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Probing the extremes of physical laws in quantized black holes.

Rencontres de Blois,
France

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Gravitation is arguably the most elementary force in physics. It appears to be directly linked to a fundamental principle:

invariance of physical laws under general coordinate transformations in space and time.

Combining this law with what is known about quantum mechanics seems to be nigh impossible

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What does an observer see when he goes with the speed of light?

A. Einstein

Example of an extreme physical setting
$\rightarrow$ Special Relativity, $E = mc^2$

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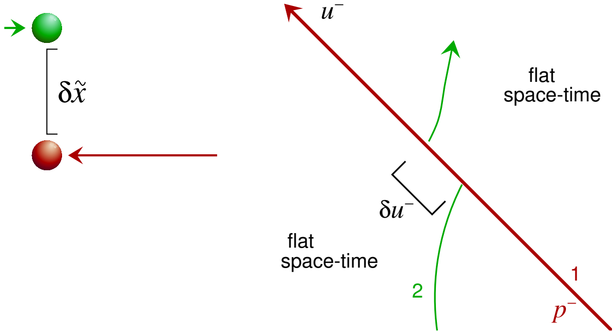

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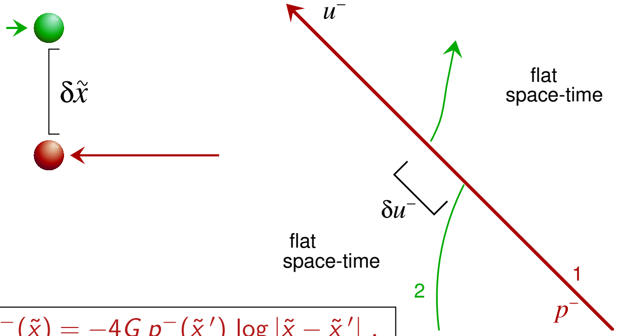

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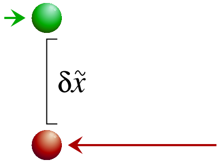

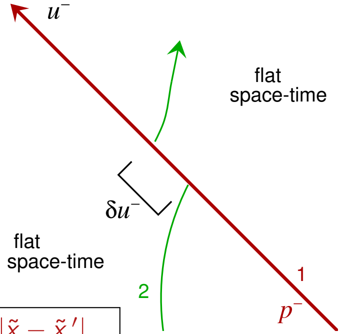

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Shapiro Effect

$$\tilde{\Delta}^2 u^-(\tilde{x}) = -8\pi G\, p^-(\tilde{x})\,,$$

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Here, $p^-(\tilde{x})$ is the <u>sum</u> of all momenta p^- at transverse coordinates $\tilde{x}$;
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Argue: *add* all momenta p^- to find a *total shift* of the positions $u^-_{\rm tot}$.

All particles have $[u^i,\, p_j] = i\delta_{ij}$. But don't forget

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All particles have $[u^i,\, p_j] = i\delta_{i\,j}$. But don't forget $\tilde{\Delta}^2$ operator.

It is tempting to forget that this rule requires to add *all* momenta and to average over *all* positions.

Be careful with second quantization !

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But we do know how to use it to do quantum field theory on the curved space-time of a black hole.

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The Shapiro shift then becomes the decisive engine for understanding BH evolution.

This can be made to work!

Unfortunately, these ideas still haven't been picked up by most other investigators. Problems:

- string theories do not obviously apply to find the right answers
- quantum entanglement is used as a popular notion, but must be handled with care.
  preferrably: first disentangle, then compute ...
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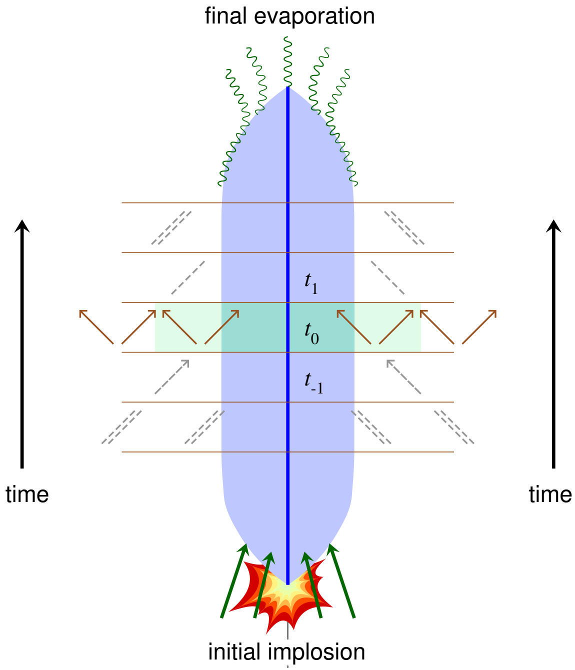
The correct procedure:


final evaporation
t_1
t_0
t_{-1}
time
time
initial implosion

It's all a question of interpretation of Quantum Mechanics

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The best way to describe a unitary evolution law is to first postulate the complete set of all states at a *given time slice,* $\Delta T \approx R_{\rm BH}$.

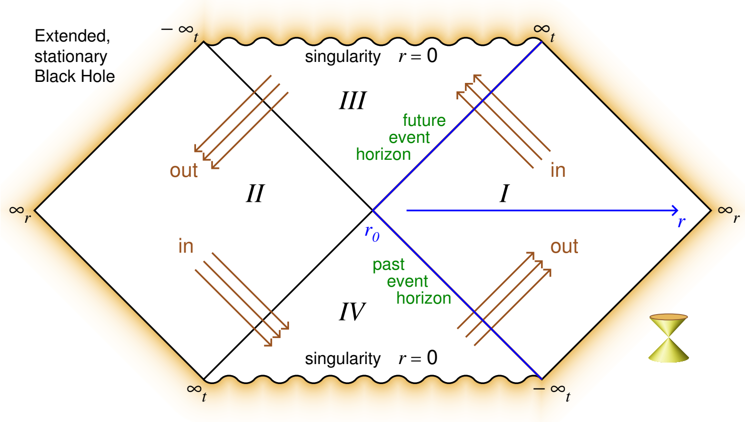
There, one needs a background space-time, in the form of the Schwarzschild metric in the outside world.

Only a few particles move around, not affecting the metric much.

We need this configuration only for a short time period, but we *do need its analytic extension*, as we shall see.

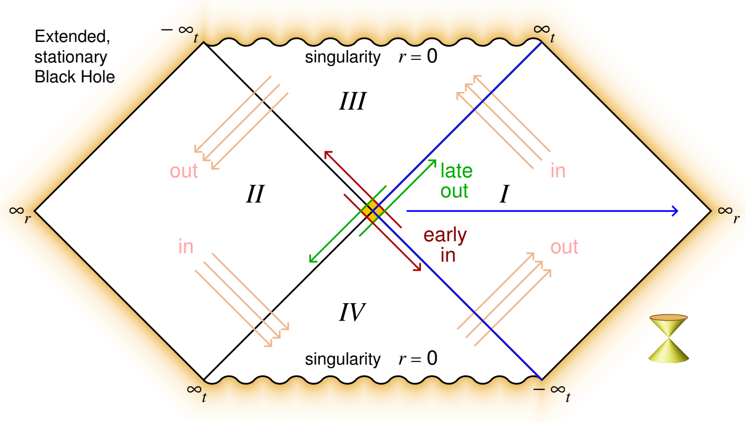
The Penrose diagram for the eternal black hole emerges.

This diagram is twice the size it should have, as it includes region *II*, *an other universe with its own asymptotic infinity.*



But how can it be that out-particles are determined by the in-particles ?

Late out-particles are affected by *early* in-particles:



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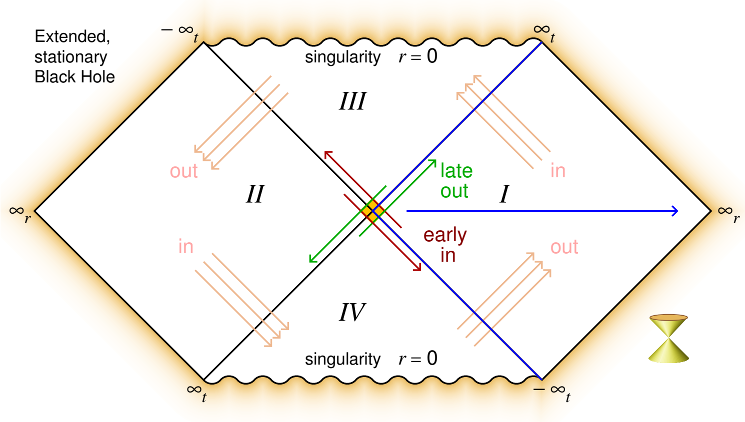


