ASTROPHYSICS

Black Hole

Event horizons, singularities, what falls in and what gets out, the observations that made them real, and a 10-question practice set with full solutions.

SUBJECT	LEVEL	INCLUDES
Physics	High school and early college	Practice set, answer key, revision sheet

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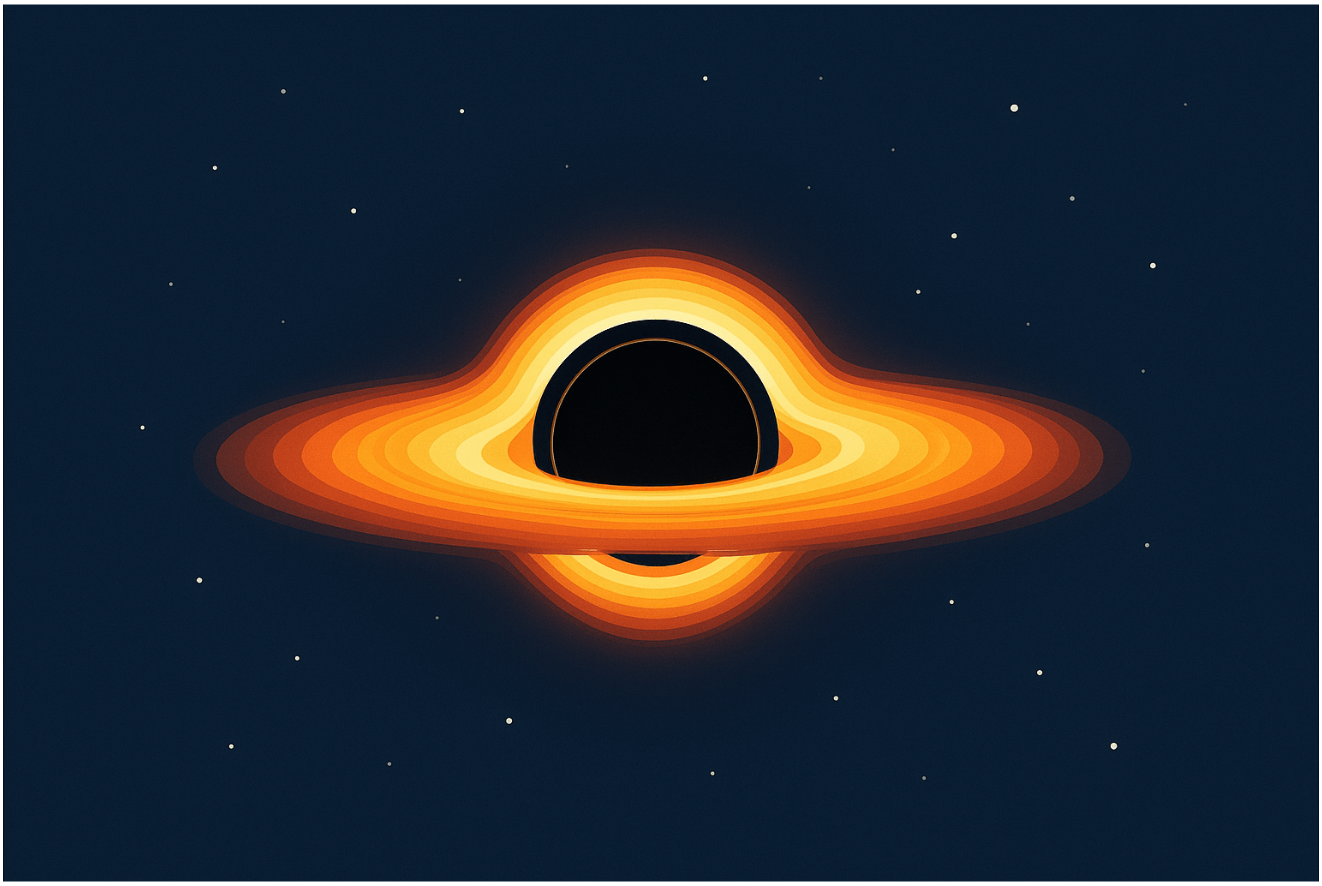
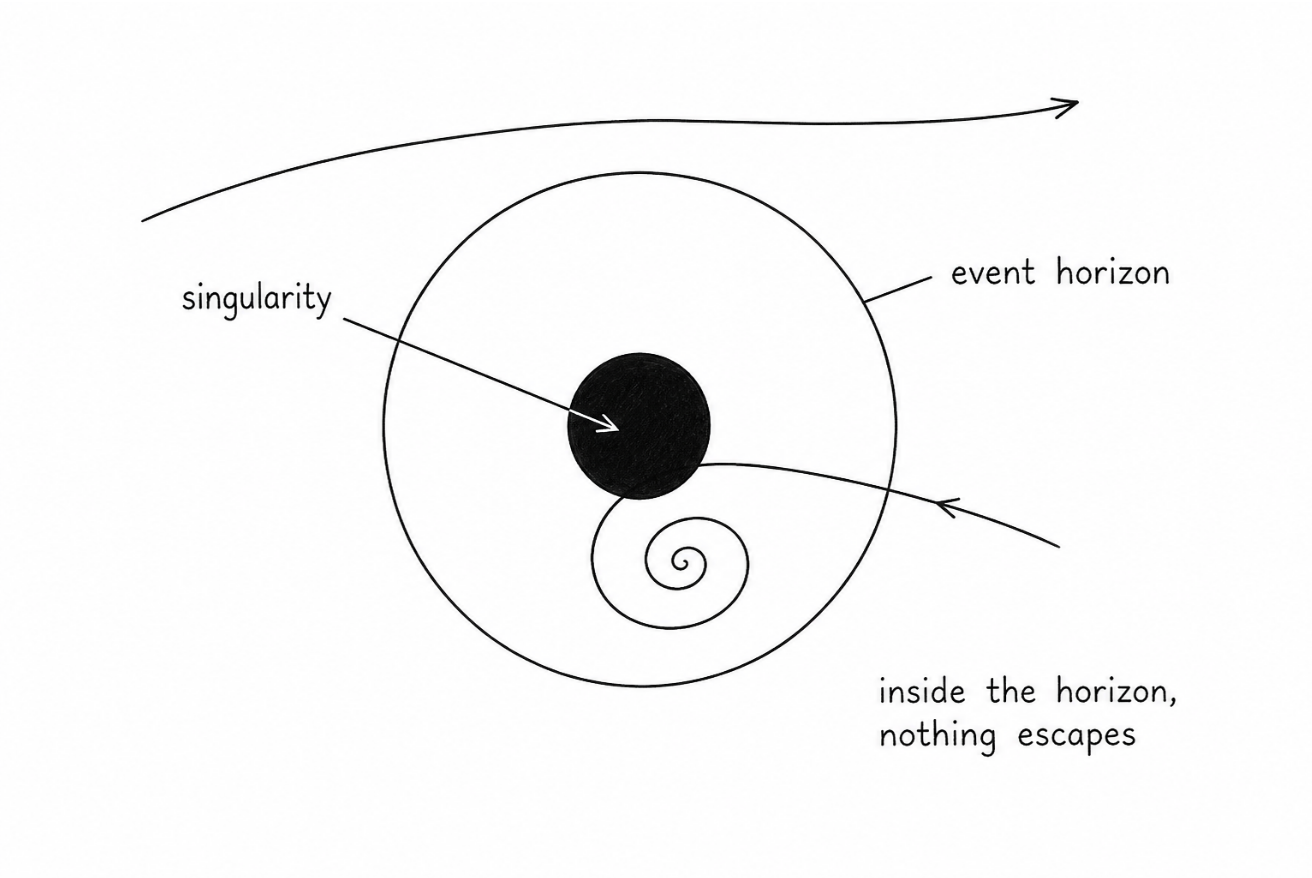
A black hole is a region of spacetime where gravity is so intense that nothing, not even light, can escape once it crosses the event horizon. A black hole forms when a massive star collapses at the end of its life, when two neutron stars merge, or (for the largest ones) through processes nobody fully understands yet at the center of galaxies. This note walks through what a black hole actually is, how it is structured, what the mathematics says, how astronomers detect them, and what the open questions in 2026 still are.



