Brightly Shining Black Holes

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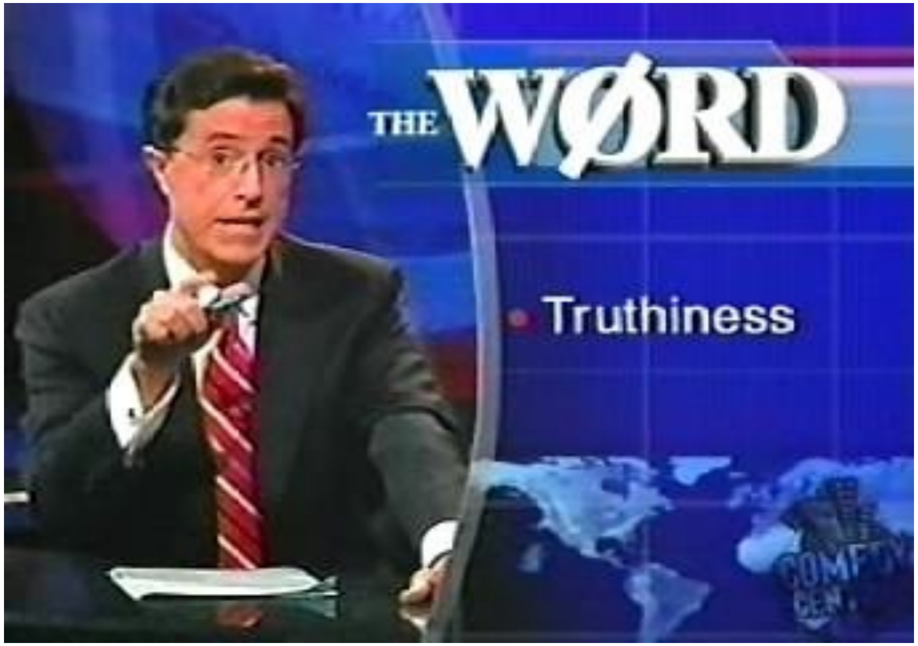
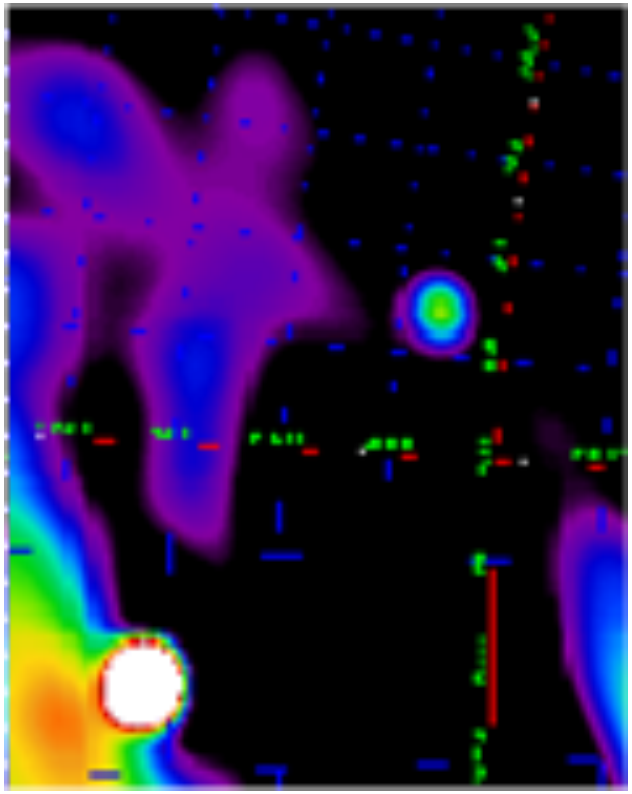
The Popular Picture of Black Holes

The darkest objects in the Universe

Popular View more "Truthy" than True



The Closest Real Black Hole
(6000 lt-yr from Earth)



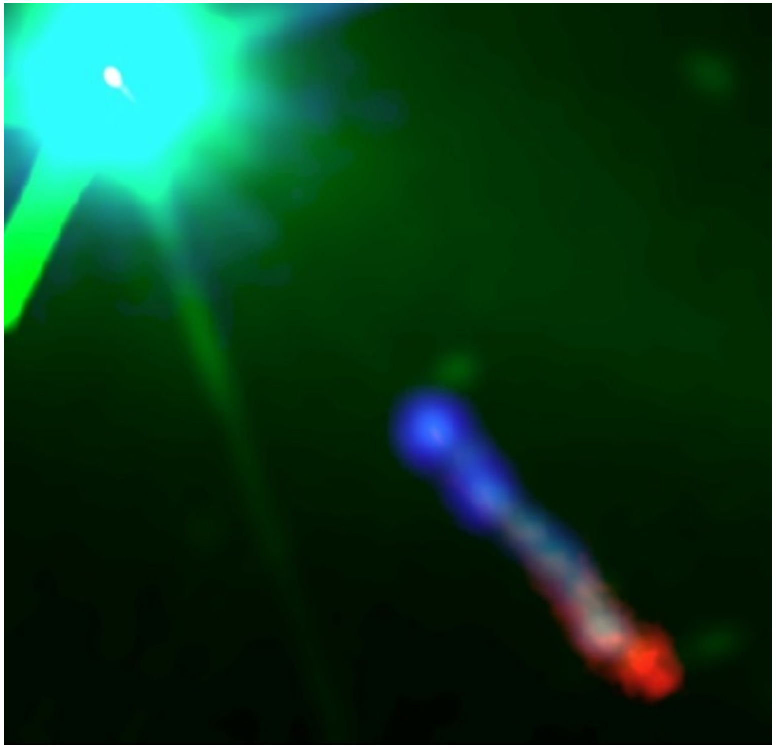
Cygnus X-1: false color X-rays

X-ray power ~10,000 x total Solar power

Mass ~10 Solar masses

A Distant Black Hole

(2 x 10^9 lt-yr from Earth)



3C 273: green = visible light

blue = X-rays

red = IR

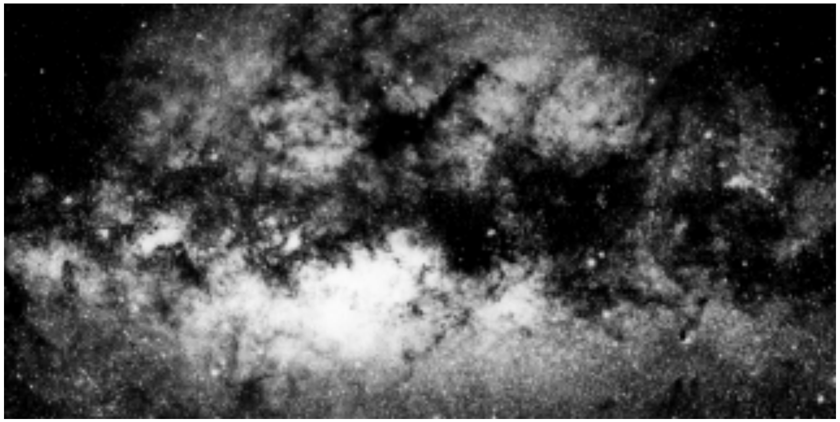
Total power (IR + visible + UV + X-ray) ~

