# THE INSIDES OF BLACK HOLES

PROBLEM SET #7 ON WEBWORK – DUE MONDAY, 11/18

MOVIE NIGHTS – FRIDAY, NOV. 15 AND MONDAY, NOV. 18 IN B&L 106

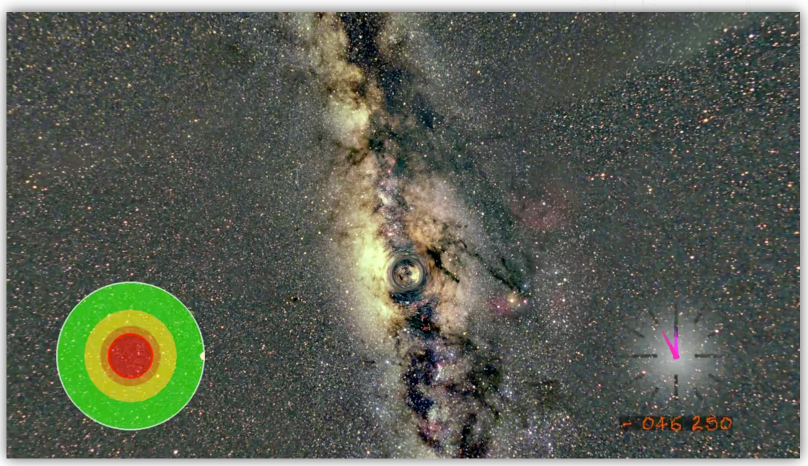


## THE INSIDES OF BLACK HOLES

Exotic matter

Physics & metaphysics, positivism and idealism: should we consider the interior of a black hole to be real?

Assuming that we do: physics inside the event horizon, and the nature of the quantum-gravitational object at the center, the mass-density singularity




*Visualization of falling into a black hole. (Andrew Hamilton)*

# HAWKING RADIATION IS RELATIVELY INSIGNIFICANT

Hawking radiation is really small and usually insignificant compared to other sources of light commonly found near black holes. That is why it takes massive black holes so long to evaporate. Consider how it works for a $2M_{\odot}$ black hole.

Luminosity, if accreting at its maximum (Eddington) rate:

$$L = 2.5{\times}10^{38}\ \mathrm{erg/s} = 6.6{\times}10^{4} L_{\odot}$$

Luminosity due to Hawking radiation:

$$L = 2.3{\times}10^{-22}\ \mathrm{erg/s} = 5.9{\times}10^{-56} L_{\odot}$$



# EXOTIC MATTER

Part of the explanation for Hawking radiation should strike you as weird: How can the black hole *consume* a particle and wind up *decreasing* in mass and energy?

- In the strongly warped spacetime near the horizon, virtual particles made from vacuum fluctuations turn out to have negative energy density.
  - **Energy density** = energy per unit volume
- These particles have positive mass – look at the one that escaped! – but their mass is distributed very strangely over spacetime. (Quantum-mechanically speaking, particles have nonzero volume; this is an aspect of the wave-particle duality.)
- Matter with negative energy density is generally called **exotic matter**.

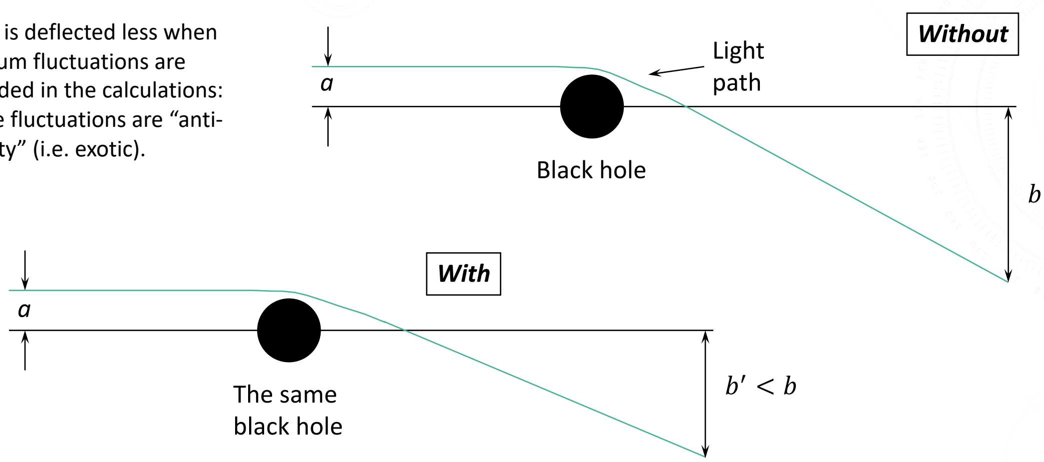
# EXOTIC MATTER

Theoretical details of exotic matter, according to the present partial combination of general relativity and quantum mechanics (incompletely known; only extensively studied since 1985) include:

- Quantum mechanical vacuum fluctuations in flat spacetime – far from any strong gravitational field – always have zero net energy density; they can never be exotic.
- In warped spacetime, vacuum fluctuations are in general exotic: their net energy density is negative, according to a distant observer measuring the energy density by observing the deflection of light by the ensemble of fluctuations. The stronger the curvature, the more negative the energy density looks.



