The Einstein-Weyl Equations,

Scattering Maps,

and

Holomorphic Disks

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SUNY Stony Brook

Joint work with

Lionel Mason
University of Oxford

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University of Oxford

Some overlap
with results of

Fuminori Nakata
Tokyo Institute of Technology

Weyl's 1918 gauge theory

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based on Weyl connections $([g], \nabla)$:

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$$\nabla_v g \propto g \quad \forall v$$

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where $\nu = d \log u$.

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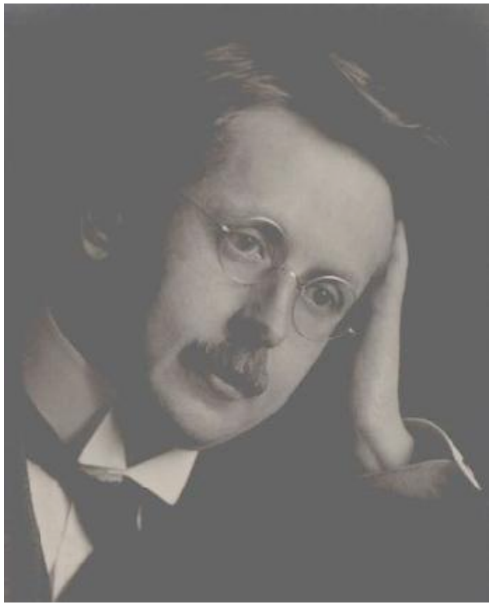
Hermann Weyl



$$\mathfrak{B} = (\mathfrak{G} + \alpha \mathfrak{l}) + \frac{\varepsilon^2}{4}\sqrt{g}\{1 - 3(\varphi_i \varphi^i)\},$$

$$\Gamma^r_{ik} = \left\{ {ik \atop r} \right\} + \tfrac{1}{2}\varepsilon^2(\delta^r_i \varphi_k + \delta^r_k \varphi_i - g_{ik}\varphi^r).$$

Unter Vernachlässigung der winzigen kosmologischen Terme erhalten wir hier also genau die klassische Maxwell-Einsteinsche Theorie der Elektrizität und Gravitation. Um Übereinstimmung mit den in § 34 verwendeten

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for some function f.

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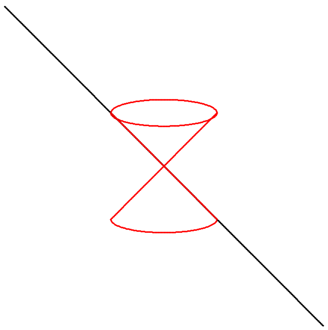

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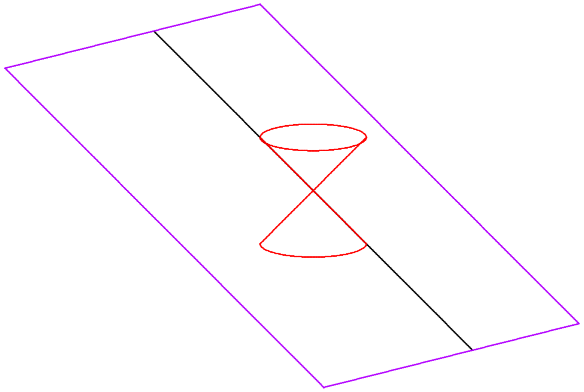

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$$\begin{cases} [\omega_1 \Omega_{23}] = [\omega_2 \Omega_{31}] = [\omega_3 \Omega_{12}], \\ [\omega_2 \Omega_{12}] + [\omega_3 \Omega_{31}] = 0, \\ [\omega_3 \Omega_{23}] + [\omega_1 \Omega_{12}] = 0, \\ [\omega_1 \Omega_{31}] + [\omega_2 \Omega_{23}] = 0. \end{cases}$$

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THÉORÈME. — *Les espaces de Weyl à trois dimensions qui admettent ∞^2 plans isotropes dépendent essentiellement de quatre fonctions arbitraires de deux arguments.*

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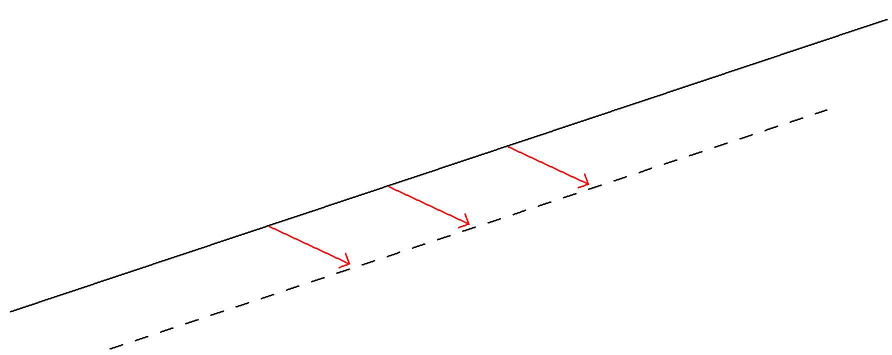

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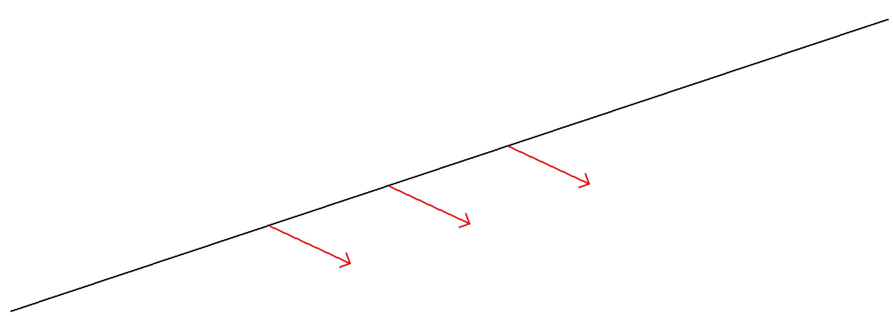

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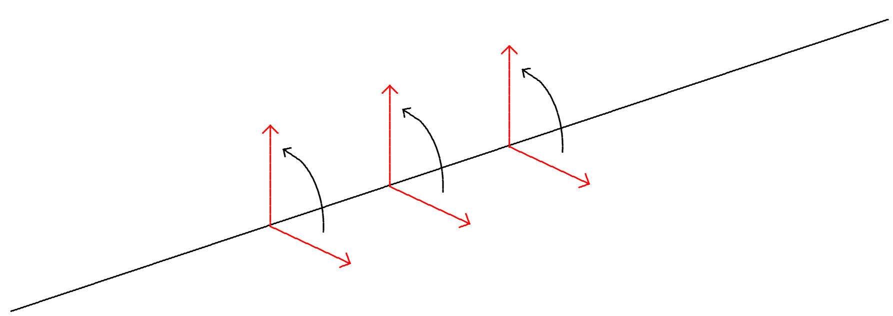

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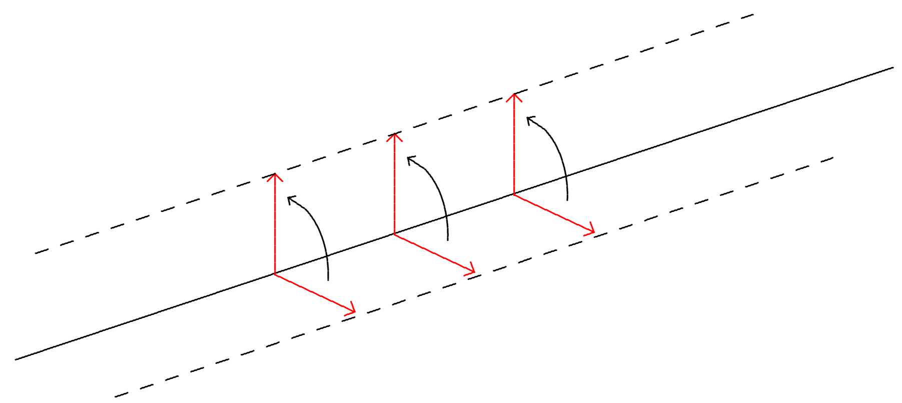
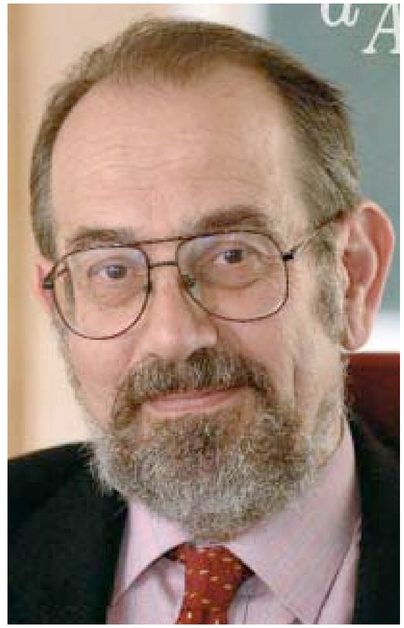


Nigel Hitchin



and so if

$$R(U \times V, U)U = U \times R(V, U)U, \tag{2.2}$$

then we can define a linear map

$$J(V) = U \times V \tag{2.3}$$

which satisfies

$$J^2(V) = U \times (U \times V) = (U, V)U - (U, U)V = -V$$

We thus have a real complex surface G with a family of real lines of self-intersection number 2. It can be shown that any such surface may be obtained by the above geodesic construction, but using a Weyl structure rather than a Riemannian structure. The integrability condition (2.2) is then the analogue of Einstein's equations ($R_{(ij)} = \Lambda g_{ij}$) for the Weyl structure (see [10]). This is the

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- *smooth, space-time-oriented, conformally compact, globally hyperbolic Lorentzian Einstein-Weyl* 3*-manifolds* $(M, [g], \nabla)$*; and*

- *orientation-reversing diffeomorphisms*

$$\psi : \mathbb{CP}_1 \to \mathbb{CP}_1.$$

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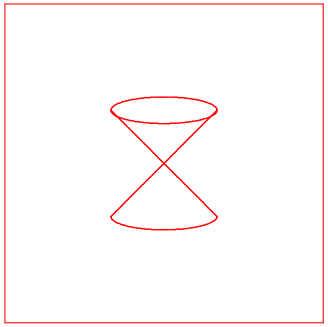

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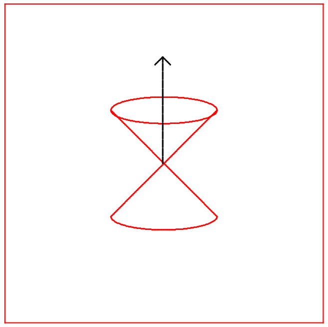