1000 x total light power of our galaxy ~

10^{13} x total Solar power, Mass ~? 10^9 Solar masses

The Black Hole in Our Own Galaxy's Center

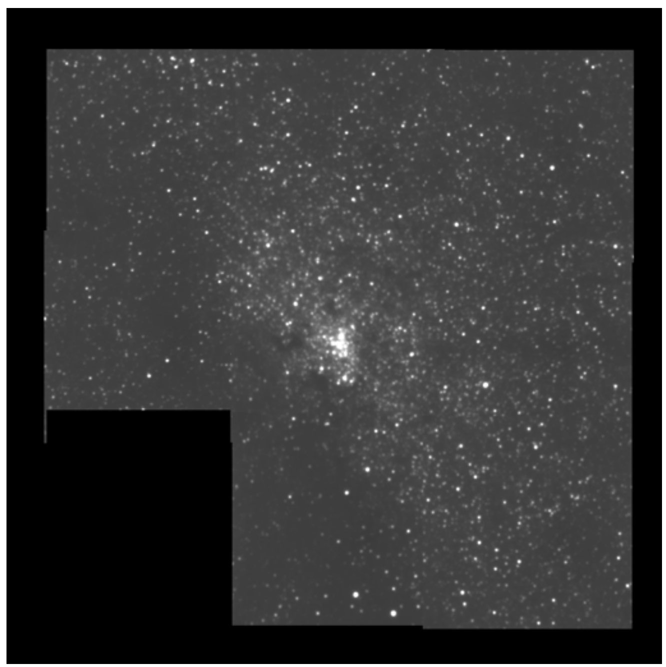
3000 light-years



visible light

3000 light-years

IR light

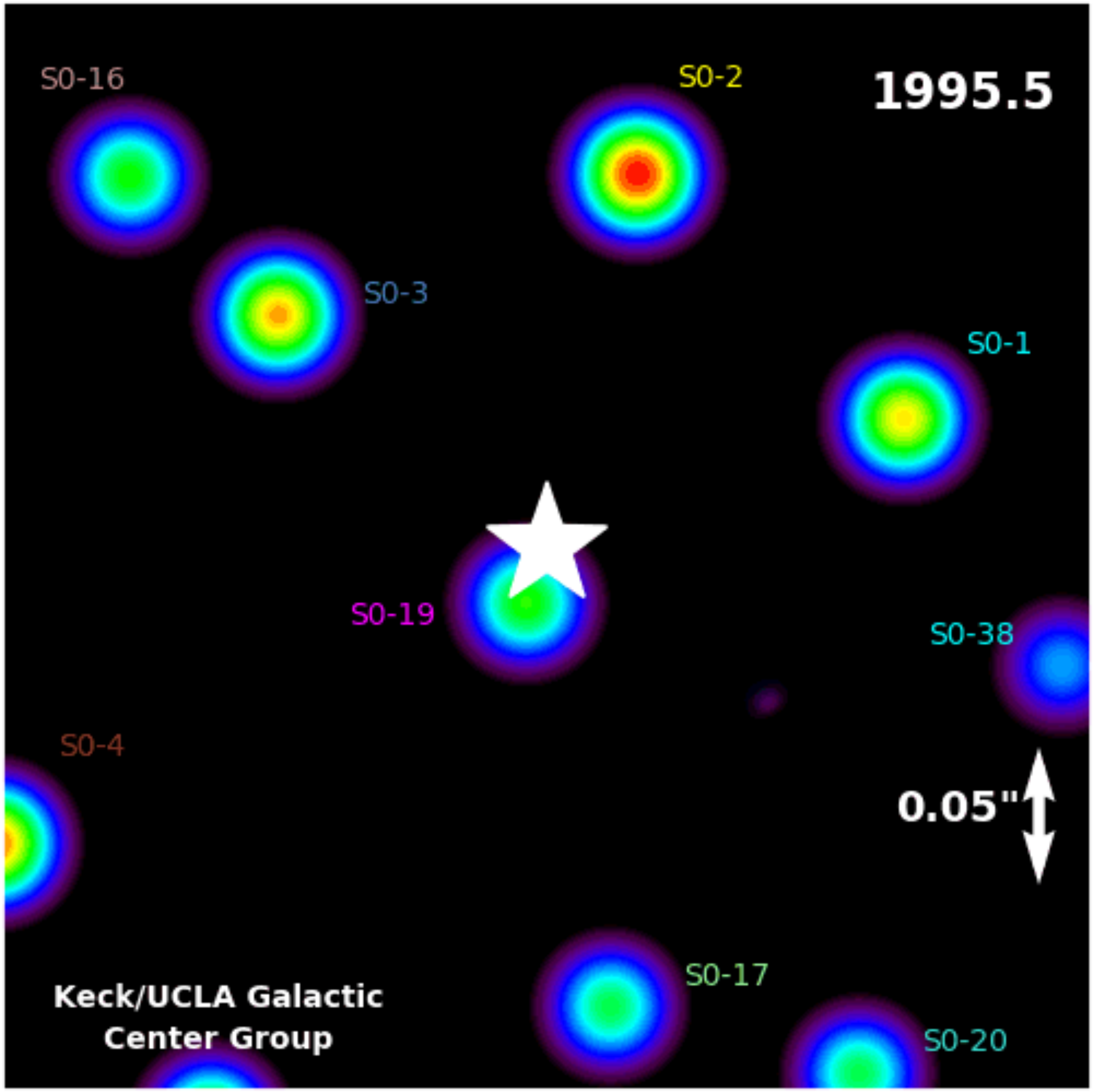


30 light-years

zoom to the star cluster at the center

Stellar Orbits Reveal the Mass at the Center

4 light-days
= 800 AU



M ~ 4 x 10^6 Solar masses

Ghez et al.,
cf. Genzel et al.

Why Are Some So Bright?