Light is deflected less when vacuum fluctuations are included in the calculations: these fluctuations are “anti-gravity” (i.e. exotic).




## EXOTIC MATTER

Results of **theoretical calculations** of deflection of light by a black hole, with and without vacuum fluctuations.

## A BRIEF REVIEW

What is entropy?

A. A measure of the number of rearrangements of a system that could be made without changing its overall appearance.
B. A measure of the size and scale of vacuum fluctuations present in a system.
C. A measure of the mass density of the horizon of a black hole.
D. All of the above.
E. None of the above.



## INSIDE THE HORIZON

We are about to discuss the physics of the interior of black holes and first must deal with a more philosophical question:

- If information from the interior can never get out, why are we even talking about a black hole's interior? Isn't such a study uncomfortably close to metaphysics instead?

(Note:

- **Physics** is the study and description of the workings of the world accessible to our senses, measurements, and reasoning.
- **Metaphysics** is the study by logic of the world of ideal forms and eternally-existing, changeless objects; a world which is not accessible to our senses, only to our reasoning.

This distinction was first explicitly drawn by Aristotle around 340 BC.)

# PHYSICS : METAPHYSICS :: POSITIVISM : IDEALISM

Humans who reflect upon the distinction between physics and metaphysics fall into two categories:

- **Positivists** (or **empiricists**) hold that the real world is accessible to the senses, and that this is the only real world, since all our knowledge of reality has its origin in sense input. It is not helpful to speculate about any other world, since we can know nothing about it; **physics is the study of reality**.

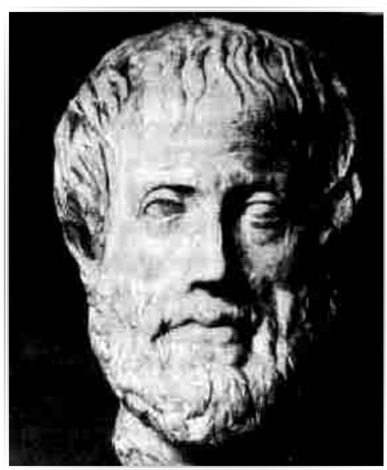
*Friedrick Nietzsche, the definitive anti-metaphysicist*



# PHYSICS : METAPHYSICS :: POSITIVISM : IDEALISM

- **Idealists** assert that the real world is the world of forms and ideal patterns, accessible to our logic acumen and our ability of abstraction, but inaccessible to our senses and measurements. The objects in the apparent world are merely ephemeral representations of the objects in the ideal world; **metaphysics is the study of reality**.

**Science, by and large, is a positivistic activity**, since it requires experimental validation of theory.



*Aristotle, graduate student of the definitive metaphysicst*

# POSITIVISTS & IDEALISTS

## Some famous positivists

- Francis Bacon
- David Hume
- Johann W. v. Goethe
- Auguste Compte
- John Stuart Mill
- Friedrich Nietzsche
- Sigmund Freud
- Albert Einstein
- Bertrand Russell
- Ludwig Wittgenstein — Logical positivism

## Some famous idealists

- Parmenides
- Plato
- Aristotle

Classical philosophers

- Avicenna
- St. Thomas Aquinas
- Rene Descartes
- Immanuel Kant
- Georg W.F. Hegel — Hegelian philosopher
- Martin Heidegger
- Carl Jung