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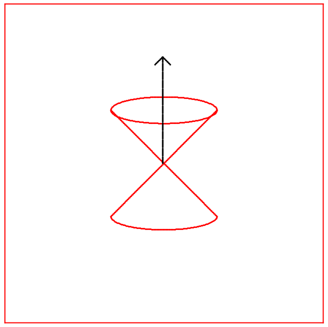

$\Longrightarrow$ M also oriented, in usual sense.

globally hyperbolic

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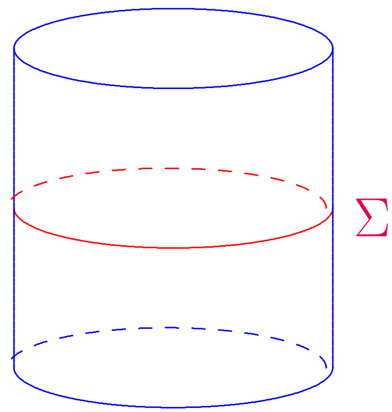

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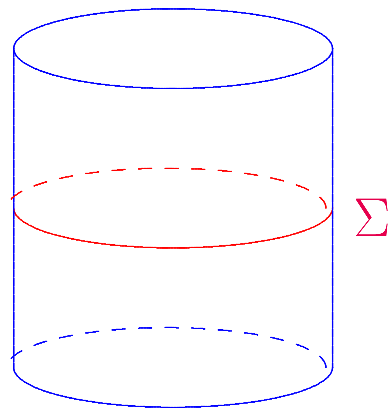

$\Longrightarrow M \approx \Sigma \times \mathbb{R}$

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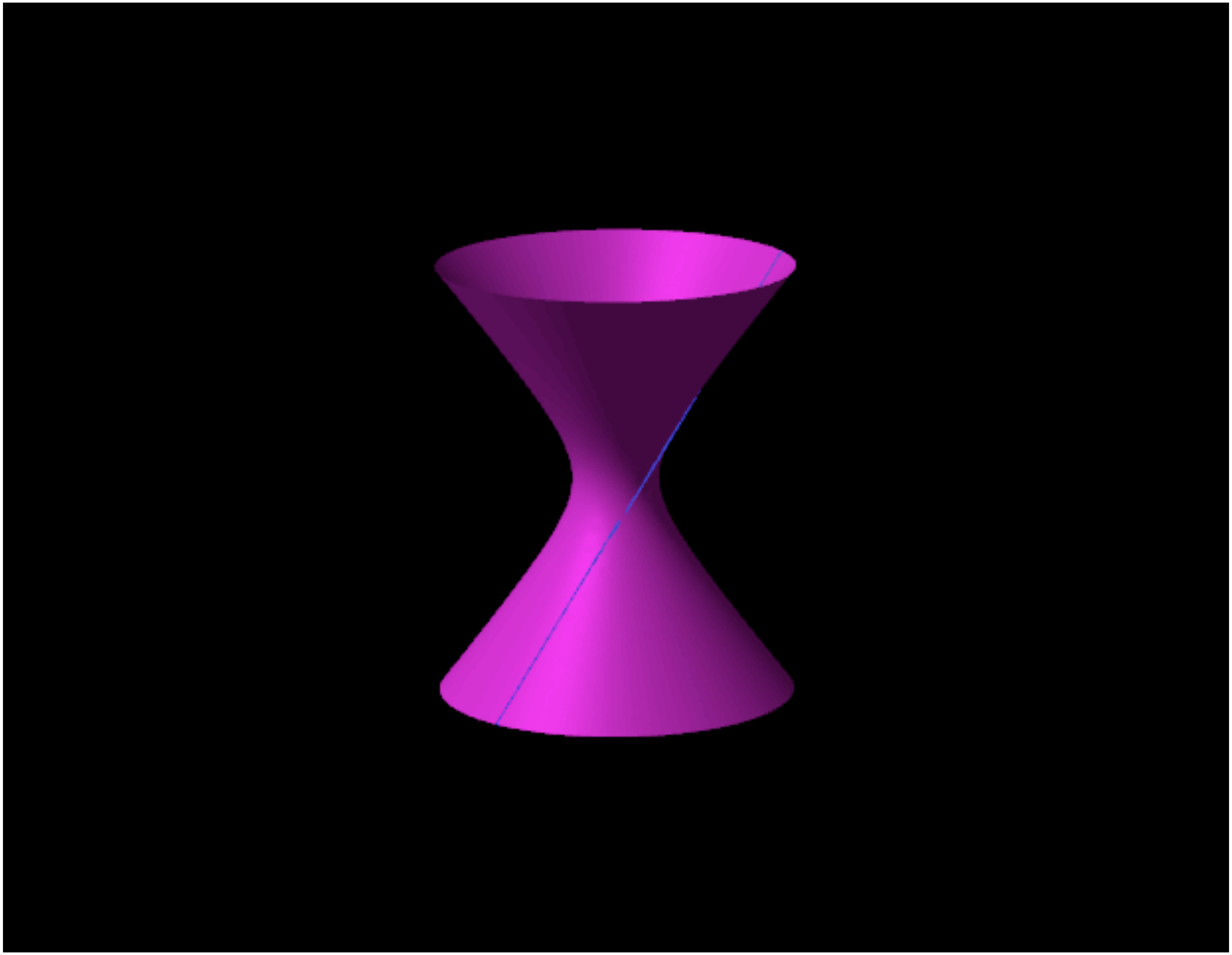