Energy Conservation under Gravity

James Joule (1818-1889)

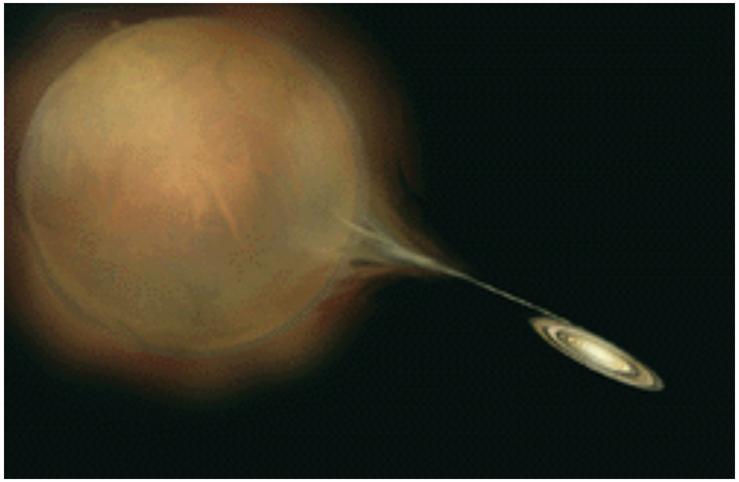
Objects falling under gravity change potential energy into kinetic energy

If they lose that kinetic energy at the bottom, chances are it goes into heat

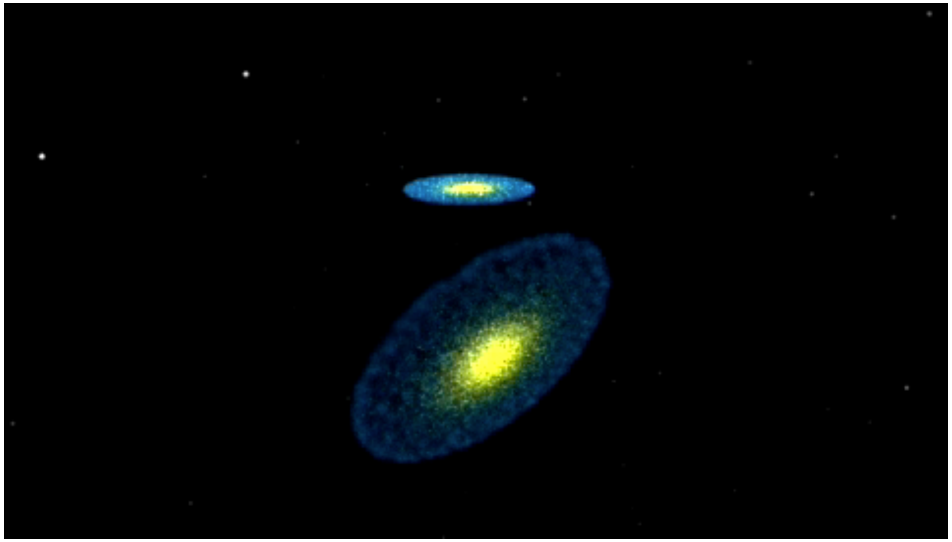
(an additional 0.8C at the bottom of Niagara Falls)

How Is Mass Delivered to a Black Hole?

Option 1: in a stellar binary (like Cyg X-1), through tidal action

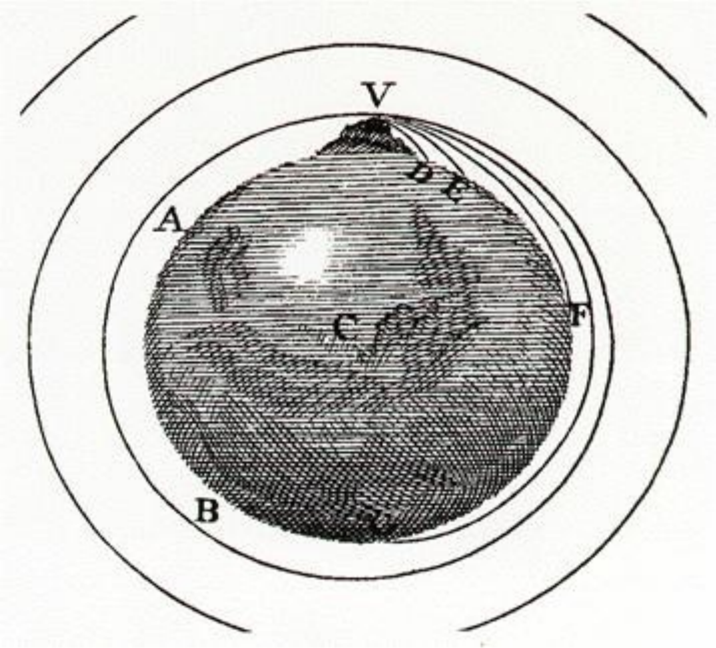


Option 2: in a galactic center, from capturing interstellar gas: maybe from a galactic collision?

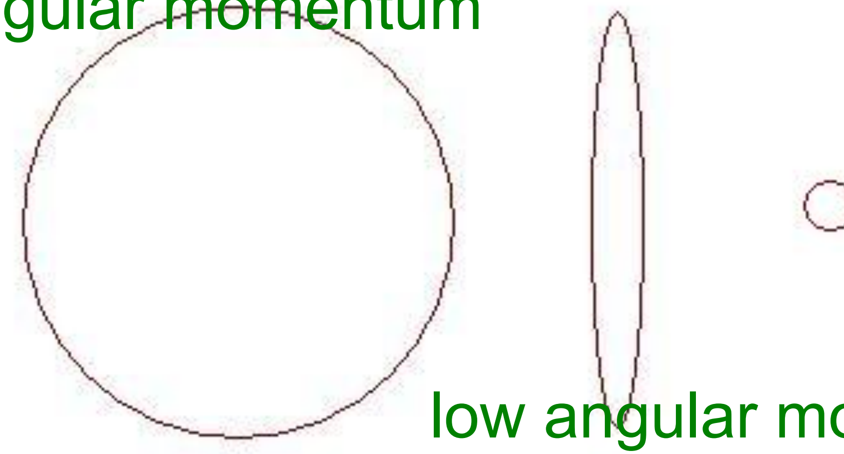


How Do Objects Fall into Black Holes?

Far from a black hole, orbits are just like Newton described them



Orbits Governed by Conserved Quantities: Energy and Angular Momentum



But Very Tight Orbits Are Different

In Newtonian gravity, circular orbit $v = (GM/r)^{1/2}$

implies $v = c$ when $r = GM/c^2$

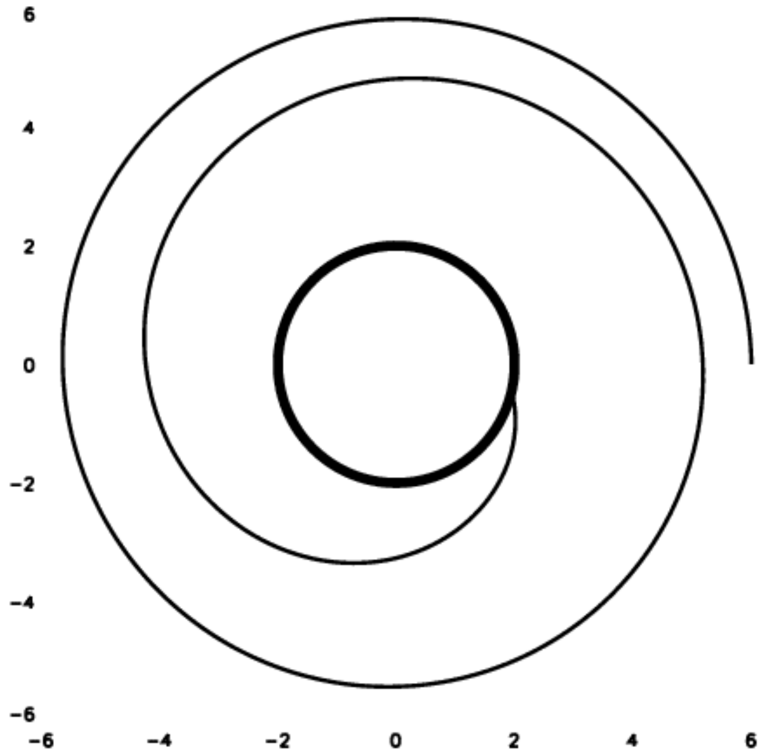
Call GM/c^2 the "gravitational radius"

$r_g = 1.5$ (M/Msun) km

Einsteinian gravity (general relativity) becomes important when r gets close to r_g

Inside a few r_g, gravity is so strongly non-Newtonian that its inward force overwhelms rotational motion

No Stable Circular Orbits Too Close to a Black Hole!



