KerrNullGeodesics

The `KerrNullGeodesics`` package contains functions for calculating the null geodesic motion in the Kerr metric. The public functions in this package are:

`KerrNullGeo[`*a*`,` *xs*`,` *ps*`]`	returns a KerrNullGeoFunction which stores information about the trajectory of a light–ray starting from specified initial conditions. The black hole spin *a*, position *xs*, and wavevector *ps* are assumed to be given in units of the BH mass, unless mass M is specified (optional argument).
`KerrNullGeoDistant[`*a*`,` *θo*`,` *α*`,` *β*, *radiusLimit_ : 0*`]`	returns a KerrNullGeoDistantFunction which stores information about the trajectory of a geodesic coming from infinity. The spin *a*, and Bardeen's impact parameters *α*,*β* are assumed to be given in units of the BH mass
`KerrNullGeoFunction[`*a*`,` *xs*`,` *ps*`, M,` *assoc*`]`	an object for storing the trajectory and its parameters in the *assoc* association
`KerrNullGeoDistantFunction[`*a*`,` *θo*`,` *α*`,` *β*`,` *assoc*`]`	an object for storing the trajectory and its parameters in the *assoc* association

First, load the paclet:

```
In[256]:= Needs["BlackHoleImages`"]
```

The Conventions in This Package

Throughout the paclet, we assume the Kerr geometry characterized by the black hole's mass *M* and its spin parameter *a*. In this package, the unit convention *c=G=M=1* is used, so that all the calculations are dimensionless.

We use the standard Boyer-Lindquist coordinates (t, r, θ, ϕ), and parametrize the geodesics with the Mino time λ defined by $\frac{d x^{\mu}}{d \lambda} = \frac{r^2 + a^2 \mathrm{Cos}[\theta]}{E}\, p^{\mu}$.

The constants of motion are in the referred to as $\ell = \frac{L}{E}$, the angular momentum over energy at infinity, and $\eta = \frac{Q}{E^2}$, where Q is the Carter integral.

The Distant Observer Case

For generating the null geodesics in the case of an observer far away from the black hole, the `KerrNullGeoDistant` function is implemented.

First of all, it is necessary to use a characterization of the angular displacement projected on the observer’s celestial sphere, which would not be proportional to the distance *r*. This is often done using so-called Bardeen coordinates (found in Bardeen’s lecture in

Houches Ecole d'ete de Physique Theorique, isbn 978-0-677-15610-1), defined as $\alpha = -r_o \frac{p^{[\phi]}}{p^{[t]}}$, $\beta = -r_o \frac{p^{[\theta]}}{p^{[t]}}$, where the indices in square brackets denote the four-momentum measured by local observer, whose $r = r_o$ and $\theta = \theta_o$ coordinates are fixed and who possesses zero angular momentum. The Bardeen coordinates can be used to calculate the integrals of motion and their straight-forward interpretation is useful for plotting images in the case $r_o \to \infty$.

The time coordinate t cannot be readily obtained from the relations found in Gralla & Lupsasca, arXiv:1910.12881v3 in the distant observer case, however one can obtain sensible relation for $\Delta v = v_f - v_i$, where we define the null time `v = t + r + 2 Log[r / 2]`. We here assume the geodesic begins at the spatial infinity and moves in time towards the coordinate centre.

A single geodesic can be generated with the `KerrNullGeoDistant` function by specifying:

a	The spin parameter.
θo	The distant observer's θ coordinate.
α, β	The bardeen coordinates of the geodesic.
radiusLimit	Optional parameter which specifies the maximal radius (given in multiples of the black hole's mass) at which an accration disk is considered.

Additional options can be given:

Option	**Default**	**Description**
"Rotation"	"Counterclockwise"	Sets the direction of rotation of the black hole. The default option is "Rotation"-> "Counterclockwise". The opposite is "Rotation"-> "Clockwise".
"PhiRange"	{-Infinity, Infinity}	Sets the range of output of the azimuthal angle. The default is "PhiRange"-> {-∞, ∞}, which starts the coordinate at 0 and does not take the modulus of it after full windings. Typical options could be {-π, π} or {0, 2π}, but other option values in the format {bottomvalue, topvalue} are valid as well.

