The hidden horizon and black hole unitarity

François Englert and Philippe Spindel   [arXiv:1009.6190]

I. The Hawking radiation and the information paradox

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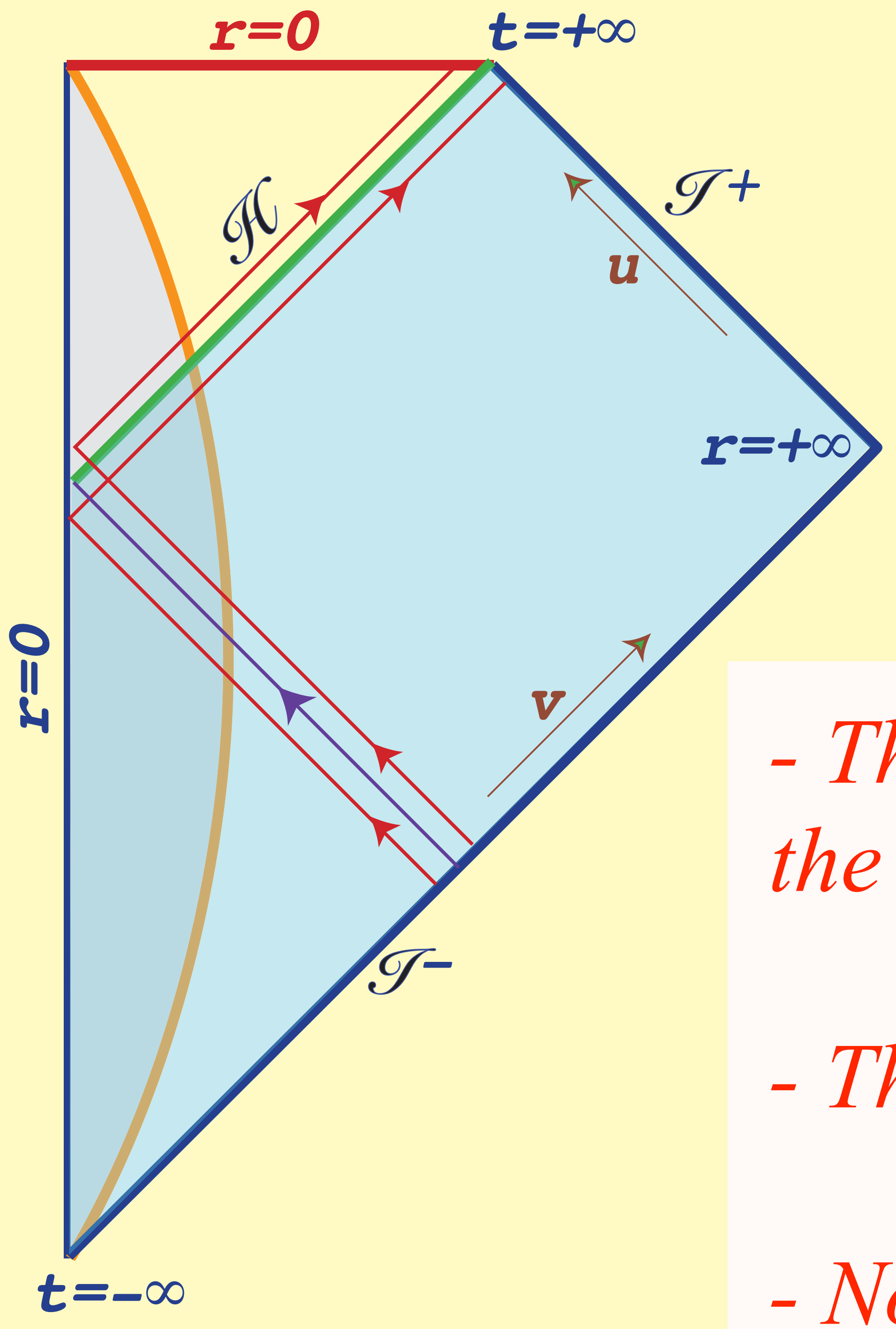
I. The Hawking radiation and the information paradox

HR of an incipient black hole in absence of back reaction



Time dependent process → pair creation

Horizon universality

Trace on $\mathscr{H}$ → thermal density matrix on $\mathscr{I}^+$

$$T = \frac{1}{8\pi M}$$

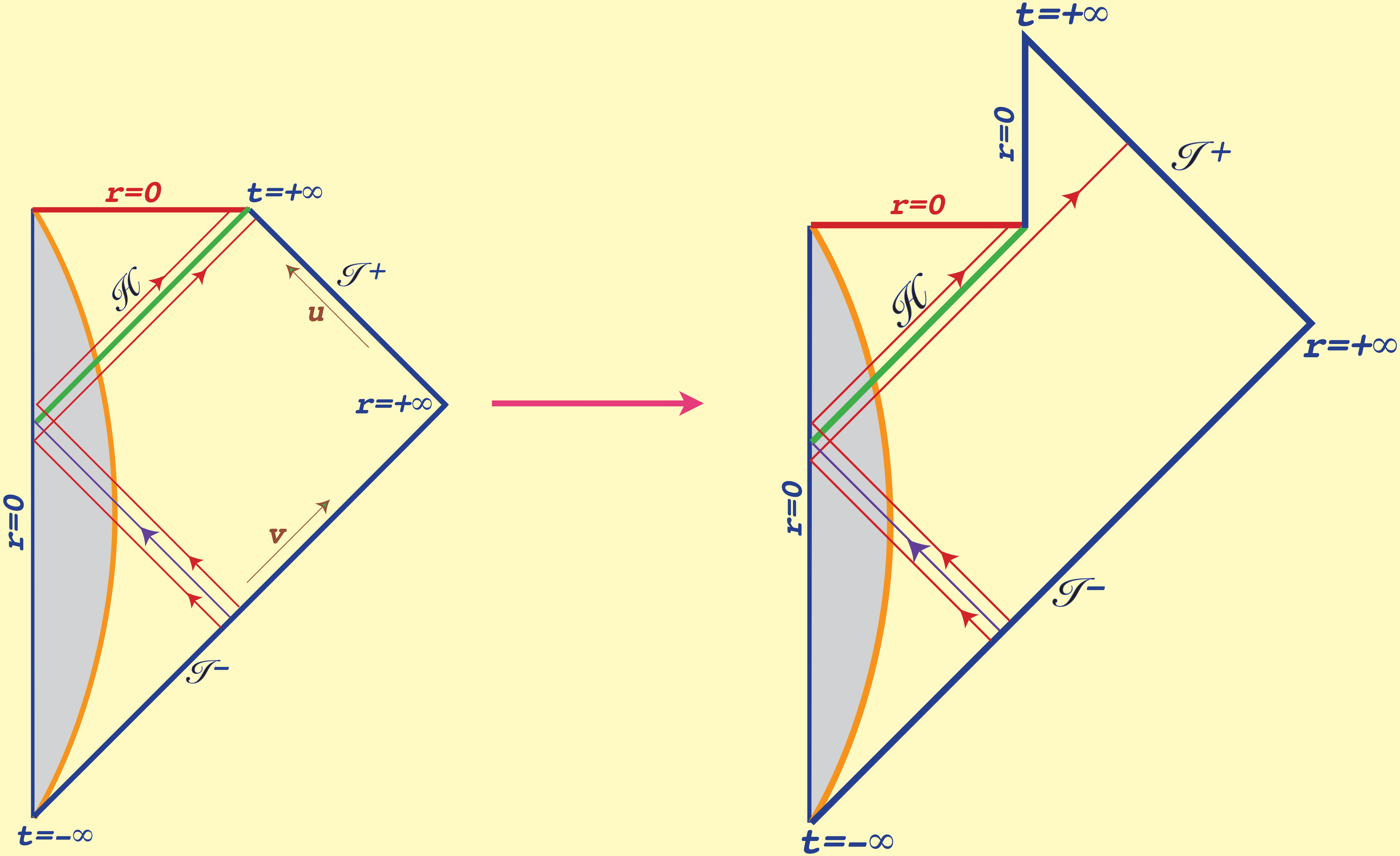
- The HR arises solely from the region outside the horizon