When the black hole doesn't rotate, the critical radius is 6 r_g, and the edge of the black hole is at 2 r_g

How Does Gas Lose Energy And Angular Momentum?

Light can carry away energy, but little angular momentum

So to get to small radius means losing angular momentum:

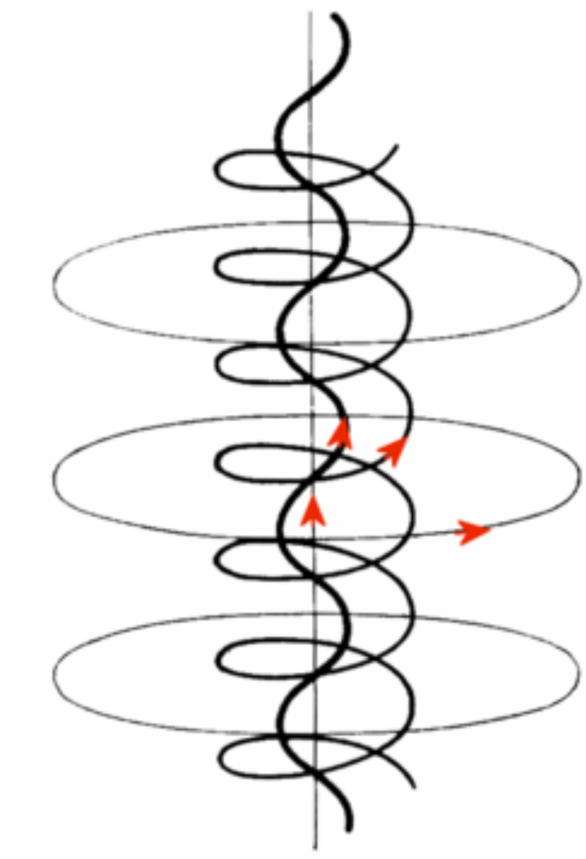
But how?

Magnetic “Rubber Bands”

Charged particles can only orbit around magnetic fieldlines, not cross them.

So ionized gases likewise cannot cross magnetic fieldlines.

Ionized gases (or any good electrical conductor) are said to be “frozen to the magnetic fieldlines”.



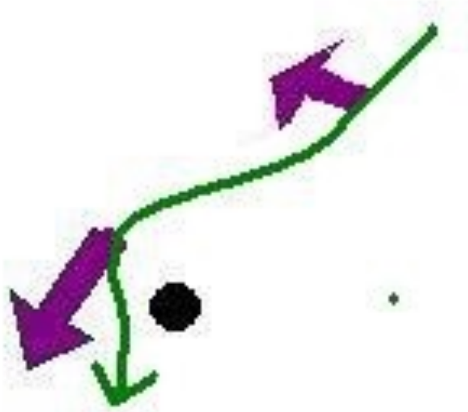
Origin of Magnetic "Tension"

Magnetic fields possess energy: energy density increases with intensity

Stretching field at constant field intensity increases field energy, requiring work =>

