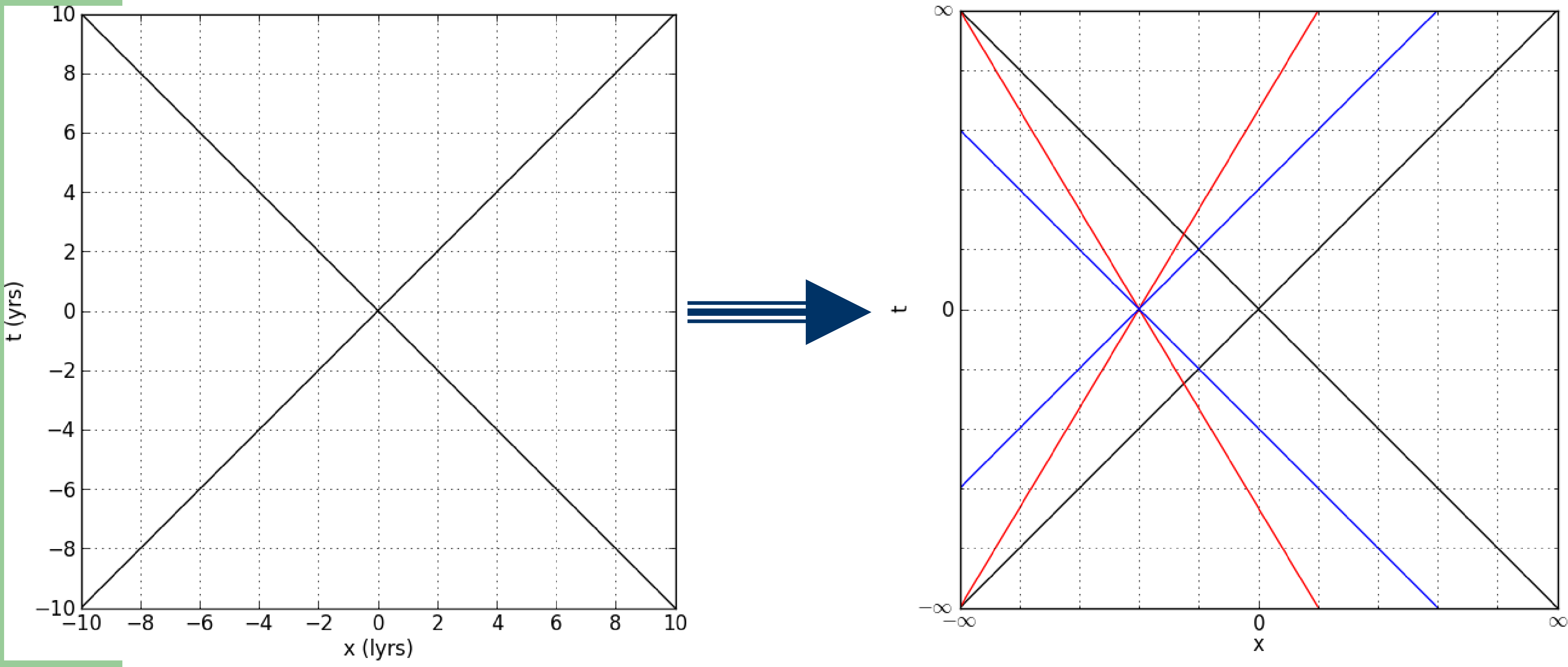
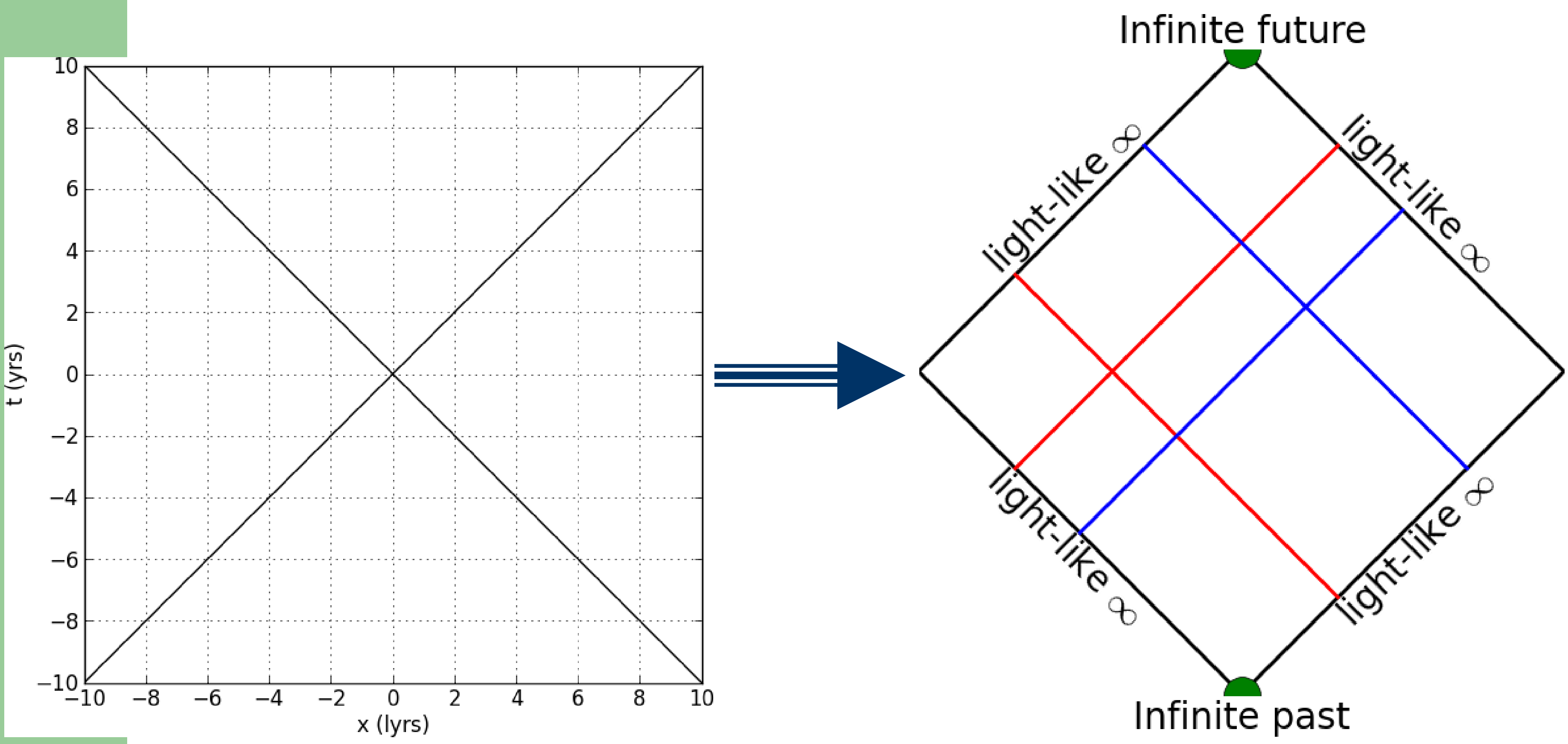
BlackHoles I

A Stopover: Conformal Diagrams

- In GR we care about the edges of space-time.



