

# BOUNDARY RIGIDITY WITH PARTIAL DATA

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ABSTRACT. We study the boundary rigidity problem with partial data consisting of determining locally the Riemannian metric of a Riemannian manifold with boundary from the distance function measured at pairs of points near a fixed point on the boundary. We show that one can recover uniquely a conformal factor near a strictly convex point where we have the information. In particular, this implies that we can determine locally the isotropic sound speed of a medium by measuring the travel times of waves joining points close to a convex point on the boundary.

The local results leads to a global uniqueness results assuming that the manifold is foliated by strictly convex hypersurfaces.

## 1. INTRODUCTION AND MAIN RESULTS

Travel time tomography deals with the problem of determining the sound speed or index of refraction of a medium by measuring the travel times of waves going through the medium. This type of inverse problem, also called the inverse kinematic problem, arose in geophysics in an attempt to determine the substructure of the Earth by measuring the travel times of seismic waves at the surface. We consider an anisotropic index of refraction, that is the sound speed depends on the direction. The Earth is generally isotropic. More recently it has been realized, by measuring these travel times, that the inner core of the Earth exhibits anisotropic behavior with the fast direction parallel to the Earth's spin axis, see [4]. In the human body, muscle tissue is anisotropic. As a model of anisotropy, we consider a Riemannian metric  $g = (g_{ij})$ . The problem is to determine the metric from the lengths of geodesics joining points on the boundary.

This leads to the general question of whether given a compact Riemannian manifold with boundary  $(M, g)$  one can determine the Riemannian metric in the interior knowing the boundary distance function joining points on the boundary  $d_g(x, y)$ , with  $x, y \in \partial M$ . This is known as the *boundary rigidity problem*. Of course, isometries preserve distance, so that the boundary rigidity problem is whether two metrics that have the same boundary distance function are the same up to isometry. Examples can be given of manifolds that are not boundary rigid. Such examples show that the boundary rigidity problem should be considered under some restrictions on the geometry of the manifold. The most usual of such restrictions is simplicity of the metric. A Riemannian manifold  $(M, g)$  (or the metric  $g$ ) is called *simple* if the boundary  $\partial M$  is strictly convex and any two points  $x, y \in M$  are joined by a unique minimizing geodesic. Michel conjectured [19] that every simple compact Riemannian manifold with boundary is boundary rigid.

Simple surfaces with boundary are boundary rigid [27]. In higher dimensions, simple Riemannian manifolds with boundary are boundary rigid under some a-priori constant curvature on the manifold or special symmetries [1], [11]. Several local results near the Euclidean metric are known [36], [17],

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[2]. The most general result in this direction is the generic local (with respect to the metric) one proven in [38]. Surveys of some of the results can be found in [14], [39], [7].

In this paper, we consider the boundary rigidity problem in the class of metrics conformal to a given one and with partial data, that is, we know the boundary distance function for points on the boundary near a given point. Partial data problems arise naturally in applications since in many cases one doesn't have access to the whole boundary. We prove the first result on the determination of the conformal factor locally near the boundary from partial data without assuming analyticity. We develop a novel method to attack partial data non-linear problems that will likely have other applications.

We now describe the known results with full data on the boundary. Let us fix the metric  $g_0$  and let  $c$  be a positive smooth function on  $M$ . The problem is whether we can determine  $c$  from  $d_{c^{-2}g_0}(x, y)$ ,  $x, y \in \partial M$ . Notice that in this case the problem is not invariant under changes of variables that are the identity at the boundary so that we expect to be able to recover  $c$  under appropriate a-priori conditions. This was proven by Mukhometov in two dimensions [21], and in [22] in higher dimensions for the case of simple metrics. Of particular importance in applications is the case of an isotropic sound speed that is when we are in a bounded domain of Euclidean space and  $g_0$  is the Euclidean metric. This is the isotropic case. This problem was considered by Herglotz [12] and Wieckert and Zoeppritz [46] for the case of a spherical symmetric sound speed. They found a formula to recover the sound speed from the boundary distance function assuming  $\frac{d}{dr}(\frac{r}{c(r)}) > 0$ . Notice that this condition is equivalent in the radial case to non-trapping and is more general than simplicity.

From now on we will call  $d$  the function  $d_{c^{-2}g_0}$ .

The partial data problem, that we will also call the *local boundary rigidity problem*<sup>1</sup>, in this case is whether knowledge of the distance function on part of the boundary determines the sound speed  $c$  locally. Given another smooth  $\tilde{c}$ , here and below we define  $\tilde{L}$ ,  $\tilde{\ell}$  and  $\tilde{d}$  in the same way but related to  $\tilde{c}$ . We prove the following uniqueness result:

**Theorem 1.1.** *Let  $n = \dim M \geq 3$ , let  $c > 0$ ,  $\tilde{c} > 0$  be smooth and let  $\partial M$  be strictly convex with respect to both  $g = c^{-2}g_0$  and  $\tilde{g} = \tilde{c}^{-2}g_0$  near a fixed  $p \in \partial M$ . Let  $d(p_1, p_2) = \tilde{d}(p_1, p_2)$  for  $p_1, p_2$  on  $\partial M$  near  $p$ . Then  $c = \tilde{c}$  in  $M$  near  $p$ .*

As mentioned earlier, this is the only known result for the boundary rigidity problem with partial data except in the case that the metrics are assumed to be real-analytic [17]. The latter follows from determination of the jet of the metric at a convex point from the distance function known near  $p$ .

The boundary rigidity problem is closely connected to the lens rigidity one. To define the latter, we first introduce the manifolds  $\partial_{\pm}SM$ , defined as the sets of all vectors  $(x, v)$  with  $x \in \partial M$ ,  $v$  unit in the metric  $g$ , and pointing outside/inside  $M$ . We define the lens relation

$$L : \partial_-SM \longrightarrow \partial_+SM$$

in the following way: for each  $(x, v) \in \partial_-SM$ ,  $L(x, v) = (y, w)$ , where  $y$  is the exit point, and  $w$  the exit direction, if exist, of the maximal unit speed geodesic  $\gamma_{x,v}$  in the metric  $g$ , issued from  $(x, v)$ . Let

$$\ell : \partial_-SM \longrightarrow \mathbf{R} \cup \infty$$

be its length, possibly infinite.

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<sup>1</sup>It is local in the sense that  $d(x, y)$  is known locally and depends on  $c$  locally; the term *local* has been used before to indicate that the metric is a priori close to a fixed one.

The *lens rigidity* problem is whether the lens relation  $L$  (and possibly,  $\ell$ ) determine  $g$  (and the topology of  $M$ ) up to an isometry as above. The lens rigidity problem with partial data for a sound speed is whether we can determine the speed near some  $p$  from  $L$  known near  $S_p\partial M$ . For general metrics, we want to recover isometric copies of the metrics locally, as above.

We assume that  $\partial M$  is strictly convex at  $p \in \partial M$  w.r.t.  $g$ . Then the boundary rigidity and the lens rigidity problems with partial data are equivalent: knowing  $d$  near  $(p, p)$  is equivalent to knowing  $L$  in some neighborhood of  $S_p\partial M$ . The size of that neighborhood however depends on a priori bounds of the derivatives of the metrics with which we work. This equivalence was first noted by Michel [19], since the tangential gradients of  $d(x, y)$  on  $\partial M \times \partial M$  give us the tangential projections of  $-v$  and  $w$ , see also [35, sec. 2]. Note that local knowledge of  $\ell$  is not needed for either problems, and in fact,  $\ell$  can be recovered locally from either  $d$  or  $\ell$ .

Vargo [45] proved that real-analytic manifolds satisfying an additional mild condition are lens rigid. Croke has shown that if a manifold is lens rigid, a finite quotient of it is also lens rigid [7]. He has also shown that the torus is lens rigid [3]. G. Uhlmann and P. Stefanov have shown lens rigidity locally near a generic class of non-simple manifolds [41]. The only result we know for the lens rigidity problem with partial data is for real-analytic metric satisfying a mild condition [41]. While in [41], the lens relation is assumed to be known on a subset only, the geodesics issued from that subset cover the whole manifold. In contrast, in this paper, we have localized information.

We state below an immediate corollary of our main result for this problem. For the partial data problem instead of assuming  $d = \tilde{d}$  locally, we can assume that  $L = \tilde{L}$  in a neighborhood of  $S_p\partial M$ . To reduce this problem to Theorem 1.1 directly, we need to assume first that  $c = \tilde{c}$  on  $\partial M$  near  $p$  to make the definition of  $\partial_{\pm}SM$  independent of the choice of the speed but in fact, one can redefine the lens relation in a way to remove that assumption, see [41].

**Corollary 1.1.** *Let  $M$ ,  $c$ ,  $\tilde{c}$  be as in Theorem 1.1 with  $c = \tilde{c}$  on  $\partial M$  near  $p$ . Let  $L = \tilde{L}$  near  $S_p\partial M$ . Then  $c = \tilde{c}$  in  $M$  near  $p$ .*

*Remark 1.1.* The theorem or its corollary does not preclude the existence of an infinite set of speeds  $c_j$  all having the same boundary distance function (or lens data) in  $U \times U$ , where  $U \subset \partial M$  is some fixed small set but not coinciding in any fixed neighborhood of  $p$ . One such case is when the neighborhood of  $U$ , which can be covered with strictly convex surfaces, which continuously deform  $U$ , shrinks when  $j \rightarrow \infty$ . Then the theorem does not imply existence of a fixed neighborhood of  $p$ , where all speeds equal. If one assumes that a priori, the sound speeds have uniform bounded derivatives of some finite order near  $p$ , this situation does not arise.

The linearization of the boundary rigidity and lens rigidity problem is the tensor tomography problem, i.e., recovery of a tensor field up to ‘‘potential fields’’ from integrals along geodesics joining points on the boundary. It has been extensively studied in the literature for both simple and non-simple manifolds [10, 24, 25, 26, 20, 28, 33, 30, 37, 40, 43]. See the book [31] and [26] for a recent survey. The *local* tensor tomography problem has been considered in [15] for functions and real-analytic metrics and in [16] for tensors of order two and real-analytic metrics. Those results can also be thought of as support theorems of Helgason type. The only known results for the local problem for smooth metrics and integrals of functions is [44].