# PHYSICS (METAPHYSICS) OF THE SINGULARITY

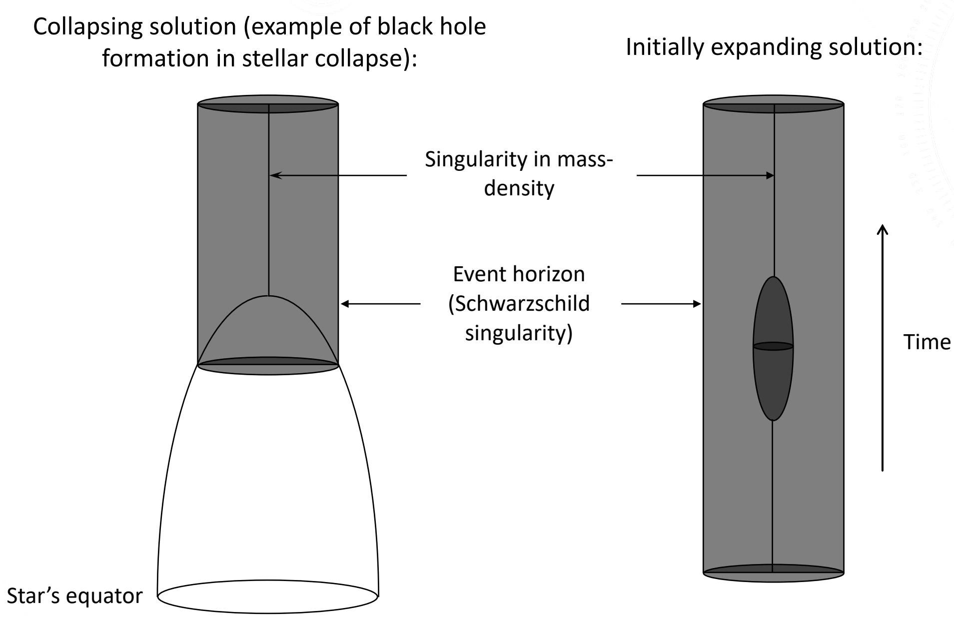
Why might a positivist find it useful to study the interiors of black holes, even if it is initially a purely theoretical pursuit without experimental constraint?

- **Naked mass-density singularities may exist.** Computer solutions to Einstein's field equation sometimes appear to produce the central mass-limit singularity without an event horizon – at least temporarily.
- **It may be possible to enter and exit certain combinations of black holes.** We will investigate one type of these called wormholes.
- **The Big Bang may be similar to a black hole interior.** The Universe started out as a singularity; this may have observable consequences.

# INSIDE A BLACK HOLE

- Solutions of the Einstein field equations for the outsides of black holes occur that are stable in time (**static**), like the solutions originally obtained by Schwarzschild.
- However, for a mass (or collection of masses) distributed within a space smaller than the corresponding event horizon, there turn out to be **no static solutions** to the field equations. The solutions are of two kinds:
  - **Collapsing** solutions: All the matter quickly converges at the center as time passes, and a **singularity** in the mass density appears there in the solutions.
  - **Expanding** solutions: The matter can briefly expand within the horizon volume before collapsing to form a singularity (again).





# INSIDE A BLACK HOLE

Recall the following comments about singularities in the equations of physics and astronomy:

A formula is called singular if, when you plug in the right set of numbers, the result is either infinity or not well defined. The particular combination of numbers is called the singularity.

Singularities often arise in the formulas of physics and astronomy. They usually indicate either

- That not all of the physical laws have been accounted for in the formula (no big deal)
- That the singularity is not realizable (no big deal)
- That a mathematical error was made in obtaining the formula (just plain wrong)
- That the singularity exists (a big deal, and also extremely rare)



# INSIDE A BLACK HOLE

This inevitable-collapse and singularity-formation behavior was first theoretically demonstrated for collapsing, spherical stars in 1939 by J. Robert Oppenheimer and his group:

- Oppenheimer and Volkoff obtained field-equation solutions for static (neutron) stars larger than the horizon.
- Oppenheimer and Snyder dealt with the realm past the limit of neutron degeneracy pressure and showed that all solutions collapse as time goes on, ending with a singularity.

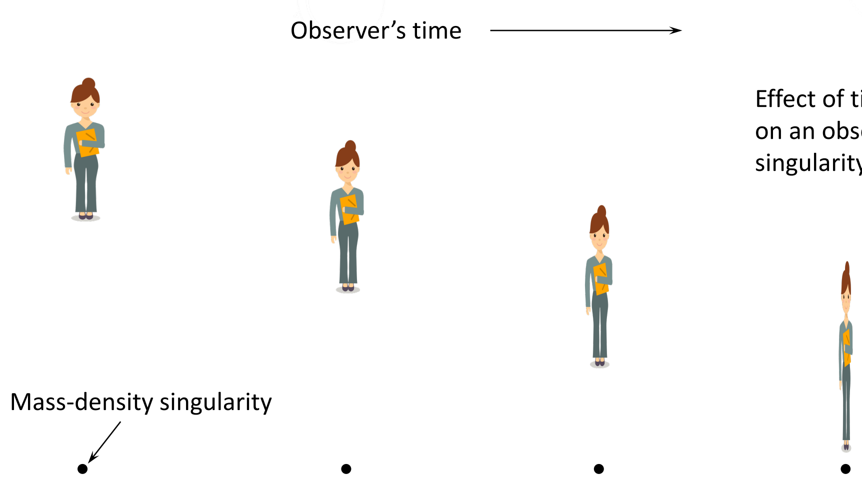
  This, again, is the **mass-density singularity** (not to be confused with the Schwarzschild singularity = event horizon).