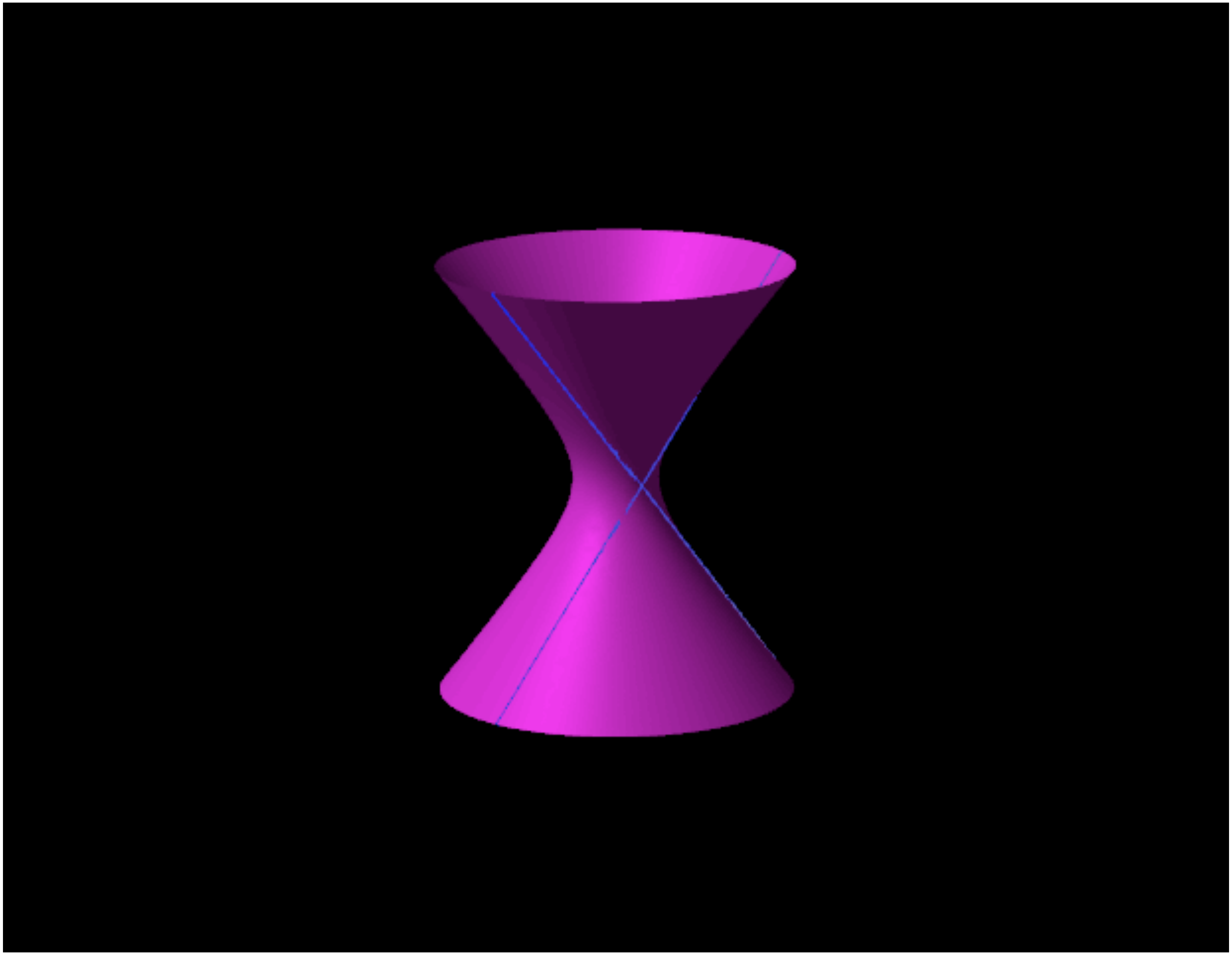

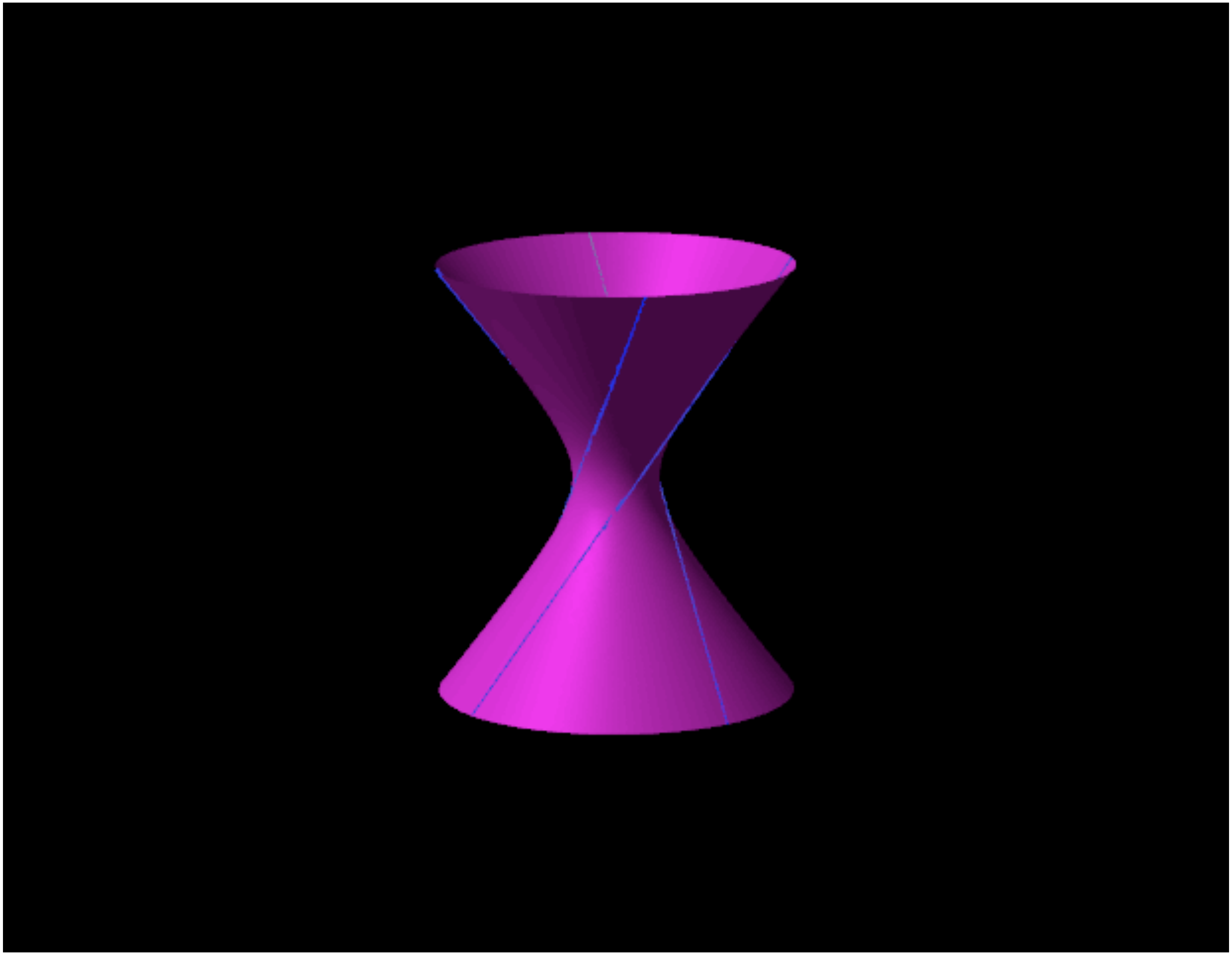

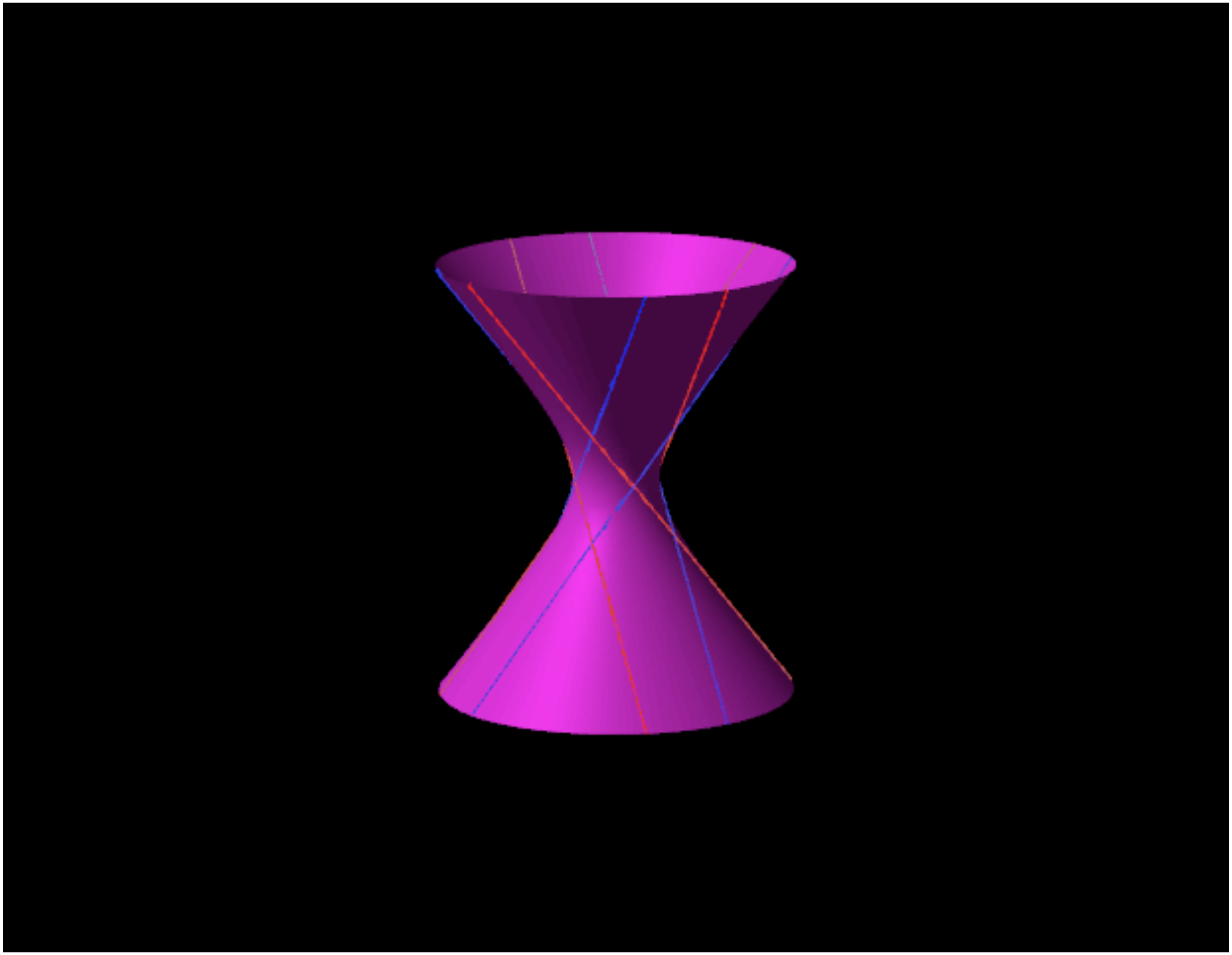

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Setting $\tau = 2\tan^{-1}(t + \sqrt{t^2+1})$,

$$g = \csc^2(\tau)\left[-d\tau^2 + h\right]$$

where h = standard metric on S^2.

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where $u = \sin\tau$.

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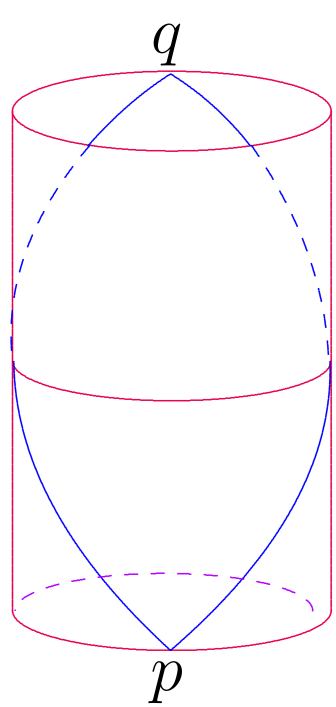

