

# Small, dark, and heavy... but is it a black hole ?

Matt Visser  
New Plymouth  
14 October 2008





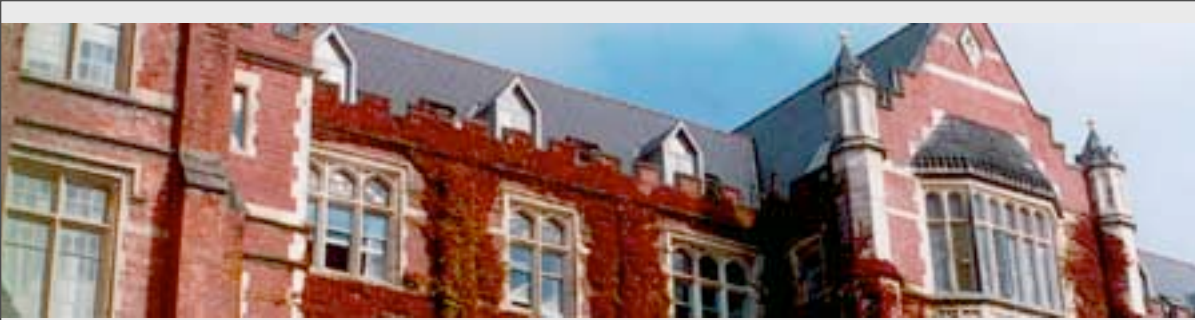
## Abstract:

Astronomers have certainly seen things that are  
small, dark, and heavy...

But are these small, dark, heavy objects really black holes  
in the sense of general relativity ?

(The consensus opinion is simply “yes”,  
and there is very little “wriggle room”.)

In this talk I’ll discuss the observational situation,  
and the very limited alternatives...



# Do black holes exist?



Do you want me to answer as a:

a Mathematician,  
a Physicist,  
or an Astronomer?





Mathematician:



## General relativity:

Black holes certainly exist mathematically,  
as vacuum solutions in general relativity...

Classical black holes (future event horizons)  
certainly exist mathematically as the  
end result of classical collapse.

Black holes exist...

(within a certain mathematical framework).



Physicist:

The physical evidence in favour of general relativity  
is overwhelming.

General relativity predicts black holes.

Physically plausible models of stellar collapse  
lead to black holes...

Black holes exist...

(within a certain physical framework [theory]  
that we have good reason to believe  
corresponds to empirical reality)



Warning:

When a physicist uses the word “theory”,  
he/ she does not mean “wild guess”.

The word “theory” is reserved for the  
“laws of nature”.

These are concepts/ rules /formulae that are so well  
established by observation and experiment that it  
would simply be perverse to not accept them as  
fundamental aspects of empirical reality.



“It is important to keep an open mind; just not so open that your brains fall out”

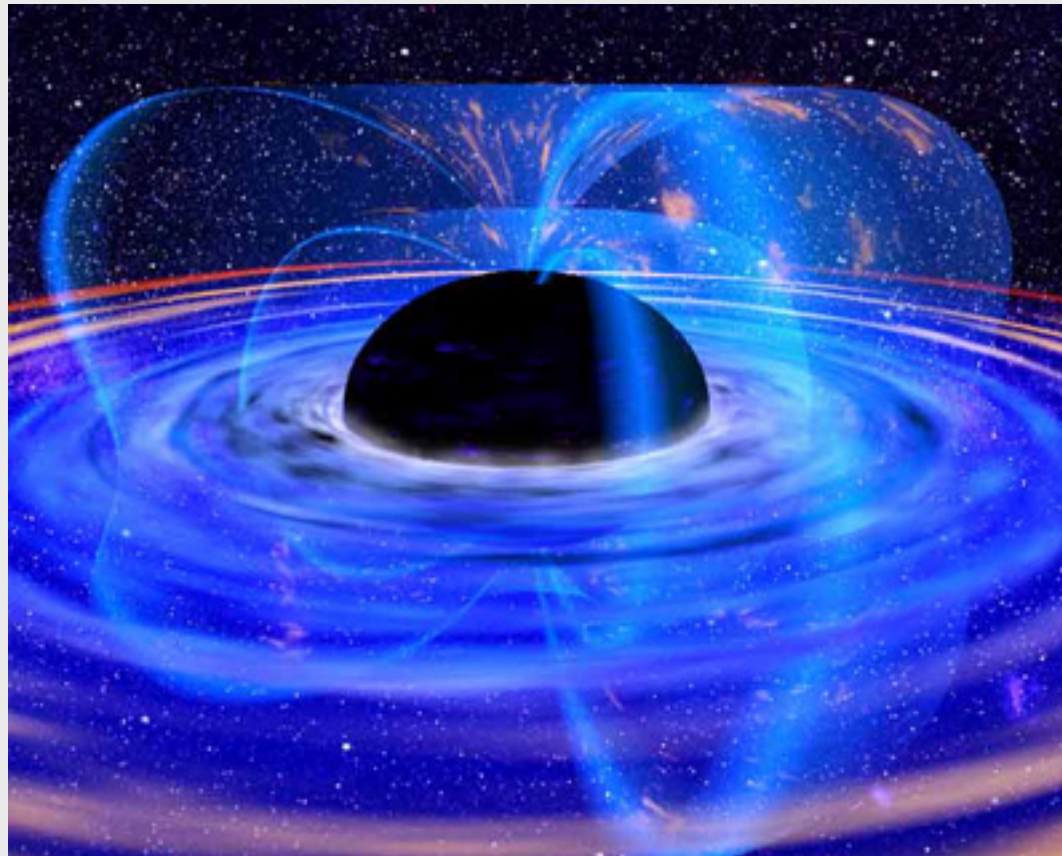
--- **Albert Einstein**





Astronomer:

# What is a black hole? (Astronomer's perspective.)



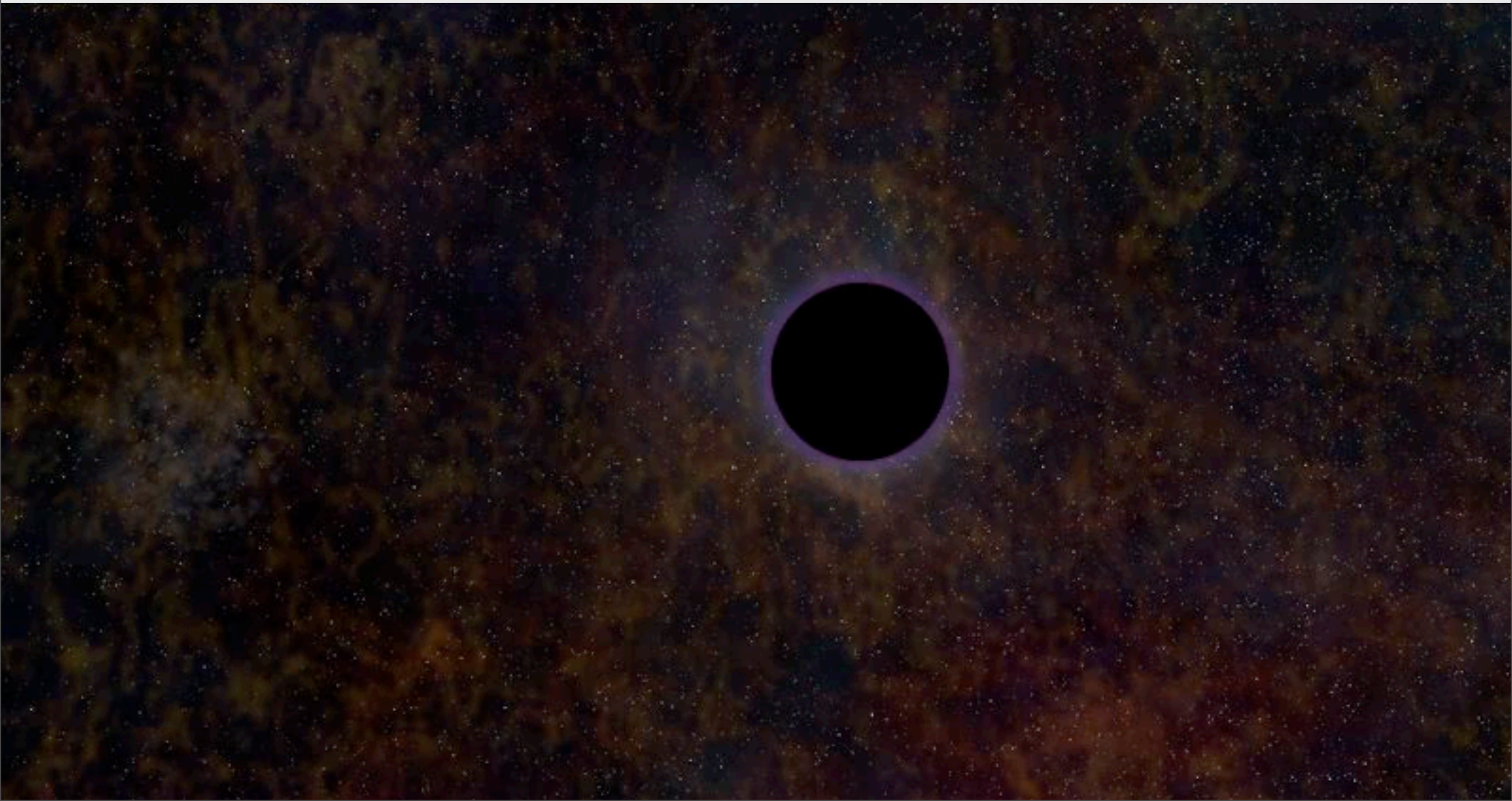
Look for something small, dark, and heavy...





# Do black holes “exist” ?

So how would you actually see a black hole?





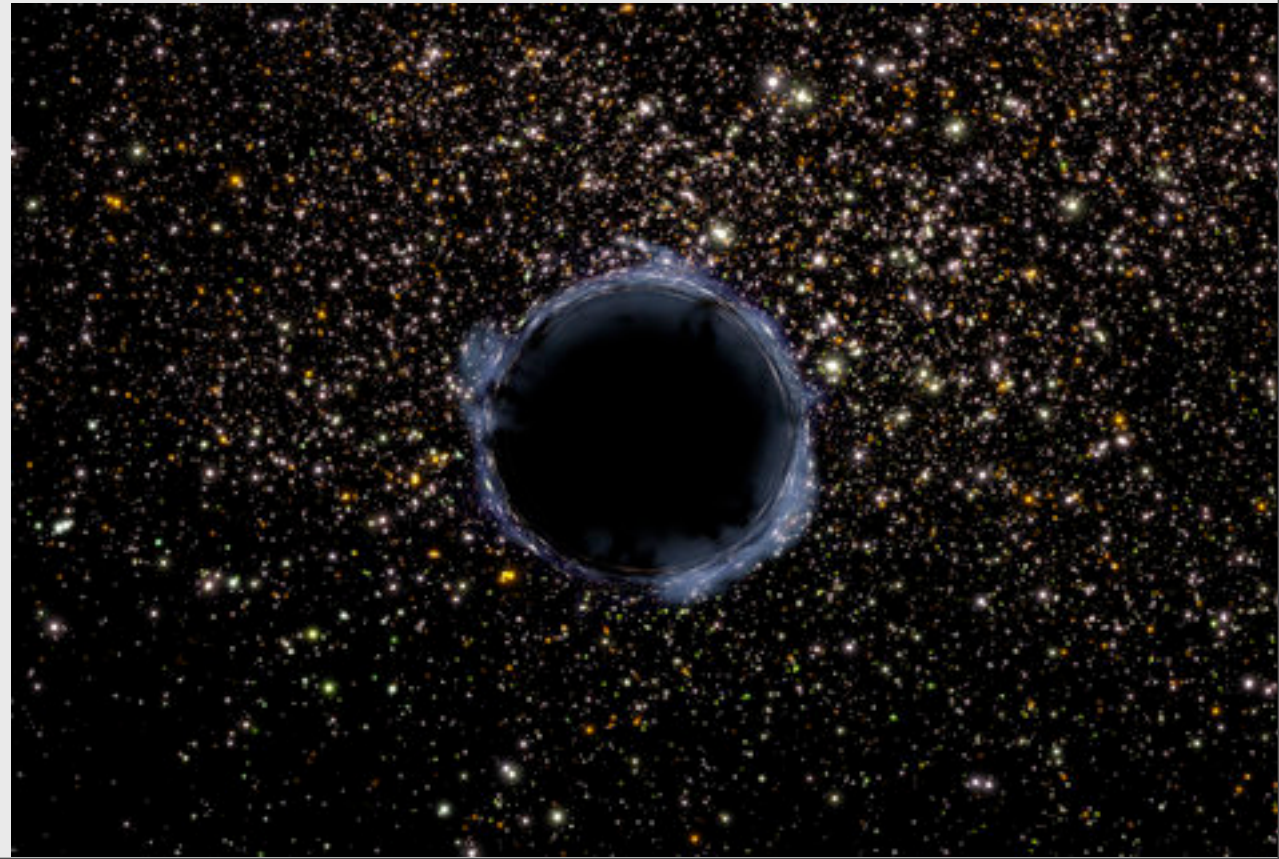


# Do black holes “exist” ?

## Observational astronomy:

You cannot see the black hole itself...

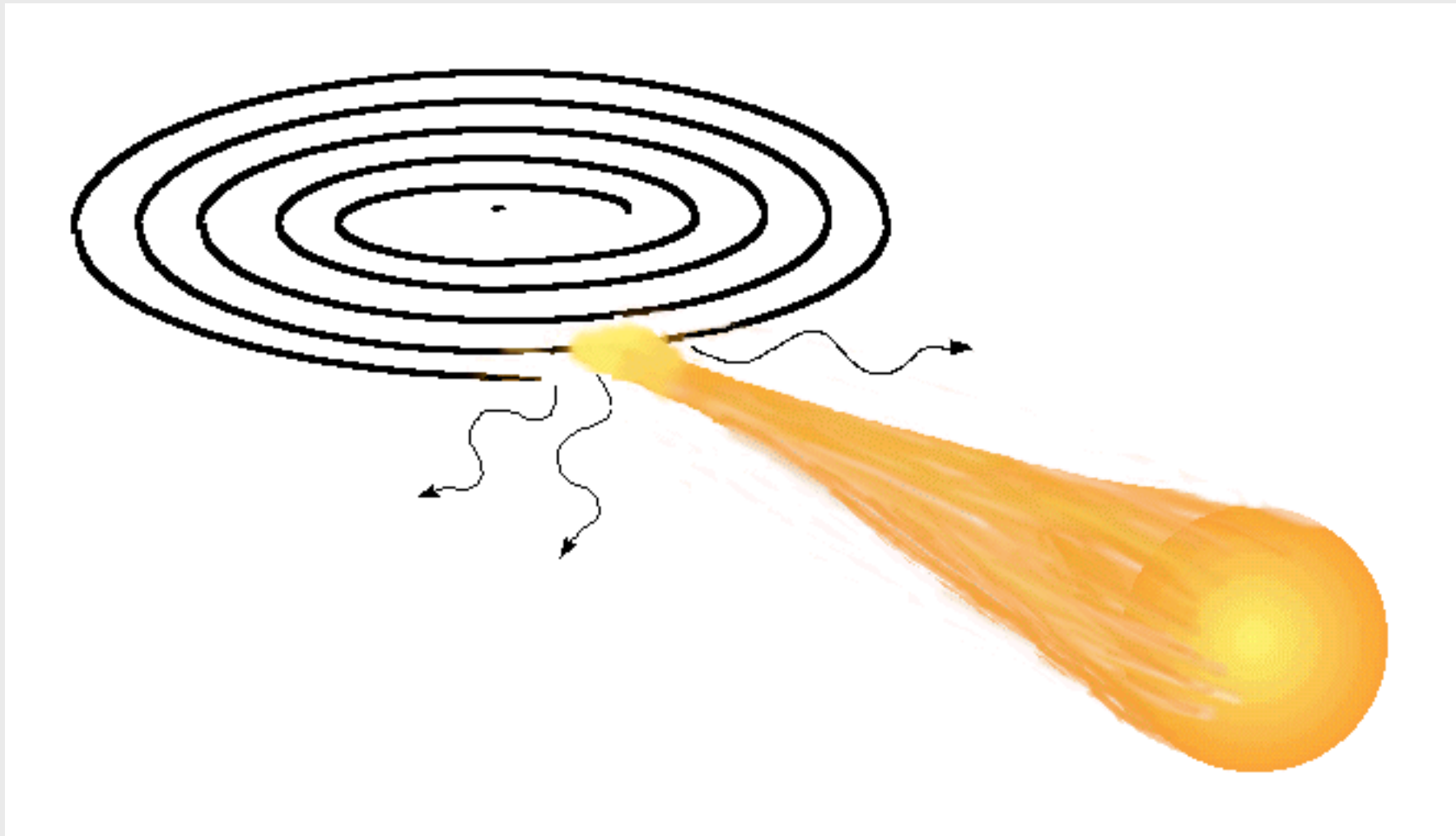
So what do you  
look for?





# Do black holes “exist” ?

Look for the stuff that is being sucked in...

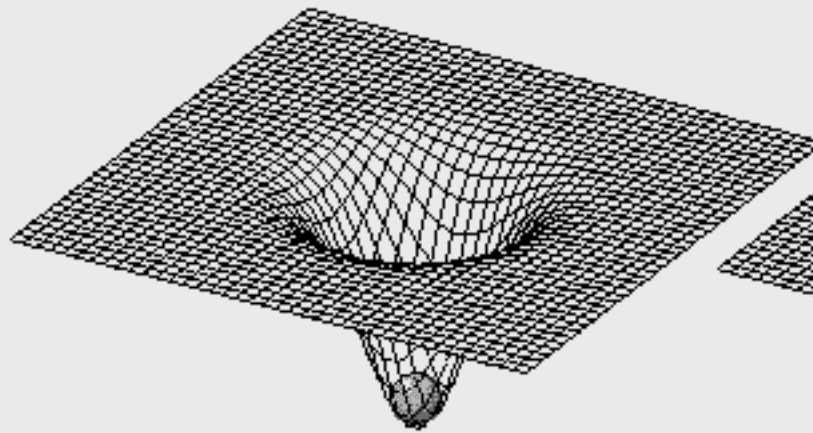




Aside:

What is a black hole?

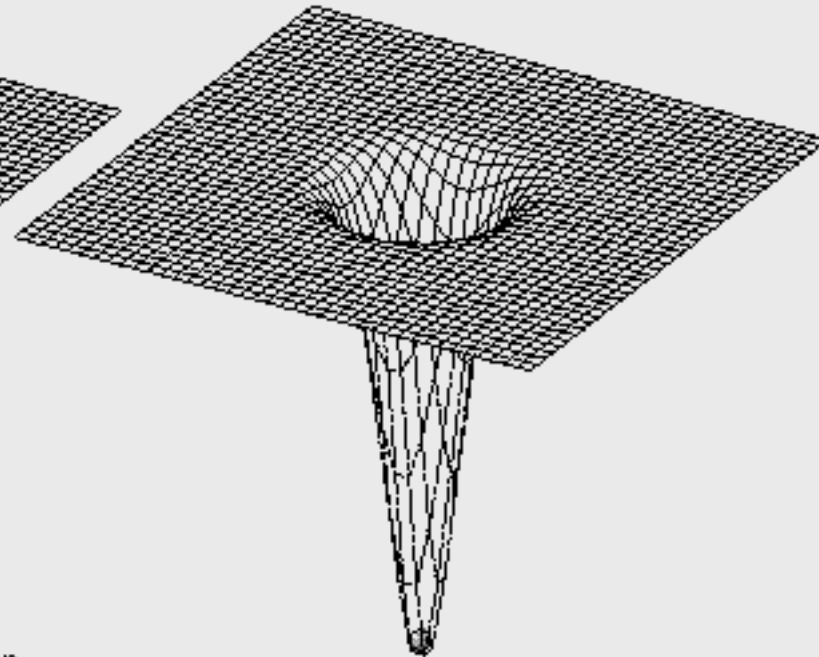
(Theorist's perspective.)



Usual star

**General Relativity :**

Einstein describes gravity as a deformation  
of space-time around a massive object.



Neutron star

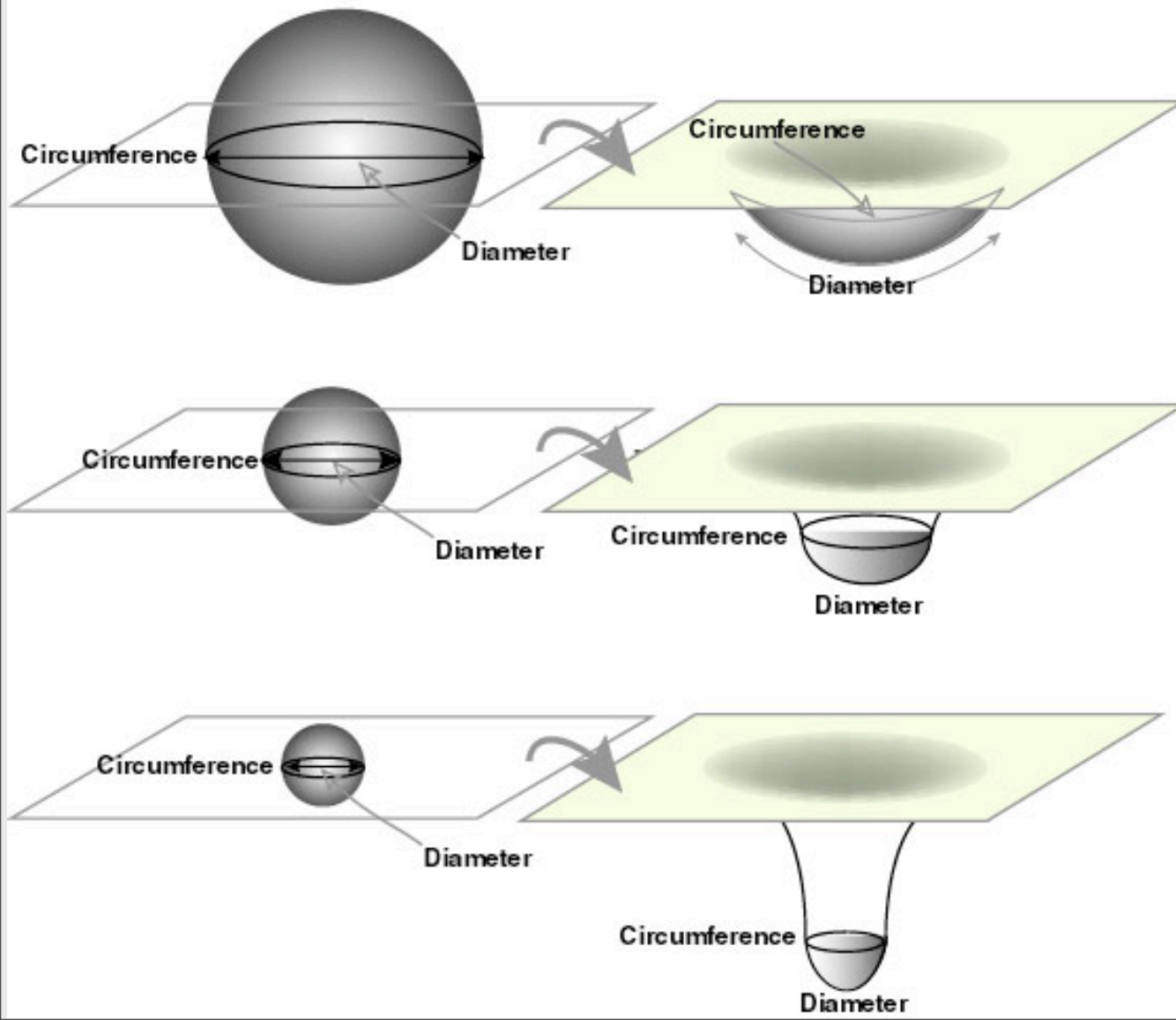
Euclid's geometry is not the final answer...