A Stopover: Conformal Diagrams



Conformal Diagrams: Rules

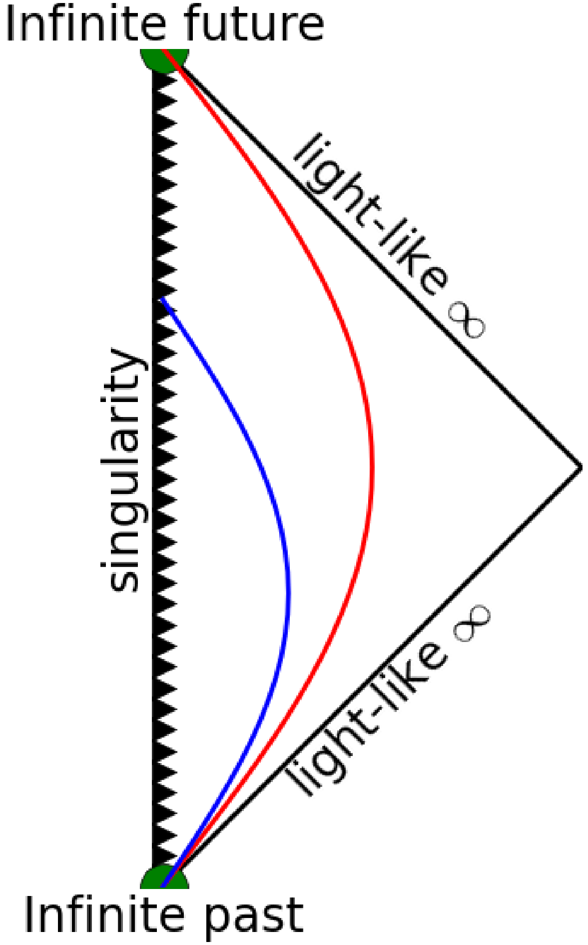
- Light-like world lines still go at 45^o.
- A complete (conformal) space-time diagram can have only infinities or singularities as boundaries.
- Infinities are always light-like, i.e. they run at 45^o.
- Singularities are either exactly vertical (purely time-like) or exactly horizontal (purely space-like).

Conformal Diagrams: Rules

- All time-like or space-like world lines begin and end at the intersection of infinities or at singularities.
- All light-like world lines that connect intersections of infinities with singularities are called *horizons*.

