Class 9 : Kerr Black Holes

ASTR398B Black Holes (Fall 2015)
Prof. Chris Reynolds

RECAP

- Schwarschild Solution
  - Describe non-spinning, uncharged black hole
  - Spherically Symmetric spacetime
  - External observers see infalling objects freeze/fade at the event horizon $r=2GM/c^2$
  - From point of view of infalling observer, pass through the event horizon and hit the spacetime singularity at the center
  - Tidal forces will stretch (Spaghettify) observer before they reach the center
- Uncovered two aspects of the event horizon
  - Surface at which gravitational redshift is infinite
  - Region within horizon cannot causally affect outside

THIS CLASS

- Kerr (spinning) black holes!
  - No-hair theorem
  - Twisting of spacetime (“frame-dragging”)
  - Ergosphere and “black hole machines”
  - Orbits around black holes

I : Roy Kerr

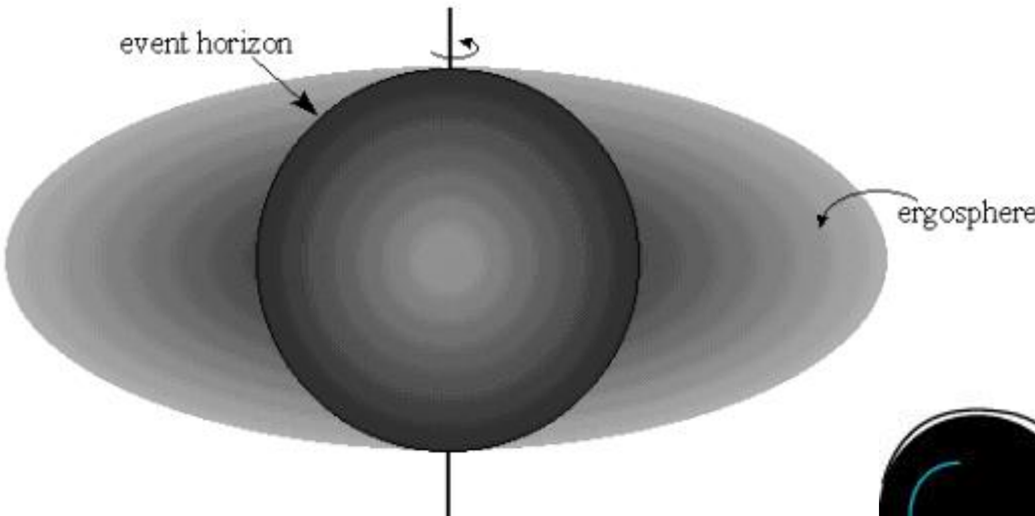
- Roy Kerr (1934-)
  - Discovered exact solutions of Einstein's equations describing a spinning black hole
  - Was later shown that this solution is unique… any spinning (uncharged) black hole is described by the Kerr solution
  - Started a revolution in the theoretical understanding of real black holes

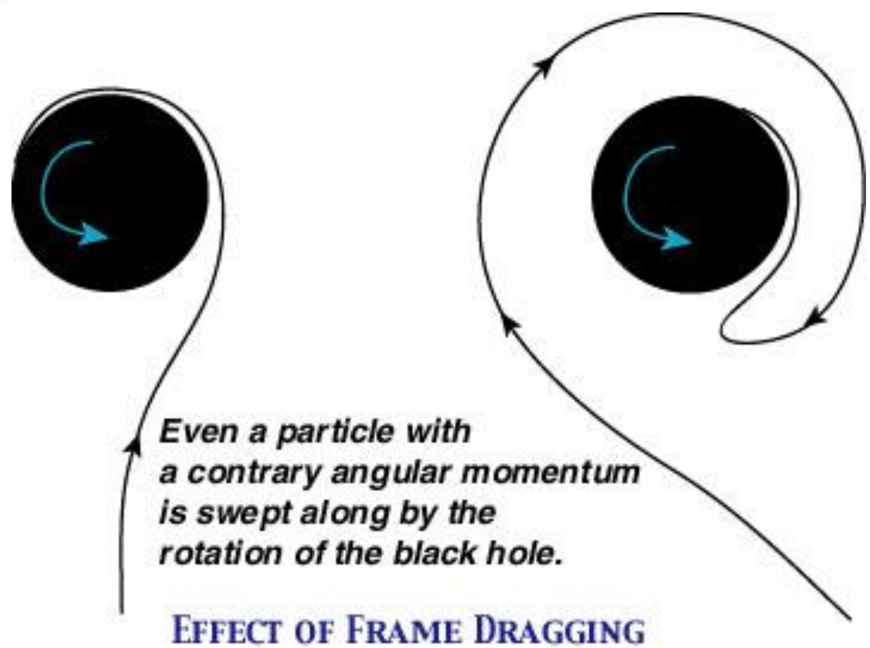
II : No hair theorem

- Any (isolated) black hole is described by just three quantities…
  - Mass
  - Spin
  - Electrical Charge

