B(\bar{\xi}, \bar{\xi})} \left[ \mu^{\frac{n+2}{2}} U(\frac{x - \xi_1}{\mu}) \right]^{p-1} \mu^{-n} Z_3 (\frac{x - \xi_1}{\mu}) Z_3 (\frac{x - \xi_1}{\mu}) dy + O(\mu^2)
\]

\[
= -p \gamma \mu^2 \int_{B(\bar{\xi}, \bar{\xi})} U^{p-1} Z_3(y) Z_3(y + \mu^{-1}(\xi_l - \xi_1)) dy + O(\mu^2)
\]

Now using the expansion (10.8) we get (4.40).
The references section includes a list of academic sources cited in the text. Each reference is numbered and formatted according to a specific style, typically that of a scientific journal or conference proceeding. The sources cover a range of topics related to differential equations, geometry, and mathematical physics, with a focus on contributions to the understanding of nonlinear phenomena and conformal invariance. The references are cited in the text to support the claims and results presented, providing a foundation for the advancements discussed in the paper.


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