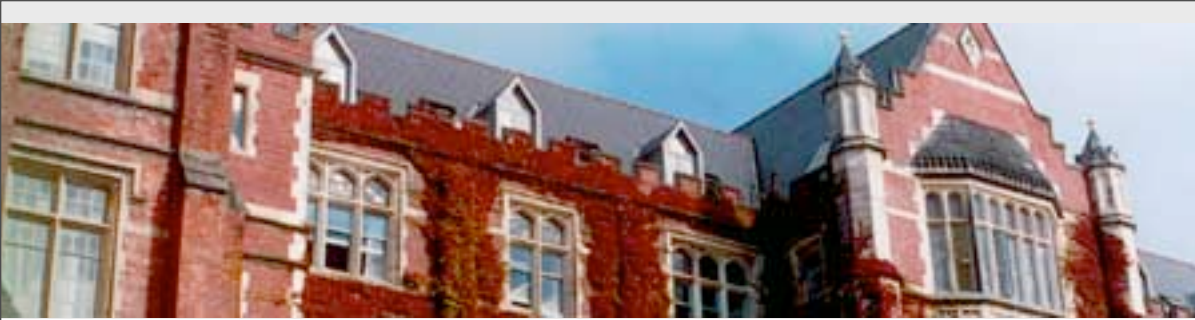


# Curved space-time:

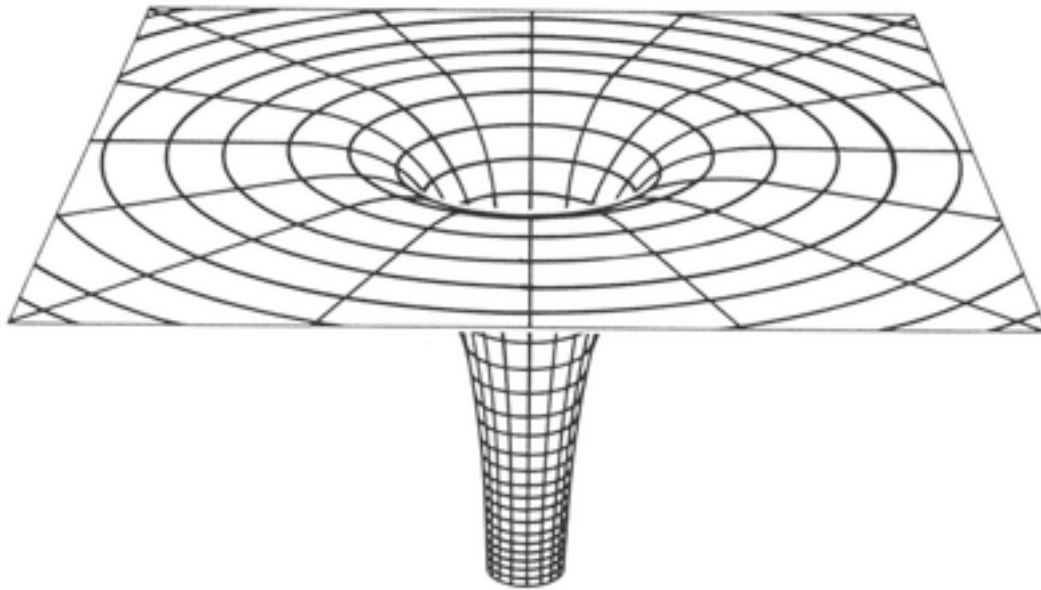
STARS WITH THE SAME MASS, BUT DIFFERENT SIZES: HOW CURVED?



Riemann's  
“curved”  
space-time  
geometry  
is needed to  
describe the  
“real world”...

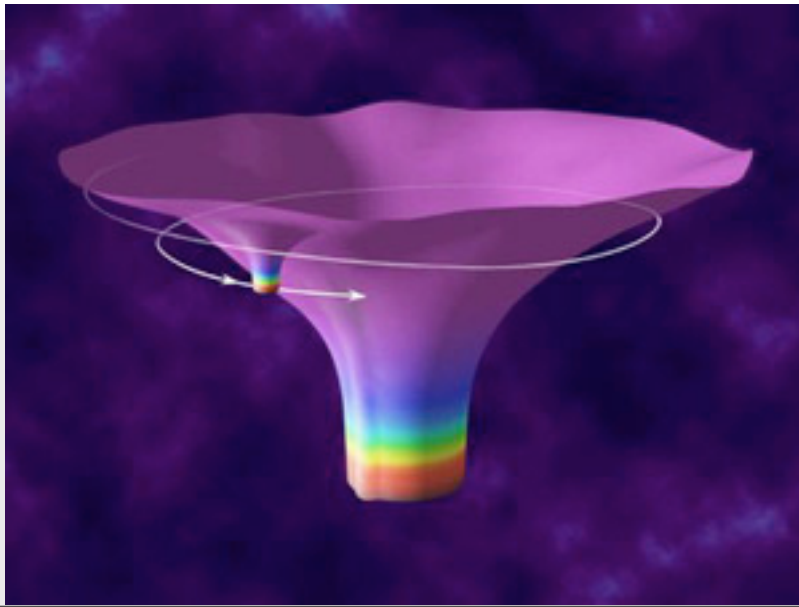


# Curved space-time:



Eventually a  
black hole  
forms...

$$R = \frac{2GM}{c^2}$$



Schwarzschild's  
black hole...

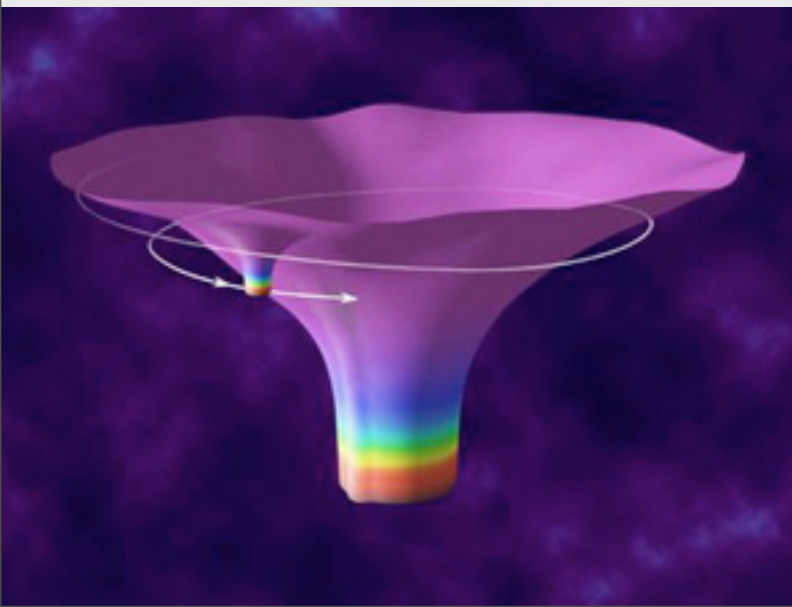


## Curved space-time:

- Black holes were predicted as long ago as 1790. They are a key prediction of Einstein's general relativity. They form when gravity becomes strong enough to trap everything, even light.

There is a quick and dirty way of estimating the Schwarzschild radius.

Use Newtonian physics and set the escape velocity equal to the speed of light:



$$\frac{1}{2} c^2 = \frac{GM}{R} \quad \text{[not the full story]}$$

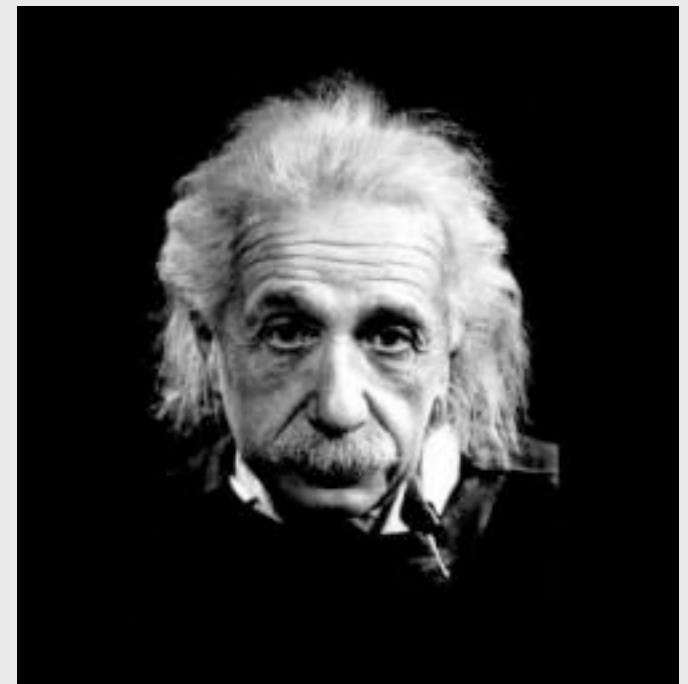
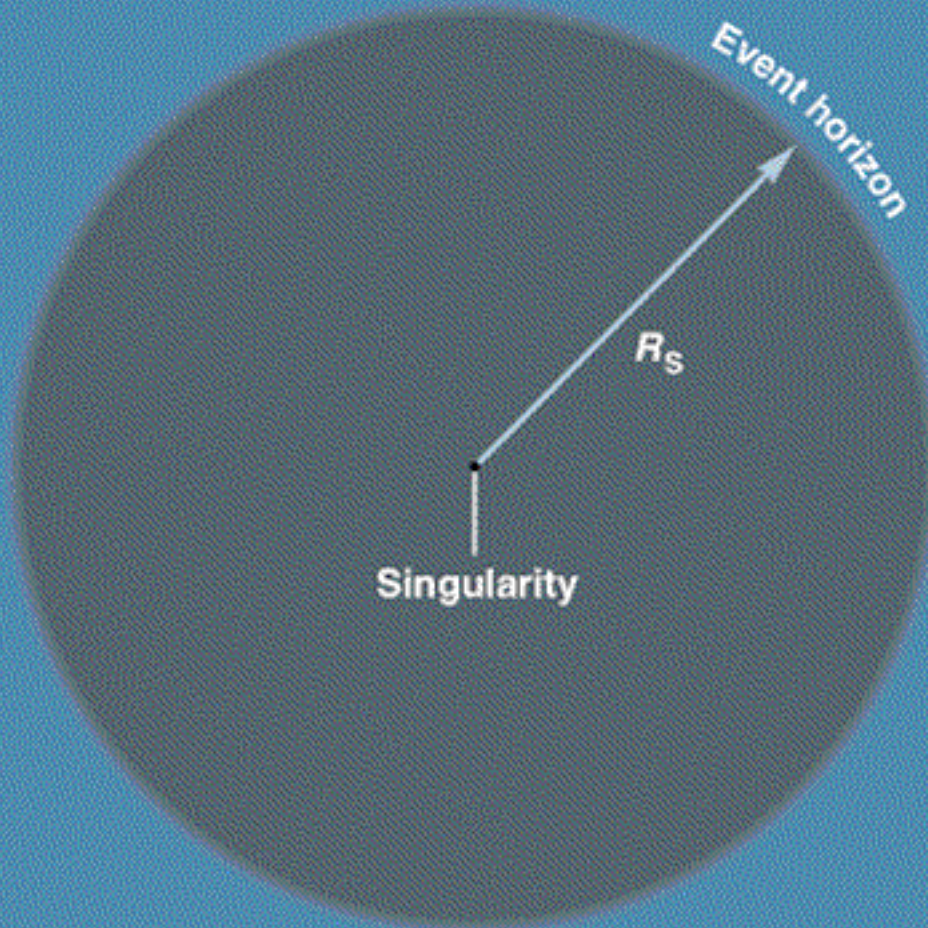




# Curved space-time:



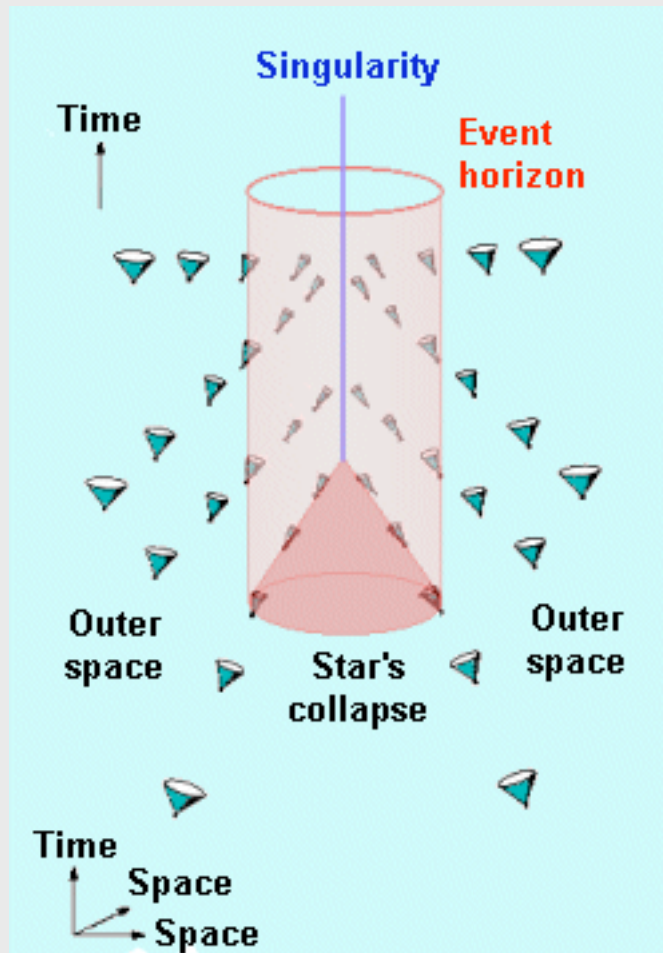
$$R = \frac{2GM}{c^2}$$







# Curved space-time:

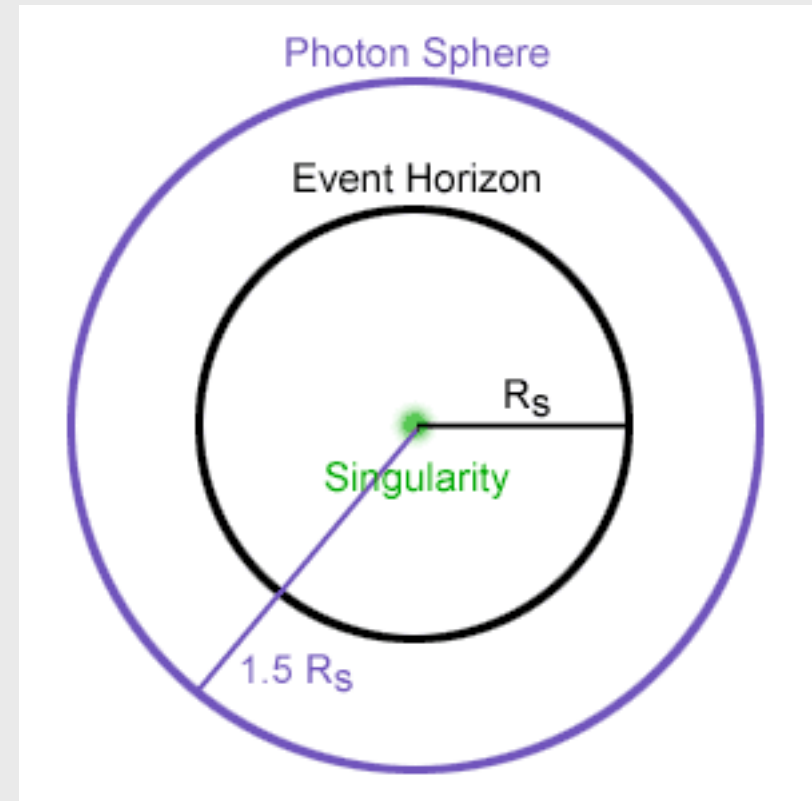
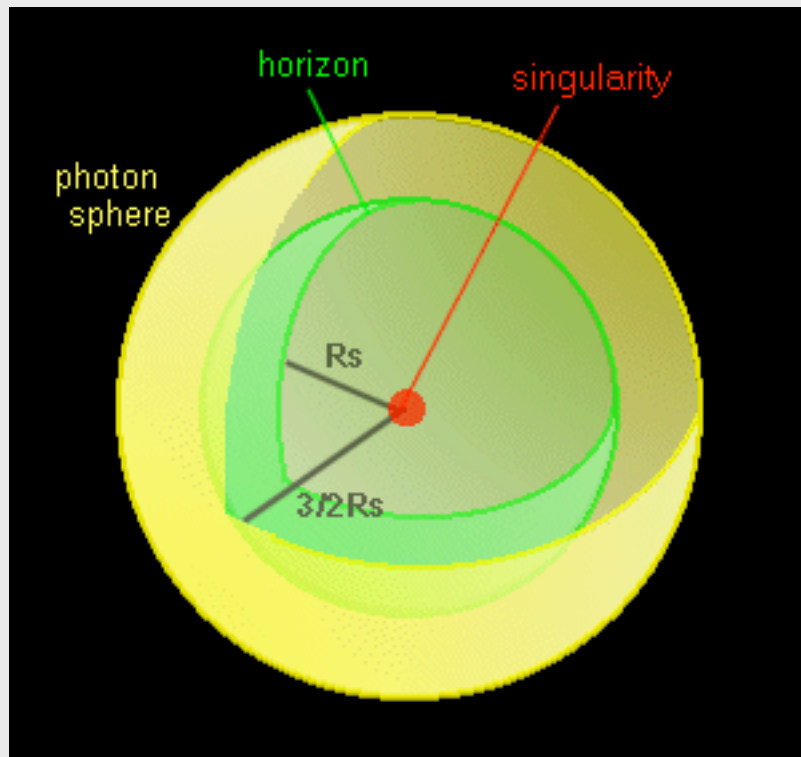


Light can no longer escape...

The “light cones” are all  
tipped inwards...