It all happens near the horizons at the Planck scale

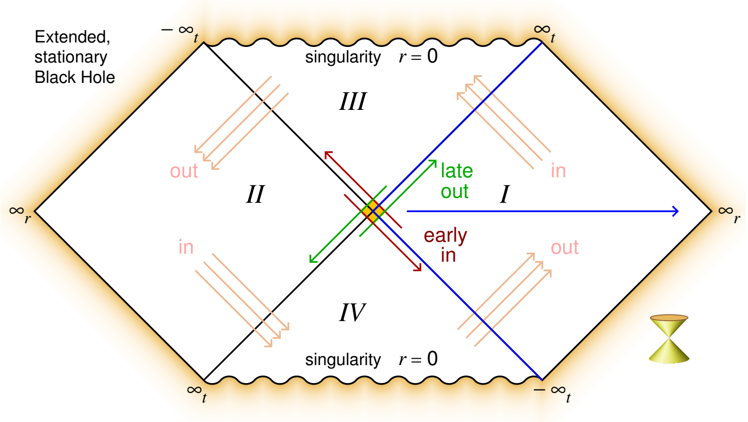
Look at what the Shapiro effect can do there!

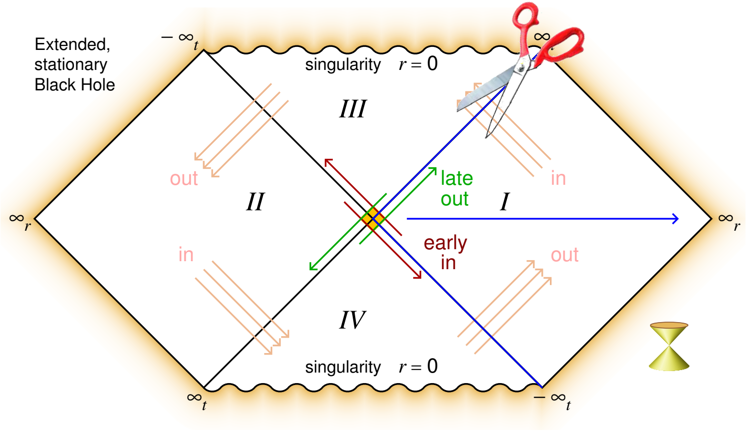
We need the Shapiro time shift effect **only** at the two horizons.

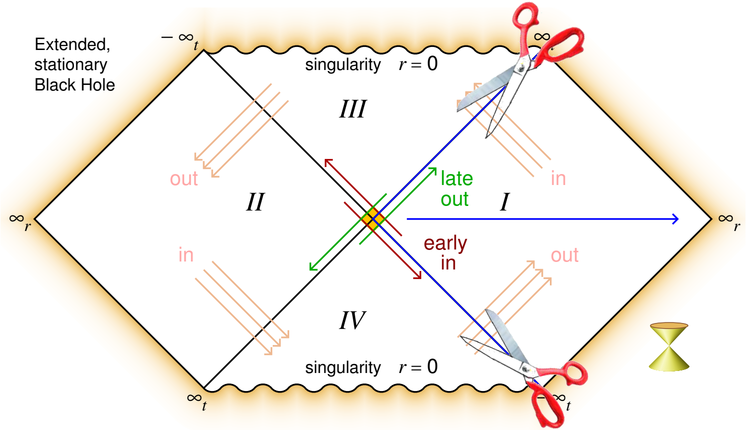
So we do ordinary QFT in one diamond, and geometry to connect the analytically extended regions.

We justify the extended Penrose diagram to describe all of space and time, a posteriori.