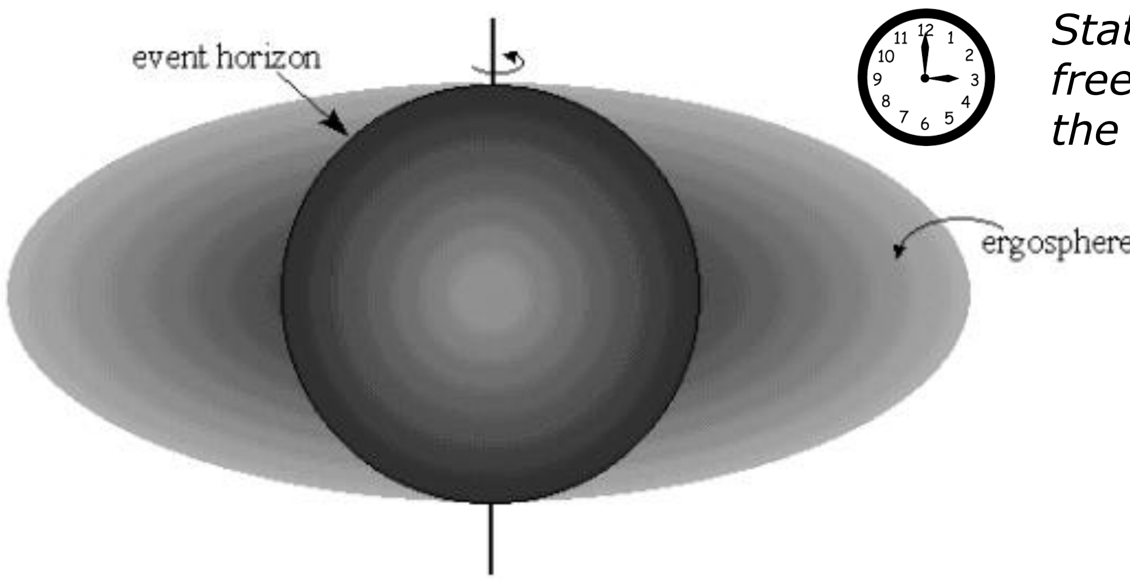
- Once these quantities are specified, the properties of the black hole exterior to the horizon (e.g. spacetime curvature) are uniquely determined.
  - There can be no lumps or bumps on a BH!

