Black hole fireworks

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In collaboration with Carlo Rovelli

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ce products
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Contact forces

Until E & M all forces on a diagram come from contact

$\vec{F}_{BM}$

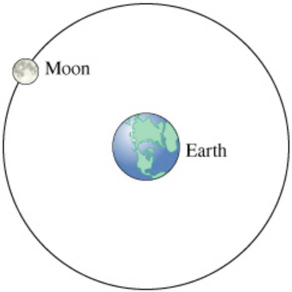
$\vec{F}_g$

$\vec{F}_g$

except for the force of gravity.

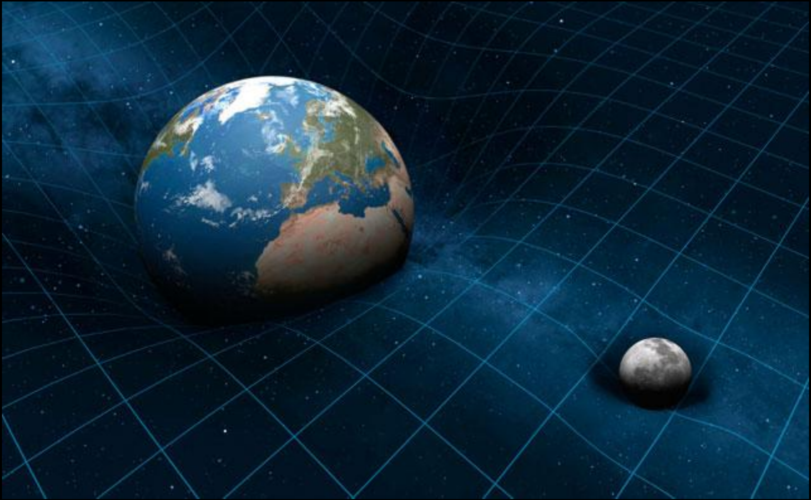
Action at a distance

$$F = G\frac{mM}{r^2}$$

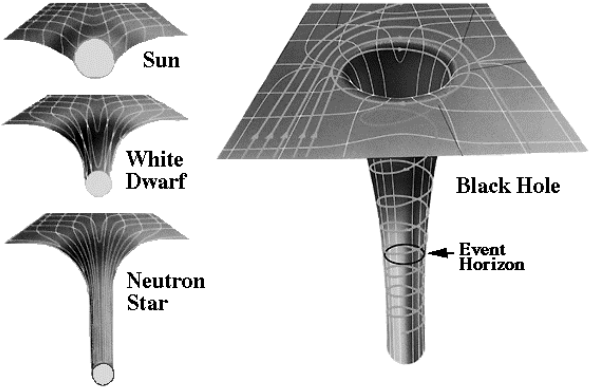


That one body may act upon another at a distance through a vacuum without the mediation of anything else, by and through which their action and force may be conveyed from one another, is to me so great an absurdity that, I believe, no man who has in philosophic matters a competent faculty of thinking could ever fall into it.

Isaac Newton



Black holes



One

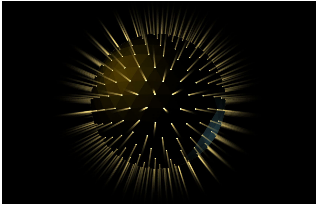
What happens to
collapsing matter?

Two

Toy model: the crystal ball

Three

Exploding black holes

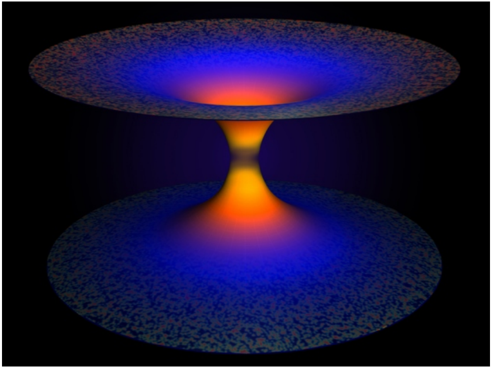


What happens near $r = 0$?

Small radii $\rightsquigarrow$ deep quantum regime. Does an effective quantum pressure develop, avoiding a singularity?

Could this "pressure" push the matter back out? This would be like a cosmological bounce.