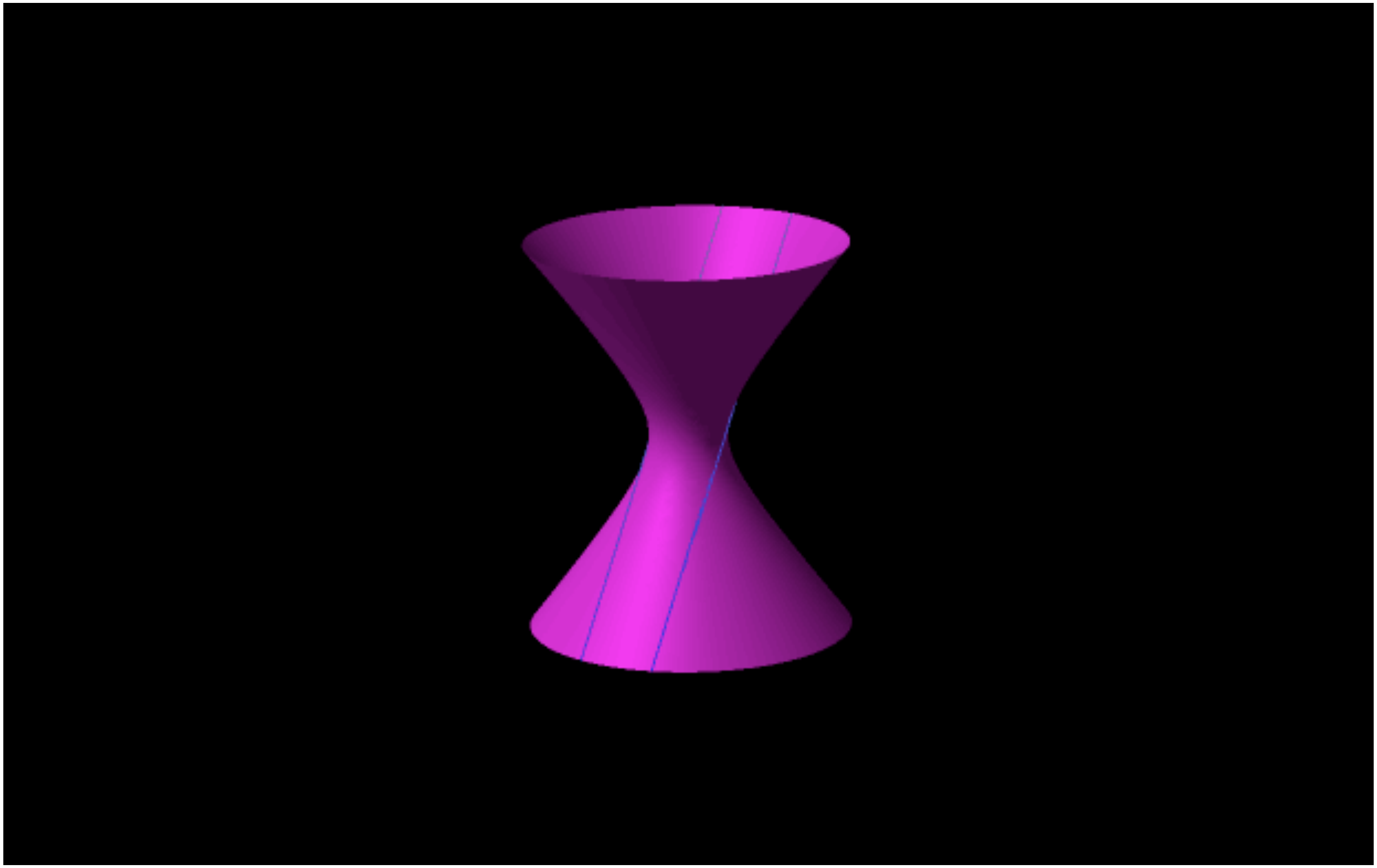

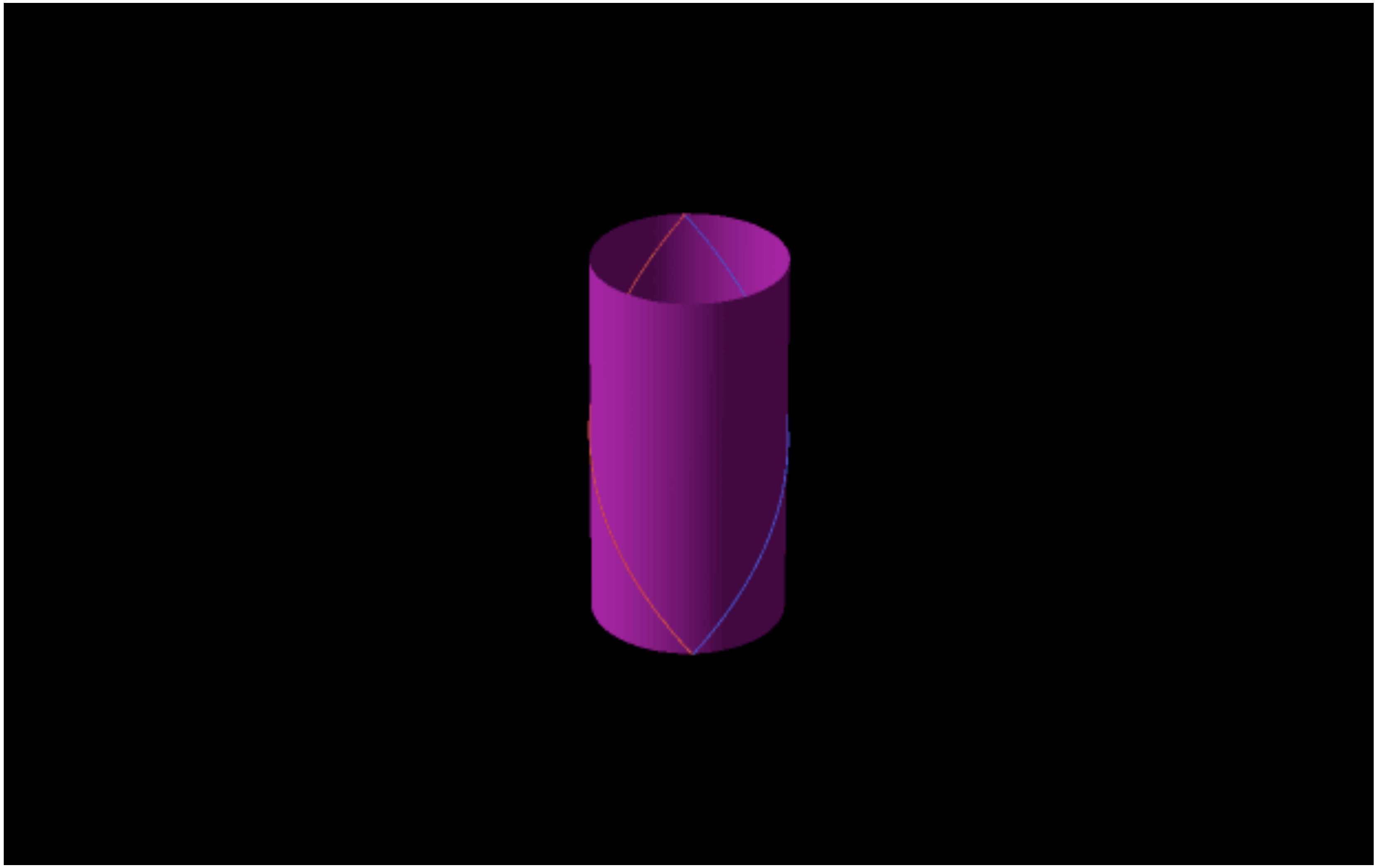

Prototypical example:

de Sitter 3-space

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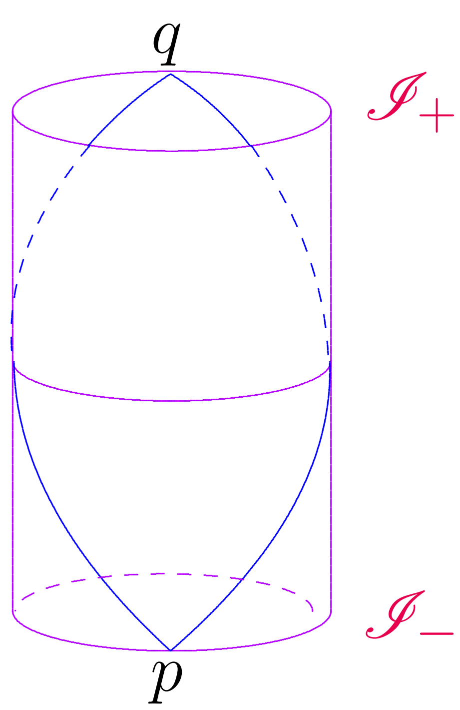

Theorem. *There is a natural one-to-one correspondence between*

- *smooth, space-time-oriented,* conformally compact, *globally hyperbolic Lorentzian Einstein-Weyl* 3*-manifolds* $(M, [g], \nabla)$*; and*

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$$\psi : \mathbb{CP}_1 \to \mathbb{CP}_1.$$

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Two orientation-reversing diffeomorphisms

$$\psi_1, \psi_2 : \mathbb{CP}_1 \to \mathbb{CP}_1$$

considered same iff

$$\psi_1 = \varphi \circ \psi_2 \circ \phi^{-1}$$

for Möbius transformations $\varphi, \phi \in PSL(2, \mathbb{C})$.

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Example: de Sitter $\longleftrightarrow$ antipodal map of $\mathbb{CP}_1$.

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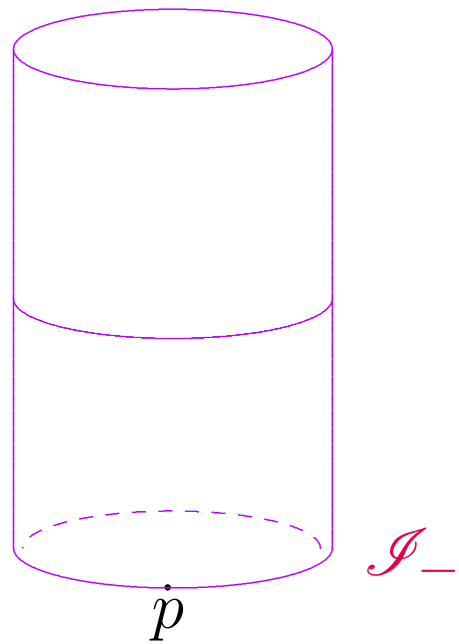
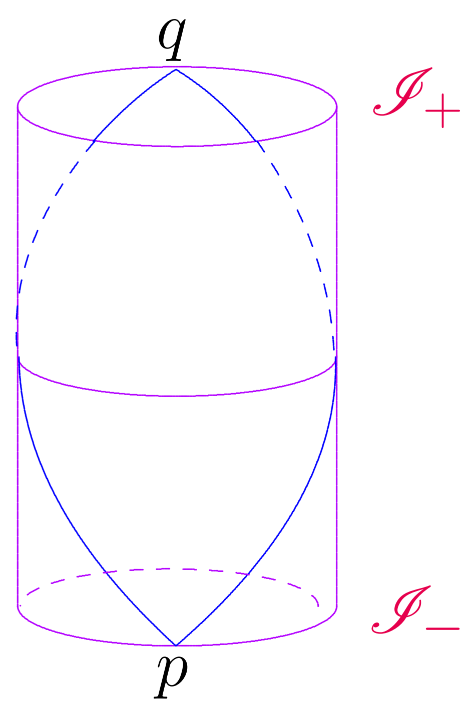
to Einstein-Weyl $(M^3, [g], \nabla)$ satisfying hypotheses.

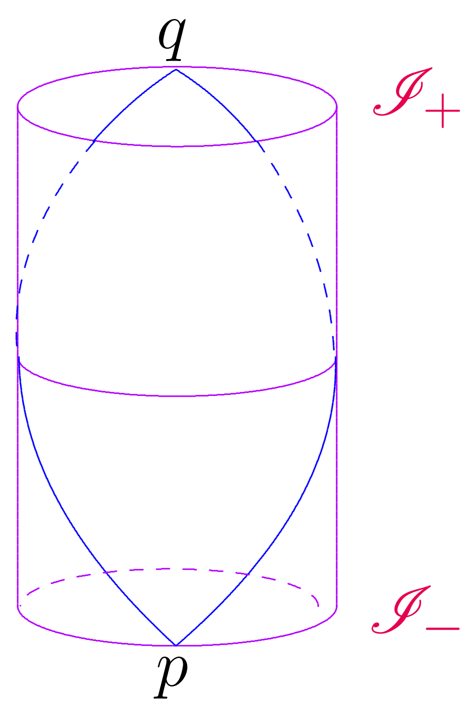
Lemma. *For an Einstein-Weyl manifold as above, let $p \in \mathscr{I}_-$ be any point of past infinity.*



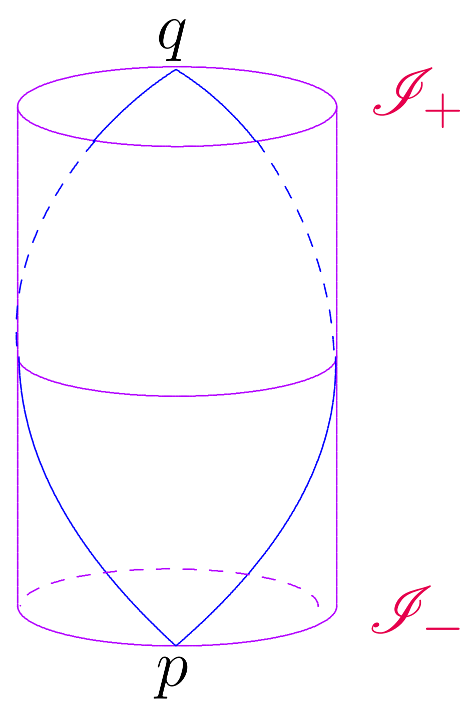
Lemma. *For an Einstein-Weyl manifold as above, let $p \in \mathscr{I}_-$ be any point of past infinity. Then all the null geodesics emanating from p refocus at a unique point $q \in \mathscr{I}_+$.*



Lemma. *For an Einstein-Weyl manifold as above, let $p \in \mathscr{I}_-$ be any point of past infinity. Then all the null geodesics emanating from p refocus at a unique point $q \in \mathscr{I}_+$. Moreover, $\mathscr{I}_\pm \approx S^2$.*



Thus define scattering map $\psi : \mathbb{CP}_1 \to \mathbb{CP}_1$ associated with $(M, [g], \nabla)$



