Title: The antipodal identification as a new boundary condition on the horizon, and how it comes about

Speakers: Gerard 't Hooft

Collection: Cosmological Frontiers in Fundamental Physics 2019

Date: September 05, 2019 - 10:45 AM

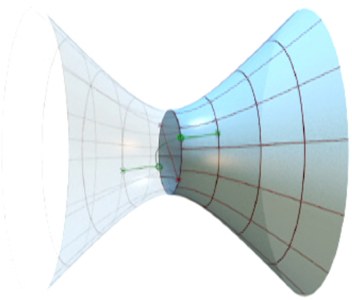
URL: http://pirsa.org/19090008

Abstract: Quantizing the black hole can be done without String Theory, fuzz balls, AdS/CFT and such. We just assume matter to keep the form of point particles until they come close to the horizon. The gravitational back reaction of these particles generates a novel relation between particles going in and particles going out, enabling us to transform in-going particles into out-going ones. This transformation removes "firewalls" along the future and past horizons, but it strongly affects space-time inside a black hole. It subsequently allows us, and indeed forces us, to identify antipodal points on the horizon. We argue that this is the only way to restore unitarity for the quantum evolution operator, and to identify the black hole microstates. Some mysteries, however, remain unresolved.

Physics Utrecht
EMMEΦ

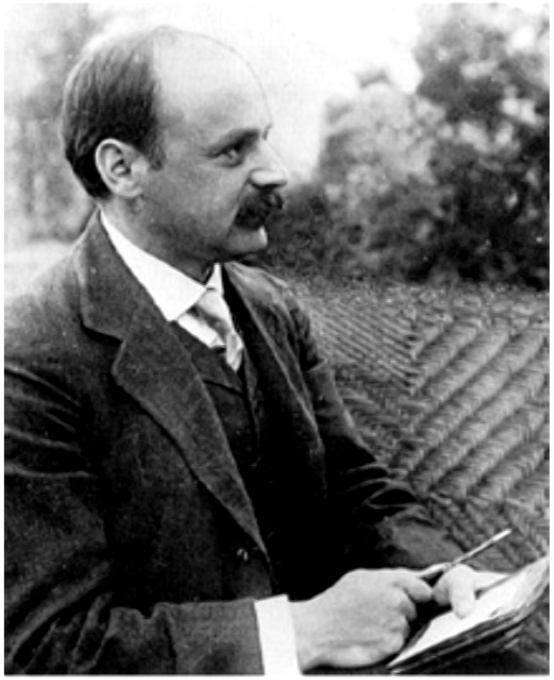
Gerard 't Hooft

The antipodal identification as a new boundary condition on the horizon,
and how it comes about



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

Presented at
"Cosmological Frontiers in
Fundamental Physics 2019",
Perimeter Institute for Theoretical Physics,
Waterloo, Ontario, Canada.
4 September 2019



Karl Schwarzschild

9 October 1873 – 11 May 1916

December 1915, shortly after Albert Einstein anounced his theory on *General Relativity*, he received a letter from the well-known German astronomer Karl Schwarzschild, showing him his exact solution of the equations for a gravitational field in the case of spherical symmetry

(derived while serving the German army at the Russian front, under heavy gun fire)

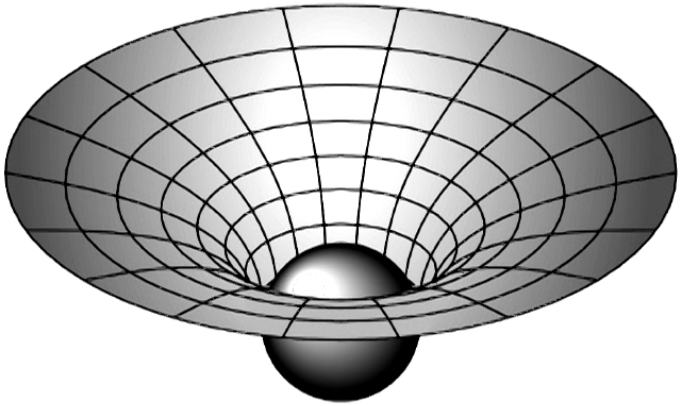
Karl died a few months after his paper was published; he never witnessed the heavy debates his solution would later give rise to.

Schwarzschild's equation (in modern notation):

$$\mathrm{d}s^2 = -(1-2GM/r)\,\mathrm{d}t^2 + \frac{\mathrm{d}r^2}{1-2GM/r} + r^2(\mathrm{d}\theta^2 + \sin^2\theta\mathrm{d}\varphi^2)\ .$$

When a star contracts due to its own gravitational attraction, this should describe the gravitational field surrounding it.

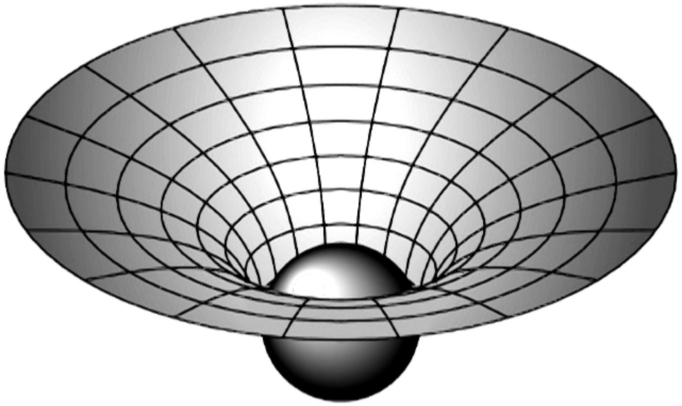
What happens at $r \to 2GM$?



At $r = 2GM$, the gravitational potential is so strong that *time* stands still there.

What happens beyond that point? Schwarzschild thought that that point must be regarded as the origin of space.

Light cannot pass that point. It is a *horizon*.



At $r = 2GM$, the gravitational potential is so strong that *time* stands still there.

What happens beyond that point? Schwarzschild thought that that point must be regarded as the origin of space.

.

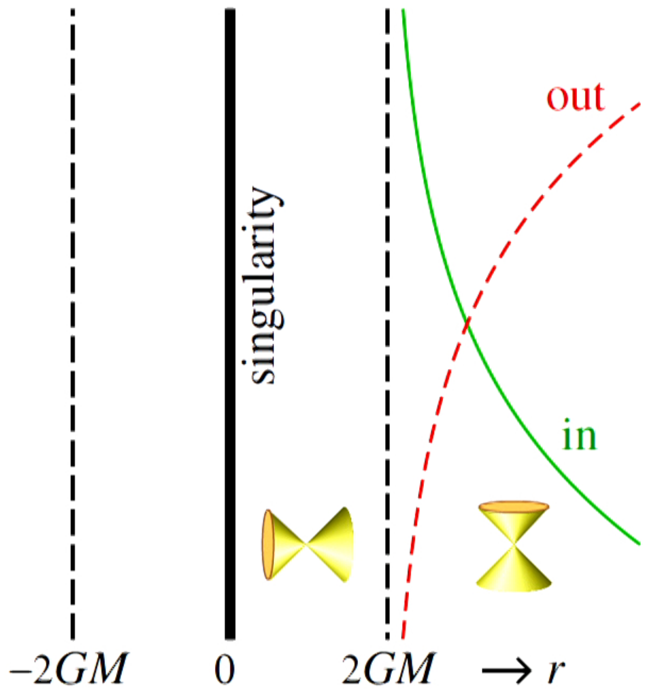
Light cannot pass that point. It is a *horizon*. However, one can compute the paths taken by light rays. A genuine *singularity* exists only at the point $r = 0$.