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho\left(1 - \frac{\rho}{\rho_{\mathrm{Pl}}}\right)$$



Quantum effects

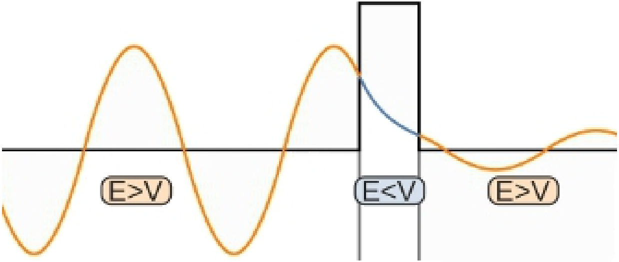
Quantum effects are relevant to black hole evolution.

In 1974 Stephen Hawking argued that black holes emit particles.

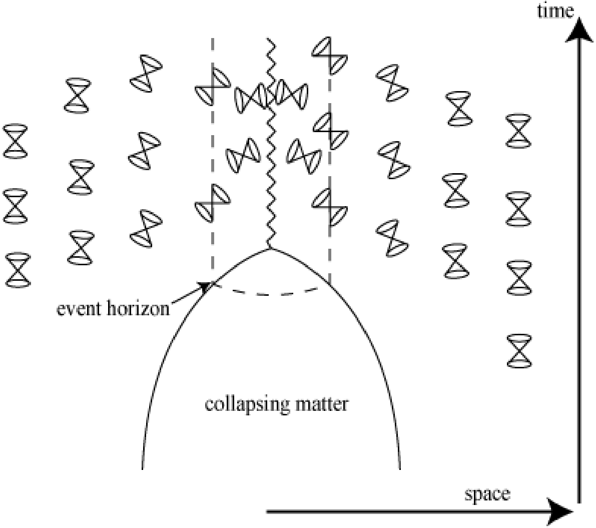
His arguments can be cast as a quantum tunneling phenomenon.

Classically, only way to get over a barrier is with enough energy.

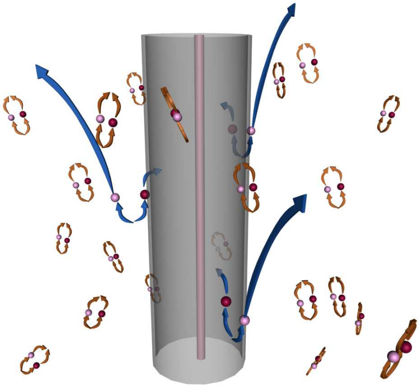
Quantum mechanically you can go through barriers.



However, the probabilities are small $\rightsquigarrow$ long times.


time
event horizon
collapsing matter
space

Hawking radiation



Vacuum is exciting—virtual pairs of particles are popping in and out of existence

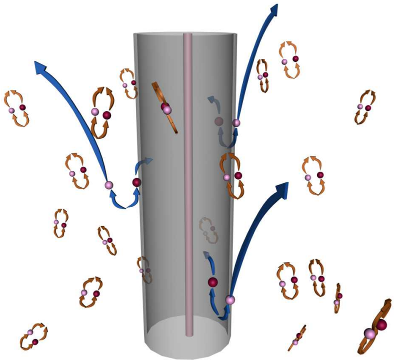
They are virtual because one has $+E$ and one $-E$

The $-E$ particle is forbidden outside the horizon—tunneling inside it becomes allowed

The $+E$ particle can escape to far away and carry some of the black hole's mass

Hawking radiation

Because Hawking radiation is due to quantum tunneling we know that it must be slow. But how slow?



Hawking radiation

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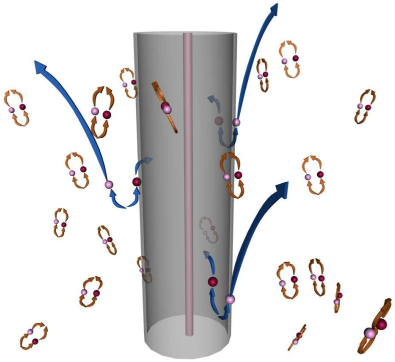
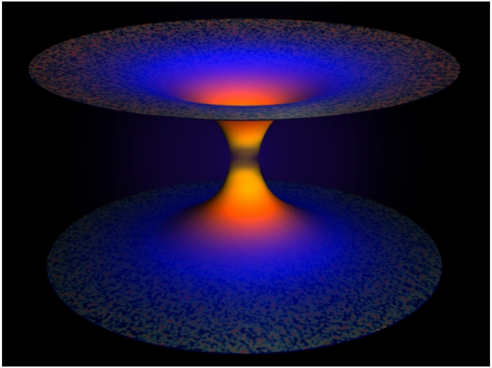


Very, very slow $T_H \sim M^3$. For a solar mass black hole it takes $T_H = 10^{75}$ secs. The age of the universe is $T_U = 10^{17}$ secs.