Now we use a layer stripping type argument to obtain a global result which is different from Mukhometov’s for simple manifolds.

**Definition 1.1.** *Let  $(M, g)$  be a compact Riemannian manifold with boundary. We say that  $M$  satisfies the foliation condition by strictly convex hypersurfaces if  $M$  is equipped with a function  $\rho : \bar{M} \rightarrow [0, \infty)$  whose level sets  $\Sigma_t = \rho^{-1}(t)$ ,  $t < T$ , are strictly convex (viewed from  $\rho^{-1}((t, \infty))$  for  $g$ ,  $d\rho$  is non-zero on these level sets), with  $\Sigma_0 = \partial M$  and  $M \setminus \cup_{t \in [0, T)} \Sigma_t$  having empty interior.*

The statement of the global result on boundary rigidity is as follows:

**Theorem 1.2.** *Let  $n = \dim M \geq 3$ , let  $c > 0$ ,  $\tilde{c} > 0$  be smooth and let  $\partial M$  be strictly convex with respect to both  $g = c^{-2}g_0$  and  $\tilde{g} = \tilde{c}^{-2}g_0$ . Assume that  $M$  can be foliated by strictly convex hypersurfaces for  $g$  and  $\tilde{g}$ . Let  $d(p_1, p_2) = \tilde{d}(p_1, p_2)$  for  $p_1, p_2$  on  $\partial M$ . Then  $c = \tilde{c}$  in  $M$ .*

A more general foliation condition is formulated in [42]. In particular,  $\Sigma_0$  does not need to be  $\partial M$  and one can have several such foliations with the property that the closure of their union is  $M$ .

We remark that spherically symmetric  $c(x)$  under the condition considered by Herglotz and Wieckert and Zoeppritz satisfy the foliation condition of the theorem; as well as manifolds of negative sectional curvature do. Also, it follows from the result of [29], that manifolds with no focal points satisfy the foliation condition. It would be interesting to know whether this is also the case for simple manifolds. As it was mentioned earlier manifolds satisfying the foliation condition are not necessarily simple. Another question is whether the foliation condition, when the boundary is strictly convex, is equivalent to non-trapping.

The linearization of the non-linear problem with partial data considered in Theorem 1.1 was considered in [44], where uniqueness and stability were shown. This corresponds to integrating functions along geodesics joining points in a neighborhood of  $p$ . The method of proof of Theorem relies on using an identity proven in [36] to reduce the problem to a "pseudo-linear" one: to show uniqueness when one integrate the function  $f =$  and its derivatives on the geodesics for the metric  $g$  joining points near  $p$ , with weight depending non-linearly on both  $g$  and  $\tilde{g}$ . Notice that this is not a proof by linearization, and unlike the problem with full data, an attempt to do such a proof is connected with essential difficulties. The proof of uniqueness for this linear transform follows the method of [44] introducing an artificial boundary and using Melrose' scattering calculus. In section 2, we do the reduction to a "pseudo-linear problem", and in section 3, we show uniqueness for the "pseudo-linear" problem. In section 4, we finish the proofs of the main theorems.

## 2. REDUCING THE NON-LINEAR PROBLEM TO A PSEUDO-LINEAR ONE

We recall the known fact [17] that one can determine the jet of  $c$  at any boundary point  $p$  at which  $\partial M$  is convex (not necessarily strictly) from the distance function  $d$  known near  $(p, p)$ . For a more general result not requiring convexity, see [41]. Since the result in [17] is formulated for general metrics, and the reconstruction of the jet is in boundary normal coordinates, we repeat the proof in this (simpler) situation of recovery a conformal factor. As in [17], we say that  $\partial M$  is convex near  $p \in \partial M$ , if for any two distinct points  $p_1, p_2 \in \partial M$ , close enough to  $p$ , there exists a geodesic  $\gamma : [0, 1] \rightarrow M$  joining them such that its length is  $d(p_1, p_2)$  and all the interior of  $\gamma$  belongs to the interior of  $M$ . Of course, strict convexity (positive second fundamental form at  $p$ ) implies convexity.

**Lemma 2.1.** *Let  $c$  and  $\tilde{c}$  be smooth and let  $\partial M$  be convex at  $p$  with respect to  $g$  and  $\tilde{g}$ . Let  $d = \tilde{d}$  near  $(p, p)$ . Then  $\partial^\alpha c = \partial^\alpha \tilde{c}$  on  $\partial M$  near  $p$  for any multiindex  $\alpha$ .*

*Proof.* Let  $V \subset \partial M$  be a neighborhood of  $p$  on  $\partial M$  such that for any  $p_1, p_2 \in V$ , we have the property guaranteeing convexity at  $p$ . Let  $x^n$  be a boundary normal coordinate related to  $g$ ; i.e.,  $x^n(q) = \text{dist}(q, \partial M)$ , and  $x^n \geq 0$  in  $M$ . We can complete  $x^n$  to a local coordinate system  $(x', x^n)$ , where  $x'$  parameterizes  $\partial M$  near  $p$ .

It is enough to prove

$$(1) \quad \partial_{x^n}^k c = \partial_{x^n}^k \tilde{c} \quad \text{in } V, \quad k = 0, 1, \dots$$

For  $k = 0$ , this follows easily by taking the limit in  $d(p, q) = \tilde{d}(p, q)$ ,  $\partial M \ni q \rightarrow p$ ; and this can be done for any  $p \in V$ . Let  $l$  be the first value of  $k$  for which (1) fails. Without loss of generality, we may assume that it fails at  $p$ , and  $\partial_{x^n}^l(c - \tilde{c}) > 0$  at  $p$ . Then  $\partial_{x^n}^k(c - \tilde{c}) = 0$  in  $V$ ,  $k = 0, \dots, l - 1$ . Consider the Taylor expansion of  $c - \tilde{c}$  w.r.t.  $x^n$  with  $x'$  close enough to  $x'(p)$ . We get  $c - \tilde{c} > 0$  in some neighborhood of  $p$  in  $M$  minus the boundary.

Now, let  $\gamma(p, q)$  be a minimizing geodesic in the metric  $g$  connecting  $p$  and  $q$  when  $q \in \partial M$  as well, close enough to  $p$ , see also [17]. Let  $I f(p, q)$  be the geodesic ray transform of the tensor field  $f$  defined as an integral of  $f_{ij} \dot{\gamma}^i \dot{\gamma}^j$  along  $\gamma(p, q)$ . All geodesics here are parameterized by a parameter in  $[0, 1]$ . Then  $I(g - \tilde{g}) > 0$  by what we proved above. On the other hand,

$$0 < I(g - \tilde{g}) = d^2(p, q) - I\tilde{g} \leq d^2(p, q) - \tilde{I}\tilde{g} = d^2(p, q) - \tilde{d}^2(p, q) = 0$$

because  $\tilde{\gamma}(p, q)$  minimizes integrals of  $g$  along curves connecting  $p$  and  $q$ . This a contradiction.  $\square$

The starting point is an identity in [36]. We will repeat the proof.

Let  $V, \tilde{V}$  be two vector fields on a manifold  $M$  (which will be replaced later with  $S^*M$ ). Denote by  $X(s, X^{(0)})$  the solution of  $\dot{X} = V(X)$ ,  $X(0) = X^{(0)}$ , and we use the same notation for  $\tilde{V}$  with the corresponding solution are denoted by  $\tilde{X}$ . Then we have the following simple statement.

**Lemma 2.2.** *For any  $t > 0$  and any initial condition  $X^{(0)}$ , if  $\tilde{X}(\cdot, X^{(0)})$  and  $X(\cdot, X^{(0)})$  exist on the interval  $[0, t]$ , then*

$$(2) \quad \tilde{X}(t, X^{(0)}) - X(t, X^{(0)}) = \int_0^t \frac{\partial \tilde{X}}{\partial X^{(0)}}(t-s, X(s, X^{(0)})) (V - \tilde{V})(X(s, X^{(0)})) ds.$$

*Proof.* Set

$$F(s) = \tilde{X}(t-s, X(s, X^{(0)})).$$

Then

$$F'(s) = -\tilde{V}(\tilde{X}(t-s, X(s, X^{(0)}))) + \frac{\partial \tilde{X}}{\partial X^{(0)}}(t-s, X(s, X^{(0)})) V(X(s, X^{(0)})).$$

The proof of the lemma would be complete by the fundamental theorem of calculus

$$F(t) - F(0) = \int_0^t F'(s) ds$$

if we show the following

$$(3) \quad \tilde{V}(\tilde{X}(t-s, X(s, X^{(0)}))) = \frac{\partial \tilde{X}}{\partial X^{(0)}}(t-s, X(s, X^{(0)})) \tilde{V}(X(s, X^{(0)})).$$

Indeed, (3) follows from

$$0 = \frac{d}{d\tau} \Big|_{\tau=0} X(T-\tau, X(\tau, Z)) = -V(X(T, Z)) + \frac{\partial X}{\partial X^{(0)}}(T, Z)V(Z), \quad \forall T,$$

after setting  $T = t - s$ ,  $Z = X(s, X^{(0)})$ .  $\square$

Let  $c, \tilde{c}$  be two speeds. Then the corresponding metrics are  $g = c^{-2}dx^2$ , and  $\tilde{g} = \tilde{c}^{-2}dx^2$ . The corresponding Hamiltonians and Hamiltonian vector fields are

$$H = \frac{1}{2}c^2 g_0^{ij} \xi_i \xi_j, \quad V = \left( c^2 g_0^{-1} \xi, -\frac{1}{2} \partial_x c^2 |\xi|_{g_0}^2 \right),$$

and the same ones related to  $\tilde{c}$ . We used the notation  $|\xi|_{g_0}^2 := g_0^{ij} \xi_i \xi_j$ .

