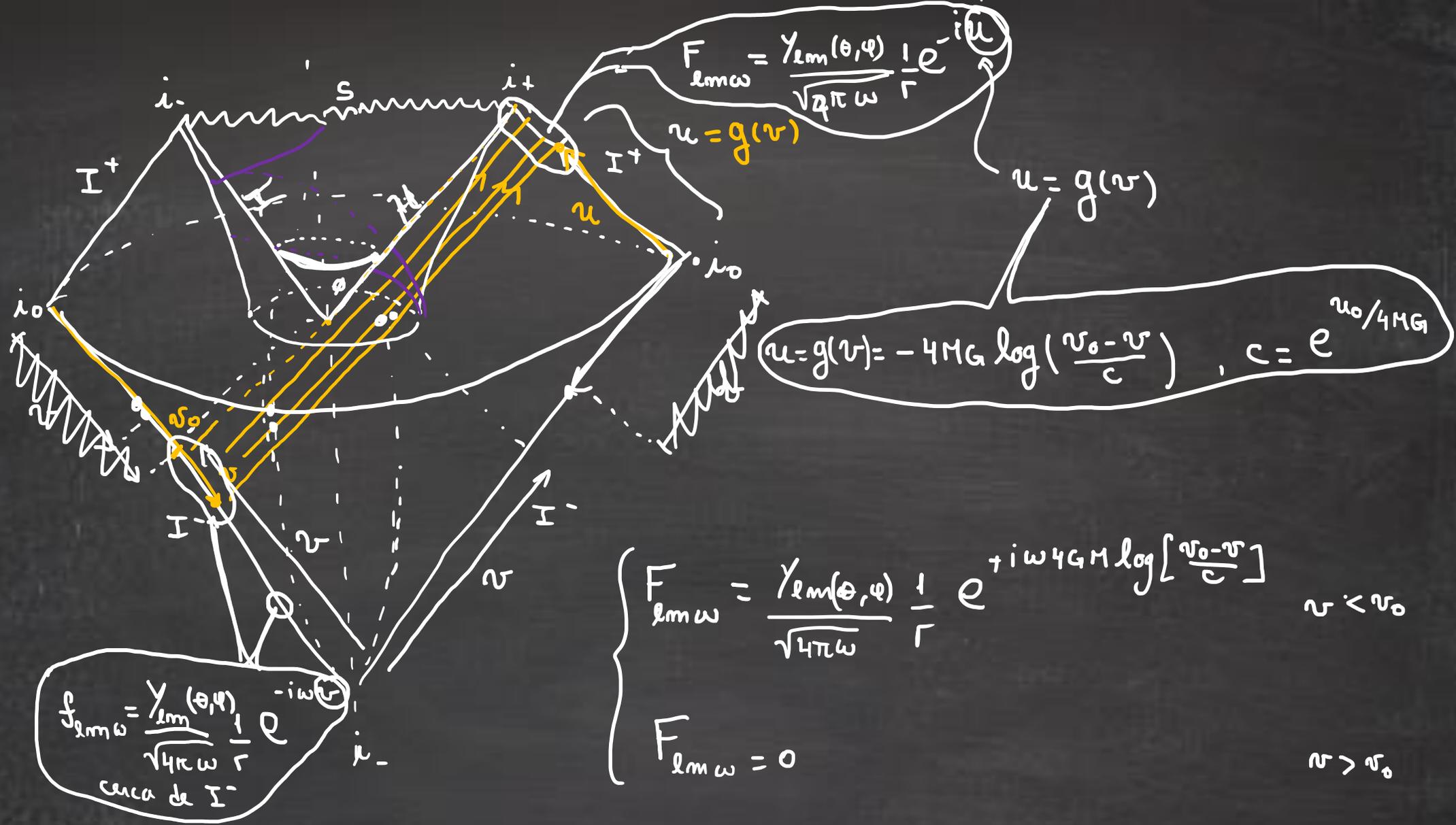


Escuela de Agujeros Negros Clásicos y Cuánticos (GRAV@UDEEC2021)



Universidad de Concepción
Enero de 2021



$$F_{lm\omega} = \frac{Y_{lm}(\theta, \varphi)}{\sqrt{4\pi\omega}} \frac{1}{r} e^{-i\omega u}$$

$$u = g(r)$$

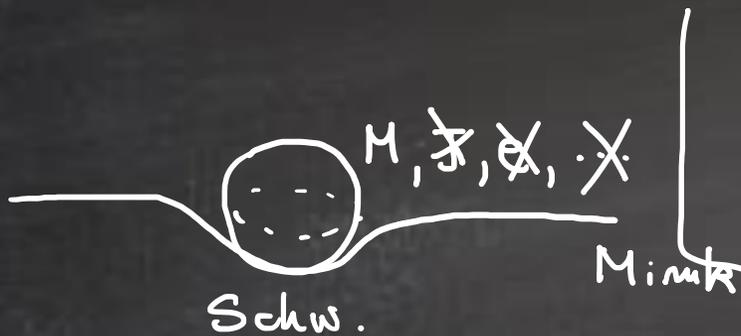
$$u = g(r)$$

$$u = g(r) = -4MG \log\left(\frac{r_0 - r}{c}\right), \quad c = e^{r_0/4MG}$$

$$f_{lm\omega} = \frac{Y_{lm}(\theta, \varphi)}{\sqrt{4\pi\omega}} \frac{1}{r} e^{-i\omega r}$$

cerca de I^-

$$\left\{ \begin{array}{l} F_{lm\omega} = \frac{Y_{lm}(\theta, \varphi)}{\sqrt{4\pi\omega}} \frac{1}{r} e^{+i\omega 4GM \log\left[\frac{r_0 - r}{c}\right]} \quad r < r_0 \\ F_{lm\omega} = 0 \quad r > r_0 \end{array} \right.$$



$$N_\omega = \sum_{\omega'} |\beta_{\omega'\omega}|^2 = \frac{1}{e^{\frac{\hbar\omega}{8\pi G M \omega}} - 1} = \frac{1}{e^{k_B T_H} - 1}$$

Hawking (1974): Es como si F viera un espectro de Planck con

$$T_H = \frac{\hbar}{k_B 8\pi G M}$$

$c=1$ T. de Hawking.

$$dE = c^2 dM = T_H dS$$

$$S = \left(\frac{1}{4}\right) \frac{c^3 k_B \text{Area}}{\hbar G} = \frac{4\pi \left(\frac{2MG}{c^2}\right)^2}{4} \frac{c^3 k_B}{\hbar G}$$

A.G. en un esp. as. plano, que no rota, ni tiene carga



} Equilibrio
Termico

QFT a $T \neq 0$

QM)

$$\langle q_f(t_f) | q_i(t_i) \rangle = \langle q_f | e^{\frac{iH}{\hbar}(t_f - t_i)} | q_i \rangle = \int \mathcal{D}q e^{\frac{i}{\hbar} S[q, \dot{q}]}$$



$$\begin{aligned} q(t_i) &= q_i \\ q(t_f) &= q_f \end{aligned}$$

$$\begin{aligned} S &= \int dt \mathcal{L}[q, \dot{q}] \\ \mathcal{L} &= \dot{q}^2 - V(q) \end{aligned}$$

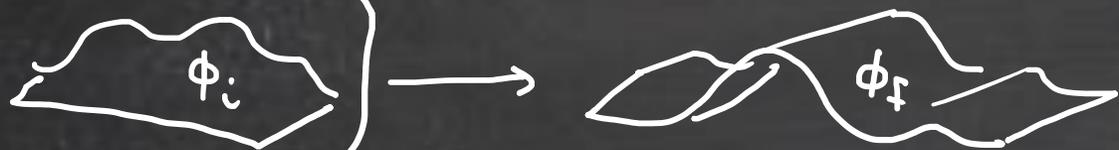
QFT)

$$\langle \phi_f(t_f) | \phi_i(t_i) \rangle = \int \mathcal{D}\phi e^{\frac{i}{\hbar} S[\phi, \nabla\phi, \phi]}$$

$$\phi(\vec{x}_i, t_i) = \phi_i$$

$$\phi(\vec{x}_f, t_f) = \phi_f$$

(\vec{x}_f, t_f)



$$S = \int dt \int d^3x \mathcal{L}(\phi, \nabla\phi, \phi)$$

$$\partial_\mu \left(\frac{\partial \mathcal{L}}{\partial (\partial_\mu \phi)} \right) - \frac{\partial \mathcal{L}}{\partial \phi} = 0 \rightarrow \text{field eq.}$$

$$\mathcal{L} = \dot{\phi}^2 - \vec{\nabla}\phi \cdot \vec{\nabla}\phi - V(\phi)$$

$$\langle \phi_f(\vec{x}_f, t_f) | \phi_i(\vec{x}_i, t_i) \rangle = \langle \phi_f | e^{\frac{i}{\hbar} H(t_f - t_i)} | \phi_i \rangle \quad \text{Ⓢ}$$

Stat. Phys.