Often forgotten: The singularity $r = 0$ is not at the center of this body, it lies in the infinite future. It will always stay at the infinite future.
Therefore: *the singularity is completely hamless physically*.

In space-time, polar coordinates, we ignore angular variables θ, φ,

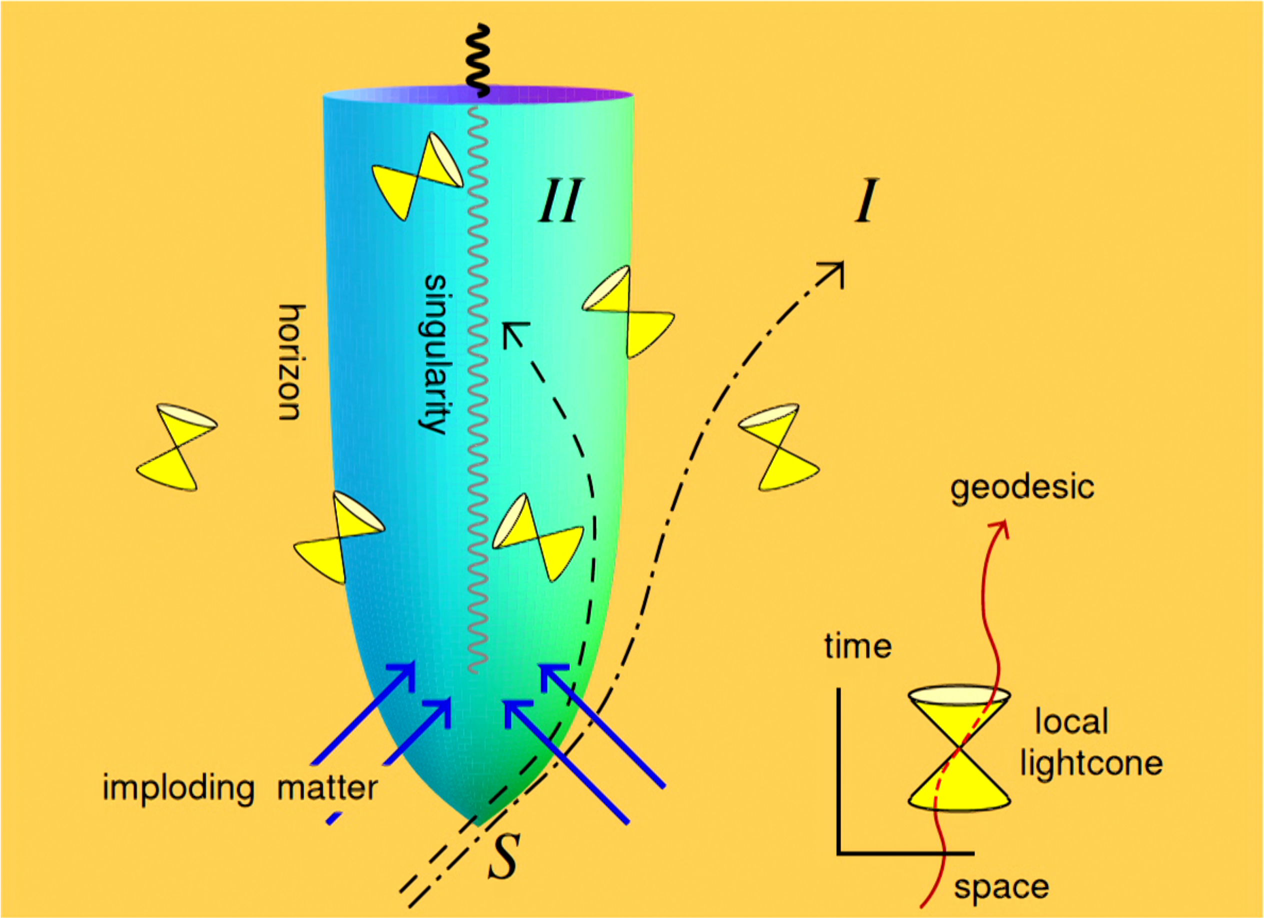
speed of light is:

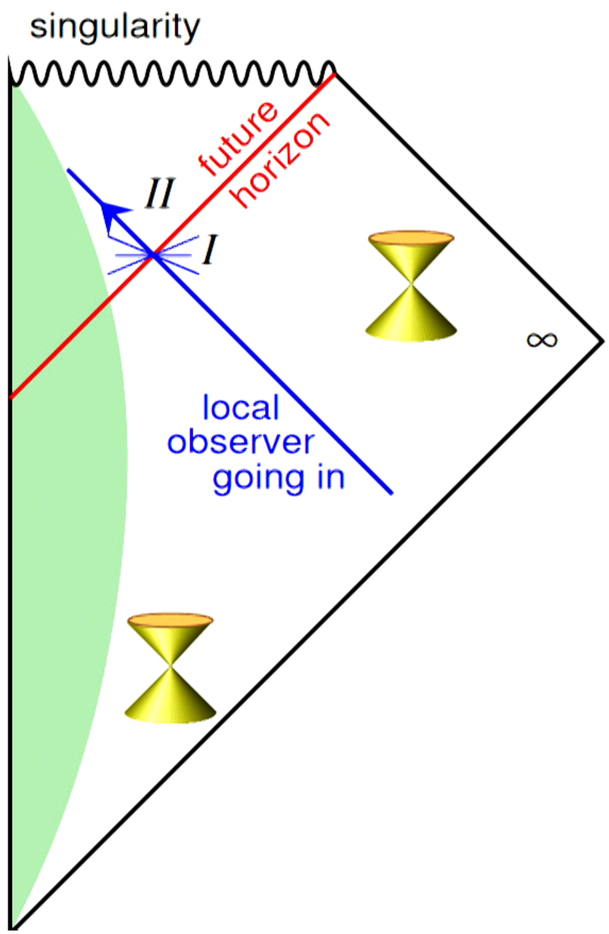
$$1 - \frac{2GM}{r} .$$



Notice how the light cone flips over.

Artist's impression of *matter imploding to give rise to a black hole:*





Penrose coodinates: deform r and t in such a way that light can maximally go under 45° everywhere: $g^{00}\,/\,g^{11} = -1$.

In these coordinates, we see that the horizon is *not* a singularity.

The $r = 0$ singularity is in the infinite future.

Now this was only "conventional physics", compared to what comes next:

theoreticians are interested in the *generic case*. What are the properties of the *complete set* of all black hole-like objects?

All evidence for the existence of black holes exclusively concerns astronomically large ones. Their behaviour is assumed to be exclusively determined by the laws of Einstein's General Relativity, and, one assumes, any corrections due to quantum effects can be safely ignored.

However, Einstein's theory does not put a lower limit to the size and mass. How small is the smallest black hole?

