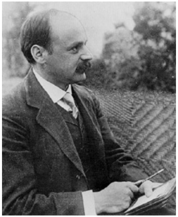
Physics Utrecht
EMMEΦ

Gerard 't Hooft

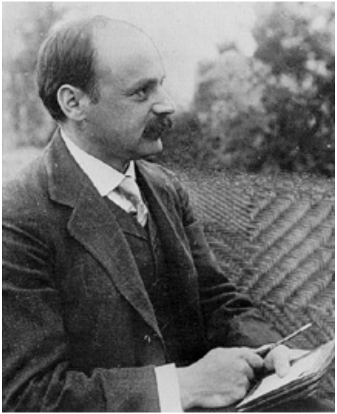
Quantum black holes



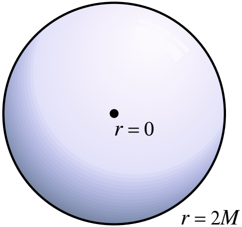
Centre for Extreme Matter and Emergent Phenomena,
Science Faculty, Utrecht University,
POBox 80.089, 3508 TB, Utrecht

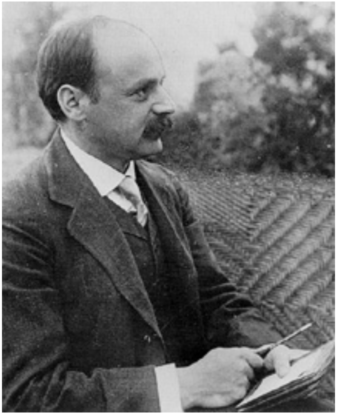
Paris

January 28, 2021



Karl Schwarzschild





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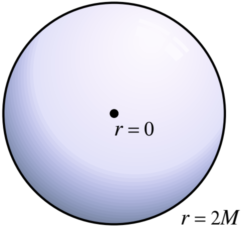
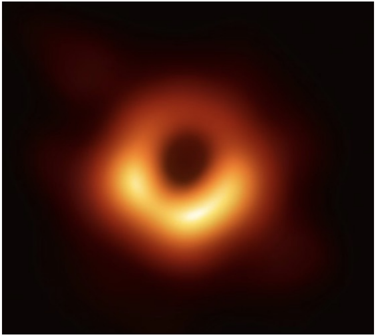


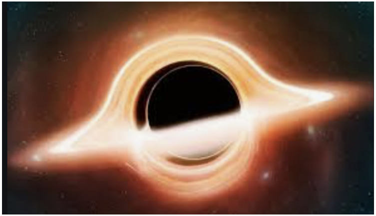
$$ds^2 = -\left(1 - \frac{2M}{r}\right) dt^2 + \frac{1}{1-2M/r} dr^2 + \\ + r^2(d\theta^2 + \cos^2\theta d\varphi^2) \ .$$

in units where $G = c = 1$.

Astronomical black holes :



At the center of
Elliptical galaxy Messier 87
Event Horizon Telescope, April 2019



Artist's impression

Introduction.

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1. If you want a theory that unifies all forces and includes the behavior of space and time themselves, it must include gravity, or, General Relativity should be part of such a theory.

2. The best way to study gravitational forces is by considering the strongest possible gravitational fields – or gravitational potentials – under given conditions, and realise that

3. The strongest gravitational force fields are near the horizon of a black hole. Therefore, go study quantum black holes first.

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How do we reconcile black holes with *quantum mechanics?*

Stephen Hawking

4. You will find that, demanding black holes to behave in a physically acceptable way, one will be forced to go beyond the known laws of physics.

   Minimise such modifications!

   Make sure that your theory is logically coherent and self-consistent.

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This talk is an advertisement of an approach that I consider very promising.
I need no string theory, no AdS/CFT, no stacks of D-branes — these might come later but I don't see the need as yet.

Firewall problems are resolved, and
entanglement issues do not arise in this framework .