We change the notation at this point. We denote points in the phase space  $T^*M$ , in a fixed coordinate system, by  $z = (x, \xi)$ . We denote the bicharacteristic with initial point  $z$  by  $Z(t, z) = (X(t, z), \Xi(t, z))$ .

Then we get the identity already used in [36]

$$(4) \quad \tilde{Z}(t, z) - Z(t, z) = \int_0^t \frac{\partial \tilde{Z}}{\partial z}(t-s, Z(s, z))(V - \tilde{V})(Z(s, z)) ds.$$

We can naturally think of the lens relation  $L$  and the travel time  $\ell$  as functions on the cotangent bundle instead of the tangent one. Then we get the following.

**Proposition 2.1.** *Assume*

$$(5) \quad L(x_0, \xi^0) = \tilde{L}(x_0, \xi^0), \quad \ell(x_0, \xi^0) = \tilde{\ell}(x_0, \xi^0)$$

for some  $z_0 = (x_0, \xi^0) \in \partial_- S^*M$ . Then

$$\int_0^{\ell(z_0)} \frac{\partial \tilde{Z}}{\partial z}(\ell(z_0) - s, Z(s, z_0))(V - \tilde{V})(Z(s, z_0)) ds = 0.$$

**2.1. Linearization near  $c = 1$  and  $g$  Euclidean.** As a simple exercise, let  $c = 1$ ,  $g_{ij} = \delta_{ij}$  and linearize for  $\tilde{c}$  near 1 first under the assumption that  $\tilde{c} = 1$  outside  $\Omega$ . Then

$$(6) \quad Z(s, z) = \begin{pmatrix} 1 & s \\ 0 & 1 \end{pmatrix} z, \quad \frac{\partial Z(s, z)}{\partial z} = \begin{pmatrix} 1 & s \\ 0 & 1 \end{pmatrix},$$

and we get the following formal linearization of (4)

$$(7) \quad \int \left( f\xi - \frac{1}{2}(t-s)(\partial_x f), -\frac{1}{2}\partial_x f \right) (x + s\xi, \xi) ds = 0,$$

where

$$(8) \quad f := c^2 - \tilde{c}^2.$$

We integrate over the whole line  $s \in \mathbf{R}$  because the integrand vanishes outside the interval  $[0, \ell(x, \xi)]$ . The last  $n$  components of (7) imply

$$(9) \quad \int \partial_x f(x + s\xi) ds = 0.$$

Now, assume that this holds for all  $(x, \xi)$ . Then  $\partial_x f = 0$ , and since  $f = 0$  on  $\partial M$ , we get  $f = 0$ .

**2.2. The general case.** We take the second  $n$ -dimensional component on (4) and use the fact that  $c^2|\xi|_g^2 = 1$  on the bicharacteristics related to  $c$ . We assume that both geodesics extend to  $t \in [0, \ell(x, \xi)]$ . We want to emphasize that the bicharacteristics on the energy level  $H = 1/2$ , related to  $c$ , do not necessarily stay on the same energy level for the Hamiltonian  $\tilde{H}$ . We get

$$(10) \quad \int \frac{\partial \tilde{\Xi}}{\partial x}(\ell(z) - s, Z(s, z))(fg_0^{-1}\xi)(Z(s, z)) ds \\ - \frac{1}{2} \int \frac{\partial \tilde{\Xi}}{\partial \xi}(\ell(z) - s, Z(s, z))(\partial_x(fg_0^{-1})\xi \cdot \xi)(Z(s, z)) ds = 0$$

for any  $z \in \partial_- SM$  for which (5) holds. As before, we integrate over  $s \in \mathbf{R}$  because the support of the integrand vanishes for  $s \notin [0, \ell(x, \xi)]$  (for that, we extend the bicharacteristics formally outside so that they do not come back). Write

$$\partial_x(fg_0^{-1}) = g_0^{-1}\partial_x f + (\partial_x g_0^{-1})f$$

to get

$$(11) \quad \int \frac{\partial \tilde{\Xi}}{\partial x}(\ell(z) - s, Z(s, z))(f g_0^{-1} \xi)(Z(s, z)) ds - \frac{1}{2} \int \frac{\partial \tilde{\Xi}}{\partial \xi}(\ell(z) - s, Z(s, z)) ((g_0^{-1} \partial_x f + f(\partial_x g_0^{-1}) \xi \cdot \xi)(Z(s, z)) ds = 0.$$

One of terms on the r.h.s. above involves  $g_0^{-1} \xi \cdot \xi$  which equals  $c^{-2}$  on the bicharacteristics of  $H$  on the level  $1/2$ .

Introduce the exit times  $\tau(x, \xi)$  defined as the minimal (and the only)  $t \geq 0$  so that  $X(t, x, \xi) \in \partial M$ . They are well defined near  $S_p \partial M$ , if  $\partial M$  is strictly convex at  $p$ . We need to write  $\frac{\partial \tilde{Z}}{\partial z}(\ell(z) - s, Z(s, z))$  as a function of  $(x, \xi) = Z(s, z)$ . We have

$$\frac{\partial \tilde{Z}}{\partial z}(\ell(z) - s, Z(s, z)) = \frac{\partial \tilde{Z}}{\partial z}(\tau(x, \xi), (x, \xi)).$$

Then we get, with  $f$  as in (8),

$$(12) \quad J_i f(\gamma) := \int \left( A_i^j(X(t), \Xi(t)) (\partial_{x^j} f)(X(t)) + B_i(X(t), \Xi(t)) f(X(t)) \right) dt = 0$$

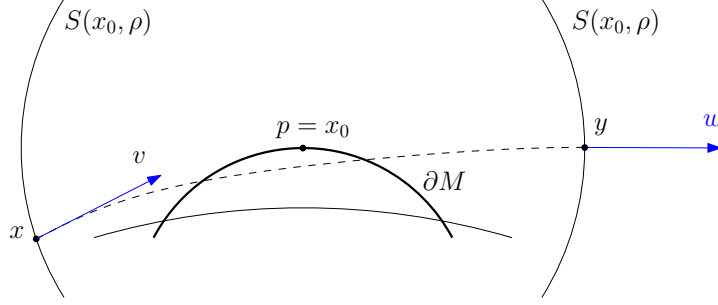
for any bicharacteristic  $X((t), \Xi(t))$  (related to the speed  $c$ ) in our set, where

$$(13) \quad A_i^j(x, \xi) = -\frac{1}{2} \frac{\partial \tilde{\Xi}_i}{\partial \xi_j}(\tau(x, \xi), (x, \xi)) c^{-2}(x),$$

$$B_i(x, \xi) = \frac{\partial \tilde{\Xi}_i}{\partial x^j}(\tau(x, \xi), (x, \xi)) g_0^{jk}(x) \xi_k - \frac{1}{2} \frac{\partial \tilde{\Xi}_i}{\partial \xi_j}(\tau(x, \xi), (x, \xi)) (\partial_{x^j} g_0^{-1}(x)) \xi \cdot \xi.$$

A major inconvenience with this representation is that the exit time function  $\tau(x, \xi)$  (recall that we assume strong convexity) becomes singular at  $(x, \xi) \in T^* \partial M$ . More precisely, the normal derivative w.r.t.  $x$  when  $\xi$  is tangent to  $\partial M$  has a square root type of singularity. On the other hand, we have some freedom to extend the flow outside  $M$  since we know that the jets of  $c$  and  $\tilde{c}$  at  $\partial M$  are the same near  $p$ : therefore, any smooth local extension of  $c$  is also a smooth extension of  $\tilde{c}$ . Then for any  $(x, \xi) \in \partial_- S^* M$  close enough to  $S_{x_0}^* M$ , the bicharacteristics originating from it will be identical once they exist  $T^* M$  but are still close enough to it. Similarly, instead of starting from  $T^* \partial M$ , we could start at points and codirections close to it, but away from  $\bar{M}$ .

With this in mind, we push the boundary away a bit. Let  $x_0$  represent the point  $p$  near which we work, in a fixed coordinate system. Let  $S(x_0, \rho)$  be the sphere in the metric  $c^{-2} dx^2$  centered at  $x_0$  with radius  $0 < \rho \ll 1$ . For  $(x, \xi)$  with  $x$  in the geodesic ball  $B(x_0, \rho)$ , redefine  $\tau(x, \xi)$  to be the travel time from  $(x, \xi)$  to  $S(x_0, \rho)$ . Let  $U_- \subset \partial_- SB(x_0, \rho)$  be the set of all points on  $S(x_0, \rho)$  and incoming unit directions so that the corresponding geodesic in the metric  $g$  is close enough to one tangent to  $\partial M$  at  $x_0$ . Similarly, let  $U_+$  be the set of such pairs with outgoing directions. Redefine the scattering relation  $L$  locally to act from  $U_-$  to  $U_+$ , and redefine  $\ell$  similarly, see Figure 1. Then  $L = \tilde{L}$  and  $\ell = \tilde{\ell}$  on  $U_-$ . We can apply the construction above by replacing  $\partial_{\pm} SM$  locally by  $U_{\pm}$ . The advantage we have now that on  $U_-$ , the travel time  $\tau$  is non-singular. Equalities (12), (13) are preserved then.

