## Gerard 't Hooft

# On the quantization of black holes 

## and consequences for

## quantum gravity, space, and time

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

## The basic, explicit, calculation

needed to generate the scattering matrix, relating all possible out-states to all possible in-states.

Keep all assumptions to an absolute minimum, and use instead the known laws of physics ...

Apart from the most basic assumption of unitary evolution, this is nothing more than applying GR and quantum mechanics

By using spherical harmonics, we shall find that this $S$-matrix factorises into expressions that require nothing but the solutions of 1 dimensional partial diff. equations

Of course there will be questions left open for discussion

Schwarzschild metric:

$$
\begin{array}{r}
\mathrm{d} s^{2}=-\mathrm{d} t^{2}\left(1-\frac{2 G M}{r}\right)+ \\
+\frac{\mathrm{d} r^{2}}{1-2 G M / r}+r^{2} \mathrm{~d} \Omega^{2} ; \\
\mathrm{d} \Omega^{2} \equiv \mathrm{~d} \theta^{2}+\sin ^{2} \theta \mathrm{~d} \varphi^{2} .
\end{array}
$$



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\end{array}
$$



## The tortoise coordinates

Kruskal-Szekeres coordinates $x, y$, defined by

$$
\begin{aligned}
x y & =\left(\frac{r}{2 G M}-1\right) e^{r / 2 G M} \\
y / x & =e^{t / 2 G M}
\end{aligned}
$$

In these coordinates, the metric stays regular at the horizon $(r \rightarrow 2 G M) . \quad x$ and $y$ are light cone coordinates.


For the outside observer, time stands still at the horizon
(the origin of this diagram)

The Einstein - Rosen bridge


$$
\begin{aligned}
& x(\tau)=x(0) e^{-\tau} \\
& y(\tau)=y(0) e^{\tau} \\
& \text { As time } \tau=t / 4 G M \\
& \text { goes forwards, } x \\
& \text { approaches the horizon } \\
& \text { asymptotically; } \\
& \text { as time goes } \\
& \text { backwards, } y \\
& \text { approaches the past } \\
& \text { horizon asymptotically } \\
& \text { (tortoises). }
\end{aligned}
$$

If the outside observer makes a time boost, the local observer makes a Lorentz transformation.

The black hole with surrounding universe: the Penrose diagram
Consider first the black hole metric without the effects of matter the eternal black hole.
The Penrose diagram is a conformally compressed picture of all of space-time:


Hartle-Hawking vacuum:


$$
\begin{gathered}
|H H\rangle= \\
C \sum_{E, n} e^{-\frac{1}{2} \beta E}|E, n\rangle_{I}|E, n\rangle_{I I}
\end{gathered}
$$

Time boost for distant observer $=$ Lorentz boost for local observer.

Usual interpretation:
I = outside
$\|=$ inside [?] $\rightarrow$
quantum entanglement becomes entropy: $\rightarrow$ a thermal state ...

In- and out-going particles: energies $E$ for distant observer stay small. But for the local observer, energies of in-particles in distant past, as well as the out-particles in distant future, rapidly tend to infinity.

The real black hole is usually not eternal; there will be:

- imploding matter in the far past, removing region $I V$, and
- Hawking particles in the late future. If these are left in the Hartle-Hawking state, they have no effect on the metric, but if we project out any measured bass element of Fock space, this will generate firewalls, blocking away region III.

Another way to phrase the problem:

1) If we allow large time translations, infinitely many Hawking particles will crowd both the future and the past horizon.
2) The particles going in do not seem to affect particles going out: no unitarity in the evolution process.

The information problem:
The black hole does not seem to respond to our messages, and it houses infinitely many particles, with no bounds on their energy-momentum.

Thus, we phrase the problem in a time-reversal-invariant manner. Important: when we wish to discuss pure quantum states, using pure QM and GR, our system will stay time-reversal-symmetric.

We have to justify the use of the eternal Penrose diagram with regions III and IV. This will be done a posteriori.