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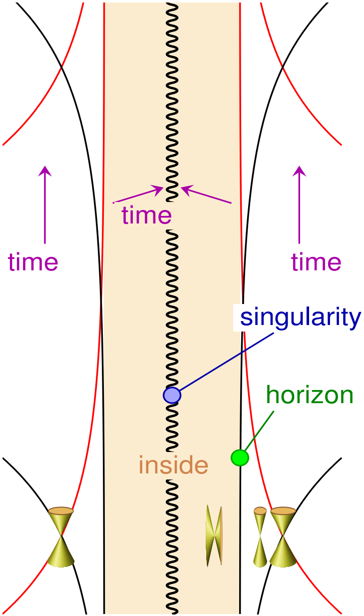
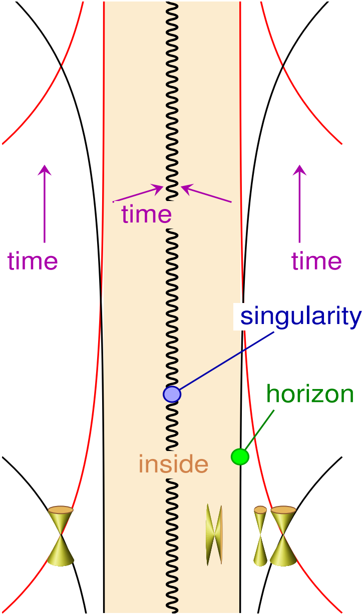
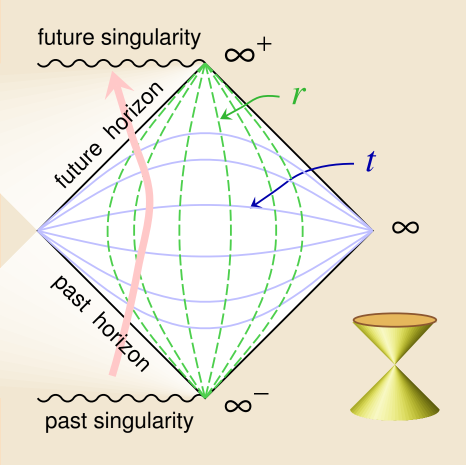
. . . First, we need to understand what happens with particles that are near, but not (yet) inside, a black hole

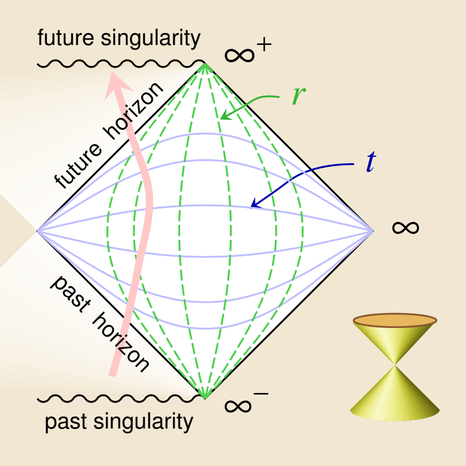

time
time
time
singularity
horizon
inside





Penrose diagram
(conformal mapping in (r, t) space)

In these coordinates space-time stays smooth across both horizons.



What happens beyond the horizon ?

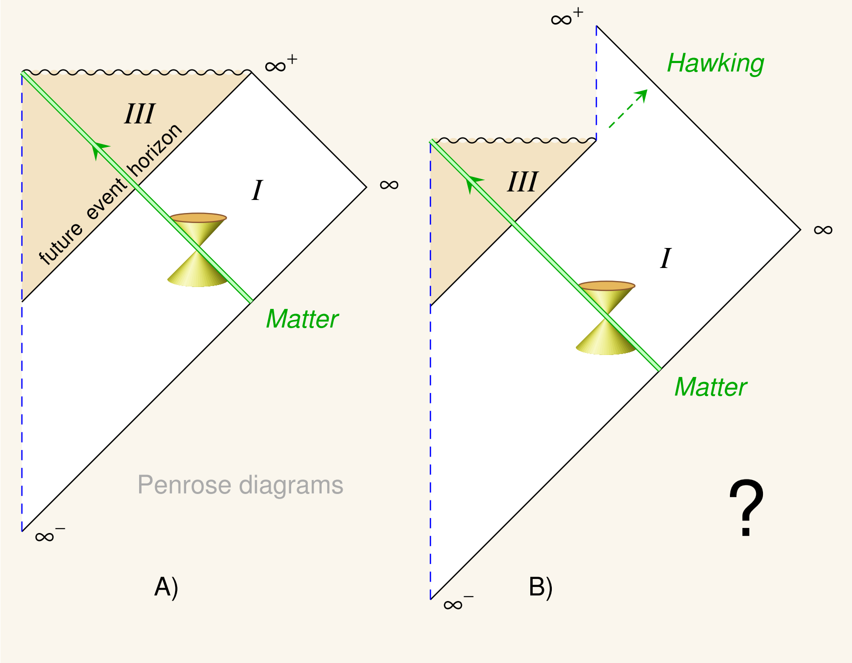
It depends on whether we keep the in and/or out going particles in *one single entangled quantum state,* or we consider measuring their states, at which they can be assumed to be in many different states.