$$H = \dot{q}^2 + V(q)$$

$$Z(\beta) = \sum_{\{\text{config}\}} e^{-\beta E} = \text{Tr}_{\mathcal{H}} [e^{-\beta H}] = \sum_{|m\rangle \in \mathcal{H}} \langle m | e^{-\beta H} | m \rangle =$$

$|m\rangle \in \mathcal{H}$
 \uparrow base de autoest. de H

$$\beta = (k_B T)^{-1}$$

$$-i\beta = \frac{(t_f - t_i)}{\hbar}$$

$$= \sum_{|m\rangle} \underbrace{\langle \phi = \phi_f | e^{+i \frac{\beta H \hbar}{t}} | \phi = \phi_i \rangle}_{\text{en el caso que } \phi_f = \phi_i} = \sum_{|\phi\rangle} \langle \phi | e^{i \frac{(t_f - t_i) H}{\hbar}} | \phi \rangle =$$

$\forall \phi$ periódicos
 con período $\sim \beta$
 en el \mathbb{T} imaginario

$$\tau = i t$$

$$T = \frac{\hbar}{k_B (\tau_f - \tau_i)}$$

$$\hbar \beta \equiv \frac{\hbar}{k_B T} = i (t_f - t_i) \equiv \tau_f - \tau_i$$

SF) H a T



QM) QFT) H evol. it periódic.

$$Z(\beta) = [\dots] = \sum_{|\phi\rangle} \langle \phi = \phi_f | e^{\frac{iH}{\hbar}(-i\beta)} | \phi = \phi_i \rangle = \textcircled{*}$$

$$= \sum_{|\phi\rangle} \underbrace{\int \mathcal{D}\phi}_{\phi_f(x_f, t_f) = \phi_f(x_i, t_i) = \phi} e^{\frac{i}{\hbar} S[\phi, \phi, \nabla\phi]} =$$

periódica com β

$$= \int \mathcal{D}\phi e^{\frac{i}{\hbar} \int dt \int d^3x \mathcal{L}[\dot{\phi}^2 - (\nabla\phi)^2 - V(\phi)]}$$

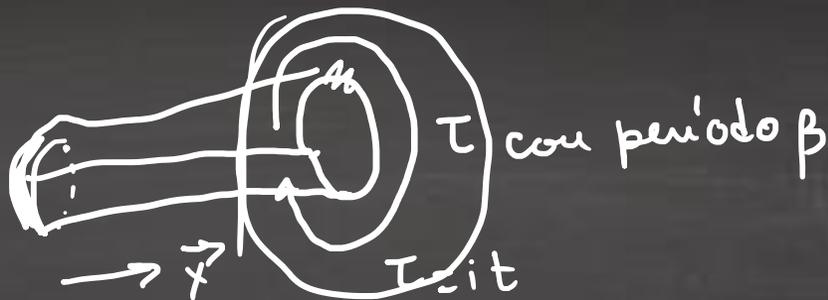
$\forall \phi$ periódicas

$$\textcircled{-} \beta \hbar \left(\frac{d}{d\tau} \right) \frac{d}{dt} = i \frac{d}{d\tau} \rightarrow +\dot{\phi}^2 \rightarrow -\dot{\phi}^2$$

$$= \int \mathcal{D}\phi e^{\frac{1}{\hbar} \int_0^{\beta\hbar} d\tau \int d^3x [-\dot{\phi}^2 - (\nabla\phi)^2 - V(\phi)]}$$

$-S_E$ \swarrow Euclídea

$\int \mathcal{D}\phi e$
periódicas com
período $\beta = (\tau_f - \tau_i)/\hbar$



$$Z(\beta)$$

$$\mathbb{R}^3 \times \mathbb{R}$$

$$\mathbb{R}^3 \times S^1$$

I. $S[\phi, \dot{\phi}, \ddot{\phi}; g_{\mu\nu}]$

II. $t \rightarrow \tau = it$

III. τ periódico

IV. nome $\beta = \tau / \hbar$

$$Z(\beta)$$

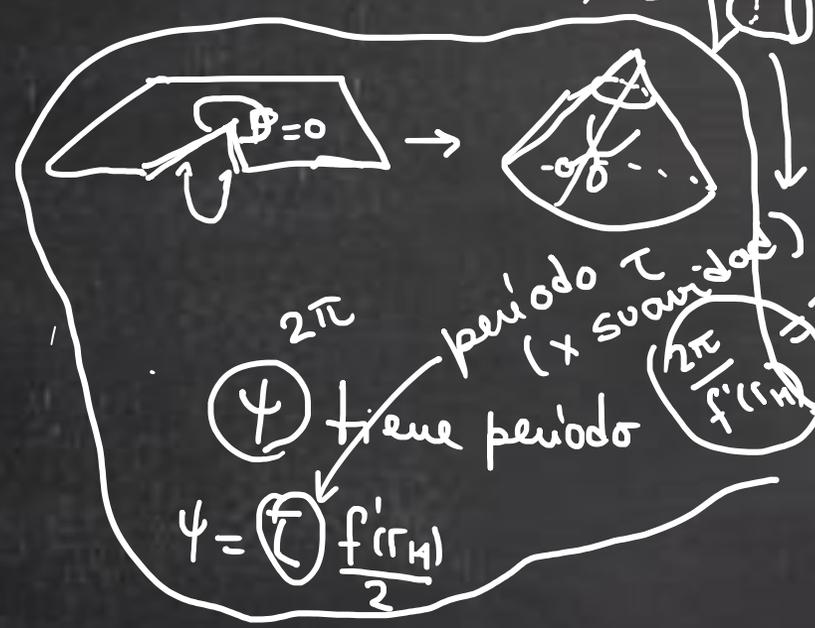
$$\beta = \frac{1}{k_B T}$$

I) $ds^2 = \underbrace{-f(r)dt^2}_{+f(r)d\tau^2} + \underbrace{\frac{dr^2}{f(r)}}_{g(r)} + \overbrace{r^2(d\Omega^2)}^{(r > r_H)} = +f(r)d\tau^2 + \frac{dr^2}{f(r)} + r^2 d\Omega^2$

\uparrow
 $d\theta^2 \sin^2\theta + d\phi^2$

$(r \approx \infty) \quad \mathbb{R}^3 \times S^1$ 

$(r \approx r_H) \quad (r=r_H \leftrightarrow p=0)$
 analizamos cerca de $f(r_H) \approx 0$ i.e. cerca de $r=r_H$

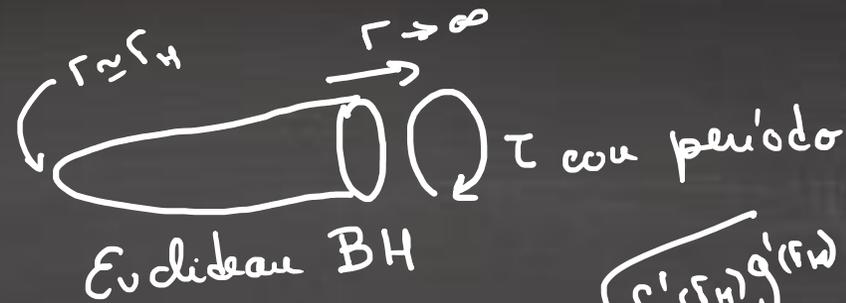


$ds_E^2 = f(r) d\tau^2 + \frac{dr^2}{f(r)} + r^2 d\Omega^2 \approx_{r \approx r_H}$

$\approx + \left(\frac{f'(r_H)}{2}\right)^2 p^2 d\tau^2 + dp^2 + r_H^2 d\Omega^2$

$(p^2 d\psi^2 + dp^2) \times S^2$

$f(r) \approx f(r_H) + f'(r_H) p$
 $p \equiv 2 \sqrt{\frac{r-r_H}{f'(r_H)}}$



$$\beta = \frac{\tau}{\hbar} = \frac{4\pi}{f'(r_H)\hbar} = \frac{1}{k_B T}$$

$f'(r_H)g'(r_H)$

$$T = \frac{\hbar f'(r_H)}{k_B 4\pi}$$

Gibbons-Hawking

E.g. Schwarzschild - (A)DS - RN

$$f = 1 - \frac{2MG}{r} - \frac{\Lambda}{3}r^2 + \frac{GQ^2}{r^2}$$

$$f(r_H) = 0 \rightarrow f(r_H) = 1 - \frac{2MG}{r_H} - \frac{\Lambda}{3}r_H^2 + \frac{GQ^2}{r_H^2}$$

$$T = \frac{\hbar f'(r_H)}{k_B 4\pi} = T(r_H)$$

Ejemplo
 $Q = \Lambda = 0$

$$T_H = \frac{\hbar}{8\pi G M k_B}$$

$$T = f_{ij} a, \quad V \approx f_{ij} \sigma$$



$$F = E - TS$$

μ

$$T = \frac{f'(\Gamma_N) \hbar}{4\pi k_B}$$

$$S = \frac{A_{\text{area}} k_B}{4G \hbar}$$



$$I \sim \omega^3 \frac{1}{e^{\frac{\omega t}{k_B T_H}} - 1}$$



Planck's spectrum
(Estado térmico)

$$|\psi_1\rangle = \sum c_1^i |\varphi_i\rangle$$

$$|\psi_2\rangle = \sum c_2^i |\varphi_i\rangle$$

...

