LQG suggest the existence of

a quasi-stable particle with mass ~ 20μg

which can interact gravitationally only

carlo rovelli, EDSU Tools 2024

1) LQG suggest the existence of a quasi-stable particle with mass ~ 20μg

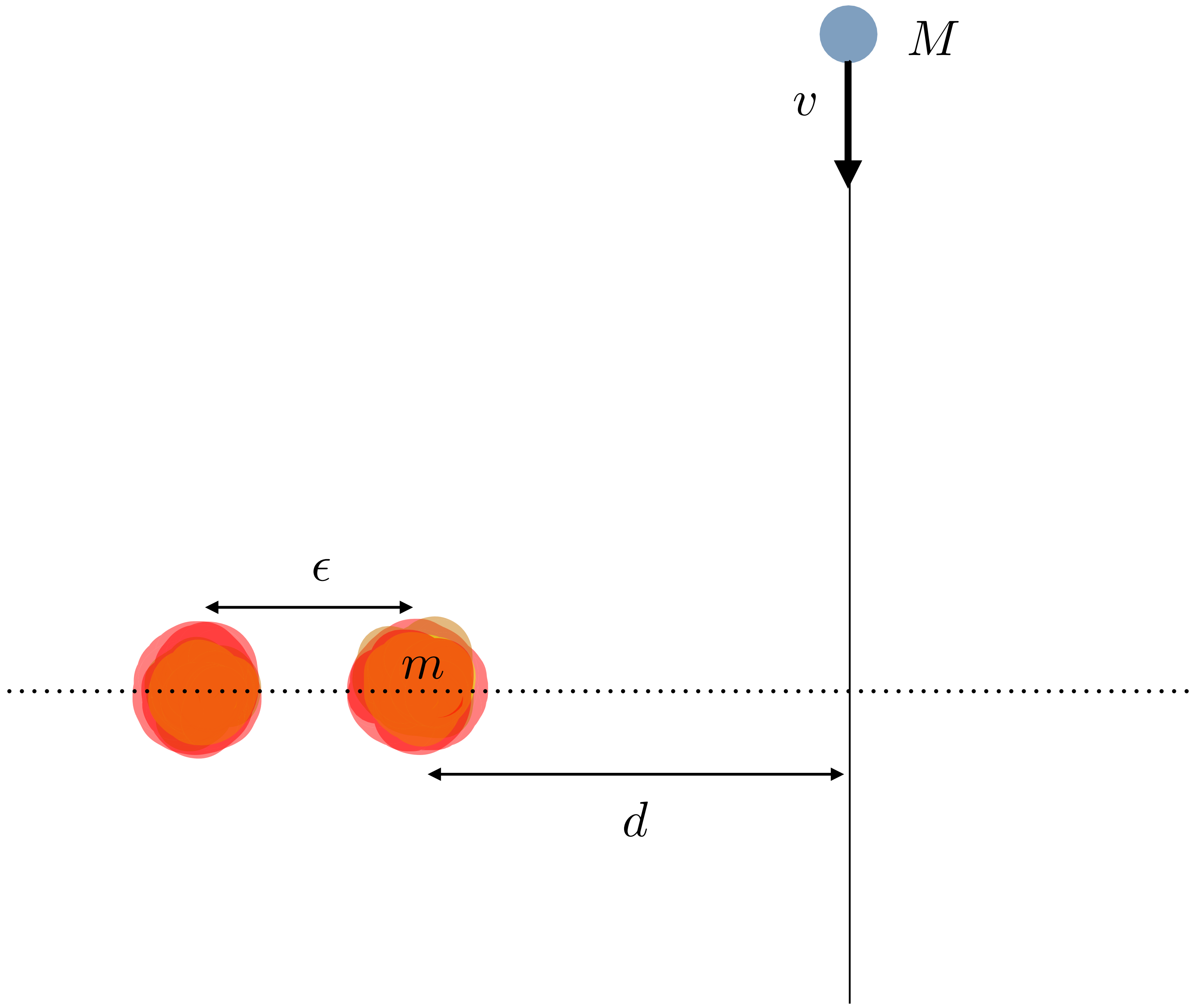
2) This particle can be detected

3) It is a natural candidate for Dark Matter

4) It can be generated by the complete evaporation of an old black hole

$$m_{Plank} = \sqrt{\frac{\hbar c}{G}} \sim 22 \mu g$$

Direct detection. In Principle

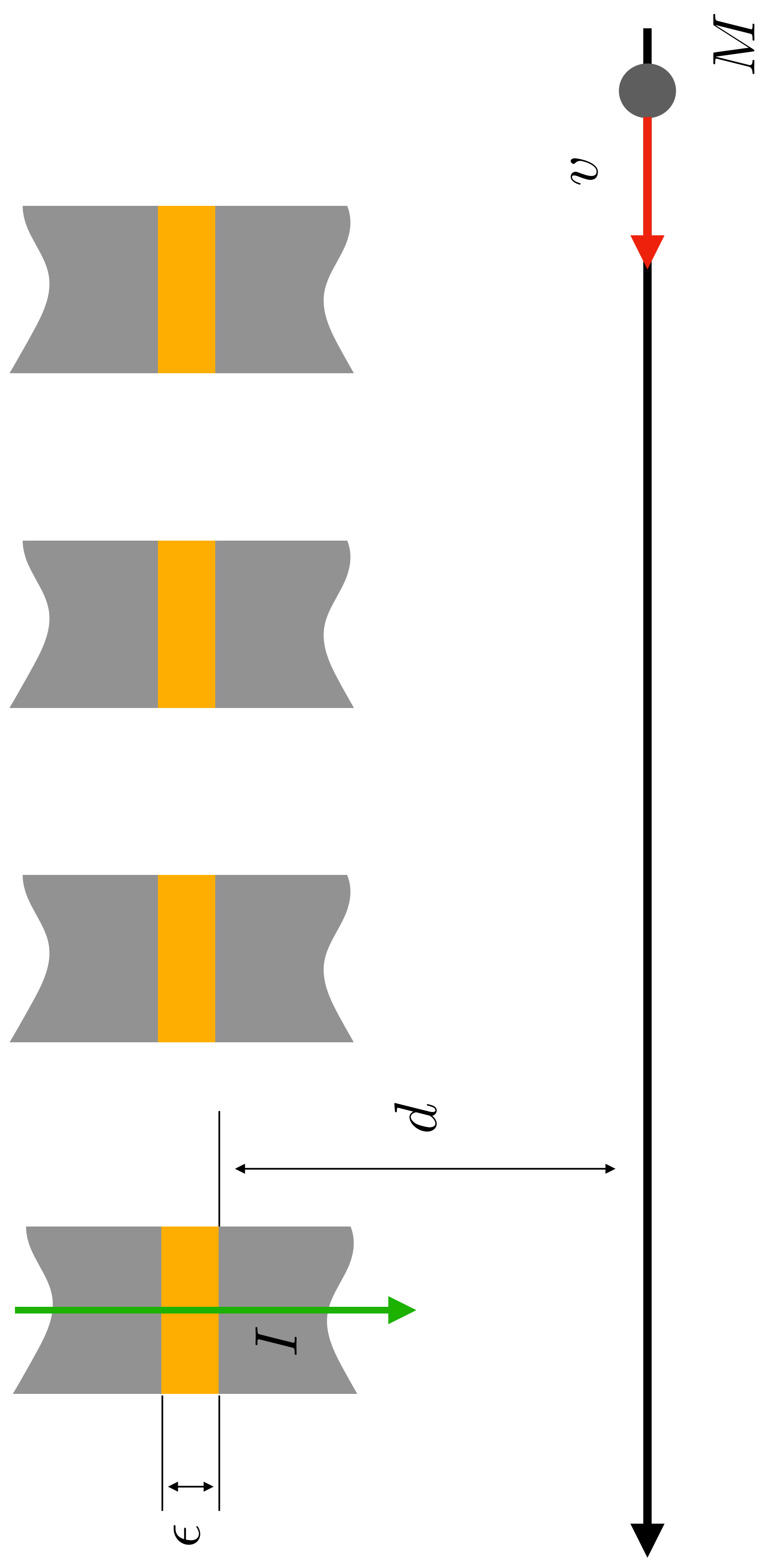


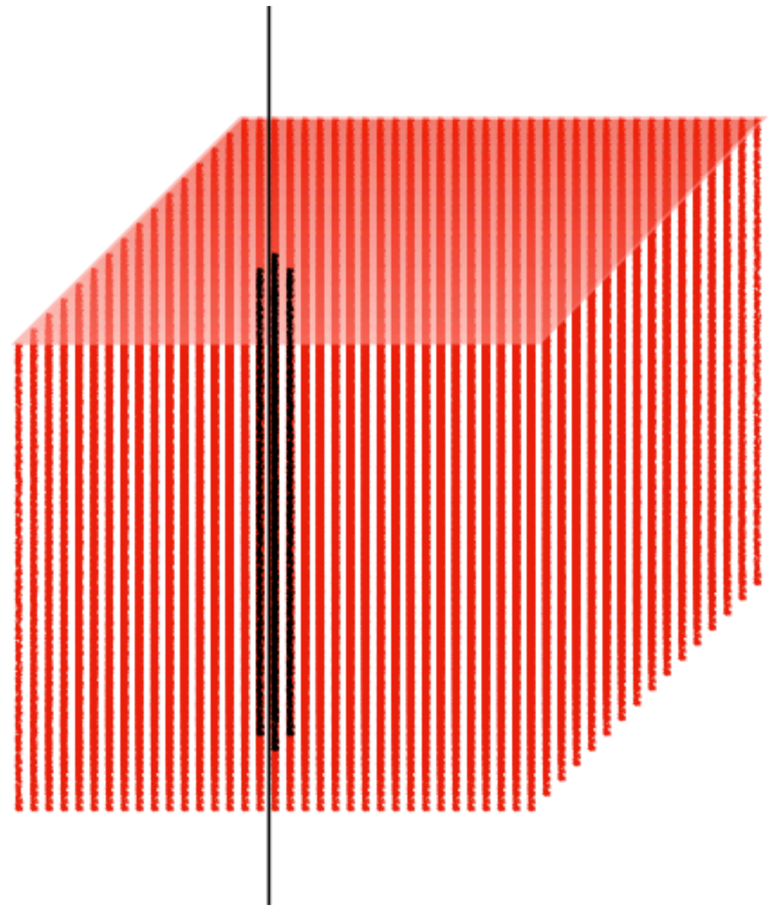