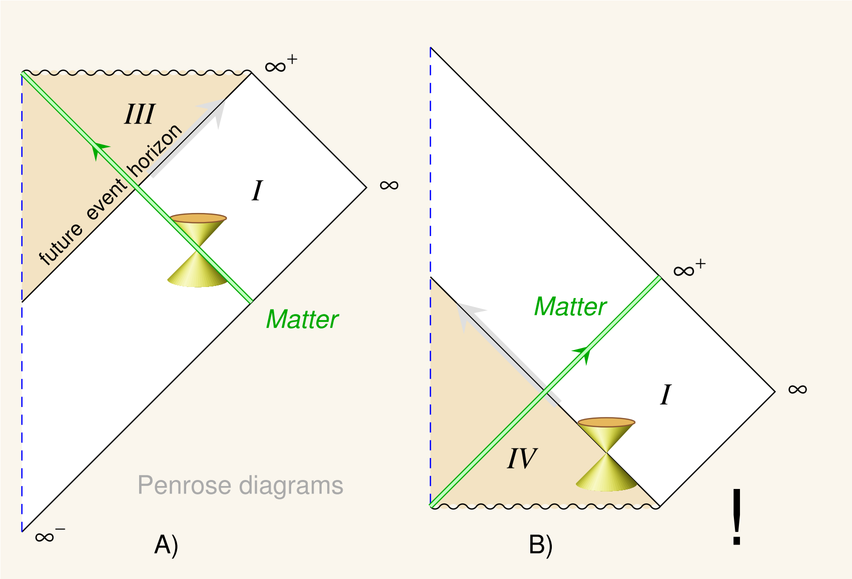
If they are entangled in one state, their gravitational effect disappears

– why is that so? – ,

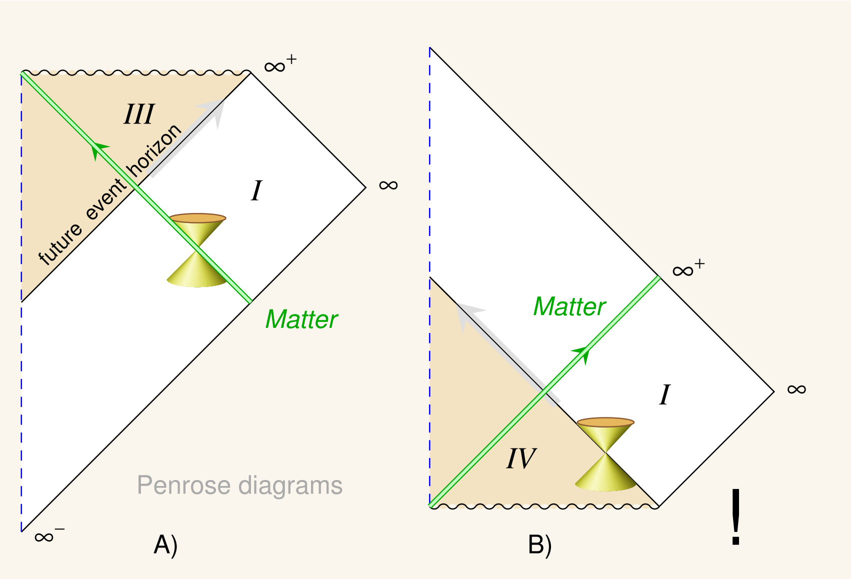
otherwise, their effect on space-time diverges with (external) time coordinate.

This is where new physics is required – not understood by most authors, even Hawking.)