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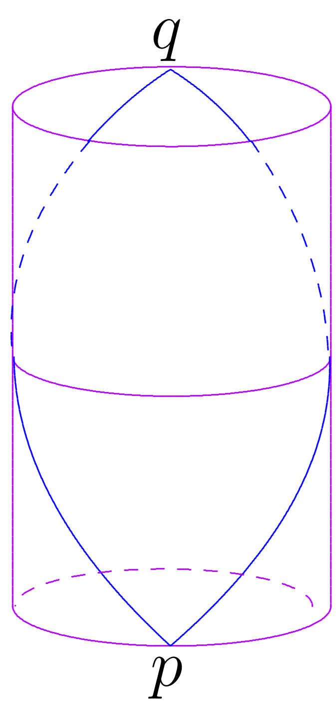

$\mathscr{I}_+$

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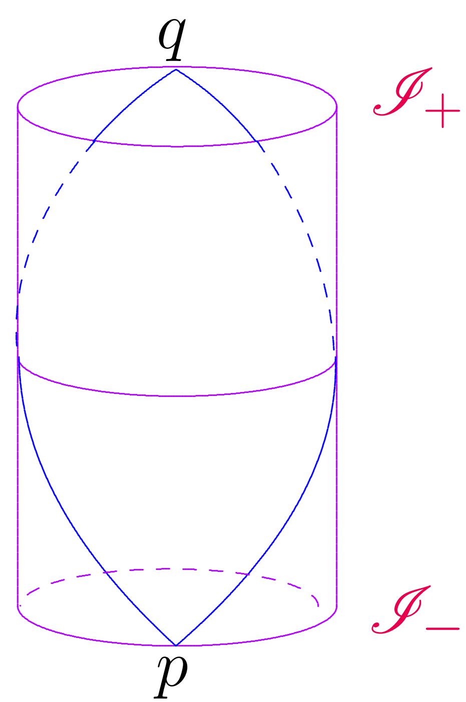
Thus define scattering map $\psi : \mathbb{CP}_1 \to \mathbb{CP}_1$ associated with $(M, [g], \nabla)$ to be function given by $\mathscr{I}_- \ni p \mapsto q \in \mathscr{I}_+$ after some choice of oriented conformal isomorphisms $\mathscr{I}_\pm \cong \mathbb{CP}_1$.



Inverting correspondence:

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Graph of orientation-reversing diffeomorphism

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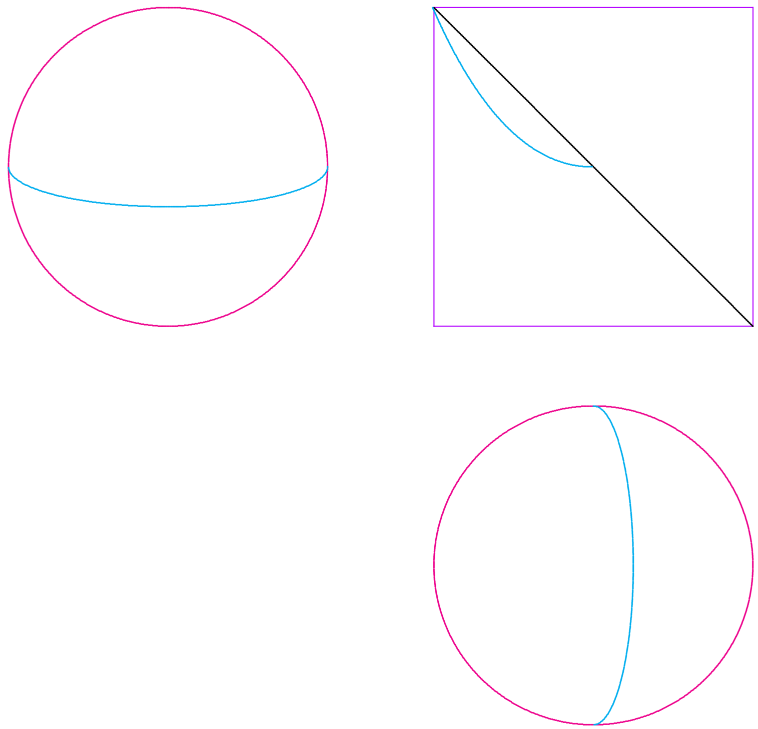
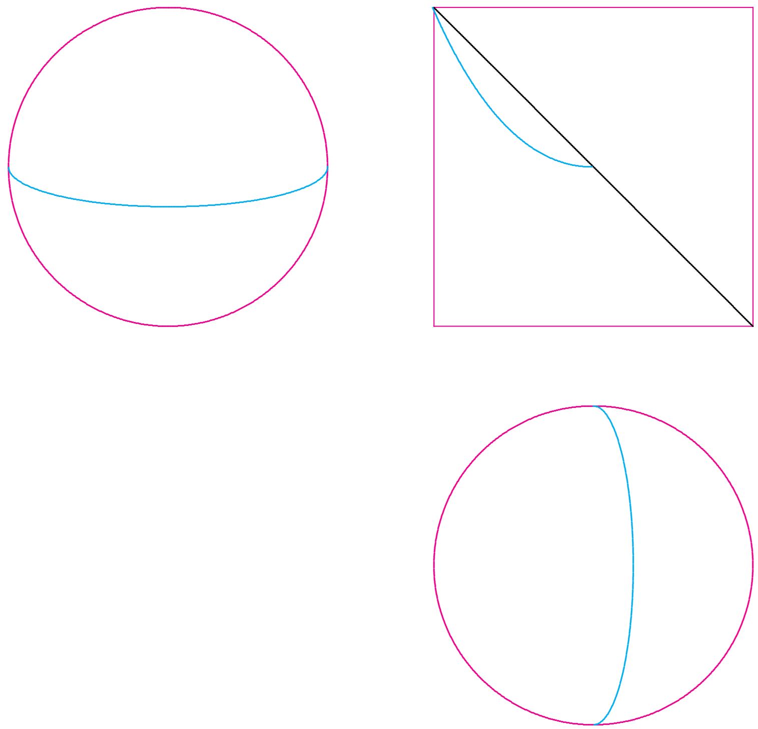
Strategy: construct 3-manifold $M = M_\psi$ as moduli space of holomorphic disks D in $Z = \mathbb{CP}_1 \times \mathbb{CP}_1$ with ∂D on $P \subset Z$.



When ψ is the antipodal map,
disks are explicitly given by

$$\zeta \longmapsto ([a\zeta + b : c\zeta + d], [-\overline{d}\zeta - \overline{c} : \overline{b}\zeta + \overline{a}])$$

as ζ ranges over the unit disk $|\zeta| \leq 1$ in $\mathbb{C}$.



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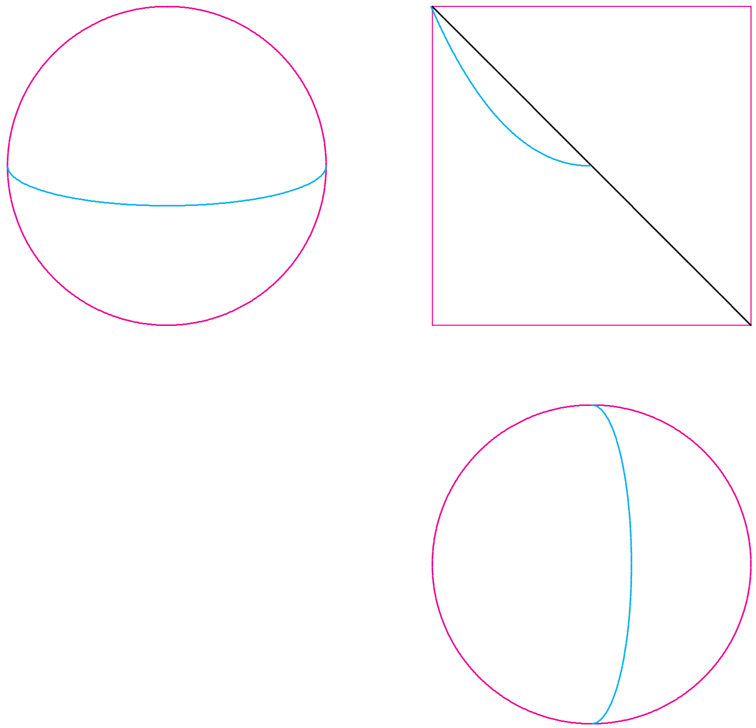
Moduli space M of disks mod reparameterization:
de Sitter space $SL(2, \mathbb{C})/SL(2, \mathbb{R})$.



Now deform $P \hookrightarrow \mathbb{CP}_1 \times \mathbb{CP}_1$

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by replacing graph of anti-podal map with graph of orientation-reversing diffeomorphism

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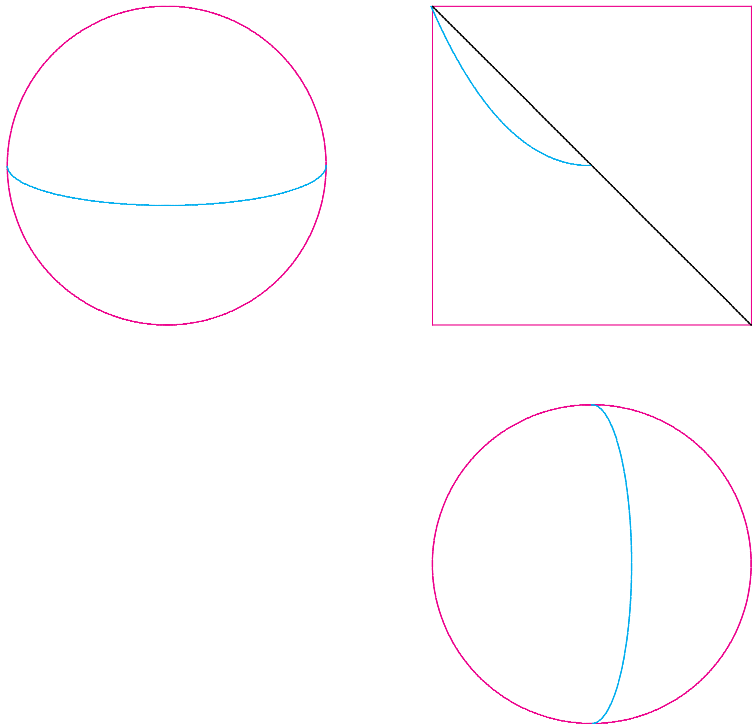