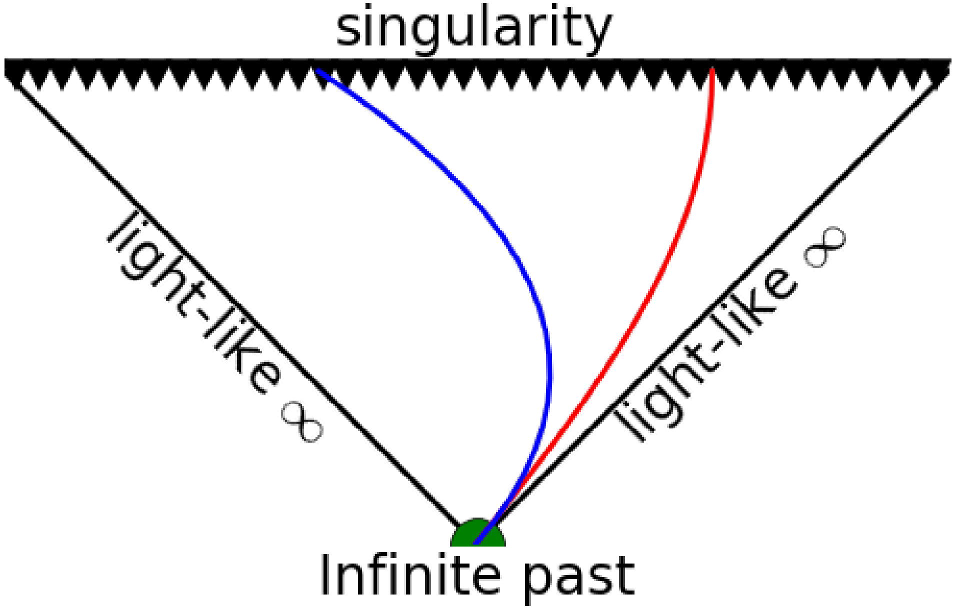
Conformal Diagrams: Examples

- Watch-your-step Universe

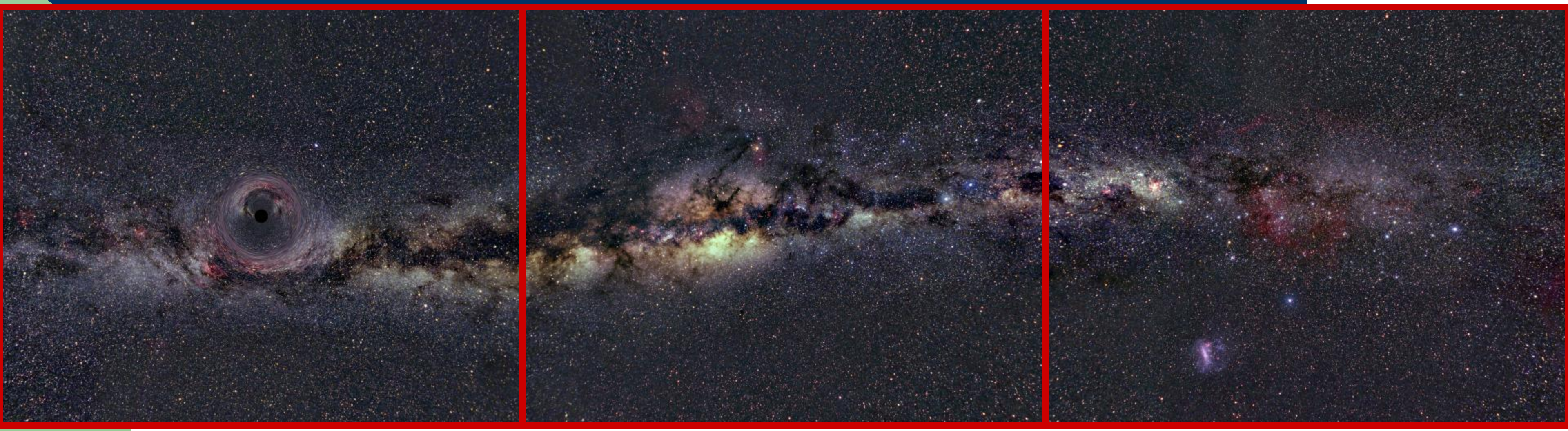


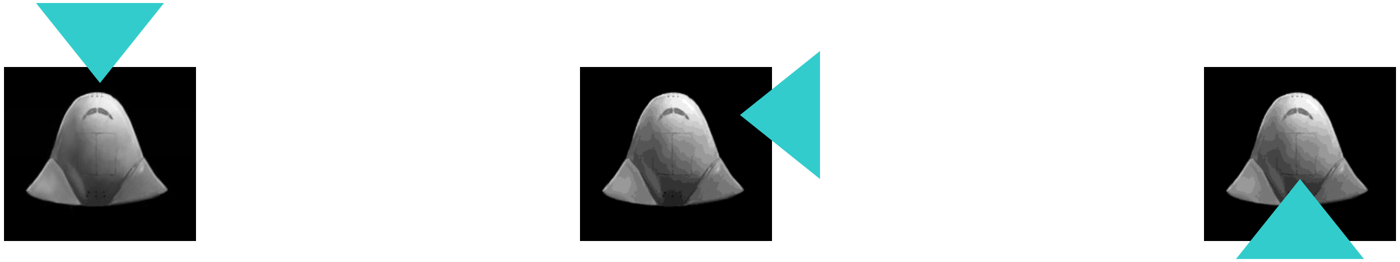
Conformal Diagrams: Examples

- Armageddon Universe

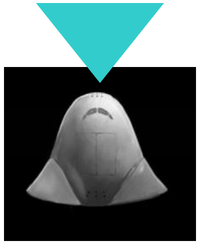


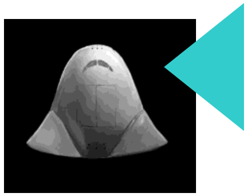
Falling into a Black Hole: 100 R_s

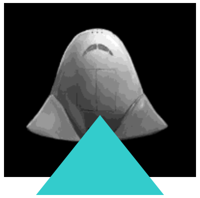




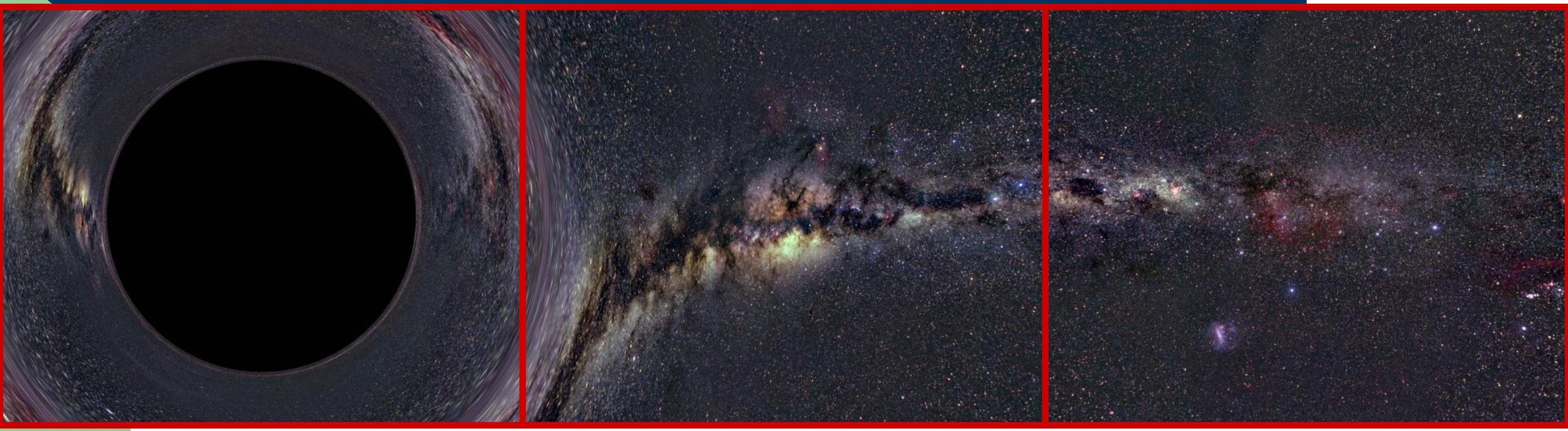
Falling into a Black Hole: 20 R_s

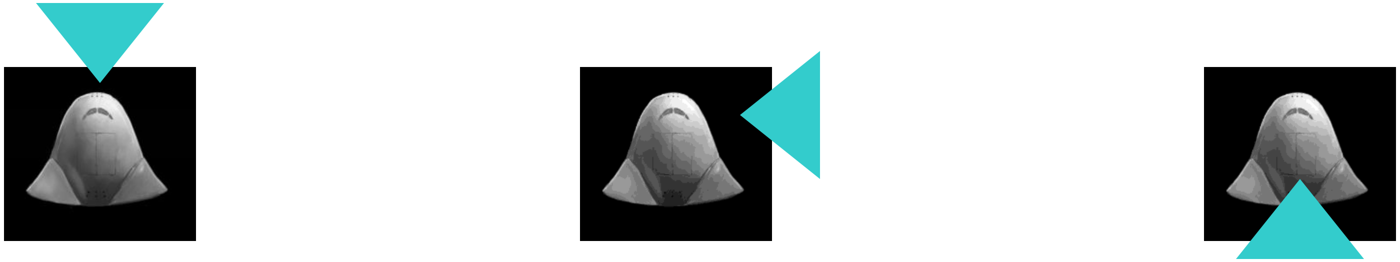




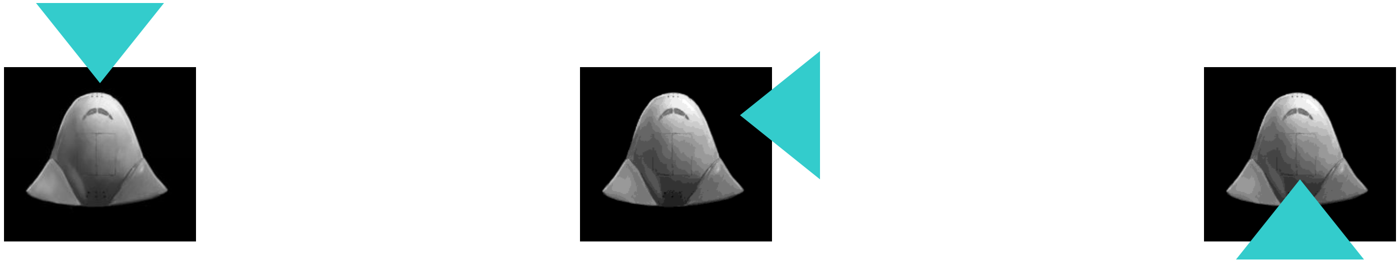


Falling into a Black Hole: 4.5 R_s

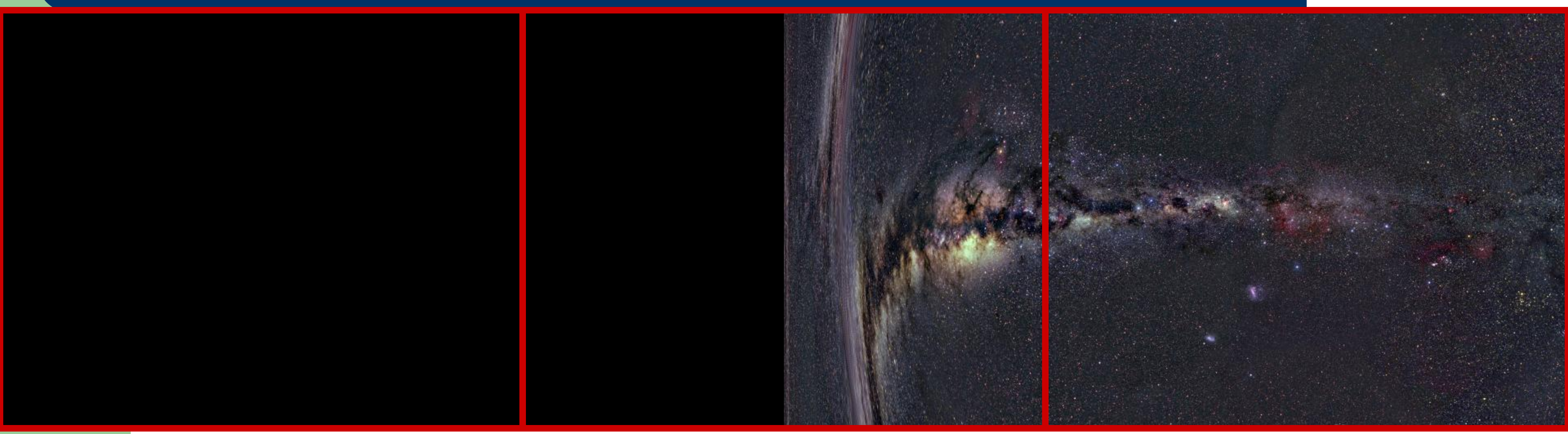


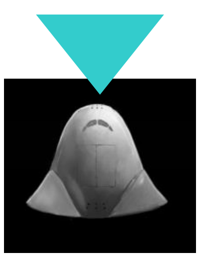


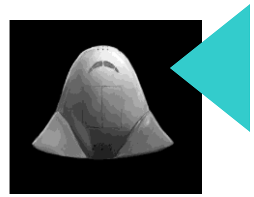
Falling into a Black Hole: 2.5 R_s



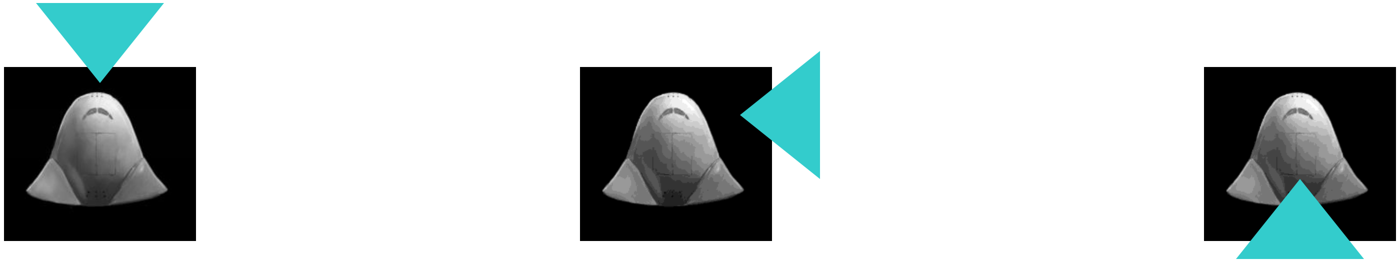
Falling into a Black Hole: 1.5 R_s