- The process is unitary

- No information in the radiation

The singularity issue

The “conventional” description of back reaction



Is information lost in the singularity ?

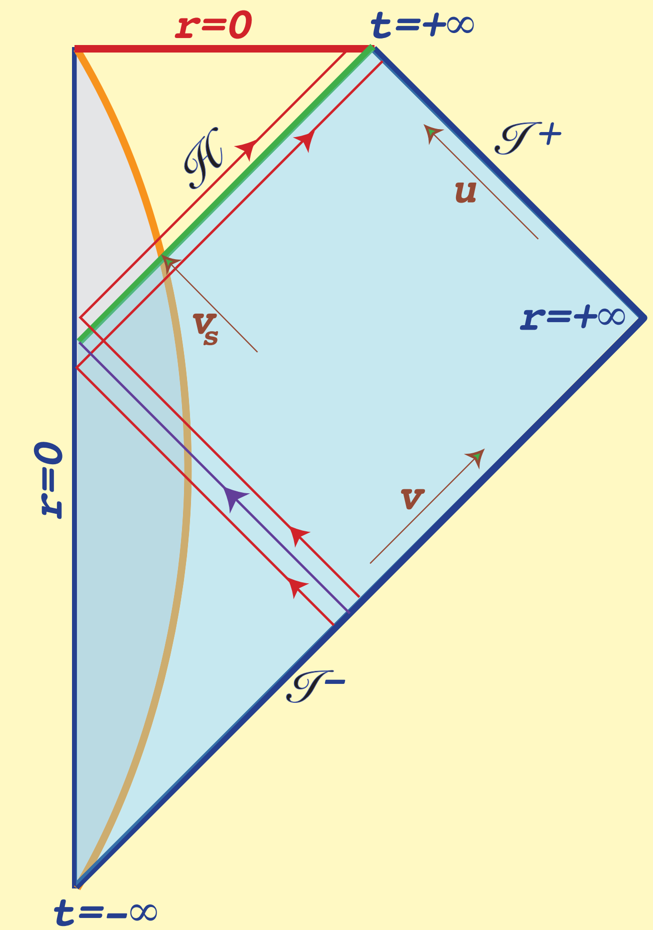
The transplanckian issue and the horizon problem

Onset of the Hawking radiation

$$u = t - r^\star \qquad v = t + r^\star$$

$$dr = (1 - \frac{2M}{r}) dr^\star$$

$$ds^2 = \left(1 - \frac{2M}{r}\right) du\, dv - r^2 d\Omega^2$$



$$1 - \frac{2M}{r_s} \simeq \exp \frac{v_s - u}{4M} \qquad [t = t_0 \quad r_s = O(M)]$$

Transplanckian frequencies during evaporation

$$\omega_f \simeq \frac{T}{\sqrt{(g_{00})_f}} \simeq T \exp \frac{u_f - v_s}{8M} \simeq T \exp \frac{t_f - t_0}{4M} = O(\frac{1}{M} \exp \xi M^2)$$

Is the horizon stable against transplanckian fluctuations ?

How can unitarity be restored ?

Singularity or horizon effect ?

II. The back-reaction of quantum matter on gravity

The background for gravity-matter amplitudes

$$\langle f|i\rangle = \int_{i(\Sigma_i)}^{f(\Sigma_f)} \mathcal{D}(\{\phi_j\})\mathcal{D}(g_{\mu\nu})e^{i\mathcal{S}(\{\phi_j\},g_{\mu\nu})}$$

$\{\phi_j^{(t)}\}, g_{\mu\nu}^{(t)}$ *is a field configuration on a hypersurface* Σ_t $[\sim x_t]$

$i(\Sigma_i)$ *is a functional of the field configurations on the hypersurface* $[\sim \psi(x_i)]$

Black hole $: \{\phi_j\} = \phi, \{\Phi_j^c\}$

$$\langle f|i\rangle = \int_{i(\Sigma_i)}^{f(\Sigma_f)} \mathcal{D}(\phi)\mathcal{D}(g_{\mu\nu})e^{i[\mathcal{S}_\phi(\phi,g_{\mu\nu},\{\Phi_j^c\})+\mathcal{S}_g(g_{\mu\nu},\{\Phi_j^c\})]}$$