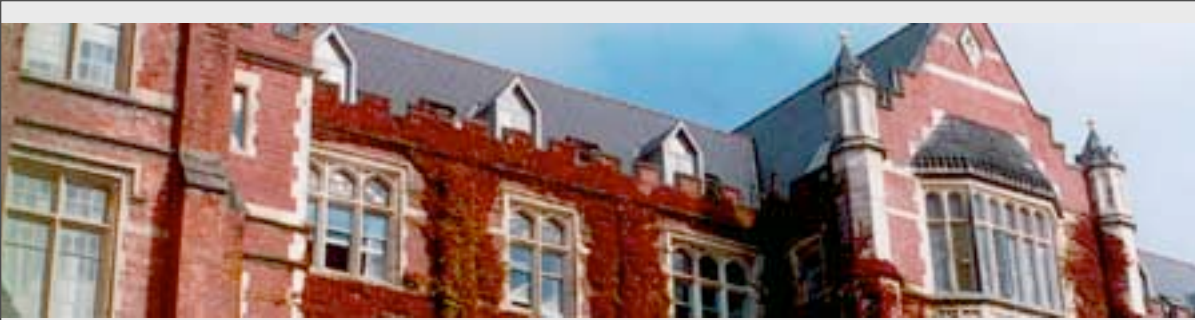


# Curved space-time:



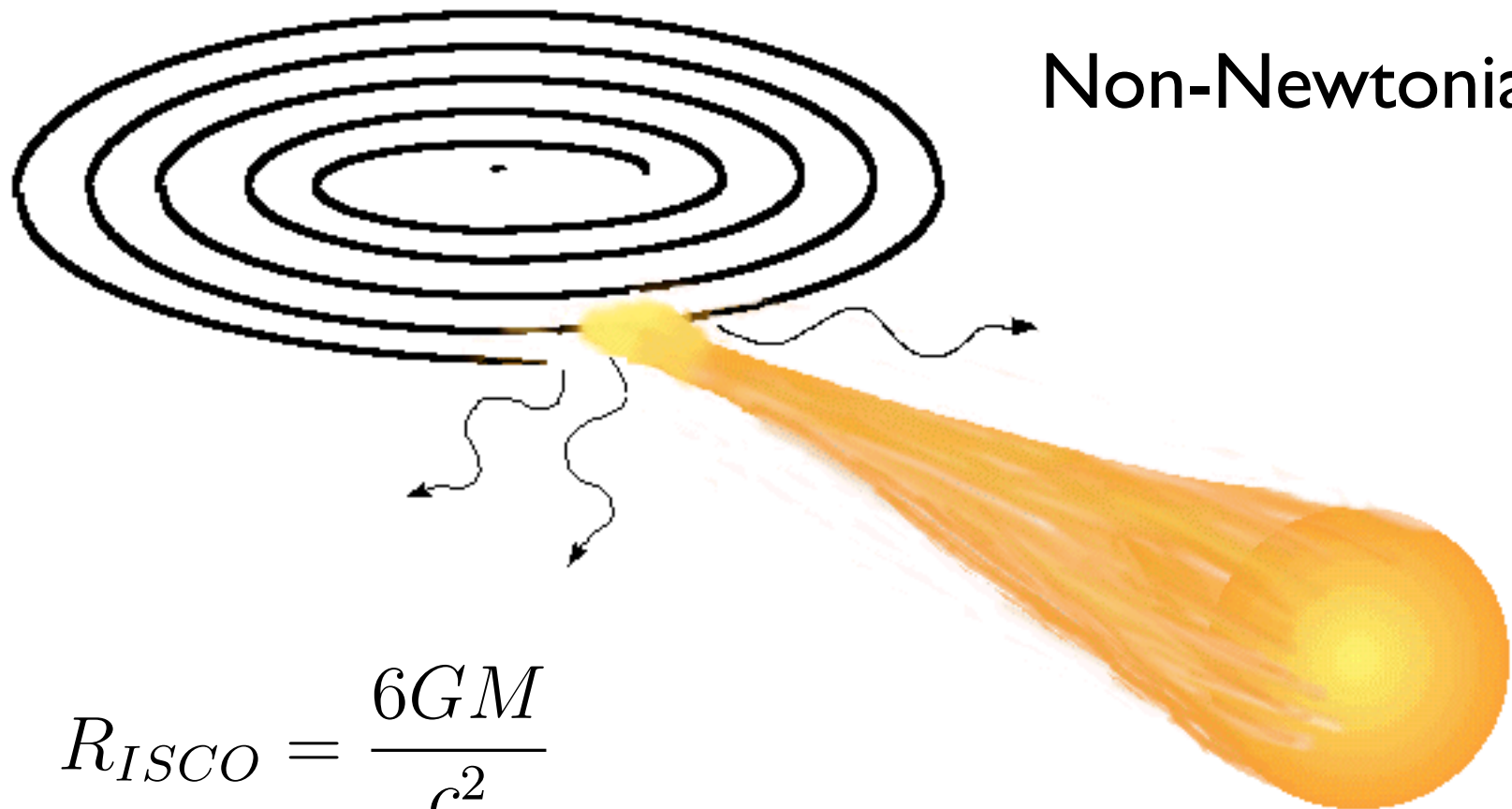
Light can now “orbit” the black hole at:  $R_{\gamma} = \frac{3GM}{c^2}$

Horizon is at:  $R = \frac{2GM}{c^2}$



# Curved space-time:

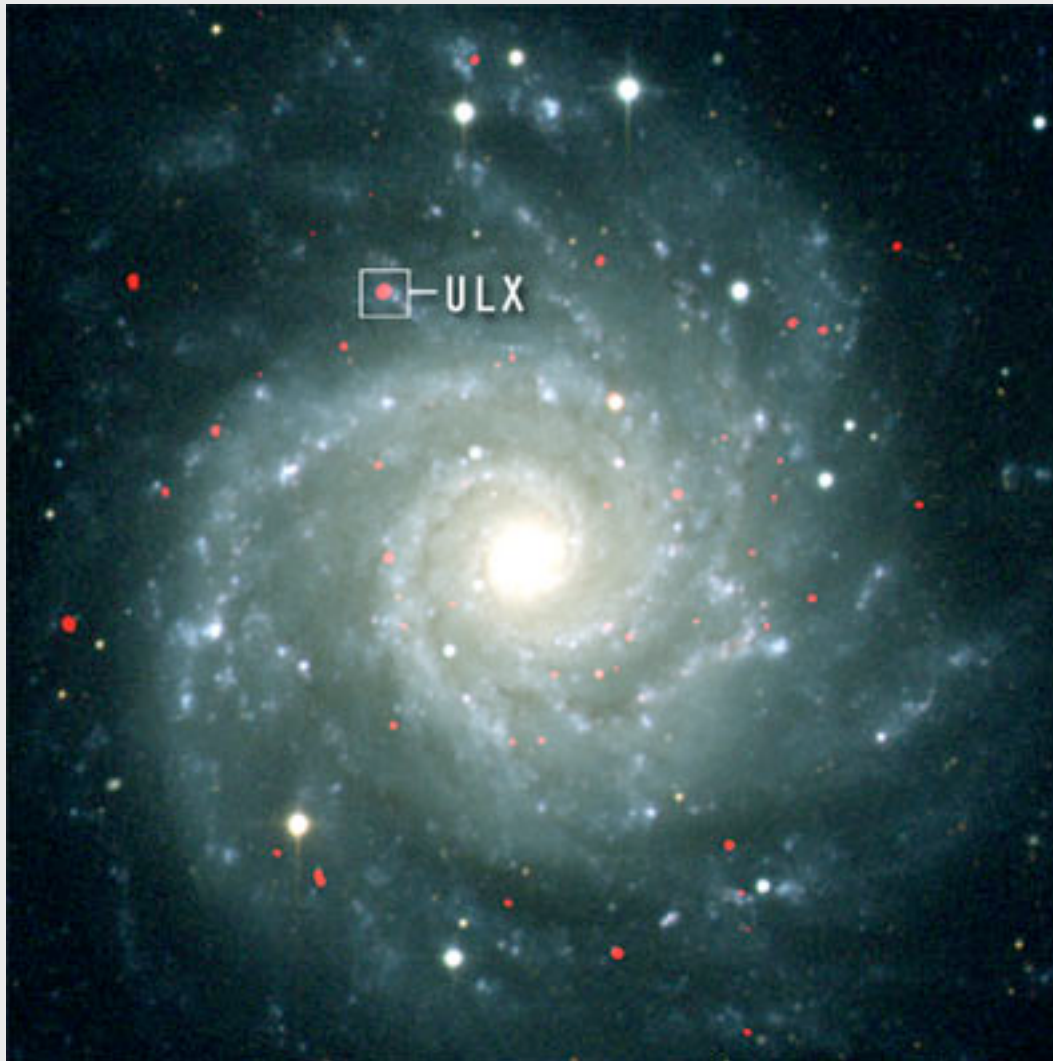
Innermost stable circular orbit [ISCO]...



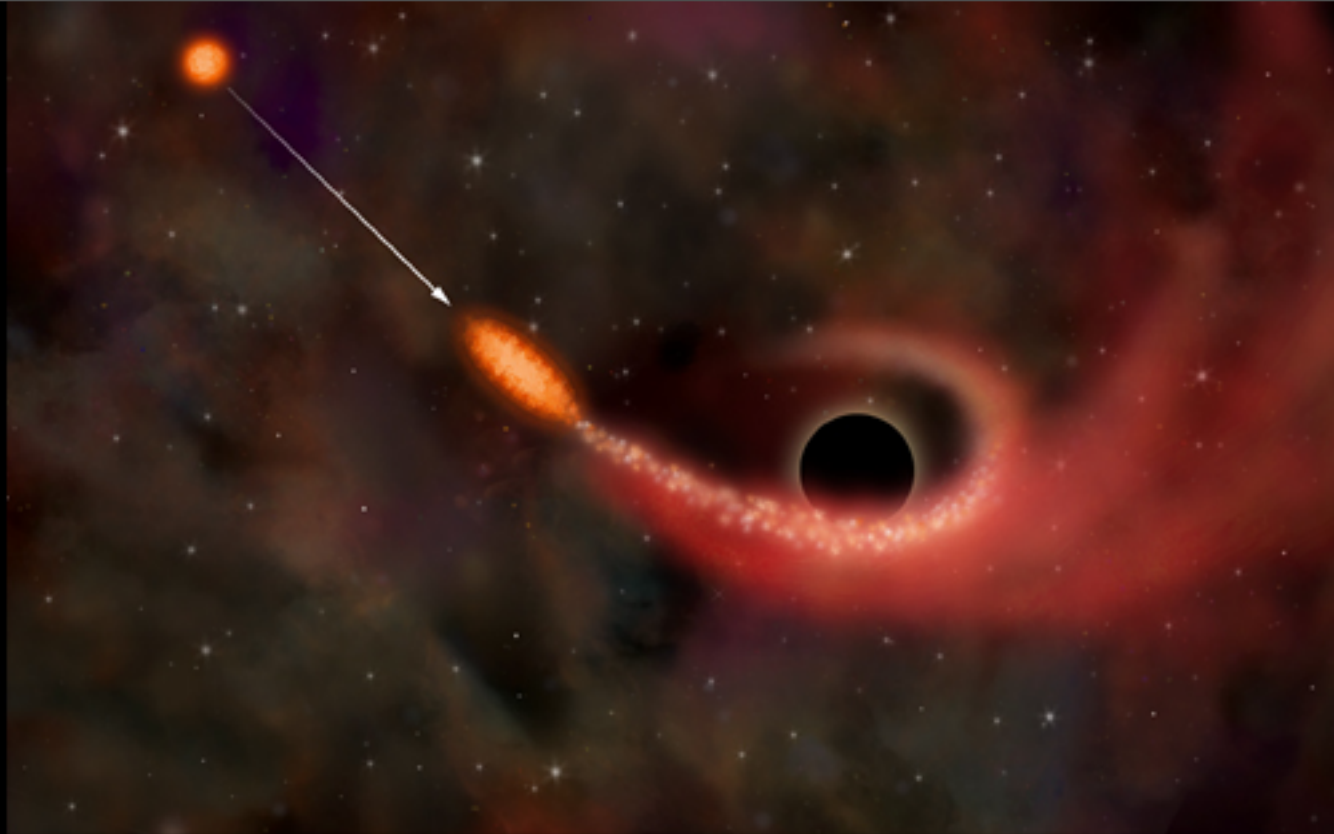




# Observational astronomy:



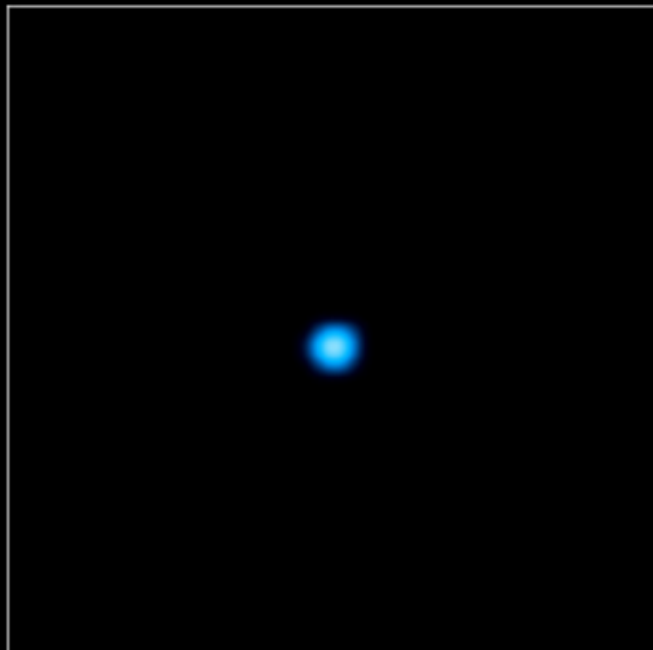
Look for X-ray sources  
in the sky...



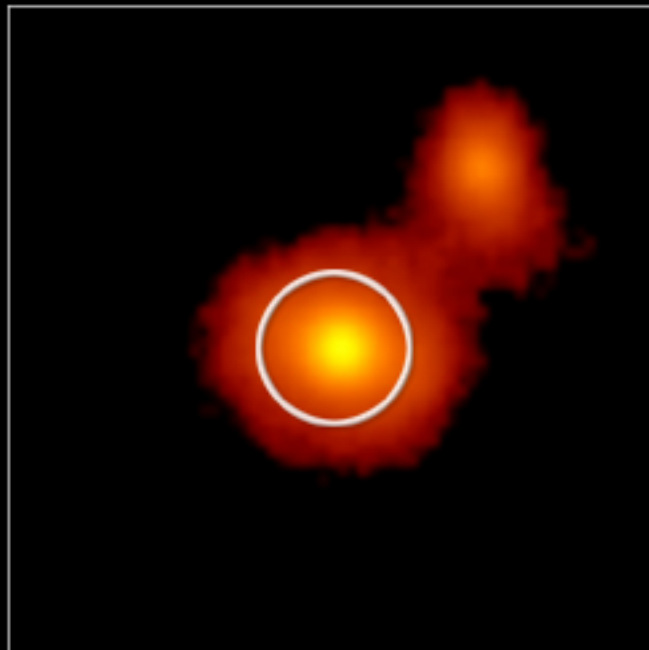
Compact:  
heavy,  
small.

Strong gravity:  
rips stars apart

Look for radiation  
from the stuff  
falling in



CHANDRA X-RAY



ESO OPTICAL

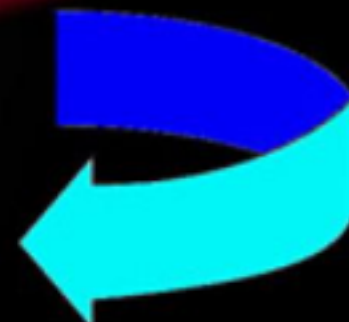


**Obscured central  
black hole**

**X-ray emission  
region**



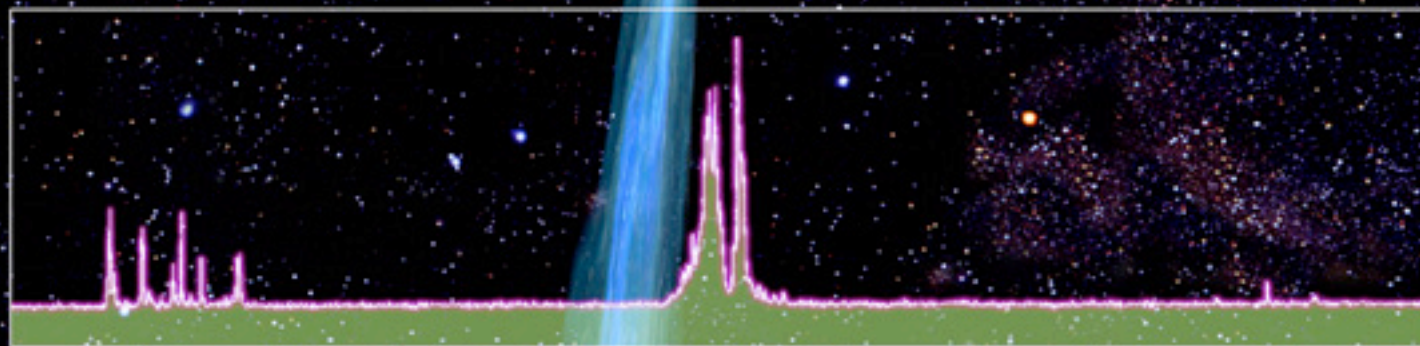
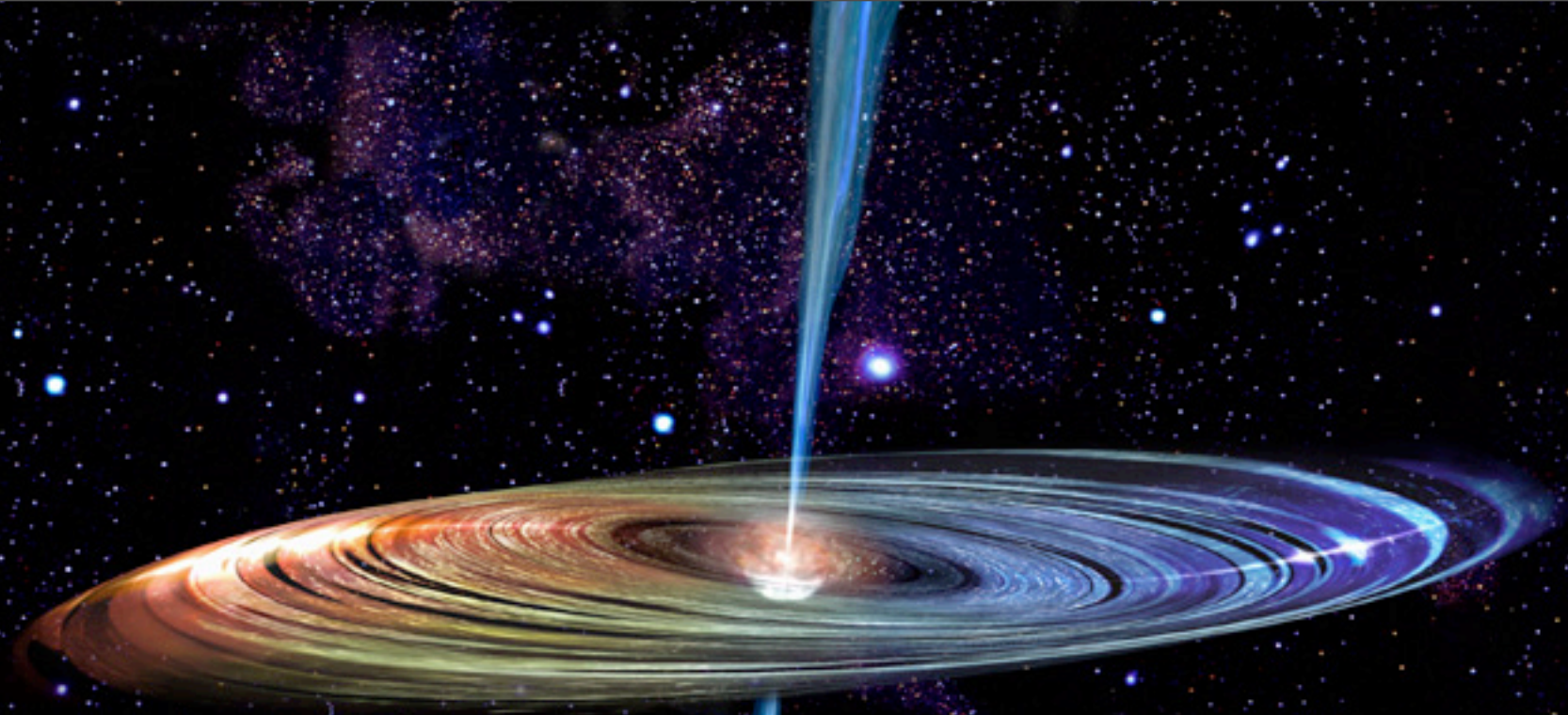
**Emitters moving away:  
lower energy (redshift)**



**Emitters approaching  
higher energy (blueshift)**

**Jet of particles**





1000

0

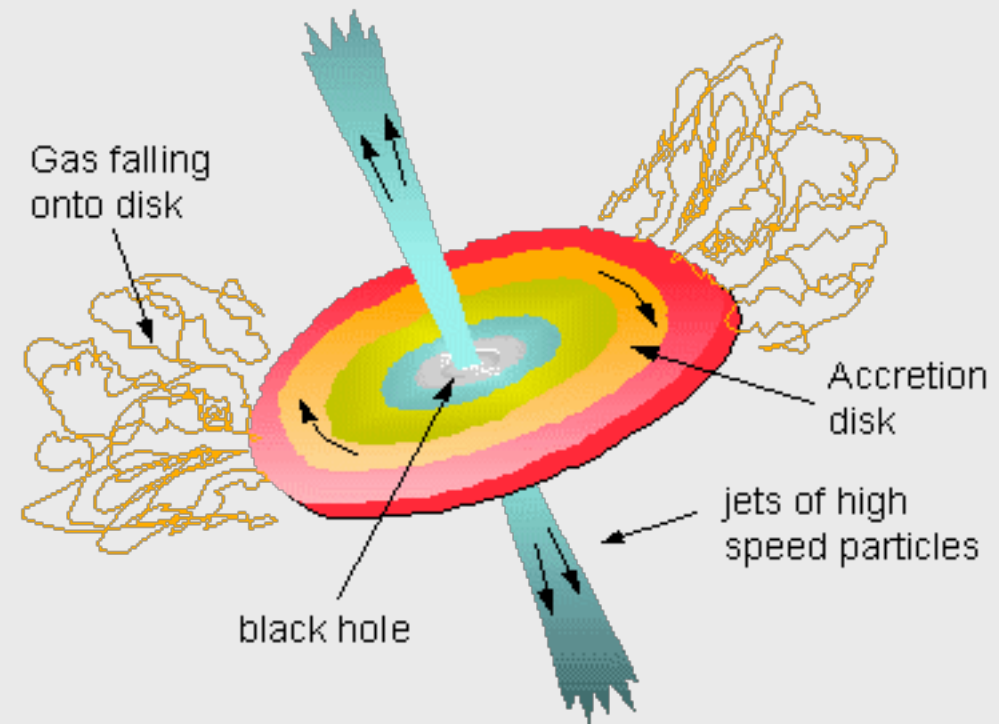
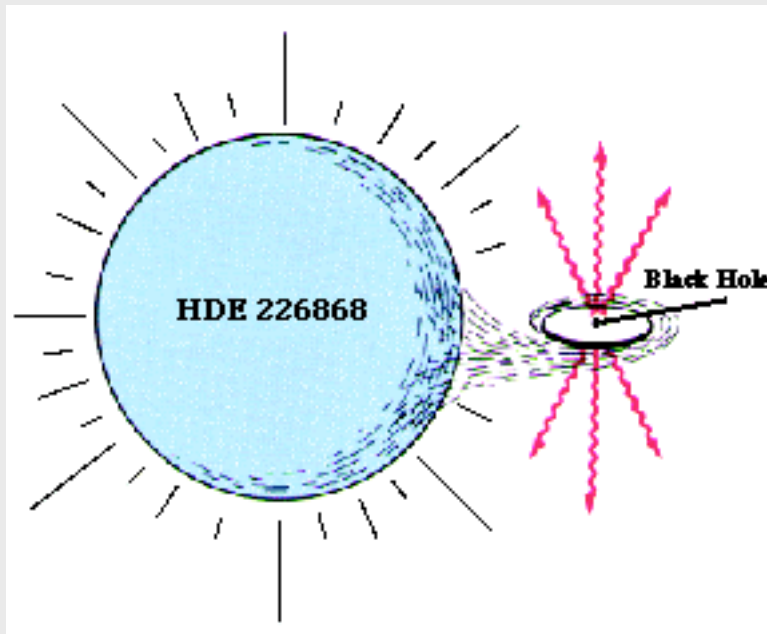
-1000km/s





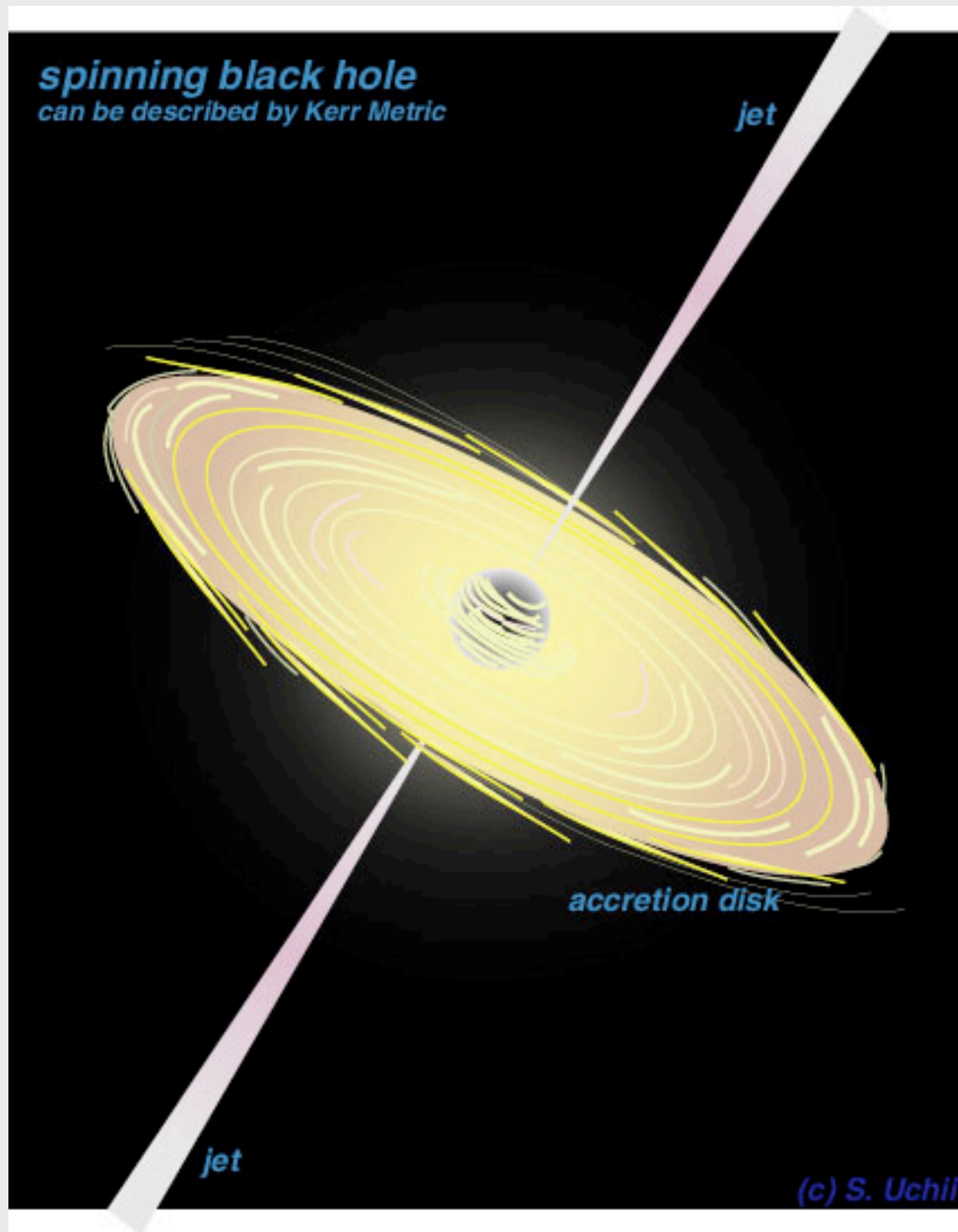
# Theoretical astrophysics:

What we think is going on:



Accretion disks are very important for astrophysics...