The `KerrNullGeoDistant` function returns a `KerrNullGeoDistantFunction` object which stores information about the trajectory of a geodesic coming from infinity in an association accepting the following keys:

"Trajectory"	Returns a list of trajectory coordinates {Δv, r, θ, φ} as functions of the Mino time λ.
"ConstantsOfMotion"	Returns a list of the constants of motion of the geodesic {l, η}.
"RadialRoots"	Returns the radial roots in a list {r1, r2, r3, r4}, as are defined in Gralla & Lupsasca, arXiv:1910.12881v3.
"EquatorIntersectionMinoTimes"	Returns the Mino times when $\theta=\pi/2$ in a list from smallest (closest to the observer) to largest.
"EquatorIntersectionCoordinates"	Returns the coordinates {Δv, r, φ} in "EquatorIntersectionMinoTimes".
"TrajectoryType"	Returns one of the following trajectory types: "PhotonCapture" if the trajectory crosses the horizon, or else "PhotonEscape".
"MinoTimeOfCapture"	Returns the Mino time,when the photon crosses the outer horizon if "TrajectoryType" is "PhotonCapture", or the Mino time when the photon scatters back to infinity.
"EscapeCoordinates"	If "TrajectoryType" is "PhotonEscape", returns the {θ, φ} coordinates in "MinoTimeOfCapture", otherwise returns {−1, −1}.
"EmissionCoordinates"	If the trajectory crosses the equatorial plane at some r>rISCO, returns a list of coordinates at the first occurrence.
"EmissionParameters	If the trajectory crosses the equatorial plane at some r>rISCO, at the first occurrence returns a list {κ, θloc, φloc} defined as the ratio between energy at infinity and the locally measured energy on a circular equatorial geodesic, and the locally measured impact angles respectively. Otherwise returnes {−1, −1, −1}.

As an example, let us generate a geodesic in a geometry defined by the spin parameter $a = 0.4$ coming from $\theta o = \pi / 3$ and possessing the Bardeen coordinate $\alpha = 5, \beta = 5$:

```
In[80]:= geod = KerrNullGeoDistant[0.4, π / 3, 5, 5];
```

Let us see if the geodesic crosses the horizon or stays outside of it:

```
In[81]:= If[geod["TrajectoryType"] == "PhotonCapture",
          Print["Crosses the horizon."], Print["Stays outside of the horizon."]]

         Stays outside of the horizon.
```

From e.g. Gralla & Lupsasca, arXiv:1910.12881v3, we know that the geodesics scattering on the black hole should have all the roots of the radial potential real. Let us check if that is the case:

```
In[82]:= geod["RadialRoots"]

Out[82]= {-7.9589 + 0. i, 0.047651 + 0. i, 2.38086 + 0. i, 5.53039 + 0. i}
```

Let us also look at the constants of motion:

```
In[83]:= Print["ℓ = ", geod["ConstantsOfMotion"][[1]]]
         Print["η = ", geod["ConstantsOfMotion"][[2]]]
```

$\ell = -\frac{5\sqrt{3}}{2}$

$\eta = 31.21$

To visualize the geodesics, we might want to know what the Mino time of the geodesic's escape to infinity λ_∞ is:

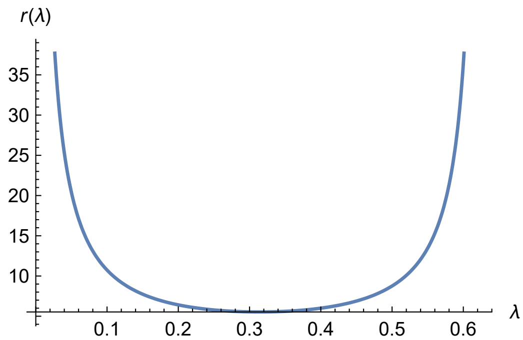
In[85]:=
```
λ∞ = geod["MinoTimeOfCapture"]
```

Out[85]=
```
0.627646
```

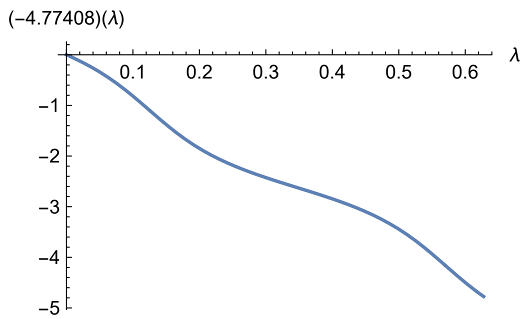
To access the coordinate as functions of the Mino time, one does not need to specify the "Trajectory" key, the value of Mino time suffices.

