LQG suggest the existence of

a quasi-stable particle

with mass ~ 20μg

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

2) This particle can be detected

3) It can be originated by the complete evaporation of an old black hole

4) It is a natural candidate for Dark Matter

Lecture notes (review paper) in dropbox

https://rb.gy/q23joa

Also on the site of the Loop24 school

Planck stars, White Holes Remnants, and Planck-mass quasi-particles

The quantum gravity phase in black holes' evolution and its manifestations

DRAFT

Carlo Rovelli[bcde], Farshid Soltani[a], Francesca Vidotto[ab]

[a] *Physics Department, Western Ontario University, 1151 Richmond St London N6A5B7, Canada*
[b] *Department of Philosophy and the Rotman Institute of Philosophy, Western Ontario University.*
[c] *Aix-Marseille University, Université de Toulon, CPT-CNRS, F-13288 Marseille, France.*
[d] *Perimeter Institute, 31 Caroline Street N, Waterloo ON, N2L2Y5, Canada and*
[e] *Santa Fe Institute, 1399 Hyde Park Road Santa Fe, New Mexico 87501, USA*

We review recent developments in the exploration of quantum gravity aspects of black hole physics.

CONTENTS

I. INTRODUCTION

Quantum gravity is a theory with a mass scale: $m_P = \sqrt{\hbar c/G}$, a fraction of microgram. This is very small in astrophysics and very large in high-energy physics. It is reasonable to study the possibility that the spectrum of the theory could include a stable or semi-stable non-perturbative object at this scale: a Planck-mass quasi-particle. Recent developments in classical general relativity and in loop quantum gravity bring credence to this possibility.

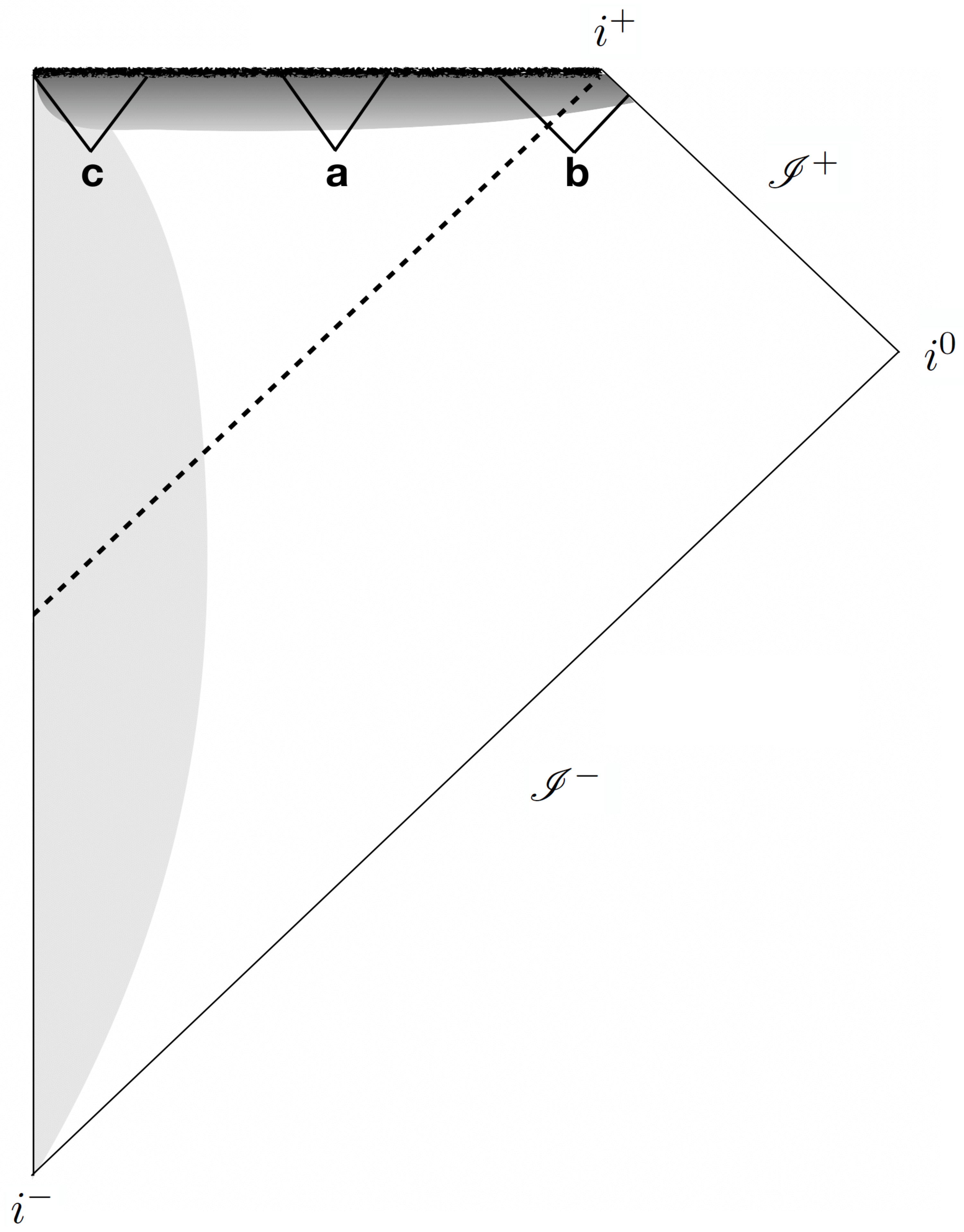
These developments regard the dynamics of black holes. We expect black holes to evolve into spacetime regions dominated by strong quantum gravity effects. These regions have not been much explored in the traditional literature on quantum effects on black holes, often focused on what happens before the hole reaches these regions, for instance at Page time. But a number of recent lines of research have addressed these regions revealing a plausible physical scenario, which we detail in the next section, for the full evolution of a black hole [1].

Several ingredients have contributed to this scenario. These include a new solution of the Einstein equations [2] showing that a trapping horizon can evolve into an anti-trapping one, a better understanding of the interior of white holes and black holes, and numerous applications of a variety of Loop Quantum Gravity techniques – canonical, covariant, and numerical– to describe the genuine non-perturbative regions.