III : Frame dragging and the ergosphere



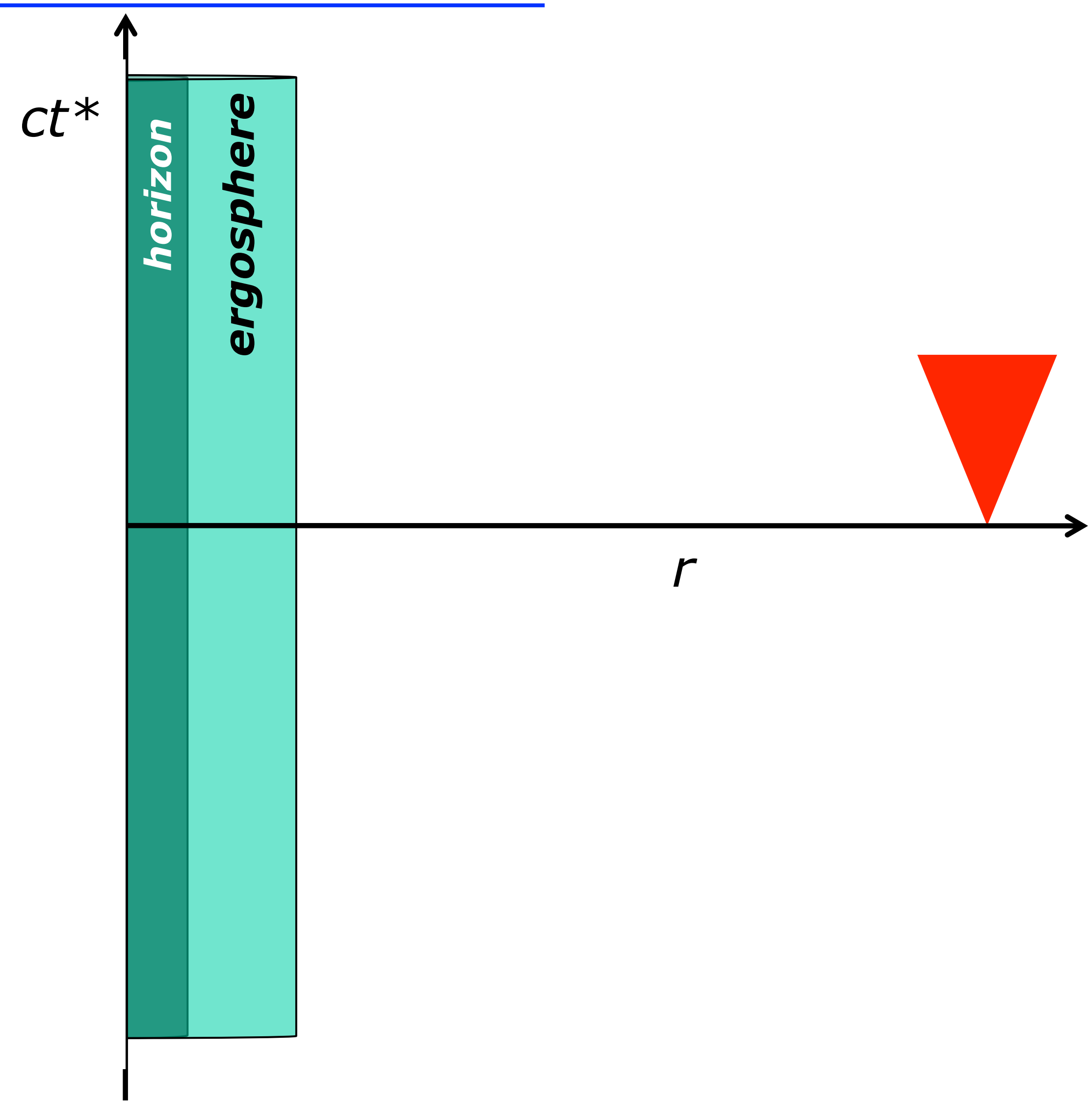


Graphics: University of Winnipeg, Physics Dept.

