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Meta-Material Analogs of Static Spherically Symmetric Spacetimes

M. Nouri-Zonoz, A. Parvizi and H. Forghani

ABSTRACT

We introduce a direct exact simulation of the light ray trajectories in the metamaterial analogs of spherically symmetric black hole spacetimes. The spacetime index of refraction, assigned to the corresponding metamaterials, is the only element borrowed from the spacetime geometry to perform these simulations. The light ray trajectories could be simulated for different impact parameters. Specifically, as unstable light trajectories, the photon spheres form in these metamaterial analogs at exactly the same radial distances as expected from the corresponding black hole geometries. Using these simulations we find a simple analog of a black hole shadow in the metamaterial analog of a Schwarzschild black hole, eclipsing a line of light sources (as part of an accretion disk) near its analog horizon.

INTRODUCTION

Metamaterial analogs of different spacetimes have attracted a lot of attention in recent years. Historically one could trace back this analogy to the analogy between a spacetime and a material medium with respect to light propagation through which one could assign an index of refraction as well as other optical characteristics to the corresponding spacetime. Through this analogy, one could establish a correspondence between geometric entities of a curved spacetime and the electromagnetic features of a medium such as its electric permittivity and magnetic permeability. In this opto-geometric relation one could start from a given spacetime and find its optical characteristics, and based on them, design its (meta)material analog in which the light trajectories mimic the null geodesics of the corresponding spacetime.

THEORY : SPACETIME INDEX OF REFRACTION

Applying Fermat's principle to light rays in stationary spacetime, in the context of threading formulation of spacetime decomposition, we are led to the following relation:

$$\delta \int \frac{1}{\sqrt{g_{00}}}\left(\frac{dl_c}{dl_f}\right) dl_f = 0$$

dl_c and dl_f are the spatial line element in the curved and flat spacetimes, respectively. metamaterial analog of a static spacetime could be assigned with the following index of refraction:

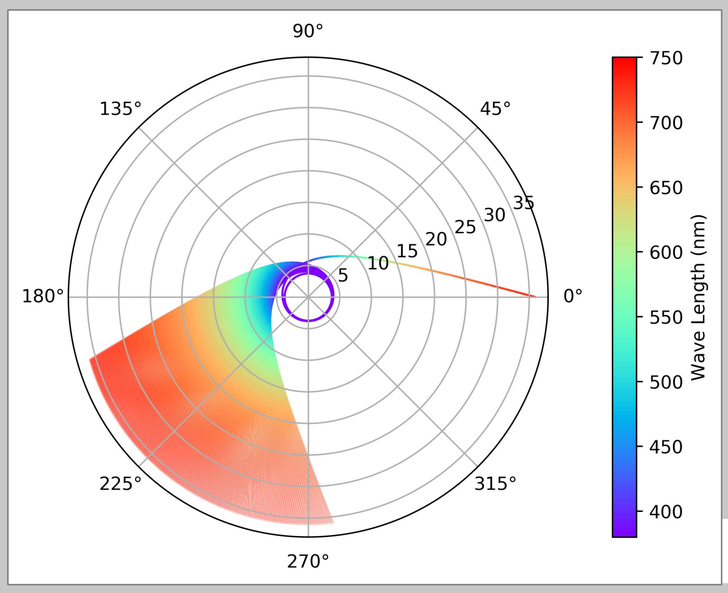
$$n_f = \frac{1}{\sqrt{g_{00}}}\left(\frac{dl_c}{dl_f}\right)$$

in which, the light ray trajectories in the designed metamaterial mimic the null geodesics in the corresponding spacetime. For Schwarzschild blackhole geometries we are led to the following index of refraction:

$$n_{Sch} = \frac{\left(1+\frac{2M}{\rho}\right)^3}{\left(1-\frac{2M}{\rho}\right)}$$