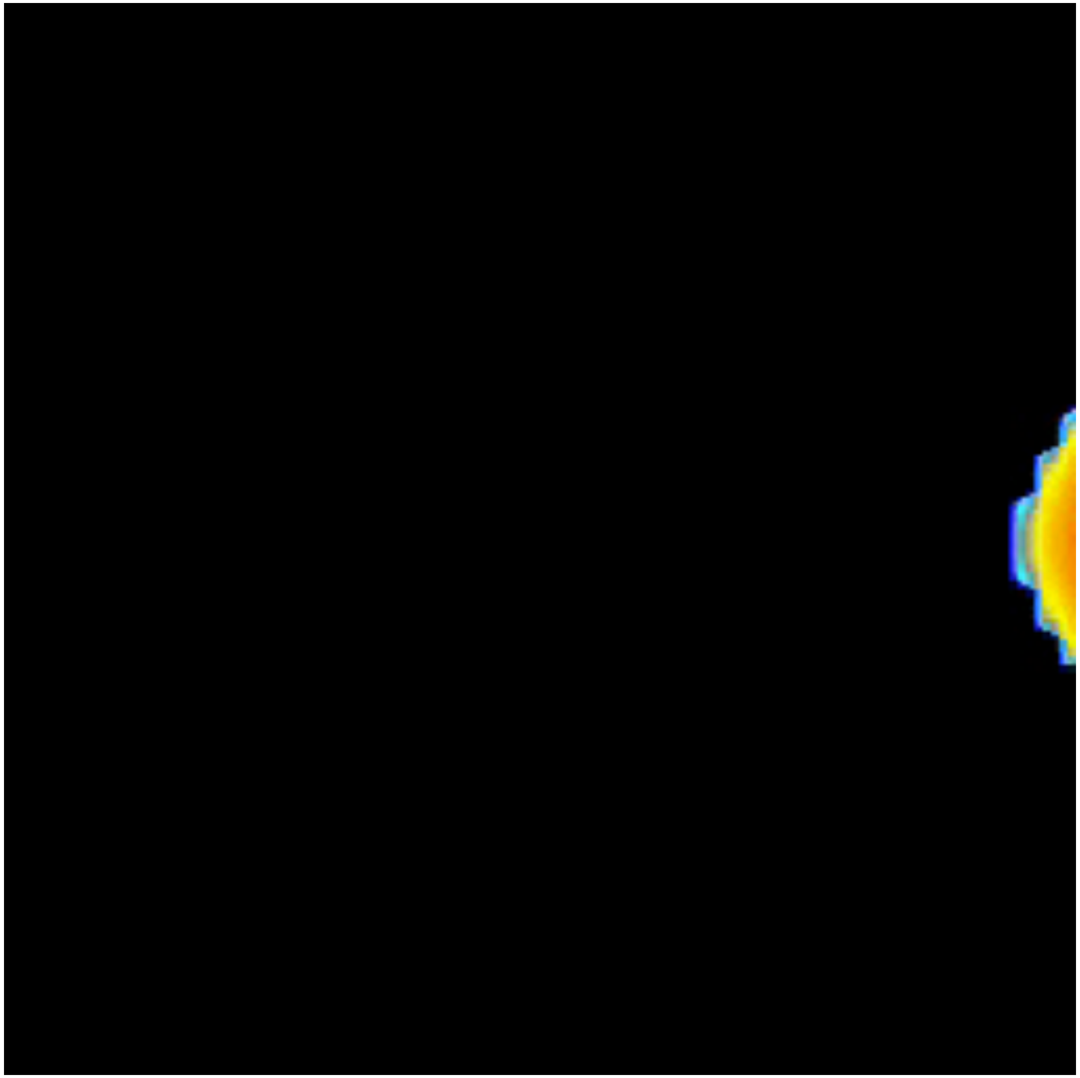
tension

Mix Magnetic Tension with Orbital Shear



Result: inner fluid slowed down, outer fluid accelerated

Net Result: Turbulence and Inflow



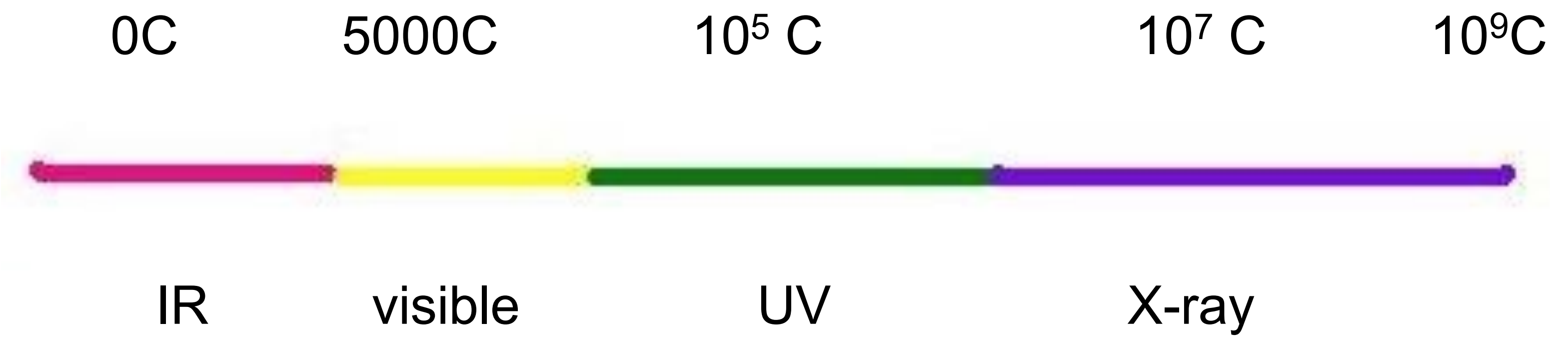
Turbulence Dissipates into Heat

Gravitational potential energy available from falling close to a black hole:

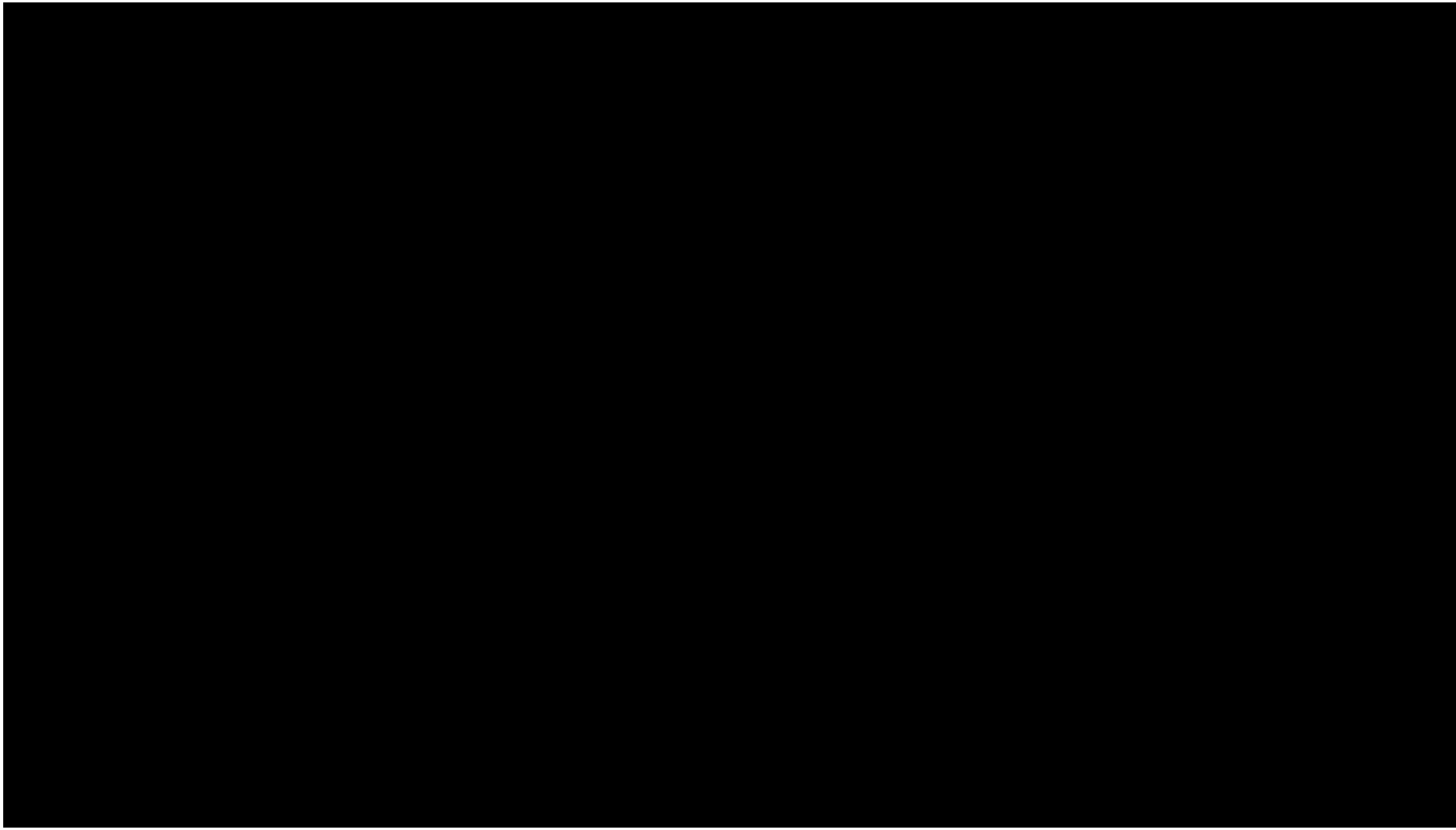
the equivalent of 10^{12} C!

Cf. the Sun's surface temperature, 5200 C.
In practice, radiative cooling keeps the temperature near black holes down to merely 10^5 – 10^7 C (except for where it rises to 10^9C!)