FIGURE 1. The redefined lens relation  $(x, v) \mapsto (y, w)$ 

We now have

$$(14) \quad \begin{aligned} A_i^j(x_0, \xi) &= -\frac{1}{2} \frac{\partial \tilde{\Xi}_i}{\partial \xi_j}(\rho, (x_0, \xi)) c^{-2}(x_0), \\ B_i(x_0, \xi) &= \frac{\partial \tilde{\Xi}_i}{\partial x^j}(\rho, (x_0, \xi)) g_0^{ik}(x_0) \xi_k - \frac{1}{2} \frac{\partial \tilde{\Xi}_i}{\partial \xi_j}(\rho, (x, \xi)) (\partial_{x^j} g_0^{-1}(x_0)) \xi \cdot \xi. \end{aligned}$$

When  $\rho = 0$ , we have  $A_i^j(x_0, \xi) = -\frac{1}{2} c^{-2}(x_0) \delta_i^j$ . In particular,  $\{A_i^j(x_0, \xi)\}$  is an invertible matrix, uniformly in  $\xi \in S_{x_0}^* M$ . When  $0 < \rho \ll 1$ , this property is preserved. We fix such an  $\rho$ . Then

$$(15) \quad \{A_i^j(x_0, \xi)\} \text{ is an invertible matrix.}$$

**2.3. A new linear problem.** The arguments above lead to the following linear problem:

**Problem.** Assume (12) holds for all geodesics  $\delta$ -close to the ones originating from  $S_{x_0}^* \partial M$  (i.e. initial point  $x_0$  and all unit initial co-directions tangent to  $\partial M$ ), for some  $\delta > 0$ . Assume that  $\partial M$  is strictly convex at  $x_0$  w.r.t. the speed  $c$ . Assume (15) with some  $A_i^j, B_i$  so that (15) holds for some  $f$  supported in  $M$ . Is it true that  $f = 0$  near  $x_0$ ?

We show below in Proposition 3.3, that the answer is affirmative. Note that this reduces the original non-linear to a linear one but this is not a linearization.

### 3. LINEAR ANALYSIS

We first recall the setting introduced in [44] in our current notation. There the scalar X-ray transform along geodesics was considered, namely for  $\beta \in SM$ ,

$$(If)(\beta) = \int_{\mathbb{R}} f(\gamma_\beta(t)) dt,$$

where  $\gamma_\beta$  is the geodesic with lift to  $SM$  having starting point  $\beta \in SM$ . Here  $M$  is assumed to have a strictly convex boundary, which can be phrased as the statement that if  $\rho$  is a defining function for  $\partial M$ , then  $-\frac{d^2}{dt^2}(\rho \circ \gamma_\beta)|_{t=0} \geq C > 0$  whenever  $\beta \in T\partial M$ . One then considers a point  $p \in \partial M$ , and another function  $\tilde{x}$ , denoted in [44] by  $\tilde{x}$ , such that  $\tilde{x}(p) = 0$ ,  $d\tilde{x}(p) = -d\rho(p)$ , and the level sets of  $\tilde{x}$  near the 0 are strictly concave when viewed from the superlevel sets (which are on the side of  $p$  when talking about the  $c$ -level set with  $c < 0$ ), i.e.  $\frac{d^2}{dt^2}(\tilde{x} \circ \gamma_\beta)|_{t=0} \geq C > 0$  if  $\beta \in T\{\tilde{x} = c\}$ , i.e. if  $\frac{d}{dt}(\tilde{x} \circ \gamma_\beta)|_{t=0} = 0$ . For  $c > 0$ , we denote  $M \cap \{x > -c\}$  by  $\Omega_c$ ; we assume that  $c_0 > 0$  is such that  $\overline{\Omega_{c_0}}$  is compact on  $M$ , and the concavity assumption holds on  $\Omega_{c_0}$ . Then it was shown that the X-ray transform  $I$  restricted to  $\beta \in S\overline{\Omega_c}$  such that  $\gamma_\beta$  leaves  $\Omega_c$  with both endpoints on  $\partial M$



(i.e. at  $\rho = 0$ ) is injective if  $c > 0$  is sufficiently small, and indeed one has a stability estimate for  $f$  in terms of  $If$  on exponentially weighted spaces.

To explain this in detail, let  $x = x_c = \tilde{x} + c$  be the boundary defining function of the artificial boundary,  $\tilde{x} = -c$ , that we introduced; indeed it is convenient to work in  $\tilde{M}$ , a  $C^\infty$  manifold extending  $M$  across the boundary, and defining  $\hat{\Omega} = \hat{\Omega}_c = \{x_c > 0\}$  as the extension of  $\Omega$ , so  $\bar{\hat{\Omega}}$  is a smooth manifold with boundary, with only the artificial boundary being a boundary face. Then one writes  $\beta = (\lambda, \omega) = \lambda \partial_x + \omega \partial_y \in S_{x,y} \tilde{M}$  relative to a product decomposition  $(-c_0, c_0)_x \times U_y$  of  $\tilde{M}$  near  $p$ . The concavity condition becomes that for  $\beta$  whose  $\lambda$ -component vanishes,

$$2\alpha(x, y, 0, \omega) = \frac{d^2}{dt^2} (x \circ \gamma_\beta)|_{t=0} \geq 2C > 0,$$

with a new  $C > 0$ , see the discussion preceding Equation (3.1) in [44]. For  $\chi \in C_c^\infty(\mathbb{R})$ ,  $\chi \geq 0$ ,  $\chi(0) > 0$ , one considers the map

$$L_0 v(x, y) = \int_{\mathbb{R}} \int_{S^{n-2}} x^{-2} \chi(\lambda/x) v(x, y, \lambda, \omega) d\lambda d\omega$$

defined for  $v$  a function on  $S_{\bar{\hat{\Omega}}} \tilde{M}$ . This differs from [44] in that the weight  $x^{-2}$  differs by 1 from the weight  $x^{-1}$  used in [44]; this simply has the effect of removing an  $x^{-1}$  in [44, Proposition 3.3], as compared to the proposition stated below. If  $c$  is sufficiently small, or instead  $\chi$  has sufficiently small support, for  $(x, y) \in \bar{\hat{\Omega}}$ ,  $I$  only integrates over points in  $\beta \in S_{\bar{\hat{\Omega}}}$  such that  $\gamma_\beta$  leaves  $\Omega_c$  with both endpoints on  $\partial M$ , i.e. over  $\beta$  corresponding to  $\Omega_c$ -local geodesics – the set of the latter is denoted by  $\mathcal{M}_c$ . We refer to the discussion around [44, Equation (3.1)] for more detail, but roughly speaking the concavity of the level sets of  $x$  means that the geodesics that are close to being tangent to the foliation, with ‘close’ measured by the distance from the artificial boundary,  $x = 0$ , then they cannot reach  $x = 0$  (or reach again, in case they start there) without reaching  $x = c'$  for some fixed  $c' > 0$ ; notice that the geodesics involved in the integration through a point on the level set  $x = \tilde{c}$  make an angle  $\lesssim \tilde{c}$  with the tangent space of the level set due to the compact support of  $\chi$ . Then we consider the map  $P = L_0 \circ I$ . The main technical result of [44], whose notation involving the so-called scattering Sobolev spaces  $H_{sc}^{s,r}(\bar{\hat{\Omega}})$  and scattering pseudodifferential operators  $\Psi_{sc}^{s,r}(\bar{\hat{\Omega}})$  is explained below, was:

**Proposition 3.1.** (See [44, Proposition 3.3 and Lemma 3.6].) *For  $F > 0$  let*

$$P_F = e^{-F/x} P e^{F/x} : C_c^\infty(\bar{\hat{\Omega}}) \rightarrow C^\infty(\bar{\hat{\Omega}}).$$

*Then  $P_F \in \Psi_{sc}^{-1,0}(\bar{\hat{\Omega}})$ .*

*Further, if  $c > 0$  is sufficiently small then for suitable choice of  $\chi \in C_c^\infty(\mathbb{R})$  with  $\chi(0) = 1$ ,  $\chi \geq 0$ ,  $P$  is elliptic in  $\Psi_{sc}^{-1,0}(\bar{\hat{\Omega}})$  on a neighborhood of  $\bar{\hat{\Omega}}$ .*

*Shrinking  $c$  further if needed,  $P_F$  satisfies the estimate*

$$(16) \quad \|v\|_{H_{sc}^{s,r}(\bar{\hat{\Omega}})} \leq C \|P_F v\|_{H_{sc}^{s+1,r}(\bar{\hat{\Omega}})}$$

*for  $v$  supported in  $M \cap \bar{\hat{\Omega}}$ .*

We now briefly explain the role of the so-called scattering pseudodifferential operators and the corresponding Sobolev spaces (which are typically used to study phenomena ‘at infinity’) in our problem (where there is no obvious ‘infinity’); we refer to [44, Section 2] for a more thorough exposition. These concepts were introduced by Melrose, [18], in a general geometric setting, but on  $\mathbb{R}^n$  these operators actually correspond to a special case of Hörmander’s Weyl calculus [13],

also studied earlier by Shubin [34] and Parenti [23]. So consider the reciprocal spherical coordinate map,  $(0, \epsilon)_x \times \mathbb{S}_\theta^{n-1} \rightarrow \mathbb{R}^n$ , with  $\mathbb{S}^{n-1} \subset \mathbb{R}^n$  (unit sphere), and map  $(x, \theta) \mapsto x^{-1}\theta \in \mathbb{R}^n$ . This map is a diffeomorphism onto its range, and it provides a compactification of  $\mathbb{R}^n$  (the so called radial or geodesic compactification) by adding  $\{0\}_x \times \mathbb{S}_\theta^{n-1}$  as infinity to  $\mathbb{R}^n$ , to obtain  $\overline{\mathbb{R}^n}$ , which is now diffeomorphic to a ball. Now for general  $U_y$  above, we may regard, at least locally<sup>2</sup>  $U_y$  also as a coordinate chart in  $\mathbb{S}^{n-1}$ , and thus obtain an identification of  $\overline{\Omega}$  with a region intersection  $\overline{\mathbb{R}^n}$ , thus our artificial boundary  $x = 0$  corresponds to infinity at  $\mathbb{R}^n$ . In particular, notions from  $\mathbb{R}^n$  can now be transferred to a neighborhood of our artificial boundary. Since the relevant vector fields on  $\mathbb{R}^n$  are generated by translation invariant vector fields, which are complete under the exponential map, the transferred analysis replaces the incomplete geometry of standard vector fields on  $\overline{\Omega}$  by a complete one. Concretely, these vector fields, when transferred, become linear combinations of  $x^2\partial_x$  and  $x\partial_{y_j}$ , with smooth coefficients. In particular, these are the vector fields with respect to which Sobolev regularity is measured. Thus,  $H_{sc}^{s,r}(\overline{\Omega})$  is the so-called *scattering Sobolev space*, which is locally, under the above identification, just the standard weighted Sobolev space  $H^{s,r}(\mathbb{R}^n)$ , see [44, Section 2], while  $\Psi_{sc}^{s,r}(\overline{\Omega})$  is Melrose's *scattering pseudodifferential algebra*, which locally, again under this identification, simply corresponds to quantizing symbols  $a$  with  $|D_z^\alpha D_\zeta^\beta a| \leq C\langle z \rangle^{r-|\alpha|}\langle \zeta \rangle^{s-|\beta|}$  on  $T^*\mathbb{R}^n = \mathbb{R}_z^n \times \mathbb{R}_\zeta^n$ , see again [44, Section 2] for more detail.