$$\omega_1 \approx 100\%$$

$$\omega_2 \approx 1\%$$

$$\sum_i \omega_i = 1$$

$$P = \begin{bmatrix} \omega_1 & & \\ & \omega_2 & \\ & & \dots \end{bmatrix} \quad \text{Tr}(P) = 1$$

Est. Puro

$$\omega_i = \delta_{i2}$$

~~$$P = \begin{bmatrix} 1 & & \\ & 0 & \\ & & \dots \end{bmatrix}$$~~

$$\omega_i = \frac{1}{N}$$

Est. Térmico

$$P = \text{diag}(\frac{1}{N}, \frac{1}{N}, \dots, \frac{1}{N})$$



$$|\psi_i\rangle = |\psi\rangle_{(t_1)}$$

$$\xrightarrow{e^{\frac{iH(t_2-t_1)}{\hbar}}} |\psi\rangle_{(t_2)}$$

$$\xrightarrow{e^{\frac{iH(t_3-t_1)}{\hbar}}} |\psi\rangle_{(t_3)}$$

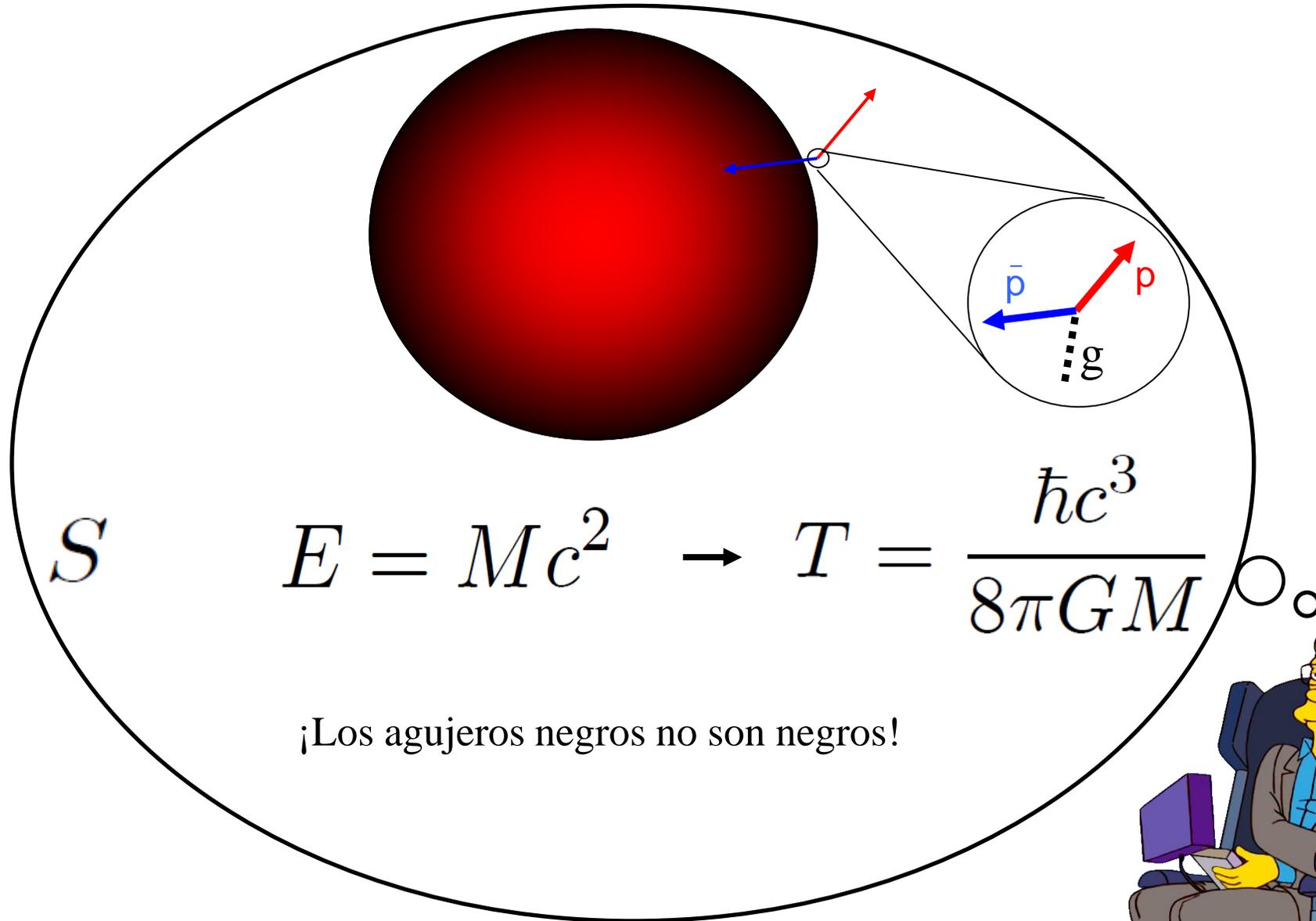
$$\xrightarrow{e^{iH(t_4-t_1)}} |\psi_i\rangle$$

$$\rho = \begin{bmatrix} 1 & & & \\ & 0 & & \phi \\ & & 0 & \\ \phi & & & 0 \end{bmatrix}$$

\nexists hamiltonian evl.
Info. Paradox!!!

$$\rho = \begin{bmatrix} 1/2 & & & \\ & 1/2 & & \\ \phi & & \dots & \\ & & & 1/2 \end{bmatrix}$$

La radiación de Hawking

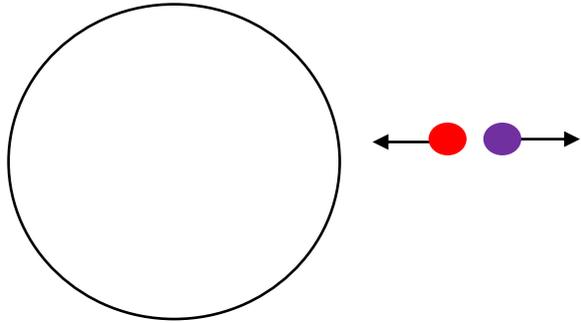


¡Los agujeros negros no son negros!



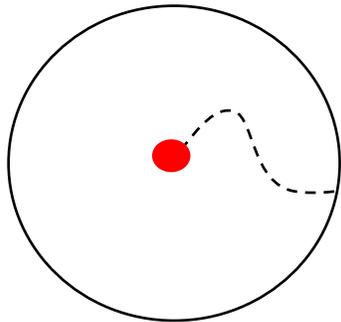
La radiación de Hawking

como creación de pares



$$T = \frac{\hbar c^3}{8\pi G M}$$

como efecto túnel



$$\int dX_A P(X_A|X_B) = \int dX_A \int_{X_A}^{X_B} DX e^{-\frac{i}{\hbar} S[X]}$$

La radiación de Hawking

Espectro de cuerpo negro: $I = \frac{\hbar\omega^3}{2\pi^2c^2} \frac{1}{e^{\frac{\hbar\omega}{kT}} - 1}$

...con una temperatura: $T = \frac{\hbar c^3}{8\pi GM} \simeq 1,227 \cdot \frac{10^{23} \text{ Kg}}{M} K$

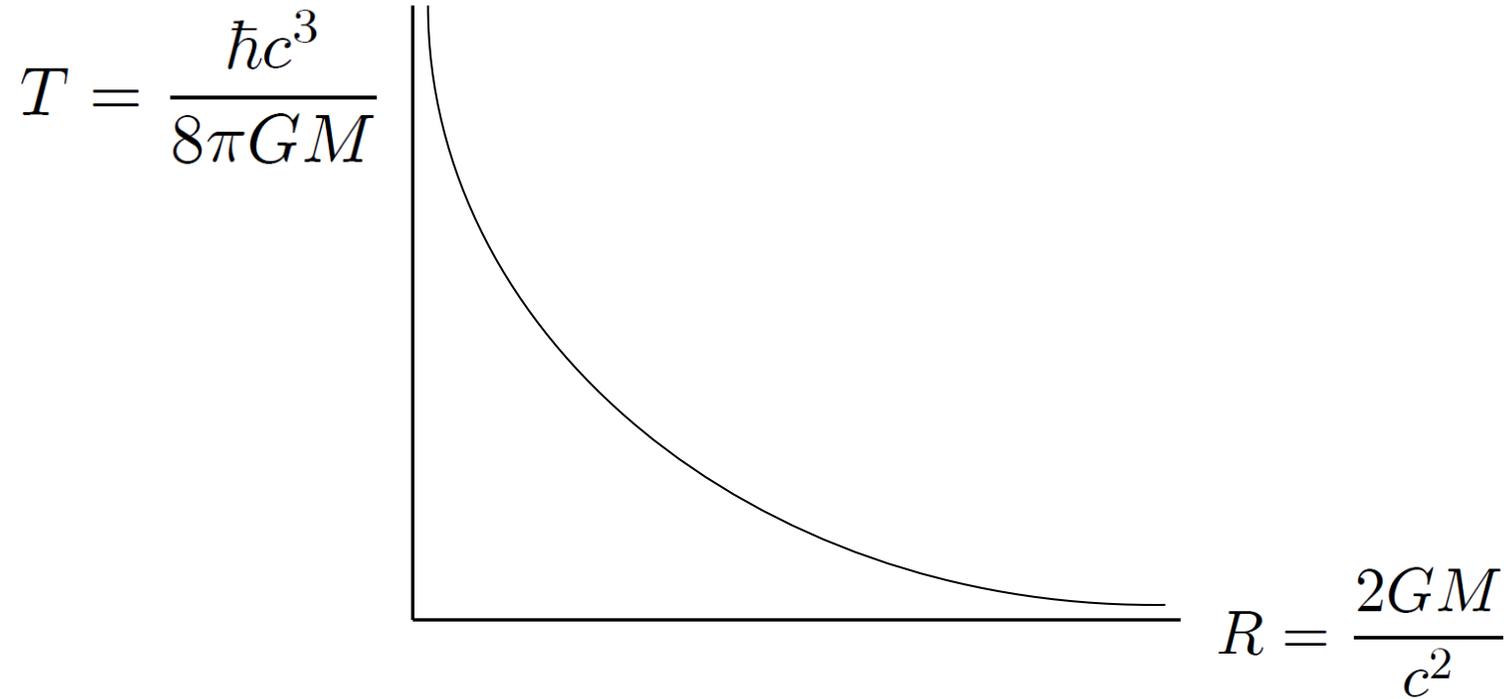
Para agujeros negros estelares: $T \simeq 180 \cdot 10^{-9} K$