Actually, only the parts of III and IV infinitesimally close to the horizons will be used.

It will be shown that the unwanted firewall particles
can be transformed away.
This will seem like a new law of physics, but it follows from careful analysis. This transformation will form an essential new ingredient in Qu. Gravity. It is due to
the gravitational back reaction,
the main gravitational interaction between in- and out-particles that can be taken into account exactly.

The gravitational effect of a fast, massless particle is easy to understand: Schwarzschild metric of a particle with tiny rest mass $m \ll M_{\text {Planck }}$ :

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

curvature
flat space

This gives us the gravitational backreaction:

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

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.

Now 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, $\delta u$, which only depends on the angular variables $(\theta, \varphi)$, not on $u$.


Thus, the data are shifted right across the horizon. Ignoring this fact causes confusion.
Same happens with past event horizon, by time reversal!

## Hard and soft particles

The particles populating this space-time: their energies may diverge beyond $M_{\text {Planck }}$.

If so, we call them hard particles: they cause shifts in the orbits of the soft particles
This effect is strong and chaotic: no observer trying to cross such a curtain of particles can survive: firewalls

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Almheiri, Marolf, Polchinski, Sully (2013)
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Particles whose energies, in a given Lorentz frame, are small compared to $M_{\text {Planck }}$ will be called soft particles.

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Their effects on curvature are small compared to }\mp@subsup{L}{\mathrm{ Planck, and}}{
will be ignored (or taken care of in perturbative Qu.Gravity).
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During its entire history, a black hole has in-going matter (grav. implosion) and out-going matter (Hawking).
If we want to express these in terms of pure quantum states, one might expect firewalls both on the future and past event horizon.
(The pure quantum theory must be CPT symmetric)

Such firewalls would form a natural boundary surrounding region I That can't be right
Derivation of Hawking radiation asks for analytic extension to region III Time reversal symmetry then asks for analytic extension to region IV In combination, you then also get region //


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All this suggests that firewalls can be switched on and off: the firewall transformation.
(1.) Note: Hawking's wave function seems to form a single quantum state (if we assume both regions I and II of the Penrose diagram to be physical! - see later). A firewall would form infinitely many quantum states. What kind of mapping do we have? Aren't we dealing with an information problem here??
(2.) Region I/ would have its own asymptotic regions: $\infty^{\prime}, \infty^{\prime+}$, and $\infty^{\prime-}$. What is their physical significance?

Wait and see...

We start with only soft particles populating space-time in the Penrose diagram.


We now first wish to understand the evolution operator for short time intervals only. Firewalls have no time to develop.

The evolution law for the soft particles is fully dictated by QFT on curved space-time.

At $|\tau|=\mathcal{O}(1)$, particles going in, and Hawking particles going out, are soft.

However, during our short time interval, some soft particles might pass the borderline between soft and hard: they now interact with the out-particles.
The interaction through QFT forces stay weak, but the gravitational forces make that (early) in-particles interact strongly with (late) out-particles.

Effect of gravitational force between them easy to calculate ...

Calculate Shapiro shift,
Every in-particle with momentum $p^{-}$at solid angle $\Omega=(\theta, \varphi)$ causes a shift $\delta u^{-}$of all out-particles at solid angles
$\Omega^{\prime}=\left(\theta^{\prime}, \varphi^{\prime}\right):$

$$
\delta u^{-}\left(\Omega^{\prime}\right)=8 \pi G f\left(\Omega^{\prime}, \Omega\right) p^{-} ; \quad\left(1-\Delta_{W}\right) f\left(\Omega^{\prime}, \Omega\right)=\delta^{2}\left(\Omega^{\prime}, \Omega\right)
$$

Many particles: $p^{-}(\Omega)=\sum_{i} p_{i}^{-} \delta^{2}\left(\Omega, \Omega_{i}\right) \rightarrow$

$$
\delta u^{-}\left(\Omega^{\prime}\right)=8 \pi G \int \mathrm{~d}^{2} \Omega f\left(\Omega^{\prime}, \Omega\right) p^{-}(\Omega) .
$$