Notice that (16) implies the estimate

$$\|f\|_{e^{F/x}H_{sc}^{s,r}(\overline{\Omega})} \leq C\|Pf\|_{e^{F/x}H_{sc}^{s+1,r}(\overline{\Omega})}$$

for the unconjugated operator, valid when  $f$  is supported in  $M \cap \overline{\Omega}$ . Rewriting  $P$  as  $L_0 \circ I$ , this gives that for  $\delta > 0$ ,  $s \geq -1$ ,

$$\|f\|_{e^{(F+\delta)/x}H^s(\overline{\Omega})} \leq C\|If\|_{e^{F/x}H^{s+1}(\mathcal{M}_c)};$$

see the discussion in [44] after Lemma 3.6.

After this recollection, we continue by generalizing (12) to regard the functions  $\partial_{x_j}f$  and  $f$  entering into it as independent unknowns, while restricting the transform to the region of interest  $\Omega = \Omega_c$ . So let  $\tilde{J}_i$  be defined by

$$\tilde{J}_i(u_0, u_1, \dots, u_n)(\beta) := \int_{\gamma_\beta} \left( A_i^j(X(t), \Xi(t))u_j(X(t)) + B_i(X(t), \Xi(t))u_0(X(t)) \right) dt,$$

where  $\gamma_\beta$  is the geodesic with lift to  $S\Omega$  having starting point  $\beta \in S\Omega$ . Let  $\tilde{J} = (\tilde{J}_1, \dots, \tilde{J}_n)$ . This is a vector valued version of the geodesic X-ray transform considered in [44], and described above, sending functions on  $\Omega$  with values in  $\mathbb{C}^{n+1}$  to functions with values in  $\mathbb{C}^n$ . We then define  $L$  as a map from  $\mathbb{C}^n$ -valued functions on  $S\Omega$  to  $\mathbb{C}^n$  valued functions on  $\Omega$  by

$$Lv(x, y) = \int_{\mathbb{R}} \int_{\mathbb{S}^{n-2}} x^{-2} \chi(\lambda/x) v(x, y, \lambda, \omega) d\lambda d\omega$$

as in [44]; this is a diagonal operator:  $L = L_0 \otimes \text{Id}$ . Then we consider the map  $P = L \circ \tilde{J}$ . The main technical result here is:

**Proposition 3.2.** *For  $F > 0$  let*

$$P_F = e^{-F/x} P e^{F/x} : \mathcal{C}_c^\infty(\overline{\Omega}; \mathbb{C}^{n+1}) \rightarrow \mathcal{C}^\infty(\overline{\Omega}; \mathbb{C}^n).$$

<sup>2</sup>That is, possibly at the cost of shrinking it; in fact all concepts below are essentially local within  $\mathbb{S}^{n-1}$ , thus even in full generality one can reduce scattering objects to (conic regions near infinity in)  $\mathbb{R}^n$  this way, much as standard Sobolev spaces and pseudodifferential operators are so reduceable to subsets of  $\mathbb{R}^n$  with compact closure

Then  $P_F \in \Psi_{\text{sc}}^{-1,0}(\overline{\Omega}; \mathbb{C}^{n+1}, \mathbb{C}^n)$ .

Further, if  $\mathfrak{c}$  is sufficiently small then for suitable choice of  $\chi \in \mathcal{C}_c^\infty(\mathbb{R})$  with  $\chi(0) = 1$ ,  $\chi \geq 0$ , if we write  $P_F = (P_0, \tilde{P})$ , with  $P_0$  corresponding to the first component,  $\tilde{P}$  the last  $n$  components, in the domain space, then  $\tilde{P}$  is elliptic in  $\Psi_{\text{sc}}^{-1,0}(\overline{\Omega}; \mathbb{C}^n, \mathbb{C}^n)$  in a neighborhood of  $\overline{\Omega}$ .

*Proof.* This is simply a vector valued version of [44, Proposition 3.3] and [44, Lemma 3.6], recalled above in Proposition 3.1. In particular, to show  $P \in \Psi_{\text{sc}}^{-1,0}(\overline{\Omega}; \mathbb{C}^{n+1}, \mathbb{C}^n)$ , it suffices to show that  $P$  is a matrix of pseudodifferential operators  $P_{ij} \in \Psi_{\text{sc}}^{-1,0}(\overline{\Omega})$ ,  $i = 1, 2, \dots, n$ ,  $j = 0, 1, 2, \dots, n$ . But for  $j > 0$ , with  $j = 0$  being completely analogous,  $P_{ij}w$  has the form

$$\int_{\mathbb{R}} \int_{\mathbb{S}^{n-2}} x^{-2} \chi(\lambda/x) \int A_i^j(X_{x,y,\lambda,\omega}(t), \Xi_{x,y,\lambda,\omega}(t)) w(X_{x,y,\lambda,\omega}(t)) dt d\lambda d\omega$$

The only difference from [44, Proposition 3.3] then is the presence of the weight factor

$$A_i^j(X_{x,y,\lambda,\omega}(t), \Xi_{x,y,\lambda,\omega}(t)).$$

It is convenient to rewrite this via the metric identification, say by  $g_0$ , in terms of tangent vectors. Changing the notation for the flow, in our coordinates  $(x, y, \lambda, \omega)$ , writing now

$$(\gamma_{x,y,\lambda,\omega}(t), \gamma'_{x,y,\lambda,\omega}(t)) = (X_{x,y,\lambda,\omega}(t), Y_{x,y,\lambda,\omega}(t), \Lambda_{x,y,\lambda,\omega}(t), \Omega_{x,y,\lambda,\omega}(t))$$

for the lifted geodesic  $\gamma_{x,y,\lambda,\omega}(t)$ ,

$$\tilde{A}_i^j(X_{x,y,\lambda,\omega}(t), Y_{x,y,\lambda,\omega}(t), \Lambda_{x,y,\lambda,\omega}(t), \Omega_{x,y,\lambda,\omega}(t))$$

replaces  $A_i^j(X_{x,y,\lambda,\omega}(t), \Xi_{x,y,\lambda,\omega}(t))$ . As in [44, Proposition 3.3] one rewrites the integral in terms of coordinates  $(x, y, x', y')$  on the left and right factors of  $\overline{\Omega}$  (i.e. one explicitly expresses the Schwartz kernel), using that the map

$$\Gamma_+ : SM \times [0, \infty) \rightarrow [\tilde{M} \times \tilde{M}; \text{diag}], \quad \Gamma_{\pm}(x, y, \lambda, \omega, t) = ((x, y), \gamma_{x,y,\lambda,\omega}(t))$$

is a local diffeomorphism, and similarly for  $\Gamma_-$  in which  $(-\infty, 0]$  takes the place of  $[0, \infty)$ ; see the discussion around [44, Equation (3.2)-(3.3)]. Here  $[\tilde{M} \times \tilde{M}; \text{diag}]$  is the *blow-up* of  $\tilde{M}$  at the diagonal  $z = z'$ , which essentially means the introduction of spherical/polar coordinates, or often more conveniently projective coordinates, about it. Concretely, writing the (local) coordinates from the two factors of  $\tilde{M}$  as  $(z, z')$ ,

$$z, |z - z'|, \frac{z - z'}{|z - z'|}$$

give (local) coordinates on this space. Further,

$$(x, y, \lambda, \omega, t) \mapsto \gamma'_{x,y,\lambda,\omega}(t)$$

is a smooth map  $SM \times \mathbb{R} \rightarrow \mathbb{R}^n$  so composing it with  $\Gamma_{\pm}^{-1}$  from the right, one can reexpress the integral giving  $P_{ij}w$  away from the boundary as

$$\int w(z') |z - z'|^{-n+1} b\left(z, \frac{z - z'}{|z - z'|}, |z - z'|\right) dz'$$

as in [44, Equation (3.7)], with

$$b\left(z, \frac{z - z'}{|z - z'|}, 0\right) = \tilde{\chi}\left(z, \frac{z' - z}{|z' - z|}\right) \tilde{A}_i^j\left(z, \frac{z' - z}{|z' - z|}\right) \sigma\left(z, \frac{z' - z}{|z' - z|}\right)$$

with  $\sigma > 0$ , bounded below by a positive constant, a weight factor, and where  $\chi(\lambda/x)$  is written as  $\tilde{\chi}(x, y, \lambda, \omega)$ . Recall from [44, Section 2] that coordinates on Melrose's scattering double space,

on which the Schwartz kernels of elements of  $\Psi_{\text{sc}}^{s,r}(\bar{\Omega})$  are conormal to the diagonal, near the lifted scattering diagonal, are

$$x, y, X = \frac{x-x'}{x^2}, Y = \frac{y-y'}{x}.$$

Then, similarly, near the boundary as in [44, Equation (3.13)], one obtains the Schwartz kernel