$$dE = c^2 dM = T dS = \frac{\hbar c^3}{4\pi GM} \frac{8\pi GM}{\hbar c} dM$$

El radio de Schwarzschild: $R = \frac{2GM}{c^2} \longrightarrow S = \eta \frac{c^3}{4G\hbar} \text{Area}$

$\eta = 1$

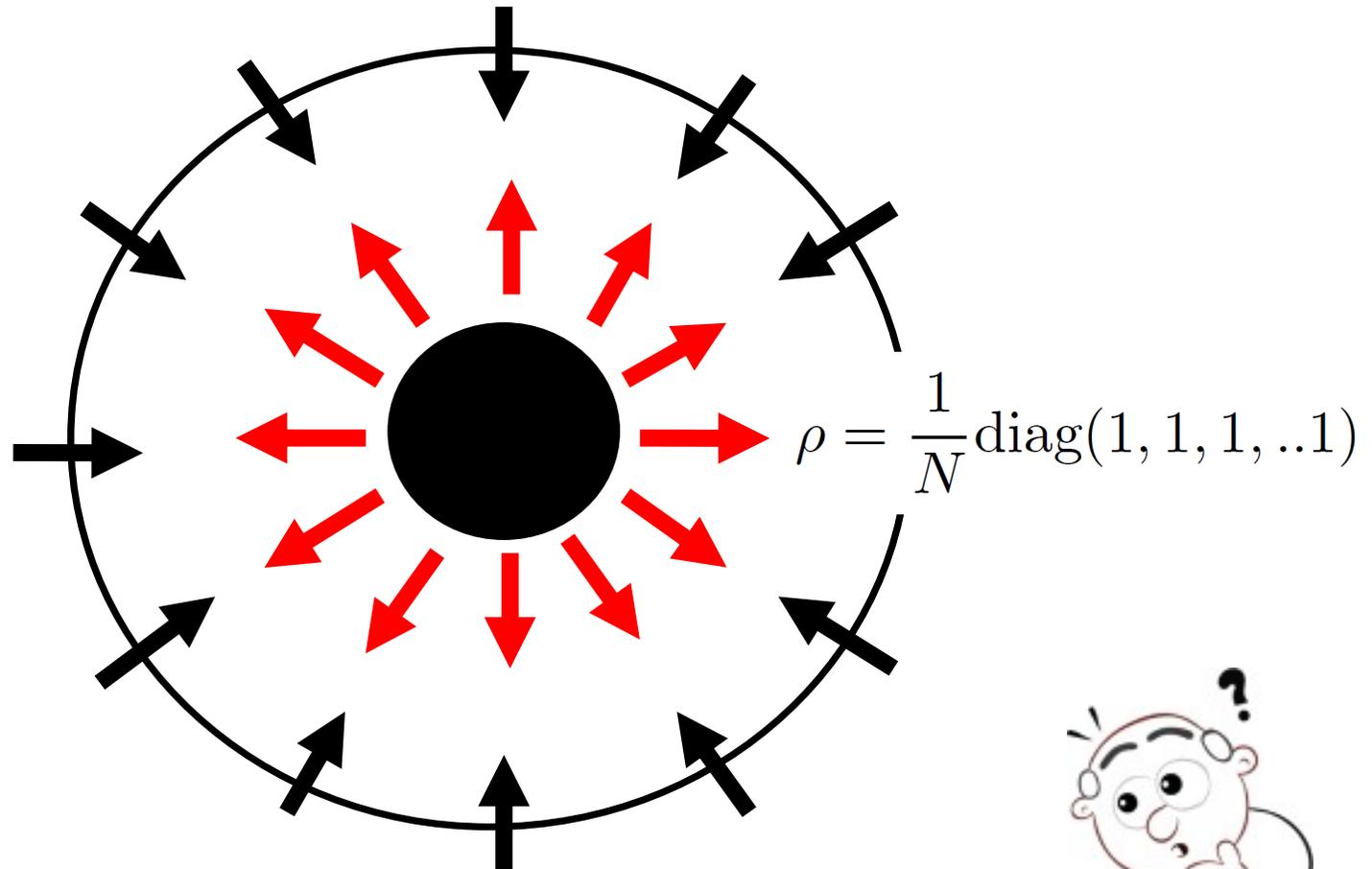
La radiación de Hawking



$$P = \frac{dE}{dt} \propto \text{Area} \times T^4 \sim \frac{1}{M^2} \simeq 2,7 \cdot 10^{-28} \text{ Watts}$$

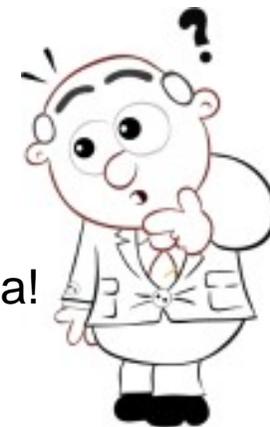
$$t_{\text{evap}} \simeq 10^{67} \text{ years} \gg 10^{10} \text{ years}$$

