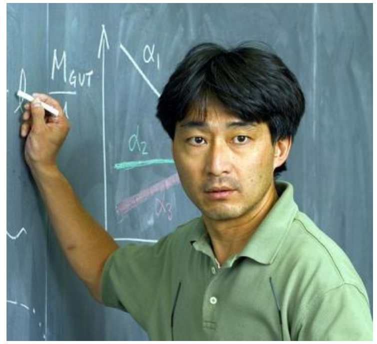
Black Holes as a Window into Quantum Gravity

Yasunori Nomuraa

UC Berkeley; LBNL; RIKEN iTHEMS; Kavli IPMU

My career with Hitoshi



~25 years, 6 papers

Compact Supersymmetry #1
Hitoshi Murayama (UC, Berkeley and LBL, Berkeley and Tokyo U., IPMU), Yasunori Nomura (UC, Berkeley and LBL, Berkeley), Satoshi Shirai (UC, Berkeley and LBL, Berkeley), Kohsaku Tobioka (Unlisted, JP and Tokyo U., IPMU and Tokyo U.) (Jun, 2012)
Published in: *Phys.Rev.D* 86 (2012) 115014 • e-Print: 1206.4993 [hep-ph]
pdf DOI cite claim reference search 46 citations

More visible effects of the hidden sector #2
Hitoshi Murayama (UC, Berkeley and LBL, Berkeley), Yasunori Nomura (UC, Berkeley and LBL, Berkeley), David Poland (UC, Berkeley and LBL, Berkeley) (Sep, 2007)
Published in: *Phys.Rev.D* 77 (2008) 015005 • e-Print: 0709.0775 [hep-ph]
pdf DOI cite claim reference search 112 citations

Simple Scheme for Gauge Mediation #3
Hitoshi Murayama (LBL, Berkeley and UC, Berkeley), Yasunori Nomura (LBL, Berkeley and UC, Berkeley) (Jan, 2007)
Published in: *Phys.Rev.D* 75 (2007) 095011 • e-Print: hep-ph/0701231 [hep-ph]
pdf DOI cite claim reference search 86 citations

Gauge Mediation Simplified #4
Hitoshi Murayama (LBL, Berkeley and UC, Berkeley), Yasunori Nomura (LBL, Berkeley and UC, Berkeley) (Dec, 2006)
Published in: *Phys.Rev.Lett.* 98 (2007) 151803 • e-Print: hep-ph/0612186 [hep-ph]
pdf DOI cite claim reference search 143 citations

Wilson lines and symmetry breaking on orbifolds #5
Lawrence J. Hall (UC, Berkeley and LBL, Berkeley), Hitoshi Murayama (UC, Berkeley and LBL, Berkeley), Yasunori Nomura (UC, Berkeley and LBL, Berkeley) (Jul, 2001)
Published in: *Nucl.Phys.B* 645 (2002) 85-104 • e-Print: hep-th/0107245 [hep-th]
pdf DOI cite claim reference search 134 citations

Viable ultraviolet insensitive supersymmetry breaking #6
Nima Arkani-Hamed (UC, Berkeley and LBL, Berkeley), David E. Kaplan (Chicago U., EFI and Argonne), Hitoshi Murayama (UC, Berkeley), Yasunori Nomura (UC, Berkeley) (Dec, 2000)
Published in: *JHEP* 02 (2001) 041 • e-Print: hep-ph/0012103 [hep-ph]
pdf DOI cite claim reference search 107 citations

Two pillars of modern physics

Quantum mechanics

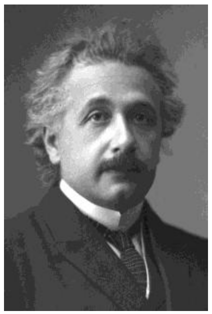
$$i\hbar \frac{\partial}{\partial t}|\Psi> = \mathcal{H}|\Psi>$$

General relativity

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




…



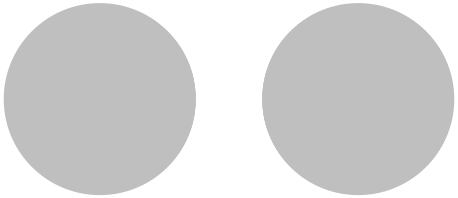
photos: Nobel Foundation archive

not get along well

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

p e^-

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



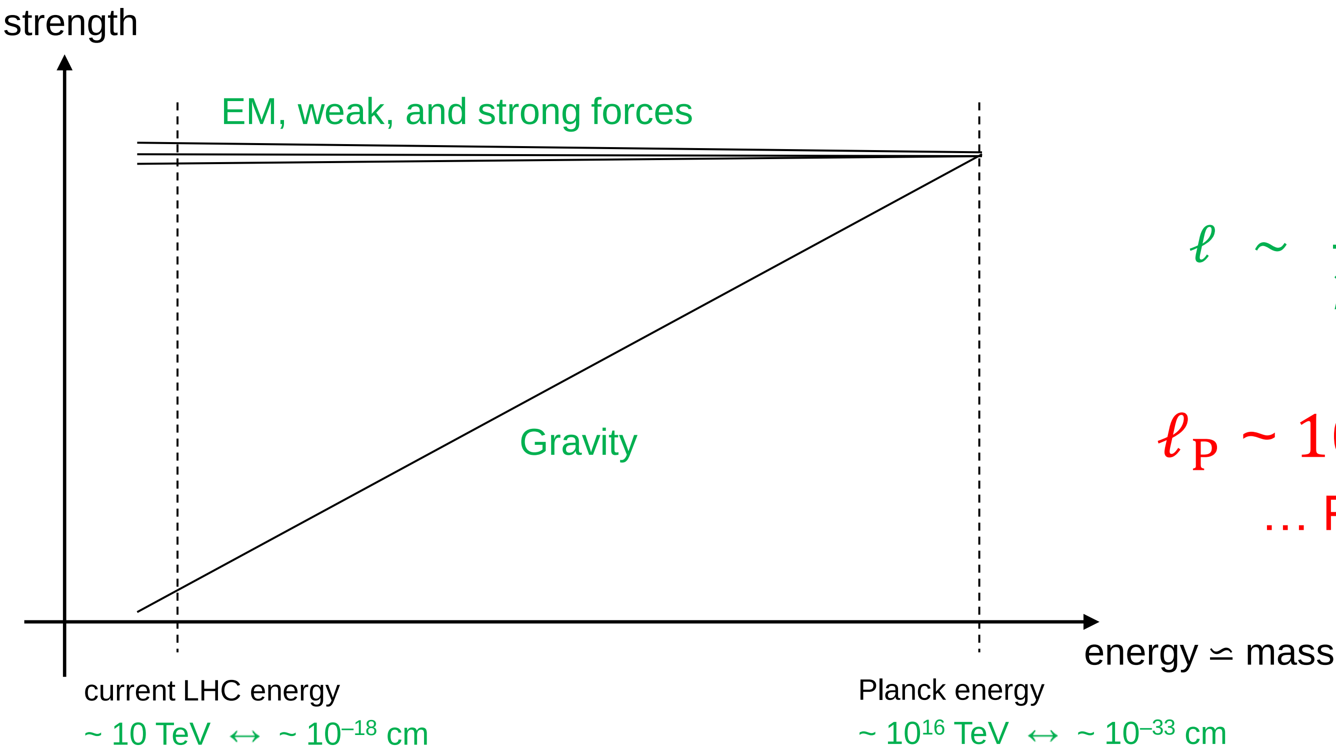
macroscopic body
($N \gg 1$ particles)

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



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

$$\ell_P \sim 10^{-33}\,\text{cm}$$

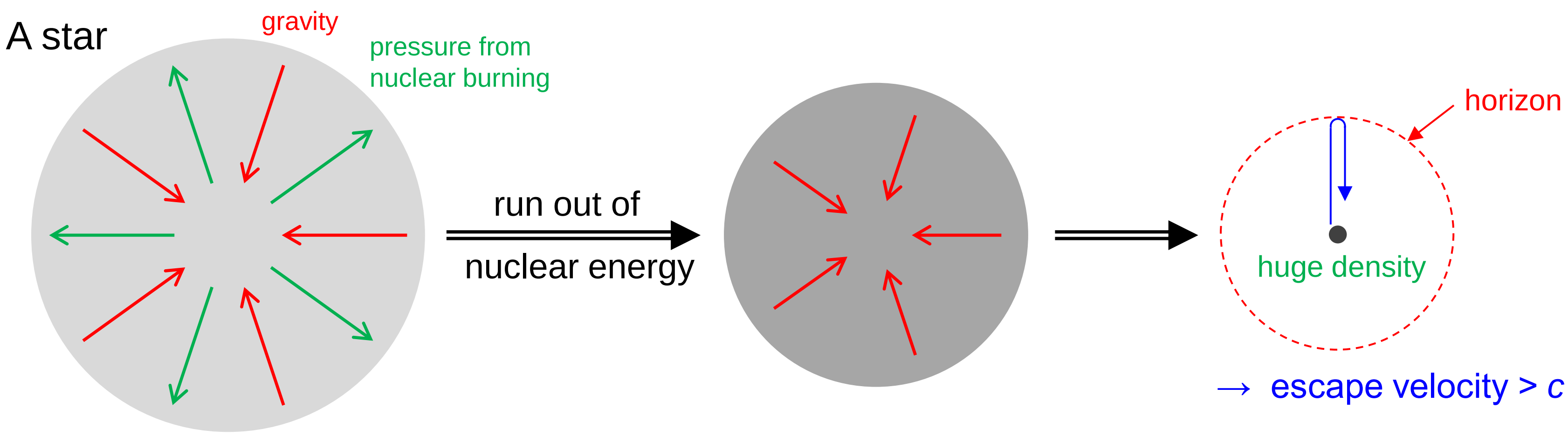
… Planck length

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)

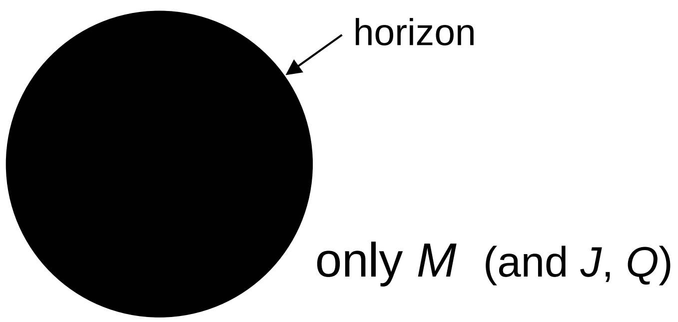
Unusual situations can occur at long distances:

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

$S = k_B \ln W$

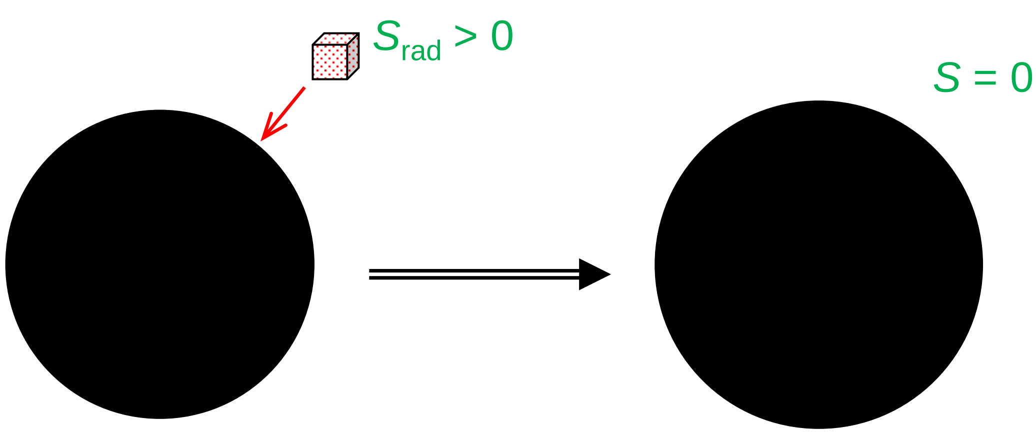
(below, $k_B = 1$)

photo: Univ. Frankfurt

for any system ⟹ for all practical purposes

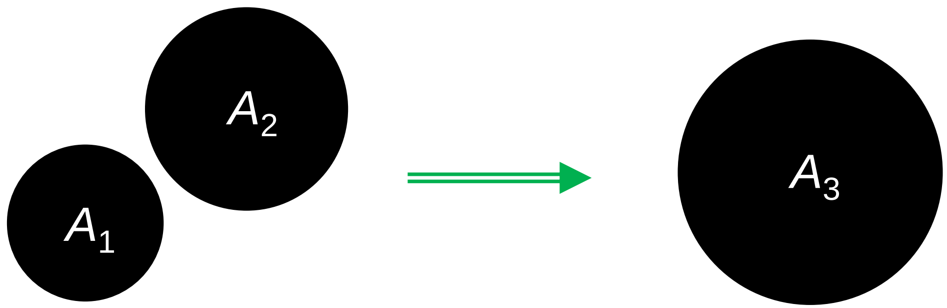
$$\Delta S \geq 0$$

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.

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

Note: $G_{\mathrm{N}} = \ell_{\mathrm{P}}^2 \sim (10^{-33}\,\mathrm{cm})^2 \;\longrightarrow\;$ huge entropy

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

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

Does this make sense?

$\dfrac{A}{4G_{\mathrm{N}}} = 4\pi G_{\mathrm{N}} M^2$

$$\frac{\partial S}{\partial E} = \frac{1}{T} \quad \longrightarrow \quad \text{finite temperature}$$

M

Doesn't a BH only absorb stuff?

Black holes radiate [Hawking, 1974]

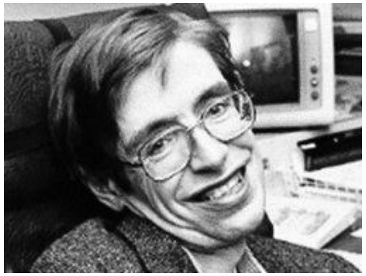


photo: NASA

The horizon is “smooth.”

⇓ Quantum mechanical effect

There must be radiation corresponding to $T_{\mathrm{H}} \sim \dfrac{1}{8\pi M G_{\mathrm{N}}}$.

Hawking temperature

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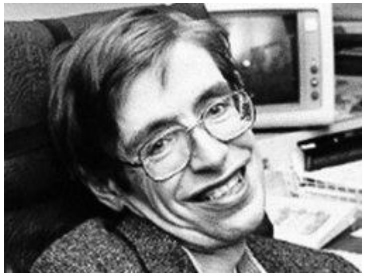

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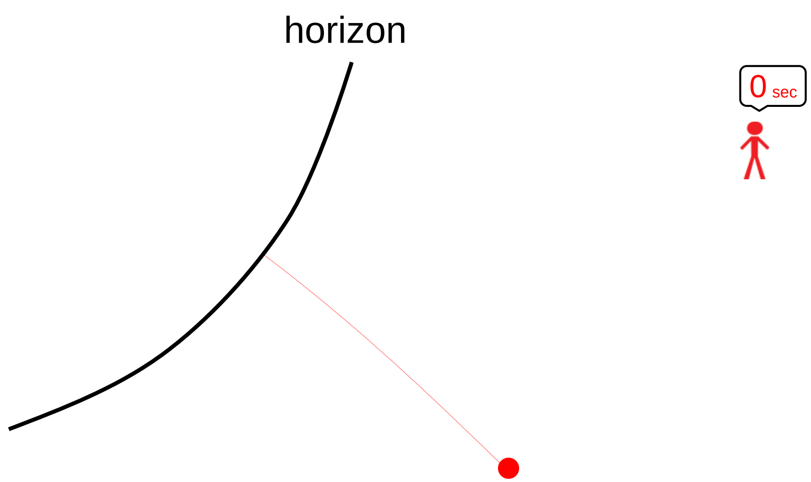

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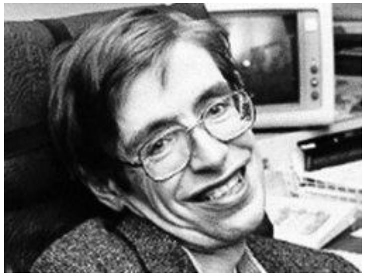

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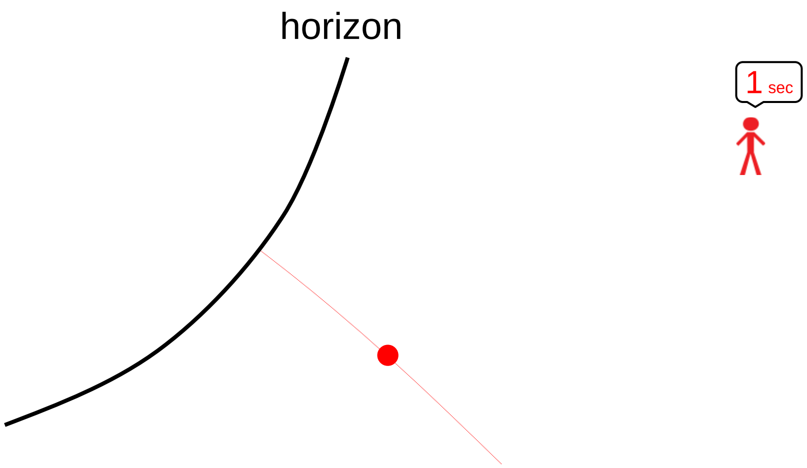

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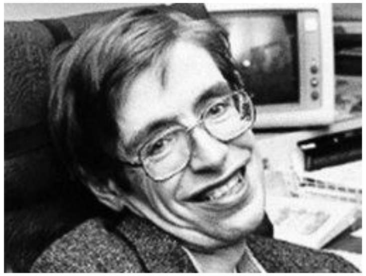
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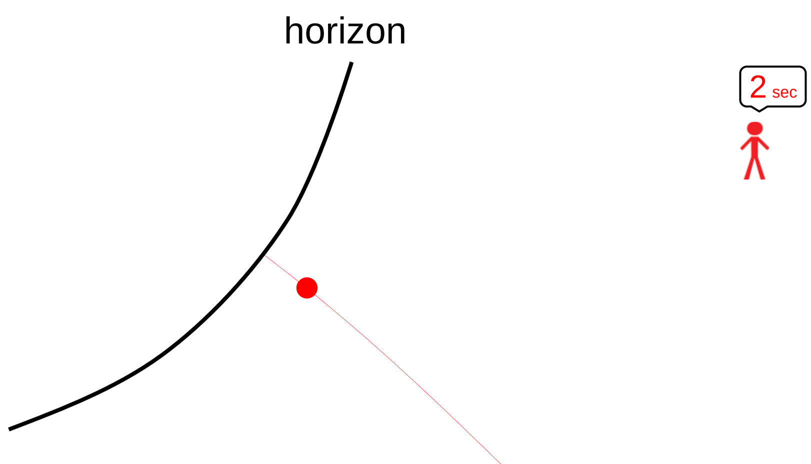

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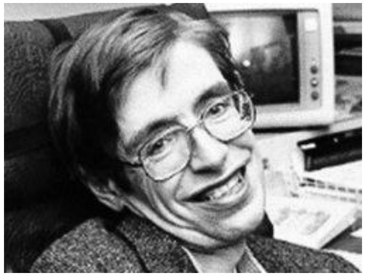

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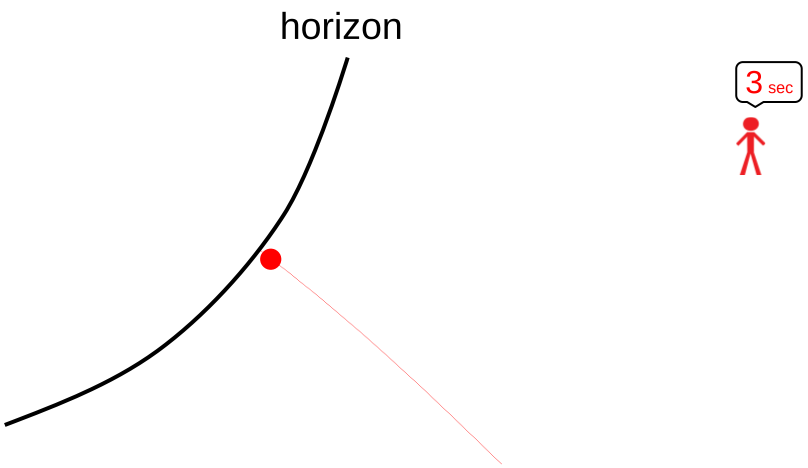

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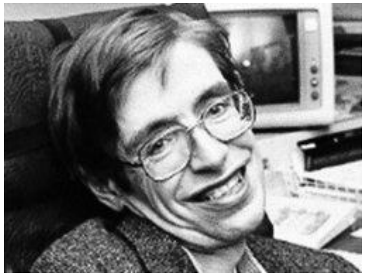

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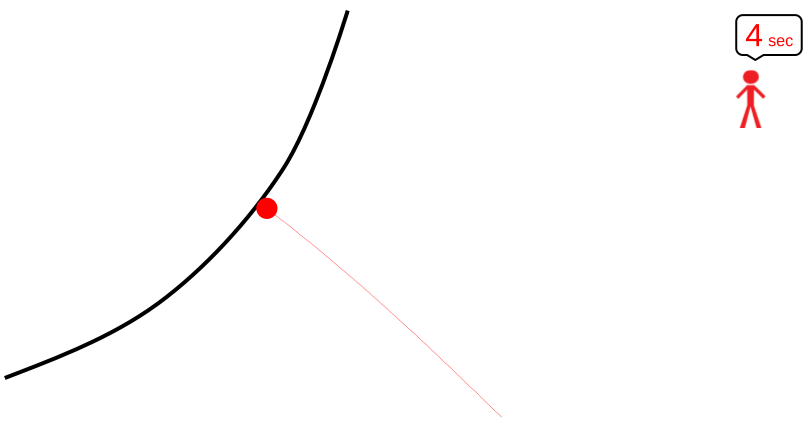

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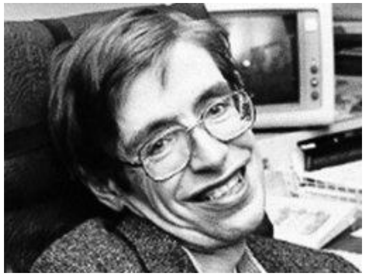

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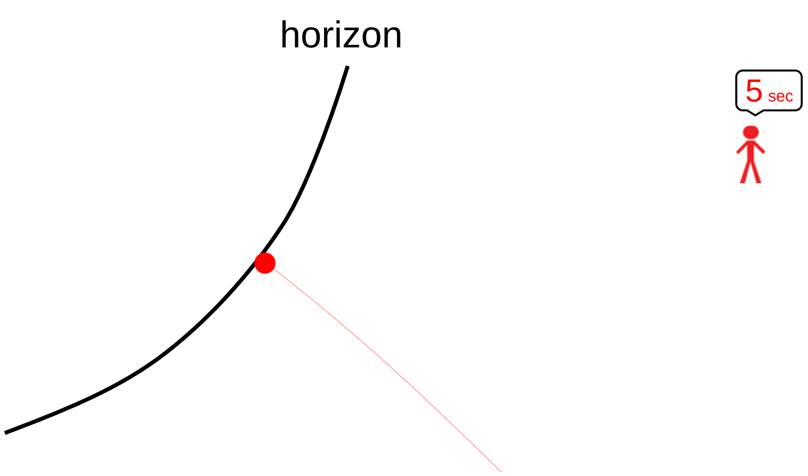

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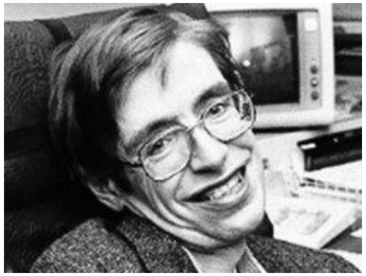

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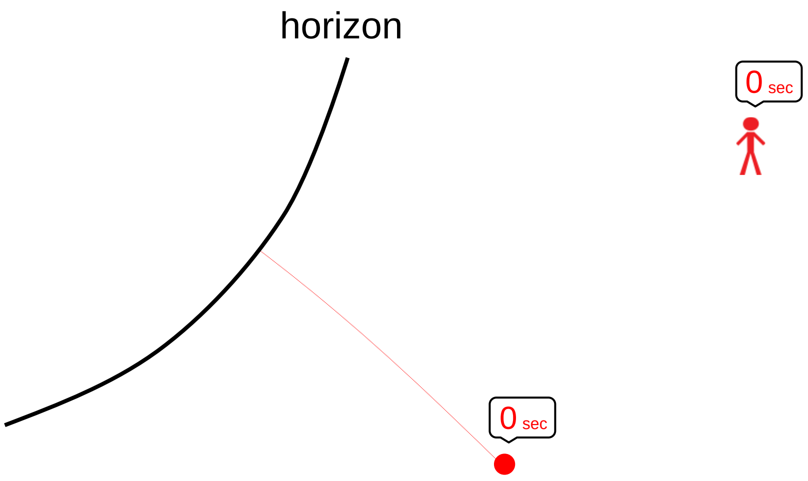

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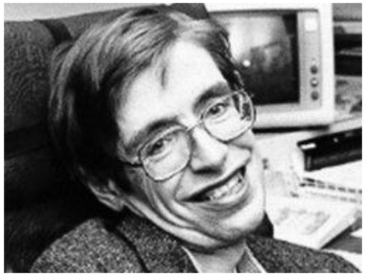

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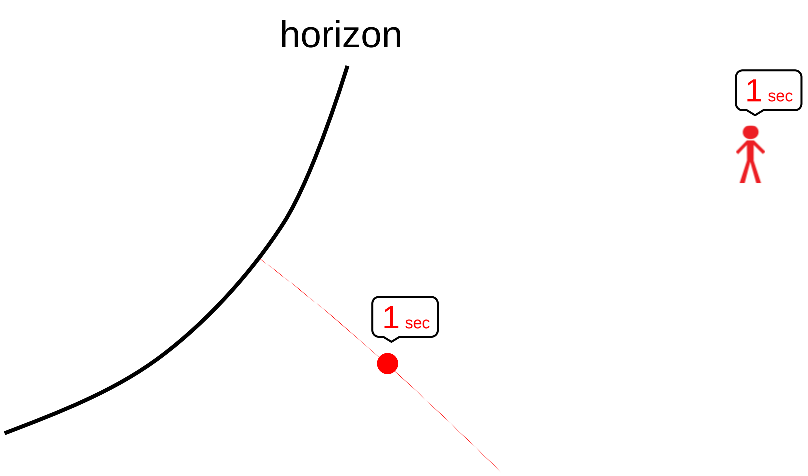

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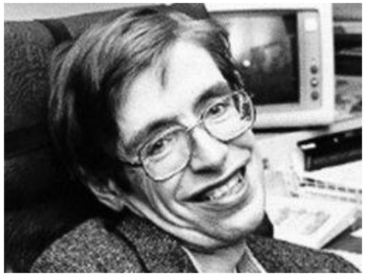

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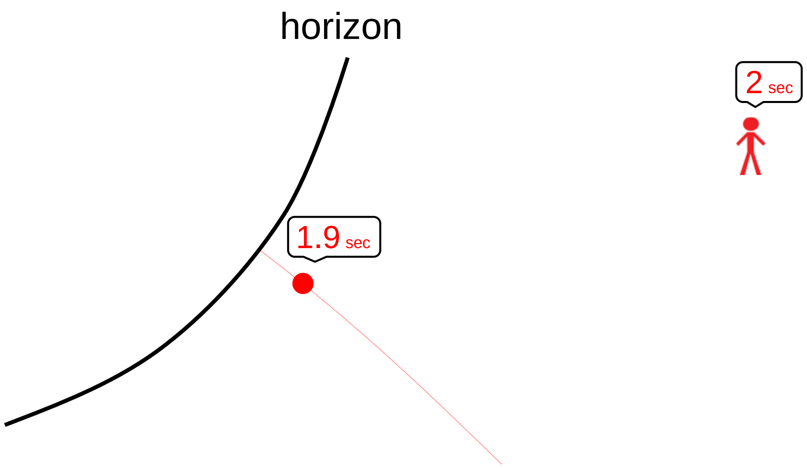

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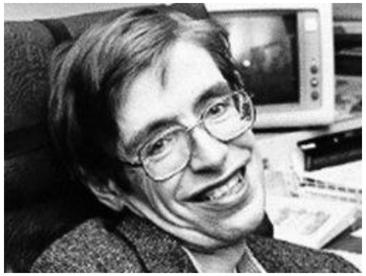

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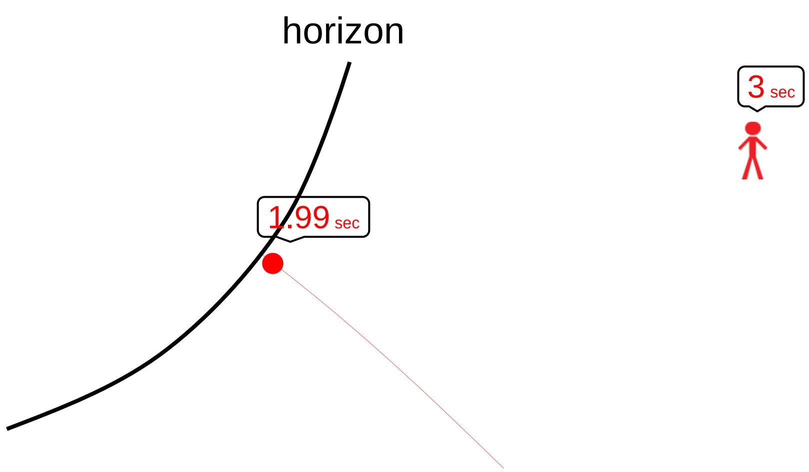

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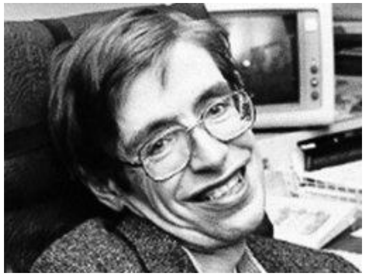

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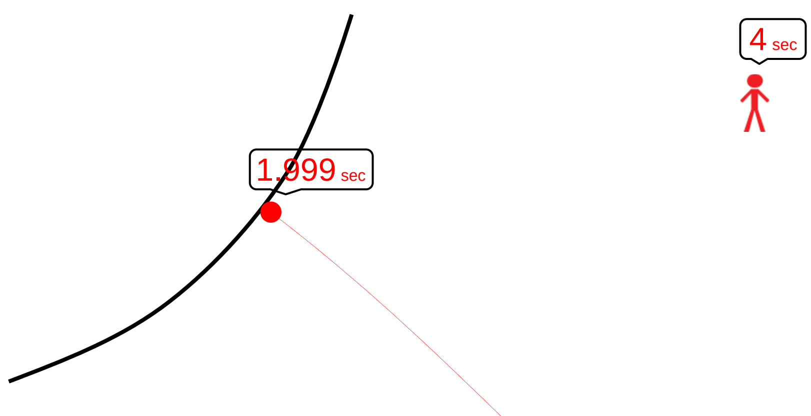

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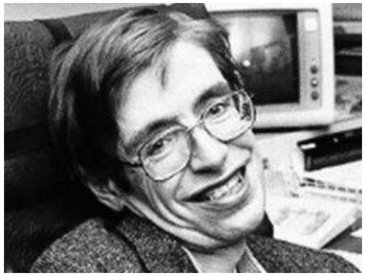

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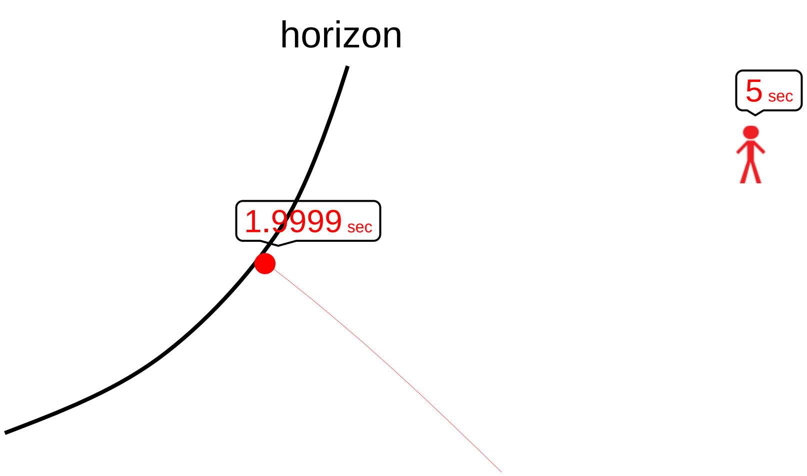

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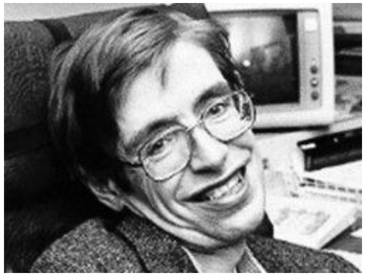

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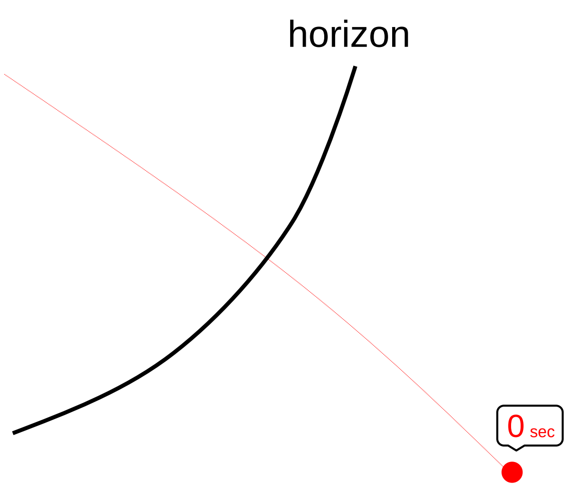

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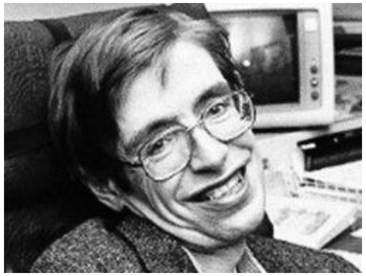

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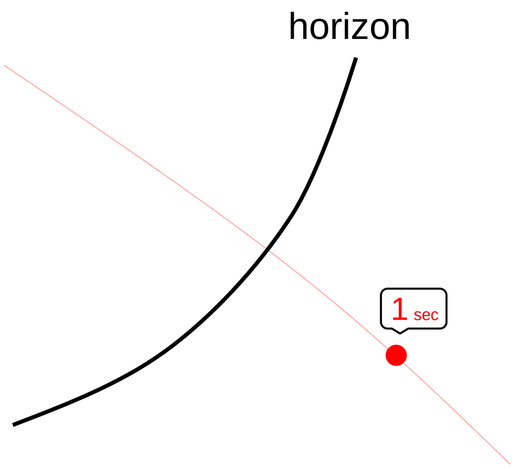

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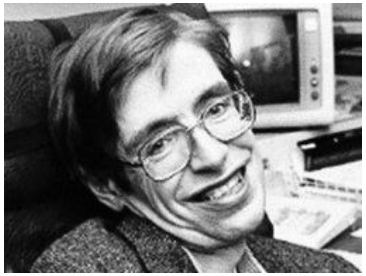

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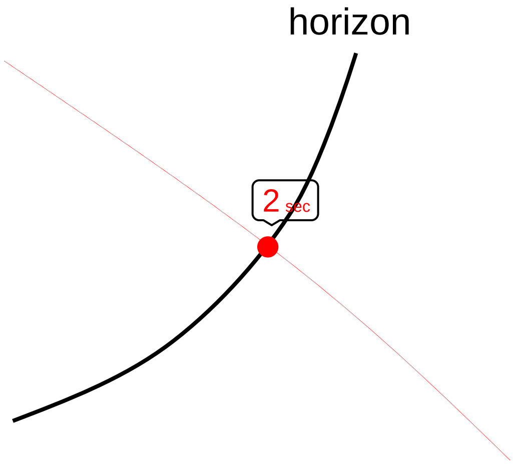

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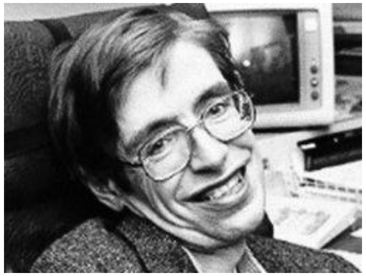

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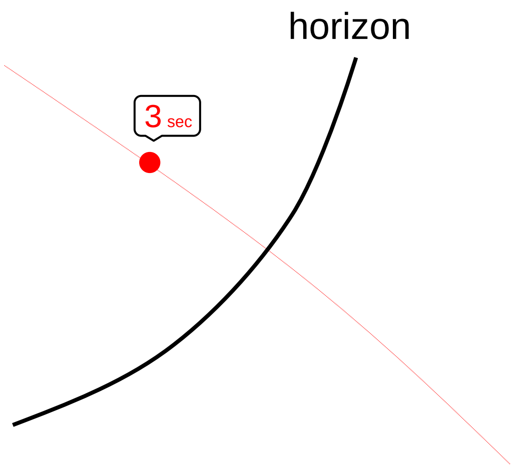

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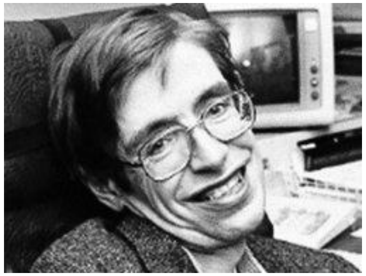

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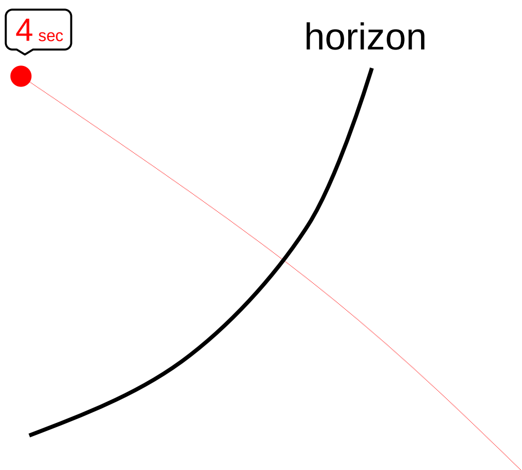

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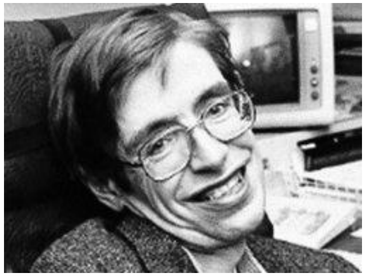

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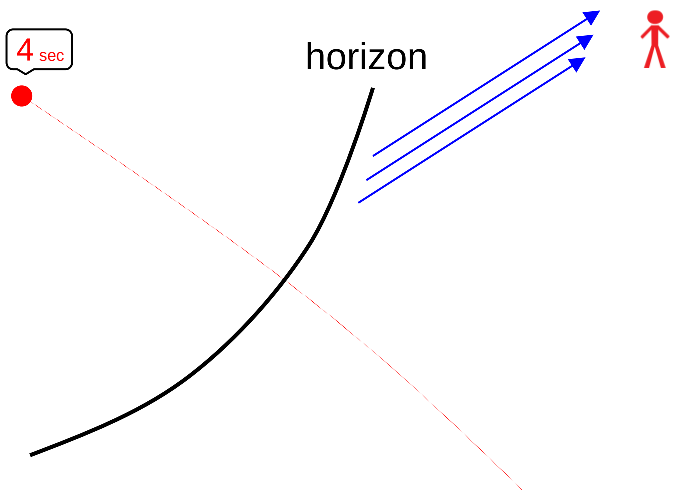
BHs are thermodynamic objects.

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



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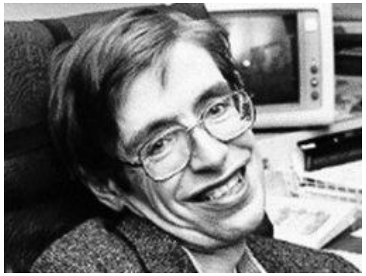

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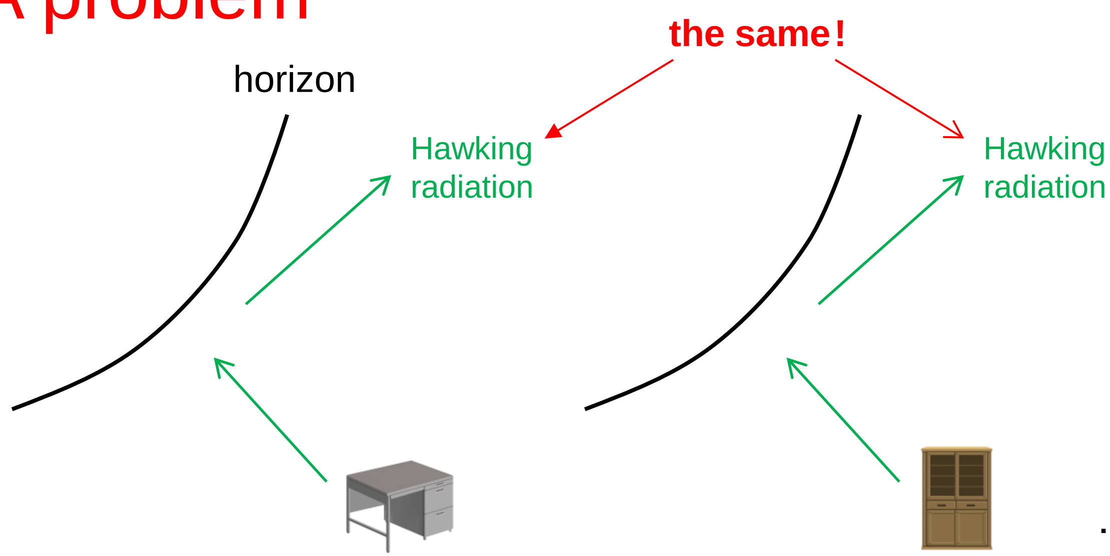
A problem



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

… (the original form of)
BH information problem

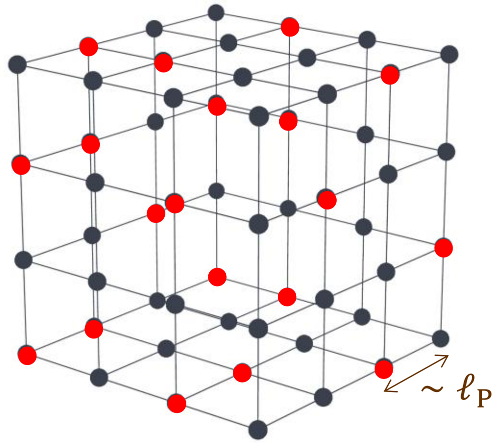
Holography

A clue comes from the BH physics itself

A BH is the highest entropy state of the region,

and still $S \propto \frac{A}{\ell_P^2}$

Strange!



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

$(\ell_P \sim 10^{-33}\text{cm})$

The concept that spacetime exits down to $\sim \ell_P$ 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]

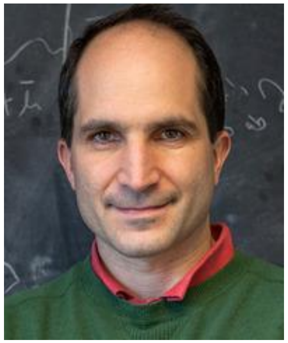
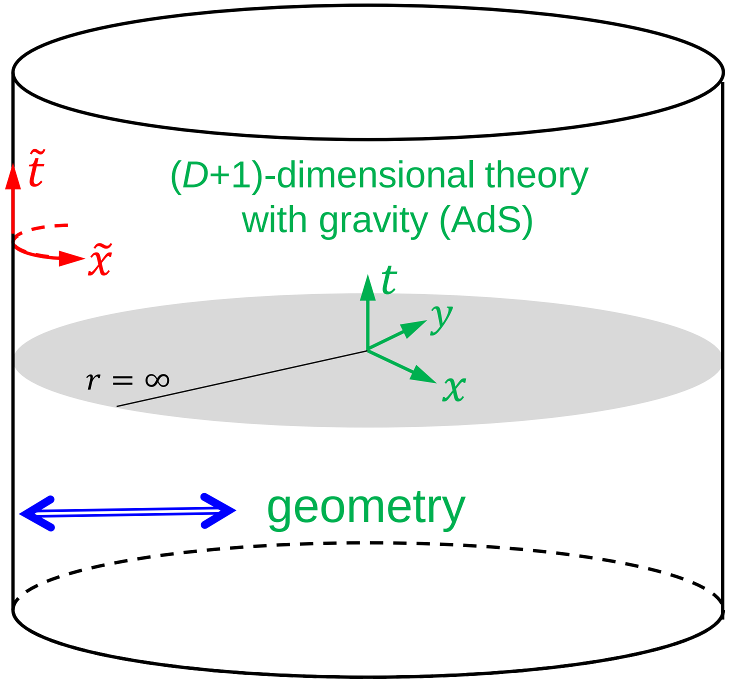


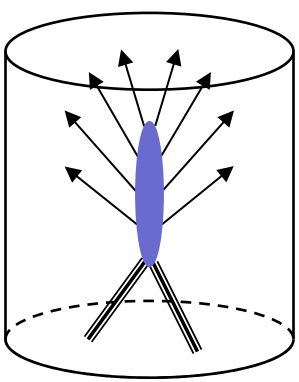
photo: IAS

D-dimensional theory **without** gravity (CFT)



quantum information

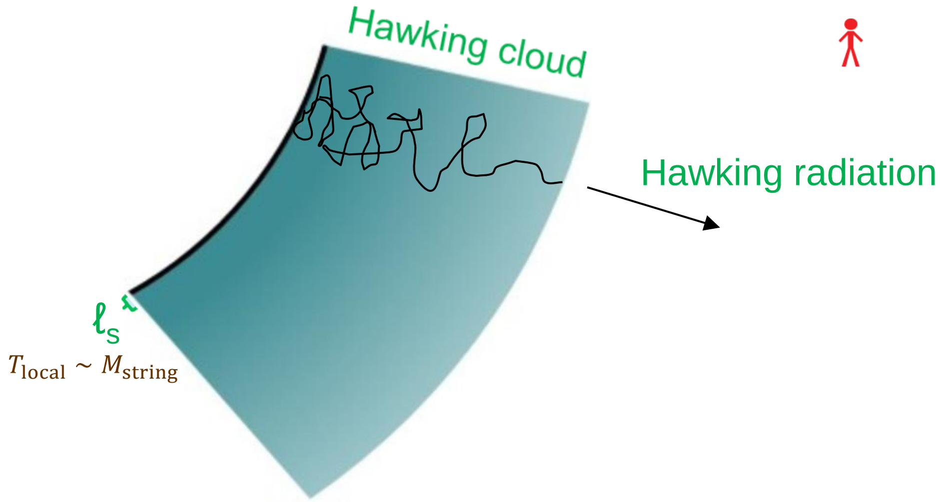
BH evolution **must be** unitary.



=

A process in non-gravitational (unitary) theory

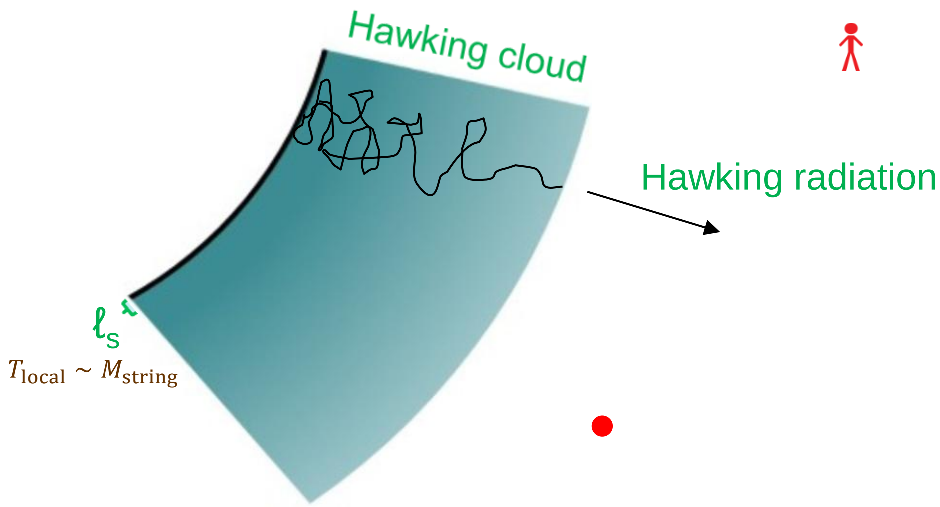
BH at the quantum level



The horizon behaves
as the surface of regular material.

… no issue with unitarity

BH at the quantum level



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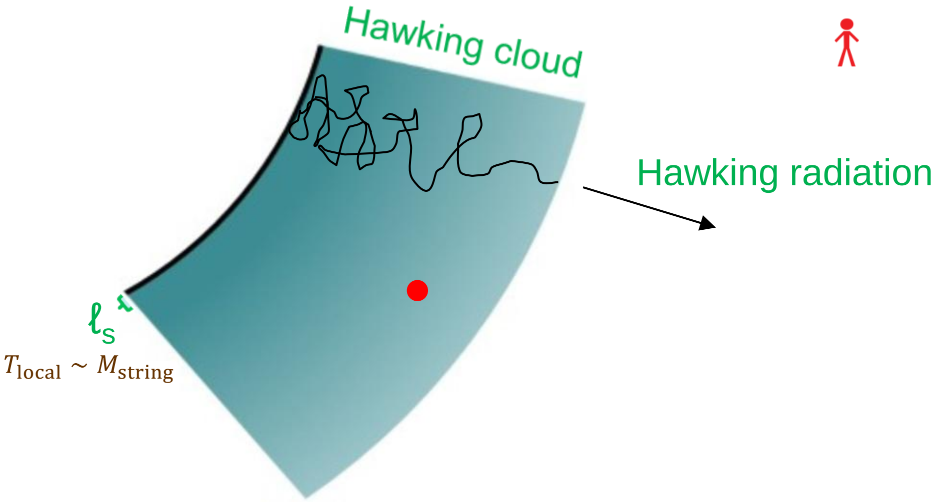

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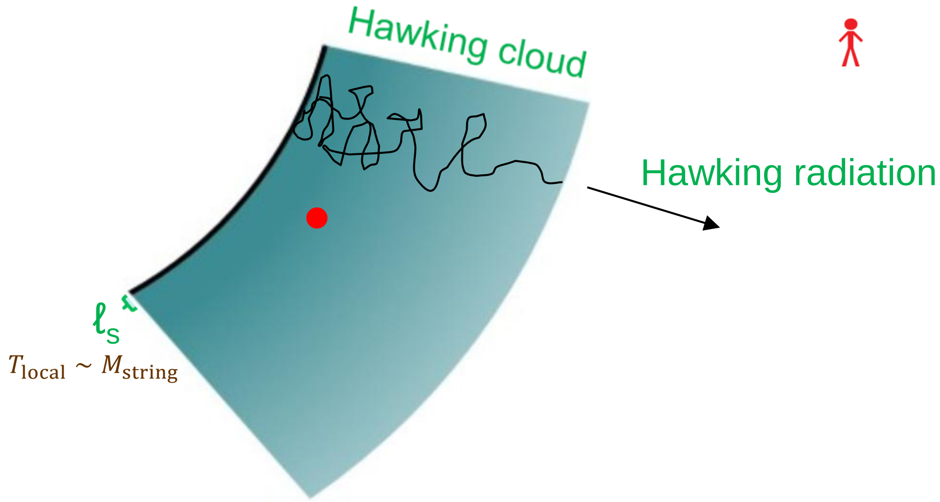

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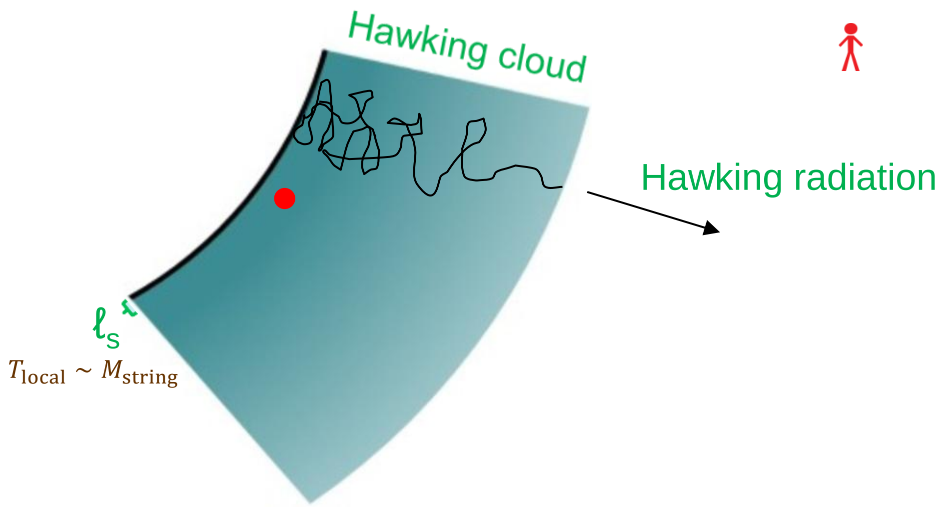

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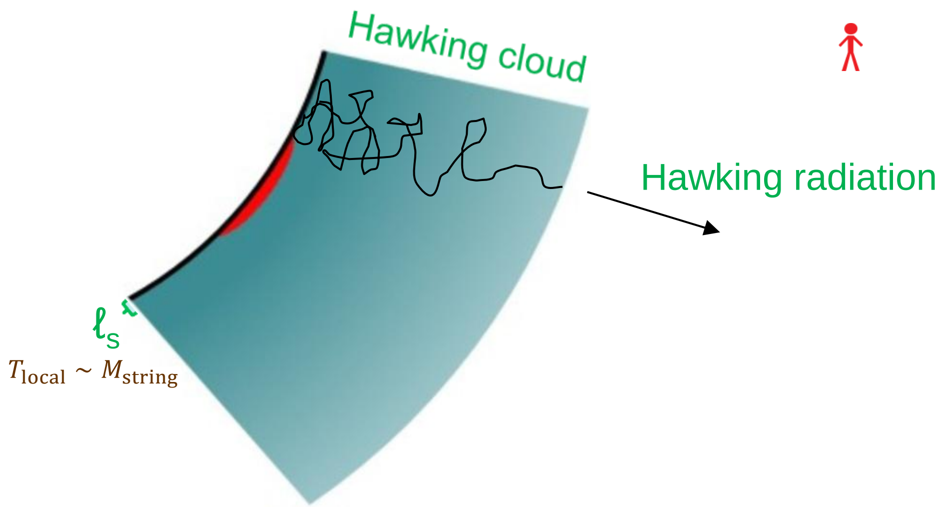

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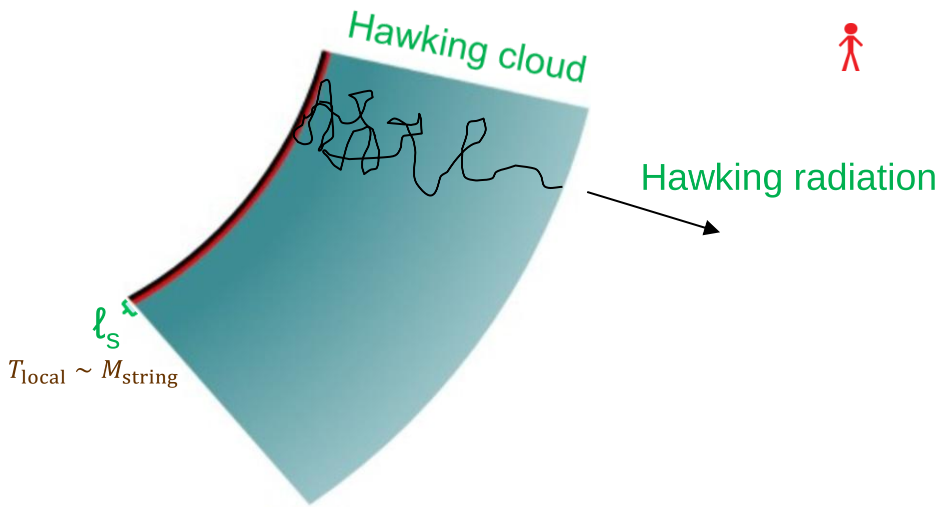

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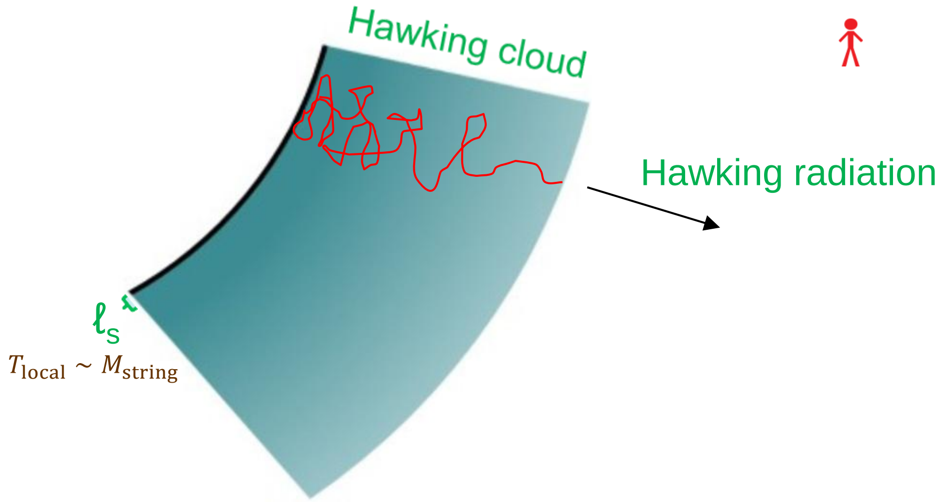

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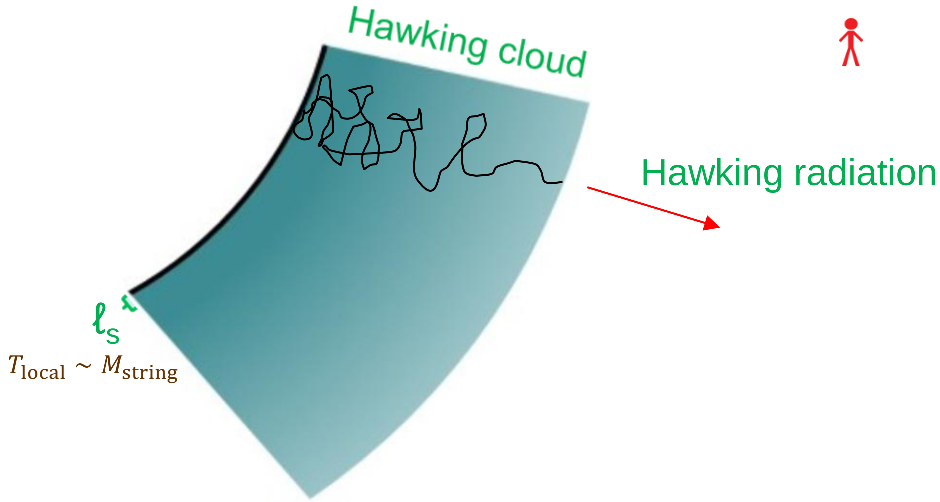

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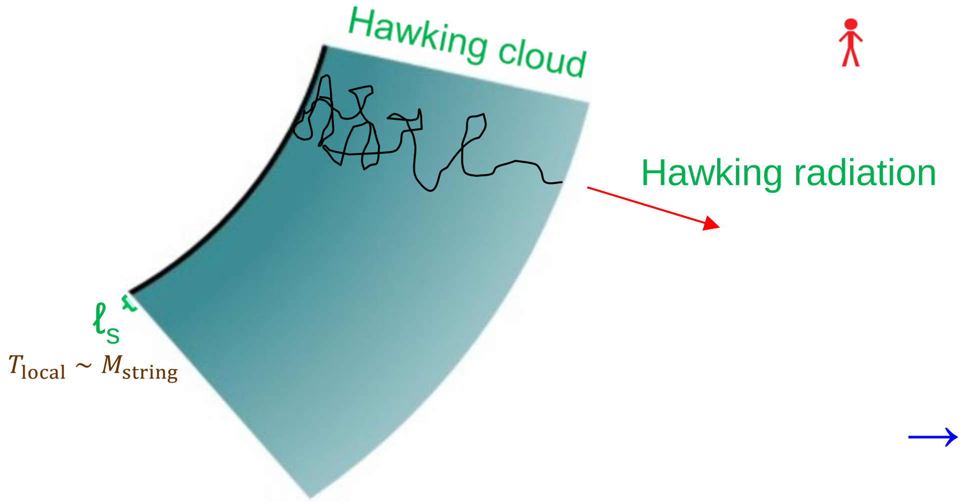

The horizon behaves
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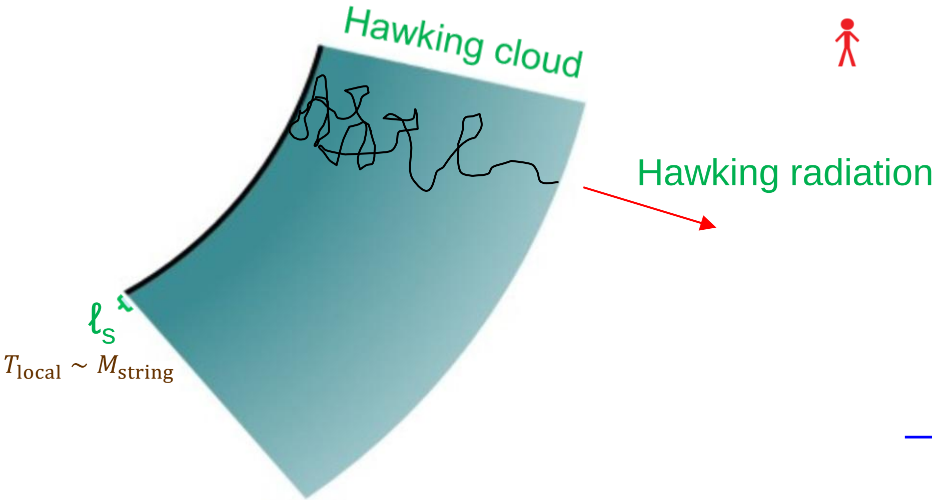
… no issue with unitarity

→ What about the interior?

BH at the quantum level



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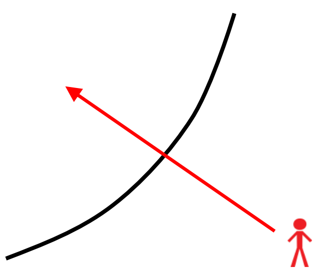
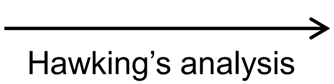
→ What about the interior?

Alternatively





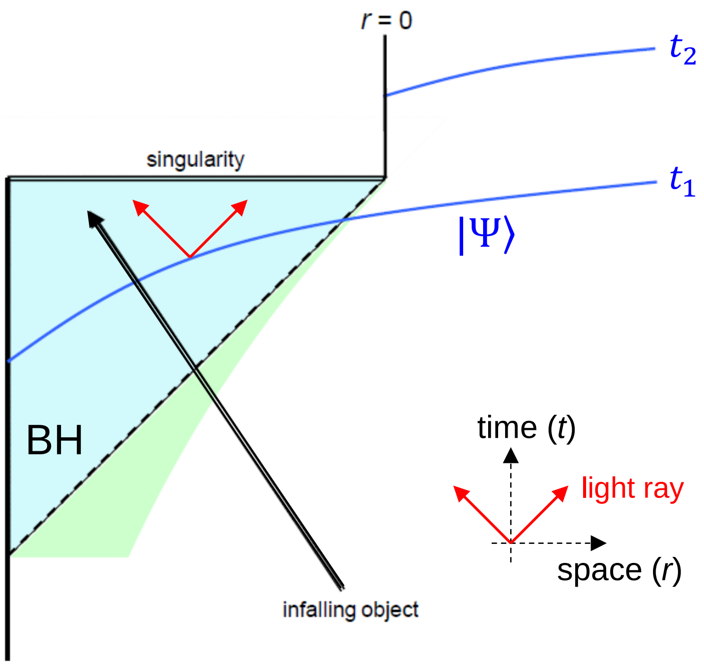
information loss

→ What was wrong with Hawking's analysis?

Recent Progress I

— replica wormholes —

Start with “global spacetime”



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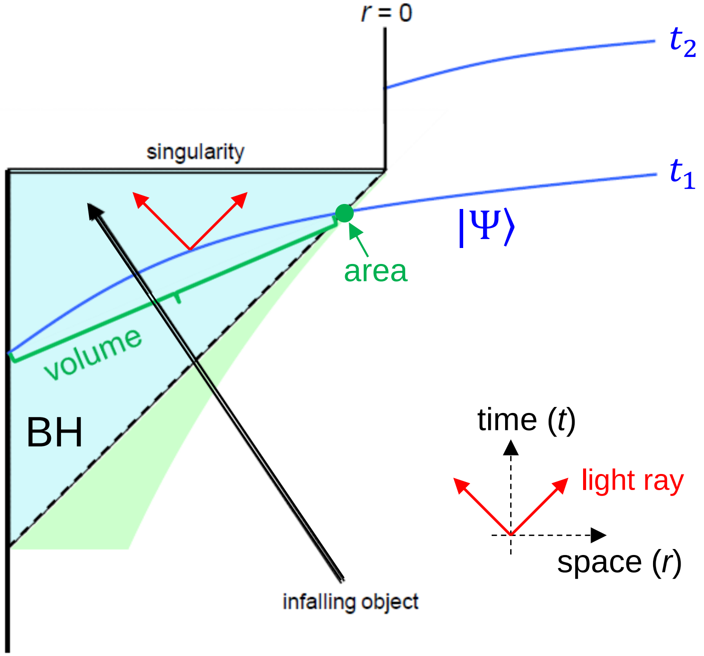
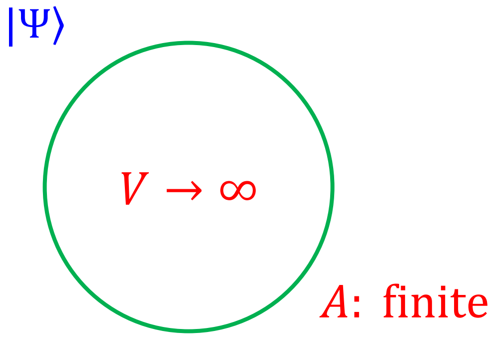
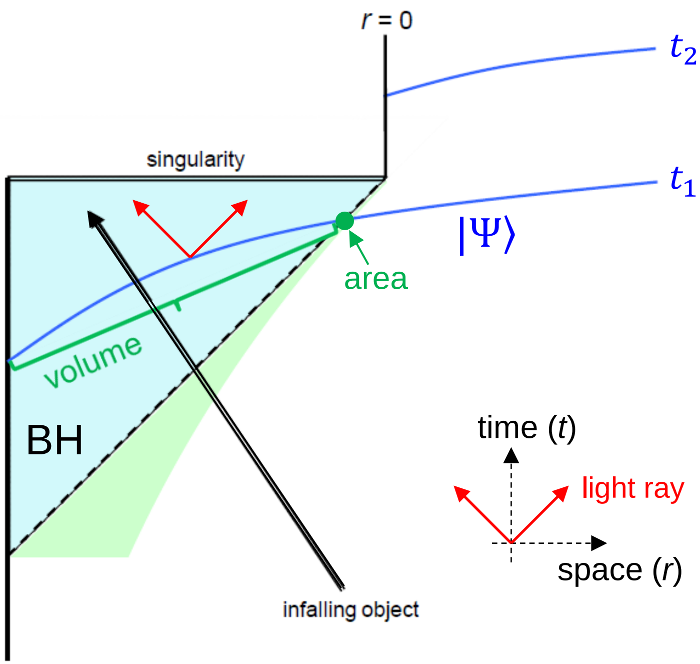


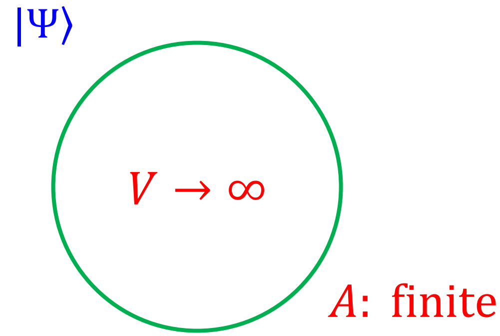


… at odds with $S = \frac{A}{4\ell_P^2}$

Hugely redundant!

Start with "global spacetime"





… 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

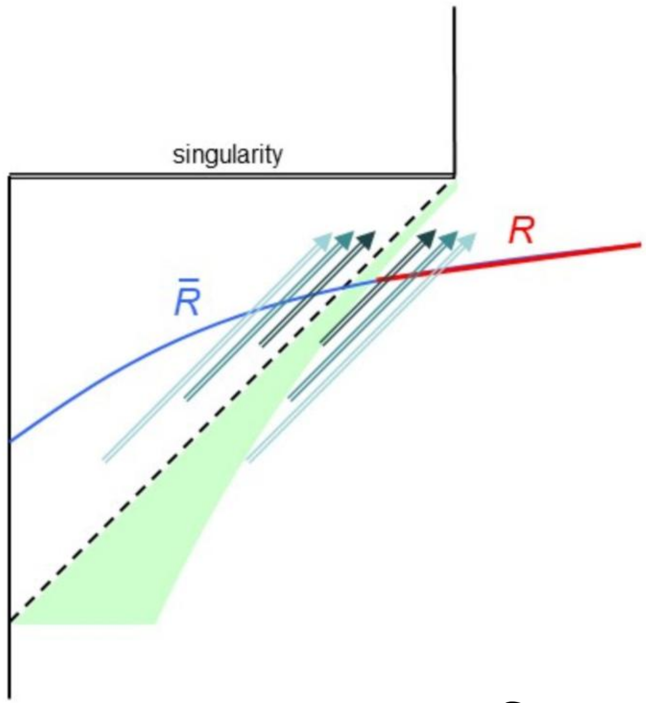
… only e^S independent states

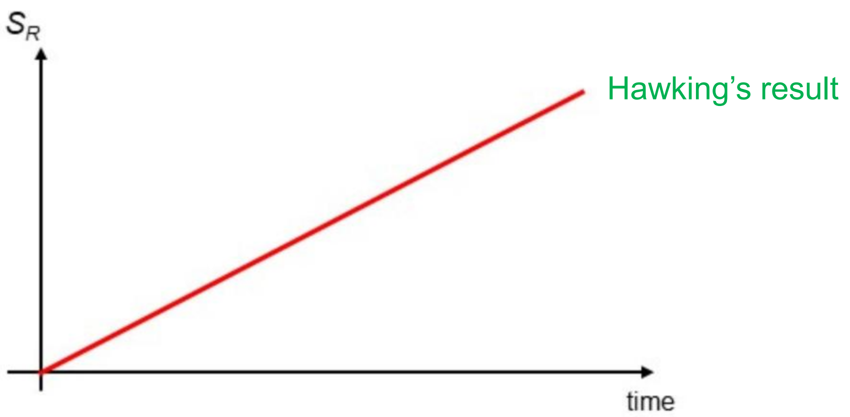
$$|\Psi\rangle = \sum_{i=1}^{e^S} c_i |\psi_i\rangle \qquad c_i \sim e^{-\frac{S}{2}}$$

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

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

Unitarity of Hawking evaporation

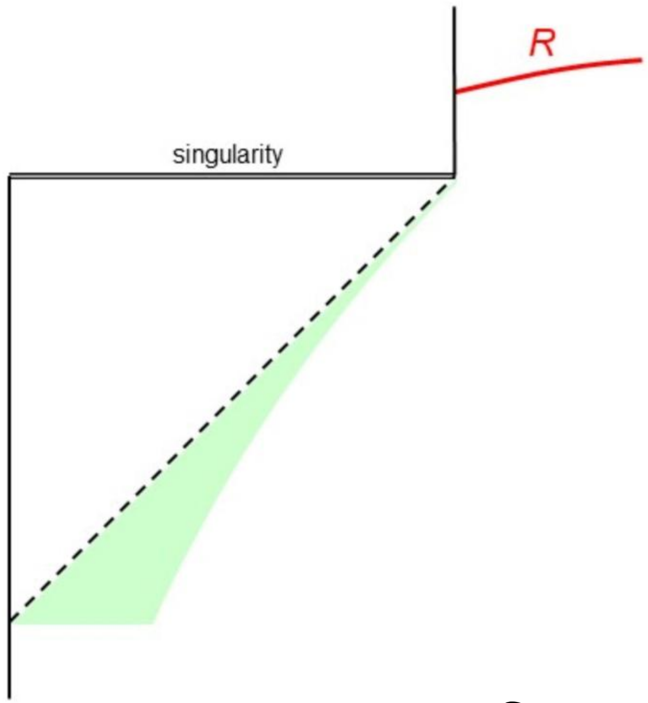


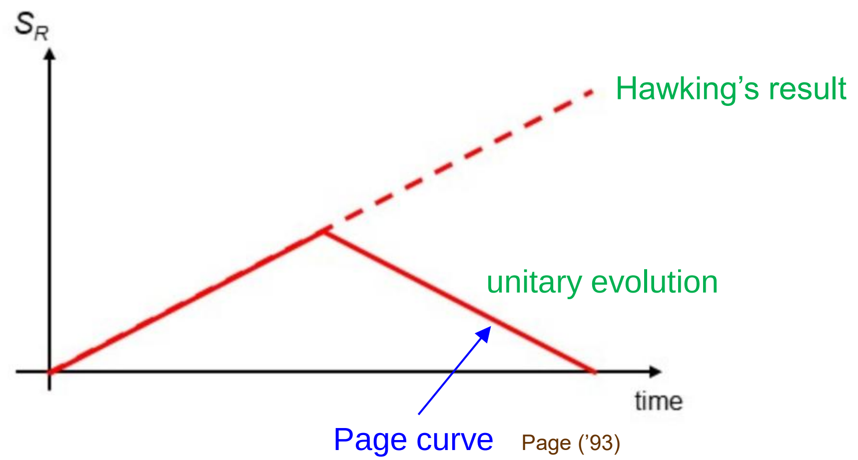


$$S_R = -\mathrm{Tr}[\rho_R \ln \rho_R] \qquad (\rho_R = \mathrm{Tr}_{\bar{R}} |\Psi\rangle\langle\Psi|)$$

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

Unitarity of Hawking evaporation





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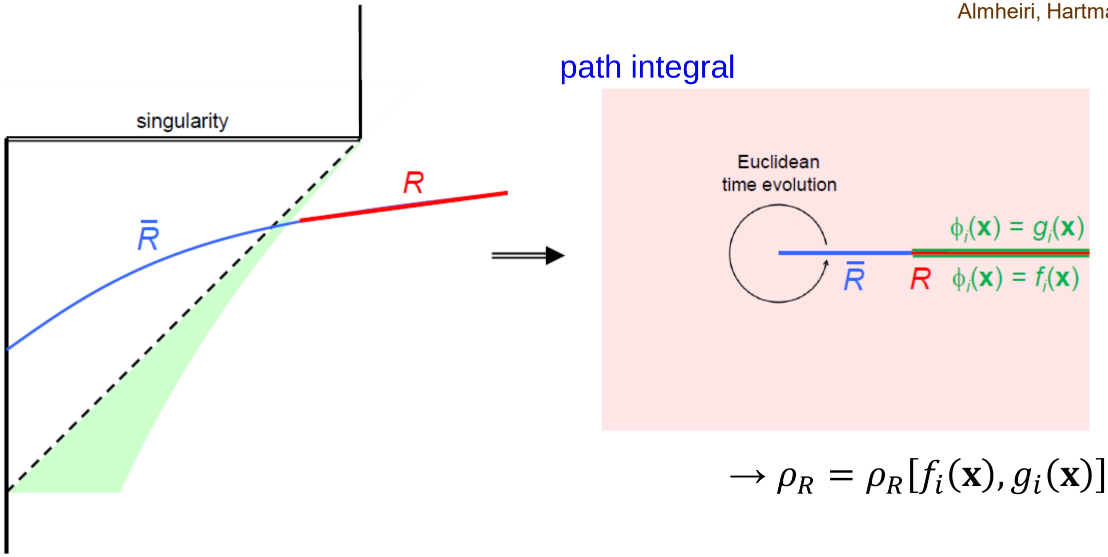
→ How to get this curve?

Page curve from replica wormholes

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



$\rightarrow \rho_R = \rho_R[f_i(\mathbf{x}), g_i(\mathbf{x})]$ (~ 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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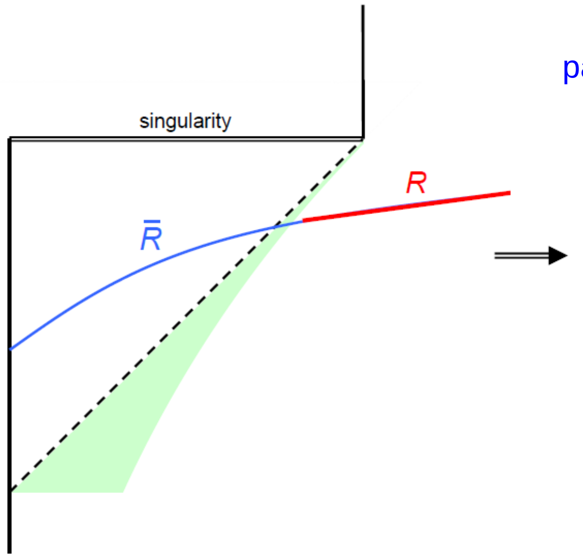
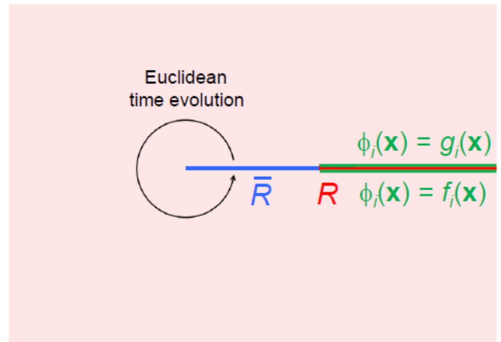


path integral



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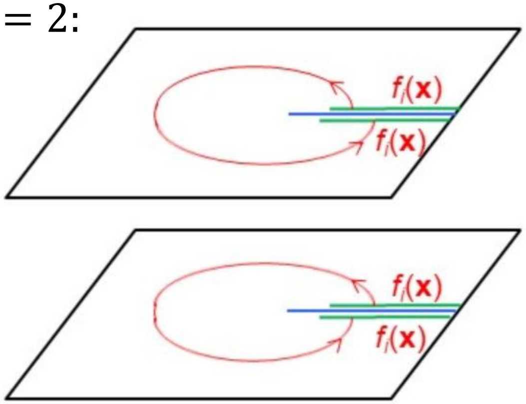
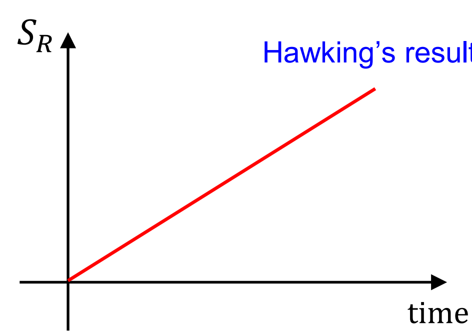
$n = 2$:





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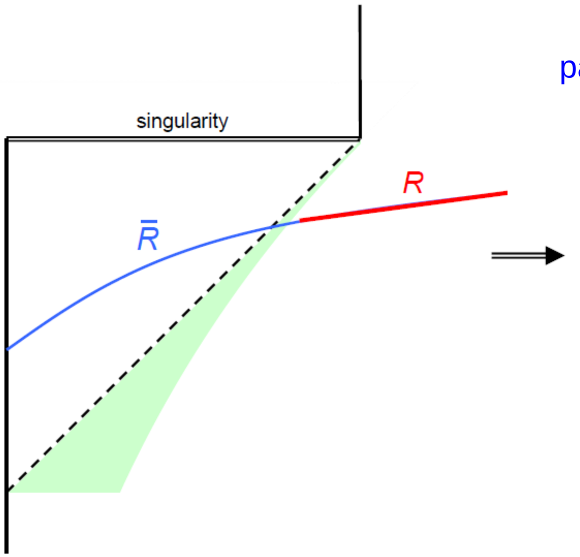

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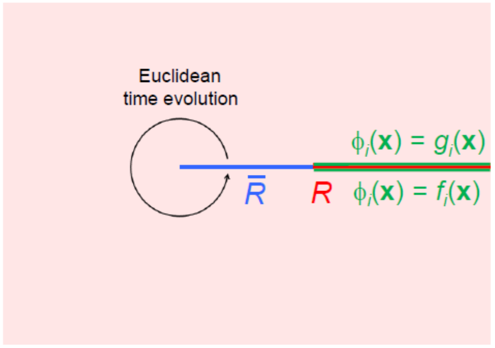

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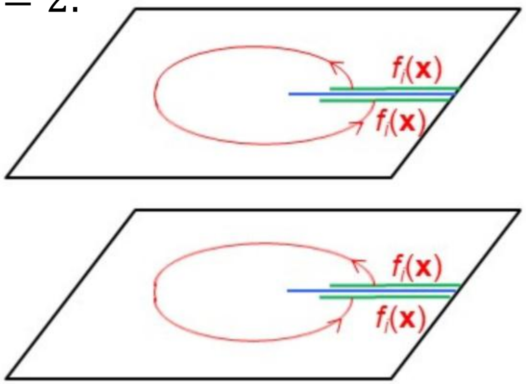
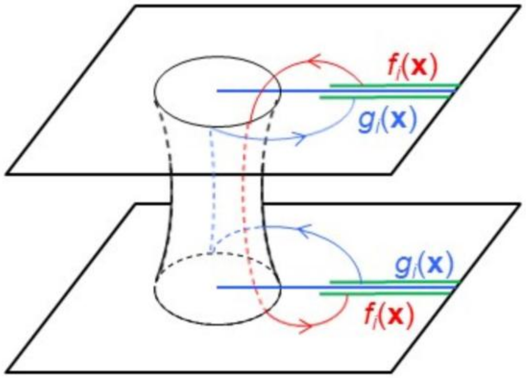
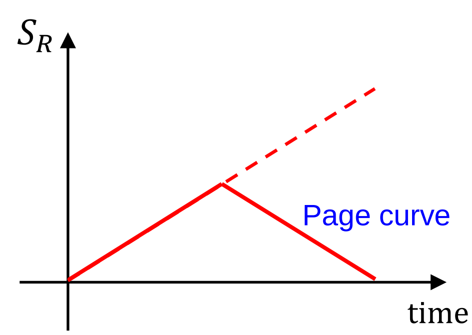


+



replica wormhole (nonperturbative effect)



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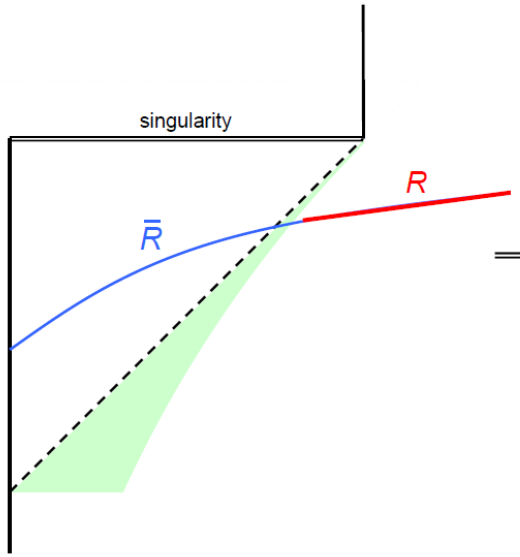
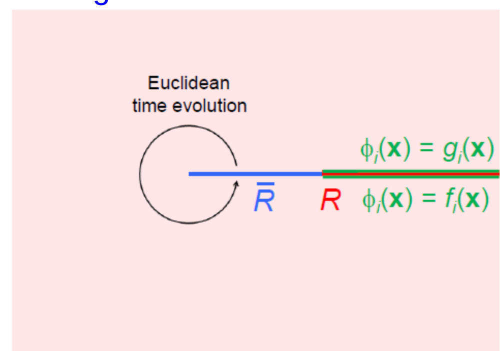


path integral



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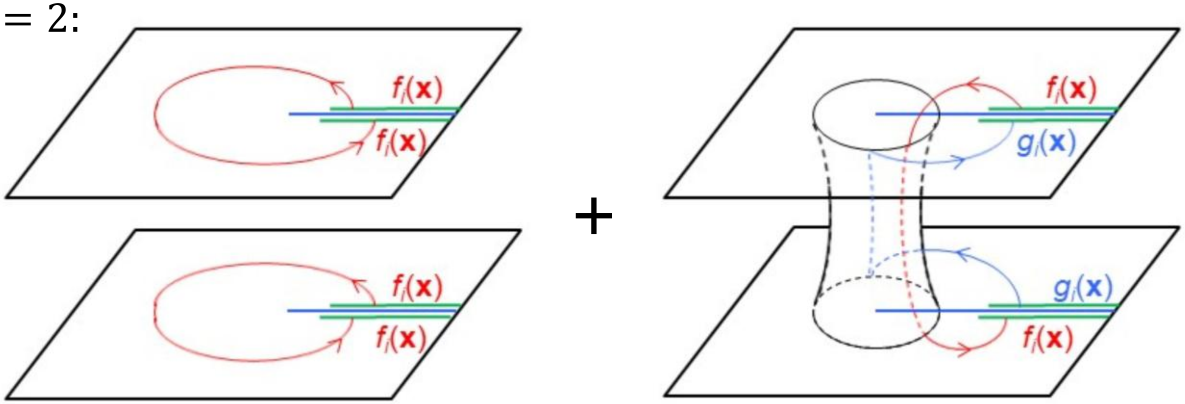

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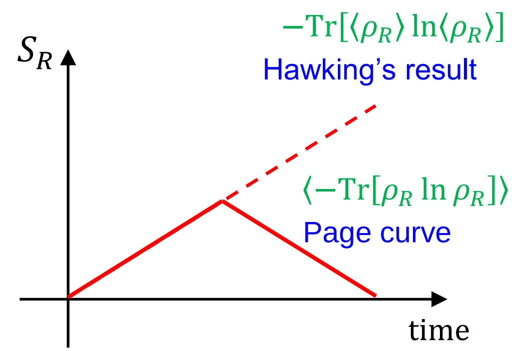
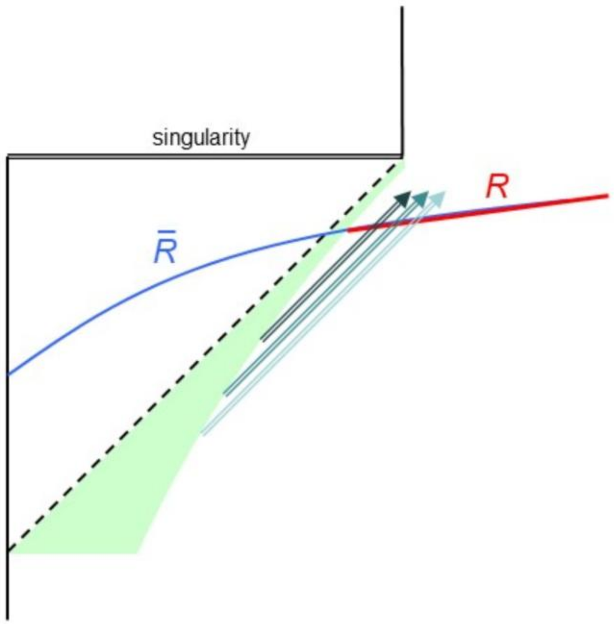


Redundancy in the Hawking process



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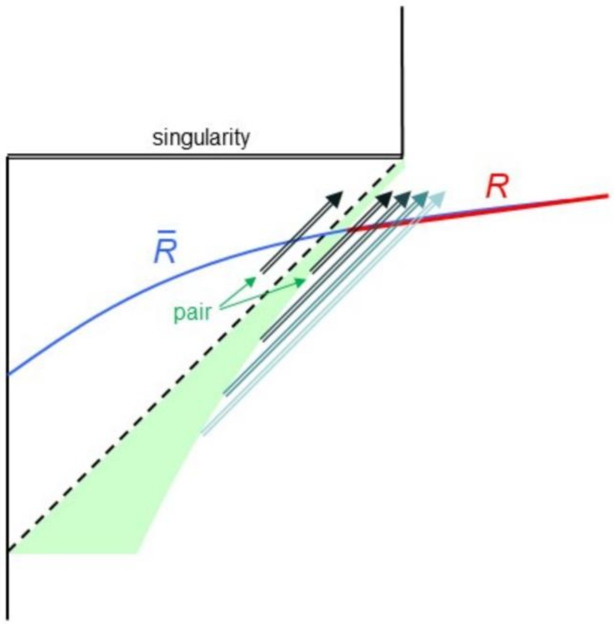

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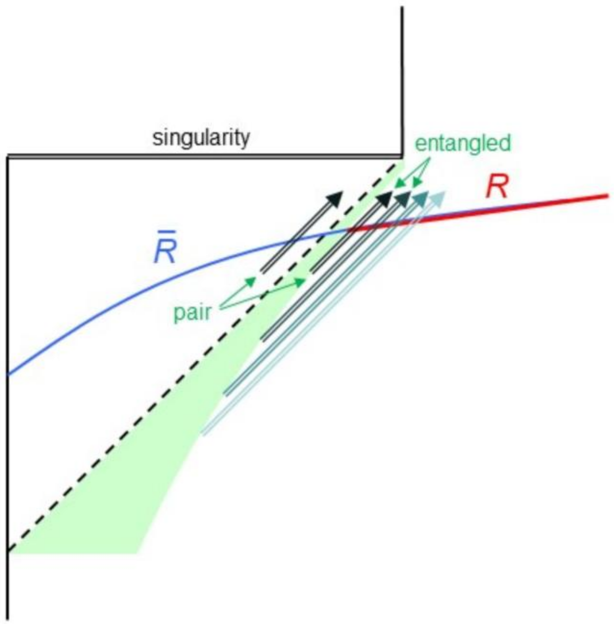

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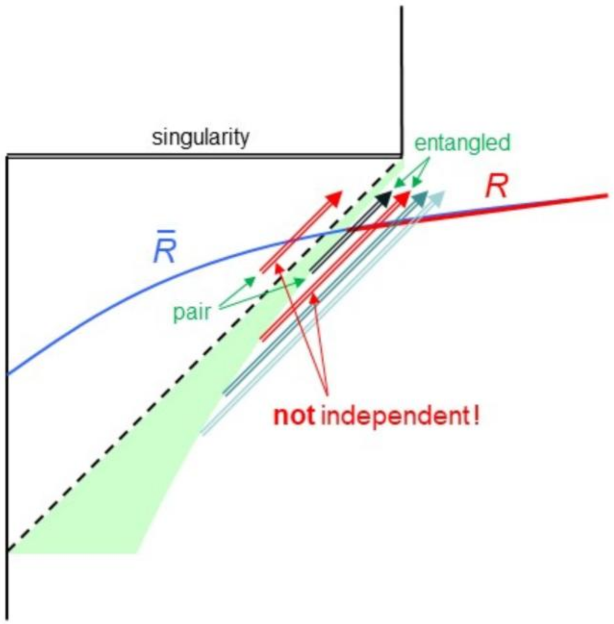
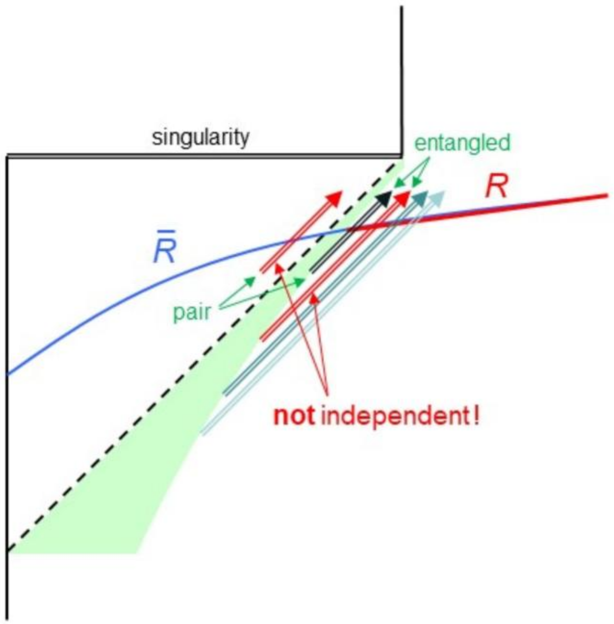


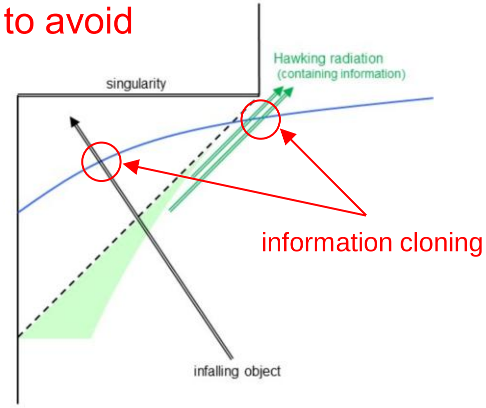
→ Hawking radiation emitted earlier is
not independent of the interior d.o.f.s!

…; Maldacena, Susskind ('13); …

Redundancy in the Hawking process



- needed to avoid



- consistent because of causality

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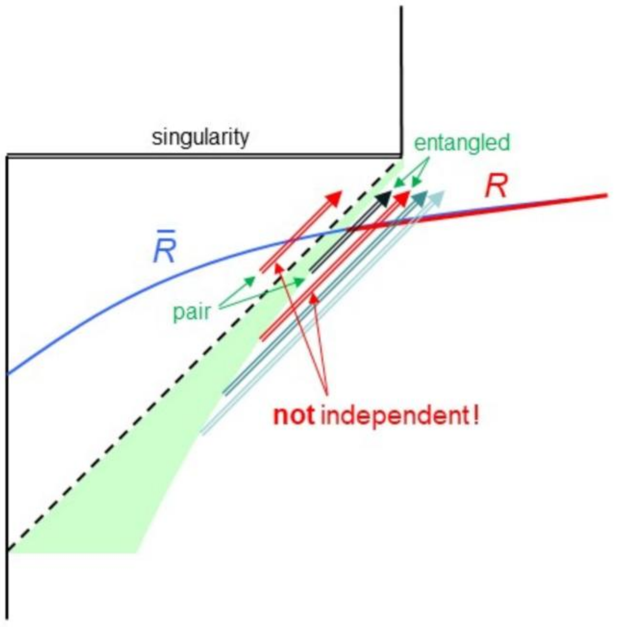

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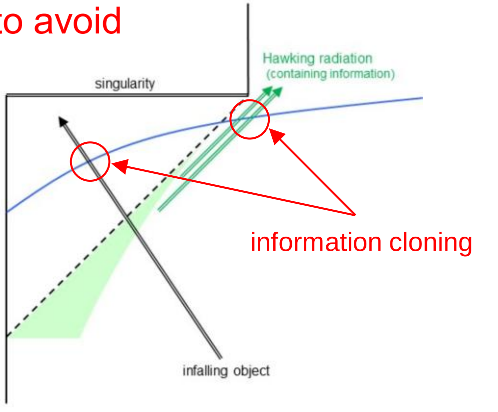


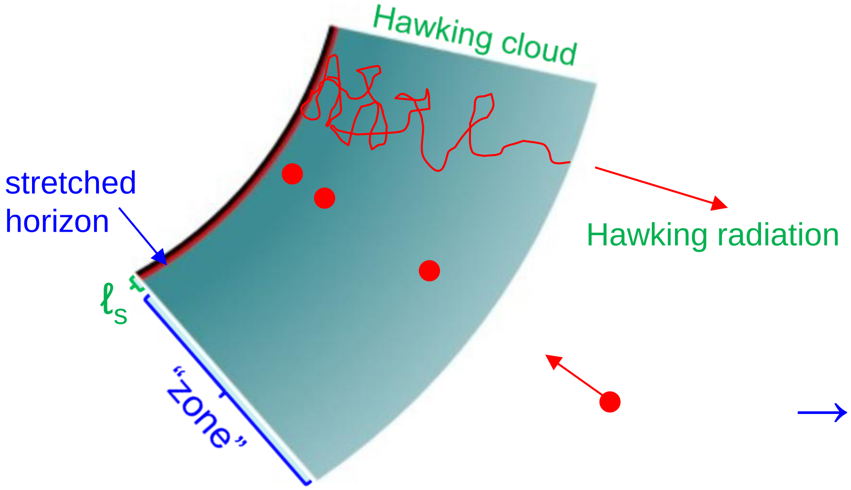
- consistent because of causality

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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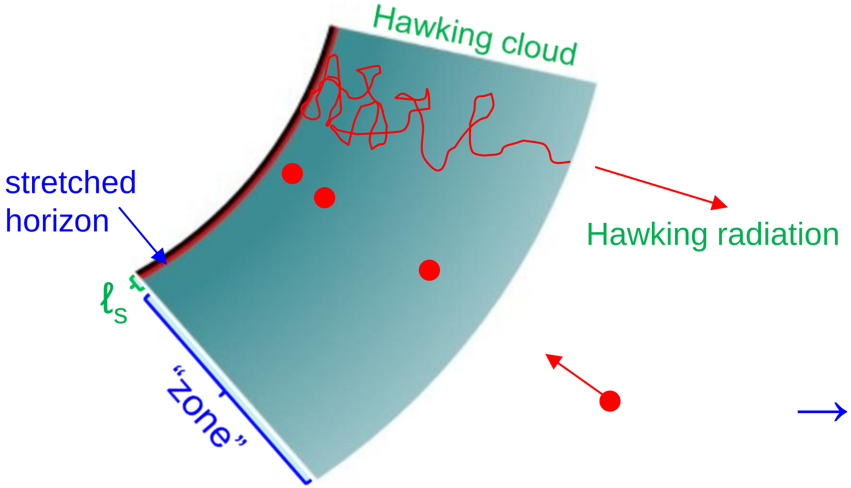

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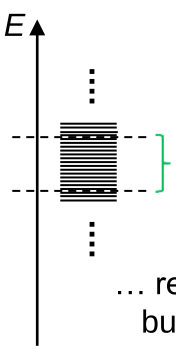
Key features Y.N. (’19, 20)

— defining characteristics of BHs

(I) Exponentially dense spectrum



$e^{S_{\rm BH}} \rightarrow \Delta E \sim e^{-S_{\rm BH}}$

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

(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)

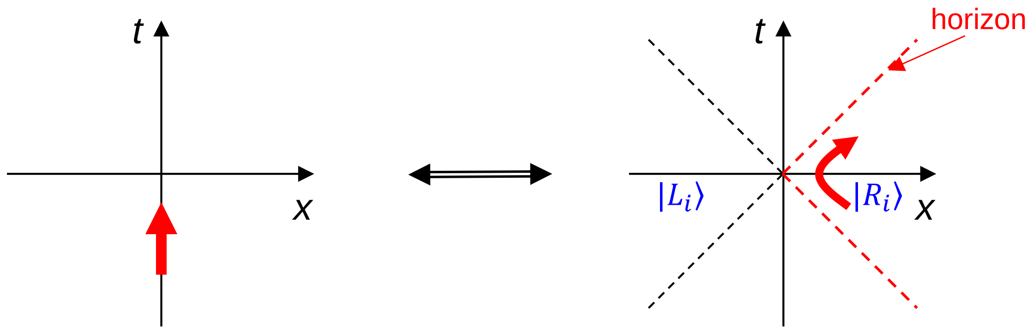
(*e.g.* no global symmetry)

→ “ultimate” thermalization

… **universal** across all low energy species

Emergence of the interior

Minkowski   Rindler



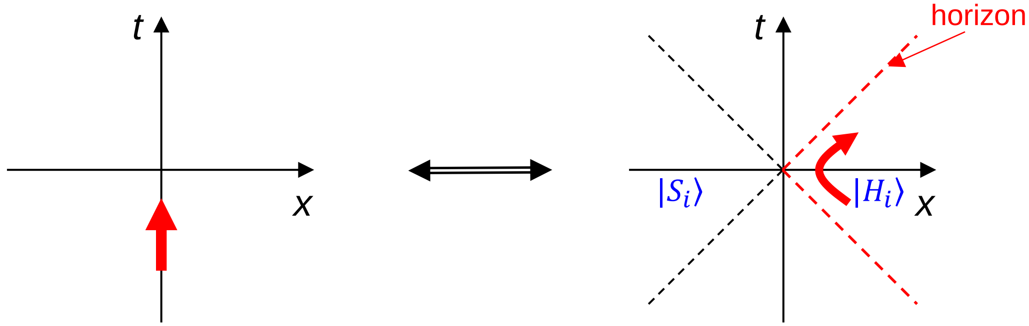
$$|0\rangle \qquad \propto \sum_i e^{-\frac{E_i}{2T}} |R_i\rangle |L_i\rangle$$

… thermal state

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

Emergence of the interior

Minkowski | Rindler



$|0\rangle$ $\quad\longleftrightarrow\quad$ $\propto \sum_i e^{-\frac{E_i}{2T}} |R_i\rangle |L_i\rangle$ … thermal state

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

Near empty
Interior spacetime

(An object thrown "sees" interior spacetime)

frame change

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

Hard mode states → $|H_i\rangle$

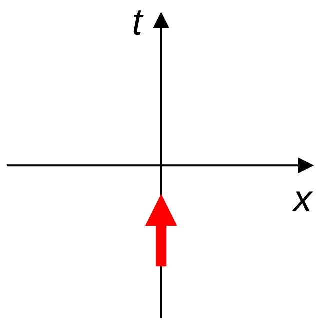
Soft mode states → $|S_i\rangle$ (representing their collective excitations)

$|S_i\rangle$ … play the role of the mirror partners

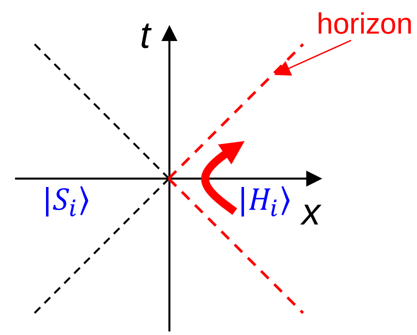
… universally thermal

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

Hard mode states

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

… play the role of the mirror partners

Soft mode states
(representing their collective excitations)

… universally thermal

string dynamics

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

At late times, the BH is entangled with radiation

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

Hard mode states ($|H_i\rangle$)

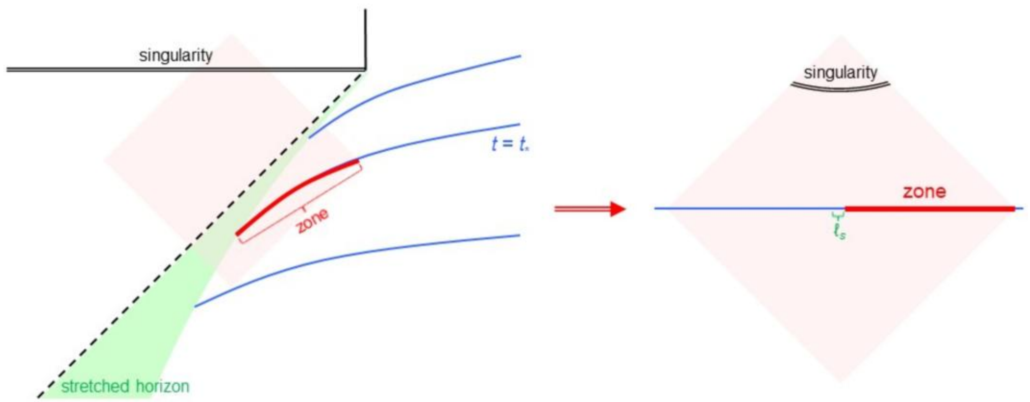
… play the role of the mirror partners ($|(S+R)_i\rangle$)

Soft and far (radiation) mode states

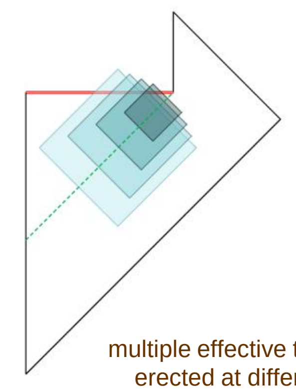
(representing collective excitations of these modes)

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

Effective theory of the interior



… describe only a limited spacetime region



multiple effective theories
erected at different times

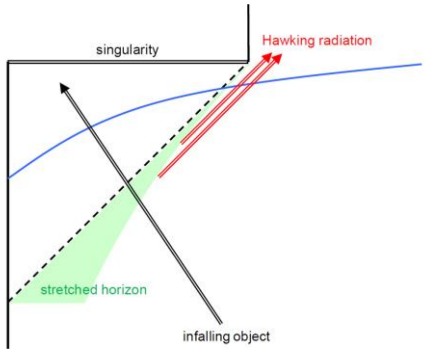
Distant description
(manifestly **unitary**)

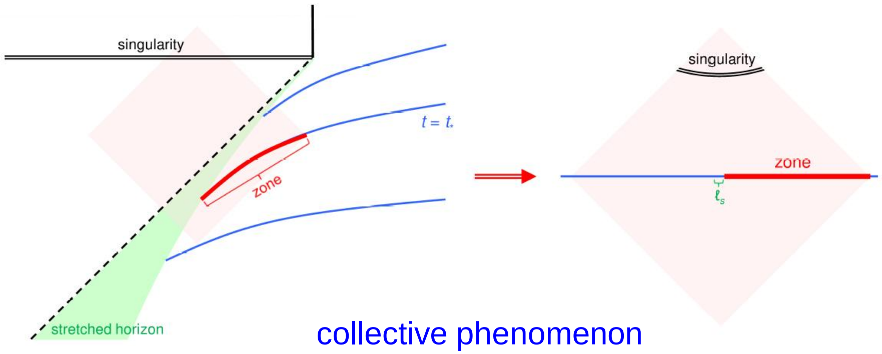
Collective phenomena

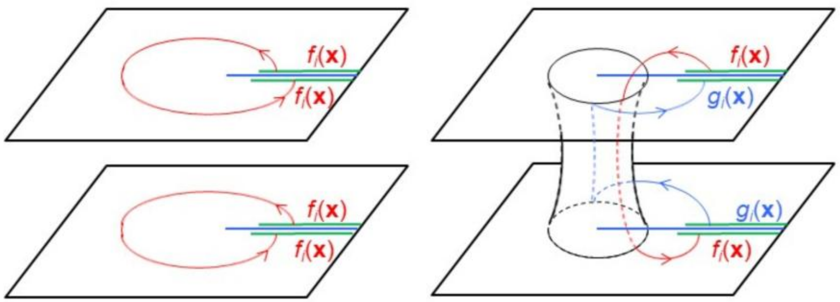
Interior spacetime
(effective emergence)

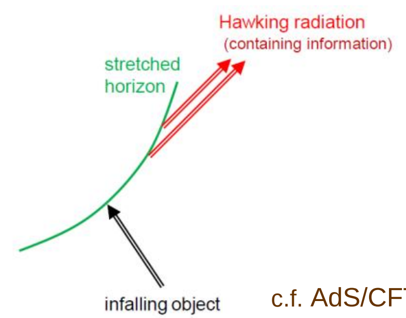
Structure of Quantum Gravity

	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 $\langle \Psi_1 \vert \Psi_2 \rangle \sim e^{-S_{\rm BH}/2}$ $\rightarrow$ $e^{S_{\rm BH}}$ states (+ null states)	Hilbert space of dimension $e^{S_{\rm BH}}$ can host $e^{e^{S_{\rm BH}}}$ approximately orthogonal states.





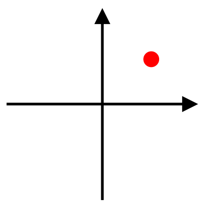




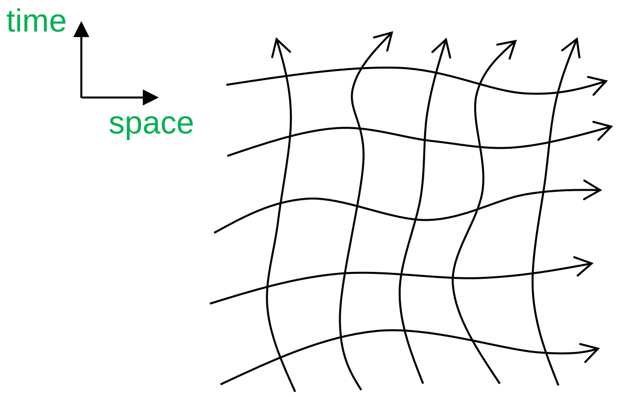
Langhoff, Y.N. ('20); Chakravarty ('20)

Redundancies of the description

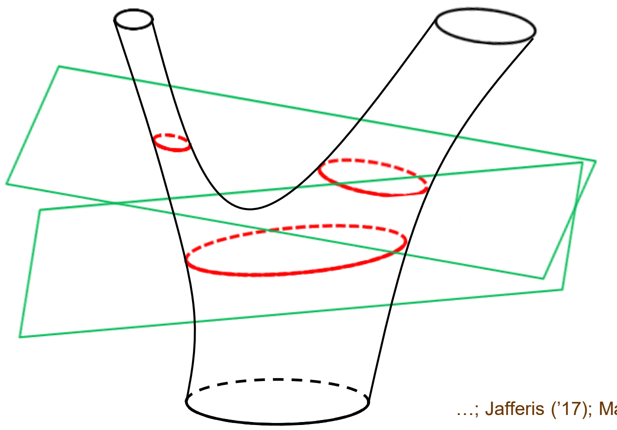
- General covariance (perturbative)



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



- 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

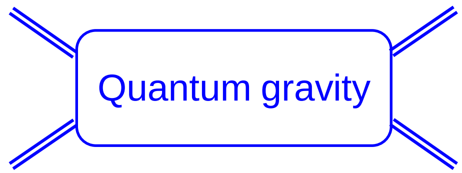
⇓

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]

Real Summary

Happy Birthday, Hitoshi!