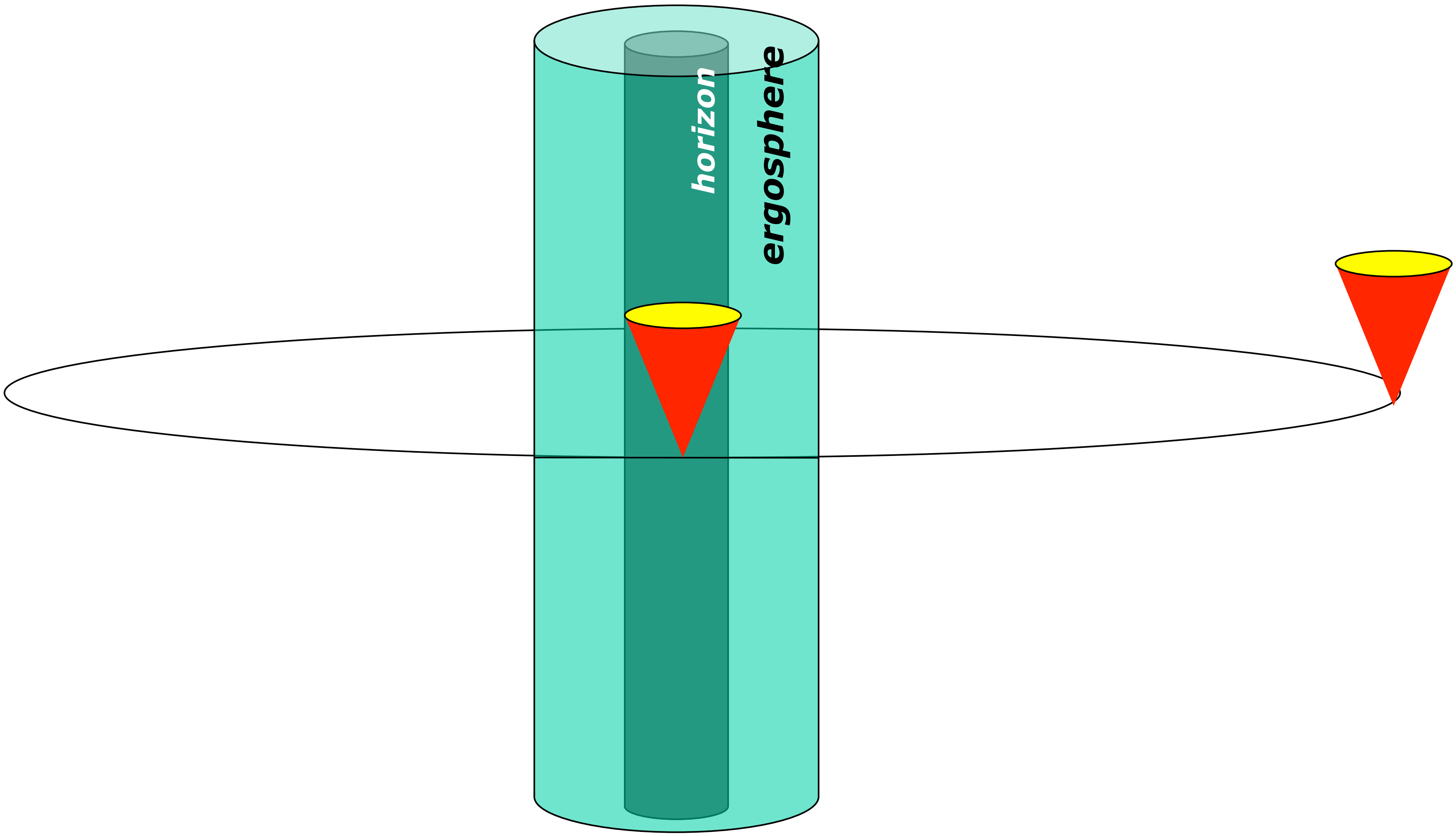


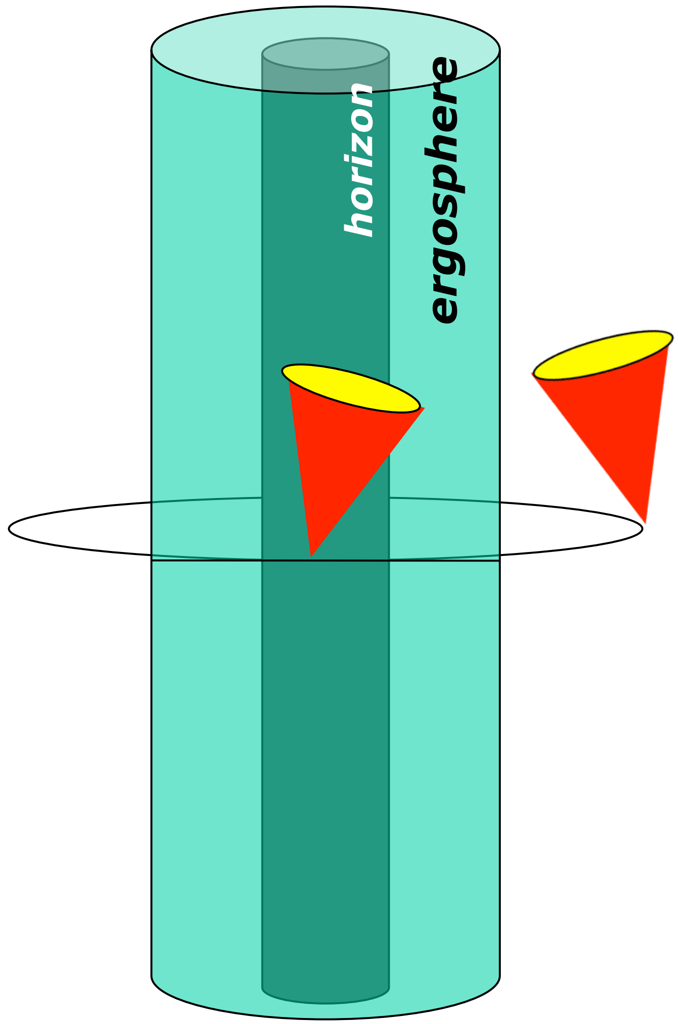
*Stationary clock appears to freeze/stop at the edge of the **ergosphere**.*