Bounce?

Hawking radiation focuses attention on the matter—what about the geometry?



Our ideas:

- E is conserved at ∞ $\rightsquigarrow$ elastic bounce
- Neglect Hawking radiation
- Quantum process $\rightsquigarrow$ tunneling of geometry Begins outside horizon
- GR is time reversal invariant—black to white hole bounce

How can these ideas be consistent with causality?

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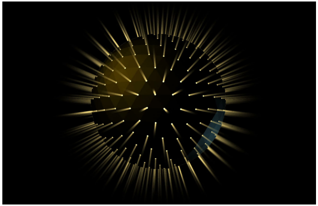
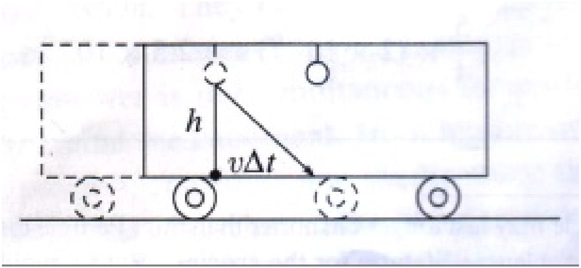




On the train: $\Delta t_0 = \frac{h}{c}$

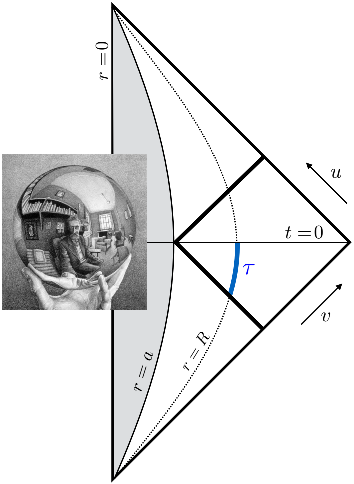
On the ground: $\Delta t = \frac{\sqrt{h^2+(v\Delta t)^2}}{c} \quad \Longrightarrow \quad \Delta t = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}\Delta t_0$

"Moving clocks run slow!"

Because gravity bends *spacetime*, a clock lower in a gravitational potential runs slow!

How long does it take a shell of light to bounce off a mirrored ball?

$$\tau_R = \sqrt{1 - \frac{2M}{R}}\left(R - a - 2M \ln \frac{a - 2M}{R - 2M}\right)$$



How classical?

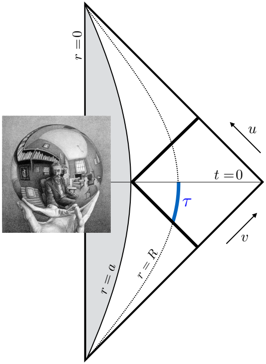
$$\tau_R = \sqrt{1 - \frac{2M}{R}} \left(R - a - 2M \ln \frac{a - 2M}{R - 2M} \right)$$

Classicality parameter

$$q = \ell_{\mathsf{Pl}} \mathcal{R} \tau_R ,$$

here $\mathcal{R} \sim \frac{M}{R^3}$ is a measure of strength of curvature and $q << 1$ means classical.

q can be near 1 for $a \sim 2M$ and τ_R large enough. It has a maximum at $R_q = \frac{7}{6}(2M)$ (outside horizon!) and requiring $q \sim 1$ gives $\tau_q \sim M^2$.



Quantum gravity effects can take hold outside the horizon!

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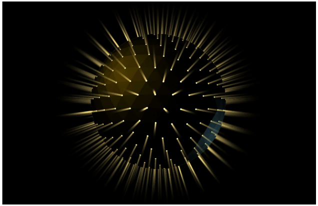
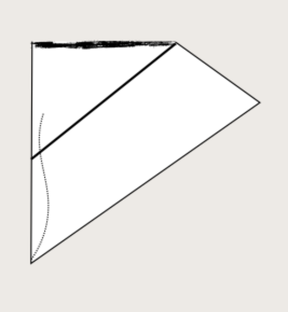
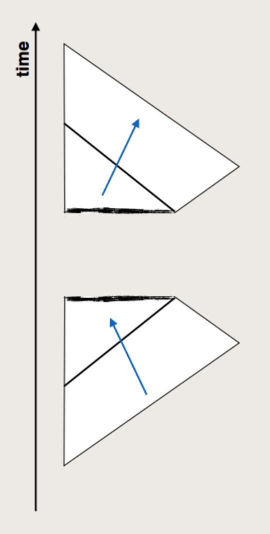