La paradoja de la información y los Agujeros Negros

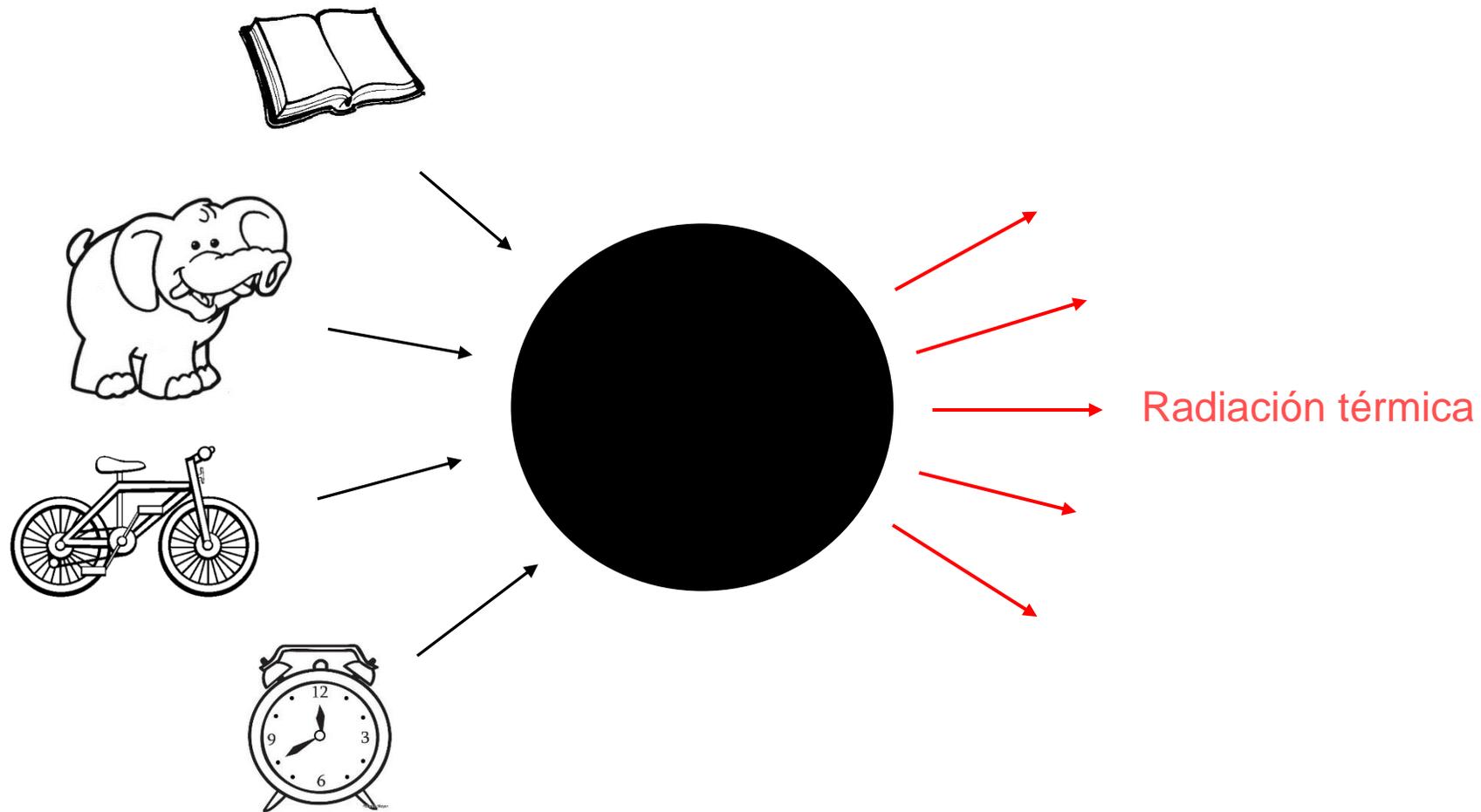


¡Esto no es compatible con la unitariedad de la mecánica cuántica!

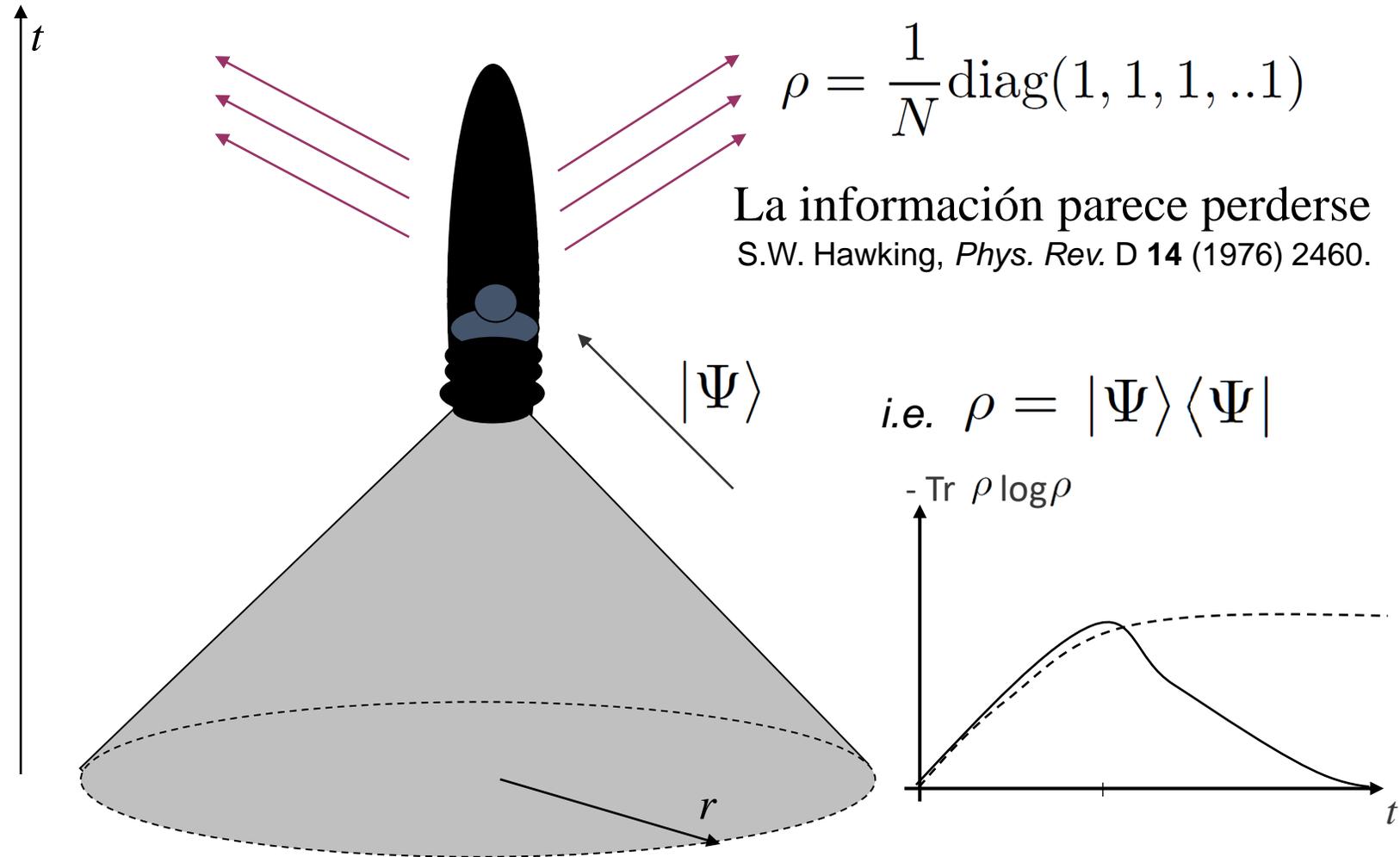
$$\rho = |\Psi\rangle\langle\Psi| \longrightarrow \rho = \frac{1}{N} \text{diag}(1, 1, 1, \dots, 1)$$



La paradoja de la información y los Agujeros Negros



La paradoja de la información y los Agujeros Negros



Según Hawking, en 1976, “[este] no es meramente un resultado de nuestra ignorancia de la teoría correcta, sino que representa una limitación fundamental de nuestra capacidad de predecir el futuro.”

La paradoja de la información y los Agujeros Negros

La Unitariedad de la
Mecánica Cuántica

vs

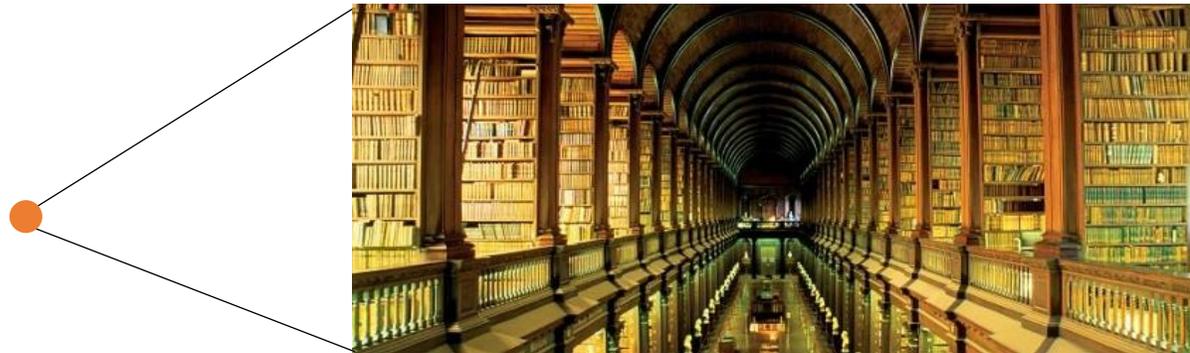
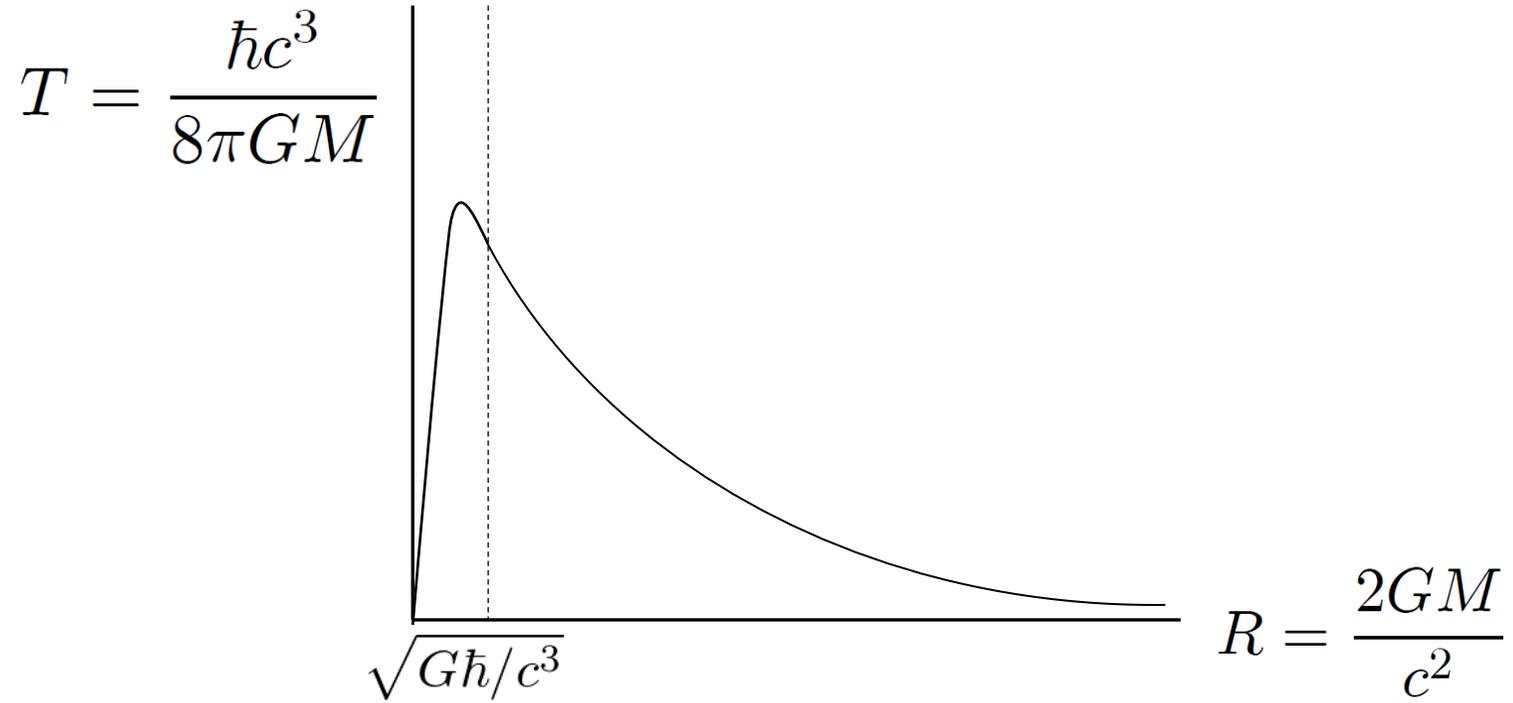
El Principio de Equivalencia
de la Relatividad General



