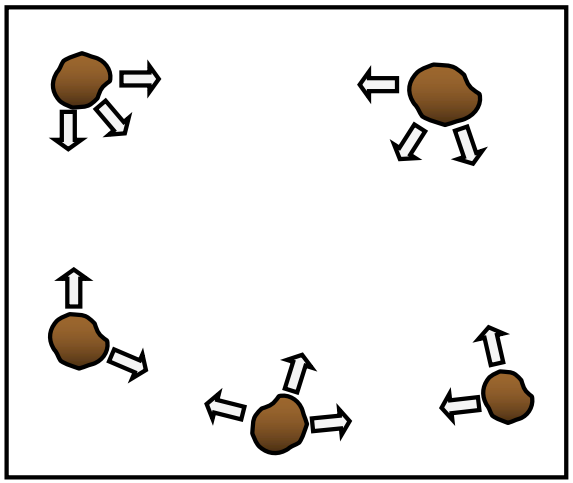
13. Black Holes

Topics:
1. Newtonian Black Holes
2. Relativistic Black Holes

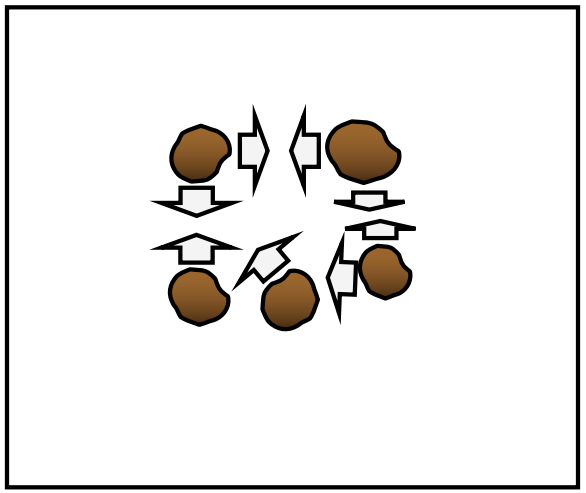
1. Newtonian Black Holes

- Consider Newtonian gravitational collapse.
- (Newtonian gravitational force) $\propto 1/(\text{distance})^2$
- *Ex*. Decreasing the distance by half increases the force by 4.



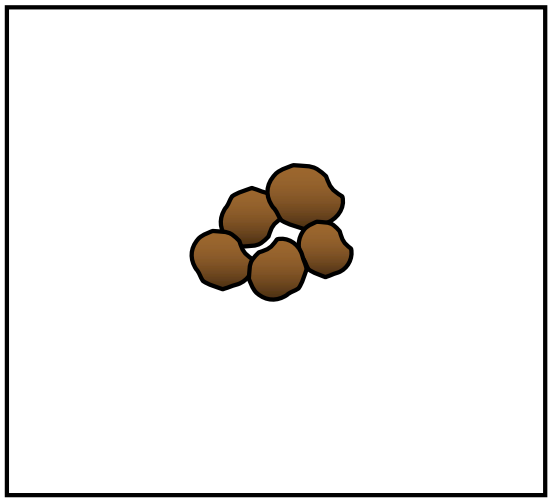
matter widely dispersed in space - grav. force weak