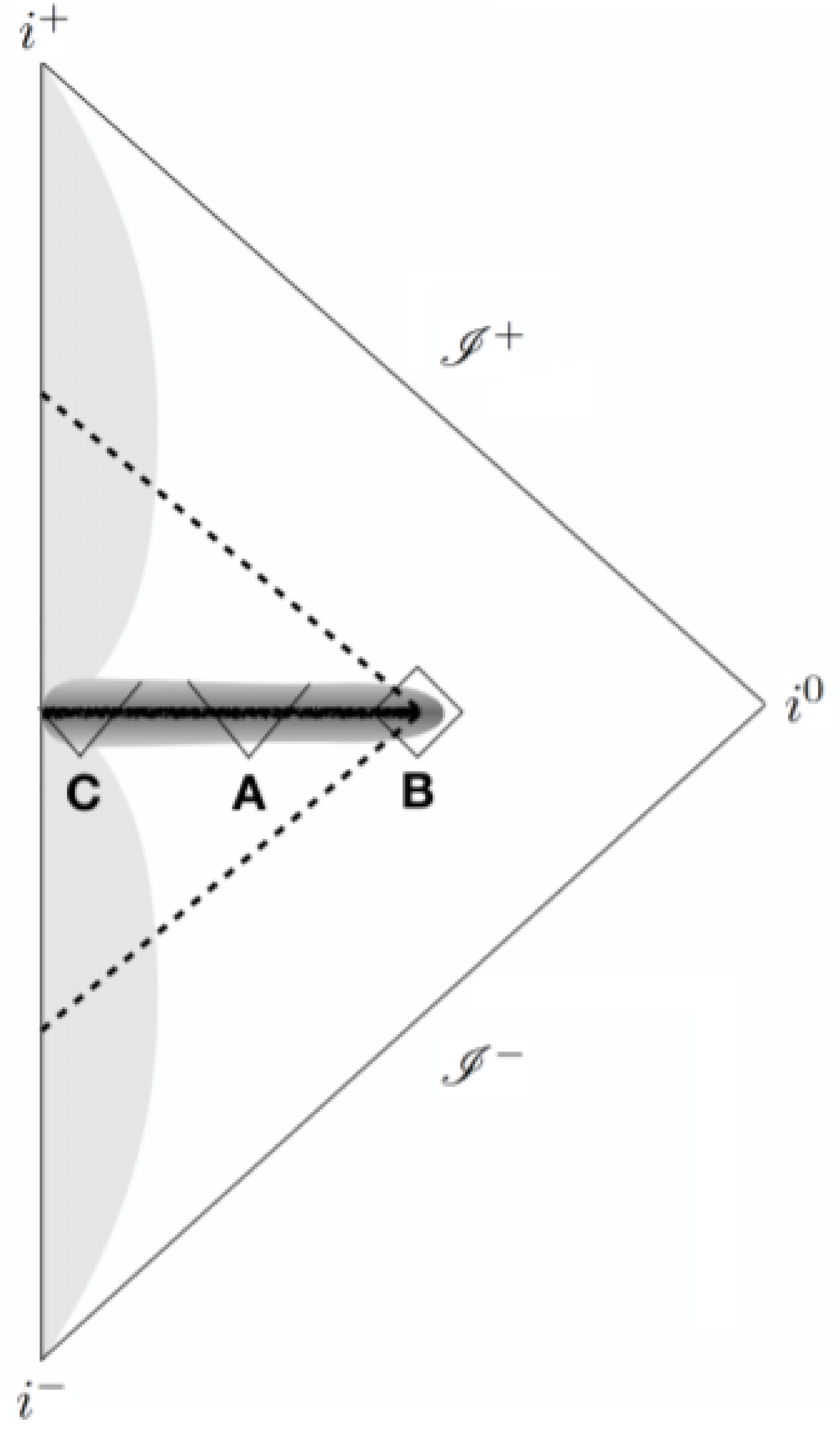
Three aspects of this scenario are particularly appealing. It provides a candidate for dark matter that does not require any new physical hypothesis (such as new fields, particles, or modifications of the field equations): just general relativity and its possible quantum properties [3]. (On the idea that primordial black holes could play a key role for dark matter, see also [4, 5].) It offers a natural solution to the black hole information 'paradox'. It is in principle, and perhaps even in practice, directly testable: Planck-mass quasi-particle may be [6].

The scenario includes distinct quantum phenomena happening in different spacetime regions. It includes dissipative as well as non-dissipative aspects. Its analysis employs different approximations and truncations for treating these different phenomena. Because of this complexity, it can only be addressed 'à la Fermi', estimating the relevance and the import of the various physical effects, rather than within a single mathematical-physics idealization. This complexity motivates the present review paper, which brings together the various ingredients of this scenario, scattered in the literature.

We start with a quick sketch of the scenario (Section I A) and an analysis of the regions where classical GR is unreliable (Section I B). Then we break the presentation into two parts: a first part (Section II) where we discuss the non dissipative aspects of the global dynamics of a