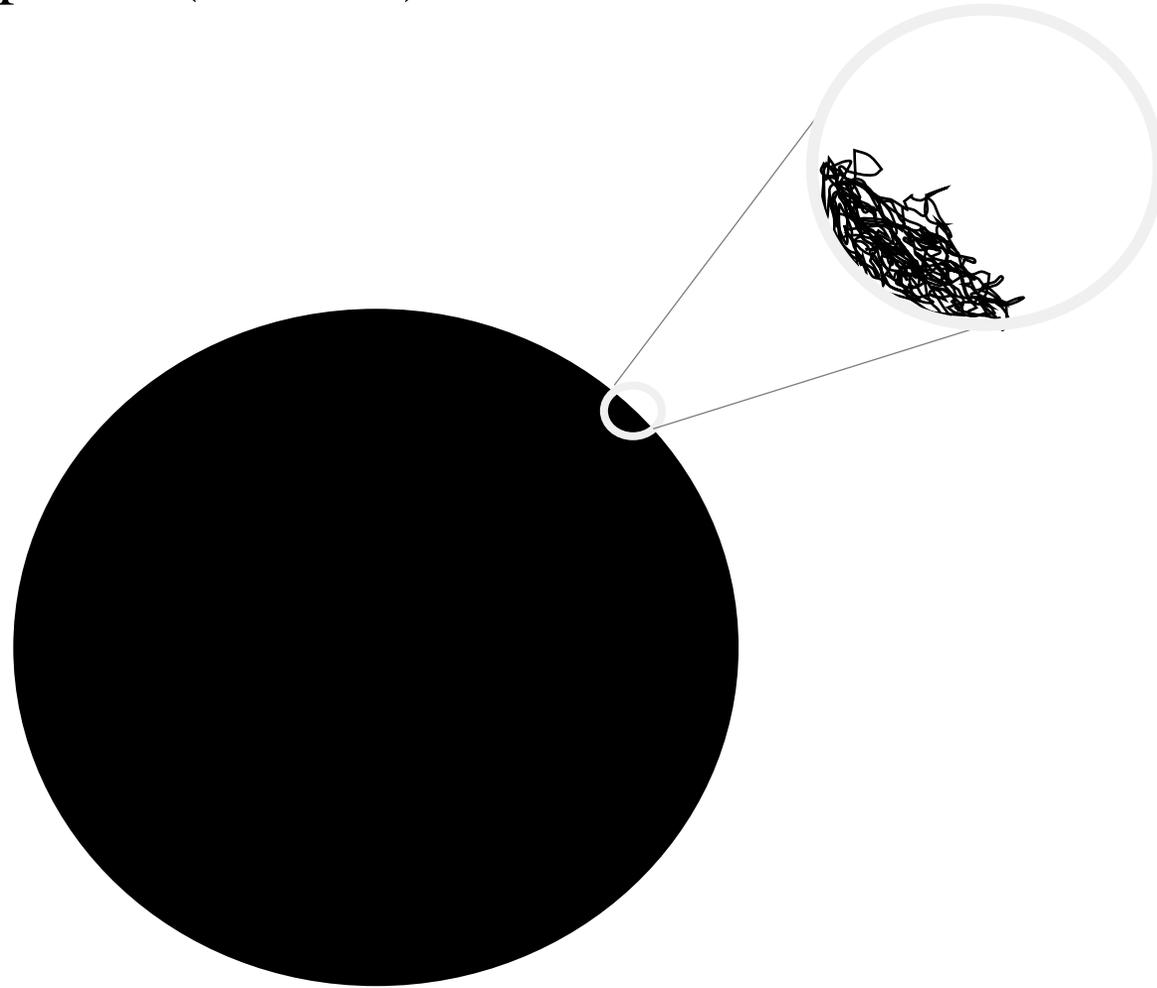
La paradoja de la información y los Agujeros Negros

- Indiferencia
- Remanentes
- Un universo no eterno
- Colapso selectivo
- Abandonar la unitariedad
- Abandonar el principio de equivalencia