$$(17) \quad K^b(x, y, X, Y) = e^{-FX/(1+X)} \chi\left(\frac{X}{|Y|} + |Y|\tilde{\Lambda}(x, y, x|Y|, \frac{x|X|}{|Y|}, \hat{Y})\right) \\ \tilde{A}_i^j\left(\Gamma^{-1}(x, y, x|Y|, \frac{xX}{|Y|}, \hat{Y})\right) |Y|^{-n+1} J\left(x, y, \frac{X}{|Y|}, |Y|, \hat{Y}\right),$$

with the density factor  $J$  smooth, positive,  $= 1$  at  $x = 0$ . Here

$$x, y, |Y|, \frac{X}{|Y|}, \hat{Y}$$

are valid coordinates on the blow-up of the scattering diagonal in<sup>3</sup>  $|Y| > \epsilon|X|$ ,  $\epsilon > 0$ , which is the case automatically on the support of the kernel due to the argument of  $\chi$ , cf. the discussion after [44, Equation(3.12)], so the argument of  $\tilde{A}_i^j \circ \Gamma^{-1}$  is smooth. We can evaluate this argument: for instance, by [44, Equation(3.10)],

$$(\Lambda \circ \Gamma^{-1})(x, y, x|Y|, \frac{xX}{|Y|}, \hat{Y}) = x\frac{X}{|Y|} + x|Y|\tilde{\Lambda}(x, y, x|Y|, \frac{xX}{|Y|}, \hat{Y})$$

with  $\tilde{\Lambda}$  smooth, while the subsequent equation in the same location gives

$$(\Omega \circ \Gamma^{-1})(x, y, x|Y|, \frac{xX}{|Y|}, \hat{Y}) = \hat{Y} + x|Y|\tilde{\Omega}(x, y, x|Y|, \frac{xX}{|Y|}, \hat{Y})$$

with  $\tilde{\Omega}$  smooth. This proves the first part of the proposition as in [44, Proposition 3.3].

To prove the second part, note that in view of (17) (which just needs to be evaluated at  $x = 0$ ), [44, Lemma 3.5] is replaced by the statement that the boundary principal symbol of  $P_{ij}$  in  $\Psi_{\text{sc}}^{-1,0}(\bar{\Omega})$  is the  $(X, Y)$ -Fourier transform of

$$e^{-FX} \chi\left(\frac{X - \alpha(0, y, 0, \hat{Y})|Y|^2}{|Y|}\right) \tilde{A}_i^j(0, y, 0, 0, \hat{Y}) |Y|^{-n+1},$$

while for  $P_{i0}$  it is the  $(X, Y)$ -Fourier transform of

$$e^{-FX} \chi\left(\frac{X - \alpha(0, y, 0, \hat{Y})|Y|^2}{|Y|}\right) \tilde{B}_i(0, y, 0, 0, \hat{Y}) |Y|^{-n+1},$$

with  $\tilde{B}_i$  defined analogously to  $\tilde{A}_i^j$ . (Recall that  $2\alpha(x, y, \lambda, \omega)$  is the  $x$  component of  $\gamma''_{x,y,\lambda,\omega}(0)$ , and the convexity assumption on  $x$  is that  $\alpha$  is positive; see [44] above Equation (3.1).) For  $\tilde{A}_i^j = -\frac{1}{2}c(x_0)^{-2}\delta_i^j$ , the invertibility of the principal symbol, with values in  $n \times n$  matrices, of the principal symbol of  $\tilde{P}$  follows when  $\chi$  is chosen as in [44, Lemma 3.6], for it is  $-\frac{1}{2}c(x_0)^{-2}$  times the boundary symbol in [44, Lemma 3.6] times the  $n \times n$  identity matrix. In general, due to the perturbation stability of the property of invertibility, the same follows for  $c$  sufficiently small.  $\square$

<sup>3</sup>This is an example of projective coordinates for a blow-up.

**Corollary 3.1.** *With the notation of Proposition 3.2, there is  $\tilde{c} > 0$  such that if  $0 < c < \tilde{c}$ , then  $P_F$  satisfies the estimate*

$$(18) \quad \|u\|_{H_{sc}^{s,r}(\bar{\Omega})} \leq C \|P_F u\|_{H_{sc}^{s+1,r}(\bar{\Omega})} + C \|u_0\|_{H_{sc}^{s,r}(\bar{\Omega})}$$

for  $u$  supported in  $M \cap \bar{\Omega}$ , with the constant  $C$  uniform in  $c$ .

*Proof.* By the density of elements of  $\dot{C}^\infty(M \cap \bar{\Omega})$  in  $H_{sc}^{s,r}(\bar{\Omega})$  supported in  $M \cap \bar{\Omega}$ , it suffices to consider  $u \in \dot{C}^\infty(M \cap \bar{\Omega})$  to prove (18).

Consider  $s = 0, r = 0$ . Let  $\Lambda \in \Psi_{sc}^{1,0}(\Omega)$  be elliptic and invertible (one can e.g. locally identify  $\Omega$  with  $\mathbb{R}^n$ ; then on the Fourier transform side multiplication by  $\langle \xi \rangle$  works). Thus,  $\Lambda P_F$ , with  $\Lambda$  acting diagonally on  $\dot{C}^\infty(\Omega; \mathbb{C}^n)$ , is in  $\Psi_{sc}^{0,0}(\bar{\Omega}; \mathbb{C}^{n+1}, \mathbb{C}^n)$  and  $\Lambda \tilde{P} \in \Psi_{sc}^{0,0}(\bar{\Omega}; \mathbb{C}^n, \mathbb{C}^n)$  is elliptic in  $\Psi_{sc}^{0,0}(\bar{\Omega}; \mathbb{C}^n, \mathbb{C}^n)$  locally in a neighborhood of  $\Omega$ . This implies, as presented in [44] after Lemma 3.6, relying on the arguments at the end of Section 2 there, that if  $c > 0$  is sufficiently small then  $\Lambda \tilde{P}$  satisfies

$$(19) \quad \|w\|_{L_{sc}^2(\bar{\Omega})} \leq C_0 \|\Lambda \tilde{P} w\|_{L_{sc}^2(\bar{\Omega})}$$

for  $w$  supported in  $\bar{\Omega}$ . Here  $L_{sc}^2(\bar{\Omega}) = H_{sc}^{0,0}(\bar{\Omega})$  is the  $L^2$  space relative to a non-degenerate scattering density — the latter are equivalent to the lifted Lebesgue measure from  $\mathbb{R}^n$ , thus are bounded multiples of  $\frac{dx dy}{x^{n+1}}$ .

We recall the essential part of this argument briefly. One considers the whole family of domains  $\bar{\Omega}_c$ , which can be identified with each other locally in the region of interest by the maps  $\Phi_c(\tilde{x}, y) = (\tilde{x} + c, y)$ , i.e. simply translation in the  $\tilde{x}$ -coordinate, so instead of considering a family of spaces with an operator on each of them, one can consider a fixed space, denote this by  $\bar{\Omega}_0$ , with a continuous family of operators,  $T_c$ , namely  $T_c = (\Phi_c^{-1})^* \Lambda \tilde{P} \Phi_c^*$ . Notice that we are interested in the region  $\Omega_c$ , and that there is a continuous function  $f$  on  $\mathbb{R}$  with  $f(0) = 0$  and  $x_c \leq f(c)$  on  $\Omega_c$ . Correspondingly, in the translated space,  $\tilde{x} \leq f(c)$  on the image of  $\Omega_c$ ; notice that this region shrinks as  $c > 0$  goes to 0. On the other hand, there is a fixed open set  $O \subset \bar{\Omega}$ , a neighborhood of  $x_0$ , on which the operators  $T_c$  are elliptic in  $\Psi_{sc}^{0,0}(\bar{\Omega})$  for  $0 \leq |c| < c_0$ . Let  $K_0$  be a compact subset of  $O$ , still including a neighborhood of  $x_0$ ,  $\phi \in \mathcal{C}_c^\infty(O)$  be identically 1 on a neighborhood of  $K$ . Then the elliptic parametrix construction (which is local, and uniform in  $c$  by the continuity) produces a parametrix family  $G_c \in \Psi_{sc}^{0,0}(\bar{\Omega}; \mathbb{C}^n, \mathbb{C}^n)$ ,  $G_c T_c = \text{Id} + E_c$ , where  $E_c \in \Psi_{sc}^{0,0}(\bar{\Omega}; \mathbb{C}^n, \mathbb{C}^n)$  only, but  $\phi E_c \phi \in \Psi_{sc}^{-\infty, -\infty}(\bar{\Omega}; \mathbb{C}^n, \mathbb{C}^n)$ , uniformly in  $c$ . Then (multiplying the parametrix identity by  $\phi$  from left and right and applying to  $v$ ) for  $v$  supported in  $K$ ,  $(\text{Id} + \phi E_c \phi)v = \phi G_c T_c v$ . Now, the Schwartz kernel of  $\phi E_c \phi$  is Schwartz, i.e. is bounded by  $C(x x')^N$  for any  $N$ , uniformly in  $c$ . (Here we write, say, the Schwartz kernel relative to scattering densities, but as  $N$  is arbitrary, this makes little difference.) For  $c > 0$ , let  $\phi_c$  be supported, say, in  $\tilde{x} \leq 2f(c)$ , identically 1 near the region  $\tilde{x} \leq f(c)$ ; one may assume that  $\phi \equiv 1$  on  $\text{supp } \phi_c$  by making  $c > 0$  small. Then, by Schur's lemma,  $\phi_c \phi E_c \phi \phi_c$ , acting say on  $L_{sc}^2(\bar{\Omega})$  (i.e. the  $L^2$ -space relative to scattering densities) is bounded by  $f(c)^N$  for any  $N$ . Thus, there is  $c_1 > 0$  such that  $\text{Id} + \phi_c \phi E_c \phi \phi_c = \text{Id} + \phi_c E_c \phi_c$  is invertible for  $0 < c < c_1$  on  $L_{sc}^2(\bar{\Omega})$ . In particular, for  $v$  supported in  $\tilde{x} \leq f(c)$ , so  $\phi_c v = v$ ,  $(\text{Id} + \phi_c E_c \phi_c)v = \phi_c G_c T_c v$ , so inverting the factor on the left and then undoing the transformation  $\Phi_c$  gives the desired conclusion (19).