Generally,

All evidence for the existence of black holes exclusively concerns astronomically large ones. Their behaviour is assumed to be exclusively determined by the laws of Einstein's General Relativity, and, one assumes, any corrections due to quantum effects can be safely ignored.

However, Einstein's theory does not put a lower limit to the size and mass. How small is the smallest black hole?

Generally, this is assumed to be somewhere near the Planck size, 1.6×10^{-33} cm, and mass, 22 μg. This is deeply inside the domain where QM effects *are* assumed to dominate.

Quantum black holes are not expected to be experimentally accessible in any foreseeable future.

Why are they important?

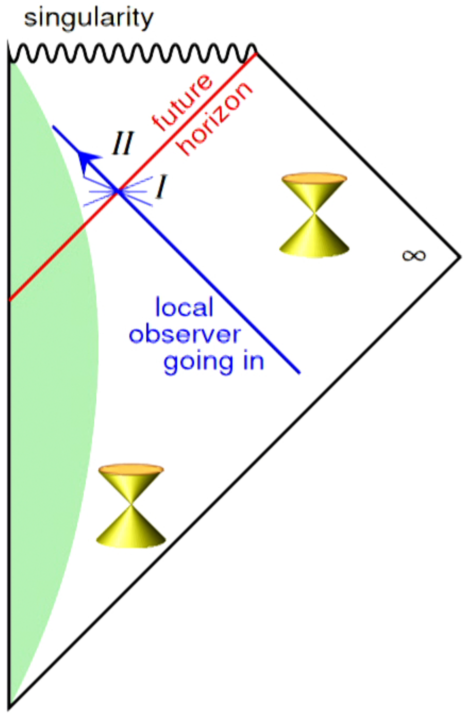
All evidence for the existence of black holes exclusively concerns astronomically large ones. Their behaviour is assumed to be exclusively determined by the laws of Einstein's General Relativity, and, one assumes, any corrections due to quantum effects can be safely ignored.

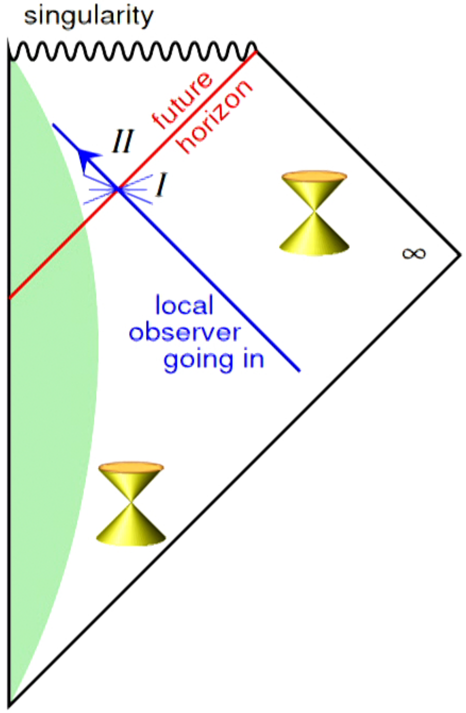
However, Einstein's theory does not put a lower limit to the size and mass. How small is the smallest black hole?

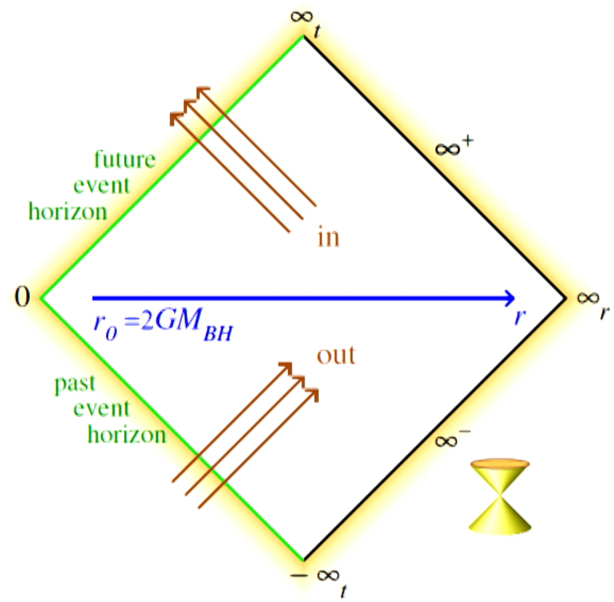
Generally, this is assumed to be somewhere near the Planck size, 1.6×10^{-33} cm, and mass, 22 μg. This is deeply inside the domain where QM effects *are* assumed to dominate.

Quantum black holes are not expected to be experimentally accessible in any foreseeable future.

Why are they important? They are very important !!


singularity
future
horizon
II
I
∞
local
observer
going in





Stephen W. Hawking asked the question:

"How do we apply QFT in the space-time of a black hole?"

First ask: "What is the vacuum state in that space-time?"
Note that the vacuum is defined as being the lowest energy state.
But since the black hole environment disturbes the energies of particles, the lowest energy state in the presence of the black hole will be different from the usual one. Actually,

As long as you have a black hole, there is no 'lowest energy state'!
The lowest energy state is the state with no black hole at all.

The mathematics of quantized fields tells us:
if an in-going observer detects no particles at all, an observer outside sees particles going in and out.. *This is not just an 'optical effect':*

A black hole decays, through tunnelling, by emitting particles.

The intensity of this radiation can be computed:

As the black hole loses mass, its radiation must intensify . . .

This must end with a gigantic explosion !!

What are the physical laws for the exposion?

This is much more difficult to derive.

We should be able to use all physics we know, to do the precise calculation.

The intensity of this radiation can be computed:

As the black hole loses mass, its radiation must intensify . . .

This must end with a gigantic explosion !!

What are the physical laws for the exposion?

This is much more difficult to derive.

We should be able to use all physics we know, to do the precise calculation.

Why is this so difficult?

The intensity of this radiation can be computed:

As the black hole loses mass, its radiation must intensify . . .

This must end with a gigantic explosion !!

What are the physical laws for the exposion?

This is much more difficult to derive.

We should be able to use all physics we know, to do the precise calculation.

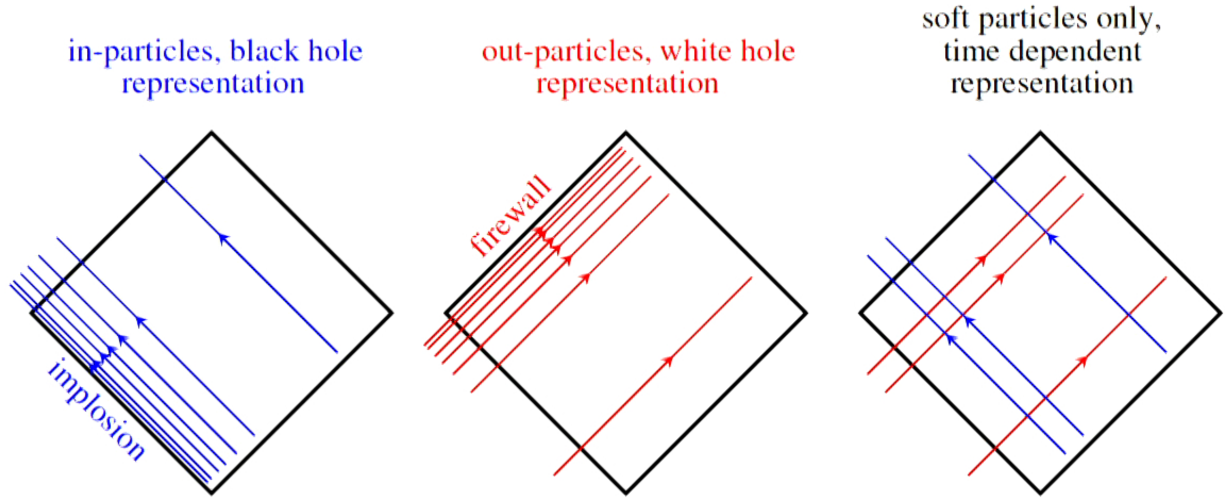
Why is this so difficult?