Los remanentes

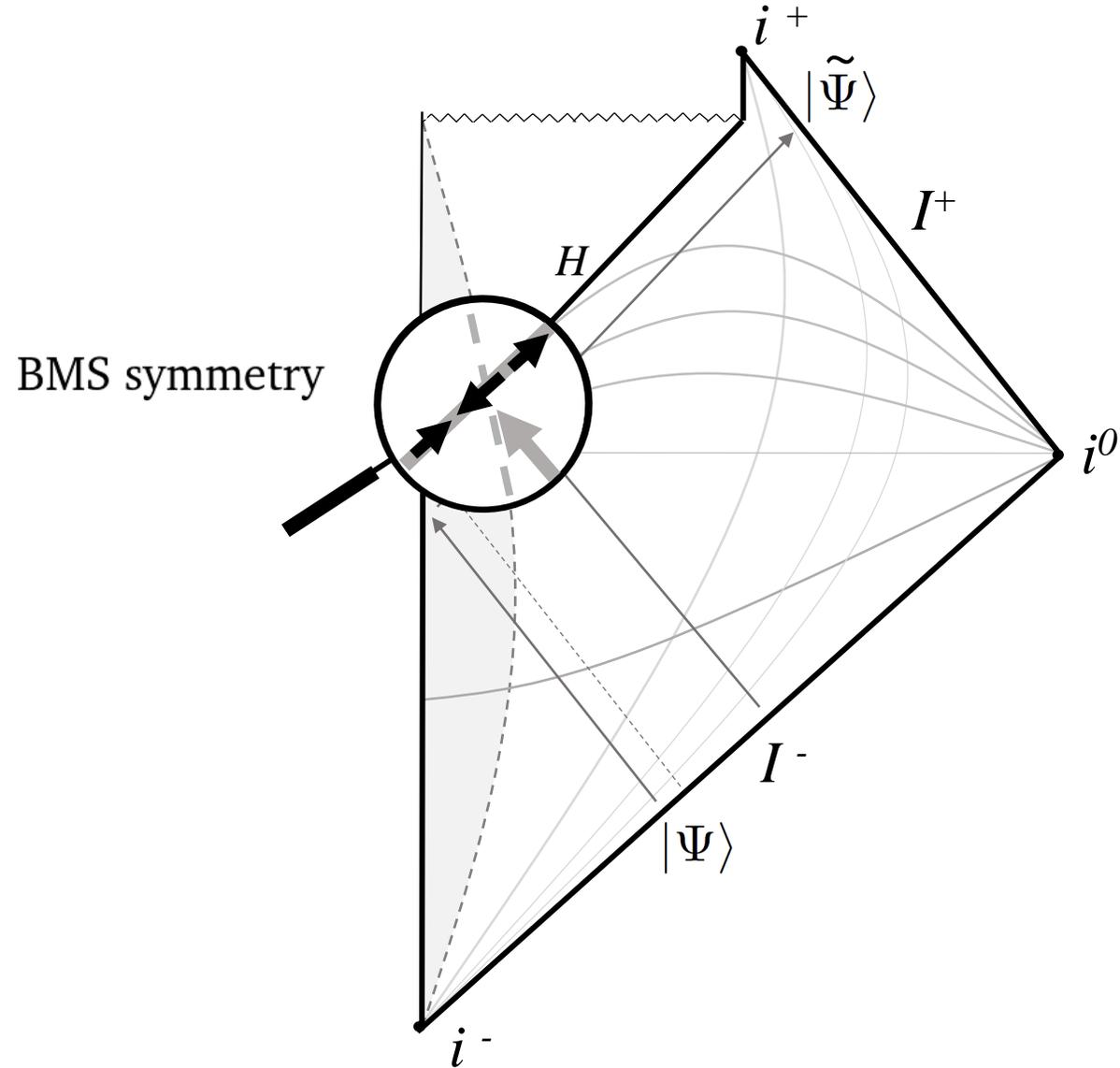


La pelusa (fuzzball), o las esferas difusas



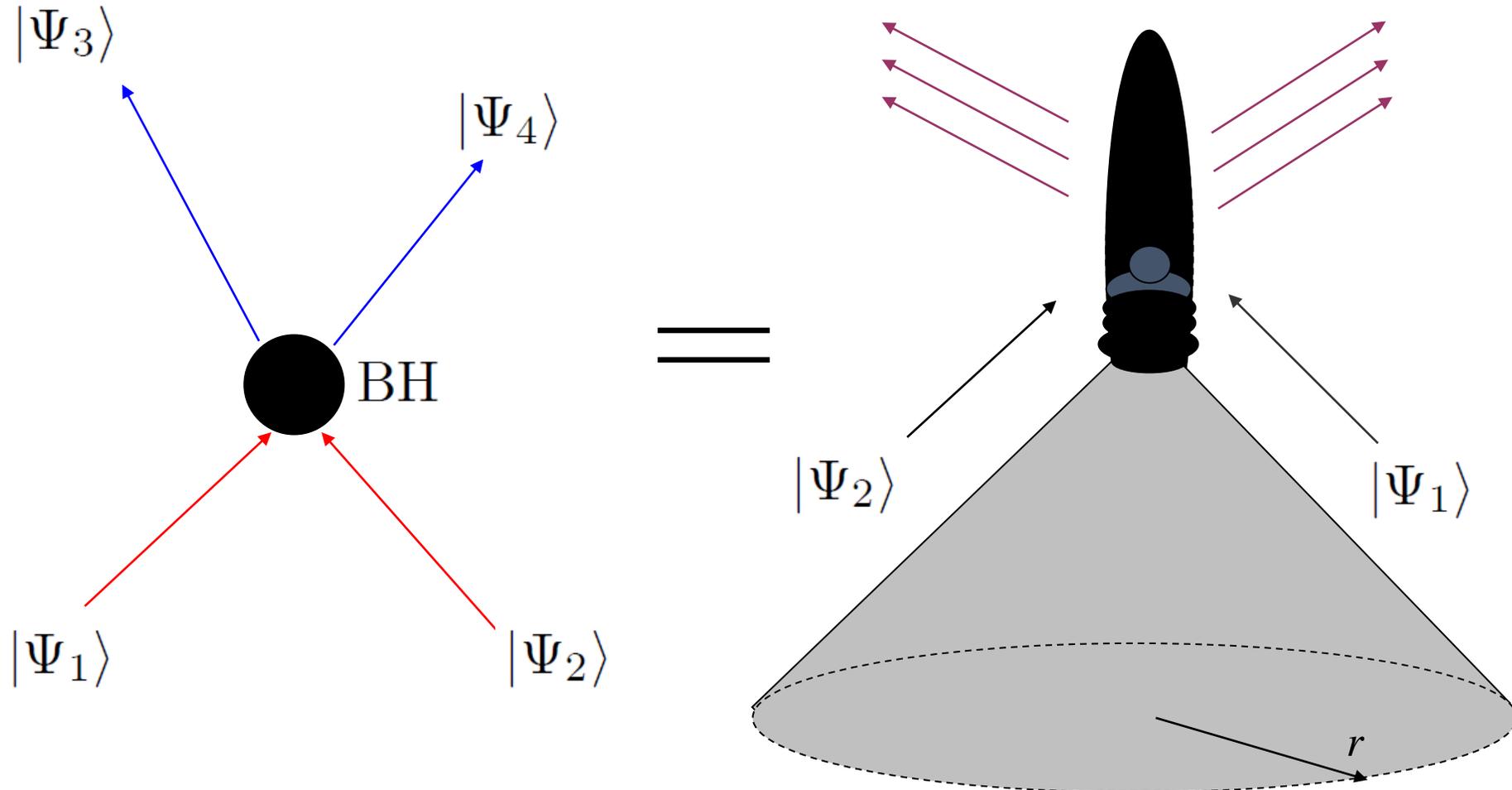
Mathur & Lunin 2002

Efectos de memoria en el horizonte



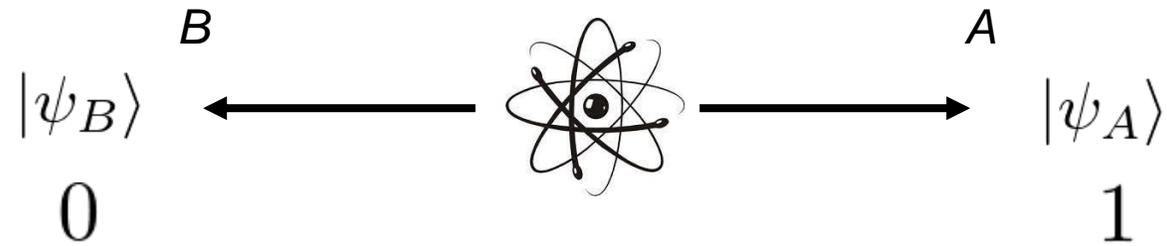
La correspondencia AdS/CFT

Radiación de los agujeros negros como un proceso (unitario) de scattering



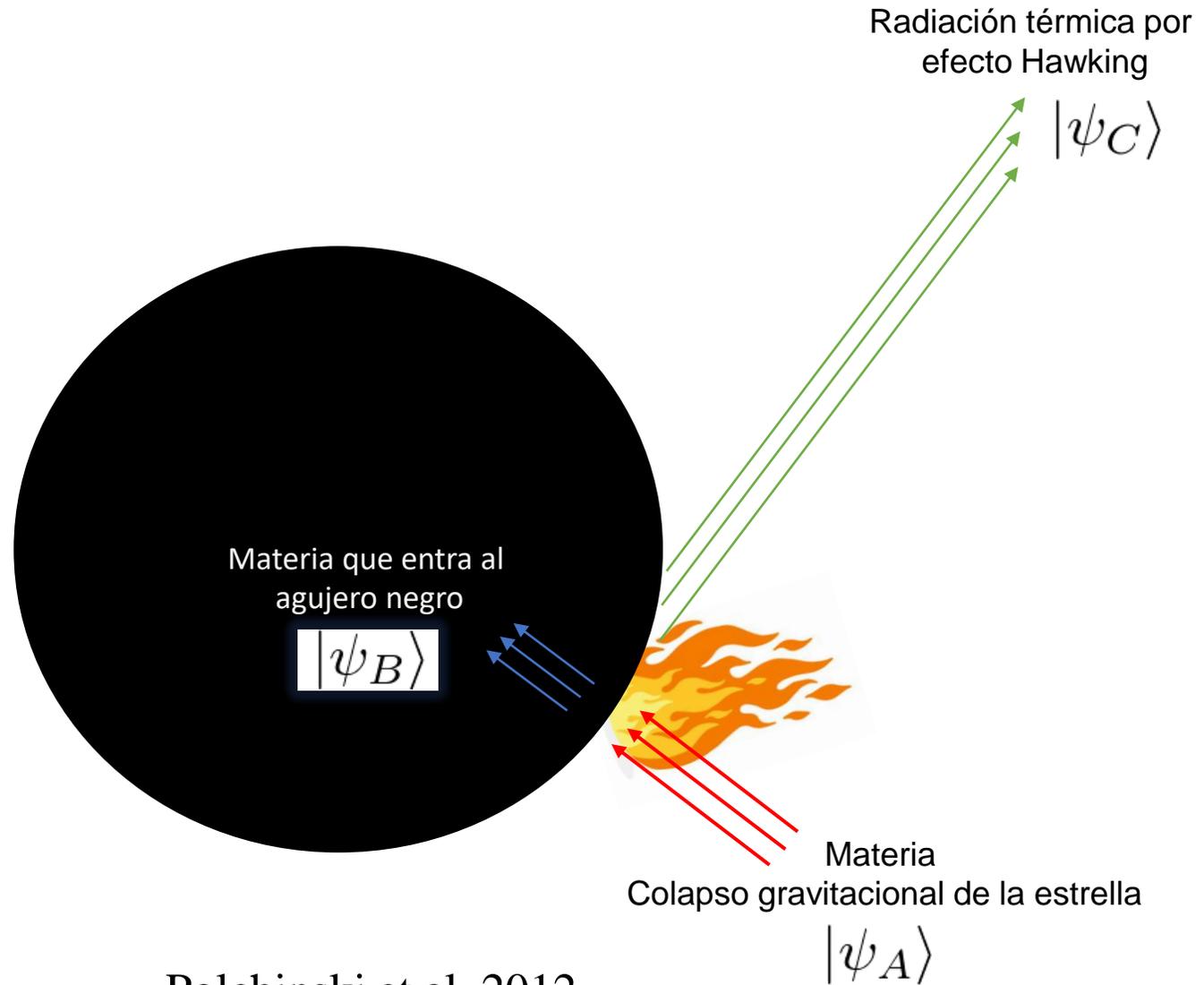
Maldacena 2001

Radiación de Hawking y entrelazamiento cuántico