Thus, with  $u = (u_0, \tilde{u})$ , we have, with all norms being  $L^2_{\text{sc}}(\overline{\Omega})$ -norms,

$$\|\Lambda P_F u\|^2 = \|\Lambda P_0 u_0 + \Lambda \tilde{P} \tilde{u}\|^2 = \|\Lambda \tilde{P} \tilde{u}\|^2 + \langle \Lambda \tilde{P} \tilde{u}, \Lambda P_0 u_0 \rangle + \langle \Lambda P_0 u_0, \Lambda \tilde{P} \tilde{u} \rangle + \langle \Lambda P_0 u_0, \Lambda P_0 u_0 \rangle.$$

By (19),  $\|\Lambda \tilde{P} \tilde{u}\| \geq C_0 \|\tilde{u}\|$ ,  $C_0 > 0$ . On the other hand,  $\|\Lambda P_0 u_0\| \leq C_1 \|u_0\|$ ,  $\|\Lambda \tilde{P} \tilde{u}\| \leq C_1 \|\tilde{u}\|$  as elements of  $\Psi_{\text{sc}}^{0,0}(\Omega)$  are  $L^2$ -bounded. Using the Cauchy-Schwartz inequality, for  $\delta > 0$ ,

$$|\langle \Lambda P_0 u_0, \Lambda \tilde{P} \tilde{u} \rangle| \leq \frac{\delta}{2} \|\tilde{u}\|^2 + \frac{C_1^2}{2\delta} \|u_0\|^2.$$

Thus, the last three terms are bounded by  $\delta \|\tilde{u}\|^2 + (1 + \delta^{-1}) C_1^2 \|u_0\|^2$  in absolute value, so we conclude that, with  $\delta = C_0^2/2$ ,

$$(20) \quad \frac{C_0^2}{2} \|\tilde{u}\|^2 \leq \|\Lambda P_F u\|^2 + C_1^2 (1 + 2C_0^{-2}) \|u_0\|^2,$$

completing the proof of the corollary if  $s = r = 0$ .

The general case follows via conjugating  $P_F$  by an elliptic, invertible, element of  $\Psi_{\text{sc}}^{s,r}(\overline{\Omega})$ , which is thus an isomorphism from  $H_{\text{sc}}^{s,r}(\overline{\Omega})$  to  $L^2 = H_{\text{sc}}^{0,0}(\overline{\Omega})$ . Note that such a conjugation does not change the principal symbol, thus the ellipticity.  $\square$

We now remark that the even simpler setting of the *scalar transform with a positive weight*  $A$ ,  $I_A$ , which was not considered in [44], and which can be considered a special case of  $\tilde{J}$  with  $(u_0, u_1, \dots, u_n)$  simply replaced by  $u$ , the argument gives that  $P_F$  is elliptic and one has the estimate

$$\|f\|_{H_{\text{sc}}^{s,r}(\overline{\Omega})} \leq C \|P_F f\|_{H_{\text{sc}}^{s+1,r}(\overline{\Omega})},$$

which gives, as discussed in [44] after Lemma 3.6 the following corollary:

**Corollary 3.2.** *The weighted scalar transform with a positive weight  $A$*

$$(I_A f)(\beta) = \int_{\mathbb{R}} A(\gamma_\beta(t)) f(\gamma_\beta(t)) dt,$$

*satisfies that for  $F > 0$  there is  $c_0 > 0$  such that for  $\delta > 0$ ,  $0 < c < c_0$ ,  $s \geq -1$ , we have*

$$\|f\|_{e^{(F+\delta)/x} H^s(\Omega_c)} \leq C \|I_A f\|_{e^{F/x} H^{s+1}(\mathcal{M}_c)};$$

We now return to the actual case of interest and apply Corollary 3.1 with  $u_0 = e^{-F/x} f$ ,  $u_j = e^{-F/x} \partial_j f$ . If we show that given  $\tilde{\delta} > 0$  there is  $c_0 > 0$  such that  $\|u_0\|_{L^2} \leq \tilde{\delta} \|\tilde{u}\|_{L^2}$ , i.e.  $e^{-F/x} f$  is bounded by a small multiple of a derivative of  $f$  times  $e^{-F/x}$  in  $L^2$ , when  $f$  is supported in  $\overline{\Omega}_c$ , then for  $\tilde{\delta} > 0$  sufficiently small (18) proves that if  $P_F u$  vanishes, then so does  $u$ , i.e. in this case so does  $f$ , for the  $u_0$  term can then be absorbed into the left hand side of (18):

$$(21) \quad (1 - \tilde{\delta} C) \|u\|_{H_{\text{sc}}^{0,0}(\overline{\Omega})} \leq C \|P_F u\|_{H_{\text{sc}}^{1,0}(\overline{\Omega})}.$$

Further, rewriting this by removing the weights  $e^{-F/x}$ , and estimating the norms in terms of the standard  $L^2$ -based space, cf. the discussion after [44, Lemma 3.6] already referenced above,<sup>4</sup> gives, for  $\delta > 0$ ,

$$\|f\|_{e^{(F+\delta)/x} H^1(\Omega_c)} \leq C \|\tilde{J}(f, \partial_1 f, \dots, \partial_n f)\|_{e^{F/x} H^1(\mathcal{M}_c)}.$$

But this can now be easily done: let  $V$  be a smooth vector field with  $Vx = 0$ , so  $V$  is tangent to the boundary of  $\Omega_c$  for every  $c$ , and make the non-degeneracy assumption that, for some  $c_1 > 0$ ,

<sup>4</sup>The  $\delta$  loss is actually just the loss of a power of  $x$ , due to change of the measure.

there is a continuous  $T : [0, c_1) \rightarrow \mathbb{R}$  such that  $T(0) = 0$  and the  $V$ -flow takes every point in  $\overline{\Omega_c}$  to  $\partial M$  in time  $\leq T(c)$  (i.e. outside the original manifold). Then the Poincaré inequality for  $V$  gives

$$(22) \quad \|v\|_{L^2_{sc}} \leq C_2 T(c) \|Vv\|_{L^2_{sc}},$$

for  $v$  vanishing outside  $M$ , hence the constant is small if  $T(c) > 0$  is small. (Here the  $L^2$  space we need is the scattering  $L^2$ -space,  $L^2_{sc}$ , which is  $x^{(n+1)/2}$  times the standard  $L^2$ -space, but the extra weight does not affect the argument, since  $V$  commutes with multiplication by powers of  $x$ .)

To see (22), we recall a standard proof of the local Poincaré inequality: in order to reduce confusion with the notation, let  $(z_1, \dots, z_n) = (z', z_n)$  be the coordinates,  $z_1 = 0$  being the boundary of  $\Omega$  (so  $x$  would be  $z_1$ ), and assume that the flow of  $\partial_{z_n}$  flows from every point in  $\Omega$  to outside the region in ‘time’  $\leq \delta$ . To normalize the argument, assume that  $z_n \geq 0$  in  $\Omega$ , and we want to estimate  $v$  in  $z_n \leq \delta$ . We assume that the  $L^2$  space is given by a density  $F(z') |dz|$ . Then, for  $v \in \mathcal{C}^\infty(\mathbb{R}^n_+)$ ,  $\mathbb{R}^n_+ = [0, \infty)_{z_1} \times \mathbb{R}^{n-1}$ , with support in  $z_n \geq 0$ , by the fundamental theorem of calculus and the Cauchy-Schwartz inequality,

$$\begin{aligned} |v(z', z_n)| &= \left| \int_0^{z_n} \partial_n v(z', t) dt \right| \leq \left( \int_0^{z_n} 1 dt \right)^{1/2} \left( \int_0^{z_n} |\partial_n v(z', t)|^2 dt \right)^{1/2} \\ &\leq \delta^{1/2} \left( \int_0^\delta |\partial_n v(z', t)|^2 dt \right)^{1/2}. \end{aligned}$$

Squaring both sides, multiplying by  $F(z')$ , and integrating in  $z', z_n$  (to  $z_n = \delta$ ) gives

$$\int_{z_n \leq \delta} |v(z', z_n)|^2 F(z') dz \leq \delta^2 \int_{t \leq \delta} |\partial_n v(z', t)|^2 dt F(z') dz'.$$

This says that actually

$$\|v\|_{L^2(\mathbb{R}^n_+; F(z') |dz|)} \leq \delta \|\partial_n v\|_{L^2(\mathbb{R}^n_+; F(z') |dz|)},$$

proving the claim (using  $F(z') = z_1^{-n-1}$ ) in view of the quasi-isometry invariance (which gives a constant factor) of the bound (22). Even if there is more complicated topology, so there are no global coordinates and vector fields as stated, dividing up the problem into local pieces and adding them together gives the desired result: taking steps of size  $\delta$ , one needs  $T/\delta$  steps to cover the set, using cutoff functions to localize is easily seen to give a bound proportional to  $T$ .

On the other hand, in view of the strict convexity of the boundary, one can construct such a  $V$  and  $T$ . With  $v = e^{-F/x} f$ , this is exactly the desired conclusion since  $V(e^{-F/x} f) = e^{-F/x} V f$ .

