

# Close-Up Black Hole

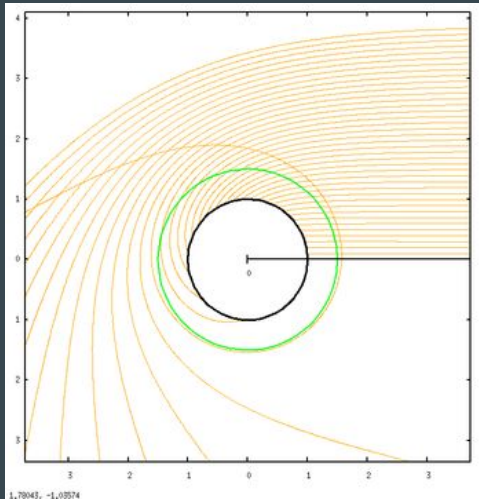
A 3D rendered scene featuring a golden dragon in the foreground, a black hole in the center, and a room with red and blue walls. The dragon is positioned in the lower center, facing left. The black hole is a dark circular void in the center of the white wall, surrounded by a ring of light. The room has a white floor and walls, with a red wall on the left and a blue wall on the right. A bright light source is visible at the top of the white wall.

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Hemisphere Sampling  
256 samples/pixel  
64 shadow rays  
5 max ray depth  
1920x1080

# Ray Tracing in General Relativity

- Light bends near massive objects
- Curves that light travel on are determined by non-linear ODE
- Solution : Numerical integration



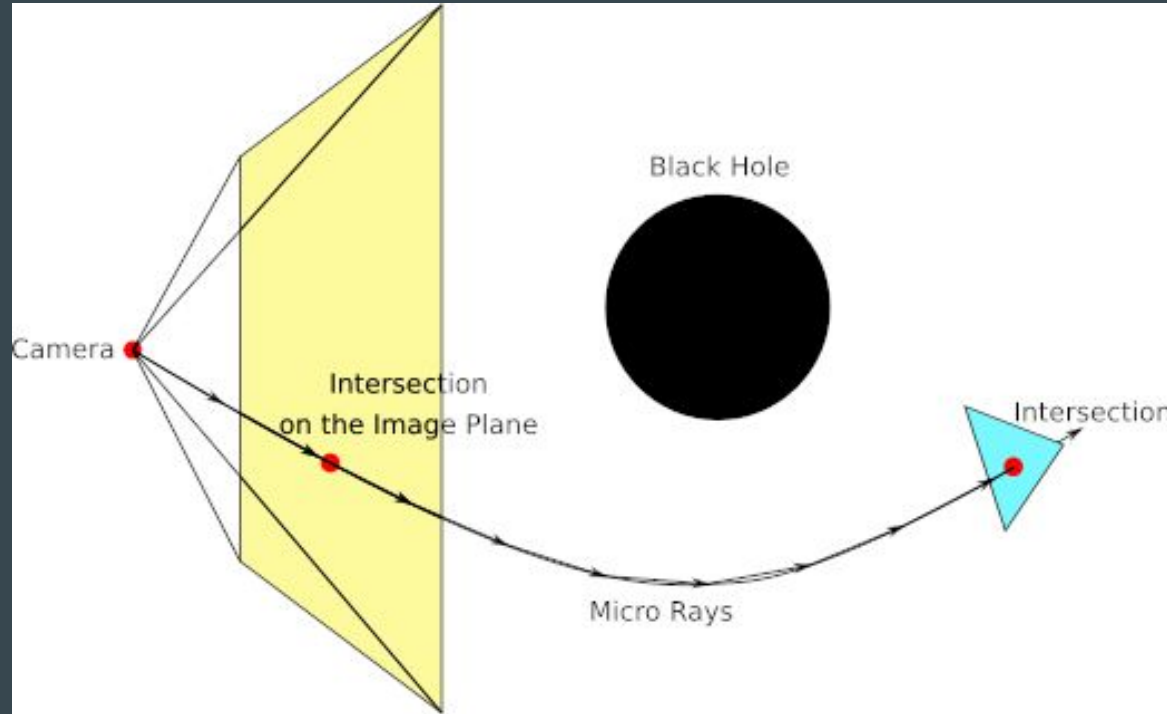
Graph of light geodesics for a Schwarzschild black hole

(Source : <http://spiro.fisica.unipd.it/~antonell/schwarzschild/>)