∞+
III
future event horizon
I
∞
Matter
∞−
A)
Penrose diagrams
∞+
Hawking
III
I
∞
Matter
?
∞−
B)



∞^+
III
future event horizon
I
∞
Matter
Penrose diagrams
∞^-
A)
∞^+
Matter
I
∞
IV
!
B)



Rules: in-repres.: *Matter* in → entangled Hawking configuration out ;
out represent.: Entangled Hawking matter in → observable matter out.

We now propose to change the rules again: the interaction representation:

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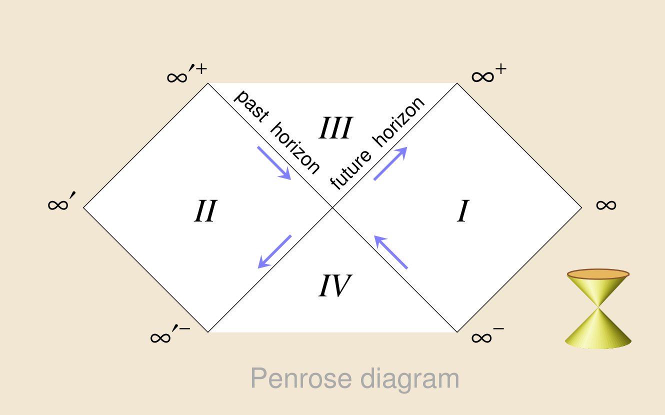
One must consider exactly *all* of Hilbert space generated by the Standard Model, augmented with *low energy* gravitons (i.e. *perturbative* gravity).

In our work, we show that early in going matter and late out going matter can all be put in the entangled state in such a way that the local observer sees no matter at all.

Then, we add slowly moving particles without disturbing the background matter too much.

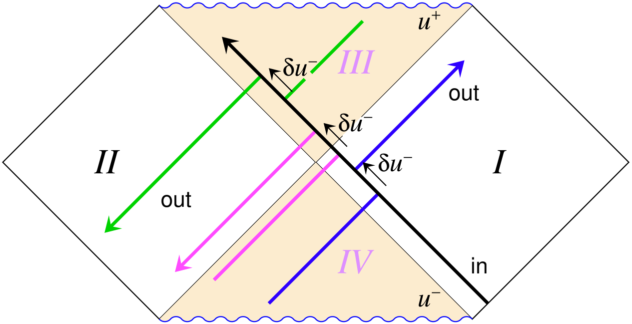
This gives a future and a past horizon:



Surprise:

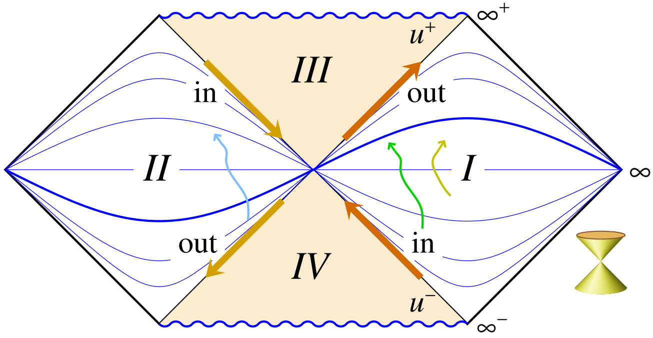
In the absence of (heavily gravitating) matter, Schwarzschild's solution may be exactly valid, but, when analytically continued, it features *two* universes, regions *I* and *II* , connected by a wormhole.

By exchange of gravitational forces, articles in universe *I* and universe *II* are found to interact directly with each other.



This implies that they should not be regarded as describing two different black holes — they are *the same* black hole.

But further calculations suggest that regions *I* and *II* describe this one black hole back-to-back: they are each other's *antipodes*.



Following a path – that has to be faster than light at some places – from region *I* to region *II*. How do these two worlds connect? Surprises again:

This has to go through a *CPT* transformation:

$$I \Leftrightarrow II$$
$$\vec{x} \Leftrightarrow -\vec{x}$$
$$t \Leftrightarrow -t$$
$$\text{particle} \Leftrightarrow \text{antiparticle}$$

$t \Leftrightarrow -t$ suggests also for the Hamiltonian: $H \Leftrightarrow -H$, but this can't be: energy is always positive.
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Instead, we find:

$$H \quad \Leftrightarrow \quad E^{\,\mathrm{max}} - H \ .$$

Or: the vacuum in II will be seen as an *anti-vacuum* (a region completely filled with energy) for observers in I.