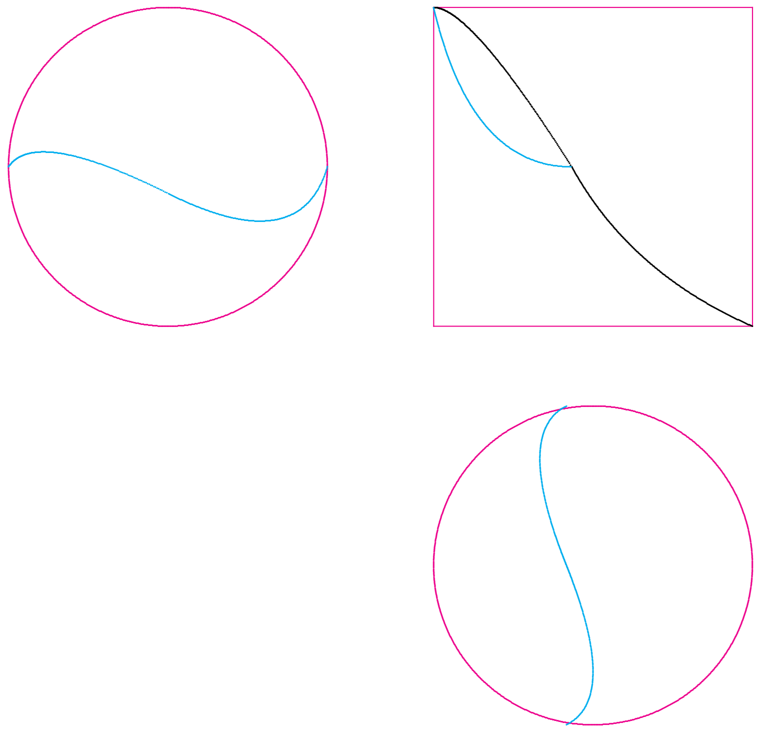

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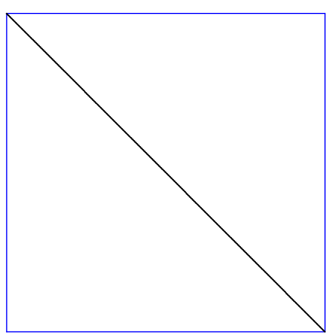

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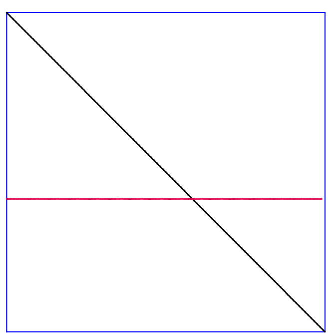

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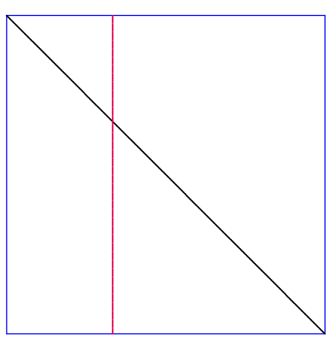

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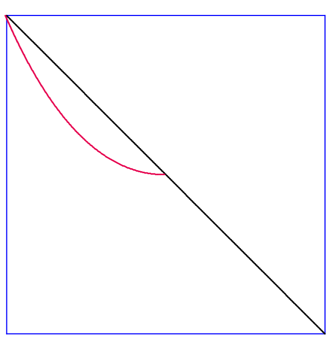

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If $(\Sigma, \partial\Sigma) \to (Z, P)$ *is any holomorphic curve with boundary representing* $\mathbf{a}$*, then* Σ *is either a holomorphic disk as above, or is a factor* $\mathbb{CP}_1$ *of* $Z = \mathbb{CP}_1 \times \mathbb{CP}_1$*.*

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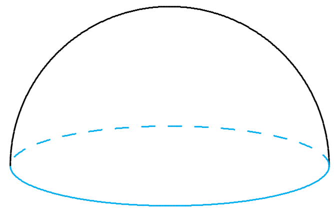

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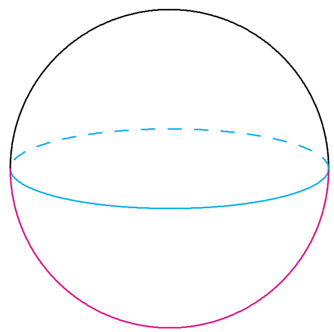

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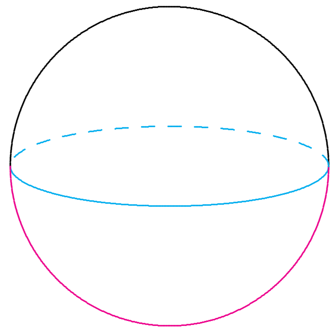

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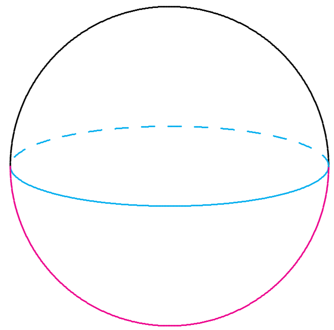

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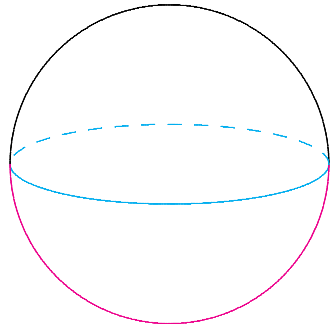

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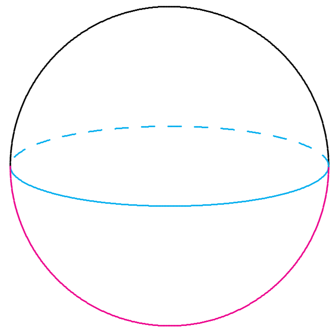

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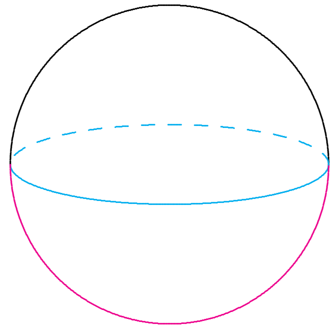
Proof. Consider abstract double $D \cup_{\partial D} \overline{D}$.



and continuous map

$$\Phi : D \cup_{\partial D} \overline{D} \longrightarrow \mathbb{CP}_1$$

$$\Phi|_D = \varpi_1 \circ F$$
$$\Phi|_{\overline{D}} = \psi^{-1} \circ \varpi_2 \circ F$$

Then

$$\int_{D \cup_{\partial D} \overline{D}} \Phi^* \omega_1 = \int_D F^* \omega = 4\pi = \int_{\mathbb{CP}_1} \omega_1$$

So $\deg \Phi = 1$.

Φ orientation-preserving; $\Longrightarrow$ homeomorphism.

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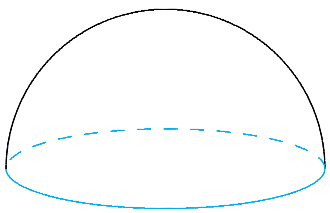

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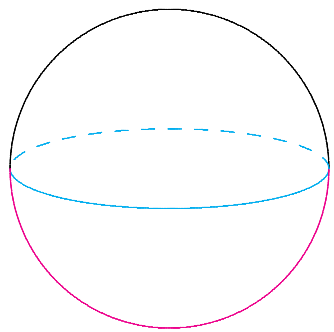

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Equals 2 in our case:

$$E \cong \mathcal{O}(2).$$

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$$h^1(\mathbb{CP}_1, \mathcal{O}(2)) = 0$$
$$h^0(\mathbb{CP}_1, \mathcal{O}(2)) = 3$$

cf. Kodaira's Theorem
on deformation of complex submanifolds

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Disks all have same ω-area. $\Longrightarrow$
any sequence has convergent subsequence. . .

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Tricky point: disks can degenerate to factor $\mathbb{CP}_1$.

Introduce function

$$\mathcal{A} : M_\psi \longrightarrow (0, 4\pi)$$

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Since ψ is continuous deformation of antipodal,

Continuity method $\Rightarrow$ each level set non-empty!

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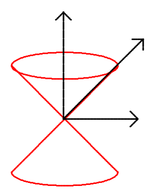
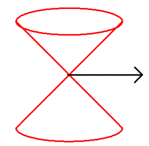
$\Rightarrow$ up to homothety $T_D M$ carries Lorentz metric, modelled on Killing form of $\mathfrak{sl}(2, \mathbb{R})$.

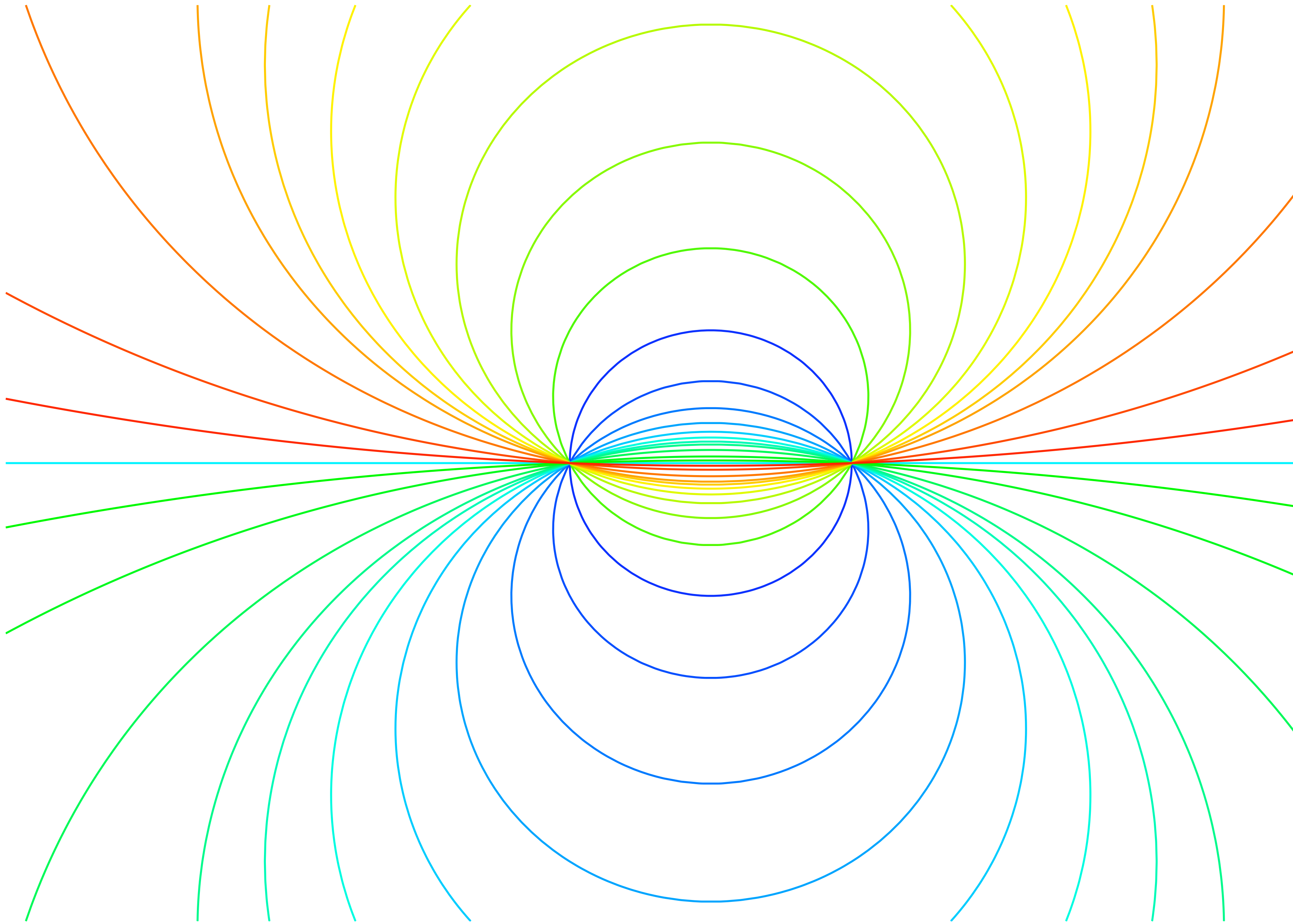
Trichotomy:

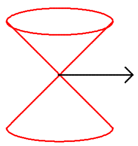
TM	$\mathfrak{sl}(2, \mathbb{R})$
space-like	hyperbolic
null	parabolic
time-like	elliptic





Space-like vector = infinitesimal variation with two distinct zeroes on ∂D.