# Integrating the Geodesic Equation : Schwarzschild Black Hole

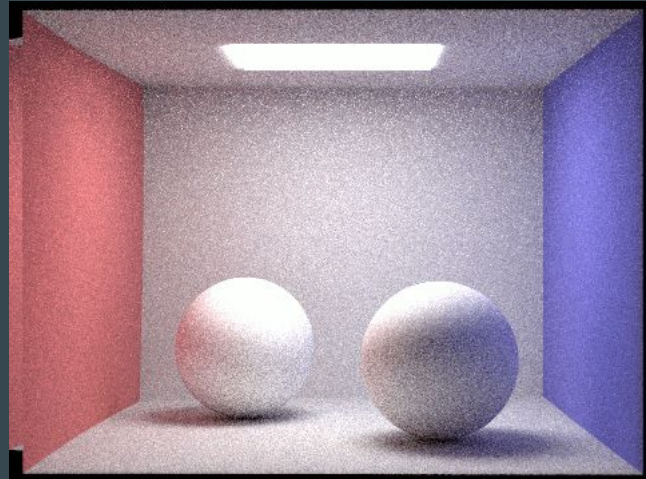
- Strategy: adapt project 3 to cast rays as geodesics instead of lines
  - Cast a ray into the scene
  - Determine the next point on the geodesic using numerical integration
  - Use the ray defined as connecting the original point to the next point & intersect with scene
  - If not continue ad infinitum (or user defined bound)
- Ray curve determined by a non-linear differential equation
  - $u'' + u = 3r_s u^2/2$ , where  $u(\theta) = 1/r(\theta)$
  - Initial conditions given by ray origin and direction
- Use 4<sup>th</sup> order Runge Kutta numerical integration for improved numerical stability at same step size
  - Steps can be much larger speeding up rendering

# Integrating the Geodesic Equation : Schwarzschild Black Hole



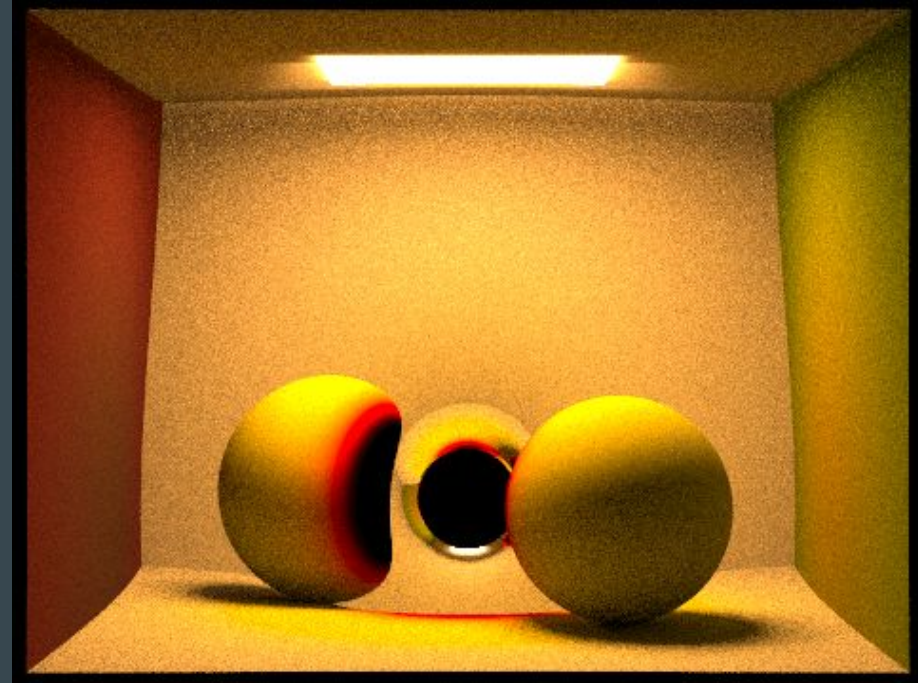
# Black Hole Warping

- Key features
  - Spherical distortion
  - Gravitational lensing
    - Notice that the black hole focuses the light onto the wall
  - Ghost image
    - I.e. the colored wall appears as an inverted image within the spherical distortion



# Gravitational Doppler Effect

- So far ignored wave nature of light
- Spacetime changes the speed of light, thus changing wavelength of light ray
- Light redshifts away from gravitational source, blueshifts towards
- Used spectral data from [cornell box](#)
- Notice light spectrum redshifts towards the camera



# Next Steps (hopefully)

- Implement a Kerr black hole with spin (different differential equation) and corresponding Doppler shift
  - Very hard, 5 equations must be solved simultaneously
  - Spherical symmetry is broken
- Implement numerical metric to support construction of arbitrary black hole configuration