## THE PHYSICS OF MASS-DENSITY SINGULARITIES

Implications of the Oppenheimer-Snyder solution:

- Any matter inside the horizon falls into the center, collapsing to a single point in spacetime (i.e. a mass-density singularity). Formally, **spacetime ends at this point**.






Effect of tides (spacetime curvature) on an observer falling into the singularity: **spaghettification**

## APPROACHING THE MASS-DENSITY SINGULARITY

At the singularity, the **curvature of spacetime is infinite,** as is anything that gets stronger with more spacetime curvature; tidal forces, for example, also become infinite.

# NO TIME AT THE MASS-DENSITY SINGULARITY

- Recall the Minkowski absolute interval from special relativity (which applies to flat spacetime):

$$\Delta s^2 = \Delta x^2 - c^2 \Delta t^2$$

  The spacetime coordinate that we experience as **time** enters the formula with a **minus** sign in flat spacetime. Coordinates that we experience as **space** or distance enter with **plus** signs.
- In the more complicated form for the absolute interval in field-equation solutions just outside the singularity, all coordinates enter the equation with plus signs. The four dimensions of spacetime all act like space; **there is no such thing as time at the mass-density singularity**.
- (We will see this again: it is why the answer to "What was there before the Big Bang?" is "There is no such thing.")



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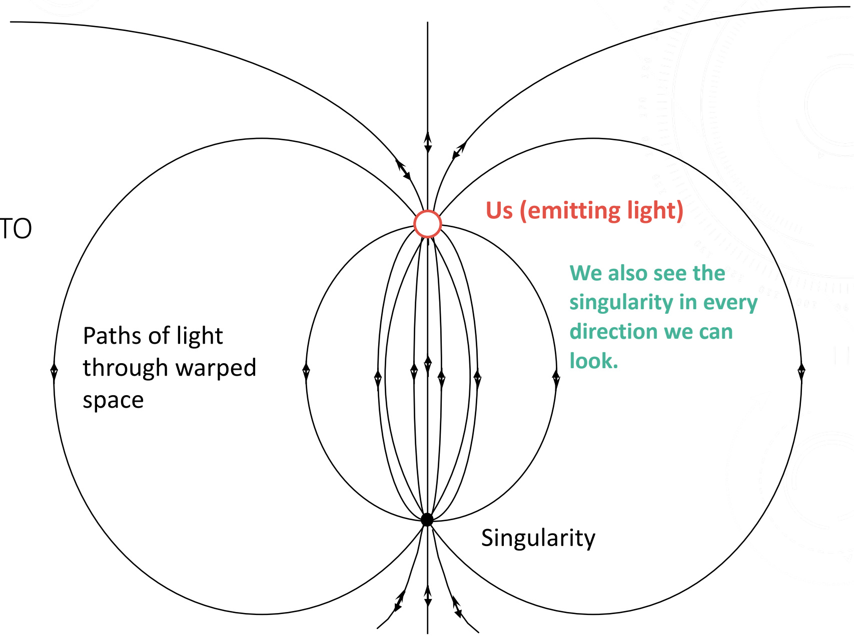
- All **geodesics** (the paths followed by photons) that matter can follow terminate in the mass-density singularity. Therefore, the region inside the horizon is disconnected from the rest of the universe.

ALL PATHS WITHIN THE EVENT HORIZON LEAD TO THE MASS-DENSITY SINGULARITY



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We know that no mathematical error was made by Oppenheimer and Snyder. Is the mass-density singularity realizable in nature like the Schwarzschild singularity (**#1**), or have crucial physical effects been left out of the calculation that would prevent this singularity from forming (**#2**)?

# THE VACUUM NEAR THE SINGULARITY

Curvature and related things like tidal force (= temperature at the horizon) get very large close to the mass-density singularity. Based on what we have previously discussed about the affect of warped spacetime on the vacuum, what effects on the vacuum might we expect to encounter close to the mass-density singularity?