In[86]:=
```
Plot[geod[λ][[2]], {λ, 0, λ∞}, AxesLabel → {λ, r[λ]}]
Plot[geod[λ][[4]], {λ, 0, λ∞}, AxesLabel → {λ, ϕ[λ]}]
```

Out[86]=



Out[87]=

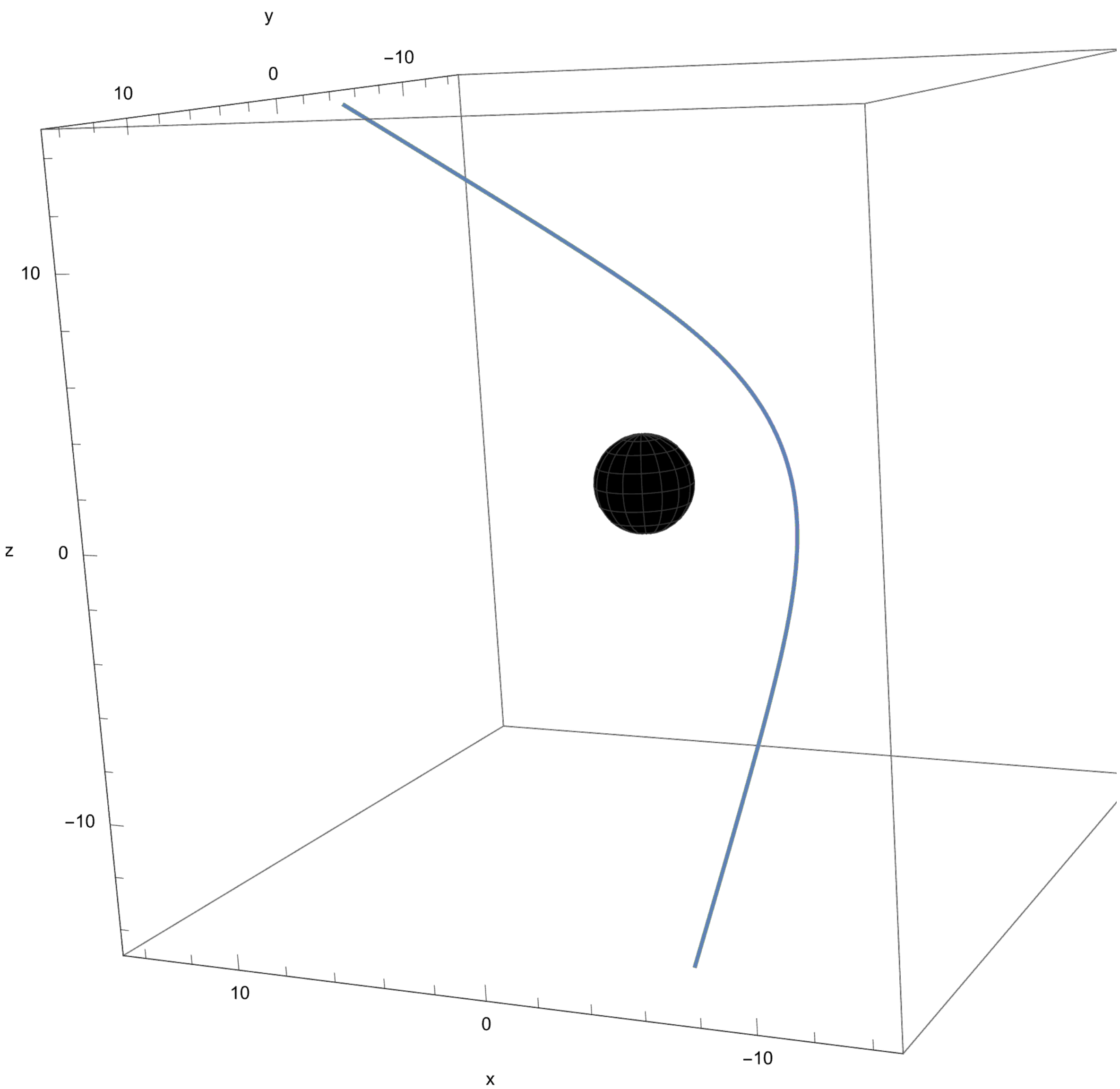


Note that since we did not specify the option "PhiRange" of `KerrNullGeoDistant`, the ϕ as a funtion of λ is not a priori bounded.

