Building Interstellar's Black Hole: The Gravitational Renderer

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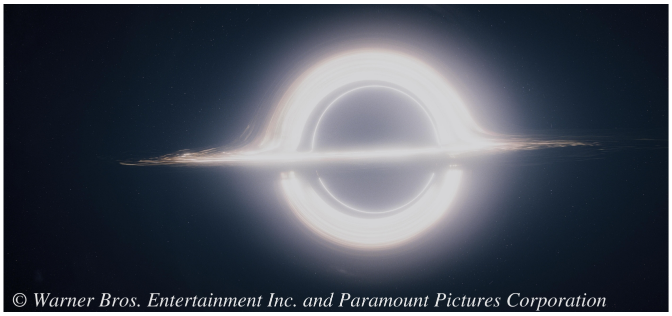

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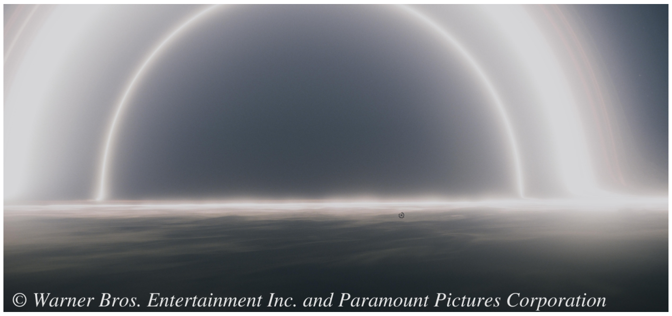

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1 Introduction

Interstellar is the first feature film to attempt depicting a black hole as it would actually be seen by somebody nearby. A close collaboration between the production's Scientific Advisor and the Visual Effects team led to the development of a new renderer, DNGR (Double Negative Gravitational Renderer) which uses novel techniques for rendering in curved space-time. Following the completion of the movie, the code was adapted for scientific research, leading to new insights into gravitational lensing.

Just as a comet can be deflected by the gravity of the sun, light is also deflected by a massive body. This has been observed directly in the case of galaxies acting as gravitational lenses, magnifying and distorting more distant galaxies. Gravitational lensing by a black hole has not been directly observed, but the predictions from Einstein's equations have been well studied.

Gravitational lensing causes the accretion disk (a hot disk of gas orbiting the hole) to appear to wrap over the top of the black hole's shadow and underneath it; distant stars appear to move in complex swirling patterns as the camera orbits the hole; sometimes images of stars get amplified in brightness, split into double images, or a pair of images merge and annihilate in a flash of light. These effects combine to create the iconic images of the black hole seen in the movie.

2 Our Method

As far as we're aware, all previous visualizations have been based on tracing the trajectory of infinitely thin rays. Instead, we consider small bundles of rays (*light-beams*) incident on the film plane of our virtual camera and solve the equations for the propagation of these bundles through the curved spacetime. Our beams have an elliptical cross-section, initially intersecting a small circle on the camera's image plane, roughly the diameter of a pixel. As we trace these beams backwards in time their cross-sections get stretched and squeezed by the warped spacetime. The motion of the camera leads to the beams being swept through space during the the brief exposure time of each image. We take an analytic approach to motion blur by computing a first order approximation of this sweep.

By computing the evolving shape of these swept beams and integrating all the stars and sections of accretion disc that intersect it, we maintain the point-like nature of distant stars and get noise-free motion blur at low computational cost. Additionally, we use the beams' change in cross-section to calculate the amplification in intensity of starlight, predicted by geometric optics.

Relativistic aberration and Doppler shift are included in our calculations and we apply distortion and lens flare measured from the production's IMAX lenses.

3 Caustics and Wormholes

Using beams in our calculations made it a straight-forward process to adapt DNGR to study the caustics in the pattern of light arriving at the camera [James et al. 2015a]. These patterns are the the generalisation of an Einstein Ring for a spinning black hole and have never previously been studied for a nearby observer.

DNGR also traces light beams through wormholes, hypothetical regions of warped space [James et al. 2015b]. These would appear like a crystal ball through which you could observe and travel to a different part of the universe.

References

JAMES, O., VON TUNZELMANN, E., FRANKLIN, P., AND THORNE, K. S. 2015. Gravitational lensing by spinning black holes in astrophysics, and in the movie *Interstellar*. *Classical and Quantum Gravity 32*, 6, 065001.

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