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

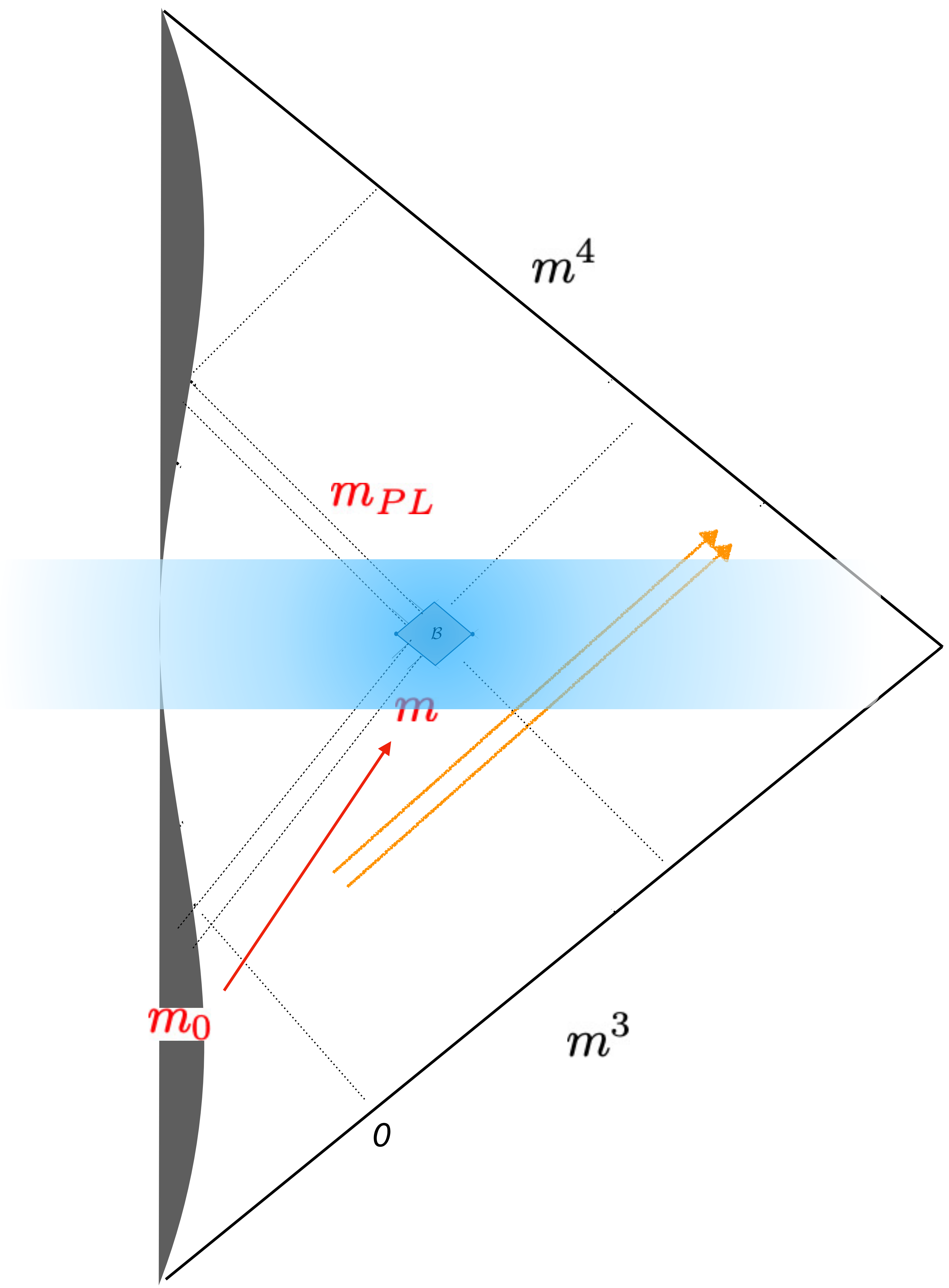
E. Bianchi, M. Christodoulou, F. D'Ambrosio, H. M. Haggard, CR, 2018