Let us plot the geodesic's space-like coordinates as spherical coordinates in the Euclidian space:

```
In[144]:= Spherical2Cartesian[list_] := {list[[2]] × Sin[list[[3]]] × Cos[list[[4]]],
             list[[2]] × Sin[list[[3]]] × Sin[list[[4]]], list[[2]] × Cos[list[[3]]]};
          plotA = ParametricPlot3D[Spherical2Cartesian[geod[λ]],
             {λ, 0, λ∞}, PlotPoints -> 1000, PlotRange -> {{-15, 15}, {-15, 15}, {-15, 15}}];
          plotB = SphericalPlot3D[1 + √(1 - 0.4^2), {θ, -π, π}, {ϕ, 0, 2 π}, PlotStyle -> Directive[Black],
             PlotRange -> {{-15, 15}, {-15, 15}, {-15, 15}}, AxesLabel -> {"x", "y", "z"}];
          Show[{plotA, plotB}, AxesLabel -> {"x", "y", "z"}]
```

Out[147]=



As a final example, let us compute the angle δ between the incoming direction of the geodesic and the direction after scattering:

```
In[92]:= {θe, ϕe} = geod["EscapeCoordinates"];
         θo = π / 3;
         δ = ArcCos[-Sin[θe] × Sin[π - θo] × Cos[ϕe] + Cos[θe] × Cos[π - θo]];
         Print["δ = ", δ, " rad"]

      δ = 1.23853 rad
```

The Observer at Finite Distance

If the initial data are given at a point at finite distance from the black hole, one can use the `KerrNullGeo` function.

The geodesic in this case is generating by specifying the following values:

a	The spin parameter.
xs	Initial position 4 – vector.
ps	Initial momentum.

This can be further modified with the following options:

Option	**Default**	**Description**
"Momentum"	"Momentum"	Specifies whether the user provided 4 – momentum or wave 4 – vector as ps. The default option is "Momentum" –> "Momentum". If the user provided the wave 4 – vector, the option "Momentum" –> "WaveVector" should be specified.
"PhiRange"	{-Infinity, Infinity}	Sets the range of output of the azimuthal angle. The default is "PhiRange"–> {−∞, ∞}, which starts the coordinate at 0 and does not take the modulus of it after full windings. Typical options could be {−π, π} or {0, 2π}, but other option values in the format {bottomvalue, topvalue} are valid as well.

Similarly to `KerrNullGeoDistant`, the `KerrNullGeo` function returns a `KerrNullGeoFunction` object which stores information about the trajectory of a geodesic in an association accepting the following keys:

"Trajectory"	Returns a list of trajectory coordinates {t, r, θ, φ} as functions of the Mino time λ.
"ConstantsOfMotion"	Returns a list of the constants of motion of the geodesic {l, η}.
"RadialRoots"	Returns the radial roots in a list {r1, r2, r3, r4}, as are defined in Gralla & Lupsasca, arXiv:1910.12881v3.
"EquatorIntersectionMinoTimes"	Returns the Mino times when $\theta=\pi/2$ in a list from smallest (closest to the observer) to largest.
"EquatorIntersectionCoordinates"	Returns the coordinates {t, r, φ} in "EquatorIntersectionMinoTimes".
"TrajectoryType"	Returns one of the following trajectory types: "PhotonCapture" if the trajectory crosses the horizon, or else "PhotonEscape".
"MinoTimeOfCapture"	Returns the Mino time,when the photon crosses the outer horizon if "TrajectoryType" is "PhotonCapture", or the Mino time when the photon scatters back to infinity.
"EscapeCoordinates"	If "TrajectoryType" is "PhotonEscape", returns the {θ, φ} coordinates in "MinoTimeOfCapture", otherwise returns {−1, −1}.
"EmissionCoordinates"	If the trajectory crosses the equatorial plane at some r>rISCO, returns a list of coordinates at the first occurrence.
"EmissionParameters	If the trajectory crosses the equatorial plane at some r>rISCO, at the first occurrence returns a list {κ, θloc, φloc} defined as the ratio between energy at infinity and the locally measured energy on a circular equatorial geodesic, and the locally measured impact angles respectively. Otherwise returnes {−1, −1, −1}.