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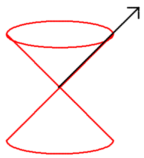

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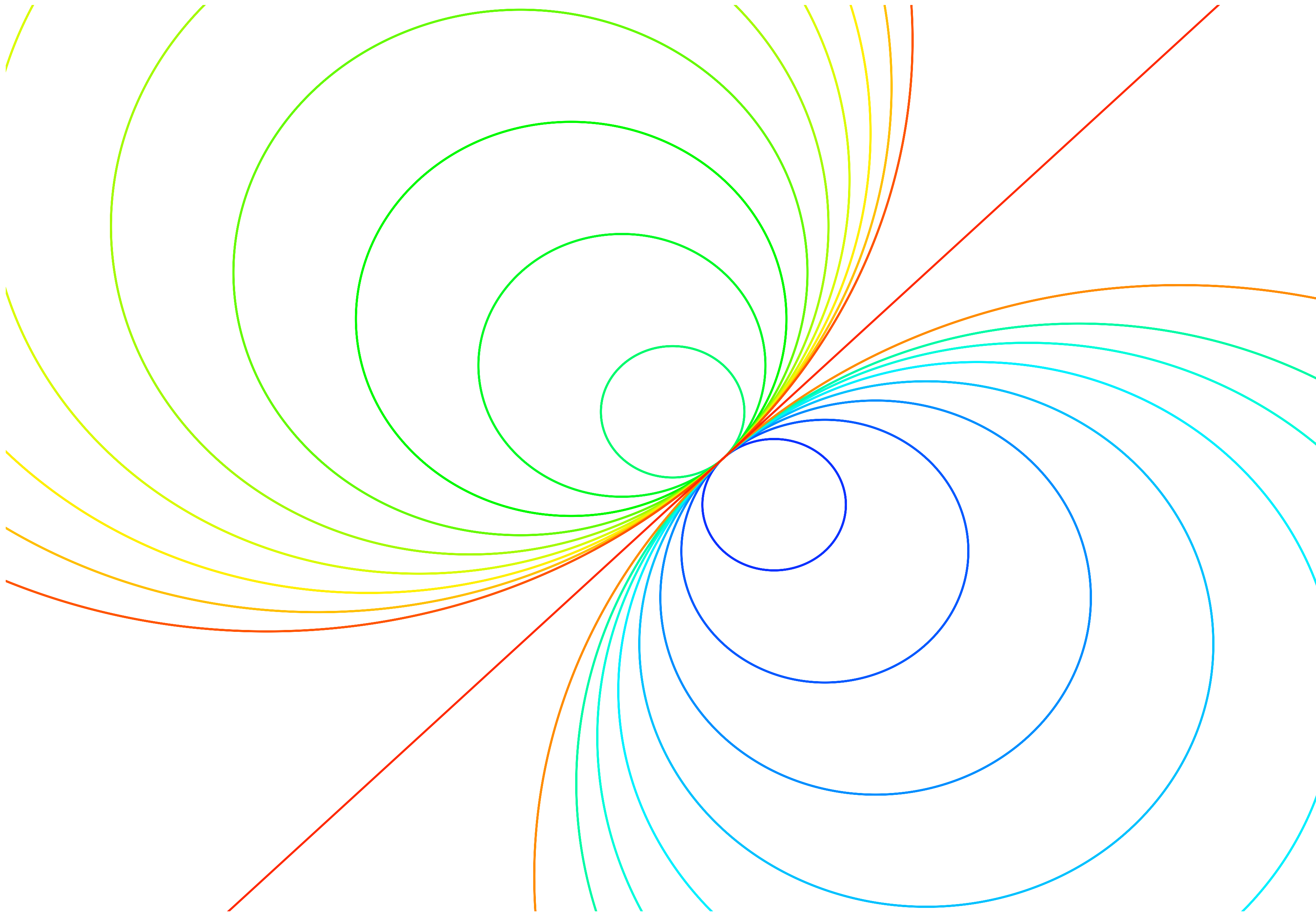

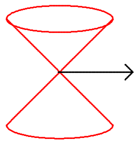

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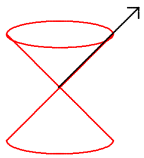

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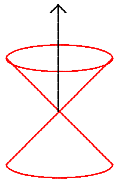
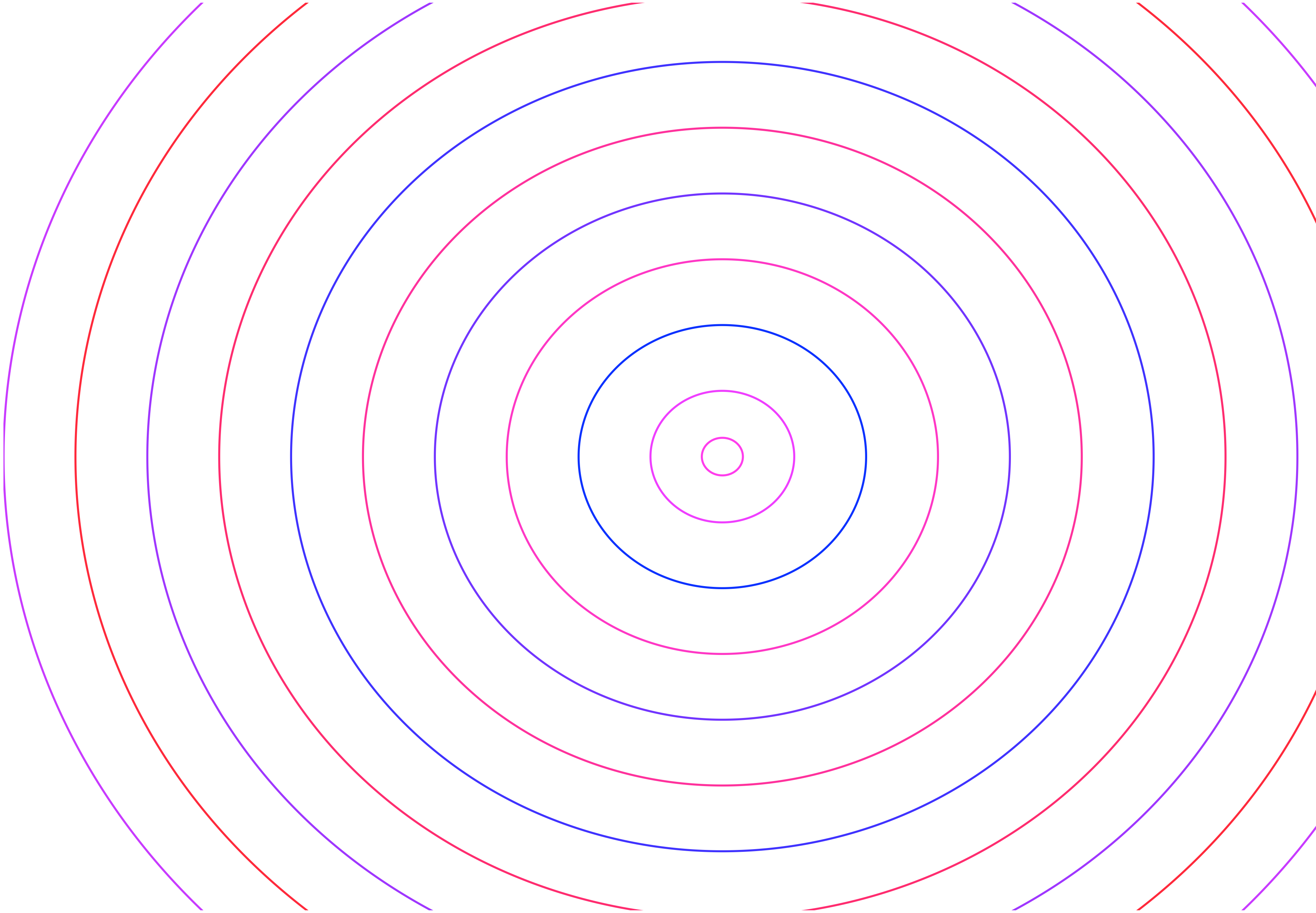


Time-like vector = infinitesimal variation with a single zero in interior of D: none along ∂D.



Hence area function $\mathcal{A}$ has derivative $\neq 0$
in any time-like direction.

$\mathcal{A}$ is time function on $(M_\psi, [g]_\psi)$!

$\therefore$ No critical points.

$\therefore$ Gromov-compactness $\Rightarrow$ for all $c \in (0, 4\pi)$,
level set $\mathcal{A}^{-1}(c)$ are compact surfaces

Every endless time-like curve goes from
$\mathcal{A} = 0$ to $\mathcal{A} = 4\pi$.

So $\mathcal{A}^{-1}(c)$ is Cauchy surface.

M globally hyperbolic!

By deformation: Cauchy surface topologically S^2.