The outcome makes no sense!

That is, to some of us . . .

Patiently applying all physical laws known to us removers most of the difficulties. Let's see . . .

The Penrose diagrams for the universe surrounding a black hole *describe* early in-particles and late out-particles *exponentially compressed.*
This way, they form barriers whose gravitational effects strongly deform the part of space-time behind them.
The ideal way to represent the quantum states of a black hole is to consider all possible states that do not have such barriers.
Other researchers talk of *firewalls*. They are basically the same things.
Our proposal is to consider the removal of these barriers as being symmetry transformations, like in gauge theories.



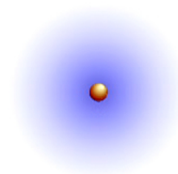
All quantum states of a black hole can be obtained by considering only soft particles (particles that are moving sifficiently slowly so as not producing significant gravitational deformations), in this extended space-time.

Amazingly, this works, after 2 more steps are taken.

Step 1: the gravitational interaction between in- and out going particles must be taken into account.

The *gravitational effect* of a fast, massless particle is easy to understand:

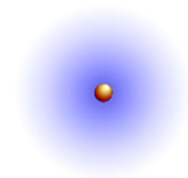
Schwarzschild metric of a particle with tiny rest mass $m \ll M_{\mathrm{Planck}}$:



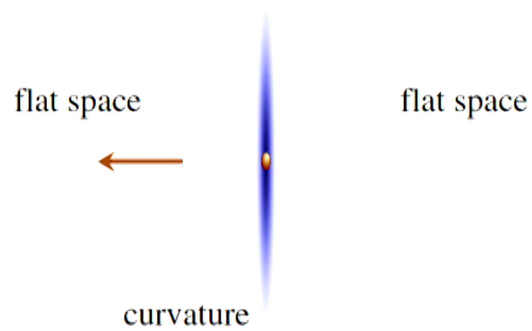
And now apply a strong *Lorentz boost*, so that $E/c^2 \gg M_{\mathrm{Planck}}$:

The *gravitational effect* of a fast, massless particle is easy to understand:

Schwarzschild metric of a particle with tiny rest mass $m \ll M_{\rm Planck}$:

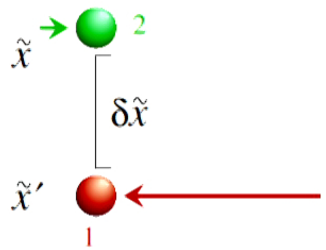


And now apply a strong *Lorentz boost*, so that $E/c^2 \gg M_{\rm Planck}$:



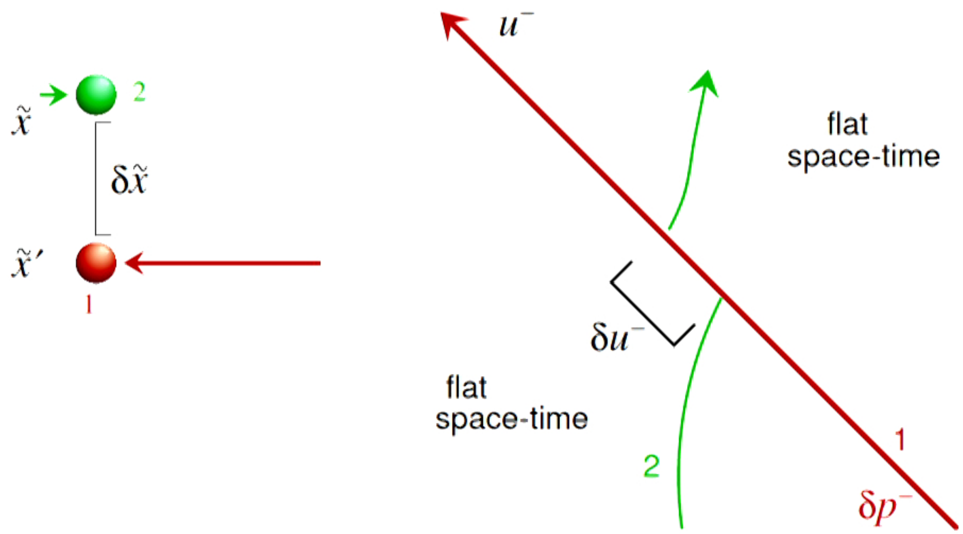
This gives us the
gravitational backreaction:

Lorentz boosting the light (or massless) particle gives the *Shapiro time delay* caused by its grav. field:



This gives us the
gravitational backreaction:

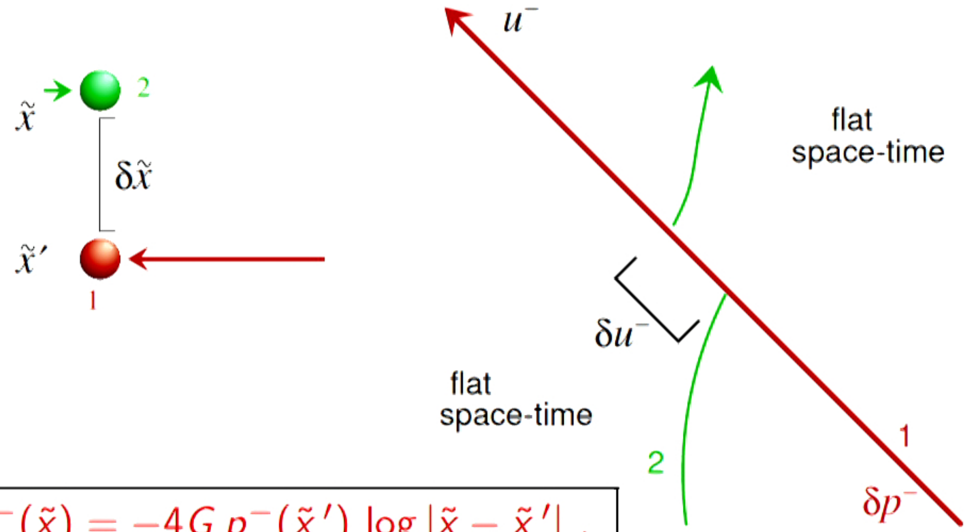
Lorentz boosting the light (or massless) particle gives the *Shapiro time delay* caused by its grav. field:



This gives us the

gravitational backreaction:

Lorentz boosting the light (or massless) particle gives the *Shapiro time delay* caused by its grav. field:



$$\delta u^-(\tilde{x}) = -4G\, p^-(\tilde{x}\,')\, \log|\tilde{x} - \tilde{x}\,'|\ .$$

P.C. Aichelburg and R.U. Sexl, J. Gen. Rel. Grav. **2** (1971) 303,
W.B. Bonnor, *Commun. Math. Phys.* **13** (1969) 163,
T. Dray and G. 't Hooft, *Nucl. Phys.* **B253** (1985) 173.