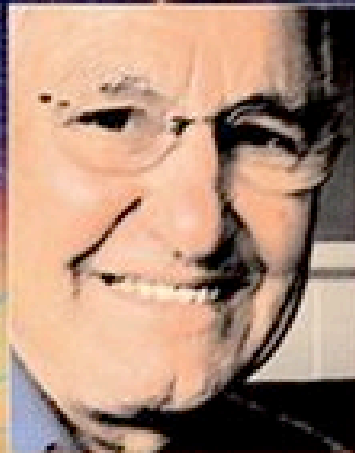
Most astrophysical  
black holes are  
expected to rotate...

Schwarzschild's black  
hole is not good  
enough as a model...

Need to use Roy  
Kerr's rotating  
black hole...

# The Kerr Spacetime

Rotating Black Holes in General Relativity



Edited by  
David L. Wiltshire  
Matt Visser and  
Susan M. Scott

CAMBRIDGE

1916: GR

1916: Schwarzschild

1963: Kerr

47 years to solve the  
Einstein equations  
for a rotating  
black hole...

New book:

Coming soon...

[not light reading]

Schwarzschild spacetime (non-rotating):

Curved  
space-time:

$$ds^2 = - \left[ 1 - \frac{2m}{r} \right] dt^2 + \frac{dr^2}{1 - 2m/r} + r^2(d\theta^2 + \sin^2 \theta d\phi^2),$$

Kerr spacetime (rotating):

$$\begin{aligned} ds^2 = & - \left[ 1 - \frac{2mr}{r^2 + a^2 \cos^2 \theta} \right] dt^2 - \frac{4mra \sin^2 \theta}{r^2 + a^2 \cos^2 \theta} dt d\phi \\ & + \left[ \frac{r^2 + a^2 \cos^2 \theta}{r^2 - 2mr + a^2} \right] dr^2 + (r^2 + a^2 \cos^2 \theta) d\theta^2 \\ & + \left[ r^2 + a^2 + \frac{2mra^2 \sin^2 \theta}{r^2 + a^2 \cos^2 \theta} \right] \sin^2 \theta d\phi^2. \end{aligned}$$





# Do black holes “exist” ?



## Observational astronomy:

Small, dark, and heavy...

Accretion disks probe down to the ISCO:

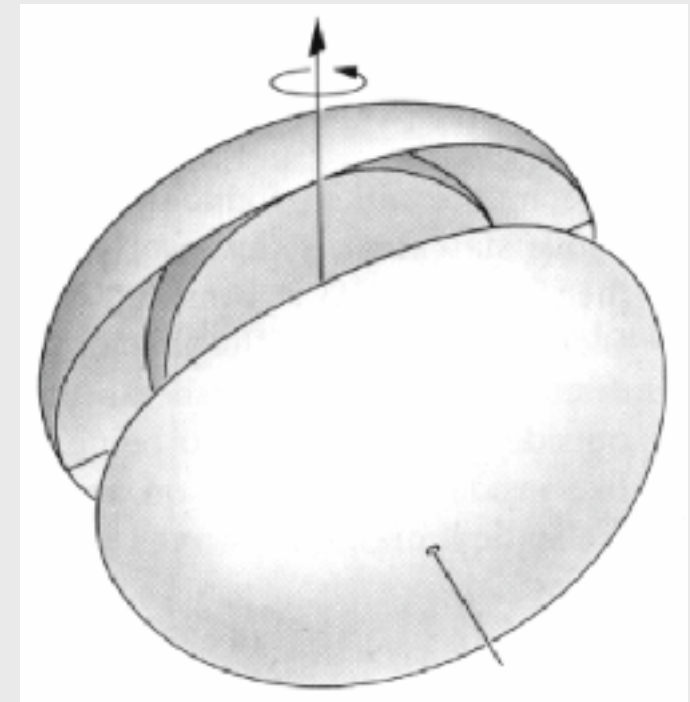
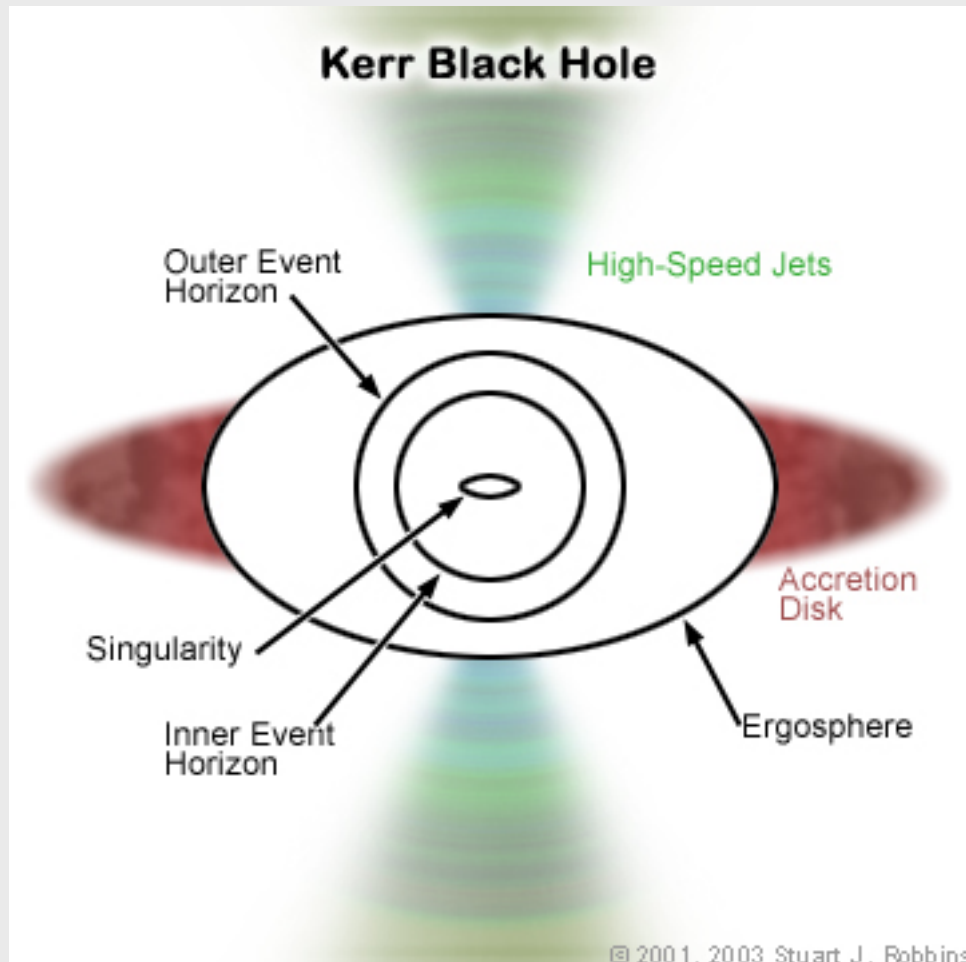
$$2m/r \sim \mathbf{1/3 !}$$

ADAFs probe down to  $2m/r \sim \mathbf{1 ?}$

Everything so far compatible with Schwarzschild/ Kerr.



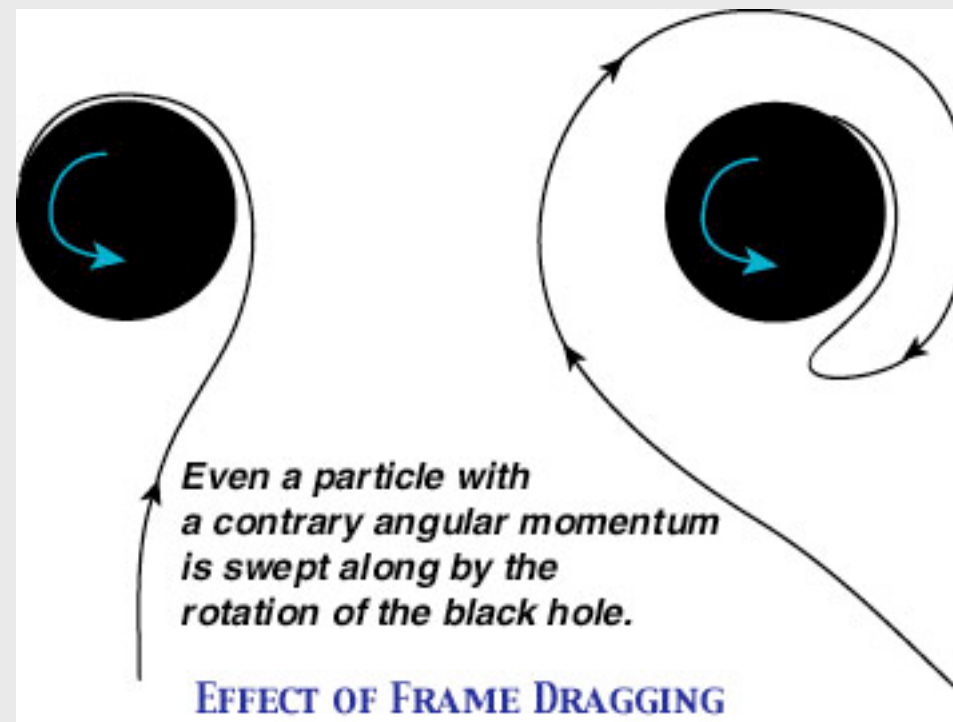
# Kerr space-time:



More than just a horizon and photon sphere...

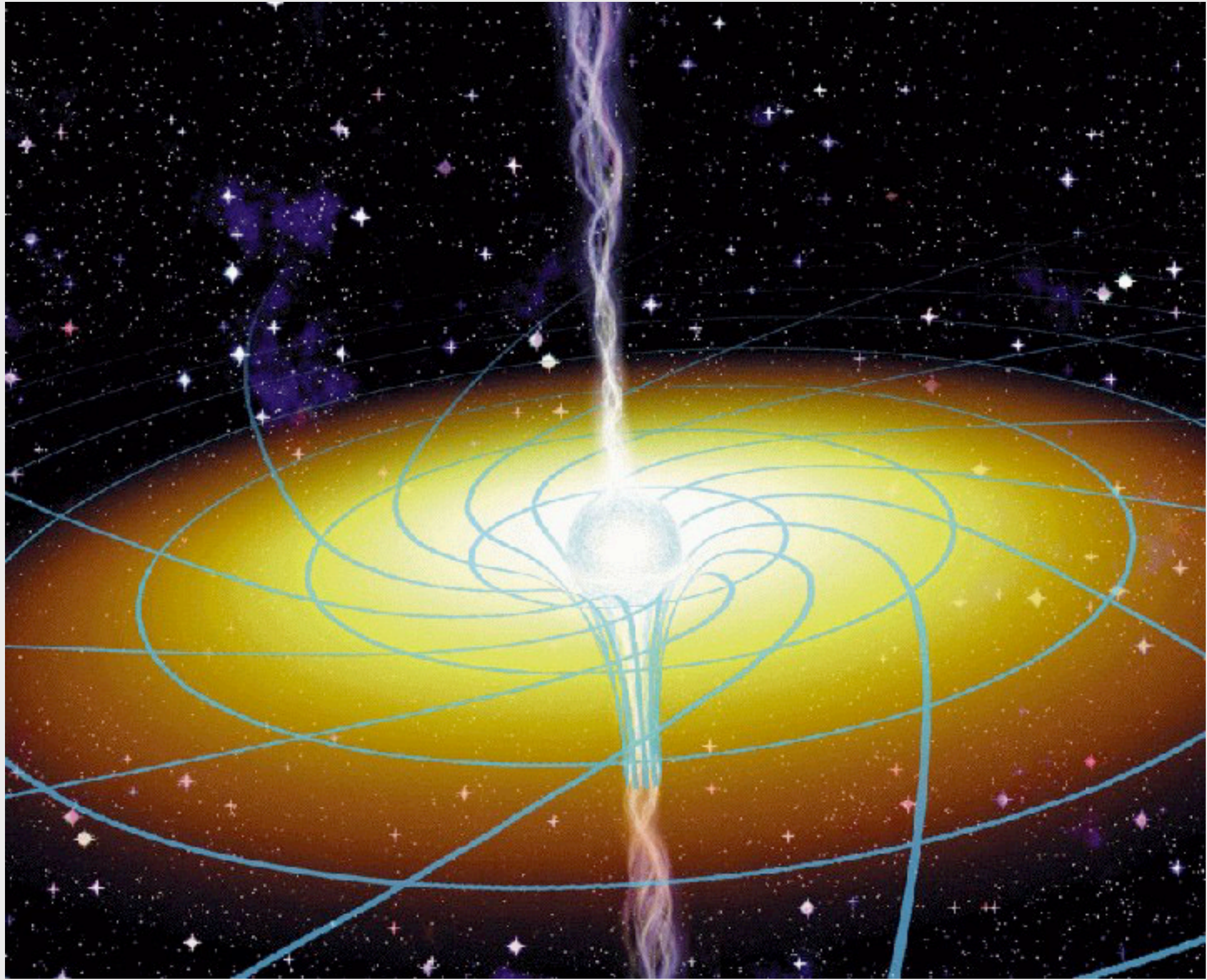


# Kerr space-time:



Gravity now has a “twist” to it as well as pointing more or less “down”...

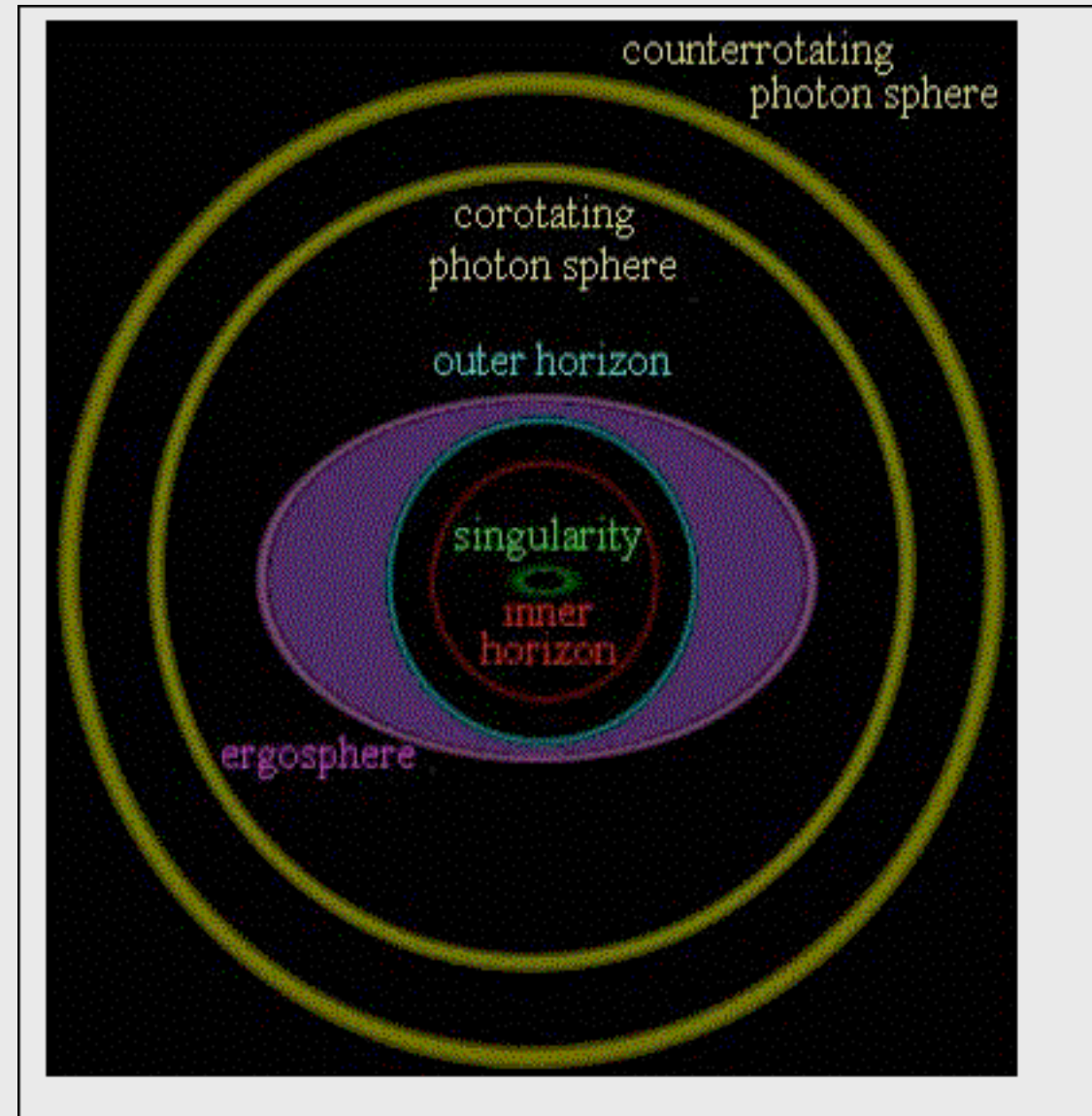
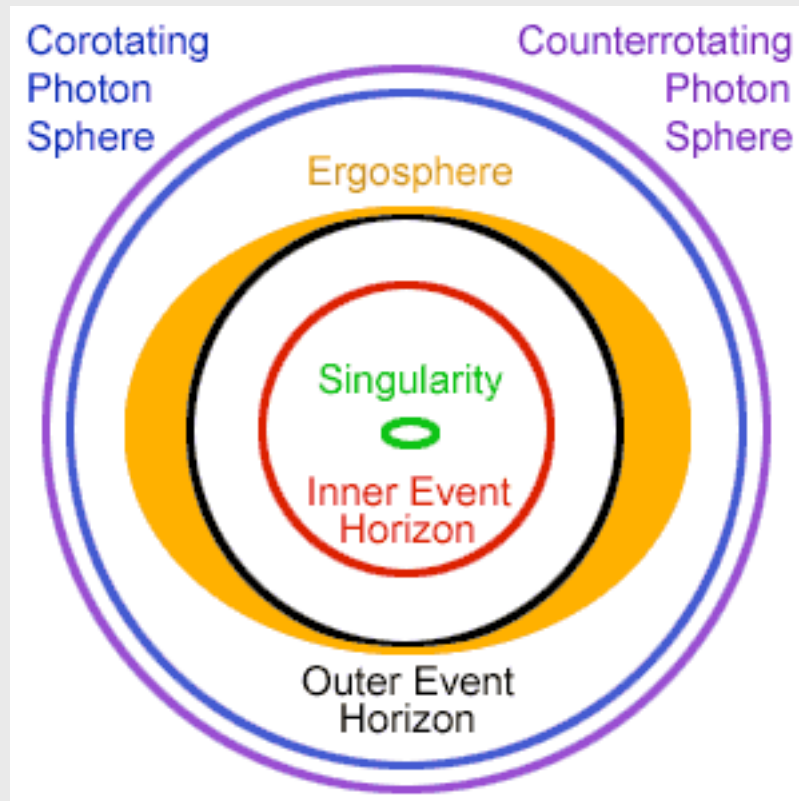








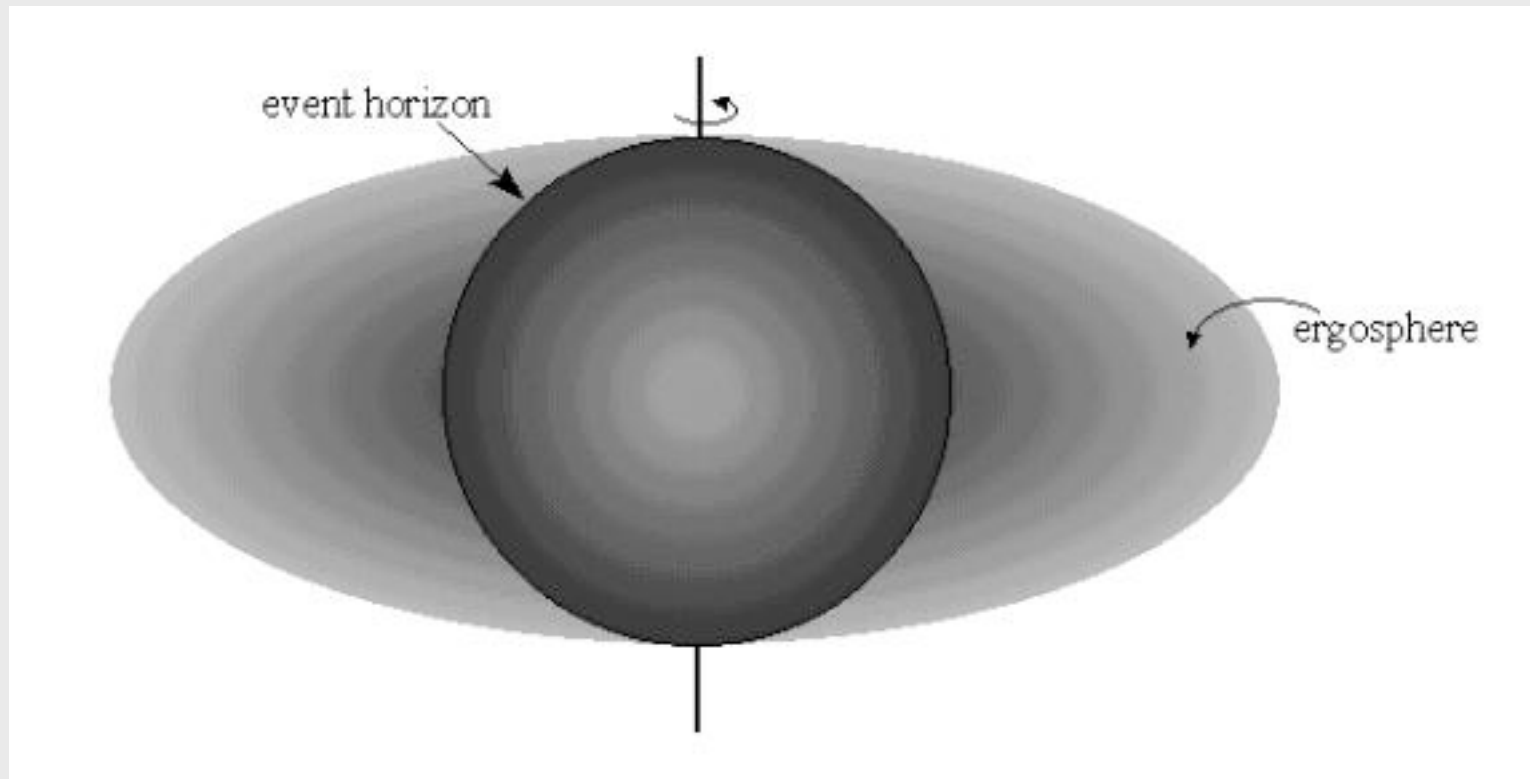
# Kerr space-time:



Now have two photon  
spheres....