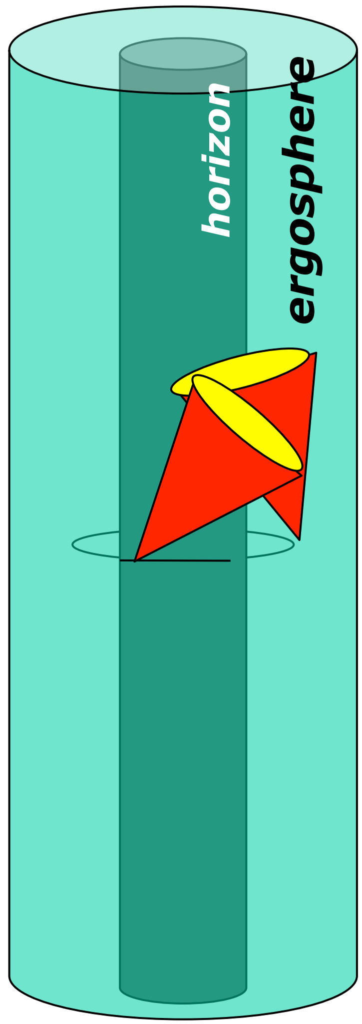
Graphics: University of Winnipeg, Physics Dept.



ct*
horizon
ergosphere
r


horizon
ergosphere


horizon
ergosphere



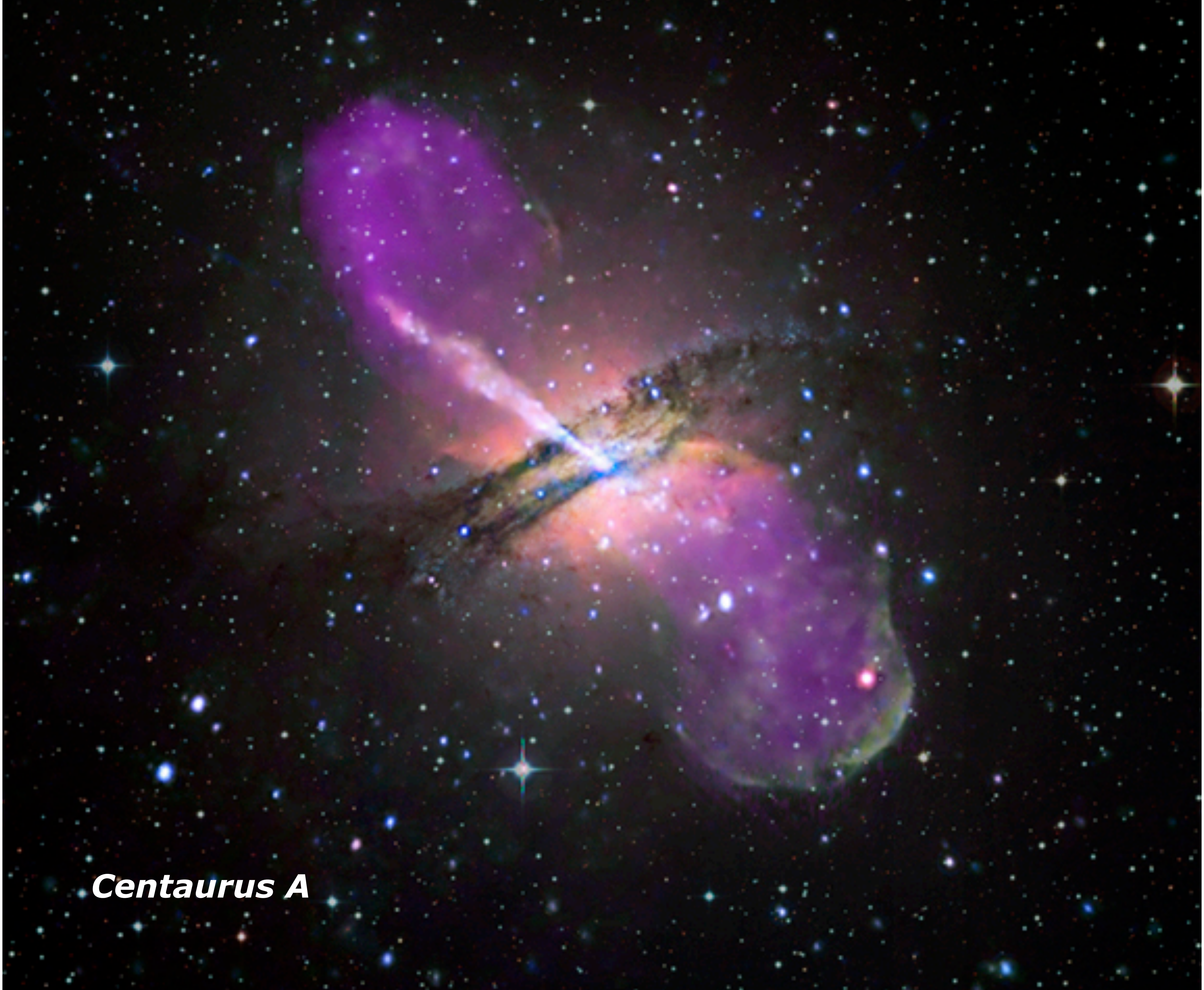
Frame dragging effects tip over light cones in direction of rotation.