Thus, step 1: in-going particles do have a gravitational effect on the out-going particles:

As time goes by, in-particles move from "future" to "past". Their momenta increase *exponentially*. The gravitational effect of that can now be calculated.

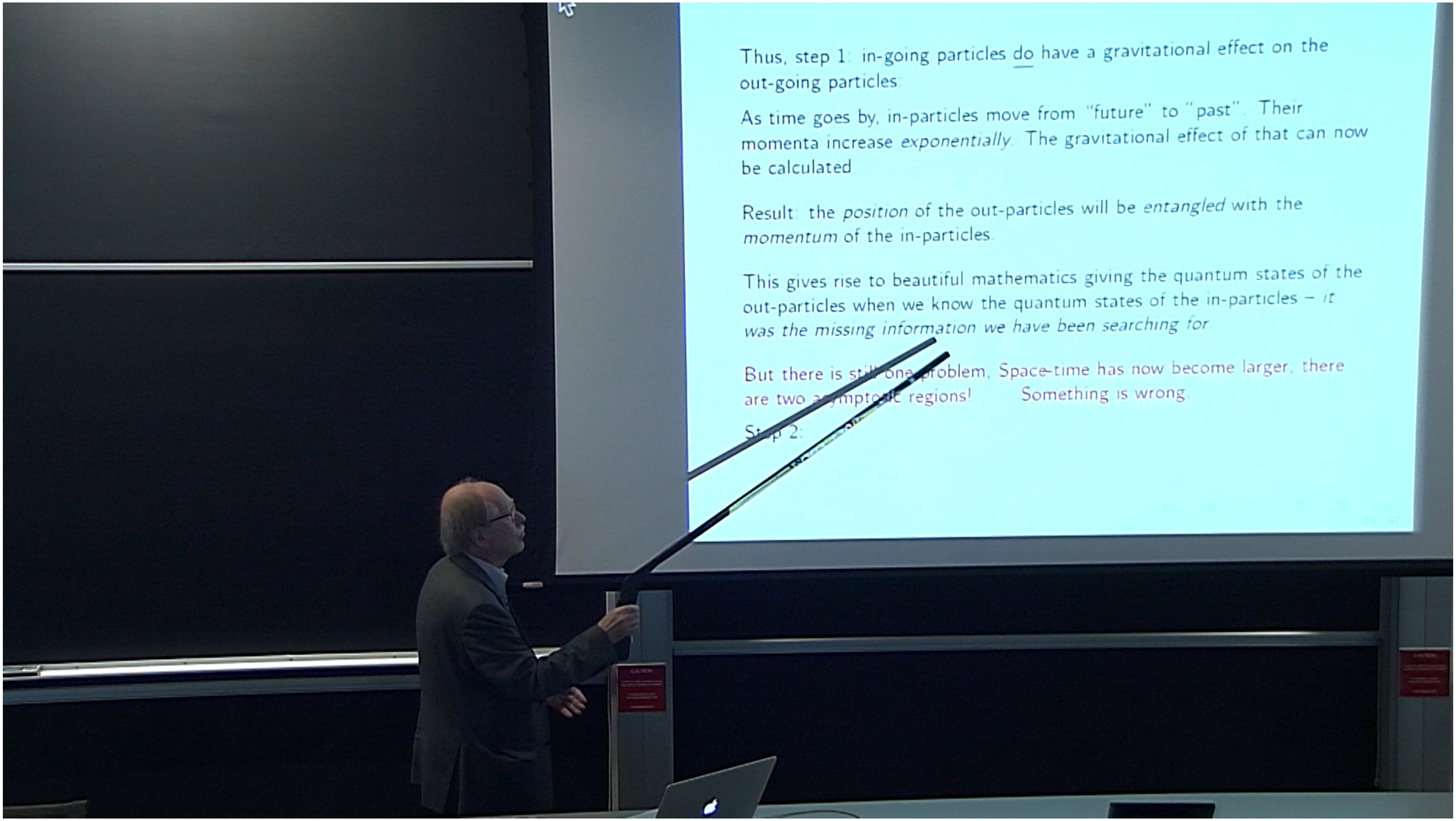
Result: the *position* of the out-particles will be *entangled* with the *momentum* of the in-particles.

This gives rise to beautiful mathematics giving the quantum states of the out-particles when we know the quantum states of the in-particles – *it was the missing information we have been searching for.*

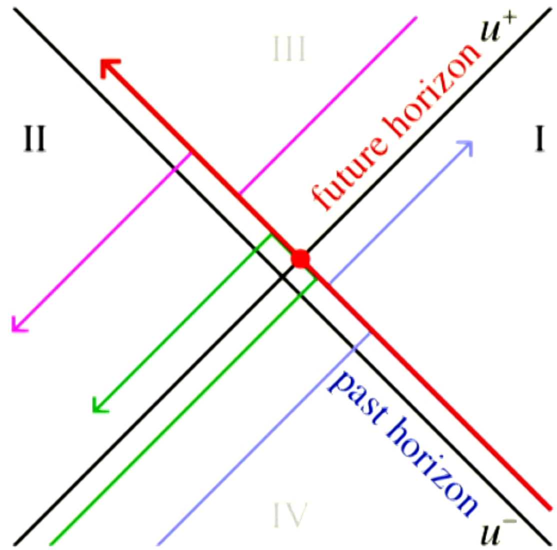
But there is still one problem, Space-time has now become larger; there are two asymptotic regions! Something is wrong.

Step 2:

the quantum states of the
states of the in-particles – it
been searching for.
has now become larger; there
Something is wrong.