Anatomy of a black hole, singularity, event horizon, photon sphere, accretion disc.

What a Black Hole Is

A black hole is defined by a single property: an event horizon. The event horizon is the boundary inside which the escape velocity exceeds the speed of light. Because nothing can travel faster than light, nothing inside the horizon can ever leave. From outside the horizon, the black hole behaves like an ordinary gravitational mass. The strangeness only begins at the boundary.



The 2 features that define a black hole: the event horizon, the point of no return, and the singularity it hides.

The defining mathematical quantity is the Schwarzschild radius, the radius of the event horizon for a non-rotating black hole. It depends only on the mass:

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

Plug in numbers: for a black hole with the mass of the Sun $M_\odot \approx 1.989 \times 10^{30}$ kg, $r_s \approx 2.95$ km. That is, if the Sun were compressed into a sphere about 6 km across, it would become a black hole. For the Earth's mass, $r_s \approx 8.87$ mm. The mathematics is clean. The compression required is the hard part.

How a Black Hole Forms

Stellar-mass black holes (typically 5 to 50 solar masses) form when a star more massive than roughly 20 solar masses runs out of nuclear fuel. The core collapses under gravity, the outer layers blow off as a supernova, and what remains exceeds the Tolman-Oppenheimer-Volkoff limit (the mass beyond which neutron-degeneracy pressure cannot support the star). At that point gravitational collapse continues all the way to a singularity.

Intermediate-mass black holes (100 to 100,000 solar masses) are harder to explain. The current best candidates involve runaway mergers in dense star clusters or the leftover seeds of early massive stars. Direct detections of intermediate-mass black holes via LIGO-Virgo became possible only after 2019.

Supermassive black holes (millions to billions of solar masses) sit at the centers of most large galaxies, including our own. Sagittarius A* at the center of the Milky Way is about 4.3 million solar masses. How supermassive black holes grew so large so early in the universe is one of the major open questions in 2026.

Structure of a Black Hole

From the inside out, a non-rotating Schwarzschild black hole has three concentric regions worth naming.

Singularity

At the geometric center sits the singularity, where general relativity predicts the curvature of spacetime becomes infinite and the laws of physics, as we know them, stop describing the situation. The singularity is not a place inside space; it is a moment in the future of anything that crosses the event horizon. Quantum gravity should eventually replace the classical singularity with something finite, but we do not yet know what that something is.

Event Horizon

The event horizon at radius $r_s = 2GM/c^2$ is a one-way membrane. From outside, the horizon is the surface from which no information can ever reach the outside universe. Time dilation diverges at the horizon: a clock falling in appears to a distant observer to slow asymptotically to a stop and never quite reach the horizon, though the falling clock itself crosses cleanly without noticing anything locally peculiar.

Photon Sphere

At $r = 1.5\,r_s$, light can orbit the black hole on circular geodesics. The photon sphere is what gives Event Horizon Telescope images their iconic bright ring: photons whip around once or several times before escaping toward the camera. The 2019 image of M87* and the 2022 image of Sagittarius A* are the photon ring made visible.

Types of Black Holes

TYPE	MASS RANGE	ORIGIN	EXAMPLES
Stellar-mass	5 - 50 M☉	Collapse of massive star	Cygnus X-1, V404 Cygni
Intermediate	100 - 10^5 M☉	Star cluster mergers (theorized)	HLX-1 candidate
Supermassive	10^6 - 10^{10} M☉	Galactic center, unknown growth path	Sagittarius A*, M87*
Primordial	Tiny - planetary	Early universe (hypothesized)	None confirmed

Hawking Radiation

Stephen Hawking showed in 1974 that black holes are not perfectly black. Quantum field effects near the event horizon cause the black hole to emit a faint thermal radiation with temperature inversely proportional to its mass:

$$T_H = \frac{\hbar c^3}{8\pi G M k_B}$$

For a stellar-mass black hole this temperature is around 10^{-8} K, far below the 2.7 K cosmic microwave background. Stellar-mass black holes therefore absorb far more from the CMB than they radiate, and effectively never evaporate within the current age of the universe. A primordial black hole of about 10^{12} kg, however, would be evaporating right now and ending its life in a final flash. None has been observed.