The functional integrals are only valid in the vicinity of stationary points

$$g_{\mu\nu} = g^0_{\mu\nu} + h_{\mu\nu}$$

$$\mathcal{S} = \mathcal{S}^0_\phi(\phi, g^0_{\mu\nu}, \{\Phi^c_j\}) + \mathcal{S}^0_g(g^0_{\mu\nu}, \{\Phi^c_j\}) + \int \left(\frac{\delta \mathcal{S}_g}{\delta g_{\mu\nu}}\right)_0 h_{\mu\nu} + \int \left(\frac{\delta \mathcal{S}_\phi}{\delta g_{\mu\nu}}\right)_0 h_{\mu\nu} + \cdots$$

$$\langle f|i\rangle_0 = e^{i\mathcal{S}^0_g} \int_i^f \mathcal{D}(\phi) e^{i\mathcal{S}^0_\phi}$$

$$\langle f|i\rangle = \langle f|i\rangle_0 \int_i^f \mathcal{D}(h_{\mu\nu}) \exp\left[\int i \left(\frac{\delta \mathcal{S}_g}{\delta g_{\mu\nu}}\right)_0 h_{\mu\nu}\right] \left(1 + \frac{i \int_i^f \mathcal{D}(\phi) e^{i\mathcal{S}^0_\phi} \int \left(\frac{\delta \mathcal{S}_\phi}{\delta g_{\mu\nu}}\right)_0 h_{\mu\nu}}{\int_i^f \mathcal{D}(\phi) e^{i\mathcal{S}^0_\phi}} + \cdots\right) \cdots$$

$$= \langle f|i\rangle_0 \int_i^f \mathcal{D}(h_{\mu\nu}) \exp i \left[\int \left(\frac{\delta \mathcal{S}_g}{\delta g_{\mu\nu}}\right)_0 h_{\mu\nu} + \frac{\int_i^f \mathcal{D}(\phi) e^{i\mathcal{S}^0_\phi} \int \left(\frac{\delta \mathcal{S}_\phi}{\delta g_{\mu\nu}}\right)_0}{\int_i^f \mathcal{D}(\phi) e^{i\mathcal{S}^0_\phi}} h_{\mu\nu} + \cdots\right]$$

$$\downarrow$$

$$\frac{\sqrt{-g}}{2} \frac{\langle f|\hat{T}^\phi_{\mu\nu}|i\rangle_0}{\langle f|i\rangle_0}$$

$$\frac{\langle f|\hat{T}^{\phi}_{\mu\nu}|i\rangle_0}{\langle f|i\rangle_0} \equiv T^{fi}_{\mu\nu[weak]}$$

↓

$$R^0_{\mu\nu} - \frac{1}{2} g^0_{\mu\nu} R^0 - 8\pi\, T^0_{\mu\nu}(\{\Phi^c_j\}) = 8\pi\, T^{fi}_{\mu\nu[weak]}$$

$T_{\mu\nu\,[weak]}$ ***drives the quantum matter back-reaction on gravity amplitudes***

Linear approximation

$$R^{\bar{0}}_{\mu\nu} - \frac{1}{2} g^{\bar{0}}_{\mu\nu} R^{\bar{0}} - 8\pi\, T^{\bar{0}}_{\mu\nu}(\{\Phi^{\bar{c}}_j\}) = 0$$

$$\mathcal{A}^{\rho\sigma}_{\mu\nu}\, \delta g^{fi}_{\rho\sigma} = 8\pi \frac{\langle f|\hat{T}^{\phi}_{\mu\nu}|i\rangle_{\bar{0}}}{\langle f|i\rangle_{\bar{0}}}$$

Post-selection: exclusive and inclusive background geometries

Y. Aharonov, P.G. Bergmann and J.L. Lebowitz, *Phys. Rev.* **B134** (1964) 1410; Y. Aharonov, D. Albert, A. Casher and L. Vaidman, *Phys. Lett.* **A124** (1987) 199.
S. Massar and R. Parentani, *Phys. Rev.* **D54** (1996) 7444 [arXiv:gr-qc/9502024]; R. Brout, S. Massar, R. Parentani and Ph. Spindel, *Phys. Rept.* **260** (1995) 329 [arXiv:0710.4345].
F. Englert, *"Stockholm 1994, The Oskar Klein centenary"* (1994) 138 [arXiv:gr-qc/9502039].

post-selection

$$|i(t_0)\rangle \longrightarrow |f(t_1)\rangle, |i(t_0)\rangle$$

$$A^{fi}_{[weak]} = \frac{\langle f(t_1)|U(t_1,t)\hat{A}\,U(t,t_0)|i(t_0)\rangle}{\langle f(t_1)|U(t_1,t_0)|i(t_0)\rangle} = \frac{\langle f|\hat{A}(t)|i\rangle}{\langle f|i\rangle}$$

$$\sum_f p_f\, A^{fi}_{[weak]} = \langle i|\hat{A}(t)|i\rangle \qquad p_f = |\langle f|i\rangle|^2$$

partial post-selection

$$\mathbf{H} = \mathbf{H}_1 \otimes \mathbf{H}_2 \qquad \text{no post-selection on } \mathbf{H}_2 \qquad |f^j_{\mathbf{H}_1}\rangle \in \mathbf{H}_1$$

$$A^{f\,i}_{[weak]} \equiv \frac{\langle f|\hat{A}|i\rangle}{\langle f|i\rangle} = \frac{tr|f\rangle\langle f|\hat{A}|i\rangle\langle i|}{tr|f\rangle\langle f|i\rangle\langle i|}$$

$$\downarrow$$

EPR conjugates

$$A^{f^j_{\mathbf{H}_1}\;i}_{[\underline{weak}]} = \frac{tr\Pi_{\mathbf{H}_2}|f^j_{\mathbf{H}_1}\rangle\langle f^j_{\mathbf{H}_1}|\hat{A}\,|i\rangle\langle i|}{tr\Pi_{\mathbf{H}_2}|f^j_{\mathbf{H}_1}\rangle\langle f^j_{\mathbf{H}_1}|i\rangle\langle i|} = \frac{\langle i|f^j_{\mathbf{H}_1}\rangle\langle f^j_{\mathbf{H}_1}|\hat{A}\,|i\rangle}{\langle i|f^j_{\mathbf{H}_1}\rangle\langle f^j_{\mathbf{H}_1}|i\rangle}$$

$$\sum_j p_{f^j_{\mathbf{H}_1}}\, A^{f^j_{\mathbf{H}_1}\;i}_{[\underline{weak}]} = \langle i|\hat{A}|i\rangle \qquad p_{f^j_{\mathbf{H}_1}} = \langle i|f^j_{\mathbf{H}_1}\rangle\langle f^j_{\mathbf{H}_1}|i\rangle$$

no post-selection

$$A^{i}_{[\underline{weak}]} = \frac{tr\Pi_{\mathbf{H}}\hat{A}\,|i\rangle\langle i|}{tr\Pi_{\mathbf{H}}|i\rangle\langle i|} = \langle i|\hat{A}(t)\,|i\rangle$$

From exclusive to inclusive amplitude

post-selection	$\|i\rangle \longrightarrow \|f\rangle \in \mathbf{H} = \mathbf{H}_1 \otimes \mathbf{H}_2$	***exclusive***
partial post-selection	$\|i\rangle \longrightarrow \langle f^j_{\mathbf{H}_1}\|i\rangle\|f^j_{\mathbf{H}_1}\rangle$	↓
no post-selection	$\|i\rangle \longrightarrow \|i\rangle$	***inclusive***