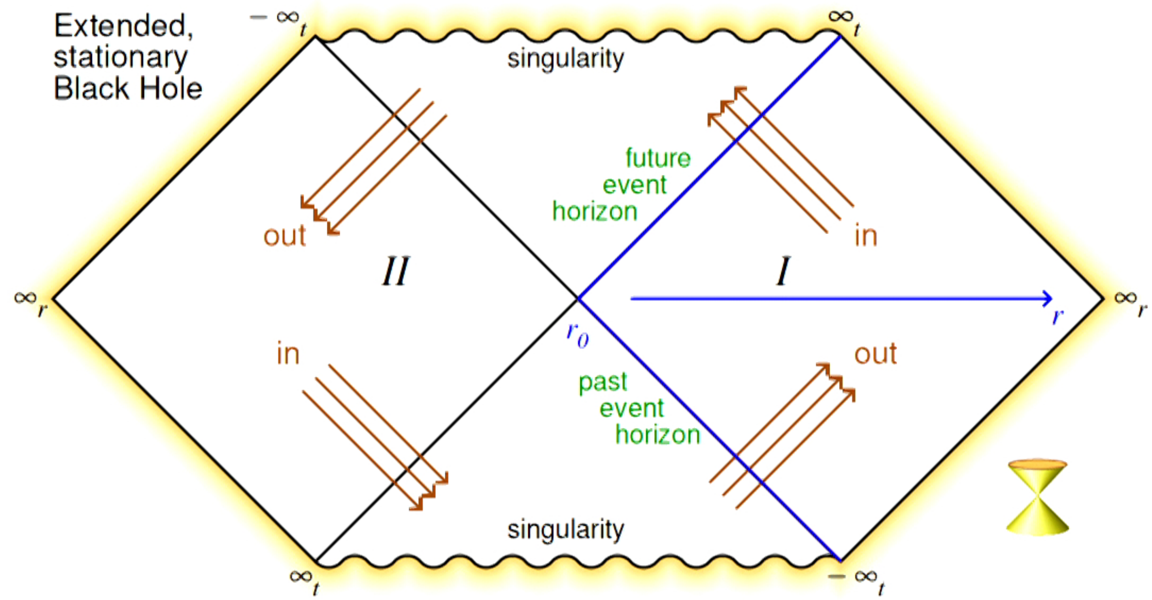

Thus, step 1: in-going particles do have a gravitational effect on the out-going particles:
As time goes by, in-particles move from "future" to "past". Their momenta increase exponentially. The gravitational effect of that can now be calculated.
Result: the position of the out-particles will be entangled with the momentum of the in-particles.
This gives rise to beautiful mathematics giving the quantum states of the out-particles when we know the quantum states of the in-particles – it was the missing information we have been searching for.
But there is st roblem, Space–time has now become larger, there are two mpto regions!
Something is wrong.
p 2:

Step 2. We see what the gravitational back reaction does to the data distribution: a given in-going particle (red line) causes all out-going particles (colored lines) to be shifted by the same amount, δu, which only depends on the angular variables (θ, φ), not on u. See slide # 11



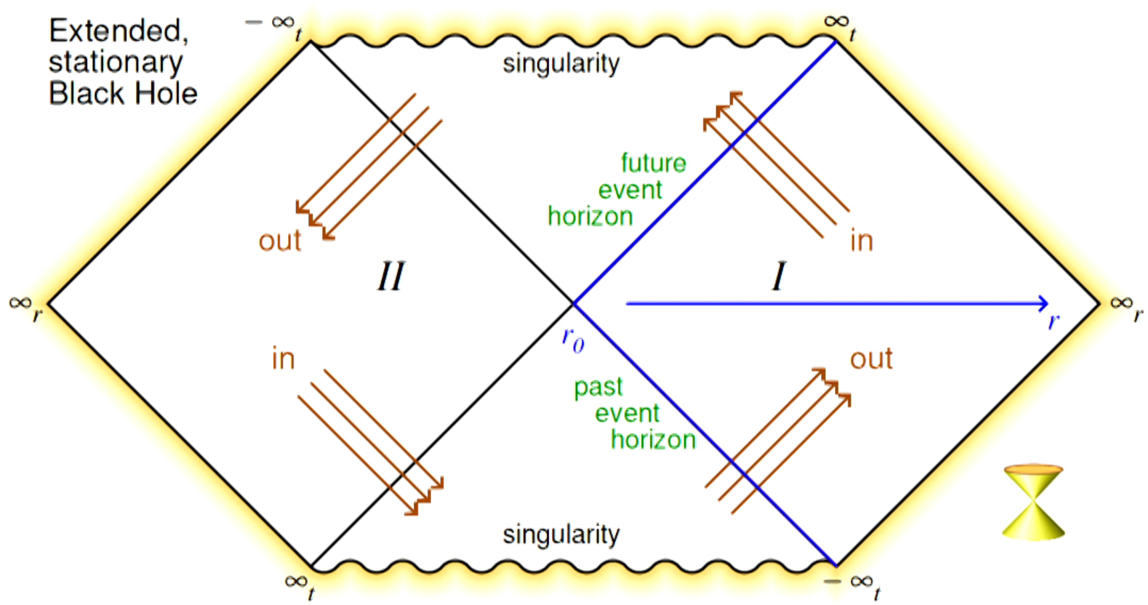
Thus, the data are shifted right across the horizon. Ignoring this fact causes confusion.

Same happens with past event horizon, by time reversal!



In-particles may be replaced by out-particles: momentum-in ↔ position out.
This transformation removes all high-mometum in- and out-particles.
Consequently, we may restore the empty netric Penrose diagram, *which now features two asymptotic regions*, or two external universes.

We may not ignore these other regions in the black hole Penrose diagram . . .



In-particles may be replaced by out-particles: momentum-in ↔ position out.

This transformation removes all high-mometum in- and out-particles.

Consequently, we may restore the empty netric Penrose diagram, *which now features two asymptotic regions*, or two external universes.

We may not ignore these other regions in the black hole Penrose diagram . . .

Step 2, cont'd:
We now have *two* quadrangles describing the outside space-time, where we started with only one.

What is the physical interpretation of this second domain?

It was first thought that region *II* refers to whatever is happening inside the black hole

But this

Step 2, cont'd:

We now have *two* quadrangles describing the outside space-time, where we started with only one.

What is the physical interpretation of this second domain?

It was first thought that region *II* refers to whatever is happening inside the black hole

But this cannot be right. Both regions have the same kinds of asymptotic domains at their boundaries.
They are both entire universes. What is this second universe?

Then it was thought that the second universe describes a second black hole, in an other universe, or very far away in our universe.
These two black holes were thought to be "entangled".

But ths cannot be right either. We find that these two black holes exchange information.
Entangled objects, such as the photons in the Einstein-Rosen-Podolsky paradox, do *not* interact.

The correct answer is probaly a more spectacular one:

This region *II* must represent *the other side* of the black hole.

This must mean that space-time is 'folded up' – as a result of our procedure of removing the firewalls, at both horizons.

At the horizon of the black hole,

all points are *identified* with their antipodes,

the antipodal identification.

A peculiar aspect of this: in regions *I* and *II*,

time runs in opposite directions.

One might have thought that

The correct answer is probaly a more spectacular one:

This region *II* must represent *the other side* of the black hole.

This must mean that space-time is 'folded up' – as a result of our procedure of removing the firewalls, at both horizons.