Within ergosphere, light cones tipped such that all futures rotate in sense of black hole.

In other words, within ergosphere it is impossible to stand still!

- Why is it called the ergosphere?

- It is the region of spacetime that holds the rotational energy of the black hole (Roger Penrose 1969)
  - Penrose conducted (rather artificial) thought experiments to show that the BH rotational energy can be extracted from within ergosphere
  - Roger Blandford and Roman Znajek (1977) showed that realistic magnetic fields interacting with the BH can achieve the same affect.


Centaurus A

IV : The event horizon

- Ergosphere is outside of the event horizon… we can travel in and out, and can see emission from within!
- Actual event horizon has familiar properties…
  - Surface of infinite redshift, even for clocks/sources that are co-rotating with the spacetime.
  - Seals off the interior space from view
- But rotation has an effect on the location of the event horizon.
  - Define spin parameter "a" (proportional to the angular momentum of the BH)
  - a=0 means non-spinning,
  - a=1 means spinning at maximum rate

- Then the **event horizon** is at:

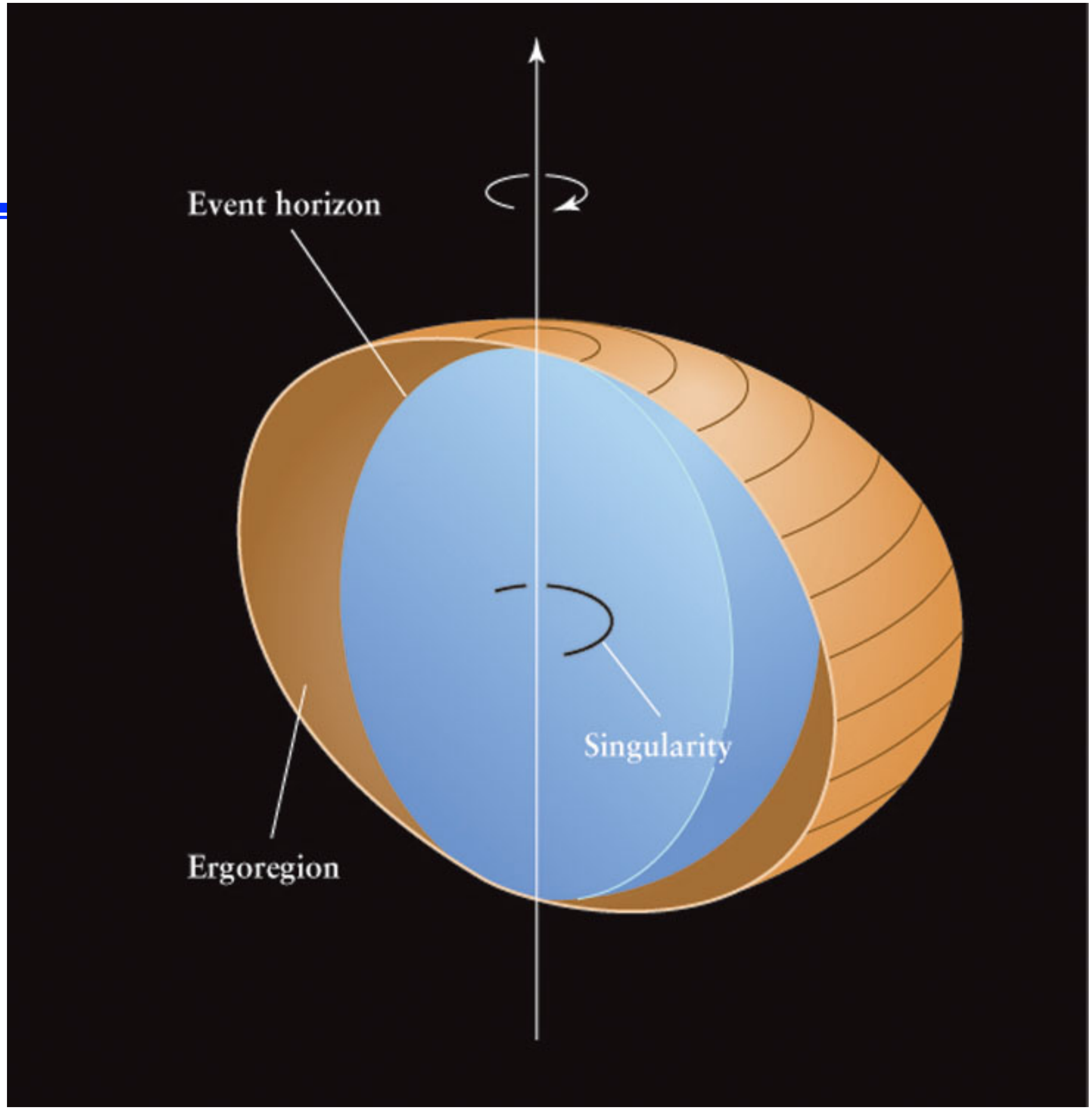
$$R_{evt} = \left(1 + \sqrt{1 - a^2}\right)\frac{GM}{c^2}$$