How We Detect Black Holes

- **X-ray binaries.** A black hole in a binary system pulls matter from its companion star. The infalling gas heats to millions of kelvin and emits X-rays. Cygnus X-1 was identified this way in 1971.
- **Stellar orbits.** Stars orbiting an invisible massive object reveal the central mass. Andrea Ghez and Reinhard Genzel won the 2020 Nobel Prize for tracking stellar orbits around Sagittarius A*.
- **Gravitational waves.** LIGO and Virgo detect the ripples in spacetime produced when two black holes merge. The first detection, GW150914, was announced in 2016 and earned the 2017 Nobel Prize.
- **Event Horizon Telescope.** A planet-scale very-long-baseline interferometry array imaged the photon ring of M87* (2019) and Sagittarius A* (2022). These are the first direct images of black-hole shadows.

Open Questions in 2026

Black-hole physics remains one of the most active areas of theoretical and observational physics. A short list of questions that remain unresolved:

- **Information paradox.** What happens to the information about matter that falls in? Unitary quantum mechanics says it must be preserved. Hawking radiation appears thermal and therefore information-free. Recent (2019 onward) calculations using the replica trick and quantum extremal surfaces suggest the information does come back, but the mechanism is not fully understood.
- **Singularity resolution.** What does the actual interior look like once quantum gravity is included? String theory and loop quantum gravity make different predictions; no observation can yet distinguish them.
- **Supermassive black hole origins.** JWST has revealed mature supermassive black holes at redshift 7+, less than a billion years after the Big Bang. The growth mechanism remains an open problem.
- **Firewalls and complementarity.** Is the equivalence principle violated at the horizon for an infalling observer? The AMPS firewall argument suggests yes; ER=EPR-type arguments suggest no.

Related study notes: Special Relativity, Einstein Field Equations, The Four Fundamental Forces.

Practice Questions

Work each question before reading its solution. The set runs from direct recall and substitution to the applied questions that exams actually use to separate grades.

Q1. Define a black hole and its event horizon.

SOLUTION

A region where gravity has curved spacetime so severely that no signal, light included, can escape from inside a boundary called the event horizon. The horizon is not a surface of material; it is a one-way causal boundary in spacetime. Crossing it is unremarkable locally, irreversible globally.

Q2. Compute the Schwarzschild radius for the Sun ($M = 2 \times 10^{30}$ kg) and for Earth (6×10^{24} kg).

SOLUTION

$r_s = \frac{2GM}{c^2}$. Sun: $\frac{2 \times 6.67 \times 10^{-11} \times 2 \times 10^{30}}{9 \times 10^{16}} \approx 3$ km. Earth: about 9 mm, a marble. Any mass has a Schwarzschild radius; a black hole is what exists when the mass actually fits inside it.

Q3. If the Sun were replaced by a solar-mass black hole, what would happen to Earth's orbit?

SOLUTION

Nothing. Outside the original solar radius the external gravitational field is identical: orbits depend on the mass, not on how compactly it is packaged. Black holes do not vacuum up their surroundings; they are only "inescapable" inside a few Schwarzschild radii. Earth would freeze in the dark, on exactly the same orbit.

Q4. How do stellar-mass black holes form, and what mass range do they occupy?

SOLUTION

When a star above roughly 20 solar masses exhausts its fuel, the core's collapse can no longer be halted by neutron degeneracy pressure, and it implodes past its own horizon while the envelope explodes as a supernova. The remnants observed run from about 3 to 150 solar masses, with LIGO's mergers filling in the census.

Q5. What sits at the centers of galaxies, and what is the evidence in our own?