A Perez, M Christodoulou, CR,

Detecting Gravitationally Interacting Dark Matter with Quantum Interference,

2024

Direct detection. In Practice: Piles of Josephson Junctions





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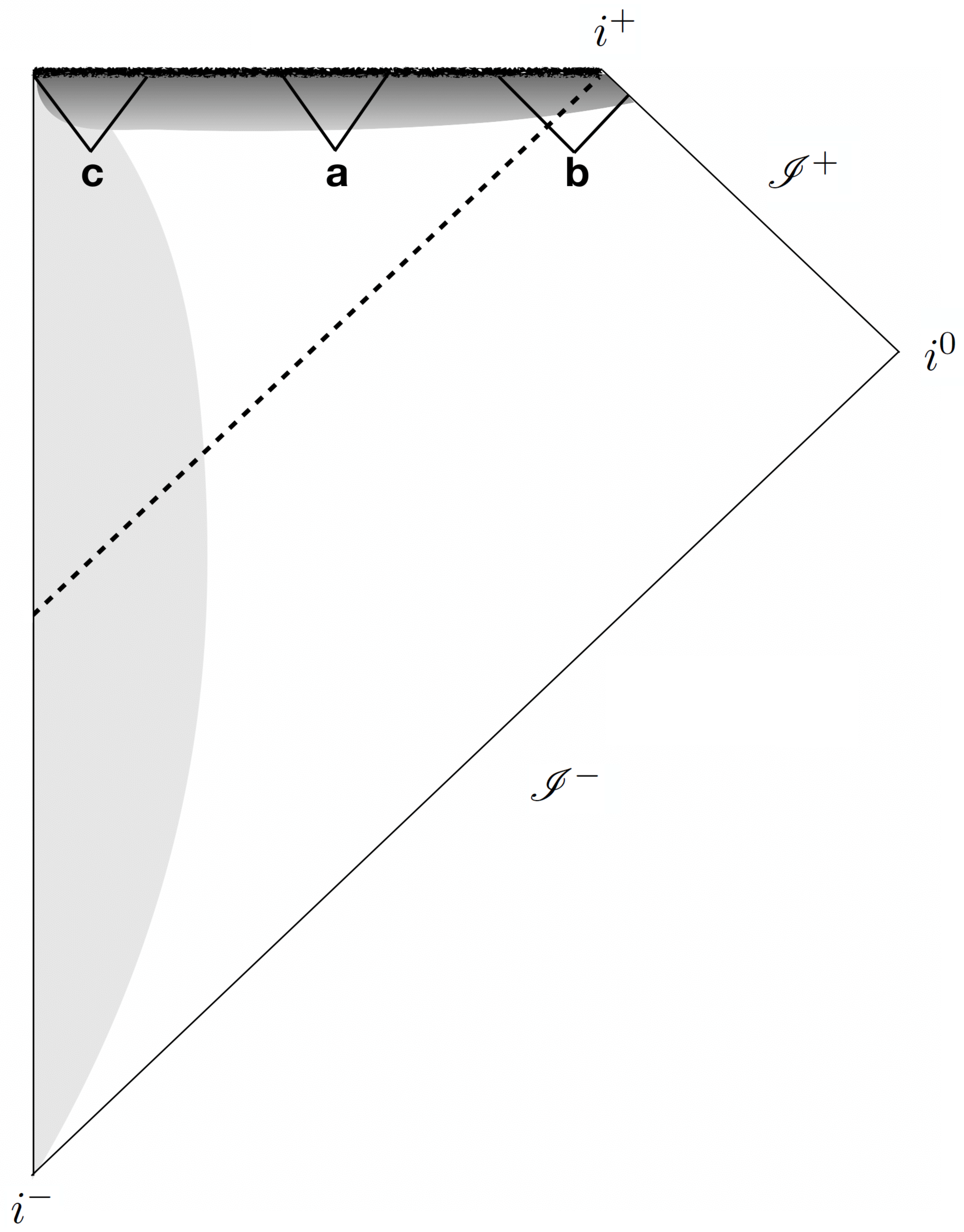
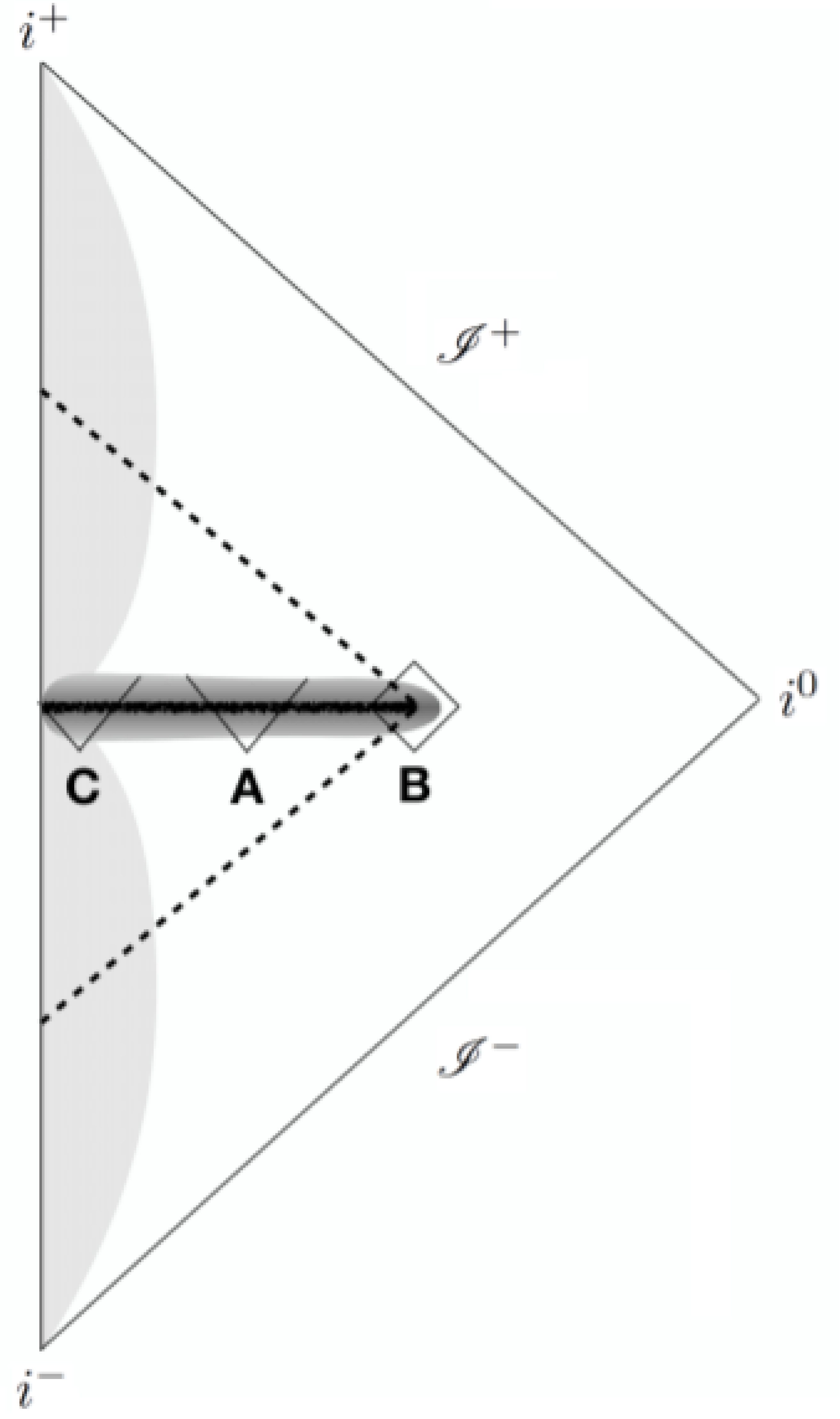


There are three independent physical phenomena happening at the end of the BH evaporation



A. Asktekar, B. Bojowald, 2005

F. Vidotto, CR, 2014

H. Haggard, CR, 2015

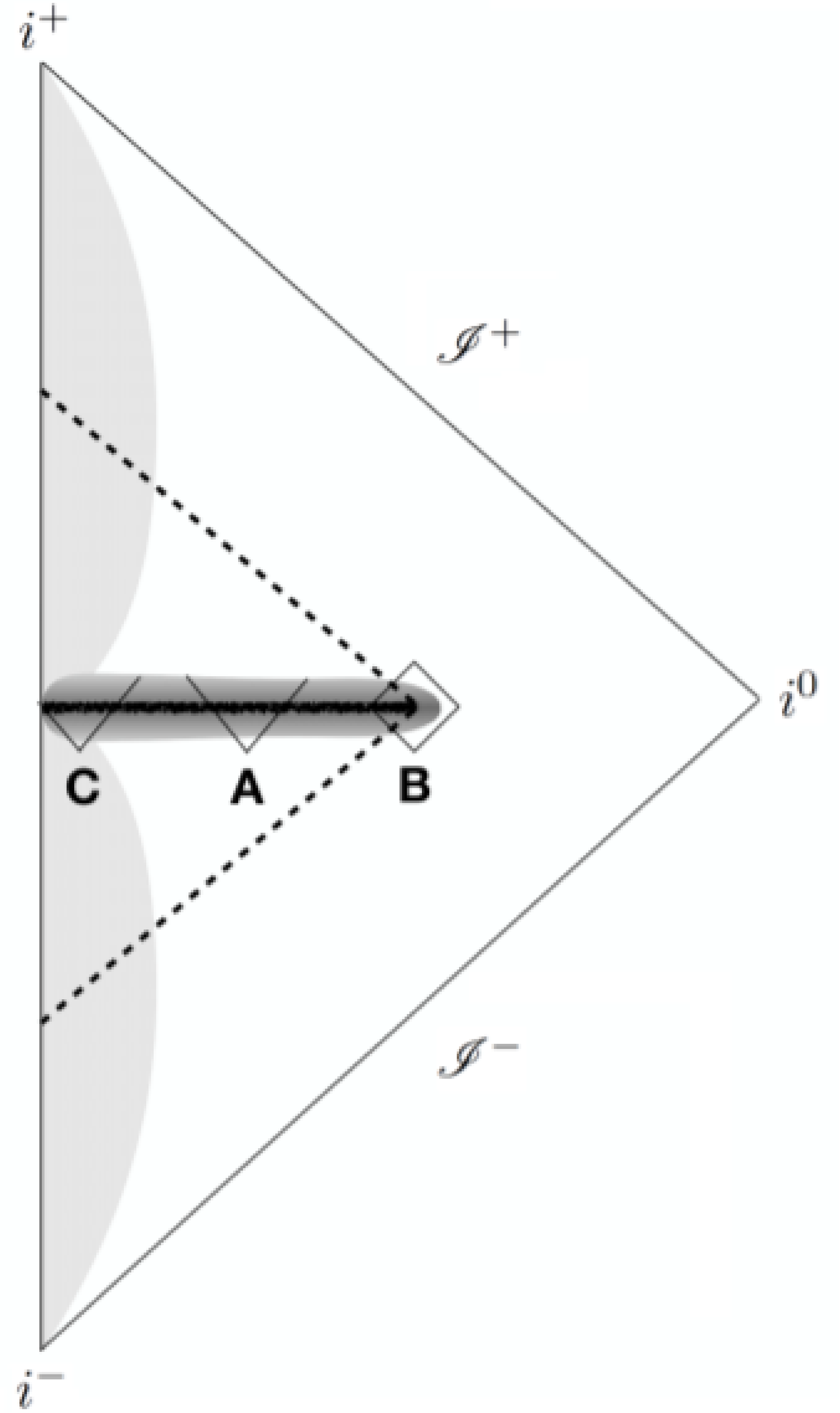
E. Bianchi, M. Christodoulou, F. D'Ambrosio, H. M. Haggard, CR, 2018

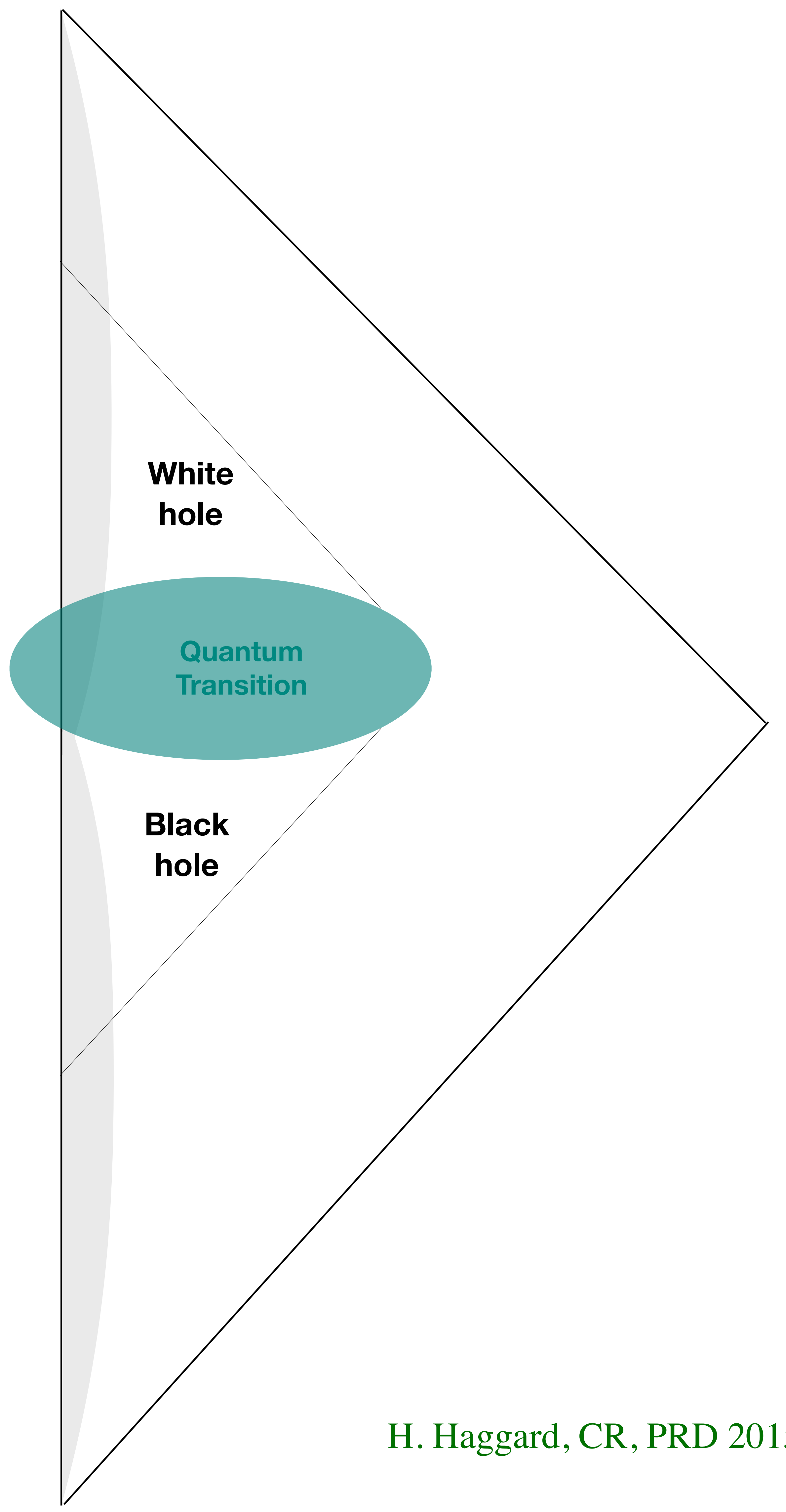
Lewandowski, Ma, Yang, Zhang, 2023

Husain, Kelly, Santacruz, Wilson-Ewing, 2022

A Rignon-Bret, CR, 2021

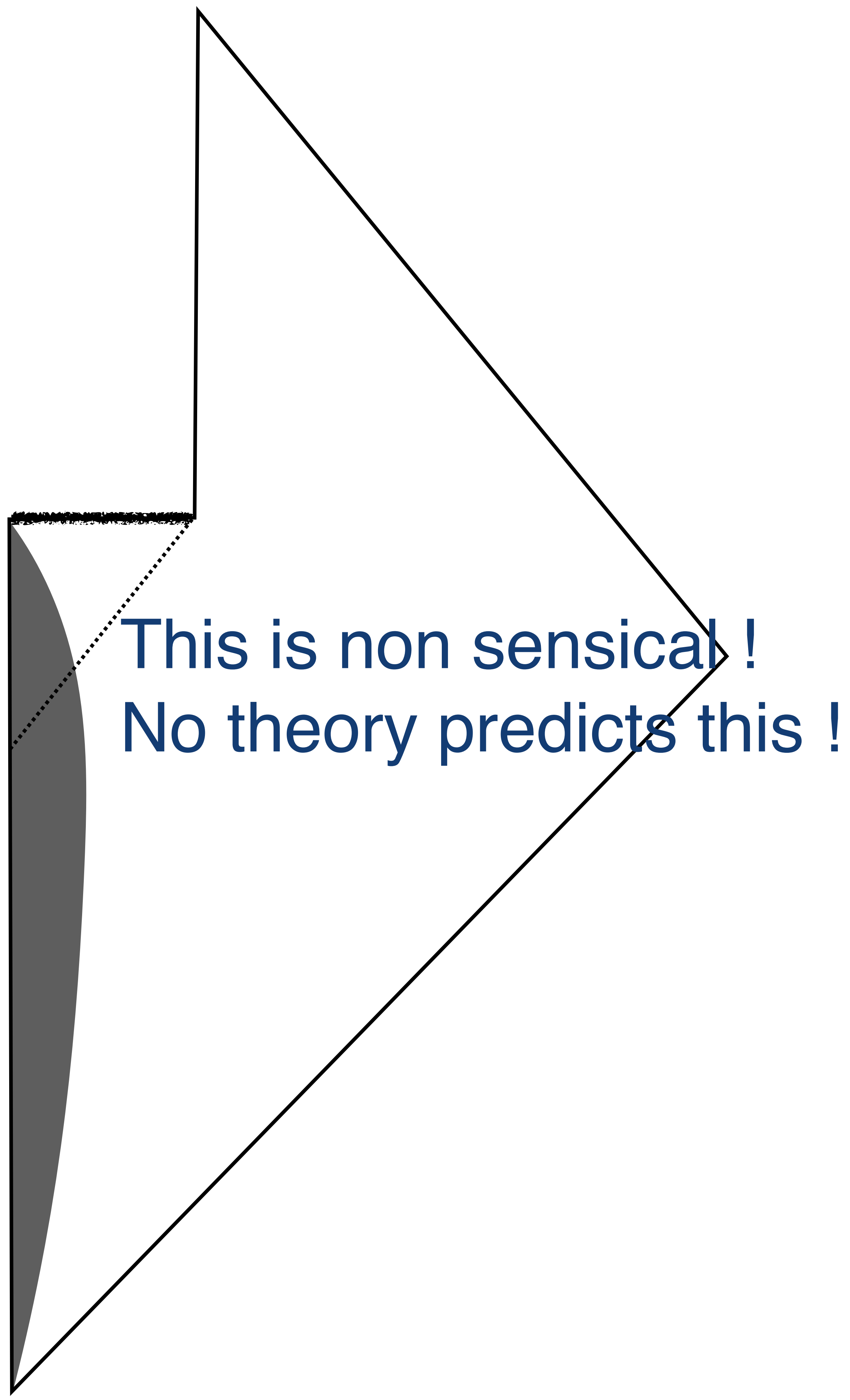
M Han, CR, F. Soltani 2023

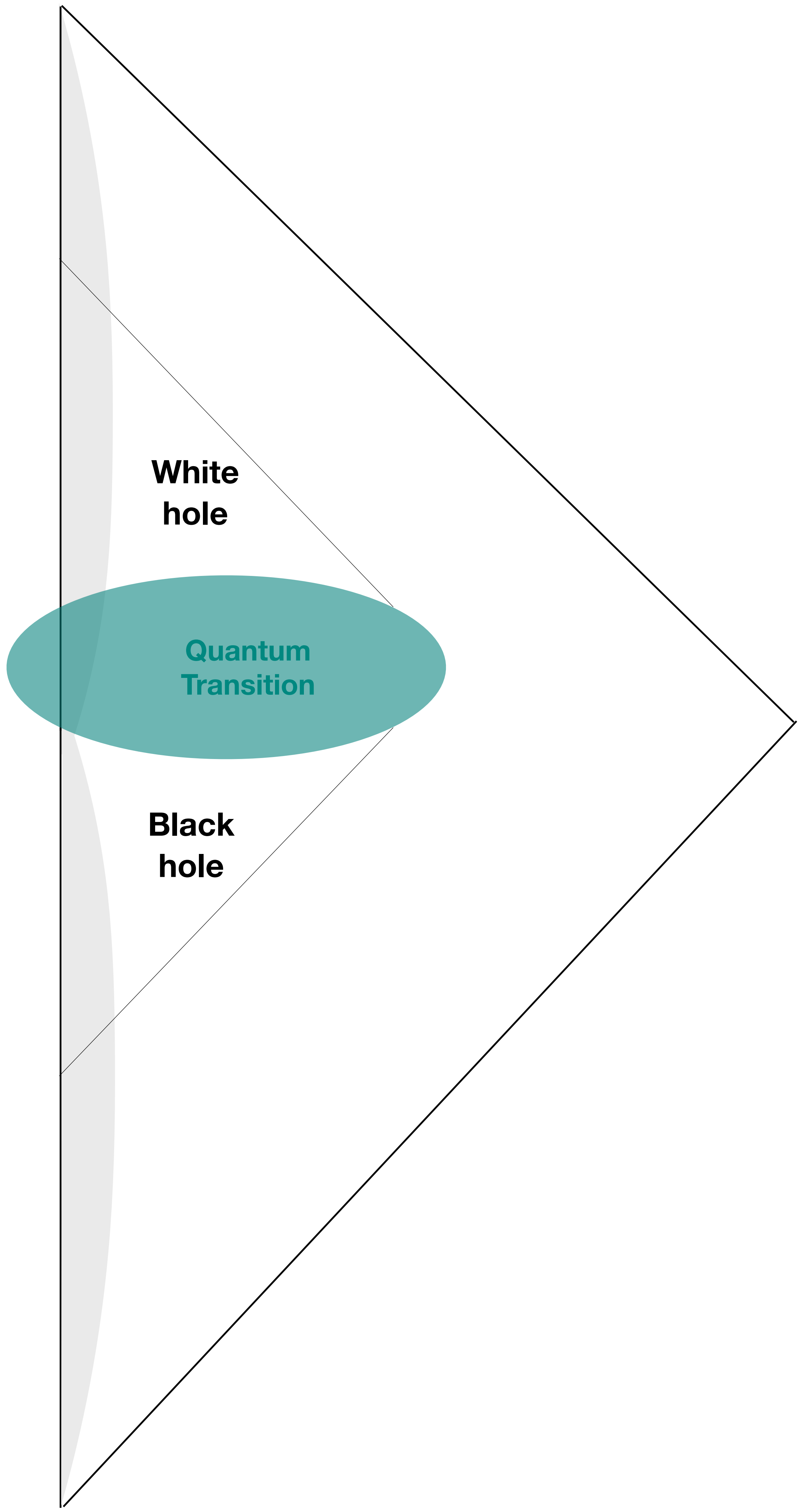




H. Haggard, CR, PRD 2015, arXiv:1407.0989

E. Bianchi, M. Christodoulou, F. D'Ambrosio, H. M. Haggard, CR,
"White holes as remnants: A surprising scenario for the end of a black hole,"
CQG 2018, arXives: 1802.04264.


This is non sensical !
No theory predicts this !