$\Rightarrow$



grav. force increases as distance decreases

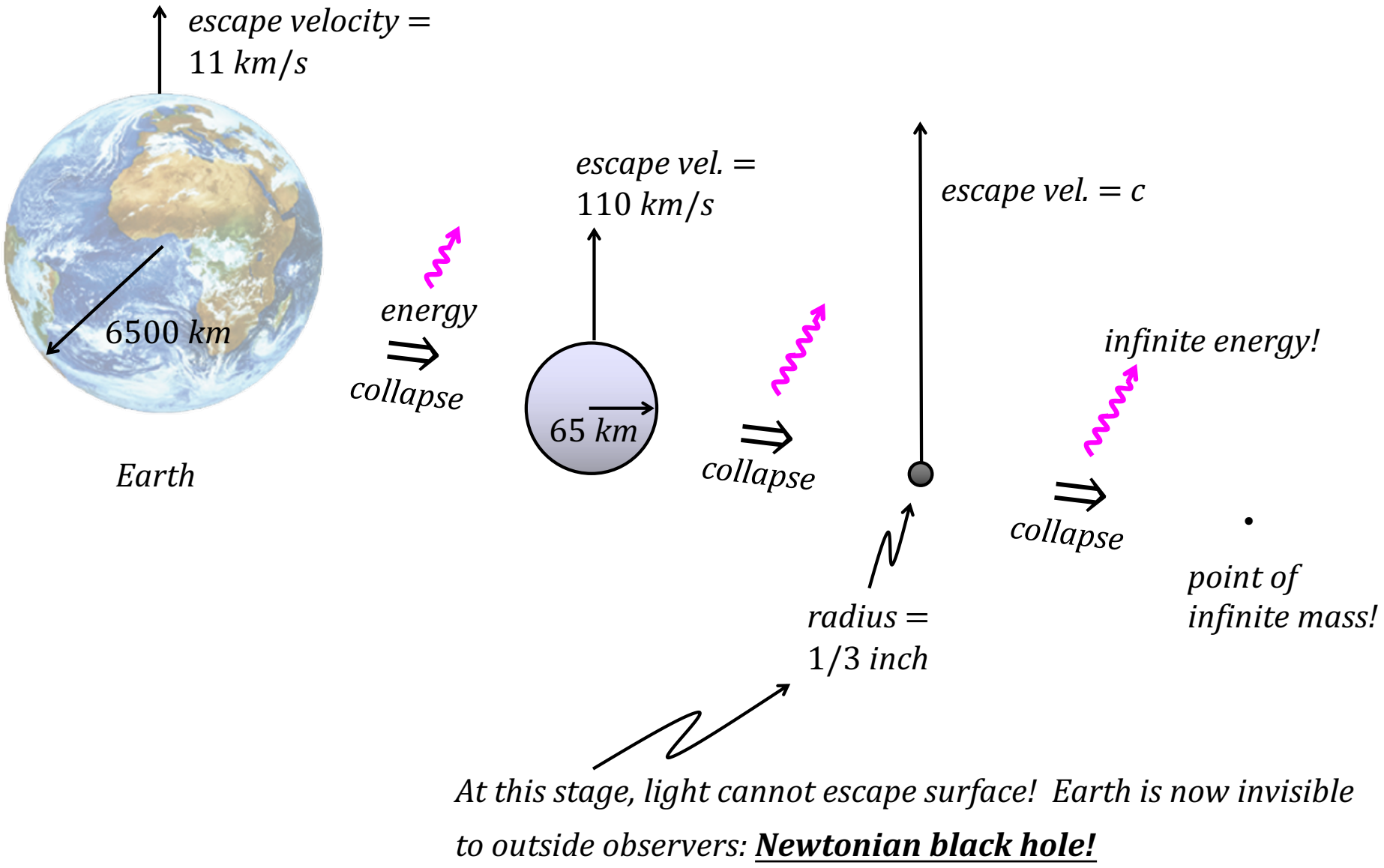
$\Rightarrow$



collapse accelerates

- This is the process of star and planet formation.
- For planets, mechanical halting forces prevent collapse.
- For stars, heat halting forces prevent collapse.

If nothing intervenes, matter collapses to a point with infinite energy release.



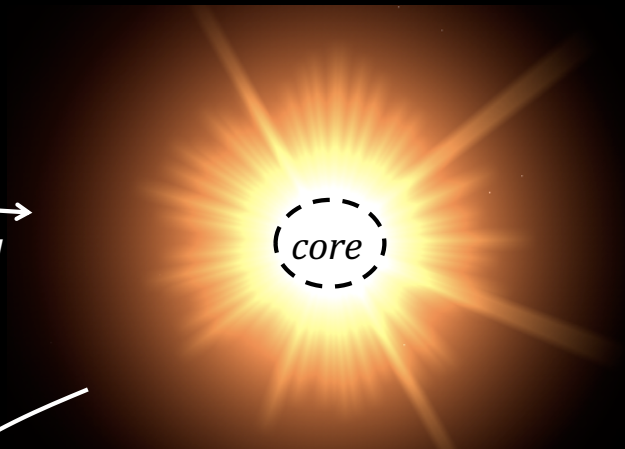
Gravitational collapse and stars

Hydrogen gas cloud

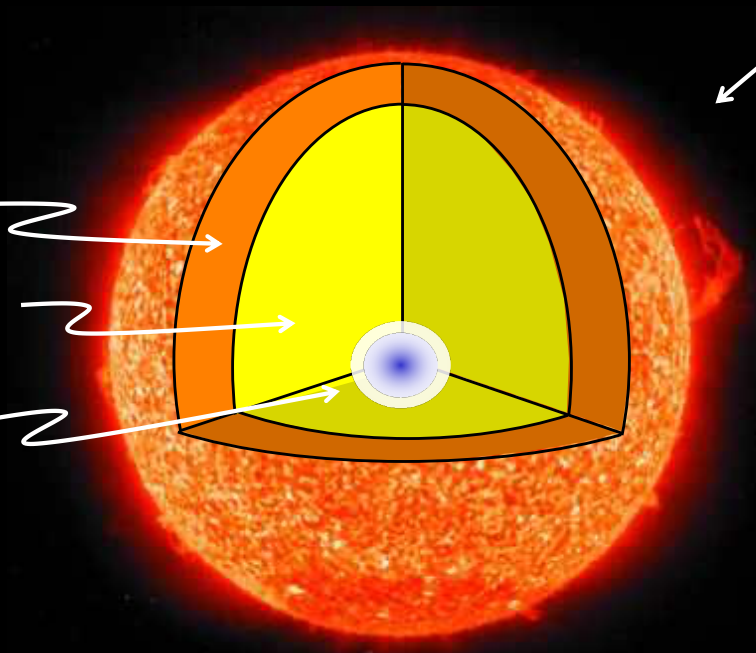
collapse

Heated by energy released in collapse.

several million years



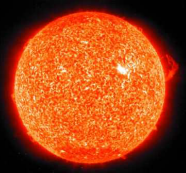
Core becomes sufficiently hot for nuclear fusion:
$H + H \rightarrow He +$ *lots of energy*



Gravitational collapse balanced by energy released by fusion.

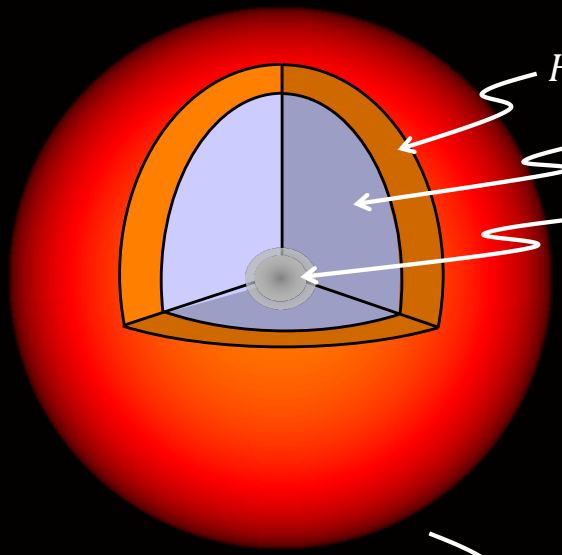
Our sun:

- *Formed 4.5 billion years ago*
- *Will continue in this phase for ~5 billion more years*



main sequence star

initial mass
= 1.3 solar masses



Red Giant

Expansion due to greater energy release overcoming grav. pressure.

initial mass
< 1.3 solar masses

initial mass
> 1.3 solar masses

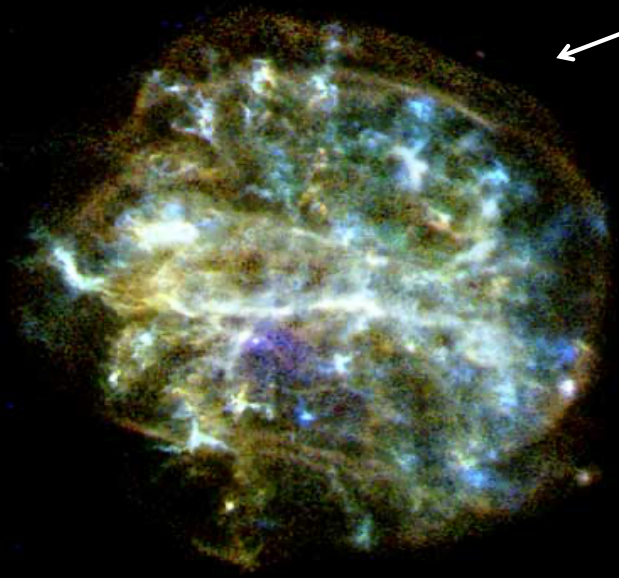
- *Greater density causes stronger fusion reactions.*
- *Elements break into fundamental particles (protons, neutrons).*

White Dwarf

Supported by electron degeneracy pressure

Black Dwarf

Supernova possible

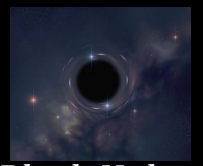


initial mass
< 2-3 solar masses

Neutron Star

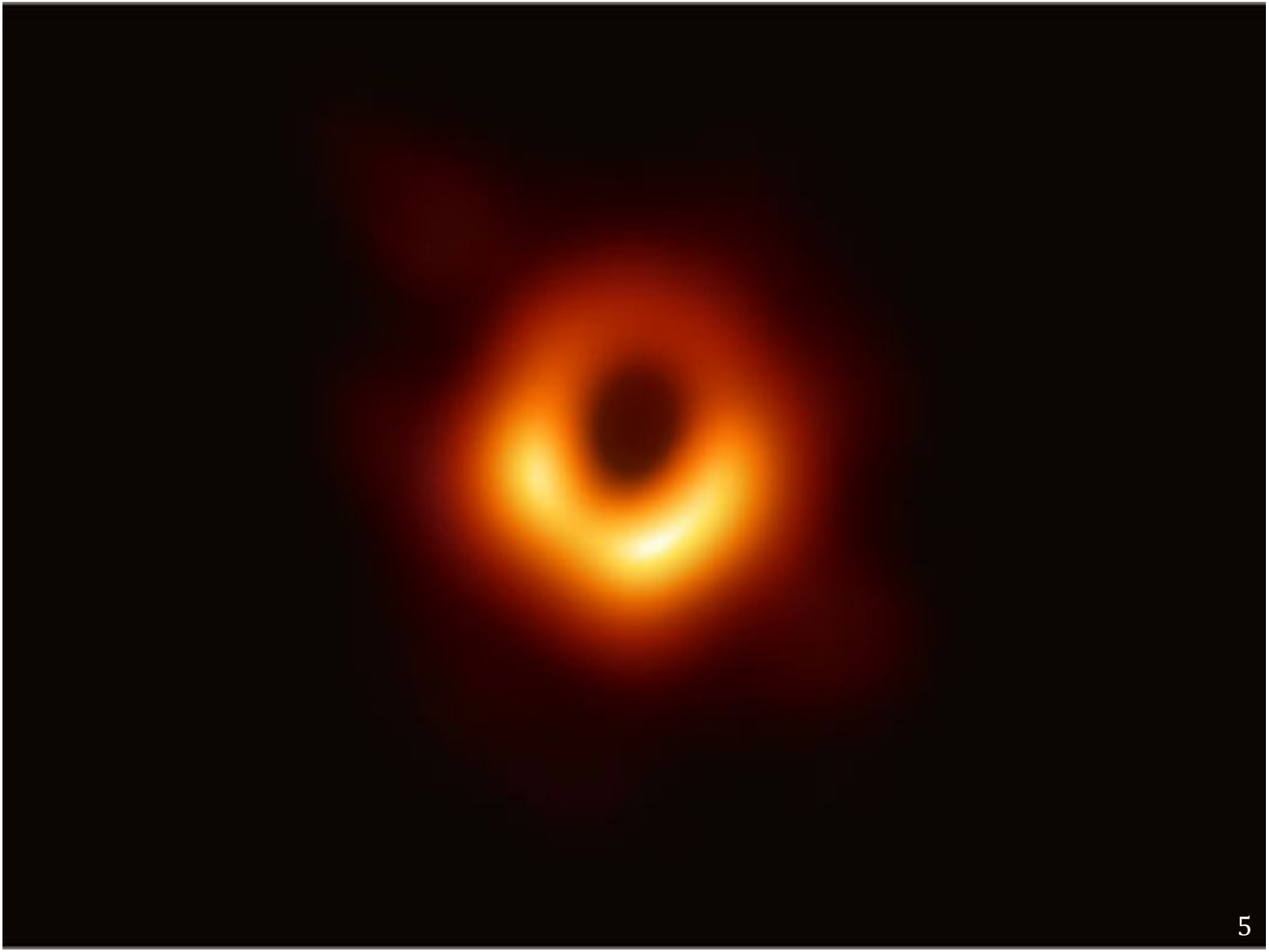
Supported by neutron degeneracy pressure.

initial mass
> 2-3 solar masses



Black Hole

Total gravitational collapse.