Lewandowski, Ma, Yang, Zhang, 2023

Husain, Kelly, Santacruz, Wilson-Ewing, 2022

A Rignon-Bret, CR, 2021

M Han, CR, F. Soltani 2023



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

Good coordinates for past patch

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

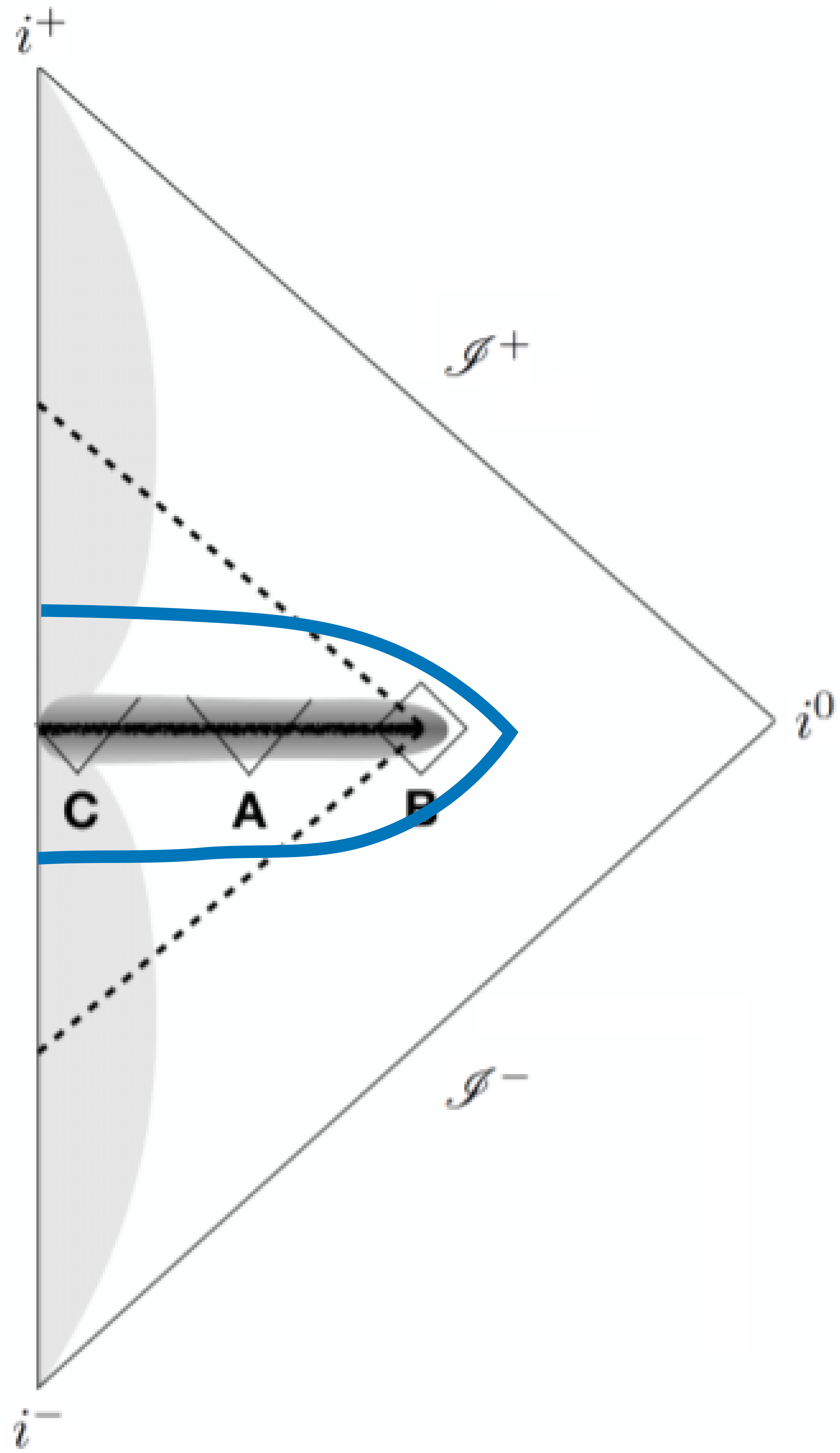
Good coordinates for future patch

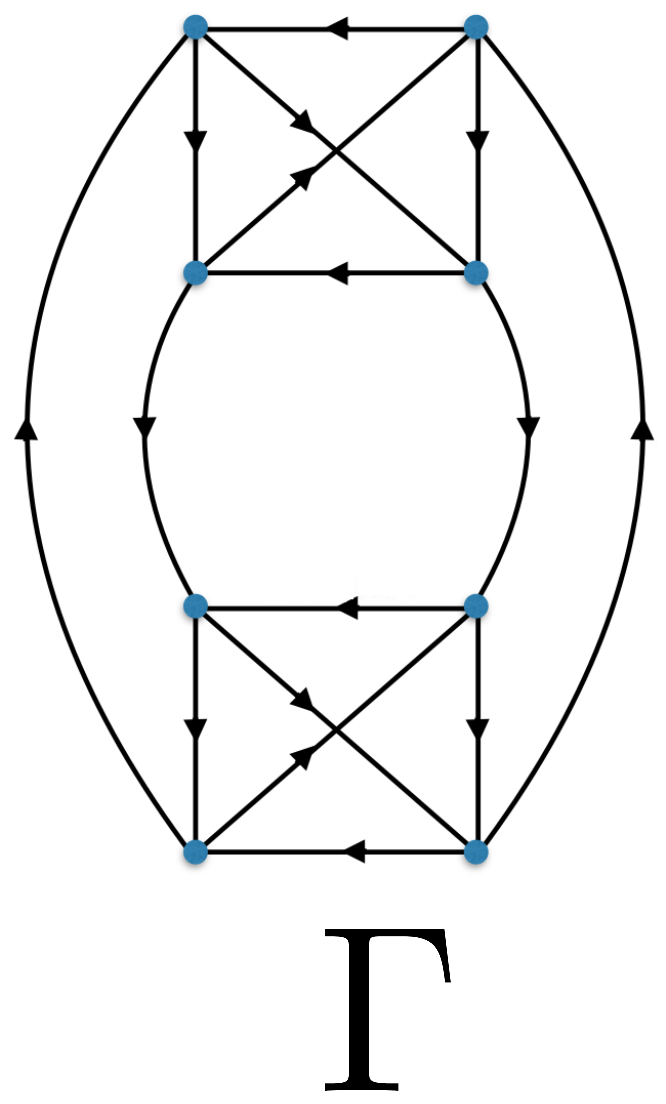
$$ds^2 = -F(r)du^2 - 2dudr + r^2 d\Omega^2$$

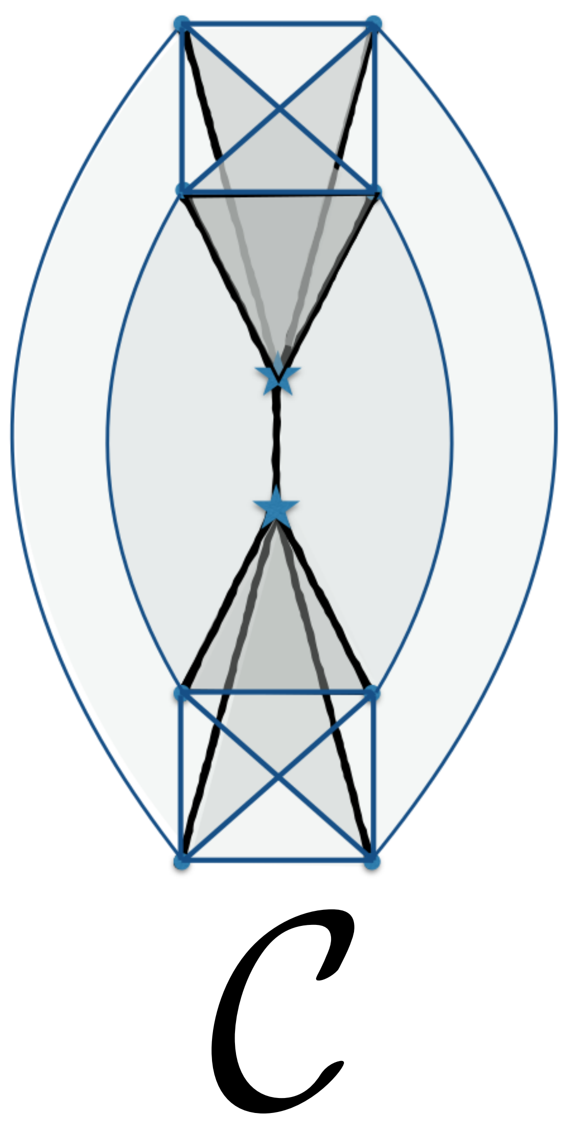
$$F(r) = 1 - \frac{2m}{r} + \frac{Am^2}{r^4}$$

Overlap

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







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

F. D'Ambrosio, M. Christodoulou, P. Martin-Dussaud, CR, F. Soltani, 2020.

F. Soltani, CR, P. Martin-Dussaud, 2021

F. D'Ambrosio, M. Christodoulou, C. Theophilis, 2023

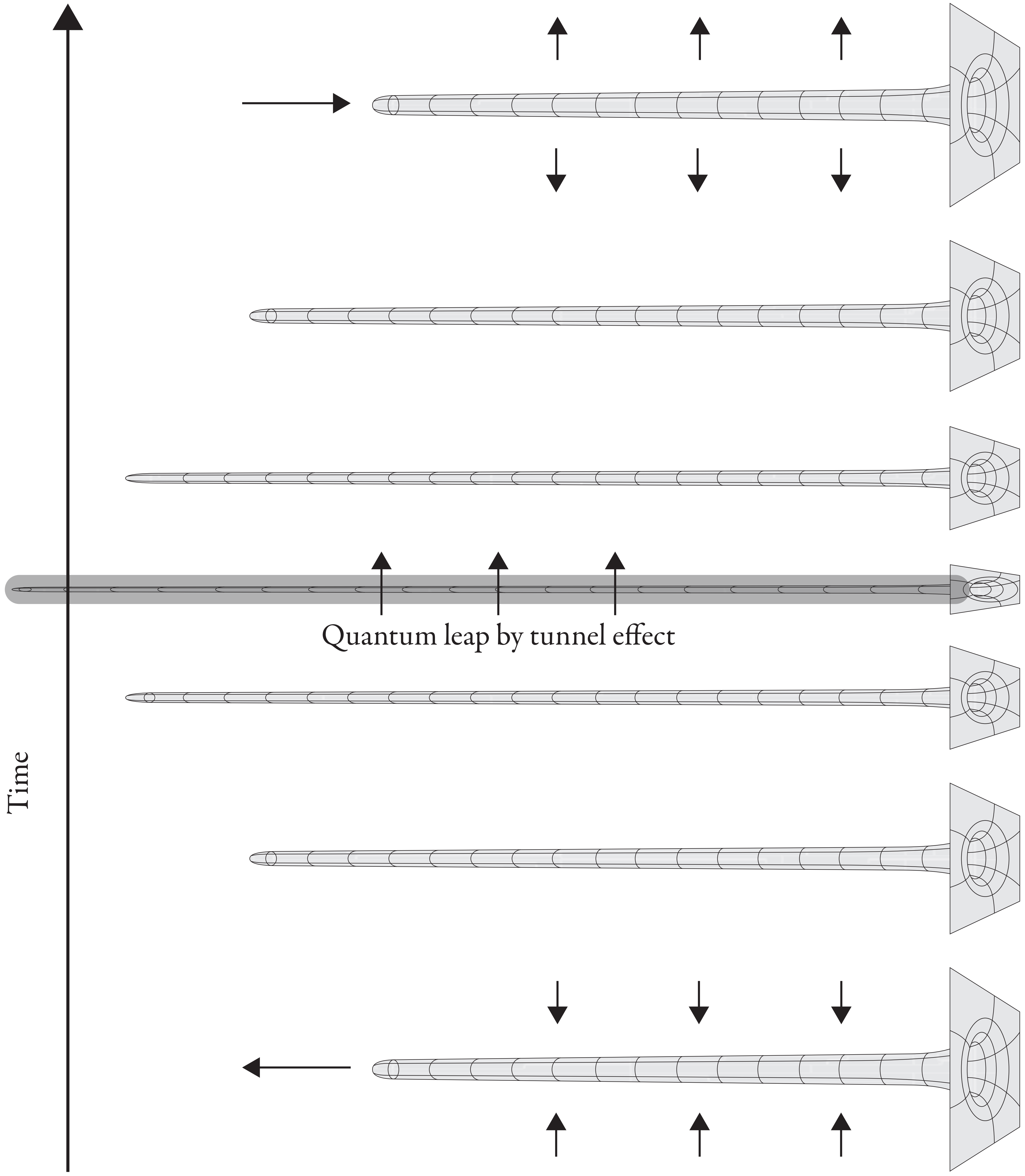
M. Han, D. Qu, C. Zhang, 2024

[Hongguan Liu lectures]

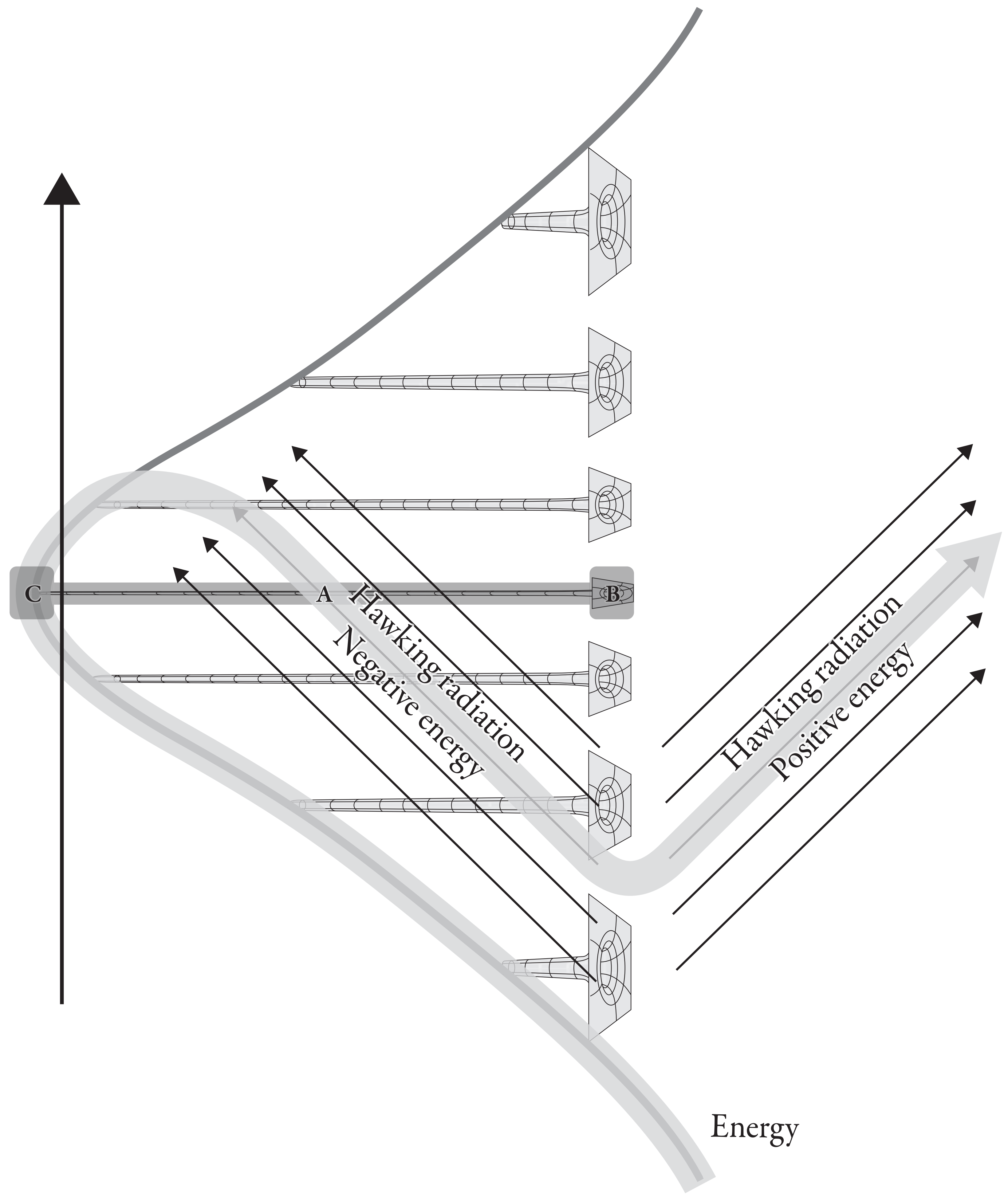
[Pietro Donà, Hal Haggard talks]

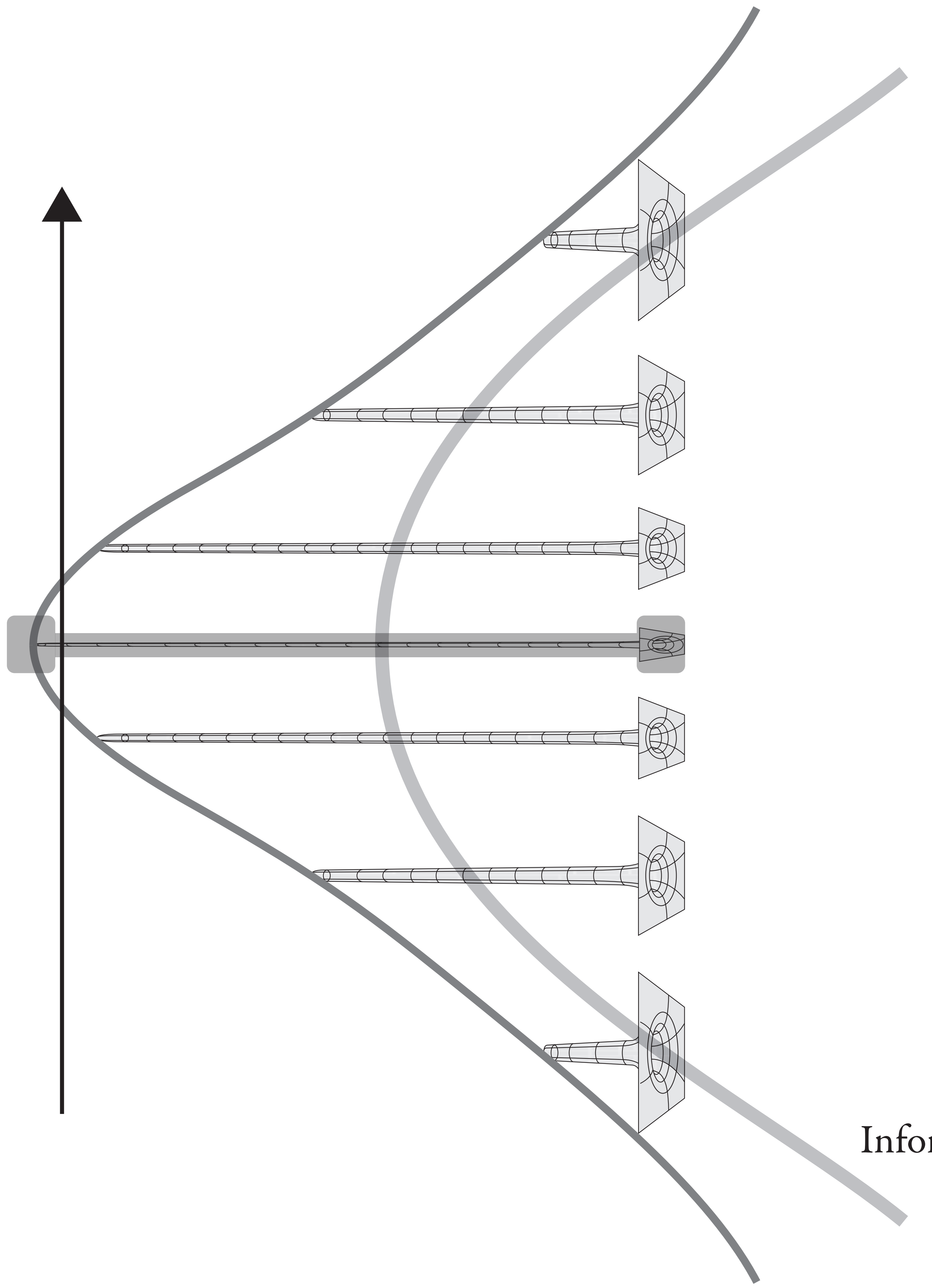
A quantum tunnelling of geometry

P Donà , H Haggard, CR, F Vidotto, 2024



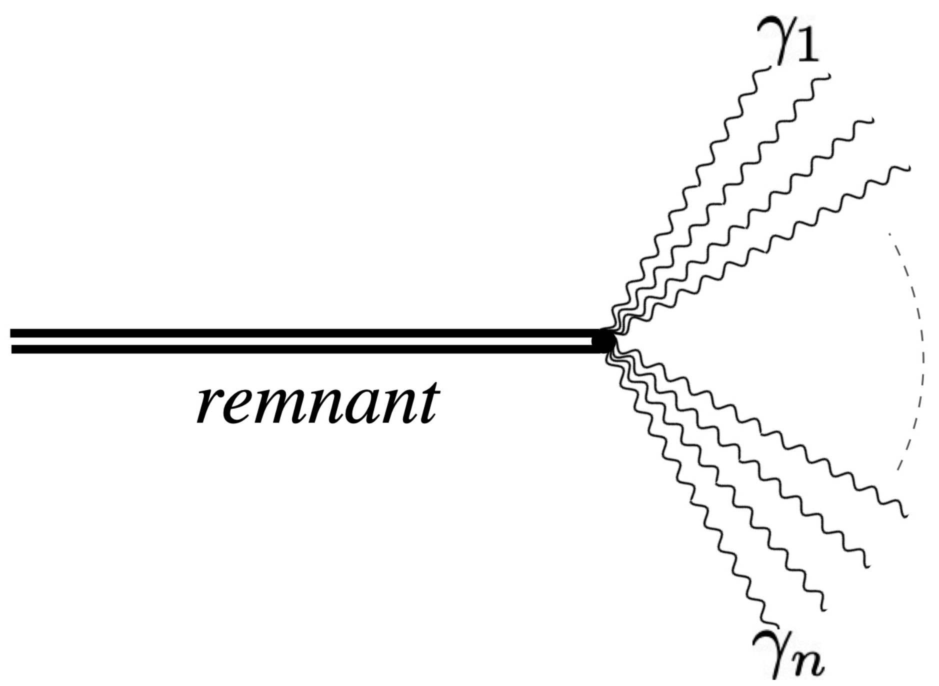
M Christodoulou, CR, How big is a black hole? PRD 2015.

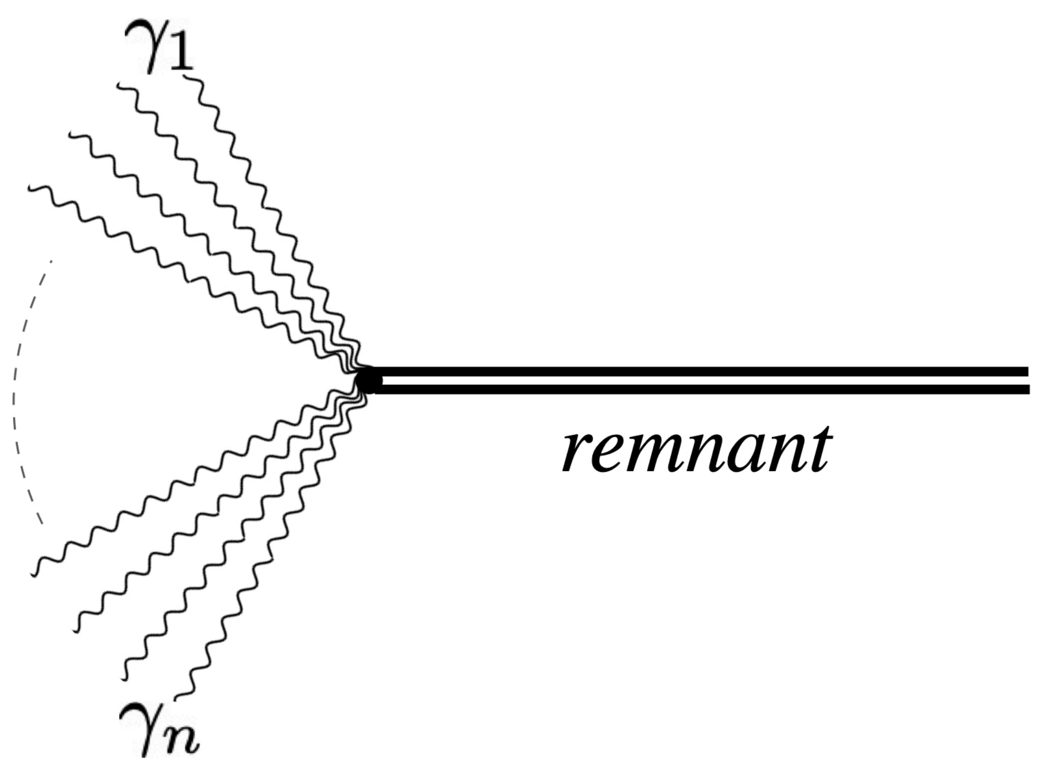

C
A
B
Hawking radiation