Let us now generate a geodesic in a geometry characterized by the spin parameter `a = 0.9`, starting from the position `xs = {0, 1.436, π / 3, 0}` with the 4-momentum `ps = {-1, 1,` $\sqrt{10}$`, 10}`. The 4-momentum in fact is not normalized to 0, which would be required from a null vector, but since only the sign of the radial component of the 4-momentum is used in the code, it plays no role.

```
In[3]:= geod1 = KerrNullGeo[0.9, {0, 1.436, π / 3, 0}, {-1, 1, Sqrt[10], 10}];
```

Let us see if the geodesic crosses the horizon or stays outside of it:

```
In[115]:= If[geod1["TrajectoryType"] == "PhotonCapture",
            Print["Crosses the horizon."], Print["Stays outside of the horizon."]]

          Crosses the horizon.
```

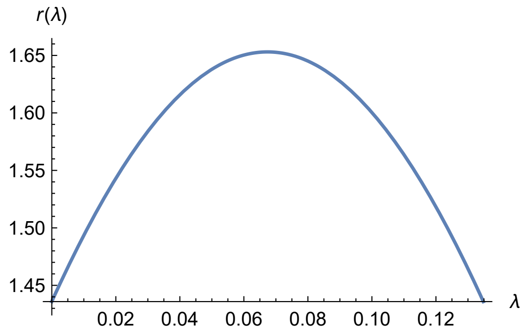
We can check that all the roots of the radial potential are real and the initial radial coordinate is smaller then r_3 meaning that the geodesics never escapes to the spatial infinity but falls back on the horizon.

```
In[162]:= ro = 1.436;
          {r1, r2, r3, r4} = geod1["RadialRoots"]
          If[ro < r3, Print["ro<r3"], Print["ro>r3"]]

Out[163]= {-12.74 + 0. i, 0.151701 + 0. i, 1.65306 + 0. i, 10.9352 + 0. i}

          ro<r3
```

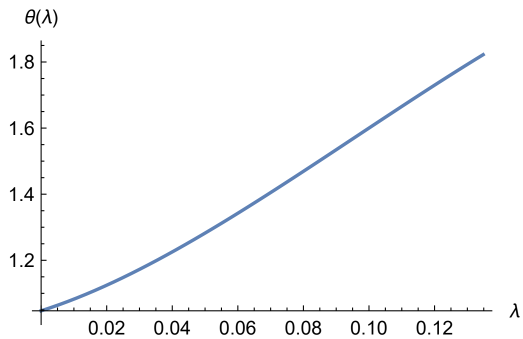
Let us get the Mino time of the photon falling on the outer horizon and plot the radial and polar coordinates as functions of λ:

```
In[166]:= λx = geod1["MinoTimeOfCapture"]
          Plot[geod1[λ][[2]], {λ, 0, λx}, AxesLabel → {λ, r[λ]}]
          Plot[geod1[λ][[3]], {λ, 0, λx}, AxesLabel → {λ, θ[λ]}]

Out[166]= 0.134814
```