The (semi) inclusive amplitude is a linear superposition of exclusive amplitudes

From exclusive to inclusive background

$$R^0_{\mu\nu} - \frac{1}{2} g^0_{\mu\nu} R^0 - 8\pi\, T^0_{\mu\nu}(\{\Phi^c_j\}) = 8\pi\, T_{\mu\nu[\underline{weak}]}$$

post-selection	$T_{\mu\nu[\underline{weak}]} \equiv T^{fi}_{\mu\nu[weak]}$	***exclusive***
partial post-selection	$T_{\mu\nu[\underline{weak}]} \equiv T^{f^j_{\mathbf{H}_1}\ i}_{\mu\nu[\underline{weak}]}$	↓
no post-selection	$T_{\mu\nu[\underline{weak}]} \equiv T^{i}_{\mu\nu[\underline{weak}]} = \langle i\|\hat{T}_{\mu\nu}\|i\rangle$	***inclusive***

The (semi) inclusive background is an AVERAGE over exclusive backgrounds

III. The back-reaction of the Hawking radiation

Inclusive amplitudes : no post-selection $T^i_{\mu\nu[\underline{weak}]} = \langle i|\hat{T}_{\mu\nu}|i\rangle$

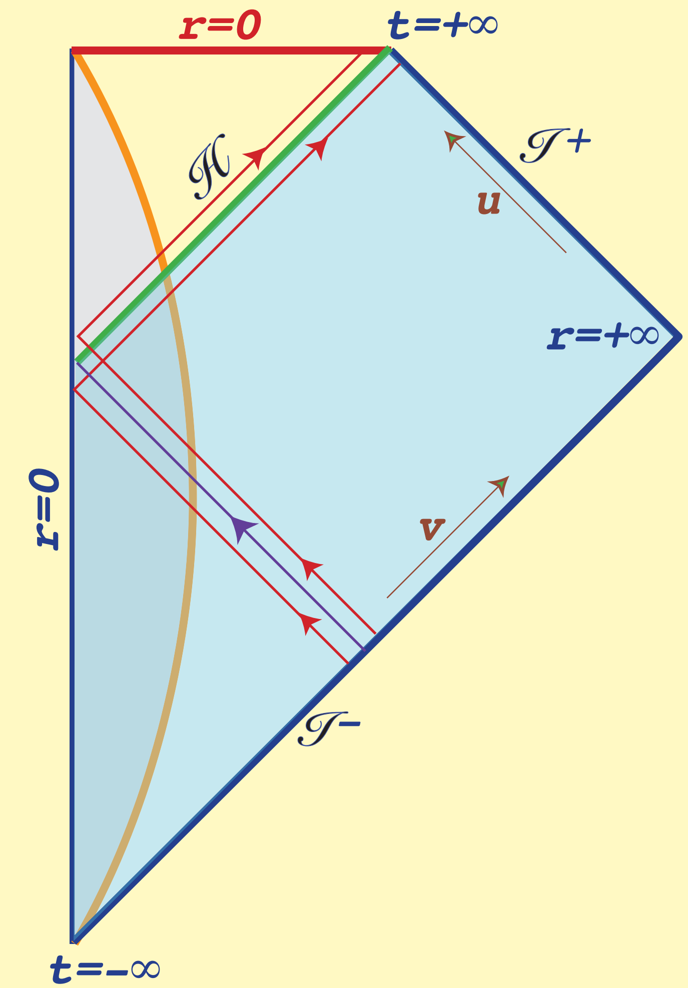
s-waves without the relativistic barrier

$$ds^2 = \left(1 - \frac{2M}{r}\right) du\ dv$$

$$\langle i|\hat{T}^{(2)}_{uv}|i\rangle = -\frac{1}{96\pi}(1 - \frac{2M}{r})R = -\frac{1}{24\pi}\frac{M}{r^3}(1 - \frac{2M}{r})$$

$$\langle i|\hat{T}^{(2)}_{vv}|i\rangle = \frac{1}{12\pi}\left[-\frac{M}{2r^3}(1 - \frac{2M}{r}) - \frac{M^2}{4r^4}\right]$$

$$\langle i|\hat{T}^{(2)}_{uu}|i\rangle = \frac{1}{12\pi}\left[-\frac{M}{2r^3}(1 - \frac{2M}{r}) - \frac{M^2}{4r^4}\right] + t_u(u)$$



$$t_{u(u\to\infty)} = \frac{1}{(4M)^2}\frac{1}{48\pi}$$

collapse
(Unruh vacuum)

$$t_u = 0$$

no collapse
(Boulware vacuum)

$$\langle i|\hat{T}^{(2)}_{vv}|i\rangle = \frac{1}{12\pi}\left[-\frac{M}{2r^3}(1-\frac{2M}{r}) - \frac{M^2}{4r^4}\right] \quad \stackrel{r\to 2M}{\longrightarrow} \quad \frac{1}{(4M)^2}\frac{-1}{48\pi}$$

$$\langle i|\hat{T}^{(2)}_{uv}|i\rangle = -\frac{1}{24\pi}\frac{M}{r^3}(1-\frac{2M}{r}) \quad \stackrel{r\to 2M}{\longrightarrow} \quad (1-\frac{2M}{r})\frac{1}{(4M)^2}\frac{-1}{12\pi}$$

$$\langle i|\hat{T}^{(2)}_{uu}|i\rangle = \frac{1}{12\pi}\left[-\frac{M}{2r^3}(1-\frac{2M}{r}) - \frac{M^2}{4r^4}\right] + \frac{1}{(4M)^2}\frac{1}{48\pi} \quad \stackrel{r\to 2M}{\longrightarrow} \quad (1-\frac{2M}{r})^2\frac{1}{(4M)^2}\frac{1}{12\pi}$$

Geodesic fall

$$\frac{du}{ds} \quad \stackrel{r\to 2M}{\longrightarrow} \quad [C(1-\frac{2M}{r})]^{-1}$$

$$\frac{dv}{ds} \quad \stackrel{r\to 2M}{\longrightarrow} \quad C$$

$\longrightarrow$ $\langle i|T^{(2)}_{\mu\nu}|i\rangle\, u^\mu u^\nu$ is regular on the horizon

Coordinate invariant characterization of the Unruh vacuum

$$\langle T^2\rangle^{(2)}_{Unruh} = \langle i|T^{(2)}_{\mu\nu}|i\rangle\langle i|T^{\mu\nu\,(2)}|i\rangle = 2T^{(2)}_{uu}(g^{uv})^2T^{(2)}_{vv} + 2T^{(2)}_{uv}(g^{uv})^2T^{(2)}_{uv}$$

$$\stackrel{r\to 2M}{\longrightarrow} \frac{1}{(4M)^4}\frac{1}{24\pi^2}$$

Linear back-reaction in absence of post-selection

$$\langle T^2\rangle_{Unruh} \stackrel{r\to 2M}{\longrightarrow} O\left(\frac{1}{M^8}\right)$$