White hole
Quantum Transition
Black hole

Good coordinates for past patch

$$ds^2 = -F(r)dv^2 + 2dvdr + r^2 d\Omega^2$$

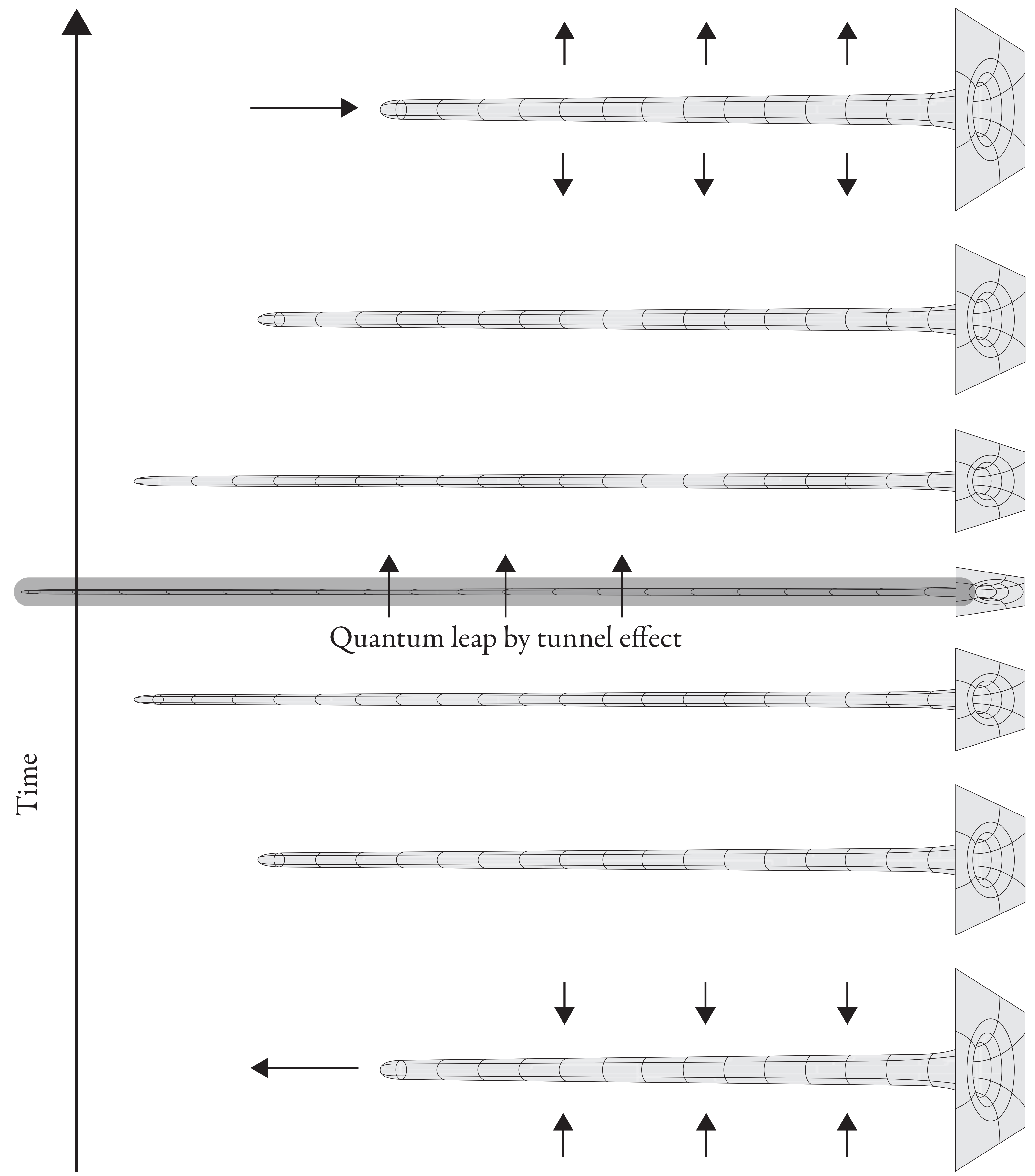
Good coordinates for future patch

$$ds^2 = -F(r)du^2 - 2dudr + r^2 d\Omega^2$$

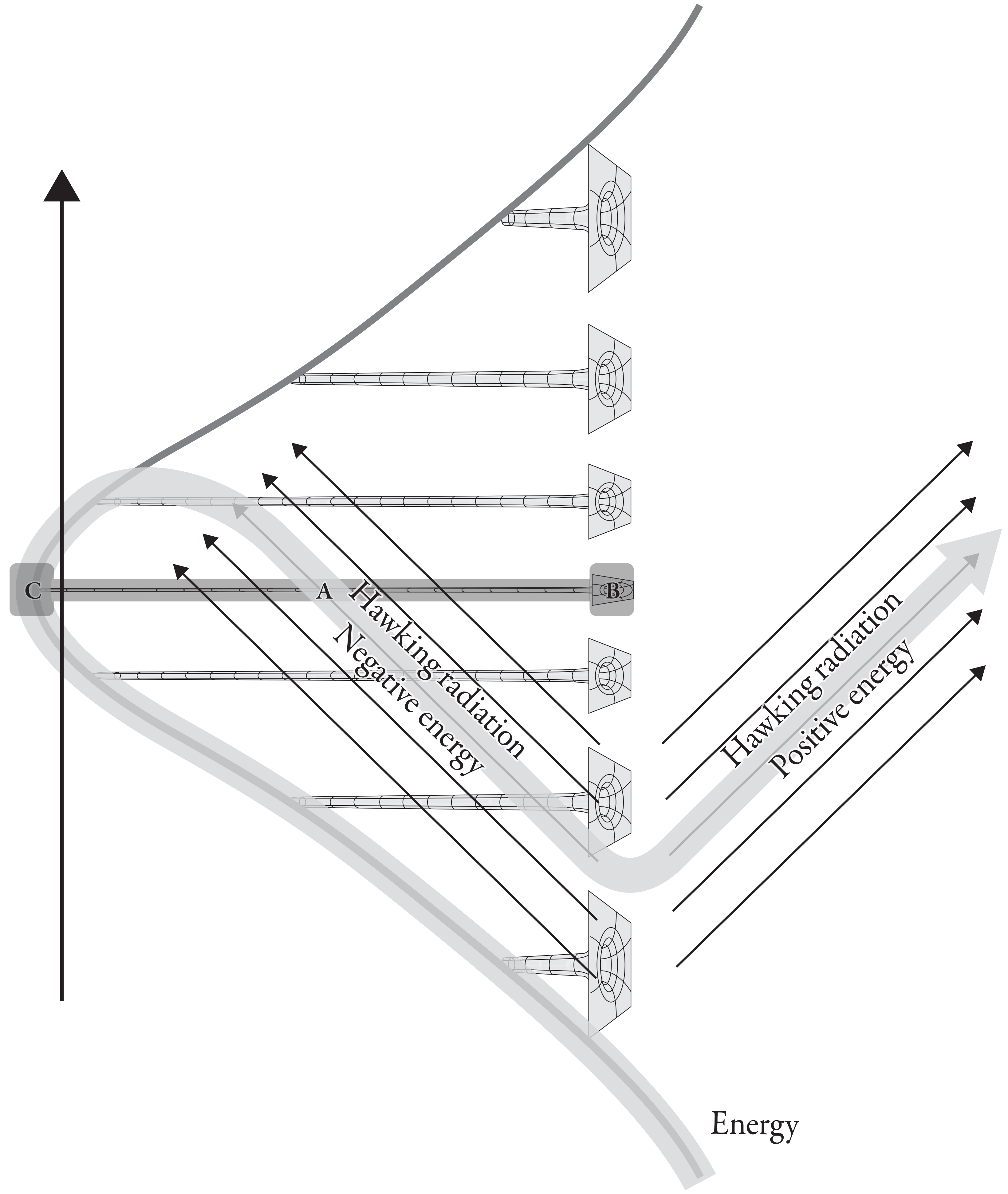
$$F(r) = 1 - \frac{2m}{r} + \frac{Am^2}{r^4}$$

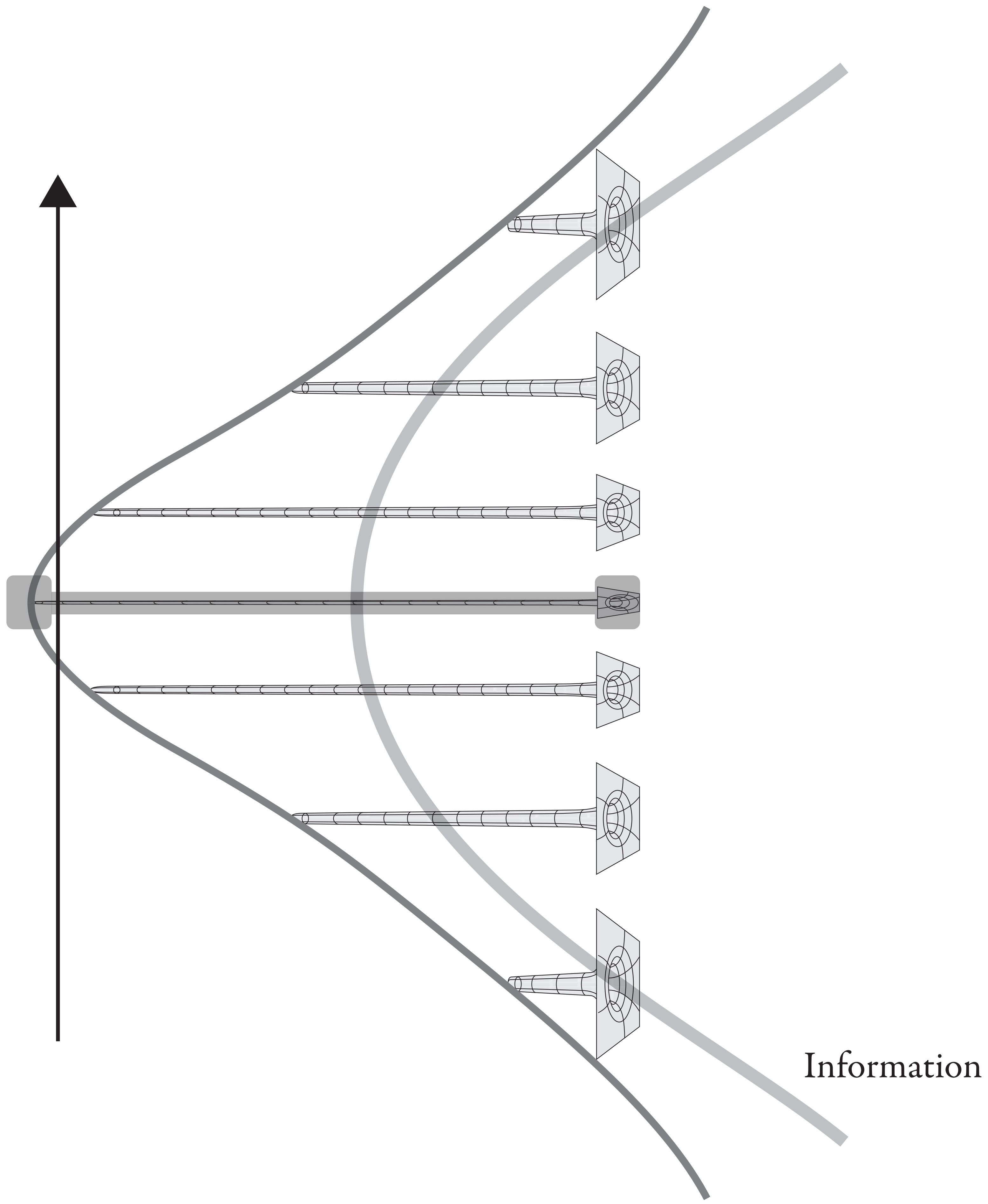
Overlap

$$2r_*(r) = v + u \qquad dr_* = \frac{dr}{F(r)}$$



M Christodoulou, CR, How big is a black hole? PRD 2015.