At the horizon of the black hole,

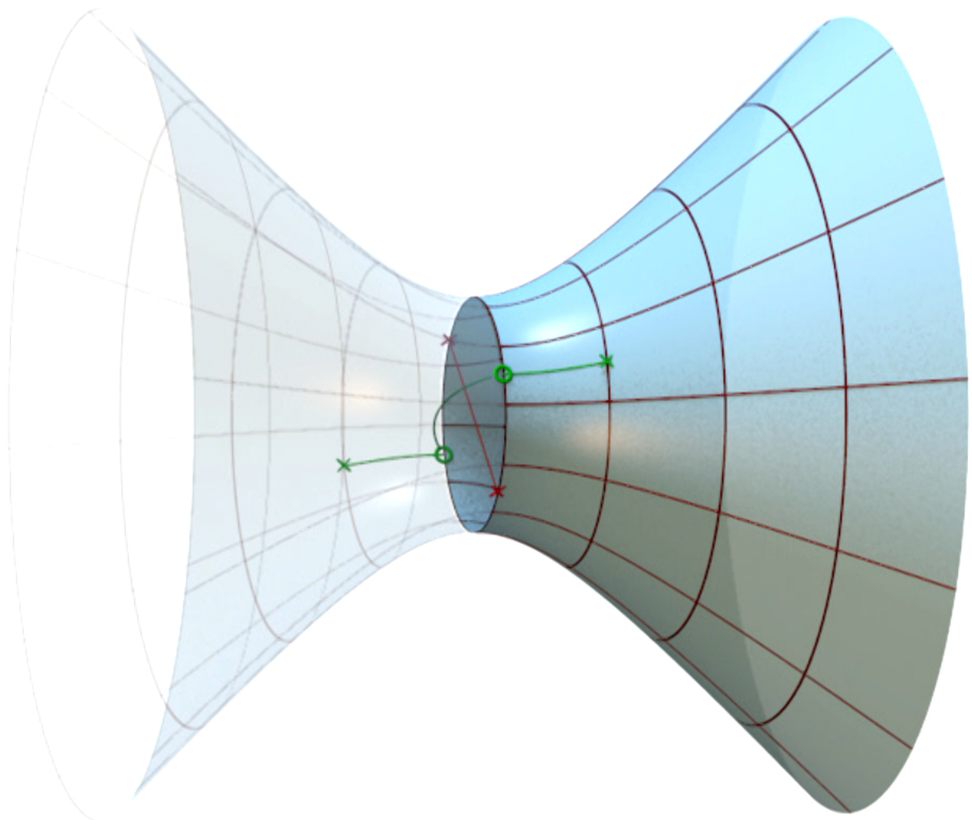
all points are *identified* with their antipodes,

the antipodal identification.

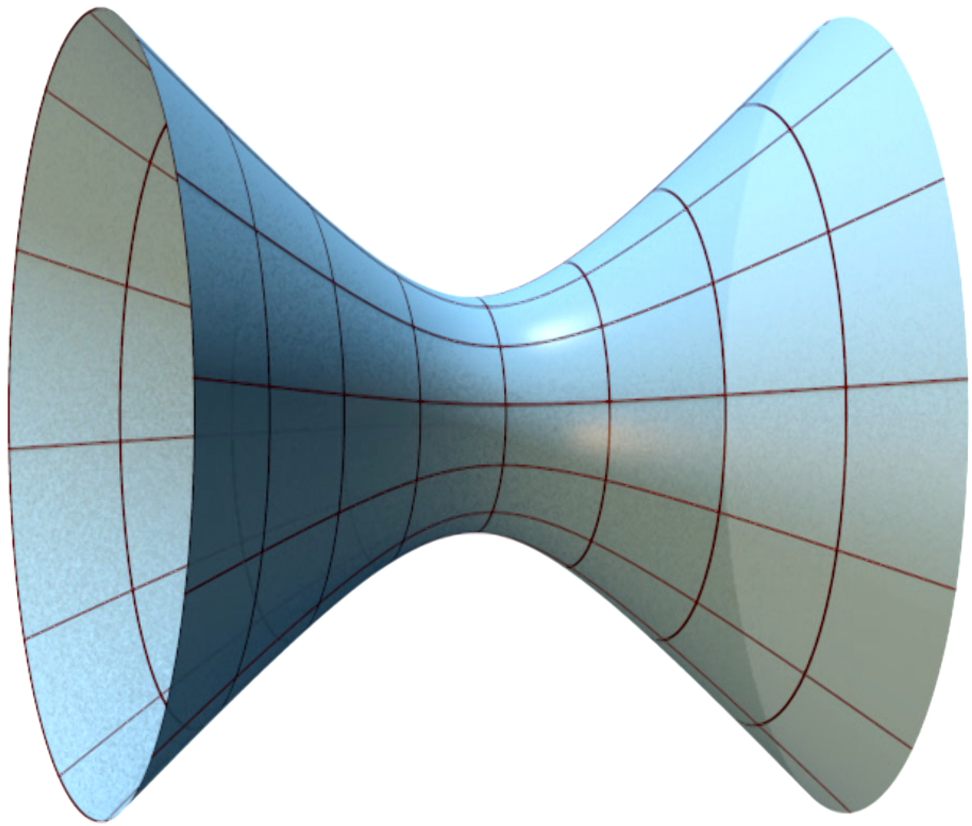
A peculiar aspect of this: in regions *I* and *II*,

time runs in opposite directions.

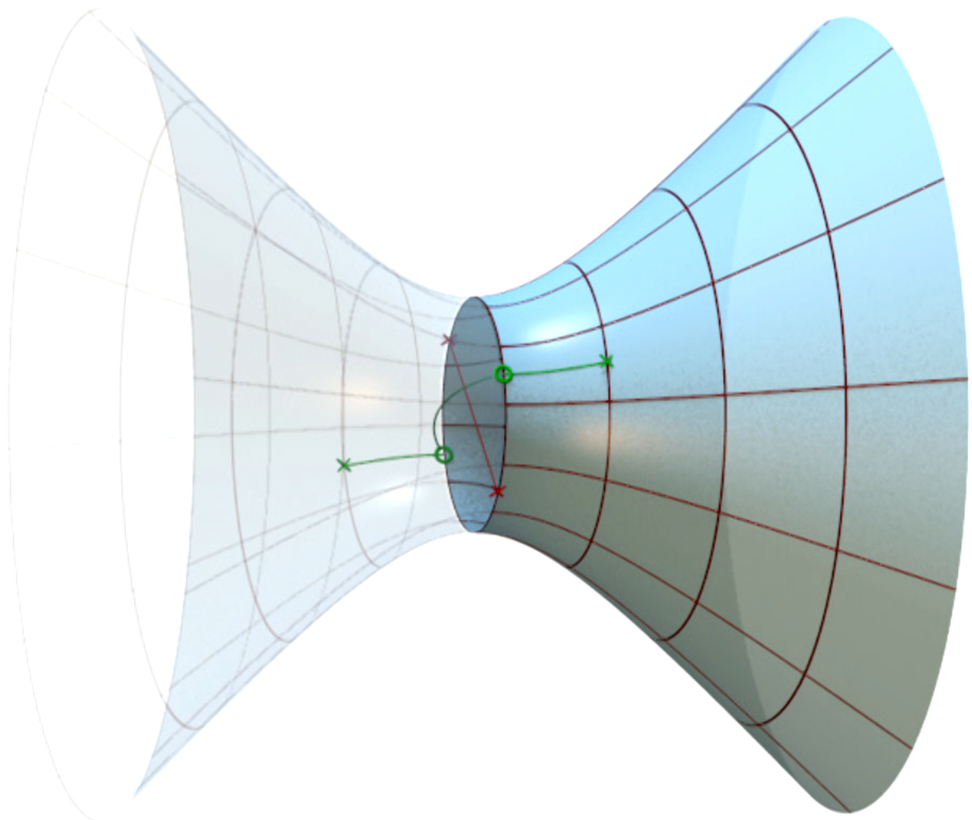
One might have thought that this violates causality, but, when inspecting the equations, it does not. To the contrary, the antipodal identification restores causality. Without it, we would have information travelling faster than light, to go from one black hole to the other black hole that it is entangled with.