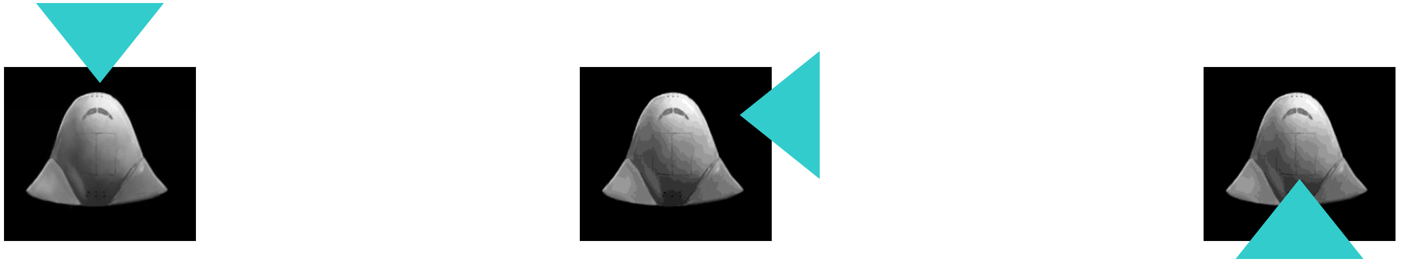




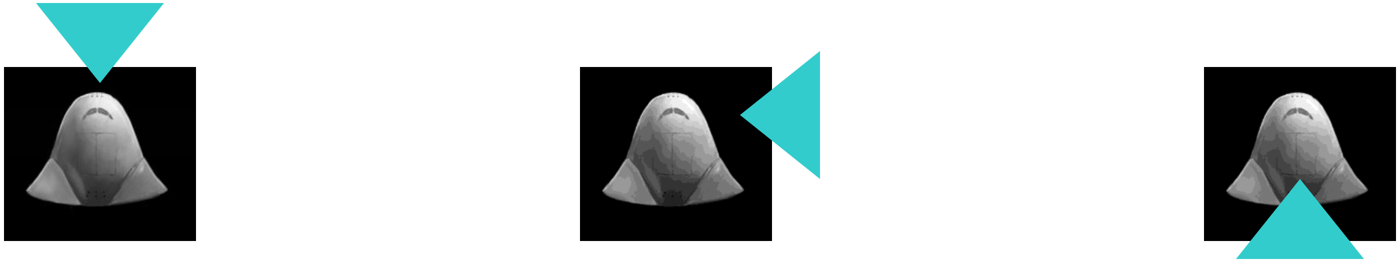
Falling into a Black Hole: 1.2 R_s



Falling into a Black Hole: 1.05 R_s



Falling into a Black Hole: 1.005 R_s

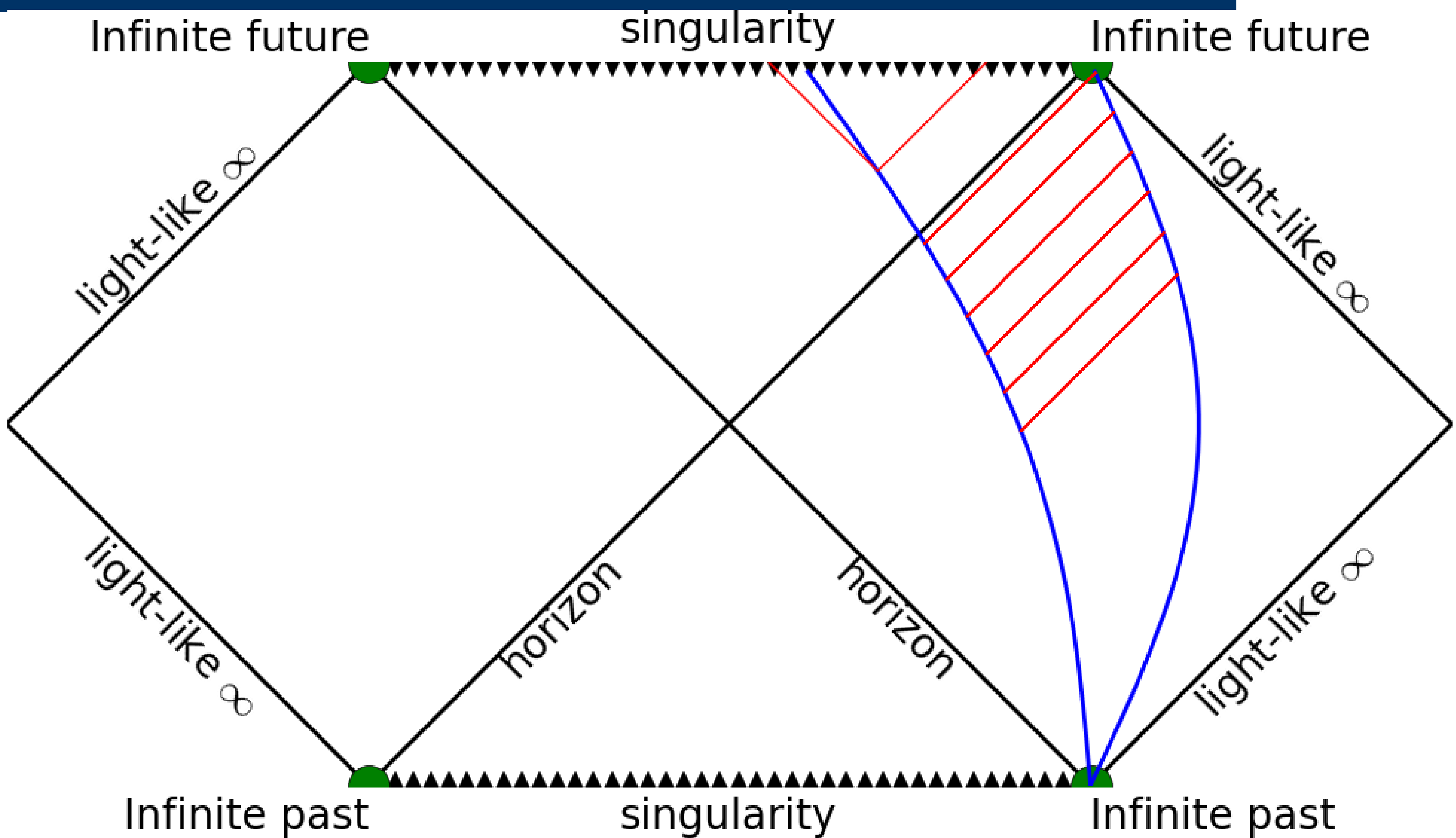


Falling into a Black Hole: Movie

Sci-Fi Question

- Imagine that in 2513 a spaceship was orbiting a neutron star somewhere in the Galaxy. Suddenly, the neutron star started collapsing and quickly turned into a black hole. What would happen to a spaceship?
  - **A**: Nothing.
  - **B**: It will get sucked into a black hole.
  - **C**: It will lose balance and will fly away.
  - **D**: Tidal forces will crash it instantly.

Schwarzschild Black Hole



Schwarzschild Black Hole

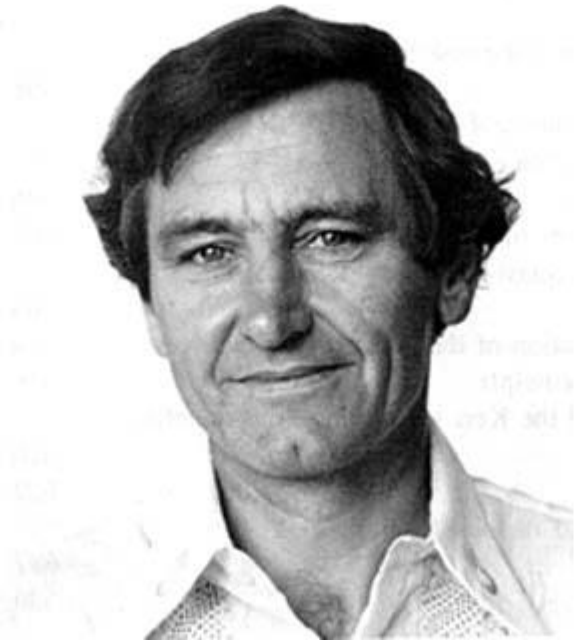
- Let Olga be an observer well outside a black hole, and Fred be an observer falling into a black hole.
- Olga will never see Fred crossing the horizon.
- Fred will reach singularity (and death) in a finite proper time.
- If Fred emits light at equal intervals, Olga will see the last flash, which will be the last flash Fred emitted before crossing the horizon.

Schwarzschild Black Hole

- Olga will see Fred being squeezed along his path.
- Fred will feel very strong tidal forces that will stretch him along its path and will eventually tear him apart.
- No material object within three Schwarzschild radii can freely orbit a black hole.
- Light can orbit a black hole at 1.5 Schwarzschild radii.

Rotating (Kerr) Black Hole

- Roy Kerr from New Zealand found a solution of Einstein equations that describes a rotating black hole.
- In addition to the event horizon, Kerr black hole has a region called *ergosphere*.



b. 1934

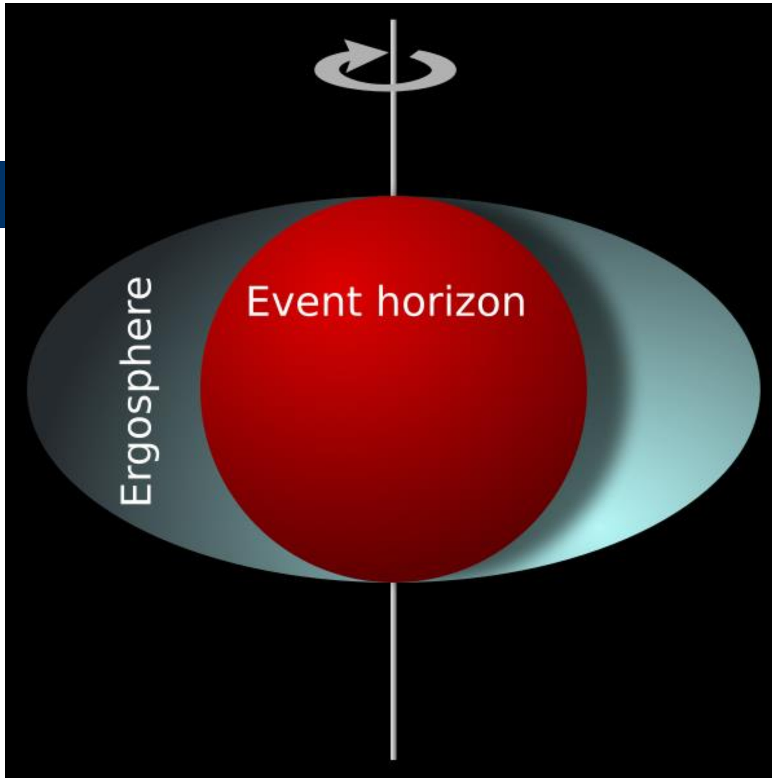
Rotating (Kerr) Black Hole

Schwarzschild BH

Kerr BH

Ergosphere

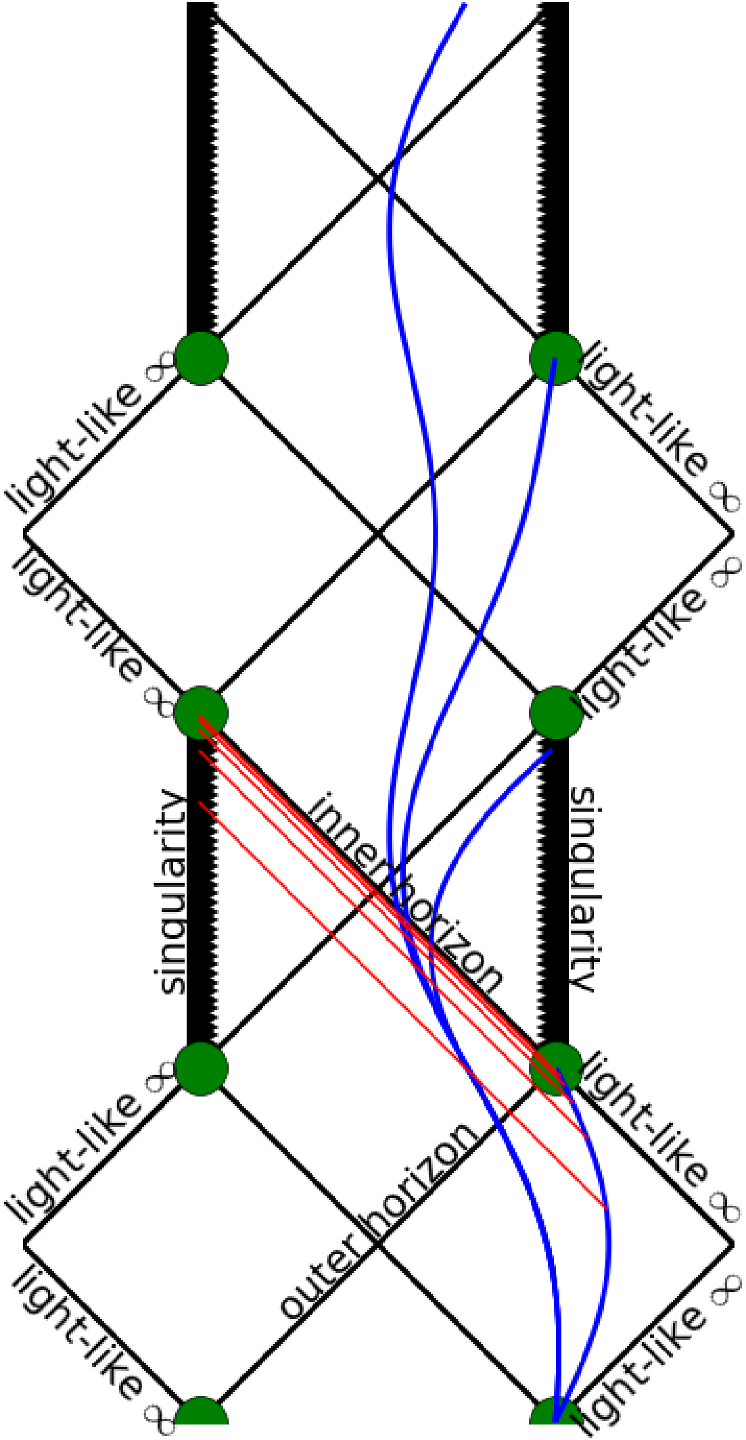
- In ergosphere no object or light can remain at rest with respect to distant stars: it has to rotate in the same direction as the black hole itself!



- This is called “dragging of inertial frames”, i.e. all inertial frames rotate around the black hole inside the ergosphere.

Kerr BH

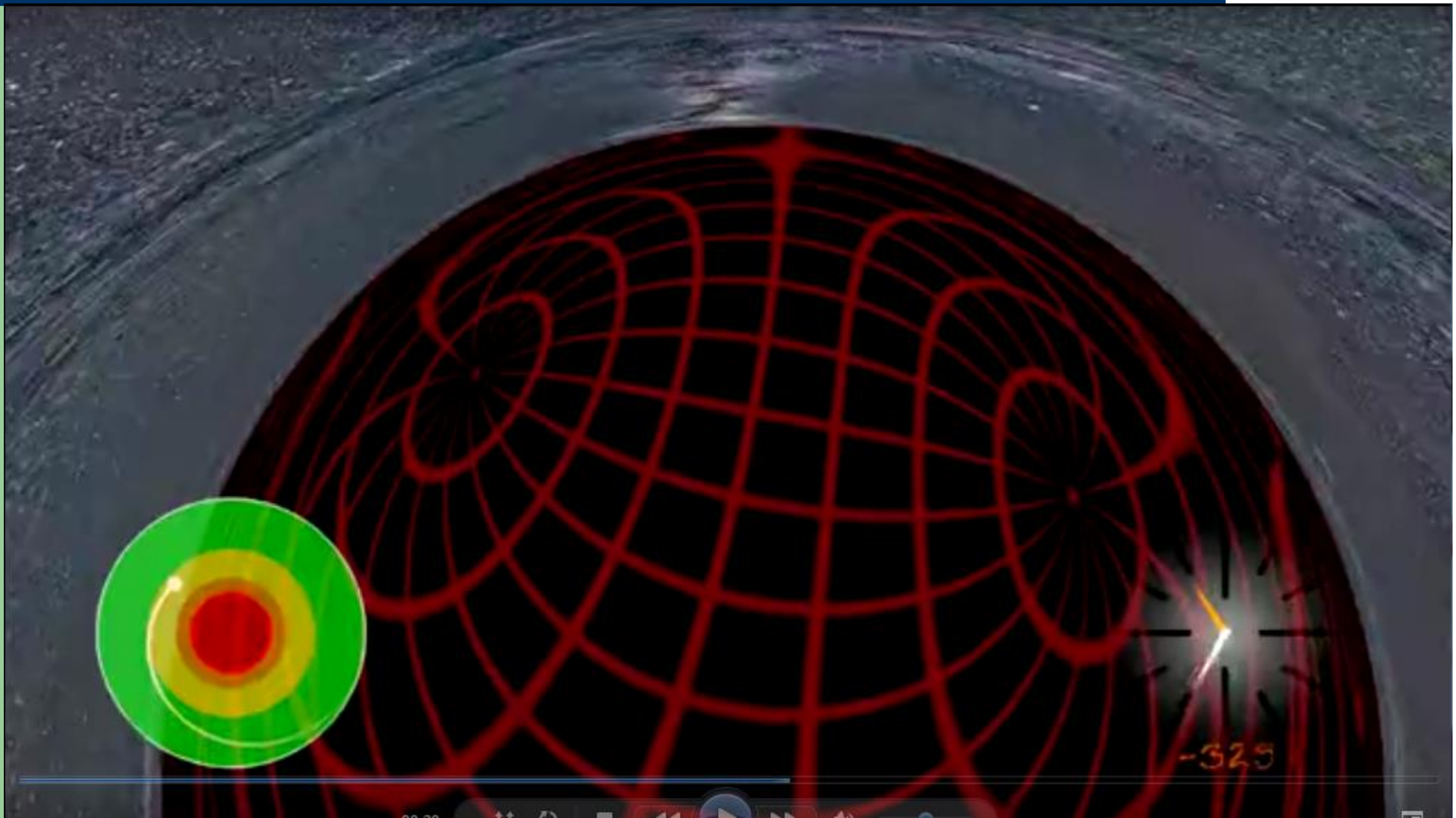
- Singularity in Kerr BH has a shape of a ring and it is *time-like*, i.e. an in-falling observer can bypass it and exit into a different universe from a *white hole*.