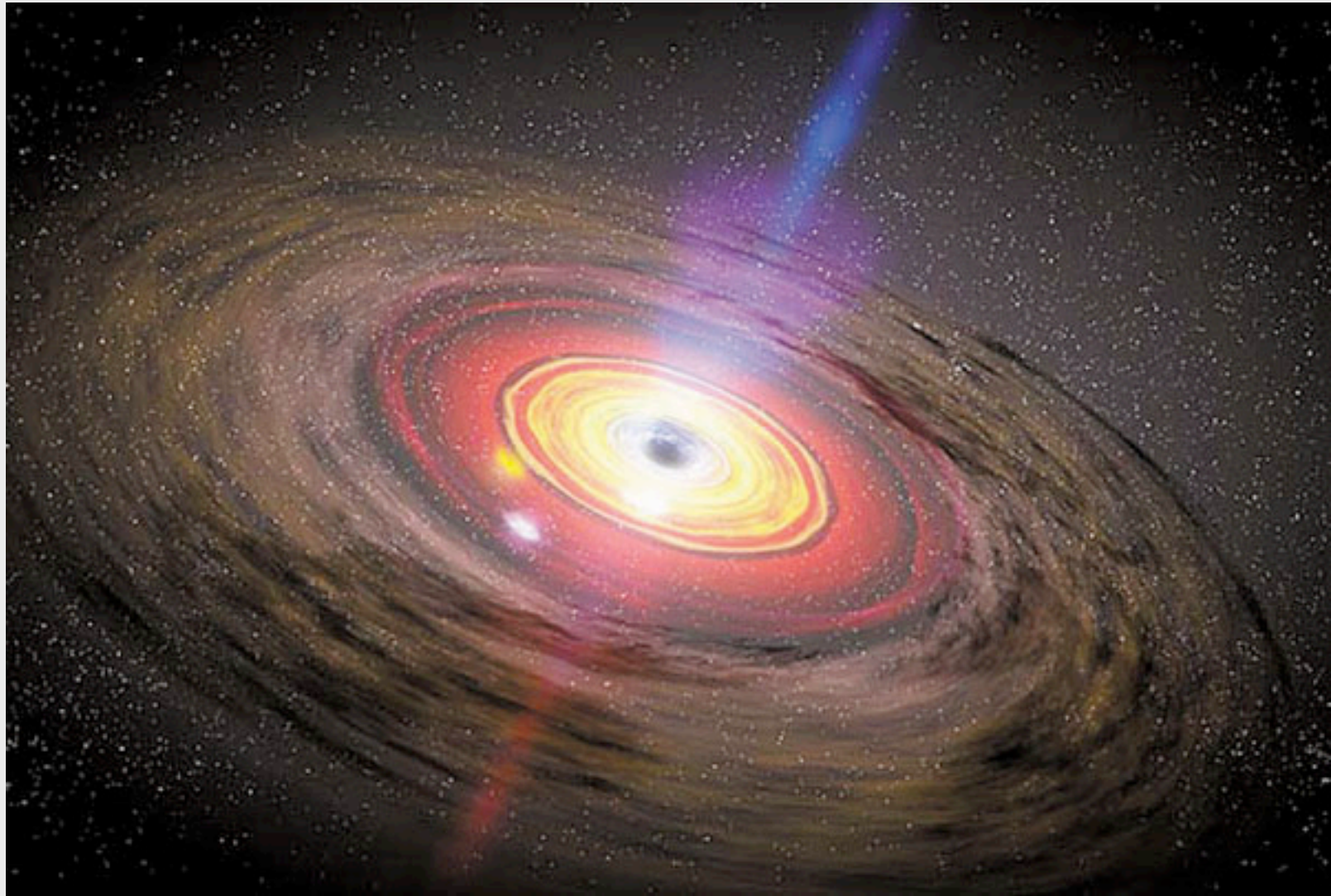


# Kerr space-time:

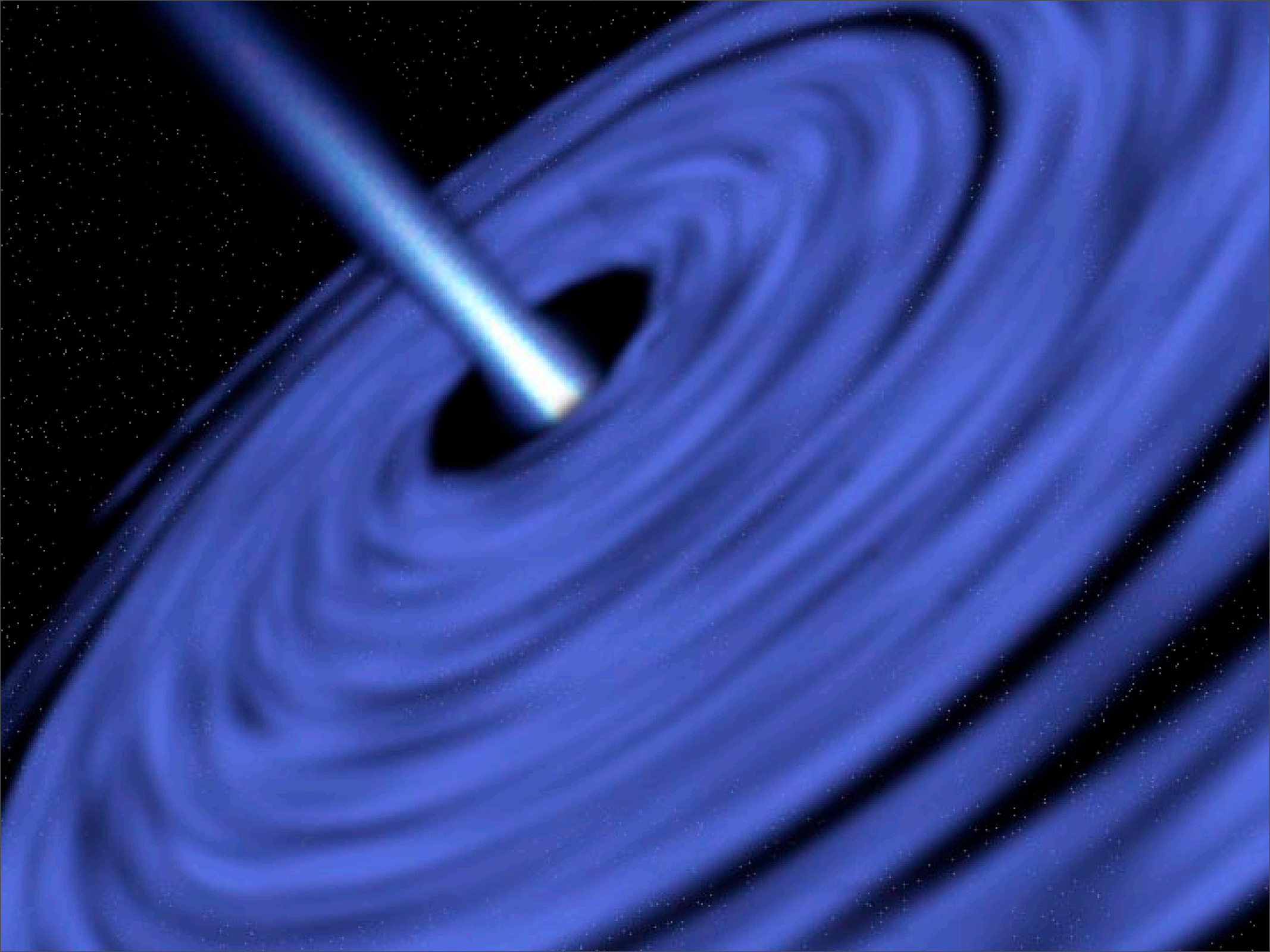


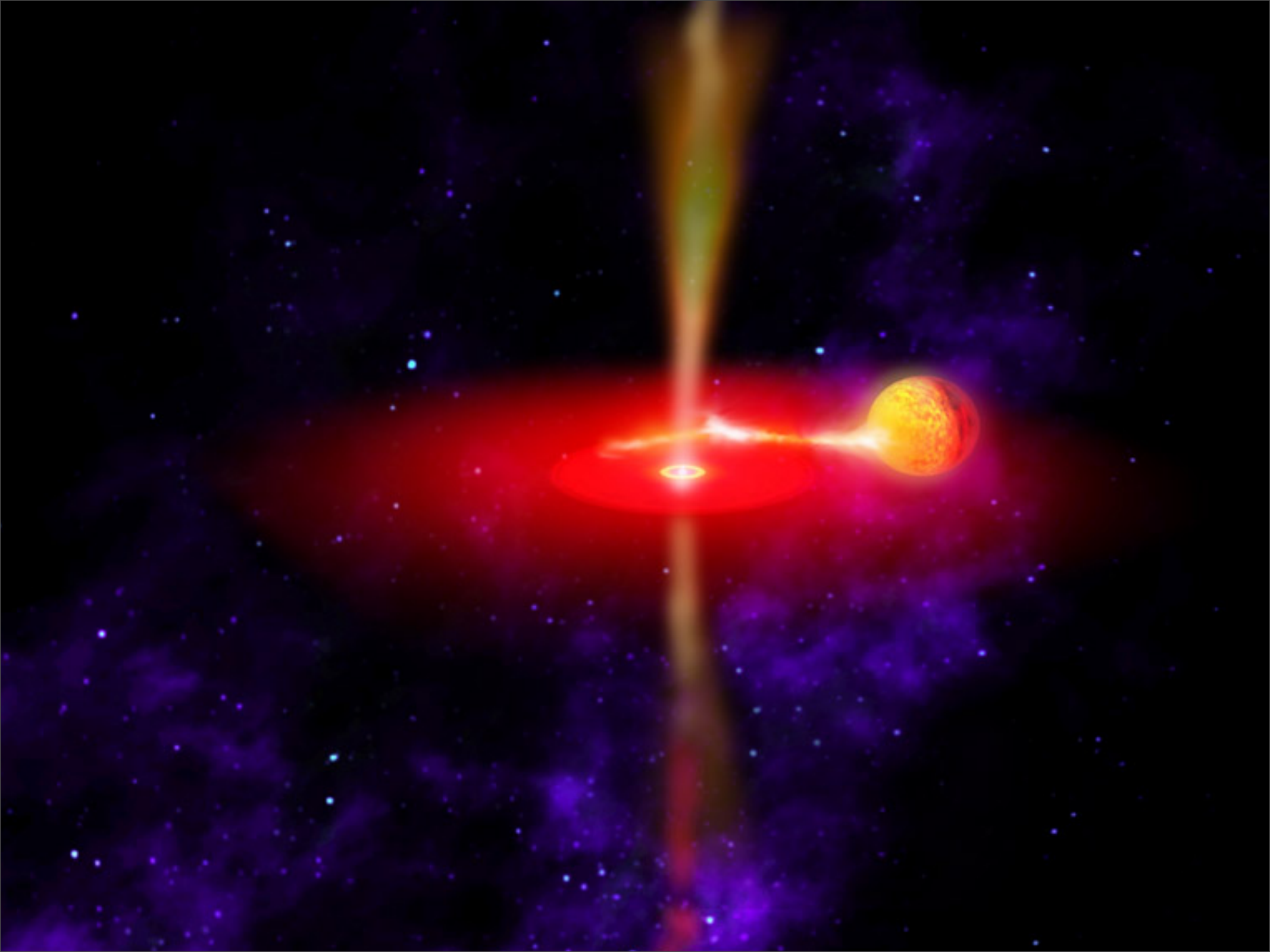
From the outside, ergoregion and horizon is all you will ever see --- internal “structure” will be invisible...



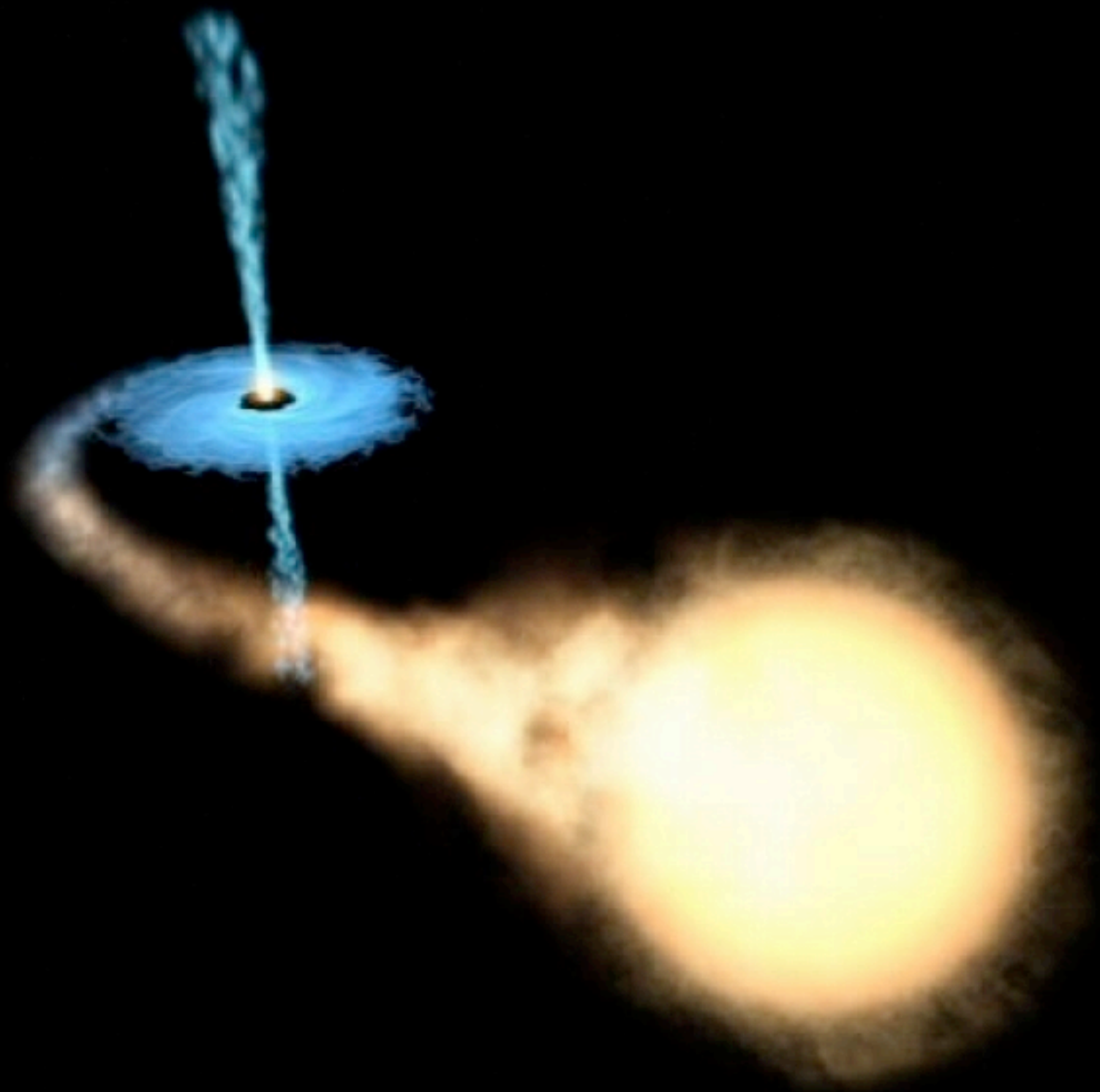


With a little dramatic licence...

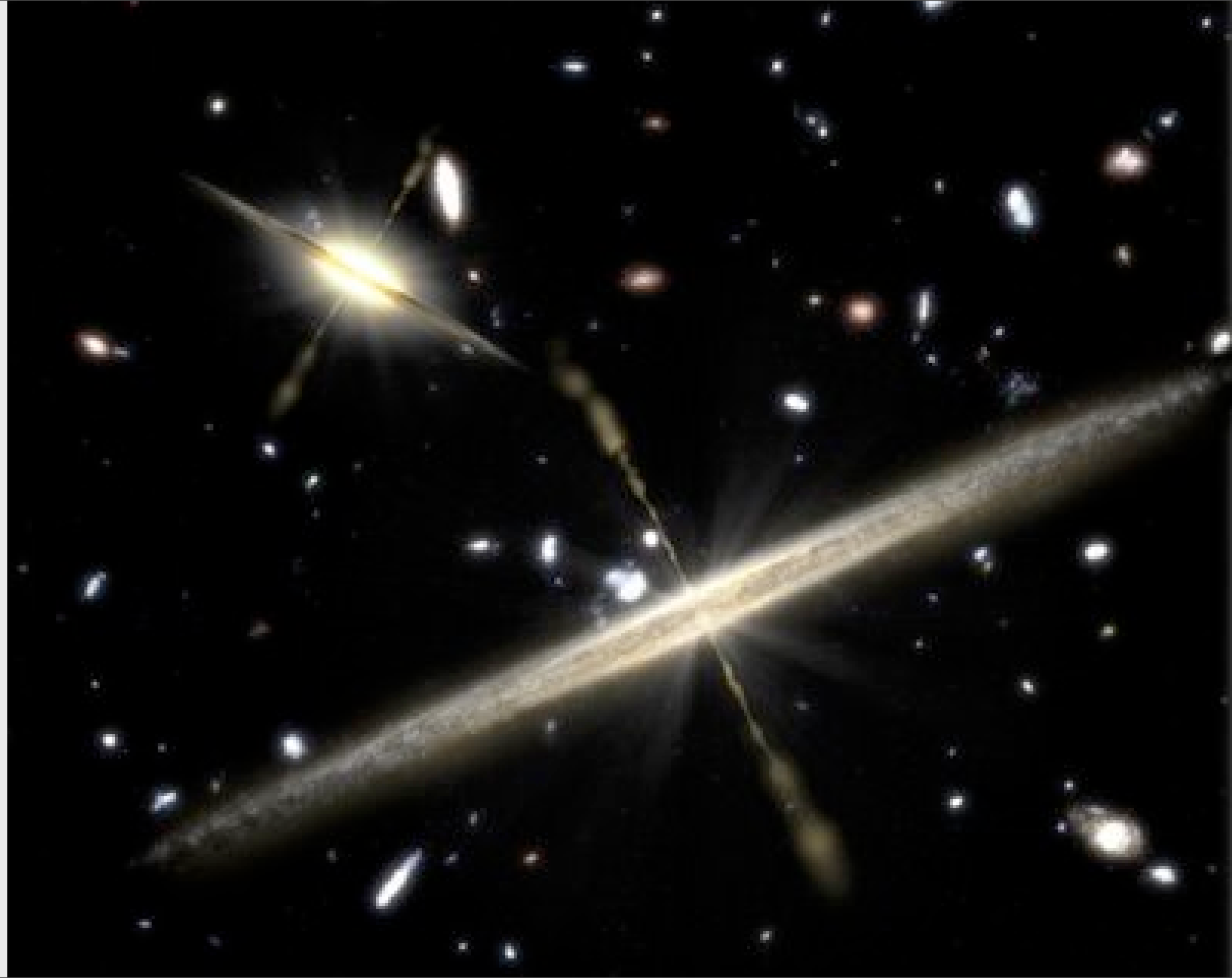


















Some real  
data...