24 / 67

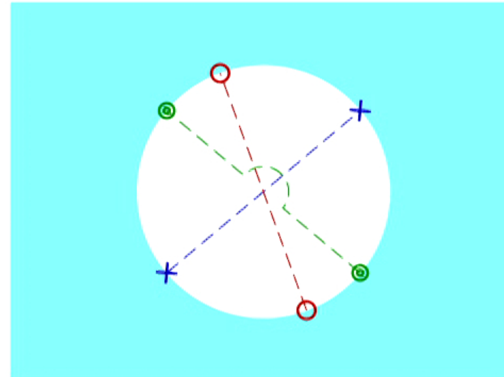


23 / 67



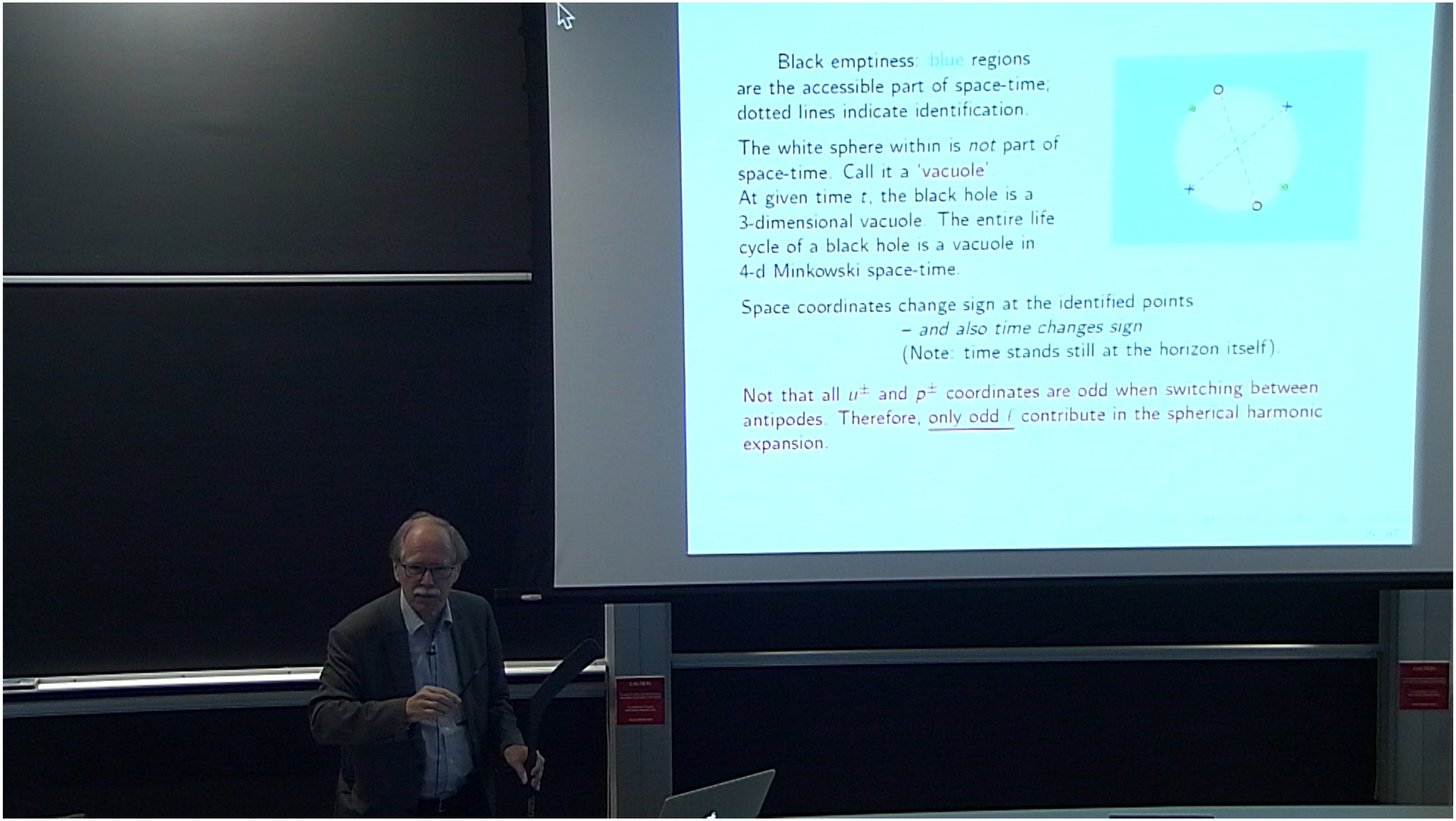
Black emptiness: blue regions are the accessible part of space-time; dotted lines indicate identification.

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



Space coordinates change sign at the identified points
– *and also time changes sign*
(Note: time stands still at the horizon itself).

Not that all $u^{\pm}$ and $p^{\pm}$ coordinates are odd when switching between antipodes. Therefore, only odd ℓ contribute in the spherical harmonic expansion.


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'.
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.
Space coordinates change sign at the identified points
– and also time changes sign
(Note: time stands still at the horizon itself).
Not that all u± and p± coordinates are odd when switching between antipodes. Therefore, only odd ℓ contribute in the spherical harmonic expansion.

If $\varrho_p \to \varrho_p + \lambda$, then simply $u \to u\, e^{-\lambda}$, $p \to p\, e^{\lambda}$, a symmetry of the Fourier transform.

This symmetry here corresponds to *Energy conservation.*

Use this symmetry to write plane waves:

$$\tilde\psi_{\sigma_u}(\varrho_u) \equiv \breve\psi_{\sigma_u}(\kappa)\, e^{-i\kappa\varrho_u} \quad \text{and} \quad \hat{\tilde\psi}_{\sigma_p}(\varrho_p) \equiv \hat{\breve\psi}_{\sigma_p}(\kappa)\, e^{i\kappa\varrho_p} \quad \text{with}$$

$$\hat{\breve\psi}_{\sigma_p}(\kappa) = \sum_{\sigma_p=\pm 1} F_{\sigma_u\sigma_p}(\kappa)\breve\psi_{\sigma_u}(\kappa)\ ; \quad F_\sigma(\kappa) \equiv \int_{-\infty}^{\infty} K_\sigma(\varrho) e^{-i\kappa\varrho} \mathrm{d}\varrho\ .$$

Thus, we see left-going waves produce right-going waves. Then, just do the integral

The Fourier operator for these states is:

$$F_\sigma(\kappa) = \tfrac{1}{\sqrt{2\pi}} \int_0^\infty \frac{\mathrm{d}y}{y} y^{\frac12 - i\kappa}\, e^{-i\sigma y} \ = \ \tfrac{1}{\sqrt{2\pi}}\, \Gamma(\tfrac12 - i\kappa)\, e^{-\frac{i\sigma\pi}{4} \,-\, \frac{\pi}{2}\kappa\sigma}\ .$$

This gives us the
gravitational backreaction:

Lorentz boosting the light (or massless) particle gives the *Shapiro time delay* caused by its grav. field: