Black Hole Complementarity and Quantum Gravity

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Two pillars of modern physics

Quantum mechanics

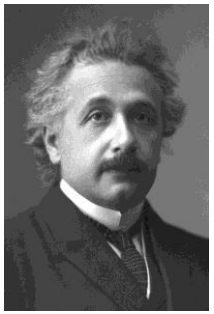
$$i\hbar \frac{\partial}{\partial t} |\Psi> = \mathcal{H} |\Psi>$$




...

General relativity

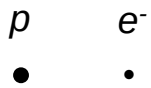
$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G_N}{c^4} T_{\mu\nu}$$



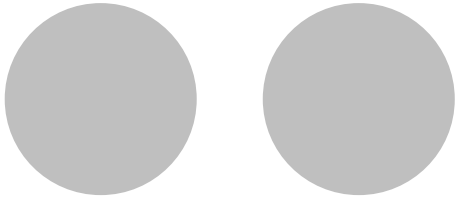
photos: Nobel Foundation archive

not get along well

No problem in "usual" circumstances (below, $c = \hbar = 1$)



$$G_N \frac{m_p m_e}{r^2} \sim 10^{-39} \frac{e^2}{4\pi\varepsilon_0 r^2}$$



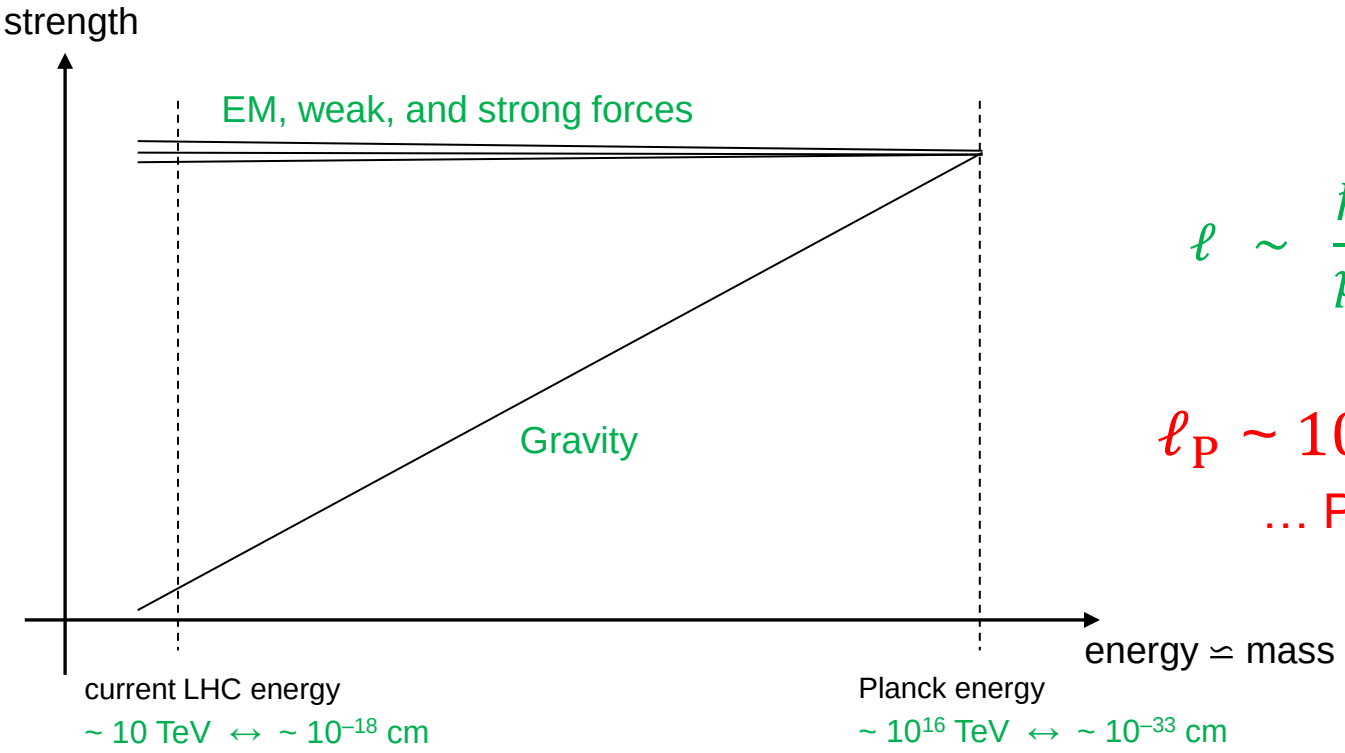
macroscopic body
($N \gg 1$ particles)

quantum interference ~ $\epsilon^N \ll 1$

→ A "patchwork" is enough.

Interesting things occur in “unusual” situations

cf. $v \gg v_{\text{usual}}$ in Newtonian mechanics



$$\ell \sim \frac{\hbar}{p} \sim \frac{\hbar}{E/c}$$

$$\ell_{\mathrm{P}} \sim 10^{-33}\mathrm{cm}$$

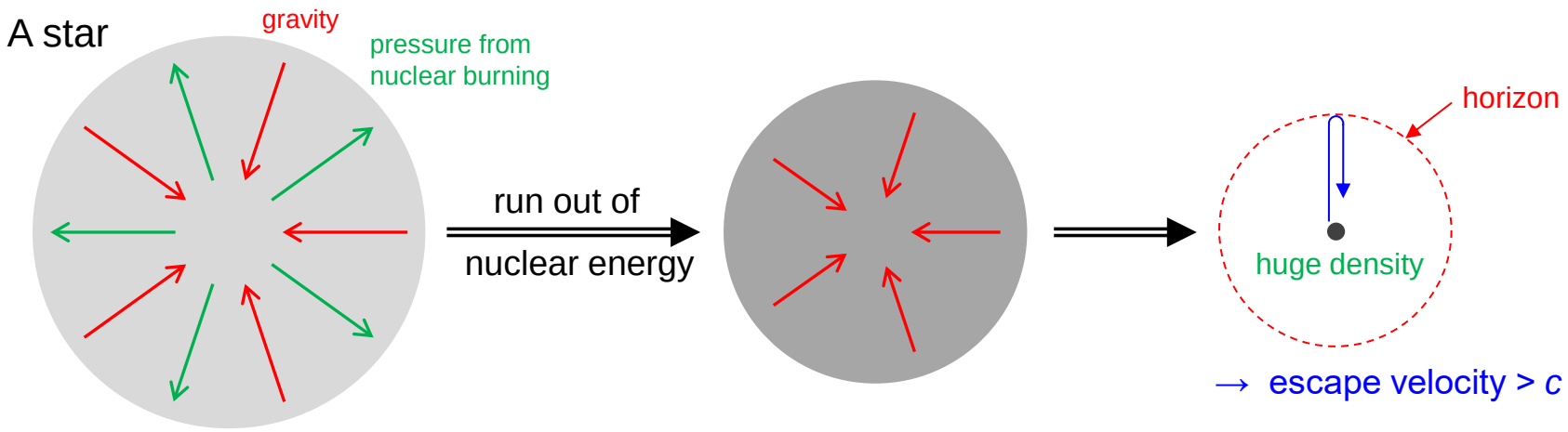
… Planck length

At ~ ℓ_{P}, theoretical control of quantum field theory (point particles in continuous spacetime) is lost. → string theory

There is a problem that the current formulation of string theory cannot (directly) address. (today’s theme)

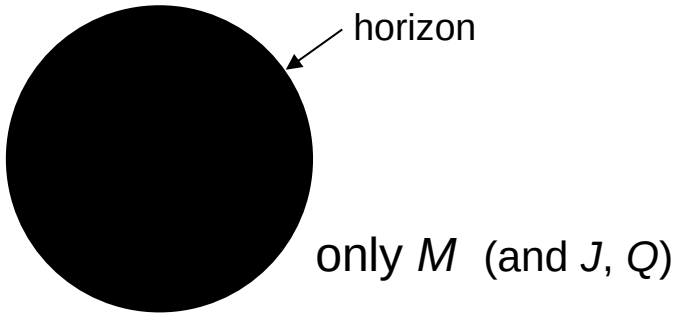
Unusual situations can occur at long distances:

Black Holes



The interior cannot be seen *from the outside*.

— "No hair" theorem



⟹ What are the quantum properties?

Black Hole Thermodynamics

A puzzle

Another pillar of modern physics

Statistical mechanics

$S = k_B \ln W$

(below, $k_B = 1$)

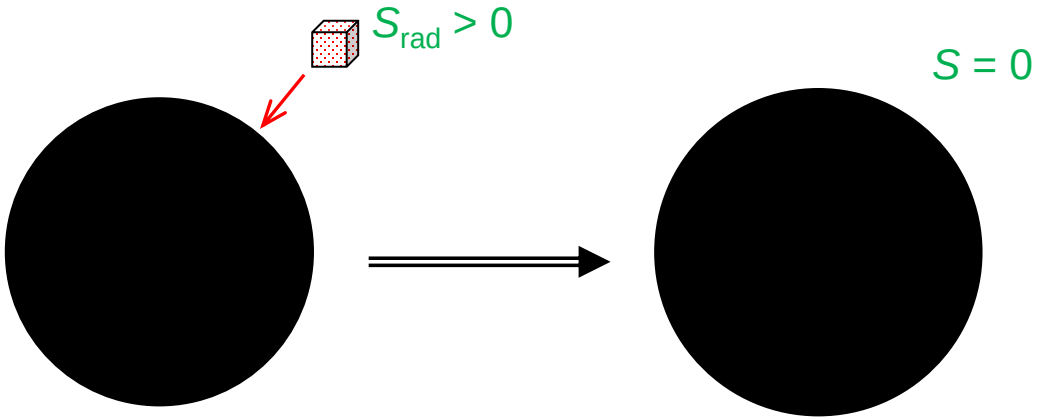
photo: Univ. Frankfurt

for any system

for all practical purposes

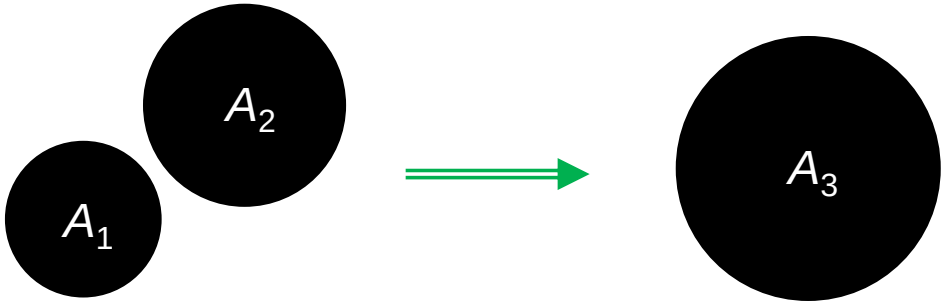
$\Delta S \geq 0$

What happens if matter falls into a black hole?



... $\Delta S < 0$!?

A peculiar property of BHs in general relativity



$A_3 \geq A_1 + A_2$

A proposal [Bekenstein, 1973]

photo: APS

The entropy of a BH is proportional to its horizon area.

$$S_{\rm BH} = \frac{A}{4G_{\rm N}}$$

Note: $G_N = \ell_P^2 \sim (10^{-33}\,\text{cm})^2 \rightarrow$ huge entropy

e.g. A solar mass BH has $S \sim 10^{78}$ while the sun has $\sim 10^{60}$.

Indeed, $\Delta\left(\frac{A}{4G_{\rm N}} + S_{\rm matter}\right) \geq 0$

Does this make sense?

$\frac{A}{4G_{\rm N}} = 4\pi G_{\rm N} M^2$ → $\frac{\partial S}{\partial E} = \frac{1}{T}$ → finite temperature

M →

Doesn't a BH only absorb stuff?

Black holes radiate [Hawking, 1974]

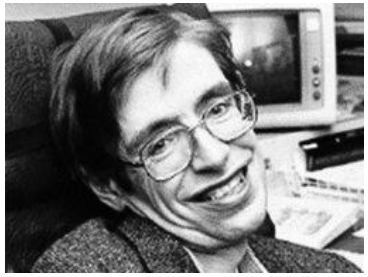


photo: NASA

The horizon is “smooth.”

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There must be radiation corresponding to $T_{\mathrm{H}} \sim \frac{1}{8\pi M G_{\mathrm{N}}}$. (Hawking temperature)

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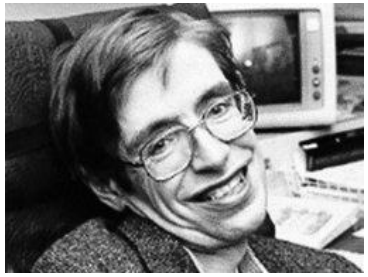

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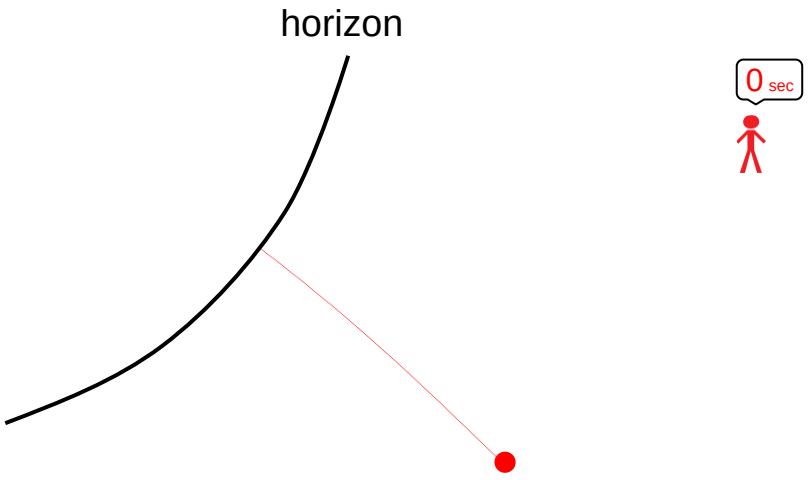

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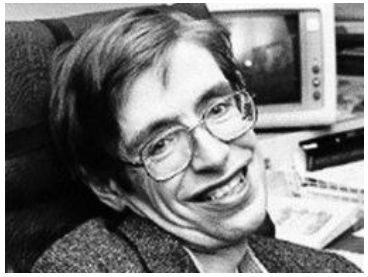

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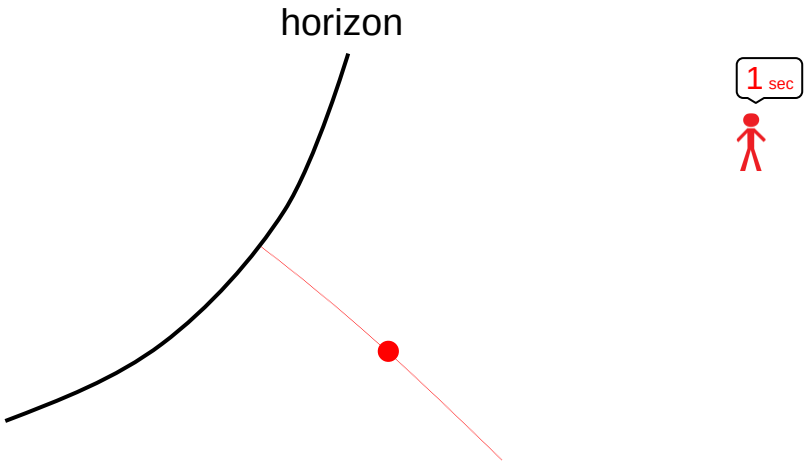

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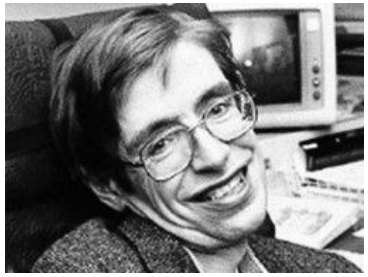

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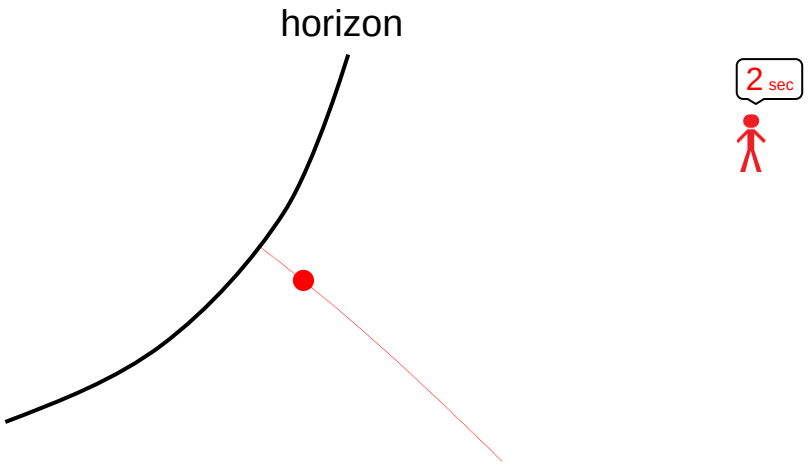

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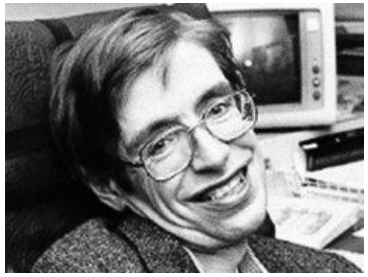

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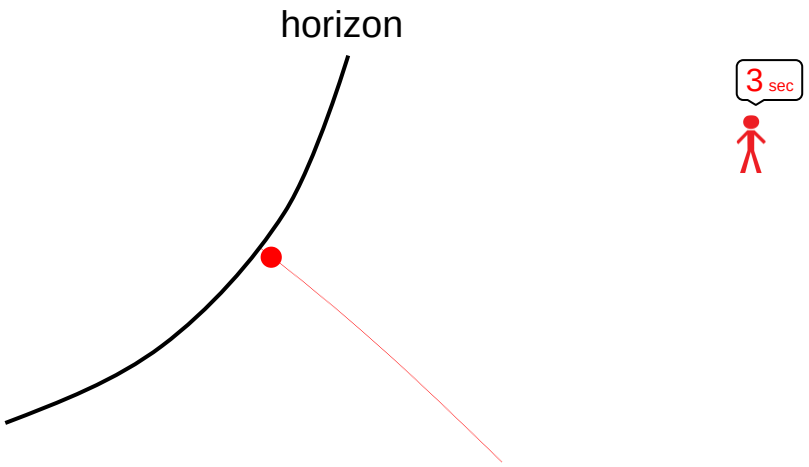

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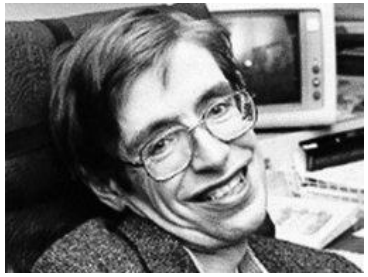

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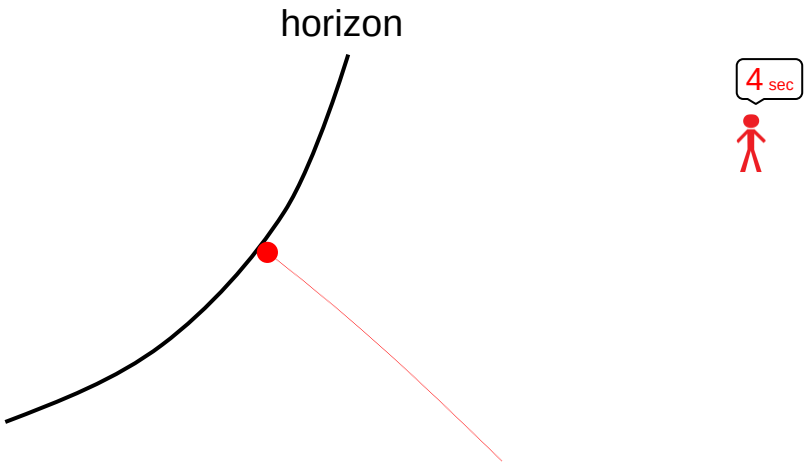

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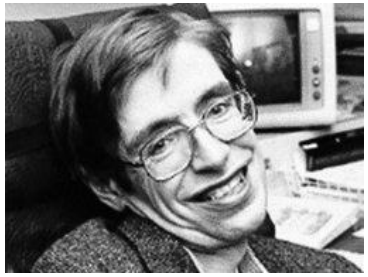

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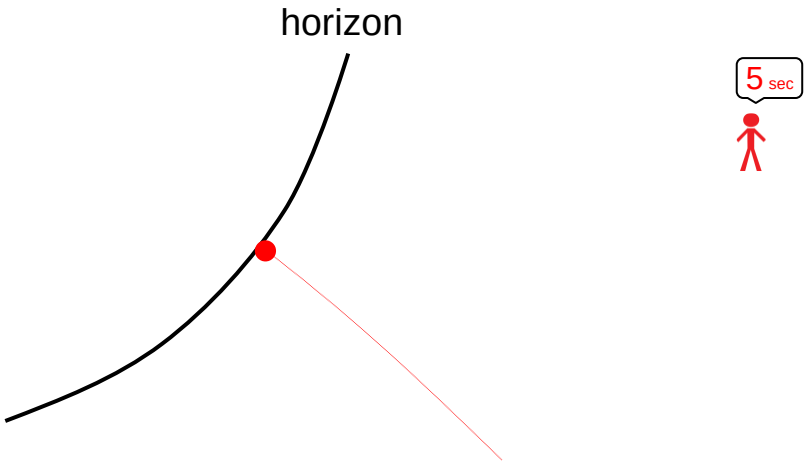

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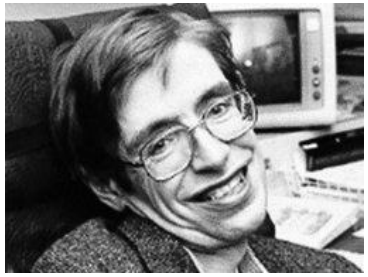

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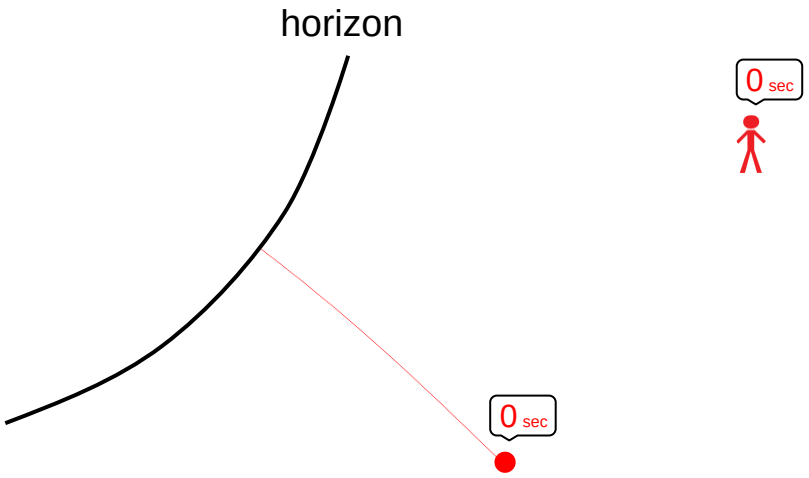

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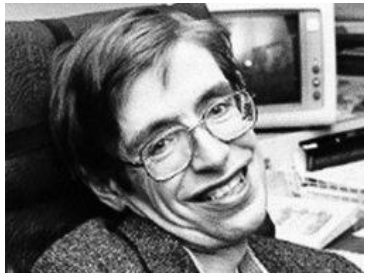

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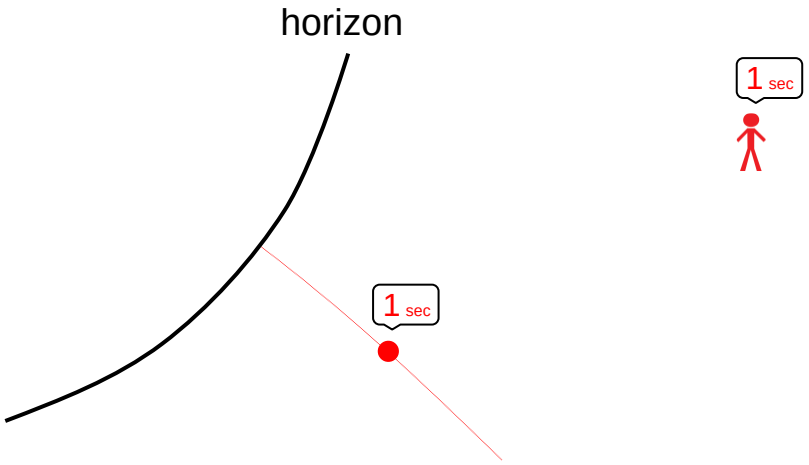

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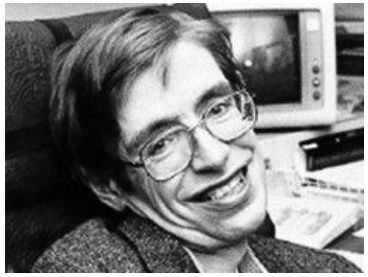

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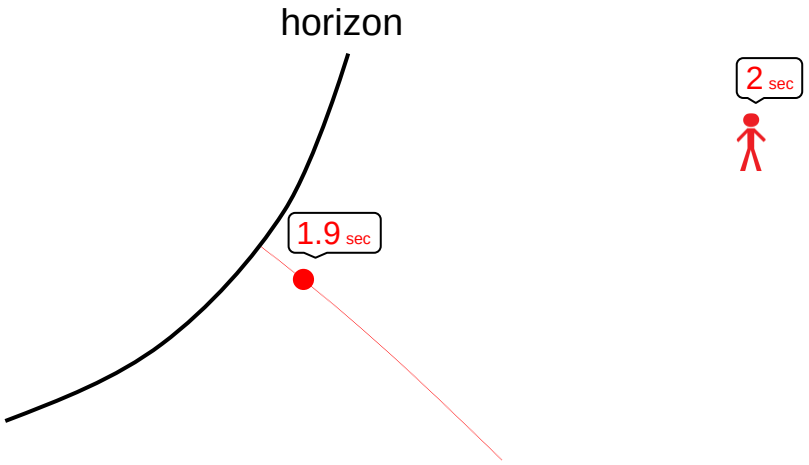

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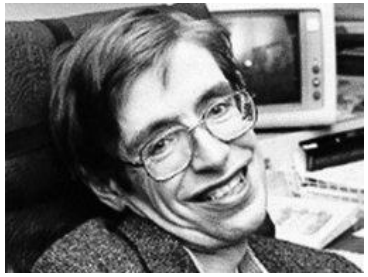

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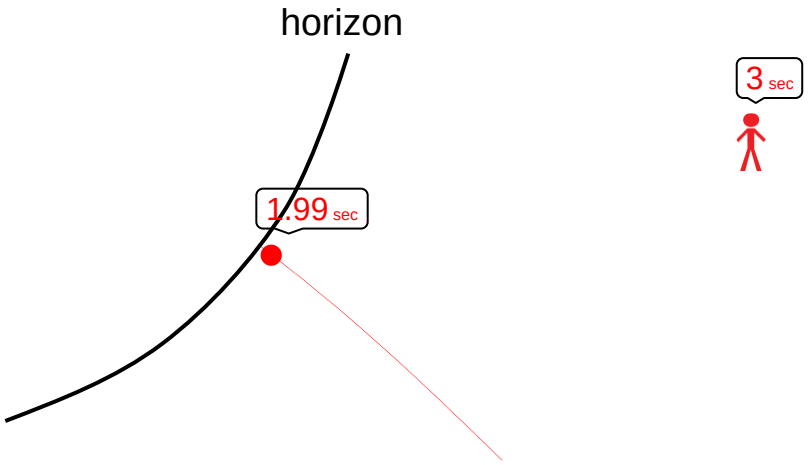

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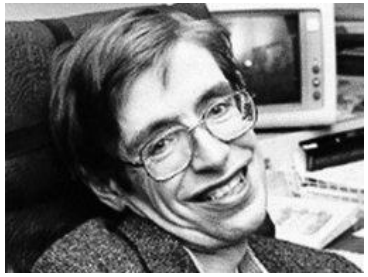

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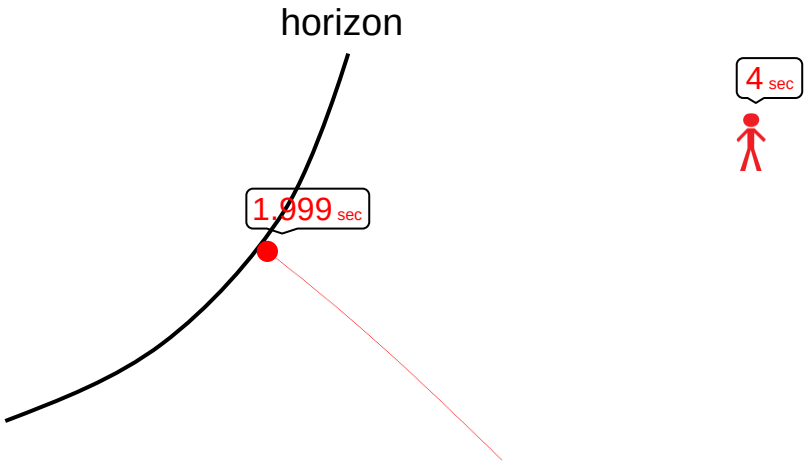

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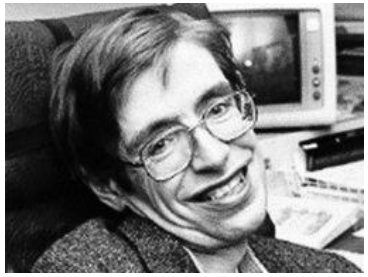

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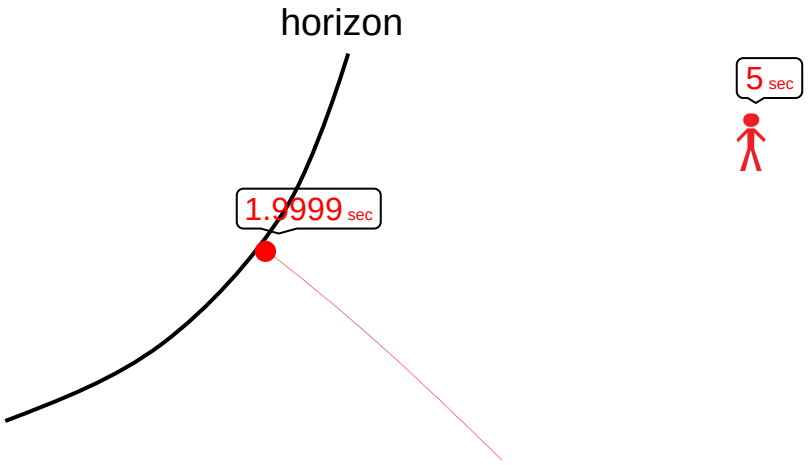

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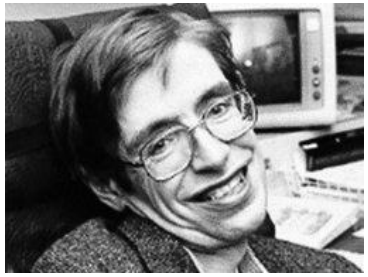

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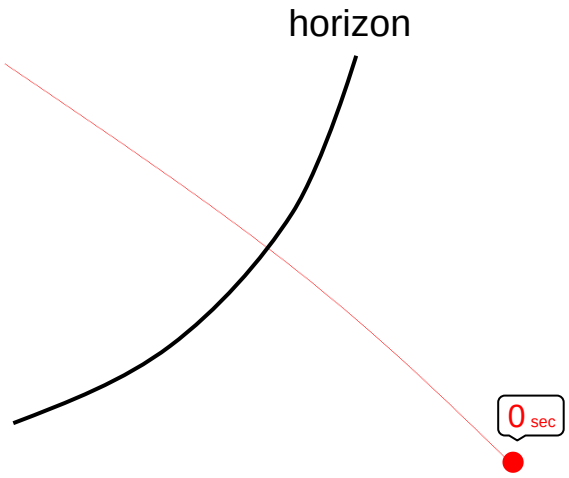

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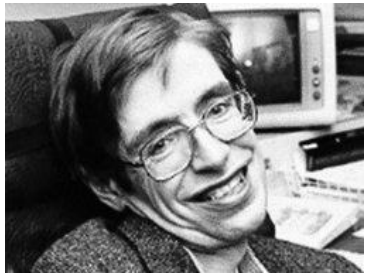

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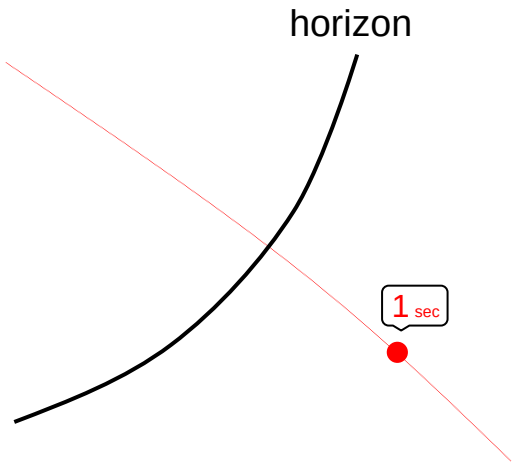

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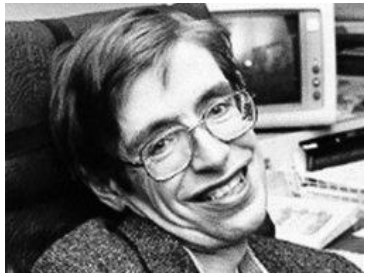

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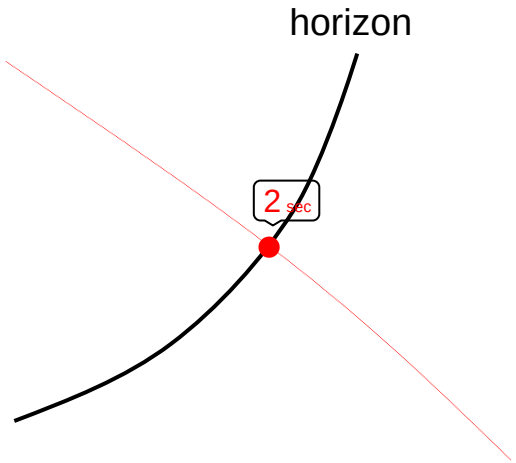

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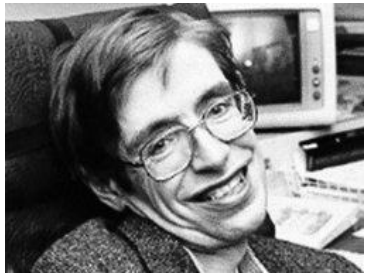

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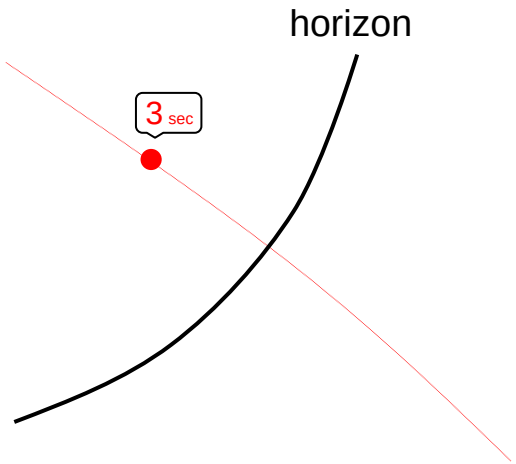

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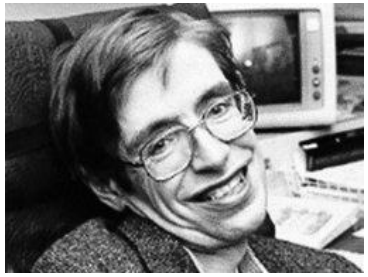

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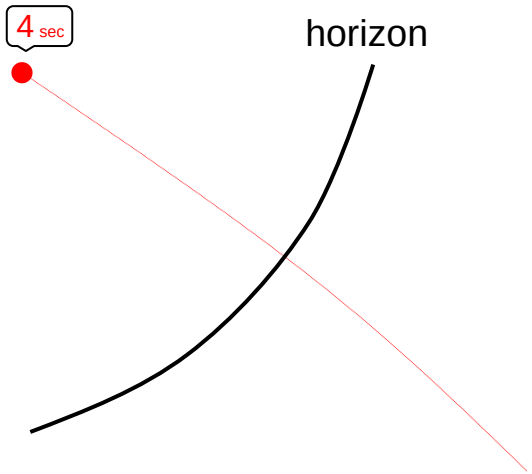

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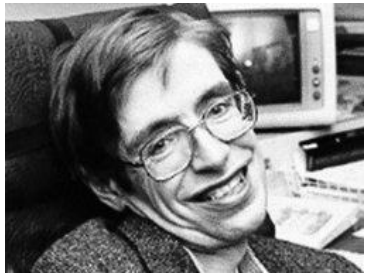

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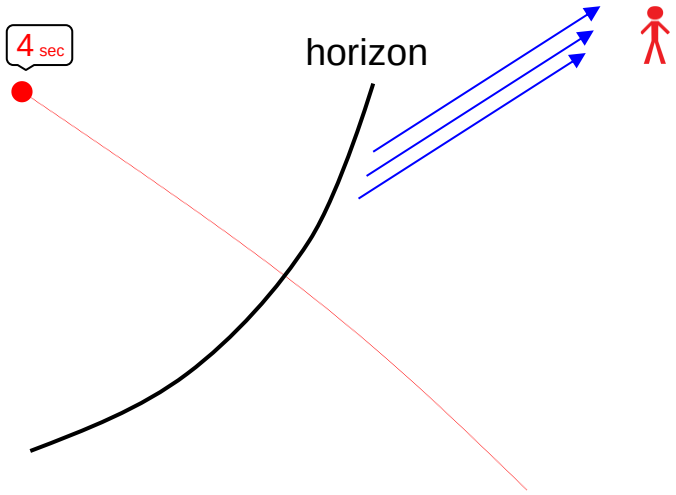
BHs are thermodynamic objects.

→ Spacetime is composed of microscopic d.o.f.s!



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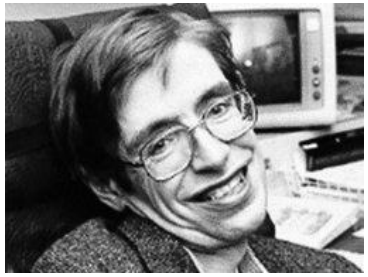

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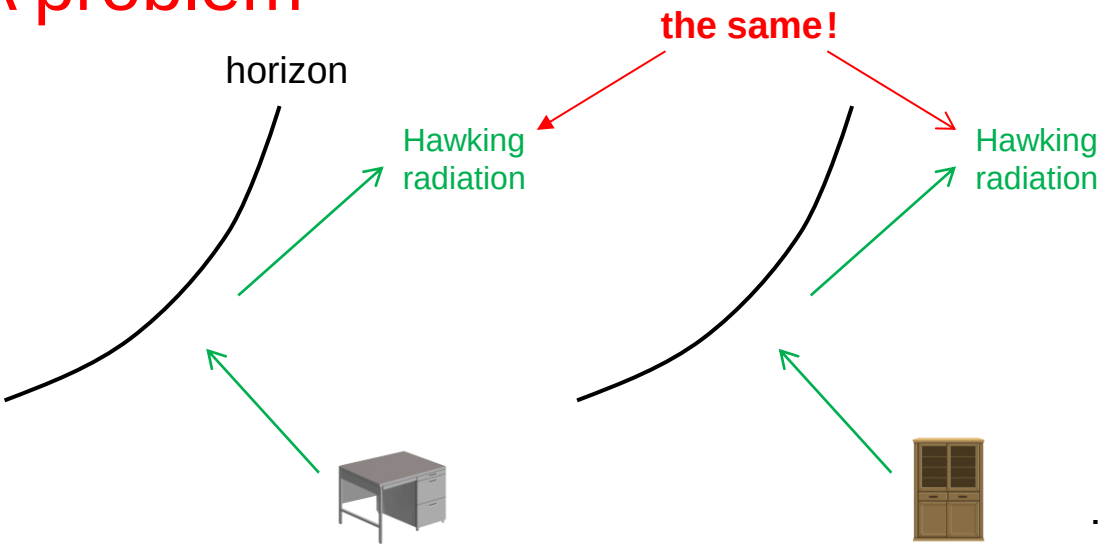
A problem



The time evolution is **not** one-to-one!
(not unitary)

… (the original form of)
BH information problem

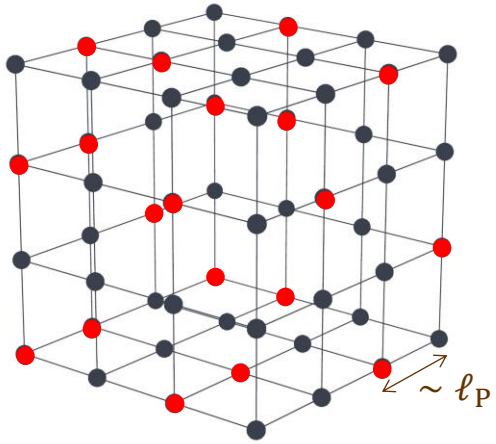
Holography

A clue comes from the BH physics itself

A BH is the highest entropy state of the region,

and still $S \propto \frac{A}{\ell_{\rm P}^2}$

Strange!



$$S \sim \ln 2^{V/\ell_{\rm P}^3} \propto \frac{V}{\ell_{\rm P}^3} \ggg \frac{A}{\ell_{\rm P}^2}$$

$(\ell_{\rm P} \sim 10^{-33}\text{cm})$

The concept that spacetime exits down to $\sim \ell_{\rm P}$ is an illusion!

→ suggests that there is a formulation of quantum gravity
in spacetime **one less dimension** than the naïve one.

Sounds crazy?

AdS/CFT correspondence [Maldacena, 1997]

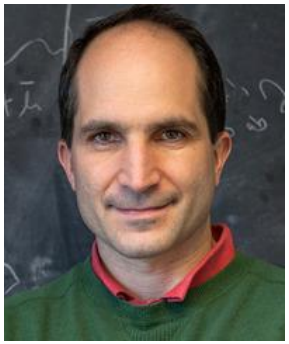
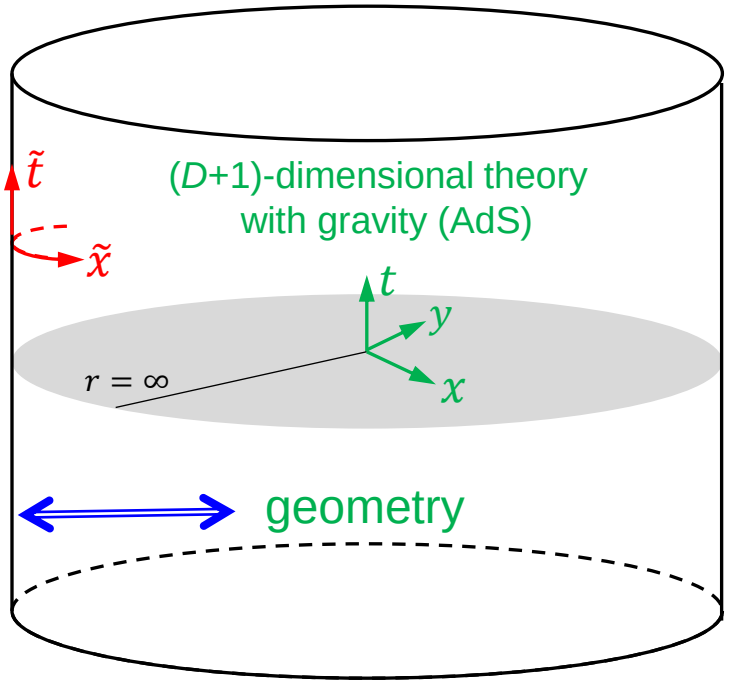


photo: IAS

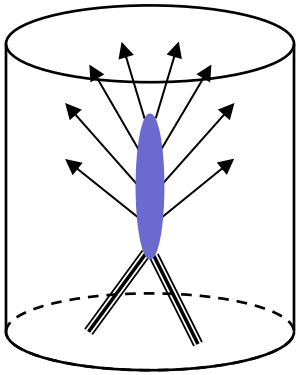
D-dimensional theory
without gravity (CFT)



quantum
information

⟷ geometry

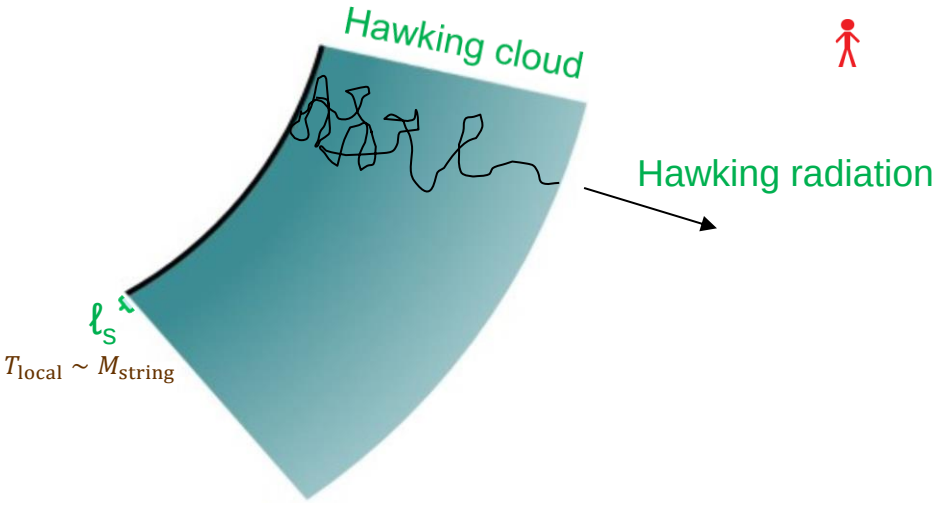
BH evolution **must be** unitary.



=

A process in non-gravitational
(unitary) theory

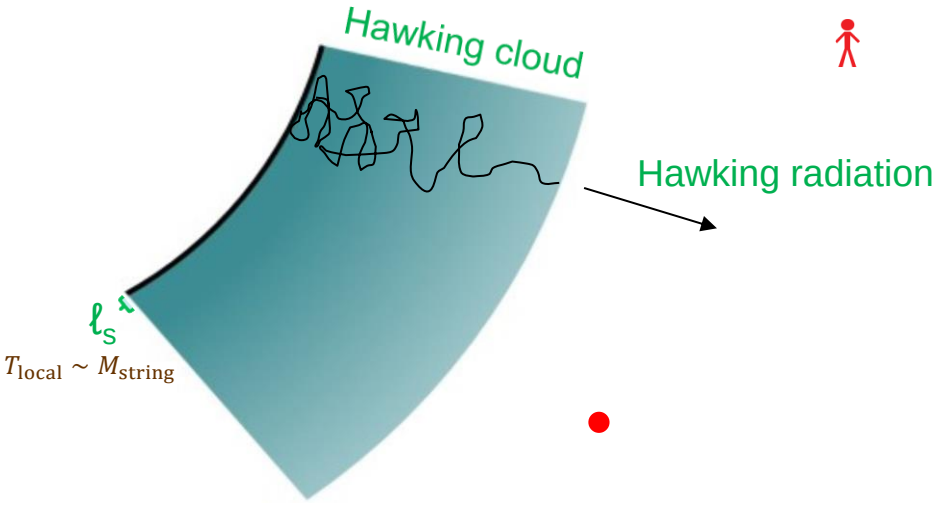
BH at the quantum level



The horizon behaves
as the surface of regular material.

… no issue with unitarity

BH at the quantum level



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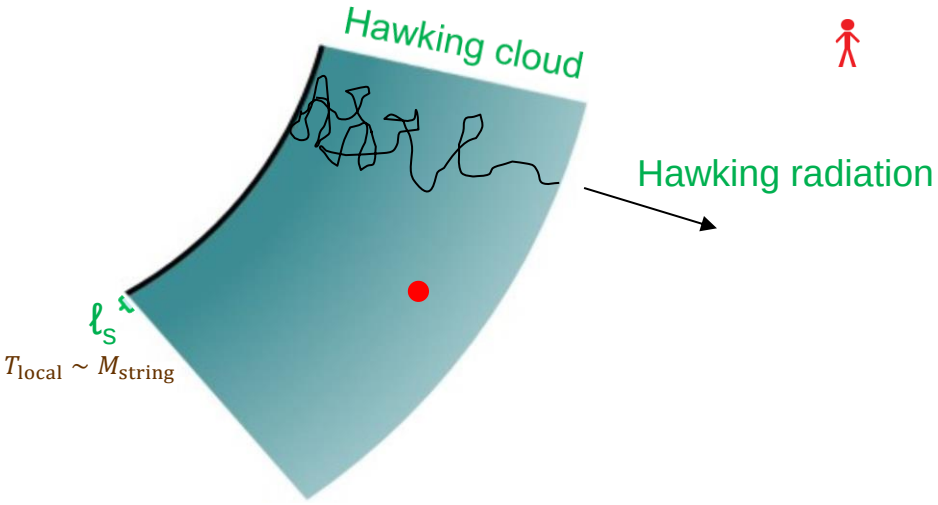

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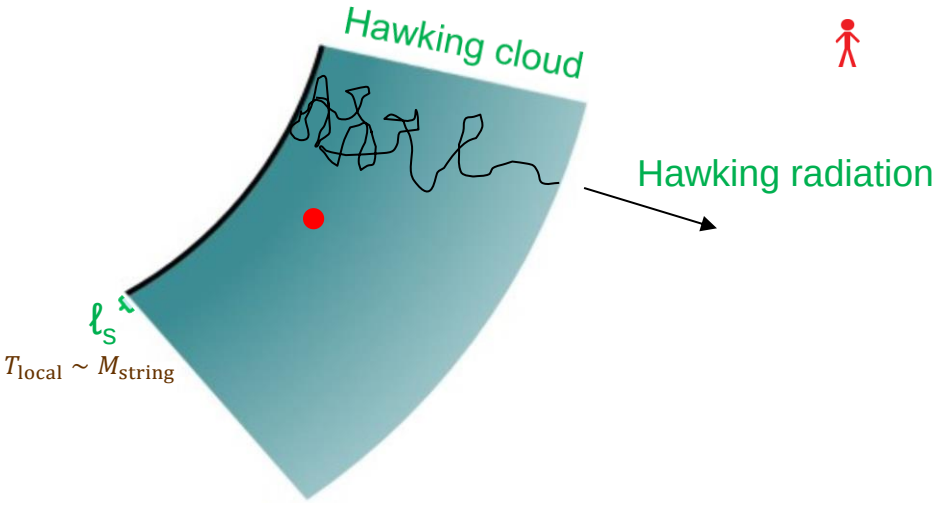

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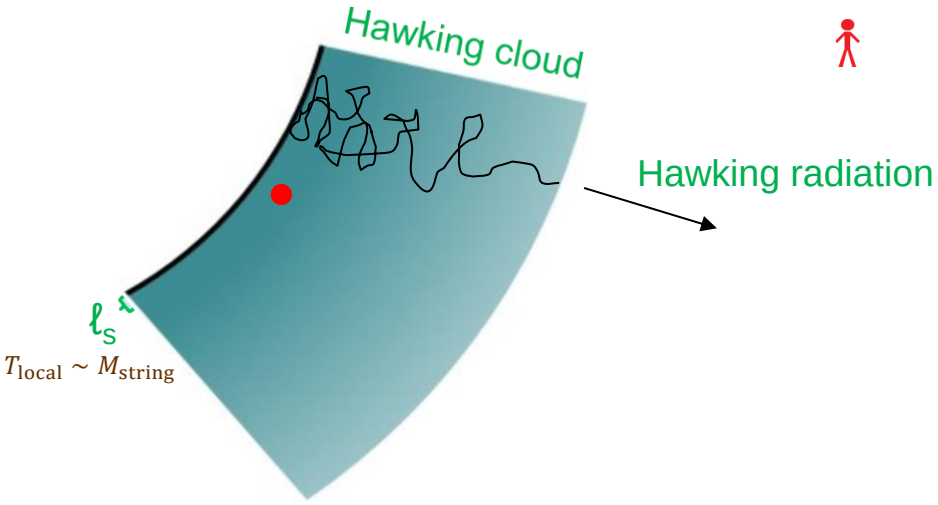

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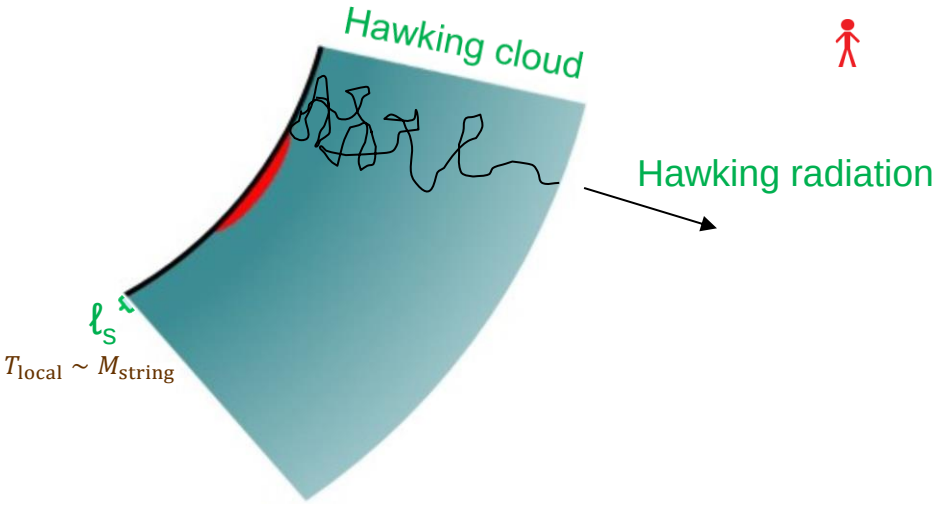

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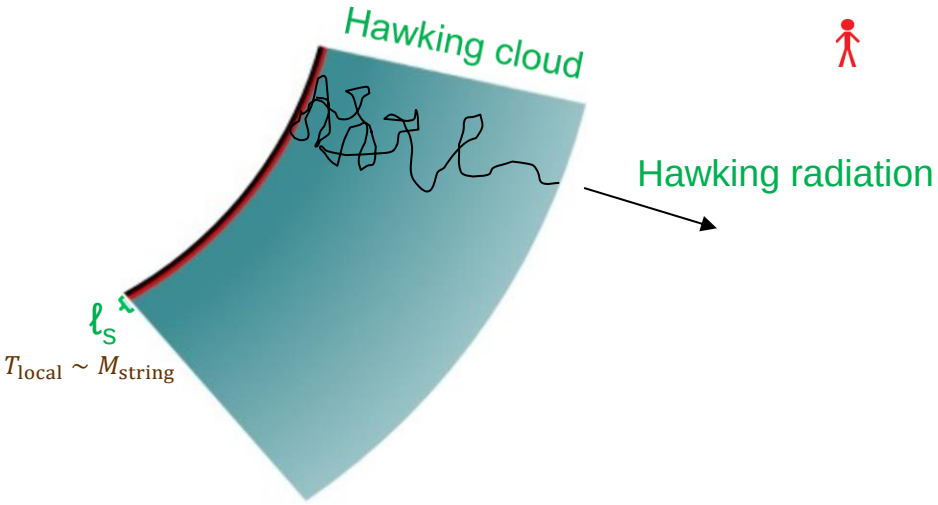

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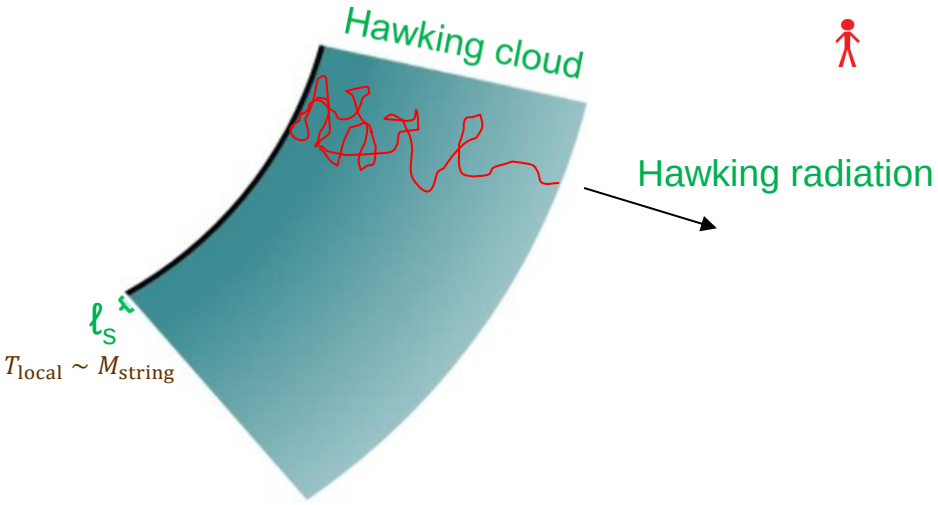

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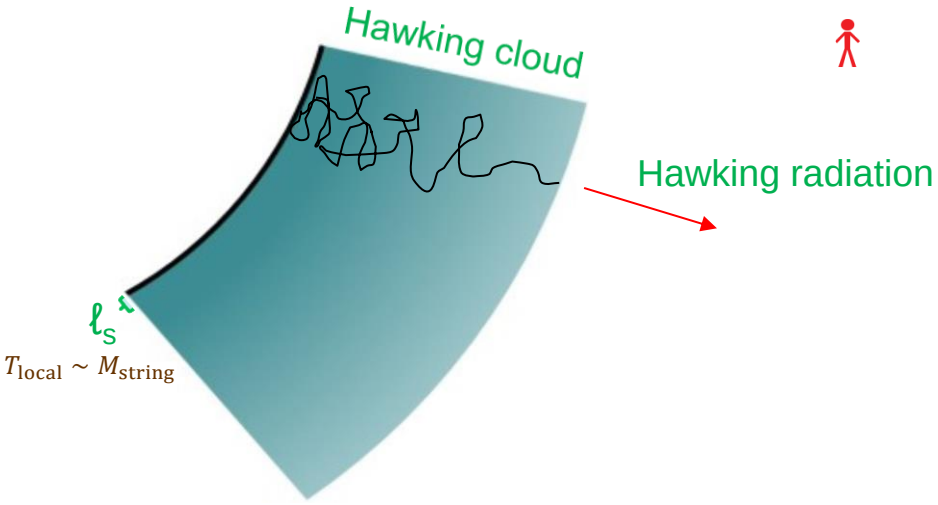

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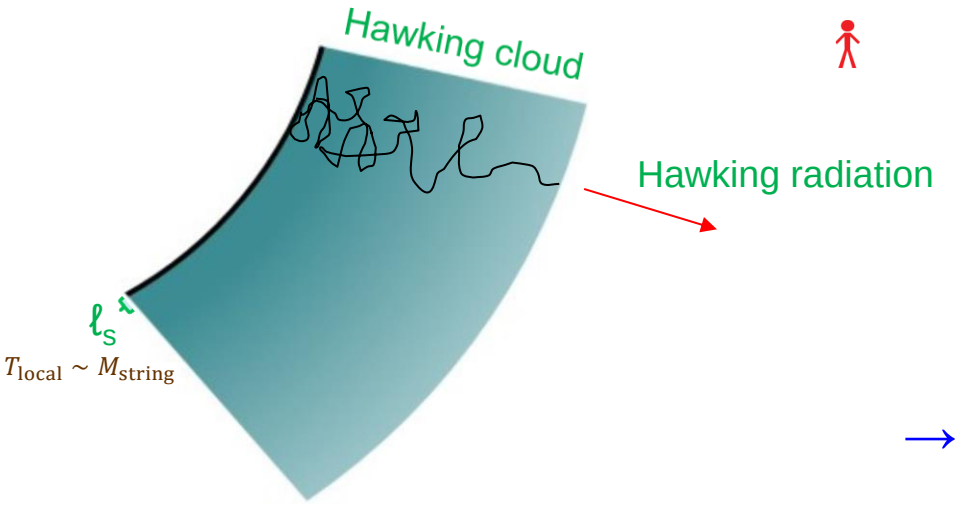

The horizon behaves
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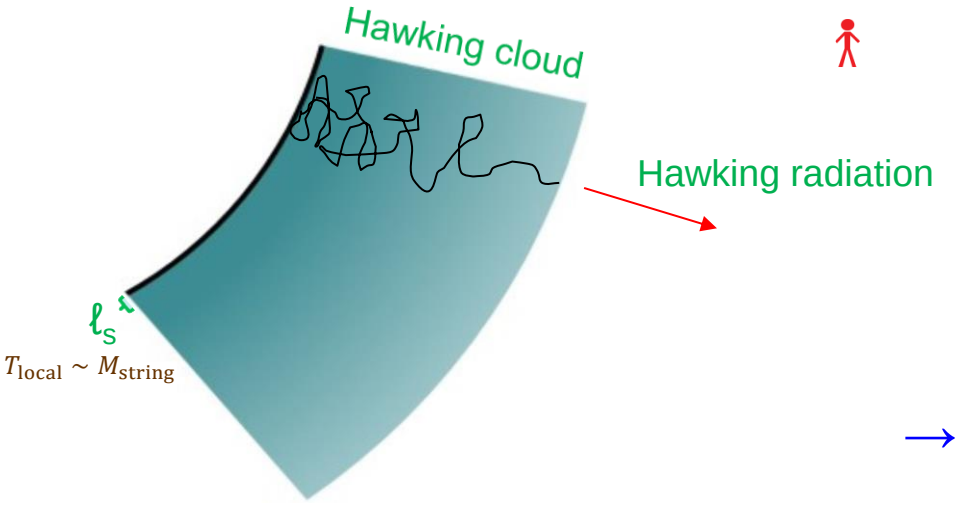
… no issue with unitarity

→ What about the interior?

BH at the quantum level



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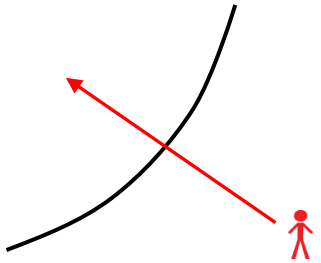
Alternatively



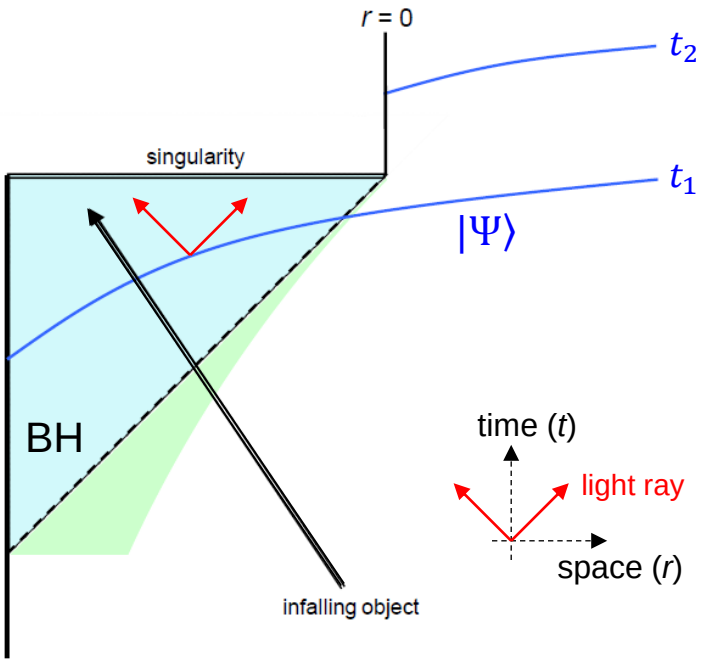
Hawking's analysis → information loss

→ What was wrong with Hawking's analysis?

Recent Progress I

— replica wormholes —

Start with “global spacetime”



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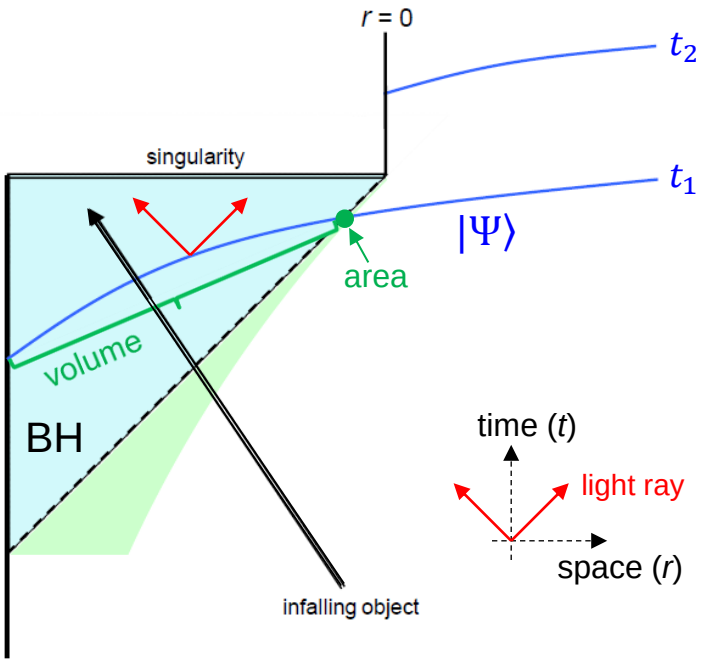
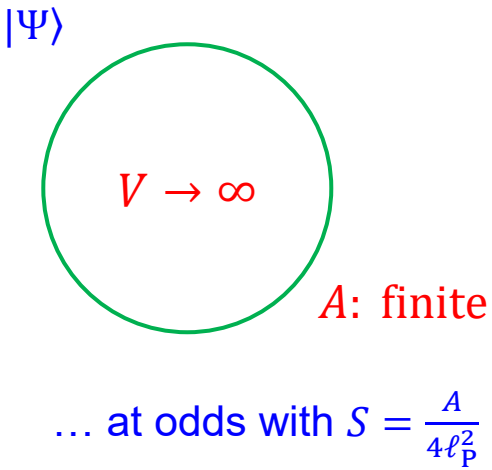
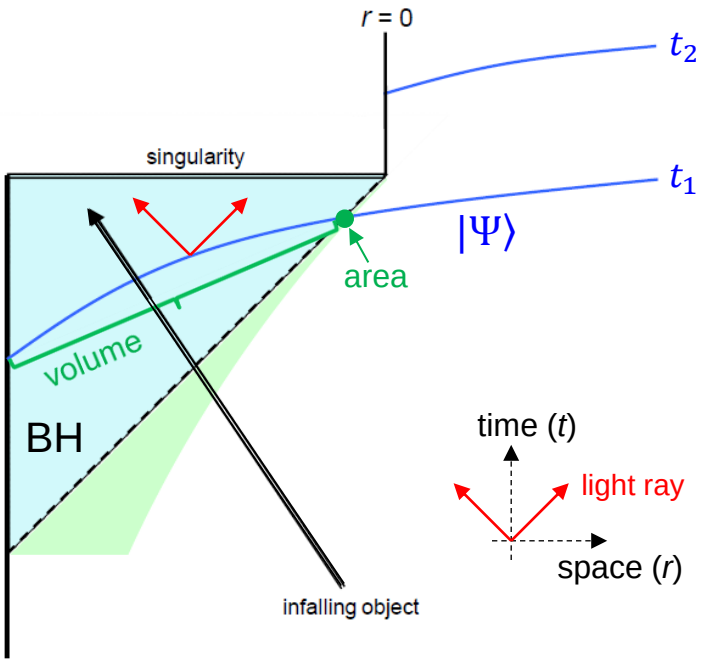


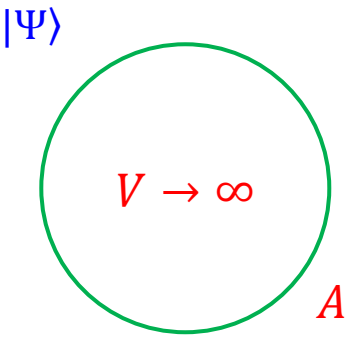


… at odds with $S = \frac{A}{4\ell_P^2}$

Hugely redundant!

Start with “global spacetime”





A: finite

… at odds with $S = \frac{A}{4\ell_P^2}$

Hugely redundant!

$$\langle\Psi_1|\Psi_2\rangle = 0 \longrightarrow \langle\Psi_1|\Psi_2\rangle \sim e^{-\frac{S}{2}}$$

semiclassical
(QFT in curved spacetime)

quantum gravity

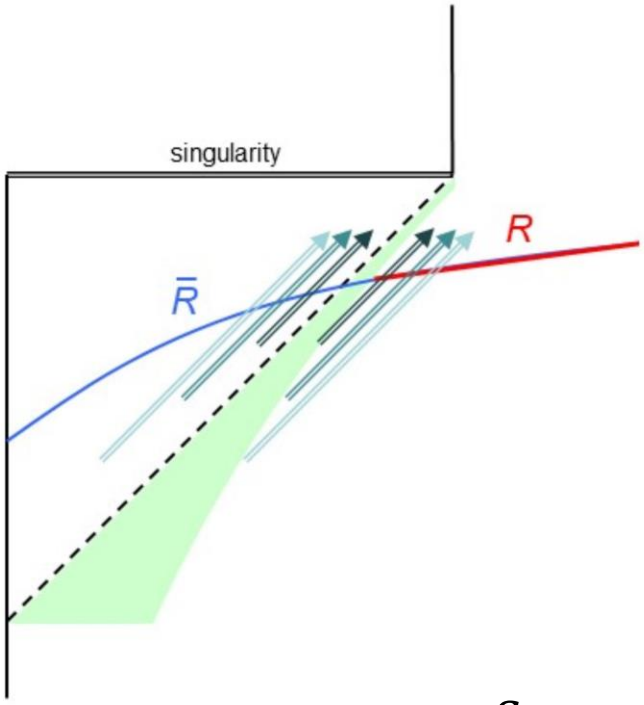
… only e^S independent states

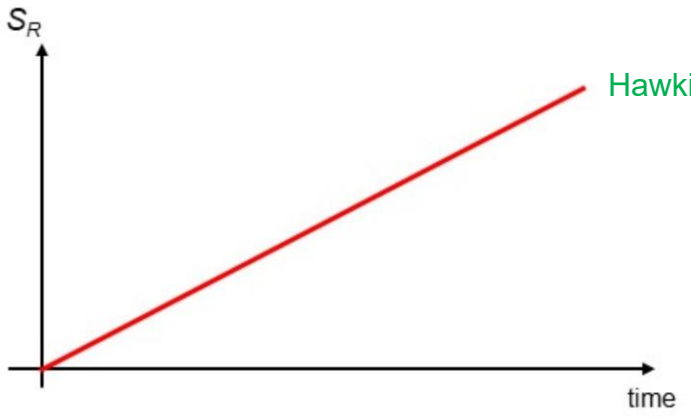
$$|\Psi\rangle = \sum_{i=1}^{e^S} c_i|\psi_i\rangle \qquad c_i \sim e^{-\frac{S}{2}}$$

$$\langle\Psi_1|\Psi_2\rangle = \sum_{i=1}^{e^S} c_{1,i}^* c_{2,i} \sim e^{\frac{S}{2}} e^{-S} \sim e^{-\frac{S}{2}}$$

$\to e^{e^S}$ approximately orthogonal states

Unitarity of Hawking evaporation

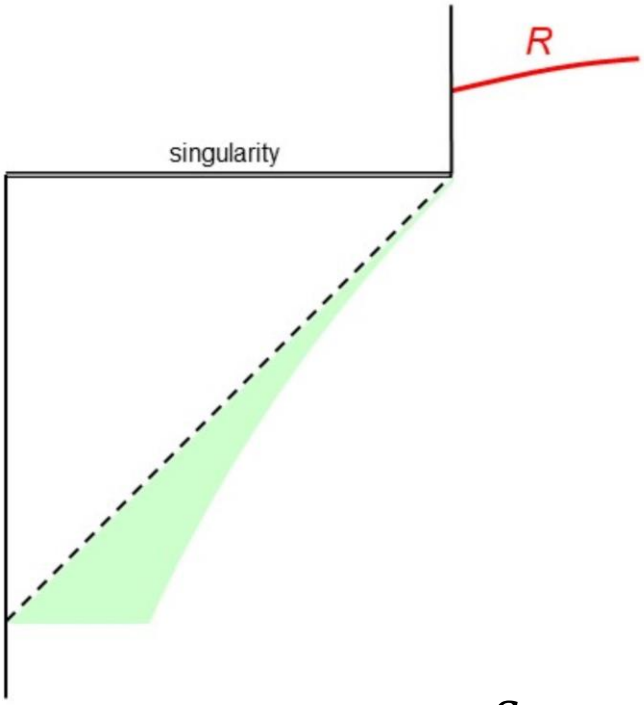


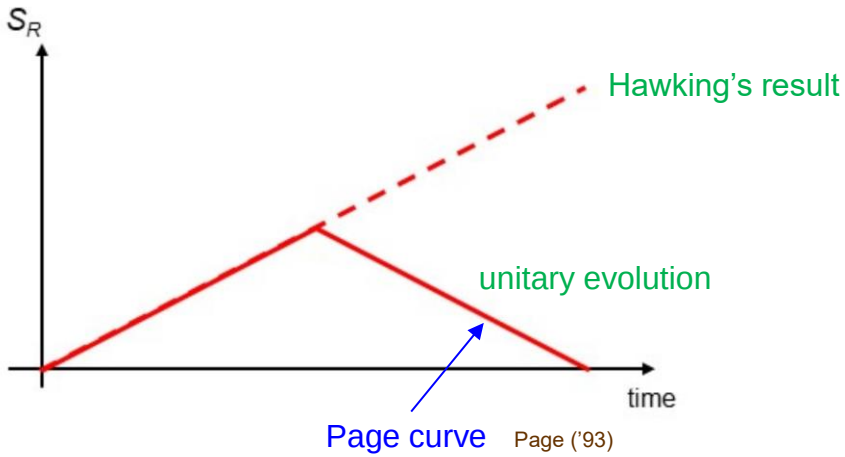


$$S_R = -\mathrm{Tr}[\rho_R \ln \rho_R] \qquad (\rho_R = \mathrm{Tr}_{\bar{R}} |\Psi\rangle\langle\Psi|)$$

~ the # of EPR particles in R whose partners are in $\bar{R}$

Unitarity of Hawking evaporation





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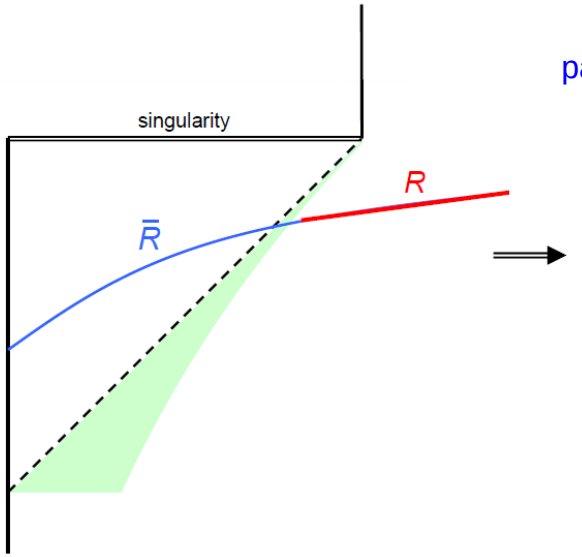
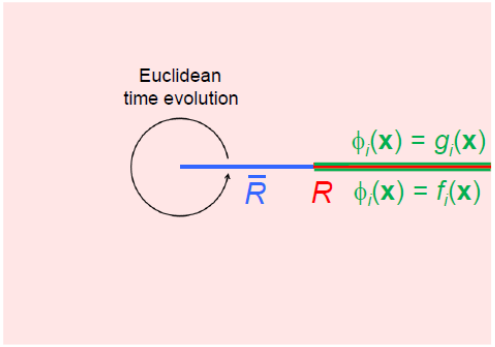
→ How to get this curve?

Page curve from replica wormholes

Penington ('19); Almheiri, Engelhardt, Marolf, Maxfield ('19); …
Penington, Shenker, Stanford, Yang ('19);
Almheiri, Hartman, Maldacena, Shaghoulian, Tajdini ('19)



path integral



$\rightarrow \rho_R = \rho_R[f_i(\mathbf{x}), g_i(\mathbf{x})]$ (~ coefficient of $|g_i(\mathbf{x})\rangle\langle f_i(\mathbf{x})|$)

$$S_R \equiv -\mathrm{Tr}[\rho_R \ln \rho_R] = \lim_{n\to 1} \frac{1}{1-n} \ln \mathrm{Tr}[\rho_R^n]$$

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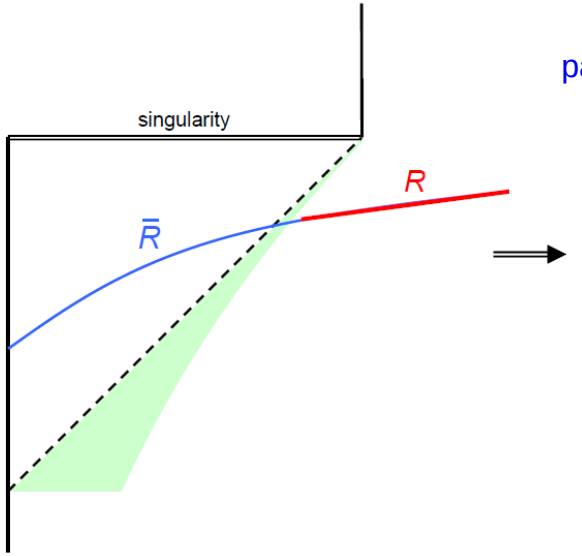

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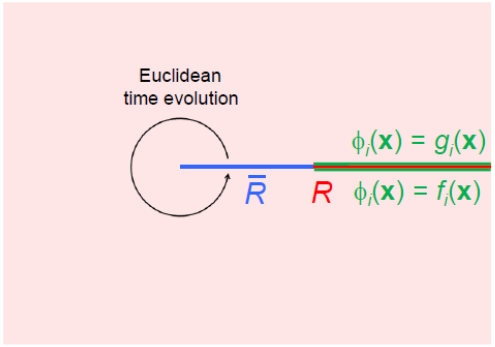

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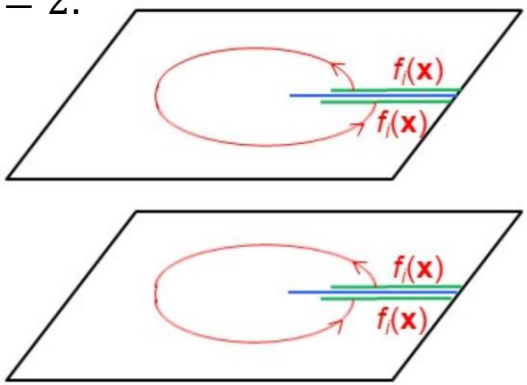

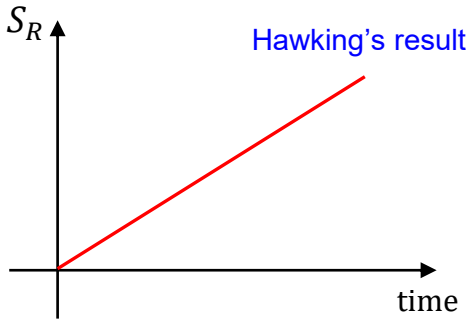

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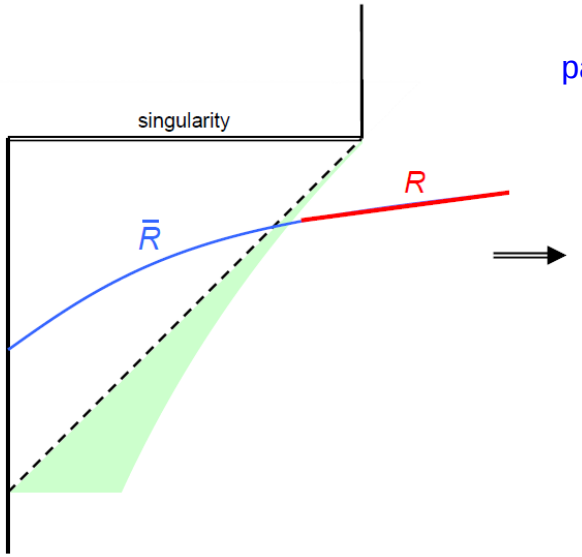

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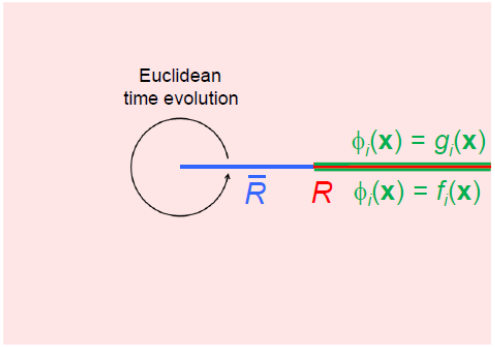

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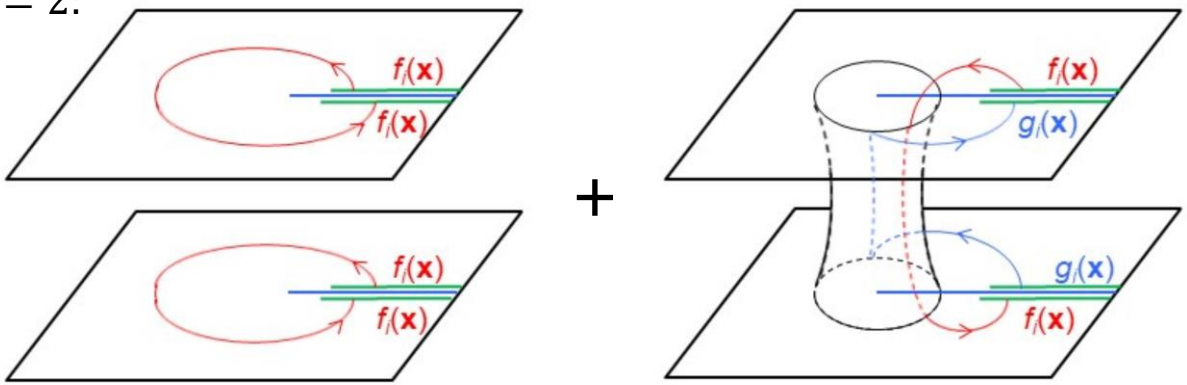
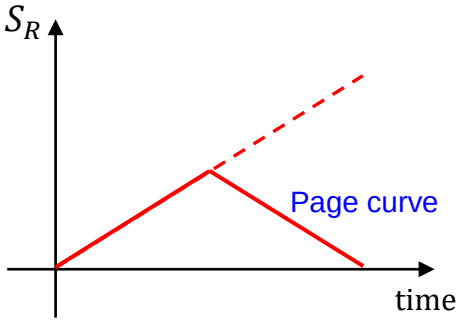
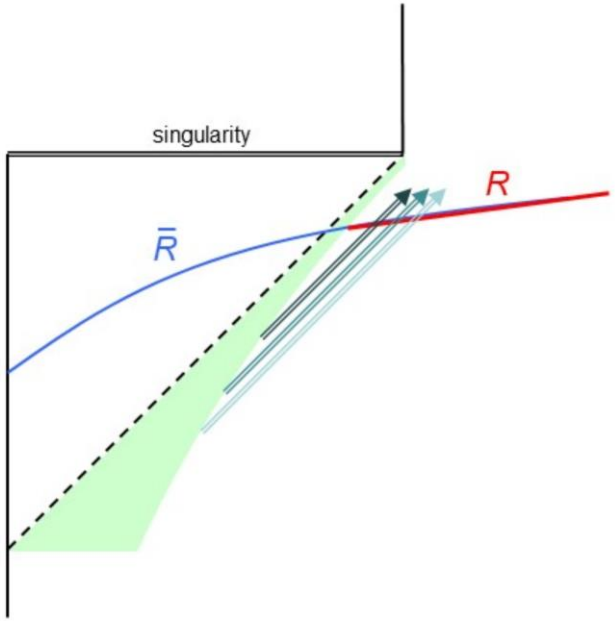


replica wormhole (nonperturbative effect)



Redundancy in the Hawking process



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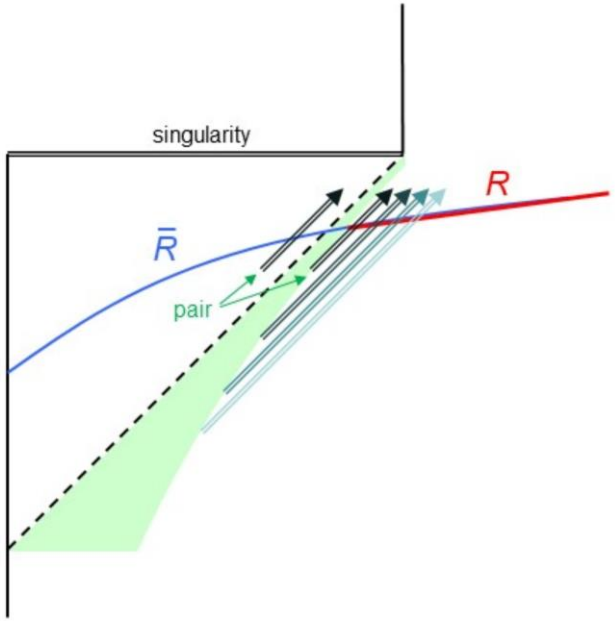

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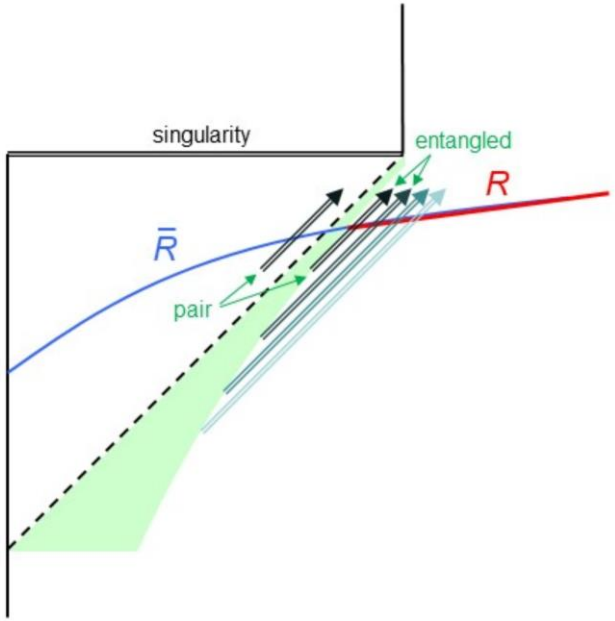

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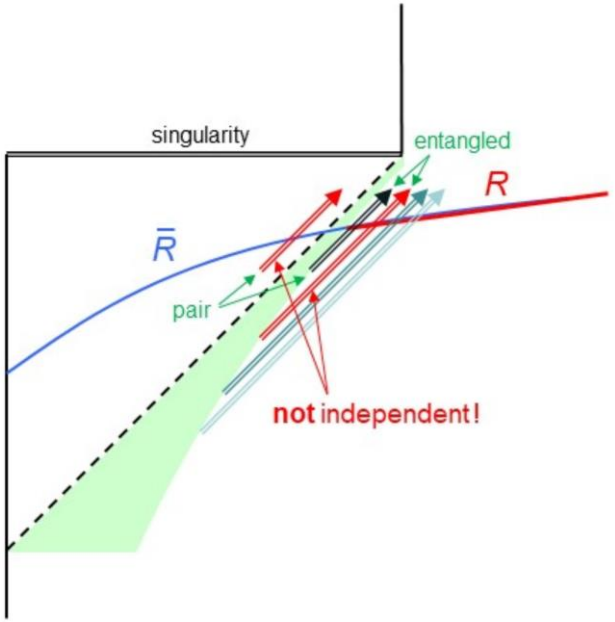
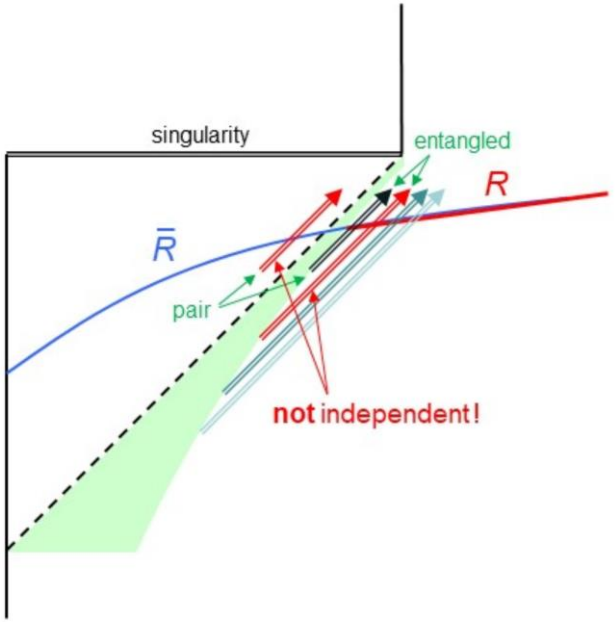


→ Hawking radiation emitted earlier is
not independent of the interior d.o.f.s!

…; Maldacena, Susskind ('13); …

Redundancy in the Hawking process



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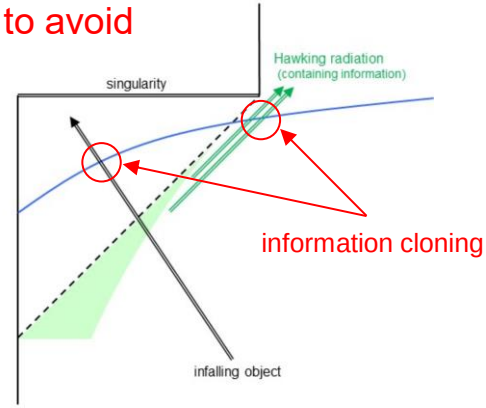
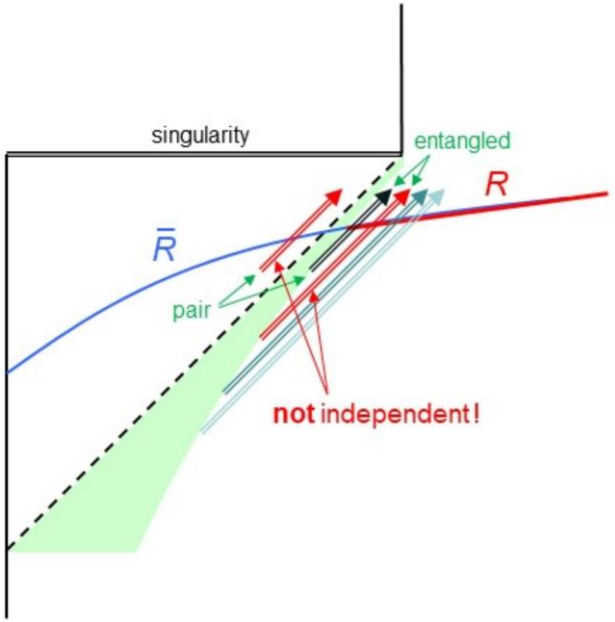
- needed to avoid



- consistent because of causality

Redundancy in the Hawking process



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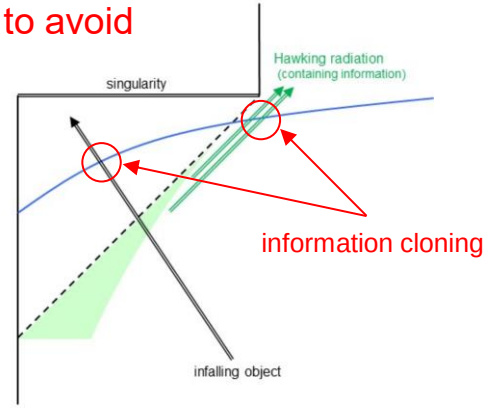


- consistent because of causality

Global spacetime
(embracing the **interior**)

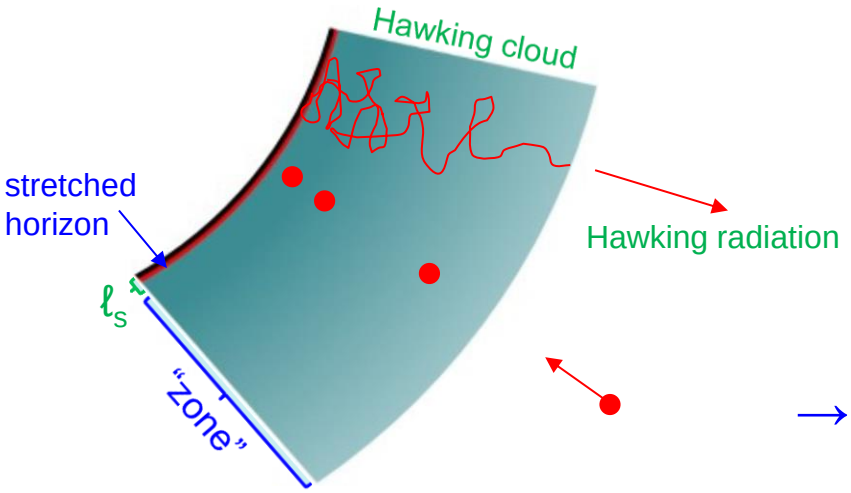
Replica wormholes
(nonperturbative effects of gravity)

Page curve
(signifying **unitarity**)

Recent Progress II

— unitary gauge construction —

Start with a “distant” (holographic) description



The d.o.f.s outside the horizon comprise the **entire** system.

→ The evolution is unitary.

→ How does the “interior” emerge?

Papadodimas, Raju (’12–’15); Verlinde, Verlinde (’12–’13);
Y.N., Sanches, Varela, Weinberg (’12–’15); …
Y.N. (’19, 20)

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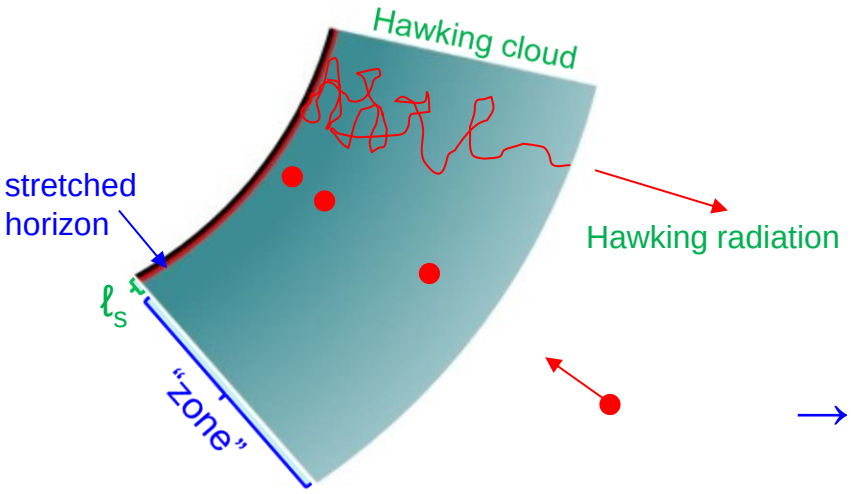

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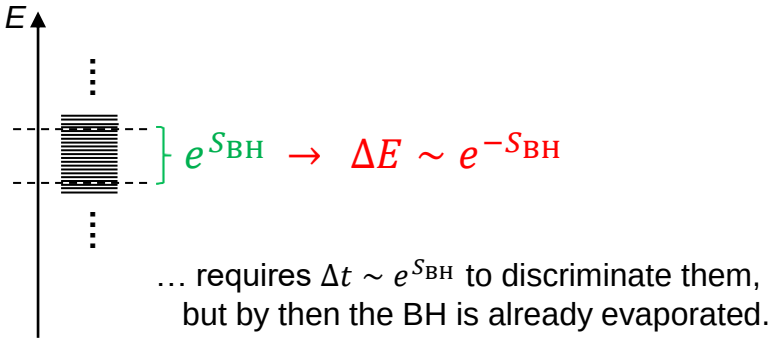
Y.N. (’19, 20)

Key features Y.N. (’19, 20)

— defining characteristics of BHs

(I) Exponentially dense spectrum



… requires $\Delta t \sim e^{S_{\rm BH}}$ to discriminate them,
but by then the BH is already evaporated.

Relevant modes:

$$\begin{cases} \text{BH} & \begin{cases} \text{horizon} \\ \text{zone} \end{cases} \Big\} \text{ soft (cloud)} \\ & \supset \text{hard (objects)} \\ \text{far} \end{cases}$$

(II) Dynamics at the stretched horizon

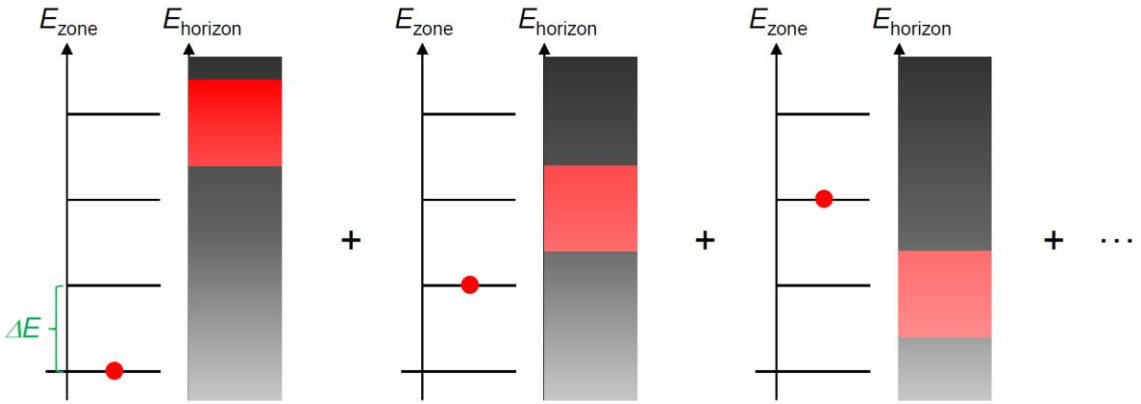
$T_{\rm local} \sim M_{\rm string}$

… string dynamics

- quantum chaos — Maldacena, Shenker, Stanford ('15)
- fast scrambling — Hayden, Preskil ('07); Sekino, Susskind ('08)
- universal — Banks, Seiberg ('10); …; Harlow, Ooguri ('18)

(*e.g.* no global symmetry)

→ "ultimate" thermalization



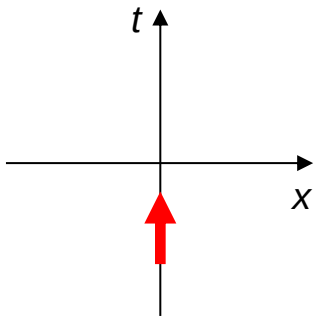
$$\sum_{i=1}^{e^{S_{\rm bh}(M)}} c_i^{(0)}\,|0\rangle|\Psi_i^{(0)}\rangle \;+\; \sum_{i=1}^{e^{S_{\rm bh}(M-\Delta E)}} c_i^{(1)}\,|1\rangle|\Psi_i^{(1)}\rangle \;+\; \sum_{i=1}^{e^{S_{\rm bh}(M-2\Delta E)}} c_i^{(2)}\,|2\rangle|\Psi_i^{(2)}\rangle \;+\; \cdots$$

$$\xrightarrow[c_i^{(0)} \sim c_i^{(1)} \sim c_i^{(2)} \sim \cdots]{} \propto |0\rangle\langle 0| + e^{-\frac{\Delta E}{T_{\rm H}}}|1\rangle\langle 1| + e^{-\frac{2\Delta E}{T_{\rm H}}}|2\rangle\langle 2| + \cdots$$

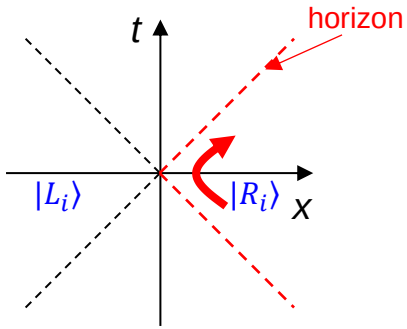
… **universal** across all low energy species

Emergence of the interior

Minkowski



Rindler



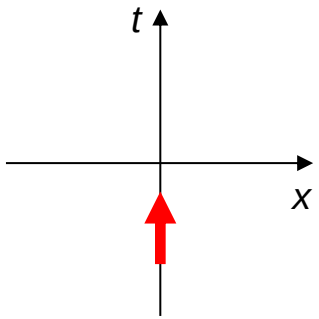
$$|0\rangle \propto \sum_i e^{-\frac{E_i}{2T}} |R_i\rangle |L_i\rangle$$

… thermal state

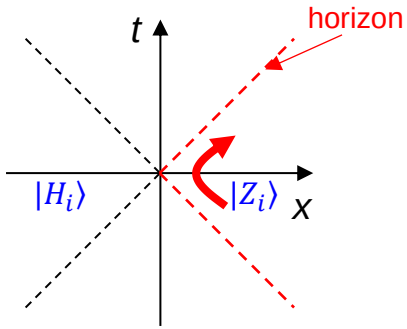
Fulling ('73); Davies ('75); Unruh ('76)

Emergence of the interior

Minkowski



Rindler



$$|0\rangle \propto \sum_i e^{-\frac{E_i}{2T}} |R_i\rangle |L_i\rangle$$

… thermal state

Fulling ('73); Davies ('75); Unruh ('76)

Near empty
Interior spacetime

(An object thrown "sees" interior spacetime)

frame change

$$|\Psi_{\mathrm{BH}}\rangle \propto \sum_i e^{-\frac{E_i}{2T_{\mathrm{H}}}} |H_i\rangle |S_i\rangle$$

Hard mode states

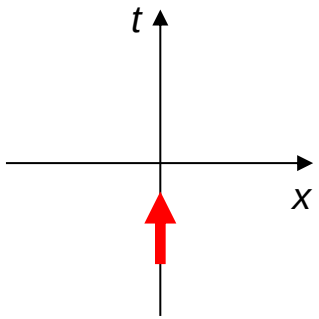
Soft mode states
(representing their collective excitations)

… play the role of the mirror partners

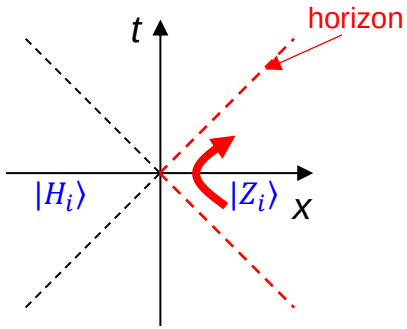
… universally thermal

Emergence of the interior

Minkowski



Rindler



$$|0\rangle \qquad \propto \sum_i e^{-\frac{E_i}{2T}} |R_i\rangle\,|L_i\rangle$$

… thermal state

Fulling ('73); Davies ('75); Unruh ('76)

Near empty
Interior spacetime

(An object thrown "sees" interior spacetime)

frame change

$$|\Psi_{\mathrm{BH}}\rangle \propto \sum_i e^{-\frac{E_i}{2T_{\mathrm{H}}}} |H_i\rangle\,|S_i\rangle$$

Hard mode states

Soft mode states

(representing their collective excitations)

… play the role of the mirror partners

… universally thermal

string dynamics

(**not** the case for the surface of regular material)

At late times, the BH is entangled with radiation

$$|\Psi_{\mathrm{BH}}\rangle \propto \sum_i e^{-\frac{E_i}{2T_{\mathrm{H}}}} |H_i\rangle\, |(S+R)_i\rangle$$

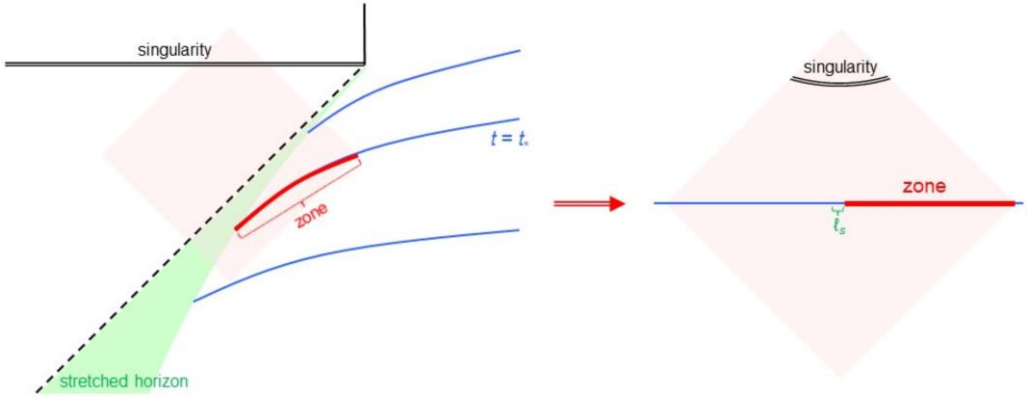
Hard mode states

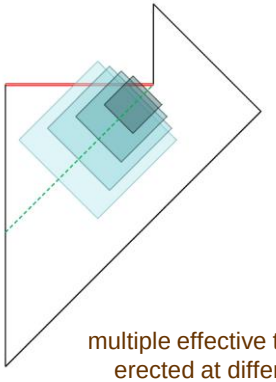
… play the role of the mirror partners

Soft and far (radiation) mode states
(representing collective excitations of these modes)

… Interior d.o.f.s involve early Hawking radiation !

Effective theory of the interior





multiple effective theories
erected at different times

… describe only a limited spacetime region

Distant description
(manifestly **unitary**)

Collective phenomena

Interior spacetime
(effective emergence)

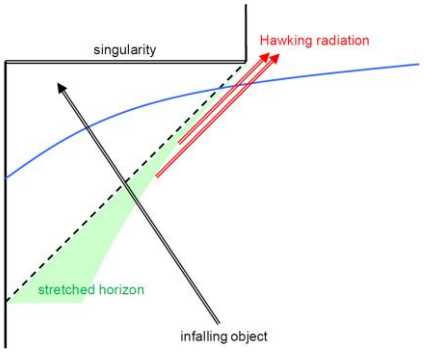
Structure of Quantum Gravity

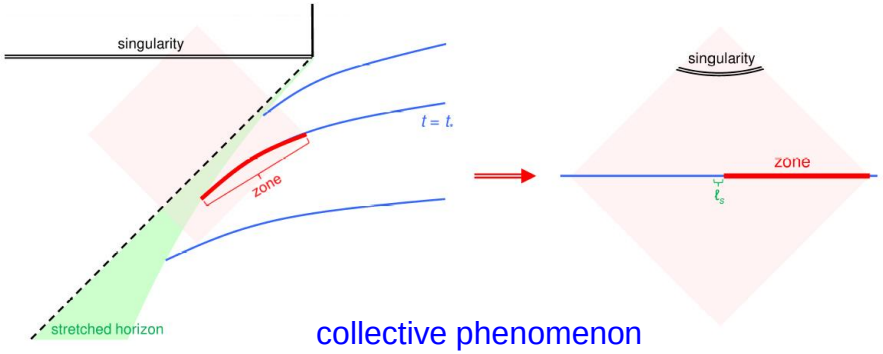
Global spacetime
— General relativity —

Unitary / holographic
— Quantum mechanics —

- Interior

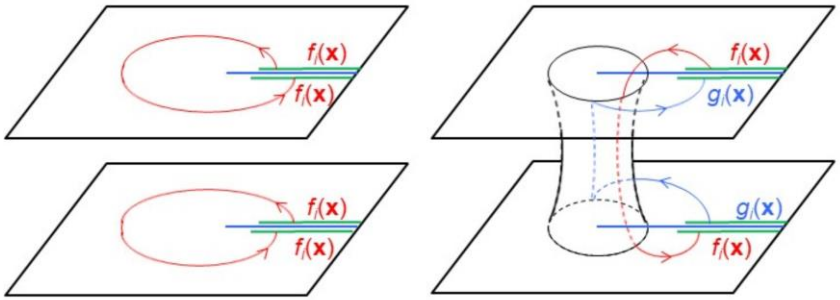
Evident





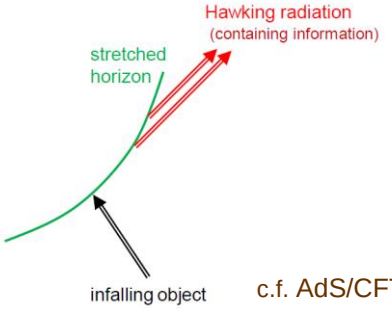
collective phenomenon

- Unitarity



replica wormholes

By construction



c.f. AdS/CFT

- Apparent violation of BH entropy

huge interior spatial volume at late times

Effective theory of the interior has a finite maximal volume.

- Ensemble nature

semiclassically orthogonal states

in fact have $\langle\Psi_1|\Psi_2\rangle \sim e^{-S_{\rm BH}/2}$

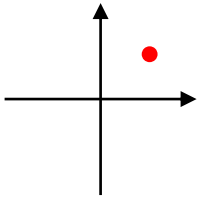
$\rightarrow$ $e^{S_{\rm BH}}$ states (+ null states)

Hilbert space of dimension $e^{S_{\rm BH}}$ can host $e^{e^{S_{\rm BH}}}$ approximately orthogonal states.

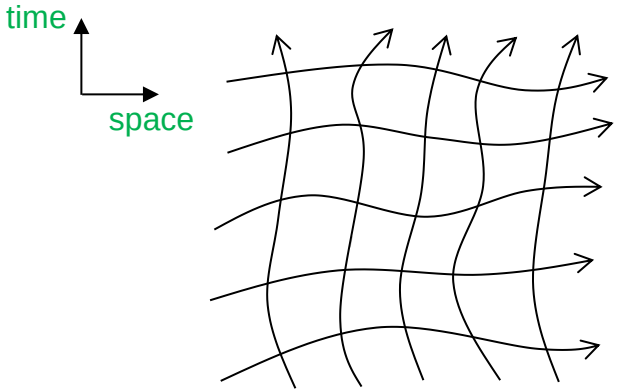
Langhoff, Y.N. ('20); Chakravarty ('20)

Redundancies of the description

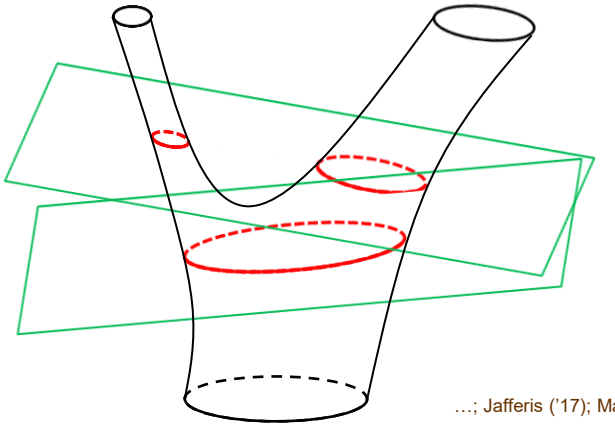
- General covariance (perturbative)



$$\begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} 1 \\ 1 \end{pmatrix} \leftrightarrow \begin{pmatrix} r \\ \theta \end{pmatrix} = \begin{pmatrix} \sqrt{2} \\ \pi/4 \end{pmatrix} \leftrightarrow \ \ldots$$



- Nonperturbative redundancies



…; Jafferis ('17); Marolf, Maxfield ('20); …

… allows for making (only) one of the two pillars manifest,
but the theory still accommodates both of them (QM + GR).

Summary

Black hole conundrum

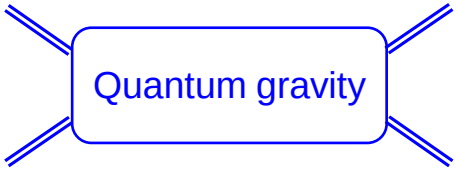
⇓

Structure of quantum gravity

⊃ Quantm mechanics & General relativity, but in a subtle manner!

High energy / Astro physics
(Black holes, gravity, …)

Quantum information science
(Holography, …)



Many-body physics (cond. matter & AMO)
(Chaos, fast scrambling, …)

…

"From the Black Hole Conundrum to the Structure of Quantum Gravity"
Y.N., *Mod. Phys. Lett.* **A36** (2021) 2130007 [arXiv:2011.08707 [hep-th]]

"Complementarity for a Dynamical Black Hole"
B. Concepcion, Y.N., K. Ritchie, S. Weiss, arXiv:2405.15849 [hep-th]

• Activities at Berkeley

"Geoflow" collaboration

Berkeley/Stanford/Duke/Brandies/Bookhaven

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Altman, Bousso, Y.N., Penington, Siddiqi, Zaletel