Small modification: replace $\delta u_{\text {out }}^{-}$by $u_{\text {out }}^{-}$, then:

$$
u_{\text {out }}^{-}(\Omega)=8 \pi G \int \mathrm{~d}^{2} \Omega^{\prime} f\left(\Omega, \Omega^{\prime}\right) p_{\text {in }}^{-}\left(\Omega^{\prime}\right)
$$

adding an in-going particle with momentum $p_{\mathrm{in}}^{-}$, corresponds to displacing all out-going particles by $u_{\text {out }}^{-}$as given by our equation.

All $u_{\text {out }}^{-}$are generated by all $p_{\text {in }}^{-}$.

A mapping of the momenta $p_{\text {in }}^{-}$of the in-particles onto the positions $u_{\text {out }}^{-}$of the out-particles. Agrees with time evolution:

$$
\begin{aligned}
p_{\text {in }}^{-} \rightarrow p_{\text {in }}^{-}(0) e^{\tau}, & u_{\text {in }}^{+} \rightarrow u_{\text {in }}^{+}(0) e^{-\tau} ; \\
p_{\text {out }}^{+} \rightarrow p_{\text {out }}^{+}(0) e^{-\tau}, & u_{\text {out }}^{-} \rightarrow u_{\text {out }}^{-}(0) e^{\tau} .
\end{aligned}
$$

What we calculated is the footprint of in-particles onto the out-particles, caused by gravity.

And then: $\delta u^{-} \rightarrow u^{-}$implying that now the in-particles are to be replaced by the out-particles. The out-particles are just footprints!

This makes sense: $u^{-}$is the particle $p^{+}$in position space just Fourier transform the quantum state!
Footprints promoted to the status of particles themselves. Avoids double counting: only describe the in-particle or its footprint (the out-particle), not both, as in the older equations.
Note: hard in-particles generate soft out-particles and vice versa.
This way, replace all hard particles by soft ones.
This removes the firewalls: the firewall transformation.

Authors of older papers, when encountering "firewalls", did not take into account that neither in-going nor out-going particles should be followed for time intervals $\delta \tau$ with $|\delta \tau| \gg \mathcal{O}(1)$.

This evolution law involves soft particles only. Is it unitary?

> Authors of older papers, when encountering "firewalls", did not take into account that neither in-going nor out-going particles should be followed for time intervals $\delta \tau$ with $|\delta \tau| \gg \mathcal{O}(1)$.

This evolution law involves soft particles only. Is it unitary?
Yes, provided only the variables $p^{ \pm}(\Omega)$ and $u^{ \pm}(\Omega)$ are involved.
No quantum numbers like baryon, lepton...
$p^{ \pm}(\Omega)$ are like vertex insertions in string theories.
Postulating that this respects unitarity makes sense ...
First amendment on Nature's Constitution:
A particle may be replaced by its gravitational footprint: At a horizon, out-particles are the Fourier transforms of in-particles.

Second problem:
What is the relation between regions I and II ?
Both have asymptotic domains: two universes!
a) Wave functions $\psi\left(u^{+}\right)$of the in-particles live in region $I$, therefore $u^{+}>0$.
b) Out-particles in region I have $\psi\left(u^{-}\right)$with $u^{-}>0$.

$c, d)$ In region II, the in-particles have $u^{+}<0$ and the out-particles $u^{-}<0$.