  - Smaller event horizons for spinning black holes

$$a = 0 \Rightarrow R_{evt} = \frac{2GM}{c^2}$$

$$a = 1 \Rightarrow R_{evt} = \frac{GM}{c^2}$$

  - What happens when a>1? Called **superspinners**. Kerr solution still gives an answer, but there is no event horizon! We have a **naked singularity**!
  - **Cosmic Censorship Hypothesis** asserts that nature does not allow naked singularities and hence forbids a>1 black holes.


Event horizon
Singularity
Ergoregion

V : Orbits around black holes

- Very far from black hole…
  - Gravity behaves just as Newton says!
  - Velocity of a circular orbit is

$$V = \sqrt{\frac{GM}{r}}$$

  - Orbit is **stable**… if something on a circular orbit is nudged, the orbits just becomes slightly elliptical.
- As you get closer to the black hole, gravitational force becomes more and more non-Newtonian

Heading inwards…

- Come across two special orbits…

- Innermost stable circular orbit (ISCO)
  - $R_{ISCO}=6GM/c^2$ (Schwarzschild)
  - At and within this location, a particle on a circular orbit is no longer stable… a small nudge and it will spiral into the black hole!
  - Very important for accretion disks (more later!)
- Photon circular orbit
  - $R_{ph}=3GM/c^2$ (Schwarzschild)
  - Only at this one radius, photons can travel in circles around the black hole
  - Nothing can be in orbit inside of this radius.