The stationary situation will continuously match these states, so one may expect the locally empty metric to represent a state where, for global observers, the crossing point of the horizons is half-filled with particles. These are the matter particles that made the black hole, long ago, and they later materialise as Hawking particles.

The gravitational interaction linking in-particles with out-particles (see slide #12) actually links the data of the momenta of the in-particles with the positions of the out-particles, and *vice versa*
(by re-positioning out-particles in accordance with the momenta of the in-particles, one can say that the in-particles leave all their information as foot prints in the out particles.

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The foot-prints replace the bothersome firewall.

First order calculations enabled us to derive the **quantum evolution operator** for the black hole along these lines.

This operator emerges as being *perfectly unitary*
(positions are the Fourier transformations of momenta, and the Fourier transformation is a unitary operation).

Thus, also the so-called ‘information paradox disappeared.

What was arrived at, along these lines, is a completely coherent picture of the evolution equations for a quantum black hole. The final trick not yet emphasised here, is that, as time proceeds, What was arrived at, along these lines, is a completely coherent picture of the evolution equations for a quantum black hole. The final trick not yet emphasised here, is that, as time proceeds, particles near the past horizon increase their energies exponentially, while in the other time direction, the particles separate exponentially fast from the future event horizon. What just remained to be done is to replace the information in the momenta of in-particles by information on the positions of the out-particles.

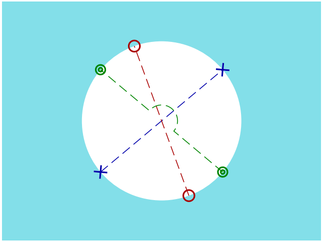
This is carried out almost automatically.

And there is no physics at all 'inside' the horizon.

Opening up (collapse) and closing in (final evaporation) of a black hole:

Black emptiness: blue regions are the accessible part of space-time; dotted lines indicate identification.

The white sphere within is *not* part of space-time. Call it a 'vacuole'.



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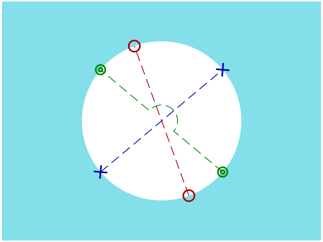

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At given time t, the black hole is a 3-dimensional vacuole. The entire life cycle of a black hole is a vacuole in 4-d Minkowski space-time: *an* **instanton**

N.Gaddam, O.Papadoulaki, P.Betzios (Utrecht PhD students)

Space coordinates change sign at the identified points

– *and also time changes sign*

(Note: time stands still at the horizon itself).

The unitary *Black hole scattering matrix* is readily derived:

$$\sigma = \pm 1 \ , \qquad -\infty < \varrho < \infty:$$

$$\psi_{\rm in}(\varrho, \sigma) = \psi_\sigma^{\rm in}\, e^{-i\kappa(\varrho+\tau)} \ ; \qquad \psi_{\rm out}(\varrho, \sigma) = \psi_\sigma^{\rm out}\, e^{i\kappa(\varrho-\tau)}$$

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The Fourier transformation gives at fixed ℓ, m

$$\begin{pmatrix}\psi^{\rm out}_+\\ \psi^{\rm out}_-\end{pmatrix} = \frac{e^{-\frac{\pi i}{4}}}{\sqrt{2\pi}}\Gamma(\tfrac12 - i\kappa)\begin{pmatrix} e^{-\frac12\pi\kappa} & ie^{+\frac12\pi\kappa}\\ ie^{+\frac12\pi\kappa} & e^{-\frac12\pi\kappa}\end{pmatrix} e^{-i\kappa\log\left(8\pi G/(\ell^2+\ell+1)\right)}\begin{pmatrix}\psi^{\rm in}_+\\ \psi^{\rm in}_-\end{pmatrix}$$

Of course, the Fourier transform is unitary. Here, unitarity follows from:

$$|\Gamma(\tfrac12 - i\kappa)|^2 = \frac{\pi}{\cosh\pi\kappa}$$

Many questions remain:

1. State counting: still qualitative
2. Rewrite in-out momentum and position amplitudes in terms of the SM particles in and out
3. Horizon is very similar to, but not the same as, the string world sheet. Particles are vertex insertions, Find Kac-Moody algebras etc.
4. Further understanding of the vacuole - instanton (virtual emerging and disappearing black hole)
5. Further ideas about connection with SM and with deterministic quantum schemes (the "anti-vacuum")

See explanation in lecture format on my home page:

https://webspace.science.uu.nl/~hooft101/lectures/GtHBlackHole_latest.pdf

More work done by N.K. Gaddam, O. Papadoulaki and P. Betzios.
Undergraduates: W. Vleeshouwers and P. Groenenboom.

Foundations / Emergence of QM: arxiv:2010.02019

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THANK YOU

We benefited from discussions with P. Betzios, N. Gaddam,
O. Papadoulaki, S. Mathur, L. Susskind, J. Maldacena and many others.

See: G. 't Hooft, arxiv:1612.08640 [gr-qc] + references there;
arxiv:1804.05744 [gr-qc], arXiv:1809.05367.

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See also:

P. Betzios, N. Gaddam and O. Papadoulaki, The Black Hole S-Matrix from Quantum Mechanics, JHEP 1611, 131 (2016), arxiv:1607.07885.

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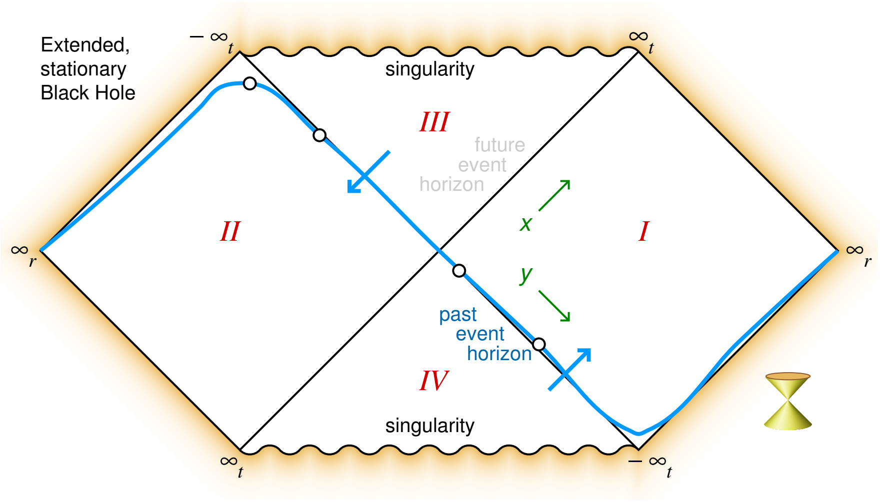
∞ THE END ∞

The following are spare slides. Not ordered very well . . .

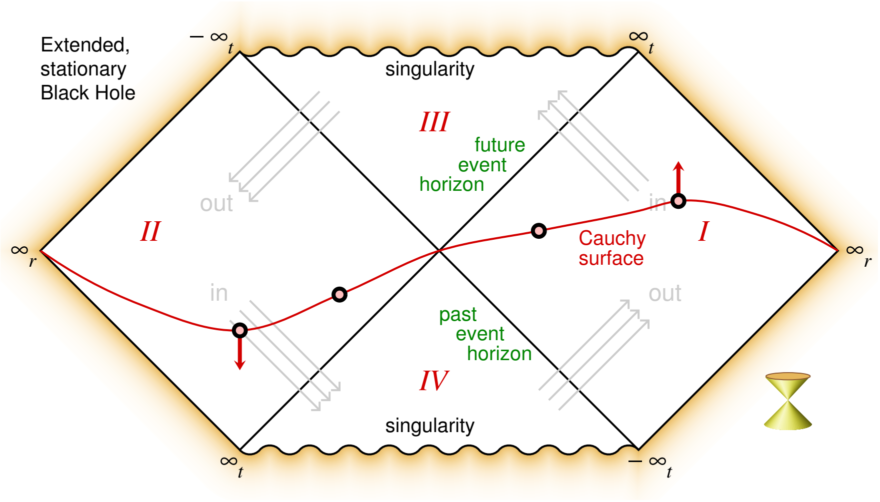
The gravitational back reaction *shifts* the data on the Cauchy surface across the horizon. Inevitable consequence:

Cauchy surfaces must be drawn from ∞_r in region II to ∞_r in region I.