White Holes

- No white holes was ever found, and no mechanism is known for them to form.
- Time-like singularities are unstable. Any object falling into them will cause a formation of a space-like singularity, a-la Schwarzschild black hole.
- So, perhaps, all black holes are like Schwarzschild ones.

Falling into a Kerr BH: Movie



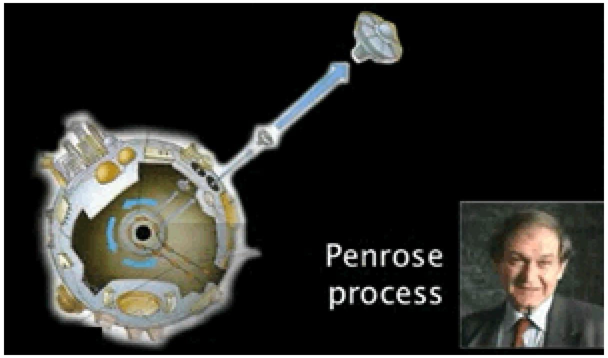
Kerr BH

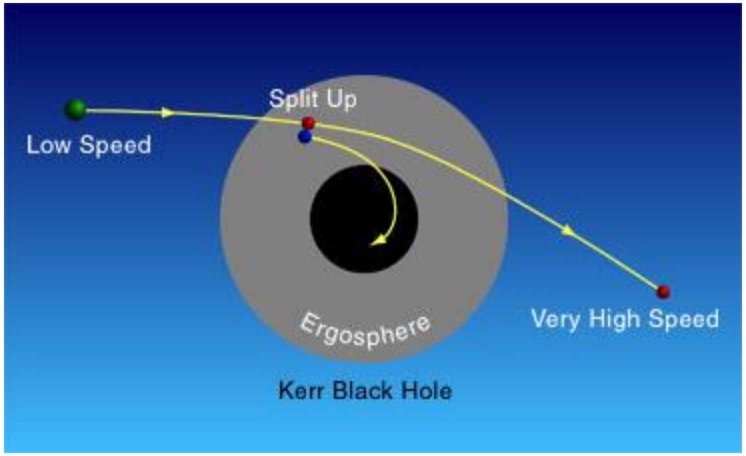
If that was not enough:

- In Kerr black hole there exist closed time-like geodesics – i.e., one can go back in time!
- You can only do that inside the black hole, though, so don't plan on going back into the past after the final is graded and retaking it again with a perfect score.

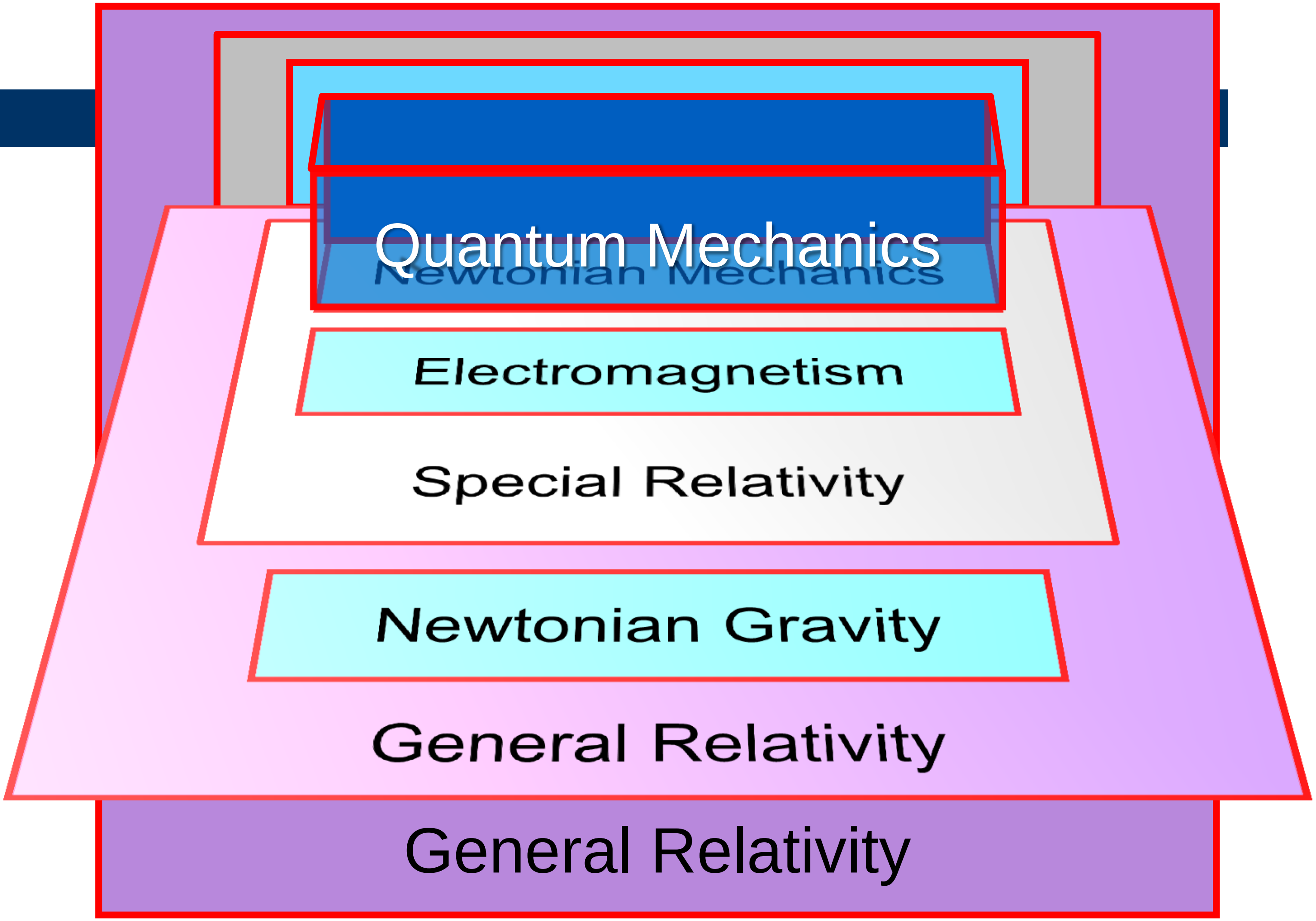
Penrose Process

- British physicist Roger Penrose realized that one can *extract* energy from a rotating black hole.
- All you need to do is to throw something into it just right.

