Status and recent advancements in the black-to-white hole transition scenario

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International Loop Quantum Gravity Seminar

17 October 2023

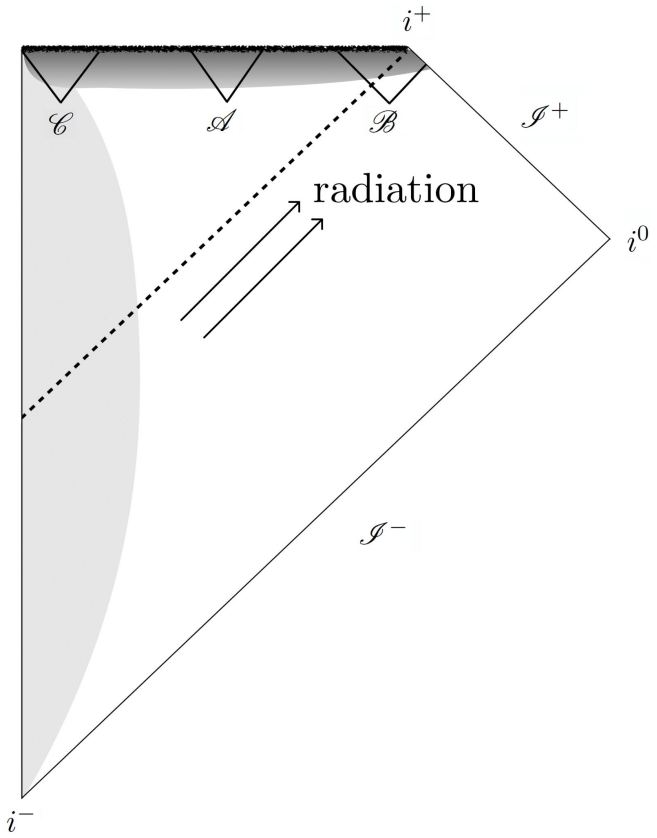
Outline

1. What is the black-to-white hole transition?

2. Construction of the black-to-white hole spacetime

3. Quantum physics of the horizon

Quantum region of a black hole spacetime

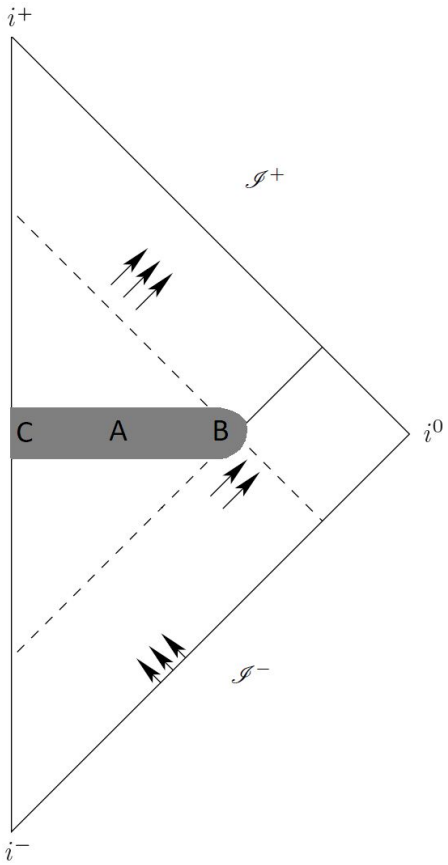


Quantum gravitational effects cannot be neglected in:

- Region A: large curvature near classical singularity
- Region B: physics of the horizon at the end of the evaporation
- Region C: quantum gravity regime of the collapsing matter

Ashtekar-Bojowald paradigm

Ashtekar and Bojowald (2005)



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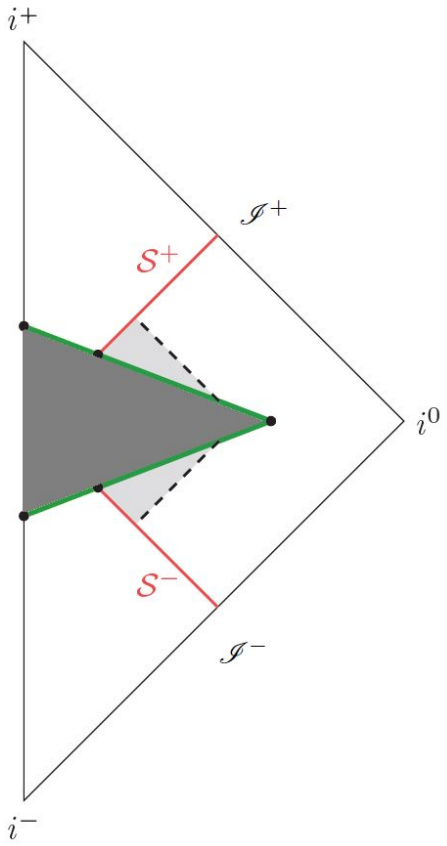
What is the black-to-white hole transition?