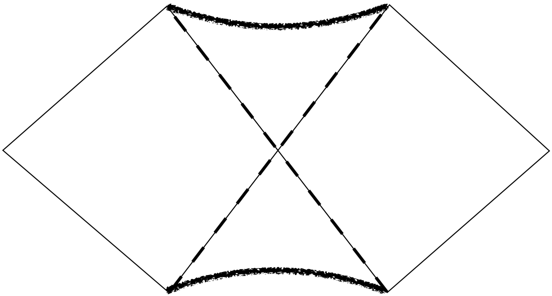
Let's try to build a solution of Einstein's equations where collapsing matter bounces back out.

- Idea: glue a black hole to a white hole.





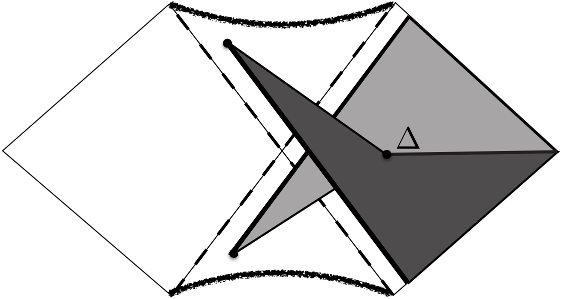
In fact, a glued version of these two space times exists



but it's upside down.

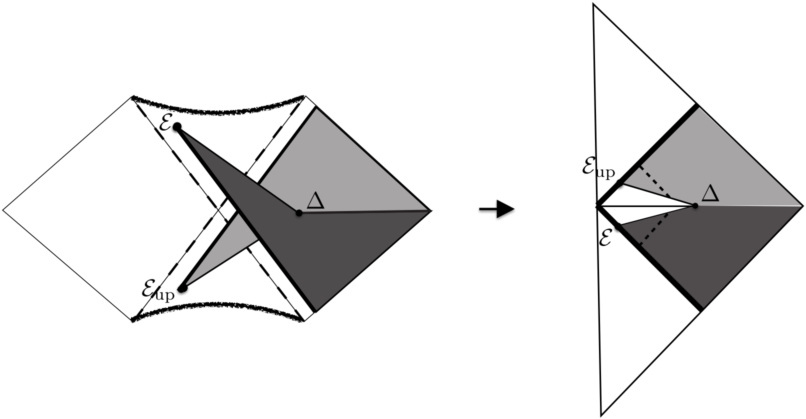
Can we cut it up?

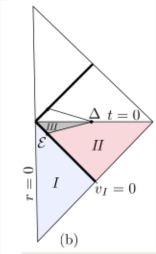
Yes! Use the crossed fingers —



… and sew it all up…

The spacetime





Full metric: join the pieces

Spherical symmetry:

$$ds^2 = -F(u,v)dudv + r^2(u,v)(d\theta^2 + sin^2\theta d\phi^2)$$

Region I (Flat): $F(u_I, v_I) = 1, \qquad r_I(u_I, v_I) = \dfrac{v_I - u_I}{2}.$

Bounded by: $v_I < 0.$

Region II (Schwarzschild): $F(u,v) = \dfrac{32m^3}{r} e^{\frac{r}{2m}} \qquad \left(1 - \dfrac{r}{2m}\right) e^{\frac{r}{2m}} = uv.$

Matching: $r_I(u_I, v_I) = r(u,v) \quad \longrightarrow \quad u(u_I) = \dfrac{1}{v_o}\left(1 + \dfrac{u_I}{4m}\right) e^{\frac{u_I}{4m}}.$

Region III (Quantum): $F(u_q, v_q) = \dfrac{32m^3}{r_q} e^{\frac{r_q}{2m}}, \qquad r_q = v_q - u_q.$

Conclusions

- Collapsing matter bounces in a short time locally but a long time from far away, $\sim M^2$.
  Solar mass: $\tau_q \sim 10^{32}$ sec, $\tau_H \sim 10^{75}$ sec, $\tau_U \sim 10^{17}$ sec.

- Possible to describe using a metric with no singularity, two trapped regions, and all matter exiting $\rightsquigarrow$ all info escapes

- Could a black hole be a bouncing star seen in super slow motion? With the constructed metric we can attack this question rigorously.

- I want to calculate the WKB amplitude for a gravitational instanton giving this bounce process; now I can in principle!