Outside the star : $R^0_{\mu\nu}R^{\mu\nu\,0} = 64\pi^2\langle T^2\rangle_{Unruh}$

With no post-selection, the back-reaction of the radiation is small

The classical horizon is not sensitive to such back reaction

Partial post-selection: $\mathbf{H} = \mathbf{H}_{\mathcal{J}+} \otimes \mathbf{H}_{\mathcal{H}}$ *, no post selection on* $\mathbf{H}_{\mathcal{H}}$

$$|\psi\rangle \in \mathbf{H}_{\mathcal{J}+} \qquad \langle i|\psi\rangle \in \mathbf{H}_{\mathcal{H}}$$

$$T^{\psi\, i\, (2)}_{\mu\nu[weak]} = \frac{\langle i|\psi\rangle\langle\psi|\hat{T}^{(2)}_{\mu\nu}\,|i\rangle}{\langle i|\psi\rangle\langle\psi|i\rangle}$$

$$\hat{T}^{(2)}_{\mu\nu} = :\hat{T}^{(2)}_{\mu\nu}: + \langle i|\hat{T}^{(2)}_{\mu\nu}|i\rangle \qquad :\hat{T}^{(2)}_{\mu\nu}:|i\rangle = ::\hat{T}^{(2)}_{\mu\nu}::|i\rangle + C$$

$$T^{\psi\, i\, (2)}_{uu[weak]} = \frac{\langle i|\psi\rangle\langle\psi|\hat{T}^{(2)}_{\mu\nu}|i\rangle}{\langle i|\psi\rangle\langle\psi|i\rangle}$$

$$= \frac{\langle i|\psi\rangle\langle\psi|::\hat{T}^{(2)}_{\mu\nu}::|i\rangle}{\langle i|\psi\rangle\langle\psi|i\rangle} + \frac{\langle\Omega|:\hat{T}^{(2)}_{\mu\nu}:|i\rangle}{\langle\Omega|i\rangle} + \langle i|\hat{T}^{(2)}_{\mu\nu}|i\rangle$$

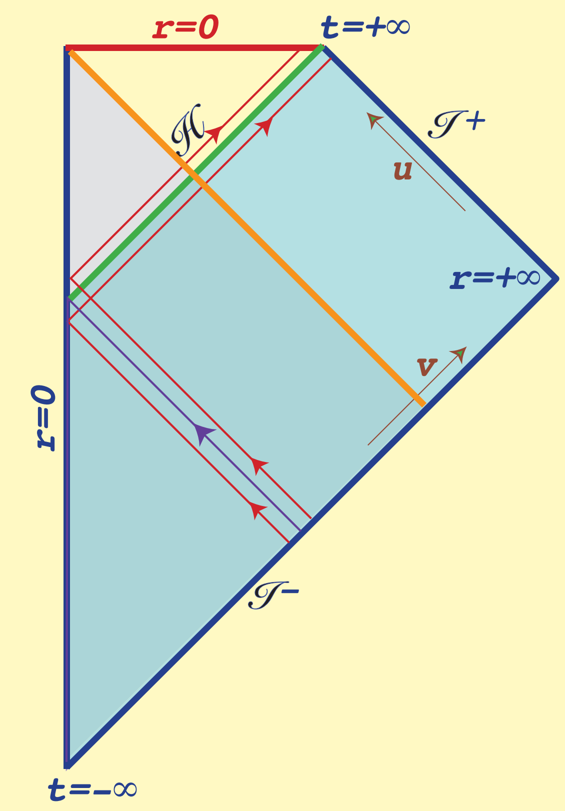
regular on the horizon : Unruh vacuum

H.R. contribution to $|\psi\rangle$

singular on the horizon : Boulware vacuum

S. Massar and R. Parentani, *Phys. Rev.* **D54** (1996) 7444 [arXiv:gr-qc/9502024]; F. Englert, S. Massar and R. Parentani, Class. Quant. Grav. **11** (1994) 2919 [arXiv:gr-qc/9404026].

s-waves without the relativistic barrier $\rightarrow \partial_u \partial_v \Phi = 0$ **light-like shell**



$$\Phi(u,v) = \int_0^\infty d\omega \, [|-\omega^{out})a^{out}_{-\omega} + |+\omega^{out})a^{out}_{+\omega} + h.c.]$$

$$|-\omega^{out}) = \frac{1}{\sqrt{4\pi\omega}}\left[\Theta(-v)\exp(i4M\omega\ln\frac{-v}{a}) - \exp(-i\omega u)\right]$$

$$|+\omega^{out}) = \frac{1}{\sqrt{4\pi\omega}}\Theta(v)\exp(-i4M\omega\ln\frac{v}{a})$$

$$|\pm\omega^{in}) = \frac{\exp(\pm\omega 2\pi M)}{\sqrt{8\pi\omega \ \sinh(\omega 4\pi M)}}\Theta(v)\exp(\mp i4M\omega\ln\frac{v}{a}) + \frac{\exp(\mp\omega 2\pi M)}{\sqrt{8\pi\omega \ \sinh(\omega 4\pi M)}}\left[\Theta(-v)\exp(\mp i4M\omega\ln\frac{-v}{a}) - \exp(\pm i\omega u)\right]$$

$$a^{in}_{\pm\omega} = \alpha_\omega a^{out}_{\pm\omega} - \beta_\omega a^{out\dagger}_{\mp\omega} \qquad \alpha_\omega = \frac{\exp(\omega 2\pi M)}{\sqrt{2\sinh(\omega 4\pi M)}} \qquad \beta_\omega = \frac{\exp(-\omega 2\pi M)}{\sqrt{2\sinh(\omega 4\pi M)}}$$

$$|i\rangle = \langle\Omega|i\rangle \exp\left[\int e^{\frac{\beta_\omega}{\alpha_\omega}} a^{out\dagger}_{-\omega} a^{out\dagger}_{+\omega} d\omega\right]|\Omega\rangle \qquad |\Omega\rangle = |\Omega_{\mathcal{H}}\rangle|\Omega_{\mathcal{J}^+}\rangle$$

Hawking radiation $tr\Pi_{\mathbf{H}_{\mathcal{H}}}|i\rangle\langle i| = \frac{1}{Z}\exp\left(-8\pi M\right)H$

$$: \hat{T}^{(2)}_{uu} : |i\rangle = \lim_{u',u''\to u} \int\int d\omega d\omega' \left[\partial_{u'}| -\omega^{in}\,)^\star a^{in\dagger}_{-\omega} + \partial_{u'}| +\omega^{in}\,)^\star a^{in\dagger}_{+\omega}\right]$$

$$\left[\partial_{u''}| -\omega'^{\,in}\,)^\star a^{in\dagger}_{-\omega'} + \partial_{u''}| +\omega'^{\,in}\,)^\star a^{in\dagger}_{+\omega'}\right] |i\rangle$$

$$a^{in\dagger}_{\pm\omega}\, a^{in\dagger}_{\mp\omega'} |i\rangle = \left[\frac{1}{\alpha_\omega \alpha_{\omega'}} a^{out\dagger}_{\pm\omega}\, a^{out\dagger}_{\mp\omega'} - \frac{\beta_\omega}{\alpha_\omega}\delta(\omega-\omega')\right] |i\rangle$$

Vacuum terms

$$\langle i|\hat{T}^{(2)}_{uu}|i\rangle = \frac{1}{12\pi}\left[-\frac{M}{2r^3}(1-\frac{2M}{r}) - \frac{M^2}{4r^4}\right] + \frac{1}{(4M)^2}\frac{1}{48\pi}$$

$$\frac{\langle\Omega| : \hat{T}^{(2)}_{uu} : |i\rangle}{\langle\Omega|i\rangle} = -\frac{1}{2\pi}\int_0^\infty d\omega \frac{\omega}{e^{8\pi M\omega}-1} = \frac{-1}{(4M)^2}\frac{1}{48\pi}$$

The radiation term : $\dfrac{\langle i|\psi\rangle\langle\psi| :: \hat{T}^{(2)}_{\mu\nu} :: |i\rangle}{\langle i|\psi\rangle\langle\psi|i\rangle}$

$$\sum_i = \frac{\tau}{2\pi}\int d\omega \qquad \tilde{a}_{\omega_i} = \left(\frac{2\pi}{\tau}\right)^{\frac{1}{2}} a_\omega$$

$$|P_\gamma\rangle = \frac{1}{\sqrt{n_1!\, n_2! \dots n_n!}} (\tilde{a}^{out\dagger}_{-\omega_1})^{n_1} \dots (\tilde{a}^{out\dagger}_{-\omega_n})^{n_n} |\Omega_{\mathcal{J}^+}\rangle$$

$$\frac{\langle i|P_\gamma\rangle\langle P_\gamma| :: \hat{T}^{(2)}_{uu} :: |i\rangle}{\langle i|P_\gamma\rangle\langle P_\gamma|i\rangle} = \frac{1}{\tau}\sum_l \omega_l^{(\gamma)} n_l^{(\gamma)} = \frac{1}{2\pi}\int_0^\infty n(\omega)\omega\, d\omega$$

$$|\psi\rangle = \sum_\gamma \alpha_\gamma |P_\gamma\rangle \qquad T^{(2)\,rad}_{uu} \equiv \frac{\langle i|\psi\rangle\langle\psi| :: \hat{T}^{(2)}_{uu} :: |i\rangle}{\langle i|\psi\rangle\langle\psi|i\rangle} = T^{(2)\,rad\,D}_{uu} + T^{(2)\,rad\,ND}_{uu}$$

$T^{(2)\,rad\,D}_{uu} = \frac{1}{\tau}\frac{\sum_\gamma |\alpha_\gamma|^2 p^T_\gamma E_\gamma}{\sum_\gamma |\alpha_\gamma|^2 p^T_\gamma} \rightarrow$ divergent on the horizon except if $= \frac{1}{\tau}\sum_\gamma p^T_\gamma E_\gamma$

$T^{(2)\,rad\,ND}_{uu} \rightarrow$ divergent oscillations when approaching the horizon

Coordinate invariant characterization of generic weak values

$$T^{\psi\, i\, (2)}_{uu[weak]} \overset{r\to 2M}{\longrightarrow} -\frac{1}{(4M)^2}\frac{1}{48\pi} + O(\frac{1}{M^2}) = O(\frac{1}{M^2})$$

$$\delta(r) = \int_{2M}^{r} g_{rr}^{1/2}(r')dr' \simeq (8M)^{\frac{1}{2}}(r-2M)^{\frac{1}{2}} \qquad g_{uv} = 1 - \frac{2M}{r} \simeq \frac{r-2M}{2M} \simeq \frac{\delta^2}{M^2}$$

$$\langle T^2\rangle^{(2)}_{weak} = T^{(2)}_{\mu\nu\,[weak]}\; T^{\mu\nu\,(2)}_{[weak]} \overset{r\to 2M}{\longrightarrow} \simeq \langle T^2\rangle^{(2)}_{Boulware} = \frac{1}{\delta^4}\frac{1}{288\pi^2}$$

Linear back-reaction in presence of a generic post-selection on $\mathcal{J}^+$

$$\langle T^2\rangle_{weak} \overset{r\to 2M}{\longrightarrow} O\left(\frac{1}{\delta^4 M^4}\right) \underbrace{O\left(\frac{M^4}{\delta^4}\right)}_{\text{Number of modes}} = O\left(\frac{1}{\delta^8}\right)$$

Outside the star : $R^{0}_{\mu\nu}R^{\mu\nu\,0} = 64\pi^2\langle T^2\rangle_{weak}$