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disks passing though a pair of distinct points
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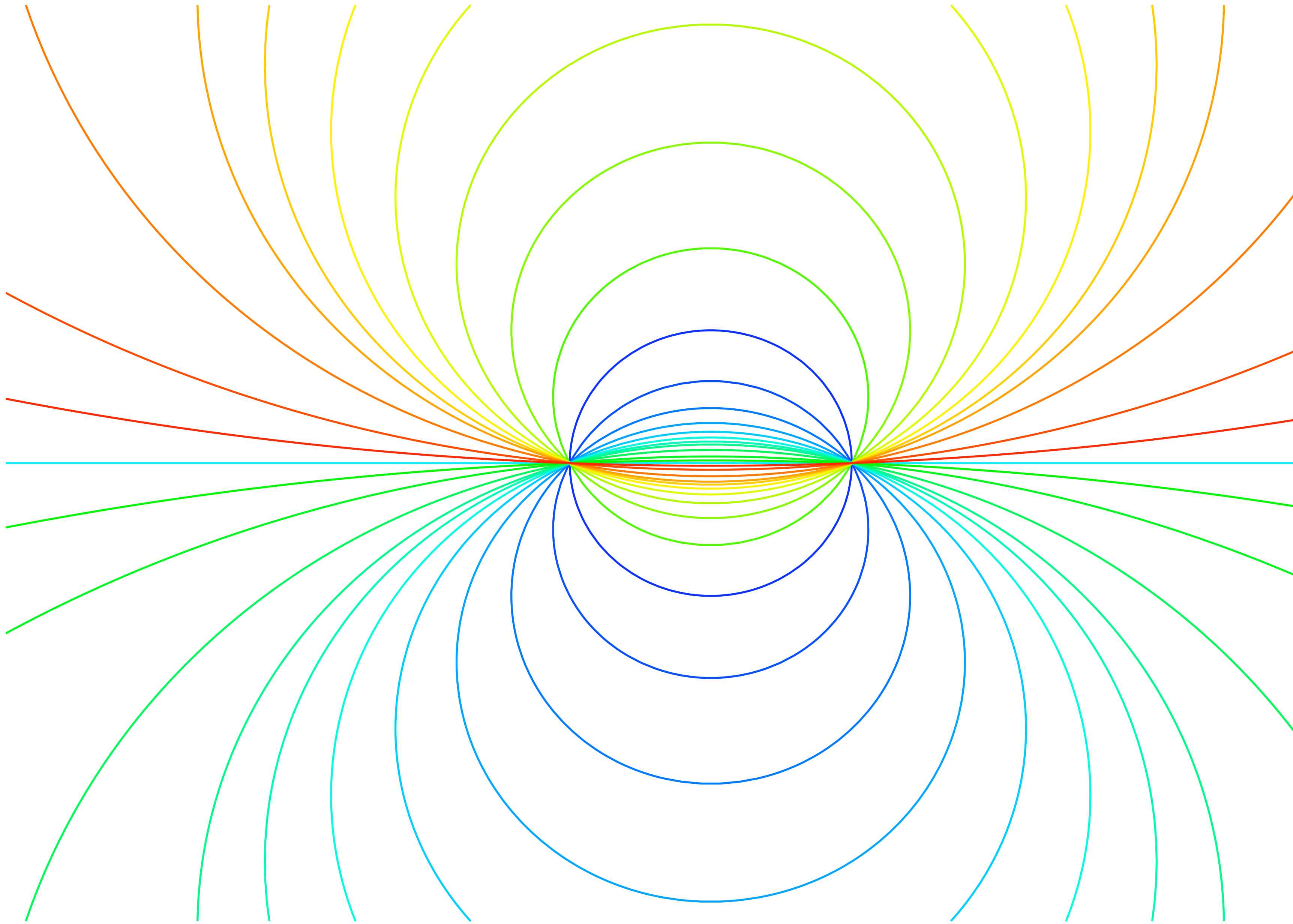

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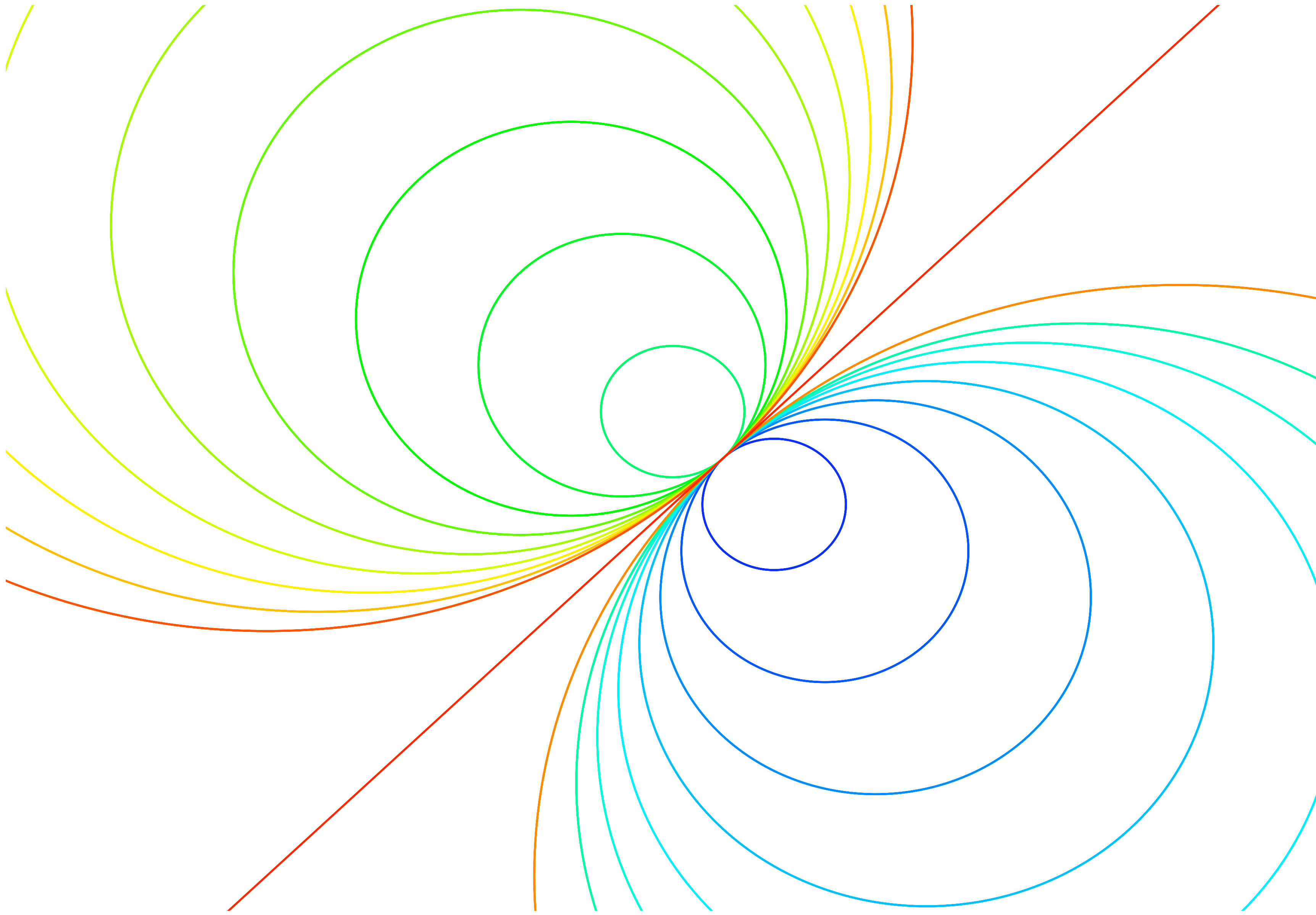

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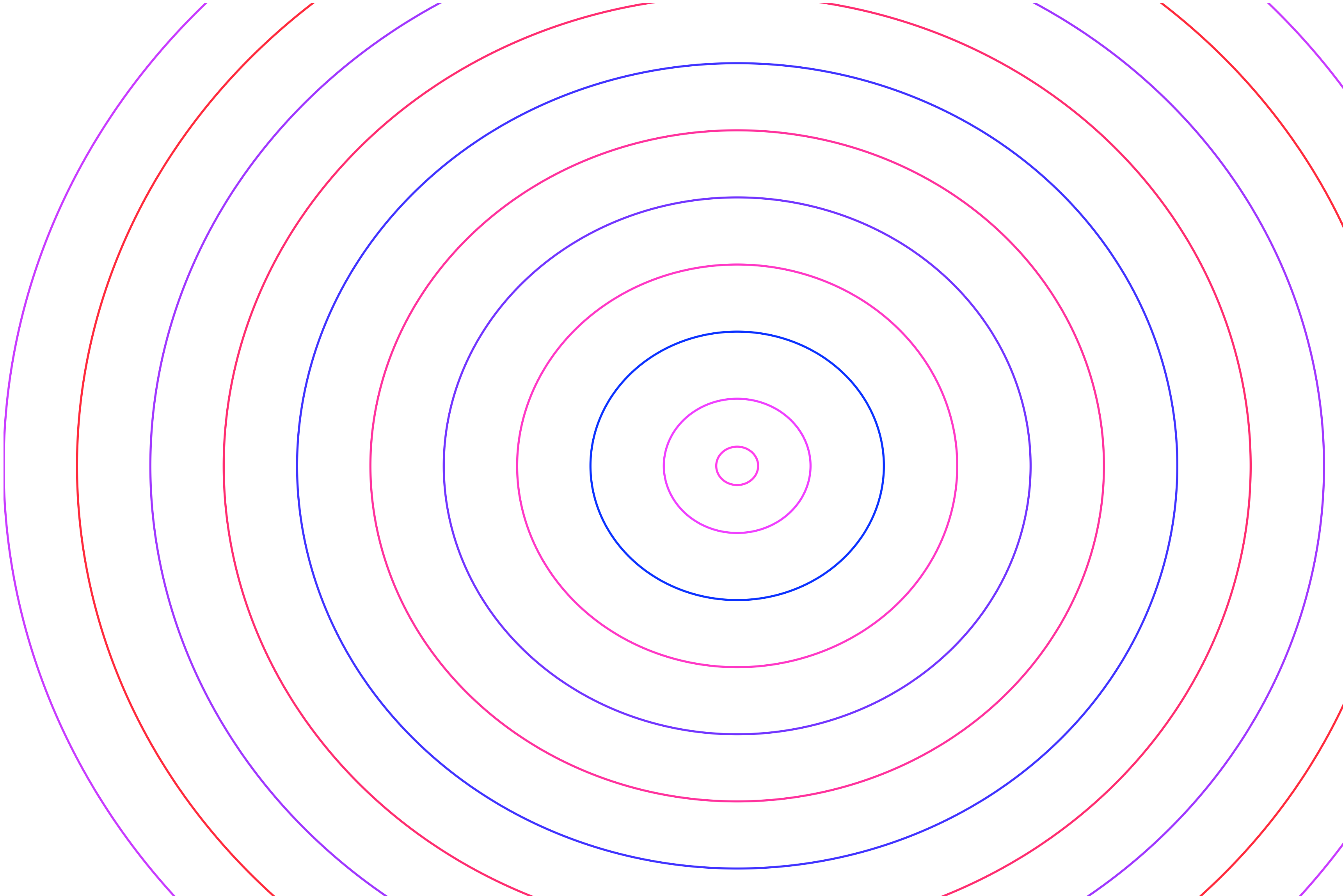

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Also gives direct proof of conformal compactness.