All doubt vanishes when expanding in spherical harmonics:
$\Omega \equiv(\theta, \varphi)$

$$
\begin{array}{rr}
u^{ \pm}(\Omega)=\sum_{\ell, m} u_{\ell m} Y_{\ell m}(\Omega), & p^{ \pm}(\Omega)=\sum_{\ell, m} p_{\ell m}^{ \pm} Y_{\ell m}(\Omega) ; \\
{\left[u^{ \pm}(\Omega), p^{\mp}\left(\Omega^{\prime}\right)\right]=i \delta^{2}\left(\Omega, \Omega^{\prime}\right),} & {\left[u_{\ell m}^{ \pm}, p_{\ell^{\prime} m^{\prime}}^{ \pm}\right]=i \delta_{\ell \ell^{\prime}} \delta_{m m^{\prime}} ;} \\
u_{\text {out }}^{-}=\frac{8 \pi G}{\ell^{2}+\ell+1} p_{\text {in }}^{-}, & u_{\text {in }}^{+}=-\frac{8 \pi G}{\ell^{2}+\ell+1} p_{\text {out }}^{+},
\end{array}
$$

$$
p_{\ell m}^{ \pm}=\text {total momentum in of }{ }_{\text {in }}^{\text {out }} \text {-particles in }(\ell, m) \text {-wave }
$$

$$
u_{\ell m}^{ \pm}=(\ell, m) \text {-component of c.m. position of }{ }_{\text {in }}^{\text {out }} \text {-particles. }
$$

Factorisation: because we have linear equations, all different $\ell, m$ waves decouple, and for one $(\ell, m)$-mode we have just the variables $u^{ \pm}$and $p^{ \pm}$. They represent only one independent coordinate $u^{+}$, with $p^{-}=-i \partial / \partial u^{+}$.

Great advantage of the expansion in spherical harmonics:
At every $(\ell, m)$, we get a single wave function in 1 space- and 1 time coordinate, and we can see that it evolves in a unitary way.

All we need to do is regard the positions $u$ and the momenta $p$ as canonical operators as always in QM. As soon as we replace the momenta $p$ of the hard particles, by the shifted positions $u$ of the soft particles, we get rid of the firewalls, and we see unitary evolution.

The in-particles can now be replaced by their footprints in the out-particles. The Fourier transform is unitary !

The in-particles never get the opportunity to become truly hard particles.

Like a "soft wall"-boundary condition near the origin of the Penrose diagram. Wave functions going in reflect as wave functions going out. Soft in-particles emerge as soft out-particles.

No firewall, ever.
The total of the in-particles in regions I and I/ are transformed (basically just a Fourier transform) into out-particles in the same two regions.

Regions III and IV are best to be seen as lying somewhere on the time-line where time $t$ is somewhere beyond infinity

The antipodal identification
Sanchez(1986), Whiting(1987)
Regions I and I/ of the Penrose diagram are exact copies of one another. Does region II represent the "inside" of the black hole?
NO! There are asymptotic regions. Region I is carbon copy of region II.
We must assume that region /I describes the same black hole as region I. It represents some other part of the same black hole. Which other part?
The local geometry stays the same, while the square of this $O(3)$ operator must be the identity.

Search for $A \in O(3)$ such that: $A^{2}=\mathbb{I}$, and
$A x=x$ has no real solutions for $x$.
$\Rightarrow$ All eigenvalues of $A$ must be -1 . Therefore: $A=-\mathbb{I}$ :
the antipodal mapping.

We stumbled upon a new restriction for all general coordinate transformations:

## Amendment \# 2 for Nature's Constitution"

For a curved space-time background to be used to describe a region in the universe, one must demand that every point on our space-time region represent exactly one point in a single universe
(not two, as in analytically extended Schwarzschild metric)
The emergence of this non-trivial topology needs not be completely absurd, as long as no signals can be sent around. We think that this is the case at hand here.

It is the absence of singularities in the physical domain of space-time that we must demand.

Note that, now, $\ell$ has to be odd!



I

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: an instanton
N.Gaddam, O.Papadoulaki, P.Betzios (Utrecht)

Space coordinates change sign at the identified points

- and also time changes sign
(Note: time stands still at the horizon itself).

