LQG suggest the existence of

a quasi-stable particle with mass ~ 20μg

which can interact gravitationally only

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

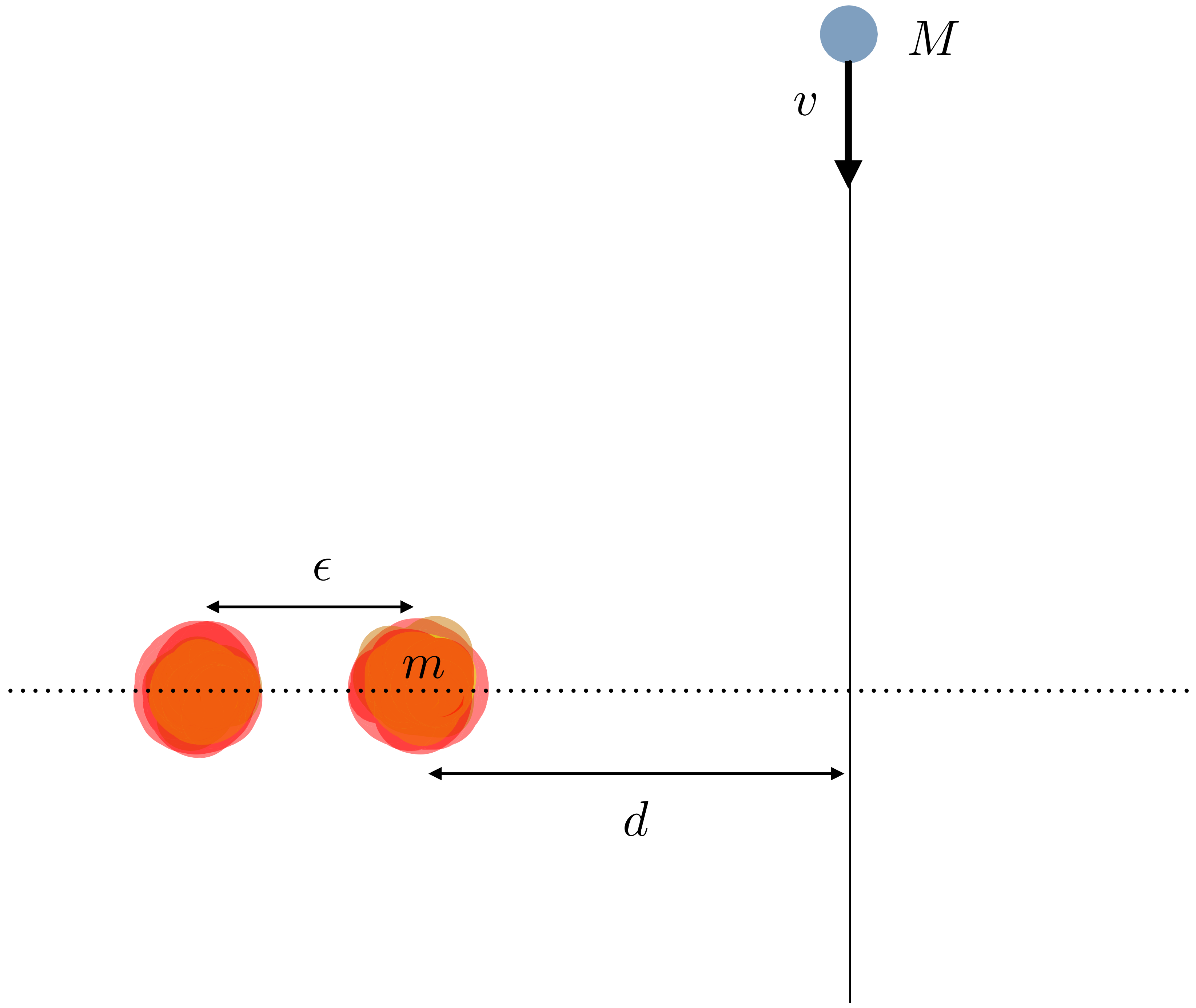
2) This particle can be detected

3) It is a natural candidate for Dark Matter

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

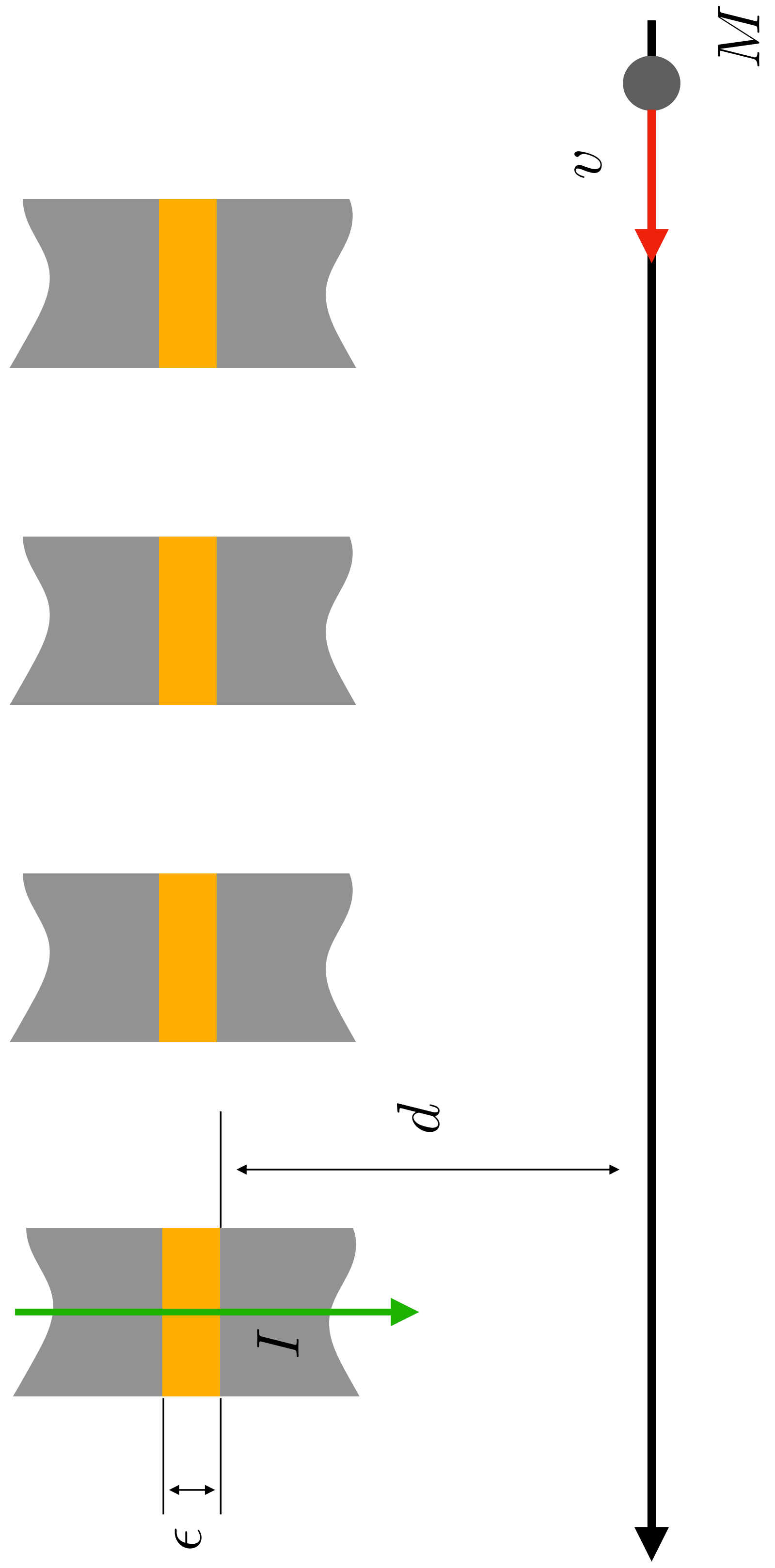
$$m = \sqrt{\frac{\sqrt{3}\gamma\hbar c}{4G}} \sim 1.43\sqrt{\gamma}\ \mu g$$

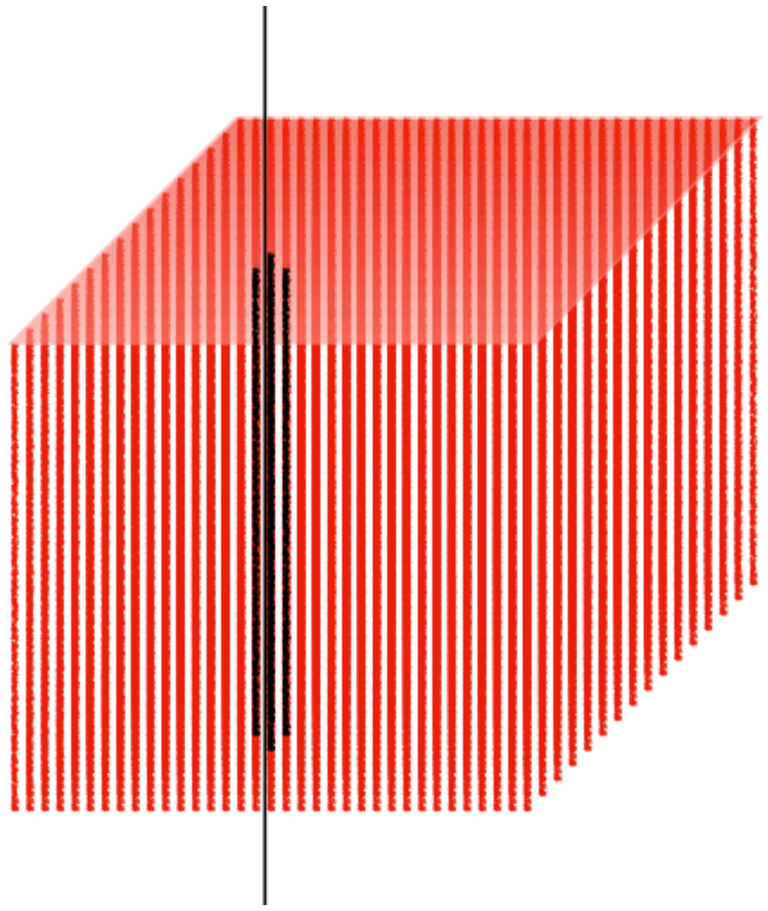
Direct detection. In Principle



A Perez, M Christodoulou, CR,
Detecting Gravitationally Interacting Dark Matter with Quantum Interference,
2024

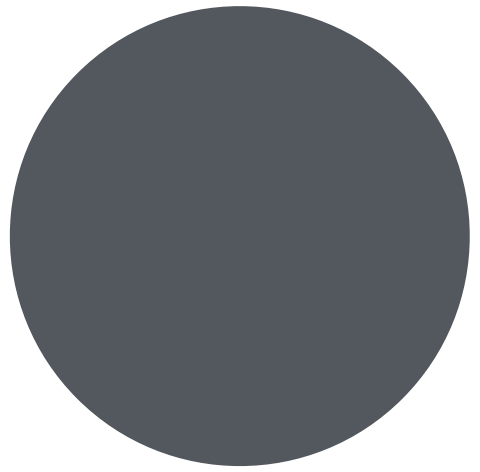
Direct detection. In Practice: Piles of Josephson Junctions





A Perez, M Christodoulou, CR,
Detecting Gravitationally Interacting Dark Matter with Quantum Interference,
2024

- The area of a black hole horizon is quantized (LQG).
- An isolated black hole radiates (dissipation) and its area decreases (Hawking theory)
- The last transition from the minimal area to nothing is highly suppressed (Conservation of information).



black hole

$$ds^2 = -dt^2 + (dr + \sqrt{2m/r}\, dt)^2 + r^2 d\Omega^2$$

horizon:

Area $16\pi m^2$

Extrinsic curvature $\sqrt{2m/r^3}$

white hole

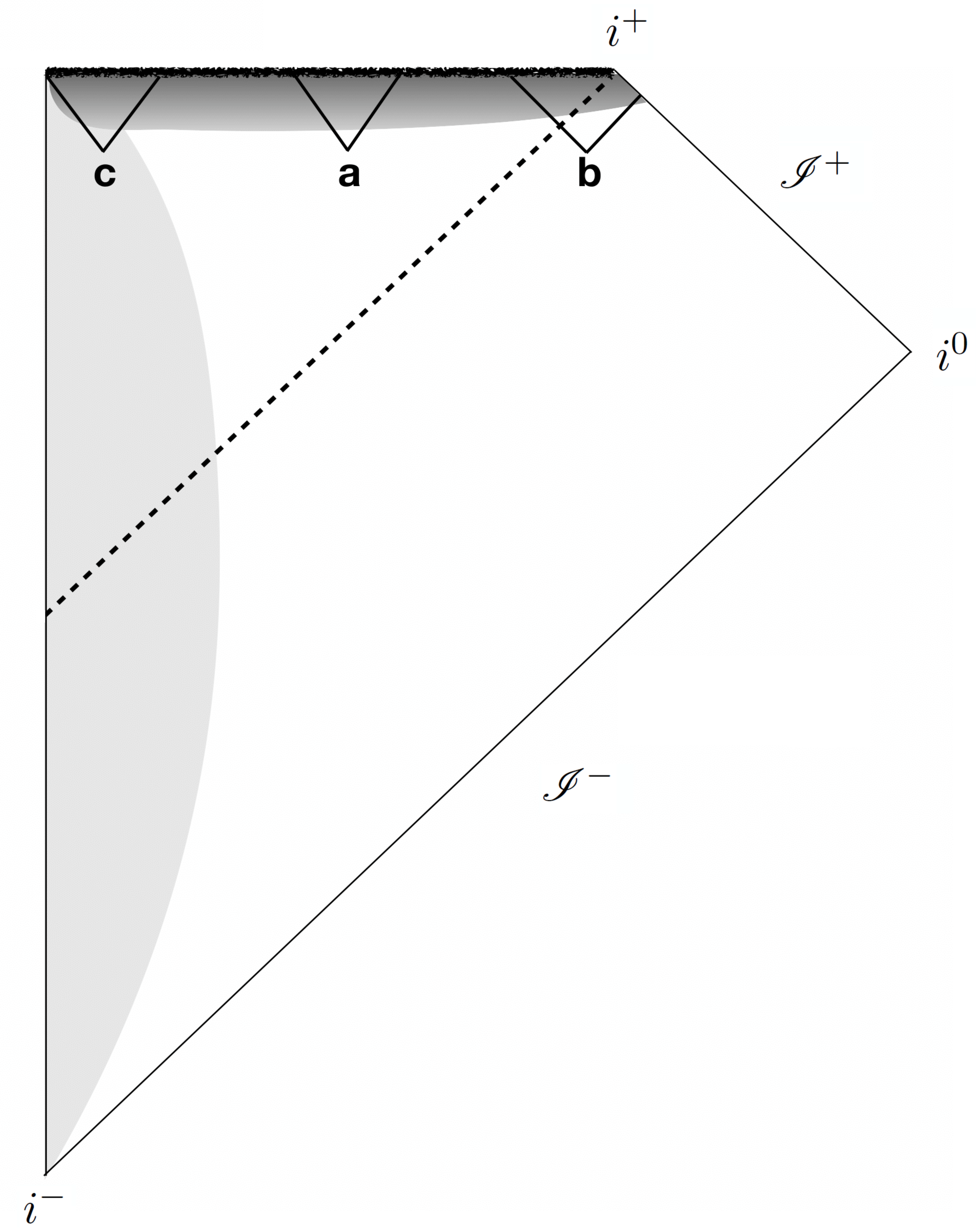
$$ds^2 = -dt^2 + (dr - \sqrt{2m/r}\, dt)^2 + r^2 d\Omega^2$$

Area $16\pi m^2$

Extrinsic curvature $-\sqrt{2m/r^3}$

In the quantum theory, Area and Extrinsic curvature cannot be both sharp, but we can have semiclassical coherent states, as long as A is large.
But the Area decreases by dissipation, until its minimum (area gap) value.
At this point, the Extrinsic curvature must be maximally spread.

That is, we will have **a superposition of black and white hole**.



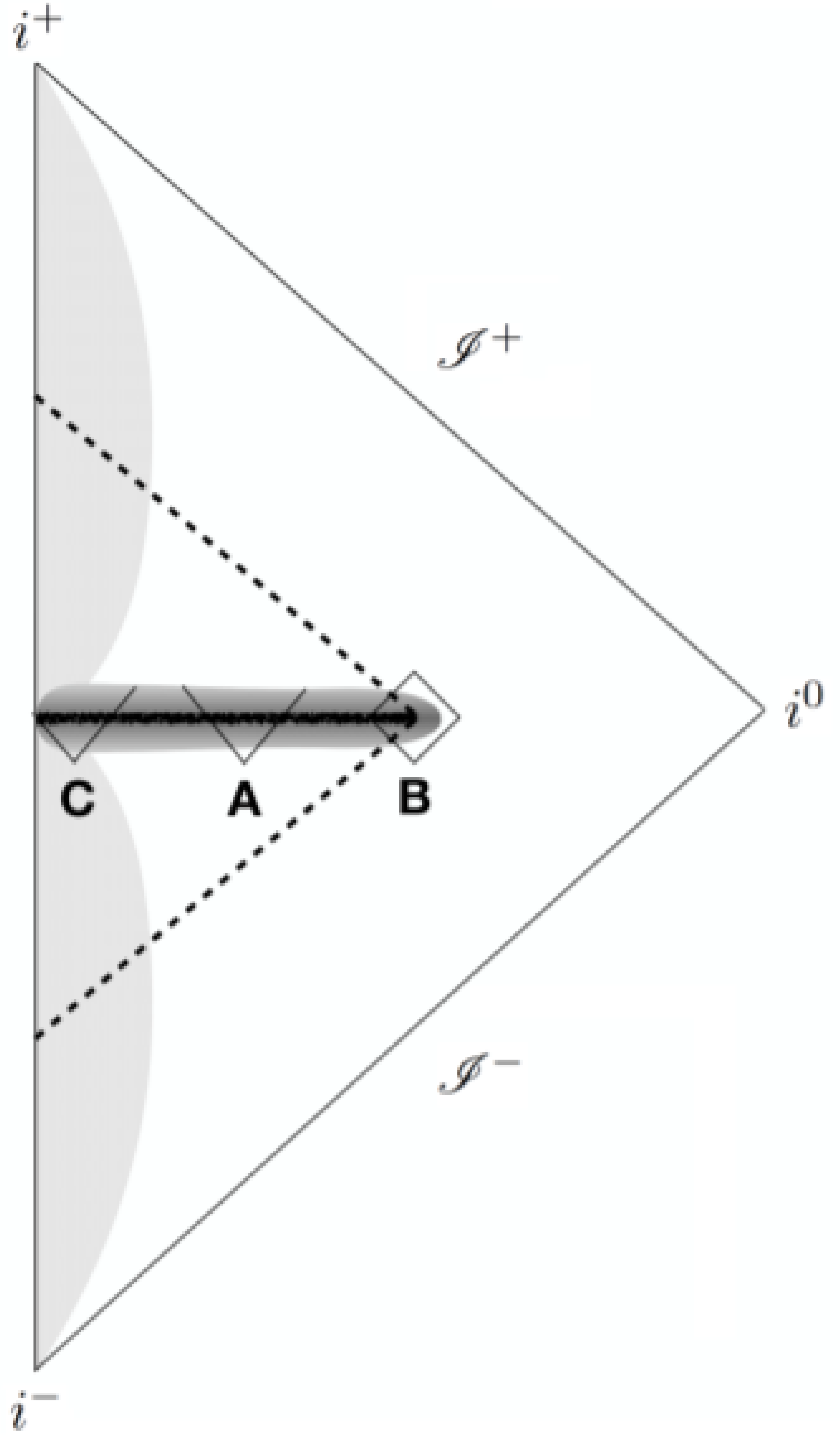
There are three independent physical phenomena happening at the end of the BH evaporation

The interior of a (classical) black hole is not stationary

No stationary picture of a quantum black hole makes sense

Black holes are not eternal, because of dissipation (Hawking radiation)

No eternal picture of a quantum black hole makes sense



A. Asktekar, B. Bojowald, 2005

F. Vidotto, CR, 2014

H. Haggard, CR, 2015

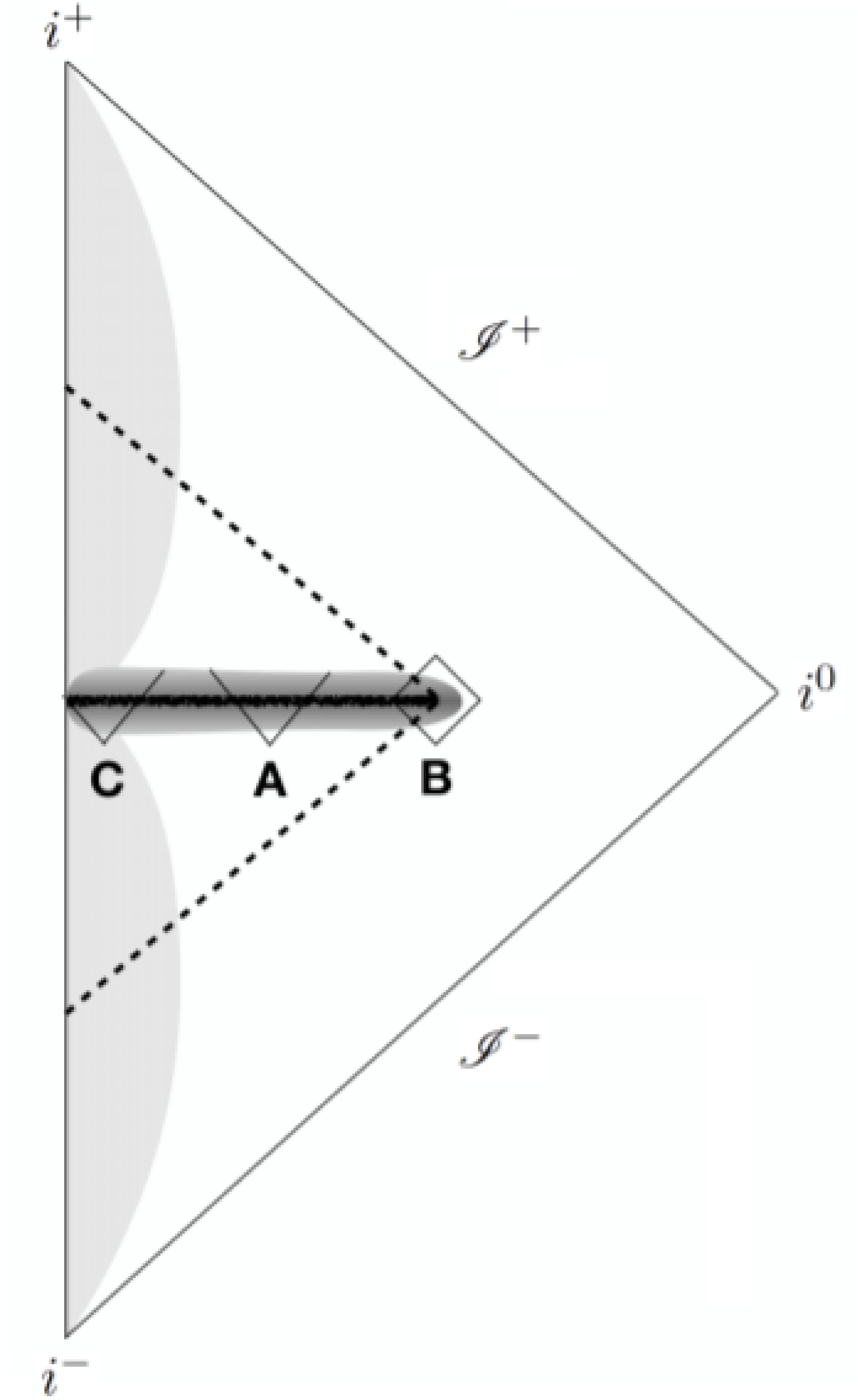
E. Bianchi, M. Christodoulou, F. D'Ambrosio, H. M. Haggard, CR, 2018

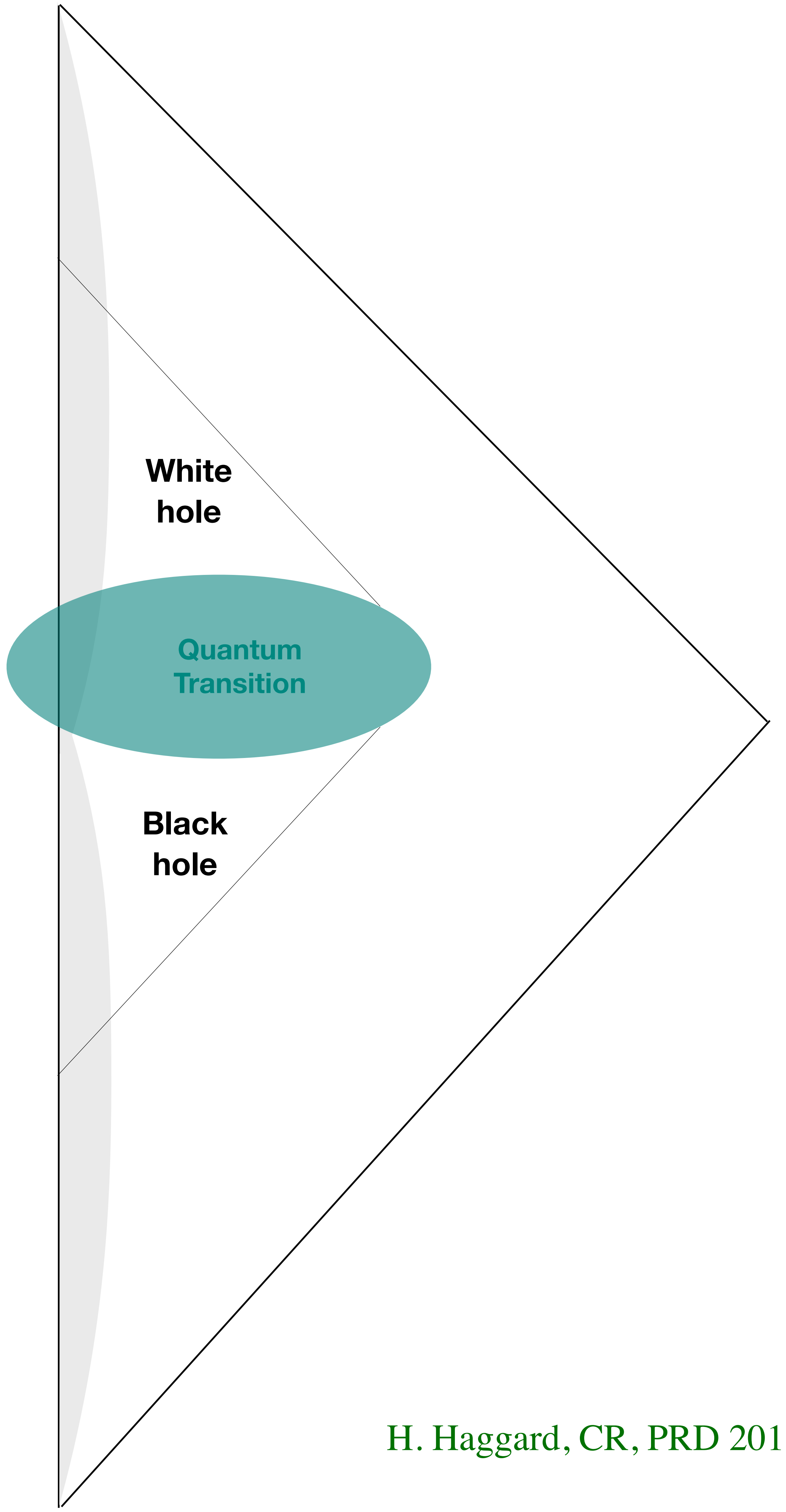
Lewandowski, Ma, Yang, Zhang, 2023

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.

Good coordinates for past patch

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

Good coordinates for future patch

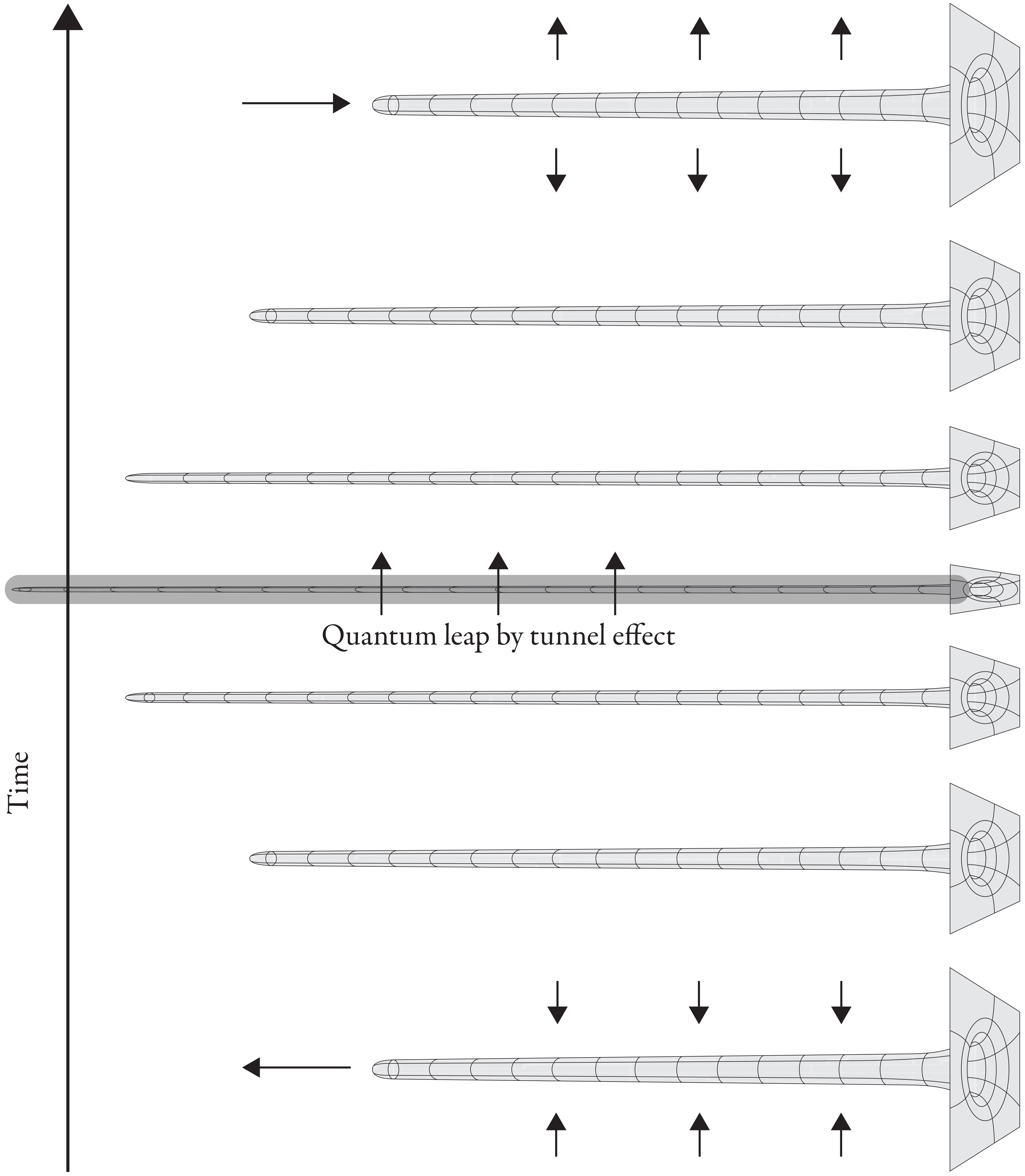
$$ds^2 = -F(r)du^2 - 2dudr + r^2 d\Omega^2$$

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

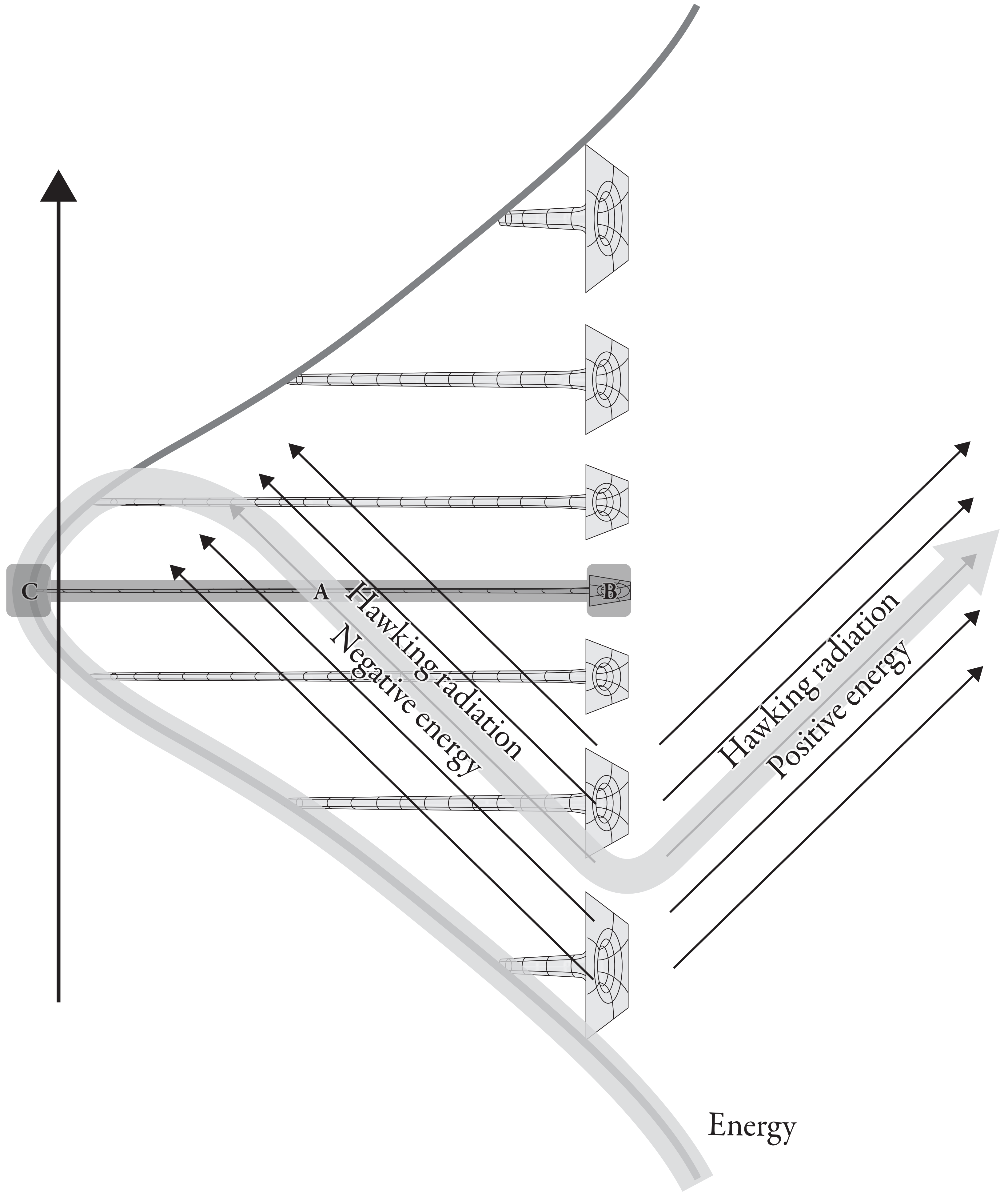
Overlap

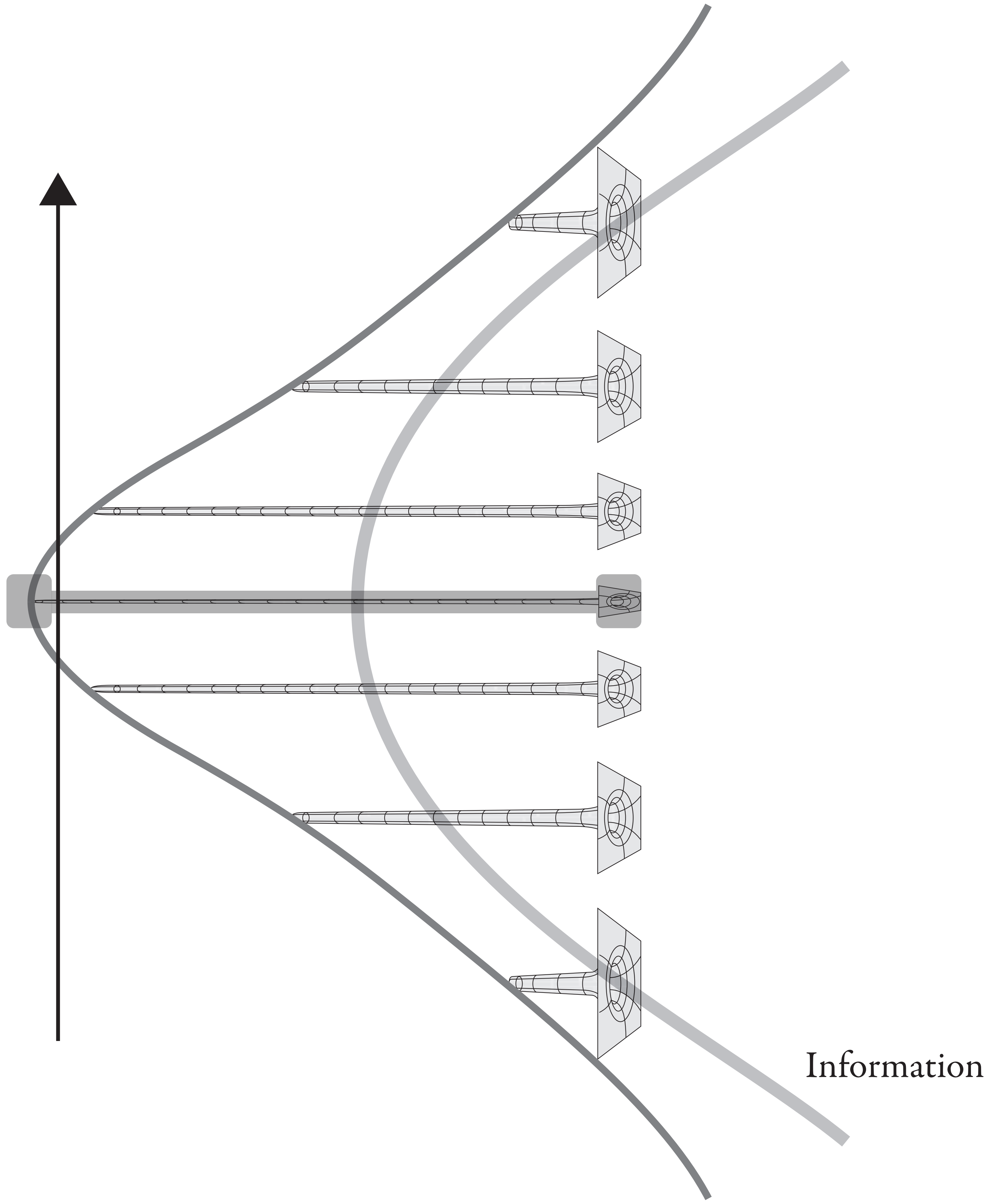
$$2r_*(r) = v + u \qquad dr_* = \frac{dr}{F(r)}$$

M Han, CR, F. Soltani 2023



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


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


Information

Transition probability

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

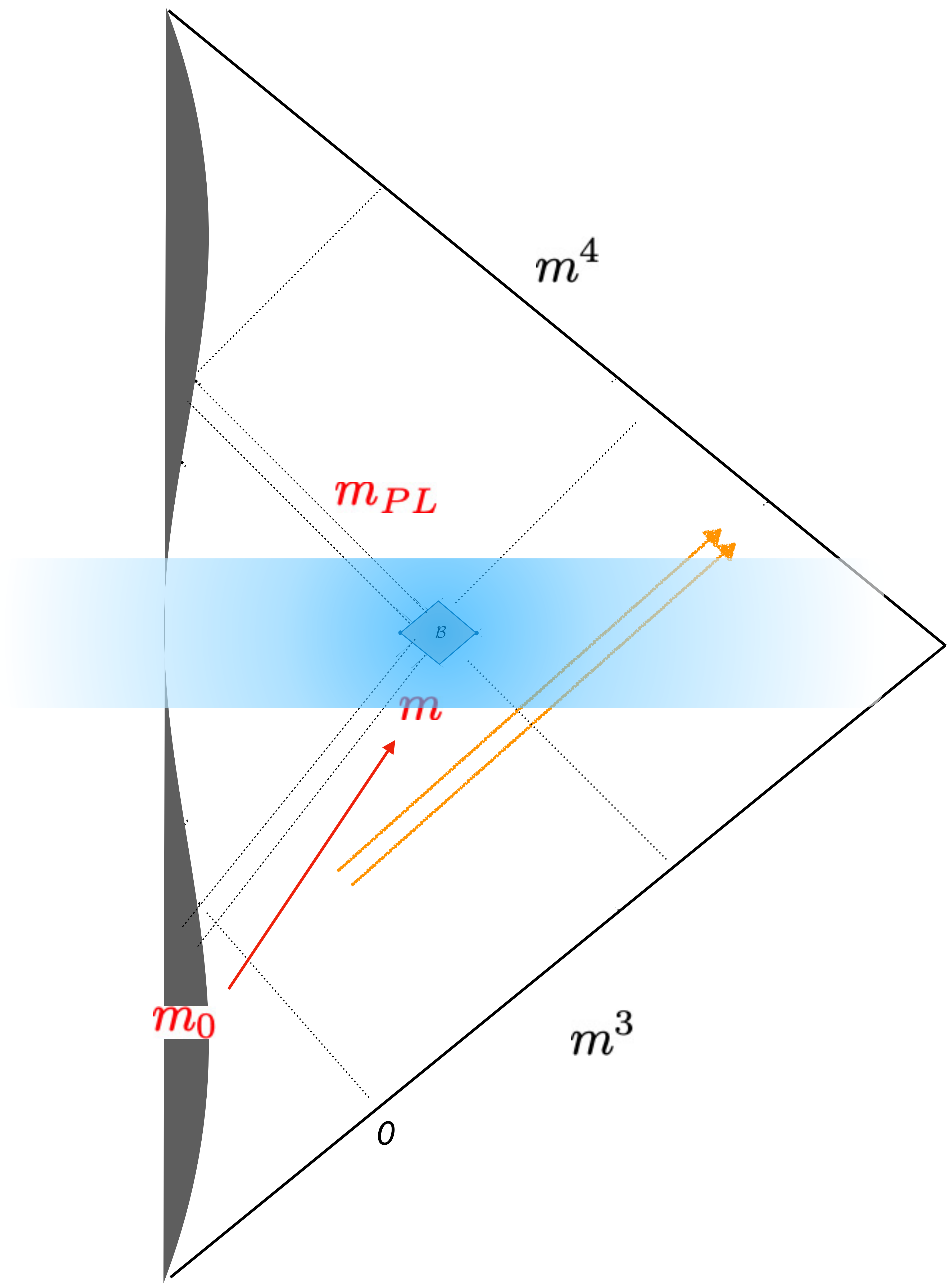
A quantum tunnelling effect

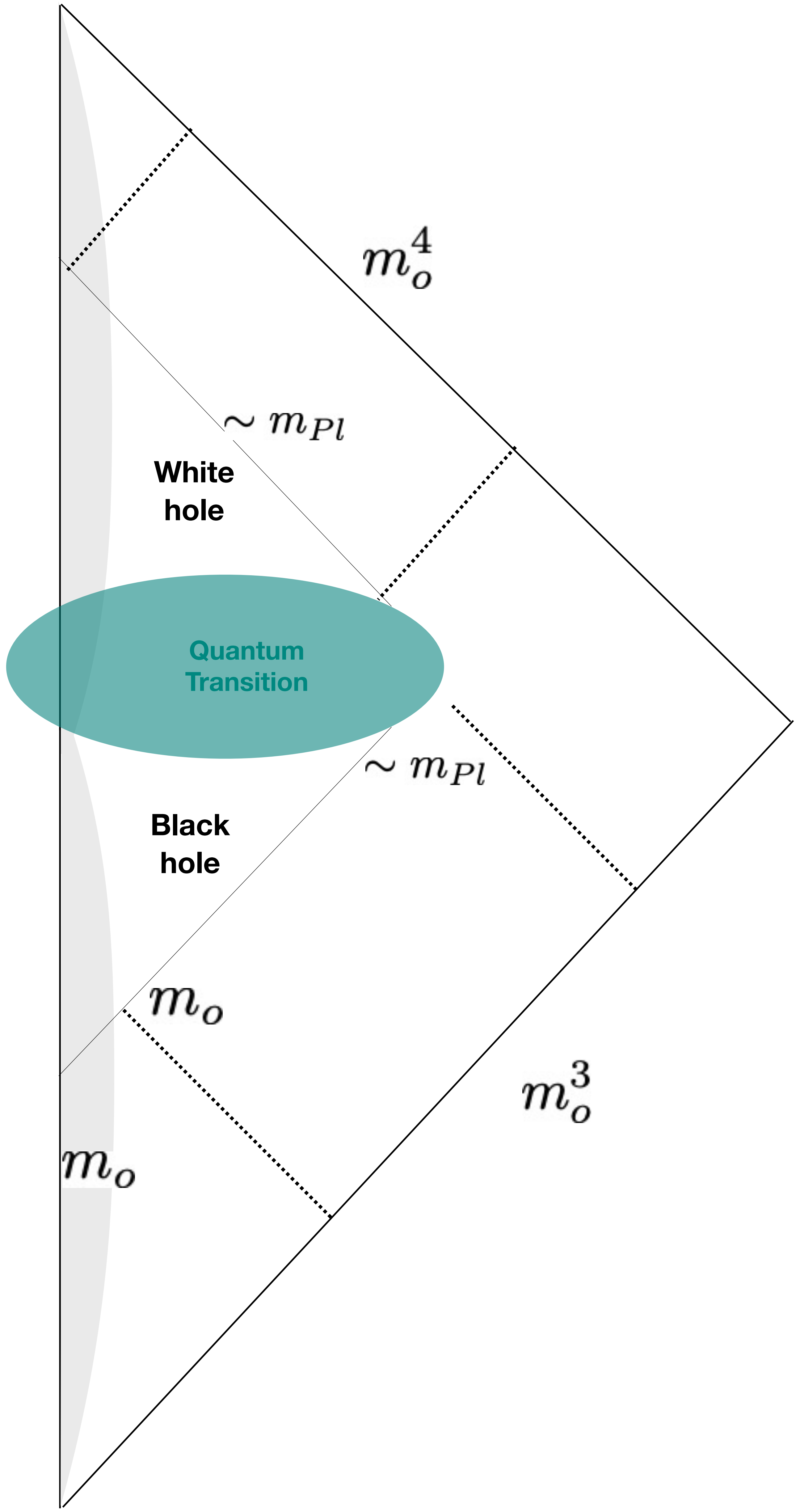
P Donà , H Haggard, CR, F Vidotto, arXives: 2402.09038

- 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



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.

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

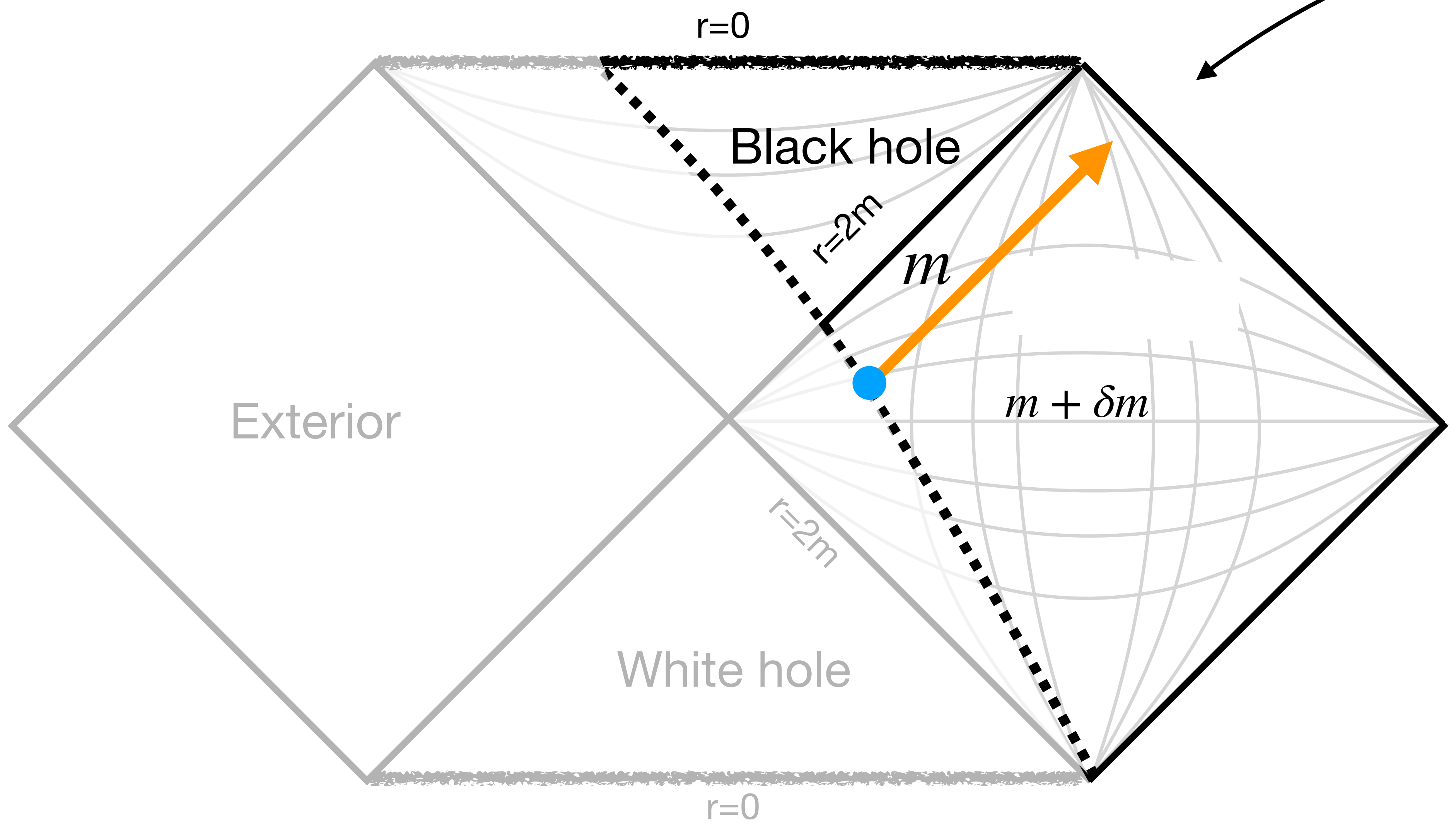
$$S = \frac{2\pi}{3} LT, \qquad E = \frac{1}{6} LT^2.$$

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

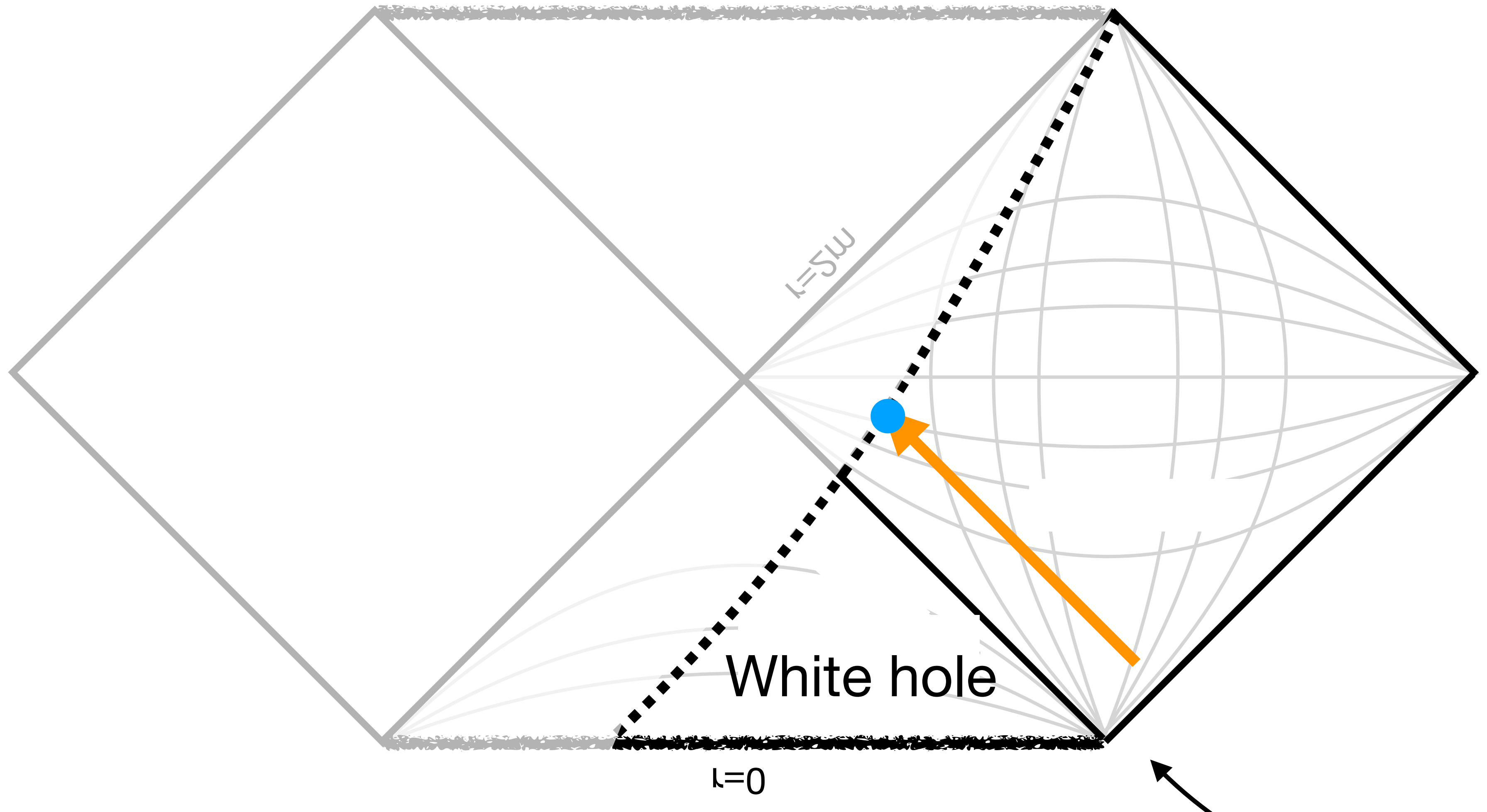
$$\tau_W \sim 6m^4$$

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

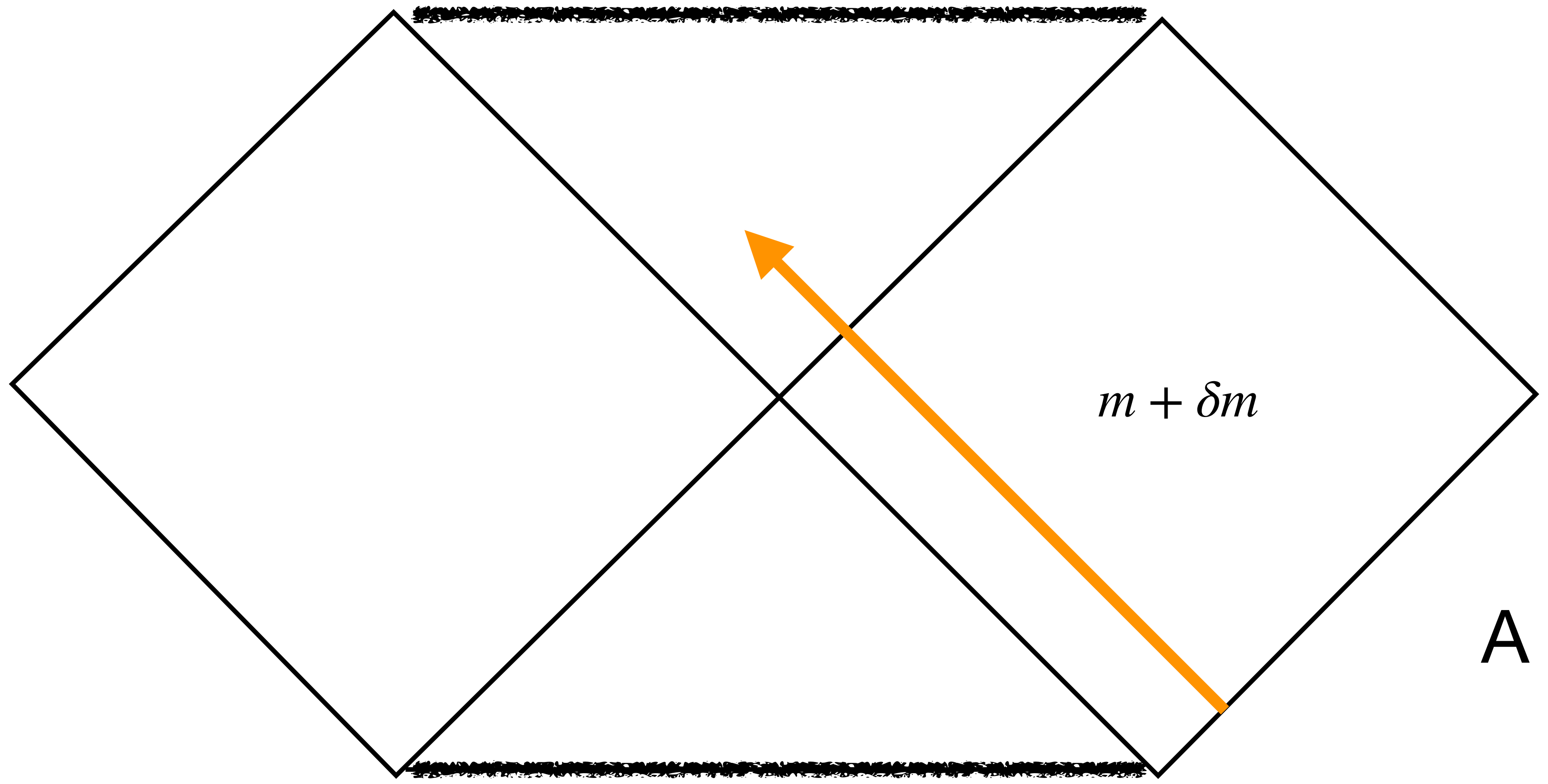
White holes are unstable



The energy pulse cannot
be too much in the future



The energy pulse cannot
be too much in the past

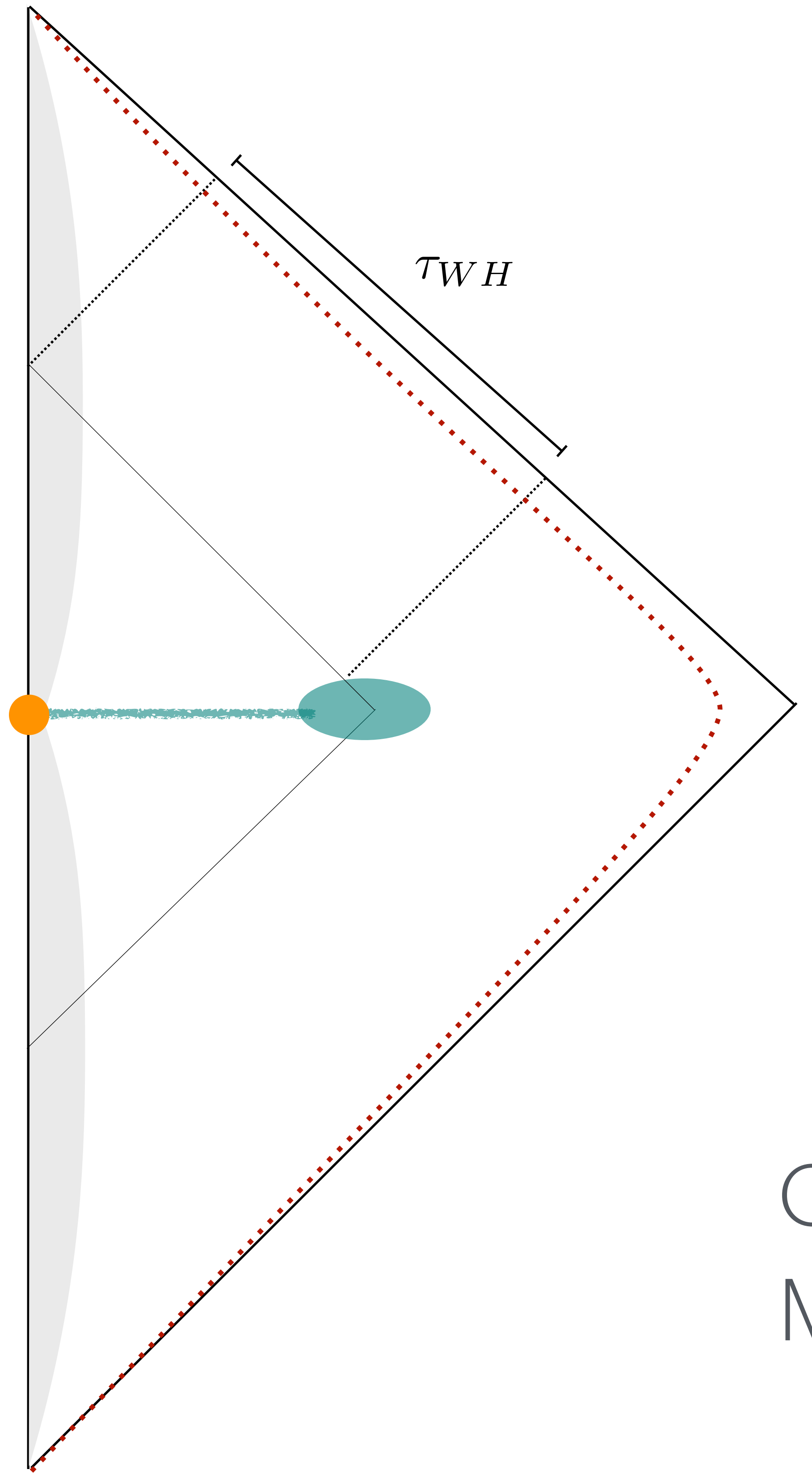


A white hole is unstable toward becoming a black hole

Are remnants stable?
They are stabilized by quantum gravity

Area gap = minimum
non vanishing mass

$$A_{min} = 4\gamma\sqrt{3}\pi\,\hbar G$$



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

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

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

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

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

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

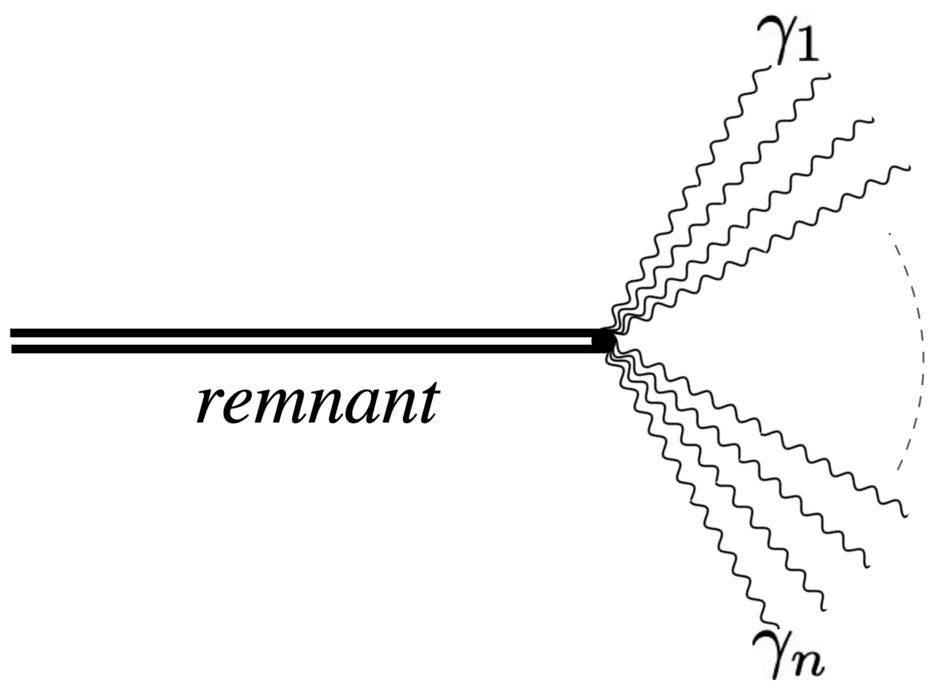
Vidotto, CR 2018.

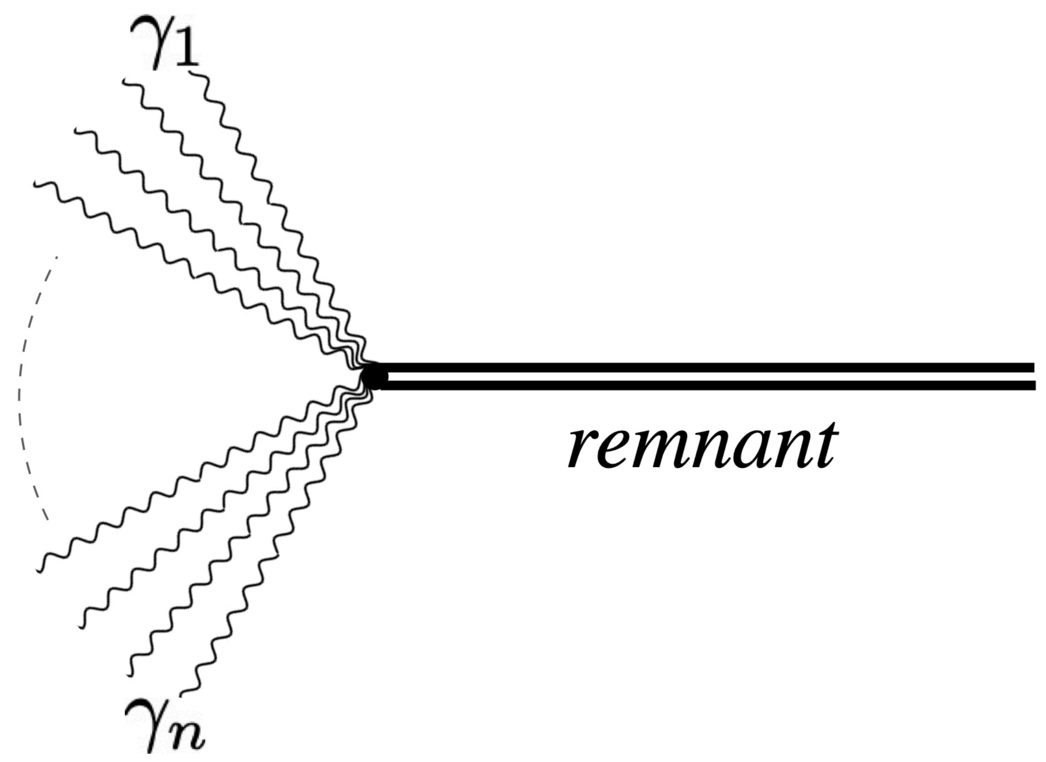
Quasi stable remnants of
Mass ~ 14μg

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?

Area gap = minimum
non vanishing mass

$$m = \sqrt{\frac{\sqrt{3}\gamma\hbar c}{4G}} = 14.3\sqrt{\gamma}\ \mu g$$

Quasi stable
remnants of
Mass ~ 10μg

Dark matter?

LQG suggest the existence of

a quasi-stable particle with mass ~ 14μg

which can interact gravitationally only