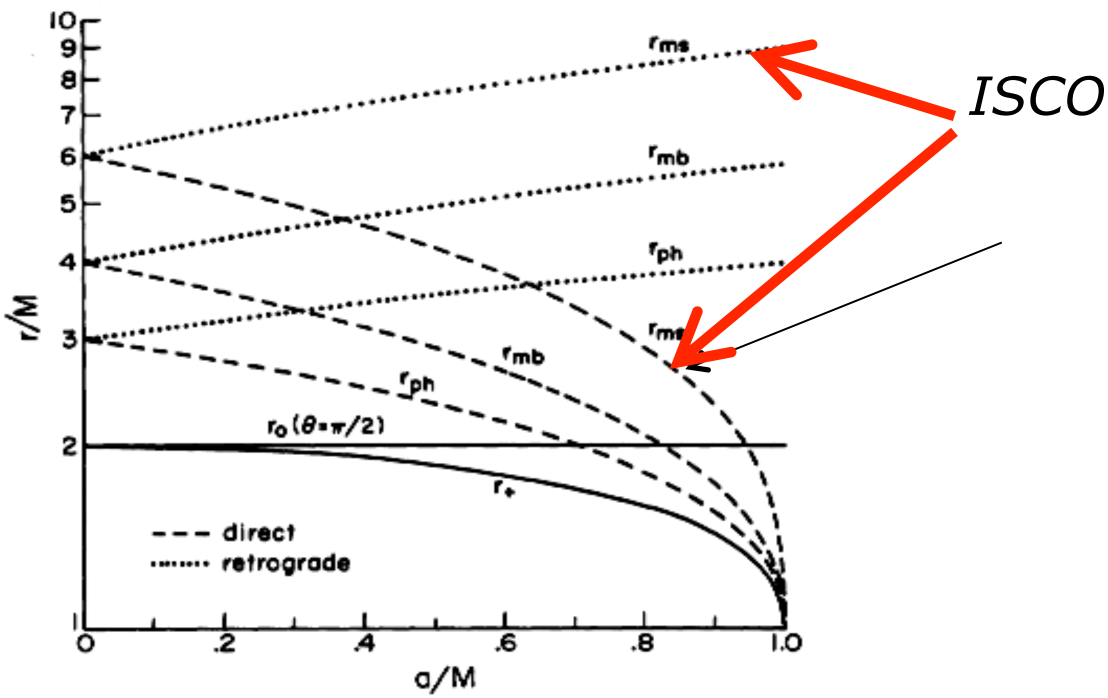
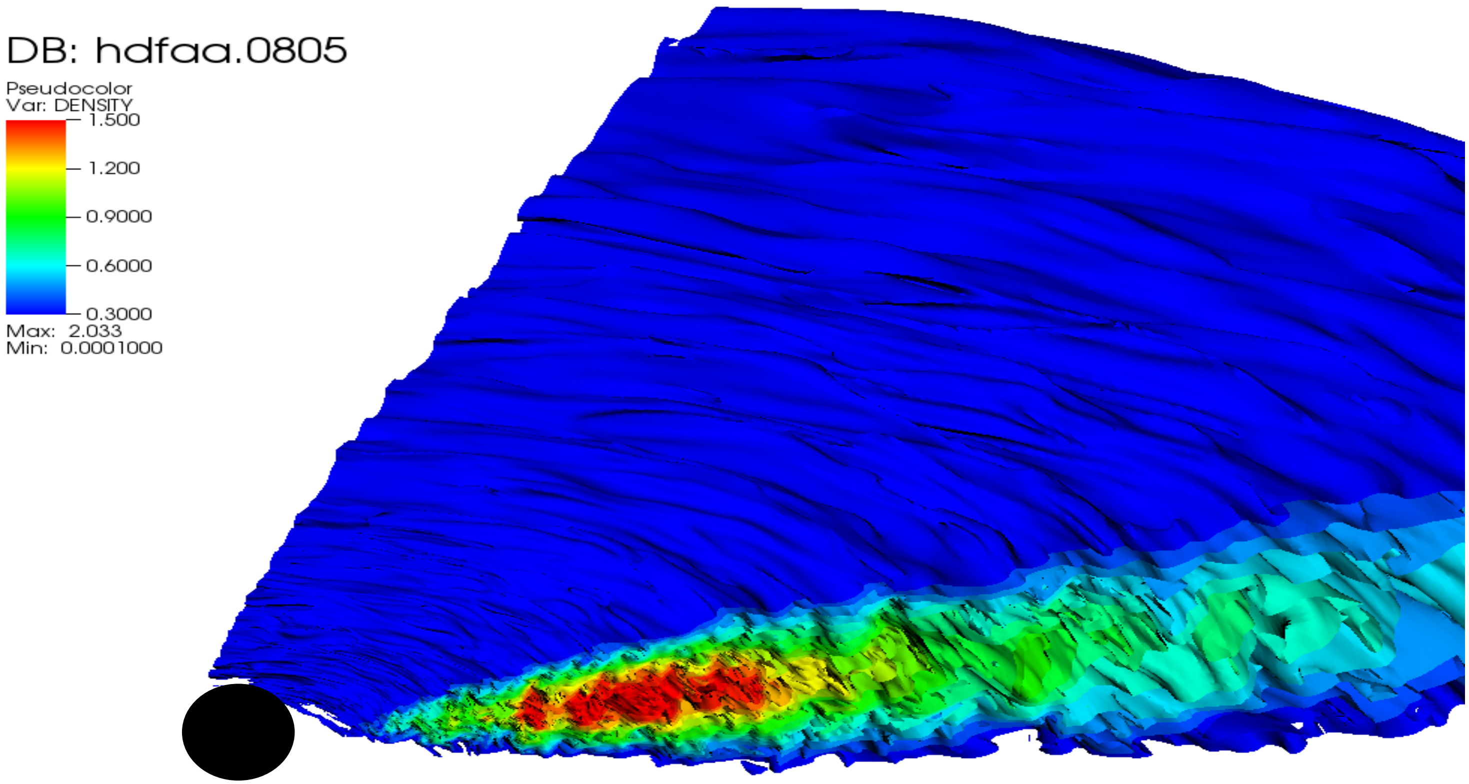


FIG. 1.—Radii of circular, equatorial orbits around a rotating black hole of mass M, as functions of the hole's specific angular momentum a. Dashed and dotted curves (for direct and retrograde orbits) plot the Boyer-Lindquist coordinate radius of the innermost stable (ms), innermost bound (mb), and photon (ph) orbits. Solid curves indicate the event horizon (r_+) and the equatorial boundary of the ergosphere (r_0).


DB: hdfaa.0805
Pseudocolor
Var: DENSITY
1.500
1.200
0.9000
0.6000
0.3000
Max: 2.033
Min: 0.0001000