Extended,
stationary
Black Hole



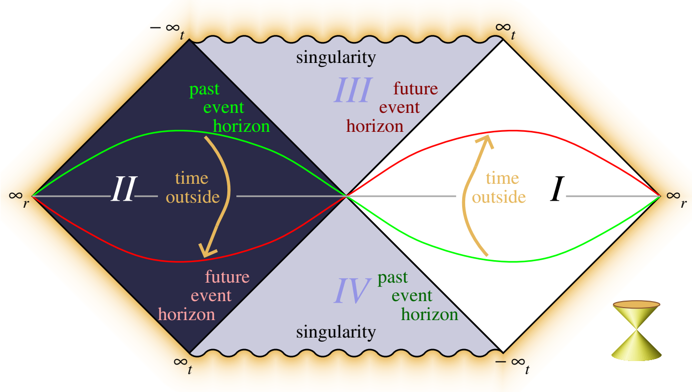

Extended,
stationary
Black Hole
− ∞ t
∞ t
singularity r = 0
III
out
in
late
out
II
I
∞ r
∞ r
in
early
in
out
IV
singularity r = 0
∞ t
− ∞ t



The Shapiro effect tells us how to connect the horizons together to restrore analyticity.

All gravitational effects due to in- and out-going particles, can then be replaced by cut-and-paste procedures, *a posteriori.*

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



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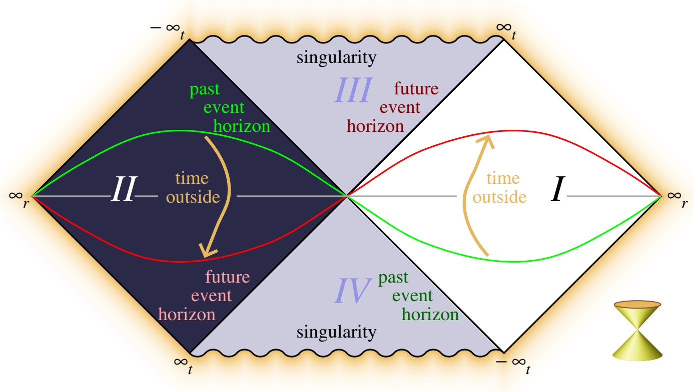

In region II, time is inverted. Particles "move backwards in time". But, according to local observer, free particles with negative energies do not exist. So, we must write

$E_{II} \to E^{\max} - E_I$, where $E^{\max}$ is the *energy of the 'antivacuum'*.

By the cut-and-paste procedure, we *replaced all in-going particles by out-going ones.* or vice-versa. This allows for quantisation, using

$$[u^{\pm}(\tilde{x}),\, p^{\mp}(\tilde{x}\,')] = i\delta^2(\tilde{x}, \tilde{x}\,').$$

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THANK YOU

Correct theory for black hole quantization comes as a *package deal*:

1) Matter particles may only be considered during small time steps, $T_{\mathrm{scrambl}} = \mathcal{O}(M_{\mathrm{BH}})$. In QM, you can't include collapsing matter or late evaporation. These would act as projection operators that ruine unitarity.

2) One has to use the metric of the eternal black hole as background.

3) The metric must be divided by $\mathbb{Z}_2$, to restore a single asymptotic region.

4) The only way to do that is by *antipodal identification*.

5) Time outside runs *backwards* in region *II*. This implies that the local states to be compared with the black hole states must approch the *antivacuum* in region *II*. Creating a particle near the black hole corresponds to creating a particle in *I* or annihilating a particle in *II*.

6) In-particles at $t \ll t_0$ generate a Shapiro shift along past event horizon; out-particles at $t \gg t_0$ generate Shapiro shift along future event horizon. These form *firewalls* that can be removed by re-arranging the corrections at the horizons (cut-and-paste).

7) This links the *positions* of the out particles to the momenta on the in-particles, and *vice versa* ($\rightarrow$ unitary evolution.)

8) initial imploding matter and the final evaporating matter have decisive effects in the horizons. Initial and final black holes are mere *seeds*, to be described as gravitational *instantons*.

9) Use *spherical harmonics* for optimal use of linearity of the equations. The different spherical harmonics decouple, as in the hydrogen atom.

The mathematics works correctly only when these views are all combined. In particular, we may *only* compare states in a background metric to states as seen from the outside, if the mapping on the Cauchy surfaces is 1 to 1.

This enforced the antipodal mapping (it cannot be avoided).

Note that this mapping keeps all information visible on the Cauchy surfaces; we have no information loss.

We have complete time-reversal invariance.
http://arxiv.org/abs/2106.11152.