Next step: introduce the tortoise coordinates.
Let there be two operators, $u$ and $p$, obeying the commutator equation

$$
[u, p]=i, \quad \text { so that } \quad\langle u \mid p\rangle=\frac{1}{\sqrt{2 \pi}} e^{i p u}
$$

Split both $u$ and $p$ in a positive part and a negative part:

$$
\begin{aligned}
& u \equiv \sigma_{u} e^{\varrho_{u}}, \quad p=\sigma_{p} e^{\varrho_{p}} ; \quad \sigma_{u}= \pm 1, \quad \sigma_{p}= \pm 1, \quad \text { and } \\
& \tilde{\psi}_{\sigma_{u}}\left(\varrho_{u}\right) \equiv e^{\frac{1}{2} \varrho_{u}} \psi\left(\sigma_{u} e^{\varrho_{u}}\right), \quad \tilde{\hat{\psi}}_{\sigma_{p}}\left(\varrho_{p}\right) \equiv e^{\frac{1}{2} \varrho_{p}} \hat{\psi}\left(\sigma_{p} e^{\varrho_{p}}\right) ;
\end{aligned}
$$

normalized: $|\psi|^{2}=\sum_{\sigma_{u}= \pm} \int_{-\infty}^{\infty} \mathrm{d} \varrho_{u}\left|\tilde{\psi}_{\sigma_{u}}\left(\varrho_{u}\right)\right|^{2}=\sum_{\sigma_{p}= \pm} \int_{-\infty}^{\infty} \mathrm{d} \varrho_{p}\left|\tilde{\hat{\psi}}_{\sigma_{p}}\left(\varrho_{p}\right)\right|^{2}$.
Then $\tilde{\hat{\psi}}_{\sigma_{\rho}}\left(\varrho_{\rho}\right)=\sum_{\sigma_{u}= \pm 1} \int_{-\infty}^{\infty} \mathrm{d} \varrho K_{\sigma_{u} \sigma_{p}}(\varrho) \tilde{\psi}_{\sigma_{u}}\left(\varrho-\varrho_{p}\right)$, with $K_{\sigma}(\varrho) \equiv \frac{1}{\sqrt{2 \pi}} e^{\frac{1}{2} \varrho} e^{-i \sigma e^{\varrho}}$.

If $\varrho_{p} \rightarrow \varrho_{p}+\lambda$, then simply $u \rightarrow u e^{-\lambda}, p \rightarrow p e^{\lambda}$, a symmetry of the Fourier transform. Here, it corresponds to Energy conservation.

Use this symmetry to write plane waves:

$$
\begin{aligned}
& \tilde{\psi}_{\sigma_{u}}\left(\varrho_{u}\right) \equiv \breve{\psi}_{\sigma_{u}}(\kappa) e^{-i \kappa \varrho_{u}} \text { and } \tilde{\hat{\psi}}_{\sigma_{p}}\left(\varrho_{p}\right) \equiv \breve{\hat{\psi}}_{\sigma_{p}}(\kappa) e^{i \kappa \varrho_{P}} \quad \text { with } \\
& \breve{\hat{\psi}}_{\sigma_{p}}(\kappa)=\sum_{\sigma_{P}= \pm 1} F_{\sigma_{u} \sigma_{p}}(\kappa) \breve{\psi}_{\sigma_{u}}(\kappa) ; \quad F_{\sigma}(\kappa) \equiv \int_{-\infty}^{\infty} K_{\sigma}(\varrho) e^{-i \kappa \varrho_{\mathrm{d}} \varrho .}
\end{aligned}
$$

Thus, we see left-going waves produce right-going waves. On finds (just do the integral):

$$
F_{\sigma}(\kappa)=\int_{0}^{\infty} \frac{\mathrm{d} y}{y} y^{\frac{1}{2}-i \kappa} e^{-i \sigma y}=\Gamma\left(\frac{1}{2}-i \kappa\right) e^{-\frac{i \sigma \pi}{4}-\frac{\pi}{2} \kappa \sigma} .
$$