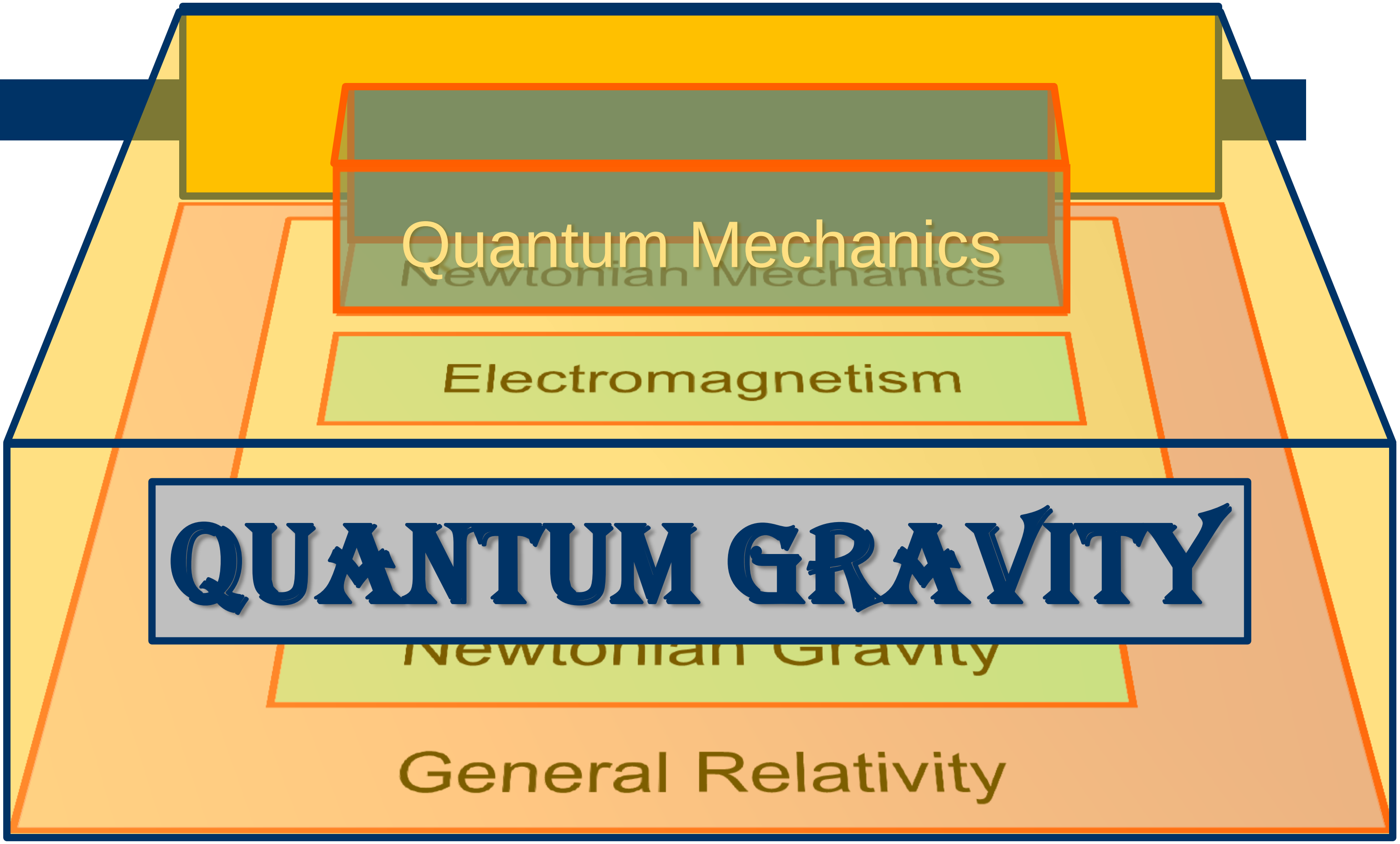




Black Holes and Quantum Mechanics

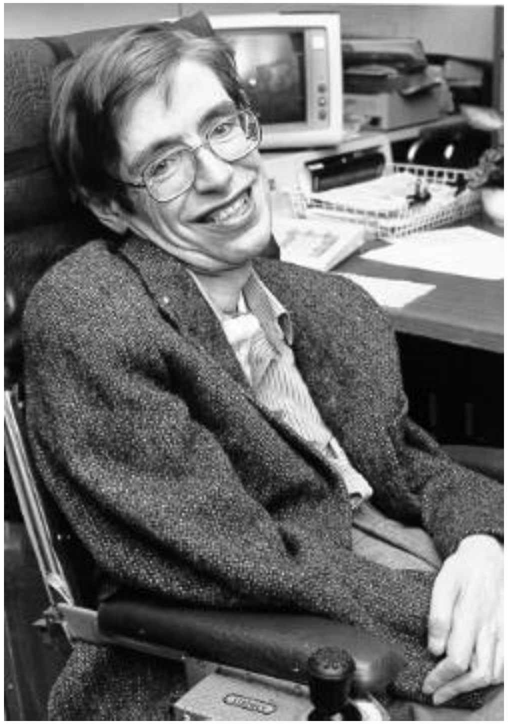


Black Holes and Quantum Mechanics



Black Holes and Quantum Mechanics

- In 1973 British physicist Steven Hawking realized that black holes should emit radiation (we call it Hawking radiation now).
- What does this imply for the evolution of their mass?
  A. It should increase.
  B. It should decrease.
  C. It should stay the same.



b. 1942

Layover: Quantum Mechanics

- In particle physics every normal particle has an anti-particle. An anti-particle has all the same properties as a normal particle, up to a sign – the same mass, opposite electric charge, etc.
- When a particle and antiparticle collide, they annihilate into light – the only way to extract all of their rest energy (mc^2)!

Uncertainty Principle

- German physicist Walter Heisenberg's formulated the ***Uncertainty Principle.***

Werner Heisenberg
(1901 – 1976)

Uncertainty Principle

- In Quantum Mechanics usual conservation laws are allowed to be violated for a very short time and on very small spatial scales.

$$\Delta p \Delta x \geq \frac{1}{2}\hbar$$

$$\Delta E \Delta t \geq \frac{1}{2}\hbar$$

Virtual Pairs

- The Uncertainty Principle allows the energy conservation to be violated on time-scales $\Delta t < t_{\mathrm{PL}} = 10^{-43}\mathrm{sec}$.
- Paul Dirac realized that such a violation would lead to “virtual particle pairs”.
- His famous quote: “The aim of science is to make difficult things understandable in a simpler way; the aim of poetry is to state simple things in an incomprehensible way. The two are incompatible.”

Black Holes and Virtual Pairs

- Hawing realized that if a virtual pair is created near the black hole horizon, with one particle inside the horizon and the other one outside, then the pair may become real.
- The mass of the black hole then must decrease, for the energy to be conserved beyond $10^{-43}\mathrm{sec}$.
- Black hole evaporation is very slow – a solar mass black hole will evaporate in 10^{65} years.