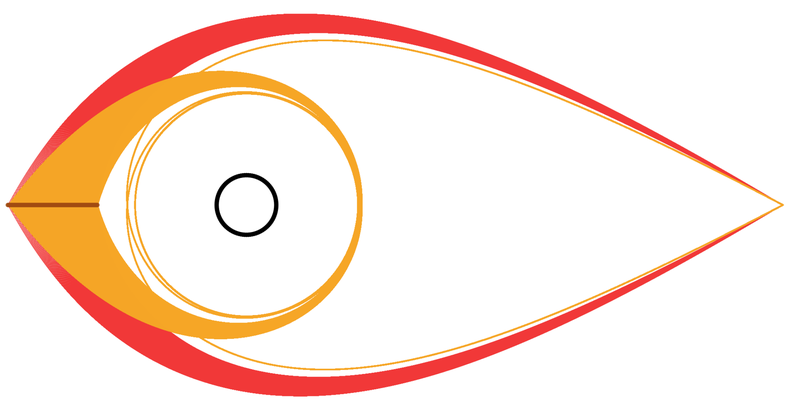
SIMULATION: THE LIGHT TRAJECTORIES

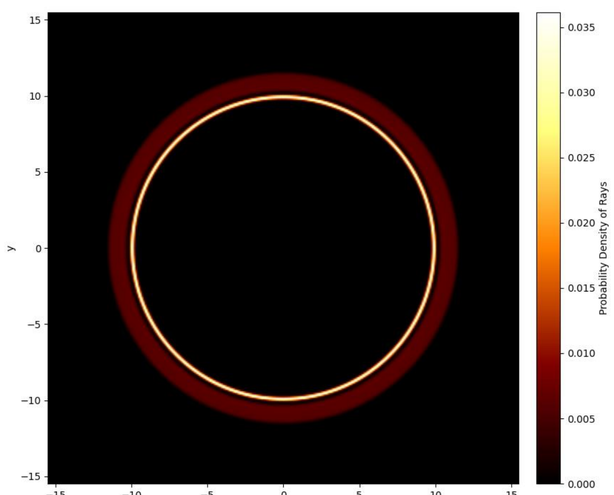
The results of simulation for a congruence of light ray trajectories in a metamaterial analog of the Schwarzschild black hole leading to the formation of photon sphere are shown: $\boldsymbol{\rho_{CDA} \approx 3.7321\rho_{sch}}$

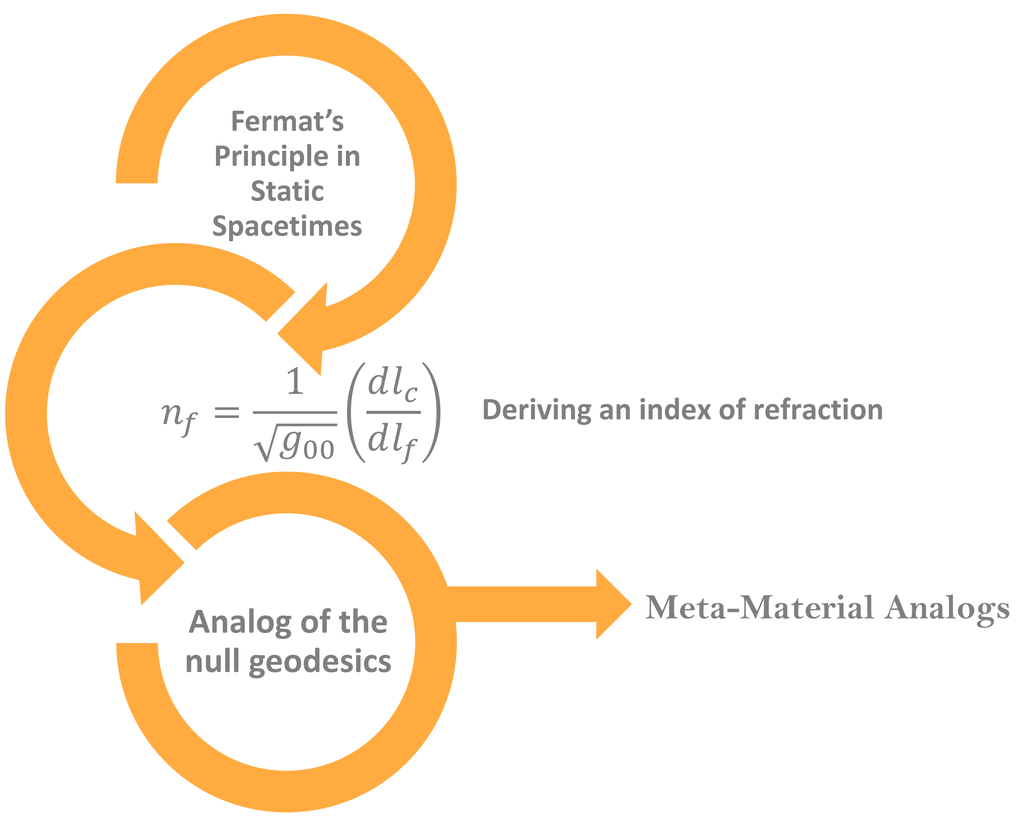


Metamaterial analog of a simple black hole shadow

We consider a metamaterial analog of a simple Schwarzschild black hole shadow. The results of simulation for a line of light sources placed at $5.07\rho_{\text{sch}} - 8.06\rho_{\text{sch}}$ and eclipsed by the analog of a black hole region in a close proximity of its analog horizon are shown in the figures. Light rays emanating from each source inside and at the edge of their corresponding cone of avoidance are strongly deflected to reach a distant observer, forming the analog of a black hole shadow.







CONCLUSION:

Here we introduced a new direct and at the same time exact simulation of light ray trajectories in the metamaterial analogs of static spherically symmetric black holes, based only on their indices of refraction (which are adapted from the corresponding spacetimes). The simulated trajectories are *exact* duplicates of those in the corresponding spacetime. In particular we find the analog of black hole photon spheres in their metamaterial analogs at the same exact radial distance as expected from the spacetime geometry.

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