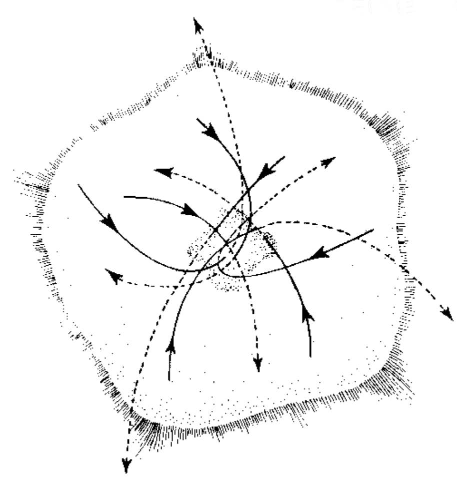
A. Vacuum fluctuations are very strongly exotic (antigravity).
B. Virtual particles of large mass have larger influence on the surroundings than they would at the horizon.
C. A continual bubbling of matter from the singularity, similar to Hawking radiation but settling back in short order.
D. All of the above.
E. None of the above.



# POSSIBILITY #1: IS THE MASS-DENSITY SINGULARITY REALIZABLE?

**Khalatnikov and Lifshitz** (1961): No. You only get that for a perfectly spherical non-spinning star implosion; any deviation from this, however minor, leads to explosion. In other words, the Oppenheimer solution is unstable to small perturbations.

*In an asymmetric collapse, infalling particles each fall toward a different point; since they do not meet in the center, they "sling" against each other's gravity and explode.*



## POSSIBILITY #1: IS THE MASS-DENSITY SINGULARITY REALIZABLE?

**Penrose** (1964): Yes it is. It is possible to prove mathematically, and quite generally, the **horizon-singularity theorem**:

> **Any** solution to the Einstein field equation that involves the formation of a horizon also involves the formation of a central mass-density singularity.

**Belinsky, Khalatnikov, and Lifshitz** (BKL, 1964): Oops. There is a stable, singular solution after all that works no matter how asymmetric the star was. Penrose is right.

- Stable solution: BKL, or mixmaster, singularity (BKL, Misner). Curvature inside horizon oscillates in time and space; the oscillation increases in strength as you approach the singularity.



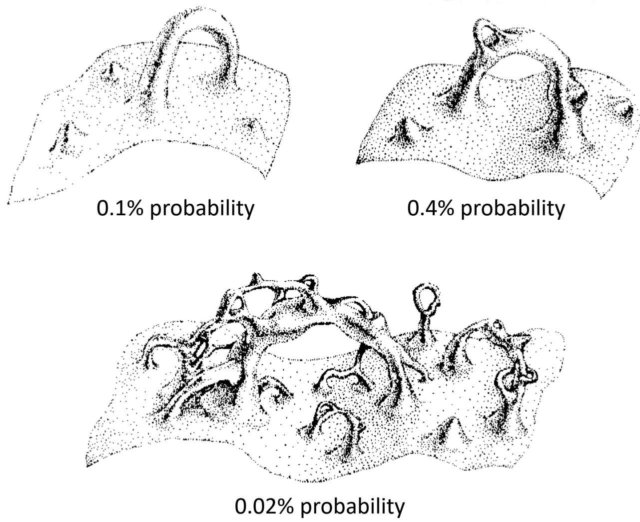
## POSSIBILITY #2: HAVE ALL THE NECESSARY PHYSICAL LAWS BEEN INCLUDED?

**Wheeler**: No, obviously, because quantum mechanics has been left out.

- No matter how massive the black hole is, its quantum-mechanical wavelength must still be nonzero.
- If the mass collapses to a size comparable to, or smaller than, its wavelength, then its wave properties become prominent. This seems to be the case for the mass-density singularity: it is a **quantum-gravitational object**.
- The wave properties, whatever their details turn out to be, will serve to spread the singularity out.
- The details are not yet known, unfortunately. There is no successful, consistent quantum theory of gravity yet.

# POSSIBILITY #2: HAVE ALL THE NECESSARY PHYSICAL LAWS BEEN INCLUDED?

- Best guess: the mass-density singularity consists of a randomly-connected four-dimensional space (no time): **quantum foam.** Here are embedding diagrams for configurations of two of the four dimensions.






# EXPANDING AND COLLAPSING SINGULARITIES

We do not know enough about quantum gravity to understand the properties of this "foam" in much detail, but:

- An infinite variety of "foam" configurations are possible; a particle falling into a mass-density singularity has a certain non-zero probability of finding each possible configuration.
- The next infalling particle would most likely find it (or cause it to be) in a different configuration.
- Since time does not exist in the foam, there is no natural tendency for this "time origin" to connect in any predetermined way to spacetime outside the mass-density singularity.