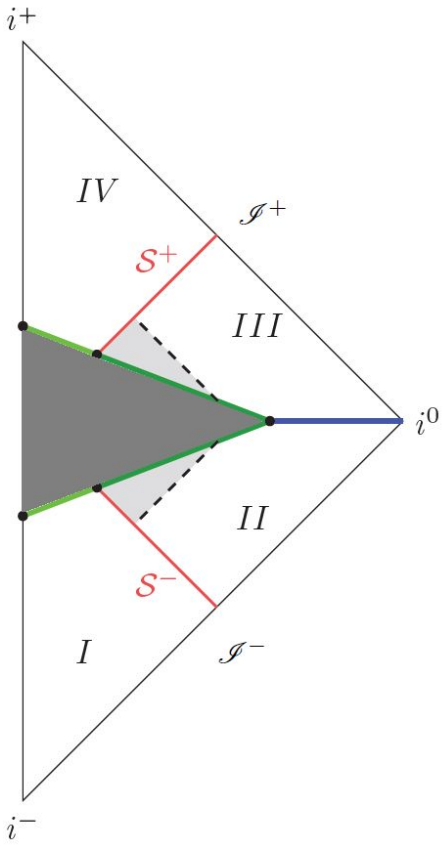
Rovelli and Vidotto (2014)
Haggard and Rovelli (2015)

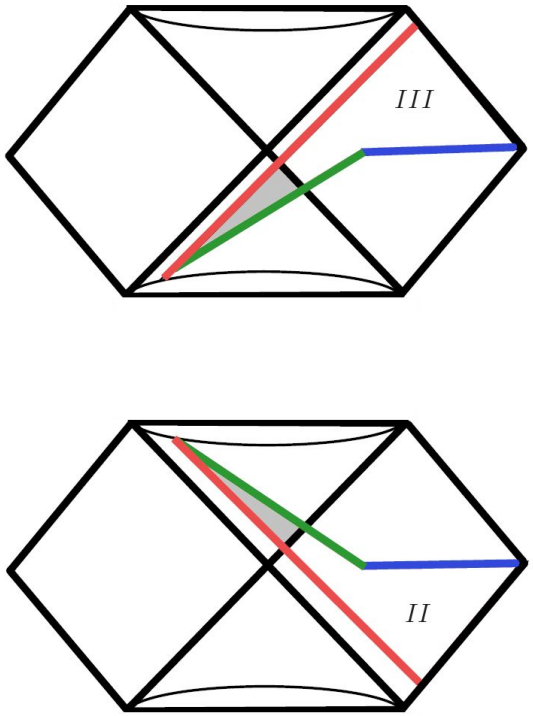


- Unique asymptotically flat region
- The quantum region extends beyond the horizon
- Einstein equations exactly satisfied everywhere

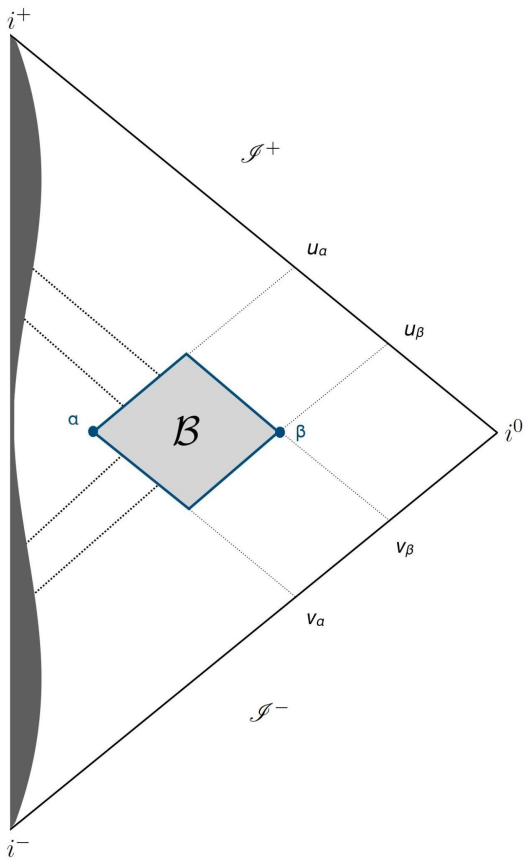
What is the black-to-white hole transition?

Haggard and Rovelli (2015)
Christodoulou and D'Ambrosio (2018)





State of the art



- Effective metric for the black-to-white hole transition including non-singular black hole interior

  [Han, Rovelli, FS (2023)]

- Spinfoam transition amplitude for the horizon transition in region B

  [Christodoulou et al. (2022)]
  [FS, Rovelli, Martin-Dussaud (2022)]

- Analytical and numerical investigations of the spinfoam transition amplitude for the Haggard-Rovelli black-to-white spacetime

  [Christodoulou, D'Ambrosio, Theofilis (2023)]
  [Frisoni (2023)]

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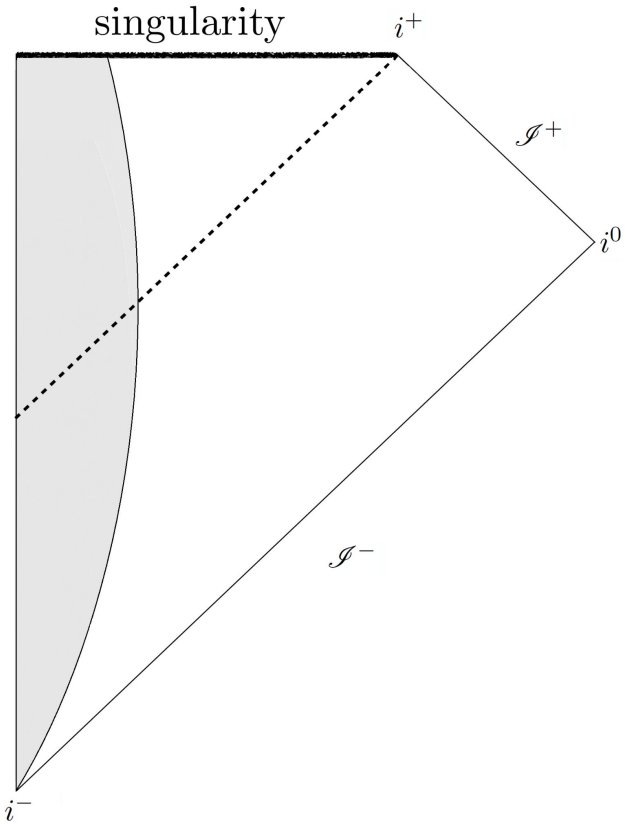
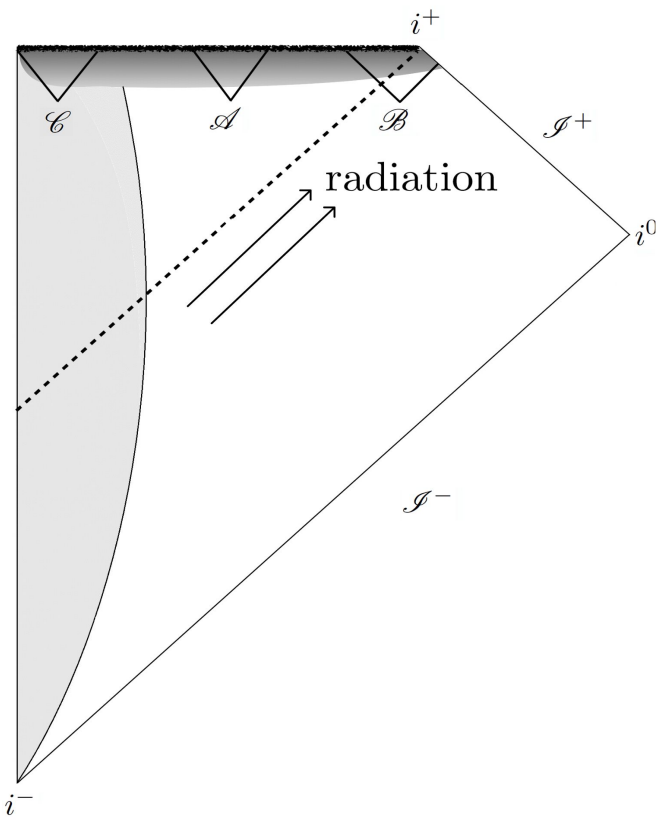
Oppenheimer–Snyder collapse



- The star is modeled as homogeneous and isotropic dust

Oppenheimer–Snyder collapse



- The star is modeled as homogeneous and isotropic dust
- Quantum gravitational effects cannot be neglected in the dark gray area
- The physics of regions A and C has been extensively studied

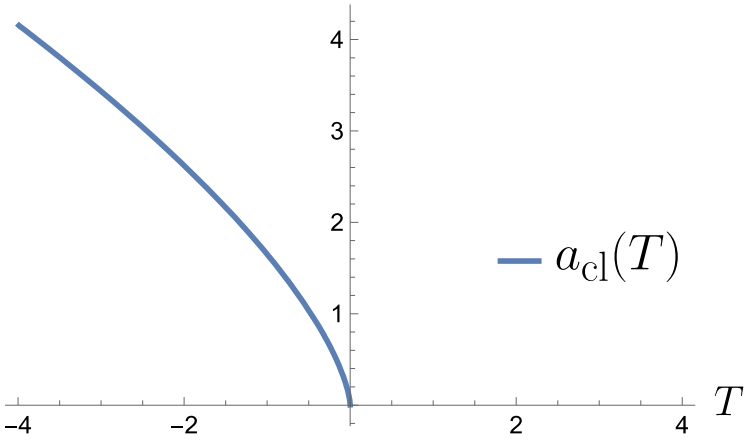
  [Ashtekar, Olmedo, Singh (2023)]

Interior of the star (region C)

Classical case

$$\mathrm{d}s^2 = -\,\mathrm{d}T^2 + a^2(T)\left(\mathrm{d}R^2 + R^2\,\mathrm{d}\Omega^2\right)$$

$$\frac{\dot{a}^2}{a^2} = \frac{8\pi}{3}\rho \quad \Rightarrow \quad a(T) = \left(\frac{9mT^2}{2R_{\mathrm{star}}^3}\right)^{1/3}$$



Quantum case

Planck units $(c = G = \hbar = 1)$

Interior of the star (region C)

Kelly, Santacruz, Wilson-Ewing (2020)

Classical case

$$\mathrm{d}s^2 = -\,\mathrm{d}T^2 + a^2(T)\left(\mathrm{d}R^2 + R^2\,\mathrm{d}\Omega^2\right)$$

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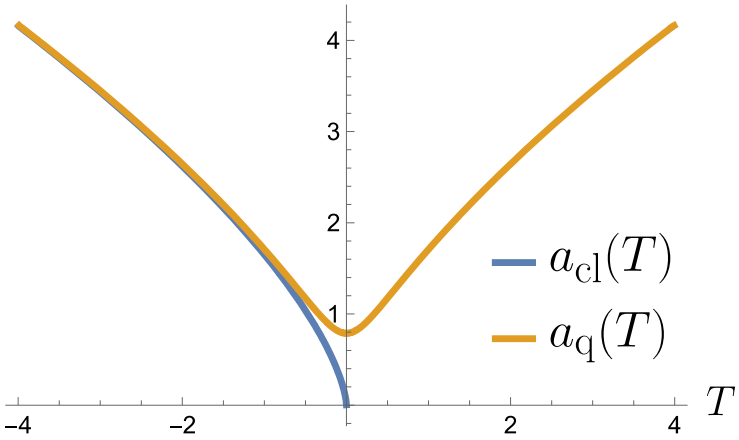


Quantum case

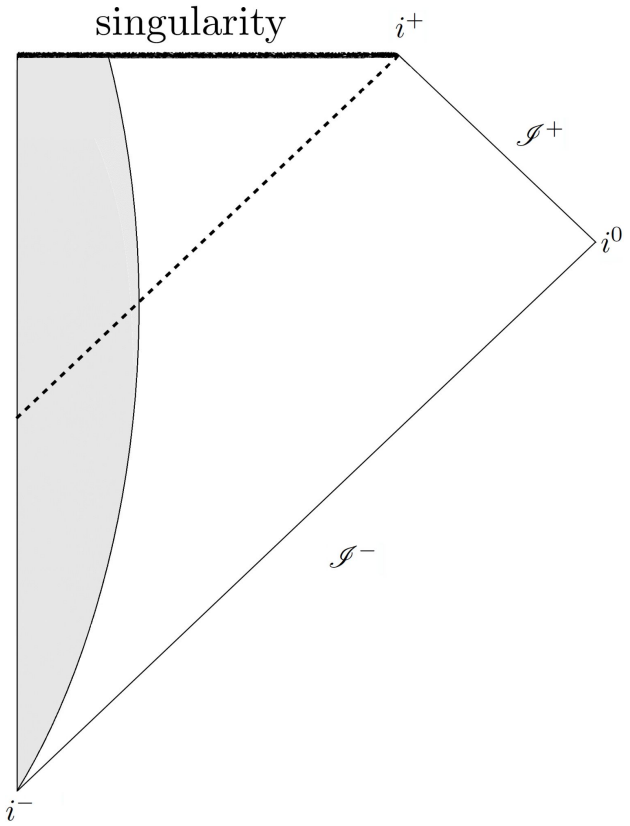
$$\frac{\dot{a}^2}{a^2} = \frac{8\pi}{3}\rho\left(1 - \frac{\rho}{\rho_c}\right)$$

$$A = \frac{3}{2\pi\rho_c}$$

$$a(T) = \left(\frac{9mT^2 + Am}{2R_{\mathrm{star}}^3}\right)^{1/3}$$

Planck units ($c = G = \hbar = 1$)

Exterior of the star (region A)



Classical case

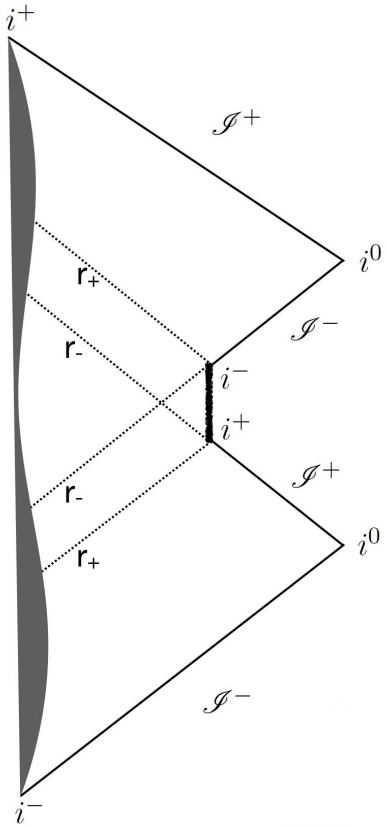
$$\mathrm{d}s^2 = -f(r)\,\mathrm{d}t^2 + f^{-1}(r)\,\mathrm{d}r^2 + r^2\,\mathrm{d}\Omega^2$$

$$f(r) = 1 - \frac{2m}{r}$$

$$r_{\mathrm{h}} = 2m$$

Beware: the isometry of the black hole interior with the Kantowski-Sachs spacetime cannot be used here!

Exterior of the star (region A)



$$\left(A = \frac{3}{2\pi\rho_c} \ll m^2\right)$$

Quantum case

$$\mathrm{d}s^2 = -f(r)\,\mathrm{d}t^2 + f^{-1}(r)\,\mathrm{d}r^2 + r^2\,\mathrm{d}\Omega^2$$

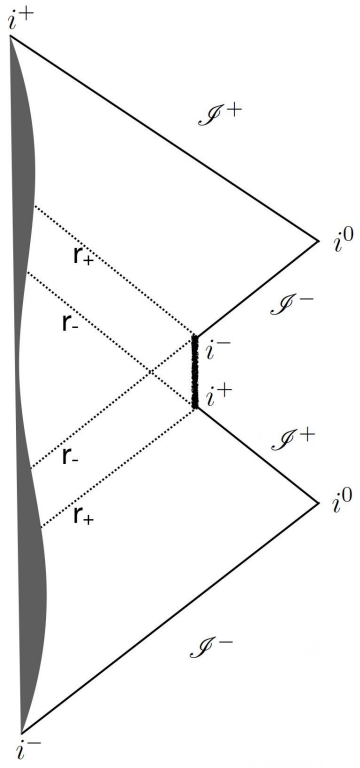
$$f(r) = 1 - \frac{2m}{r} + \frac{Am^2}{r^4}$$

$$r_+ = 2m + O(A/m)$$

$$r_- = \sqrt[3]{Am/2} + O\left(A^{2/3}/m^{1/3}\right)$$

Kelly, Santacruz, Wilson-Ewing (2020)
Lewandowski, Ma, Yang, Zhang (2023)
Bobula and Pawlowski (2023)
Fazzini, Rovelli, FS (2023)

Physics of the horizon (region B)



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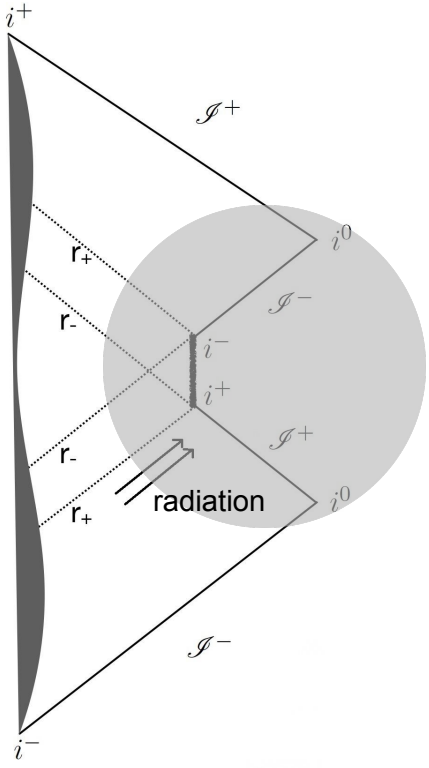
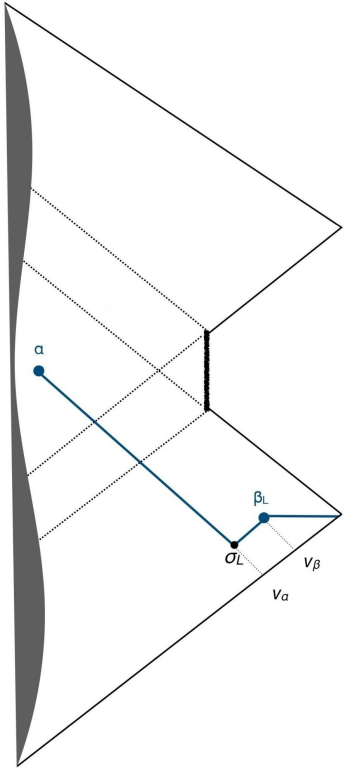


Physics of the horizon (region B)

Han, Rovelli, FS (2023)



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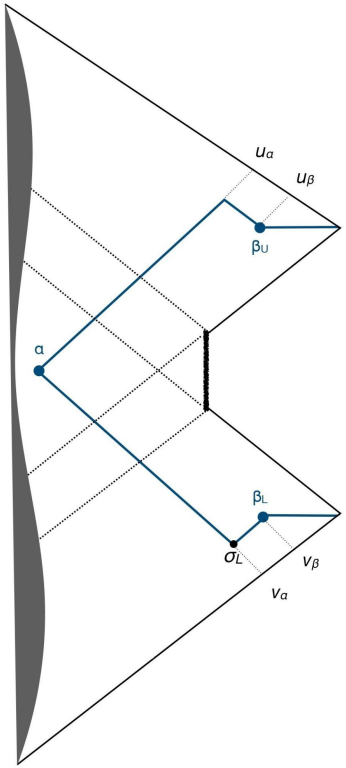

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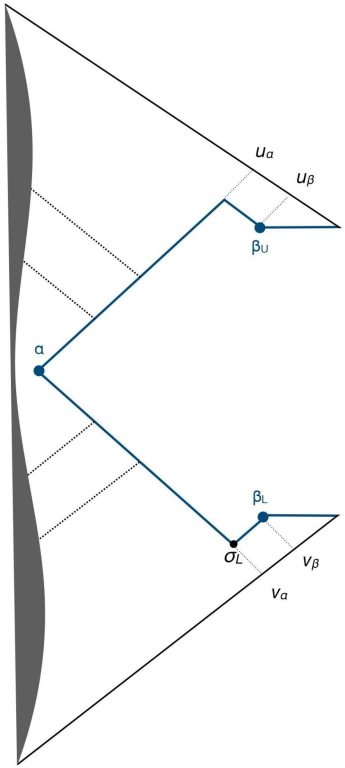

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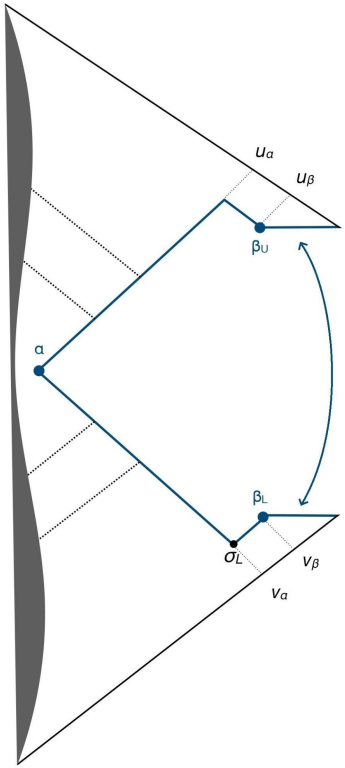

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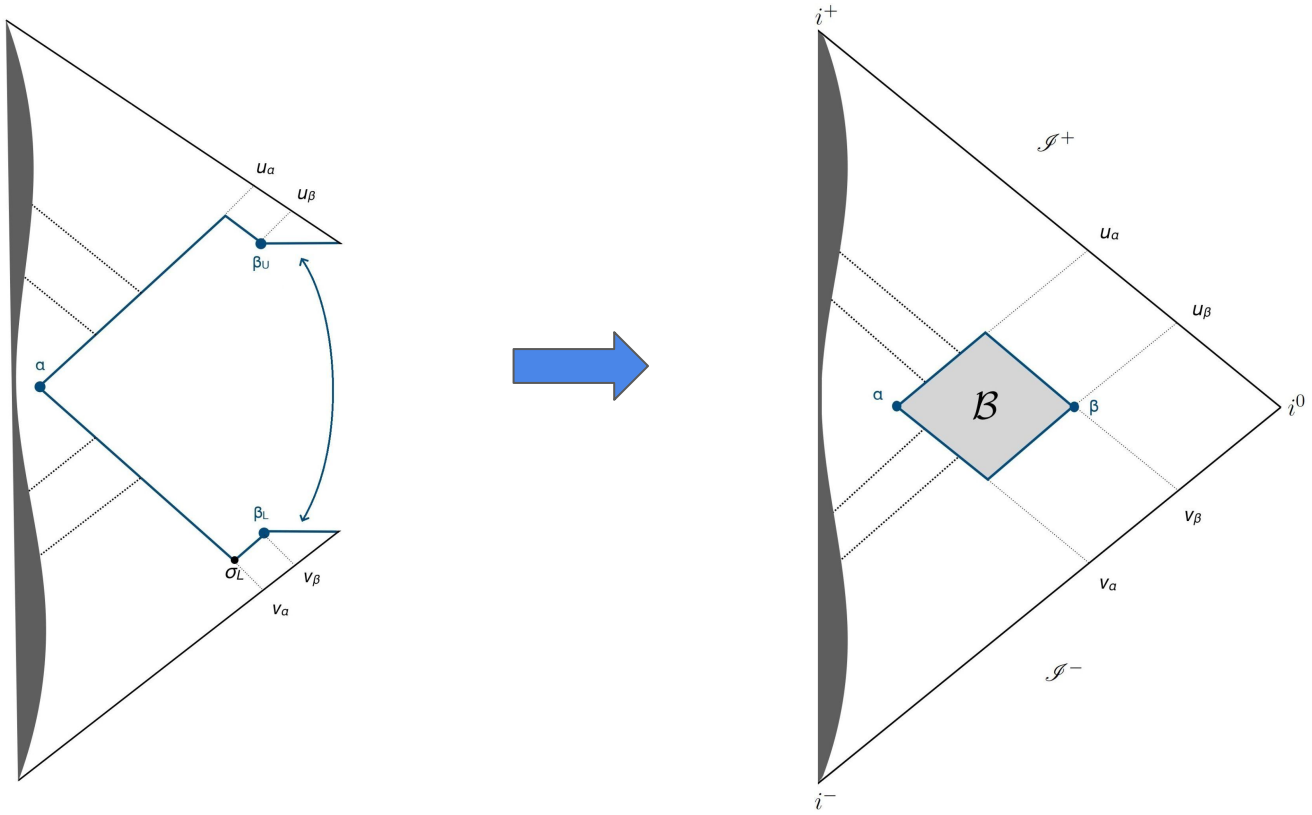
Han, Rovelli, FS (2023)



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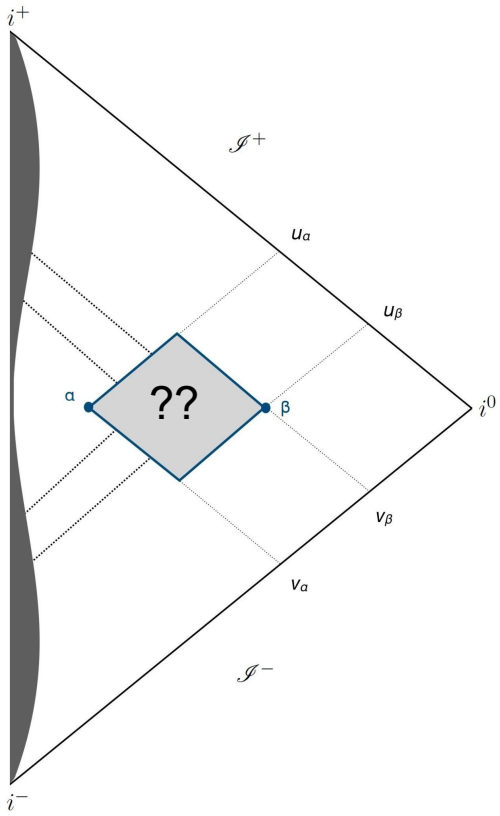
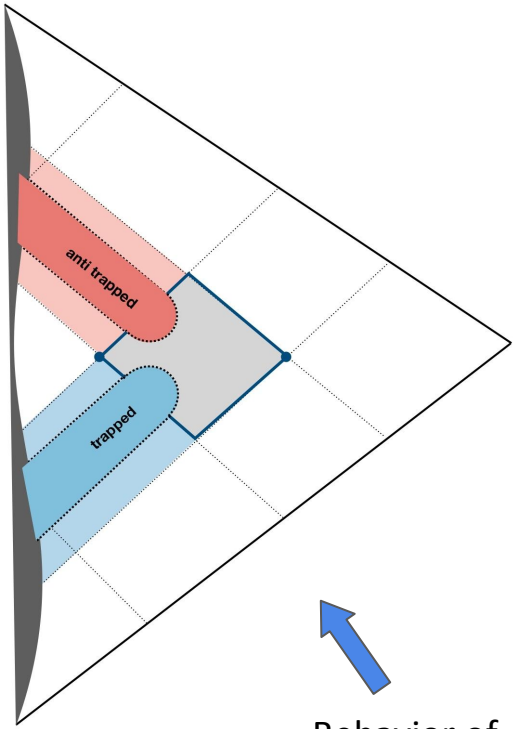
What happens inside region B?



What do we expect to find inside region B?

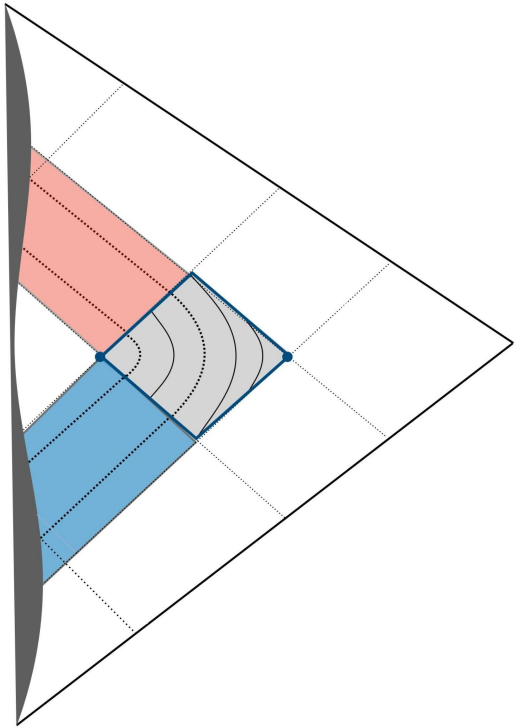
- Effective metric whose dynamics can be studied perturbatively
- Deep quantum geometry where classical concept of metric lose any meaning

Physics of the horizons



- There is a natural extension of the black-to-white metric inside of region B
  [Han, Rovelli, FS (2023)]

- It provides a proof of concept for the existence of an effective metric in region B

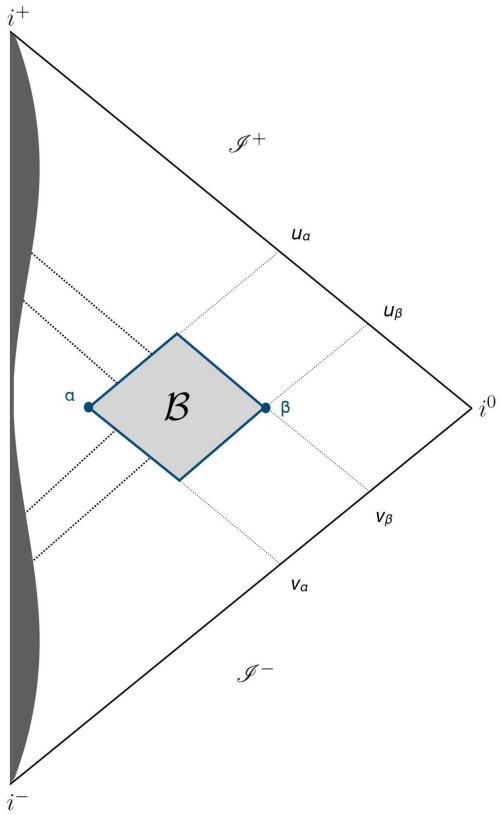


Behavior of trapped regions

Behavior of r=const. surfaces

Spin foam framework

Han, Rovelli, FS (2023)



- The black-to-white hole geometry depends on 4 parameters: $(m, \mathcal{T}, v_\alpha, v_\beta)$

Spin foam framework

Christodoulou, D'Ambrosio, Martin-Dussaud, Rovelli, FS (2022)
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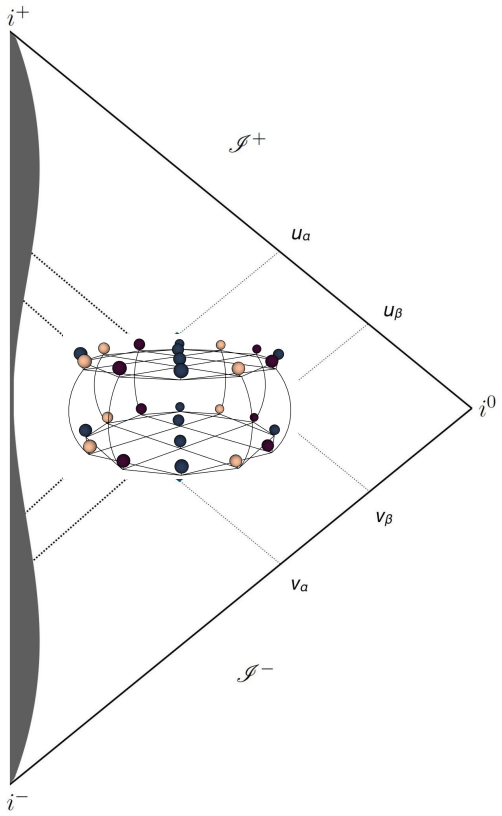

- The black-to-white hole geometry depends on 4 parameters: $(m, \mathcal{T}, v_\alpha, v_\beta)$
- A discretization Γ of the boundary can be defined starting from the 3d induced geometry and a Hilbert space $\mathcal{H}_\Gamma$ assigned to it
- A coherent state $\Psi(m, \mathcal{T}, v_\alpha, v_\beta)$ peaked on the boundary geometry can be defined in $\mathcal{H}_\Gamma$

Spin foam framework

Christodoulou, D'Ambrosio, Martin-Dussaud, Rovelli, FS (2022)
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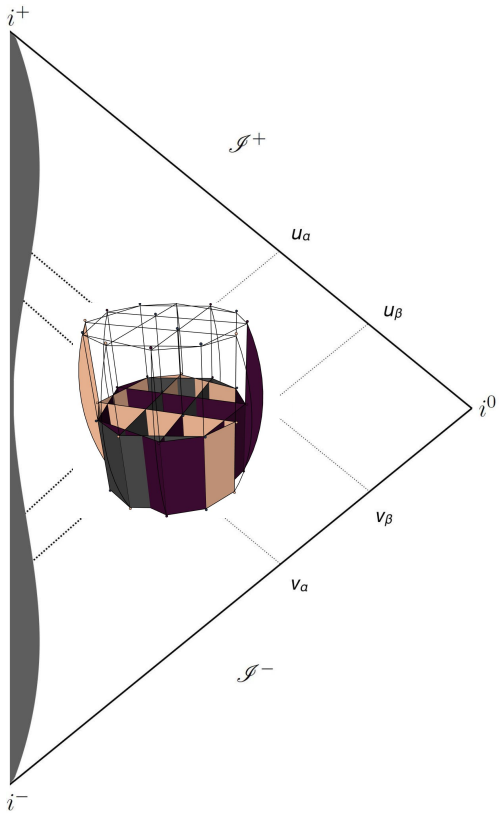

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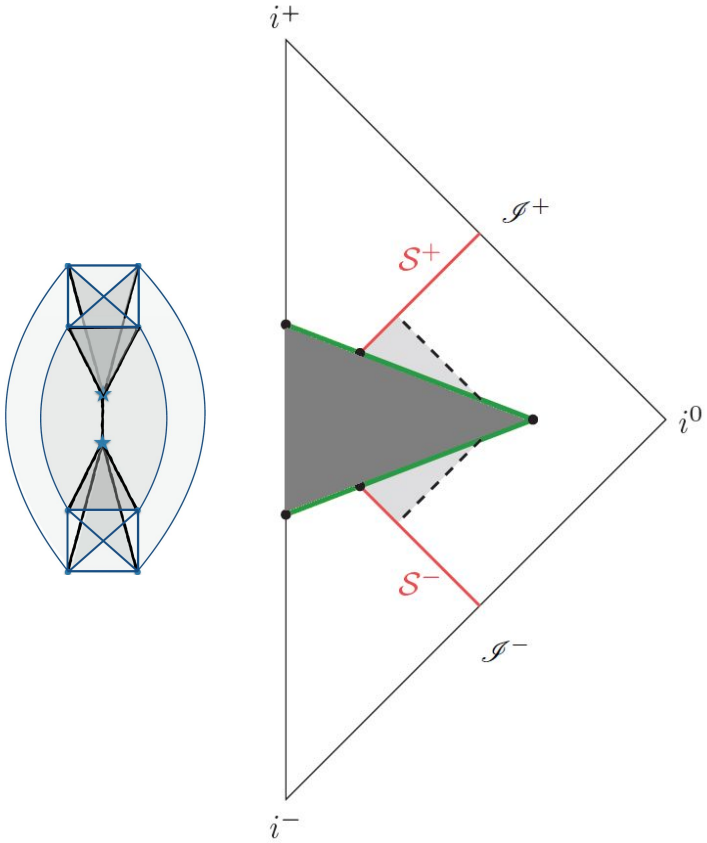
- A discretization Γ of the boundary can be defined starting from the 3d induced geometry and a Hilbert space $\mathcal{H}_\Gamma$ assigned to it
- A coherent state $\Psi(m, \mathcal{T}, v_\alpha, v_\beta)$ peaked on the boundary geometry can be defined in $\mathcal{H}_\Gamma$
- A spinfoam describing the quantum transition can be constructed
- The EPRL-KKL transition amplitude $W(m, \mathcal{T}, v_\alpha, v_\beta)$ can be computed

Investigations of the transition amplitude



- Performed on original Haggard-Rovelli black-to-white hole spacetime

  [Haggard and Rovelli (2015)]
  [Christodoulou, Rovelli, Speziale, Vilensky (2016)]

- Analytical investigation of the EPRL transition amplitude gives

$$p \sim e^{-\alpha\, m^2/m_{\rm pl}^2}\,, \qquad \tau \sim m\, e^{\alpha\, m^2/m_{\rm pl}^2}$$

  [Christodoulou and D'Ambrosio (2018)]
  [Christodoulou, D'Ambrosio, Theofilis (2023)]

- These results have been recently confirmed numerically

  [Frisoni (2023)]

Conclusions and outlook

- The black-to-white hole transition is a natural scenario for the end of the evaporation of a black hole
- A concrete effective metric describing the black-to-white hole spacetime and its non-singular interior has been constructed
- The spinfoam formalism is able to describe the quantum transition and give estimates for the values of the free parameters of the model

This should be seen as a starting point for more refined analyses

Dynamics of horizons

Improvement of analytical and numerical estimates

Addition of angular momentum

Better understand analogy with non-relativistic tunneling