Heat Makes Light

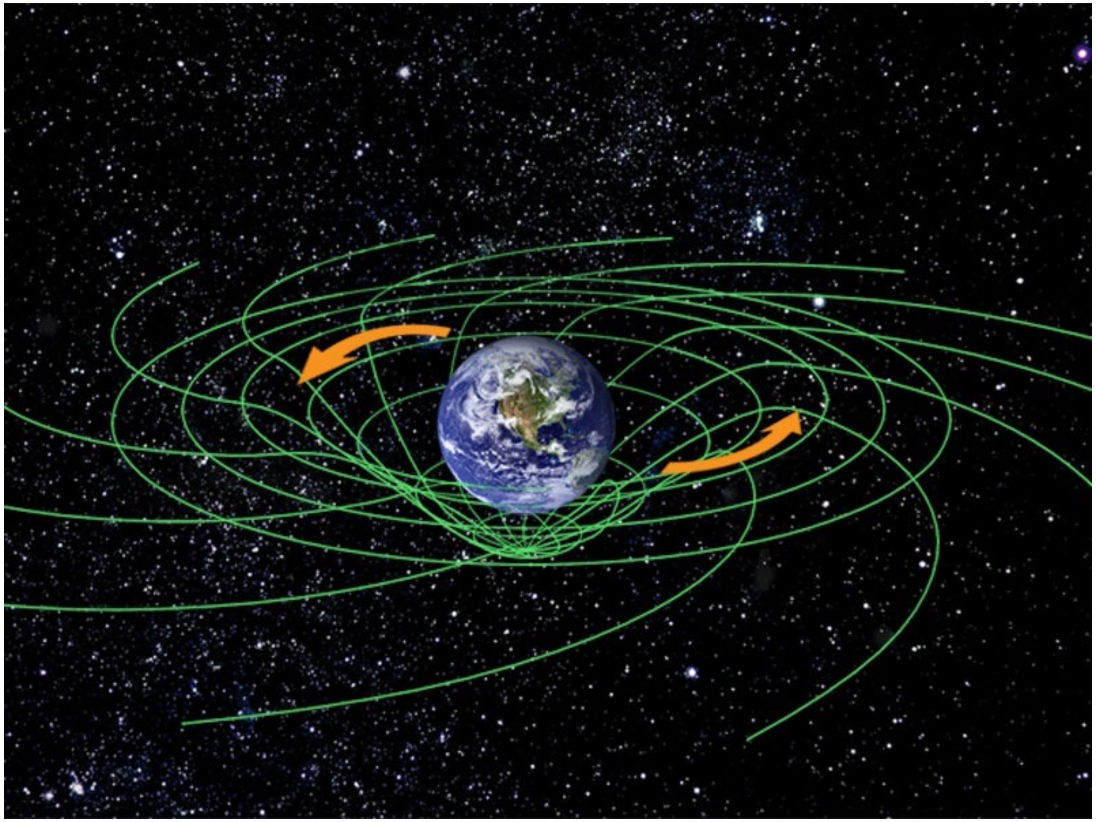


An Animated Black Hole Map

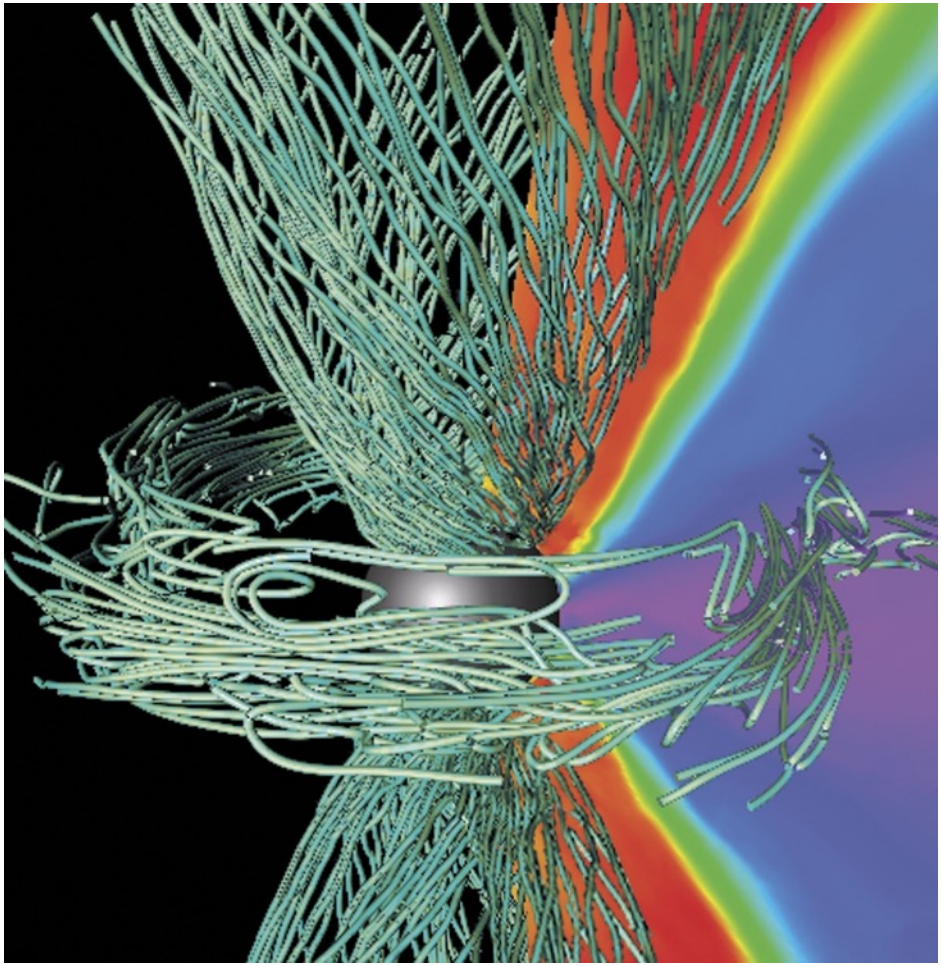


With a Special Twist for Spinning Black Holes

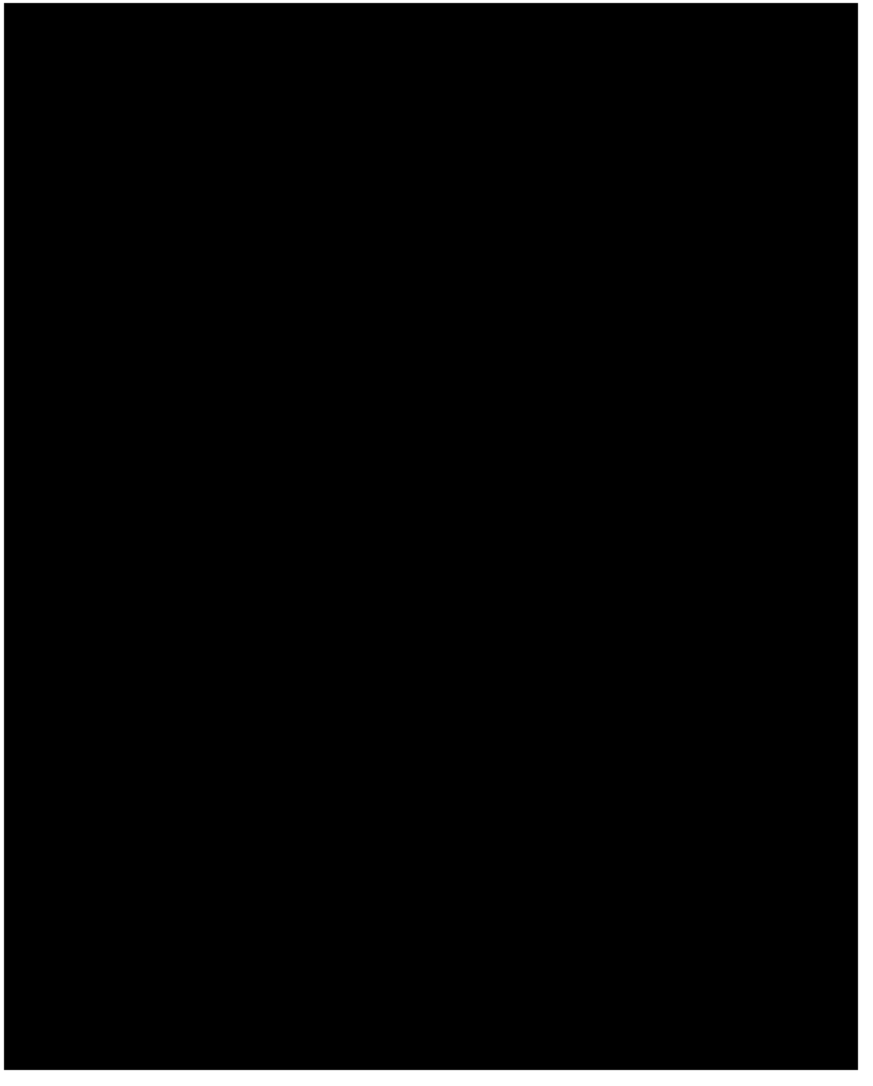
Rotating masses force nearby spacetime to rotate with them