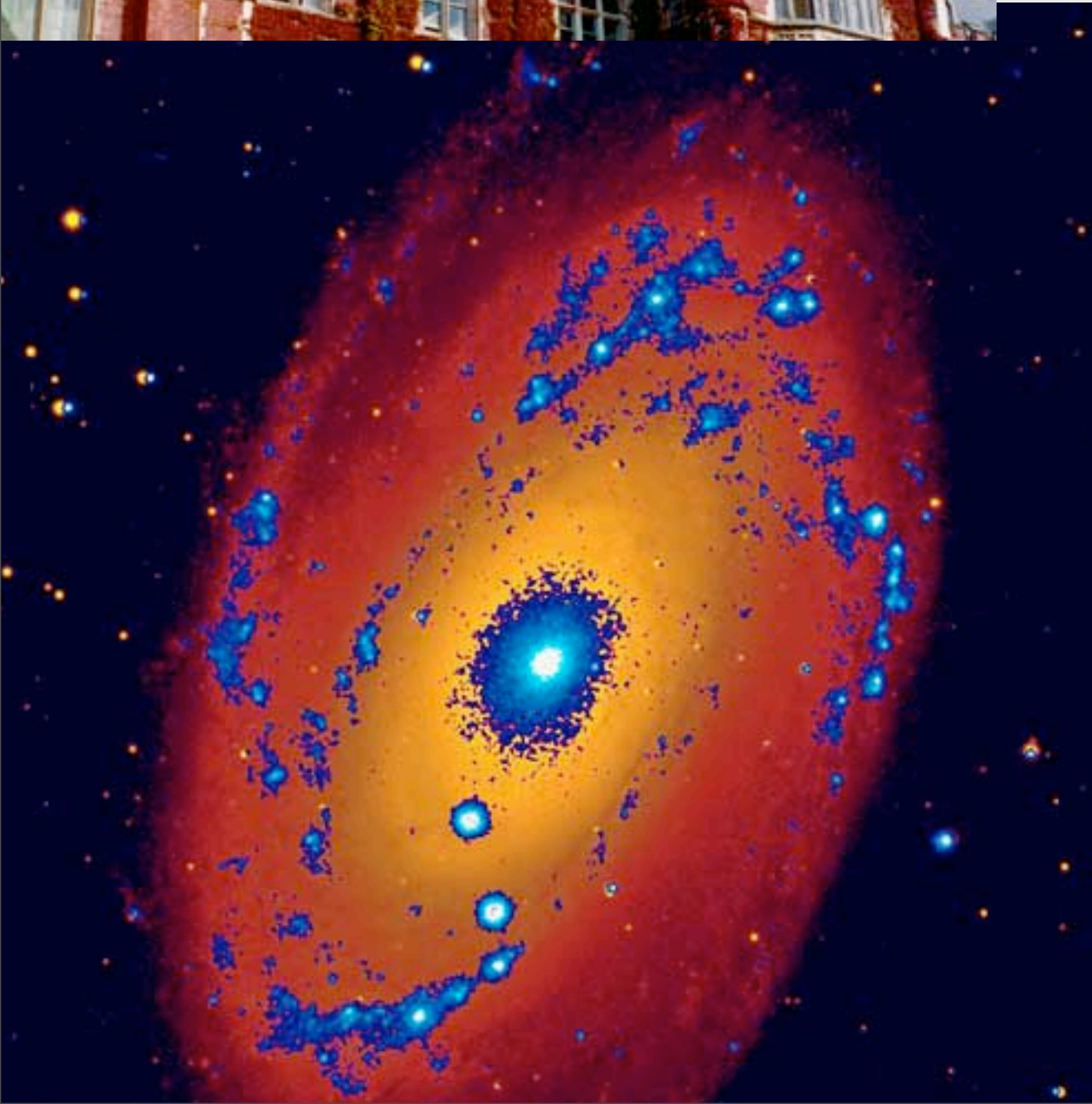
Galaxy M81 --- with a big black hole in the center...



## M81 again...

This view of M81, obtained by a telescope aboard a space shuttle mission, shows the galaxy in both visible (red and yellow) and ultraviolet (blue) wavelengths. The blue regions are much hotter than the others, and outline the galaxy's spiral arms and its nucleus.

The nucleus may contain a supermassive black hole.



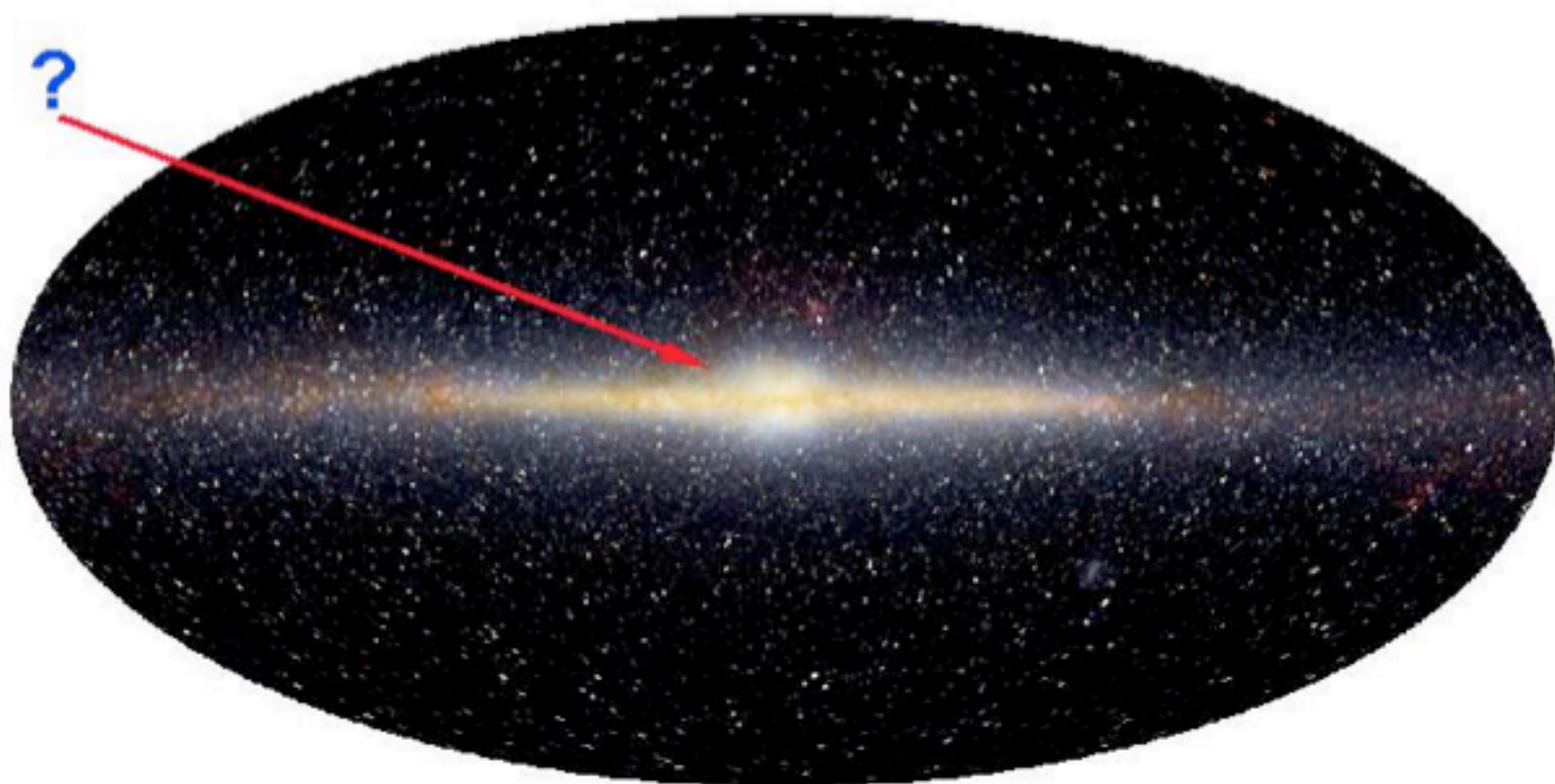


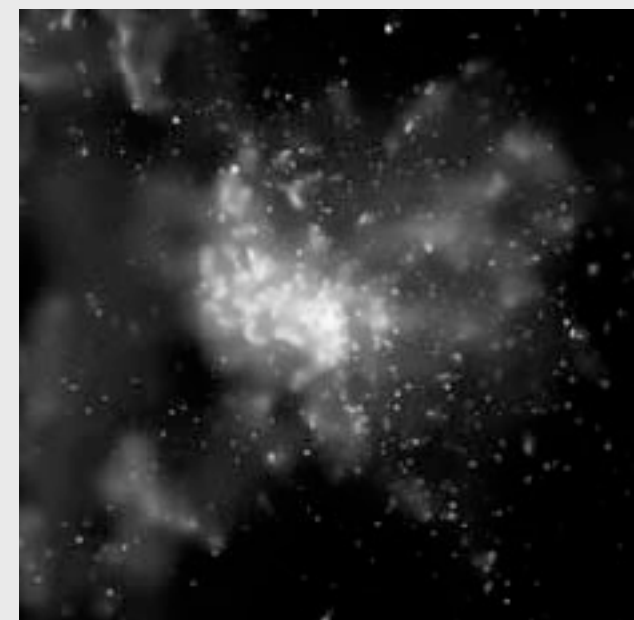
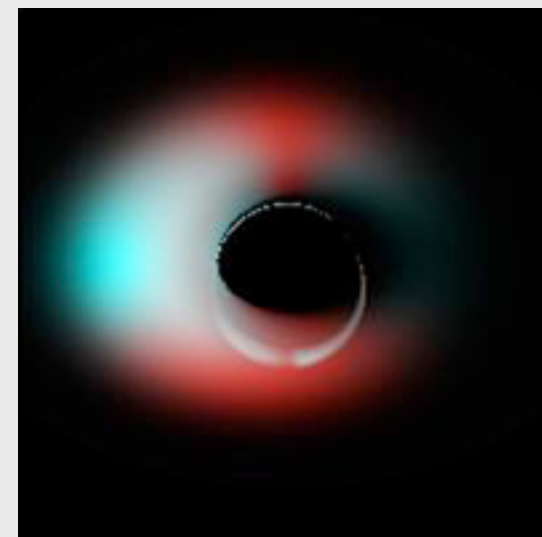
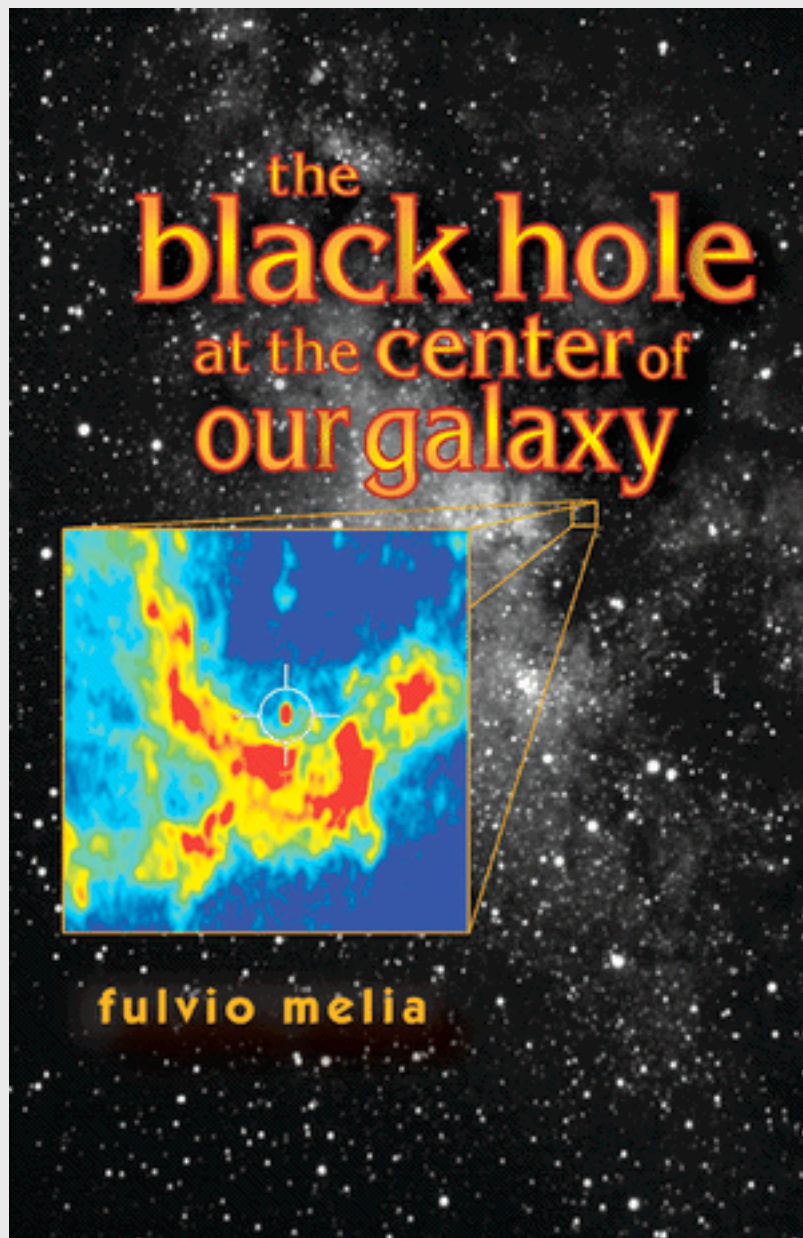


# Is there a black hole in the center of the Milky Way?



- The Milky Way is our galaxy
  - Many galaxies are thought to have black holes in their centers
  - Remnants of dead quasars which formed after the Big Bang

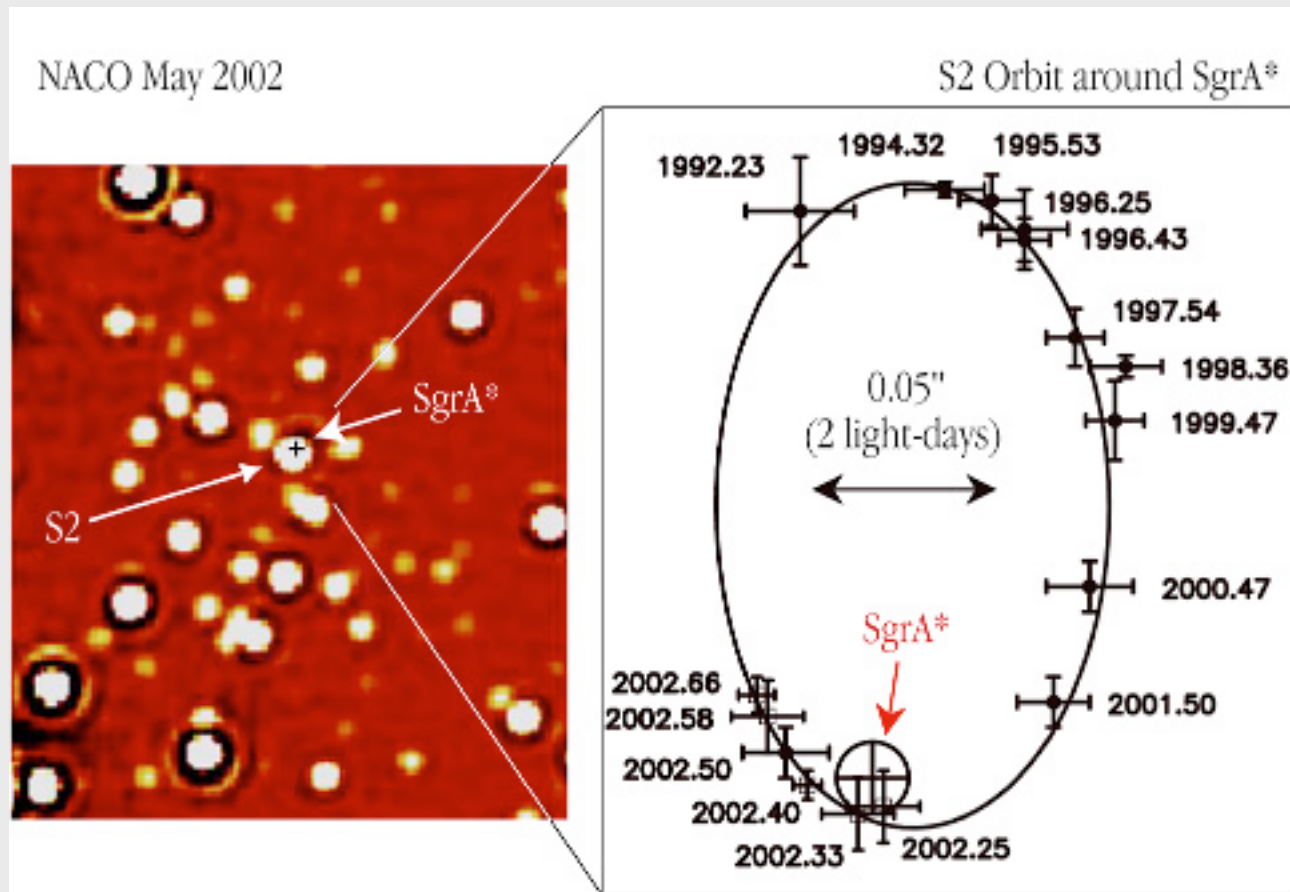








Stars orbiting  
around the  
central black  
hole of our  
own galaxy...

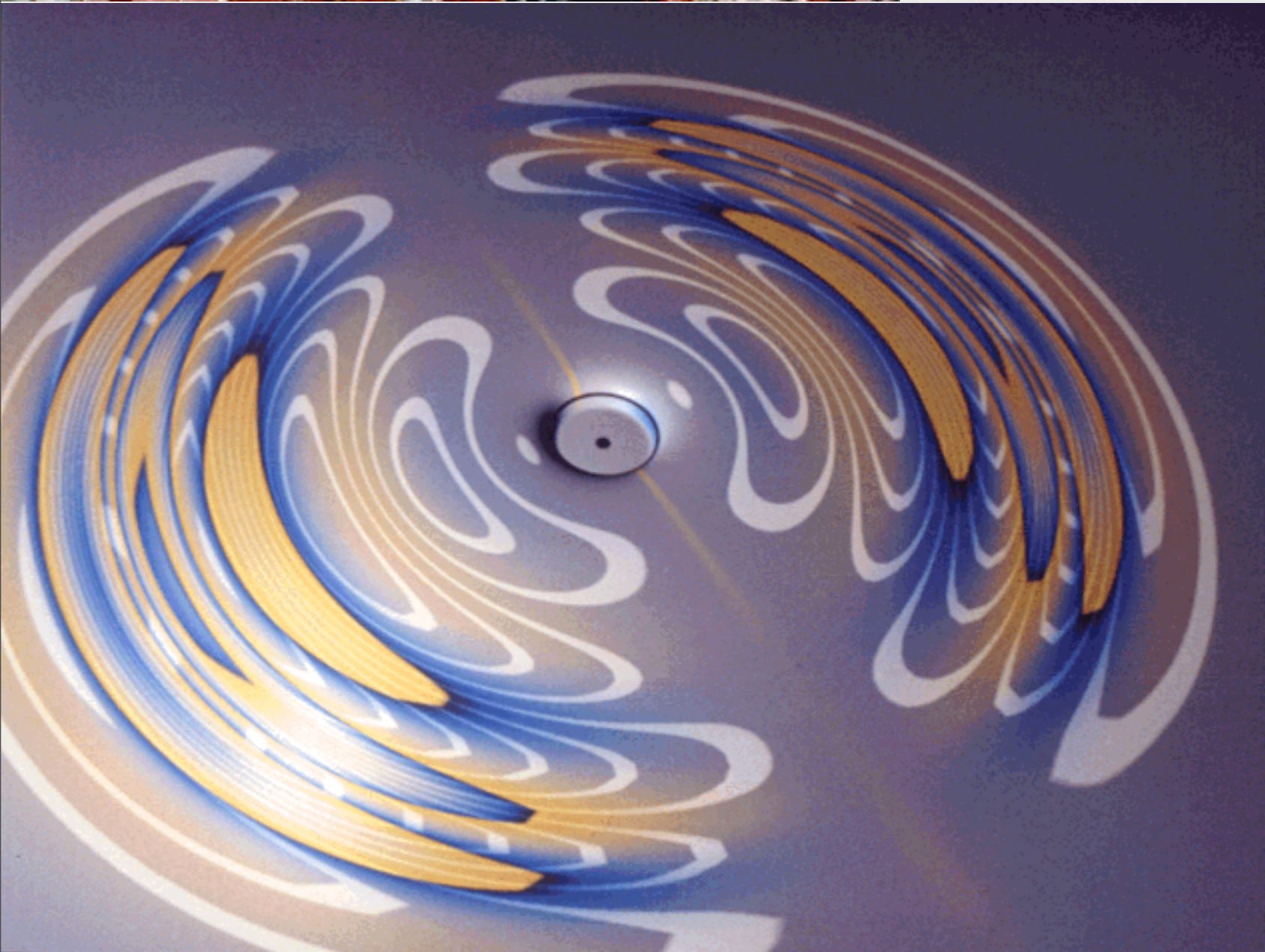


The Motion of a Star around the Central Black Hole in the Milky Way





# Gravity waves



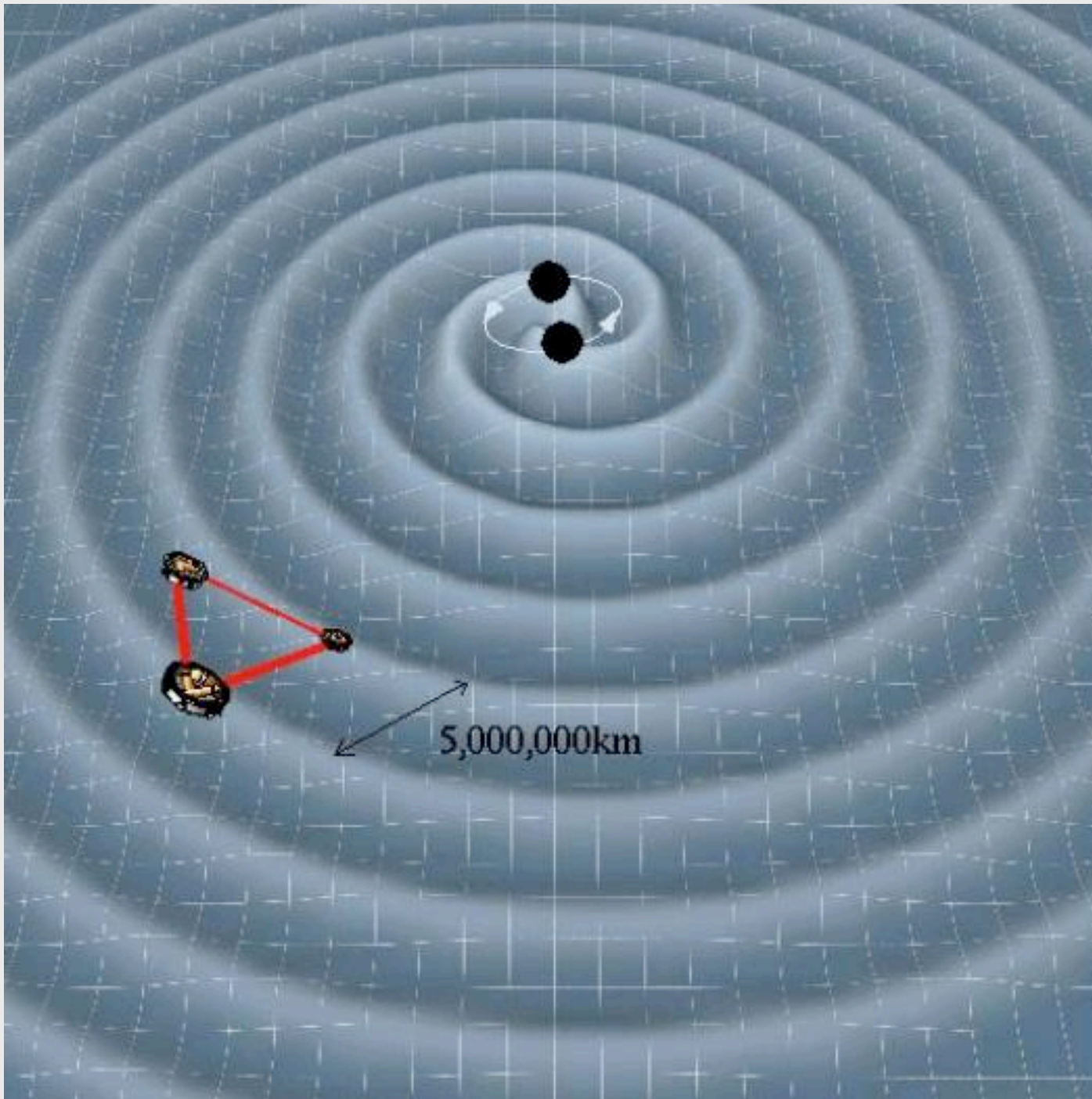
Ripples  
in  
space-time

Still  
collecting  
data...