SOLUTION

Supermassive black holes of millions to billions of solar masses. In the Milky Way, decades of infrared tracking showed stars whipping around an invisible point, Sagittarius A*, at up to 7,000 km/s, pinning 4×10^6 solar masses inside a Mercury-orbit-sized region; the work won the 2020 Nobel Prize, and the EHT imaged the object's shadow in 2022.

Q6. Describe spaghettification, and explain the surprising size-dependence of horizon tides.

SOLUTION

Tidal stretching: gravity on your feet exceeds gravity on your head, elongating you while compressing sideways. Tides scale as M/r^3, and since $r_s \propto M$, tidal force AT the horizon scales as $1/M^2$: a stellar black hole shreds you well outside its horizon, while at a billion-solar-mass horizon the tides are gentler than Earth's. Bigger is safer, briefly.

Q7. What is Hawking radiation, and why does it matter more in principle than in practice?

SOLUTION

Quantum field theory near the horizon lets black holes radiate as thermal bodies with $T \propto 1/M$, slowly evaporating. A solar-mass hole radiates at 10^{-7} K, colder than the cosmic microwave background, and would need 10^{67} years to evaporate: unobservably slow. Its importance is conceptual: it links gravity, quantum theory, and thermodynamics, and spawned the information-loss debate.

Q8. An astronaut falls in while you watch from far away. Compare the 2 accounts of the crossing.

SOLUTION

The astronaut crosses the horizon in finite time by their own clock, noticing nothing special locally. You see their signals slow, redshift, and dim asymptotically: they appear to freeze at the horizon, never quite crossing. Both accounts are correct; gravitational time dilation diverges at the horizon for the distant observer. Relativity permits different stories that never contradict in any shared measurement.

Q9. What did the Event Horizon Telescope photograph in 2019, and what exactly is the dark patch?

SOLUTION

M87's central black hole, 6.5×10^9 solar masses, imaged by a planet-wide radio interferometer. The dark region is the "shadow": the set of sky directions whose light paths end on the horizon, framed by the lensed glow of hot accreting gas. It is not a photo of the horizon surface but of its silhouette against the light behind and around it, matching general relativity's predicted size within 10%.

Q10. Could the LHC create a dangerous black hole? Answer with the physics.

SOLUTION

Any micro black hole it could conceivably make (only in speculative extra-dimension models) would weigh micrograms and, by Hawking's $T \propto 1/M$, evaporate in $\sim 10^{-27}$ s. More decisively, cosmic rays strike Earth's atmosphere daily at energies far beyond the LHC's and have for 4.5 billion years without incident. The planet's continued existence is the completed experiment.

Answer Key

QUICK ANSWERS

Q1 a no-escape region; the horizon is its boundary **Q2** ~3 km; ~9 mm **Q3** the orbit is unchanged; black holes don't suck **Q4** core collapse of massive stars; ~3-150 $M_\odot$ **Q5** Sgr A*: 4 million $M_\odot$, orbit-tracked and imaged

Q6 tides $\propto 1/M^2$ at the horizon **Q7** thermal evaporation, $T \propto 1/M$; negligible today **Q8** they cross; you see an eternal fade **Q9** M87*'s shadow ringed by lensed accretion light **Q10** no: instant evaporation, and cosmic rays already ran the test

Revision Sheet

The radius

$r_s = \frac{2GM}{c^2}$: 3 km per solar mass. Inside it, escape needs $v > c$.

Tides

$\propto M/r^3$, so horizon tides $\propto 1/M^2$: small holes shred sooner.

No vacuum cleaner

External orbits depend only on mass. Danger begins only within a few r_s.

Hawking

$T \propto 1/M$: real physics, negligible rate; solar-mass lifetime 10^{67} yr.

The census

Stellar (3-150 $M_\odot$, from collapse) and supermassive (10^6-10^9 $M_\odot$, galaxy centers).

Evidence

Star orbits at Sgr A* (2020 Nobel), LIGO mergers, EHT images of M87* and Sgr A*.

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