Negative energy
Hawking radiation
Positive energy
Energy


Information

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

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





This also solve the old problem:

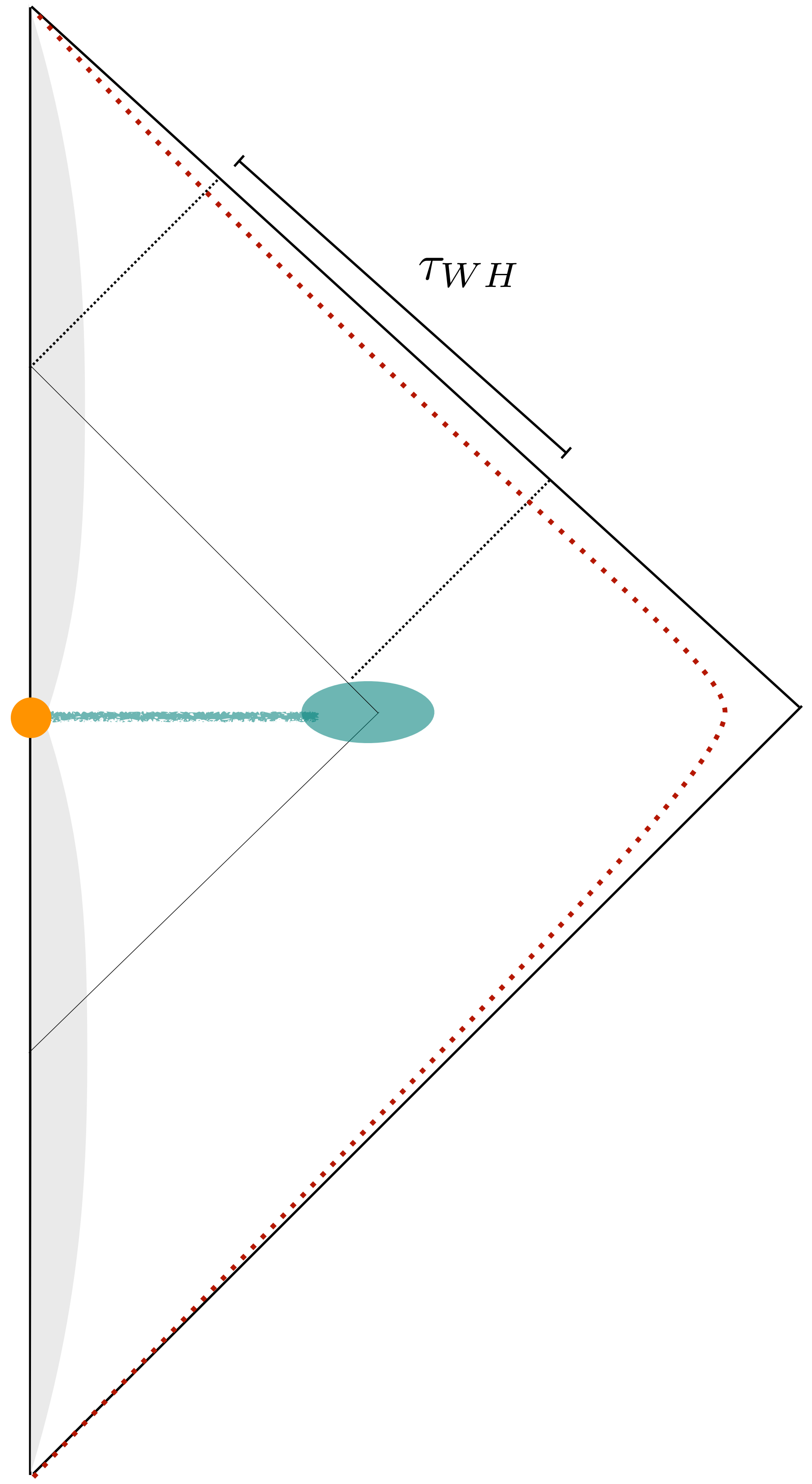
Why WH are not easily produced?