Newtonian Picture

Unrestrained gravitational collapse ⇒ infinite energy release + singular point of infinite matter density + background spacetime unaffected

⇓

Transition to General Relativity

equivalence of matter and energy

Curvature of spacetime fixed by matter density

⇓ ⇓

Relativistic Picture

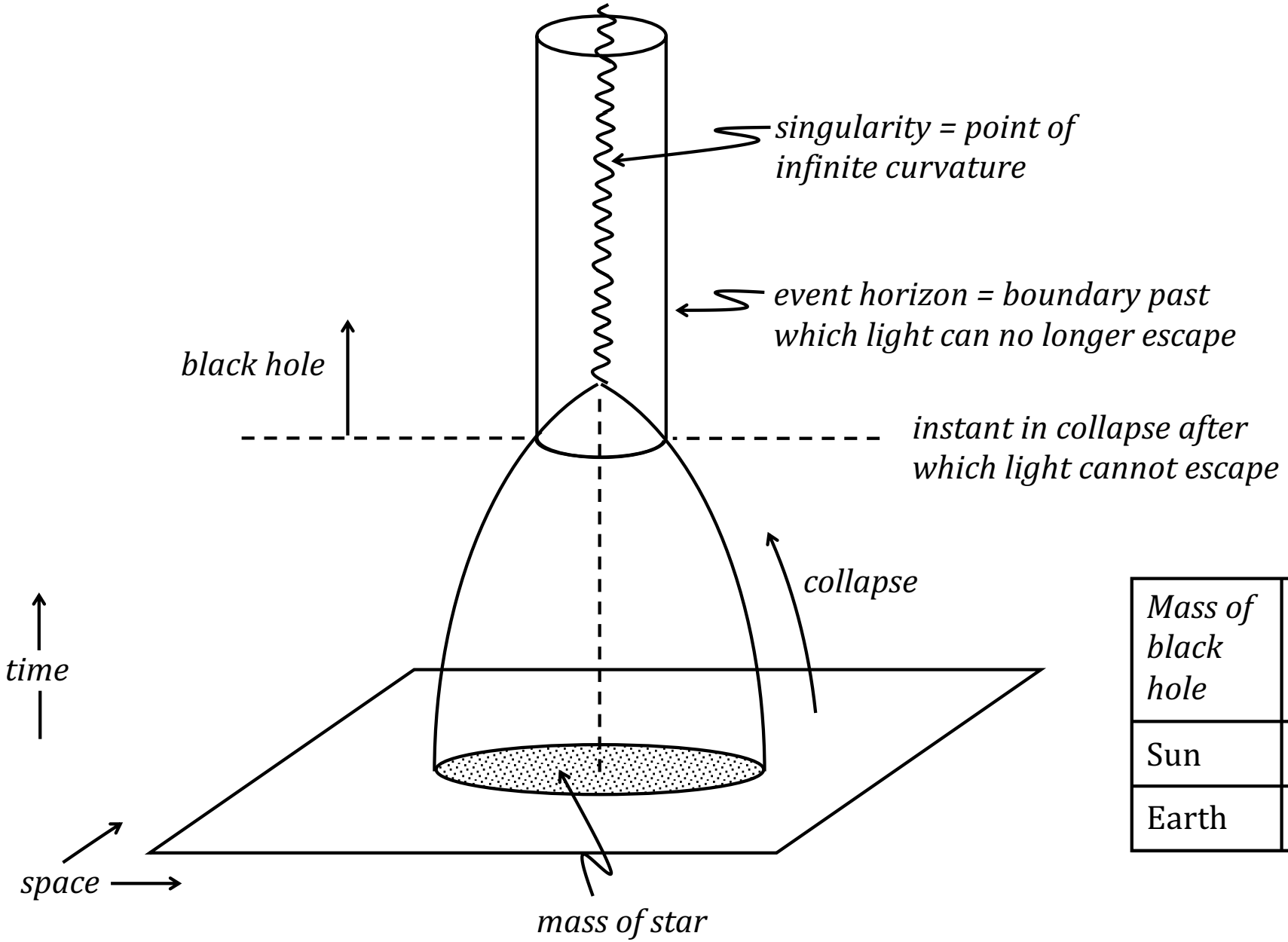
Unrestrained gravitational collapse ⇒ finite energy release + singular point of infinite spacetime curvature

An improvement...

...but at what cost?