Out[167]=



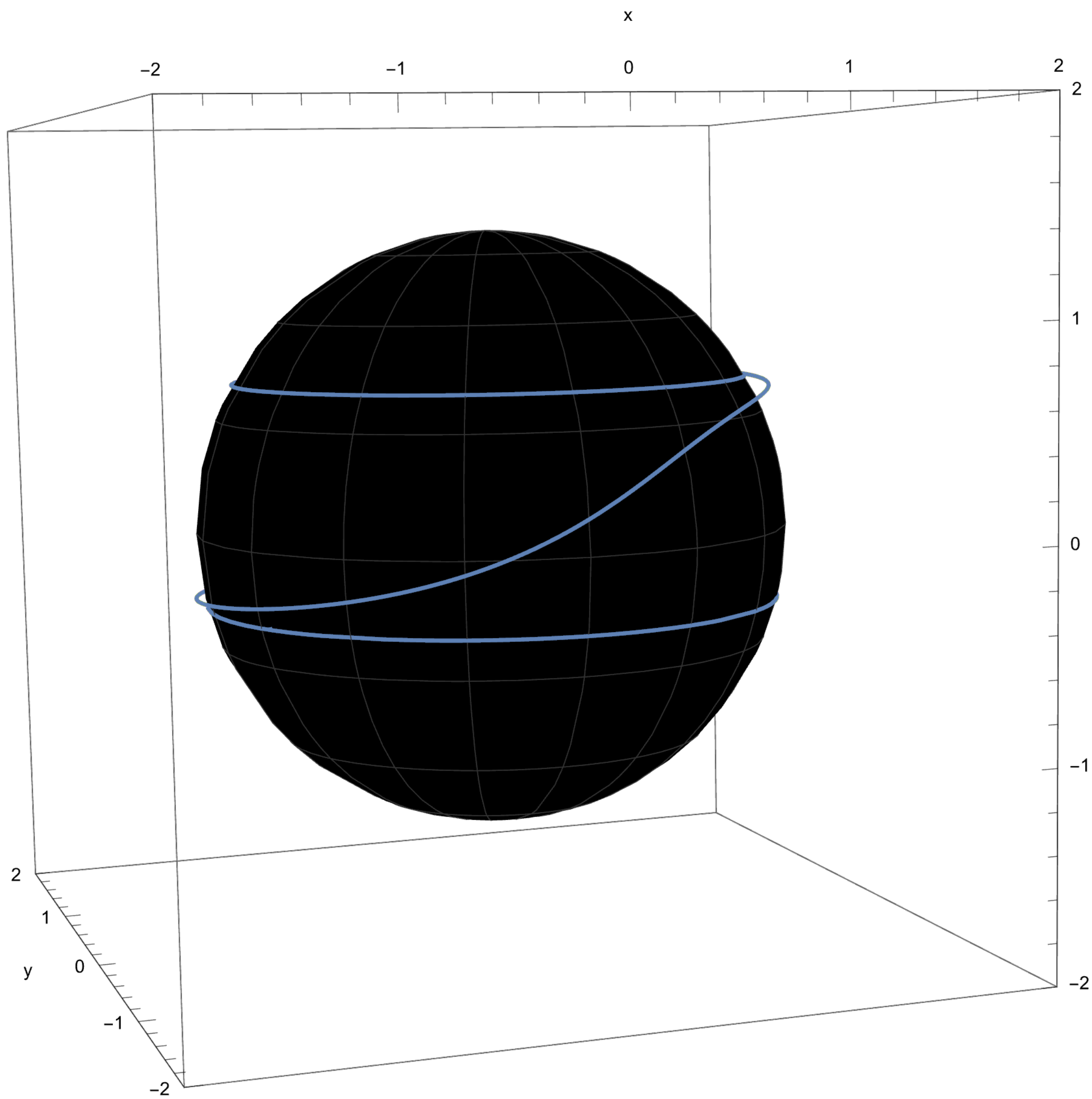
Out[168]=



Let us plot the geodesic's space-like coordinates as spherical coordinates in the Euclidian space:

In[178]:=
```
plot1A = ParametricPlot3D[Spherical2Cartesian[geod1[λ]],
   {λ, 0, λx}, PlotPoints -> 1000, PlotRange -> {{-2, 2}, {-2, 2}, {-2, 2}}];
plot1B = SphericalPlot3D[1 + √(1 - 0.9^2), {θ, -π, π}, {ϕ, 0, 2 π},
   PlotStyle -> Directive[Black], PlotRange -> {{-2, 2}, {-2, 2}, {-2, 2}}, AxesLabel -> {"x", "y", "z"}];
Show[{plot1A, plot1B}, AxesLabel -> {"x", "y", "z"}]
```

Out[180]=



.

We see that the geodesic crosses the equatorial plane one time. Let us see the Mino time and coordinates of that intersection:

In[4]:=
```
λeq = geod1["EquatorIntersectionMinoTimes"][[1]];
{teq, req, ϕeq} = geod1["EquatorIntersectionCoordinates"];
Print["λeq = ", λeq]
Print["teq = ", teq[[1]]]
Print["req = ", req[[1]]]
Print["ϕeq = ", ϕeq[[1]]]
```

λ_{eq} = 0.0955312

t_{eq} = −29.9771

r_{eq} = 1.6137

ϕ_{eq} = −8.15944

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