Are remnants stable?

They are stabilized by quantum gravity

Area gap = minimum non vanishing mass

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



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

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

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

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

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

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

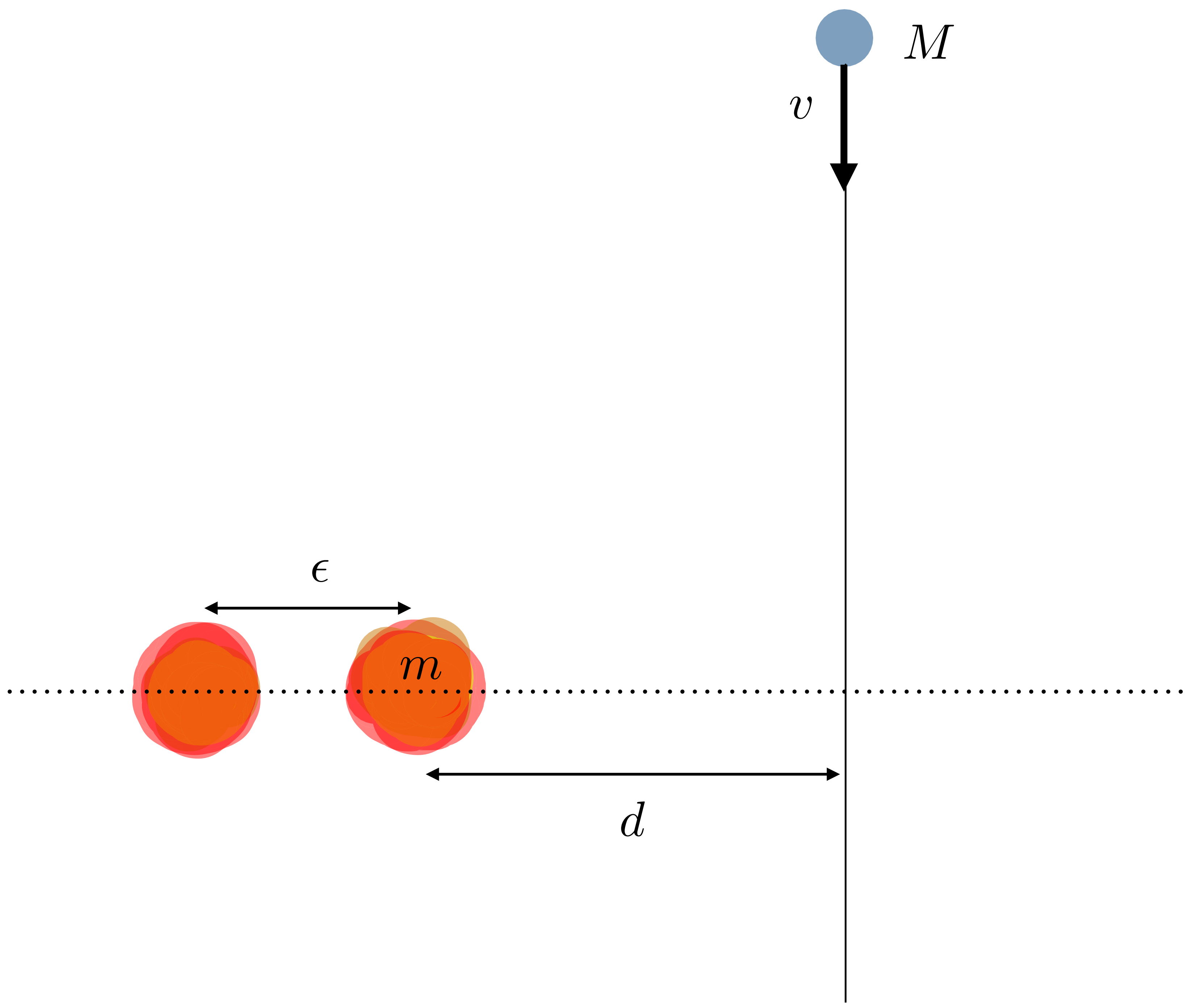
Vidotto, CR, 2018

Quasi stable remnants of

Mass ~ 20μg

Dark matter?

Direct detection



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

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

2) This particle can be detected

3) It can be originated by the complete evaporation of an old black hole

4) It is a natural candidate for Dark Matter

LQG suggest the existence of

a quasi-stable particle

with mass ~ 20μg