2. Relativistic Black Holes

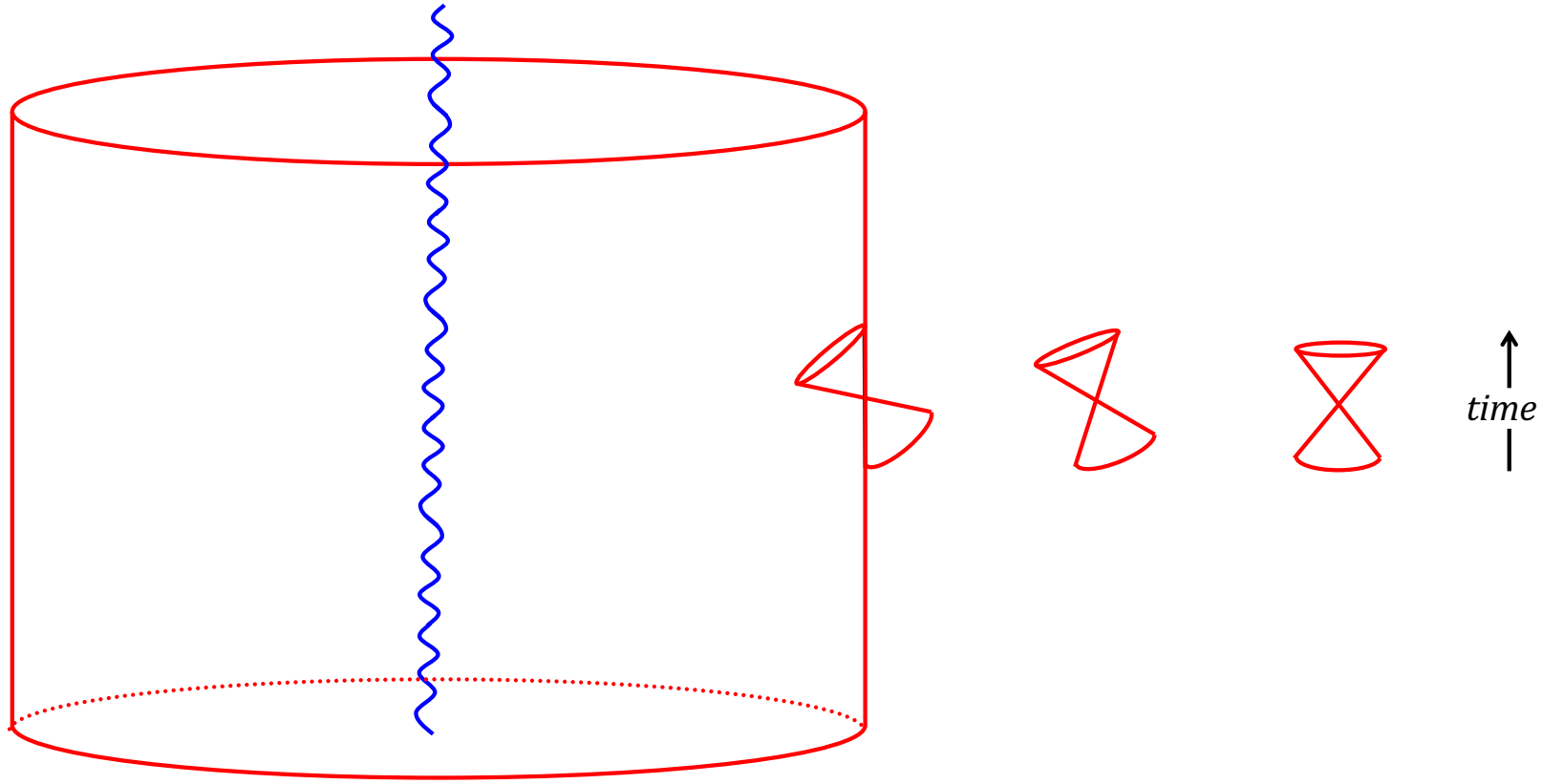
Simplest case: Schwarzschild Solution (no charge or rotation).



Mass of black hole	*Radius of event horizon*
Sun	2.95 *km*
Earth	8.86 *mm*

Causal Structure of Event Horizon

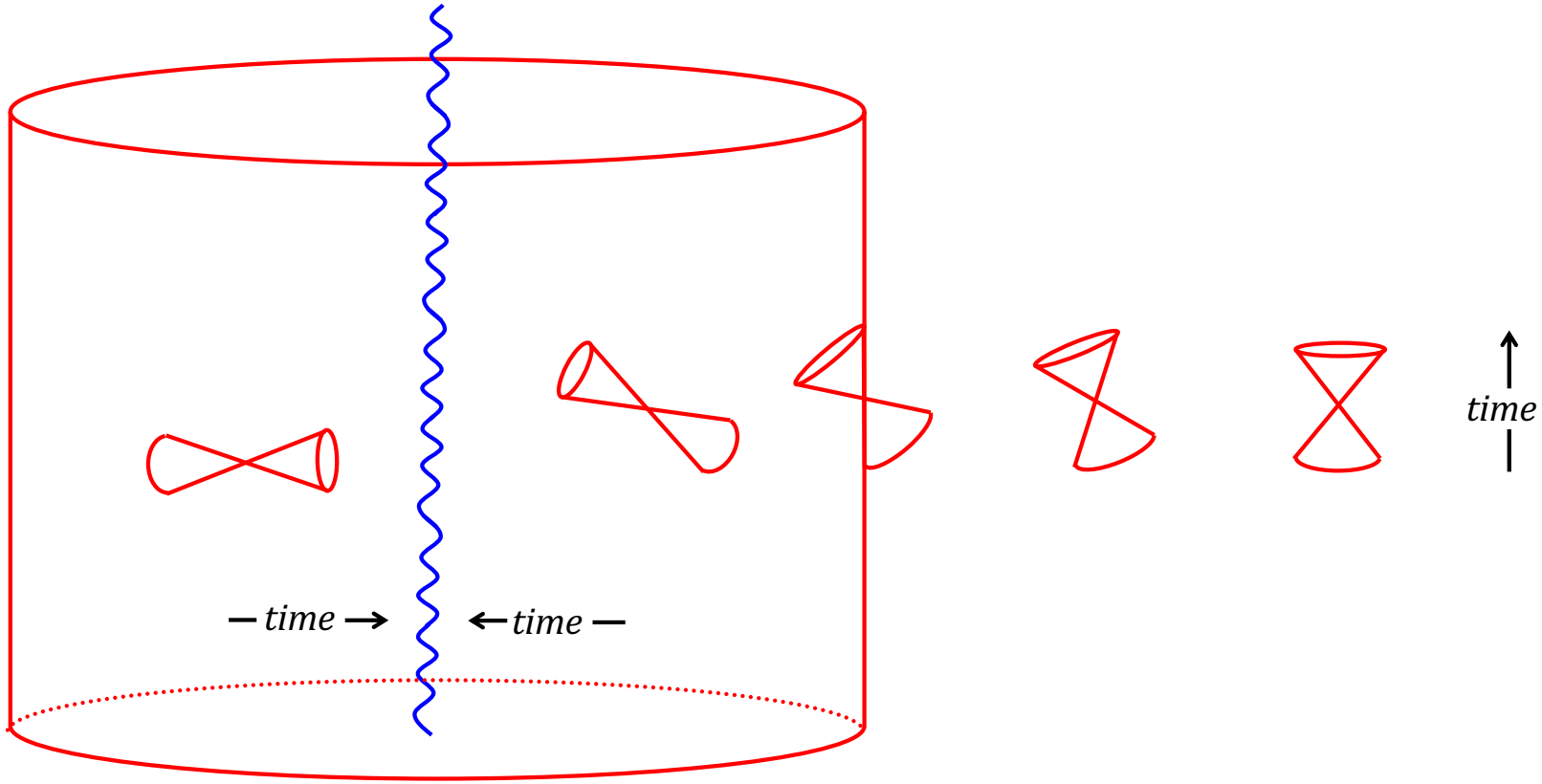
- Lightcone orientation and width depends on the curvature of spacetime.
- *So*: Can use lightcones to represent curvature in a spacetime diagram!



- Far from event horizon, lightcones point upward (flat Minkowski spacetime).
- Lightcones tip in regions closer to event horizon.
- At event horizon, future lightcone is fully inside; light cannot escape.
- *What this means*: Event horizon forms a *lightlike* surface.

Causal Structure of Event Horizon

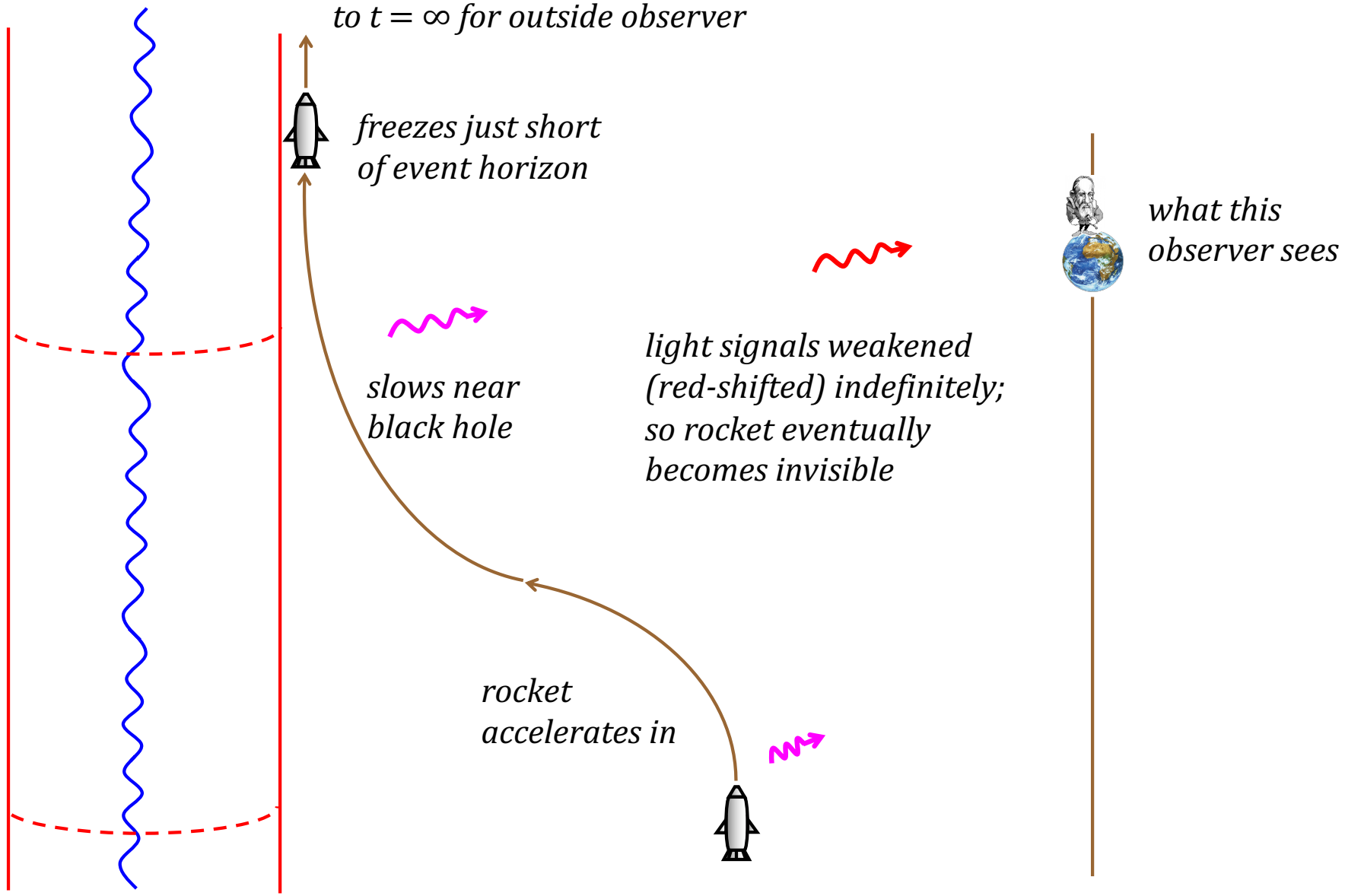
- Lightcone orientation and width depends on the curvature of spacetime.
- *So*: Can use lightcones to represent curvature in a spacetime diagram!



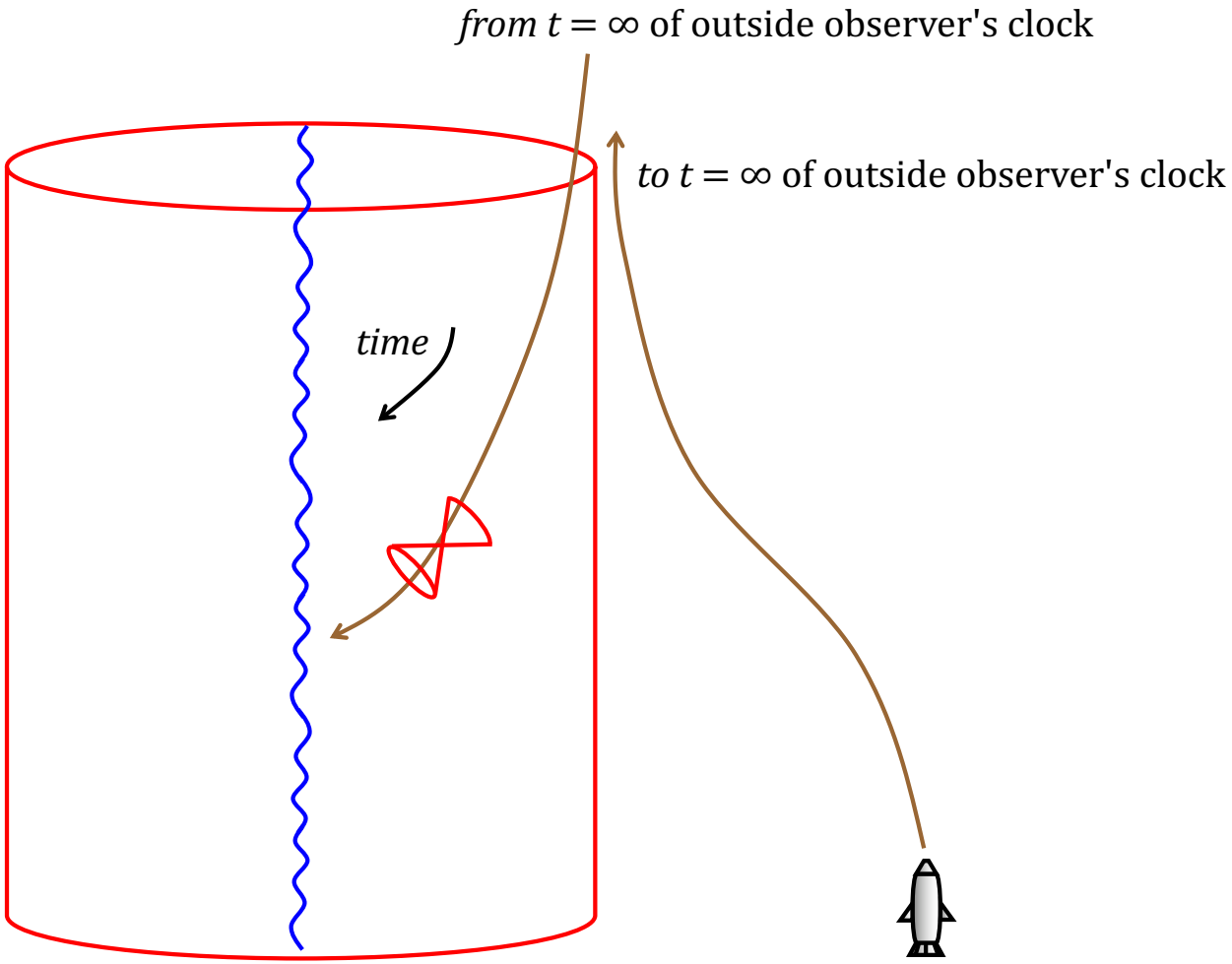
- Inside event horizon, future lightcones see singularity as only future.
- *What this means*: Singularity forms a *spacelike* surface: a surface perpendicular to all timelike curves inside event horizon.