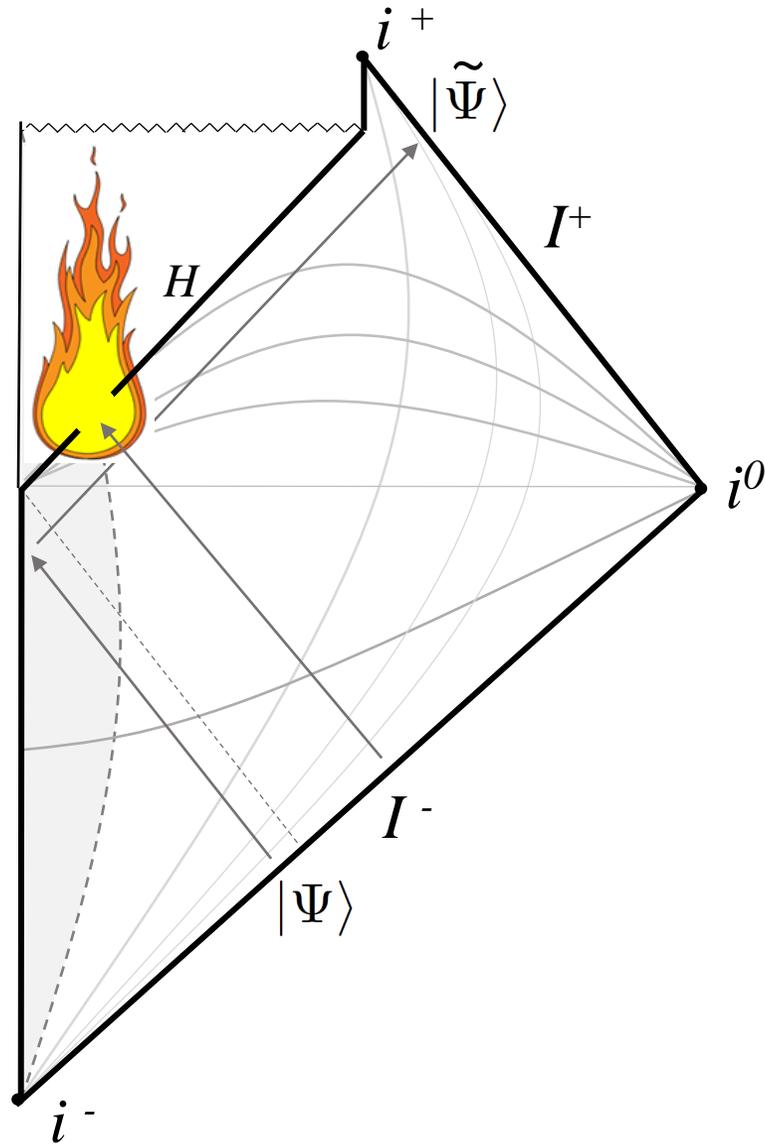
$$|0\rangle \otimes |1\rangle + |1\rangle \otimes |0\rangle$$

La pared de fuego



Polchinski et al. 2012

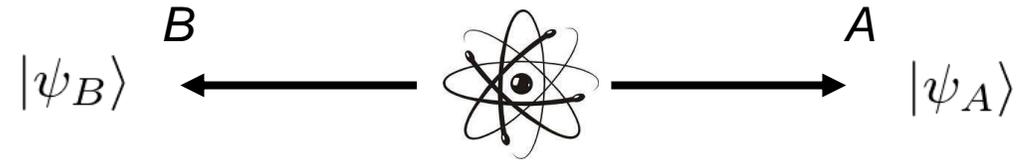
La pared de fuego



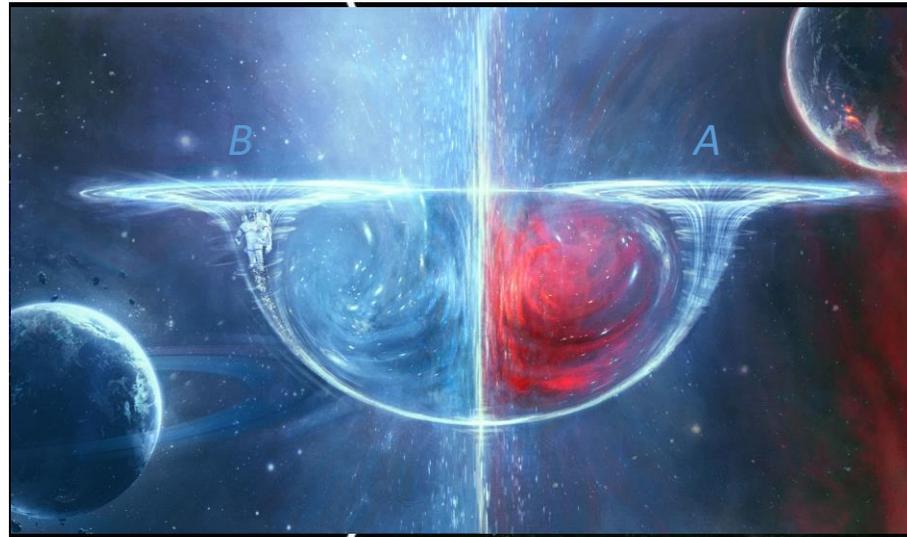
$$\text{EPR} = \text{ER}$$

o “la superflua ausencia de Podolsky”

Einstein-Podolsky-Rosen

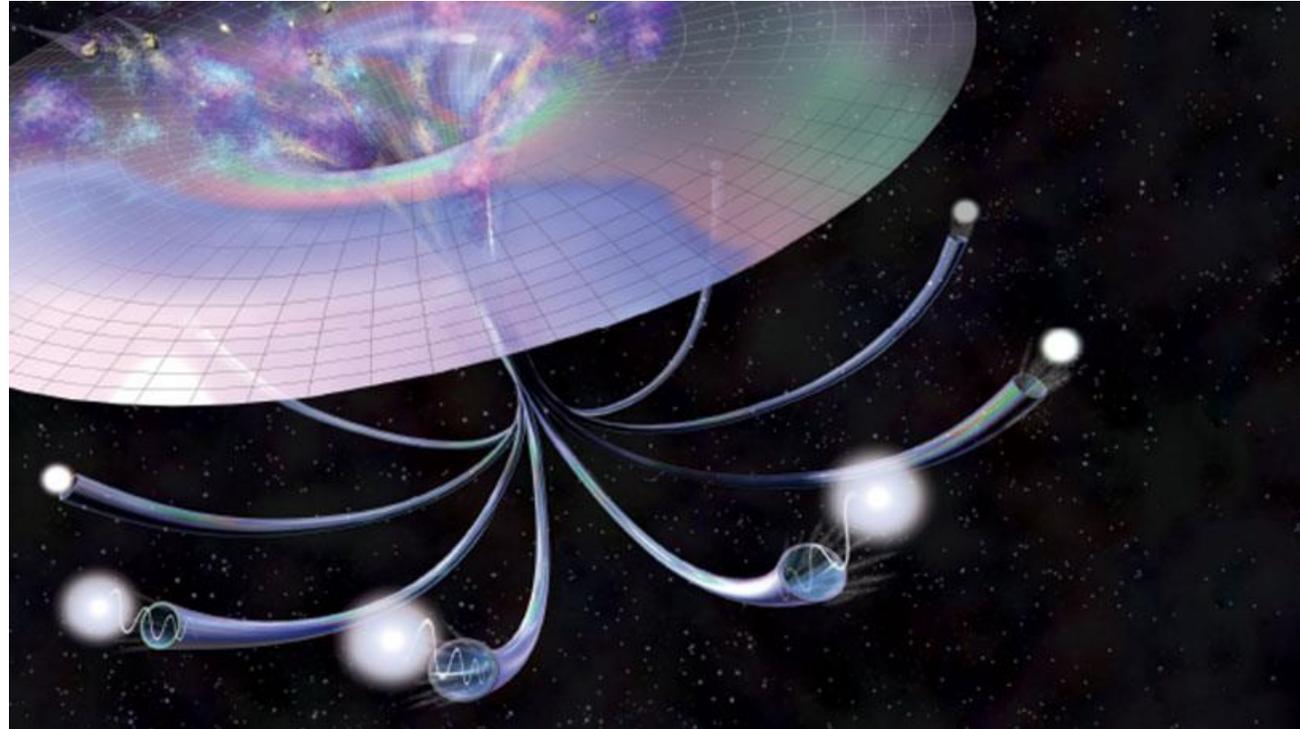


Einstein-Rosen



$$\text{EPR} = \text{ER}$$

o “la superflua ausencia de Podolsky”



Maldacena & Susskind 2013