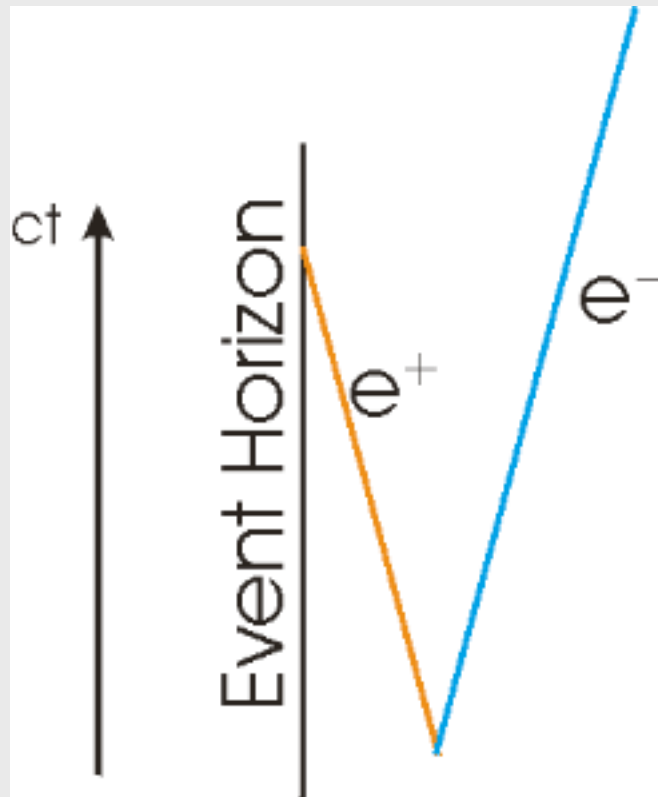
LIGO



# Gravity waves? We're looking...



LISA...

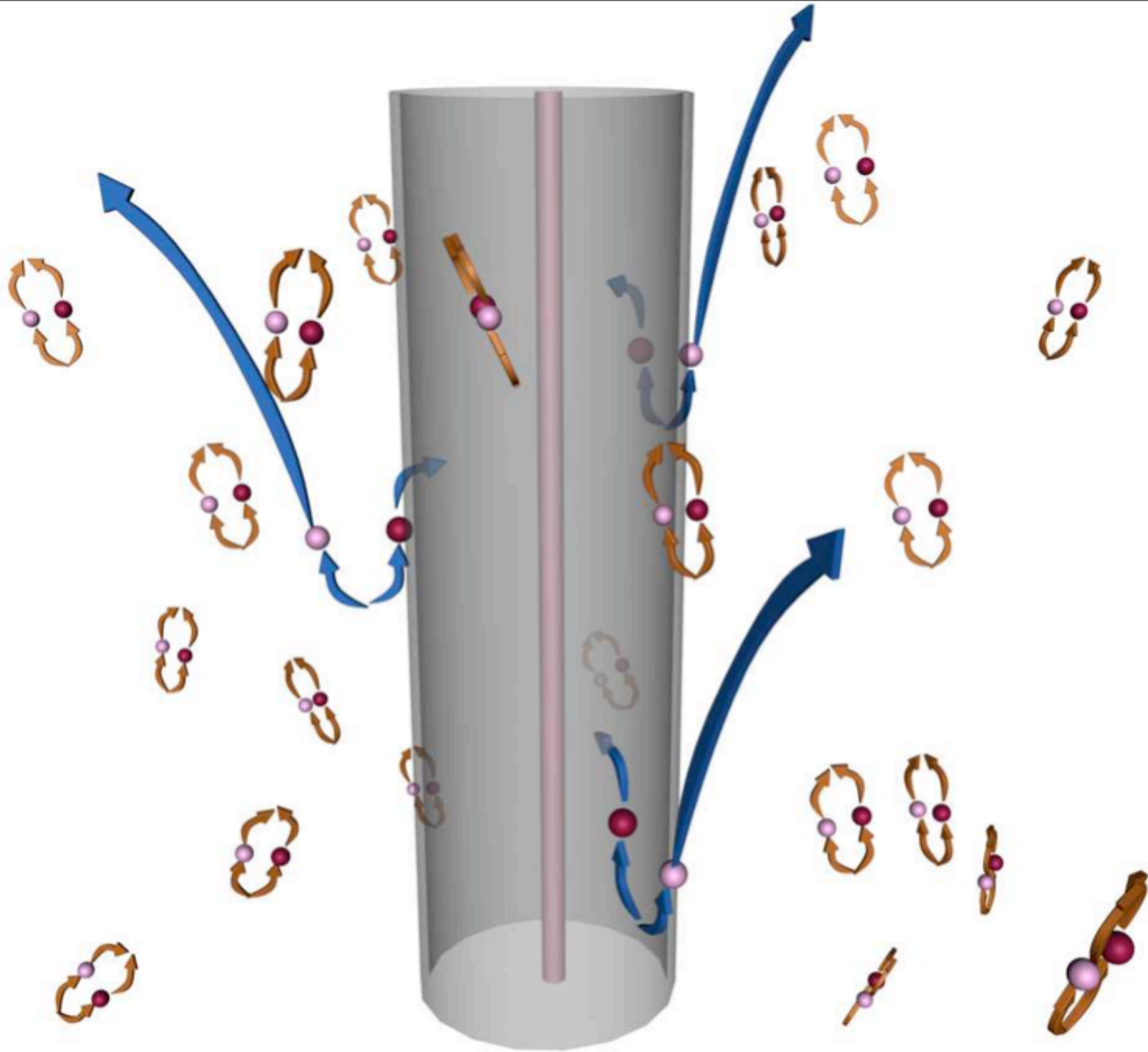


# Stephen Hawking:

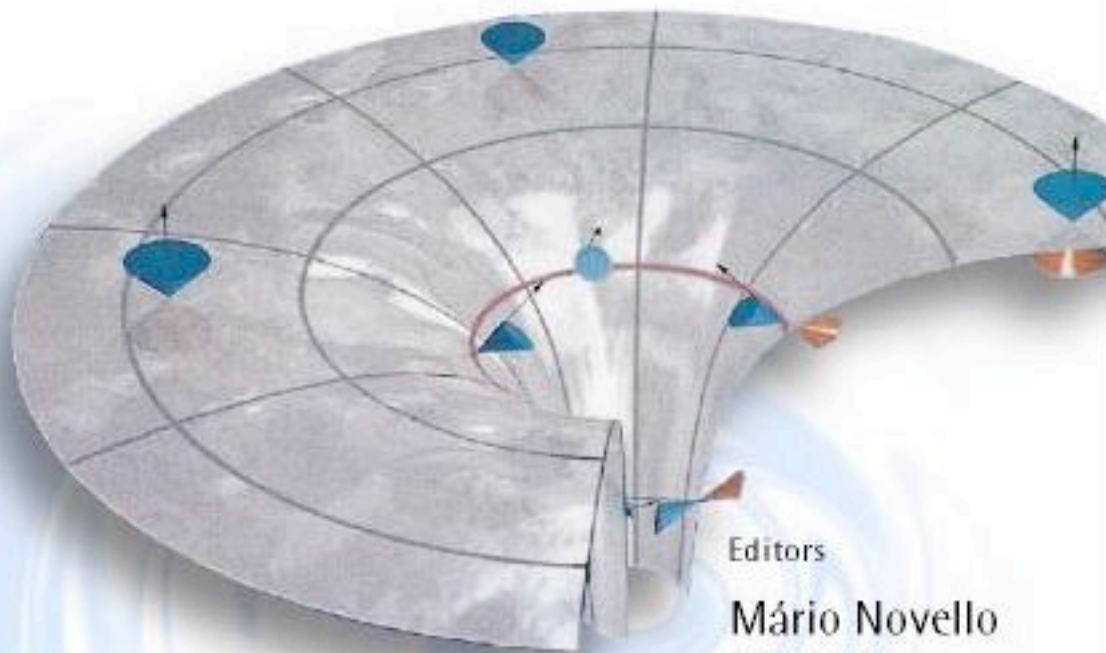
Black holes will eventually  
evaporate due to  
subtle quantum effects...

We're still calculating...





# ARTIFICIAL BLACK HOLES



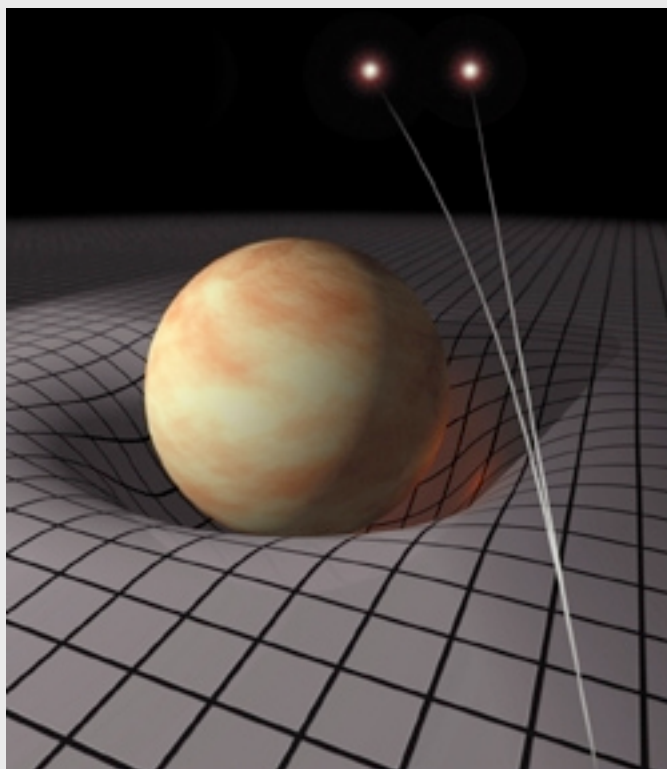
Editors  
Mário Novello  
Matt Visser  
Grigori Volovik

World Scientific

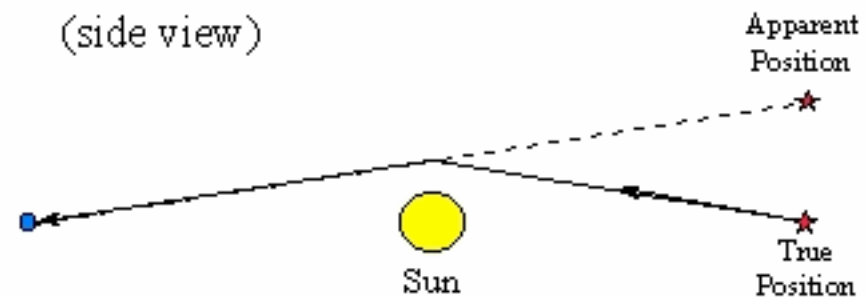
Scientists are trying to  
test Hawking radiation  
by simulating it in  
simpler systems...



# Bending of starlight

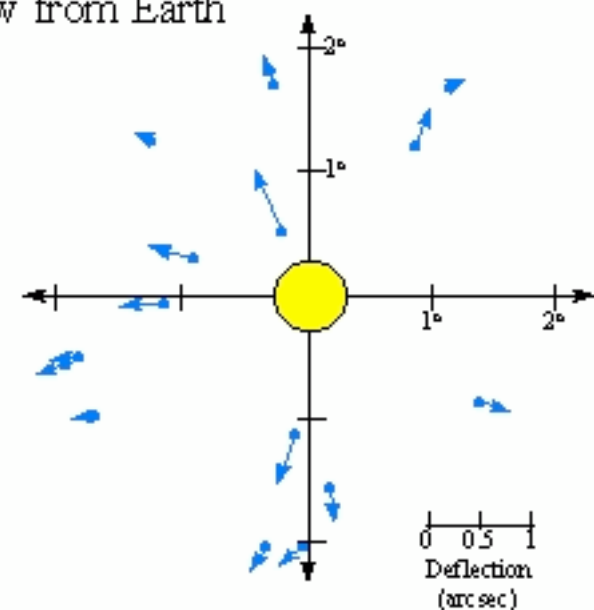


## Bending of Starlight (side view)



Scale is exaggerated

## View from Earth

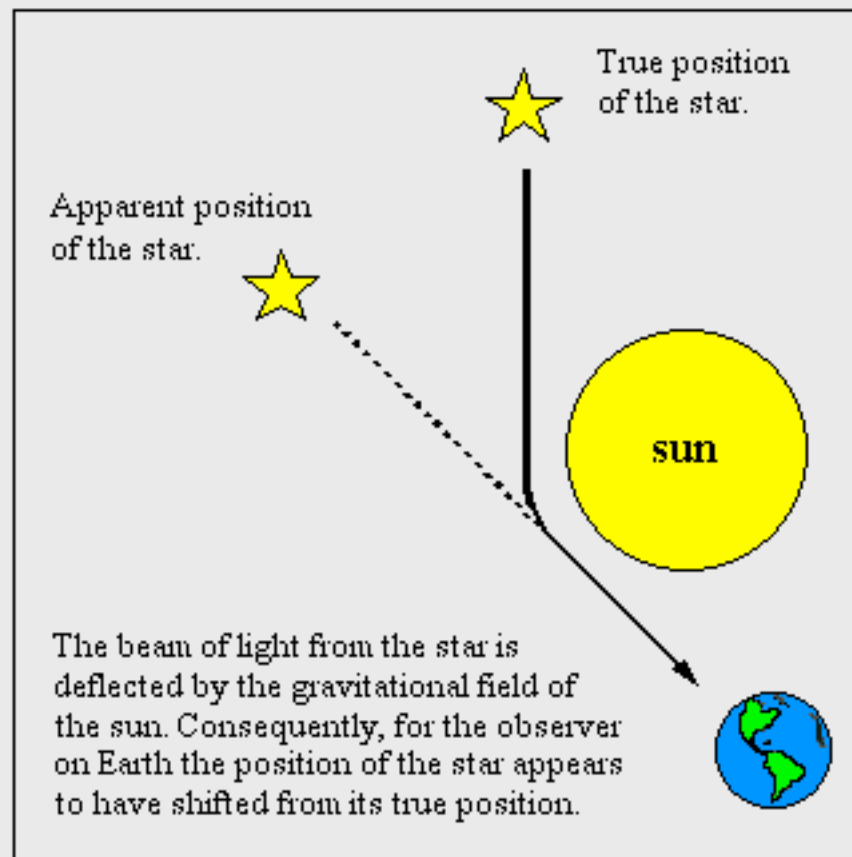


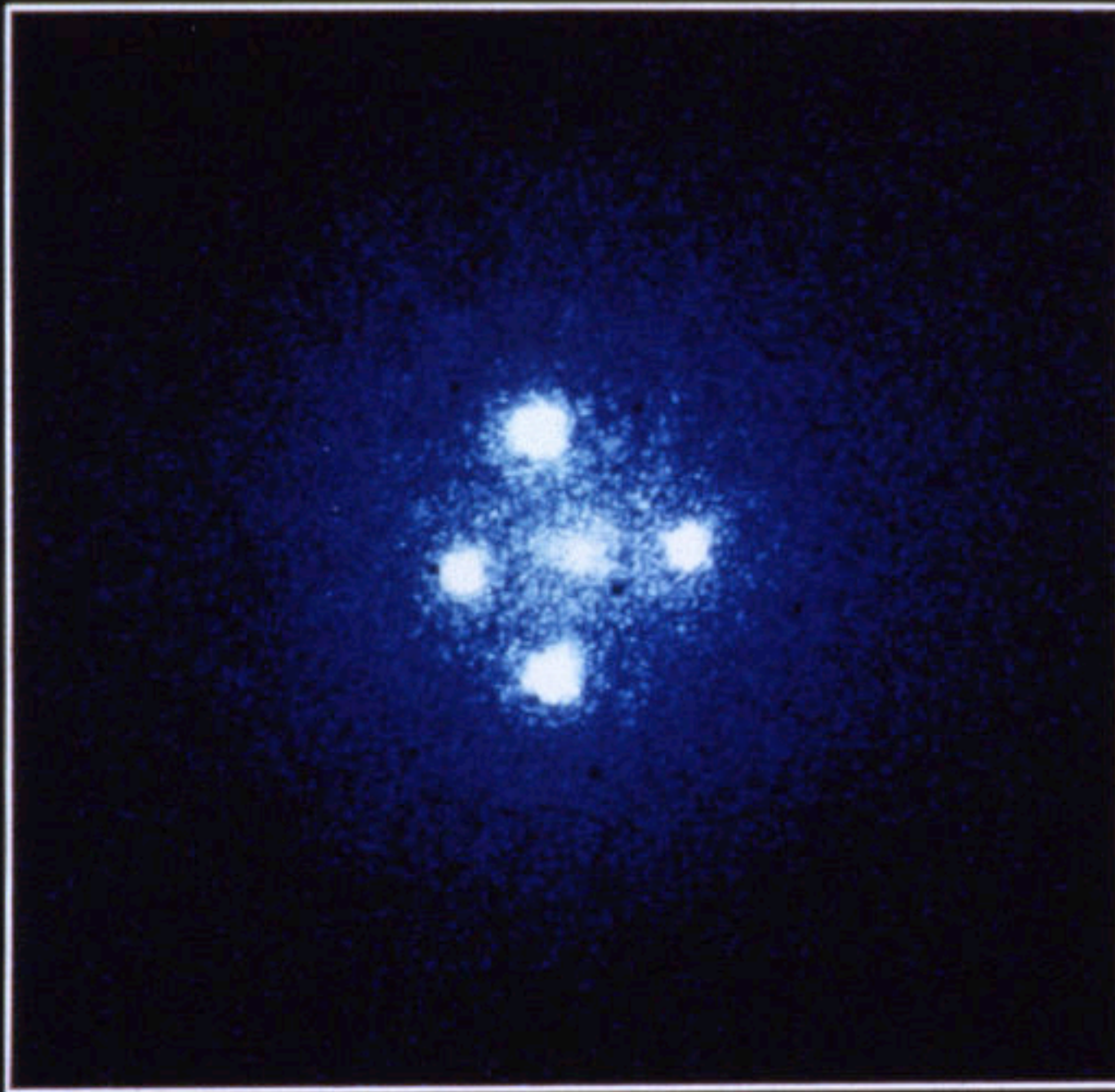
1879 - 1955





## Bending of starlight:





**Gravitational Lens G2237+0305**









## Bending of starlight:



**Gravitational Lens in Abell 2218**

**HST · WFPC2**

PF95-14 · ST ScI OPO · April 5, 1995 · W. Couch (UNSW), NASA



# Do black holes “exist” ?



Can one avoid black hole formation with a suitably weird equation of state ?

Can one avoid black hole formation with semi-classical quantum effects ?

Can one avoid black hole formation with “quantum gravity” ?

The possibilities are rather tightly constrained.