Falling into a black hole

The view from a distance



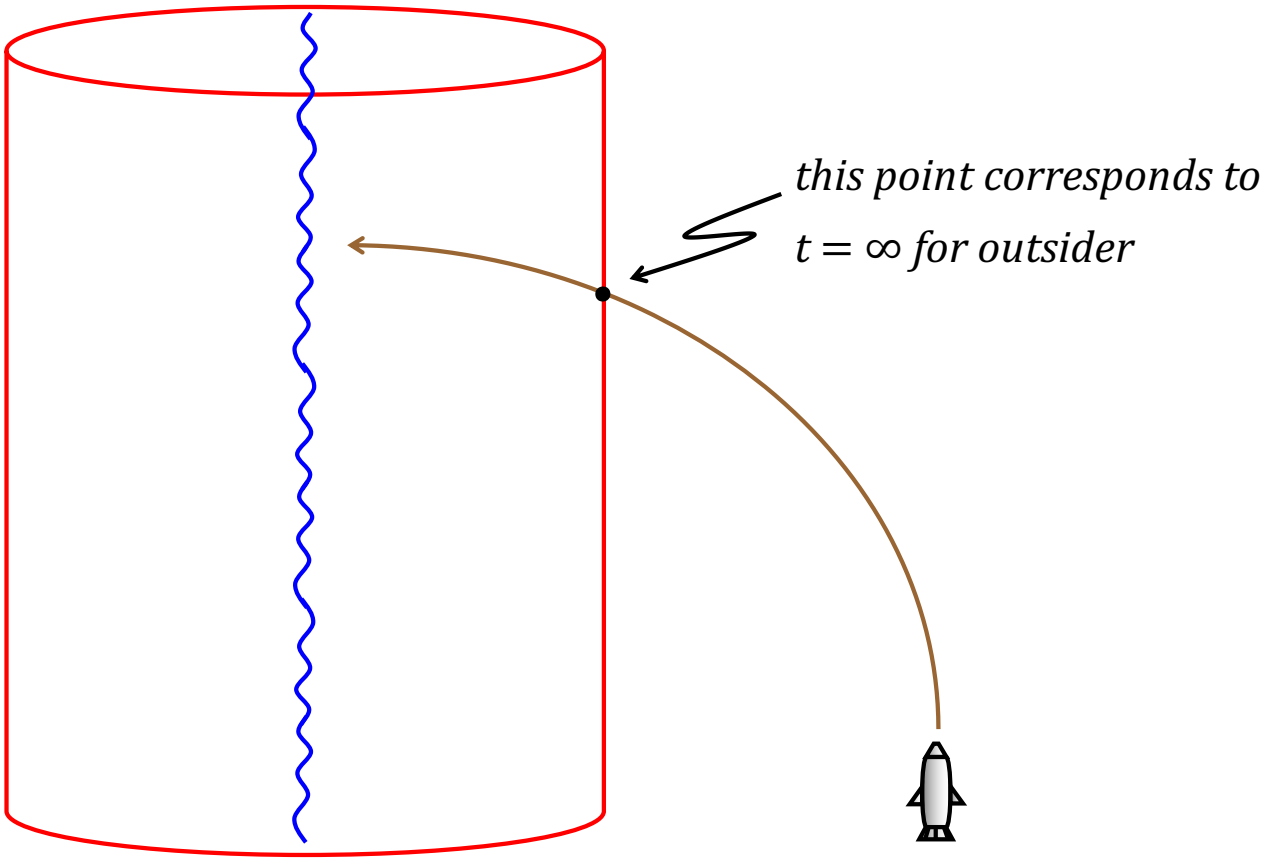
What rocket sees



- Rocket rapidly passes $t = \infty$ of outside observer's clock.
- Crosses over event horizon (no "bump").
- Falls into singularity. (0.0001 *sec* inside event horizon for black hole of 1 solar mass)

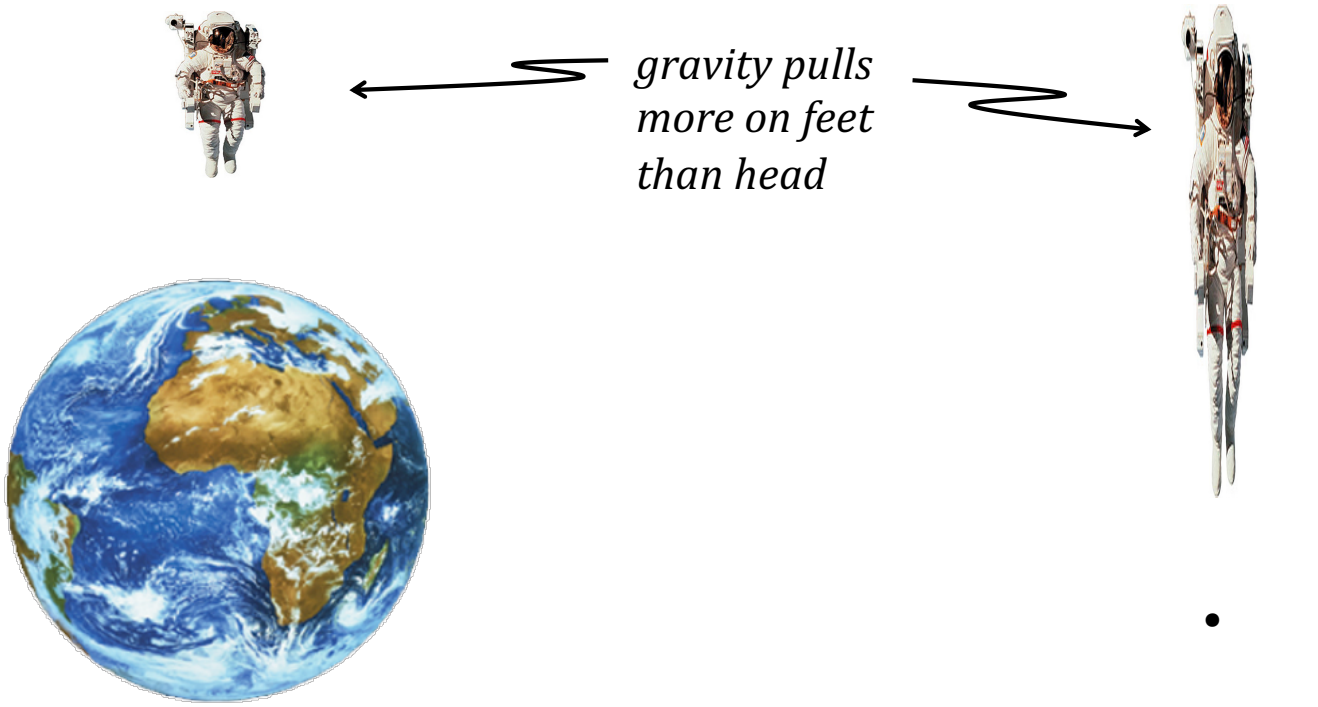
- Standard spacetime diagram must now include *discontinuous* curves.
  - *But the rocket's trajectory is really smooth.*

- *Problem*: How can we represent such smooth trajectories?



Tidal Forces

- Tidal forces are due to the uneven gravitational forces acting on an extended object due to a gravitational source.
- For extremely massive gravitational sources, they can have unpleasant effects...



Tidal Forces

- Tidal forces are the cause of ocean tides.
- Oceans "bulge" due to moon's gravitational force.
- Earth rotates, bulge remains stationary, producing ocean tides.