In summary we have proved that with  $L^2(\Omega) = L^2(\Omega_c)$  the standard  $L^2$ -space now (as the exponential weight  $e^{-F/x}$  maps such  $f$  to  $L^2_{sc}(\widehat{\Omega})$ ), see also the discussion after Lemma 3.6 in [44]:

**Proposition 3.3.** *There is  $c_0 > 0$  such that for  $0 < c < c_0$ , if  $f \in L^2(\Omega_c)$  and  $\tilde{J}(f, \partial_1 f, \dots, \partial_n f) = 0$ , then  $f = 0$ . In fact, for  $F > 0$  there is  $c_0 > 0$  such that for  $\delta > 0$ ,  $0 < c < c_0$ , we have*

$$\|f\|_{e^{(F+\delta)/x} H^1(\Omega_c)} \leq C \|\tilde{J}(f, \partial_1 f, \dots, \partial_n f)\|_{e^{F/x} H^1(\mathcal{M}_c)}.$$

#### 4. PROOF OF THEOREM 1.1 AND THEOREM 1.2

##### Proof of Theorem 1.1

Let  $c$  and  $\tilde{c}$  be as in the theorem. Redefine the scattering relation  $\mathcal{L}$  as in Figure 1. By Proposition 2.1, we get  $J_j f(\gamma) = 0$ , see (12) for all geodesics close enough to the ones tangent to  $\partial M$  at  $p$ . The weights are given by (14), in the new parameterization, with the ellipticity condition (15) satisfied. Then Proposition 3.3 implies  $f = 0$  in a neighborhood of  $p$ , where  $f = c^2 - \tilde{c}^2$  as in (8).

##### Proof of Theorem 1.2

Theorem 1.2 is now an easy consequence of Theorem 1.1 using a layer stripping argument. Let  $f = c^2 - \tilde{c}^2$ . Assume  $f \neq 0$ , then  $\text{supp } f$  has non-empty interior. On the other hand, let  $\tau = \inf_{\text{supp } f} \rho$ ; if  $\tau \leq T$  we are done, for then  $\text{supp } f \subset M \setminus \cup_{t \in [0, T]} \Sigma_t$ . Thus, suppose  $\tau < T$ , so  $f \equiv 0$  on  $\Sigma_t$  for  $t < \tau$ , but there exists  $x \in \Sigma_\tau \cap \text{supp } f$  (since  $\text{supp } f$  is closed). Now we use Theorem 1.1 on  $\rho^{-1}(\tau, \infty)$  to conclude that a neighborhood of  $x$  is disjoint from  $\text{supp } f$  to obtain a contradiction.

## REFERENCES

- [1] G. Besson, G. Courtois, and S. Gallot. Entropies et rigidités des espaces localement symétriques de courbure strictement négative. *Geom. Funct. Anal.*, **5** (1995), 731–799.
- [2] D. Burago and S. Ivanov, Boundary rigidity and filling volume minimality of metrics close to a flat one. *Ann. Math.*, **171** (2010), 1183–1211.
- [3] C. Croke. Scattering rigidity with trapped geodesics. preprint, 2012.
- [4] K. C. Creager. Anisotropy of the inner core from differential travel times of the phases PKP and PKIPK, *Nature*, **356**(1992), 309–314.
- [5] C. B. Croke. Rigidity for surfaces of nonpositive curvature. *Comment. Math. Helv.*, 65(1):150–169, 1990.
- [6] C. B. Croke. Rigidity and the distance between boundary points. *J. Differential Geom.*, 33(2):445–464, 1991.
- [7] C. B. Croke. Rigidity theorems in Riemannian geometry. In *Geometric methods in inverse problems and PDE control*, volume 137 of *IMA Vol. Math. Appl.*, pages 47–72. Springer, New York, 2004.
- [8] C. B. Croke and N. S. Dairbekov. Lengths and volumes in Riemannian manifolds. *Duke Math. J.*, 125(1):1–14, 2004.
- [9] C. B. Croke and B. Kleiner. Conjugacy and rigidity for manifolds with a parallel vector field. *J. Differential Geom.*, 39(3):659–680, 1994.
- [10] N. S. Dairbekov. Integral geometry problem for nontrapping manifolds. *Inverse Problems*, 22(2):431–445, 2006.
- [11] M. Gromov. Filling Riemannian manifolds. *J. Diff. Geometry* **18** (1983), 1–148.
- [12] G. Herglotz. Über die Elastizität der Erde bei Berücksichtigung ihrer variablen Dichte. *Zeitschr. für Math. Phys.*, 52:275–299, 1905.
- [13] L. Hörmander. *The analysis of linear partial differential operators*, vol. 1-4. Springer-Verlag, 1983.
- [14] S. Ivanov. Volume comparison via boundary distances. *Proceedings of the International Congress of Mathematicians, vol. II*, 769–784, New Delhi, 2010.
- [15] V. Krishnan. A support theorem for the geodesic ray transform on functions. *J. Fourier Anal. Appl.* 15 (2009), 515–520.
- [16] V. Krishnan and P. Stefanov. A support theorem for the geodesic ray transform of symmetric tensor fields. *Inverse Problems and Imaging*, **3** (2009), 453–464.
- [17] M. Lassas, V. Sharafutdinov, and G. Uhlmann. Semiglobal boundary rigidity for Riemannian metrics. *Math. Ann.*, 325(4):767–793, 2003.
- [18] R. B. Melrose. Spectral and scattering theory for the Laplacian on asymptotically Euclidian spaces. *Spectral and scattering theory (Sanda, 1992)*. Lecture Notes in Pure and Appl. Math., 161, 85–130, Marcel Dekker, 1994.
- [19] R. Michel. Sur la rigidité imposée par la longueur des géodésiques. *Invent. Math.*, 65(1):71–83, 1981/82.
- [20] R. G. Mukhometov. The reconstruction problem of a two-dimensional Riemannian metric, and integral geometry. *Dokl. Akad. Nauk SSSR*, 232(1):32–35, 1977.
- [21] R. G. Muhometov. On a problem of reconstructing Riemannian metrics. *Sibirsk. Mat. Zh.*, 22(3):119–135, 237, 1981.
- [22] R. G. Muhometov and V. G. Romanov. On the problem of finding an isotropic Riemannian metric in an  $n$ -dimensional space. *Dokl. Akad. Nauk SSSR*, 243(1):41–44, 1978.
- [23] C. Parenti, Operatori pseudo-differenziali in  $R^n$  e applicazioni, *Ann. Mat. Pura Appl.* (4), **93** (1972), 359–389.
- [24] G.P. Paternain, M. Salo and G. Uhlmann. Tensor tomography on simple surfaces, arXiv:1109.0505, to appear in *Invent. Math.*
- [25] G.P. Paternain, M. Salo, G. Uhlmann. The attenuated ray transform for connections and Higgs fields, *Geom. Funct. Anal.* **22** (2012) 1460–1489.
- [26] G.P. Paternain, M. Salo and G. Uhlmann. Tensor tomography: progress and challenges, preprint, arXiv:1303.6114.
- [27] L. Pestov and G. Uhlmann. Two dimensional compact simple Riemannian manifolds are boundary distance rigid. *Ann. of Math.* (2), 161(2):1093–1110, 2005.



- [28] L. N. Pestov and V. A. Sharafutdinov. Integral geometry of tensor fields on a manifold of negative curvature. *Sibirsk. Mat. Zh.*, 29(3):114–130, 221, 1988.
- [29] A. Ranjan and H. Shah. Convexity of spheres in a manifold without conjugate points. *Proc. Indian Acad. Sci. (Math. Sci.)*, **112** (2002), 595–599.
- [30] V. Sharafutdinov, M. Skokan, and G. Uhlmann. Regularity of ghosts in tensor tomography. *J. Geom. Anal.*, 15(3):499–542, 2005.
- [31] V. A. Sharafutdinov. *Integral geometry of tensor fields*. Inverse and Ill-posed Problems Series. VSP, Utrecht, 1994.
- [32] V. A. Sharafutdinov. A problem in integral geometry in a nonconvex domain. *Sibirsk. Mat. Zh.*, 43(6):1430–1442, 2002.
- [33] V.A. Sharafutdinov, Variations of Dirichlet-to-Neumann map and deformation boundary rigidity of simple 2-manifolds, *J. Geom. Anal.* **17** (2007), 147–187.
- [34] M. A. Shubin, *Pseudodifferential operators in  $R^n$* , Dokl. Akad. Nauk SSSR, **196** (1971), 316–319.
- [35] P. Stefanov. Microlocal approach to tensor tomography and boundary and lens rigidity. *Serdica Math. J.*, 34(1):67–112, 2008.
- [36] P. Stefanov and G. Uhlmann. Rigidity for metrics with the same lengths of geodesics. *Math. Res. Lett.*, 5(1-2):83–96, 1998.
- [37] P. Stefanov and G. Uhlmann. Stability estimates for the X-ray transform of tensor fields and boundary rigidity. *Duke Math. J.*, 123(3):445–467, 2004.
- [38] P. Stefanov and G. Uhlmann. Boundary rigidity and stability for generic simple metrics. *J. Amer. Math. Soc.*, 18(4):975–1003, 2005.
- [39] P. Stefanov and G. Uhlmann. Boundary and lens rigidity, tensor tomography and analytic microlocal analysis. In *Algebraic Analysis of Differential Equations*. Springer, 2008.
- [40] P. Stefanov and G. Uhlmann. Integral geometry of tensor fields on a class of non-simple Riemannian manifolds. *Amer. J. Math.*, 130(1):239–268, 2008.
- [41] P. Stefanov and G. Uhlmann. Local lens rigidity with incomplete data for a class of non-simple Riemannian manifolds. *J. Differential Geom.*, 82(2):383–409, 2009.
- [42] P. Stefanov and G. Uhlmann. Recovery of a source term or a speed with one measurement and applications, to appear in *Trans. Amer. Math. Soc.*, 2013.
- [43] P. Stefanov and G. Uhlmann. The geodesic X-ray transform with fold caustics. *Anal. PDE*, **5**, 219–260, 2012.
- [44] G. Uhlmann and A. Vasy. The inverse problem for the local geodesic ray transform. *preprint*, arXiv:1210.2084.
- [45] J. Vargo. A proof of lens rigidity in the category of analytic metrics, *Math. Research Letters*, **16** (2009), 1057–1069.
- [46] E. Wiechert and K. Zoeppritz. Über Erdbebenwellen. *Nachr. Koenigl. Gesellschaft Wiss. Göttingen*, 4:415–549, 1907.

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