# Do black holes “exist” ?

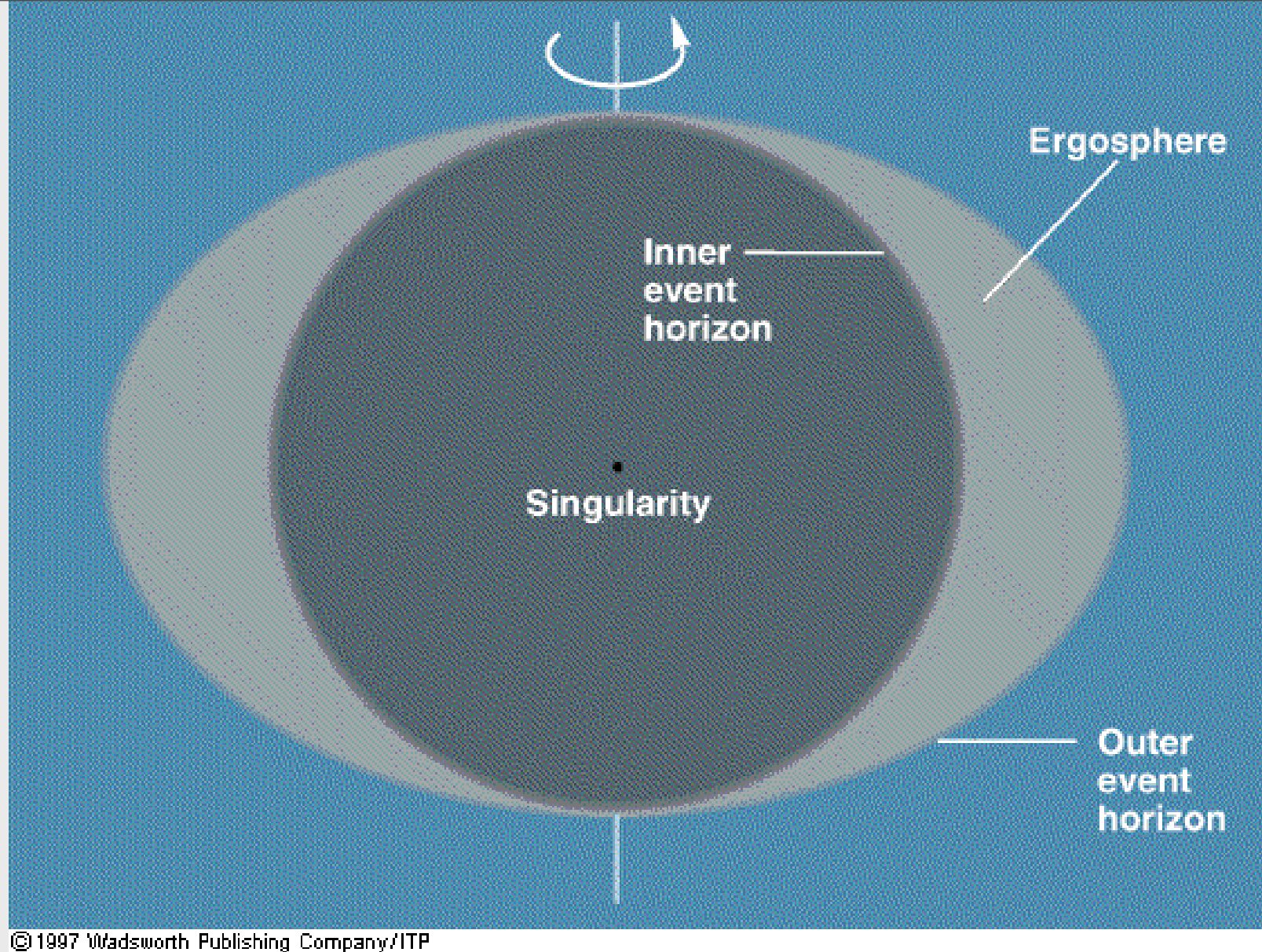
There is of course the utter gibbering crackpot fringe...

(Names suppressed to protect the guilty.)

“Physically reasonable” alternatives to black hole formation are counted on the fingers of one (severely mutilated) hand...

(For selected values of “physically reasonable”.)





(even the physics-challenged have  
access to graphics software...)

[Warning: The diagram above is utter gibbering nonsense.]



## Do alternatives “exist” ?

Quark stars, Q-balls, boson-stars?

Gravastars: Mazur--Mottola variants.

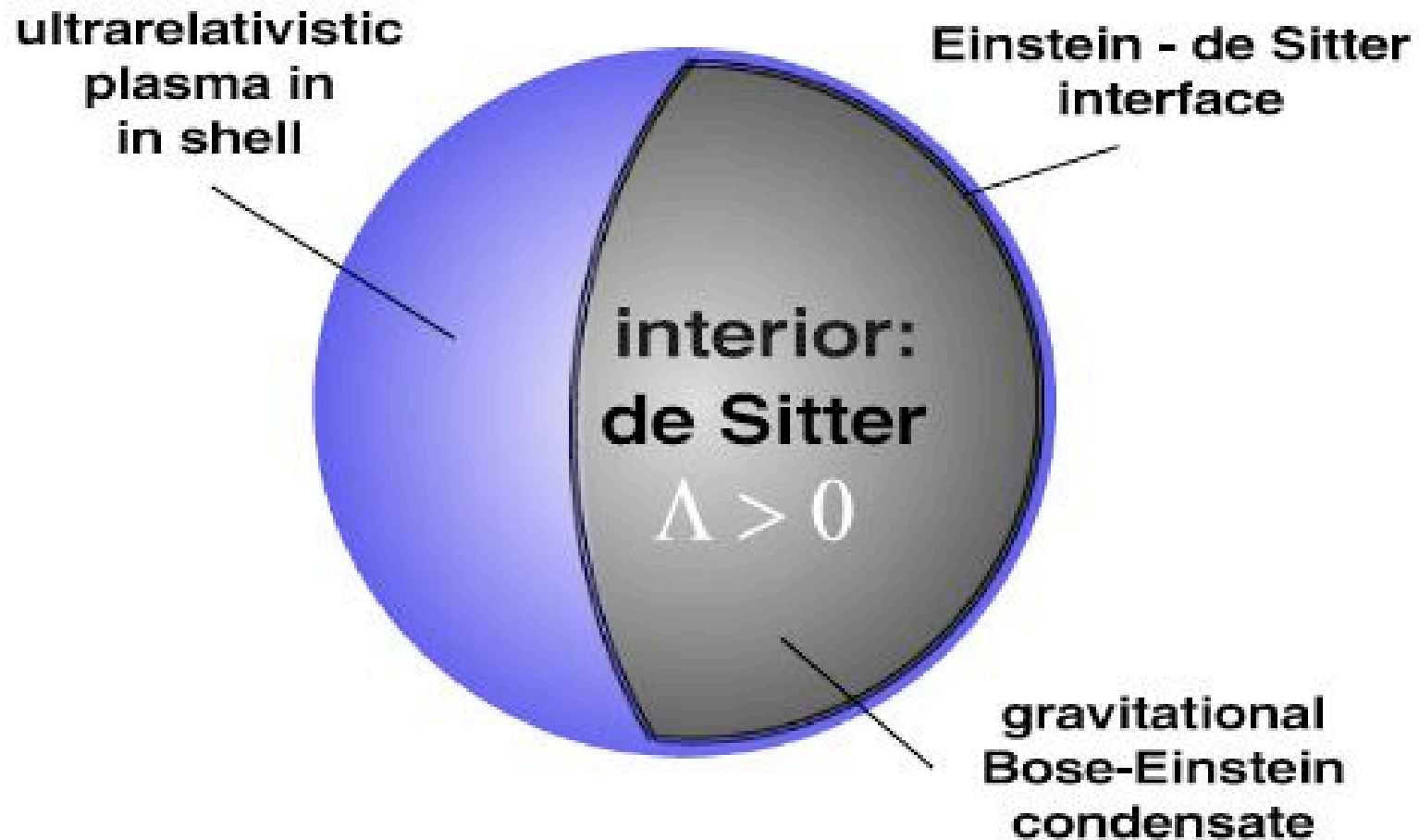
Gravastars: Laughlin-et-al variants.

Fuzz-balls: Mathur-et-al variant.

Fuzz-balls: Amati variant.

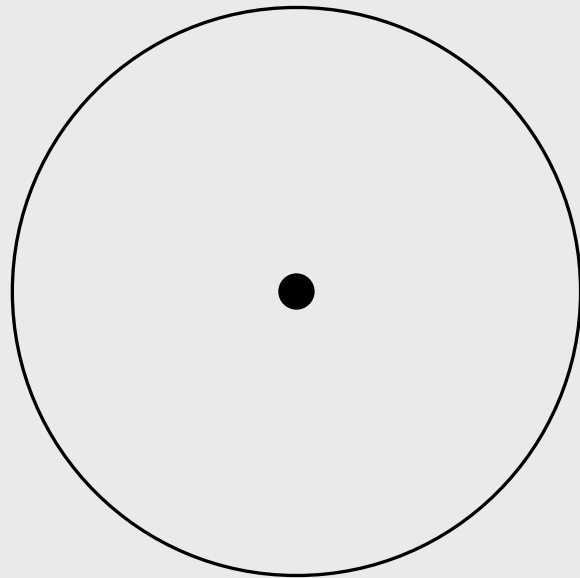
Need to reproduce standard GR up to the event horizon, and possibly slightly beyond...

# Gravastar

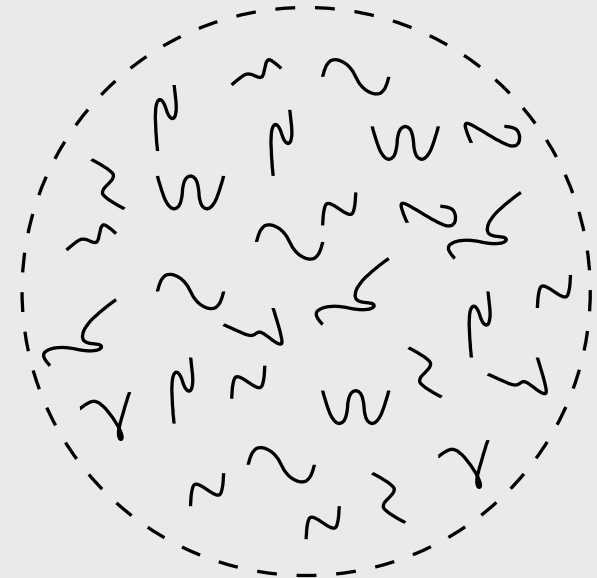


**exterior:** Schwarzschild vacuum  
*non-rotating*





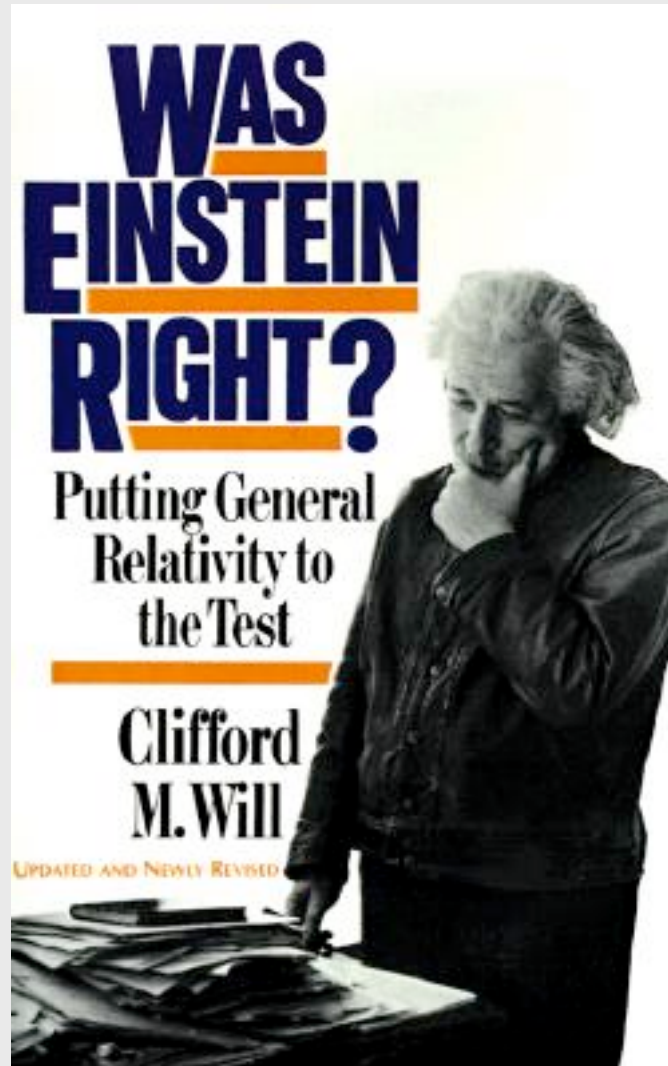
GR



Fuzz ball

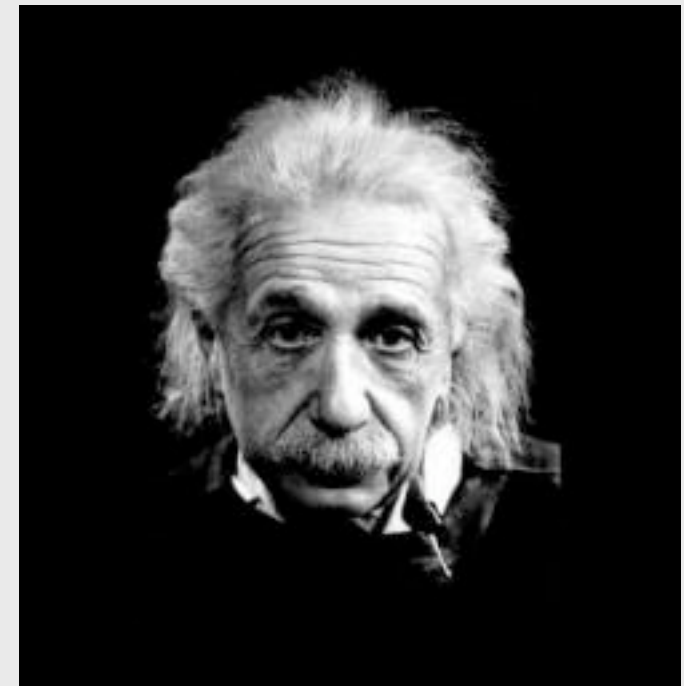


# Do black holes “exist” ?



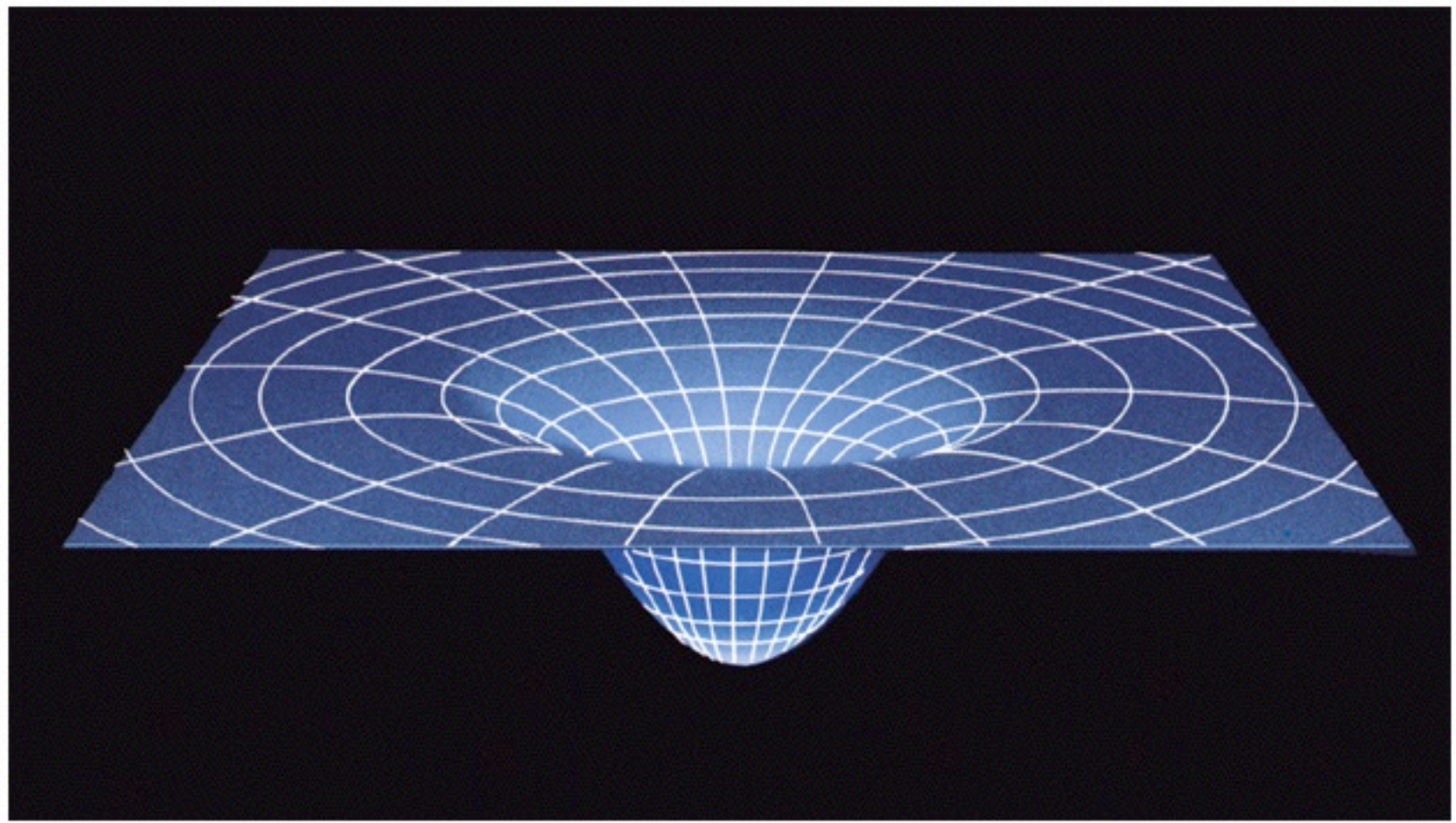


Yes...



Long answer: Standard special and general relativity are completely compatible with present day experiment...

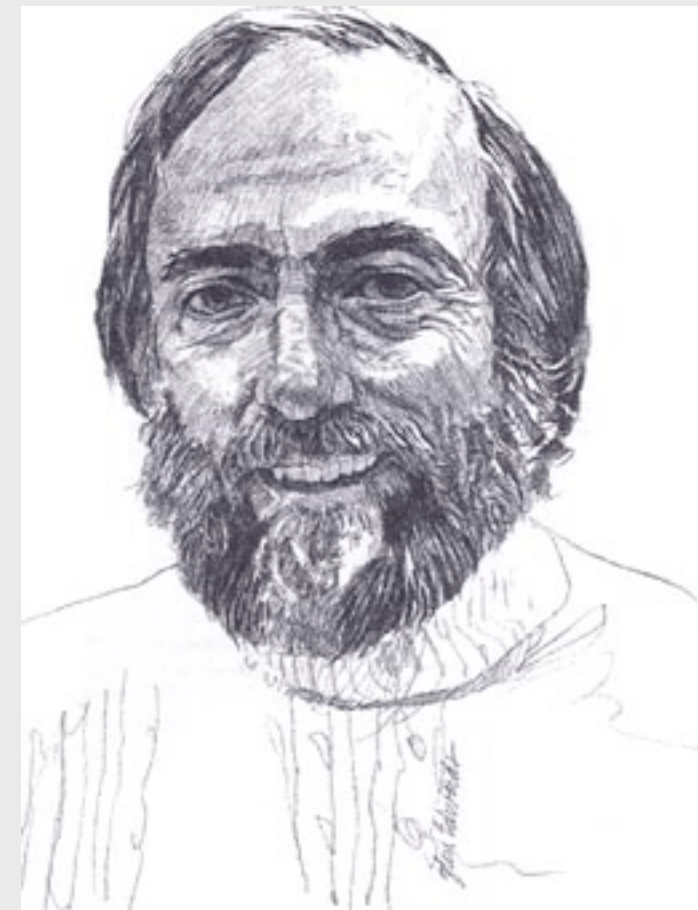
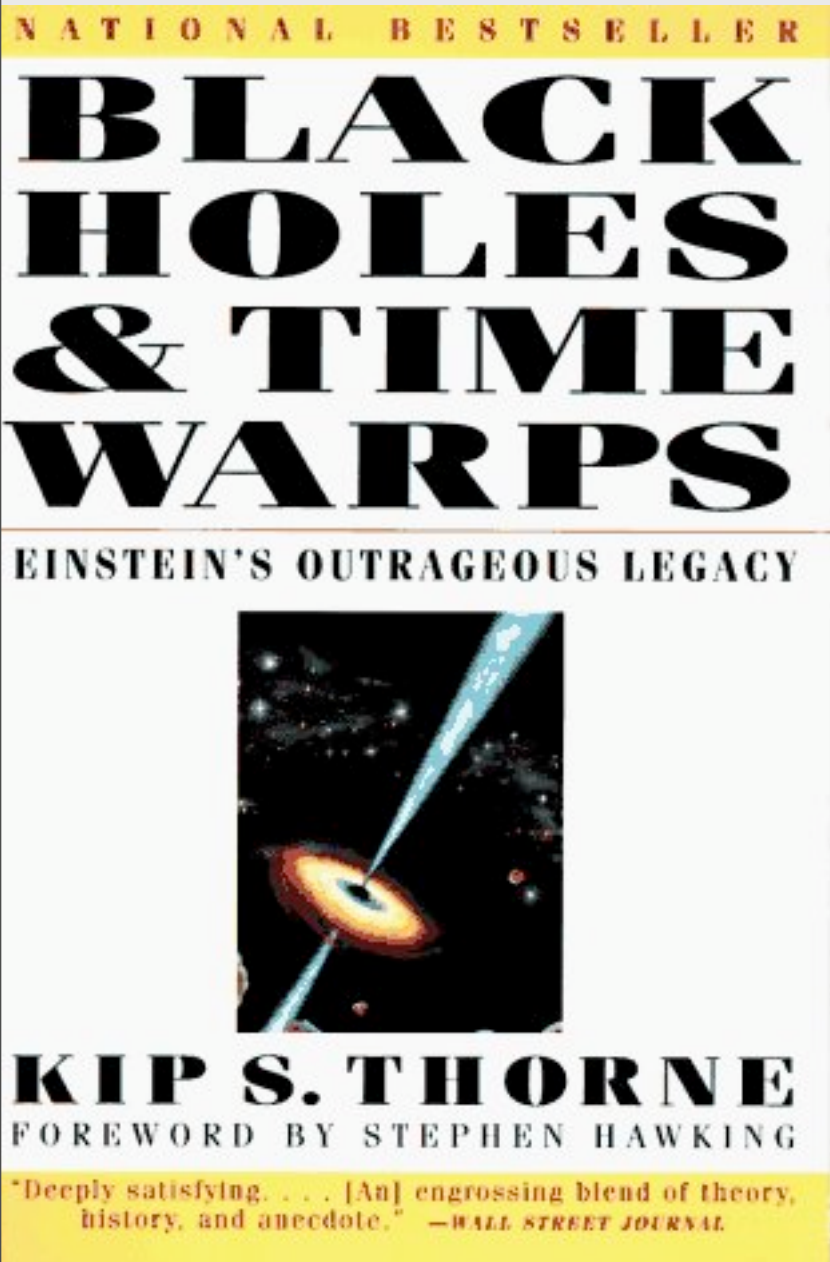




Spacetime curves --- in the manner Einstein predicted.



Some  
light reading:



[Kip S. Thorne](#)

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