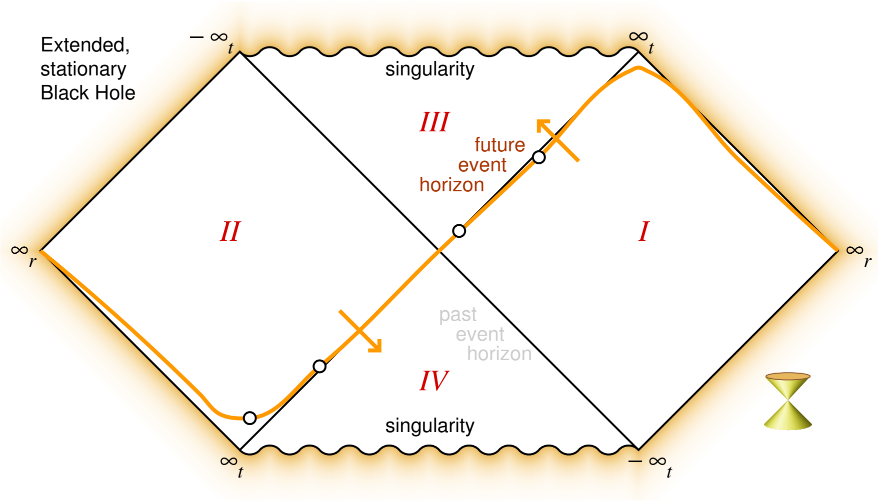
For local observers, the Cauchy surface goes from down to up in both regions.

For distant observers, the direction of time switches in region *II*.

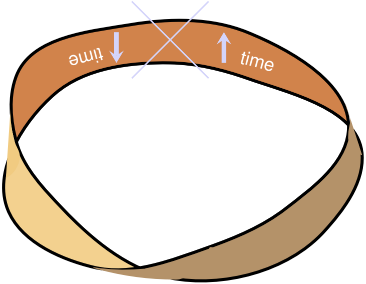


The regions *I* and *II* are exact copies of one another.

Susskind and Maldacena: two "entangled" black holes. This is disputed: they are not just entangled; they *interact* (See slide **??**)



A timelike Möbius strip



Draw a spacelike closed curve:
Begin on the horizon at a point
$r_0 = 2GM \ , \ t_0 = 0 \ , \ (\theta_0, \varphi_0) \ .$

Move to larger r values, then
travel to the antipode:

$r_0 = 2GM \ , \ t_0 = 0 \, , \ (\pi - \theta_0, \varphi_0 + \pi) \ .$
You arrived at the same point,
so the (space-like) curve is closed.

Continuously transport $\mathrm{d}x$ around the curve.
Identification at horizon:

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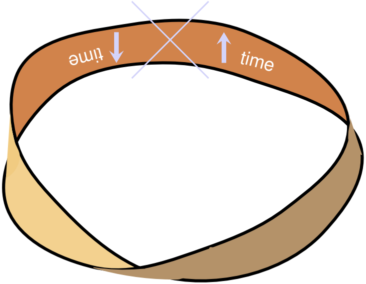

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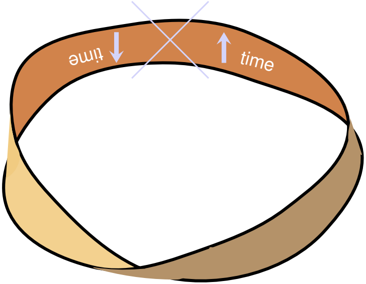
Identification at horizon:

$$\mathrm{d}x \Leftrightarrow -\mathrm{d}x\ , \quad \mathrm{d}t \Leftrightarrow -\mathrm{d}t\ .$$

This is a Möbius strip, making a T C and P inversion when going around the loop.

A timelike Möbius strip



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No clash with Standard Model,
which is invariant under product C, P and T .