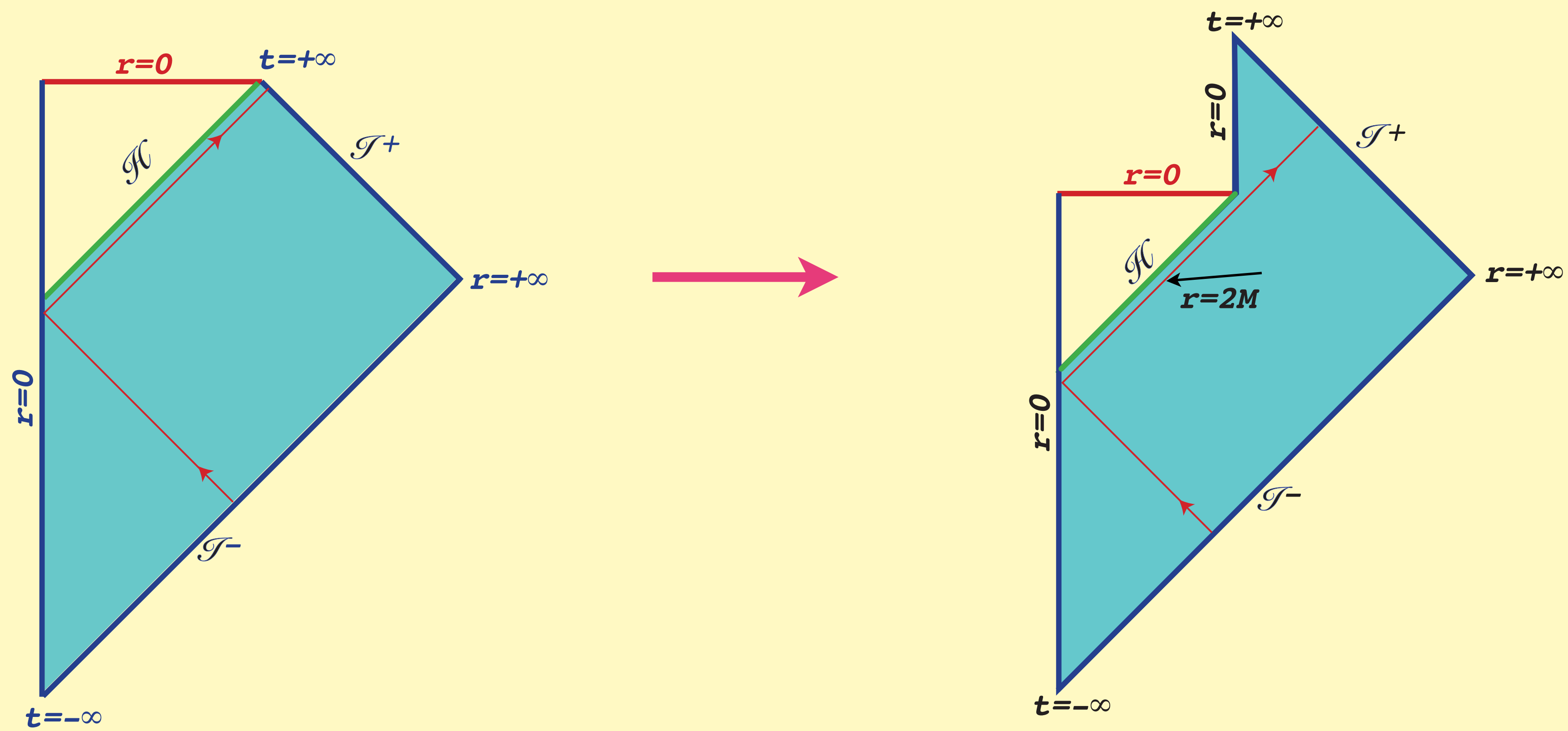
The back-reaction of generic weak values is prohibitively large