Matrix $\left(\begin{array}{ll}F_{+} & F_{-} \\ F_{-} & F_{+}\end{array}\right)$is unitary: $F_{+} F_{-}^{*}=-F_{-} F_{+}^{*}$ and $\left|F_{+}\right|^{2}+\left|F_{-}\right|^{2}=1$.
Look at how our soft particle wave functions evolve with time $\tau$
Hamiltonian is the dilaton operator (N.Gaddam, O.Papadoulaki, P.Betzios)

$$
\begin{gathered}
H=-\frac{1}{2}\left(u^{+} p^{-}+p^{-} u^{+}\right)=\frac{1}{2}\left(u^{-} p^{+}+p^{+} u^{-}\right)= \\
i \frac{\partial}{\partial \varrho_{u^{+}}}=-i \frac{\partial}{\partial \varrho_{u^{-}}}=-i \frac{\partial}{\partial \varrho_{p^{-}}}=i \frac{\partial}{\partial \varrho_{p^{+}}}=\kappa
\end{gathered}
$$

Add the scale factor $\frac{8 \pi G}{\ell^{2}+\ell+1}$, to get, if $u^{ \pm}=\sigma_{ \pm} e^{\varrho^{ \pm}}$,

$$
\begin{align*}
& \psi_{\sigma_{+}}^{\text {in }} e^{-i \kappa \varrho^{+}} \rightarrow \psi_{\sigma_{-}}^{\text {out }} e^{i \kappa \varrho^{-}}  \tag{1}\\
& \psi_{\sigma_{-}}^{\text {out }}=\sum_{\sigma_{+}} F_{\sigma_{+} \sigma_{-}}(\kappa) e^{-i \kappa \log \left(8 \pi G /\left(\ell^{2}+\ell+1\right)\right)} \psi_{\sigma_{+}}^{\text {in }}
\end{align*}
$$

These equations generate the contributions to the scattering matrix from all $(\ell, m)$ sectors of the system, where $|m| \leq \ell$. At every $(\ell, m)$, we have a contribution to the position operators $u^{ \pm}(\theta, \varphi)$ and momentum operators $p^{ \pm}(\theta, \varphi)$ proportional to the partial wave function $Y_{\ell m}(\theta, \varphi)$. The signs of $u^{ \pm}(\theta, \varphi)$ tell us whether we are in region I or region II. The signs of $p^{ \pm}(\theta, \varphi)$ tell us whether we added or sutracted a particle from region I or region II.

## A timelike Möbius strip



Draw a spacelike closed curve:
Begin on the horizon at a point

$$
r_{0}=2 G M, t_{0}=0,\left(\theta_{0}, \varphi_{0}\right) .
$$

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

$$
r_{0}=2 G M, t_{0}=0,\left(\pi-\theta_{0}, \varphi_{0}+\pi\right) .
$$

You arrived at the same point, so the (space-like) curve is closed.
Now look at the environment $\{\mathrm{d} x\}$ of this curve. Continuously transport $\mathrm{d} x$ around the curve. The identification at the horizon demands

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

So this is a Möbius strip, in particular in the time direction. Note that it makes a CPT inversion when going around the loop.

There are no direct contradictions, but take in mind that the Hamiltonian switches sign as well. Demanding that the external observer chooses the point where the Hamilton density switches sign as being on the horizon, gives us a good practical definition for the entire Hamiltonian.
Note that the soft particles near the horizon adopted the dilaton operator as their Hamiltonian. That operator leaves regions / and // invariant. Also, the boundary condition, our "scattering matrix", leaves this Hamiltonian invariant. Therefore, indeed, breaking the Hamiltonian open exactly at the horizon still leaves the total Hamiltonian conserved. So indeed, there are no direct contradictions.

However, this is a peculiarity that we have to take into consideration.

More to be done. Searching for like-minded colleagues.

See: G. 't Hooft, arxiv:1612.08640 [gr-qc] + references there;
id. Virtual Black Holes and SpaceTime Structure, Found.Phys., to be publ,10.1007/s10701-017-0133-0, see
http://link.springer.com/article/10.1007/s10701-017-0133-0
P. Betzios, N. Gaddam and O. Papadoulaki, The Black Hole S-Matrix from Quantum Mechanics, JHEP 1611, 131 (2016), arxiv:1607.07885.