C
A
B
Hawking radiation
Negative energy
Hawking radiation
Positive energy
Energy


Information

The non existence of the information paradox

The thermodynamical entropy $$\Delta S_T = \int \frac{dQ}{T}$$

measures the number of states $$S_T = k \log W \qquad S_T = k \log \dim \mathcal{H} = k \log N$$

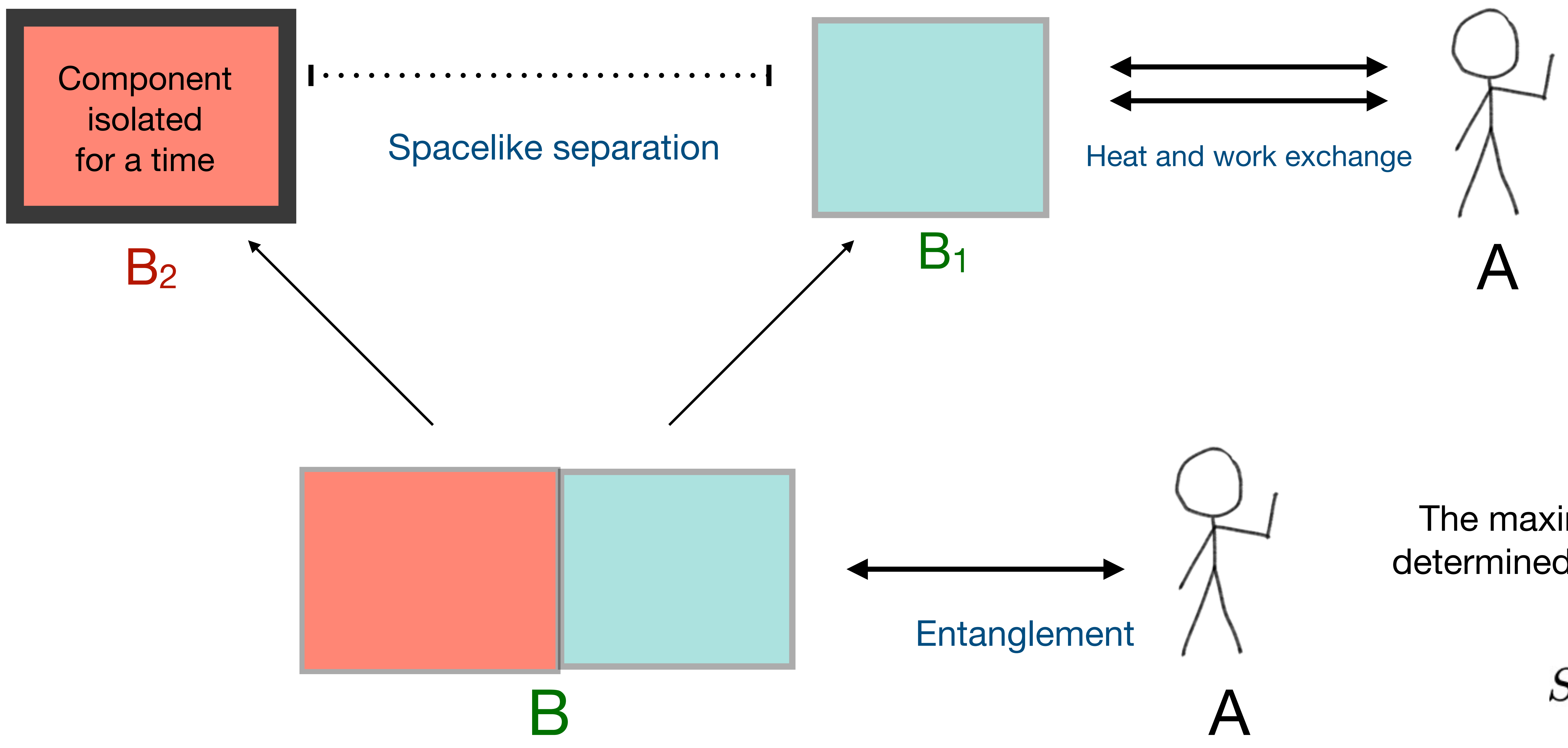
This is only true under (severe) conditions !

The von Neumann entropy measures entanglement $$\rho_A = Tr_B \Big[|\Psi_{AB}\rangle\langle\Psi_{AB}| \Big]$$

$$S_{vN} = -k \; Tr[\rho_A \log \rho_A]$$

It is maximized by $\rho_a = \frac{1}{N}\mathbb{1}$ $\quad S_{vN} < k \log N$

$$\boxed{S_{vN} \leq S_T}$$



The thermodynamical entropy is determined by the number of states of B1

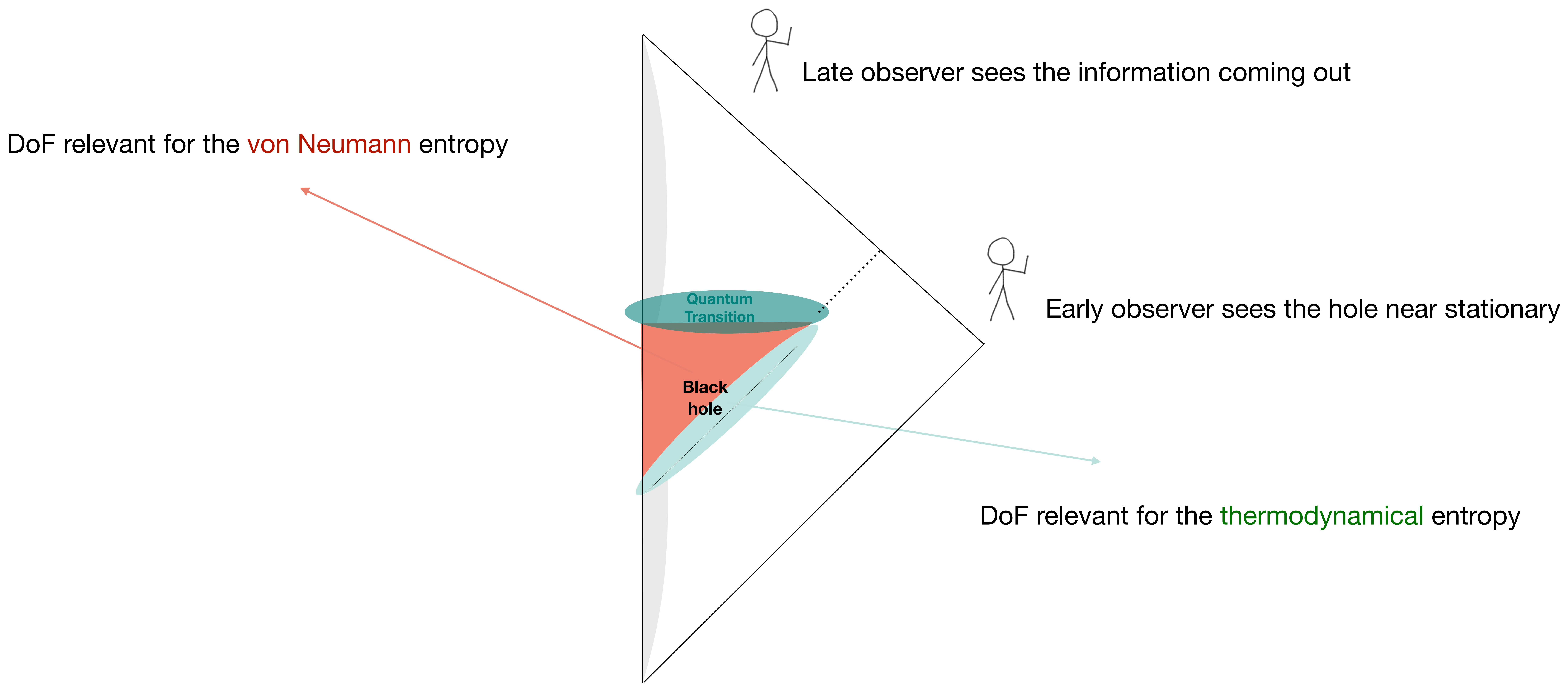
$$S_T = k \log \dim \mathcal{H}_{B_\infty} = k \log N_{B_1}$$

The maximal von Neumann entropy is determined by the **total** number of states of B

$$S_{vN} < -k \log N_B$$

$S_{vN} \leq S_T$	Does not hold anymore!

The von Neumann can be higher that the thermodynamical entropy.



CR, The subtle unphysical hypothesis of the firewall theorem, Entropy 2019.

CR, Black holes have more states than those giving the Bekenstein-Hawking entropy: a simple argument, CQG 2018, arXives:1710.00218

Transition probability $A \sim e^{-\frac{Gm^2}{c\hbar}}$

How to think about this:

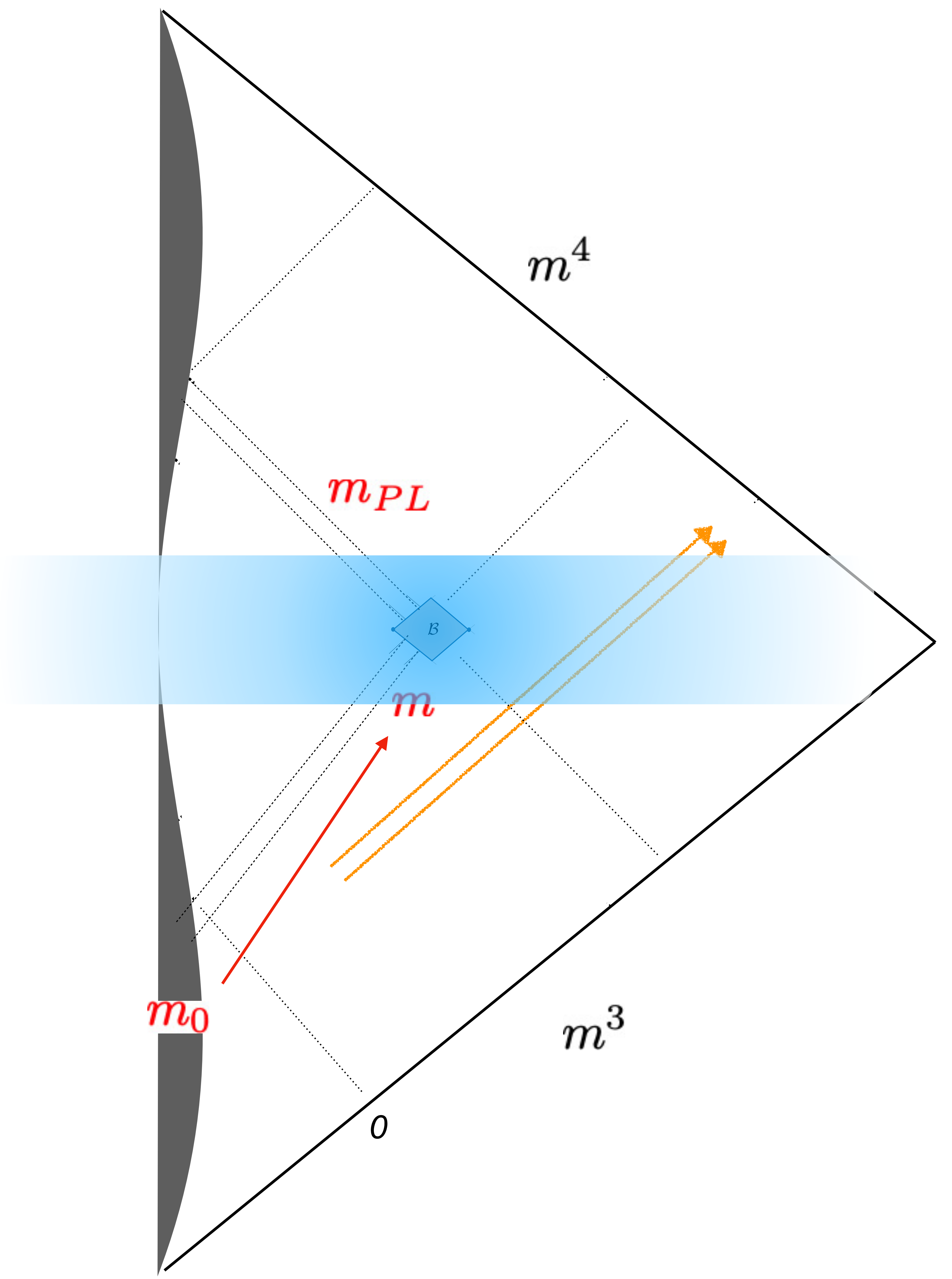
- A quantum tunnelling effect [Hal Haggard at Loop24]

P Donà , H Haggard, CR, F Vidotto, arXives: 2402.09038

- The amplitude is approximated in the semiclassical regime by

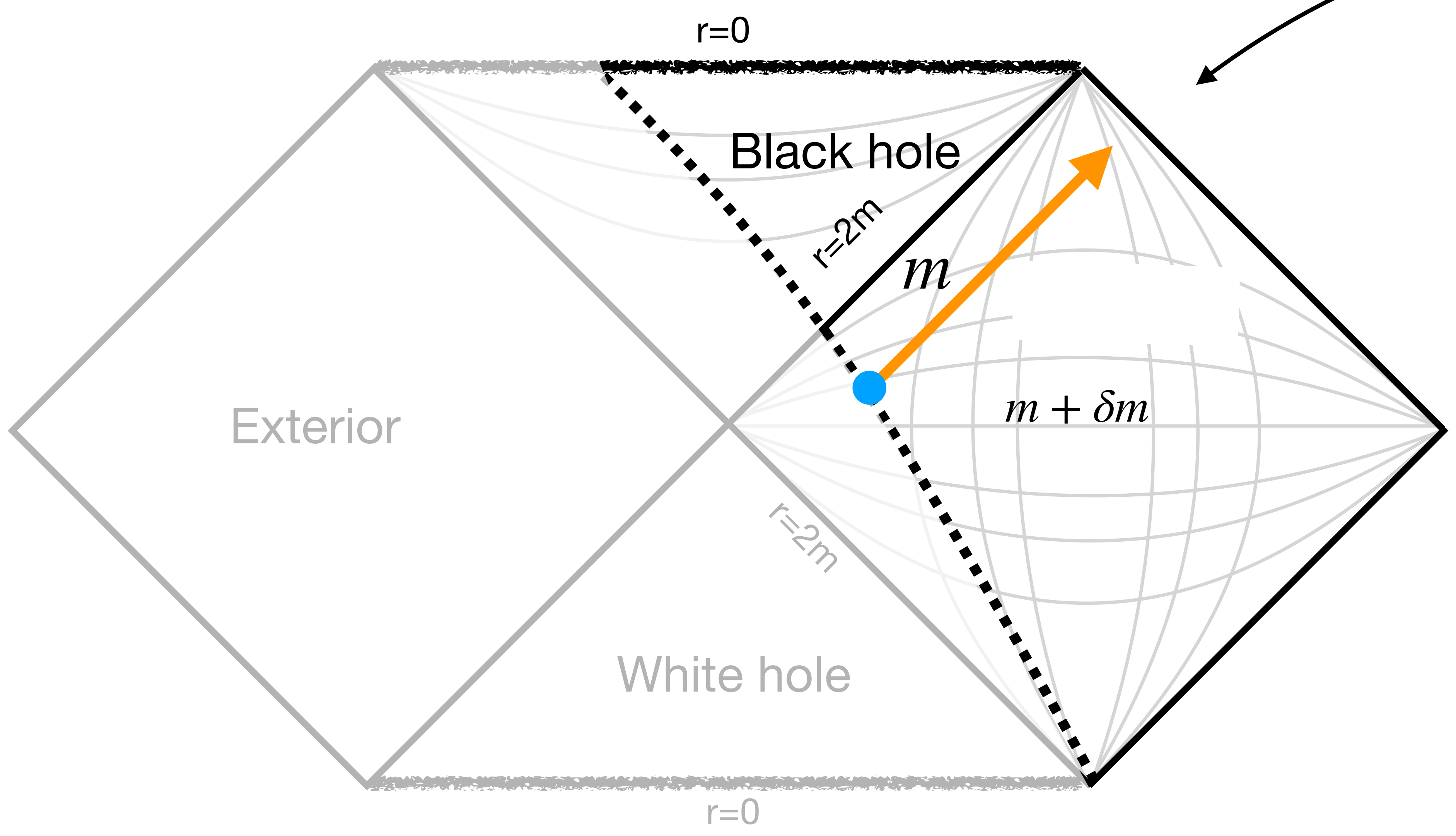
$$A \sim e^{i\, S_{Regge}} \sim e^{i\, \sum_f j_f \theta(j_j)} \sim e^{-\sum_f Area_f}$$

The transition is suppressed for large BH !

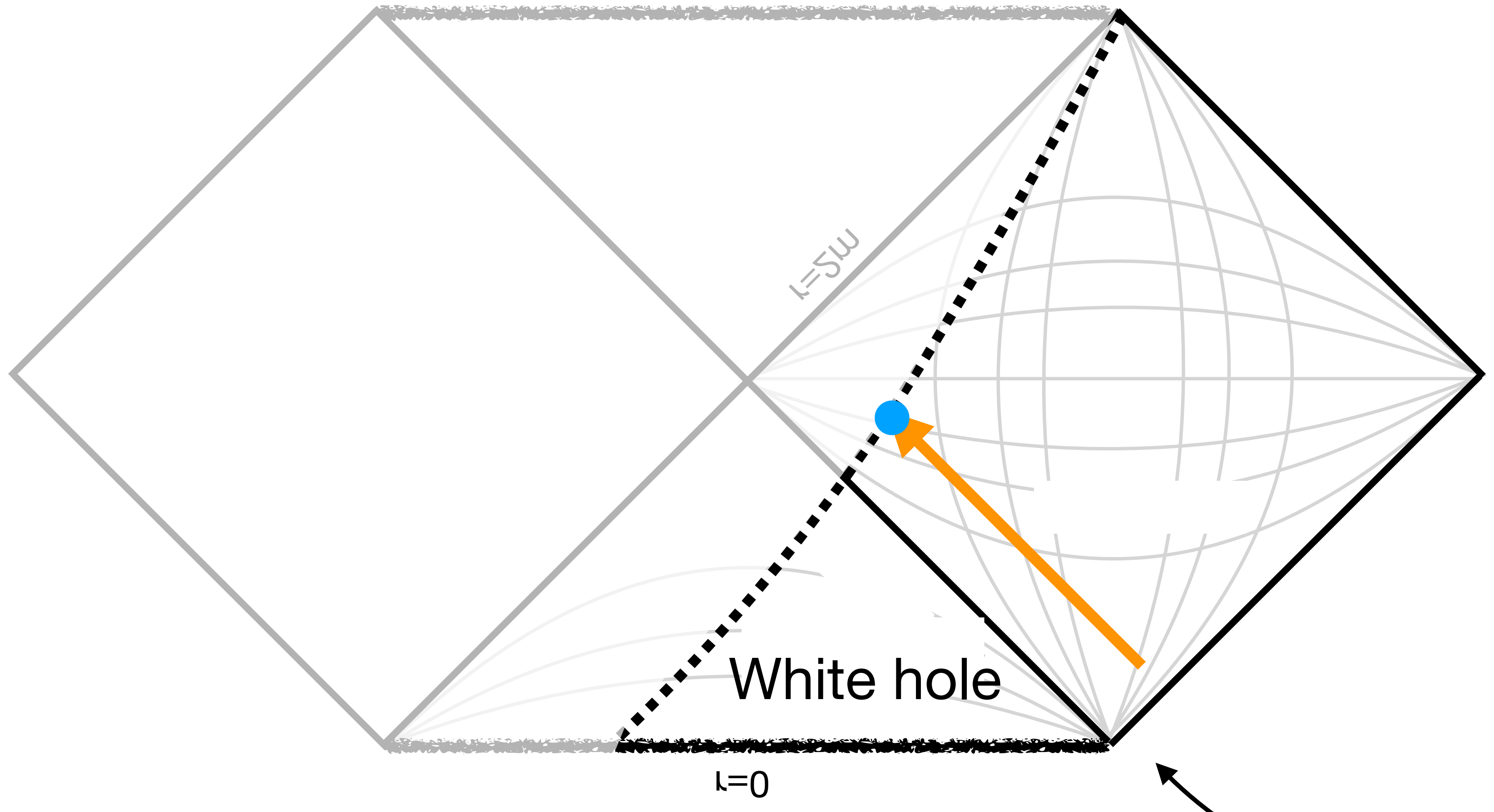


m^4
m_{PL}
$\mathcal{B}$
m
m_0
m^3
0

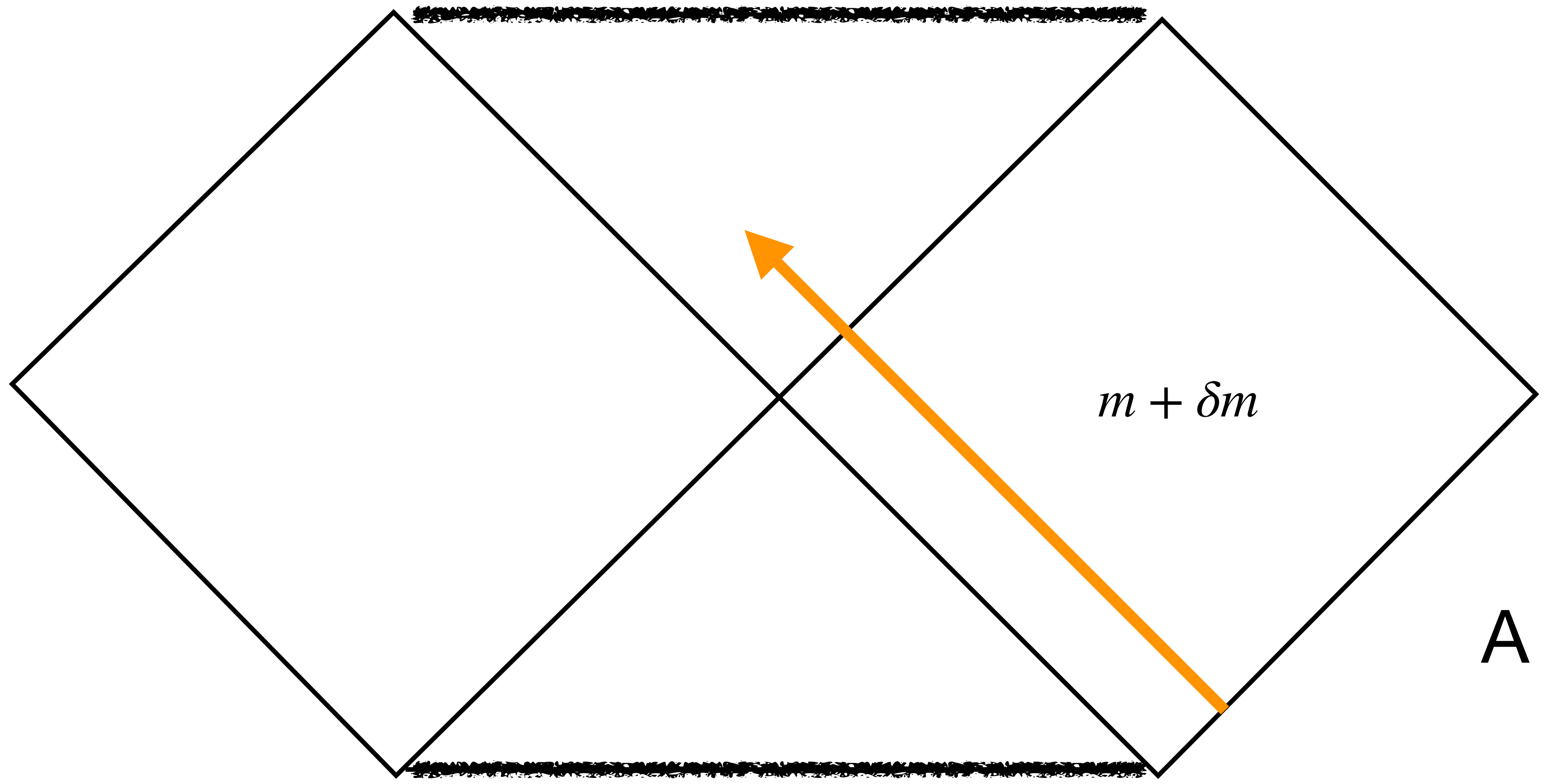
White holes are unstable



The energy pulse cannot be too much in the future



The energy pulse cannot be too much in the past

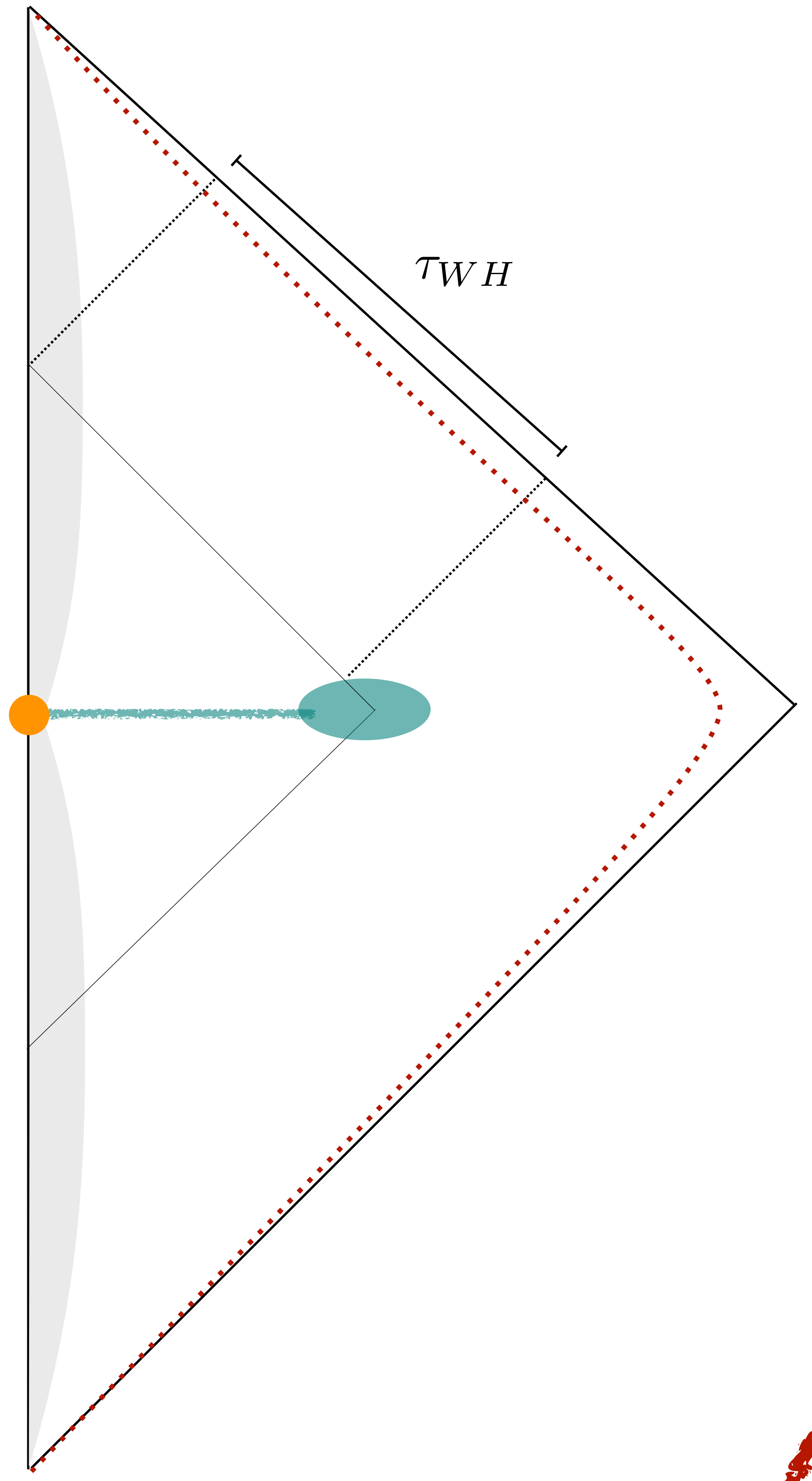


A white hole is unstable toward becoming a black hole

Are remnants stable?
They are stabilized by quantum gravity

Area gap = minimum non vanishing mass

$$A_{min} = 4\frac{\sqrt{3}}{\pi}\gamma\hbar G/c^3$$



$$|m_o, m\rangle_B \xrightarrow[\text{tunnelling}]{} |m_o, m\rangle_W$$

$$|m_o, m\rangle_W \xrightarrow[\text{instability}]{} |m_o, m\rangle_B$$

$$H = \begin{pmatrix} m + 3\sqrt{3}\; i\pi m_o^2 \frac{\partial}{\partial v} - i\,\frac{\hbar^2}{m^2}\frac{\partial}{\partial m} & b\frac{\hbar}{m} \\ c\frac{\hbar}{m}e^{-m^2/\hbar} & m - 3\sqrt{3}\; i\pi m_o^2 \frac{\partial}{\partial v} \end{pmatrix}$$

$$|\psi\rangle = \begin{pmatrix} B(m,v) \\ W(m,v) \end{pmatrix}$$

$$|R\rangle = \frac{\sqrt{\frac{a}{b}}|B,\mu\rangle - |W,\mu\rangle}{\sqrt{1+\frac{a}{b}}}$$

$$|m_o, m\rangle = \alpha|m_o, m\rangle_W + \beta|m_o, m\rangle_B$$

Vidotto, CR 2018.

Quasi stable remnants of Mass ~ 1μg

Dark matter?

Are remnants stable?
They are stabilized by quantum gravity

Area gap = minimum
non vanishing mass

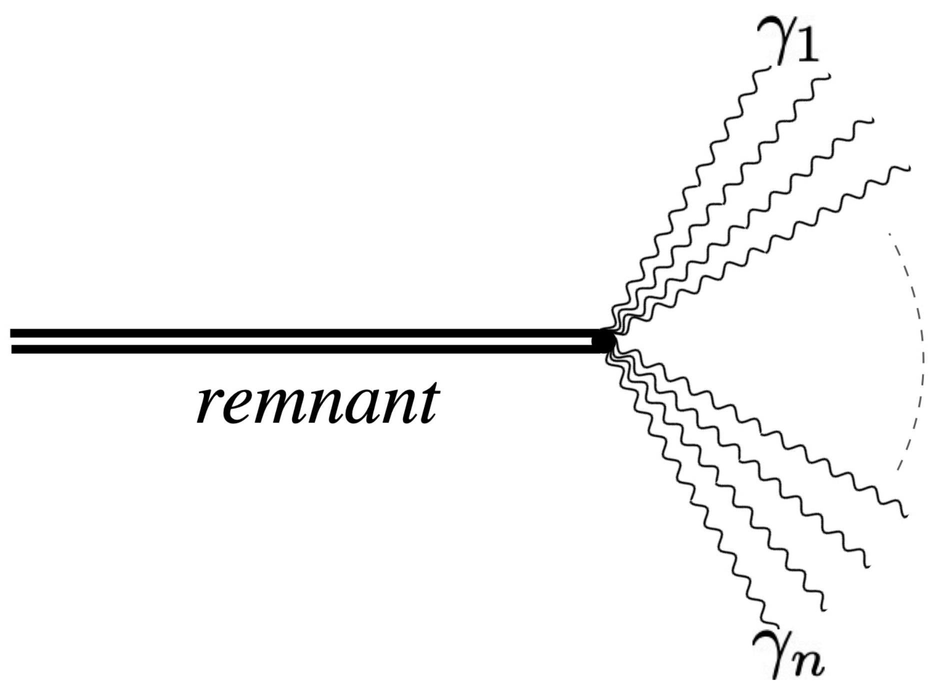
$$A_{min} = 4\frac{\sqrt{3}}{\pi}\gamma\hbar G/c^3$$

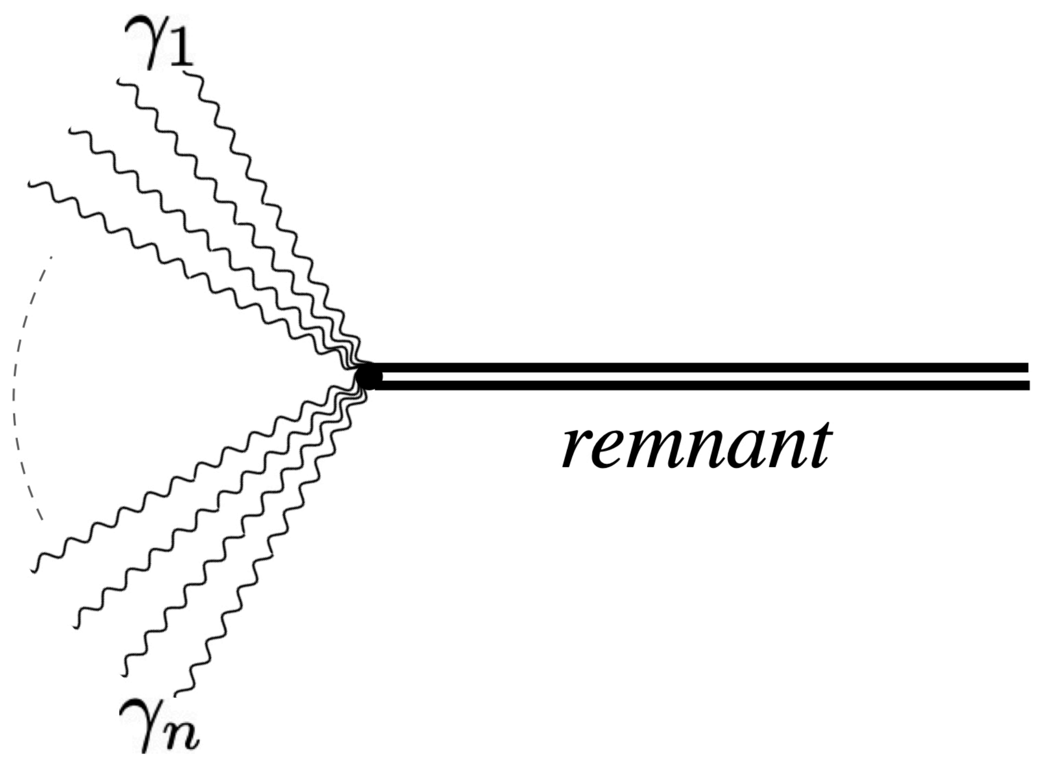
Quasi stable
remnants of
Mass ~ 1μg

Dark matter?

$$\xrightarrow[\text{collapse}]{} |m_o, m_o\rangle_B \xrightarrow[\text{black hole}]{\tau_{WH}\sim m_o^3} |m_o, m_{P\ell}\rangle_B \xrightarrow[\text{tunnelling}]{\tau_T\sim m_{P\ell}} |m_o, m_{P\ell}\rangle_W \xrightarrow[\text{white hole}]{\tau_{WH}\sim m_o^4} |m_{P\ell}, m_{P\ell}\rangle_W \xrightarrow[\text{end}]{} .$$

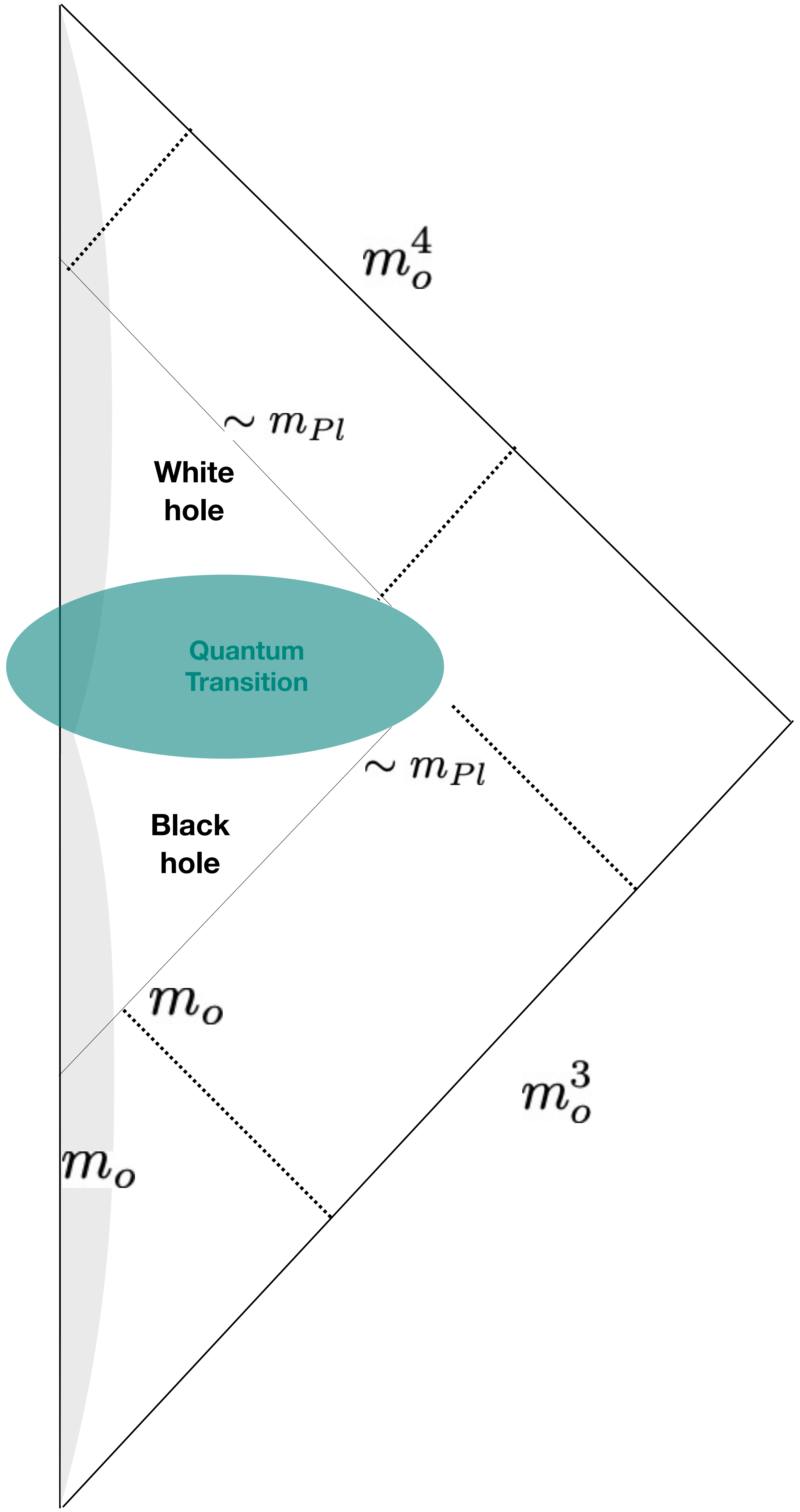
$|m_o, m_P\rangle \to |0\rangle$ suppressed!





This also solve the old problem:

Why WH are not easily produced?



E. Bianchi, M. Christodoulou, F. D'Ambrosio, H. M. Haggard, CR,
"White holes as remnants: A surprising scenario for the end of a black hole," CQG 2018, arXives: 1802.04264.

$$S \sim \frac{A}{4} = 4\pi m^2$$

$$S = \frac{2\pi}{3} LT, \qquad E = \frac{1}{6} LT^2.$$

$$L = \frac{3S^2}{8\pi^2 E} = 6m^4, \qquad T = \frac{4\pi E}{S} = \frac{1}{m^2}$$

$$\tau_W \sim 6m^4$$

S. Kazemian, M Pascual, F Vidotto, 2022, arXiv:2207.06978.

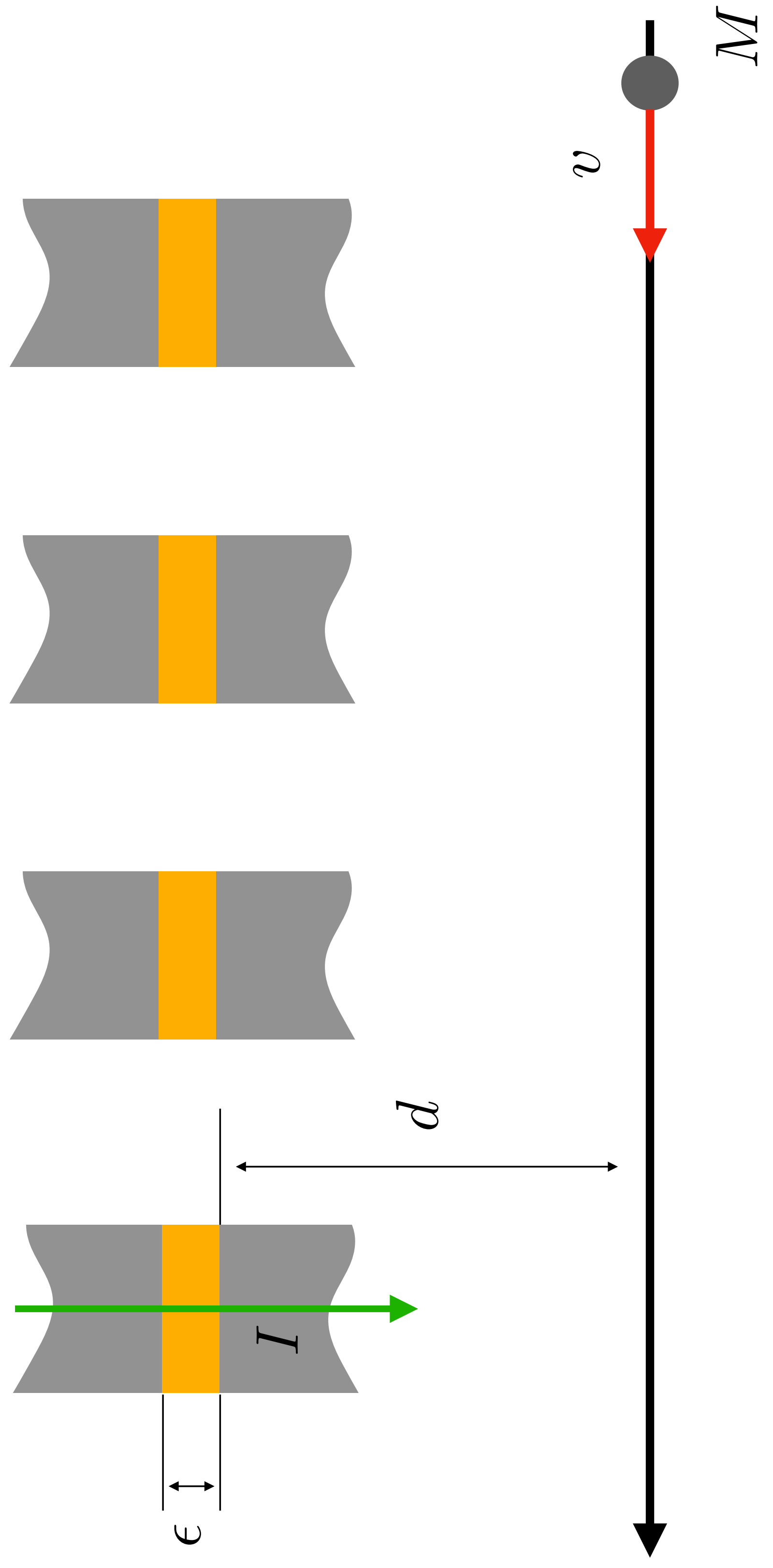
Emission

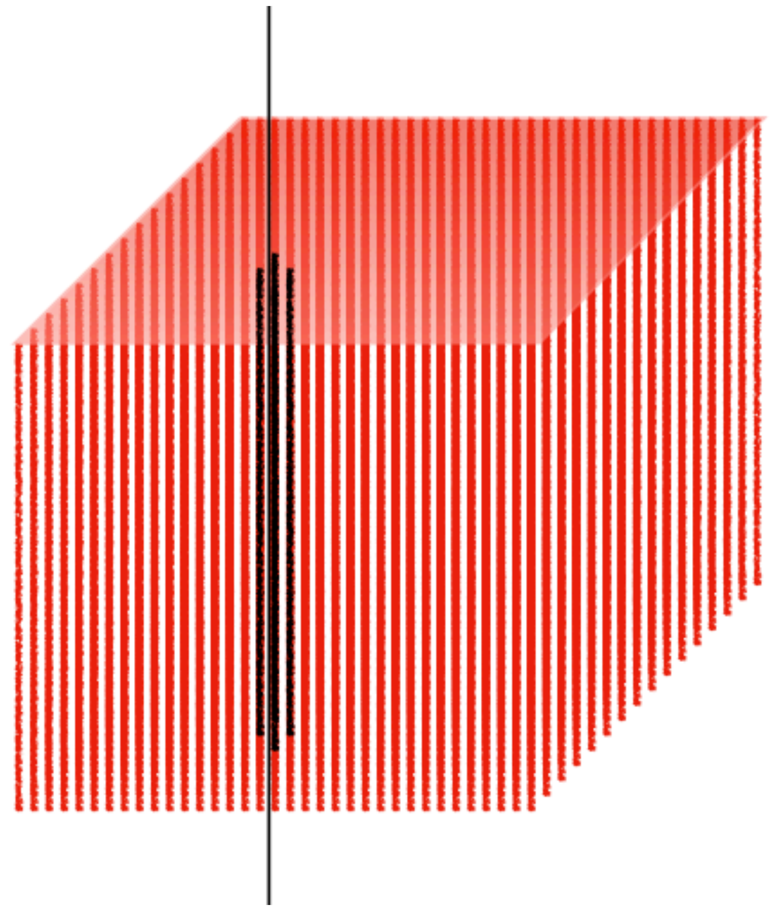
$$m = 10^{x-5} gr, \quad \nu = 10^{-2x+32} Hz, \quad \rho_{rad} = \sinh\left(\frac{10^{61} - 10^{3x}}{10^{4x} - 10^{3x}}\right)\rho_{rem}$$

$$x = \log_{10}(m/m_{Pl}) \in [15, 20]$$

S. Kazemian, M. Pascual, CR, F. Vidotto, “Diffuse emission from black hole remnants,” CQG 2023.

Direct detection. In Practice: Piles of Josephson Junctions





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