The classical horizon may not survive post-selection

IV. Black hole unitary S-matrix and classical physics

Exclusive amplitudes: the unitary S-matrix

Extrapolating from the Hawking back-reaction



Post-selection on $\mathcal{J}^+ \rightarrow$ exclusive S-matrix amplitude

- The classical horizon does not survive in exclusive S-matrix amplitudes

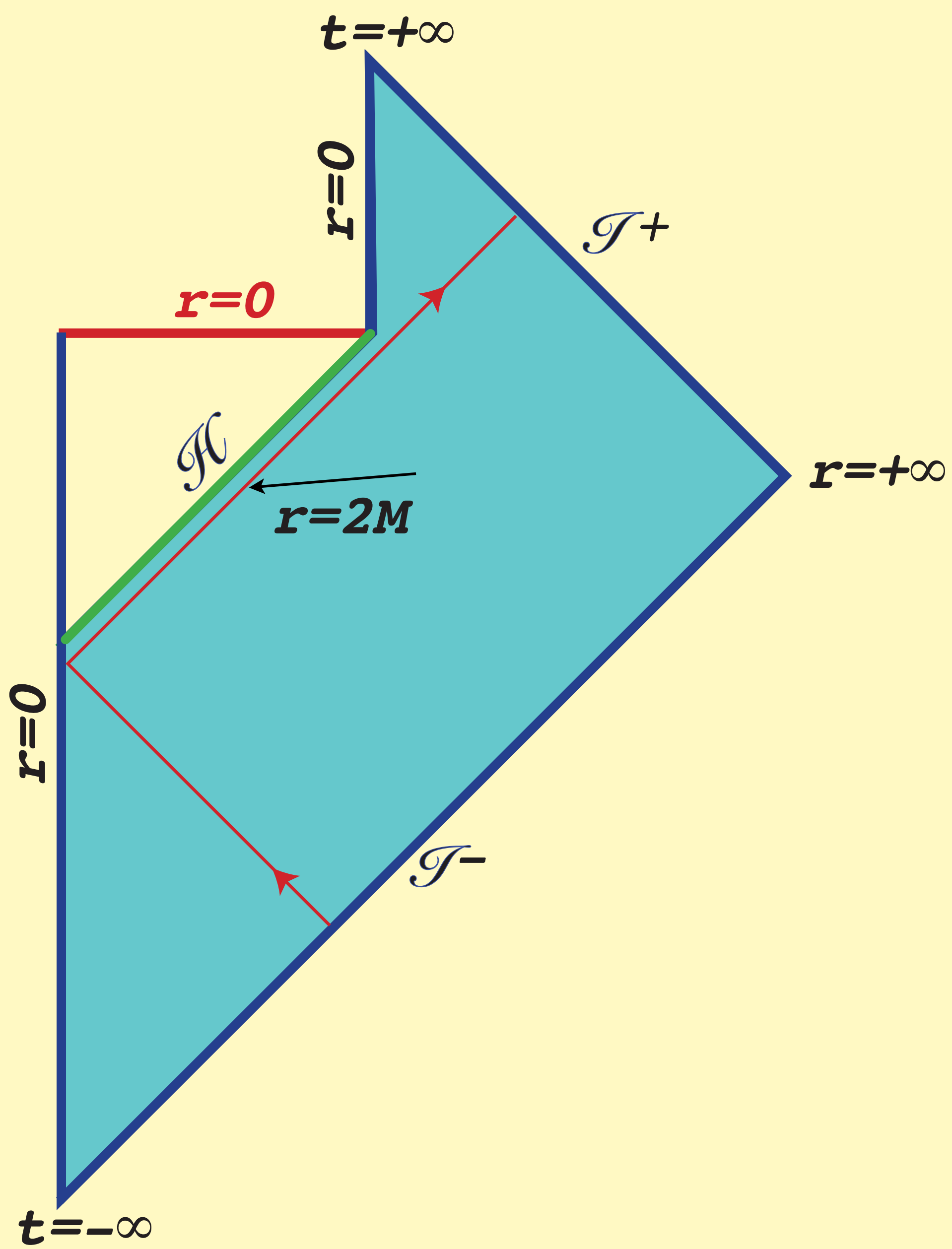
- No horizon → The S-matrix is unitary

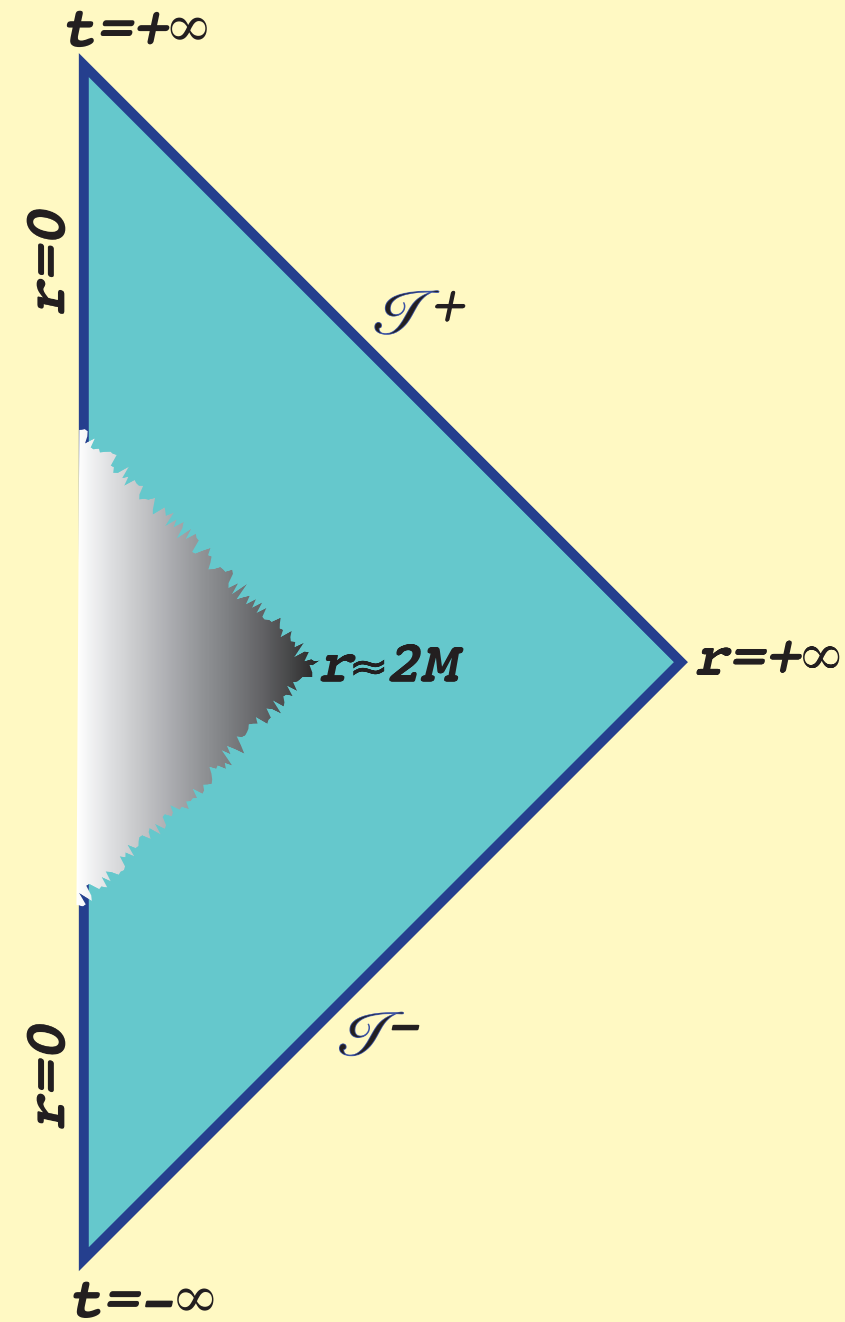
- The S-matrix is TCP invariant

G. ‘t Hooft, *Nucl. Phys.* **B256** (1985) 727; *Nucl. Phys.* **B335** (1990) 138; C.R. Stephens, G. ‘t Hooft and B. F. Whiting, *Class. Quant. Grav.* **11** (1994) 621 [gr-qc/9310006].

Schematic description of a unitary black hole S-matrix

The approximate space-time representation of the quantum black hole in-out amplitudes in asymptotic flat space is limited to a region outside the would-be horizons





Inclusive backgrounds and classical physics

Extrapolating from the Hawking linear back-reaction

The classical approximation for a quantum black hole is taken to be the inclusive S-matrix background (no transplanckian fluctuations)

$$E^0_{\mu\nu} \equiv R^0_{\mu\nu} - \frac{1}{2} g^0_{\mu\nu} R^0 = 8\pi\, T^i_{\mu\nu[\underline{weak}]} = \langle i | \hat{T}^{\{\phi_j\}}_{\mu\nu} | i \rangle$$

$$E^{0\,(fi)}_{\mu\nu} \equiv R^{0\,(fi)}_{\mu\nu} - \frac{1}{2} g^{0\,(fi)}_{\mu\nu} R^{0\,(fi)} = 8\pi\, T^{fi}_{\mu\nu[weak]}$$

$$\boxed{E^0_{\mu\nu} = \sum\nolimits_f |\langle f | i \rangle|^2 E^{0\,(fi)}_{\mu\nu}}$$

- Horizon is recovered in the inclusive background

- Classical geometry and horizon appear as coarse-grained averages

- The average is over "fuzzball-like" configurations $\quad \mathbf{S} = 4\pi M^2 = \ln N$

J.M. Bardeen, B. Carter and S.W. Hawking, *Comm. Math. Phys.* **31** (1973) 161 [hep-th/9306069]; T. Jacobson, *Phys. Rev. Lett.* **75** (1995) 1260 [gr-qc/9504004]; E. Elizalde and P.J. Silva, *Phys. Rev.* **D78** (2008) 061501 [arXiv:0804.3721]; R. Brustein and M. Hadad, *Phys. Rev. Lett.* **103** (2009) 101301 [arXiv:0903.0823]; E. Verlinde [arXiv:1001.0785].
S.D. Mathur, Class. Quant. Grav. 23 (2006) R115 [hep-th/0502050]; K. Skenderis and M. Taylor, Phys. Rept. 467 (2008) 117 [arXiv:0804.0552].
L. Susskind, L. Thorlacius and J. Uglum, *Phys. Rev.* **D48** (1993) 3743 [hep-th/9306069].

Summary

- Black hole unitarity "follows" from exclusive S-matrix amplitudes

- Classical physics "follows" from the inclusive S-matrix background

- Horizon and classical geometry are coarse-grained averages

- The quantum S-matrix (exclusive amplitudes) void of horizons contains the information left by an object crossing the horizon (inclusive background amplitude)

- The scheme follows from conventional quantum physics: while the computation of unitary amplitudes would require a detailed theory of quantum gravity, the scheme itself does not

- It makes contact with the fuzzball conjecture