Making the Magnetic Field Rotate

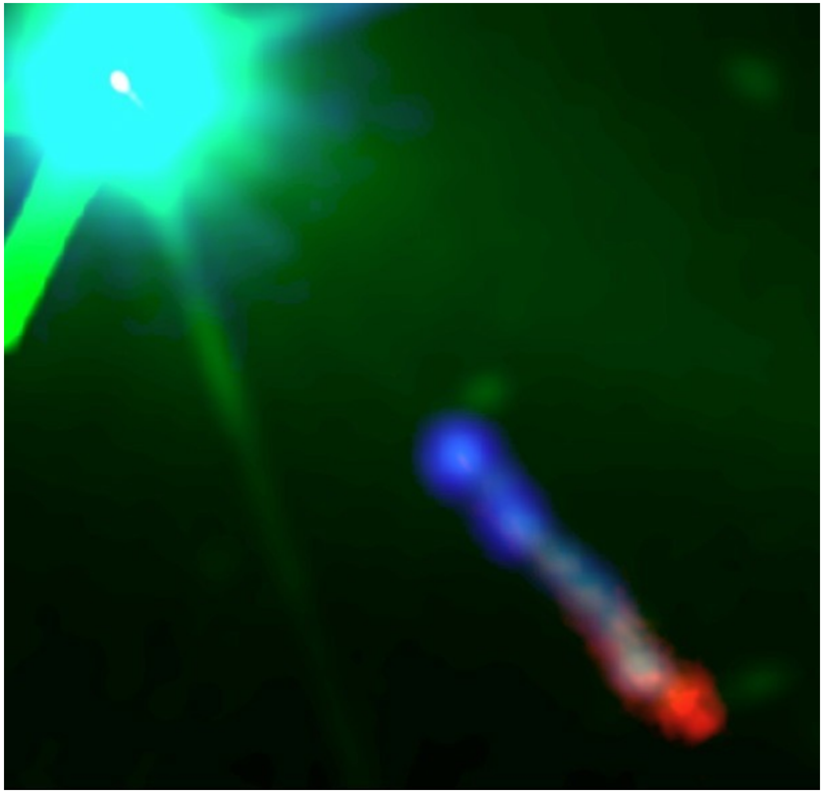


And Driving a Relativistic Jet

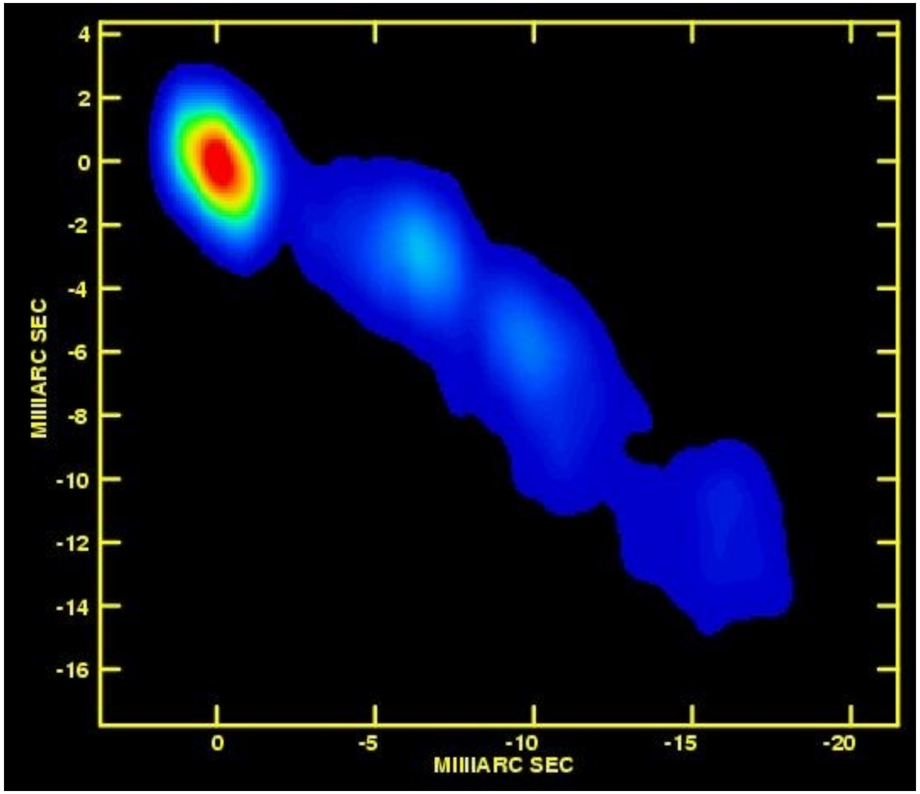


As in 3C 273

visible/X-ray/IR

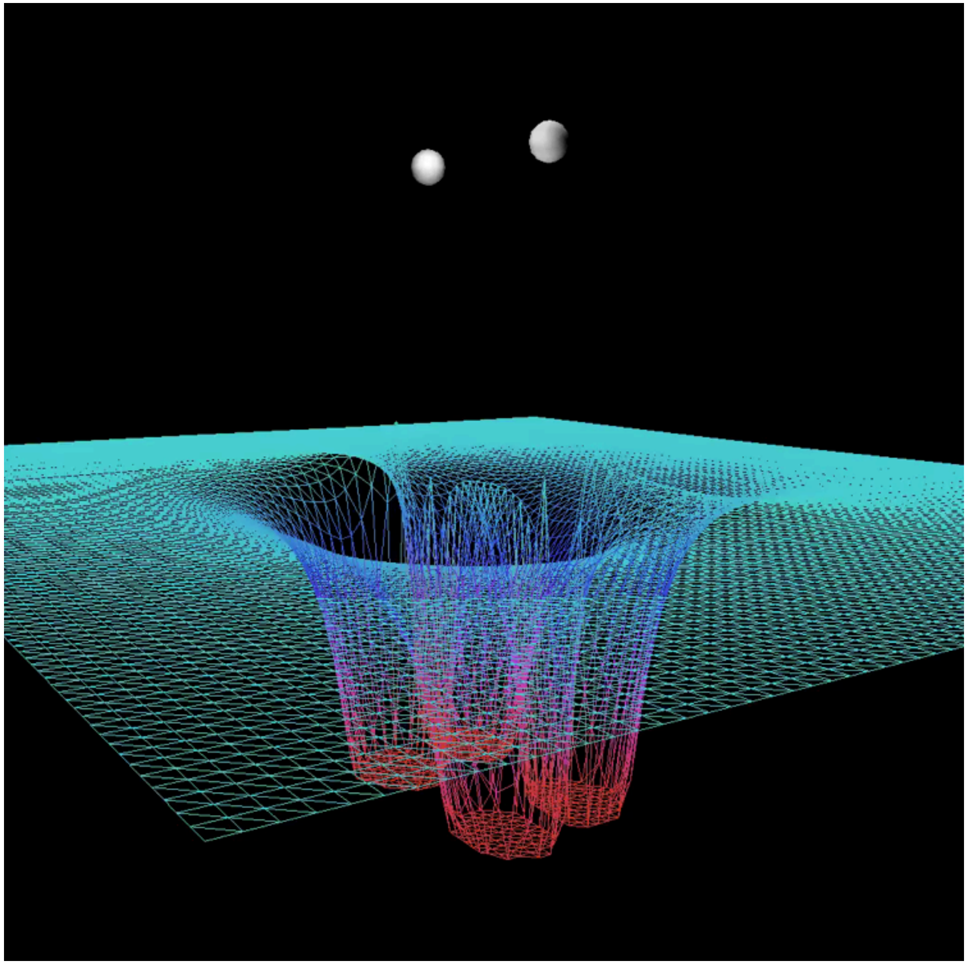


radio



Little peaks in radio brightness move outward at ~9c!

A New Kind of Brightness: Gravitational Waves

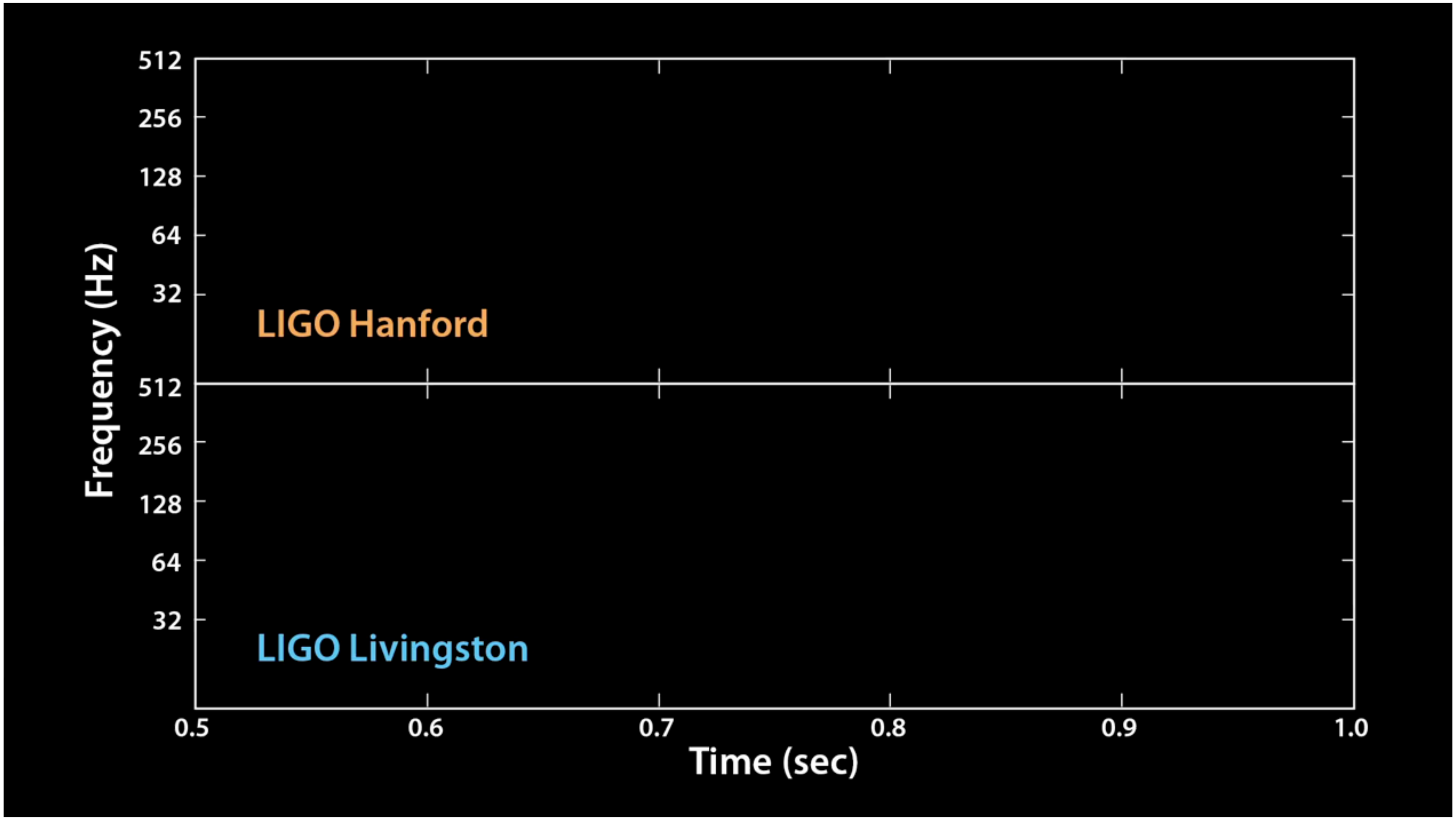


Accelerating mass-energy stirs spacetime; binary black hole mergers are strong sources

Which Can Now Be Detected!

LIGO station, Livingston LA

Inside LIGO, Hanford WA


512
256
128
64
32
LIGO Hanford
512
256
128
64
32
LIGO Livingston
Frequency (Hz)
0.5
0.6
0.7
0.8
0.9
1.0
Time (sec)

Summary

- Black holes can be exceedingly bright!
- Power comes from matter falling under gravity

  Inflow made possible by magnetic fields
- High temperatures make energetic radiation
- Black hole spin twists space itself, creates jets
- Black hole mergers radiate gravitational waves!